APS Division of Particles and Fields Response to European Strategy Group Call for White Papers: Community Planning and Science Drivers

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Abstract

This white paper describes the community strategic planning process organized by APS DPF, and summarizes U.S. particle physics community input on activities and aspirations. This is the first of two documents, covering the five P5 Science Drivers.

1 U.S. community planning for particle physics

The American Physical Society (APS) Division of Particles and Fields (DPF) drives the U.S. particle physics community planning process, and connects to a broader international community. The analogous process to the community input stage of the European Strategy Group (ESG) process in the U.S. is the "Snowmass" community planning exercise, which is organized by DPF. The Snowmass activities take place every 5-10 years, and the resulting study documents serve as input to the funding agencies' prioritization process. The most recent Snowmass was about a year-long process, involving multiple preparatory meetings and culminating in a several-week-long meeting in summer 2013. The proceedings comprised an extensive description of physics activities and plans over many subfields [R+14b]. The Snowmass exercise does not explicitly prioritize; rather, it aims to describe aspirations. Snowmass output is intended to represent a community consensus on preferred physics directions.

The output of the 2013 Snowmass served as input to the Particle Physics Project Prioritization Panel (P5) in 2013-2014. P5 is a subpanel of the High Energy Physics Advisory Panel (HEPAP) charged with explicit prioritization of proposed projects, subject to specified funding constraints. The P5 report [R+14a], "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context," provided recommendations to the funding agencies (Department of Energy Office of Science and the National Science Foundation). This report was well received by the community and the agencies, and its recommendations have been followed.

P5 summarized the Snowmass inputs into five "intertwined science Drivers" for the field:

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

In the context of these Drivers, P5 made recommendations under three possible funding scenarios. The main efforts recommended by P5 and their approximate timescales are shown in Fig. 1. Note that in this figure, the experiment that is now DUNE was included as part of "LBNF." Most of the recommended activities involve the international community.

The community strategy since the 2014 P5 report has been to closely follow its recommendations. This strategy has been tremendously successful and current levels of funding exceed the higher levels considered by P5. The horizon for specific P5 recommendations is approximately the mid-2020's. Beyond this timescale, the community will need to update its strategic planning, given progress in physics discovery as well as an evolving international landscape. The DPF plans to launch a new Snowmass process in 2020, after the final ESG report is approved by CERN Council, and to be continued over the following year. The next P5 process will take place following these community activities. It is anticipated that the full U.S. planning process will be concluded in time for the results to be incorporated into planning for the FY2024 or FY2025 budget.

The remaining sections of this document briefly address recent progress on the P5 recommendations. The focus of this document, however, is to describe research interests in the U.S. particle physics community beyond the P5 timescale. As the U.S. planning process described above has not yet commenced, we are unable to supply a comprehensive or prioritized summary of U.S. plans. For purposes of this document, editors representing the experimental and theoretical side of each science driver were identified [see Addendum] and asked to summarize the status of their sub-field. The DPF Executive Committee and the editors of this document sought and incorporated input from the community regarding future interests as well as feedback on preliminary drafts. This document does not claim to fully speak for the U.S. community, but the editors have attempted to produce an accurate summary of the current state of thinking in the U.S. particle physics community for consideration by the ESG based on input provided to us. An additional document submission describes other important activities within the U.S. and global particle physics communities: theory, accelerator development, computing, and detector R&D. For brevity we are omitting details and references about many of the initiatives mentioned in these white papers, given that independent white papers on specific initiatives are being submitted in parallel and information can easily be found online.

Figure 1: P5 report Fig. 1 [R+14a]:"Approximate construction (blue; above line) and expected physics (green; below line) profiles for the recommended major projects, grouped by size (Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly."

The U.S. and European particle physics programs are deeply intertwined and collaboration is critical for the success of our joint endeavors. We aim for effective coordination of efforts and look forward to continued collaborations, as well as to projects and initiatives in Europe that complement those in the United States.

2 Use of the Higgs boson as a tool for further inquiry

The Higgs boson is a crucial tool for exploring the nature of electroweak symmetry breaking. Future explorations will focus predominantly in four areas discussed below: (1) The possibility of more Higgs bosons, (2) Precision measurements of Higgs couplings, (3) non-Standard Model production or decay modes of the Higgs, and (4) Exploring the scalar potential.

