Tools, Techniques, and Technology Connections of Particle Physics

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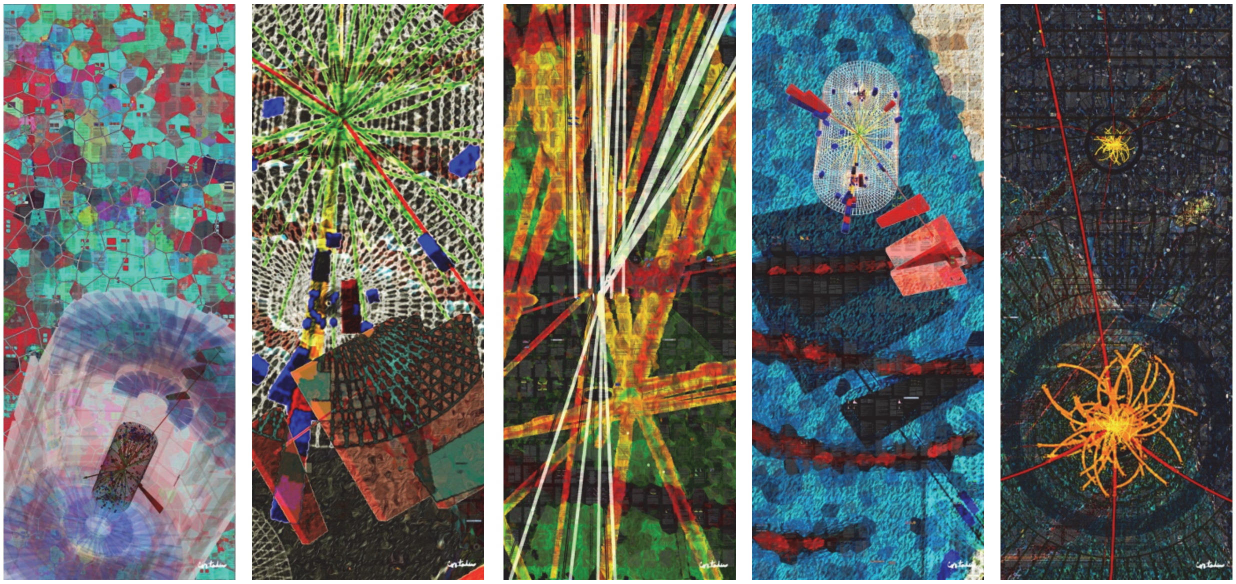

U.S. DEPARTMENT OF
ENERGY
Office of Science

Front Cover

The cover image is the digital tapestry "In Search of the Higgs Boson" (2013) by artist Xavier Cortada, with the participation of Pete Markowitz (http://www.xaviercortada.com/?page=2013CERN). Xavier Cortada is artist in residence at the Florida International University, College of Architecture and The Arts, Miami Beach, Florida.

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Acknowledgements

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This report would not have been possible without the expertise, assistance and support of Program Manager Lali Chatterjee and AAAS Science & Technology Policy Fellow Michael Cooke from the DOE Office of High Energy Physics. The valuable insight and advice from Laura Biven, senior science and technology advisor in the DOE Office of Science, is also much appreciated. To help collect information regarding the connections and synergies of the tools, techniques and technologies used in particle physics, a number of experts were consulted who contributed to the development and writing of this report. The support of these consultants, listed below, is greatly appreciated.

Laci Andricek, *Max-Planck-Gesellschaft Halbleiterlabor*
Tim Antaya, *Massachusetts Institute of Technology*
Makoto Asai, *SLAC*
David Asner, *Pacific Northwest National Laboratory*
Vineer Bhansali, *PIMCO*
Ian Bird, *CERN*
Amber Boehnlein, *SLAC*
Glenn Boyd, *PANNIA*
Michael Campbell, *CERN*
Manuela Cirilli, *CERN*
Bruce Chai, *Crystal Photonics GmbH*
Dhiman Chakraborty, *Northern Illinois University*
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Executive Summary

Particle physics shares with other basic sciences the need to innovate, invent, and develop tools, techniques, and technologies to carry out its mission to explore the nature of matter, energy, space, and time. This dedicated research and development has not only advanced the current state of technology for particle physics, but has also enabled basic scientific research and applications in numerous other areas. At the same time, particle physics has benefited tremendously from advances in other areas of science.

The history of particle physics contains many stories of invention that illustrate the interplay between different fields of science and society. For example, the development of superconducting materials by the materials science community drove nuclear and particle physicists to adopt superconductivity for particle accelerators. Techniques used in the construction of pixel detectors for high-performance particle tracking led to the discovery of a new function of the retina of the eye. And in the area of computing, IBM's Blue Gene supercomputers were greatly influenced by efforts of the particle physics and nuclear physics communities to develop a machine purposely built for Lattice Quantum Chromodynamics (LQCD) calculations. Today's advanced supercomputers are in turn crucial for particle physics simulations and computations.

These are but a few of the historic examples of connections that have hailed from the interaction between particle physics, other scientific disciplines, and industry. Many more opportunities lie ahead to advance scientific discovery and accelerate improvements to the world in which we live.

This report showcases some of the key tools, techniques, and technologies that connect particle physics to other science disciplines, to industry, and to society as a whole. It does not cover external connections that originated from other scientific disciplines. It responds to a charge from the DOE's Associate Director for the Office of Science, Office of High Energy Physics, Dr. James Siegrist, to articulate these particle physics connections and to highlight potential opportunities for advancing scientific discovery and accelerating the pace of innovation in an effective manner.

Potential opportunities identified in this report include:

- Highlighting specific areas of interdisciplinary interest that, upon further evaluation, could enable rapid technological advancements to the benefit of the involved disciplines and the broader scientific community. Initial evaluation through joint workshops could establish a dialogue between leaders in fields with primary interest in these technologies. Some areas, such as instrumentation development with the nuclear and x-ray communities, may already be prepared to move forward with collaborative projects. Promising areas could include

  - Detector materials in partnership with materials science, including designer materials for radiation detection
  - Instrumentation for next-generation light sources and particle physics experiments in partnership with both user communities
  - Lattice algorithms and computational techniques in partnership with condensed matter physics
  - Detector technology advancement in collaboration with nuclear physics
  - Advanced simulation, data management tools, data analysis techniques, and advanced computing architectures in partnership with the computer science community.
- Harnessing the capabilities of particle physics facilities to advance connected fields of science as well as the particle physics mission, and investigating whether the joint construction model that has proved successful for sky surveys might be applicable to other new facilities. The potential would need to be further evaluated, but initial investigation points to a few facilities that might show particular near-term value:
  - A facility for stopped muon beams
  - Neutrino detectors for geophysics
  - Ultra-high vacuum facilities at test beams for atmospheric studies.
- Exploring whether the large, complex, multinational construction model in which particle physics has significant expertise may aid other sciences.
- Developing multidisciplinary training opportunities that can be carried out in partnership with other fields. The objective of such training would be to grow a workforce skilled in the development of scientific tools and techniques and able to identify and apply them in a variety of fields, to the benefit of the broader scientific community.

This report should be viewed only as a first, incomplete attempt to survey the connections between the tools and techniques of particle physics and other science disciplines and to identify future opportunities. Further investigation and evaluation is expected to uphold the idea that the formulation of joint strategies with other fields to address technological challenges, and the creation of multidisciplinary, multi-institutional research projects structured to address grand science challenges, could expedite technological progress for all disciplines.

