APS Division of Particles and Fields Response to European Strategy Group Call for White Papers: Tools for Particle Physics

DPF Executive Committee and Strategy Whitepaper Editing Group
dpfstrategy@fnal.gov

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Abstract

The U.S. particle physics strategy process is summarized in a companion white paper that also describes U.S. activities related to the five P5 science drivers. Additional activities within the U.S. particle physics program that are critical to progress in our field are described here.

1 Theory

With the milestone discovery of the Higgs boson, we have for the first time in history established a relativistic, quantum-mechanical and self-consistent theory, the Standard Model (SM) of particle physics, that may be valid to an exponentially high scale, perhaps all the way to the Planck scale. Nevertheless, the SM leaves us with profound questions that need to be answered. Puzzles that remain to be resolved include the nature of the electroweak symmetry breaking (EWSB) and the electroweak phase transition, the stability of the Higgs mass or the electroweak scale relative to the Planck scale, the nature of particle dark matter, a complete picture of neutrino masses and mixing, and the origin of the baryon and anti-baryon asymmetry, including more comprehensive studies of CP violation. Is there a unified description of the SM forces that could ultimately include gravity? Does nature make use of additional space-time symmetry principles like Supersymmetry (SUSY)? What drives inflation in the early Universe? What is the origin of dark energy? In seeking the answers to these fundamental questions, creative new ideas and perhaps new principles will need to be developed.

The Standard Model is based on the framework of Quantum Field Theory, which itself needs to be further developed. Lattice gauge theory pioneers the non-perturbative formulation of quantum-chromo-dynamics (QCD) and has been extremely successful in calculating quantities that are relevant to experiments. Recent developments in the determination of scattering amplitudes have not only helped facilitate efficient perturbative calculations to compare with observables in collider experiments, but have also lead to deeper understanding of field theories in general.

Advances in Quantum Gravity and Quantum Field Theory, having its origin in String Theory, led to discovery of field theory/gravity dualities with important implications for strongly interacting particle physics models, such as QCD and models of dark matter. Gravity/field theory dualities have also had an important impact on advancements in Quantum Information Theory. Advances in String Theory compactification in the strongly coupled regime (F-theory) led to new insights into the geometric origin of particle physics. In view of all of the considerations presented here, it is clear that healthy and vibrant theoretical programs need to be strongly supported in the exciting years to come.

2 Future accelerators

Particle physics has enjoyed many discoveries over the last five decades, with much of this success owing to major advancements in accelerator technology that have enabled increasingly higher energies and higher luminosities. Looking ahead, the field faces extraordinary challenges, particularly in collider physics. The LHC and HL-LHC will improve our understanding of the properties of the Higgs boson, with the possible inclusion of the Higgs self-coupling to the list of achievements. These measurements could yield surprising discrepancies with the SM. Nevertheless, the ability to make significant advances will require major new machines.

There is a growing backlog of particles (i.e. the top quark and Higgs boson, but also the W and Z) that need to be studied with the exquisite precision that is only possible with a high energy e^+e^- collider. An e^+e^- collider Higgs factory would improve the precision of coupling measurements by an order of magnitude or more in some cases. There is great interest in and support for e^+e^- colliders within the U.S. particle physics community. They could enable experiments to find discrepancies with the SM that herald indirect evidence for new physics with enough precision to distinguish among classes of new physics involving new particles coupling to the Higgs, for example. They'd provide much needed guidance in our quest to resolve the puzzles we now face.

