Fermilab Physics Advisory Committee Report

16-18 January, 2019

Executive Summary:

The Physics Advisory Committee (PAC) met at Fermilab on 16-18 January, 2019 to review the status of the laboratory in a period of important programmatic and strategic developments in the international particle physics community. The Committee noted progress on the execution of the ongoing program and was briefed on planning exercises to evaluate and set the thematic and strategic directions for the laboratory. The laboratory continues to strongly leverage its core strengths and capabilities and align with the Particle Physics Project Prioritization Panel (P5) report: "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context", while also effectively responding to the strategic DOE/HEP-QIS initiatives in multiple areas connecting fundamental HEP research with advancements in quantum engineering and fundamental quantum science.

The Committee was thoroughly impressed and congratulates the Laboratory for the success of the recent remarkable run of **ProtoDUNE-SP** at the CERN Neutrino Platform, which followed an aggressive schedule. This represents a major milestone in validating the single phase design for the DUNE far detector and the DUNE effort overall. The Committee also heard an update from the **LBNC** that provides oversight for DUNE, including those aspects of LBNF which directly impact the experiment. The last review in December, 2018 included progress in the dual phase design, the near detector concept, and the computing model. A phased review of the Technical Design Report was also put in place with the goal of finalizing the document in July.

The Committee was presented with updates on the status of **SBN (SBND and ICARUS)**, including the successful outcome of the Director's Review in December 2018, and the formation and activities of several SBN-wide physics analysis, trigger and technical groups. The Committee encourages the Laboratory to continue emphasizing the importance of further developing these joint activities towards a coherent SBN technical operations and physics analysis framework and keeping the program on schedule, **both of which are essential to the success of the SBN program**.

Fermilab continues to be the anchor for the US-CMS effort, which is the largest national group in the collaboration, and also for the **CMS HL-LHC Upgrades.** The committee commends the continued role of the Laboratory and the US-CMS groups in the prodigious physics output from the experiment and its response in strengthening the organization following the HL-LHC CMS Upgrade review, leading to the successful resolution of the related Technical Review toward CD1 and PEMP Notable Outcome for the novel MIP Timing Detector in December 2018. The PAC encourages the Laboratory to continue supporting the Upgrade Management team and ensuring seamless communications with the relevant DOE counterparts towards a successful CD1 in June 2019. The committee views the continued vitality of the FNAL CMS group as essential to sustaining the US-CMS effort through this critical time.

The Committee commends the Laboratory for the **Accelerator Complex** remarkable performance, with beam deliveries close to, and at times exceeding, design for all parts of the program (BNB, Muon, NuMI, Test Beam) in FY18. The PIP-1+ program to reach 900 kW delivery to NuMI was presented. The Committee is looking forward to the March 15 PIP-II groundbreaking. This 700-foot-long, state-of-the-art machine is the first U.S. particle accelerator to be built with major international contributions. It will be the new heart of the Fermilab particle accelerator complex. The Committee is impressed with the **Fermilab Test Beam Facility (FTBF)** that supports approximately 200 users per year across a broad swath of the world high energy and nuclear physics community. The facility has an excellent track record and is responding to a recent review to further optimize its operations by unifying DAQ, slow control, and trigger support. It is also preparing for the long shutdown at CERN, when the demand for the facility will be particularly acute and critical. These include plans for an irradiation test facility promptly needed for HL-LHC and further useful for the nuclear and neutrino physics communities at large. The Committee heard a report on **EMPHATIC**, a new test bean experiment (T-1396) and collaboration of FNAL with Canadian and Japanese Institutions. The experiment aims to perform precise hadron scattering measurements relevant for reducing flux and cross section uncertainties in accelerator-based neutrino beams and atmospheric neutrinos. Following an engineering run in 2018, which studied proton-carbon scattering, a spectrometer is under development to allow a full suite of hadron-nucleus scattering studies.

The Committee commends the Laboratory on the **IOTA physics and accelerator technology program. IOTA** is a dedicated accelerator R&D test facility with nearly 30 collaborating institutions. The ring has been constructed and operated with the FAST electron injector, with the proton injector now being completed. The program includes a number of studies aimed at improving accelerator performance, including nonlinear optics, optical stochastic cooling, and electron lenses. The ability to store a single electron in the ring was recently demonstrated, attracting considerable interest also from the quantum science community.

The Committee congratulates the Laboratory for formulating the vision and strategy for the laboratory's **Cosmic Frontier** program. A draft document regarding the Cosmic Frontier strategy was presented to the Committee, which calls for consolidation of dark matter efforts and growth of the CMB program, with explicit plans in response to different budget scenarios. Likewise the Laboratory **Quantum Science** strategy presented to Committee aligns well with the Laboratory's strengths and core capabilities and leverages effective partnerships and collaborations. The Committee was presented with a proposal from the **MAGIS-100** collaboration to build a 100 meter-scale atomic interferometer in the NuMI shaft to search for certain classes of dark matter particles and to demonstrate mid-band gravitation wave sensitivity. The committee was impressed by the successful demonstration at Stanford of a 10 meter interferometer and the proposed physics program and recommends Stage 1 approval for the project that has also received Moore Foundation funding in 2018.