1. Introduction

Particle physics seeks to understand the formation and structure of the universe at its most fundamental level. Like other basic sciences, it relies on innovative tools, technologies, and techniques to accomplish its mission through experiments, theory, simulation, and computation. Advanced particle accelerators, cutting-edge particle detectors, and sophisticated computing techniques are the hallmarks of particle physics research. These tools and technologies depend critically on advances from other fields, and their value extends far beyond particle physics to other areas of science and society.

The web of connections is extensive between the tools and techniques of particle physics, other fields, and industry. For example, the worldwide particle physics community's critical need to share data globally led to the creation of the World Wide Web, which has revolutionized worldwide business and communication. Similarly motivated distributed computing models allow communication, data sharing, and data analysis by numerous scientific collaborations spread around the globe. Today's advanced particle accelerators rely on superconducting materials discovered by materials scientists. Silicon-based tracking detectors at the heart of many particle physics experiments are made possible by the semiconductor industry's advances in photolithographic techniques.

This report highlights some of the many interconnections between particle physics research and the broader scientific ecosystem in the area of tools, technologies, and experimental techniques. It does not address similar connections that originated from other scientific disciplines. It responds to a charge from Dr. James Siegrist, the DOE's Associate Director for the Office of Science, Office of High Energy Physics, to "identify connections with the potential to advance the HEP mission as well as articulate the important impact that particle physics research has on other disciplines, technology and industry." As defined in this report, there are clear opportunities for expanding and strengthening these connections to better contribute to national and global science and technology while advancing the research goals of the particle physics community.

This report begins with an overview of the broad array of fields where particle detector technologies are being developed and deployed, and how detector R&D has benefited from advances in other science disciplines. A description of the connections between particle physics and other fields in computing, software, and data management follows. Interdisciplinary connections in particle accelerators are next, with a focus on current and near-future developments. Also provided are select examples of the uses of particle physics facilities by other fields, and the joint development of facilities that benefit multiple fields.

Following observations on challenges in the joint development of tools, technologies and techniques, as faced by particle physicists and their colleagues in other fields, the report concludes with an overview of the most promising opportunities.

Society has a poor record in forecasting the impacts of science and technology research. For example, Ken Olsen, founder of Digital Equipment Corporation, said in 1977 about computers: "There is no reason anyone would want a computer in their home" [1]. Using history as a guide, however, there can be no doubt of the continued widespread benefits resulting from inquiry-based research in particle physics and its connected fields. Basic research will not only further explore the wonders of the cosmos, but also continue to play a critical role in the modern innovation ecosystem that drives improvements to everyone’s quality of life.

Detector Technology

As in many science disciplines, particle physicists are driven by scientific inquiry to develop tools that are not available in the private sector. While their original objective was never commercial, in many instances the instrumentation they developed was adopted by other sciences and society at large, sometimes with profound and long-lasting impact.

At the same time, advanced tools and techniques developed by other scientific disciplines have been very beneficial for the progress of particle physics. The recent discovery of the atomic layer deposition process by materials science is being used to make photo detectors with much higher gain and much longer lifetime. Photocathodes continue to be improved in spectral response and higher quantum efficiency through advances in materials science. Furthermore, the tremendous advances in photonics are being integrated into every particle physics experiment, and the community is also seizing upon new developments in the semi-conductor industry.

Silicon Technology

A pivotal technology for particle physics has been the development of planar silicon technology. Following the development of lithographic techniques by the semi-conductor industry in the late 1970s, the particle physics field seized upon the opportunity to develop silicon-based strip detectors, and has adopted it with phenomenal success. This technology has been critical in the measurement of charm and bottom lifetimes, the discovery of the top quark, and the recent discovery of the Higgs boson. The efforts by particle physicists to make integrated circuits resistant to intense radiation has in turn been beneficial to the semi-conductor industry for dedicated applications.

Silicon detectors have played a crucial role in establishing the Standard Model of particle physics and in identifying and characterizing its constituents. Yet the discoveries enabled by this technology have not been limited to particle physics. Silicon-based hybrid pixel detectors were used on a large scale for the first time in the LHC experiments. The Paul Scherrer Institute (PSI) in Switzerland, one of many institutions working on the CMS pixel detector, recognized that such detectors are also very efficient at detecting x-rays and began exploring their use for x-ray science. After a decade of scientific research, the company DECTRIS was spun-off in September 2006 and has been wildly successful in its short history. Every major synchrotron light source currently employs detector systems developed by DECTRIS. By early 2012, 3,000 of their flagship PILATUS systems had been sold for use in studies ranging from crystallography to vaccine development [2] [3].

During the construction of prototype pixel detectors for the LHC experiments, radioactive sources were used to test the system integrity. These tests revealed that pictures were being taken of the sources themselves, which led to the development of a device for x-ray detection reminiscent of a camera. An informal collaboration was launched, and the Medipix1 chip was produced in 1997. The chip was used extensively to test Gallium Arsenide, a sensor material particularly well suited to the detection of x-ray photons in the low-energy part of the diagnostic spectrum, a region used in mammography. The chip was also combined with silicon as sensor, and these devices were used in applications ranging from soft x-ray imaging to beta-ray imaging, and even as a detector in an electron microscope.

The success of the first Medipix chip stimulated a growing interest in the approach, and the team designed a new version that built on their experience developing pixel readout architectures for the nuclear physics experiment ALICE at CERN. The new circuit had not one, but two, thresholds per pixel. This meant that the pixel was sensitive to charge deposits lying between a lower threshold and an upper threshold, the idea being to move towards spectroscopic or “color” x-ray imaging. The Medipix2 chip was produced in 2005 after a four-year development cycle, followed by the Timepix chip that is also sensitive to particle arrival time [4] [5].

The two chips have generated over 150 refereed scientific papers and were

Medipix and Timepix Readout Chip

While testing the quality of the connections of hybrid pixel detectors between pixel sensor and readout chip for particle physics experiments, it was noted that the readout chip was imaging the diagnostic source itself.

The first Medipix chip was developed as a side project. Its potential quickly realized, the second generation of the chip was licensed by the company PANalytical, and is at the core of the PIXCel system, of which more than 500 systems are currently being deployed worldwide.

The experience gained in the continued development of these imaging circuits has come full circle and the latest chip in this series, Timepix3, meets the requirements for the LHCb upgrade experiment with minor modifications.

Color image of a bumblebee taken with Medipix3 on silicon, 55µm pitch, 7x8 tiles, 20kV / 100µA / Mag. 4x, Object height ~25mm. Image from the Ph.D. dissertation of Simon Procz, University of Freiburg.

important components of a large number of PhD theses. The devices are used in a wide range of applications, only some of which were foreseen, including electron microscopy, neutron imaging, nuclear power plant decommissioning, adaptive optics, dosimetry in space, readout of gas detectors with time resolution, and beam collimation studies for the upgrade of the LHC.

An important partner for the Medipix2 and Timepix collaborations has been the x-ray materials analysis industry [6]. This segment of industry utilizes highly scientific x-ray analysis technology in their commercial products that provides researchers (in industrial as well as in scientific laboratories) the tools to study materials. The early commitment to the Medipix2 chip provided the collaboration with the motivation (and the money) to take the chip beyond the prototype stage to an industry-standard level. This “diversion” into imaging has not only proven to be beneficial for the non-particle physics community, but also for the field itself. The latest version of the Timepix chip meets nearly all the specifications for the upgraded vertex pixel detector for the LHCb experiment at the LHC, saving significantly on development time.