Among Higgs factory proposals, the International Linear Collider (ILC), with a center of mass energy of 250 GeV has the potential to upgrade to 0.5 or even 1 TeV. At CERN, a more ambitious proposal, the multi-TeV Compact Linear Collider (CLIC), could potentially reach 3 TeV. The ILC has been under consideration for decades and its design is mature. The higher collision energies possible with CLIC make possible searches for new particles at significantly higher masses. Two proposals for circular e^+e^- colliders have appeared more recently: the "Future Circular Collider" (FCC-ee) at CERN and the "Circular Electron-Positron Collider" (CEPC) in China. These are also ambitious, large-scale projects. They would not be able to extend into the multi-TeV regime and so would have physics programs comparable to the first phase of operation of either of the linear colliders. They do however have several important new attractions that include the potential for higher luminosities and thus higher precision, the ability to operate multiple experiments simultaneously, the use of somewhat more well-established technologies, and finally the construction of 100 km circular tunnels that could one day house hadron colliders that reach energies in the realm of 100 TeV.

The energy frontier is now the domain of CERN and will remain as such for a long time with the LHC and HL-LHC programs. It is however extremely important to prepare the path to much higher energies. For this reason, the U.S. hadron collider community is very interested in the decisions that CERN will make in regard to its future involvement in the energy frontier. The international particle physics community is awaiting a decision by the Japanese government about the construction of the ILC in Japan. A positive decision here has the potential to reshape global plans beyond the HL-LHC.

As alluded to above, ambitious plans have been proposed to upgrade the FCC and CEPC to hadron colliders (the FCC-hh and SPPC, respectively) by means of state-of-the-art superconducting magnets installed in the arc sections of the 100 km rings in order to enable a collision energy of order 100 TeV. Among the definite benefits of such a machine are the following: (i) it would facilitate studies of Higgs boson properties that would complement those of the lepton colliders and (ii) it could enable us to fully understand the nature of EWSB. The study of high energy WW scattering would provide deep insights into the role of the Higgs boson in the EWSB mechanism and could also help to resolve whether or not the Higgs boson is a fundamental or composite particle. Such a machine would also open up huge regions of phase space to search for new particles and for rare processes.

The U.S. hadron collider community would certainly welcome the construction of a 100 TeV machine but there are serious technical and financial hurdles. In addition, it is clear that such a machine would not be realized for a very long time. The pursuit of a 100 TeV machine remains an important goal for the field but it could be important, particularly if a lepton collider is built outside of CERN, for CERN to be prepared to maintain the vibrancy of the energy frontier with an intermediate but significant step in energy on a shorter timescale. To this end, many in the U.S. collider community are interested in CERN's consideration of a high energy upgrade of the LHC to somewhere near 30 TeV. This High Energy LHC (HE-LHC) option would follow the HL-LHC. It would make use of the existing tunnel and replace LHC magnets with $\sim$16 Tesla magnets that are being developed for the FCC-pp. The mean number of interactions per crossing is expected to rise with the higher energy to between 160 and 800. The higher energy would provide access to new phenomenon at multi-TeV scales, enable higher precision studies of a wide variety of phenomena including Higgs couplings to SM particles that are not accessible at a lepton collider, as well as its coupling to itself. Of course it could also provide access to heavy new particles. From a practical standpoint it would provide an opportunity to gain experience with the production and operation of high field magnets on a much lower cost scale than that of the FCC-pp, while providing a great physics program in the interim period ahead of a 100 TeV machine.

We note that the LHC, FCC and CEPC have alll explored options for an e-p collider that could provide interesting precision SM measurements that are not always accessible to the other configurations of these machines. Among lepton colliders, there is community interest in muon colliders that can reach much higher collision energies than e^+e^- colliders.

In the mean time, there are vibrant accelerator programs in the intensity frontier. Super KEKB will investigate in great detail the Flavor Changing Neutral Current processes in B-meson decays while the record intensity proton beams of the Proton Improvement Plan (PIP-II) linac complex (1.2 MW on target) and the PIP-III upgrade (2.4 MW on target) will assure a successful neutrino program at DUNE and enable a program of precision experiments using, for example, high-intensity beams of neutrinos, muons, and protons.

