Fermilab Physics Advisory Committee Report

18-21 July, 2019

Executive Summary:

The Fermilab Physics Advisory Committee (PAC) met in Chicago on 18-21 July 2019. The meeting comes as a number of important milestones for Fermilab are approached in the context of the 2014 Particle Physics Projection Prioritization Report (P5), “Building for Discovery: Plan for US Particle Physics in the Global Context”. The Committee was impressed with the activities, progress, and planning at FNAL across many areas which are critical to the success of the P5 plan.

The Committee was updated on progress on LBNF/DUNE and PIP-II. For LBNF, the excavation design has been completed, with contracting and pre-excavation work underway. PIP-II, the driver for the most intense neutrino beam in the world and the first accelerator with significant international involvement, had a formal groundbreaking ceremony in March. With agreements on all major international deliverables in place, PIP-II is on-track for baselining and a CD-2/3 review in January.

In the Cosmic Frontier, the Dark Energy Survey completed its sixth year of observations and is aiming to make the most precise measurement of dark energy parameters. World-leading results for two classes of dark matter, axions and sub-GeV particles, were reported from ADMX and SENSEI, respectively. A major approaching milestone is Critical Decision (CD)-0 for the CMB-S4 effort, in which the Laboratory is increasing its activities.

In accelerator and magnet R&D, major developments included a gradient of 50 MV/meter achieved in a superconducting RF (SRF) cavity and 14.1 Tesla magnetic field in a dipole magnet, both new records. Using Nb_3Sn, a critical current (J_c) record was also achieved, exceeding the specifications for the Future Circular Collider (FCC). The development of the new IOTA facility, operated as a partnership with several national laboratories dedicated to Intensity Frontier accelerator R&D, continues to make progress.

Fermilab maintains a strong outreach program. In addition to long-standing programs such as Saturday Morning Physics, it has accumulated more than a quarter million subscribers on its YouTube channel, with over six million views. Fermilab has engaged nearly a hundred thousand members of the public through various events and lecture series. Fermilab is also participating in the VetTech program, which places military veterans into internships. A vigorous program of ensuring inclusivity and respectfulness in the workplace is also in place, with workshops, training, and mentoring of staff at all levels.

With the European Strategy for Particle Physics process underway, and preparations for the next US Snowmass community planning exercise starting, the Laboratory has been actively preparing through its All Scientists Retreats and engaging in both the European and US planning activities. The committee was impressed with the depth and breadth of the engagement of scientists within the Laboratory in its future planning exercises and its presence at the European Strategy process. The committee encourages the Laboratory to continue to ramp up its engagement with the US process.

Fermilab is increasing its activities in quantum information science (QIS) with a new internal organization and a plan to co-lead a proposal for a National Quantum Center. The Committee applauds the wide range of efforts in collaborating with industrial and university partners while maintaining its focus on HEP needs. High-Q SRF cavities are a particularly promising avenue for FNAL engagement in this area.

The Committee heard a report from the FNAL Chief Information Officer regarding the vision and strategy for scientific computing. Among the key challenges for the Laboratory and the US community as a whole is the transition to exploiting Exascale computing facilities. While a few success cases exist, Fermilab is expanding efforts and aiming for leadership in data management and storage, access to heterogeneous computing, core software development and R&D, data acquisition, and artificial intelligence and machine learning. The Laboratory is also revamping its committee structure with the new Fermilab Computing Resource Scrutiny Group to replace the existing SCPMT to address local resource prioritization issues and to complement the International Computing Advisory Committee (ICAC), which addresses high-level strategic and planning issues. We encourage the Laboratory to expedite this transition, which will enhance the ability of the Laboratory to proactively assist and manage the computing needs of its program.

MicroBooNE recently became the longest operating Liquid Argon Time Projection Chamber (LArTPC) in a neutrino experiment, accumulating 3.8×10^{20} protons-on-target in FY2019. The collaboration has recently released important neutrino cross sections and continues to pioneer technical and analysis developments for LArTPCs. The Committee was presented with results from a new major software release (MCC9), which incorporates significant improvements in detector modeling and event reconstruction. The experiment will continue to take data in FY20 to accumulate more data with its cosmic ray tagger. Guidelines for evaluating further data requests were discussed.

The Committee heard a report on the SBN detectors (SBND and ICARUS) and the SBN organization. ICARUS is on track to start cryogenic operation by the end of October, while SBND is scheduled to install its LArTPC in early 2020. The SBN Oversight Board recently reached an agreement on a “Statement of Principles for Data Sharing, Analyzing, and Publication within the SBN program”. A multi-institutional memorandum of understanding between Fermilab, funding agencies, and universities providing resources to build SBN, a prototype for similar agreements for DUNE, is now under review at DOE.

The EMPHATIC collaboration proposed a program of hadron-nucleus scattering measurements at the Fermilab Test Beam Facility to improve neutrino flux predictions. With contributions and collaborators from Canada, Japan and the US, the experiment can have substantial impact on the world accelerator-based neutrino program. Results from a 2017 test run were presented, and the program will result in measurements complementary to those made at large aperture experiments like NA61/SHINE. The Committee recommends Stage 1 approval for EMPHATIC.

The FNAL g-2 experiment has made rapid progress, accumulating more than two times the data sample of the BNL experiment in its March-June 2019 run showing substantial progress on all fronts, with a well-performing storage ring and detector despite some residual technical difficulties. Extensive investigations on calibrations to reduce systematics, including a new absolute field calibration method, were presented to the Committee. Analysis methods,

including blinding techniques, are well-developed. The Committee looks forward to the first results from the experiment towards the end of this year.