The development of monolithic active pixel detectors for the nuclear physics experiments STAR at Brookhaven National Laboratory and ALICE at CERN also illustrates the synergistic and complementary relationship between the nuclear and particle physics communities in the area of detector development. Over the course of their histories, both fields have improved upon technologies initiated by the other. In the case of ALICE, the nuclear physics community is maturing a technology originally initiated by particle physics by constructing a 25-gigapixel tracking detector—the largest pixel detector ever built [7]. This complementary development of specialized tools by the two communities results in sophisticated technology, avoids duplication, and allows each community to build on the advances made by the other.

Silicon strip technology, developed by particle physics, is well suited for the study of the retinal output of the eye. Silicon-based particle physics detectors are enabled through nanofabrication techniques, custom-designed multichannel readout integrated circuits with low-noise analog amplifiers and multiplexed output, and high-density wirebonding for interconnects. These same ingredients were used to implement a “neuro-board,” an electrode array with very fine pitch readout electrodes that detects the electrical signals generated by hundreds of neurons in the retina. The neuro-board also uses a wireless brain activity recording system for studies of awake, naturally-behaving animals. These studies have discovered a new functional type of primate retinal output (ganglion) cell that may be involved in motion perception. It has also led to the creation of a functional connectivity map of the primate retina at the resolution of individual cones and individual retinal output cells [8].

Silicon strip technology as developed by particle physics is also being explored for medical imaging, notably in the current development of proton-computed tomography (pCT) [9] [10]. In a pCT scanner, the trajectory of a proton of well-defined momentum is measured before entering and after leaving the patient, as is its energy after passing through the patient. The proton energy loss is correlated with the particle trajectory to image, for example, the brain to locate tumors, which can then be treated through ion therapy. Particle trajectories are measured based on the silicon strip technology developed for the ATLAS experiment at the LHC and for the Fermi/GLAST experiment. For medical imaging purposes, a crucial parameter is the sustained data rate needed for an image to be acquired in an acceptable time frame of a few minutes. The data acquisition for the pCT system has been patterned on the architecture of GLAST/Fermi but with a 100-fold increase in speed. The ability to reconstruct a billion events per scan has been made possible by software developed for particle physics.

Scintillating Crystals

Another excellent illustration of the successful interplay between particle physics, industry, and other branches of science is the development of scintillating crystals.

Bismuth Germanium Oxide (BGO) scintillating crystals were discovered in the 1970s; they have very good performance characteristics for the detection of electromagnetic showers. In the late 1980s, the L3 experiment at the electron-positron collider, LEP, at CERN decided to build the first BGO crystal calorimeter, consisting of 11,400 BGO crystals with a total volume of 1.5 m^3. The Shanghai Institute of Ceramics (SIC) was selected to be the supplier of the crystals. Although at the time the L3 order was a one-shot market for SIC, the large production volume required by the experiment led to the development of multicrucible growth technology that allowed the growth of up to 36 crystal ingots per oven. This breakthrough opened up the BGO medical market. GE Healthcare has since built more than 1,500 PET scanners with SIC BGO crystals.

Bismuth Germanium Oxide Crystals

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More than 1,500 Positron Emission Tomography scanners have been built with SIC BGO by GE Healthcare at a cost of $250k – $600k each.

About 1.5 million PET scans are performed per year in the United States.

Jens Langner / Wikimedia Commons / Public Domain

The requirement of radiation hardness of crystals for the LHC experiments also led to the development of a new type of crystal. Lutetium Orthosilicate (LSO) crystals were invented in the 1990s at Schlumberger. Radiation damage studies of scintillating crystals for the LHC experiments showed that thermal annealing of the crystals in an oxygen atmosphere and yttrium doping were quite effective for improving crystal radiation hardness. These radiation damage studies were noticed by faculty at the College of Optics & Photonics at the University of Central Florida. Its application to LSO crystals led to the invention in 2005 of Lutetium Yttrium Orthosilicate (LYSO) scintillating crystals. With brighter and faster scintillation light than BGO, LYSO now dominates the market for PET scanners, with thousands of LYSO-based PET scanners marketed to date by GE and Phillips. Closing the circle, LYSO-based crystal calorimeters are being considered for future particle physics experiments such as the Muon-to-Electron Conversion (Mu2e) Experiment at Fermilab.

Synergies around Other Detector Technologies

Particle physics experiments at colliders share the need for cost-effective, large-area particle detectors with the developers of next-generation PET scanners. While particle physics brought crystal development into the cost-effective industrial production domain, the technology remains too expensive and not well suited for full-body PET scanners. An option now being studied for such scanners is the resistive plate chamber technology developed for particle physics to provide very good temporal and spatial resolution over large areas at low cost [11]. Given the high sensitivity, good resolution, and complete field of view of this technology, small tumors can be detected with a much lower injected activity dose per patient. Measuring time is also reduced, which allows more patients to be scanned at lower cost per examination.

A very different type of imaging is also benefiting from resistive plate chamber technology. Volcanologists, collaborating with particle physicists, are using resistive plate chambers to build a precise tool for volcano tomography. The TOMUVOL experiment (TOmography with atmospheric MUons of VOLcanos) uses glass resistive plate chambers developed for the International Linear Collider (ILC) as trackers for transmission imaging of volcanoes [12]. By continuously measuring the atmospheric muon flux passing through the volcano, and comparing the measured flux with the expected flux, the integrated density along the muon path is determined. The higher the density, the more muons are absorbed. The Puy de Dôme, a volcano near Clermont Ferrand that has been dormant for over 12,000 years, has been imaged this way.

The MU-RAY project [13] will perform volcano radiography of Mount Vesuvius and Stromboli, using a detector based on plastic scintillator bars with wavelength-shifting fibers. The scintillation signals are detected with silicon photomultipliers and are read with an application-specific integrated circuit developed for calorimetry at the ILC. Yet another project [14] uses scintillating strips and Cherenkov counters for imaging Maya ruins.

Cosmological surveys provide overwhelming evidence for the existence of dark matter. The composition of the constituents of dark matter, however, is currently unknown. To detect these exceedingly weakly interacting particles, without being fooled by possible background signals, particle physicists have invented transition edge detectors. The sensors are tiny, exceedingly sensitive calorimeters that operate in the transition region from superconducting to normal conducting. The sensors can be tuned for various frequency ranges, including millimeter-wave, submillimeter, optical, and x-ray. Cosmologists, astronomers, and particle physicists now use these devices to study the cosmic microwave background radiation that probes the physics of the inflationary epoch when the universe was born.

There are many unexpected areas where particle physics detectors are being used or where tools and techniques are being incorporated in new developments. One example of the former is the development of a particle physics readout circuit now being used in handheld perioperative gamma cameras for lymphoscintigraphy [15]. Silicon pixel detector technology and its associated data-acquisition systems are also being adopted in the development of the major two-dimensional imaging x-ray detectors for the European X-ray Free Electron Laser, the Adaptive Gain Integrating Pixel Detector (AGIPD), the Large Pixel Detector (LPD), and the DEPFET based Sensor with Signal Compression (DSSC).

Instrumentation developed by and for the field of particle physics has clearly found widespread use outside the field itself, often with tremendous impact. Particle physics has similarly imported tremendously valuable expertise from other disciplines. The path in which this has come about is often serendipitous. Sometimes, enlightened management has allowed a project with no apparent direct benefit to particle physics to continue for a couple of years, which then led to the development of innovative instrumentation. Sometimes it has literally been the crossing of the paths of two physicists who recognized the value of each other’s ideas.