The discovery of new Higgs-like particles would be a clear signature for physics beyond the Standard Model. Many theoretical models that attempt to explain the observed pattern of particle masses or the nature of dark matter contain such particles. Observation of multi-TeV Higgs-like particles will require the highest possible energy colliders. States that have small production rates or difficult decay signatures can be explored at the HL-LHC and HE-LHC. It is also possible that new scalars are extremely light (GeV or MeV scale), leading to novel production and decay chains. Dedicated low energy experiments can search for these particles.

The Standard Model of particle physics predicts the Higgs boson's couplings to fermions and gauge bosons; verification of these predictions is a crucial task for the future. ATLAS and CMS project that the HL-LHC and a HE-LHC will make measurements of Higgs Yukawa couplings to gauge bosons and third generation fermions at the % level and to the charm and μ somewhat less precisely, with the major gain in precision coming from high luminosity. The interpretation of these results will require a dedicated effort to ensure that the theoretical predictions match the experimental precision. Both Standard Model calculations of Higgs properties and calculations in models of new physics are needed for comparison with the experimental results. Electron-positron machines can improve on the accuracy of the Higgs coupling measurements, with typical precision at the sub-percent level. Polarization of the e^+e^- in a linear collider such as the ILC allows for a suite of measurements enabling extremely precise global fits to Higgs couplings. Any deviation from the Standard Model predictions would indicate new high-scale physics.

It is possible that the Higgs boson will have production mechanisms or decay modes not present in the Standard Model, such as the flavor changing decay $H \to \mu\tau$, or production through new particles in loops. The decay of the Higgs to invisible particles also probes potential new physics. The search for these effects is an important goal of all future machines. Similarly, the measurement of the Higgs total width is a window to new physics; future e^+e^- machines are particularly suited for this measurement.

The most challenging area for future Higgs physics is the experimental study of the Higgs potential, which will require direct observation of the production of two Higgs bosons in order to obtain a measurement of the Higgs self-coupling. This is a difficult task at all proposed machines, and motivates the highest possible energy both for a hadron collider and an e^+e^- collider. Indirect evidence for the shape of the Higgs potential can be found from global fits to single and double Higgs production at the HL-LHC and at an e^+e^- collider. Since the sensitivity to the Higgs self-coupling is so small in the Standard Model, double Higgs production is extremely sensitive to the existence of new scalar resonances in the few hundred GeV range.

3 Investigation of the physics of neutrino mass

Introduction – Understanding the properties of neutrinos moved to front and center at the end of the twentieth century with the discovery of neutrino oscillations. Many important questions remain: Is CP-invariance violated in the lepton sector? What are the precise values of the entries of the leptonic mixing matrix? How are the neutrino masses ordered? Are neutrinos Dirac or Majorana fermions? What are the values of the neutrino masses? What is the origin of the neutrino masses? The U.S. has embarked on a program to study neutrinos that can make major advances on these key questions. We also need to be prepared for surprises. Additional new physics in the neutrino sector can manifest itself in a variety of ways and large deviations from the three-massive-neutrinos paradigm are allowed by existing data. Exploration of the neutrino sector is a high priority for the global particle physics community, and the U.S. is strongly invested in neutrino physics, now and in the future. The following describes the core of the U.S.-hosted neutrino program with opportunities for future partnerships and continued collaboration. We concentrate on accelerator-based activities, which are the main thrust of the European Particle Physics Strategy, and only comment briefly on non-accelerator-based activities.

Long-Baseline Neutrinos – The U.S.-based NOvA experiment allows unique sensitivity to the mass ordering and precision tests of neutrino mixing. The successful execution of the NOvA physics program is a very high priority for U.S. particle physics. NOvA will run into the 2020s and is expected to quadruple its data set with planned Fermilab accelerator improvements to 900+kW of proton beam power, enabling 5σ sensitivity to the neutrino mass ordering in favorable scenarios. The NOvA program provides an excellent opportunity for European scientists to engage in a long-baseline neutrino experiment that is currently running and that will collect very large samples of neutrino and antineutrino data.