The Committee heard an update on CMS activities at FNAL. As the lead lab for the US-CMS, FNAL has had a critical role in the successful Run 2 operations of the experiment and its prodigious physics output, as well as the Phase-I upgrades. The Committee was impressed with the progress on the Phase-2 upgrades, which are now on track for completing a CD-1 review in October. Challenges in the computing effort were reported, where software must adapt to function on high performance computing platforms. The Committee applauds Fermilab's leadership in this area but is concerned about the urgent timing and resources needed for a successful transition. Persistent budget pressures have resulted in continuing reduction of personnel in the CMS group, as well as scaling back of the highly successful and impactful Distinguished Researchers program at the LHC Physics Center hosted by Fermilab.

The Committee thanks the speakers for their clear and informative presentations. In addition to presentations specifically addressing the charge to the Committee, we are grateful for additional presentations from Petra Merkel (Strategy and Vision of detector R&D at the Laboratory), Josh Frieman (Report on the CMB-S4 and SuperCDMS Experiment and on the Cosmic Physics Center), Peter Shanahan (Report on the NOvA experiment), Andy Lankford (Report from the ILC Committee), and Hugh Montgomery (Report from LBNC), as well as materials received offline from the MINERvA collaboration, the SCRF-DM effort, and the MAGIS-100 collaboration.

We also express our appreciation to the FNAL Directorate and the Scientific Secretary for the effective organization of the meeting.

The Physics Advisory Committee:

Present: Ayana Arce, Florencia Canelli, Alexander Friedland, Ines Gil-Botella, André de Gouvea, Francis Halzen, Andreas Hoecker, Kevin McFarland, Stefano Miscetti, Hugh Montgomery, Kate Scholberg, Christoph Simon, Hirohisa Tanaka

Regrets: Elena Aprile, Alex Szalay

Scientific Secretary: Anadi Canepa

Directorate: Hema Ramamoorthi

Report on Fermilab Plans and Roles in the Community Strategic Planning: *We ask the committee to review Fermilab's role and contributions to the European Strategy Planning and to the U.S. Strategy Planning.*

Findings/Observations:
The Committee heard an informative overview of Fermilab's activities in the European and US planning processes. Fermilab was effectively represented at the Open Symposium for the European Particle Physics Strategy in Granada, with five Fermilab contributors to the editorial team of the US community submission organized by DPF, five other submissions from Fermilab-led endeavors, and one Fermilab member of the Physics Preparatory Group. The Laboratory's planning for Snowmass includes activities leading up to and following the annual retreat organized by the Fermilab Scientist Advisory Council (SAC). Fermilab is also considering contributing white papers on the Laboratory's capabilities and future and could enhance these efforts through options such as supporting Snowmass studies through LDRD awards. The PAC encourages Fermilab to continue to strengthen these early planning efforts for Snowmass.

Summary of the All Scientists Retreat: *We ask the committee to review the process and outcome of the 'All Scientists Retreat' and to assess whether progress towards the integration in the Laboratory's Strategic Planning is being made.*

Findings/Observations:
The Committee was presented with an update on the vibrant activities of the Scientific Advisory Council (SAC), which organized the third of a series of retreats to discuss the future of the laboratory science program. The All Scientists Retreat was organized into physics working groups (cosmic, energy frontier, neutrino, and precision science) and technology working groups (quantum science, accelerators, computational science, and detectors). The 2019 retreat was preceded by a survey of the scientific interests and aspirations of the laboratory scientific staff, to ensure that the retreat would be representative of these views, as well as regular meetings of the working groups.
The results of the poll and subsequent retreat discussions include strong support by the lab community for investment in accelerator R&D and interest in investigating a future collider or precision neutrino experiment at Fermilab, as well as endorsement of the newly developed strategies of the Cosmic Frontier program, Computing Division and Quantum Working Groups. The retreat's mandate included the planned continuation of discussions beyond the summary session, with a specific focus on using these discussions as a springboard for Fermilab contributions to the Snowmass community planning process. The SAC proposed that its next retreat be a pre-Snowmass activity which would be open to the community beyond Fermilab. The SAC and the Integrated Program Planning Management (IPPM), which organizes the Laboratory's strategic planning, have some overlap in membership and have had several meetings over the course of the calendar year, signaling that channels of communication are open between these groups as they fulfill their very distinct missions.

The PAC welcomes the improved communication between SAC and IPPM. The PAC received very interesting information on the interests of the Fermilab community and looks forward to the results of future discussions. The PAC also welcomes the initiative of the SAC in planning to take a leading role in the organization of the Snowmass-focused workshop.

Recommendations:

- The PAC recommends that the Laboratory consider organizing a timely workshop dedicated to Snowmass to which the HEP community is invited, as proposed by the SAC.

Report on the QIS program: *We ask the committee to review the progress made towards the implementation of the vision presented at the January 2019 PAC meeting.*

Findings

The PAC learned about plans to enhance the already flourishing QIS effort at Fermilab, including a new internal organization to be put into place by October 1, and a plan to co-lead a proposal for a National Quantum Center.

We received an update on the promising quantum sensing activities using high-Q Superconducting RF (SRF) cavities. We commend the lab for the ongoing efforts to leverage these cavities for the purposes of quantum sensing to address important HEP questions. The Laboratory is engaging external partners and making investments in this area, including a second test stand and a strategic quantum hire. We heard about interesting ongoing efforts in quantum communication (FQNET), including engagement with AT&T and university partners. The Laboratory's activity on QIS-related theory, which include exploring potential applications of quantum computing to HEP questions, has resulted in publications and connects with industry partners such as Google. Finally, we learned about interesting efforts on cryogenic electronics, including a recent workshop.

Fermilab's quantum strategy is to focus on HEP needs, but also to leverage its unique capabilities. The lab's recent initiatives on QIS are consistent with this strategy.