Advanced materials are now being discovered and developed at an accelerated pace as materials scientists, supported by new computational techniques, begin to produce materials by design. Tremendous advances are occurring in nanophotonics, transition metals, and quantum computing. It is critical for particle physics to tie in to these communities in order to take advantage of these and other breakthroughs to further advance detection techniques and make them more cost-effective. In some cases, strong connections have already been identified and can be fostered towards testing and implementation via pilot projects or feasibility studies.

3. Computing, Software, and Data Management

Particle physics research, often in partnership with other fields, has pushed the boundaries of computational techniques and sometimes even the hardware itself. As a result of this continued partnership with industry and other disciplines, particle physics has also benefited, as the technology has been transformed into more sophisticated versions. The scale of these activities—defined by the hundreds of petabytes of data volumes and worldwide interest in this area of research—has given rise to a well-established history of collaboration that reaches across international and technology boundaries.

Particle physics' role in the creation of the World Wide Web has been highlighted in a report from the President's Council of Advisors on Science & Technology (PCAST) [16]. The Web was developed at CERN in the 1990s as a response to a new need for scientific collaboration; since then, it has pervaded every corner and every aspect of society and social interaction. It represents arguably the most striking example of a disruptive technology that originated out of particle physics.

The development of distributed "grid" computing technology has provided the next step as a response to the need for increased data analysis power that can be made available by accessing remote computer installations in widely dispersed institutes. With the construction of the LHC came the need to develop tools and infrastructure for large international collaborations to manage, distribute, and analyze very large amounts of data. By launching grids in Europe and the United States to support the LHC, particle physics demonstrated the capability and operability to unite globally distributed computing resources into a coordinated computing service [17]. The European and U.S. grids are now used by a wide spectrum of sciences ranging from archeology to astronomy, and from computational chemistry to materials science.

GEANT4 (GEometry ANd Tracking software toolkit) is another example of the interplay between particle physics computing and the broader scientific community [18] [19] [20]. A sophisticated toolkit, GEANT4 was developed by the particle physics community for the simulation and tracking of particle interactions in complex devices using Monte Carlo methods. GEANT4 is an "all particle" code that supports complex geometries, can handle motion in magnetic and electric fields (including time-varying fields), uses a modern programming language (C++), and, very important to its wider success, is open and free for use. Users have the capability in GEANT4 to describe intricate geometries, define the unique material properties of every element

Monte Carlo Simulation Packages

The Monte Carlo simulation package FLUKA (FLUktuierende KAskade) is a fully integrated Monte Carlo simulation package for the interaction and transport of particles and nuclei in matter developed by the particle physics community. The code has been used to study the effect of cosmic radiation on air travel and flight crews.

A particular study has developed a mathematical model of an Airbus-340 and determined the effective dose and ambient dose equivalent rates inside the aircraft at several locations along the fuselage, at a typical civil aviation altitude of 10,580 m. Opportunities for aircraft shielding of the galactic component of cosmic rays were provided to mitigate the effect of radiation on passengers and aircraft crews.

Adrian Pingstone / Wikimedia Commons / Public Domain a particle encounters on its path, and track the passage of particles through matter, keeping track of their primary and all secondary interactions. GEANT4's ability to simulate particle physics processes quickly and accurately is critical to the success of particle physics, and has become a vital tool for advances in a number of other fields and industries, including medicine, aerospace, nuclear physics, accelerator modeling, nanoscale science, and geophysics.

In proton therapy, pencil-like beams are obtained through collimation. The protons hitting the collimator will occasionally produce a neutron, which could pose a significant hazard to the patient. GEANT4 is used to determine the dose a patient receives from these undesirable, but unavoidable, background neutrons. In space science, GEANT4 is at the core of tools used by Boeing and Lockheed Martin to evaluate the radiation effects and protection of shielding and single-event effects of semiconductor devices in space environments. Boeing, which also uses GEANT4 to estimate the radiation dose of flight crews, hosted the 7th GEANT4 Space Users workshop in 2010.

Lattice Quantum Chromodynamics (LQCD) uses advanced computing techniques to solve the nonperturbative regime of QCD on a space-time lattice. Quarks and gluons that make up many of the observed particles of matter (called "hadrons") are held together and interact via QCD, historically called "strong interactions." LQCD relies on high-performance computing (HPC) and advanced software to provide precision computational results and predictions for explaining experiments and exploring new physics. The LQCD community is comprised of particle physicists and nuclear physicists studying different aspects of strong interactions of particles and nuclei. LQCD tools and techniques are developed collaboratively by the two disciplines, eliminating duplicative effort.

The LQCD community has been an avid user of advanced computing platforms and one of the major drivers and contributors to early developments in the supercomputing industry. Interactions between LQCD and computer designers go back as far as 1982 at the founding of the Thinking Machine Corporation. At the time, famed physicist Richard Feynman and his son Carl were working on the network of the Connection Machine and optimizing LQCD algorithms. This was followed by the development of "QCD on a chip," or QCDOC computers, by a group from Columbia University [21]. A collaborator from the Columbia group went on to join IBM and design the closely related commercial product, the BlueGene/L [22].

Lattice QCD connections with advanced computing continue today with collaborations of both particle and nuclear physics researchers with the computing science community and IBM, NVIDIA, and Intel Corporation. Such partnerships between the scientific communities and the computing and software communities and industry allow this area of particle physics access to cutting-edge computing technology, avoid duplication of effort among fields and with industry, and continue to drive advanced computing platforms.

LQCD techniques are also applied to condensed matter physics. Such systems intrinsically involve physical lattices (rather than space-time constructs like those used in lattice gauge theories); they exhibit a rich variety of nonperturbative phenomena, and their properties are often controlled by gauge symmetries. Systems of interest in both fields are frequently studied with Monte Carlo methods, and in both cases fermionic degrees of freedom make these studies challenging. Algorithms and calculational methods developed in each of these fields have been transferred to the other. For example, hybrid Monte Carlo algorithms invented in lattice gauge theory have been used to study models of high-temperature superconductivity. Continued interaction between the two communities is likely to yield further fertile ground for cross-seeding of methods.

Modeling and simulation of cosmological probes of interest to particle physics has an intimate connection with astronomy and astrophysics, particularly the clustering and physical properties of galaxies, galaxy groups, and clusters. Large-scale cosmological simulations studying different aspects of the “dark universe,” dominated by the mysterious duo of dark energy and dark matter, make significant use of leading-edge supercomputing architectures and are one of the important drivers of hardware and software co-design for future extreme-scale systems.

The computational and data challenges of “big science” projects such as the LHC experiments are not limited to the unprecedented size of the “big data” generated. The highly distributed locations of researchers who need to access and analyze the data require sophisticated workload and distributed data management systems. One of these, developed in the U.S. and used primarily by the ATLAS experiment at the LHC, is PanDA (Production and Distributed Analysis System) [23]. This system supports data-intensive science by delivering transparency of data and processing in a distributed and heterogeneous computing environment. Communities outside particle physics have recognized this, and PanDA is becoming a broader enabling technology fostered by partnerships with computing and software communities.

In the area of networking, for more than a decade, large-scale particle physics data flows have been the primary driver for the evolution of the architecture and implementation of the Energy Sciences Network. ESnet is a high-bandwidth network that connects and enables the research of scientists at national laboratories and universities across the country. Spurred by the needs of particle physics, ESnet developed the virtual circuit service called OSCARS, the On-demand Secure Circuits and Reservation System. This software service creates dedicated bandwidth channels for scientists who need to move massive, time-critical data sets around the world. OSCARS received a 2013 R&D 100 award and is now used by other data-intensive science communities [24]. In addition, major international network traffic exchange locations associated with Office of Science programs are also driven by the requirements of particle physics.

