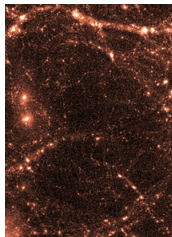
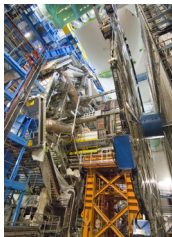
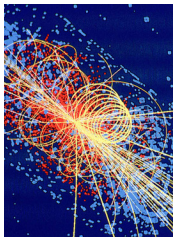
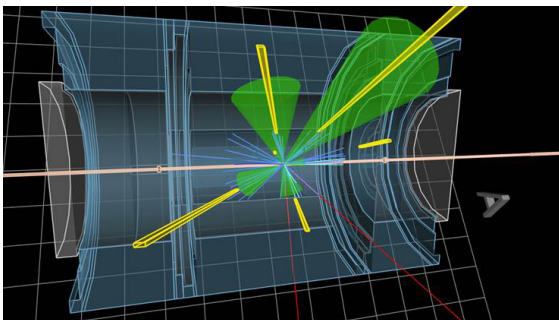


HEP

HIGH ENERGY PHYSICS



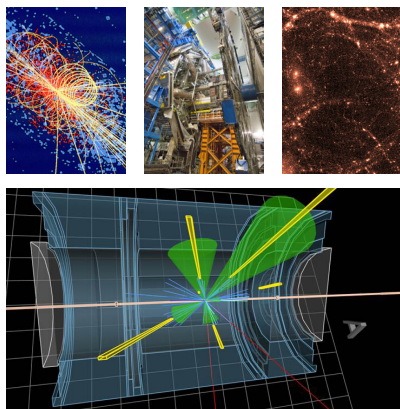
EXASCALE REQUIREMENTS REVIEW



An Office of Science review sponsored jointly by
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On the cover:

Top left: Protons collide at 14 TeV in this simulation from CMS, producing four muons. Lines denote other particles, and energy deposited is shown in blue.

Top center: The ATLAS detector under construction at CERN in 2007.

Top right: Zoomed-in image of a region of the universe in the trillion-particle 'Outer Rim' simulation.

Bottom: Visualization of a simulated collision event in the ATLAS detector.

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HIGH ENERGY PHYSICS

U.S. DEPARTMENT OF ENERGY

An Office of Science review sponsored jointly by
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*White Papers

§Case Studies

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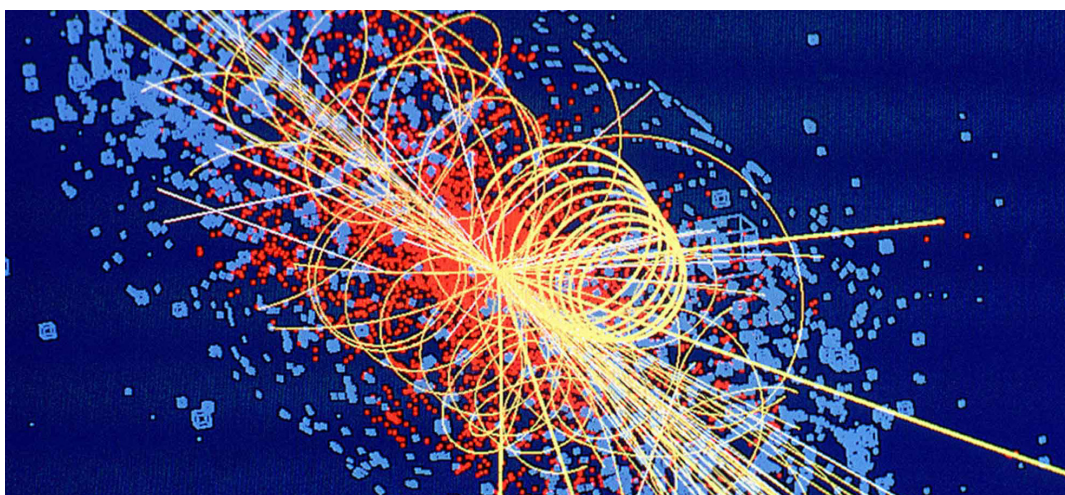
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EXECUTIVE SUMMARY

Abstract

The U.S. Department of Energy (DOE) Office of Science (SC) Offices of High Energy Physics (HEP) and Advanced Scientific Computing Research (ASCR) convened a programmatic Exascale Requirements Review on June 10–12, 2015, in Bethesda, Maryland. This report summarizes the findings, results, and recommendations derived from that meeting. The high-level findings and observations are as follows.

- Larger, more capable computing and data facilities are needed to support HEP science goals in all three frontiers: Energy, Intensity, and Cosmic. The expected scale of the demand at the 2025 timescale is at least two orders of magnitude — and in some cases greater — than that available currently.
- The growth rate of data produced by simulations is overwhelming the current ability of both facilities and researchers to store and analyze it. Additional resources and new techniques for data analysis are urgently needed.
- Data rates and volumes from experimental facilities are also straining the current HEP infrastructure in its ability to store and analyze large and complex data volumes. Appropriately configured leadership-class facilities can play a transformational role in enabling scientific discovery from these datasets.
- A close integration of high-performance computing (HPC) simulation and data analysis will greatly aid in interpreting the results of HEP experiments. Such an integration will minimize data movement and facilitate interdependent workflows.
- Long-range planning between HEP and ASCR will be required to meet HEP's research needs. To best use ASCR HPC resources, the experimental HEP program needs (1) an established, long-term plan for access to ASCR computational and data resources, (2) the ability to map workflows to HPC resources, (3) the ability for ASCR facilities to accommodate workflows run by collaborations potentially comprising thousands of individual members, (4) to transition codes to the next-generation HPC platforms that will be available at ASCR facilities, (5) to build up and train a workforce capable of developing and using simulations and analysis to support HEP scientific research on next-generation systems.



Protons collide at 14 TeV in this simulation from CMS, producing four muons. Lines denote other particles, and energy deposited is shown in blue.

ES.1 High Energy Physics: Vision and Grand Challenges

High energy physics is entering a challenging and exciting period over the next decade with new insights into many of the fundamental mysteries of the Universe moving tantalizingly within reach. The discovery of a Higgs boson in 2012 was just the first of many anticipated discoveries as new Large Hadron Collider (LHC) runs are performed at greater energy and luminosity, giving rise to myriad questions: Are there many Higgs? Is supersymmetry correct? Are there new fundamental forces of nature yet to be discovered? Is there physics beyond the Standard Model, and if so, what form does it take? Next-generation experiments aim to solve the current mysteries of neutrino physics: What is the origin of neutrino masses and how are the masses ordered? Do neutrinos and antineutrinos oscillate differently? Are there additional neutrino types or interactions? Are neutrinos their own antiparticles? As cosmological surveys and dark matter experiments come online, a flood of new data will become available to help answer fundamental questions: What is dark matter? What is dark energy? What is the origin of primordial fluctuations?

The high energy physics community — both theoretical and experimental researchers — is actively seeking answers to these questions, and there is a strong anticipation and sense of excitement that we are on the threshold of paradigm-shifting discoveries. Success in these endeavors, however, requires many new tools of discovery. Forefront among them, as in so many scientific fields today, is a need to perform massive computations on an unprecedented scale and to collect, store, and analyze complex datasets at never-before-seen rates and volumes.

ES.2 Computing Needs/Requirements

The HEP community has historically leveraged HPC capabilities primarily to address theory and modeling tasks. Energy Frontier-related experimental efforts are now also beginning to employ HPC systems. The estimated computational needs for these experiments far exceed the expected HEP investment in computational hardware that will be required to execute the envisioned HEP science program by 2025. Thus, partnering with ASCR is essential to the scientific success of the HEP community.

The 2025 timeline will define a phase transition in terms of HEP data flows. Three new facilities will come online and the landscape will change dramatically. The high-luminosity LHC will be operating, producing data samples at unprecedented scales. Fermi National Accelerator Laboratory's (Fermilab's) flagship Deep Underground Neutrino Experiment (DUNE) will be operating, as will the next-generation dark energy survey experiment, the Large Synoptic Survey Telescope (LSST). Data sizes produced each year could be 200 times greater than what is being produced by today's operating experiments. In addition, these new experiments will each require a simulation program that dwarfs what we are doing today in order to take advantage of the expected improvement in statistical precision.

ES.3 Path Forward

One of the primary goals of computing within HEP will be to transition to HPC capability when appropriate. This will require success at a number of levels. Critical components of the HEP code base will have to be refactored to take advantage of HPC architectures. Equally importantly, the HPC environment will need to adapt to HEP use cases, including the adoption of “edge” services, networking modifications and optimizations, available storage cache at the facilities to optimize data transfer, and associated workflow management and diagnostic tools. Taking these steps will be essential to addressing escalating computing and data demands in the HEP community and, more precisely, to informing HEP scientific programs about computing opportunities and challenges in the future exascale environment.

1 INTRODUCTION

1.1 Goal of Exascale Reviews

On June 10–12, 2015, in Bethesda, Maryland, the DOE SC convened a programmatic Exascale Requirements Review that included leading researchers and program managers in high energy physics, scientific and HPC experts from ASCR facilities and scientific computing research areas, and DOE HEP and ASCR staff. The goal of the review was to discuss the needs of the HEP scientific community in the emerging exascale environment. This was the first in a series of DOE SC Exascale Science Requirements Reviews conducted by DOE ASCR HPC facilities to identify mission-critical computational science objectives in the 2020–2025 timeframe. The reviews are also aimed at ensuring that ASCR facilities will be able to meet SC needs through the specified timeframes. The review was co-organized by the HEP Forum for Computational Excellence (HEP-FCE).

1.2 Meeting Structure, Report Preparation, and Report Organization

The review began with a series of talks discussing the HEP science drivers, focusing on the scientific goals over the next decade and how exascale computing would play a role in achieving them. Key topics included a deeper understanding of the properties of the Higgs boson and its implications for the fundamental laws of nature via collider experiments (HEP’s Energy Frontier); the construction of a new scientific facility at Fermilab that will host an international effort to understand the neutrino sector with unprecedented precision (Intensity Frontier); and large-scale sky surveys to investigate the nature of dark energy and dark matter, the neutrino mass sum, and the origin of primordial fluctuations (Cosmic Frontier).

Following the scientific overview, the computational use cases were divided into two areas: *compute-intensive*, referring to the use of HPC resources in accelerator modeling, lattice quantum chromodynamics (QCD), and computational cosmology; and *data-intensive*, referring to the use of HPC, as well as other computational resources (e.g., cloud computing), to tackle computational tasks related to large-scale data streams arising from experiments, observations, and HPC simulations. The use of HPC resources is well established in the compute-intensive arena, whereas the data-intensive set of use cases is an emerging application for HPC systems. The evolution of the above computational streams, and their interaction, will function as an important driver for a future exascale environment that encompasses elements of computing, data transfer, and data storage. For this reason, the review participants not only discussed the computing requirements, but also articulated how the entire computational fabric (e.g., networking, data movement and storage, cybersecurity) needs to evolve in order to best meet HEP requirements. All of the HEP facilities plan enhancements that will significantly increase the data volume, velocity, and data complexity, as well as lead to an increased demand for much-improved modeling and simulation of scientific processes. A common concern related to these plans is whether the current scientific computing and data infrastructure will be able to handle the impending demand for computational resources.

Review participants later assembled into breakout sessions to discuss the key issues associated with the demands imposed on compute-intensive and data-intensive computing resources. These discussions amplified the points made in a series of white papers and case studies (Appendices C and D) prepared by the HEP community in advance of this review.

The review provided a rare opportunity for experts from all of the ASCR facilities and ASCR research and development (R&D) programs and the HEP scientists to interact as a community and learn about each other’s expertise, the challenges faced, and the exciting opportunities made possible by the exascale computing environment. The review generated the following specific findings, which are detailed in the body of this report.

- Compute-intensive applications in accelerator modeling, lattice QCD, and computational cosmology continue to remain a critical need for HEP, and their requirements are expected to escalate. These groups have the scientific needs and the expertise to use next-generation HPC systems at extreme scale.
- HEP is expanding its range of HPC expertise to data-intensive use cases. The expansion is driven by large data streams from simulations and from experiments. The HEP experimental software stack, however, is currently not well-suited to run on HPC systems and will need to be significantly modified to use these resources more effectively.
- A strong partnership between ASCR and HEP is necessary to optimize systems design for the exascale environment, taking into account the range of requirements set by the compute-intensive, as well as the data-intensive, applications.
- Long-range planning of computational resources is of paramount importance to HEP programs. Stability of ASCR systems and services (which are typically allocated annually) must align with HEP timescales to allow for proper planning and to optimize design and use of ASCR resources for HEP science campaigns.
- In many ways, the current ASCR and HEP computing facilities are complementary: ASCR resources are more focused toward compute-intensive applications, while HEP facilities are more oriented toward data storage, high-throughput computing (HTC) (the grid), and complex scientific workflows. As the two interact more closely in a future driven by mission needs, it is important that they evolve in a coordinated and mutually beneficial fashion.
- Effective uniformity of the computing environment across the ASCR facilities would be very helpful to the user community and important to simplifying engagement with HEP experimental workflows. A federated authentication/cybersecurity model would be very desirable.
- As part of establishing useful partnerships, it was considered desirable to have ASCR staff partially embedded in HEP science teams.
- To enhance opportunities for establishing long-term partnerships across the ASCR and HEP programs, a pilot ASCR/HEP institute was suggested to foster long-term collaborations that develop capabilities benefiting both programs.

As a broader message, participants agreed that a mission-oriented ASCR/HEP partnership for long-range activities should be initiated.

Prior to the meeting, a number of white papers and case studies were collected that describe, in broad terms, the current computational activities across the HEP science spectrum (white papers) and then detail specific examples (case studies) to provide concrete data in a number of representative applications. The case studies cover both compute-intensive and data-intensive examples and vary in size from “mid-scale” to “extreme-scale” applications (by this terminology, we mean the distinction between small [mid-scale] and large [extreme scale] computational footprints on facility-sized computing platforms). Both the white papers and the case studies project needs in their areas on the 2020–2025 timescale.

Following the review, the organizing and steering committees prepared this detailed report, which describes the HEP community’s vision and grand challenges (Section 2), HEP computing needs and requirements (Section 3), and the path forward for HEP and ASCR. The appendices contain meeting materials, including a list of the HEP Exascale Requirements Review organizers and participants (Appendix A), the meeting agenda (Appendix B), and the white papers and case studies prepared in advance of the review and presented in the format submitted by the community (Appendices C and D).

2 HIGH ENERGY PHYSICS: VISION AND GRAND CHALLENGES

Particle physics is the study of both the very small and the very large, with the underlying goal to understand matter and energy at a fundamental level. In the realm of the very small — at the highest energies probed by accelerator experiments — the current particle physics Standard Model does a remarkable job of describing the physical world we live in. But because it is not complete, it also points to new directions in which exciting progress can be made with experiments operating at new energy, precision, and data-collection thresholds.

On the largest scales, the expanding universe connects particle physics to cosmology, allowing fundamental physics to be probed using the universe as a laboratory, with telescopes as the analogs of detectors in accelerator experiments. By the very nature and scale of these activities, most of the exploration of nature in high energy physics is, by definition, “Big Science.” The tools required to explore both the quarks and the cosmos are, at the same time, massive, yet exquisite in the precision achieved by the eventual measurements.

2.1 HEP Vision

Over the past few years, the entire U.S. HEP community came together to embark on an extensive planning exercise, “to develop an updated strategic plan for U.S. high energy physics that can be executed over a 10-year timescale, in the context of a 20-year global vision for the field” [1].

Through this process, a great number of exciting scientific opportunities were identified. Five intertwined science drivers for the field categorize the essence of these opportunities:

1. Use the Higgs boson as a new tool for discovery
2. Pursue the physics associated with neutrino mass
3. Identify the new physics of dark matter
4. Understand cosmic acceleration: dark energy and inflation
5. Explore the unknown: new particles, interactions, and physical principles

A report organized around these drivers — the P5 report — was produced detailing the path forward for HEP, in the United States and internationally, based on a realistic funding scenario [1]. (See also the white papers from the Snowmass 2013 Study [2], which provided important input into the P5 process.) Together, the HEP program and community pursue the science drivers identified in the P5 report — which are broadly categorized by the HEP categories of the Energy, Intensity, and Cosmic Frontiers — via experimental paths that are closely linked to technological advances and to progress in theory, modeling, and simulation; computing plays an essential role in all these aspects. Over the next decade, several new projects will be brought online that are potential game changers for HEP. These include the Cosmic Frontier projects LSST, Cosmic Microwave Background-Stage 4 (CMB-S4), and Dark Energy Spectroscopic Instrument (DESI); the Intensity Frontier projects DUNE and Muon-to-Electron Conversion Experiment (Mu2e); and Energy Frontier projects including the High-Luminosity LHC, among others. Results from any of these could profoundly alter our understanding of the world we live in.

2.2 Computing Ecosystem

Computing has always been — and continues to be — an integral and essential part of all activities in high energy physics, which is a data- and compute-intensive science. As the field of particle physics advances, computing must continue to evolve in order to satisfy the ever-increasing appetite of its researchers. For example, the volume of physics data from LHC experiments already stresses both the computing infrastructure and related computational expertise, and LHC operations in the next decade will likely result in order-of-magnitude increases in data volume and analysis complexity. The data needs associated with experiments exploring the cosmos will greatly expand as vast new surveys and high-throughput instruments come online. Cosmological computing is making significant progress in connecting fundamental physics with the structure and evolution of the Universe at the necessary level of detail. Lattice QCD provides the most precise values of heavy quark masses and the strong coupling constant, important for using Higgs boson decays at the LHC to test the Standard Model and probe new physics. Precision perturbative QCD and electroweak calculations are also beginning to use large-scale computational resources. The use of HPC is advancing full 3-D simulations of nearly all types of accelerators. The aim is to enable “virtual prototyping” of accelerator components on a much larger scale than is currently possible, potentially alleviating the need for costly hardware prototyping. All of these use cases will see significant enhancements and improvements in the future.

The HEP community fully recognizes the significance of exascale computing and is counting on its availability as an essential resource for the next set of major HEP projects early in the next decade. Broadly speaking, there are two types of HEP use cases relevant to the exascale computing environment. The first are *compute-intensive*, referring to the use of HPC systems in HEP applications such as lattice QCD, computational cosmology, and accelerator modeling. The second are *data-intensive*, referring to the use of HPC and other computational resources (e.g., analysis clusters, cloud resources, HTC systems) to manage and analyze data streams arising from experiments, observations, and HPC simulations. As the quality of simulation and modeling improves, and the associated datasets become more complex, a number of applications are emerging that merge the two categories by being simultaneously compute- and data-intensive.

Historically, the HEP theoretical community has been a long-standing customer of ASCR HPC resources, a relationship that has been further nurtured by partnerships initiated and continued by the Scientific Discovery through Advanced Computing (SciDAC) program. The situation with HEP experiments has been somewhat different; for the most part, experiments in all three HEP Frontiers have been responsible for handling their own computational needs, which have been mostly satisfied using distributed HTC (“the grid”).

The data from HEP experiments is growing at a rapid rate in terms of volume and throughput. It is now doubtful that experimental HEP will, as a field, own all of the computing resources it needs moving forward. Provisioning will be, at best, capable of meeting steady-state demands — the HEP community will need to find creative ways to meet peak demands. At the same time, to extract the best possible results from the observations, joint analysis with sophisticated theoretical predictions is needed; such analysis comes with its own set of large-scale data and computational needs.

The emerging exascale computing landscape offers many opportunities for HEP both in terms of compute-intensive HPC use cases, as well as the data-intensive use cases — for example, using HPC machinery (or what it evolves into) to perform data reconstruction and simulation tasks that have historically fallen within the domain of HTC systems in Energy Frontier experiments. The data-intensive community is increasingly becoming aware of the value of the HPC resources and expertise available. These use cases bring new challenges in the form of data movement and storage, data persistence, and integrating these technologies into the scientific workflows of the experiments.

A number of white papers and case studies are presented in Appendices C and D. The white papers provide broad coverage of HEP science and describe the science cases and modes of computational usage. The case studies present individual examples that provide more details about computational methodologies and requirements.

The aim of this Exascale Requirements Review is to understand the requirements that must be satisfied for ASCR facilities to be able to meet HEP needs through the 2020–2025 timeframe. The approach taken in this review is broad, covering the entire range of HEP activities and taking into account not just ASCR computing systems, but the broader environment of data storage and transfer, software evolution, and, the desired characteristics of the exascale environment in the face of HEP’s data-intensive needs, a relatively new requirement. In this broader context, the specific examples discussed above are connected to a number of important issues that are central to the review. These are:

- **Simulations:** The ability to effectively perform simulations is paramount for successful HEP science. As experimental and observational datasets grow — with ever-higher-resolution detectors — the demand for finer-grained, higher-precision simulation will continue to increase, requiring an increase in computational resources and the overall efficiency with which they are used.
- **Architectures:** In order to satisfy increasing computational demands and keep abreast of technological changes, the field needs to make better use of next-generation computing architectures. With increased concurrency at the nodal level and more complex memory and communication hierarchies, the complexity of software and systems will continue to increase, and such systems need to be better exploited and managed.
- **Data Access:** Distributed storage access and network reliability are essential for data-intensive distributed computing, a hallmark of HEP experimental practice and a growing issue for other applications. Emerging network capabilities and data access technologies improve researchers’ ability to optimally use resources independent of location. Treating networks as a resource that needs to be managed and planned for is an important area of future ASCR and HEP interaction. This will require close collaboration between HEP scientists and networking experts from the Energy Sciences Network (ESnet).
- **Training:** As a field, HEP, across all frontiers and applications, must continue to develop and maintain expertise and re-engineer frameworks, libraries, and physics codes to adapt to the emerging hardware landscape, as mentioned above. There is a large code base that needs to be re-factored and re-engineered, and there is a shortage of trained experts to do it. Training the next generation of HEP computational scientists and software developers requires urgent attention.

2.3 Scientific Fields of Exploration

It is convenient to subdivide the field of particle physics into three broad categories of scientific pursuit: the Energy Frontier, Intensity Frontier, and Cosmic Frontier. Taken as an ensemble, these three fields together address the five science drivers outlined in the P5 program and listed in Section 2.1. The computational needs do not divide as neatly as the scientific ones, however, and there are significant areas of overlap, as well as unique needs, in computational use cases and requirements across the three frontiers.

The Energy Frontier focuses on studying the fundamental constituents of matter and conditions in the very early universe by accelerating charged particles to very high energies in particle colliders; massive detectors are used to study the resulting collision events. The primary science direction in the Energy Frontier is the search for hints of physics beyond the Standard Model of particle physics and the investigation of the properties of the recently discovered Higgs boson [3, 4]. Intensity Frontier experiments use intense particle beams to generate rare events searched for by sensitive

detectors, characterized by well-understood backgrounds and background rejection methods. The primary arena of investigation in the Intensity Frontier is the neutrino sector, in particular neutrino masses and the neutrino mixing matrix [5]. Cosmic Frontier experiments detect particles from space to investigate the nature of cosmic acceleration, primordial fluctuations, and neutrino masses (via optical surveys and cosmic microwave background radiation measurements)[6] and search for dark matter candidates using direct and indirect detection strategies [7].

In addition to the three Frontiers, the HEP program also has an important enabling technology component in the areas of particle accelerators and advanced detectors and instrumentation. These areas also have significant computational requirements.

2.3.1 Energy Frontier

Located at the LHC in Geneva, Switzerland, are two general-purpose detectors that are designed to investigate a broad program of physics opportunities at the Energy Frontier. The two detectors are CMS (Compact Muon Solenoid) [8] and ATLAS (A Toroidal LHC Apparatus) [9] (Figure 1).

These detectors are designed to record the “interesting” high-energy proton-proton collisions and keep track of the position, momentum, energy, and charge of each of the resulting particles from the collision event. Utilizing this information, combined with simple conservation laws, scientists attempt to reconstruct what particles were generated by the collision and the physical processes that created it. By looking at ensembles of events, the hope is to gain a deeper insight into the fundamental laws of nature that operate at high energies and, therefore, to also gain improved understanding of the physics of the early universe.

LHC scientists pursue two different types of physics analyses: in the first, they collect precise measurements to improve the Standard Model parameters and identify small deviations, and in the second, they search for the unexpected, which could lead to completely new physical models and theories.

Over the next decade, LHC scientists will characterize the newly found Higgs boson to see whether it behaves as expected. There may be more hidden surprises as they explore the new energy regime. Signatures of supersymmetry, a well-developed theory that provides the “unification mechanism” required by the Standard Model, have not been observed so far [10]. Scientists on the LHC will be looking for the myriad super-particles that are predicted. Of course, at these higher energies, they may encounter surprises that they have not yet envisioned.