Following the successful NOvA program, plans are well underway for LBNF-DUNE, the largest next-generation long-baseline neutrino experiment to be hosted by the U.S. DUNE consists of 70 ktons of liquid argon detectors, to be located a mile underground in South Dakota, receiving an intense wide-band beam of neutrinos produced by LBNF, a significantly upgraded Fermilab accelerator complex and near-detector facility. DUNE aims at unprecedented sensitivity to CP-invariance violation in the neutrino sector and, because of the high-resolution detector and the broadband beam, will also test the three-massive-neutrinos paradigm at a level far beyond that which has been previously achieved. The deep underground location will also allow for a broad physics program that includes the study of atmospheric and supernova burst neutrinos as well as searches for nucleon decay and BSM processes (including dark matter, Lorentz and CPT violation, and new particles and interactions, overlapping with Sections 4 and 6). The DUNE collaboration is a global organization including more than 1000 scientists from 32 countries. DUNE represents the convergence of a substantial fraction of the worldwide neutrino physics community around the opportunity provided by the large investment planned by the DOE and Fermilab. The DUNE program has been developed to meet the requirements set out in the U.S. P5 Report and also takes into account the recommendations of the 2013 European Strategy for Particle Physics, which classified the long-baseline neutrino program as one of the four scientific objectives that require international coordination. There is already significant involvement of the European physics community in DUNE through the successful CERN Neutrino Platform, liquid argon TPC R&D, and design and planning for the DUNE far detector modules. The CERN Neutrino Platform hosts and played a central role in the recent construction and commissioning of the DUNE prototype detectors (protoDUNEs), followed by the successful collection of beam data.

Full exploitation of the physics potential of the long-baseline neutrino program will require excellent understanding of the neutrino beam and of neutrino–nucleon and neutrino–nucleus scattering. These will require sophisticated theoretical computations, including nuclear effects, and, potentially, new ancillary experimental efforts. In the case of DUNE, the significant investment being made in LBNF and the new neutrino beam invites the community to consider a suite of next-next-generation neutrino experiments, both at short and long baselines. For the far site, there are ongoing R&D efforts to develop additional far detector technologies. One possibility would be a new large-scale water-based liquid scintillator detector such as THEIA that would allow a rich program of physics including precision long-baseline neutrino oscillations, low-energy solar neutrinos, and neutrinoless double beta decay. The development of THEIA leverages the work already done by the European LENA collaboration as well as the European effort underway for JUNO. At the near site, high precision near detectors will be able to take advantage of the world's most intense accelerator neutrino beam to pursue a broad spectrum of physics. In addition, the DUNE science program is expected to produce raw data volumes similar in scale to those currently recorded by the LHC experiments, so there are opportunities to develop novel techniques for processing these very large, image-like data samples.

Longer term, more precise neutrino oscillation experiments will likely be required, and furthermore precision measurements of neutrino scattering cross sections will allow extension of the physics reach of conventional beams. It is important to consider other opportunities in the Fermilab facility beyond LBNF-DUNE, as well as other intense neutrino sources, such as intense meson-decay-at-rest beams and muon storage rings. Fermilab encourages proposals for new detectors besides DUNE in the LBNF beam, and also the development of other neutrino beams.

Short-Baseline Neutrinos – The so-called short-baseline anomalies from LSND, MiniBooNE, and short-baseline reactor neutrino experiments are still the subject of intense experimental scrutiny. A new generation of reactor experiments, including PROSPECT in the U.S., aim to resolve the reactor anomalies. The IsoDAR collaboration is developing a novel cyclotron induced decay-at-rest ^{8}Li neutrino source to use for a definitive electron antineutrino disappearance experiment that would be complementary to the reactor experiments. The Short-Baseline Neutrino (SBN) program at Fermilab, which consists of ICARUS, MicroBooNE, and SBND, is aimed at definitively testing the anomalies revealed by LSND and MiniBooNE. MicroBooNE has been operating successfully for the past three years and has produced a large body of results that are informing our understanding of neutrino-argon interactions and the liquid argon TPC technology. The addition of the ICARUS and SBND detectors to the same beamline has been made possible through a joint partnership between the U.S., CERN, Italy, U.K., Switzerland, and Brazil. ICARUS is on track to start taking neutrino data in 2019 with SBND to soon follow. If the current generation of short-baseline experiments reveals the existence of additional new physics in the neutrino sector, measuring this new physics will become a very high priority and will require a new generation of ambitious neutrino experiments. It is important to be prepared for such an event, which may require new neutrino sources, perhaps not unlike what may be required to go beyond conventional beams in long-baseline neutrino experiments.

Other Accelerator Neutrino Experiments – Coherent elastic neutrino-nucleus scattering was observed for the first time by the COHERENT collaboration in 2017. In the near and intermediate future, coherent elastic neutrino-nucleus scattering is expected to provide complementary information on neutrino properties, including the existence of new neutrino states, a nonzero neutrino magnetic moment, and new neutrino interactions. The success of COHERENT underscores the important interplay between neutrino and dark matter experiments, a symbiosis that is expected to remain very fruitful in the future. At higher energies, beam-dump experiments – including the DUNE near detectors and the SHiP proposal at CERN – remain intense sources of neutrinos and are sensitive to new neutrino states and properties. Other accelerator-based experiments remain interesting tools for understanding neutrino properties, including the nature of neutrinos – Majorana versus Dirac. These include the LHC, future high energy colliders, meson facilities, and charged-lepton experiments, including searches for $\mu^- \to e^+$-conversion in nuclei, which may be performed in parallel to search for $\mu^- \to e^-$-conversion in, for example, the Mu2e experiment, currently under construction at Fermilab. These may provide unique information concerning the origin of nonzero neutrino masses.