While "Current Projects" shown in Table 1 are either well defined technically, under construction, or in operation, the "Future Projects" require substantial R&D toward either cost-reduction or demonstration of the technical feasibility, as summarized below:

- HE-LHC, FCC-hh, and SPPC: R&D for 16 T or higher SC magnet technology;
- ILC energy upgrades, FCC-ee and CEPC: R&D for economical SRF cavities;
- CLIC: R&D on cost reduction for normal-conducting cavities and overall facility power efficiency;
- Muon colliders: R&D on muon beam cooling;

Table 1: HEP accelerator programs with the currently existing efforts and possible future projects.

	Current Projects	Future Projects
Hadron Colliders	HL-LHC: 14 TeV/3 ab^{-1}	HE-LHC: 27 TeV/15 ab^{-1} FCC-hh: 100 TeV/30 ab^{-1} SPPC: 100 TeV/30 ab^{-1}
Lepton Colliders	SuperKEKB: 3.5 GeV e^+ on 7 GeV $e^-/8 \times 10^{35}/\text{cm}^2/\text{s}$ C-Tau at BINP: 2-5 GeV/$1 \times 10^{35}/\text{cm}^2/\text{s}$ ILC: 250 GeV/2 ab^{-1}, 80% & 30% pol.	ILC: 0.5 (1) TeV/4 (8) ab^{-1} CLIC: 0.38,1.5,3 TeV/0.5,1.5,3 ab^{-1} FCC-ee: 250 GeV/ 5 ab^{-1} CEPC: 240 GeV/ 5 ab^{-1} $\mu^+\mu^-$ colliders: 0.125, 3, 14 TeV e^+e^-1(3) TeV plasma colliders
Lepton-Hadron Colliders		LHeC: 60 GeV$\oplus$7 TeV/1 ab^{-1} FCC-eh: 60 GeV$\oplus$50 TeV/2 ab^{-1}
Intensity Frontier	J-PARC : 1.3 MW upgrade PIP-II: 1.2 MW/200 kton·MW·years for DUNE and >1.5 MW for precision program	PIP-III: 2.4 MW/ 700 kton·MW·years for DUNE Neutrino Factory: 10 GeV/$5 \cdot 10^{20}\nu$/yr

- TeV scale plasma wakefield colliders: require initial proof of the feasibility of staging and energy efficiency of the PWA method for both e^+ and e^-;
- LHeC and FCC-eh: R&D on efficient SRF ERLs;
- PIP-III: R&D on multi-MW neutrino targets and loss-free acceleration in rapid cycling synchrotrons
- Neutrino factories: R&D on practical muon production, initial cooling and fast acceleration.

Many of these research topics are under active development in the US, Europe and Asia.

We foresee a healthy and vibrant program world-wide driven by the bneed for future accelerators to explore Nature at new levels of precision and mass scales. In accordance with the US P5 recommendations, the current efforts on HL-LHC, SuperKEKB, ILC Higgs factory, and PIP-II are strongly supported. Looking to the future, the upgrade to PIP-III will assure a successful neutrino program for DUNE. The HE-LHC proposal would significantly extend the physics reach beyond the HL-LHC plan and should be seriously considered. Continuing progress in particle physics calls for at least one future Higgs factory (linear or circular machine) and energy frontier facility (very high energy proton, electron, or muon collider). The next 5 to 10 years will make it clear whether the challenges listed above can be adequately addressed and which facilities will be meet performance, technology and cost constraints.

3 Computing

Each of the key science Drivers considered in mapping the future of the U.S. particle physics program, and indeed all of the small, medium, and large scale projects planned to meet the goals of these drivers will face significant challenges in computation, data management, and data analysis in the decades to come. For many years, particle physics collaborations have been growing in size and becoming more international. This has had and continues to have significant impact on the nature of the computational challenges they face, as well as on their solutions. The particle physics community had to develop systems that enable science on a large distributed scale because commercial solutions were not available. The LHC collaborations are currently the largest world-wide distributed science endeavors, formed by scientists from hundreds of institutions spanning the whole globe. The social aspects of global resource provisioning led to the creation of the Worldwide LHC Computing Grid (WLCG) infrastructure. Other large experiments - LSST, SKA, DUNE, Belle II and HyperK will be coming on board over the next decade, and will join the realm of international computing collaborations. Some are already organizing their computing models after that of the LHC.

