9/16/2018

Fermilab
Physics Advisory Committee Report
Chicago, July 16-19, 2018

Executive Summary

The Physics Advisory Committee (PAC) met in Chicago on July 16-19, 2018 to review the progress and strategic development of the full portfolio of the Laboratory research program.

The PAC was impressed with the Laboratory's research program execution, innovation and synergies across all frontier projects of experimental high energy particle physics currently producing science results, and those in construction that are the foundation of the future of this science in the US and Internationally and aligned with the Particle Physics Project Prioritization Panel (P5) report: "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context.".

On the neutrino frontier, the PAC heard the science yield and plans of the currently running experiments namely the NOvA experiment and the groundbreaking MicroBooNE LArTPC experiment. It is NOvA's fourth year of full operation and the collaboration presented their latest results in the Neutrino 2018 conference in Heidelberg, Germany. With the expected increased NuMI beam power delivery through 2024, NOvA's experimental results will continue to push the constraints on CP violation, neutrino mass hierarchy and octant observables. The PAC commends the Laboratory and the NOvA collaboration for their continued outstanding science yield and program towards their future goals. MicroBooNE has recently moved from a period of commissioning and engineering running to their full science run. MicroBooNE is the first large LArTPC detector in the US. The PAC is impressed with the collaboration's pioneering work to establish the understanding of a complex detector technology towards important neutrino physics results that will also shed light on possible beyond the Standard Model effects seen in past experiments. The operational experience gained by MicroBooNE is crucial for future LArTPC neutrino experiments planned at the Laboratory, namely the upcoming Short Baseline Neutrino (SBN) program and the DUNE/LBNF international megaproject in South Dakota. The PAC commends the Laboratory for their continuing support of MicroBooNE and looks forward to the major physics results and updated projected capabilities from the collaboration in

On the upcoming SBN Fermilab program the PAC congratulates the Laboratory and the ICARUS collaboration for the arrival of the ICARUS detector at Fermilab on July 26, 2018, shortly after this review took place, and the successful installation of the detector in the experimental hall on August 16, 2018. Specifically, the two ICARUS cold vessels were successfully sealed and vacuum tested, and using a rigging company, the cold vessels were moved into the building and placed in their final location. The PAC commends the Laboratory and the SBN program on their attention to meeting the schedule and their preparations for the operation of ICARUS and SBND as well as the well-coordinated joint analysis efforts. At the next PAC meeting, the Committee is looking forward to seeing an updated sensitivity study based on the latest software framework. The PAC encourages the collaborations to develop a strategy for the cross section measurements with an eye towards maximizing input towards DUNE, and to work with the Laboratory to develop a detailed computing strategy.

The PAC reviewed the progress towards the DUNE Technical Design Report (TDR) and the input from the protoDUNEs program. The PAC is impressed with the successful completion of DUNE's Interim Design Report for the Far Detectors, the completion of ProtoDUNE Single-Phase design and the progress on the ProtoDUNE Dual-Phase design. The PAC is looking forward to the Conceptual Design Report for the near detector currently planned for 2019 and expects the CDR will include in-depth assessment of the sources of systematic uncertainties and realistic strategies for reducing them at the time of the Far Detector TDR. The PAC encourages the Laboratory to put in place structures and mechanisms to identify a set of US contributions to DUNE that are well-matched to the capabilities and interests of participating US institutions. The PAC applauds the DUNE collaboration plans to submit a White Paper to the European Strategy Group and press the case for enlarging the European participation in DUNE as part of raising the level of international contribution to the global LBNF facility.

On the precision beyond-the-Standard Model measurement frontier using muons, the PAC reviewed progress towards the first g-2 physics result, and the prospects for achieving the design sensitivity given the anticipated future performance of the accelerator and experiment. The PAC finds that the experiment is on track for reaching the required data statistics and sensitivity goals and applauds the collaboration for their strategic approach of reducing systematic uncertainties. The PAC endorses the g-2 operation for 2019, 2020 and is looking forward to results and publications in 2019. The PAC applauds the continuing communications of the experiment with the Laboratory on sustainable resources to extract the science in the coming years. On the same frontier, the Mu2e experiment at Fermilab searches for the charged lepton flavor violation process of a muon converting to an electron in the orbit of a nucleus. The PAC commends the Laboratory for the Mu2e impressive progress since the last review with most of its scope progressing very well. The committee notes the importance of Mu2e recording a sufficiently large physics data sample ahead of the LBNF long shutdown, to maintain a competitive advantage over COMET. The PAC endorses the Mu2e-II upgrade request of dedicated R&D funding and encourages them to engage the Laboratory and funding agencies into identifying the required resources.

On the hadron collider energy frontier, the PAC commends USCMS and Fermilab for breakthrough results on the Higgs sector couplings to the top and bottom quarks. The LHC has made momentous observations in the summer of 2018 on these channels. Fermilab pioneered the search for Higgs decays to bottom quarks at the Tevatron, leading to the first evidence for these decays in 2012; this is now sealed by the LHC experiments. The PAC notes the continuing leadership of the Laboratory in the management of CMS at CERN (past two years CMS

Spokesperson Joel Butler and as of publication of this report Deputy CMS Spokesperson Patricia McBride). The PAC encourages the Laboratory to ensure that the HL-LHC CMS upgrade CD-1 review process is completed as soon as possible in order to meet international deadlines and applauds the Laboratory's efforts on the novel picosecond timing CMS detector project. The PAC appreciates the USCMS and Fermilab computing efforts to address the HL-LHC computing challenges. These need close collaborations between physicists and computational scientists to develop efficient solutions. Based on Fermilab's legacy on scientific computing and its longstanding remarkable success and leadership at the LHC, the PAC encourages the Laboratory to continue engaging in strategic planning for the success of computing and software in the HL-LHC era including novel Artificial Intelligence applications in HEP.