Non-Accelerator Neutrinos – Neutrinos produced in the Sun, the atmosphere, supernova explosions, and other extreme events in the universe carry invaluable information on particle physics and astrophysics. DUNE and other large detectors used in long-baseline experiments are expected to collect large samples of nature-made neutrinos. Future dark matter experiments will also serve as solar neutrino experiments with very low backgrounds and exquisite energy resolution. Upgrades to the neutrino telescopes IceCube and ANTARES are high priorities for the cosmic ray community and new technologies are being developed in order to look for even higher energy astrophysical neutrinos. Cosmologically, neutrino properties are expected to leave an imprint in different probes of large-scale structure. Near-future observations, including those with Advanced ACT, SPT-3G, and the Simons Observatory, are expected to provide nontrivial information concerning neutrino properties while unprecedented neutrino information is expected from CMB-S4 and the large surveys DESI and LSST. A direct measurement of the relic neutrino background remains a formidable challenge. A few promising ideas, however, are currently being developed, including the PTOLEMY project in the U.S.

The KATRIN experiment is expected to stretch the kinematic sensitivity to nonzero neutrino masses beyond current bounds. In the U.S., Project-8 provides a very interesting possible avenue for improving on the sensitivity of KATRIN and is well on its way to proving whether it is indeed a viable option. The most sensitive probes of lepton-number violation – capable of addressing the nature of the neutrinos – are searches for neutrinoless double-beta decay. A world-wide campaign to look for neutrinoless double-beta decay is currently underway, and ton-scale experiments are expected by the end of the next decade.

4 Investigation of the physics of dark matter

Understanding the nature of dark matter requires a comprehensive approach that makes use of direct-detection experiments, indirect-detection experiments, and colliding-beam and fixed-target experiments. While a Weakly Interacting Massive Particle (WIMP) remains a well-motivated dark matter candidate, many other well-motivated dark matter candidates exist and need to be explored.

Searches for WIMP dark matter: direct detection– The WIMP hypothesis, with a possible supersymmetric origin, has provided guidance over the last two decades, resulting in more than 20 searches worldwide using technologies that concentrate on identifying the expected nuclear recoils in the face of a larger electron recoil background. With the recognition that coherent neutrino scattering represents an irreducible background to nuclear recoil counting experiments, and that funding sources are limited, the U.S. funding agencies in 2014 selected two complementary technologies with the purpose of reaching the "neutrino floor" under the WIMP hypothesis over the next decade: the LZ experiment for high-mass WIMPs and SuperCDMS for low-mass WIMPs and other light dark matter candidates.

The LZ experiment at the U.S. Sanford Underground Research Facility is a liquid Xe TPC which can scale to the large exposures required to cover most of the high-mass WIMP region. The U.S. is also a major player in two noble liquid experiments at LNGS: the XENON nT liquid xenon TPC experiment and the DarkSide-20k low-radioactivity argon TPC. All three experiments are expected to approach the neutrino floor within the next decade. For the next step, the US will need to partner with Europe and Asia on one large international generation-3 detector. This could be a LXe detector, with DARWIN as a likely model, or attention could turn to a LAr TPC, following the longterm plan for Darkside-20k, which would grow to include participation from the entire argon community.

Three solid state experiments are also poised to approach the neutrino floor over the next decade, but at masses down to 500 $\mathrm{MeV/c^2}$. SuperCDMS (U.S./Canadian-funded cryogenic Si and Ge at SNOLAB), EDELWEISS (European-funded cryogenic Ge at Modane), and CRESST (European-funded cryogenics scintillating crystals at LNGS). SuperCDMS SNOLAB will start with a payload of 4 towers (24 detectors), but has room for 31 towers within the shielded, underground cryostat. The modular nature of the technology means that SuperCDMS SNOLAB is a facility which can accommodate multiple users and experiments, thus providing a strategy for future cooperation with European collaborations, although this is expected to happen after CRESST and EDELWEISS finish running in their current locations. Collaborative R&D on new cryogenic detectors with even lower thresholds would open up a rich phenomenology in hidden sector dark matter and other non-WIMP candidates accessible to the next generation of cryogenic solid state detectors that can be installed in the SuperCDMS SNOLAB facility.