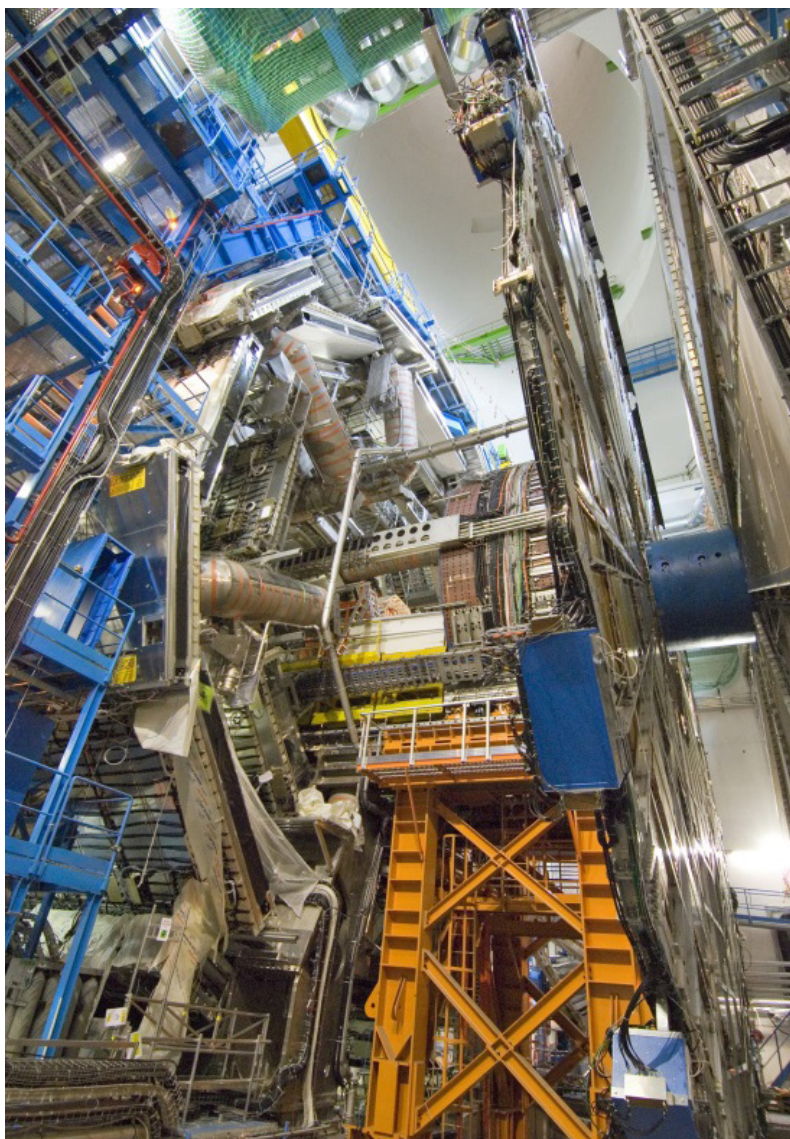


Figure 1. The ATLAS detector under construction at CERN in 2007.

White papers in this report relevant to the Energy Frontier include *C.3 Lattice QCD*, *C.4 HPC in HEP Theory* (compute-intensive), *C.5 Energy Frontier Experiments*, and *C.6 HEP Experiments: Data Movement and Storage* (data-intensive). The case studies are *D.6 Lattice QCD (MILC/USQCD)*, *D.7 Event Generation (Sherpa)*, and *D.8 Energy Frontier Experiment (ATLAS)*.

2.3.2 Intensity Frontier

The Intensity Frontier comprises the set of experiments that require intense particle beams and/or highly sensitive detectors to study rare processes with ever-greater precision and sensitivity. The neutrino sector is a primary area of interest in the Intensity Frontier. We now know that neutrinos exist in three types (lepton flavors) and that they undergo quantum oscillations (i.e., they change flavor as they propagate in space and time). The observed oscillations imply that neutrinos have masses (neutrinos of given flavors are different superpositions of the mass eigenstates). Many aspects of neutrino physics are puzzling, and the experimental picture is incomplete. Powerful new facilities are needed to move forward, addressing the following questions: What is the origin of neutrino mass? How are the masses ordered (referred to as the mass hierarchy problem)? What are the masses? Do neutrinos and antineutrinos oscillate differently? Are there additional neutrino types or interactions? Are neutrinos their own antiparticles? The answers to these questions can have profound consequences for understanding the current makeup of the universe and its evolution. A special facility at Fermilab [11] is being built to provide a high-flux beam necessary to perform this science. The flagship future program in the Intensity Frontier is DUNE, designed to study neutrino oscillations [12] (Figure 2). Although Intensity Frontier experiments have historically not been at the forefront of computation, computationally intensive lattice QCD calculations have been important for these experiments.

Other experiments in the Intensity Frontier include (1) Muon g-2 [13], which tracks the precession of muons in an external magnetic field in order to precisely measure the anomalous magnetic moment of the muon and look for evidence of new physics; (2) Mu2e [14], which will investigate the very rare — currently unobserved — process of muon-to-electron conversion; and (3) Belle II [15], which will investigate sources of CP violation and provide precision tests of the Standard Model at Japan’s SuperKEKB high-luminosity collider.

Intensity Frontier white papers are *C.3 Lattice QCD* (compute-intensive) and *C.8 Intensity Frontier Experiments* (data-intensive). The associated case study is *D.6 Lattice QCD (MILC/USQCD)*.

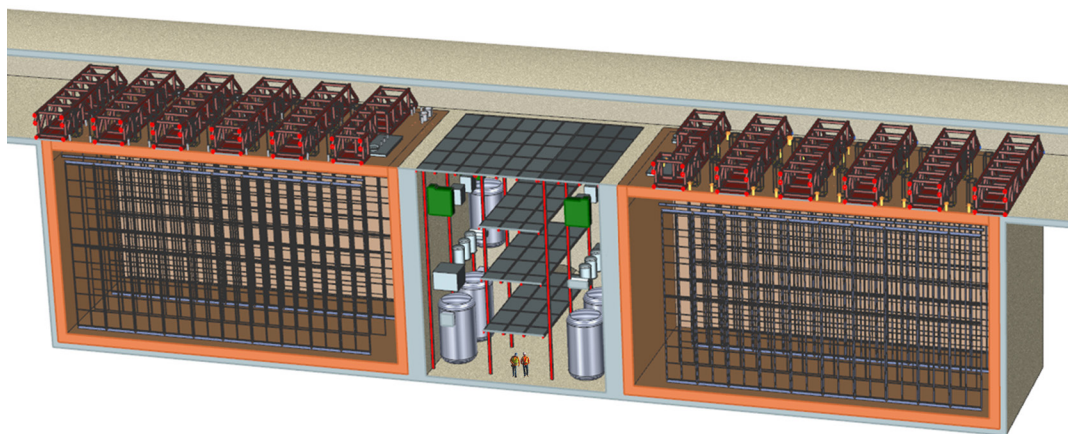


Figure 2. Engineering design study of 10-kiloton Cryogenic Detector Modules for DUNE.

2.3.3 Cosmic Frontier

Unlike the other two frontiers that are predominantly accelerator-based and study very small length scales, the Cosmic Frontier program focuses on the detection and mapping of galactic and extra-galactic sources of radiation utilizing a variety of well-instrumented telescopes, both ground- and satellite-based, to better understand the fundamental nature of the dynamics and constituents of the Universe. The primary science thrusts within this frontier are (1) understanding the nature of cosmic acceleration (investigating dark energy); (2) discovering the origin and physics of dark matter, the dominant matter component in the universe; and (3) investigating the nature of primordial fluctuations, which is also a test of the theory of inflation. A number of sky surveys in multiple wavebands are now scanning the sky to shed light on these questions. Near-future observations will be carried out by the DESI [16] and LSST [17] surveys in the optical band (Figure 3), and by the CMB-S4 survey [18] in the microwave band. These surveys will generate extremely large datasets in the hundreds of petabytes (PB). Very large radio surveys, such as the Square Kilometre Array (SKA) [19], are also in planning stages.

Dark matter detection experiments fall under this Frontier. These include direct detection experiments that use cryogenic detectors (e.g., LZ [20] and SuperCDMS [21]) and indirect detection that uses high-energy particles from space (e.g., Fermilab [22] and High-Altitude Water Cherenkov Observatory [HAWC] [23]). Computational requirements in this sector are small- to medium-scale and do not reach the extreme requirements of large-scale sky surveys.

Cosmic Frontier white papers are *C.2 Computational Cosmology at the Exascale* (compute-intensive) and *C.7 Cosmic Frontier Experiments* (data-intensive). Case studies are *D.3 Computational Cosmology (HACC)*, *D.4 Cosmic Reionization (ART)*, *D.5 Dark Energy Survey in Hindsight*, and *D.9 Cosmic Microwave Background (TOAST)*.

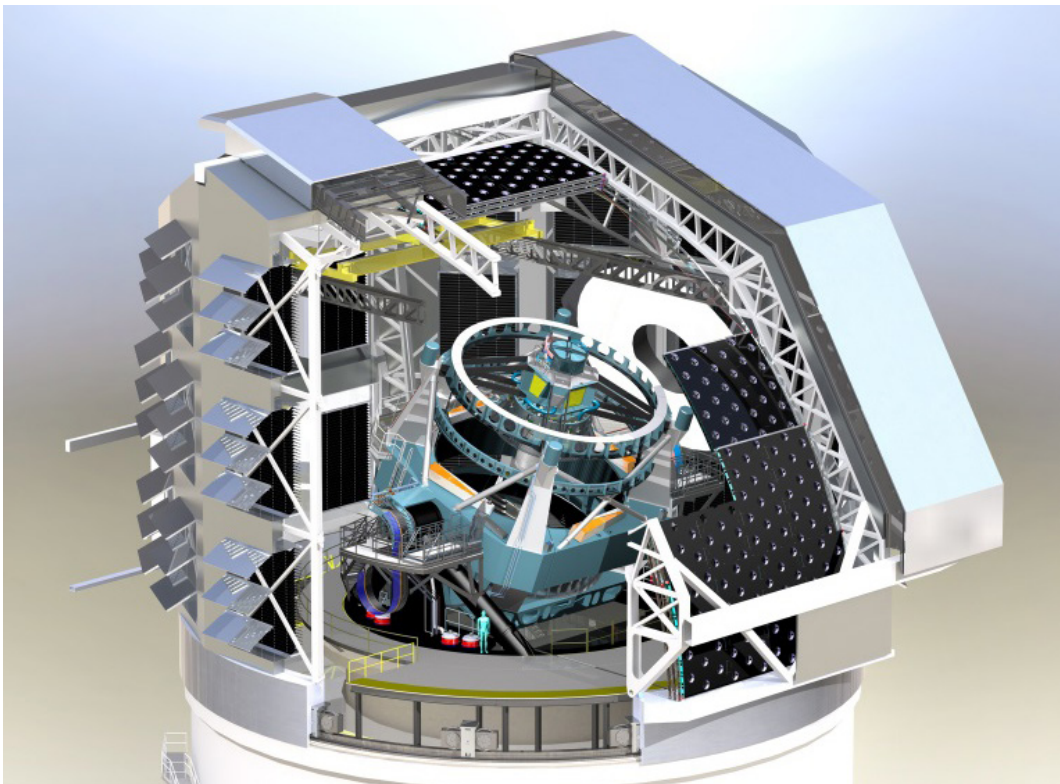


Figure 3. LSST: Cutaway of the dome showing the telescope within.

3 COMPUTING NEEDS/REQUIREMENTS

HEP computing can be roughly divided into two broad categories — compute- and data-intensive — as discussed in the previous sections. Historically, the two have been addressed in very different ways, using different architectures and facilities.

3.1 HPC Applications

The category of compute-intensive tasks in HEP belongs primarily to the HPC realm. The principal use cases of HPC within the HEP community include groups working on accelerator modeling, cosmology simulations (Figure 4), and lattice QCD; all have been long-time partners with the ASCR community. These users possess considerable computational sophistication and expertise; they leverage significant state-of-the-art computing resources to solve, at any one time, a single, complex, computationally demanding problem.

Very large datasets can be generated by these HPC applications — potentially much larger than those from any experiment. Analyzing these datasets can prove to be as difficult a problem as running the original simulation. Thus, data-intensive tasks currently go hand in hand with many HPC applications that were originally viewed as being only compute-intensive.

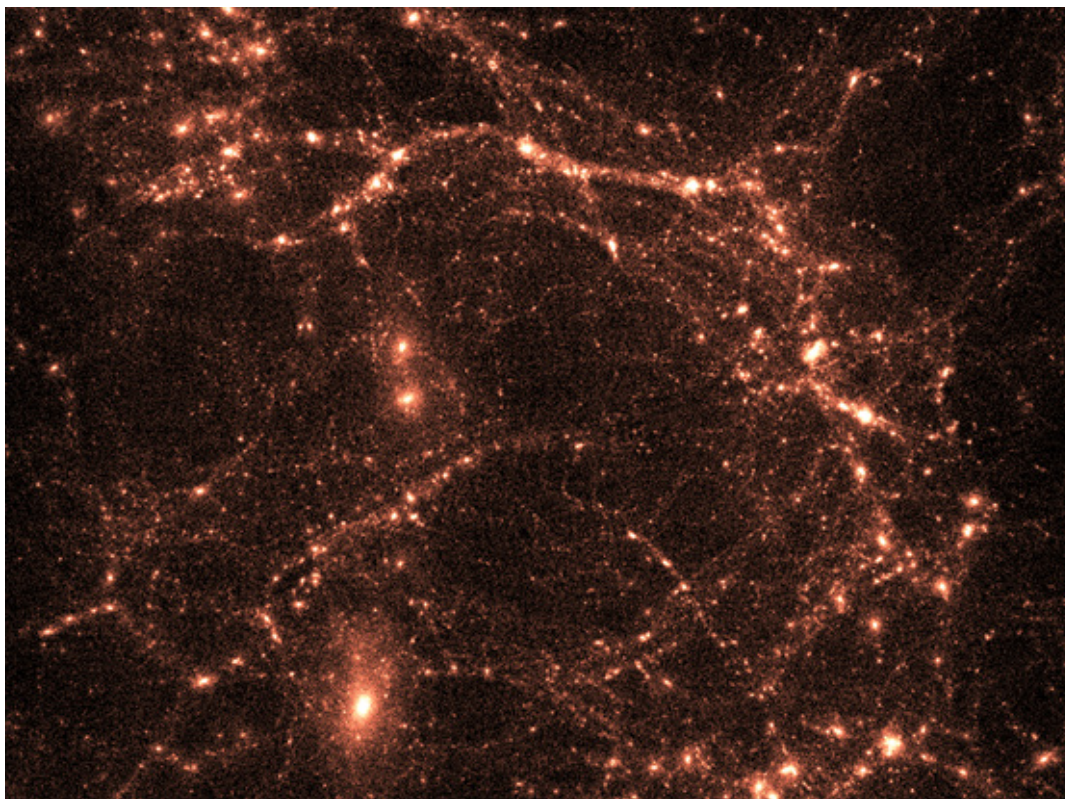


Figure 4. Zoomed-in image of a region of the universe in the trillion-particle 'Outer Rim' simulation.

3.2 HTC Applications

In contrast to HPC applications, the data-intensive use cases in HEP experiments exploit HTC systems to take advantage of the inherent parallelism of event-centric datasets. HEP teams have built large computing grids based on commodity hardware in which each computing node handles a computing problem from start to end. A typical example of an HTC application is event simulation (Figure 5) and reconstruction in Energy and Intensity Frontier experiments.

The HEP community that has primarily focused on HTC applications is actively considering the use of HPC resources. Sherpa, for example, has been ported to HPC systems, and ATLAS and CMS have ongoing efforts that use HPC resources for event simulation. It is fair to state, however, that the community is at an early phase of learning how to leverage HPC resources efficiently to address their computing challenges.

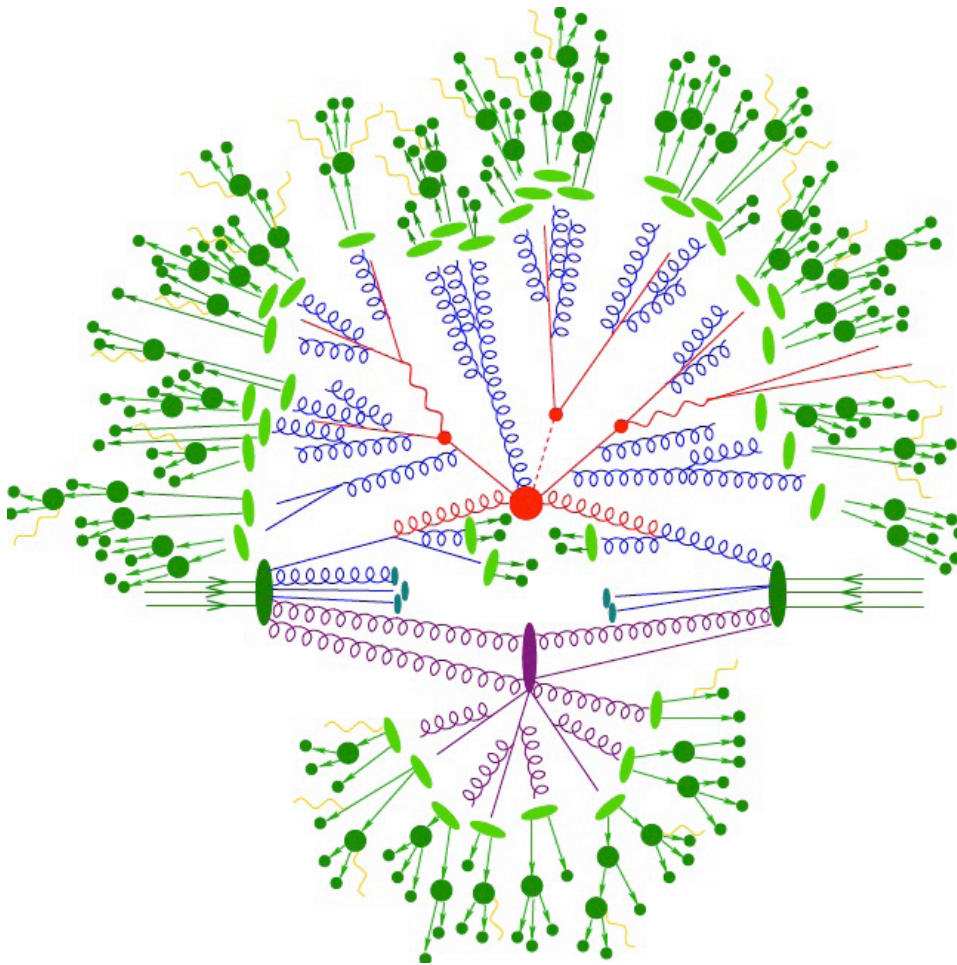


Figure 5. Collision event generated with Sherpa.

3.3 Future Architectures and Portability

A common problem that both the compute- and data-intensive communities within HEP face is the possible proliferation of “swim lanes” in future computational architectures and the difficulty with writing portable code for these systems. Currently, and in the next generation of large ASCR systems (“pre-exascale”) (Figure 6), there are only two types of computational architectures available: CPU/GPU (accelerated) and many-core (non-accelerated). While HPC users can

imagine running codes on these two types of architectures — and even this is limited to only a few teams — data-intensive users have a much more difficult planning decision to make. Disruptive changes cannot be made often to the HEP experiment software stack, and even then, only with considerable difficulty. This means that it is very likely that future evolution of this software will follow conservative trends, which for now, appear to lead down the many-core path. Although we cannot predict the detailed future of the exascale environment with precision, from what is currently known, this strategy would appear to make sense. The above argument suggests that a parallel effort in developing portable programming models for the exascale would be particularly beneficial for data-intensive applications. These are not typically characterized by a few highly-tuned kernels, but by a number of chained subprograms that may not be individually tuned for performance (nor is there usually an attempt to apply global optimization). Therefore, in this case, portability may not necessarily be accompanied by an unavoidable loss in performance, as is the case for the vast majority of HPC applications.

3.4 Evolution of HPC Architectures

The evolution of HPC architectures is driven by a number of technological, financial, and power-related constraints. Although system peak performance is continuing to follow a Moore's Law scenario (Figure 6), future architectures are focusing performance within relatively loosely coupled nodes, with high local concurrency and less RAM per core than in current systems. Optimization of computational efficiency will likely drive the use of simpler data structures and communication-avoiding algorithms in HPC applications.

System Attributes	NERSC Now	OLCF Now	ALCF Now	NERSC Upgrade	OLCF Upgrade	ALCF Upgrades	
Name Planned Installation	Edison	TITAN	MIRA	Cori 2016	Summit 2017-2018	Theta 2016	Aurora 2018-2019
System Peak	2.6	27	10	>30	150	>8.5	180
Peak Power (MW)	2	9	4.8	<3.7	10	1.7	13
Total system memory	357 TB	710TB	768TB	-1 PB DDR4+ High Bandwidth Memory (HBM)+1.5 PB persistent memory	>1.74 PB DDR4 + HBM + 2.8 PB persistent memory	>480 TB DDR4 + High Bandwidth Memory (HBM)	>7 PB High Bandwidth On-Package Memory Local Memory and Persistent Memory
Node Performance (TF)	0.460	1.452	0.204	>3	>40	>3	>17 times Mira
Node Processors	Intel Ivy Bridge	AMD Opteron Nvidia Kepler	64-bit Power PC A2	Intel Knights Landing many core CPUs Intel Haswell CPU in data partition	Multiple IBM Power9 CPUs and multiple Nvidia Volta GPUs	Intel Knights Landing Xeon Phi many core CPUs	Knights Hill Xeon Phi many more CPUs
System size (nodes)	5,600 nodes	18,688 nodes	49,152 nodes	9,300 nodes 1,900 nodes in data partition	~3,500 nodes	>2,500 nodes	>50,000 nodes
System Interconnect	Aries	Gemini	5D Torus	Aries	Dual Rail EDR-1B	Aries	2nd Generation Intel Omni-Path Architecture
File System	7.6 PB 168 GB/s Lustre®	32 PB 1 TB/s Lustre®	26 PB 300 GB/s GPFS™	28 PB 744 GB/s Lustre®	120 PB 1 TB/s GPFS™	10 PB 210 GBs Lustre Initial	150 PB 1 TB/s Lustre®

Figure 6. Evolution of the main computational systems at the ASCR HPC facilities from the current petascale systems to the near-future pre-exascale systems, continuing the two swim lanes of many-core and CPU/GPU nodes (Note the increase in peak performance and the reduction in the ratio of system memory to performance — a trend shared by the ratio of inter-node bandwidth compared with peak flops. These trends are part of the challenge posed by next-generation systems.)

At the same time, there is a general trend to investigate the notion — if not to immediately adopt it — that future HPC platforms should be able to perform some subset of scientifically important data-intensive tasks. This trend is attributable to the need for more computational power from data-intensive applications, but also to the substantial advantages associated with having data analysis performed on the same systems where the underlying detailed theoretical modeling and simulations are also being run.

In order to optimize HPC architectures for HEP data-intensive applications, it would be desirable for the future HPC environment to provide more balanced I/O on local and global scales and to make more memory available per core, or to present faster access to remote memory. Availability of node-local NVRAM cannot only provide I/O-related benefits (“burst buffers”) but will also allow a write-once, read-many (WORM) capability that can be exploited by data-intensive applications (e.g., for holding detector description/status databases). In addition, there are issues related to the global infrastructure: How is data moved to the facility, transferred to the compute cores, and then moved off again in a timely fashion? Furthermore, addressing the need for automated work/data flows is a key requirement (partly connected to cybersecurity and partly to interactions with schedulers), which adds a requirement for elasticity. HPC systems do not currently implement such elasticity, not so much because of technological limitations but because of implementation of usage policies. It is not uncommon today for HEP data-intensive users running scientific workflows — from a single console — to launch thousands of jobs each day on facilities located all over the world without logging into each facility separately.

As a further complication to data-intensive computing, many experimental software stacks are very complex; enabling some of them to run on HPC systems will likely require use of software containers as essential resources. The expertise to rewrite the software may not be available on the required timescale. Fortunately, rapid progress is being made in this area.

3.5 Resource Management

It is important to keep in mind that the scale of HEP science is very large; there are almost no “single-investigator” activities in areas of HEP science relevant to this review, including research in theory and modeling. HEP experiments typically plan 5–10 years out, for example, in terms of accelerator luminosity, but also in terms of data and computing resources. Competing annually for major allocations, the procedure currently used by ASCR facilities, creates an uncertainty that is close to unacceptable for large HEP-supported projects or science campaigns in all three frontiers. Large resource fluctuations can seriously jeopardize attainment of the HEP community’s science goals. A mechanism to provide the necessary resource stability is required.