Many experiments are, or will be, producing multi-petabyte size datasets and some will even enter the *exabyte* domain. In the past several years, industry has surpassed scientific data volumes many times over. The full exploitation of industry solutions will be important in the future.

It will also be important to find common solutions for the software that enables the science and the various components of distributed computing infrastructures. A global coordination and development effort is needed to tackle these challenges, especially where they cross historical scientific boundaries. The international community, under the guidance of the HEP Software Foundation (HSF), has prepared a Community White Paper (CWP) [A+17] aimed at facilitating coordination and common efforts in HEP software and computing internationally and to provide a structure for the community to set goals and priorities for future work.

All this is supported by a strong collaboration and constructive interaction between the physicists working on the experiments, computer scientists who have technical expertise and experience that can be applied to our problems, and the funding agencies that have provided mechanisms to support both groups individually and collaboratively. Long-term success will require the continual attention of all involved, and the stable support of physicists and computing professionals who work in this area.

Based on input from the US particle physics community (e.g. ATLAS, CMS, DUNE/LBNF, etc), the broader high energy particle astrophysics and observational cosmology communities (LSST, CMB S4, etc), and accelerator simulations, we highlight the following areas in this document:

Algorithms and Advanced Hardware: HEP uses complicated devices to detect the rarest and highest energy particle interactions. The design, construction and operation of the components of these devices require extensive domain knowledge. This domain knowledge translates into the development of the software to reconstruct the device signals as input to the process to extract physics results. These software products are developed and maintained by hundreds of experimental researchers, who are typically not software experts. Reconstruction software is predominantly written in `C++`, and experiments use `C++` frameworks to schedule reconstruction algorithms and implement an event data model. Recent hardware trends limit the memory and memory bandwidth per processing core more and more, requiring the use of multi-threading techniques. Future advanced hardware trends of GPUs, FPGAs and other "linear-algebra accelerators" will require more sophisticated software development to use them efficiently. Although domain experts are familiar with the intricacies of the algorithms that are needed to reconstruct detector signals, they are using programming techniques that are in many cases no longer suited for current and future hardware architectures. In the future, there will be the need for core computing professionals working in tandem with domain experts to write (preferably) open-source software. It will be important to foster the sharing of modules and code via the development of libraries of algorithms and physics modules, as well as the development of standards for data structures.

Facilities and distributed computing: The needs for processing capacity for data reconstruction and simulations are large and will increase significantly in the future. Both high-throughput computing (HTC) resources of loosely coupled processing units and high-performance computing (HPC) resources with low-latency interconnected processing capacity are currently being used. Due to the distributed nature of our science, the infrastructure cannot be concentrated in a single location but must be distributed across the globe. We will have to support resource provisioning solutions to combine globally distributed resources efficiently and cost-effectively. In addition to traditional institutional clusters accessed through the grid infrastructure, new resource forms will become important. Commercial cloud providers are on the verge of becoming cost competitive, especially considering peak demand needs. HPC centers are being built and upgraded in the pursuit of further optimizing the flops/watt capabilities and to reach the exascale. They will be available to run a significant part of the HEP workloads. However, HPC architectures are significantly different from traditional cluster setups and also follow a refresh schedule that deploys new hardware architectures and enhanced capabilities and capacities every 5-6 years. This will require significant and continuing software development efforts to be able to use these resources efficiently, keeping an eye on interoperability to lower the cost of ownership of software while maximizing its flexibility to be executed on different resource forms. Workload distribution and execution across this diverse distributed resource landscape will have to evolve to support the efficient usage of the available resources using minimal operational effort. This can be achieved by either executing the same workflows on different architectures, or specializing workflow steps for particular hardware combinations. This will be an ongoing field for optimization and R&D.