At SNOLAB, two other technologies will start data-taking next year: the PICO-500 bubble chamber experiment with the best sensitivity to spin-dependent interactions and the NEWS-G 1.4 m diameter spherical gas proportional chamber. The U.S. plays a major role in PICO. Additional R&D could allow for other target materials to probe spin-dependent interactions, which may have substantially lower neutrino floors. The U.S. is also playing a major role in the existing DAMIC-100 experiment at SNOLAB, which uses "ordinary" CCDs to explore the low mass WIMP region. The next generation SENSEI and DAMIC-M experiments, which use Skipper CCDs, will focus mostly on non-WIMP dark matter (see subsection below).

The motion of the Earth and the solar system through the galactic dark matter halo produces a time-varying signal which can be seen above backgrounds and thus provides a path to sensitivities below the neutrino floor. The U.S. is involved in two experiments to reproduce or refute the DAMA annual modulation, now that the problem of acquiring ultra-pure NaI(Tl) crystal has been solved. COSINE-100 in the Yangyang Lab (Korea) has already shown that NaI crystals do not show the enhancement seen at DAMA, and SABRE will begin a proof of principle run soon at LNGS and in Australia (as well as a South Pole proposal). Several annual modulation cycles will be available by the end of the decade in both the northern and southern hemispheres.

There has been a recent resurgence in R&D on gas-based high-resolution tracking detectors capable of detecting diurnal directional oscillation. The US groups working on this have joined the international CYGNUS collaboration, which is designing a large-scale, competitive detector. There are synergies between this work and readout R&D aimed at ILC trackers and large LAr time projection chambers. This work is well poised to search below the neutrino floor once this decade of counting experiments are complete.

Searches for WIMP dark matter: indirect detection– Terrestrial, balloon-borne, and satellite experiments can search for dark matter annihilation or decay products, which include the stable leptons (electrons, positrons, and the three neutrinos), hadrons, and photons. Satellites include the Fermi Gamma-ray Space Telescope (funded by NASA and the DOE with European partners) and AMS-02. The continuing operation of Fermi is determined by NASA mission reviews every 3 years; the next one is scheduled for Spring 2019.

Ground-based observatories include the Atmospheric Cherenkov Telescopes, such as VERITAS (U.S.), MAGIC (Spanish-German), and HESS (German-African). VERITAS is currently funded through NSF and the Smithsonian Observatory to run through 2019, with a proposal in review to run through 2022. The Cherenkov Telescope Array (CTA) represents the future international effort. Dwarf spheroidal galaxies are an important observational target for CTA to search for signs of dark matter annihilation. In addition, several dwarf spheroidal galaxies will likely be discovered with LSST and followed-up with spectroscopic surveys. There is thus an opportunity for synergistic observations between LSST, CTA, and spectroscopic surveys, which will require coordination between U.S. and European groups.

U.S. groups involved in both VERITAS and the CTA have funding to complete the prototype Schwarzschild-Couder Telescope (pSCT), which is expected to be operated as a fifth telescope in the VERITAS array. The U.S. and Mexico are also heavily invested in a Water Cherenkov Telescope called HAWC, a successor to Milagro, which will be taking data into the next decade. At the South Pole, the IceCube neutrino observatory started data taking in 2005 and can look for signatures of dark matter annihilation and/or decay in the Sun and Galactic halo. An IceCube upgrade received initial NSF funding beginning October 2018. The deployment of the IceCube upgrade instrumentation will occur during the polar season 2022/23 and it will be integrated into IceCube operations. In some cases an integrated system of detection and analysis across a network of experiments, like the multi-messenger follow-up of neutron star mergers, could be very useful.

Searches for WIMP dark matter: colliders– The LHC has been searching for dark matter that is produced either directly in the proton-proton collisions in association with another Standard Model particle, or in the decay of other beyond the Standard Model states. In the former case, the signal will consist of missing energy plus, for example, a single jet, Z-boson, or photon. In the latter case, the signal will also consist of missing energy, but could contain various additional Standard Model states depending on the cascade. The LHC provides constraints on WIMP-nucleon cross sections for mediators between 1 GeV to 1 TeV, with the HL-LHC possibly improving the constrains on the cross sections by a factor of 100. The LHC will continue to be an important probe for dark matter in the coming decades.

