Fermilab Physics Advisory Committee Meeting
June 20-22, 2016
Comments and Recommendations

Introduction

The Physics Advisory Committee (PAC) met at the Chicago Gleacher Center to consider the Fermilab program and its alignment with the recommendations in the Particle Physics Project Prioritization Panel (P5) report: "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context."

This PAC meeting took place just before the summer conferences. The neutrino community is expecting with excitement the release of NOvA's latest results at Neutrino 2016. The new data might perhaps strengthen the hints for the normal hierarchy and large CP violation in the neutrino sector. MicroBooNE will also present their first physics results at this conference, setting the stage for the start of the Fermilab Short Baseline Neutrino Program. At the energy frontier the excellent performance of the LHC, which has recently reached a peak luminosity of well over $8\times10^{33}cm^{-2}s^{-1}$ and delivered over 6 fb^{-1} to both CMS and ATLAS, will allow many exciting results to be presented early August 2016 when ICHEP will take place in Chicago.

The PAC continues to find the program of the Laboratory well aligned with the P5 strategic plan and congratulates the Director and his leadership team for the high moral of the Laboratory and its increased vitality. The great status of the Laboratory has led to a record number of attendees at this year Users Meeting and a large number of applications for its Wilson Fellowship program.

The PAC commends the Laboratory for the success achieved by Mu2e CD3c and the LCLS-II CD3 reviews. The PAC is pleased with the support provided to CMS and is delighted with the election of Fermilab scientist Joel Butler as the spokesperson of CMS.

The Committee notes the great performance of the first full-aperture-model quad for the LHC high luminosity upgrade which was assembled at LBNL with coils from Fermilab and CERN. The PAC is impressed with the increase in the RF cavity accelerating gradient achieved at Fermilab using nitrogen doping of niobium and

looks forward to further improvements that could be obtained by using Nb_3Sn. The PAC is also pleased that the Illinois Accelerator Research Center (IARC) is gaining traction with partners and becoming an important center for technology transfer. The Committee congratulates IARC for receiving the Innovation Award at the National Innovation Summit two years in a row.

New initiatives are also taking place in scientific computing including the establishment of a new Center for Computational Excellence, establishing a Terabit link between ANL and FNAL, and investigating possible research efforts in collaboration with the quantum computing community.

The PAC is delighted by the DOE support to improve the Fermilab campus and believes that it will bring great benefits to the Fermilab users. The PAC is concerned about the lack of funding for the PIP-II upgrade of the accelerator complex, which is necessary for the long term future of the Laboratory. It also believes that the accelerator R&D opportunities facilitated by FAST/IOTA are critical for Intensity and Energy Frontier facilities and hopes that this advanced accelerator R&D can be funded adequately.

The Committee recognizes that the Laboratory resources are stretched at this time and that it is currently difficult to entertain new opportunities. In order to encourage the development of new science proposals while also fostering an efficient and competitive review process, the PAC recommends consideration of a regular PAC cycle for evaluation of proposed initiatives that require significant Laboratory investment or support.

At this meeting the PAC has been asked to report on:

- The progress made on advancing the future neutrino Long Baseline Program by the Collaboration Working Groups including addressing the open R&D questions and the LBNC-identified LBNF and DUNE focus areas listed in the January PAC report.

- The current situation, the progress being made, and the expectations for the coming year for NOvA, MicroBooNE, MINERvA and ANNIE.

- The scientific case to fund an inflector for the Muon g-2 project using some of the available contingency, taking into account programmatic priorities and funding constraints.

- The summary presentation being prepared for the DOE FY16 Comparative Review (July 25-28) of Lab Cosmic Frontier Research Programs.

- New initiatives for CMB Stage-4, neutrinoless double-beta-decay, and non-oscillation physics that could be pursued with scintillation-based neutrino detectors.

- The activities of the Fermilab scientists on CMS. Are the scopes and focus of these activities appropriate for the laboratory? Is there a good balance and fair distribution between the scientific and operational activities within the group?

- The updated Strategic Plan of the Fermilab Theory group focusing on evaluating its strength, its unique and essential contribution in support of the U.S. experimental particle physics community, and its strategic relationships with other U.S. laboratories and university theory groups

The Committee greatly appreciates the time and effort required of the presenters to prepare the excellent reports for this PAC meeting. In addition, the PAC thanks Steve Geer for the excellent organization and Hema Ramamoorthi for her logistical support.