Data management tools developed in particle physics experiments have been used successfully in condensed matter experiments at DOE Light Sources [25]. This has initiated discussions to establish multidisciplinary partnerships between condensed matter scientists, particle physicists, and computer scientists to address the challenges of big data via collaborations that may drive better tools and avoid duplication.

Particle physics research, in collaboration with the astronomy and astrophysics communities, has innovated special data systems to deal with "big data" as part of its quest to probe the universe via the Cosmic Frontier. The particle physics community's expertise in building very complex facilities and processing very large data sets was used in the Sloan Digital Sky Survey (SDSS) [26], whose science goals served both the particle physics and astronomy communities.

The Scientific Linux operating system developed by Fermilab and CERN is another example of a system developed "along the way" to particle physics discovery but which now powers other sciences. Scientific Linux runs on the International Space Station as well as the majority of the campus grid at the University of Wisconsin-Madison, for example, powering student research from economics to engineering.

The particle physics community has recently taken steps to identify and recommend future promising partnership efforts in the development of computing tools and techniques, along with training, R&D efforts, and an expert group to guide continuing development [27]. These steps build on established collaborative research on algorithms and other tools and techniques, along with studies of synergistic data tools undertaken with the computer science community [28] [29].

4. Accelerator Technology

The history and continuing development of particle accelerators and the interconnections among multiple scientific fields, medicine, and industry is well known. The first particle accelerators were invented in the early 20th century and became a critical technology for any research needing high-energy, high-intensity particle beams. Today's accelerators power research in particle and nuclear physics and drive light sources that enable discoveries in biology, materials science, and other diverse fields. For every accelerator used for scientific discovery, thousands more are used every day in industry and medicine to produce better products and to treat disease [30].

Multidisciplinary expertise continually drives accelerator technology forward. Materials scientists work in tandem with accelerator scientists to develop better and more sophisticated cavity materials and magnet components. Advances in computing make possible much more accurate and thorough simulations that inform accelerator construction and improve the performance of operating machines. Laser and plasma physics discoveries propel the development of new types of accelerators with extremely high gradients. Much of this work is driven by the needs of particle physics in coordination with particle physics researchers.

Superconducting radio-frequency (SRF) technology is one of the major R&D thrusts for the next generation of particle accelerators, due to its potential to drive high-intensity, high-power, low-beam-loss accelerators. The technology was incorporated into the recent upgrade of the Jefferson Lab's CEBAF accelerator, and is being investigated for possible future nuclear and particle physics accelerators and light sources.

The further development of this technology is driven by collaborations that include accelerator science, particle physics, nuclear physics, materials science, and advanced computing. As an example of how other fields contribute critically to SRF R&D, techniques in materials depositions have enabled the manufacture of improved accelerator cavities. Further advances in this area of science, such as depositing superconducting alloys as thin films on other materials, may prove critical to placing very-high-energy future colliders within an achievable cost range. Better understanding of phenomena such as magnetic vortices, which interfere with superconductivity and limit the performance of cavities, could lead to breakthroughs in achievable gradients.

As the energies of particle colliders needed for particle physics research continue to increase, leaps forward may be required both in the gradients achievable by accelerators and in reductions in the cost to achieve those gradients. Two promising current areas of accelerator R&D for future

Accelerators for a Cleaner Environment

In the 1970s researchers in Japan and the United States began studying the possibilities of using electron beams to treat flue gases and wastewater. The idea continues to be pursued in the United States, Asia, Europe, and the Middle East.

In Korea, an electron-beam accelerator in a textile factory removes toxic dyes from 10,000 cubic meters of wastewater per day. In Poland, a power station uses an accelerator to simultaneously remove sulfur dioxides and nitrogen oxides from about 270,000 cubic meters of flue gas per hour. China has started to use electron beams to control air pollution, and a similar facility is under construction in Bulgaria.

For flue gases from the smokestacks of factories and power plants, the objective is to destroy sulfur dioxides and nitrogen oxides, pollutants that create acid rain and smog. Conventional treatment uses two separate scrubbing techniques and creates wastewater. Electron beams remove both pollutants at once and, instead of generating waste, generate ammonium sulfate and ammonium nitrate that can be sold as ingredients for fertilizer.

Traditional wastewater treatment plants use a three-step process to kill microorganisms, extract suspended solids, and distribute the treated water. Electron-beam treatments need only one process to take water from hazardous to benign, resulting in a nutrient-rich liquid that can be used as fertilizer.

While accelerators show great promise to reduce harmful emissions in air and water, R&D to reduce size and cost and increase reliability is needed for widespread commercial adoption.

(Adapted with permission from Symmetry Magazine)

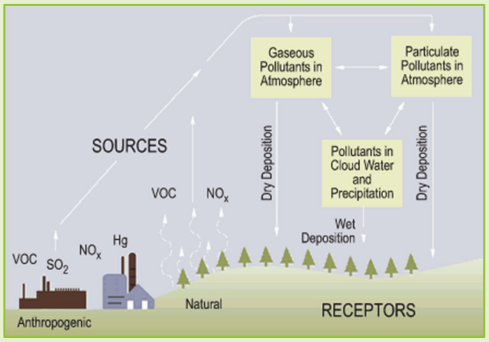

Image courtesy Environmental Protection Agency high-gradient accelerators—both intimately connected to other scientific fields, notably plasma physics—are laser-driven and beam-driven plasma wakefield accelerators.

Laser-driven acceleration has demonstrated gradients of greater than 100 GeV/m, but the concept faces many R&D challenges on the road to use in a high-energy collider. Challenges include ultrafast infrared lasers in the Joule-class energy range, new lasing materials, terawatt to petawatt peak power, kilowatt average power, greater than 15% efficiency, and kHz repetition rate. Laser-driven acceleration relies on other sciences to deliver the solutions to these challenges in laser performance, and in some cases they are already delivering. For example, national initiatives drove the development of the high-efficiency pump diodes that have helped enable the powerful lasers used by BELLA at LBNL. The plasma physics community also contributes critical scientific and technological advances to these accelerator R&D projects. Such technological advances would not only benefit laser-driven acceleration, but also electron-positron accelerators, light sources, and medical accelerators.

Significant progress has already been made over the last five years in surveying the landscape of accelerator connections, identifying the most critical accelerator R&D needs that benefit all fields of science and industry, and charting the best paths forward to joint development of tools and technologies to meet these needs.

Seeking to understand the broad impacts of accelerator science and technology development, DOE's Office of High Energy Physics sponsored the Accelerators for America's Future workshop in 2009. This brought together 300 experts in accelerator technology to discuss the current uses, needs, and future of accelerator technology [31]. The workshop report highlighted the diverse applications that use accelerators, including irradiating tumors, cross-linking polymers to improve tire durability, treating flue gases to remove pollutants, and inspecting cargo containers for contraband, among many others. Following this, the Accelerator R&D Task Force [32] was called up in 2011 to provide initial evaluation of opportunities and obstacles to developing a successful cross-cutting program. The task force was followed by two topic-area workshops on Ion Beam Therapy [33] and Laser Technology for Accelerators [34]. A long-term Accelerator R&D Stewardship program is now being developed within the DOE Office of Science with input from this four-year-long community input process [35].

5. Particle Physics Facilities

The particle physics community forms large, international collaborative teams to build, operate, and use complex accelerator, detector, and computing facilities. The primary goal of particle physics facilities is a greater understanding of matter, energy, space, and time. Some facilities, however, are also of interest to researchers in other disciplines as tools well-suited to meet their scientific goals.