The PAC commends the Laboratory for the August 2018 milestone achievement of beam at the Integrable Optics Test Accelerator, an innovative test bed dedicated to the science of particle acceleration. The PAC reviewed the result of the Laboratory's Magnet Task Force. The PAC feels that Fermilab's confirmed expertise in Nb3Sn magnet technology makes it a natural place for the dedicated research effort proposed by the task force, following upon a successful completion of the GARD program to achieve an accelerator quality dipole magnet in the range of 15-20 Tesla field strength. The PAC feels that the DOE should consider asking Fermilab to lead, in coordination with the existing LBNL HF magnet leadership, a national planning effort that lays out a comprehensive R&D program including HTS magnets, while also encouraging younger researchers in the field, following the internal Fermilab exercise.

The PAC reviewed the updated vision, prospects, and plans for the Particle-Astrophysics Group at Fermilab. The PAC strongly encourages the planning group to take a broad view of neutrino cosmology and astrophysics as they develop ideas for this effort and explore connections with the Laboratory neutrino program and DUNE science priorities. The committee also reviewed the status and plans of the Laboratory theory group, including the alignment of the groups' activities with the ongoing and future program at the laboratory. The PAC has identified the need for a significant senior and junior theory recruitment effort in areas of priority of the Laboratory experimental program. The PAC commends the Laboratory theorists for their participation in the recent exciting quantum initiatives where theory plays an essential role. The PAC encourages the Laboratory theorists to continue in this direction and maintain communications with the Laboratory management to explore options for additional resources in these areas. On the quantum science frontier, the PAC reviewed the MAGIS-100 science goals, scope and appropriateness of the support requested. The PAC enthusiastically supports the science goals and request by MAGIS-100 for engineering and drafting resources. The PAC looks forward to receiving a MAGIS-100 proposal in the near future.

The PAC appreciated the report on Fermilab's very successful second all-scientists retreat (April 2018) on all areas of science and technology at the Laboratory, which was widely attended by laboratory scientists. The PAC applauds these Laboratory retreats that explore ideas related to long-range plans across the Fermilab science program. The PAC also heard a report on the very successful LDRD (Laboratory Directed Research and Development) program that maintains scientific and technical vitality attracting the youngest and brightest in the Laboratory. The PAC also heard an invited contribution from the DPF on the plans for the US contribution to the European Strategic Plan. In Executive Session, the PAC heard very informative and detailed reports on the ProtoDUNE and MicroBooNE computing requirements. The PAC will request further reports in the future on the upcoming neutrino experiments computing requirements and plans leading to DUNE computing requirements.

The PAC congratulates the Laboratory for the three Early Career Awards it received by DOE as announced in the Summer of 2018 for i) exploring the lifetime frontier with new detectors and new searches ii) microwave single-photon sensors for dark matter searches and precision neutrino measurements and iii) table-top neutrino detectors for 10-kilogram skipper-CCD experiments.

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1. NOvA

Given the current status of neutrino measurements and the present expectations for beam delivery, we ask the committee to comment on the NOvA Collaboration's science strategy and the expected timeliness of NOvA results with respect to the competition.

The PAC commends the NOvA collaboration on their recent progress and world-leading results. The observation of electron antineutrino appearance, recently presented at the Neutrino 2018 conference, is a major development for the field, and the NOvA joint fit incorporating all neutrino and antineutrino appearance and disappearance results, yields competitive parameter constraints. NOvA has also pioneered novel machine-learning-based analysis techniques.

NOvA's primary competition for CP violation, mass ordering, and octant observables is the T2K experiment. With the expected beam delivery through 2024, NOvA and T2K will play complementary roles: NOvA is expected to dominate the sensitivity to the mass ordering, while T2K will provide competitive sensitivity to CP violation. The planned increases to the NuMI beam power and the analysis improvements resulting in reduction of systematic errors are critical towards achieving NOvA's physics reach.

The NOvA collaboration's testbeam strategy aims for better tuning of the light/scintillator response model, benchmarking of Convolutional Neural Networks-based selection algorithms, and calibration improvements. The PAC recognizes that the testbeam activities offer important detector instrumentation and data acquisition-related training opportunities for the junior researchers, thus sustaining relevant expertise.

NOvA has demonstrated, via tuning their model of neutrino interactions with a model of multinucleon knockout processes, the ability of their near detector to reduce systematics on the oscillation measurement. An expanded program of measurements, particularly ones that correlate lepton and hadron side observables, could play a significant role in reducing systematics.

The PAC encourages the Laboratory and the NOvA collaboration to consider paths to support the testbeam and expanded near detector research program with appropriate resources. The PAC is pleased to hear NOvA's plan to publish their current best GENIE tune and encourages its timely release. The PAC welcomes NOvA's recently formed task force to study in depth neutron-related systematics and underscores the importance of these studies. The PAC encourages the Laboratory to maintain continuous communication with the experiment on sustainability of the resources for the production of the NOvA science in the coming years.

NOvA has already begun a program to develop a joint analysis with T2K and is planning a collaborative generator tuning project with MINERvA. The PAC commends these efforts. In particular, the joint analysis with T2K could significantly expand the physics impact of both experiments.

2. MicroBooNE

The committee is asked to comment on progress towards understanding the ultimate sensitivity of the experiment and the plan to get to the signature MicroBooNE result. In addition, we ask the PAC to comment on the importance of future MicroBooNE data taking.

The PAC commends MicroBooNE on its continued progress. The collaboration is improving our understanding of the LArTPC detector and to developing increasingly effective and efficient reconstruction strategies. They have produced valuable technical publications and recently submitted their first publication of results on neutrino interactions. The collaboration's track record of student and postdoc mentoring is impressive.