The Committee also heard presentations on a dark sector search using SRF cavities, which exploit the extraordinarily high Q-values in these cavities to probe dark photon couplings (**SRF-based Dark Matter Search)**. This is an example of a unique accelerator- sourced core competency of the lab that connects with the Quantum Science effort and investigation of dark sectors. The Committee is enthusiastic about this thrust of research and looks forward to seeing the progress

and the formulation of a related proposal for such a program in the Summer 2019 PAC meeting. Other feasibility studies for a beam-based dark matter search, such as **LDMX**, were presented.

The committee commends the Laboratory for the **Scientist Advisory Council and Strategic Planning Workshops**, which engage the Fermilab community in discussions on future directions and annual planning for the laboratory. The Committee heard on the status of the European Strategy Planning process, currently under way, that includes several submissions related to the Fermilab program. The next step of the process is an open symposium at Granada in May 2019.

In executive session, the PAC heard a report on the **ASIC group at Fermilab** that provides critical support for various ASIC efforts and projects, including DUNE and CMS. The group has responded to increased project demand with a new hire and partnerships with ASIC groups at other institutions to form effective collaborations in pushing these projects to completion while supporting new R&D efforts. The committee commends these efforts and notes the importance for Fermilab to maintain this world-class capability and explore enhancements through partnerships with universities.

The committee heard a presentation from the new Chief Information Office on the status and future challenges of computing in the field. The Laboratory has been working on a strategic computing plan that includes HPC capacity (through the HEPCloud and elasticity models developed at Fermilab) and interfaces with DOE Exascale computing efforts. The Committee is looking forward to hearing the developed Fermilab Computing strategic plan in terms of both core and scientific computing for the HL-LHC, SBN and DUNE programs in the Summer PAC meeting.

The Committee thanks all the speakers for their highly informative presentations, and the Scientific Secretary and Directorate for their excellent organization of the meeting.

The next PAC meeting will be held 18-21 July, 2019 in Chicago.

The Physics Advisory Committee:
Ayana Arce, Florencia Canelli, Alexander Friedland, Andre de Gouvea, Inés Gil-Botella, Francis Halzen, Katrin Heitmann, Andreas Hoecker, Kevin McFarland, Stefano Miscetti, Hugh Montgomery (LBNC), Kate Scholberg, Christoph Simon (remote), Maria Spiropulu (chair), Hirohisa Tanaka (chair-elect)

Regrets : Elena Aprile, Alex Szalay

Scientific Secretary: Anadi Canepa
Fermilab Directorate: Hema Ramamoorthi

ProtoDUNE: *We ask the committee to review the status of the experiment, preliminary results from the recent data taking period, plans for the (post-)shutdown program and to comment on remaining technical challenges to be addressed including the feasibility of the 600kV dual phase demonstrator.*

The PAC applauds the DUNE collaboration for finishing the construction and commissioning of the ProtoDUNE-SP detector within a tight timeframe. Built in two-and-a-half years, from excavation of the pit to data taking, ProtoDUNE-SP represents a major validation of the feasibility and performance of the DUNE far detector technology. Information on the detector performance and on the measured energy and momentum resolution is being contributed to the DUNE TDR. Lessons learned in electronics and cryostat technology have already been incorporated into the design of the SBND detector.

ProtoDUNE-SP has exceeded a number of important technical specifications, including those for the electronics noise and electron lifetime. All but ~50 of the 15,360 TPC channels are fully functioning. ProtoDUNE-SP also quickly reached the design field for DUNE of 500 V/cm. The 6 ms electron lifetime that was achieved made high-quality beam data collection in the entire volume possible, and the event displays are a convincing demonstration of the data quality.

Significant steps have been taken in the validation of the ionization and tracking performance, even in the presence of the challenging cosmic ray rate and space-charge effects associated with operation on the surface. Data collected at ProtoDUNE-SP reveals that an existing model significantly underpredicts the amount of space charge; work to understand the source of this discrepancy and to improve the model is underway. This will allow accurate tracking and dE/dx measurements. This study should also be beneficial for future surface liquid argon time projection chambers (LArTPCs).
Work has also begun on evaluating the performance of the three light system prototypes installed in ProtoDUNE-SP. First results on energy reconstruction from the light signal that were shown to the committee look promising. The committee looks forward to final results comparing all three systems.

Every early indication is that ProtoDUNE-SP has physics quality samples that can be used to study the calorimetric response to positrons, pions, and protons, and exclusive reactions for pions and protons, in an energy range relevant for understanding the LArTPC detector response. These results would validate or improve the simulations of the energy resolution of DUNE. ProtoDUNE-SP represents the first test-beam calibration data for a LArTPC large enough to contain the charged particles produced by multi-GeV hadrons. **The committee strongly encourages the DUNE collaboration to organize the resources necessary to carry out a timely analysis of this data aimed at these measurements.**

Continued running of ProtoDUNE-SP with cosmic rays to demonstrate long-term stability and to further study detector performance will be important. Plans for this run have been presented to the PAC, which include studies to understand the limiting factors on electron lifetime, to investigate the origin of observed high voltage instabilities, and to collect data on fluid and space-charge dynamics. Similar operation of ProtoDUNE-DP will also be valuable to demonstrate the feasibility of the dual phase technology. The collaboration has requested additional beam running of both detectors in 2021-22. A strong physics and technical case will be required to secure approval and to justify the resources required to mount such a major effort. A list of goals for this run has been presented to the PAC. These include calibration with a neutron generator, incorporation of the final DUNE photo-detection system, and the addition of the planned light enhancement system.