An exascale HPC environment that possesses a significant data-intensive computing capability would be extremely attractive to the HEP community. As an example of synergy, HEP computing facilities could leverage the associated technology and provision their own data centers in accordance with the larger ASCR facilities. Not only would this strategy be cost effective, it would also allow the design of a uniform HEP code base for the system architectures adopted by both the HEP and the ASCR facilities. This strategy would simplify code maintenance, expand the pool of experts who can leverage these resources effectively, and enable HEP users to execute their scientific workflows based solely on availability and not on the machine architecture.

4 PATH FORWARD

4.1 Challenges Ahead for HEP

In this section, we cover specific technical, organizational, and other challenges facing the HEP community as it moves forward to take advantage of the next generation of computational systems and data storage and data transfer technologies. Exascale users will face a number of difficulties, such as stability in hardware and software, system resilience issues, evolving programming models, complex system hierarchies, etc. — some of which are merely extensions of current problems and some of which will be new to the exascale environment. Here, we focus on the issues that are particularly relevant to HEP applications.

4.1.1 Compute-Intensive Applications

The computational challenges ahead for the HEP community have been broadly outlined in the white papers. The papers cover, in principle, most of HEP's HPC-oriented computational practice. The compute-intensive areas are covered in the following white papers: *C.1 Exascale Accelerator Simulation*, *C.2 Computational Cosmology at the Exascale*, *C.3 Lattice QCD*, and *C.4 HPC in HEP Theory*. These white papers discuss current science topics and computational approaches, as well as future plans.

From the point of view of computational needs, given the science targets, the raw demand in terms of core-hours (from all of the white papers, individually and together) seems to be very reasonable and completely consistent with the expected availability of computational resources at the Leadership Computing Facilities (LCFs) and National Energy Research Scientific Computing Center (NERSC) on the 2020–2025 timescale; the HEP requirements, in terms of core-hours, amount to roughly 10% of the total that is likely to be available. It is important to note, however, that the different applications make demands on HPC systems in different ways: computational cosmology and lattice QCD have the highest computational density, and computational cosmology codes are also memory-limited (as are a few examples in accelerator simulation). To run the problems at the required scales, even next-generation systems are on the smaller side of the requirements. The HEP theory use case is more of a mid-scale computing example and makes relatively light demands on the HPC system network.



One of seven tape libraries at the Feynman Computing Center at Fermilab. Tape libraries house data from Energy, Intensity, and Cosmic Frontier experiments; each library can hold 10,000 tapes. Over 150PB of experimental and observational data is stored (the total storage capacity exceeds 1000PB).

The HEP compute-intensive community is abreast of the current computational state of the art, although new algorithm development continues for a variety of tasks. Other work includes performance optimization and adoption of better software engineering practices. The evolution to next-generation systems is less clear, however. Certain teams within the lattice QCD and computational cosmology groups already have extensive experience with GPUs and many-core hardware, but these two options should be viewed as a disruptive set of technologies for most applications. The SciDAC program and other opportunities, such as the Early Science Projects at the LCFs and the NERSC Exascale Science Applications Program (NESAP), will help accelerate the adoption of new programming paradigms.

Participants agreed that what is needed in this area is a set of common tools across architectures — efficient parallel primitives — that are separately optimized for each. These tools should possess flexible data layouts so that codes can adapt to different memory hierarchies. Examples include operators such as shift, scan, reduce, transform, scatter-gather, geometry remapping, etc. Moreover, it should be possible to easily replace primitives with hand-tuned code, when needed. It would be useful to compile a list of desired primitives and define appropriate interfaces. It is important to note here that there is no desire for heavy-duty frameworks and libraries that would be hard to develop, maintain, and modify. The emphasis is primarily on lightweight tools, especially because the future computing environment is expected to evolve considerably. A possible suggestion is that a few application codes should function as testbeds for developing the envisioned toolkits. In addition, emphasis should be placed on the benefits of having better network fabrics on the HPC systems and on increased memory/node. At a lower level, there is some concern directed at the problems of node-level memory management. A common interface for managing data placement and movement across different levels of the memory hierarchy would be very desirable.

As noted in two of the white papers (C.2 and C.3), data storage and transfer will become significant issues. In fact, it can be argued that for the compute-intensive field of computational cosmology, the point where current needs are not being met has already been crossed.

Finally, as mentioned in Section 3.1, compute-intensive applications can generate very large amounts of data — potentially significantly larger than the data volume from the experiments — that then must be processed in different ways. This issue is of particular concern to the lattice and computational cosmology groups, who either have their own resources for off-line analysis and storage (lattice) or are also leveraging other approaches, such as in-situ analysis and use of software containers and virtualization (cosmology). This general area is currently characterized by a number of *ad hoc* approaches; achieving production-level status in the next 2 years is an important goal, so as to keep in sync with the arrival of next-generation systems at the LCFs and NERSC.

4.1.2 Data-Intensive Applications

Up to this point, the data-intensive HEP community has been very successful in terms of its ability to leverage computing technology to carry out its science. Yet, there are significant challenges ahead that must be overcome before HEP groups can effectively exploit large-scale HPC resources for many of their applications. The relevant white papers here are *C.5 Energy Frontier Experiments*, *C.6 HEP Experiments: Data Movement and Storage*, *C.7 Cosmic Frontier Experiments*, and *C.8 Intensity Frontier Experiments*. Currently, the Cosmic Frontier and Intensity Frontier experiments generate relatively modest amounts of data, and the primary use cases are the two LHC experiments. In the future, the other Frontiers will be characterized by significantly larger data volumes, but they are unlikely to stress the available resources in a way comparable to the LHC needs. Except for a few cases in the Cosmic Frontier, all of HEP's data-intensive computing uses the grid model; forecasts of future computing needs versus what the HEP grid can provide are making it very clear (see white papers C.5 and C.7) that access to alternative computational resources will be necessary.

With some very rare exceptions, it is not an easy task to run the HEP experiment software stack “out of the box” in an efficient way on HPC systems. The current code base is not well-suited to run on HPC machines (designed for HTC and not for HPC resources, lack of vectorization, threading, unsuitable code organization, heavy I/O with small files), and it will need to be significantly modified and appropriately refactored to use these resources efficiently.

This is a significant problem, and the HEP workforce as it stands does not possess the skill set to tackle it on the required timescale. Training — through summer schools, boot camps, and mentors — will therefore become increasingly important. ASCR expertise can play a significant role in helping to modernize the HEP workforce in this area. An effort is now underway to develop a set of “mini-apps” [24] through the HEP-FCE — for both data- and compute-intensive applications — to help HEP researchers understand the new computing environment and ensure that HEP codes can scale appropriately with reasonable performance levels. The mini-apps can also be used as testbeds for prototype exascale hardware to ensure that HEP applications and workflows will perform adequately.

More generally, however, the problem is that it is simply not possible to train thousands of HEP researchers to become HPC experts, nor is it desirable. The goals of the training program would be (1) to develop a core of expertise within HEP, which would allow structured refactoring of the current code over time; and (2) to construct usable frameworks that would allow thousands of scientists to run large-scale analysis or other data-intensive tasks without having to become HPC experts.

The complexity of the current HEP experiment software base (many millions of lines), a substantial fraction of which needs to be available at the level of the compute nodes, and the fact that it changes on relatively short timescales, are significant problems for HPC systems. Fortunately, these problems can be substantially mitigated by the use of software containers, such as Docker. Although HPC systems currently do not offer this capability, the hope is that they soon will.

One of the significant issues facing data-intensive applications in the exascale environment involves incorporating HPC machines into the experiments’ workflows. One difficulty is that Energy Frontier applications require real-time remote access to resources such as databases while the associated jobs are running. Because of the fine-grained nature of the computational tasks, the associated I/O bandwidth requirements are a potentially significant issue and need to be properly characterized, not only for the systems being used, but also at the facility scale. A second difficulty is that HPC systems are scheduled for maximal utilization in a way that is problematic for large-scale complex workflows, especially those that require true real-time access. The problem is that a given workflow may require widely varying resources as it runs, in ways that may not be easily predictable beforehand. This mode of operation is essentially orthogonal to current batch scheduling implementations on HPC systems. Moreover, truly addressing the elasticity requirement implies a substantial degree of overprovisioning, which is hard to imagine implementing at current HPC facilities. Note that having containers available will not solve the problem of elasticity, although it will help by potentially providing the ability to quickly spin up and spin down machine partitions dedicated to a particular workflow.

A significant barrier at the moment is that each of the ASCR facilities is configured differently. There is little uniformity with respect to scheduling jobs, cybersecurity, staging data, etc. It would be significantly easier if all HPC systems could be accessed via a uniform fabric. “Edge Servers” needed to stage data outside of the facility firewall will play an important role in data-intensive applications, including potentially addressing access control issues on HPC systems. A uniform implementation of access protocols would make interfacing to the facilities much simpler. Lastly, uniformity in cybersecurity protocols across the facilities would be very desirable. A single, federated model that works at all three centers would be ideal.

The volume of data produced by experiments is rising rapidly. The current LHC output is on the order of 10 PB/year, and in the HL-LHC era (2025), this number is expected to rise to 150 PB/year. No experiment in the Cosmic or Intensity Frontier will come close to this data rate or total volume (exabyte [EB] scales). For the most part, one can expect that if the volume is sufficiently large, the projects will budget for and purchase the required storage. Below a certain threshold, the ASCR HPC centers provide disk storage in parallel file systems and much larger archival tape storage managed using HPSS (High-Performance Storage System). The timescale over which this storage continues to exist is subject to success or failure in the ASCR Leadership Computing Challenge (ALCC) and Innovative and Novel Computational Impact on Theory and Experiment (INCITE) process (and to a much lesser extent at NERSC). In any case, if the HPC systems are used as a data-intensive computing resource, much more attention will have to be paid to storage resources in terms of capacity, latency, and bandwidth (as is also the case for compute-intensive applications that generate large amounts of data, as described in Sections 2.2 and 4.1.1). In particular, high-performance, reliable, and predictable data transfer across multiple storage endpoints would be an essential requirement.

4.2 Potential ASCR/HEP Paradigms

In the context of a future exascale environment — or even in the near term — a number of needs for the HEP computing program have been identified thus far, as described in Section 3. These needs include programming on new architectures and associated algorithm development, data storage and transfer, refactoring of a potentially significant fraction of the code base (over ten million lines of code), co-evolution of ASCR and HEP facilities, and training of HEP personnel. To address these needs, the HEP community is very interested in identifying and exploring new ways to partner with ASCR. The exascale environment opens up exciting new scientific opportunities; the knowledge and expertise that ASCR has are invaluable to the HEP community in its pursuit of new scientific opportunities.

One difficulty is that current partnership opportunities are limited under today’s organizational structure. Outside of the SciDAC programs and informal contacts, there are limited established mechanisms to develop long-term partnerships between the two communities. This is an area that calls for serious attention.

A possibility discussed at the Exascale Requirements Review is to enhance or redirect partnerships where some entity — like a joint ASCR/HEP institute (and similar entities for other sciences if appropriate) — would provide multi-faceted partnerships with ASCR research and facilities divisions. These new entities would have broad-ranging computational expertise and be dedicated to the scientific success of the community they are supporting, forming valuable additions and expansions to the successful SciDAC Program. As an important example, the fact that a complex HEP software suite needs to run “everywhere” requires an approach whereby staff belonging to a joint ASCR/HEP group of experts (“embedded power teams”) work together to solve the associated portability problems within the larger computational context of a given project. In this mode, scientists across different domains would get to know each other, establish a common language, and have enough long-term commitments to tackle difficult problems. In other words, the broader computational support model should involve working with large collaborations, as well as with small teams.

Another issue involves long-range planning to ensure availability of resources; such planning is essential for HEP experiments because of their extended lifetimes of 5 years or more (Section 4.5). As outlined in the white paper *C.5 Energy Frontier Experiments*, “it is possible that by 2025, most processing resources will be supplied through dynamic infrastructures that could be accessed opportunistically or through commercial providers.” If such a scenario is to become reality, close interaction will be needed not only between the ASCR computing facilities and HEP

counterparts to support programmatic needs, but also between HEP and ESnet to make sure that networking resources are adequately provisioned. Joint design of “Edge Servers” (Section 5.1.2) and co-evolution of HEP facilities (Section 4.5.) would also be facilitated by such an interaction. To summarize, a mission-oriented ASCR/HEP partnership for long-range activities needs to be initiated.

4.3 Summary of HEP Requirements

The purpose of this section is to summarize the quantitative estimates of computing, storage, and networking that are presented in the white papers. The white papers addressed (1) the individual compute-intensive HEP applications (accelerator modeling, computational cosmology, lattice QCD, and HEP theory); (2) data-intensive computing requirements from experiments at the three frontiers; and (3) a separate white paper on Energy Frontier experiment data movement and storage and on the evolution of HEP computational facilities. The authors of the white papers were asked to collate information from all the major use cases in their domains, and in particular, to provide an assessment of the science activities and computational approaches on the 2020–2025 timescale, as well as estimates for the computing, data, and services needs over the same period. The case studies presented in Appendix D are meant to provide more in-depth examples of specific use cases, which can range from medium-scale computing to full-machine exascale simulations.

It is not easy to assess requirements roughly a decade into the future for a diverse set of scientific applications because new breakthroughs and unexpected obstacles are, by definition, difficult to predict. The difficulty is compounded by the fact that two architecture changes are expected over this timeframe: the change from multi-core to many-core (GPUs included in this classification) at all the major ASCR computing facilities (pre-exascale) followed by another architecture change at the exascale/beyond-exascale level, which could be significantly disruptive. In addition, computational needs in different areas do not have equal priority. Much depends on which computations are considered more relevant at a certain time for HEP science and which can be pushed into the future. Computational needs driven by ongoing projects and those planned or under construction have been taken into account in the white papers. The future, however, may turn out differently if the associated timelines change in ways that lead to lack of coordination with the evolution of the computational resources.

Given these caveats, it is nevertheless encouraging to note that the compute-intensive HEP applications have kept pace with hardware evolution — including key pathfinder roles in several cases (e.g., lattice QCD for the IBM Blue Gene systems and computational cosmology for Roadrunner, the world’s first petaflop system). In addition, as noted in the white papers, the science drivers show no sign of letting up in their hunger for computational resources. The situation in the case of experiments is more difficult to assess. In the case of the Cosmic Frontier, it is becoming clear that the future will lie in using ASCR facilities (NERSC is the host for DESI and also the likely host for LSST-Dark Energy Science Collaboration [DESC] computing; the LCFs will provide additional resources) as the dominant source of computational resources. HEP Energy Frontier experiments have historically not used HPC sites for computing, although this is rapidly changing. Intensity Frontier experiments have not been major consumers of computational resources, but this situation is also changing, even on the current timescale. How quickly all of these areas will be able to take full advantage of ASCR resources depends on the pace with which the relevant components of the HEP production and collaboration software are refactored, as well as how the ASCR facilities evolve — in their turn — to address the HEP use cases.

We now consider the computational, data, and networking requirements that can be extracted from the white papers. Unless explicitly stated, the numbers in this section (in core-hours for a standard 2015 X86 core) refer only to the computational requirements associated with HEP use of ASCR facilities. The disk storage requirements are given as an aggregate number, but it is conceivable that this storage can be split between ASCR and HEP facilities, depending on the particular use case. Wide area network (WAN) bandwidth requirements are given in a few cases in which we expect that the requirement will potentially stretch ESnet capabilities. Local bandwidth within the facilities is assumed to be at least as good as the wide area requirement.

Accelerator modeling can be divided into the following: (1) electromagnetics and beam dynamics simulations for current and near-future technology machines and (2) dedicated simulations to help in the design of future accelerators. Currently, both electromagnetics and beam dynamics consume on the order of 10M core-hours annually each. These numbers are expected to scale up to 10–100 billion (G) core-hours by 2025, depending on the use cases being run. Large-scale simulations for future accelerators (machines that may be built on the 2030+ timescale) focus on plasma-based acceleration schemes. While these simulations are currently at the 10M-core-hours level, they can scale up to an annual requirement of 1G–100G core-hours (or more) by 2025, but there is significant uncertainty regarding the upper value. Storage (or networking) has historically not been a major issue for accelerator modeling, and this is unlikely to change in the future.

Computational cosmology will have to support a large number of Cosmic Frontier projects, some of which are quickly reaching the scale of HEP experiments in terms of collaboration size. Current annual simulation usage is at the 100M–1G core-hours scale and is expected to increase to 100G–1,000G core-hours by 2025. In addition, large-scale cosmology simulations are already memory-limited, and they are likely to saturate the system memory of machines in the exascale era. Storage requirements are likely to be large; they are already at the level of 10PB of disk storage, and they are likely to easily exceed 100PB by 2025. Furthermore, because large-scale distributed analysis will be needed by the collaborations, there will be significant networking requirements. Currently, a pilot project with ESnet is aiming to establish a 1PB/week production transfer rate for moving simulation data. By 2025, the burst requirements will be approximately 300Gb/s, which is roughly the same scale as that required by Energy Frontier experiments.

Lattice QCD has a long history of efficient use of supercomputing resources, and this trend will continue into the foreseeable future. Current annual usage is in the 1G~core-hour class; this number is expected to increase to 100G–1,000G core-hours by 2025. Memory requirements (unlike for computational cosmology) are nominal. Disk storage, which has historically not been a major requirement, will only increase slowly, from ~1PB currently to ~10PB by 2025. Theory requirements (event generation, perturbative QCD) are at 1M–10M core-hours currently; these will likely increase to 100M–1G core-hours by 2025. Memory and storage needs for this effort will likely remain at easily satisfiable levels.

Cosmic Frontier experiments are currently running at the 10M–100M core-hours scale on HPC resources; on the 2025 timescale, this is likely to increase to 1G–10G core-hours. Disk storage requirements are currently at the ~PB scale and are likely to increase to 10–100PB by 2025. Network requirements are unlikely to stress future capabilities at the same level as Energy Frontier experiments.

Energy Frontier experiments have begun using HPC systems relatively recently, primarily for event simulation tasks. However, annual usage has already reached the 100M core-hour level on ASCR resources. This usage level should be compared with the total U.S. contribution to LHC computing, which is on the order of 100M–1G core-hours annually on HTC systems. By 2025, the requirement on HPC resources could reach 10G–100G core-hours, with extensive storage needs, exceeding 100PB of disk space (the total global storage requirement will reach the exabyte scale). The network requirements will also be high, at the level of 300 Gb/s (more in a continuous mode, rather than burst operation).

Intensity Frontier experiments are at the ~10M core-hour level of annual usage. This number is expected to increase to 100M–1G core-hours annually. Storage requirements are at the ~PB level currently and are expected to increase to 10–100PB by 2025.

The information discussed in this section is summarized in Table 1. The sum of HEP requirements, although difficult to pin down precisely because of the uncertainties discussed, is projected to be ~10% of the expected ASCR facility resources at the ALCF, NERSC, and OLCF by 2025.

Table 1. Approximate exascale requirements for HEP computational tasks¹.

Computational Task	Current Usage	2025 Usage	Current Storage (Disk)	2025 Storage (Disk)	2025 Network Requirements (WAN)
Accelerator Modeling	~10M–100M core-h/yr	~10G–100G core-h/yr			
Computational Cosmology	~100M–1G core-h/yr	~100G–1000G core-h/yr	~10PB	>100PB	300Gb/s (burst)
Lattice QCD	~1G core-h/yr	~100G–1000G core-h/yr	~1PB	>10PB	
Theory	~1M–10M core-h/yr	~100M–1G core-h/yr			
Cosmic Frontier Experiments	10M–100M core-h/yr	~1G–10G core-h/yr	~1PB	10–100PB	
Energy Frontier Experiments	~100 core-h/yr	~10G–100G core-h/yr	~1PB	>100PB	300Gb/s
Intensity Frontier Experiments	~10M core-h/yr	~100M–1G core-h/yr	~1PB	10–100PB	300Gb/s

¹ All quantitative estimates are for HEP requirements at ASCR facilities (i.e., no HEP facility estimates are included). If no numbers are provided, the usage is considered to be small enough that it should be well within the facility specifications. The nature of the uncertainties in the estimates is discussed in the text.

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6 ACRONYMS AND ABBREVIATIONS

ACE3P — Advanced Computational Electromagnetics 3-D Parallel

ALCF — Argonne Leadership Computing Facility

AMR — Adaptive Mesh Refinement

ART — Adaptive Refinement Tree

ASCR — Advanced Scientific Computing Research

ASTA — Advanced Superconducting Test Accelerator

ATF — Accelerator Test Facility

ATLAS — A Toroidal LHC ApparatuS

AWA — Argonne Wakefield Accelerator

BAO — Baryon Acoustic Oscillations

BELLA — Berkeley Lab Laser Accelerator

Belle II — B detector at SuperKEKB

BES — Basic Energy Sciences

BOSS/eBOSS — (extended) Baryon Oscillation Spectroscopic Survey

CEBAF — Continuous Electron Beam Accelerator Facility

CKM — Cabibbo-Kobayashi-Maskawa

CMB — Cosmic Microwave Background

CMS — Compact Muon Solenoid

CORAL — Collaboration of Oak Ridge, Argonne, Livermore

CP — Charge Parity

CPU — Central Processing Unit

CUDA — Compute Unified Device Architecture

DES — Dark Energy Survey

DESI — Dark Energy Spectroscopic Instrument

DOE — Department of Energy

DUNE — Deep Underground Neutrino Experiment

DWA — Dielectric Wakefield Accelerator

FACET — Facility for Advanced Accelerator Experimental Tests

FCC — Future Circular Collider

FASTMath — Frameworks, Algorithms, and Scalable Technologies for Mathematics

FFT — Fast Fourier Transform

FRIB — Facility for Rare Isotope Beams

GPFS — General Parallel File System

GPU — Graphics Processing Unit

HACC — Hardware/Hybrid Accelerated Cosmology Codes

HAWC — High-Altitude Water Cherenkov Observatory

HEP — High Energy Physics

HEP-FCE — High Energy Forum for Computational Excellence

HL-LHC — High Luminosity Large Hadron Collider

HPC — High Performance Computing

HTC — High Throughput Computing

HTTP — Hypertext Transfer Protocol

INCITE — Innovative and Novel Computational Impact on Theory and Experiment

IOTA — Integrable Optics Test Accelerator

JLSE — Joint Laboratory for System Evaluation

LArTPC — Liquid Argon Time Projection Chamber

LCF — Leadership Computing Facility

LCLS — Linac Coherent Light Source

LHC — Large Hadron Collider

LHCb — Large Hadron Collider beauty experiment

LPA — Laser-Plasma Accelerators

LSST — Large Synoptic Survey Telescope

LSST-DESC — LSST Dark Energy Science Collaboration

LZ — Merger of LUX and ZEPLIN dark matter experiments

MILC — MIMD Lattice Computation

MPI — Message-Passing Interface

MSSM — Minimal Supersymmetric Standard Model

NCSA — National Center for Supercomputing Applications

NERSC — National Energy Research Scientific Computing Center

NESAP — NERSC Exascale Science Applications Program

NP — Nuclear Physics

NUMA — Non-Uniform Memory Access

NVRAM — Non-Volatile Random-Access Memory

OLCF — Oak Ridge Leadership Computational Facility

OpenCL — Open Computing Language

OpenMP — Open Multi-Processing

OSG — Open Science Grid

P5 — Particle Physics Project Prioritization Panel

PGAS — Partitioned Global Address Space

PIC — Particle-In-Cell

PIP-II — Proton Improvement Plan-II

PM — Particle-Mesh

P3M — Particle-Particle Particle-Mesh

PPM — Piecewise Parabolic Method

PWFA — Plasma Wakefield Accelerators

QCD — Quantum Chromodynamics

QUEST — Quantification of Uncertainty in Extreme Scale Computations

RAC — Real Application Clusters

SAM — Semi-Analytic Modeling

SCET — Soft-Collinear Effective Theory

SciDAC — Scientific Discovery through Advanced Computing

SDSC — San Diego Supercomputer Center

SKA — Square Kilometre Array

SPH — Smoothed Particle Hydrodynamics

SUPER — Sustained Performance, Energy, and Resilience

SuperCDMS — Super Cryogenic Dark Matter Search

T2K — Tokai to Kamioka neutrino experiment

TOAST — Time-Ordered Astrophysics Scalable Tools

UMER — University of Maryland Electron Ring

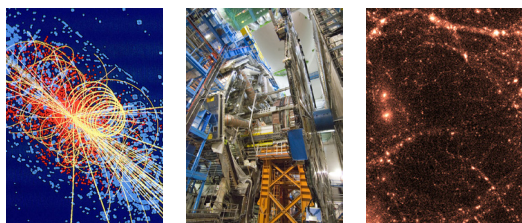
UQ — Uncertainty Quantification

WORM — Write-Once, Read-Many

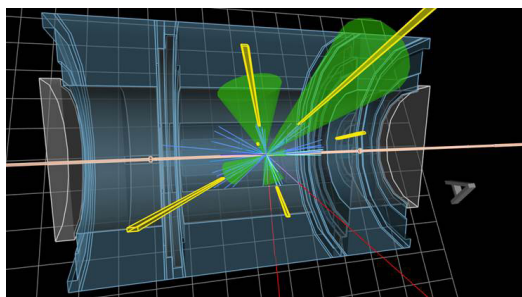
XSEDE — Extreme Science and Engineering Discovery Environment