MicroBooNE's development of reconstruction algorithms and software benefits DUNE and the overall SBN program. MicroBooNE currently has four parallel analyses in progress for addressing the "signature" low-energy excess (LEE). This approach of multiple analyses, while resource intensive, has advantages in exploring creative and effective techniques to fully exploit the capabilities of the LArTPC technology. **The PAC encourages the collaboration to explore a strategic choice of a baseline analysis avenue to focus their resources in the coming year and hit their science targets according to their schedule.**

MicroBooNE has currently collected 9.6×10^{20} POT of data, 40% of which includes the Cosmic Ray Tagger (CRT). They expect to nearly achieve their goal of 13.2×10^{20} POT by the summer shutdown in 2019.

Qualitative arguments were made by MicroBooNE that the dominant backgrounds in the LEE analyses can be reduced with further algorithm development. MicroBooNE also stated that this development might be more effective in the data with the CRT. MicroBooNE provided the PAC with sensitivity for the one photon + one proton LEE analysis. To benefit from increased data, this analysis would require significant reduction in beam related backgrounds and control of systematic uncertainties. The collaboration also presented qualitative evidence that their data could provide useful information about nuclear effects in neutrino interactions on argon based on current results. **The PAC is looking forward to the projection of future sensitivity in the LEE analyses as a function of POT and further refinement in the strategy for improving the understanding of neutrino-argon interactions.**

Measurements shown to the PAC were based on Run 1, which is 15% of the total protons on target accumulated thus far. The PAC encourages MicroBooNE and the Laboratory to continue the important work to reduce the time required to process the full data set to mitigate delays in completion of analyses.

The PAC encourages MicroBooNE to prepare comprehensive sensitivity assessments for their highest priority and most promising LEE and non-oscillation analyses. These assessments will be essential in providing the case for future running and will help the experiment to focus its efforts in analysis improvements. The PAC believes that the developments in algorithms and code that result from analysis of MicroBooNE's data will continue to benefit and inform the DUNE and SBN program, and

it recognizes the value of continued analysis beyond the end of data taking currently planned for the end of FY 2019.

Operational experience gained by MicroBooNE is valuable for future LArTPC experiments. The PAC notes that such experience will also be gained in the near term from the operation of protoDUNE and SBND, which are more similar to DUNE than MicroBooNE, as well as ICARUS.

3. SBN

The committee is asked to comment on progress and plans towards implementing the SBN program. In particular, we ask the committee to comment on (i) the management and organization for commissioning and operations, and (ii) the organization and plans for joint analyses.

The PAC heard two presentations on the SBN program pertaining to the preparations for the operation of ICARUS, SBND as well as the joint analysis effort.

i) The Committee commends the laboratory for its dedicated efforts to finalize the cost and schedule of the SBN program. The PAC believes that additional help is needed to a) complete the SBN MoUs with key partners and move forward on major deliverables such as the SBND cryostat, which is now on the critical path, and b) prioritize as needed the lab resources in survey/rigging and other technical resources needed to keep the SBN construction and installation on schedule. **The PAC is pleased that by the time of the publication of this report, there is considerable progress both on the MOU and the Laboratory resource allocation front.**

A concern is the aggressive schedule for the far detector. Especially demanding is the installation of the proximity cryogenics which involves CERN resources and the *Demaco* company that requires three months advance notice to schedule their work. The projected schedule to fill ICARUS in one year from now depends strongly on this cryogenics installation and commissioning. **The committee encourages the Laboratory to explore paths to involve, if possible, engineers and technicians who were previously involved with the cryogenics when ICARUS was installed at LNGS.**

ii) The Committee was pleased to see the continued development of the joint SBN analysis effort, with regular meetings and workshops that have led to an agreement to implement a common simulation and reconstruction framework based on LArSoft and a unified analysis scheme for sterile neutrino oscillation searches. The effort has successfully generated simulated neutrino events for both SBND and ICARUS, and is jointly developing aspects of the simulation such as the cosmic ray and photon detection systems, as well as reconstruction and selection algorithms. The joint effort is augmented by a new collaborative effort that includes the Fermilab Theory group.

The Committee encourages the SBN analysis effort to maintain its momentum, especially in preparation for early data coming out of the commissioning of the ICARUS detector. **At the next PAC meeting, we look forward to seeing an updated sensitivity study based on the latest software framework. We also encourage the collaborations to develop a strategy for the cross section**

measurements with an eye towards maximizing input towards DUNE, and to work with the Laboratory to develop a detailed computing strategy.

4. DUNE

The LBNC reviews progress and gives advice on LBNF and DUNE. We ask the PAC to comment on recent progress on DUNE, including (i) the IDR and progress towards the TDR, and (ii) the protoDUNE measurement plan and how it will inform the TDR.

The PAC congratulates DUNE on the successful completion of the Interim Design Report (IDR) for the DUNE Far Detectors and, together with CERN, the completion of protoDUNE-SP and ongoing progress on protoDUNE-DP. The IDR represents the first major output from the newly formed detector subsystem consortia and a critical intermediate step forward toward Technical Design Reports next spring. Since it relies on design and integration of components that are the basis for the DUNE Far Detectors, the protoDUNEs are key engineering prototypes for the TDR and a source of calibrated performance data for the DUNE Far Detectors.

The LBNC has laid out guidance and planning for development and review of the IDR as a first step towards an eventual Technical Design Report in Spring 2019. The first step was a face-to-face review of the recently completed IDR in May 2018. The LBNC produced an initial assessment at the end of the May meeting in the form of an interim report, also made available to the PAC. A second face-to-face review is scheduled for Aug 1-3, 2018 and a detailed in-person review of the dual phase component of the IDR is planned at CERN in December 2018. The LBNC will then provide a final assessment and advice to DUNE for the TDR.