ProtoDUNE-SP has operated at the design 500V/cm field over a 3.6m drift length. Several options are being evaluated to achieve the necessary technology demonstrations of electron lifetime and purity, high voltage, and detector performance with these long drifts in the next several years. Some of these, such as tests of HV feedthroughs and cables for 600kV, are already underway. An end-to-end test stand demonstrating 500 V/cm over a 12m drift would be a significant new effort. **The committee encourages DUNE to move forward swiftly to finalize the plan for these studies.**

Report on the High-Level Organization of the SBN Program: *We ask the committee to comment on the progress and success of the SBN program in all areas: organization, joint analysis groups efforts (trigger/calibration/software/analysis), installation/commissioning, deliverables and goals, etc.*

The committee heard a progress report on the status of the ICARUS and SBND experiments. Together they define the SBN program. Detailed updates regarding the SBN organization, including the joint analysis effort between the two experimental collaborations, and other related activities were presented. The PAC is impressed with the excellent technical progress of SBN detectors construction and installation. The Committee also congratulates SBN for the fast and significant progress on the organization of SBN since the last PAC meeting, and on the efforts to build a fruitful collaborative program. **The PAC encourages both ICARUS and SBND to continue pursuing these efforts in order to guarantee that optimal physics results from SBN can be extracted timely, effectively and efficiently.**

The PAC heard the positive comments and recommendations of the last Director's Progress Review, which took place in December of 2018. The committee is also pleased to learn that key SBN multi-institutional MOUs have been drafted and are being iterated, addressing the recommendation stated in the last PAC report.

The SBN Physics Program is expected to definitely address the short-baseline anomalies observed in the LSND and MiniBooNE experiments. While the sensitivity of the SBN program is traditionally quantified in the context of the fourth-neutrino interpretation of the short baseline anomalies, SBN is also well positioned to address most other possible new physics interpretations of the short baseline anomalies, as long as the new physics is broadly related to neutrino properties or neutrino sources. Definitively addressing the short-baseline anomalies is a high priority for particle physics in general and for neutrino physics in particular. In the context of the overall Fermilab neutrino program, the optimal time-window of opportunity to the SBN Program is well defined. **Potential delays to the start of the SBN program will negatively impact its ability to optimally pursue its physics program.** The SBN report highlighted two potential sources of delay, both of which were also flagged by the the last Director's Progress Review: the possible late arrival of requested extra funds in FY19 for key procurements for SBND, and the absence of a definitive agreement among DOE, CERN, and INFN regarding the details of the final design of the SBND cryostat. **Both of these issues need to be addressed promptly.**

Report on the SBN Analysis Groups*: We ask the committee to comment on the progress and success of the SBN program in all areas: organization, joint analysis groups efforts (trigger/calibration/software/analysis), installation/commissioning, deliverables and goals, etc.*

The PAC commends SBN for the organization of joint working groups in analysis, DAQ, slow control. cosmic taggers and offline computing to develop key aspects for SBN operation and physics analysis. We heard a detailed presentation from the SBN Analysis Groups. The Committee is pleased with the efforts to develop an analysis group with an internal organizational structure responsible for the multi-detector oscillation analysis at SBN, including common simulation, reconstruction and analysis methods and tools. We appreciate the concrete and detailed simulation and analysis milestones for the next two years. These will serve to clearly demonstrate the success in coordinating the analysis effort between ICARUS and SBND. **The PAC looks forward to the first deliverables, including, in March of 2019, the reproduction of the sensitivity of the appearance and disappearance oscillation channels reported in the SBN proposal, and,**

in the Summer of 2019, the first reassessment of the same sensitivities using more realistic estimates of backgrounds and systematics.

CMS HL-LHC Upgrades: *We ask the committee to comment on the status of the CMS HL-LHC Upgrade and on the outcome of the PEMP Notable.*

The PAC heard a report on the status of the CMS High-Luminosity LHC (HL-LHC) upgrade. In the framework of the Update of the European Strategy for Particle Physics, the LHC collaborations have completed a broad reassessment of the HL-LHC physics reach building on the experience of the Run 2 physics analyses. The projected reach in terms of precision measurements of the Higgs boson couplings has improved over previous studies for both CMS and ATLAS, offering potential for percent-level combined measurements of Higgs-boson to electroweak-boson coupling strengths, a few percent precision for the Higgs-boson to top-quark coupling, and strong reaches in searches for new weakly coupled particles. The PAC congratulates the Fermilab CMS group and the collaboration for the high-profile and profuse physics output during 2018 that continues to exceed expectations. Recent highlights were the observation of Higgs boson interactions with third generation fermions. The CERN accelerator complex just entered a two-year technical stop. CMS is on schedule towards completion of its Phase I upgrade work for Run 3 during the stop.

The US CMS effort is by far the largest national group in CMS, and Fermilab as the US lead laboratory has crucial responsibility for the experiment. The High-Luminosity phase of the LHC commences data taking in 2026 and poses an unprecedented experimental challenge to the LHC experiments and accelerator complex. Pileup rates of up to 200 must be controlled, defining the conditions for the significant upgrade of the detectors. In preparation of this upgrade, CMS has produced four Technical Design Reports (TDR), one interim TDR and one Technical Proposal, which have been approved by the LHC Committee (LHCC) and the CERN Research Board. Fermilab has core deliverables for the upgrades of the CMS Outer Tracker, the High Granularity Endcap Calorimeter (HGCAL), Endcap MIP Timing Detector (MTD), and the Trigger and Data Acquisition systems, taking advantage of unique on-site infrastructure such as the silicon detector lab, scintillator fabrication facility and test beam, as well as expertise in ASIC engineering. In particular, CMS plans to start using the new and unique Irradiation Test Area at MTEST in April 2019 to validate sensors for the Outer Tracker. **The availability of this facility is critical to meet the CMS testing and qualification schedule.** Fermilab also carries a central role in developing the software and computing framework for the HL-LHC.