Searches for non-WIMP dark matter– The QCD axion has long been recognized as another compelling dark matter candidate, but has been challenging to explore due to its tiny couplings to

Standard Model particles across much of the interesting mass range. ADMX has taken data since January 2017 and its first results in 2018 have covered the QCD axion in a mass range of 2.66-2.81 micro-eV with sensitivity to the predicted DFSZ axion-photon coupling. This unprecedented sensitivity is enabled by the combination of sub-Kelvin cryogenics and near quantum-limited amplifiers to reduce the receiver noise temperature by a factor of $\sim$10. ADMX will continue to take data through 2021 to probe higher masses up to 8 micro-eV (2 GHz).

The last $\sim$10 years have seen significant advances in dark matter theory, which have highlighted new compelling (non-WIMP) dark matter candidates over a wide mass range – from 10^{-22} eV to 1 GeV – and many ideas for their detection. This includes not only new ideas to detect the remaining regions of the QCD axion, but also new ideas to detect other ultralight as well as hidden-sector dark matter particles. The U.S. community summarized the science case and several detection concepts in a Community Report [B+17]. In addition, in October 2018, the U.S. DoE held a Basic Research Needs Workshop on Dark Matter Small Projects New Initiatives to assess the science landscape and identify new opportunities for dark matter particle searches. The report of this workshop is expected to be available in early 2019.

Several experiments using new theoretical insights and/or recent technological advances have received funding for R&D or for first experiments to probe part of the mass range 10^{-22} eV to 1 GeV. These include new direct-detection experiments (SENSEI, LBECA, and DAMIC-M) and new accelerator-based searches (MiniBooNE, NA64, PADME, SBN, COHERENT) to probe dark matter with MeV-to-GeV masses; and new experiments using lumped-element circuits (DM Radio, ABRACADABRA), quantum metrology techniques (QuantISED consortium), nuclear magnetic resonance [CASPEr], and atom interferometry (MAGIS) to search for axion, scalar, and dark-photon dark matter. Several proposals based on proven technologies exist for new direct-detection, accelerator-based, and ultralight dark matter searches, which will cover large regions of unexplored parameter space. Some of these proposals are ready for further development but are in need of funding. In addition, R&D funding of promising technologies could turn more detection ideas into experimental reality, allowing the entire 10^{-22} eV to 1 GeV mass range to be probed.

New dedicated searches have also been proposed to probe low-mass hidden sectors more generally, such as dark photons, dark Higgs bosons, heavy neutral leptons, axion-like particles, and others. These particles could be short- or long-lived, and be produced in electron, muon, or proton fixed-target/beam-dump experiments or in colliding beam experiments that use electrons+positrons or protons+protons. APEX and HPS will search for dark photons at Thomas Jefferson National Accelerator Facility and are scheduled to take data in 2019 after previous successful test runs. Belle II has already begun recording data in electron-positron collisions and will build on the successes of BaBar and Belle to probe a variety of hidden sectors, including sub-GeV dark matter.

It is worth emphasizing that several accelerator-based experiments that will search for sub-GeV dark matter or more general hidden sectors are proposed to make use of U.S. facilities, but could benefit from European participation; these include BDX and DarkLight (at JLab), COHERENT (at ORNL), MMAPS (at Cornell), and SBN and SeaQuest (at FNAL). Other proposed experiments would use European facilities but could benefit from US participation, including CODEX-b, FASER, MATHUSLA, milliQan, and SHiP (at CERN), MAGIX (at MAMI), and PADME (at Frascati). Finally, some proposed experiments could make use of either US or European facilities, including LDMX (at SLAC or CERN).

5 Investigation of the physics of dark energy and cosmic inflation

Introduction– The current epoch of cosmic acceleration seems to require an extension to the Standard Model. One possibility is that the cosmological constant (CC) is driving acceleration. This is a solution that would require the addition of a single new parameter to the Standard Model, but that raises longstanding questions for fundamental theory. A more general possibility that encompasses the CC is dubbed dark energy, in which the cosmic acceleration is driven by the potential energy of a new field, with some mechanism to dynamically relax it to a small value. These dynamical dark energy models offer the simplest extension of the CC model and some of them address the coincidence problem – why is the energy density in the accelerating component comparable with that in matter at this cosmic epoch? Another more radical proposal is to maintain the standard set of particles and fields, but require that General Relativity breaks down at very low energies/low densities/large scales, implying that it must be replaced with a new theory of modified gravity. Constructing viable modified gravity models has proven to be very challenging.