HEP

HIGH ENERGY PHYSICS



APPENDICES: MEETING MATERIALS



An Office of Science review sponsored jointly by
Advanced Scientific Computing Research and High Energy Physics



APPENDIX A: HIGH ENERGY PHYSICS ORGANIZERS AND MEETING PARTICIPANTS

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ALCF	Argonne Leadership Computing Facility
ANL	Argonne National Laboratory
BNAL	Brookhaven National Accelerator Laboratory
FNAL	Fermi National Accelerator Laboratory
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
NERSC	National Energy Research Scientific Computing Center
PNNL	Pacific Northwest National Laboratory
SLAC	SLAC National Accelerator Laboratory

APPENDIX B: HIGH ENERGY PHYSICS MEETING AGENDA

WEDNESDAY, JUNE 10

- 9:00** **Welcome from ASCR and HEP**
Carolyn Lauzon, ASCR; Lali Chatterjee, HEP
- 9:05** **Requirements Reviews and Impact**
Barbara Helland, ASCR Facilities Director
- 9:20** **Meeting Purpose, Organization, and Logistics**
Salman Habib, ANL; Rob Roser, ANL; Richard Gerber, NERSC
- 9:30** **P5 Science Drivers: Accelerator Experiments**
Panagiotis Spentzouris, FNAL
- 9:45** **P5 Science Drivers: Cosmic Surveys**
Peter Nugent, LBNL
- 10:00** **P5 Science Drivers: Theory**
Stefan Hche, SLAC
- 10:25** **Break**
- 10:40** **Data Movement and Storage**
Brian Bockelman, U. Nebraska; Joe Metzger, ESNet
- 11:20** **HEP Science Workflows**
Torre Wehaus, BNAL; Don Petravick, NCSA
- 12:10** **Working Lunch: ASCR Facility Plans**
Sudip Dosanjh, NERSC, ALCF, OLCF representatives
- 1:30** **HEP Facility Plans**
Lothar Bauerdick, FNAL
- 2:00** **Traditional HPC Needs**
Richard Brower, Boston University; Katrin Heitmann, ANL;
Jean-Luc Vay, LBNL
- 2:45** **Use of HPC by Data-Intensive Projects**
Tom LeCompte, ANL; Peter Nugent, LBNL
- 3:30** **Break**
- 3:45** **ASCR Connections with HEP and Future Trends**
Steve Binkley, DOE Associate Director for Advanced Scientific Computing Research
- 4:00** **HEP Computing Challenges**
James Siegrist, DOE Associate Director for High Energy Physics
- 4:15** **Open Discussion with Directors “Exascale Environment
and Co-Evolution of Facilities”**
Salman Habib, ANL; Richard Gerber, NERSC – moderators
- 5:00** **General Discussion**
- 5:30** **Adjourn/Committee Meeting**
Organizing and Program Committees

THURSDAY, JUNE 11

- 9:00** **Day 1 summary and charge to the breakout groups**
Salman Habib, Rob Roser, Richard Gerber
- 9:30** **Breakouts**
Breakout 1: Traditional HPC: Accelerators, Cosmology, LQCD
**Breakout 2: Non-Traditional HPC: Energy, Intensity, Comsic Frontiers;
Energy/Intensity Theory**
- 10:30** **Break**
- 10:45** **Breakouts (continued)**
- 12:30** **Working Lunch**
- 1:30** **Reports from morning breakouts and discussion**
All
- 3:00** **Break**
- 3:30** **Breakouts reassemble and craft high-level findings**
- 4:30** **Presentation of high-level findings from breakouts**
All
- 5:30** **Adjourn**

FRIDAY, JUNE 12

- 9:00** **Report Preparation**
Report authors
- 1:00** **Adjourn**

APPENDIX C: HIGH ENERGY PHYSICS WHITE PAPERS

The HEP computational landscape is diverse but can be sensibly categorized by the type of computing (compute-intensive or data-intensive) and by the individual application areas. The bulk of the HPC-relevant computing in HEP is carried out in the areas of accelerator modeling, computational cosmology, and lattice field theory. All of these topics, as well as a smaller, but growing effort in HEP theory, are represented by individual white papers. The bulk of the computing in experimental HEP areas is dominated by data-intensive applications, in which simulations also play an important role. The three HEP frontiers – Cosmic, Energy, Intensity – have their own white papers, and there is a separate one to address data movement and storage in Energy Frontier experiments, as this is a very significant component of HEP’s computational program.

The white papers provide compact introductions to each area’s current science activities and computational approaches, and their expected evolution on the 2020 – 2025 timescale. Based on the relevant requirements, estimates are presented for the compute, data, and services needs in each area on the 2020–2025 timescale. We emphasize that each white paper attempts to represent a broad activity comprising many researchers, scientific problems, and varied computational tools. For this reason, the information in the white papers is necessarily incomplete. References are provided separately with each white paper to improve the coverage and include access to more detailed information. The second Appendix on case studies gives more specific examples of HEP science use cases and goes into detail on the computational needs for these selected examples..

CONTRIBUTORS

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C.1 EXASCALE ACCELERATOR SIMULATION

Authors: J. Amundson, R. Ryne (leads), B. Cowan, W. Mori, C.-K. Ng, J. Power, J. Qiang, and J.-L. Vay

C.1.1 Current Science Activities and Computational Approaches

Current research in accelerator simulation [1] can be divided into three main categories: beam dynamics [2], electromagnetics and advanced accelerators. In beam dynamics, the problems involve single- and multi-pass transport in externally applied fields, self-fields, and fields generated by the beam-environment interaction. In electromagnetics, simulations are performed in order to obtain detailed predictions of fields in accelerator components, primarily RF structures. Advanced accelerator research focuses on future-generation concepts such as laser-plasma accelerators (LPA or LWFA), plasma wakefield accelerators (PWFA), and dielectric wakefield accelerators (DWA). All the above are heavy consumers of contemporary high-performance computing resources.

Along with these three areas, another important topic involves simulating the interaction of beams with materials [3]. Such simulations are important for designing shielding systems and for predicting radioactivation from particle loss. This also includes the simulation of particle production in high power targets and simulation of machine-detector interface phenomena.

Nearly all the major accelerator codes are multi-physics codes. Beam dynamics codes involve nonlinear optics, space charge, wakefield, and other effects [4, 5]. Additional phenomena of importance are beam-beam effects [6] (for collider studies), spin dynamics, and secondary particle emission (for electron-cloud and other studies). Virtual prototyping involves multi-physics analysis including electromagnetic, thermal and mechanical effects [7]. Such simulations are used, e.g., to control microphonics in superconducting structures. Codes used for advanced accelerator modeling [8–11] model the interaction of beams, lasers, and plasmas, but also require the inclusion of ionization, radiation reaction, single quantum events, spin polarized beams, and recombination. Modeling is essential to explore and gain insight into the complex phenomena of laser- and plasma-based concepts.

The techniques most widely used for simulations involving beams, lasers, and/or plasmas are variations on the particle-in-cell (PIC) approach, including electrostatic, quasi-static, and fully electromagnetic PIC. LPA simulations also use laser-envelope models. Electromagnetic simulations involving complicated geometries generally use finite element techniques or cut cell techniques.

Until recently, the dominant computing model in the field has been a pure MPI approach. However, in recent years many accelerator applications have moved to a hybrid MPI-OpenMP approach. The most recent advances include ports to multiple GPU- and Intel Phi-based architectures, including hybrid MPI-OpenMP/CUDA approaches. While a substantial amount of progress has been made in this area, most mainstream applications are using pure MPI or MPI+OpenMP hybrids.

C.1.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

In light of the P5 report [1], the computational needs for 2020/2025 fall into three categories: simulations in support of (1) high-priority domestic facilities at Fermilab, (2) high-priority off-shore facilities (i.e., LHC upgrades), and (3) R&D in advanced technologies (i.e., laser-/beam-plasma and dielectric accelerators).

1. *Simulations in support of high-priority domestic facilities:* The evolution of these activities is dominated by the shifted role of Fermilab to the Intensity Frontier. This includes PIP-II, DUNE, Mu2e, g-2, and PIP-III R&D. Successful execution of PIP-II depends on current activities including electromagnetics simulations for the PIP-II linac and beam dynamics simulations of all the various components of the Fermilab accelerator complex. Accelerator simulation efforts for PIP-III will require greater fidelity simulations with better statistics than ever before, due to the extremely small loss requirements that will follow from extreme high-power running.
2. *Simulations in support of LHC upgrades:* The evolution of these activities is dominated by the High Luminosity LHC Upgrade (HL-LHC). Similar to the previous paragraph, the emphasis on higher intensity in the injector chain will require large-scale, multi-physics simulations in order to predict losses, explore mitigation strategies, and optimize performance. In addition, the increased intensity and number of bunches will present new challenges to the beam-beam simulations. Such simulations are needed to maximize luminosity and hence discovery potential.
3. *Simulations in support of R&D in Advanced Concepts:* This area focuses on creating the next generation of accelerating structures (either plasma or dielectric), which can be excited by short, intense beams or laser pulses to sustain extremely high accelerating gradients. LPA and PWFA activities currently emphasize ≥ 10 GeV stages, improved emittance and energy spread control, and staging. DWA activities are focused on beam breakup control of the drive beam in the presence of large wakefields, and structure heating. Major activities are the BELLA Center [13], FACET[14], AWA [15], and potential upgrades on the 2020/2025 time scale.

Structure design and optimization cuts across all these areas. Virtual prototyping has the potential to dramatically reduce the time and cost to develop structures, to optimize their performance, and to reduce risk. End-to-end integrated simulation of the PIP-III linac consisting of multiple cryomodules will require 2-3 orders of more computing resources than current simulations of a single cryomodule.

For all the above, exascale modeling will involve scaling to $> 1\text{M}$ cores, new data structures for GPUs and Xeon Phi, new programming approaches, and new algorithms. Along with these priorities, DOE HEP supports other accelerator projects that will benefit from future HPC resources. Examples include ASTA, ATF, IOTA, UMER, R&D in high-field magnets, and R&D to understand effects that limit gradients in room temperature and superconducting cavities. Exascale activities will, in general, be carried out through collaborations involving national labs and universities.

In the 2020/2025 time scale we will have to accelerate three current trends: the move to deeper multi-level parallelism, the increased use of multithreaded shared memory programming techniques, and the improved utilization of instruction-level vectorization. The latter will probably require both advances in compilers as well as modifications of programming practices. Use of multithreaded techniques currently exists in OpenMP-based and CUDA-based GPU methods. While current efforts typically target scalability to a few threads or small number of GPUs, future efforts will require scalability that encompasses many threads and/or GPUs. Multi-level parallelism has its current realization primarily in multi-level MPI, hybrid MPI-OpenMP, MPI-CUDA, and MPI-OpenMP-CUDA. Some instances are application-specific, as with bunch-bunch train splitting. Multi-level parallelism is also used

for parallel optimization. The architectures of the exascale era will push us to 4- or 5-level parallelism, and involve scaling to millions of cores.

To make use of millions of cores, we will need software whose performance has been optimized for the exascale. This includes parallel FFTs, linear solvers scalable in memory and on multi-core computer architectures, parallel AMR capabilities, and technologies for load balancing such as parallel particle- and field-managers, all capable of running at exascale.

We expect even greater impetus for multi-physics modeling. Simulations that combine beam dynamics, electromagnetics, lasers, plasmas, and beam-material interactions would open a new era in accelerator design. It would enable, e.g., self-consistent modeling of radioactivation from dark current, from halos and ultra-low losses in high-intensity beams, and complete advanced concepts-based collider designs. The architectural complexity of exascale systems will present a challenge to efficiently componentize and share computational capabilities and components.

C.1.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

Raw CPU power is the driver for the majority of the needs of accelerator modeling. Storage needs are typically small compared with other areas of computational HEP. As an example of the CPU requirements, consider PIP-III. A 2015 INCITE project that included PIP-II [16] estimated that 8-bunch simulations over 4500 turns of the Main Injector and Recycler would require 10M core-hours on a current BG/Q system. Scaling for better statistics ($10\times$), longer simulations ($5\times$) and full machines (from 8 bunches to 588 bunches) require nearly 4,000 times the CPU. This represents only a fraction of the total effort required for a campaign of end-to-end simulations. Another example is provided by beam-beam modeling for HL-LHC [17]: Runs with 4000 coupled bunches, with 4 working points optimization (not even including the 8 crab cavity multipoles), with 3-level parallelization (with modest $100\times 100\times 512$ cores), would easily use a fraction of an exascale system. In regard to structure design, estimates indicate an expected need for 50M core-hrs/yr [18]. Finally, modeling of advanced concepts demands exascale resources [19]. This is especially true when simulating staged systems, and for parametric studies for tolerance to non-ideal effects. Such simulations can use 100 million CPU-hours per run or more, although reduced models can lower requirements to be in accord with available resources.

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C.2 COMPUTATIONAL COSMOLOGY AT THE EXASCALE

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C.2.1 Current Science Activities and Computational Approaches

Large-scale simulations play key roles in cosmology today, including: 1) exploring fundamental physics and probes thereof, e.g., dark energy, dark matter, primordial fluctuations, and neutrino masses, 2) providing precision predictions for a range of cosmological models, important for data analysis, 3) generating detailed sky maps in different wavebands to test and validate analysis pipelines, 4) understanding astrophysical systematics, e.g., baryonic effects, and 5) providing covariance estimates.

Cosmology simulation codes fit into two main categories: gravity-only (“N-body”) solvers and “hydrodynamics” codes that also include gas physics and associated subgrid modeling (e.g., cooling, astrophysical feedback, star formation). The tasks above require four kinds of simulations using a mix of these capabilities, depending on the specific application: 1) gravity-only and hydrodynamics simulations over a range of cosmological models to address the first and second tasks, 2) very high resolution large volume gravity-only simulations (for, e.g., large galaxy catalogs) and medium resolution large volume hydrodynamics simulations (for, e.g., thermal Sunyaev-Zel’dovich maps and Lyman-alpha investigations) to address the third task, 3) very high resolution hydrodynamics simulations including treatment of feedback effects to address the fourth task, and 4) a very large number (well beyond thousands) of moderately accurate gravity-only simulations to address the fifth task.

Approaches used today for the gravity-only solvers include particle-mesh plus short-range solvers (particle-particle or tree methods) [1, 2], pure tree methods [3, 4], and pure grid methods. Codes that include hydrodynamics coupled with an N-body representation of dark matter include grid-based hydro methods, typically using Adaptive Mesh Refinement (AMR) [5–8], Smooth Particle Hydrodynamics (SPH) [9], and Moving Mesh Methods [10].

Analysis of the data generated in the simulations is fundamental to addressing the research goals. Currently most of this occurs in post-processing, but the large amount of data from future simulations and increased computational expense due to more complex analyses will result in more reliance on in-situ approaches.

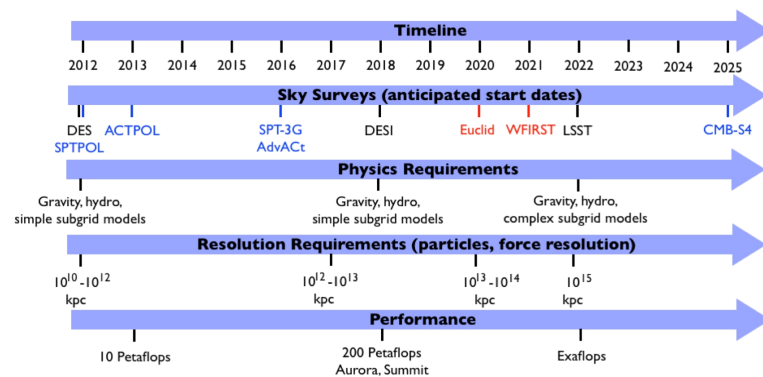


Figure 1: Timelines for cosmological surveys (blue: CMB, black: optical, ground-based, red: optical/NIR satellite) and supercomputing resources as well as simulation requirements. DOE HEP plays a major role in the ground based optical surveys and in some of the CMB surveys.

C.2.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

Figure 1 is an overview of the cosmological surveys that will dictate our science activities until 2025. Future activities will be similar to those today, but the simulations will have to keep up with observational improvements. Requirements are most stringent for optical surveys since they probe much smaller scales than CMB surveys. With increasing depth, fainter galaxies at

larger distances need to be resolved, requiring larger simulations (larger volumes and more particles) with more detailed physics implemented in the hydrodynamics codes.

For gravity-only simulations, the ultimate goal is to have enough mass resolution to resolve dark matter halos that host dwarf galaxies in a cosmological volume. These simulations will be needed for surveys such as LSST. In the next decade, we want to cover volumes of several Gpc and achieve a mass resolution of 10^6 - $10^7 M_\odot$. This means that we have to simulate up to a hundred trillion to a quadrillion particles, leading to memory requirements of ~ 4 -40 PB. In addition, the requirement to capture small-scale structure in large-volume simulations will demand finer force resolution, leading to very compute-intensive runs. Although the general approach to gravity-only simulations will likely not change much in the next decade, two main challenges exist: 1) global load balance and efficient communication to enable use of large parts of supercomputers (e.g., FFTs), 2) local load-balancing to follow the formation of complex sub-structure. Despite these challenges, no other major roadblocks are anticipated in the future.

In the case of grid-based hydrodynamics, scientific targets include modeling the Lyman-alpha forest at scales relevant to baryon acoustic oscillation measurements (with box-sizes of ~ 1 Gpc) while maintaining resolution to resolve density fluctuations responsible for the forest (~ 10 kpc). This leads to memory requirement in the range of 4-64 PB. Another challenge in modeling the forest arises from the fact that with future precision requirements the ionizing background can no longer be treated as uniform; radiation transport – and probably multigroup radiation transport – is going to become the norm. This will be computationally costly and will present enormous scaling challenges, depending on the method used. Similar requirements arise in other areas of cosmological hydrodynamic studies, e.g., in the study of clusters of galaxies, or the evolution of galaxies. The resolution needed to build physically reliable subgrid models for star formation and feedback, as well as AGNs, is much more stringent and of the order 100 pc, bringing again the total memory requirements into the PB range.

Improvements in grid-based hydrodynamics codes will focus both on on-node performance and load balancing. We will need to make effective use of all the cores on the new many-core nodes subject to low-memory per core and on-chip NUMA effects. This will require new approaches for working on domain-decomposed or block-structured AMR blocks of data using finer granularity. “Logical tiling”, used to control the working size of the block of data being operated on, can improve performance due both to improving the use of cache and allowing threading over blocks rather than loops. “Regional tiling” alters the layout of the data on a node by optimizing for the on-node NUMA effects. Both of these strategies fit well into the AMR paradigm in which the cost of metadata is minimized by keeping the size of individual AMR grids large.

SPH codes provide a different approach to the hydrodynamics problem. They have the advantage of computational efficiency compared to AMR codes but have suffered from problems such as lack of mixing in the past. Significant progress has been made recently with regard to a number of the accuracy concerns and new SPH techniques show great promise. In terms of implementations on future architectures, these improved SPH methods will be an attractive option. More work is needed in assessing the accuracy issues and also in the implementation of these new approaches on future architectures.

In addition to the performance-improving paths identified above, a major development component will be in sub-grid modeling. Here, uncertainties are currently very large and ensembles of runs will have to be carried out to understand the implications of different

modeling assumptions in detail.

Finally, as the amount of data generated by large simulations increases, we will move from primarily using post-processing for diagnostics to a mode of in-situ data analysis. This addresses the data storage issue but requires additional run-time optimization of the diagnostic routines as they will either compete with the simulation code for resources or require additional data movement to cores that will not compete with the simulation itself.

C.2.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

In general, all cosmological simulations are memory-limited. The memory requirements on next-generation supercomputers will be in the tens of PB for gravity-only simulations. Each time step would produce tens of PB of data, usually around 100 snapshots are needed for a complete analysis. This amount of data will probably go beyond the available resources in 2020/2025, therefore efficient in-situ analysis frameworks will be essential. In addition to a handful of very large simulations, we will also need to carry out suites of simulations of medium size.

For the hydrodynamic simulations, the memory requirements per particle or grid element are much higher than for the gravity-only solver because of the additional fields being evolved. For both the gravity-only and hydrodynamics runs, the size of the largest runs will be dictated by the total memory available on the supercomputer. As mentioned above, ensembles of runs will be carried out to explore the effects of different sub-grid models.

The current usage for cosmological simulations is roughly 400M core-hours at the LCFs and NERSC. Simulation requirements for surveys are still being processed by the community but are expected to be very substantial. The demand will scale faster than the available compute because of the need for multiple runs. The hydrodynamics runs will add a multiplicative factor of 20 beyond the N-body requirements. Finally, while some of the science can be accomplished using run-time diagnostics that do not require the storage of the solution, a large community would like to use the results for a variety of additional science tasks. This means that the storage of the output from at least several key runs of different types is highly desirable. Storing and moving such large amounts of data is very difficult and it is not clear 1) how to efficiently serve the data, and 2) how to provide analysis capabilities that can deal with very large datasets. The community has started to address these questions, but with increasing amounts of data a more rigorous and coordinated plan over the next decade is needed to address both of these issues.

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C.3 LATTICE QCD

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C.3.1 Current Science Activities and Computational Approaches

QCD is the component of the standard model of sub-atomic physics that describes the strong interactions. It is a strong coupling theory, and many of its most important predictions can only be obtained through large scale numerical simulations within the framework of lattice gauge theory.

These simulations are needed to obtain a quantitative understanding of the physical phenomena controlled by the strong interactions, to calculate the masses and decay properties of strongly interacting particles or hadrons, to determine a number of the basic parameters of the standard model, to make precise tests of the standard model, and to search for physical phenomena that require physical ideas which go beyond the standard model for their understanding.

Lattice field theory calculations are essential for interpretation of many experiments done in high-energy and nuclear physics, both in the US and abroad. Among the important experiments that have recently been completed, or are in the final stages of their data analysis are, BaBar at SLAC, CLEO-c at Cornell, CDF and D0 at Fermilab, and Belle at KEK, Japan. New data is beginning to arrive from the LHCb experiment at the LHC, and BESIII in Beijing. In the longer term Belle II will provide very high precision data. In many cases, lattice QCD calculations of the effects of strong interactions on weak interaction processes (weak matrix elements) are needed to realize the full return on the large investments made in the experiments. The uncertainties in the lattice QCD calculations limit the precision of the standard model tests in many cases, but in some, the experimental errors are larger than those from theory. Our objective is to improve the precision of the theoretical calculations so that they are not the limiting factor. A number of calculations are now reaching sub percent level.

Having precise values of heavy quark masses and the strong coupling constant are important for using Higgs boson decays at the LHC to test the standard model and probe for new physics. The most precise values come from lattice QCD and will be improved upon in the future. Lattice QCD is also important for better understanding of neutrino production via the axial vector current. The dominant domestic US high energy experimental program will be in neutrino physics for the foreseeable future.

The anomalous magnetic moment of the muon is an important experiment that was carried out at Brookhaven National Lab and was moved to Fermilab envisioning a factor of four improvement in the precision. Currently, there is a 3-4 standard deviation difference between theory and experiment. Most of the theoretical error is due to QCD effects, and there is a major effort within USQCD (and abroad) to improve lattice QCD calculation of these effects and thus reduce the theoretical error. If the theoretical error is not reduced on a time scale commensurate with the new experiment, the experimental effort will not result in a critical test of the standard model.

Beyond lattice QCD, lattice field theory calculations are in use to explore models for dynamical symmetry breaking (in contrast to the simple Higgs mechanism) and nonperturbative aspects of supersymmetry. These calculations are likely to grow in importance and computational demand in the 2020/2025 time period.