The PAC noted that the DUNE collaboration has been working to respond to the LBNC's assessment and guidance for improvements to the upcoming TDR, including recommendations concerning physics requirements, by developing a set of tables to be adopted by the Executive Board (EB) in the coming weeks. These same requirements tables will define cases where protoDUNE test results are intended to demonstrate that the performance baseline can be met with the current design. **The PAC commends the collaboration for its rapid response to this request and looks forward to DUNE defining the basic requirements for the detector design.**

DUNE has recently made changes to the management structure of the collaboration with the aim of enhancing their ability to make timely decisions with full buy-in from relevant technical and physics leadership. The new Executive Board, a body composed of the recently formed consortia leaders, physics leaders, and technical coordination, similar to other large collaborations, met recently for the first time, so the efficacy of the new arrangement is yet to be demonstrated. However, the collaboration management described a plausible strategy for making the EB, a large group, both functional and efficient. **The PAC expects the LBNC will continue to monitor the effectiveness of this new arrangement.**

The single-phase cold electronics consortium has developed a multi-prong strategy for design and testing solutions for the front-end electronics subsystem. Options include design of a cold ADC and digitizer/serializer ASIC, undertaken by a collaboration of BNL, Fermilab and LBNL ASIC designers; a second option is a combined function ASIC (front-end amplifier, ADC, and digitizer/serializer), undertaken by SLAC and derived from a similar ASIC for nEXO; and a back-up option is a commercial off-the-shelf ADC that has been demonstrated by SBND to operate at LAr temperatures. **The PAC is looking forward to the results of the large scale testing of these options that will occur by the end of this calendar year using spare APA planes in a cold box at CERN.** Performance criteria have been established to allow down-select among these options, should several be successfully and timely demonstrated.

While the dual phase design has experienced technical setbacks in recent months, mitigation strategies and design changes have been developed and are being tested in a new special-purpose CRP cold box, which allows rapid turnaround and diagnosis of any additional problems. **The PAC is looking forward to the execution of the current plan that envisions the completion of protoDUNE-DP with the installation of two CRPs in the protoDUNE-DP cryostat by the end of the year, allowing cosmic ray data taking to validate performance in advance of the TDR. The PAC recognizes the potential risks and advantages of the dual phase design.** The latter include fewer readout channels, easier photon detection, accessible cold electronics, and orthogonal readout planes. In addition, the PAC notes that the dual phase design can attract a new set of collaborators to DUNE.

The PAC remains concerned by the lack of an overarching organizational structure encompassing the subsystem consortia contributing to the single and dual phase far detector designs. The calibration systems design is a prime example of concern. While the calibration task force is making notable progress in identifying possible approaches, such systems should be viewed in an integrated way as part of the overall design, commissioning, and operations planning, extending well after the task force has finished its work.

Results on CP violation sensitivity based on full Monte Carlo simulation and reconstruction were shown to the PAC. Such results will be a critical part of demonstrating the performance capability of the DUNE design at the time of the TDR. Based on progress in understanding neutrino interaction modelling uncertainties with the current generation of long baseline neutrino experiments (NOvA and T2K) and theoretical studies, **the PAC encourages DUNE to closely examine sources of systematic uncertainties in solidifying their sensitivity projection studies**. DUNE has constituted a Near Detector Design Group to explore concepts for the near detector design. **A set of recommendations are now under consideration by the Executive Board. The PAC is looking forward to the Conceptual Design Report for the near detector currently planned for 2019. The PAC expects that the CDR will include in-depth assessment of the sources of systematic uncertainties and realistic strategies for reducing them at the time of the Far Detector TDR.**

Given the ongoing growth in DUNE membership, the collaboration will be well-served by reinforcing its effort to welcome new groups, new ideas, and new leadership, by emphasizing the sense of collaborative spirit within DUNE, including at the level of consortia.

At the time of the CD1R review, a strawman model for US participation was constructed in a top-down manner in order to demonstrate the feasibility of constructing DUNE through US and international participation and funding. As other national communities are now organizing their contributions to DUNE in a coherent fashion through community and national agency discussions, the PAC encourages a similar process within the US community. **The PAC encourages the Laboratory to put in place structures and mechanisms to identify a set of US contributions to DUNE that are well-matched to the capabilities and interests of participating US institutions.**

The PAC notes that while the DUNE EB is a suitable mechanism for defining collaboration recommendations on design requirements and interfaces, the Experiment-Facility Interface Group (EFIG) will be the body where final decisions are taken for issues that straddle the DUNE detector and the LBNF facility. Examples include options for the near detector, some of which impact the location, size and orientation of the near experimental hall. **The PAC encourages DUNE to continue to maintain good communication with LBNF via EFIG and, in particular, make sure that LBNF is aware of design changes under consideration even before the EB has made a final proposal, not the least because LBNF may generate important and relevant information to the DUNE process.**

The PAC applauds the DUNE collaboration plans to submit a White Paper to the European Strategy Group and press the case for enlarging the European participation in DUNE as part of raising the level of international contribution to the global LBNF facility.

5. Muon g-2

We ask the committee to comment on the status of the experiment, progress towards the first physics result, and the prospects for achieving the design sensitivity given the anticipated future performance of the accelerator and experiment.

The PAC heard about the status and data-taking progress of the Muon g-2 experiment. The experiment aims to improve precision on the muon anomalous moment by a factor four (140 parts per billion) relative to the previous experiment at BNL (E821) by a large increase in statistics (x21) and a 2.4 times reduction of the systematic errors. The longstanding discrepancy between the measured and theoretically predicted values of the muon g-2 remains one of the most intriguing tensions in particle physics.

The PAC commends the initiatives taken by the collaboration to bring together the world community working on the Standard Model calculations to discuss and develop a baseline prediction. Recent improvements in Lattice QCD calculations are encouraging, in particular for the light-by-light scattering contribution that currently relies on hadronic models with difficult to assess uncertainty. The PAC welcomes the ongoing work in this area from the Fermilab Lattice QCD theorists.