Once the expansion history has been determined very precisely, the growth of structure will distinguish the dark energy idea from modified gravity, as well as test other fundamental physics. The emphasis in the next decade therefore will be not only on precision measurements of dark energy parameters, but also of the more physical measures of expansion history and growth of structure at a range of redshifts and length scales.

The most compelling explanation – inflation – for the initial perturbations that grew into today's large scale structure, requires another epoch of acceleration, at much earlier times and involving physics typically at scales many orders of magnitude larger than those probed at the LHC. Experiments that probe inflation therefore offer a window onto scales that cannot be probed by accelerators. Current and upcoming surveys will allow tests of a range of early universe effects relevant to inflation. Of particular interest for pinning down the physics are measurements of the primordial gravitational waves predicted in many inflationary models, the running with scale of the scalar perturbations, the amplitude of primordial non-Gaussianity, and the spatial curvature of the universe.

With the Large Synoptic Survey Telescope (LSST), the Dark Energy Spectroscopic Instrument (DESI), the Simons Observatory and other surveys beginning operation soon, we are entering an exciting phase during which we expect an order of magnitude improvement in constraints on the physics of the accelerating Universe. In addition, the proposed Cosmic Microwave Background - Stage 4 (CMB-S4) experiment and the space missions Euclid and WFIRST will operate in parallel with LSST for much of the 2020s. Several opportunities for new initiatives exist: the following summary is based in large part on the P5 report and the more recent Cosmic Visions reports[D$^+$16a, D$^+$16b, D$^+$18].

Participation and collaboration in existing and proposed projects The large primarily US-funded cosmic surveys of the coming decade are: LSST, DESI, WFIRST and CMB-S4. LSST and DESI are further along in the process and have full funding committed. There is already meaningful European expertise and involvement in some of these projects; increasing the level of commitment would aid both communities. Discussions for substantive European hardware and scientific contributions to WFIRST are underway, and the European-led Euclid Survey has strong U.S. participation and scientific synergies with LSST. Increasing the data-sharing and planning for the joint analysis of these two surveys would increase the scientific output.

More generally, cross-correlations between galaxy, CMB and other multi-wavelength surveys can be used to obtain new probes of dark energy and reductions of systematic uncertainties. A Multi-wavelength Virtual Observatory is discussed in the Cosmic Visions 2018 report[D$^+$18].

The U.S. and European communities working together will have the opportunity to define and lead the next generation "Stage V" surveys. There is a strong case to address fundamental physics questions with surveys that go beyond the capabilities of Stage IV surveys and would operate in the 2030s. Current studies suggest that large scale spectroscopy, transforming 2D maps into full three-dimensional maps of the sky, is likely to be one priority.

CMB-S4 is an ambitious stage 4 experiment that has brought together over 150 scientists into a large collaboration to pursue the exciting search for primordial gravitational waves created in the early Universe during a period of exponential inflation. CMB-S4 will shed light not only on inflation but also on many aspects of the dark sector: neutrinos, models with new very light particles, potential dark matter candidates and on the mechanism driving cosmic acceleration. CMB-S4 is seeking broad participation from the European community. Other radio observations that are emerging as promising are those that probe the distribution of neutral hydrogen via the redshifted 21 cm line. These 21 cm projects are just beginning to be considered. They can be partitioned into experiments that target the epoch of reionization and ones that probe the universe at later times. The science of interest for dark energy and inflation may ultimately require designs that differ from those proposed for the Square Kilometer Array.

New opportunities The actual scientific returns of LSST, Euclid and other planned surveys could vary significantly, both above and below the baseline plans. Complementary data, investments in calibration and efforts to lower the systematics floor due to known effects through specific, targeted observations could have a large payoff. The exploration of small scales beyond the current baselines by enabling a comprehensive modeling and simulation program would enhance the statistical power of cosmological surveys. The small scale modeling effort refers primarily to two-point correlations on nonlinear scales. However, there is a dazzling array of astrophysical observations on small scales, and a number of these have been identified as novel probes, offering sharp tests of fundamental physics beyond wCDM.

6 Exploration of new particles, interactions, and physics principles

The Standard Model, augmented by Lagrangian terms for neutrino masses and mixings, continues to be in good agreement with all the data obtained in particle physics experiments. Probing the limits of the Standard Model and potentially unraveling new phenomena requires a multi-prong approach, including various explorations of the energy frontier at collider experiments as well as precision experiments at lower energy. Besides specific inquiries addressed in previous sections of this white paper, such as the particle origin of dark matter, or understanding the Higgs sector, it is essential to seek the underlying laws of nature in comprehensive and generic ways.