Comments and Recommendations:

- The PAC supports the plan to put in place a new internal organization, which is very timely, as well as the plan to pursue co-leadership of a National Quantum Center.
- The high-Q SRF cavities are an area where Fermilab has an outstanding materials capability. We encourage the Laboratory to also explore their applications in the context of quantum communication and quantum networks, where the cavities could, for example, be uniquely useful for quantum memory applications. It would be natural to look for connections between the SRF cavity and FQNET efforts and to explore international partnerships.
- We encourage Fermilab to continue pursuing the quantum-computing related theory efforts, which have the potential to be disruptive for HEP in the longer term.

- We also encourage the lab to pursue the cryogenic electronics efforts in alignment with lab priorities.

Vision and Strategy for Computing: *We ask the committee to review the vision and strategy of the Scientific Computing program at Fermilab, including plans for migrating HEP computing to HP architecture. The committee is asked to assess the role of Fermilab in S&C R&D and experiments' operations in both the U.S. and the international context. The committee will review the newly introduced committee structure and assess its effectiveness.*

Findings

The Committee heard a report on the extensive vision and strategy for computing at Fermilab from the Chief Information Officer (CIO), Elizabeth Sexton-Kennedy. In the past, software development did not need to be prioritized, and policies were driven by hardware improvements. However, times have changed, and it is now necessary to develop new software tuned to exploit changing hardware architecture. In particular, power-efficient High-Performance Computing (HPC) is becoming increasingly important for computing in HEP, along with High Throughput Computing (HTC) applications. New algorithms need to be developed for Exascale machines. Some experiments are already using HPC; an example is NOvA which has used HEPCloud to do analysis on NERSC. There are complex needs requiring development of a national cyber-infrastructure, including Fermilab, but going beyond.

Fermilab experiments are in general not ready for Exascale DOE facilities. CMS is further along in its preparations than DUNE but will have increased computing needs sooner than DUNE will.

Fermilab has plans to engage ASCR more deeply. There has already been success doing this with SciDAC. Currently the Laboratory is putting together a Center for Computing Excellence (CCE) proposal with three other labs (ANL, BNL, LBL). They are also cooperating with NSF's Institute for Research and Innovation in Software for High Energy Physics (IRIS-HEP).

Drivers and opportunities for software and computing R&D were identified as: needs for CMS in the HL-LHC era and DUNE, new HPC opportunities, new machine intelligence applications for HEP reconstruction and analysis, and response to specific funding calls.

Fermilab aims for leadership in several areas: data management and storage, access to heterogeneous computing, core software development, scientific software R&D, HEP Artificial Intelligence/Machine Learning R&D, and DAQ integration. The Laboratory also aims to maintain its role as a center for physics analysis. For all of these areas, specific initiatives are underway.

There are two committees overseeing FNAL Computing activities. First, the International Computing Advisory Committee (ICAC, new since March 2019) addresses high-level strategic, programmatic, and planning issues, rather than specific implementation details. The longer-standing and more local SCPMT provides input to this committee and addresses local resource prioritization issues. The Laboratory plans to transition the SCPMT to a different committee, "Fermilab Computing Resource Scrutiny Group (FCRSG)". However, this new committee has not yet been formed. Both ICAC and SCPMT committees met and made recommendations in early 2019.

Workforce development is an area of interest. Experimental collaborators often do not have sufficient training. Fermilab Computing already engages in educational workshops.

There has been a recent reorganization of the Office of the Chief Information Officer, Scientific Computing Division (SCD), and USCMS S&C, removing a layer of management and elevating cross-cutting projects.

Fermilab is developing several community tools, with the aim of preparing for HPC and Exascale computing with DUNE as a primary target. These include the development of neutrino event generators, LArSoft, and vectorized and GPU-enabled Geant4 (GeantV).

Many other R&D efforts are underway and have not yet been prioritized.

Comments

Fermilab Computing is generally successful in providing for the needs of users of Fermilab experiments. We especially commend them for their role in MicroBooNE's recent software improvements. While in some cases interactive work with experimental collaborations has been highly successful, in other cases, earlier intervention could have prevented issues. We agree with the recognition that proactive work with experiments is important to fully optimize computing operations. Frequent interactions with scientists and user education activities are very important. Preparation for DUNE computing needs will be especially important; given that DUNE computing support is not "on project", some support by computing professionals must come from within the Laboratory.

The PAC supports the general strategy to move towards HPC computing and we believe SCD is well aware of the challenges. We agree that preparing DUNE for the Exascale era should be of high priority. In the shorter term, the Laboratory will still have conventional computing needs.

The CCE endeavor will be valuable for Fermilab's impact in a national context.

The PAC was asked to review the newly-introduced committee structure. The ICAC had a first meeting leading to a set of recommendations. The proposed FCRSG to replace the SCPMT has not yet been formed. It is too early to assess the effectiveness of the new structure, although we agree with the recent ICAC and SCPMT recommendations. The creation of the FCRSG seems appropriate in order to improve the interface between computing and scientists.

In general, the list of high priority technology strategies and the activities in each category seem to be reasonable and appropriate areas for Fermilab leadership. Some of the R&D activities are valuable for the international community, such as the development of neutrino event generators and LArSoft, which is important for the neutrino community, and the development of GPU-enabled Geant4, which will be of value to the broader HEP community.

Recommendations:

- We recommend that the Laboratory complete the transition to the new computing advisory committee structure. For the next PAC meeting, we would like detailed information on how the Laboratory has followed up on the recommendations of both ICAC and SCPMT/FCRSG committees.