Since the last report at the PAC in 2016, substantial progress has been made with the storage ring and detectors being fully installed and beam operations starting. After a pilot run in July 2017, the machine commissioning concluded in February 2018 with significant improvements of the running conditions. The first official physics run started in March 2018 with a small number of μ^+/fill. In the few months of running, a continuous optimization of the machine, from the injection to the kickers, has allowed the beam to reach operations at 50% of the planned flux. As of today, the experiment succeeded in accumulating statistics already twice that of the BNL experiment. The PAC congratulates the Laboratory and the Muon g-2 collaboration for this impressive achievement.

With the current flux, the scheduled FY19/FY20 runs will allow the experiment to reach a statistic of 14 times that of the BNL experiment. An intense roadmap towards improvement of the flux by an additional factor of 1.5 has been presented for the summer shutdown. It includes the completion of the preparation of the new inflector magnet and improvement of the kicker performance.

The PAC finds that the experiment is on track for reaching the required data statistics and sensitivity goals. The new tracking detectors, not existing on the BNL experiment, have allowed to reconstruct the beam position along the ring. The calorimeters are operating with high efficiency. A continuous gain monitoring of all channels via the laser calibration system has allowed to reach a gain stability of O(10^-4). The magnetic field has been measured to be very uniform in the storage ring improving the related systematics at level already below the BNL one. The analysis of the 2018 data is well under way with multiple teams engaged. Algorithms on the B-field and muon precession frequency measurements are being developed and blinding strategies are in place.

The PAC endorses the g-2 operation for 2019, 2020 and is looking forward to results and publications in 2019, using the already collected statistics expected to achieve an overall muon g-2 uncertainty of 400 ppb, with a systematic contribution already at the level of 100 ppb. The PAC applauds the continuing communications of the experiment with the Laboratory on sustainable resources to extract the science in the coming years.

6. Mu2e

We ask the committee to comment on progress towards the experiment.

The PAC heard a presentation about the status of the Mu2e experiment and its progress since the last report to this committee in 2015. Mu2e searches for the charged lepton flavor violation process of a muon converting to an electron in the orbit of a nucleus. The experiment's goal is to improve by four orders of magnitude the sensitivity on the ratio between the rates of muon to electron conversion and muon capture, with respect to the previous measurement, down to a discovery potential of 2×10^{-16}. Observation of this process would be an unambiguous sign of physics beyond the Standard Model. Mu2e uses 8 GeV protons from the Booster and cannot run concurrently with the Muon g-2 experiment. The success of Mu2e depends on (i) a high intensity pulsed proton beam and a very high proton extinction factor (10^{-10}) to suppress the prompt background, (ii) a solenoidal system to increase the muon stopping rate, and (iii) a high resolution tracker to separate the mono energetic conversion electron (104.96 MeV) from those arising from decay in orbit (DIO).

The Mu2e project made impressive progress since the last report with most of its scope progressing very well. CD-3 approval was achieved in July 2016, allowing the construction of all components. All major contracts have been placed with some (e.g., civil engineering) being completed. The preparation of the proton beam line is progressing well with most of the beam line elements installed or being fabricated. The procurement of the production target is underway with some R&D continuing to develop higher lifetime targets. The transport solenoid modules are being fabricated at ASG Superconducting (Italy) with good progress and the first one undergoing cold tests at Fermilab. A model coil cold test of the production (PS) and detector (DS) solenoids is under preparation at General Atomics (GA), Tupelo. Coil winding issues (machine design problems) were found in the first DS unit and GA is now modifying the winding machine. The delay in the schedule is estimated between 2 and 6 months.

The muon beamline effort is completing the integration design of the target, the beamline elements, the PS/DS vacuum systems and the stopping target monitor. The straw procurement for the tracker has been completed and the basic elements constituting a station, the panels, have a final design. The production line is being setup. For the calorimeter, one third of the CsI and SiPMs have been received and are under test; work is in progress on the mechanical integration. The calorimeter benefits from a successful DOE/INFN partnership. Trigger and data acquisition developments are progressing well aiming to complete the vertical slice tests of each component. Detailed work on a realistic simulation of the entire detector is ongoing. Reconstruction and analysis are progressing well. Simulation studies of three years data taking with a total of $6x10^{17}$ stopped muons ($3.6x10^{20}$ protons on target) predict a total background of 0.4 events dominated by cosmic rays and decay in orbit, and a single event sensitivity of $3x10^{-17}$.

The Mu2e Collaboration estimates the project to be 65% complete with the fabrication of the PS and DS on the critical path. The schedule float from CD-4 is now 16 months to Q1 of FY2023, while it was 21 months at CD-3 time. Commissioning of all components with beam is expected to occur at the end of FY22 with the first physics run scheduled for FY23. The current accelerator long-range plan foresees a long shutdown of the muon complex during CY 2024 and 2025 for LBNF. The COMET experiment at J-PARC, a direct Mu2e competitor, is planning to begin Phase-I operations (expecting about hundred times less sensitivity than Mu2e) in 2020.

The PAC commends the Mu2e Collaboration for remarkable progress made on all parts of this novel and challenging experiment. Regular and tight interactions with the vendor will be required to maintain the construction schedule for the critical solenoids. The committee notes the importance of Mu2e recording a sufficiently large physics data sample ahead of the LBNF long shutdown, to maintain a competitive advantage over COMET.

7. Mu2e Evolution EOI

We ask the PAC to comment on whether the science goals are compelling, and on the scope and appropriateness of the support requested.