Most of the HL-LHC upgrade projects are advancing well and within schedule. The two concentrator ASICs (ECONs) of the HGCAL are delayed due to insufficient expert availability. Fermilab is mitigating the problem by injecting new engineering effort. A first partial prototype of the chip is now expected for August 2019. **Given the crucial importance of the ECON ASICs for the success of the HGCAL, and other ASIC deliverables, we recommend that the Laboratory considers some reinforcement of its ASIC group to avoid risks.** Following the other upgrade projects, the MTD, a novel ultra-precise timing detector for pileup mitigation in both barrel and endcaps, is now working towards the TDR and CD-1 review. The PAC commends Fermilab for strengthening the MTD project office and organization per recommendations of the last PAC report. The MTD was also the subject of a Fermilab performance evaluation and measurement plan (PEMP) notable, which was successfully concluded end of 2018.

The CMS experiment, as the leading Fermilab energy-frontier project for the years to come, has a first-class and world leading physics program building on the outstanding and reliable performance of the LHC and its High-Luminosity upgrade. Fermilab's pivotal roles in the HL-LHC CMS detector upgrades and other areas of CMS require continuing strong support from the laboratory. The Fermilab CMS group has lost key

people because of career evolution and retirements. Without replacement, the laboratory may lose the ability to execute succession planning for its leadership in the HL-LHC upgrades as well as software and computing, posing a threat to the delivery of committed projects to CMS.

Vision and Strategy of Cosmic Program: *We ask the committee to review the vision and strategy of the Cosmic program at Fermilab and to comment on how it integrates into the US program. The committee is asked to comment on the progress on the recommendations provided at the July 2018 PAC meeting and on the summary of the DOE December 2018 Meeting (including the Strategy Document) and the B&R report at HEPAP.*

The PAC applauds the Laboratory for its leading role in the US HEP Cosmic Frontier (CF) science program and reaffirms the need for Fermilab to continue their leadership and investment in CF. We congratulate Fermilab on reaching some very important science milestones, including finishing DES observing and a successful start of the SPT-3G survey.

We commend the Laboratory for the CF program's detailed, sensible, and well-considered long-term plan presented to the Committee. The program is well balanced and addresses important areas in the Cosmic Frontier: dark matter, cosmic surveys, CMB, and theory. The Fermilab planning panel made prioritization decisions to focus and consolidate the program (e.g., 21 cm planning was dropped and LZ will be phased out). The dark matter program has been and will be further concentrated to a smaller number of efforts. In the overall CF plan, each area (DM, CMB, cosmic surveys, theory) now has contributions from several FTEs, ensuring that Fermilab can have major impact in these areas and continue its leading role in the field. Three projects have been identified for potential major lead roles for Fermilab: CMB-S4, ADMX, and a possible Stage V experiment in the 2030+ era.

The plan included different budget scenarios that emphasized the focus on CMB-S4 and the axion program with ADMX in case of budget reductions. In this case, the survey science contributions would be reduced. The PAC affirms that in a declining budget scenario it will be important to further focus the program, instead of cutting down all areas equally. The choices made were discussed with the Fermilab researchers, ensuring that the workforce is prepared and behind a possible shift in focus. The PAC took note of the Fermilab plan to be the lead lab for a potential Stage V experiment in the future (2030+ time frame). Discussions about this possible Stage V experiment and roadmap planning exercises have started in the community and Fermilab should continue to play an important role in this. However, the personnel reduction in survey science in the least favorable budget scenarios would make this option challenging. If the community plan after CMB-S4 shifts to surveys, Fermilab should be in a position to assume a leading role.

The plan presented includes potential growth areas (e.g., CMB-S4, QIS dark matter investigation, a Cosmic Physics Center). The PAC looks forward to further development of these projects and the R&D projects that would lead to the Stage V experiment mentioned above. These are extremely important to prepare projects in the 2030+ timeframe.

The PAC strongly encourages Fermilab to develop a detailed implementation strategy of the plan presented and notes that the growth plan in the CMB area could become challenging in the current funding climate - therefore a very disciplined implementation plan is needed.

While the astrophysics theory group was not explicitly discussed in the plan (which focused on the CF research program) its connections to the overall program are important. The theory effort should be well aligned with the overall CF program and new hires should be very carefully considered to strengthen the program and to ensure that they fit well with the overall CF plan. As an example, during the last summer

PAC meeting, the area of cosmic neutrino physics was highlighted as an important piece of the CF plan. The PAC encourages the Laboratory to follow up on this plan.

The PAC strongly supports the Laboratory's plan to forge even stronger connections of the Fermilab programs in Chicagoland, including Argonne, UChicago, and UIUC/NCSA. Given current funding constraints in the US HEP Cosmic Frontier program, close collaborations between the institutions are very beneficial and positively impact the field overall. The PAC encourages the Laboratory to develop targeted strategies to reach this goal, e.g., joint hires at the postdoc or staff level might provide a strong move in that direction.