The United States lattice gauge theory community, organized as the USQCD collaboration, operates computing clusters at DOE labs that currently provide around 450 million conventional core-hours per year, as well as eight million GPU hours. In addition, about 300

million hours of time from the INCITE program at DOE computing centers is distributed among the US lattice gauge theory projects. Several lattice gauge theory groups have allocations at local centers or at XSEDE centers. For example, the MILC collaboration has a 2015 allocation of about 8.6 M core hours. On Blue Waters, the USQCD collaboration has 31.5 M node-hours split between high energy and nuclear physics calculations. (Note the distinction between core-hours and node-hours.) For 2015, about 110 M units of NERSC mpp time are devoted to lattice QCD under the Office of High Energy Physics and a comparable amount is devoted to Nuclear Physics research.

C.3.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

A number of white papers and reports have addressed the needs and challenges of computing for lattice field theory [1–6]. In the space available here, we can provide only a brief summary of the scientific goals and computational needs for the 2020/2025 time period. Broadly, the field needs to provide the theoretical input required to interpret current and planned particle physics experiments. The experiments are designed to study the properties of the standard model of elementary particle and nuclear physics, and more excitingly,

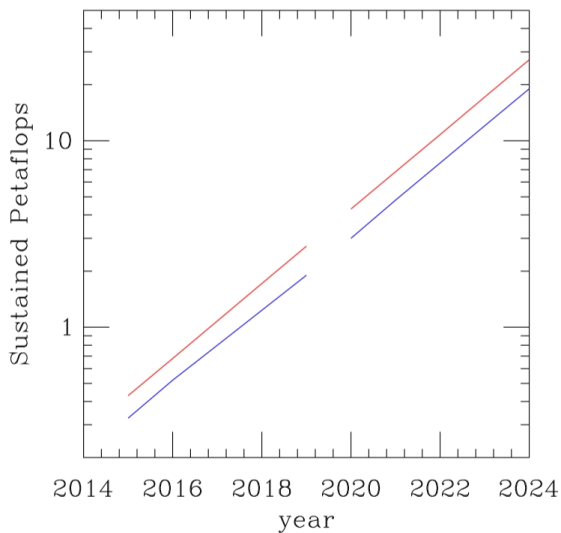


Figure 1: Sustained total performance needed on leadership (red) and capacity class (blue) systems as a function of time. Projections up to 2019 based on Snowmass Lattice Field Theory report. Future projects assume continued exponential growth.

to find evidence for new forces or new particles. Many of the parameters of the standard model such as the quark masses, strong coupling and elements of the CKM mixing matrix require input from lattice QCD to extract the parameter from experimental measurements. In many cases, more than one physical process can be used to determine a particular element of the CKM matrix. If these processes are studied and imply different values for the matrix element, that is evidence that there are additional interactions not included in the standard model. However, this requires high precision in both the measurement and the theoretical calculation. As one example, there currently is a small tension between the CKM matrix element $|V_{us}|$ determined in leptonic and semileptonic decays of the kaon. Improvements to both theoretical and experimental precision would be needed to find evidence for new physics. For kaon semileptonic decay, the error in $|V_{us}|$ from theory is about 50% larger than the experimental error.

To improve future calculations, we will reduce the spacing between grid points, increase the volume of the system, calculate with up and down quark masses at their physical values (including isospin breaking) and add electromagnetic effects. Taking into account the first three improvements, we would like to use a lattice spacing of 0.03 fm with a physical size of 7.5 fm. So, this could be a $256^3 \times 512$ grid compared to the $144^3 \times 288$ grid in production today. For the NERSC requirements study, it was estimated that we would require 160 billion (Hopper) core hours for the physics we want to do on this project, and we would be able to run on the order of 1 million cores. Including electromagnetism and isospin breaking

would increase the cost very roughly by a factor of two. Using different formulations for the lattice quarks, which helps to control systematic errors, could add up to a factor of 10, depending on the formulation.

C.3.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

An alternative planning approach is based on actual code floating point requirements. This was used in the Snowmass report which covers the period 2015 to 2019. Requirements are in terms of delivered Tflop/sec-years are presented in Table 1. The sustained speeds are not required for a single job, but for all jobs running concurrently. A greater number of jobs can be expected to run on the capacity hardware than on the leadership class computers.

The requirements are exponentially rising and in broad terms, it would be reasonable to expect that to continue beyond 2019 (see Figure 1). Of course, we hope for algorithmic improvements which have come several times in the past. However, these improvements have been used to improve the quality of results with current resources, not to reduce the requested

Year	Leadership Class (TFlop/sec-yrs)	Dedicated Clusters (TFlop/sec-yrs)
2015	430	325
2016	680	520
2017	1080	800
2018	1715	1275
2019	2720	1900

Table I: Resources assumed for the planned program. Conversion factor for sustained Tflop/sec-years, assuming 8000 hours/yr, is 1 Tflop/sec-yr = 3.0M core-hr on IBM BG/Q hardware.

resource. Perhaps that will change in the future. In any case, it is worth emphasizing that research in algorithms and investment in people who can both code efficiently and develop new algorithms are very important.

Traditionally, lattice QCD has not had very large storage requirements. This is changing to some extent because of new preconditioning techniques that require storage of many eigenvectors on each configuration. For the year starting July, 2015, members of USQCD requested 1.3 PB of disk storage and 2 PB of tape. That is split between nuclear and particle physics. For lattice field theory calculations, the required number of floating point operations grows as a higher power of the inverse lattice spacing than

the number of grid points. On that basis alone, we expect slower growth of storage needs.

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C.4 HPC IN HEP THEORY

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C.4.1 Current Science Activities and Computational Approaches

HPC computing in HEP theory can be broadly classified into activities relating to new physics searches, and efforts to make precise predictions for Standard Model (SM) reactions.

Among existing new physics models, supersymmetric extensions of the SM are promising candidates for discovery at the Large Hadron Collider (LHC) or at dark matter experiments. Even in its most minimal form (the MSSM), supersymmetry has over 100 free parameters, and models in different regions of parameter space can therefore have very different experimental signatures. Converting measurements into limits on the parameters of the theory requires a detailed simulation of a plethora of parameter points. This can be achieved, for example, in the framework of the phenomenological MSSM, or by using effective theories and simplified models. Several tools have been developed to perform the subsequent limit setting procedure in a fully automated fashion, including Atom, FastLim and CheckMate. All approaches have in common that they require large computational resources, due to a wealth of experimental data.

Scans of new physics parameter spaces typically involve generating sets of $\sim 250\text{K}$ - 500K models, and simulation of particle physics events at the LHC for each one. For a single set of models at $25/\text{fb}$, the simulation data takes up about 1-2TB and involves about 1-2M CPU-hours of computing time. Simulation data are archived. The software typically consists of single-core executables. Because of the Monte-Carlo approach used in the simulation, a trivial parallelization is easy to implement, and memory limitations on new architectures are not restrictive at present.

The computation of SM reactions at high precision has reached a high degree of automation, with next-to-leading order (NLO) QCD perturbation theory being the standard means of obtaining cross sections at collider experiments like the LHC. These calculations have been instrumental in extracting properties of the Higgs boson, and they will continue to play a dominant role in the future. The field is rapidly moving towards full automation of NLO electroweak corrections. Dedicated next-to-next-to leading order (NNLO) QCD calculations exist for important reactions such as Higgs-boson production, Drell-Yan lepton pair production, di-photon and vector-boson pair production, top-quark pair and single-top production, both at the inclusive and at the fully differential level. Many of those have been completed in the past years. First results for Higgs-boson and vector-boson plus jet calculations have just been obtained, and the first complete three-loop result for inclusive Higgs-boson production at a hadron collider was also just presented. These ultra-precise computations will become mandatory as future data leads to decreased experimental errors and theory uncertainties begin to limit our understanding of Nature. The high precision of fixed-order calculations is matched by a correspondingly high precision in resummation, obtained either through more traditional approaches or through soft-collinear effective theory (SCET). The matching of fixed-order calculations to parton shower Monte-Carlo event generators used to make particle-level predictions for experiments has been fully automated at the NLO in the past years, and first solutions at NNLO exist. The need for precise theory input to experiments requires multiple predictions from either of these calculations, leading to a strain on existing computational resources.

Typical NLO QCD calculations currently require between 50K and 500K CPU-hours each, with storage needs between 0.1 and 1.5 TB. The results can be re-analyzed to obtain predictions for different SM parameters. NNLO differential calculations require between 50K

and 1M CPU-hours each. Parton-shower matched predictions require of the order of 100K CPU hours, depending on the complexity of the final-state. Programs have been parallelized using both MPI and OpenMP, as well as POSIX threads. First studies exist for scalable applications on accelerators, and one of the generators running on Xeon Phi is ready for physics analysis. In a recent study, NNLO computations of vector/Higgs boson plus a jet have demonstrated strong scaling up to 10^6 threads using a hybrid MPI+OpenMP approach. Ideas on how to extend beyond this level are being studied.

C.4.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

Scans of new physics parameter spaces will likely be done in a manner similar to today, and they will involve a similar sample size during the course of LHC Run II. For a single set of models at the full luminosity, the simulation data will consume ~ 100 M CPU-hr of computing time and take up ~ 100 TB of storage space. If possible, simulation data will be archived, possibly on tape. No significant evolution is expected on the software side, though it can be expected that accelerators with i386 instruction set can be utilized.

Precision calculations in the SM will likely move to a stage where NNLO sets the standard in the same way that NLO sets the standard today. Matching these calculations to resummed predictions and particle-level simulations, and improving the resummation implemented in Monte Carlo programs itself will be a key task of the community over the coming years. At the same time the full exploitation of higher-order calculations to extract parton densities from experimental data will play a crucial role to reduce theoretical uncertainties stemming from the parametrization of QCD dynamics at large distances.

Computational approaches are likely to rely more and more on multi-core architectures and HPC. Current cutting edge calculations have demonstrated that HPC facilities allow to increase the final-state multiplicity in NLO calculations by at least one. Algorithmic advances will push the limits further. When using NLO calculations as an input to NNLO calculations by means of qT subtraction or jetiness subtraction, the fast evaluation of NLO results using HPC will be crucial. Similar considerations apply to NNLO calculations making use of antenna and sector improved residue subtraction.

C.4.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

Both new physics searches and precision SM calculations will require considerable support from supercomputing centers and data centers, if the pace of development shall be kept. An estimate may be extracted from the scaling of NLO calculations, performed during the past years: The calculation of W/Z/Higgs production requires an increase in computing power by a factor 3-4 for every additional jet in the final state. Memory requirements increase in a similar manner. For NNLO calculations the projection is more difficult. Complete NNLO results are available only for electroweak objects with zero or one jets in the final state, and different techniques are used to obtain these various results. The available calculations point towards an increase in computing time by about a factor of 10 for each additional object in the final state.

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C.5 ENERGY FRONTIER EXPERIMENTS

Authors: K. Bloom and O. Gutsche

C.5.1 Current Science Activities and Computational Approaches

The Energy Frontier thrust of High Energy Physics will be focused on the Large Hadron Collider (LHC) through 2025 and probably for many years beyond. The LHC, operated by CERN, the European particle physics laboratory, collides protons (and sometime ions) at the highest energies ever achieved in the laboratory. In 2015, the LHC is resuming operations after a two-year shutdown at a center-of-mass energy of 13 TeV, much greater than the 8 TeV that was achieved in 2012. The particle collision rate (instantaneous luminosity) will increase by a factor of two. These collisions are recorded by four independent multi-purpose detectors, each of which is operated by scientific collaborations of hundreds to thousands of physicists. The largest U.S. involvement is in the ATLAS and CMS experiments. In this paper we will use CMS as an exemplar; similar arguments about the evolution of the scale of resource needs would apply to ATLAS.

The 2010-12 LHC run (Run 1) had a prodigious scientific output, and the coming run could be even more remarkable, if Nature is on our side. The most significant result from the Run 1 was the discovery of the Higgs boson [1], announced in 2012 to worldwide acclaim and recognized in the awarding of the Nobel Prize in 2013. But this was just one physics result – the CMS Collaboration has submitted nearly 400 papers so far on measurements from the 2010-12 data [2]. Searches for new phenomena such as supersymmetric and/or dark matter particles will take center stage in the 2015-18 run (Run 2), as the increase in LHC collision energy will open opportunities to observe new heavy particles, should they exist.

CMS records in a typical Run 2 year about 5 PB of raw data per year; another 12 PB of raw simulations are also produced, making the Energy Frontier experiments especially data-intensive within the context of HEP. These data must be processed and then made available for analysis by thousands of physicists. The computing model for the LHC experiments has been one based around high-throughput computing (HTC) rather than high-performance computing (HPC), as the computing problem is embarrassingly parallel. CMS runs computing jobs at many independent facilities spread around the world. In general, input datasets are pre-placed at the facilities, and computing jobs are routed to the correct facility. In the coming run, there will be greater use of a worldwide data federation that makes any CMS data available to any CMS computing site with low latency [3]; this will give greater flexibility in the use of resources. The computers at the facilities are commodity machines, with x86 processors that run Linux. Jobs typically require up to 2 GB of memory. CMS is now able to run in a multi-threaded mode, with multiple jobs sharing the memory available within a processor. The resources are all available through the Worldwide LHC Computing Grid [4] and are provisioned through glideinWMS [5], a pilot system with a global job queue. There have been efforts to use facilities beyond those dedicated to CMS, such as NERSC, SDSC and cloud systems, with increasing success, but only Linux-based resources have been used. Strong demands on computing resources for the current run require us to increase usage at these centers, and in particular to make greater use of the HPC resources available there.

C.5.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

2020 will mark the start of Run 3 of the LHC [6]. The accelerator performance will only be slightly modified compared to Run 2, with instantaneous luminosities increasing only by

about 15% over the expected values in 2018. Thus no significant changes are planned for the CMS computing model at that time. Modifications will be evolutionary, to scale the Run 2 tools to handle increases in the data volume. x86 will remain the primary computational architecture, but we will expand the use of multi-core capabilities to improve memory usage. As ever-larger datasets will require expanded computing resources, there will be greater efforts to use resources beyond those owned by the experiments, such as those in academic and commercial clouds and all architectures available at ASCR computational facilities. We expect that there will be a greater reliance on data federations rather than local data access as network bandwidth improves.

2025 could lead to much more revolutionary changes. It will mark the start of the High Luminosity LHC (HL-LHC), with instantaneous luminosities a factor of 2.5 greater than those of Run 3. The experimental collaborations are planning on major upgrades to their detectors to accommodate the greater density of particles that will be produced in the collisions [7]. See Figure 1 for the expected increases in trigger rate, data volume and processing time. If we were to only take advantage of the expected growth in CPU power for fixed cost at 25% per year and in storage at 20% per year, we would expect deficits of a factor of four or twelve in CPU and a factor of three in storage under the assumption of fixed budgets for computing resources, even after accounting for potential algorithmic improvements. Clearly changes to the current paradigm must be considered. For instance, LHC computing will need to make use of advanced computing architectures, such as HPC systems, GPUs, specialized co-processors and low-power mobile platforms. Research and development efforts on the software environment for these architectures are in progress. More dynamic provisioning systems will be needed, so that experiments can control costs by purchasing resources for average usage levels and then renting additional resources needed for peak usage. It is possible that by 2025, most processing resources will be supplied through dynamic infrastructures that could be accessed opportunistically or through commercial providers. Studies on how to create an elastic virtual facility have begun. Such facilities would need to access the data that is stored on systems owned by the experiment. These systems would probably need to be served by a content delivery network that took advantage of dynamic replication, predictive placement and network awareness. Reliable high-bandwidth networks will be needed to transport the data into the clouds. A center with tens of thousands of cores would need to have multiple 100 Gb/s links to serve the input data. Fortunately such bandwidth is expected to become more commonplace between now and 2025.

C.5.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

We extrapolate the resource needs of CMS for three sets of running conditions: the start of LHC Run 3 in 2020, and the HL-LHC in two scenarios starting at 2025, one low-luminosity and one high-luminosity scenario. The extrapolations are given in Figure 1. The reference is the performance of LHC Run 2 at 30 interactions per beam crossing assuming two reconstruction passes over data and MC per year [8].

We restrict ourselves to quoting CPU needs only for central workflows and also do not include any improvements in the software into the extrapolation. From experience, a factor of two improvement in reconstruction time should be feasible; in the last four years, CMS managed a speedup of a factor of four. Analysis activities would also have to be added to determine a complete picture of resource needs.

	2016	2020	2025	2025
	LHC Run 2	LHC Run 3	HL-LHC Low Scenario	HL-LHC High Scenario
Integrated <u>Lumi</u> [/fb]	45	45	≥ 300	≥ 300
Peak Pile Up (Av./Coll.)	30	50	140	200
Data taking rate after Trigger [kHz]	1	1	5	7.5
Data taking per year [M seconds]	5	7	7	7
Number of Events: Data	6.00E+09	9.00E+09	4.00E+10	7.00E+10
Number of Events: MC (1.3 times data)	8.00E+09	1.00E+10	6.00E+10	9.00E+10
RAW data volume [PB]	5	10	148	246
Analysis data volume [PB], single pass	3	5	65	142
Simulated MC volume [PB]	12	17	85	128
Analysis MC volume [PB], single pass	3	6	84	184
Total CPU needs [<u>MCPUhrs</u>]	877	4,436	90,356	286,289

Figure 1: *Estimated resource needs for CMS.*

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- [1] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, Phys. Lett. B716, 30 (2012), 10.1016/j.physletb.2012.08.021
 - [2] See <http://cms.web.cern.ch/org/physics-papers-timeline> for a timeline of CMS physics publications sorted by physics topic.
 - [3] See for instance K. Bloom, “CMS Use of a Data Federation”, J. Phys. Conf. Ser. 513 042005 doi:10.1088/1742-6596/513/4/042005.
 - [4] See <http://wlcg.web.cern.ch> for more information
 - [5] I. Sfiligoi et al., “The Pilot Way to Grid Resources Using glideinWMS”, 2009 WRI World Congress on Computer Science and Information Engineering, Vol. 2, pp. 428-432. doi:10.1109/CSIE.2009.950.
 - [6] For details of the LHC long-range schedule, see <http://lhc-commissioning.web.cern.ch/lhc-commissioning/schedule/LHC-schedule-update.pdf>
 - [7] For many more details on the upgrades to the detectors and anticipated changes to the computing model, see CMS Phase-II Technical Proposal, in preparation, especially Chapter 8.
 - [8] Planning spreadsheet: <http://cern.ch/go/T7LB>

C.6 HEP EXPERIMENTS: DATA MOVEMENT AND STORAGE

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C.6.1 Current Science Activities and Computational Approaches

The landscape of experimental HEP is strikingly diverse. In addition to the large LHC experiments, there are a number of Intensity and Cosmic Frontier experiments at all sizes. While the LHC will continue to be the largest data producer in 2020-25, experiments like DUNE and LSST present their own challenges, and so do smaller experiments.

The ATLAS and CMS experiments produced a few tens of PB of data during LHC's Run 1, 2010-12. Roughly a third of this is from the detector, the rest is simulation. The $\sim 2:1$ relationship is likely to be stable; the output rate from the trigger system is thus a rough guide to the increase in data volume over time. Both experiments started with a data taking rate of $\sim 150\text{Hz}$ that increased to $\sim 300\text{--}600\text{Hz}$ at the end of Run 1. For Run 2 (2015-2017) the initial rate is 1kHz and is expected to reach $\sim 10\text{kHz}$ by 2025. In the ten years of HL-LHC running (roughly 2025-35) each experiment will transition from $\mathcal{O}(100)$ petabytes to $\mathcal{O}(1)$ exabyte of data.

Two copies of the RAW data are archived to tape. One is conceptualized as a “backup” copy at CERN, while the other is distributed as an active copy across the Tier-1 centers worldwide for each experiment. Only a single copy of the processed data and simulations is archived. The RAW data from the detector is understood to be the most precious, while all else can be reproduced, if corrupted or lost. Tape is the preferred archival technology because of its durability and lower cost.

It is useful to divide the path from raw data to science results into two steps. First, each collaboration centrally produces official datasets from raw data and simulation. Second, small groups of collaborators produce private custom datasets from (subsets of) the official data, and analyze them to derive publishable results. The first step is consuming ever increasing amounts of CPU power, to produce an output format optimized for maximal flexibility to support the full diversity of the LHC program, allowing for continued improvements in physics object definitions and selections. The second step typically begins with each small group producing “slimmed” and “filtered” custom datasets, resulting in smaller event sizes, fewer events, and substantially faster to process data formats; further analysis tends to be I/O limited. The custom datasets comprised $\sim 4\text{--}400\text{TB}$ per individual group during Run 1, and are expected to grow at a similar rate as the official data.

LHC computing was a huge success during Run 1. The speed and robustness with which results were produced exceeds most prior large scale experimental HEP programs, despite the significant increase in scale in data volumes and computing needs. Thus, any proposed change in how data is stored, transferred, processed, and managed, should result in cost savings without loss of speed and robustness in producing physics results. It is worth noting that the LHC program globally involves $\mathcal{O}(10\text{k})$ people. At a cost of $\$100\text{k}$ per FTE, this amounts to $\$1$ Billion in global personnel costs, dwarfing the annual LHC computing budgets worldwide. Therefore, a “cost-effective” solution must maximize the effectiveness of the global human capital, or it will invariably lead to loss of efficiency in producing science results.

C.6.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

When considering the evolution of scientific and computational activities, we distinguish “technical” and “sociological” opportunities with the aim of identifying more cost-effective solutions as just discussed above.

Among the technical drivers, we identify three high level concepts. First, the trend towards vectorization and parallelization driven by a larger number of simpler cores on commodity/HPC hardware. Second, the advent of Big Data technologies, and third the advent of highly elastic computing. The three combined with the divergence of CPU and I/O needs for the two steps discussed above are likely to drive the need for integrated workflow management across a diverse set of resource types.

In 2025, physics and detector simulation, and raw data processing may be done on three different hardware platforms. Disk buffers in front of tape archives may be minimal in size, as tape retrieval is tightly integrated into the data processing workflow. Such a workflow might be scheduling disk buffers at a remote processing center in addition to disk buffers in front of the tape archive, and the wide area network between the two disk buffers. By 2025, the majority of disk space in ATLAS and CMS may thus be in the analysis systems. These systems may be heavily I/O optimized using disk scheduling ideas from Hadoop/MapReduce, in combination with an I/O layer optimized for partial file reads that is already standard today in ROOT.

Finally, all of the above must be highly elastic. ATLAS and CMS take months to produce releases validated for large-scale simulation and data processing. Once the release is validated, the time for simulation and processing would be shrunk as much as possible, leading to large spikes in desired resource consumption. Since commercial Cloud providers already operate distributed exascale systems, it is natural that ATLAS and CMS will want to use such systems by 2025.

The most important opportunity for cost savings is in placing the divide between the (centrally produced) official data, and custom data produced by the scientists. It may be beneficial to centrally produce data formats that are much less CPU intensive to process, trading flexibility against reduced size per event. To make up for the lost flexibility, such formats might be produced more often, leading to more versions in use at a given time. Whether this will lead to more human inefficiency than gains in computational efficiency needs to be explored.

The common theme that emerges is that future computing approaches will need to be much more agile, dynamic, and elastic in order to support a more diverse set of hardware resources at scales that frequently change throughout the year.

C.6.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

Data storage and movement services needed to meet HEP needs in the 2020 timescale already exist for the LHC and other HEP experiments, but there are challenges in scaling up by a factor of 10-18 in I/O bandwidth and data volume [3], and to apply these services to collaborations, which though smaller scale in terms of data volume, can benefit from existing infrastructure and architectures. In addition, services are in the process of becoming more agile, but that process is still far from complete. Common facility Services include:

- Long term archival of data (tape storage)
- Dataset services (e.g., data location aware staging service)
- Federated storage access, local posix and WAN data access protocols
- Network infrastructure
- High throughput, low latency access storage for analysis computation
- High throughput, low latency storage for production computation
- Tape backed low latency disk cache
- Global catalog (or mappings to local catalogs)
- Management and monitoring infrastructure

Opportunities and challenges in these service areas are:

- Delivering data is still a major challenge; storage systems do not perform well with random access patterns from multiple users. Services and storage architectures need to convert inefficient patterns into efficient requests to the underlying storage hardware. An example of this is SAM [1], which understands the physical location of files on tape and attempts to optimally stage experiment defined datasets from tape to disk. A related challenge will be to effectively utilize the anticipated 2 GB/s bandwidth of tape drives.
- Smaller HEP collaborations are often limited, not by resource restrictions, but in organizing data to efficiently deliver it to computational workflows. Providing tools and architectures to aid with this could be a great benefit.
- The “storage element” (storage organized as a POSIX-like filesystem with an access interface such as GridFTP) tends to be a too-low-level abstraction, especially when multiple storage systems are involved. The human overhead of maintaining filesystem consistency is high.
- The largest data management systems (CMS’s PhEDEx, ATLAS’s Rucio) have failed to gain widescale adoption outside their respective experiments. A successful reuse example is SAMGrid, adopted by several HEP experiments. This area has had a poor track record of moving computer science innovations from R&D to production. Future experiments would benefit if data management services could be generalized and made production ready.
- The field has rallied around ROOT as a common I/O layer, allowing investments in a single software package to benefit the entire community. However, the core ROOT IO community is too small; we have the opportunity for significant improvements but not the scale of effort to achieve them.
- Standardized cloud based storage interfaces (S3, CDMI, WebDAV) have not been taken advantage of. Work is needed to assess if they can meet production processing requirements.
- Smaller scale HEP collaborations not directly affiliated with National Labs are often on their own for providing an active data archive and the expertise to manage it. Work is underway to provide storage services to these experiments on a case by case basis. A cohesive set of services for storing and retrieving data at a set of National Labs would be a significant benefit.