- We encourage the Laboratory to continue to enhance proactive interactions with experiments to clarify their computing needs before problems arise. We recommend developing a new computing request template. We would like information on new procedures, with SBN and g-2 as test cases, for the next PAC meeting, as well as Fermilab's plan for supporting DUNE computing development.
- We recommend that the Laboratory facilitate inter-collaboration information transfer about successful computing efforts and other lessons learned (*e.g.,* via workshops). We encourage continued education and workforce development efforts.
- We recommend a prioritization of software development R&D efforts, and that the Laboratory consider focusing resources on the highest priority efforts.
- We encourage the Laboratory's initiatives to engage ASCR.
- We recommend that the Laboratory clarify with DOE what the appropriate relative resource allocation between HPC and conventional computing should be for the near future.

Report on the MicroBooNE Experiment: *We ask the committee to review the short-term analysis plans for collaboration over the next year, as well as its plans beyond this time scale, particularly in regard to the low energy excess analyses.*

Findings/Comments

The Committee was pleased to hear that MicroBooNE accumulated data equivalent to 3.8×10^{20} protons-on-target (POT) during FY19 and continues to operate well. It is the longest running LAr TPC for a neutrino experiment. Over the last several years the collaboration has learned invaluable lessons on liquid argon purity, drift high voltage, scintillation light, and the stability of cold electronics. The PAC congratulates MicroBooNE on these pioneering technical achievements.

The MicroBooNE collaboration presented the progress on low-level and high-level reconstruction that is encapsulated in its recent "MCC9" software release. Improvements to low-level reconstruction and simulation are coupled with improvements in the processing infrastructure. The latter significantly reduce the file size necessary for the high-level reconstruction. Early indications are that this release will significantly improve the reconstruction and agreement between reconstruction and simulation. The collaboration is not yet ready to estimate the impact of MCC9 samples on purities, efficiencies and systematic uncertainties for the low energy excess analysis or for cross-section analyses.

With MCC9, MicroBooNE estimates processing time, including needed simulations, for the full dataset to be about nine months, while reprocessing it through the high-level reconstruction chain, if necessary, would take about a month. MicroBooNE aims to have sufficient data and simulation processed to analyze the entire dataset by the end of the year.

MicroBooNE has continued to make progress in completing one of its core missions: the development of low- and high-level analysis techniques for liquid argon TPCs. Lessons learned

from MicroBooNE impact the entire liquid argon program, including ProtoDUNE, SBN, and DUNE.

With the previous software release (MCC8), MicroBooNE has completed several end-to-end cross-section analyses using a subset of their data. We congratulate the collaboration on publishing studies of charged track multiplicity and neutral pion production. MicroBooNE submitted the first measurement of the inclusive charged-current differential cross-section on argon for publication in Physical Review Letters. A number of preliminary cross section studies have been made available as public notes. In the future, the full MCC9 datasets are expected to result in significantly improved statistical and systematic uncertainties for all cross-section studies.

MicroBooNE is projected to run during FY20. During this period, it is estimated that it will increase its dataset with the cosmic ray tagger from ~$6x10^{20}$ POT to ~$10x10^{20}$ POT.

Recommendations

- MicroBooNE stated that it may request an extension to run through FY21 once its "signature results" are available to guide this decision. Such a request should be accompanied by comprehensive and quantitative sensitivity assessments for the signature low-energy-excess and highest priority non-oscillation analyses. The Neutrino Division and the Computing Sector should also assess the impact of extended MicroBooNE running on the rest of the program, particularly the SNB program and DUNE. The collaboration should evaluate any impact of extra running on its ability to publish its highest priority analyses. Without this information, the PAC cannot evaluate any request for additional running.
- In preparation for the successful completion of the experiment, we recommend that MicroBooNE begin discussions with the Computing Sector, the Neutrino Division, and the funding agencies that support their researchers, to plan for continued support to complete high-priority analyses in a timely way with the full datasets.

Report on the SBN Program: *We ask the review committee to assess the progress made towards establishing the SBN collaborative program and the development of the physics program.*

Findings and observations

The Committee was pleased to hear about the steady progress on the SBN detectors, ICARUS and SBND, including key milestones and details on the technical progress. These include the completion of the ICARUS installation and first tests of the components. The top Cosmic Ray Taggers (CRT) are being finished and the side CRTs will be installed by fall 2019. Plans are to start the ICARUS cryo plant activation by end of September 2019 and the activation, commissioning, and calibration of the T600 detectors by November 2019. The ICARUS intermediate milestones were achieved according to the schedule. There is a four month delay

to start the ICARUS LAr filling due to the commitments of the CERN cryogenics group with the ProtoDUNE-DP filling, which is happening now.

The different components of the SBND TPC are nearing completion, including the anode planes, cathode frame, reflective foils assembly, electronics production, and light system. Regarding SBND cryogenics, the warm cryostat fabrication has been completed at CERN. However, the cold cryostat is in the initial phase of material ordering. The PAC looks forward to the construction of the SBND cold vessel and the TPC installation by early 2020 to be able to optimally pursue the SBN physics program.

The Committee was very pleased to hear of the additional funding for SBN from DOE that allowed the collaborations to proceed with critical procurements for both far and near detectors.

Updates regarding the SBN organization were presented. An agreement on a "Statement of Principles for Data Sharing, Analyzing, and Publication within the SBN Program" was reached in March 2019 by the SBN Oversight Board (SBN-OB). This board is now considering SBN shared operations and the role of MicroBooNE in the SBN program.

The SBN Institutional Board (SBN-IB) is formed by the representatives of each institution participating in the SBN program. The SBN-IB will define a set of rules and procedures based on the principles agreed by the SBN-OB.

The multi-institutional Memorandum of Understanding between Fermilab and the funding agencies, institutions and universities providing the resources to build the SBN program is still in draft form under DOE review. The PAC is looking forward to the progress on the document. This will lead the way for future DUNE agreements.