For example, particle physicists use high-energy muon beams to explore “deep inelastic scattering,” and low-energy muon beams to study fundamental symmetries. Low-energy and stopped positive muon beams are also of great significance to researchers in condensed matter and various technology areas due to the power of muon spin resonance (μSR). Because of maximal parity violation in weak decays, stopped muons are nearly 100% spin-polarized, which makes this technique significantly more powerful than other magnetic resonance probes such as nuclear magnetic resonance (NMR) or electron spin resonance (ESR). Because the muon spin and charge are exquisitely sensitive magnetic and electronic quantum probes of matter, they provide a unique time window for studying dynamic processes. Negative muon beams have been used for research on muon catalyzed fusion and muonic atom states [36] [37].

The Cosmics Leaving Outdoor Droplets (CLOUD) experiment [38] is the first use of a particle physics accelerator to study atmospheric and climate science. Using beams from CERN’s Proton Synchrotron, a cloud chamber is used to investigate the possible link between galactic cosmic rays and cloud formation, contributing to the fundamental understanding of aerosols and clouds and their effect on climate. The Proton Synchrotron provides an artificial source of “cosmic rays” that simulates natural conditions between ground level and the stratosphere. The ultra-vacuum technologies used by particle physicists are of interest to the atmospheric science community for their power in hosting “clean environments” for controlled experiments. Atmospheric science experiments of this kind are possible at any particle physics facility that has particle beams and vacuum technology infrastructure [39].

Proton synchrotron boosters are also used for the production of a large variety of radioactive ion beams for different experiments in the fields of nuclear physics, atomic physics, solid-state physics, materials science, and life sciences [31].

Over the last two decades light source facilities have become the workhorses of several fields, allowing researchers to use x-rays, UV, and infrared light to study materials, proteins, chemical reactions, and other phenomena in incredible detail. Light sources developed out of the recognition of the value of synchrotron radiation for a wide range of fundamental studies. While synchrotron radiation reduces the beam power useful for particle physics experiments, the radiation itself is a powerful tool for light-induced experiments. Several operating light sources—LCLS and SSRL at SLAC, CESR at Cornell, and PETRA III at DESY—have at their heart accelerators that operated for many years as particle physics machines. In turn, the success of light sources as a tool for advancing knowledge in other disciplines drives increased demand for advances in accelerator technology that will benefit particle physics.

Particle physics researchers also partner with other fields to build facilities that advance multiple disciplines right from the start. This approach has enjoyed great success in the quest to understand the phenomenon of dark energy. Particle physics expertise in detector construction has coupled with the expertise of the astronomy and astrophysics communities in building advanced telescopes to advance the scientific goals of all three fields. A rapid increase in efforts to understand dark energy followed the 1998 discovery that this universe is expanding. With no identifiable candidate for the dark energy thought to cause this expansion, the particle physics community worked closely with the astronomy community to build and operate facilities for analyzing data from large sky surveys. These data are used by particle physicists to quantify the effects of dark energy, and by many members of the astronomy community to advance a large variety of astronomical research areas. The "Connections of Particle Physics with Other Disciplines" study addresses these connections from a scientific perspective [40].

The first such sky survey built in partnership between particle physics and astronomy was the Sloan Digital Sky Survey (SDSS) [26]. The Dark Energy Survey (DES) [41] further advanced the partnership between particle physics and astronomy with the construction of the 570-megapixel camera known as DECam, which forms the heart of the survey. As with the SDSS, DES data will advance the understanding of dark energy and power discoveries in many other areas of astronomical interest. This tradition of partnership between particle physics and astronomy continues with the Large Synoptic Survey Telescope (LSST), which will place a 3200-megapixel camera on a new telescope in Chile [42].

While the expertise of particle physics in the construction of CCD cameras powers the current and future generation of sky surveys, its expertise in detecting neutrinos may also find applications farther afield. The detection of geoneutrinos using large detectors will improve the understanding of heat flow in the earth's core. The core is predicted to produce 16-42 TW of radioactive power, with approximately 20% escaping to space as neutrinos [43]. An unlikely connection was established between particle physics and glaciology

The Dark Energy Survey

The Dark Energy Camera (DECam), now installed on the 4-meter Victor M. Blanco telescope at the National Science Foundation's Cerro Tololo Inter-American Observatory in Chile, is a prime example of the successful joint construction and operation model used by the particle physics and astronomy communities.

DECam, completed in 2012, is the most powerful sky survey instrument of its kind. Scientists from the Dark Energy Survey collaboration will use its 570-megapixel digital camera to record light from more than 200 million galaxies up to 8 billion light-years away.

The particle physics community led the DECam construction project, with project management and camera construction housed at Fermi National Accelerator Laboratory. Researchers from 25 institutions and more than 100 companies in six countries came together to build the camera's 21 subsystems. The astronomy community reconfigured and now operates the telescope on which DECam is installed.

Each year for five years a fixed portion of survey time will be dedicated to operating the instrument for the Dark Energy Survey collaboration, whose science goals are part of the high-energy physics mission. The telescope is operated for the remainder of the year in support of the diverse research goals of the astronomy community.

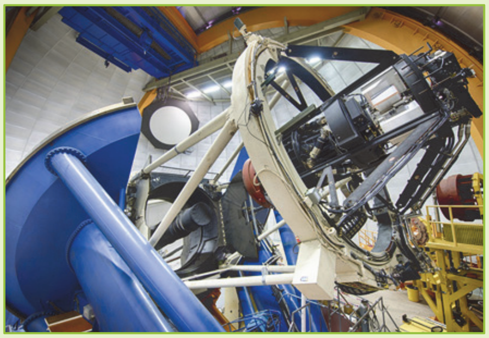

Image courtesy Fermilab

through the construction of a neutrino detector facility. The deployment of photo-detectors at a depth of 2500m in the ice of the Antarctic for the study of neutrinos has provided the most clearly resolved measurements of Antarctic dust strata during the last glacial period and can be used to reconstruct paleo-climate records in exceptional detail [44]. Neutrino detectors are also being investigated as part of a comprehensive nonproliferation program, monitoring nuclear reactor activity and the assessment of the isotopic composition of reactor fuels [45].

As part of the synergistic use of facilities by the particle physics and nuclear physics communities, the LHC devotes a fixed portion of its running time to accelerating heavy ions for the study of the quark-gluon plasma for nuclear physics research. Beams from Fermilab's accelerator complex are being used by the SeaQuest nuclear physics experiment that seeks to improve the understanding of the role antiquarks play in nucleon structure. In turn, particle physicists use the 12 GeV electron beam facility at Jefferson Lab for a heavy photon experiment.

6. Observed Challenges

Throughout the process of gathering input and information for this report from consultants and from previously published reports, various challenges and obstacles were noted that hinder closer and more successful connections between particle physics and other fields in the development and application of tools, technologies, and techniques.

An overall observation—applicable widely across all fields of science and all types of scientific facilities—is that there are still many challenges to initiating, identifying resources to support, and carrying out multidisciplinary research. This challenge is called out, for example, in the report of the Accelerator R&D Task Force [32], which noted that sufficient mechanisms do not currently exist to enable particle physicists to work collaboratively with other fields on projects of common benefit. Mechanisms suggested by those reports to overcome this challenge include interdisciplinary teams funded for specific term-duration projects, short-term personnel exchanges, and opportunities for senior researchers to spend a well-defined percentage of their time on ideas outside the mainstream of particle physics technology R&D.