The PAC heard the Expression of Interest (EOI) for an upgrade of the Mu2e experiment (Mu2e-II) to run at the PIP-II accelerator in the late 2020 to 2030 period. The scientific goal of the upgrade is to extend by a factor of 10 the Mu2e reach for muon to electron conversion to a single event sensitivity of $3x10^{-18}$ for the ratio between the rates of muon to electron conversion and muon capture, and a discovery potential of $2x10^{-17}$. The conversion process is complementary to the other charged lepton flavor violating (CLFV) searches in the muon sector, namely muon decays to three electrons and to electron plus photon. The full exploitation of these searches allows to greatly expand the new physics reach and, in case of a positive signal, to discriminate among theoretical models. The PAC recognizes that the physics case of a factor of ten sensitivity improvement is compelling for all scientific outcomes of a successful (in terms of reached sensitivity) Mu2e experiment: (i) extend the search reach if no signal was found, (ii) improve the event yield if the indication of a signal is found but significance is lacking, or (iii) study the new physics by altering the host nucleus (stopping target) if a signal was found by Mu2e.

The experimental concept of Mu2e-II is similar to that of Mu2e. To reach the desired sensitivity, a factor of hundred increase in the proton-on-target yield to $4x10^{22}$ (giving about 10^{19} stopped muons) is required, while running at lower (PIP-II) proton energy than Mu2e (800 MeV instead than 8 GeV). The lower beam energy allows to eliminate antiproton background while keeping a similar muon yield and reducing by 30% the power density on the production target. To minimize the accidental rate-per-pulse on the detector, the duty factor has to be increased from 0.25 (Mu2e) to greater than 0.9. To reduce the prompt pion background, the proton pulse must be narrower (100 ns) and the proton extinction rate (ratio of out-of-time to in-time protons) must be improved by a factor of 10 (to 10^{-11}) over that of Mu2e. Moreover, flexibility on the proton pulse structure is useful to cope with different lifetimes of the targets. PIP-II is expected to have the capability to provide to Mu2e-II the 100 kW beam power required (7.3 kW for Mu2e), as well as a flexible pulse structure and a high intrinsic extinction factor with a bunch-by-bunch "chopper" optic, which is proposed to be studied through a dedicated LDRD project submission to the Laboratory. All these changes are demanding in terms of power consumption and radiation requirements. The radiation delivery on the production target, solenoids and the detector are expected to increase by more than a factor of 10 over that in Mu2e. The expected power density on the very thin production target, required to last 1 year, is considered beyond the current state-of-the-art. A task force on the production target design considering, among others, cooling and material options has been setup by the collaboration and the Laboratory, and is expected to deliver a final report by January 2019. Additional R&D is required on the beam delivery to the production target. A long list of challenges is presented in the Mu2e-II EOI and also discussed in a dedicated impact statement by the Laboratory. Given the significant physics potential, the PAC endorses the continuation of the studies to develop a conceptual design for the new beam line and target. These studies should clarify the relevance of the radiation and radiation safety challenges and provide comparative options for a Mu2e-II realization.

The Mu2e-II proponents are addressing the accelerator, solenoid and target, as well as detector related questions with a set of dedicated workshops, the latest held in December 2017 at ANL and the next being prepared for August 2018 at Northwestern University. The main challenge on the detector side is to reduce the expected decay-in-orbit background to significantly below one event. This has implication on the tracker technology, which should be lower in mass than the present one, while supporting increased doses and charge deposits. The calorimeter will see a net increase of accidental rates by a factor of 3 (and radiation dose by a factor of 10), requiring faster readout schemes. The cosmic ray veto detector will have to fight accidental rates and deterioration of SiPM readout due to irradiation. The trigger and data acquisition system must support higher rates and occupancy while the electronics has to be compliant with higher doses and fluencies. Shielding on the detector has to be improved. The collaboration is actively working on identifying resources to carry out specific detector R&D on these challenges.

The PAC recommends the Mu2e-II proponents to identify the most relevant and urgent R&D items for the detector. The PAC endorses the Mu2e-II request of dedicated R&D funding and encourages them to engage the Laboratory and funding agencies into identifying the required resources.

8. CMS Upgrades and HL-LHC Computing

We ask the PAC to comment on (i) the outcome of, and the responses to, recent reviews, and (ii) prospects and plans for CMS computing in the HL-LHC era.

The PAC learned on the outcome of the recent CD-1 DOE review of the CMS upgrades for the HL-LHC. The review concluded that the Outer Tracker, High Granularity Calorimeter, and Trigger upgrade projects meet or exceed the CD-1 requirements. The novel CMS MIP precision Timing Detector (MTD) project was reviewed and approved enthusiastically by the LHCC in April 2018. The International MTD project management at the time of this review is not yet approved and the USCMS management structure, cost, risk and schedule for the MTD project are yet to be completed to meet the CD-1 approval requirements. **The PAC commends the Laboratory for taking action to strengthen the USCMS upgrade project management office structure by adding a new deputy project manager and considering the support of the project with engineering resources. The PAC congratulates the Laboratory for being granted an Early Career Award in this area. The PAC applauds the Laboratory efforts to facilitate fluid communications with the DOE for the scheduling of the CD-1 completion. The PAC encourages the Laboratory to ensure that the CD-1 review process is completed as soon as possible in order to also meet international deadlines.**

The PAC heard a very clear presentation about the CMS computing plans towards HL-LHC. **The PAC was impressed with the efforts that the Fermilab CMS group has undertaken to understand the challenges and the areas of major concerns as well as creating a plan to address them.** The PAC concurs that it is very important to start the planning and implementation of these strategies now and to not wait until the Technical Design Report which will be only available in 2022. The different planned efforts described cover a wide range of ideas, from more straightforward (consolidating data, centralized data analysis facilities, etc.) to some that will require innovative R&D (machine learning, new algorithm development, etc.). **The PAC appreciates that these efforts need close collaborations between physicists and computational scientists to develop efficient solutions. Based on Fermilab's legacy on scientific computing and its longstanding success and leadership at the LHC, the PAC encourages the Laboratory to continue engaging in strategic planning for the success of computing and software in the HL-LHC era.**

9. Magnet Task Force

We ask the PAC to comment on the conclusions of the Magnet Task Force.