Facility based long-term tape storage will be the most affordable option in the 2020 timeframe, less than \$20/TB, and capacity scales better than needed for the HL-LHC run. Tape form factors will likely be the same and libraries will likely still be sized at around 10,000 slots. Tape drive bandwidth is expected to increase by about a factor of $8\times$ to 2 GB/s [2, 4]. Providing data to these drives at full rate will be a challenge. The takeaway for storage is that tape storage and network expenditures will likely be lower, while CPU, disk and tape drive costs will likely be higher than current expenditures. Tape libraries will likely need to be refreshed prior to HL-LHC luminosity running. For more information, see Refs. [3, 4].

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C.7 COSMIC FRONTIER EXPERIMENTS

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C.7.1 Current Science Activities and Computational Approaches

The current experiments supported (directly and indirectly) by DOE HEP facilities are cosmic microwave background experiments and low redshift dark energy experiments. The CMB experiments include both space-based experiments (Planck) as well as ground-based experiments; the key science goals are inflation (including a detection of the gravitational waves from inflation), dark matter and dark energy. The dark energy experiments aim to use imaging and spectroscopic surveys to constrain the expansion and growth history of the Universe through weak gravitational lensing and observations of the galaxy distribution (including correlation functions, number counts etc). Exemplars of this are the recently completed Baryon Oscillation Spectroscopic Survey (BOSS), the extended BOSS (eBOSS) survey (ongoing) and the Dark Energy Survey.

Exact analyses of these data are computationally intractable, and therefore one must often rely on Monte Carlo methods to characterize (a) the instrument responses and biases, (b) observational effects from incomplete data/cuts, (c) statistical uncertainties and (d) astrophysical systematics. The generation and analysis of these mock catalogs is often the limiting step in every analysis. For example, to reach 1% statistical uncertainties, the Planck group at NERSC considered 10^4 realizations, each with $O(10^3)$ maps. Low redshift galaxy surveys rely on large numbers of N-body simulations to model the nonlinear formation of structure.

Traditional astronomical data sets are often 10s of terabytes, but are often broken down into very large numbers $O(10^6)$ files, making them unwieldy for storage. Tools to efficiently access these data are either often missing or have yet to see widespread usage. Traditional HPC models are often poorly suited for the analysis of such data sets. An associated challenge is the distribution of these data (and related simulations) amongst large and geographically diverse collaborations.

A third class of experiments supported by DOE HEP facilities are dark matter experiments. These can be divided into three classes – collider production (covered in the Energy Frontier), indirect detection (Fermi Gamma-Ray Space Telescope, not part of this timeline) and direct detection. Direct detection experiments use WIMP-nucleon elastic scattering to put constraints on the WIMP mass. The current Generation-2 program has two main experiments: LUX/LZ (Xenon) and SuperCDMS SNOLAB (Ge, Si) both of which will be located underground to shield them from cosmic rays. They are expected to start operating around 2018-2019.

The analysis of direct detection data closely follows the particle physics model in that there are particle reactions in a detector with associated detector information read out. Because of the low expected WIMP signal rate, a thorough understanding of backgrounds is the critical part of direct detection experiments. Monte Carlo simulations along with dedicated calibration events are used to estimate backgrounds from the detector and associated shielding. Up until now, the data sets from these experiments have been small and computing has not been a priority.

C.7.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

The next decade will see an order of magnitude increase (or larger) in data volume and science reach from the next generation of experiments. Each of the three major areas described

above have next generation experiments in the planning/construction phase – the CMB experimental community is working towards a Stage IV CMB experiment (CMB-S4) in the early 2020's; the BOSS and eBOSS surveys will be succeeded by the Dark Energy Spectroscopic Instrument (DESI) ($\sim 2019-2024$), and the Large Synoptic Survey Telescope (LSST) will be the premier imaging survey throughout the next decade ($\sim 2020-2030$). The science reach of these surveys will require significant increases in computational/storage needs, both for the analysis of the raw data and its cosmological interpretation. We discuss the needs of these surveys individually below. (An important assumption in all of this is that we will be able to maintain computational efficiency on the next generations of hardware, including the expected heterogeneous processing architectures, bandwidth to memory and storage, etc.)

The LSST survey will survey half the sky in multiple bands to unprecedented depths; in additions, it will provide a time-domain view of the sky by surveying it every few days. The primary goals of the HEP LSST effort are to probe the nature of dark matter and dark energy through weak gravitational lensing and galaxy clustering. The weak gravitational lensing signal is very subtle and easily swamped by systematic effects from the atmosphere and detector, as well as imperfections in the analysis algorithms. To quantify/mitigate these systematic effects, the LSST project is undertaking a very detailed program to simulate all aspects of this measurement. The estimated compute cost for this process is $\sim 10^7$ compute hours and 100 TB of storage. The other dominant cost for the LSST analysis are the simulations necessary for quantifying the uncertainties in the measurements. The LSST DESC collaboration estimates requiring ~ 2500 simulations, each with a cost of ~ 1 M CPU hours, for a total of $O(10^9)$ CPU hours and 100 TB of storage. The other analysis tasks are expected to be subdominant to this.

The DESI survey aims to obtain redshifts to ~ 25 M galaxies over $\sim 14,000$ sq. deg. of the sky. This represents an order of magnitude increase over current galaxy surveys. The

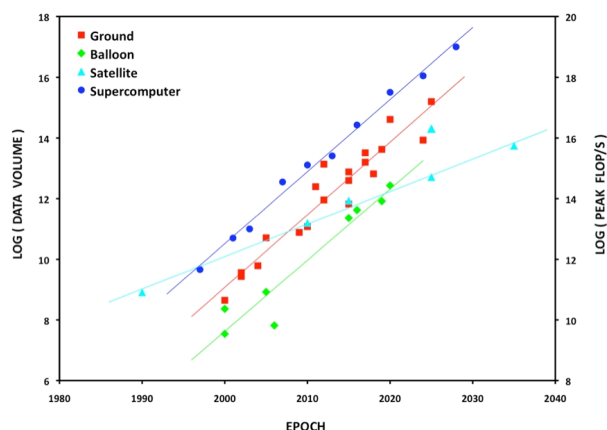


Figure 1: *Exponential growth over the past and coming 20 years of CMB data volumes gathered by ground-based, balloon-borne and satellite missions, and supercomputer peak performance using the NERSC flagship system as a proxy.*

estimated computational and storage requirements for the survey are ~ 100 M CPU hours and $O(1)$ PB of data storage. As with the other projects described here, the other dominant cost will be the simulation requirements for error quantification (although these should be less demanding than the LSST case).

The CMB-S4 experiments aim, amongst other goals, at constraining both the CMB polarization caused by gravitational waves from the inflationary epoch as well as constraining the total neutrino mass at unprecedented precision. These will provide astrophysical windows into scales impossible (or very hard) to reach by traditional particle-physics experiments. Reaching these goals will require a 1000 fold increase in the data volume compared to the Planck satellite, and

will require improvements in analysis algorithms as well as their implementations to make best use of the architectures of the next generation of supercomputers. We can estimate both storage and compute needs by scaling from experience with the Planck satellite. The

Planck satellite used 10^8 CPU-hours for its analysis, a CMB-S4 experiment will require 10^{11} CPU hours. Planck used $O(250)$ TB in 2014, but this constrained us to storing $O(10^6)$ maps instead of the full $O(10^7)$; CMB-S4 will need $O(10)$ PB in 2020.

An important set of considerations for these next generations of surveys are the large and geographically diverse collaborations and serving different views of the data to them. Furthermore, the traditional data models and file systems do not scale well to these data sets, since they often result in $O(10^9)$ files making accesses/queries time consuming. The collaborations will therefore benefit from tooling to simplify these tasks. Furthermore, different analysis tasks often have very different scales of parallelism, making them hard to chain together under traditional MPI/OpenMP models. Finally, issues of openness and reproducibility are becoming very important considerations for these collaborations.

Data volumes and processing needs for the G2 direct detection experiments, while larger than current experiments, are expected to be small. LUX/LZ expects 1.2 PB of data/year, with 250 cores needed for prompt processing and 3k cores needed to reprocess one year of data in three months. Including Monte Carlo simulations the LUX/LZ plan includes support for 10 PB of disk storage and 10k cores during operations.

SuperCDMS, which is concentrating on lower WIMP masses, will have data volumes of the order of 100 TB/year, with a very small number of cores needed for prompt processing. The plan is to adopt a very distributed computing model to be able to access as much CPU as possible at collaboration sites to minimize the time needed for data reprocessing needs and Monte Carlo production. The overall CPU needs will be similar to LUX/LZ.

C.7.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

The previous section discusses the needs of the three major cosmic frontier surveys individually. We summarize these below:

- Compute: $O(10^{11})$ CPU hours. This is dominated by the anticipated requirements of the CMB-S4 experiment, with the other two experiments, estimating about two orders of magnitude less computation. Therefore, this should be able to accommodate an expanded compute requirement from these surveys.
- Data: $O(10)$ PB. This is again dominated by CMB-S4, with the other surveys requiring an order of magnitude less data.
- Serving the raw and reduced data to large, geographically diverse collaborations.
- The ability to support a broad range of analysis/programming paradigms including (but not limited to) traditional HPC usage, massively (but trivially) parallel analysis tasks, to exploratory analyses.
- Developing the infrastructure to enable reproducibility/openness.

C.8 INTENSITY FRONTIER EXPERIMENTS

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C.8.1 Current Science Activities and Computational Approaches

Neutrino Experiments: Past and existing neutrino experiments such as MINOS, T2K, Daya Bay and Nova produce a relatively modest amount of data in comparison to LHC experiments. Data transfer, storage and production processing can be managed by a few experts exploiting a few identified institutional clusters and mass storage systems.

The reactor experiments require only fairly simple reconstruction algorithms due to the physics of their interactions and by careful design of their detectors. More important is a careful understanding of background, energy resolution and energy scale systematics. This emphasizes the need to produce large MC simulation samples. A simulation or real data processing campaign requires order 100s-1000s of CPU-months and makes use of commodity institution clusters.

Accelerator-based neutrino experiments tend to require more sophisticated reconstruction software and produce larger data volumes. T2K uses the Super-Kamiokande water Cherenkov detector is read out by about 14,000 PMTs. MINOS and Nova are scintillation detectors; Nova reads out approximately 300,000 channels. Large MC simulation samples equivalent to 10-100 \times the size of real data can be required. These detectors employ a reconstruction technique that involves fitting events to pre-generated detector response patterns. These detectors require approximately an order of magnitude more CPU than reactor experiments and their experiments tend to employ Grid resources to satisfy their needs.

Belle II Experiment: The Belle II Collaboration includes more than 600 scientists from 100 institutions in 23 countries. The U.S. membership on Belle II is now 13% of the collaboration from 14 institutions. Belle II has adopted a distributed computing model based on the grid. The Belle II computing Memorandum of Understanding states that “Each Belle II member institute provides, either by itself or in collaboration with other institutes at a regional or national level, the computing resources to produce, store, and make available for analysis a fraction of the total dataset for Belle II and to carry out a fraction of the overall physics analyses. The fraction corresponds to the fraction of PhDs in the international Belle II collaboration.”

C.8.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

Neutrino Experiments: The next generation Deep Underground Neutrino Experiment (DUNE) employs a 40kton liquid argon time-proportional chamber (LArTPC) far detector with 1.5M channels reading wires spaced every 5mm and acquiring waveforms at 2MHz for about 5ms. This produces approximately 10-20 GB per “event”. In order to be sensitive to supernova bursts the readout must be capable to sustaining 10s of seconds of data collection. Such full-stream readout can produce 100s of Exabyte per year. However, most of the ADC samples will be noise and can be discarded by using “zero suppression” technique in which low-threshold portions of the waveform are discarded. This can reduce the raw data rates to the TB/year.

The DUNE LArTPC is incredibly fine-grained compared to other neutrino detectors (except bubble chambers). Traditional reconstruction techniques will, at best, scale linearly with the number of channels and may scale as worse as N^3 and novel techniques exploiting the unique characteristics of LArTPC are envisioned. At the very least, it is expected that production processing must exploit Grid resources.

Belle II Experiment: The Belle II distributed computing system must handle ~ 85 PB data volume for each year when the SuperKEKB accelerator is operating at design luminosity. The Belle II computing model includes several tasks such as raw data processing, Monte Carlo event production, physics analysis, and data archiving. Belle II has adopted the DIRAC framework for their Grid system. DIRAC provides both a workload and data management system along with other systems, such as data creation/manipulation workflow system, metadata catalog system, etc.

The Belle II software/computing workflow has numerous elements. At the core is the standalone Belle II software framework (BASF2) and external dependencies (Geant4, ROOT, etc.). The code is currently distributed on the grid using CVMFS servers. Grid sites are deployed with commodity machines (x86 processors that run Linux) and require queuing software (HTCondor, SLURM, etc.) and Grid middleware (gridftp, voms, etc.). Currently Belle II jobs are submitted to the Grid as single core jobs, however, Belle II is developing/testing a multicore solution. Multicore jobs will reduce processing time and RAM per core. This will allow Belle II jobs to more efficiently use opportunistic resources such as Amazon EC2 and HPC clusters. Belle II has started to test jobs on HPC resources and identified some challenges when submitting jobs as backfill; these challenges are expected to be partially resolved with multicore jobs. However, most of the Belle II code and external library do not take advantage of the HPC hardware and are not compiled optimally. Moreover, only one binary is currently distributed on the Grid.

The Wide Area Network requirements for Belle II are similar to that of the LHC experiments and the needs are expected to be satisfied by the NRENs.

Belle II is currently developing extensions to the DIRAC framework to enhance the distributed computing model. Central to this effort are the “Fabrication System” and “Data Management System.”

C.8.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

Neutrino Experiments: In neutrino physics in the US, DUNE will be the driving experiment in terms of computing and expects to lean heavily on the trails blazed by MicroBooNE, the DUNE prototype detectors and other LArTPC work. If one contemplates scaling up to the DUNE FD it is expected that the traditional approach of framing out data files to a cluster of CPUs will no longer scale. It remains to be seen if even farming out data files to a Grid of clusters can scale.

Reconstruction algorithm currently used, such as PandoraPFA, will require some profiling and optimization to potentially perform at the expected rates. Moreover, there is a strong likelihood that parallelizing at the scale of each event may be required to efficiently exploit the growing CPU count in commodity cluster nodes. Methods to serve individual events and return the results of the process are needed.

This event-level parallelism marks a qualitative shift. At this scale the “batch processing” system must be aware, to some extent, of the details of the “batch job.” Developing the services to support such a processing paradigm should be best done in a way that can nonetheless remain general purpose.

Novel reconstruction techniques are being developed that may take the granularity to sub-event levels. The need to support this scale of parallel processing puts a stronger requirement on the need to develop general systems to handle farming smaller units of computing.

Finally, it is recognized that a major shift is needed in the generally monolithic development practices of “physicists-programmers” in order to exploit the high CPU-count environments in modern computational clusters such as HPC. Training in general parallel processing

techniques is needed and specifically competency in exploiting GPU co-processors must be increased if neutrino data processing will exploit modern large-scale computing resources.

Belle II Experiment: During the 2020/2025 timescale, Belle II is expected to be running at designed luminosity and generating 16Gbps of raw data. This will drive Belle II grid computing to expand the existing workflow to include all elements of the computing infrastructure such as CPU, networking, and storage locality. Additionally, provenance and simulation/modeling can provide guidance to the workflow scheduler. The end goal is for each job workflow to be properly matched to the available resources given the current and forecasted conditions of the distributed system. This would improve the overall processing efficiency and stability of the distributed computing effort. With the growing number of experiments using the Grid resource allocation is a concern.

Automation of data-centric tasks will be required in order to handle the anticipated large distributed data volume. A common solution for storage accounting, data mobility, data integrity, and data healing would benefit the DOE-HEP community. Additionally, a common DOE-HEP data availability solution should be developed to minimize cost in developing redundant solutions.

New software development should focus on profiling/optimizing existing software or writing new software to leverage the new architectures available at HPC centers. Many techniques can potentially be applied to improve the existing code. Belle II and other DOE-HEP experiments would greatly benefit from training in code optimization, parallel processing techniques and access to new hardware technologies.

C.9 EVOLUTION OF HEP FACILITIES: COMPUTE ENGINES

Authors: S. Fuess and P. Spentzouris

C.9.1 Current Science Activities and Computational Approaches

Computing for Theoretical HEP combines tasks at leadership class machines with tasks on dedicated commodity clusters that are based at HEP facilities. (At HEP facilities, the principal communities are Lattice QCD and Accelerator Modeling.) This computing is program-driven, with users allocated resources via a proposal process. The program and associated projects tend to be of long (months/years) duration, with no specific time criticality of operation. As computing for theoretical HEP is already closely aligned with ASCR, further discussion will focus on computing for experimental HEP.

Experimental HEP data processing is dominated by pleasingly-parallel event-based simulation and analysis. In HEP parlance, an event refers to both an underlying physics process and the data associated with a detector during a slice in time, often related to a beam spill or colliding beam crossing. The principal computing steps associated with data processing – event simulation, reconstruction, and analysis – are primarily performed with single-threaded, large memory, independent instances of experiment-developed applications. Multi-threaded variants of applications are beginning to appear, but performance improvement has not yet dictated a mass migration to this model.

Experimental HEP data processing is thus best matched to a High Throughput Computing (HTC) model, where the processing aspect is straightforward and much of the complication lies in moving data to and from the processing units.

The typical HTC hardware architecture is a multi-processor, multi-core x86 machine

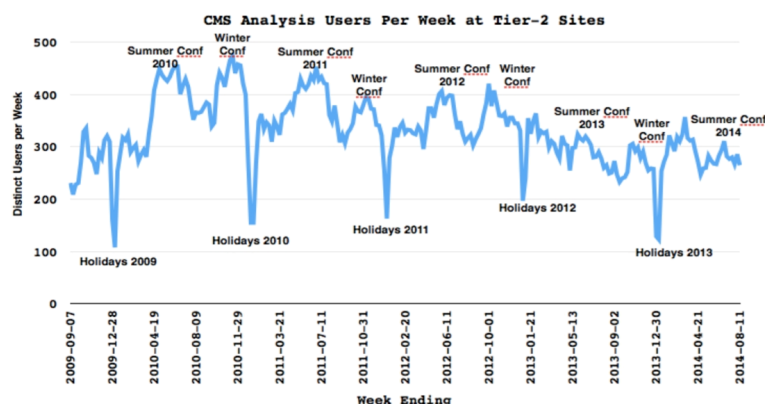


Figure 1: Time variation of CMS user jobs.

units of cores as defined above, is:

- World-wide CMS Experiment: 100K cores, including the CMS Tier-1 and Tier-2 facilities
 - US CMS: 15K cores at Fermilab, 25K cores at Tier-2 and Tier-3 sites
- General purpose (non-CMS) at Fermilab: 12K cores
- Similar (or larger) values for world-wide and US ATLAS, and for the ATLAS Tier-1 center (at BNL) and Tier-2 facilities

(currently capable of 20 to 64 applications or threads) with O(2GB) memory per core, with a multi-Gbit or 10 Gbit network interface per machine. [Note: in the following we will use the term “core” to represent an independent processing unit; processors capable of multiple threads per core (hyperthreading) are considered as the equivalent of multiple cores.]

The approximate size of the HEP computing infrastructure, in

A significant portion of HEP computation occurs in bursts, associated with new beam or detector operations, with re-processing efforts on existing data utilizing newly developed or improved algorithms, or with intensive preparations in advance of conferences or publication. As an example, Figure 1 illustrates the time variation of CMS user jobs.

The HEP computing community is in the initial stages of exploring commercial cloud resources for their processing intensive jobs. This effort has been enabled on several fronts – with grants from cloud service providers, with network peering arrangements with the principle science networks (ESnet, Internet2), and general outreach from the providers in terms of education and establishment of business relationships.

HEP data processing jobs are efficiently distributed among the processing resources, so that the average utilization (defined as a processing job occupying an available core) exceeds 95%.

A single HEP processing job is likely to be CPU limited, but the I/O resource needs of the job are likely to highly impact the architecture of the required computing systems. Event and detector simulation jobs require minimal input (but multiple simulation jobs are likely to share the same input, for example beam parameters) but produce output data files on the order of 1GB. Reconstruction (of both simulated and real data) and analysis jobs require unique input files (again, on the order of 1 GB each), possibly shared input files (for example calibration information), and produce output data files on the order of 1 GByte. Network or storage I/O rates need to be sufficient to not dominate the total processing time.

CMS computing needs are listed in Section 1.5. It contains a table from which one can calculate that a typical simulated event is of size 1.5 MB. A simulated data file of 1 GB thus contains 666 events. The table also contains information from which one can calculate that a single simulated event requires approximately 50 seconds to reconstruct on a typical current CPU; hence a 1 GB simulated data file requires approximately 9 hours. This roughly illustrates the relationship between input and output data sizes and processing time.

C.9.2 Evolution of Science Activities and Computational Approaches on the 2020/2025 Timescale

In this time period, experimental HEP will see:

- Continuing and increasing computational needs for LHC computing.
- The emergence of DUNE as the central long-baseline neutrino experiment with extensive associated simulation needs.
- Multiple smaller efforts associated with muon science and short-baseline neutrino physics.

Estimates of computational needs are given in the next section.

HEP computational techniques are expected to evolve to utilize parallel and/or accelerator assisted software algorithms. The per-core memory footprint should scale accordingly. In addition, traditional HEP Facilities such as the Fermilab facility are expected to evolve to incorporate a “rental” resource model that allows “elasticity” in provisioning of resources according to demand. HPC cycles, either programed (persistent) or opportunistic are an appealing component of this model. In order to make utilization of such resources feasible we need to work with the HPC ASCR community to develop the necessary software infrastructure that will allow us to monitor available cycles, provide integrated workflow management capabilities that will allow us to submit and monitor jobs in the HPC machines, and apply an appropriate security layer. In addition, data management will require significant networking

Step	Approx. Fraction Today	HL-LHC do nothing multiplication factor	HL-LHC do nothing CPU Increase	HL-LHC smart multiplication factor	HL-LHC smart CPU Increase
Generation	0.05	20	1	5	0.25
Simulation	0.45	5	2.25	3	1.35
Digitisation	0.05	20	1	10	0.5
Reco (MC)	0.15	100	15	15	2.25
Reco (Data)	0.1	100	10	25	2.5
Analysis	0.2	10	2	5	1
Total (in units of today's compute)	1		31.25		7.85

Figure 2: Scale increase of LHC processing estimated for HL-LHC running.

upon aggregate usage patterns, resource availability and cost, and criticality of the job.

C.9.3 Compute, Data, and Services Needs on the 2020/2025 Timescale

Figure 2 [1] provides an estimate of the scale change, relative to current needs, for the processing necessary to handle LHC data by the era of the High Luminosity LHC (HL-LHC) [2], scheduled to begin operation in approximately 2025 [3]. The message of Figure 2 is that even with optimization of algorithms to handle more complex event data, HL-LHC alone will require nearly an order of magnitude increase in processing capacity. An order of magnitude increase is consistent with hardware performance and capacity improvements expected in the same time frame.

Figure 3: Estimate of data sizes for HL-LHC.

	RAW (2 replicas)	Derived	Annual Total	Increase over now
Now	8PB/yr	x8	72PB	x1
HL-LHC do nothing	150PB/yr	x8	1350PB	x18
HL-LHC smart	150PB/yr	x4	750PB	x10

Ref. [1] also provides an estimate of data produced in the HL-LHC era, illustrated in Figure 3. An order of magnitude increase in data is again consistent with expected hardware performance and capacity improvements, with one implication that tape will likely be a required storage component.

capacity and monitoring capabilities to make this efficient.