A Transition to Operations team was created with the goal of having an Operational Readiness Review for phase 1 (Far Detector only) in early February 2020. A phase 2 including both far and near detectors will be organized once SBND is ready. An Experiment Operations Plan is developed and reviewed.

Recommendations:

- The PAC encourages both ICARUS and SBND to continue coordinating efforts through the SBN Joint Working Groups towards the development of the physics program and to be prepared for the early data from the ICARUS detector. We also encourage SBN to refine the relations between its governance bodies (e.g. Institutional Board) and the corresponding bodies within SNBD and ICARUS.
- The PAC would like to hear about the status of the SBN Data Management WG and interactions with SCD for the next PAC meeting.
- The PAC is looking forward to hearing at the next PAC meeting updated information on the progress on realistic background and systematics estimations by the SBN Joint Working Groups and implementation of common reconstruction and analysis tools in preparation for the data exploitation.

Report on the EMPHATIC Experiment: ***We ask the review committee to consider the scientific merit and appropriateness of the new initiative.***

Findings/Observations

The EMPHATIC collaboration presented its proposal and is currently requesting Stage 1 approval. EMPHATIC proposes a series of short runs at the Fermilab Test Beam Facility (FTBF) to measure low energy hadron reactions on thin nuclear targets that are poorly measured in current data and relevant for neutrino flux simulations. EMPHATIC presented the impact of their proposed program on the NuMI flux uncertainties, and the improvements are significant. EMPHATIC is also expected to reduce hadron production uncertainties in the neutrino flux prediction for DUNE and for T2K/Hyper-K.

EMPHATIC's detector is compact and relatively modest in cost. The EMPHATIC approach is complementary to large aperture detectors such as NA61/SHINE, in that it improves measurements in specific and limited kinematics but is not capable of measurements on large "replica" targets as planned at NA61. Both thin target measurements like those made by EMPHATIC and replica target measurements are needed for improving precision on neutrino flux predictions.

EMPHATIC has significant international participation, and portions of the detector are being supplied by collaborators from Japan and Canada. Collaborators plan to apply these results to current and future neutrino beams at FNAL and J-PARC. EMPHATIC would be a global collaboration that contributes to the entirety of the worldwide accelerator neutrino program. EMPHATIC has already demonstrated successful assembly of a subset of the detector, with contributions from Japan, Canada, and FNAL, and analysis of data from FTBF in a 2017 test run.

Recommendations:

EMPHATIC will make important measurements with modest resources. The global interest in and participation in the collaboration is strong. ***We recommend stage-1 approval.***

Report on the g-2 Experiment: *The committee is asked to review the results from the analysis of the data collected so far and whether the experiment is on track to achieve the expected sensitivity.*

The Committee was presented with a comprehensive update on the FNAL g-2 experiment, which has the ambitious aim of improving precision on the muon anomalous moment by a factor four (to 140 parts per billion (ppb)) relative to the previous experiment at BNL (E821) by a large increase in the data sample (x21) and a significant reduction of the systematic uncertainties. The longstanding and stable discrepancy of more than 3σ between the measured and theoretically predicted values of the muon g–2 remains one of the most intriguing tensions in particle physics. The status of the theoretical uncertainties are being assessed by the Muon g–2 Theory Initiative Working Group in anticipation of the experimental results.

After a pilot run in July 2017, the experiment has collected data in two dedicated physics runs: Run-1, from March to July 2018 for a raw data sample of 1.9 times the BNL data sample ("x BNL"), and Run-2, from March to July 2019 for a raw data sample of 2.2 x BNL. Of these, 1.4 (2018) and 1.8 x BNL (2019) can be exploited for physics analysis with a projected statistical yield of 410 ppb and 350 ppb, respectively.

Since the Run-1 data were collected under varying storage ring conditions, the fits are split into four separate run periods. The analysis target is to achieve O(200) ppb systematic uncertainty (BNL: 280 ppb) and 410 ppb statistical uncertainty. Run-2 achieved much improved stability, although it was impacted by a large delay in startup due to kicker magnet issues, as well as planned interruptions along its path. When stably running, the experiment collected 1 x BNL statistics every 25 days. Systematic uncertainties for this second run are expected to be lower than in Run-1.

Since its startup, the experiment has shown substantial progress on all fronts, with a well-performing storage ring and detector. The higher-level technical issues during Run-1 were: the presence of rare quenches and beam losses, the kickers being unable to reach full voltage leading to non-optimal beam orbits, and the loss of control of the hall temperature affecting the calorimeter SiPM gains and magnetic field tracking. All of these issues were improved between Run-1 and Run-2, with the exception of the seasonal temperature variations. An increase of the HVAC system is under completion while thermal blankets were added to the storage ring to reduce diurnal variations.

A new challenge arose due to a failure of the second lithium lens, which focuses the pions downstream of the target, with only one good lens remaining and three spares which were already used at the Tevatron. Although the lenses are run at reduced current relative to the Tevatron, the average temperature is higher (102º C vs. 62º C) due to the increased repetition rate. The first (second) lens failed after 30 million (130M) pulses, while 500M pulses are required to reach the experiment's design statistics. The gradient of the lens has been reduced by 15% to decrease the heating (and, equivalently, the muon flux) by 30%.

The collaboration discussed a preliminary blind analysis of the Run-1 data. The muon anomalous magnetic moment, a_μ, is extracted from the measured ratio of the muon precession frequency at the magic momentum (3.09 GeV) and the magnetic field, averaged along the muon profile. The magnetic field is monitored along the storage ring and running time. A first monitoring is carried out by 400 fixed NMR field probes positioned in the ring. An NMR trolley traverses the ring when beam is off for a survey typically every 2–3 days. Absolute calibration is achieved with three different methods: the historical (BNL) H_20 probe, a newly developed cylindrical probe, and a ^{3}He probe developed as a new standard. The muon distribution is measured with two straw tracker stations inside the storage ring. For the Run-1 analysis, the current (preliminary) estimate of the systematic uncertainties on the magnetic field is of O(150 ppb). The cross calibration among the different absolute-scale methods shows a spread well within the assigned systematic errors.