The lack of multidisciplinary training opportunities has been noted as another obstacle to fostering connections between fields in the areas of tools and technologies. Similarly, a lack of career paths for personnel skilled in, and dedicated to, the development of detectors, accelerators, and scientific computing techniques was seen as a major obstacle to continuing development of these tools. These challenges are particularly acute in the areas of accelerator and instrumentation R&D and operation. It is these areas that will define not only the future of particle physics but, increasingly, the future of other connected fields and segments of industry. Yet the current shortage of people skilled in accelerator and detector development, construction, and operation continues to increase [46] [47].

Contributors also noted the accelerating pace of development in other fields of science and the difficulty in keeping informed about the successes elsewhere that could have important benefits to particle physics. Joint workshops, multidisciplinary training opportunities, and expanded opportunities for interaction between particle physicists and other scientists might help address this obstacle.

7. Opportunities

By their very nature, the tools, techniques, and technologies developed by science cross the boundaries of many disciplines. As the examples presented in this report demonstrate, technologies created to address a specific scientific goal are often embraced and nurtured by other fields, which then pass their further developments on to other scientists and industry. Enabling and encouraging these multidisciplinary developments would be to the great benefit of this country's innovation ecosystem.

The following opportunities are highlighted as having the potential to facilitate and accelerate the process of innovation in the development of the tools, techniques, and technologies of particle physics and other scientific fields.

Several specific areas of interdisciplinary interest were uncovered that could enable rapid technological advancements to the benefit of the broader scientific community. In some areas small collaborative work is already underway, or previous projects have demonstrated great potential for future synergies. Initial evaluation could be performed by joint workshops that establish a dialogue between leaders in the fields with primary interest in these technologies. These areas include:

- Detector materials in partnership with materials science, including designer materials for radiation detection. With the materials genome project now underway, bringing together the fundamental materials science with the required technical challenges could prove extremely fruitful.
- Instrumentation and data tools for the next generation of light sources and particle physics experiments, in partnership with both user communities. The science potential of next-generation light sources can best be exploited with state-of-the-art instrumentation. The particle physics experience in collaborative development of highly complex systems with large data volumes could be explored for adoption for use at light sources.
- Lattice algorithm and computational techniques in partnership with condensed matter physics. Algorithmic development for high-performance computers aimed at solving complex multibody problems could provide pathways solutions in particle physics, condensed matter, and related science areas.

- Detector technology advancement in collaboration with nuclear physics. The nuclear physics community is embarking on the development of new detector technologies that are closely related to particle physics technologies. The added value of collaborative efforts could prove beneficial to both disciplines.
- Advanced computing including simulation, data management tools, data analysis techniques, and advanced computing architectures in partnership with the computer science community. Rapidly evolving computer architectures as well as the exponentially increasing data volumes require effective, cross-disciplinary approaches. Improvements would benefit the particle physics mission as well as many other scientific fields that increasingly rely on similar computing tools, techniques, and architectures.

While many of the above areas would require further evaluation, the area of instrumentation development in collaboration with the nuclear physics and x-ray detection communities is at a more advanced stage. With communication and partnership better established among these communities, the opportunity exists to establish collaborative projects to achieve identified key challenges in detector R&D.

In the area of accelerator technology, many opportunities for short- and long-term collaboration to meet the grand challenges faced by particle physics and other fields have been identified by previous workshops and reports [31] [32] [33] [34], which should be consulted for a comprehensive list.

Opportunities exist for the particle physics field to explore if the capabilities of existing facilities can advance the goals of other fields, and investigate whether the joint construction model that has proved successful for sky surveys might be applicable to other planned or proposed facilities. The potential would need to be further evaluated, but initial review points to a few facilities that might show particular near-term value:

- A facility for stopped muon beams
- Neutrino detectors for geophysics
- Ultra-high vacuum facilities at test beams for atmospheric studies.

Particle physics may also have the opportunity to help other fields surmount challenges in the construction and operation of large, complex multi-institutional and multinational projects, due to its decades-long history of developing the methodology to bring such projects to successful completion. In turn, collaboration with other fields may bring new techniques to particle physics that could improve the planning, construction, and operation of future projects.

Lastly, the opportunity exists for particle physics to work in close partnership with other fields to develop and carry out multidisciplinary trainings in the area of scientific tools and techniques. The objective of this training would be to develop and maintain a workforce skilled in the development of such tools and techniques, and educated about the possible uses in a variety of scientific fields. Such trainings could be a first step toward reducing the deficit of individuals skilled in the development and application of instrumentation, accelerators, and scientific computing.

This report is a first, incomplete attempt to identify some of the important connections between particle physics and other sciences; this list of potential opportunities is by no means comprehensive or exhaustive. The future will certainly bring transformative tools, technologies, and techniques, and greater connections between the particle physics field and others will ensure that these leaps forward benefit the entire fabric of science.

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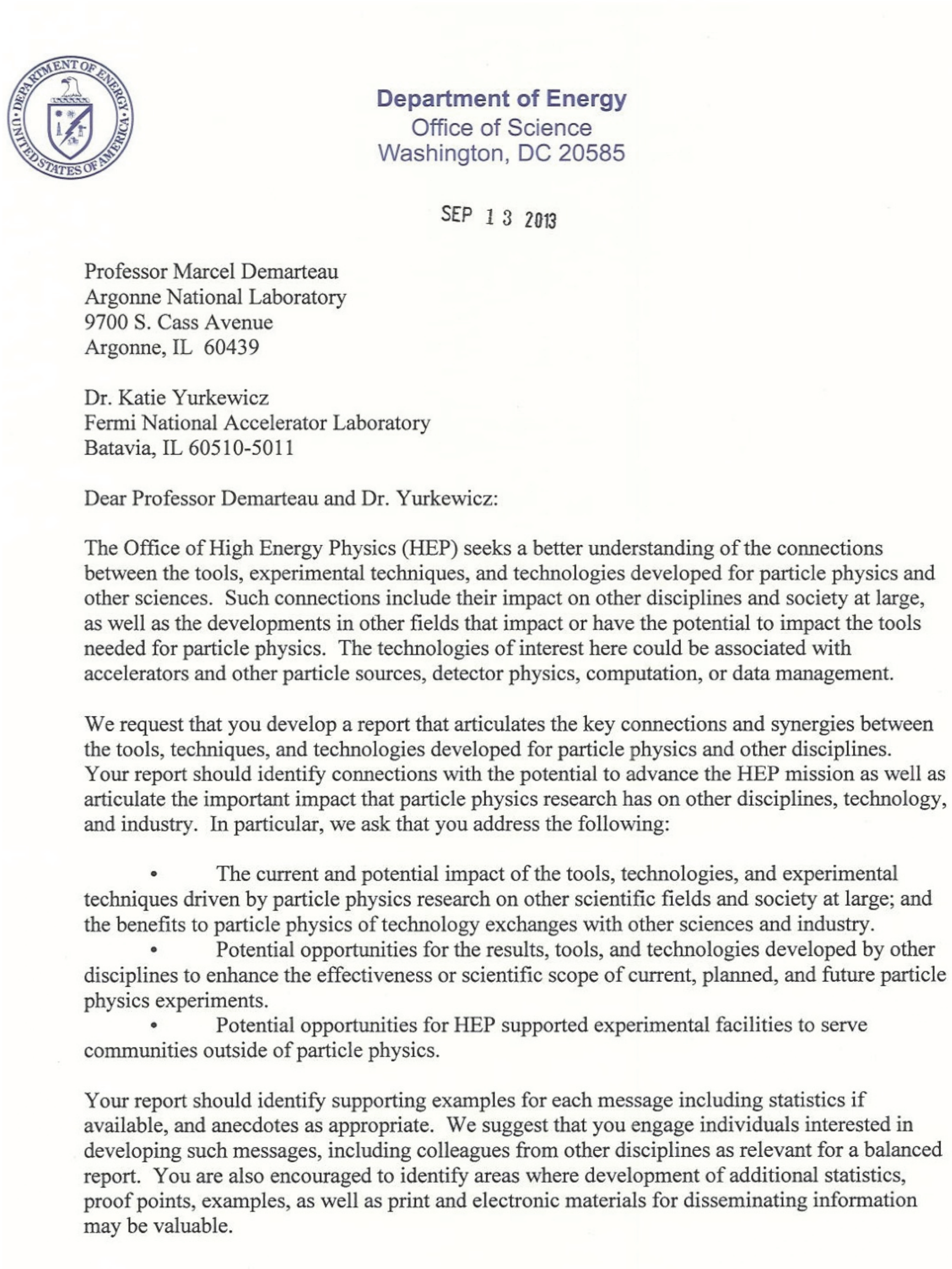
Appendix: Charge from DOE Office of High Energy Physics