The PAC is excited about the idea to build a Cosmic Physics Center and is looking forward to a plan for building such a center and identifying its resources needs. We understand that there will be different phases for building up the center and it would be important to understand the scope of the different phases and their timelines. The PAC urges the Laboratory to establish the first phase in the very near future. Fermilab has a very good track record with centers of this nature in the other two frontiers so the extension to the CF would be very natural.

Finally, as part of the planning process, it is important at every step to ensure that the CF effort fits well into the overall lab strategy. Several of the components of the program are prime examples of this and provide a clear case for why a strong CF program at Fermilab is essential for the CF overall.

Overall, the PAC commends the vision for the CF program at Fermilab, which shows a balanced plan with efforts in important areas as well as smaller efforts that are seeding future projects. This approach is reasonable and poised to lead to success. A careful implementation strategy needs to be developed to ensure full success of the new CF plan. The PAC strongly encourages the Laboratory to continue to build strong Chicagoland connections. Finally, the PAC is excited about the Cosmic Physics Center idea and is looking forward to following the implementation of a first phase of such a center.

Report on MAGIS-100 Proposal: *We ask the committee to consider the proposal for MAGIS-100 (PROPOSAL: P-1101):*

a) Is the science in the proposal interesting and/or compelling?

The science described in the proposal is interesting and compelling. As already stated in a previous PAC report, MAGIS-100 presents an exciting science opportunity. It develops sophisticated quantum science and technology and applies it to dark matter searches. It also prepares the ground for a next-generation experiment that will be a competitive mid-band gravitational wave detector.

b) Is the technique proposed appropriate for, and likely to be capable of, reaching the physics goals of the experiment?

The technique proposed is appropriate and likely capable of reaching its physics goals. The team has demonstrated that they have the expertise to conduct this type of experiment. The proposed experiment builds on an existing (10 meter scale) experiment at Stanford. The present experiment will use a different atomic species (strontium), but the associated technology is fairly mature. The experiment is the next important step in developing this technology to enable gravitational wave detection. New bounds will be delivered for some classes of dark matter candidates (ultralight dark matter fields). The experiment will help to build new capabilities in quantum information science which are broadly of interest to HEP.

c) What is the competition for reaching the physics goals of the proposed experiment? Does the proposed experiment have particular advantages or disadvantages relative to the competition?

There are other dark-matter experiments based on atomic clocks and on torsion pendula, but they are either less sensitive or less advanced. Regarding gravitational wave detection with atom interferometers, there is the MIGA project in France, which uses a complementary technique. There is also a similar project in the UK (AION), which has yet to operate a 10 meter scale prototype.

d) What is needed to make such an experiment successful?

A significant amount of funding is already in place thanks to the Moore Foundation and the partner institutions. The team is planning a supplementary DOE request in the upcoming quantum science competition. The PAC supports this plan.

Based on the compelling science and technical development program, we recommend Stage 1 approval for MAGIS.

Vision and Strategy of QIS at Fermilab: *We ask the committee to review the vision and strategy for QIS at Fermilab and to comment on how the QIS program supports the laboratory's HEP mission, leverages on and expands its core capabilities*

The vision for QIS at Fermilab is based on supporting the laboratory's core mission and leveraging its core capabilities. There are already compelling examples where this is being pursued, such as the SRF cavities being used for dark matter detection, where the sensitivity can be enhanced using quantum science methods, and the use of atomic interferometry for dark matter detection and, in the longer term, gravitational wave detection. These efforts address the core HEP science mission. There are also interesting efforts in QIS that leverage the unique capabilities at FNAL, such as using the expertise in SRF to develop quantum memories and quantum processors. **We encourage the lab to maintain this focus on its core mission and core capabilities in selecting programs to pursue in QIS.**

The lab has been successful at finding partners at universities and other national labs who bring critical complementary expertise to these projects. The capacity of the lab to compete in this rapidly developing area (e.g. in the context of the upcoming call for national quantum centers) would nevertheless be strengthened by hiring a number of staff members whose core expertise is quantum science and technology. One hire is already in course on the theory side, the PAC would support similar initiatives on the experimental side. In keeping with the above vision, these hires should be carefully targeted to expand core capabilities of the lab and to support its core mission.

The QIS effort is new and a number of interesting projects are getting started, with the possibility for strong growth given DOE's strong support. **The PAC looks forward to following the progress of the QIS program at Fermilab.**

SRF-based search for Dark Matter: *We ask the committee to comment on the science scope of the SRF based DM search experiment.*

The PAC heard a joint theory-experiment presentation about a proposed search for very light new particles. The particles in question are traditionally known in the literature as WISPs (Weakly Interacting Slim Particles), of which axions and extra U(1) gauge bosons are classic examples. Such particles have been

discussed over the last four decades in many scenarios of physics beyond the Standard Model. It has been argued, for example, that they are ubiquitous in many string-based models.

It was realized early on [Okun (1982), Anselm (1985)] that WISPs could be looked for using the technique of "light shining through walls", in which WISPs could be produced from an intense photon source, traverse an opaque region, and convert back into photons on the other side. It was further observed in the early 1990's that having high-quality resonant cavities would significantly improve the sensitivity of this method [Hoogeveen (1992)].