A significant effort leading up to this time period will be devoted to developing the cost models for utilizing the mixture of external cloud provider resources, HPC resources, or dedicated HTC resources. Each resource type may be most suitable for specific phases and functions of the HEP computational load. The selection of the resource type will be made opaque to the user submitting the job, with the decision to be determined based

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- [1] <https://indico.cern.ch/event/304944/session/15/contribution/551/material/slides/0.pdf>
 [2] HL-LHC: <http://hilumilhc.web.cern.ch/>
 [3] <http://indico.cern.ch/event/345619/session/1/contribution/23/material/slides/1.pdf>

APPENDIX D: HIGH ENERGY PHYSICS CASE STUDIES

The white papers in Appendix C presented broad coverage of each HEP focus area. The case studies in this appendix are meant to drill down to the level of an individual application (or set of applications targeted to a single science goal). The case studies focus at the level of individual computational codes (or code frameworks) and make statements about their current status and usage patterns. They also cover what work needs to be done to get ready for next-generation computing architectures and what the specific computing requirements are likely to be on the 2020–2025 timescale.

Although each case study represents a substantial unit of work, the examples covered below can provide only a cursory glimpse of HEP computational activity. They range from those requiring a relatively modest computational resource (“mid-scale”) to others that run on the largest supercomputers, or exploit very large-scale high throughput computing. The aim of this Appendix is to provide a flavor of a subset of HEP computing tasks and their future roadmaps. (The one exception is the ‘Dark Energy Survey in Hindsight’ case study that focuses on lessons learnt and not on a future roadmap.)

CONTRIBUTORS

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D.1 ADVANCED MODELING OF ACCELERATOR SYSTEMS (ACE3P)

Authors: L. Ge, K. Ko, O. Kononenko, Z. Li, C.-K. Ng, L. Xiao

D.1.1 Description of Research

Overview and Context: Accelerator modeling using high performance computing has provided the capability of high fidelity and high accuracy simulation of accelerator structures and systems for the design, optimization and analysis of accelerators. Running on DOE state-of-the-art supercomputers, parallel electromagnetics computation has enabled the design of accelerator cavities to machining tolerances and the analysis of large-scale accelerator systems to ensure accelerator operational reliability. The modeling effort has supported many operational and planned accelerator projects within the DOE accelerator complex and beyond such as LHC Upgrade and PIP-II in HEP, CEBAF Upgrade, FRIB and e-RHIC in NP, as well as LCLS, LCLS-II in BES.

Research Objectives for the Next Decade: Accelerator modeling will continue to solve challenging computational problems in accelerator projects and accelerator science by developing multi-physics capabilities and fast numerical algorithms to facilitate optimized accelerator design, hence saving time and reducing costs. Advances of enabling technologies in scalable linear algebra solvers, mesh adaptation and dynamic load balancing that are specific to large-scale finite element simulation are required to achieve the scientific goals using emerging computer architectures.

D.1.2 Computational and Data Strategies

Approach: The computational problems include the solution of a sparse linear system, whose convergence requires the use of direct solvers with reduced memory footprint, and thus the development of solvers scalable in memory and on multi-core architectures is necessary. In addition, large datasets of particle and field data generated in the time domain are transferred back to local computers for visualization. With improvement of network bandwidth, remote visualization on LCFs can mitigate the problem of data transfer of increased sizes of datasets.

Codes and Algorithms: ACE3P is a comprehensive set of parallel finite element electromagnetics codes with multi-physics thermal and mechanical characteristics for simulation on unstructured grids. The simulation workflow starts from preprocessing for model and mesh generation on desktop computers, job execution on LCF, and then postprocessing including visualization and data analysis locally or remotely. ACE3P solves for eigenvalues and harmonic excitation problems in the frequency domain, employs an implicit scheme and the particle-in-cell method in the time domain, and uses Runge-Kutta algorithms for particle tracking in electromagnetic fields.

D.1.3 Current and Future HPC Needs

Computational Hours: Currently ACE3P uses 2.5M CPU hours on NERSC computers. A computational challenging problem will be to model dark current effects in the entire linac of an accelerator such as the superconducting linac in PIP-II and its upgrade to high power operation. The problem size will be 20-30 times larger than that of current simulation. It is anticipated that a growth of more than an order of magnitude to 50M CPU hours is required in the next decade.

Parallelism: The codes use MPI for parallelism with the average number of cores in the order of 5,000. Parallelism on multi-core nodes focuses on the development of hybrid linear solvers that are scalable in memory. The average number of cores will increase by an order of magnitude to 50,000 due to the increase in problem size.

Memory: ACE3P simulation in frequency domain requires large per core memory and hence benefits from compute nodes with large memory. Currently, the simulation uses 64 GB of memory on a compute node and the aggregate memory can reach up to 2 TB for electromagnetic simulation. Future aggregate memory will increase by an order of magnitude to 40 TB for multi-physics simulation.

Scratch Data and I/O: A typical run in the time domain generates 1-2 TB of data including field and particle snapshots and checkpoint files. A total of 50 TB scratch space is required for ACE3P users to perform their simulations concurrently. The current I/O bandwidth is estimated to be 20 GB/sec. Future requirements will increase the size of output datasets to 20 TB and the I/O bandwidth to 80 GB/sec to maintain reasonable I/O percentage of the runtime, which is about 20%.

Long-term and Shared Online Data: Several of the production runs are shared for the collaboration. It is estimated 5 TB storage for long-term data is required, which will increase to 50 TB in the next decades.

Archival Data Storage: About 50 production runs need to be archived. The estimated current space is 100 TB and the future storage will increase to 800 TB.

Workflows: The data generated from simulations on LCFs are transferred back to local computing resources for analysis, and hence maintaining and enhancing adequate data bandwidth from the remote facility are essential to the scientific process. For the next decade, the use of remote processing and visualization of data will alleviate the demand for high bandwidth of data transfer.

Many-Core and/or GPU Readiness: ACE3P's current parallel implementation uses MPI. The plan to build a hybrid programming paradigm with OpenMP is under way, for example, for particle tracking. In addition, ACE3P will benefit from improvement of third-party linear algebra libraries on multi-core architectures.

Software Applications, Libraries, and Tools: N/A

HPC Services: N/A

Additional Needs: N/A

Code: ACE3P	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 2 (As a factor of column 1)
Computational core hours (Conventional)	2.5 M	15 M	50 M
Computational node hours (Homogeneous many-core)			
Computational node hours (w/GPU or accelerator)			
Memory per node	64 GB	96 GB	128 GB
Aggregate memory	2 TB	20 TB	40 TB
Data read and written per run	2 TB	10 TB	20 TB
Maximum I/O bandwidth needed	20 GB/sec	40 GB/sec	80 GB/sec
Percent of runtime for I/O	20	20	20
Scratch file system space needed	50 TB	200 TB	500 TB
Permanent online data storage	5 TB	20 TB	50 TB
Archival data storage needed	100 TB	400 TB	800 TB

Requirements Summary Worksheet

D.2 LUMINOSITY OPTIMIZATION IN HIGH ENERGY COLLIDERS USING HIGH PERFORMANCE COMPUTERS (BEAMBEAM3D)

Authors: J. Qiang

D.2.1 Description of Research

Overview and Context: The event rate in a high energy collider such as the LHC is directly proportional to the luminosity of the colliding beams. The achievement of higher luminosity (integrated) is critical for new scientific discovery. However, colliding beam effects (also called beam-beam effects) are a limiting factor for the final achievable luminosity in all high energy colliders including the LHC. The research focus is on understanding and mitigating these effects through self-consistent simulations and optimizing the collider operation/design to achieve a higher luminosity through using high performance computers.

Research Objectives for the Next Decade: The research objectives for the next decade are to study the beam-beam effects and compensation methods including long-range beam-beam effects (if possible) for the LHC operation, the HL-LHC upgrade and other future high energy colliders such as FCC to achieve optimal luminosity. This study will integrate multi-bunch simulation including both the head-on beam-beam effects and the long-range beam-beam effects, an important factor limiting luminosity lifetime, with the machine parameter optimization. The computational and data analysis/processing goals are to do multi-level parallel simulation and data analysis to identify the best machine parameter settings for the optimal luminosity.

D.2.2 Computational and Data Strategies

Approach: The computational problem is to solve multiple coupled 6D Vlasov-Poisson equations (can be on the order of a thousand) and to optimize the collider luminosity with respect to the machine setting including beam-beam effects. The strategies used to solve the equations are based on a multi-species self-consistent particle-in-cell method with evolution-based parallel machine parameter optimization.

Codes and Algorithms: The code used in this study is BeamBeam3D. The algorithm is a parallel particle-in-cell method with particle-field decomposition to achieve a perfect load balance. This algorithm will be integrated with a parallel optimization algorithm for machine parameter optimization.

D.2.3 Current and Future HPC Needs

Computational Hours: At present, we typically use about one and half million core-hours on conventional cores. We expect that it will increase to 10 to 20 million core-hours through 2020 and 2025.

Parallelism: Currently, we are using two-level parallelization: one level for multi-group parallel parameter scans and one level for parallel simulation. Our current plan to increase the level of parallelization is to use multi-thread share memory programming together with MPI, and to parallelize the multiple bunch collisions at multiple interaction points.

Memory: Currently, we are using a few million macroparticles for a single simulation run. Together with the parallel parameter scan, this requires 1-100 GB memory of a parallel computer. In future studies, we plan to increase this by one more level of parallelism to account for multi-bunch long-range beam-beam effects. In the LHC study, each beam has more than 2000 bunches. A full optimization study including colliding beam effects with

potentially a larger number of macroparticles in the simulation will require 200-2000 TB memory (DRAM).

Scratch Data and I/O: The on-line scratch storage needed in our study is on the order of 10 GB to 20 TB depending on the applications. We hope that the runtime for I/O can be controlled within 5% of the total computing time.

Long-term and Shared Online Data: The online-long-term storage that we need today is about 2 TB. In 2020 and 2025, the storage that we need is about 20 TB and 40 TB.

Archival Data Storage: Currently, we probably have stored about 4 TB archival data. We will probably need 50 TB and 100 TB in 2020 and 2025.

Workflows: N/A

Many-Core and/or GPU Readiness: Our code is not ready for this yet. We plan to add OpenMP into the code to exploit the shared memory architecture inside a node and to use MPI for cross-node communication.

Software Applications, Libraries, and Tools: N/A

HPC Services: N/A

Additional Needs: N/A

Code: BeamBeam3D	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 2 (As a factor of column 1)
Computational core hours (Conventional)	1.5 million	10 million	15 million
Computational node hours (Homogeneous many-core)			
Computational node hours (w/GPU or accelerator)		3 million	6 million
Memory per node	1 GB	1 GB	1 GB
Aggregate memory	0.1 TB	10 TB	100 TB
Data read and written per run	0.1 TB	1 TB	10 TB
Maximum I/O bandwidth needed	10 GB/sec	10 GB/sec	10 GB/sec
Percent of runtime for I/O	<5%	<5%	5%
Scratch file system space needed	1 TB	10 TB	20 TB
Permanent online data storage	2 TB	20 TB	40 TB
Archival data storage needed	4 TB	50 TB	100 TB

Requirements Summary Worksheet

D.3 COMPUTATIONAL COSMOLOGY (HACC)

Authors: H. Finkel, N. Frontiere, S. Habib, K. Heitmann, A. Pope

D.3.1 Description of Research

Overview and Context: High-fidelity cosmological surveys require immense simulation capability to make maximal use of information in, e.g., the spatial clustering of galaxies, to make cosmological inferences. Structure formation simulations are integral in survey planning, error characterization, and for calculating observable signatures to which the data will be compared. Galaxies form in highly over-dense regions but trace delicate structures that span distances of hundreds of millions of light-years, demanding dynamic ranges of roughly six order of magnitude in spatial resolution and even more in mass resolution. Much like galaxy surveys, simulation data products are rich and can be interrogated in various ways at several levels of data reduction, requiring significant resources for data archiving, access, and distribution.

Research Objectives for the Next Decade: Gravity is the dominant force on large length scales; currently HACC (Hardware/Hybrid Accelerated Cosmology Code) is gravity-only, and the effects of other interactions involved in the process of galaxy formation are modeled in post-processing using a variety of techniques. Next-generation surveys require significantly higher mass resolution and inclusion of baryons and feedback effects while maintaining survey-relevant volumes and resolutions.

D.3.2 Computational and Data Strategies

Approach: HACC's N-body methods use tracer particles to track the phase-space distribution of matter in an expanding universe. Force-splitting methods are used to calculate long-range forces using MPI distributed-memory methods and short-range forces using shared-memory methods. Individual simulations must run longer than individual job run-times (and mean-time-to-failure) requiring high performance IO for checkpoint/restart files. Particle methods should scale well for the next generations of large-scale HPC systems.

Codes and Algorithms: The HACC framework runs on all types of HPC systems, including power-efficient multi/many-core systems and accelerated systems. Long-range forces are computed by a high-order spectral particle-mesh method. Portable, custom-written MPI code is used to perform a distributed memory FFT to solve for long-range forces. Short-range force calculations are adapted to the underlying architecture. Tree methods are used to generate particle interaction lists on multi-core and many-core CPUs, while an OpenCL code employs a simpler fixed spatial-scale data structure for calculations on GPUs. Custom-written (non-collective) MPI-IO code with internal checksums is used to checkpoint/restart and output files. We will add a new higher-order smoothed-particle hydrodynamics (CRK-SPH) method to HACC in order to scale baryonic physics calculations to future HPC systems.

D.3.3 Current and Future HPC Needs

Computational Hours: Currently HACC simulations run under ALCC and INCITE awards at the scale of 200M core-hours/year. This includes running the GPU version of the code with the OLCF charging factor included in the above number. Future usage is expected to go up by a factor of $\times 20$ in the pre-exascale era, to about $\times 200$ at exascale.

Parallelism: Production runs regularly use 262,144 MPI ranks and 8 threads per rank on 32,768 nodes (524,288 cores) of IBM Blue Gene/Q systems for a total of ~ 2.1 million threads. Performance tests of the full code scaled up to ~ 6.3 million threads on 98,304 nodes

(1,572,864 cores) of IBM Blue Gene/Q at greater than 90% parallel efficiency and 69% of peak performance. Tests of the MPI-parallel FFT have scaled up to ~ 1 million MPI ranks for a 16,384 grid. The production GPU version the code regularly uses 16,384 nodes of Titan at one MPI rank per node and achieves full occupancy on the NVIDIA K20 GPUs.

Memory: Memory (DRAM) requirements driven by science cases for large-volume survey simulations already exceed next-generation system capabilities (10+PB desired versus 1+PB available). HACC strong-scales to 100MB/core, which is likely sufficient for exascale architectures. The use of NVRAM as a local memory extension is being investigated.

Scratch Data and I/O: The scratch storage requirements track the total RAM available in the machine multiplied by the number of snapshots. This can easily lead to ~ 100 +PB requirements, which will be mitigated to some extent by using in situ analysis (already included in HACC). I/O bandwidth requirements are ~ 1 TB/sec until ~ 2020 , and ~ 10 TB/sec in the 2020-2025 timescale. Obviously, we would like to minimize I/O overhead (we are thinking of how to use NVRAM to reduce this overhead to a very small fraction, if not zero.) We would like to have less than 10% of our time be lost to I/O.

Long-term and Shared Online Data: We already need ~ 10 PB of active (spinning disk) long-term storage (which we don't have). This number can easily hit the Exabyte scale by 2020-2025. Currently, we use Globus transfer services for sharing data between the LCFs and NERSC.

Archival Data Storage: Currently we have 4PB (soon to be 6PB) in archival storage (HPSS). We expect this to scale out by a factor of up to 1000 by 2025 (but everything will depend on data access bandwidth).

Workflows: We use SMAASH, a simulation management and analysis system, for workflow management. We will continue to develop SMAASH to handle large-scale simulation campaigns.

Many-Core and/or GPU Readiness: See discussion above; HACC is ready for next-generation many-core and GPU systems, with early science projects on Cori, Summit, and Theta. We tune data structures and algorithms for the short-range force calculations, the major computational hot-spot, to make efficient use of the available memory hierarchy and bandwidth on each architecture that we use at scale.

Software Applications, Libraries, and Tools: Currently we place minimal reliance on (non-vendor supported) libraries because of past experiences on HPC systems. We do not expect this to change in the near future.

HPC Services: A federated authentication system coupled to a well-tuned and supported data transfer system (e.g., Globus) would help greatly with data sharing and publication.

Additional Needs: N/A

Code: HACC	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 (As a factor of column 1)
Computational core hours (Conventional)	~200,000,000	~20x	~200x
Computational node hours (Homogeneous many-core)	~100,000,000	~20x	~200x
Computational node hours (w/GPU or accelerator)	~100,000,000	~20x	~200x
Memory per node	16-32GB	1x-32xGB	1x-32xGB
Aggregate memory	~500TB	~3-5xTB	~10-20xTB
Data read and written per run	~1,000TB	~3xTB	~10xTB
Maximum I/O bandwidth needed	~100GB/sec	~5xGB/sec	~10xGB/sec
Percent of runtime for I/O	~10%	~10%	~10%
Scratch file system space needed	~100TB	~5xTB	~10xTB
Permanent online data storage	>3,000TB	~3xTB	~10xTB
Archival data storage needed	>10,000TB	~3xTB	~10-100xTB

Requirements Summary Worksheet

D.4 COSMIC REIONIZATION (ART)

Authors: N. Gnedin

D.4.1 Description of Research

Overview and Context: The primordial anisotropies in the Cosmic Microwave Background (CMB) have been measured with great precision. Modern constraints on the dark matter, dark energy, or modifications of gravity are inconceivable without using these measurements as one of the main data sets. Hence, maximizing the achievable precision from the CMB data is crucial. As statistical errors continue to decrease, the importance of systematic uncertainties in CMB modeling increases. Of these, cosmic reionization is by far the most important. The process of reionization leads to the transition from mostly neutral to a highly ionized state for most of the cosmic gas. This ionized gas serves as a semi-transparent screen for the CMB, affecting the anisotropies in a well-understood manner. Because observational constraints on reionization are limited, theoretical modeling, including numerical simulations, plays a very important role. The Cosmic Reionization On Computers (CROC) project aims, over the course of several years, to model – fully self-consistently – all the relevant physics, from radiative transfer to gas dynamics and star formation, in simulation boxes up to 100 comoving Mpc and with spatial resolution reaching 100 pc in physical units.

Research Objectives for the Next Decade: The next decade will see three major observational advances: 1) The James Webb Space Telescope (JWST, 2018 launch), will provide orders of magnitude increase in the data sample sizes of primary reionization sources – high redshift galaxies. 2) 30-meter class telescopes will increase many-fold the number of known high-redshift quasars that serve as lightposts against which the intergalactic gas is observed. 3) radio observatories, e.g., the Hydrogen Epoch of Reionization Array (HERA) or Square Kilometer Array (SKA) will map neutral hydrogen at large scales during cosmic reionization. To match the flood of observational data, higher precision simulations will be required. The “ideal” reionization simulation for matching the new data should reach 100 pc spatial resolution and mass resolution of about 10^6 solar masses. For a 100 Mpc box, such a simulation would use over 100 billion particles/cells, and consume close to 500 million CPU-hours. At present this is unfeasible, but would be a routine calculation some time in the second half of the next decade.

D.4.2 Computational and Data Strategies

Approach: Cosmological reionization simulations model a diverse range of physical processes, from gas dynamics and gravitational collapse to cosmological radiative transfer and various atomic processes in the primordial gas. In order to achieve the high dynamic range needed for reionization simulations, we use the Adaptive Mesh Refinement (AMR) approach, implemented in the Adaptive Refinement Tree (ART) code. The large size of the existing and future simulations will present a serious problem for data storage and analysis. Hence, a substantial effort will have to go into developing efficient and scalable algorithms for dynamic data compression and on-the-fly analysis.

Codes and Algorithms: The ART code uses an N-body method to solve the Vlasov equation for dark matter and a modern Riemann solver for modeling gas dynamics. Gravity is solved on the fully refined mesh with a multi-grid relaxation solver. Approximate methods are used for modeling radiative transfer and star formation. Atomic processes are solved exactly with a sub-stepping technique and implicit solvers.

D.4.3 Current and Future HPC Needs

Computational Hours: Currently we use between 50 and 100 million hours per year. “Ideal” reionization simulations mentioned above will require of the order of 500 million hours each, and a statistical ensemble of at least 5 of them will be required, so we are talking about 2.5-3 billion CPU hours for the 2020-2025 period.

Parallelism: The current implementation of the ART code scales to about 10,000 nodes and 20 cores/node for the largest currently feasible simulation sizes. Going beyond this scaling will not be possible with the current implementation both for numerical and algorithmic reasons. We are currently starting work on the next generation of the ART code that should scale on exascale platforms (i.e., reach greater than million core scaling), with the expectation that the new code will be production ready around 2020.

Memory: All of the current and future simulations are CPU limited and the memory requirements are not critical – i.e., they are highly suitable for the future machines with low memory-to-peak-performance ratio. The total memory requirements for the “ideal” simulation described above will be of the order of 1 PB. The per-node memory requirement will depend on the particular implementation of the next version of the code, but in no case should be below 16 GB.

Scratch Data and I/O: Because of the persistent value of these simulations, a sensible number of snapshots will need to be stored. The exact storage requirement will depend on the degree of compression available to us; something in the range of 10-30 PB seems to be reasonable. The IO bandwidth will be crucial, however, and will need to exceed the IO performance of the BlueGene/Q by at least a factor of 100.

Long-term and Shared Online Data: At present we need about 300TB of active data storage. In the period 2020-2025 this requirement will grow by a factor of 10-20.

Archival Data Storage: At present we have about 1PB of archival storage used for simulation outputs. In the period 2020-2025 this requirement will grow by a factor of 10-20.

Workflows: We don’t need any workflows and do not plan to use any in the future.

Many-Core and/or GPU Readiness: The current version of the ART code is not ready for exascale and inhomogeneous architectures. As we discussed above, work on the next generation, exascale AMR code has already started, and the new code is expected to be operational by about 2020.

Software Applications, Libraries, and Tools: N/A

HPC Services: N/A

Additional Needs: N/A

Code: ART	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 (As a factor of column 1)
Computational core hours (Conventional)	100M	10	
Computational node hours (Homogeneous many-core)			3,000M
Computational node hours (w/GPU or accelerator)			3,000M
Memory per node	16-64GB	16+GB	16+GB
Aggregate memory	100TB	1000TB	1000TB
Data read and written per run	100TB	200TB	500TB
Maximum I/O bandwidth needed	GB/sec	GB/sec	GB/sec
Percent of runtime for I/O	10	10	10
Scratch file system space needed	300TB	1000TB	3000TB
Permanent online data storage	300TB	1000TB	3000TB
Archival data storage needed	1000TB	10000TB	20000TB

Requirements Summary Worksheet

D.5 DARK ENERGY SURVEY IN HINDSIGHT

Authors: D. Petravick

D.5.1 Description of Research

Overview and Context: In astronomy, the term Data Management refers to the creation (or adoption) of production codes; the configuration management needed to assemble the codes into a coherent set of pipelines; the creation of the set of services needed for a working system – including job management, and management of a collection of data; the effort to support production, assess the quality of the results, and provide all other effort to build a systematically coherent set of measurements supporting a multi-year observational program. DES is organized into a collaboration. The overall system that is now in place is constructed to maximize the collaboration’s participation in production activities.

The Dark Energy Survey itself consists of a wide area survey and a survey that focuses on type 1a supernovae. The primary set of measurements supporting the wide field survey is provided by annual data releases. The primary set of measurements supporting the supernova program is prompt processing of specially designated supernova fields, which are observed on a six-day cadence. In addition to providing measurements directly supporting the DES science outcomes, DES Data Management (DESDM) supports DES observers with prompt processing of all data, identifying which of the raw data meet survey requirements, and identifying fields which must be re-observed.

Nightly supernova processing produces measurements for the supernova working group. The central group provides front-end processing requiring re-use of the DES software stack and the use of batch-oriented production frameworks. The central group also provides a VM infrastructure to the supernova science working group for essential back-end processing of the data. Data products from this stage are placed in the central relational database.

Annual weak lensing processing is done within the weak lensing group. The collaboration has demonstrated a data ingest of shear catalogs back into the central relational database.

All in all, production is an activity that is carried out in active collaboration with the science working groups. Within the collaboration, data is not hidden as it is computed – all data products, including nightly quality assurance (which catalogs all objects albeit with crude calibrations), to the data accumulating for an annual release are available to the collaboration (though not necessarily supported by the central group). Availability of this data allows for prompt, unanticipated science results.