Data Organization, Management and Access (DOMA): In the future, we will see significant data growth from most HEP projects. Disruptive technological advances will be needed to efficiently store all this data and provide access for centralized processing and analysis. Tape is still the most cost effective form of storage. Novel solutions are needed to extend its usage without compromising the latency of accessing the data. These can range from monitoring the popularity of data through expanded usage of analytics tools, to the reduction of copies of data on disk via intelligent caching optimized for specific access patterns. The generic term of the data lake concept is currently used for future systems and infrastructures that lower the effort to operate large distributed storage systems and provide efficient access to all data in the lake. And these novel data management techniques have to be integrated into the data management and workload management systems, which all use the worldwide scientific network infrastructure. Reducing the data on disk and relying more on tape storage will put more demand on the domestic and international science networks. Advanced networking technologies might be needed to enable the efficient use of distributed storage.

Data analysis and interpretation: Interactive access for analysis is a prerequisite for timely publication of physics results. Enabling efficient access to the significantly larger datasets of the future will be a key challenge. HEP has a long and successful history of using and developing sophisticated toolkits that allow physicists to be effective. This is a strength of our community. Including industry-based analysis technologies into the traditional HEP analysis toolkit could allow us to share their development with a wider community outside HEP. The advantages of including industry solutions apply for everything mentioned before, and a coordinated and comprehensive approach could foster their introduction to the community.

Machine learning: Machine learning has been an important component of the HEP analysis toolkit for many years. The recent advances in very deeply nested machine learning algorithms and the successes obtained in industry represent an opportunity for HEP. There are several areas that are intrinsically suited for machine learning, like astrophysical images and detector signals from large time projection chambers. For other detectors like the large particle collision devices, even larger investments need to be made to develop machine learning models in the areas of, for example, fast simulation and fast reconstruction. An advantage of machine learning algorithms and their large industry-based communities is that the underlying toolkits are already optimized for advanced architectures like GPUs and TPUs and therefore they are well-suited for advanced architectures and high-performance resource forms.

A serious and supported approach to software development and education needs to be adopted in order to deliver the benefits of investments in computing models, infrastructure, and innovation to the scientific community. This is especially true in the case of algorithm development and in areas such as machine learning. Industry recognized certification in these areas for students and postdoctoral scholars could be a way to increase the employability of scientists outside of academia, as well benefit the science collaborations. The increased computing hardware complexity demands an increased number of scientific computing professionals to support the software needs of the community. This is true for each of the primary areas identified above as priorites for the US particle physics, particle astrophysics, and observational cosmology communities.

Recently, the interest in R&D efforts in the area of quantum information systems has risen dramatically in the US community. The impact of quantum information systems on HEP physics cannot be estimated for now, but could be one of the transformational technologies with the largest long term impact.

Despite all of these challenges, the community looks forward to extracting the most science out of the small, medium, and large scale projects planned in the context of the key science drivers for the future of the global particle physics program.

4 Detector R&D

Detector R&D and instrumentation development are driven by the science goals of the international community. In the US the Coordinating Panel for Advanced Detectors (CPAD[DS16]), under the auspices of the American Physical Society Division of Particles and Fields, is charged with coordinating development of instrumentation for particle physics. The 2014 US P5 report recommended a focus on near-term R&D needed for projects to be built during the next decade [R+14]. R&D for these projects is now concluding and a shift toward "balanced mix of short-term and long-term R&D" is required. Achieving this shift in a way that preserves laboratory and university infrastructure and retains and trains a strong, knowledgeable workforce, is key to future instrumentation development.

U.S. interests in particle physics include accelerator-based neutrino and collider studies; study of rare decays; dark matter searches; and particle astrophysics. Although the physics requirements among these thrusts can be quite different, they share infrastructure requirements, detector technologies, and need the presence of a strong community of physicists, students, engineers and technicians. Such a community is inherently international, with new and existing multi-national collaborations working on many innovations, and there are clear advantages to synergy between US and European efforts. In addition we must work with industry to access and develop the specialized technologies that can only be supplied by commercial vendors.