The presentation to the PAC from the Fermilab group made an important observation that its SRF cavities, with their unprecedented quality factors, could represent a unique opportunity to push the sensitivity of these classic searches to a new level. It appears that the experiments could be set up and conducted on a relatively fast time scale and in a very cost-effective manner.

This is an interesting research program that makes good use of the existing strong expertise on SRF cavities and should have significant synergy with the ongoing quantum efforts. The group is energetic and excited about the project. **The PAC encourages the team to explore this direction further and requests a roadmap for specific measurements that were discussed, including resource needs and scientific reaches of different approaches.**

Physics program at LDMX: *We ask the committee to comment on physics reach of LDMX and to review the potential role of Fermilab.*

The PAC heard a presentation regarding the LDMX and LDMX-M3 initiatives, aimed at looking for light (sub-GeV), weakly-coupled new particles that are either stable or decay invisibly, ingredients that are often encountered in models for thermal light dark matter. These experiments use an electron/muon beam experiment (for LDMX/LDMX-M3) to search for these particles using the missing momentum technique. One of the advantages of the missing momentum technique, relative to traditional beam-dump searches for dark-sector particles, is the fact that it is sensitive to the (small) effective new physics coupling squared, as opposed to other methods where the coupling is quartic.

The LDMX proposal is relatively more advanced, and a proto-collaboration, with contributions from members of Fermilab, was discussed. Potential beamlines at JLab, SLAC, and CERN are being explored. LDMX-M3, on the other hand, would make use of muon beams that are well-suited for the Fermilab Accelerator Complex. The sensitivity of LDMX-M3 would partially complement that of LDMX and, more importantly, would allow one to test interesting light-new-particle solutions to the discrepant muon g-2 anomaly. In order to evaluate the appropriate level of FNAL involvement in LDMX(M3), the PAC needs more detailed information regarding LDMX(M3.) The Committee notes that more simulation studies would be needed to understand the muon beam capabilities. Given the overlap in physics goals, FNAL's role in LDMX(M3) should be considered in the context of the recently developed vision for its Cosmic Frontier program.

Scientific program at IOTA: *We ask committee to comment on the physics program at IOTA.*

The PAC heard a presentation on the Physics Program of the IOTA (Integrable Optics Test Accelerator) storage ring. IOTA is a compact (40 meter -circumference) ring aimed to host *"dedicated*

beam experiments", both with electrons and protons, to study frontier topics in beam physics and to pave the road towards next generation high intensity machines, such as PIP-III. Open topics, of particular interest for the laboratory, are that of limiting beam losses and instabilities in high intensity, high brightness beams, and improving beam cooling in next generation colliders. The advantage of IOTA with respect to other machine R&D resides in the high efficiency of carrying out proof-of-principle experiments in a dedicated environment. Nowadays, as recognized by the latest GARD review, *IOTA together with its FAST injector, constitutes the top rank facility for intensity frontier accelerator R&D.* The FAST injector for electrons has met its design goal and has been commissioned to its full design energy of 300 MeV with a world record beam acceleration of 31.5 MV/m in the summer of 2018. The electron beam was successfully delivered to the IOTA ring for the first time on August 21, 2018, and the ring was commissioned with electrons of 47 and 100 MeV. The proton injector at 2.5 MeV is planned to be installed in FY20, at which point the proton science program will begin. The PAC commends the Laboratory for the great achievement of the IOTA/FAST team, and for the successful start of its Physics Study program.

Relevant examples on the near-term priority electron-based research items for Accelerator Science in IOTA were presented. The first flagship item is the exploration of IOTA Non-Linear Integrable Optics (NIO) with specially designed Octopole String (OS) and Non-Linear magnets (NLM). By comparing the expected tune spread figure of merit of OS (NLM) beams with that of the LHC beam, an improvement of 25 (250) is achieved. The usage of NIO optics could therefore reduce chaos in single particle motion and collective instability to generate a large cost saving for producing brighter beams. The phase one study with electrons is underway. The second item shown was the relevance of Optical Stochastic Cooling (OSC) that extends the principle of beam stochastic cooling in the optical bandwidth. This allows a factor 10^3 increase in the cooling rate with respect to the standard method. The OSC CDR is under completion and proof of principle without optical amplification is expected for the middle of FY 2019. This first step will be followed by a test with an active OSC in FY 2022. The use of an electron lens as a versatile research tool in IOTA was also presented.

IOTA has also unique capability in Quantum Science. A demonstration of Single Relativistic Electron storage for a long period of time (10 minutes) has been achieved and monitored by observation of SR emission. The storage of single electrons is now obtained in a controlled and reproducible way. A successful workshop was held for the development of Single-Electron experiments in IOTA that can test fundamental principles of Quantum Science. The PAC recognizes the high relevance and the large panorama of the proposed beam and quantum physics studies. This is well demonstrated by the large number of PhD students already participating in this first phase of the IOTA program.

Report on the accelerator complex: *We ask the committee to review the status of the accelerator complex, current plans for PIP-I+, AIP, Nova, g-2 and to comment on the outcome of the AAC meeting.*

The PAC heard a comprehensive report of the accelerator complex and of its priorities for FY2018-2019. The stability achieved by the FNAL accelerator complex, which allows science programs to run without interruptions even while the accelerator performance is pushed to new limits, is key to Fermilab's role as a world-leading facility. Indeed, in FY2018, the accelerator performance was excellent, consistently exceeding the base goals and approaching or achieving the design goals for beam delivery including:

- 5.7×10^{20} protons to NuMI with stable operations at > 700 kW;
- 3.2×10^{20} protons to BNB;
- 5.5×10^{19} protons to g-2, allowing the experiment to double the statistics of the BNL experiment;
- Beam was also delivered with good efficiency to the FTBF area, excepting a few interruptions due to failures of the MI septa or magnets.