The LHC program, including the high-luminosity run (HL-LHC), offers opportunities for testing the limits of the Standard Model in many directions. Running the LHC at a center-of-mass energy of 14 TeV and analyzing about 3000 fb^{-1} of data collected by both the ATLAS and CMS experiments will boost the discovery potential in numerous channels and is critical to exploiting the physics potential of the LHC. Enlarging the scope and number of new physics searches as much as possible will also help to take full advantage of those datasets. It is important to continue developing new strategies to tackle complicated boosted systems, low-mass resonances, displaced vertices, resonantly produced cascade decays, and other complicated final states. The HL-LHC will probe the existence of new particles with weaker couplings, as well as particles of mass in the multi-TeV range that may be produced in only a few events with negligible backgrounds. The LHC searches will provide tests for models of new physics for many years to come, so it is necessary for the search results to be as model-independent as possible, and to remain available for reinterpretation.

LHCb continues to provide multiple probes of flavor phenomena, and Belle II will add complementary information. Understanding the various flavor measurements already in tension with the Standard Model (*e.g.*, in $B \to K\mu^+\mu^-$ decays) could provide insight into the nature of new particles and interactions. For this purpose, as for any other particle physics experiment, theoretical efforts to understand the Standard Model contributions and uncertainties are crucial.

Other experiments that explore different flavor transitions are also being pursued. In particular, experiments using muons to search for charged-lepton flavor violation offer valuable probes of new physics. New results are expected in the near future from MEG, $\mu 3e$, Mu2e, and COMET, which test different sets of promising new phenomena. Proposals exist for upgraded experiments with improved sensitivity to charged-lepton flavor violation, including Mu2e-II at Fermilab.

Low-cost parasitic experiments at the LHC also have a role in studies of physics beyond the Standard Model. Proposals of this type include FASER and MATHUSLA, which would be sensitive to very long lived particles, and milliQan which would search for milli-charged particles. Some of these might be considered as a part of the program of upgrades to the LHC and its detectors. It would also be useful if plans for future colliders would incorporate some space and infrastructure for low-cost, late-arriving additions.

The results from the LHC and other experiments will inform the longer-term plans. Any discovery of physics beyond the Standard Model could dramatically change the path forward, and would need to be fully taken into account in a continuing decision process. In the meantime, long-term plans can be developed under the assumption that the current physics knowledge will not dramatically change in the near term, but with enough built-in flexibility to be able to react to potential discoveries. Long-term plans will also need to evolve should there be evidence of new physics that emerges from any of a wide range of experiments, from dark matter searches and cosmological probes of dark energy to electric dipole moment measurements and neutrino studies.

Developing and finalizing plans for building higher-energy colliders is essential for the study of the fundamental laws of nature. The proposed High-Energy LHC (HE-LHC), with proton-proton collisions at a center-of-mass energy of about 27 TeV, would provide a valuable path towards understanding physics at the 10 TeV scale. Achieving that energy in the LHC tunnel requires persistent R&D towards high-field magnets. Accumulating roughly 1.5×10^4 fb^{-1} of data at 27 TeV in each of two multi-purpose experiments would advance the explorations of the energy frontier in many outstanding ways. For example, the HE-LHC would substantially increase the reach of searches for vector-like quarks, Z' and W' bosons, colorons, diquark scalars, supersymmetric particles, heavy Higgs bosons and other new particles. Furthermore, with an increase in energy by a factor of two compared to the LHC, the discovery of truly exotic and unexpected phenomena at the HE-LHC would be possible.

A new proton-proton collider (FCC-pp) with a center-of-mass energy of about 100 TeV would also be a technologically feasible and highly desirable development. The physics capabilities of such a collider are very impressive, and are a natural continuation of the HL-LHC and the HE-LHC. The FCC-pp could close the book on electroweak supersymmetry, test for compositeness of Standard Model particles, and potentially probe leptoquarks or new gauge bosons at scales that could give rise to the current flavor anomalies. As the FCC-pp would require a new and much longer tunnel, it would be useful to consider first installing an e^+e^- collider (for more details, see the Higgs section of this white paper).

It is imperative to exploit the synergy between future colliders. If new particles at the weak scale are discovered at the LHC, for example low-mass staus, an e^+e^- collider could allow detailed studies of their properties. The development of high-field magnets for the HE-LHC could lead to center-of-mass energies for the FCC-pp exceeding 100 TeV. The optimization of the FCC-pp energy would be directly influenced by the outcome of physics explorations at the HL-LHC or the HE-LHC.

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