Department of Energy
Office of Science
Washington, DC 20585

SEP 13 2013

Professor Marcel Demarteau
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Dr. Katie Yurkewicz
Fermi National Accelerator Laboratory
Batavia, IL 60510-5011

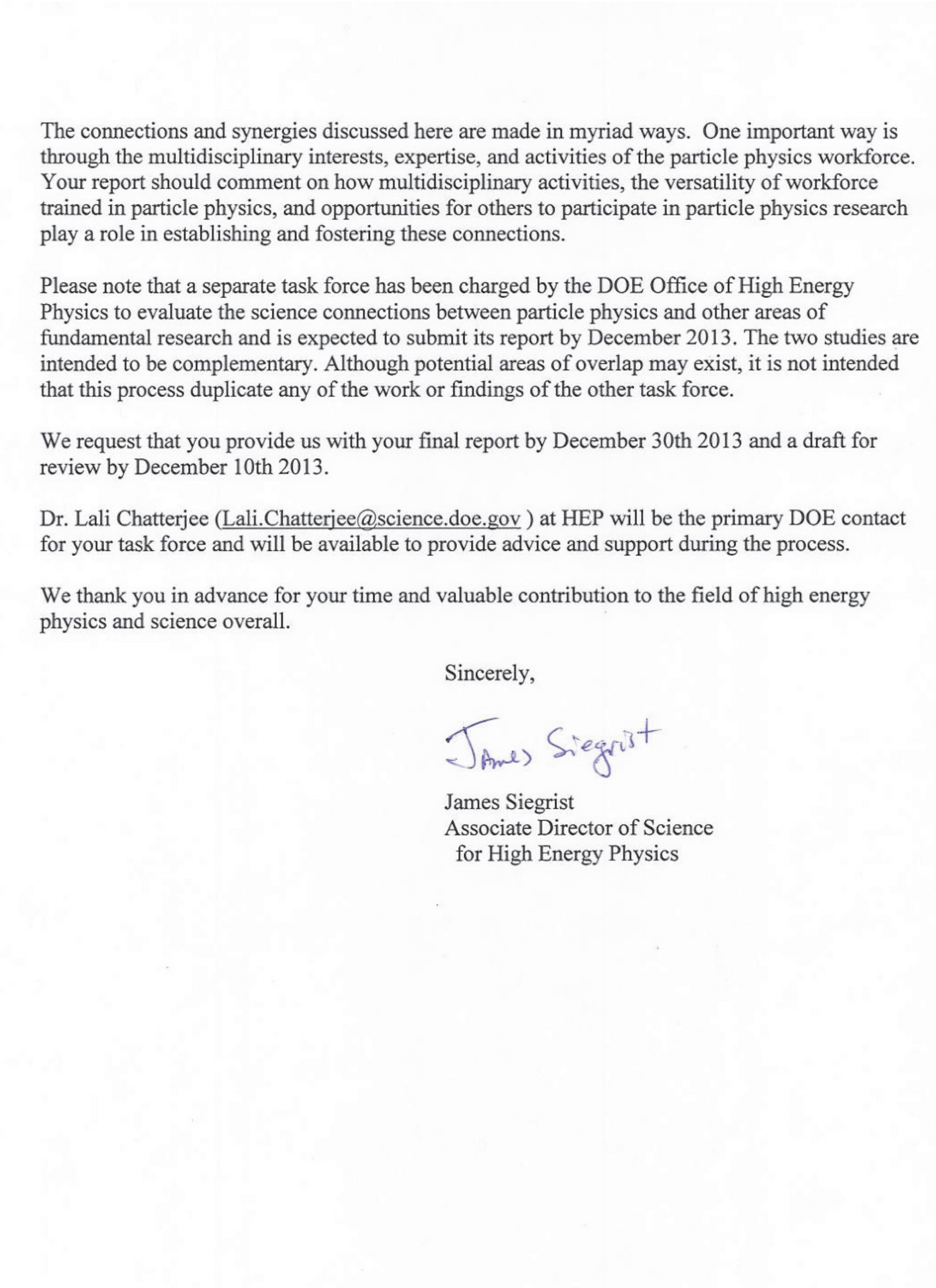
Dear Professor Demarteau and Dr. Yurkewicz:

The Office of High Energy Physics (HEP) seeks a better understanding of the connections between the tools, experimental techniques, and technologies developed for particle physics and other sciences. Such connections include their impact on other disciplines and society at large, as well as the developments in other fields that impact or have the potential to impact the tools needed for particle physics. The technologies of interest here could be associated with accelerators and other particle sources, detector physics, computation, or data management.

We request that you develop a report that articulates the key connections and synergies between the tools, techniques, and technologies developed for particle physics and other disciplines. Your report should identify connections with the potential to advance the HEP mission as well as articulate the important impact that particle physics research has on other disciplines, technology, and industry. In particular, we ask that you address the following:

- The current and potential impact of the tools, technologies, and experimental techniques driven by particle physics research on other scientific fields and society at large; and the benefits to particle physics of technology exchanges with other sciences and industry.
- Potential opportunities for the results, tools, and technologies developed by other disciplines to enhance the effectiveness or scientific scope of current, planned, and future particle physics experiments.
- Potential opportunities for HEP supported experimental facilities to serve communities outside of particle physics.

Your report should identify supporting examples for each message including statistics if available, and anecdotes as appropriate. We suggest that you engage individuals interested in developing such messages, including colleagues from other disciplines as relevant for a balanced report. You are also encouraged to identify areas where development of additional statistics, proof points, examples, as well as print and electronic materials for disseminating information may be valuable.



The connections and synergies discussed here are made in myriad ways. One important way is through the multidisciplinary interests, expertise, and activities of the particle physics workforce. Your report should comment on how multidisciplinary activities, the versatility of workforce trained in particle physics, and opportunities for others to participate in particle physics research play a role in establishing and fostering these connections.

Please note that a separate task force has been charged by the DOE Office of High Energy Physics to evaluate the science connections between particle physics and other areas of fundamental research and is expected to submit its report by December 2013. The two studies are intended to be complementary. Although potential areas of overlap may exist, it is not intended that this process duplicate any of the work or findings of the other task force.

We request that you provide us with your final report by December 30th 2013 and a draft for review by December 10th 2013.

Dr. Lali Chatterjee (Lali.Chatterjee@science.doe.gov) at HEP will be the primary DOE contact for your task force and will be available to provide advice and support during the process.

We thank you in advance for your time and valuable contribution to the field of high energy physics and science overall.

Sincerely,

James Siegrist

James Siegrist
Associate Director of Science
for High Energy Physics