Due to the late restart of the g-2 experiment, NuMI and BNB received a larger number of protons at the end of 2018/beginning of 2019. The g-2 experiment is expected to resume operation in a month or so. The installation of muon momentum cooling wedges successfully narrowed the momentum spectrum, increasing the ring acceptance by 20%.

Failures of the MI septa due to broken wires and vacuum problems had become a significant source of downtime. A spare septum is in fabrication. Since the latest upgrades of the RF station in the Booster, accelerator reliability has improved and the Proton Improvement Plan can now be considered complete. The accelerator delivered 2.7×10^{17} protons/hour when NOVA, SNB and g-2 were all taking beam.

Development and execution of the PIP-I+ improvement plan are in progress, with the immediate goal of increasing the beam power to NOvA, towards the long-term targets of a MW beam in PIP-II and 900 kW to NOvA. The plan consists of many different components, including the new NuMI target (operable up to 1 MW), the Booster defocusing magnets, the new quadrupoles for the Main Injector gamma-t jump, and the new RF cavities with higher voltage and larger aperture. Most of these upgrades are underway, and should allow the accelerator to deliver 850 kW to NOVA after the FY19 shutdown. The work scope and schedule of PIP-I+ was reviewed by the Accelerator Advisory Committee (AAC), which found the proposed plan sound.

The accelerator went through a Modernization Review that identified obsolete hardware to be replaced. The total cost of this modernization is approximately $35 million. A second modernization step is occurring on the software side: PIP-II will retire the ACNET Accelerator Control system, and replace it by a system based on a more modern architecture infrastructure (such as EPICS). The AAC suggested that the available options for controls system architecture be carefully evaluated, based on clear requirements for the present and future needs of the complex.

A program of Booster studies which would consume 1-2% of FY19 run time has been proposed to investigate issues in high intensity proton beam physics as well as to perform dedicated studies for the PIP-I+ Booster Intensity subproject (8 hour shift/month). The AAC reviewed this proposal favorably, recommending that the list of studies be prioritized, and that adding regular beam studies periods to the operation schedule be considered.

The PAC commends the laboratory for the accelerator performance and endorses both the modernization plan and the idea of adding regular beam studies to the beam schedule.

Report on the FTBF: *We ask the committee to review the status of the facility, to comment on the recent FTBF review's outcome and on the progress of the ITA.*

The PAC heard a clear presentation of the current status of the Fermilab Test Beam Facility (FTBF), and its plans for enhancements. The PAC commends the Laboratory for enabling this facility to provide comprehensive test beam infrastructure to around 200 users per year. The test beams available consist of 120 GeV protons as well as secondary beams of particles between 200 MeV and 60 GeV. The facility was used by 20 groups in 2018, with strong representation from neutrino, muon, and collider experiments, as well as other fields.

The PAC considered the outcome of the FTBF Committee review and concurs with the overall assessment that the FTBF is leveraging limited resources to provide an invaluable service to a broad physics community. FTBF is heavily used by all LHC (ATLAS, CMS, LHCb and ALICE) and non-LHC collider (sPHENIX, EIC studies) studies, as well as Intensity Frontier (neutrino, muon) experiments while dedicating a good fraction of the beam time to testing new developments in R&D and in outreach. The PAC notes

that the FTBF is responding quickly to the review recommendations by taking preliminary steps to develop a common slow control system, and planning over the next year to provide a common DAQ framework based on otsDAQ for users. The FBTF team is also moving forward to follow the recommendation of writing a paper summarizing the capabilities and performance of the facility.

The PAC was informed of the plan to quickly and economically create an irradiation facility (ITA), and strongly supports this activity. The ITA will be a unique resource in the US, and it can have immediate impact on the sensor selection for the CMS HL-LHC tracker if it becomes available by April. The ITA has been strongly endorsed across the HEP community as an investment that will make FTBF an even more attractive and useful resource.

The Committee also notes the importance of the FTBF among test beam facilities globally to provide high intensity, high energy (> GeV) hadron beams. This capability is shared only with CERN SPS/PS and Protvino beam lines, the latter of which is available only two months/year. This uniqueness will be relevant on several time-scales. During the 2019-2020 accelerator shutdown at CERN, FTBF will be the main resource for both energy frontier (HL-LHC) and intensity frontier (DUNE) detector development, and FTBF is preparing well for the increased demand. On a longer horizon, the PAC notes that test beams at CERN will also be unavailable during LS3, and thus encourages the laboratory to carefully investigate the impact of a four-year shutdown of the FTBF starting in FY24, long before the MI shutdown planned for 2026/27 and consider alternative scheduling options.