The PAC heard a talk from the High-Field Magnets task force, initiated in September 2017 with the charge to re-consider the high-field (HF) magnet R&D at Fermilab in view of enhancing the research program and improving leverage of existing resources.

Fermilab has a long and successful history of HF magnet developments, including i) the latest successes on quadrupoles for the HL-LHC, fabricated with superconducting niobium tin (Nb3Sn) technology and developed by the U.S. LHC Accelerator Research Program (US-LARP) and CERN and ii) the record superconducting RF acceleration gradient of 49 MV/m achieved for TESLA shape cavities at Fermilab, with potential impact on a future International Linear Collider.

The task force was organized in eight groups covering Nb3Sn and high-temperature superconductor (HTS) conductors and fabrication with emphasis on future high-energy (HE) colliders, other technologies, costing, quenching and instrumentation, and HF magnet design. The Magnet Task Force worked for about six months.

The task force found that:

1. re-orientation of the lab's HF magnet program would be beneficial with overall strengthened research emphasis, faster turnaround of results, and reduced effort on engineering solutions, while maintaining the capability of demonstrating improved performance and cost reduction with accelerator quality magnet;
2. involvement from younger principal investigators and postdocs should be encouraged, and six key areas for the development of HF magnets for a future HE hadron collider were identified;
3. owing to strong in-house expertise, the focus should be on Nb3Sn technology over HTS.

These draft recommendations of the Magnet Task Force have been presented to the Laboratory and the DOE. The task force proposed a program that can be built upon the huge experience available at Fermilab and noted that few people's innovative work can make a large difference in HF magnet research. The task force noted that the magnet group has large responsibilities in operations support and developments for ongoing projects. **The PAC endorses enthusiastically the proposed restructuring and orientation of the HF magnet research and General Accelerator R&D (GARD) program at Fermilab.**

The PAC feels that given the strong worldwide efforts on HF magnet research, there is a risk that the US falls behind and loses established partners. Immediate and focused R&D is required to enable US leadership in the design and fabrication of HF magnets for a future HE hadron collider. The forthcoming update of the European Strategy for particle physics may not yet identify the next European HE collider project, but will likely emphasize the preeminence of strong HF magnet research for prototyping a future HE collider in the mid 2020's. **The PAC feels that Fermilab's confirmed expertise in Nb3Sn magnet technology makes it a natural place for this dedicated research**

effort, following upon a successful completion of the GARD program to achieve an accelerator quality dipole magnet in the range of 15-20 Tesla field strength.

The PAC finds that Fermilab, as the lead HEP lab in the US, is naturally positioned to lead discussions with other international labs worldwide in terms of the future direction and needs for HF magnets. The PAC feels that the separation between management of the US HF magnet program and the Fermilab management is not efficient in terms of strategic direction of the US program and its place in the international HEP effort. The recently successful task force effort on the development of a comprehensive and more research directed Nb3Sn program can seed a model for how the US national program can be laid out. The PAC feels that DOE should consider asking Fermilab to lead, in coordination with the existing LBNL HF magnet leadership, a national planning effort that lays out a comprehensive R&D program including HTS magnets, while also encouraging younger researchers in the field, following the internal Fermilab exercise.

10. Particle Astro-Physics Vision Update

We ask the PAC to comment on the updated vision, prospects, and plans for the Particle-Astrophysics Group at Fermilab.

The PAC heard on the drivers and current status of the Cosmic Frontier (CF) strategic planning activities. With DES entering its last years of analysis, recent turnover in the CF theory program, near-future possibilities for participating in a number of large-scale projects (CMB-S4, DESI, G2 dark matter experiments, LSST and ADMX upgrades), and future planning processes such as Snowmass, P5, and the Decadal Survey, **the PAC appreciates that this is a very good time for Fermilab to develop a new leadership-oriented plan for CF activities that extends well into the next decade.** This program complements the effort at other laboratories and exploits unique capabilities at Fermilab as discussed below.

Fermilab has a widely recognized legacy of unique capabilities and staff expertise that form the basis of the proposed CF plan. This legacy includes the SiDet facility, cryogenic engineering, detector R&D, survey science and operations, project management, and theory expertise. **The PAC anticipates the Laboratory to make judicious decisions and choices in terms of how to best exploit this legacy as the Laboratory plans are further shaped.**

The loss of two senior theorists in the cosmic frontier presents a major challenge. The PAC feels that a strategic and deliberate approach to a search towards identifying replacements aligned with the final priorities of the Vision Plan, is necessary. The PAC feels that **appropriate hires are needed to maintain scientific excellence and visibility of this effort.**

The planning process has been underway for a few months and is covering a wide array of subtopics within the main thrust areas of dark matter, surveys (primarily dark energy), CMB, detector R&D, and theory. The aim is to have an initial draft of the planning document in the Fall of 2018. At the time of the review, the information available to the PAC is insufficient to make specific comments. **The PAC urges the Laboratory to develop a CF program that focuses on a prioritized set of compelling research topics and best leverage the strengths of the Laboratory. The PAC strongly supports the plan to build a stronger integrated Chicagoland approach in the Cosmic Frontier. The Committee encourages the identification of specific scientific areas and projects be called out explicitly in the planning report to ensure that a long-lasting impact is achieved.**