Collider physics– At the Energy Frontier, searches for new physics at high mass will continue along with programs of precision measurements of Higgs decays, core measurements of Higgs self-coupling, WW scattering, and standard model decays. With the HL-LHC upgrades launched as projects, detector R&D will focus on detectors for the next generation of accelerators. Candidate machines include HE-LHC, ILC, and large circular e^+e^- and pp colliders.

e^+e^- colliders will require high precision, low mass trackers and particle flow-style detailed event reconstruction using highly segmented calorimetry. Technical challenges include power delivery and cooling for very low mass trackers and vertex detectors. Calorimeters will include very fine segmentation to provide information on the character and development of electromagnetic and hadronic showers. Hadron colliders will confront extremely high event occupancy while needing to retain precision in tracking and calorimetry. Picosecond-level timing will be an important tool to identify individual events in beam crossings that may involve more than 1000 events in a $\approx$ 10cm crossing region. Muon collider detectors combine the precision needs of e^+e^- with radiation damage and occupancy challenges associated with hadron colliders. Continued development of radiation hard, low mass, pixelated detector systems capable of fast timing will be crucial to the next generation of collider detectors.

These goals are being enabled by further development of technologies that can provide time resolution, pixelization, and intelligent upstream filtering of data. We will exploit synergies with the semiconductor industry using developments such as CMOS active pixels, 3D integration, radiation hard ASICs, and development of Low Gain Avalanche Diodes (LGADs). Much of this development is enabled by direct access to industrial vendors and foundry processes. Continued community access to IC foundries, now enabled by CERN, is crucial.

Collider physics: trigger subsystems– Future HEP accelerators will produce luminosities that will challenge today's TDAQ designs and implementations. The field of particle physics needs to develop new trigger and data acquisition technologies to be able to cope with extremely large instantaneous data volume. The resulting high occupancy will necessitate high granularity detectors yielding anticipated large data rates such as about 800 TB/s from the tracking detectors and >200 TB/s from the calorimeters. This implies more than one million detector readout optical fibers at 10 Gb/s and a 10 Pb/s event builder network. An important challenge is to extract the data at high bandwidth from the tracking detectors without adding a prohibitive burden of material. The overlap of detector front end signals from different collisions and different beam crossings will increase by an order of magnitude, requiring more information and much more sophisticated algorithms.

Potential research directions could include low-power and low mass technologies for deep buffers for low deadtime; high bandwidth, low power, low mass radiation hard fiber optics and drivers; wireless data transmission; fast timing processing technologies; closer integration of embedded systems and programmable logic; Level 1 triggers more closely integrated with Level 2 processors; and advanced tools for high level firmware synthesis.

Low-energy precision measurements and rare event searches - These experiments are designed to search for evidence of new physics either by making high precision measurements or by searching for very rare processes that are sensitive to contributions from new heavy particles. Examples of experiments of this type include quark flavor physics experiments, muon experiments, and dedicated EDM experiments using stored protons or muons. New or upgraded accelerators can extend the new physics parameter space by 1-2 orders of magnitude. The opportunities provided by these planned improvements cannot be fully realized without significant detector developments to match the accelerator upgrades.

Experiments using muons to search for charged lepton flavor violation (CLFV) offer some of the deepest and broadest probes. Experiments use high-intensity stopped muon beams to search for CLFV, $\mu N \to eN$, $\mu \to e\gamma$, and $\mu \to eee$, achieving sensitivities below 10^{-14}. These experiments need momentum resolutions of 0.1%, requiring ultra-low mass trackers capable of achieving 10-100 micron position resolution while operating in vacuum and handling average rates from 10 kHz/cm^2 to 1 MHz/cm^2. Potential technologies include gas-filled aluminized mylar tubes with wall thickness less than 10 microns, drift chambers with low mass supports, and thinned CMOS sensors. A challenge for the CMOS sensors is the ability to extract heat to remote heat sinks with minimal mass. Pile-up effects can be mitigated using low mass, high rate, high granularity, radiation tolerant timing technologies with resolutions of $\approx$ 100 ps or better. Also needed are fast, radiation-hard crystals, such as BaF_2, and associated specialized photodetectors.