Additional processes, which were not envisioned in the original proposal have emerged. After DESDM provides an annual release, a Release Scientist further characterizes that release, providing additional characterization, subsetting, and augmentation. This is ingested, and integrated into the master relational table views and joins.

Lastly, work is underway for additional integration for the production of value-added catalogs that are specialized value-added data products of interest to one, or a few science working groups. The LINEA group in Brazil provides infrastructure for production of these data items, and the LINEA provided infrastructure is being directly integrated into the central relational database, which provides efficient access to the measurements computed in the annual releases.

Research Objectives for the Next Decade: N/A

D.5.2 Computational and Data Strategies

Approach: Processed data are available as FITS images and tables held in files or as relational tables accessed via SQL, as apropos. The original technical concept for the DESDM

was to provide a quick and low-cost system based on:

1. Use of grid computing, both TeraGrid (now XSEDE) and the OpenScience Grid (OSG).
2. Use of a body of community codes, in lieu of bespoke codes for important operations, including astrometry, object detection and classification, and image co-addition.
3. A distributed file system, based on independent servers and a replica catalog.
4. A system of mutually mirrored relational databases supporting a system of primary, secondary and tertiary data and production sites.
5. A production infrastructure that produces supernova pipelines, annual release processing consisting of single epoch image processing, image co-addition, weak lensing processing, photometric redshifts, and other data products.

As of 2015, the system in place has processed data from a science verification year, and two full years of survey operations. As such we are able to survey the current state of the system, with lessons learned.

DES now primarily accepts bulk computing sites on the basis of their supporting file systems and proximity to the central file store at NCSA. DES experience is as follows:

1. DES uses the Fermigrid OSG site and NERSC for processing single exposures. Jobs pull their inputs directly from the central file store to local disk on an OSG worker node, which has sufficient attached disk. Jobs push their output back to the central file store at NCSA before completing. The transport protocol is HTTP. The number of HTTP servers is scaled to support the needed bandwidth.
2. DES uses computers with a central, global file system for image co-addition. Coadd processing involves gathering all images overlapping a 0.25 sq. degree area of sky for processing. The primary resources have been the iForge Cluster at NCSA, which has a well-provisioned GPFS file system.

Codes and Algorithms: DES uses an approach based on the use of community codes. This has driven the DES production framework to adopt the assumption that all codes are “hostile”, each with a different interface, and some optimized for interactive use. Experience at NCSA has indicated that many production systems for emerging data-intensive science require production systems capable of handling hostile codes. Lessons learned include:

1. Dealing with many small files
2. Informing scientists how production was done as “how the community codes were called” instead of how “wrappers to the community codes were called”
3. Budgeting effort to include acquiring thorough acumen about these codes and effective liaison to the code developers

That said, DES’s software processes have adapted to these circumstances. DES provides a strong example of code-reuse, and has developed techniques to accept codes from its collaborators – and from the community – that are reasonably stand-alone and framework-independent.

D.5.3 Current and Future HPC Needs

Computational Hours: At the $\sim 1\text{M}$ core-hour annual use.

Parallelism: Independently parallel jobs.

Memory: Few GB/core.

Scratch Data and I/O: DES is like many emerging production efforts in other science domains, where integrating community codes results in many small files, which can be problematic for the file system.

Long-term and Shared Online Data: DES attempted to implement a file architecture similar to a data grid. Files would be held by primary, secondary, and tertiary authorized sites. The scope of this project was greater than could be realized. Given the few-petabyte scale of the persistent archive, a central file store, based on GPFS at NCSA was substituted. This gave the production system a hub-and-spoke data architecture. The central data store was implemented in the NCSA storage condominium, with Fermilab tape providing disaster recovery capabilities.

The original DES concept was to mirror the collaboration's relational data to databases at various sites. A straightforward implementation is to replay database logs into slave databases. However this technique was found to have shortcomings. An example shortcoming was that fast data ingest operations bypass the logging mechanism, dooming the system to very slow data ingest. Since DES used Oracle, DES reverted to a large central Oracle RAC, which provides a good data service to the collaboration.

Use of the relational technology is critical for DES calibration activities, and for providing subsets of data. DES has been successful in ingesting refinements to annual release, computing outside of the main production effort and has ingested data produced outside the production framework at NCSA into its relational schema, preserving object identities.

Archival Data Storage: DES archival storage is at the $\sim 1\text{ PB}$ level.

Workflows: Described above.

Many-Core and/or GPU Readiness: Not used because the community code base does not have many-core or GPU applications.

Software Applications, Libraries, and Tools: N/A

HPC Services: Careful design of a processing infrastructure would allow annual processing or reprocessing to be run in backfill mode. Service level issues, such as job scheduling would need to be addressed. DES currently mitigates job scheduling with glide in techniques.

Additional Needs: DES nightly processing requires nightly availability. Because the computational requirements for this are relatively modest and dominated by availability and reliability concerns, this is a more problematic use case for a conventional HPC environment.

D.6 LATTICE QCD (MILC/USQCD)

Authors: D. Toussaint

D.6.1 Description of Research

Overview and Context: Lattice field theory calculations are essential for interpretation of many experiments done in high-energy and nuclear physics, both in the US and abroad (e.g., BaBar at SLAC, CLEO-c at Cornell, CDF and D0 at Fermilab, and Belle at KEK, Japan). New data is beginning to arrive from the LHCb experiment at the LHC, and BESIII in Beijing. In many cases, lattice QCD calculations of the effects of strong interactions on weak interaction processes (weak matrix elements) are needed to realize the full return on the large investments made in the experiments. In all such cases, it is the uncertainties in the lattice QCD calculations that limit the precision of the standard model tests. Our objective is to improve the precision of the calculations so that they are no longer the limiting factor.

Research Objectives for the Next Decade: During the next decade we will continue our work on decays and interactions of heavy quarks, seeking to match the accuracy of experiments scheduled for the 2020 time frame. Also, lattice computations of the hadronic contributions to the magnetic moment of the muon will be essential to understanding the results of the experiment planned at Fermilab. In this time frame we expect that computations of the quark-line-disconnected contributions to masses and other properties will be increasingly important. Both the $g-2$ and the disconnected computations will require high statistics, but not necessarily much smaller lattice spacings than are currently used. Thus we expect a slowdown in the rate at which the lattice spacing has been pushed down, and the size of our simulations increased, in favor of higher statistics.

D.6.2 Computational and Data Strategies

Approach: Lattice QCD is a theory of quarks and gluons (gauge fields) defined on a four-dimensional space time grid. We use a Monte Carlo method to create gauge configurations in proportion to their weight in the Feynman path integral that defines the theory. Once a suitable ensemble of configurations is created and stored, it can be used to study a wide variety of physical phenomena. The generation of configurations is a long stochastic simulation, so must run at high speed. However, with the stored configurations, subsequent work can be done in parallel, and the speed of a single job is not critical as long as there is sufficient capacity to run multiple jobs.

Codes and Algorithms: The MILC collaboration has developed its code over a period of 20 years and makes it freely available to others. It has evolved to match our physics goals and to accommodate changes in computers. Currently containing approximately 180,000 lines, it is used by several collaborations worldwide. Our code has made increasing use of a library of specialized data-parallel linear algebra and I/O routines developed over the past several years with support from the DOE's SciDAC program. These packages were developed for the benefit of the entire USQCD Collaboration, which consists of nearly all of the physicists in the United States working on the numerical study of lattice gauge theory.

There are a number of algorithms used in the generation of gauge fields. The heart of the algorithm is a dynamical evolution similar to molecular dynamics. In order to calculate the forces driving the evolution, a multimass conjugate gradient solver is required to deal with the quarks. This solver takes the majority of the time in the calculation and it becomes increasingly important as the up and down quark masses are reduced. It has only recently become feasible to use up and down quark masses as light as in Nature.

D.6.3 Current and Future HPC Needs

Computational Hours:

Parallelism: Our codes currently use MPI at the large scale, and have the option to use OpenMP for a second level of parallelism. We also can and do use GPUs to accelerate the most computationally intensive parts of the calculation.

Memory:

Scratch Data and I/O: Some new analysis methods require temporary storage of a large number of eigenvectors, so short term (as opposed to archival) storage may be more important.

Long-term and Shared Online Data: Because lattice QCD is so computationally expensive, the groups that create the gauge configurations have often made them publicly available. These configurations can be used for a wide variety of physics topics and by sharing their configurations with other collaborations the scientific impact can be maximized. The NERSC Gauge Connection was a pioneering service in support of sharing configurations world wide and remains an important service of NERSC that relies on its storage facilities. Thus, both high-end computing and storage are essential to our research.

Archival Data Storage: In the range of 250TB by 2025.

Workflows: N/A

Many-Core and/or GPU Readiness: Lattice QCD codes are using many-core and GPU resources already.

Software Applications, Libraries, and Tools: N/A

HPC Services: N/A

Additional Needs: N/A

Code: Lattice QCD	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 (As a factor of column 1)
Computational core hours (Conventional)	66M	1	1
Computational node hours (Homogeneous many-core)	0	250M	1000M
Computational node hours (w/GPU or accelerator)			
Memory per node	GB	GB	GB
Aggregate memory	21 TB	4xC1	10xC1
Data read and written per run	0.75 TB	10 TB	25 TB
Maximum I/O bandwidth needed	GB/sec	GB/sec	GB/sec
Percent of runtime for I/O	5	5	5
Scratch file system space needed	10 TB	100 TB	250 TB
Permanent online data storage	1 TB	1 TB	1 TB
Archival data storage needed	400 TB	25000 TB	50000 TB

Requirements Summary Worksheet

D.7 EVENT GENERATION (SHERPA)

Authors: S. Hoeche

D.7.1 Description of Research

Overview and Context: High Energy Theory can be broadly classified into two sub-fields: Precision calculations in the Standard Model, and phenomenological analysis of new physics scenarios. Both are connected by Monte-Carlo event generators, which are used to make particle level predictions based on the former and used for the latter. The computation of SM reactions has reached a high degree of automation, with next-to-leading order (NLO) QCD perturbation theory being the standard means of obtaining cross sections at collider experiments like the LHC. The results have been instrumental in extracting properties of the Higgs boson, and they will continue to play a dominant role in the future. Dedicated next-to-next-to leading order (NNLO) QCD calculations exist for important reactions such as Higgs-boson production, both at the inclusive and at the fully differential level. They have been included in parton shower Monte-Carlo event generators in order to make particle-level predictions for high precision measurements in collider experiments.

Research Objectives for the Next Decade: We are rapidly moving towards full automation of NLO electroweak calculations. Tremendous progress has also been made in NNLO QCD calculations, raising hopes for an eventual automation in the future. The first complete three-loop result for inclusive Higgs-boson production paves the way for more ultra-precise SM predictions at hadron colliders. They will become mandatory as future data will have reduced experimental errors and theory uncertainties begin to limit our understanding of Nature. Predictions must eventually be made fully differentially at the particle level in order to be maximally useful for experiment, i.e. they must be interfaced to event generators.

D.7.2 Computational and Data Strategies

Approach: We use adaptive Monte-Carlo methods to integrate over the high-dimensional phase space of multi-particle production processes at hadron colliders. We also use numerical methods to solve small sets of linear equations on a point-by-point basis during the Monte-Carlo integration. We store phase-space configurations in the form of Root Ntuples for later use by experiment or theory.

Codes and Algorithms: We use C++ codes built from scratch, with minimal dependencies on external libraries. We interface Root for the storage of phase space configurations and LHAPDF for the parameterization of structure functions.

D.7.3 Current and Future HPC Needs

Computational Hours: Typical NLO QCD calculations currently require between 50k and 500k CPU-hours each. NNLO differential calculations require between 50k and 1M CPU-hours each. Parton-shower matched predictions require on the order of 100k CPU hours, depending on the complexity of the final-state.

Parallelism: Sherpa has been parallelized using both MPI and POSIX threads. First studies have been done on Xeon Phi, but the code is not ready for production. Other NLO codes (MCFM) have demonstrated scaling up to 10^6 threads using a hybrid MPI+OpenMP approach.

Memory: High-multiplicity NLO calculations currently set the limit. They require between 1 and 6 GB shared memory per node, with the aggregate memory set by the number of nodes. At current technology we expect this to be rising slowly over the next several years.

Scratch Data and I/O: Typical NLO QCD calculations currently require between 0.1 and 1.5 TB. The results can be re-analyzed to obtain predictions for different SM parameters. NNLO differential calculations are typically performed for a single set of observables, but the possibility to store phase-space configurations is investigated. We expect this to take 1 to 10 TB per calculation.

Long-term and Shared Online Data: None currently.

Archival Data Storage: None currently.

Workflows: Not standardized.

Many-Core and/or GPU Readiness: Sherpa is generally not ready for accelerators. Automated NLO generators and general-purpose MC event generators perform many different tasks, and they are typically designed in a highly object oriented way. This makes it difficult to outsource parts of the calculation in an efficient manner.

Software Applications, Libraries, and Tools: N/A

HPC Services: N/A

Additional Needs: N/A

Code: Sherpa	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 (As a factor of column 1)
Computational core hours (Conventional)	NLO QCD: 50k-500k CPU-h x 2/year NNLO QCD: 50k-1M CPU-h x 2/year NLO QCD+PS: ~100k CPU-h x 3/year	Depends on theory development at current technology, ~factor 2 per project	Depends on theory development at current technology, ~factor 4 per project
Computational node hours (Homogeneous many-core)	Same as above	Same as above	Same as above
Computational node hours (w/GPU or accelerator)	NA	NA	NA
Memory per node	1-6 GB	1-9 GB	1-12 GB
Aggregate memory	TB	TB	TB
Data read and written per run	0 - 1.5 TB	0-10 TB	0-10 TB
Maximum I/O bandwidth needed	0.1 GB/sec	0.1 GB/sec	0.1 GB/sec
Percent of runtime for I/O			
Scratch file system space needed	O(10 TB)	O(40 TB)	O(40 TB)
Permanent online data storage	TB	TB	TB
Archival data storage needed	TB	TB	TB

Requirements Summary Worksheet

D.8 ENERGY FRONTIER EXPERIMENT (ATLAS)

Authors: T. LeCompte

D.8.1 Description of Research

Overview and Context: We collide beams of particles together and then measure the trajectories of the particles created in this collision. These are then compared to simulated events at several levels – e.g., comparing the response of the detectors to particular particles with given energies or comparing the number of events of a particular topology to expectations. This is not a simple process, and we are every bit as dependent on the simulation chain as we are on the actual data chain. The ATLAS experiment uses approximately one billion CPU-hours per year to generate, simulate, digitize, reconstruct and analyze simulated data. Over 100 petabytes of data (including replicas) are stored. This is achieved primarily via the LHC Computing Grid (LCG, or just “Grid”) – these are networked clusters of commodity PCs.

Research Objectives for the Next Decade: The scientific goals are described in the P5 report (<http://www.usparticlephysics.org/p5/>) but in short the experiments are looking for new particles and phenomena, and making precise measurements of the Higgs boson properties. To do this, there exists a twenty-year plan of running the Large Hadron Collider and ultimately collecting 100× the data at nearly twice the energy. The data in hand will be tripled in roughly 2-3 years, tripled again in another 2-3 years, and then will grow linearly until 100× has been collected, around 2035. ATLAS would like to keep the ratio of simulated to real events at least constant over the next decade, although the likely funding scenarios make this impossible if we restrict ourselves to LHC resources.

D.8.2 Computational and Data Strategies

Approach: We take advantage of event-level parallelism to divide our tasks into 24-hour single PC jobs. Input and output from these jobs resides on Grid “Storage Elements”. We have just recently been using High Performance Computers (HPCs) and have over the last year offloaded about 6% of the Grid production.

Codes and Algorithms: We use dozens of codes, often with millions of lines of code. These have in general never been optimized for parallelism of any kind.

D.8.3 Current and Future HPC Needs

Computational Hours:

Parallelism: We use event-level parallelism – one event per core. We are investigating the use of accelerators; we have seen some improvement with some codes running a single thread. Whether this extends to an ensemble of cores sharing one or many co-processors remains to be seen.

Memory: Our code was developed under the assumption that 2 GB is available for every process. In some cases, with relatively minor code changes we can drastically reduce the amount of memory – more than an order of magnitude in one case. It appears that in some cases we would get better performance by using fewer cores to repurpose some memory as a RAM disk, thereby achieving an overall gain by speeding up the I/O.

Scratch Data and I/O: Everything we have run so far is I/O limited. This is driven not by the total I/O, but rather by the overhead of having millions of ranks that can potentially read or write data. Because our Grid jobs are fast (hours) and our HPC jobs are faster (20-30 minutes) we tend not to need much scratch area per job.

Long-term and Shared Online Data: All input and output must be available on the LCG. HPC sites can store additional copies, or if willing, act as Grid Storage Elements, but this must happen in some way.

Archival Data Storage:

Workflows: A job will be submitted to the production manager program, assigned to an HPC, run there, and the output placed on an SE, just as Grid jobs do. This works today, with some room for improvement. The alternative, submitting hundreds of thousands of jobs by hand, is impractical.

Many-Core and/or GPU Readiness: We are just now exploring these. The first step in transitioning is to use Cori, Theta and even Titan as a testbed, to delineate the present limitations. Then we can address them in detail.

Software Applications, Libraries, and Tools: N/A

HPC Services: Small, easy-to-use, machines like Carver provide an important resource for development, testing, and training. While the very largest machines get the most attention, I would hope that these kinds of machines figure into the planning.

Additional Needs: N/A

Code: ATLAS (Total)	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 (As a factor of column 1)
Computational core hours (Conventional)	1,000,000,000	x3	x10
Computational node hours (Homogeneous many-core)	60,000,000	x3-20	x10-70
Computational node hours (w/GPU or accelerator)	200,000	tens of millions?	hundreds of millions?
Memory per node	2 GB	2 GB	2 GB
Aggregate memory	.002 TB	.002 TB	.002 TB
Data read and written per run	<< 1 TB	<< 1 TB	<< 1 TB
Maximum I/O bandwidth needed	GB/sec	GB/sec	GB/sec
Percent of runtime for I/O	large	large	large
Scratch file system space needed	10 TB	10 TB	10 TB
Permanent online data storage	100,000 TB	300,000 TB	1,000,000 TB
Archival data storage needed	250,000 TB	750,000 TB	2,500,000 TB

Requirements Summary Worksheet

D.9 COSMIC MICROWAVE BACKGROUND (TOAST)

Authors: J. Borrill

D.9.1 Description of Research

Overview and Context: The CMB carries the imprint of the entire history of the Universe in the fluctuations of its temperature and polarization on different angular scales. To detect fainter signals in the CMB we have to gather larger datasets, resulting in exponential data growth paralleling Moore’s Law for the last and next 20 years. Such growth constrains us to reduce CMB data sets using no worse than log-linear analysis algorithms, and to follow Moore’s Law to massively parallel systems at state-of-the-art HPC facilities.

Research Objectives for the Next Decade: The quest is to measure the B-mode polarization signal, whose fluctuation spectrum contains vital information on the energy scale of inflation and the sum of neutrino masses. The program runs from a suite of 3rd generation ground-based and balloon-borne projects over the next 5-10 years, to future missions such as CMB-S4 (DOE/NSF), the LiteBIRD (JAXA/NASA), PIXIE (NASA), and CORe+ satellites (ESA), in the 2020’s and beyond. Our primary goals are (i) to increase the veracity of our simulations subject to scaling constraints, and (ii) to improve the efficiency of the simulation generation/reduction pipeline under the twin pressures of exponential data growth and increasing complexity in HPC architectures.

D.9.2 Computational and Data Strategies

Approach: Although exact solutions exist for the analysis of a CMB data set, they depend on the full data covariance matrix and scale as $O(N^3)$. Exponential data growth has made this approach intractable, so we employ approximate analysis algorithms and Monte Carlo methods for debiasing and uncertainty quantification. The dominant computational challenge is the generation and reduction of $O(10^4)$ realizations of the data. To minimize I/O costs we generate each realization of the time domain data on-the-fly and reduce it to a set of pixelized maps before any data touch disk. Since we are now constrained by spinning disk storage, in future we may need to pre-reduce the maps as well.

Codes and Algorithms: Our analysis proceeds in several steps:

- real or simulated time-ordered data are reduced to pixelized maps at each frequency,
- CMB and foreground maps are separated based on different frequency dependencies,
- fluctuation power spectra are derived from the CMB map, and
- likelihoods of the cosmological parameters are derived from the power spectra.

The first step dominates computation, particularly when simulations are required, and is implemented by the Time-Ordered Astrophysics Scalable Tools (TOAST) software, which includes time-ordered data generation and reduction capabilities, and provides hooks and memory management for experiment-specific tools; key algorithms are pseudo-random number generation and preconditioned conjugate gradient solvers, with underlying algorithms for Fourier and Spherical Harmonic transforms and sparse matrix-vector multiplication.

D.9.3 Current and Future HPC Needs

Computational Hours: For almost 20 years CMB data analysis has used about 1% of the NERSC cycles annually, with requirements growing in lockstep with NERSC’s capacity and

capability. Provided we can maintain our computational efficiency on the coming generations of systems, our needs will likely stay at around the percent level.

Parallelism: Almost all of the workhorse codes are now hybrid MPI/OpenMP; work is ongoing to upgrade or replace those which are not. Analysis of the biggest data sets (Monte Carlo simulations) is explicitly parallelized over realizations. This is managed as separate jobs running simultaneously within a batch submission, but efficiencies could be exploited using distinct MPI communicators to run different realizations independently and concurrently.

Memory: Though CMB detector data require whole-data reduction, there are subsets that localize secondary data (e.g., telescope pointing and detector properties). Current memory per core generally supports our smallest data unit (a stationary interval of samples from a single detector), and the growth in memory per node mirrors that of the next (a stationary interval from all of the detectors at one frequency). Explicit access to manage intermediate data storage (e.g., burst buffers) would be useful.

Scratch Data and I/O: We are already severely hampered by limited persistent (“project”) spinning disk space, and what we do have exhibits I/O performance so limited that we routinely pre-fetch entire data sets to fast but transient scratch disk spaces. I/O performance itself is currently mostly limited by sub-optimal data formats; this issue is being addressed.

Long-term and Shared Online Data: Our hope is to keep data spinning on persistent disk for extended periods (years) and bring analysis to the data. Currently the Planck collaboration maintains 200TB of NERSC project space as a purchased service, but such allocations (and larger) will need to be made routine for next-generation experiments.

Archival Data Storage: Absent sufficient spinning disk for active data sets, fast, reliable, flexible, automated archiving and restoration tools are vital to project data management. Ideally this would also be integrated into batch scheduling so that, for example, archived data could be restored during a job’s queuing time.

Workflows: CMB data analysis proceeds as a series of data compressions, and the reduction from time samples to map pixels marks the transition from tightly- to loosely-coupled analysis steps. From the map domain onwards, subsequent steps are typically carried out by sub-domain experts, and inspected in detail at each step, so much of traditional workflow software is inappropriate. Time domain processing is seeing a significant move towards (typically Python) scripted workflows for rapid prototyping and modularity. We will require the ability to load and execute such scripts efficiently over large fractions of the biggest HPC systems.

Many-Core and/or GPU Readiness: It will be critical for us to transition our core codes to many-core architectures. We expect to dedicate a substantial effort to this end.

Software Applications, Libraries, and Tools: We typically maintain our own installation of many libraries and users load both generic CMB and experiment-specific modules. The range of systematic effects in CMB data from different experiments requires a flexible analysis infrastructure for understanding and realistically simulating each configuration’s data. At present this is being prototyped in Python, though running this efficiently in an HPC environment is a predictable challenge.

HPC Services: CMB missions are decade-long projects with large numbers of collaborators participating the group analysis of exponentially growing data sets. We therefore need to be able to rely on access to continuously state-of-the art HPC resources, for a large number of users scattered around the world, for the duration of the mission.

Code: TOAST	Column 1: Current Usage	Future Usage: 2020 (As a factor of column 1)	Future Usage: 2025 (As a factor of column 1)
Computational core hours (Conventional)	O(100M)	30x	1000x
Memory per node	0.1 GB	30x	1000x
Aggregate memory	1 TB	30x	1000x
Data read and written per run	Read: 10 TB Write: 500 TB	Read: 30x Write: 3x	Read: 1000x Write: 10x
Maximum I/O bandwidth needed	0.1 GB/sec	10x	10x
Percent of runtime for I/O	25%	0.1x	0.1x
Scratch file system space needed	500 TB	3x	10x
Permanent online data storage	5 PB	3x	10x
Archival data storage needed	50 PB	3x	10x

Requirements Summary Worksheet