The precession frequency is obtained with a fit to the high energy positron counting rate versus muon lifetime distribution ("wiggle plot"). The calorimeter data are corrected by gain fluctuations

relying on a laser system that was not present at BNL. Six analysis teams are independently evaluating the precession frequency by fitting the wiggle plot, relying on different reconstruction algorithms and fitting methods. The data have been double-blinded: the real clock frequency is not known by the experiment and a random generated frequency offset is added for each analysis group. Statistical uncertainties are of O(450 ppb) as expected. To verify the precession analyses, a practice run was carried out by removing the relative offsets for one of the four data sample. All reconstruction methods align well within the (correlated) statistical errors. Strategies for combining the results are being developed.

The PAC congratulates the experiment for the high-quality work done on the data taking, the improvements achieved for Run-2, and the analysis, and looks forward to see the result from the Run-1 data, anticipated to be ready by the end of CY2019. A statistical projection for the complete data taking was also presented. Based on the last three months of Run-2 running, a rate of 1xBNL per month was achieved. Run-3 in FY20 and Run-4 in FY21, each with six months duration, will allow to reach 18–20 times the BNL statistics and avoid conflict with the upcoming Mu2e construction and commissioning. The experiment anticipates the following milestones for a_μ: a second publication using 3 x BNL data and improved systematic uncertainties for beginning of CY2021, a third publication with 10 x BNL for middle of CY2022, and a final publication with the entire sample and final systematic uncertainties in the following calendar year.

Observations

- Although being re-designed and replaced at the end of Run-1, the kickers are still a delicate component of the experiment and are still being operated at a reduced voltage (by 8 kV) in the latter part of Run-2. Nevertheless, it is very encouraging that good stability has been reached over the last 3 months of Run-2. The impact of the kickers on the analysis has been anticipated to be very small but should be better quantified.

Recommendations

- Concerning the lithium lens, the PAC suggests taking into consideration the possible insertion of the inflector magnet before the begin of Run-3 to recover the reduced muon flux. Technical risks, muon flux gains, and impact on schedule with respect to Mu2e have to be carefully considered.
- The PAC recommends the experiment to make a solid plan with SCD for evaluating (and organising) the resources needed for data storage and reconstruction of the upcoming production runs.

Report on the CMS Experiment: *The committee is asked to review the status of the Physics Program, Operations, and Phase 2 Upgrade.*

Findings and Comments:

The PAC heard a report on the status of the CMS experiment and the impressive array of activities within FNAL and US-CMS. CMS successfully completed Run-2 data taking with excellent efficiency and data quality, allowing the experiment to collect a record integrated luminosity of 137/fb. CMS continues its outstanding record of high-quality physics publications, with analyses now shifting to exploiting the full Run-2 dataset. The experiment is currently in a two-year technical stop maintaining and refurbishing parts of the detector (including the faulty Pixel DC/DC converters), completing the Phase-I detector upgrade, and already preparing for the large-scale Phase-II (HL-LHC) upgrade. Run-3, scheduled to begin in 2021, is expected to at least double the current dataset at higher center-of-mass energy.

The PAC congratulates Fermilab's CMS group, US-CMS, and the International CMS Collaboration for the highly successful conclusion of Run-2 operations, the exceptionally proficient physics output, and the timely completion of the Phase-I upgrade.

DOE and NSF HEP-supported scientists constitute almost 30% of the CMS scientific authors, and 17 US and 7 Fermilab physicists are members of the CMS management board. Fermilab, as the US lead laboratory, has crucial responsibility for the experiment. It manages the US CMS operations program and upgrade projects and hosts and operates the LHC Physics Center (LPC) and Remote CMS Operations Center.

Fermilab contributed significantly to the successful completion of the Phase-I upgrade, and is strongly involved in the HL-LHC upgrade of the CMS detector with core deliverables for the Outer Tracker, High Granularity Endcap Calorimeter (HGCAL), Endcap MIP Timing Detector (MTD), and the Trigger and Data Acquisition (TDAQ) systems, taking advantage of unique on-site infrastructure at Fermilab. A strengthened management team and improved schedule and cost estimates allowed Fermilab's CMS group to successfully pass the Director's Review in May 2019, with a goal to complete CD-1 review in October 2019. Work on prototyping, production and quality control setups, and scheduling is ongoing to prepare for CD-2 review in November 2020. There is good progress on all deliverables. Strengthened personnel and a simplified design have helped mitigate problems with the critical HGCAL data concentrator ASIC (ECON), for which a first prototype is now expected for July 2020. A prototype of the Endcap MTD timing layer readout chip (ETROC-0) has been received in March 2019 with promising test results so far.

The PAC is encouraged by progress on the Phase-II upgrades towards completing CD-1 in October 2019, including the MTD TDR approval by the LHCC and the positive Director's Review. The ECON ASIC design simplification appears an excellent step towards risk reduction and the consolidation of the HGCAL schedule. The PAC congratulates Fermilab for the progress made by allocating additional electronics engineering resources to the project, offering crucial engineering support where global resources are scarce.

Fermilab has a long record of carrying leading roles in almost all aspects of CMS software and computing. The Fermilab Tier-1 center is by far the largest and most reliable CMS computing resource outside CERN, representing about 40% of the CMS Tier-1 capacity and delivering a significant part of the CMS production and analysis activity. It also enables CMS to access High-Performance Computing centers (HPC) through Fermilab's HEPCloud routing system. Because of procurement delays in the replacement of end-of-life equipment there is, however, a severe

risk of future shortfalls in capacity and reliability of the Tier-1 center with respect to the WLCG commitments, with immediate negative repercussions on the CMS science output.