Neutrino physics– The mid term perspective of R&D in the field of Neutrino Physics is driven by the DUNE experiment, with the main goals of defining and enhancing the liquid argon TPC (LAr-TPC) technique for the far detectors and studying innovative solutions for the near detectors. US efforts plan to cover several aspects of LAr-TPCs including: drift high voltage, scintillation light collection, charge readout, cold electronics, and cryogenics and argon purification. Significant R&D effort is also planned for the DUNE near detectors. There is a joint US-European effort to pursue novel LAr-TPC techniques including pixelated charge readout, high efficiency photodetection, and a resistive field cage. The DUNE near detector collaboration is pursuing a suite of technologies including a LAr-TPC, and a magnetized high-pressure gas TPC with a 3D scintillating tracker. Additionally, an off-axis moveable detector is also being investigated to better understand the beam content.

Other LAr-TPC R&D activities will push on lowering energy thresholds of existing detectors for instance for searches of Supernovae neutrinos, coherent neutrino scattering processes or non standard interactions. Research on water-based scintillators and metal-loading of either water Cherenkov or scintillator detectors are being pursued as potential technologies for future large neutrino detectors. The ability to identify the prompt Cherenkov signal in a scintillator detector would allow the first large, low- threshold, directional detector, resulting in a broad physics program spanning nuclear, high-energy, astro and geophysics. Complementary developments in large area fast photodetectors (e.g. LAPPDs) have the potential to improve the performance of this category of large photon-based detectors.

Dark matter– The field of direct dark matter detection is entering an exciting era as a suite of second generation experiments begin to run. Detector R&D is split between numerous promising avenues that look further to the future: the scaling up of liquid noble and cryogenic crystal detectors to cover the WIMP mass range to the coherent neutrino floor, directional detectors that may allow future searches to reach even lower WIMP-nucleon cross-sections, and experiments that look for dark matter from a wider variety of theoretical models and mass ranges [B+17]. Such detectors go beyond coherent nuclear scatters, expand axion searches, and exploit advances in quantum sensing. Similar tools and techniques are used in the neutrino sector to probe non-standard interactions via coherent nuclear scattering, neutrinoless double-beta decay and measuring the mass of the neutrino.

The open theoretical landscape for dark matter candidates is welcoming to both the incremental expansion of the capabilities of traditional detectors, the novel use of technologies from other subfields, and the invention and development of entirely new technologies.

Cosmic surveys and particle astrophysics– Advancements in astroparticle physics detectors support both cosmological studies and multi-messenger astronomy. Planned future cosmic microwave background experiments will primarily face problems of scale for their O(500,000) sensors: the high-yield production of uniform detectors and multiplexed readout.

Existing CMB experiments employ detector arrays where individual detectors are sensitivity-limited by the irreducible fluctuation noise from the measured photons. Deployed detector systems use superconducting Transition-Edge Sensors (TES) read out with multiplexed Superconducting

Quantum Interference Device (SQUID) amplifiers. An alternative to SQUID multiplexed TES arrays are MKID arrays, which are intrinsically multiplexed. The two leading candidates for multiplexed readout are microwave multiplexers (including MKID or SQUID μMUX) operated at GHz frequencies, and Frequency Division Multiplexers (FDM) of TES operated at MHz frequencies.

Large scale cosmic surveys studying dark energy and dark matter, among other astrophysical topics, drive R&D in imaging CCD technology to produce highly segmented cameras that are low noise and sensitive from the UV to the near IR. Future surveys will be driven by greater spectroscopic multiplexing – measuring as many spectra as we can at any particular time. R&D directions include fiber positioners with small (< 5 mm) pitch and germanium-based CCDs.