Status of the Test Beam Experiment EMPHATIC*: We ask the committee to comment on the physics case and results from latest data taking campaign*

The PAC heard a report on the progress of EMPHATIC, a proposed tabletop-scale experiment to measure hadron production cross sections utilizing the FTBF. This experiment would provide the first measurement in over 50 years of key proton-carbon cross sections at low energies, and would use a variety of thin targets in addition to carbon to measure the processes that are the limiting sources of uncertainty in the LBNF neutrino flux. If EMPHATIC succeeds in measuring the proposed cross sections with around 10% uncertainty, this would improve the overall precision of neutrino flux estimates by more than a factor of 1.5. Reducing this flux uncertainty is important for the DUNE near detector physics program. While other hadron production measurements are ongoing, EMPHATIC is the unique experiment filling the important energy range below 15 GeV. EMPHATIC results would also significantly impact atmospheric neutrino experiments by improving their neutrino flux models, and could be used to improve modeling in GEANT and other simulation packages, which would have wide-ranging impact from HEP to medical physics.

The Committee heard about a proof-of-principle EMPHATIC run performed at FTBF in January 2018. These tests were carried out using both proton and pion beams at several energies, and different targets. The analysis of 31 GeV p+C data collected with the tracking detectors in this engineering run is in an advanced stage, and the Committee was shown a promising preliminary measurement. Both the result of this measurement and a full EMPHATIC proposal are expected to be delivered soon. The PAC recognizes the relevance of the proposed program.

Report from Scientist Advisory Council: *We ask the committee to comment on the SAC's plans and expected outcome for the All Scientists' Retreat.*

Report from the Strategic Planning Workshop*: We ask the committee to comment on the outcome of the strategic planning workshop.*

Report on the European Strategy Planning Process: *We ask the committee to comment on the status of the ESPP and on the submitted US and FNAL contributions.*

The committee heard three reports regarding the FNAL Scientific Advisory Council (SAC), Scientific Planning Workshop, and the European Strategy Planning Process. The committee was pleased to see the wide range of involvement and leadership, particularly from early career scientists, in these important planning and reporting activities, which strengthen cohesion within the laboratory. The SAC activities have produced a variety of important outcomes, which have already yielded new research directions and white papers. **While the SAC and Strategic Planning Workshops have different purposes, the committee recommends the laboratory explore how the grass-roots discussion in the SAC can be better integrated into the more formal Strategic Planning Workshop.**

Five white papers were submitted to the European Strategy Process that are related to Fermilab, which include specific proposals for new experiments and status and plans for facilities at Fermilab. **The Committee recommends that the Laboratory closely follow the European Strategy process. We look forward to hearing about its planning and preparations for the next Snowmass process, as well as a summary of key outcomes from the upcoming Open Council Symposium for the European Strategy in Granada.**

Report on DUNE/LBNF by LBNC: *We ask the committee to comment on the status of DUNE/LBNF.*

The PAC heard a summary of the LBNC's recent review from Hugh Montgomery, the new LBNC chair. LBNC oversees DUNE and some LBNF interface activities that feed directly into DUNE. The PAC continues to find its partnership with the LBNC in advising the lab on DUNE to be an effective model. These conclusions largely endorse findings from the LBNC.

The DUNE collaboration continues to grow; it is now at a size within a factor of two of the LHC experiments at the time of their Technical Design Reports.

DUNE continues to be committed to developing both the single and dual phase (SP and DP) technologies, with staging plans subject to the results of the ProtoDUNEs. DUNE intermediate design reports on physics and the SP were reviewed in summer 2018, and the DP in December 2018. It is expected that these reviews will inform the Technical Design Report.

The DP 1x1x3 m^3 demonstrator resulted in a number of design changes, most notably modifications to the design of the Large Electron Multipliers (LEMs) to address stability issues with high voltage on the induction planes. However, even after the redesigns motivated by the 1x1x3, there continue to be problems with the DP LEMs. The LBNC recommended a significant R&D effort to address this. In addition, the committee recommended modifications to CRP construction and QA/QC plans to address problems observed in the first two CRPs. Finally, LBNC recommended that ProtoDUNE-DP develop a detailed plan for operation and studies with cosmic rays.

ProtoDUNE-SP achieved a number of important milestones, including long lifetime, and stable operation at high voltage, which are very encouraging for the SP technology. The LBNC recommends that the team prioritize progress on the analysis of the beam and cosmic data and documentation of lessons learned in operation and analysis. The LBNC reported increasing confidence that the SP will be a viable far detector baseline technology.

The LBNC found that the near detector design has progressed to a set of detector concepts. The LBNC has recommended the design concept review, to occur in mid-2019, be explicit about the physics impact of each proposed concept. The near detector will need to progress quickly to a clear and approved timeline for the project.

The PAC recognizes the importance of DUNE's efforts to define a model for computing in order to better understand the scope of computing needs for all stages of DUNE analysis, including calibration and simulation efforts, and the resources that will be required to address them. Those resources are expected to be an important component of MOUs with international partners. The launch of the computing consortium by DUNE is an important and productive step. The PAC looks forward to further discussion of the status of computing plans in the summer 2019 PAC meeting.

The TDR for DUNE has made good progress, and the LBNC has recruited teams of international experts to review the TDR. The approach of producing and reviewing preliminary TDR sections has been effective in the review process. It will be challenging for the LBNC to have the full TDR review completed for a report to the RRB in August 2019.

The LBNC continues to assert the need for frequent and active management of technical decisions by the collaboration. The PAC recognizes that DUNE has responded to this by creation of its collaboration executive board (EB) to play this role. It is important that the DUNE EB continue to weigh in on important decisions.

The committee did not receive a detailed report on LBNF.