Fermilab plays a key role in the development and support of the CMS event processing framework, core software services, workflow, and data management. It is central to CMS HL-LHC computing developments that are needed to cope with the anticipated large data rates. An interim HL-LHC computing report is being prepared for 2020, followed by a TDR in 2022. Fermilab scientists contribute, in collaboration with the wider community such as NSF's IRIS-HEP initiative, to the development of detector simulation (*e.g.*, GeantV), storage-effective data formats (eg, Nano-AOD), a fast analysis framework (*e.g.*, Coffea), and machine learning solutions to data reconstruction that optimally exploit modern HPC architectures.

The PAC commends Fermilab for its effective use of laboratory expertise in CMS and the SCD for the development of critical cutting-edge software and computing solutions in preparation of Run-3 and the HL-LHC, which are in line with upcoming computing architectures. The PAC is looking forward to the interim HL-LHC computing strategy document to be issued in 2020.

The desire by the US funding agencies to prompt experiments towards enhanced use of HPC and accelerator technologies is to be carefully balanced against the software engineering resources and time needed for the required developments, as well as the specifics of the I/O-heavy data reconstruction and analysis workflows of CMS. It also needs to consider the international context and the strategies of other HEP funding agencies.

Fermilab scientists contribute significantly to exploiting physics opportunities provided by the CMS data in most of the relevant areas. Fermilab's expertise in software and machine learning (ML) allows the group to develop advanced analysis tools, such as the reconstruction of hadronic decays of strongly boosted Higgs bosons and of Higgs decays to charm quarks. In collaboration with Fermilab's theory department, the group develops prospects for physics in Run-3.

The CMS group at Fermilab succeeds in attracting outstanding postdocs who benefit from the Research Associate Mentoring Program at Fermilab and who achieve an excellent record of early career awards and other recognitions. A large fraction (62%) of research associates succeed in obtaining tenure-track positions in the field.

Continuing budgetary pressure on the group leads to a reduction in the group's personnel including research associates from 46.5 FTE in FY18 to expected 42 FTE in FY20. A recent new hire and a team addition strengthen the Phase-II upgrade, and a further hire is expected on ML/AI software developments.

Fermilab's LPC, including its Distinguished Researchers (DR) program, is a unique asset to the Fermilab and CMS physics communities, as well as to the upgrade, software and computing activities. It has transformed the way CMS educates young students and postdocs through schools and hands-on tutorials, thus impacting the CMS scientific output and strengthening the US-CMS collaboration. It leverages the Laboratory's resources, amplifies opportunities for its members, strengthens exchange and collaboration, and enhances Fermilab's visibility and reputation among young researchers both in the US and at CERN. The success of the LPC stimulated similar initiatives at Fermilab in the neutrino and cosmic frontier fields. **The PAC is**

concerned that the recent constraints in the research budget leading to a reduction by 50% of the DR program may severely limit the functioning and success of the LPC.

Recommendations

- We recommend the Laboratory in coordination with DOE, support CMS/LHC in their request for recruiting new personnel dedicated to supporting the HL-LHC and HPC software and computing developments, as well as continuing to support research associates.
- Given the crucial importance of the Tier-1 computing resources for the CMS physics program, the PAC endorses the request for replacement of end-of-life equipment as soon as possible given budgetary constraints. For the longer term, we recommend the development of a computing transition plan in line with DOE's strategic priorities, its international partners, the needs of the experiment, and the timeline and resources needed for the required software developments.
- We recommend the Laboratory maintain the LPC at a successfully functioning level with a long-term perspective.

APPENDIX

The Committee heard several additional presentations and received materials offline on other topics. While it was not specifically charged with providing recommendations on these topics, we include our observations for each presentation below.

Report on the CMB-S4 and SuperCDMS Experiment and on the Cosmic Physics Center

Findings/Observations

The Committee heard an informative update from Josh Frieman on activities related to the Cosmic Strategic Plan at Fermilab, following up on the long-term strategy presented at the last meeting. In accordance with this plan, the Laboratory is growing Cosmic Microwave Background (CMB) activities. It currently has lead operations roles in South Pole Telescope and is positioning itself to play major roles in CMB-S4, the next-generation CMB experiment, leveraging relevant technical capabilities leadership roles in the interim CMB-S4 project organization, and connections with ANL and University of Chicago collaborators. We encourage the Laboratory to continue to develop their involvement as CMB-S4 evolves.

Dark matter detection activities are being consolidated. FNAL is the lead laboratory for the ADMX axion search experiment and is developing quantum sensors for a next-generation axion experiment. In WIMP detection, efforts on LZ are being discontinued while involvement continues on SuperCDMS-SNOLAB, where the Laboratory has a longstanding and deep involvement. Fermilab is also hosting NEXUS, an underground test facility in the MINOS near detector hall for SuperCDMS detector response calibration. NEXUS can potentially serve as a detector calibration facility for the broader community, and also hosts a dark matter search with prototype single-charge sensitive detectors (HVeV). Skipper-CCD development is a new R&D avenue for next generation sub-GeV WIMP experiments. There are in addition a few minor efforts (accelerator-based dark matter and DarkSide/LAr) not supported by Cosmic Frontier research.

In the cosmic survey area, the Laboratory is transitioning from DES to LSST, with a small role in DESI, while the theory program has a growing focus on cosmic neutrinos.

The Cosmic Frontier Center, built on the successful LHC Physics Center example, is "soft-launching" this year, with plans to host visitors, seminars and targeted workshops to enable collaboration. The aim is to expand the efforts in the future.