Particle astrophysics, the study of astrophysical neutrinos, gamma rays, and cosmic rays, is advanced primarily through new developments in photodetectors and readout electronics. Experiments frequently require both triggering on and reading out waveforms of photodetectors, sometimes as two parallel chains. Current limiting factors include achieving high analog bandwidth and high sampling rate with high channel density, all with low noise, low cost, and low power consumption. Just as in the case of CMB sensors, detector production uniformity must be improved at larger scales to reduce the calibration burden in addition to other cost considerations. Balloon and space based cosmic ray detectors also utilize and require advancements in silicon tracking detectors, calorimeters, and large magnetic fields; all in a small volume and low mass. Reliable, robust, plug and play absolute timing and clock distribution with nanosecond or better precision is also a common necessity requiring ongoing R&D.

Photosensors– Advancements in photosensors aid the detector development and physics sensitivity of nearly all particle physics subfields. Silicon photomultipliers have become integrated into multiple detector designs, and more specialized photo detectors are also employed. General improvements in increased quantum efficiency, greater control over wavelength ranges, lower radioactivity, cryogenic temperature operation, lower power, lower noise, improved timing resolution, and lower cost per area are all desirable traits to be pursued. Large Area Picosecond PhotoDetectors (LAPPDs), previously mentioned, remain an active area of development for a variety of future experiments, and highlight the possibilities for commercialization and importance of industry partnerships.

Quantum sensors– Quantum technologies manipulate individual quantum states and make use of superposition, entanglement, squeezing and backaction evasion to enable significant improvements in sensitivity to detect new physics by sensing tiny energy shifts in quantum systems. Resonance tools, for example, can powerfully probe for the new particles predicted by nearly all Beyond Standard Model theories that seek to explain some of the biggest questions in particle physics today, such as the nature of dark matter, dark energy, gravity and the hierarchy problem. Quantum networks will take advantage of correlations across an array of sensors, linking them to each other with quantum mechanical means, such as optical entanglement.

Popular matter qubit systems, often used as quantum sensors, such as trapped ions, neutral atoms, quantum dots, or single dopants in silicon can be readily coupled to optical photons using optical nonlinearities in narrow frequency bins. Quantum techniques can also be used to improve the performance of sensor arrays already used in HEP experiments with a Gaussian (thermal) sensor output. For example, the exploitation of squeezing and entanglement in the amplifier chain can be used to implement larger arrays of transition-edge sensors (TES) similar to those used in searches for dark-matter candidates and in searches for the signature of inflation in the CMB.

The US is broadly investing in Quantum Information Science, including within the HEP community. Most recently, this has been through the "Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics" funding opportunity [qua18]. Beyond the quantum sensors discussed above, QIS also opens avenues for new discoveries in particle physics through quantum computing, and through tabletop experiments that can probe small scales for new physics related to new, and virtual, particles, new forces, fundamental symmetries and precise measurements of universal constants directly utilizing AMO and Condensed Matter techniques.

References

[A+17] Antonio Augusto Alves, Jr et al. A Roadmap for HEP Software and Computing R&D for the 2020s. 2017.

[B$^+$17] M. Battaglieri et al. US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report. In *U.S. Cosmic Visions: New Ideas in Dark Matter College Park, MD, USA, March 23-25, 2017*, 2017.

[DS16] M. Demarteau and I. Shipsey. Report from the Coordinating Panel for Advanced Detectors - New Technologies for Discovery, 2016. https://www.anl.gov/hep/coordinating-panel-for-advanced-detectors.

[qua18] Department of energy announces $218 million for quantum information science, 2018. https://www.energy.gov/articles/department-energy-announces-218-million-quantum-information-science and https://science.energy.gov/~/media/grants/pdf/foas/2018/SC_FOA_0001893.pdf.

[R$^+$14] S. Ritz et al. Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context. 2014.