In terms of survey science, Fermilab has built up world-class expertise with major participation in SDSS and DES. LSST is coming online very soon and this knowledge (calibration, validation, data quality assessment, etc.) will be crucial. **The PAC strongly supports the plan to transfer the current DES efforts to LSST as outlined in the presented plan. To maximize the impact of the Laboratory,** the PAC encourages this transition as soon as possible, working closely with already existing efforts within LSST (such as the commissioning task force, cadence planning task force, etc.). LSST, and in particular LSST DESC, provides many important opportunities where Fermilab staff have invaluable experience and can make very important and early contributions before survey data are collected. With the departure of a senior Fermilab theorist, some of these initial efforts on DESC analysis have been reduced; **the PAC notes the continuing opportunity for Fermilab CF staff to make critical contributions and urges this effort be ramped up.** Other future surveys, currently in the planning process, include CMB-S4, future spectroscopic surveys, and 21cm. **The PAC encourages the planning team to decide on the prioritization and appropriate level of engagement in these opportunities.**

A number of technologies developed at Fermilab could be the basis of exciting future experiments. The PAC fully supports continuing development of these activities, especially as there is considerable synergy with broader initiatives in quantum sensing technologies (ADMX-NG, Skipper CCDs).

The Cosmic Neutrino initiative aligns with the global Lab science direction. **The PAC strongly encourages the planning group to take a broad view of neutrino cosmology and astrophysics as they develop ideas for this effort and explore connections with the Laboratory neutrino program and DUNE science priorities.**

11.Theory

We ask the committee to comment on the status and plans of the Theory Group, including the alignment of the groups' activities with the ongoing and future program at the laboratory.

The PAC heard a report on the current status of the Fermilab Theory Group (including the particle-astro/cosmology theorists). The group strives to contribute in areas relevant to the Fermilab experimental program and to conduct world-leading theoretical research in the main thrust areas identified by P5. Priorities include expanding the neutrino theory effort, connecting with the broader experimental activities at Fermilab and the HEP community, and increasing the number of postdocs. **The PAC appreciates the effort made by the Laboratory to realign the theory activities with the**

evolving mission of the Laboratory and commends the continuing efforts to develop a strong program in neutrino physics.

Although the group is large and diverse with a distinguished history of scientific achievement, there have been several recent staff losses due to retirements, transitions to management positions, and other departures. Additionally, like most HEP Theory groups in the US, the base budget has seen a sharp reduction of ~22% over the last three years, which has further compounded the difficulty of sustaining a strong theory program. **The PAC commends the Laboratory management for their strong support of the theory program during this difficult period.** To combat the funding downturn, the group has initiated collaborative programs to increase the number of joint postdocs with universities and other laboratories and has initiated a more vigorous visitor program. The PAC applauds this effort and encourages activities in this direction.

The Laboratory Theory group has a strong presence in BSM, Higgs, and dark sector physics. The PAC concludes that given the stated group science priorities, currently there appear to be staff shortages in the areas of neutrino physics -- especially in topics directly relevant to the Fermilab experimental neutrino program: perturbative QCD, lattice QCD, and cosmic frontier theory. The PAC is concerned about building up the scientific leadership in neutrino physics through the cosmic frontier and the relevant recent loss of two senior theorists in this area. **The Committee encourages the Laboratory theory group to craft a future roadmap that involves non-incremental changes in research directions via a strong recruitment program in the areas mentioned above.**

The PAC feels that there is urgency in addressing the need for theory support in the areas directly connected to the physics program of SBN and DUNE, including hadronic effects in scattering of sub-GeV to a few-GeV neutrinos and implications of the resulting cross section uncertainties for the performance of the relevant experiments. Notably, this subject lies at the intersection of neutrino physics and QCD. Given the high relevance of this research to the experimental program, coordination between the Theory group and the neutrino program is strongly encouraged. An area of high topical relevance is astrophysical neutrinos, with applications to DUNE, and cosmological neutrinos where connections with the FNAL Cosmic Neutrino initiative should be explored. In this context, as the PAC has noted in the recent past, it would be very worthwhile for Fermilab to promote, and help organize, a Basic Research Needs (BRN) workshop to address neutrino scattering topics jointly sponsored by the HEP and NP program offices.

The PAC has identified the need for a significant senior and junior theory recruitment effort in areas of priority of the Laboratory experimental program. Addressing this need, given resource limitations, may take time, and will need to be done in a deliberate and thoughtful fashion in coordination with the Laboratory management.

The PAC commends the Laboratory theorists for their participation in the recent exciting quantum initiatives where theory plays an essential role. The PAC encourages the Laboratory theorists to continue in this direction and maintain communications with the Laboratory management to explore options for additional resources in these areas.

12. LOI: MAGIS-100

We ask the PAC to comment on whether the science goals are compelling, and on the scope and appropriateness of the support requested.

The PAC heard a detailed report covering the MAGIS-100 Letter of Intent for the next-generation MAGIS experiment. The hundred-meter MAGIS-100 experiment is an atom interferometric gradiometer that would be housed in the NuMI shaft, containing three atom sources (top, middle, bottom), associated lasers, and a high-vacuum ~100m pipe. The experiment would function as a pathfinder for a km-scale instrument (which could potentially be hosted at SURF in South Dakota) to measure low-frequency gravitational waves, an exciting and unique opportunity made possible by this technology. Additionally, MAGIS-100 will set limits on low-mass dark matter candidates in a class of scenarios predicting oscillations in a background classical field, exotic new forces, and time-dependence of fundamental constants. It will also function as a demonstrator for long-range quantum superpositions setting strict limits on certain models of intrinsic quantum decoherence.

Given the work already carried out at Stanford (MAGIS-10) and the relative maturity of the proposed strontium-based technology which will be fully tested at Stanford before bringing the experiment to Fermilab, MAGIS-100 represents both an exciting science opportunity that leverages quantum science and technology as well as one that poses a low risk for the Laboratory.

The PAC finds that the request by MAGIS-100 for engineering and drafting resources to develop a full proposal appears reasonable and strongly supports it. The PAC looks forward to receiving a MAGIS-100 proposal in the near future.