The Laboratory has secured a number of leadership roles, and overall, the Cosmic Frontier efforts are demonstrating a healthy balance. In the future, we look forward to hearing about further progress including potential strategies for taking a leading role in a major future cosmic frontier effort.

Report from the ILC Committee

Findings/Observations

The PAC greatly appreciated the informative talk on the ILC International Working Group from Andy Lankford and the process by which the international scientific community will advise

Japan's relevant ministry, MEXT, on the ILC organizational structure. The PAC is encouraged to see that Fermilab (as the lead US-HEP laboratory) is following this process carefully, as it is relevant to the FNAL/KEK-led program of addressing SRF system cost reduction.

Strategy and Vision of detector R&D at the laboratory

Findings/Observations

The PAC heard a detailed presentation from Petra Merkel, the FNAL Detector R&D coordinator. The Committee was impressed with the breadth of the detector R&D activities, which are guided by the P5 physics goals and the Coordinating Panel for Advanced Detectors (CPAD) “Grand Challenges” and coordinated via the Detector Advisory Group, consisting of about 15 experts on various detector technologies. The Laboratory maintains several common detector facilities to support a wide range of detector technologies (e.g. silicon detectors, metrology, scintillator development, thin films, etc.), as well as the ASIC development and test beam (FTBF) facilities. The productivity of the program is evidenced by the nearly 50 publications within the last year and a half resulting from all sectors of the program.

The R&D effort is coordinating with the Fermilab Scientific Advisory Council in its strategic planning exercises in preparing for detector needs and R&D directions for 2026 and beyond. Due to its leading role in US particle physics, the R&D effort at Fermilab is essential in ensuring the future success of the particle physics program across all the frontiers and the Committee congratulates the tremendous success of the program. In future planning, the Committee suggests clarifying how priorities are established across different projects, including how they interface with the overall R&D efforts within an experiment, and how such projects transition from general R&D to dedicated efforts supported directly by the experiment.

Report from the LBNC

Findings/Observations

The PAC thanks chair Hugh Montgomery for his report on the Long Baseline Neutrino Committee (LBNC), whose main purpose is to oversee the international DUNE experiment.

ProtoDUNE-SP continues to provide more analysis demonstrations and has established a strong basis for the success of the DUNE experiment. The Dual-Phase program has made enormous progress, with ProtoDUNE-DP is being filled with LAr and scheduled to take first data in late summer.

There has been significant progress in establishing the DUNE Computing Consortium, and short-term resource needs have been met. However, the path to secure sufficient support for dedicated professional effort is not yet established.

A review by the Near Detector subcommittee was carried out in June 2019. The review committee considers that the proposed movable liquid argon TPCs and MPD, when combined with the DUNE-PRISM technique and a suitable on-axis beam monitor, will allow DUNE to reach its physics goals.

The LBNC review of the DUNE Technical Design Report (TDR) is progressing well. Five TDR volumes are being prepared by the DUNE collaboration: executive summary, physics, far detector single phase, far detector dual phase, and technical coordination. LBNC is having intensive interactions with DUNE and most of the TDR chapters are in good shape. A schedule to review updated documents has been established.

Report on NOvA

Findings/Observations

The PAC commends the NOvA collaboration for the continued delivery of competitive results on the determination of the neutrino oscillation parameters, including new results obtained using the additional data taken this year. In FY2019, the far detector achieved operational efficiency of 99.1% with 5.56×10^{20} protons-on-target delivered to the experiment. A 756 kW hourly beam power record has been achieved. We look forward to the results for Neutrino 2020 with higher statistics and the improved analysis techniques presented to the Committee.

NOvA's primary competition is T2K for CP violation, mass ordering, and θ_{23} octant observables. Given the anticipated beam delivery through 2024, NOvA's sensitivity should exceed T2K's in determining the mass ordering, although it may be less sensitive to CP violation with the advertised T2K beam power plan. Planned analysis improvements and reductions in systematic uncertainties will enhance NOvA's physics reach.

The Committee heard about the progress on constructing and commissioning the test beam experiment, and articles on neutral current production of neutral pions (submitted to *Physical Review D*) and charged-current production (in collaboration review).

The PAC is pleased to hear of the plan to share the current best GENIE tune and reiterates its strong support for the timely public release of this information, which will be valuable to the community-wide effort to improve cross section modeling. We welcome the coordination of cross section tuning with the MINERVA, and strongly support the continued meetings discussing analysis challenges with the T2K collaboration. A timely joint analysis with T2K is an important opportunity to significantly expand the physics impact of both experiments.

Report on MINERvA

Findings/Observations

We received a written report on the status of MINERvA, which concluded operations in February of 2019 with over 3×10^{21} POT of data collected. The efforts of the collaboration are now focused on analyzing its complete data set. We commend the collaboration for its smooth transition to data-analysis-only mode, clear publication plan, and careful evaluation of the computing resources needed. We urge the laboratory to provide the computing and the personnel

resources necessary to guarantee the successful analysis of MINERvA's complete data set in a timely fashion. MINERvA data continues to have strong impact on the current neutrino oscillation program and will play a key role in the interpretation of data from future neutrino experiments and our understanding of neutrino-nucleus interactions. We encourage the collaboration to consider ways to maximize the impact and visibility of its upcoming results at major scientific venues such as Neutrino 2020.

Report on the SRF-DM Experiment

The PAC thanks the SRF-DM effort for its status update, and congratulates the group for its rapid progress, particularly in Run 0 and achieving first scientific results. We look forward to future updates, particularly in relation to the overall QIS efforts at the Laboratory.

Report on the MAGIS-100 Experiment

The Committee thanks the MAGIS-100 collaboration for its letter updating us on its funding status. We look forward to hearing an update from the collaboration at the next meeting.