LBNF and DUNE

LBNF continues to make good progress towards approval and initiation of the conventional facility construction at the Sanford Underground Research Facility, which requires a long lead time. A very successful CD-3a review took place in December and the Independent Cost Estimate review was conducted in January. Formal CD-3a approval is anticipated in September, pending acceptance of the planned funding profile by Undersecretary Orr. Meanwhile the project has been working towards approval to issue an RFP for a Construction Manager/General Contractor (CMGC) as a step towards initiating underground construction at the Sanford site. Final design of pre-construction excavation is underway, including the design and easement approval for a rock disposal system into a nearby open cut. A test blast program was conducted in the region of the LBNF excavation site, providing valuable data for impact on nearby facilities. The LBNF project is led by a very strong and experienced management team, with an impressive command of all aspects of the FSCF project. The PAC believes the LBNF project is on track to begin major underground construction, which would give a clear signal to the international community about the intentions of DOE to construct a U.S.-hosted world-class center for neutrino physics.

The DUNE Collaboration has continued to make impressive progress in establishing a strong and well-organized international effort for the long-baseline neutrino physics program of LBNF/DUNE.

In the last 5 months, the organizational structures for protoDUNE-SP (single phase) and protoDUNE-DP (dual phase) have been put in place as critical near-term efforts for DUNE. ProtoDUNE is the first major hardware effort by the Collaboration and its success is a key early outcome of the Fermilab-CERN partnership in neutrino physics as well as a demonstration of the important role the CERN Neutrino Platform plays in the overall strategy for LBNF/DUNE. The prototyping effort will validate the engineering design and physics performance of the DUNE Far Detector design options, and provide a foundation for planning the full-scale production of TPC components. Engineering efforts are advancing for both protoDUNE-SP and protoDUNE-DP and the Collaboration is organizing a significant influx of manpower to support assembly, commissioning, and operation of the two prototypes at the Neutrino Platform at CERN.

A detailed strategy for CD-2 preparation in Q4/2019 has been developed, which includes completion of protoDUNE demonstrations, development of a full Technical Design Report, establishment of consortia for construction of detector systems, and completion of a funding matrix. This gives a plausible pathway to the Collaboration, since it lays out key goals and milestones for tracking progress.

The three Task Force groups which were launched last September (Near Detector, Far Detector and Beam Optimization) are proceeding well. Their first results will be documented in preliminary reports in September 2016, and final reports in March 2017. These Task Forces integrate and coordinate across the Working Groups to establish timelines and goals, and focus work towards answering specific charge questions. Results that include automated reconstruction of far detector events have been shown, while optimization of algorithms and event selection continues. Complete fitting packages are now available for both the ND and FD efforts. The Beam Optimization Task Force has completed an initial assessment of a three-horn design and conceptual engineering studies will begin shortly. The Collaboration Resource Board has been established to begin the process of defining international contributions to DUNE.

Based on a recent LBNC review, a number of concerns have been raised about the protoDUNE program. The transition from R&D to construction is often difficult and protoDUNE is on a very fast timeline in order to be ready for beams before LS2 at CERN. A recent mini-review exposed significant technical challenges and

management issues, particularly in the area of the cold electronics system and systems integration for protoDUNE-SP. A very similar system is also planned on a similar timescale for SBND and the relative priorities may become an issue. The Collaboration and Fermilab management will need to address these potential issues quickly in order to establish a robust plan for the delivery of protoDUNE-SP. While the engineering designs for protoDUNE-SP and -DP can be validated with cosmic rays, the full calibration program requires SPSC-approved beam time in 2018.

The LBNC is encouraged to continue its close scrutiny of protoDUNE in particular, given the tight schedule and significant technical risks. The PAC encourages Fermilab to strengthen the LBNC membership to cover all technical areas of the DUNE project.

The PAC looks forward to progress reports in the following areas:

- LBNF:
    - Progress in bringing the CMGC on board and development of the final design plan for the CD-3a scope
- DUNE:
    - Progress against goals and milestones, and the plans for protoDUNE single- and dual-phase prototypes
    - Resolution of technical design issues, including the protoDUNE-SP cold electronics
    - Progress against goals, milestones and the plans for the three Task Force efforts (ND, FD, BO)
    - Progress in software and computing, including automated reconstruction
    - Progress against the strategy laid out for preparations in advance of CD-2/CD-3b
    - Progress in developing a responsibility matrix for protoDUNE (near-term) and DUNE construction (longer-term).

NOvA

The Committee was impressed and very pleased to hear the continuing success of the NOvA experiment, which is running extremely stably and fully exploiting the rapid gains in beam power at NuMI. There has been substantial progress in the analysis effort. The introduction of multi-nucleon effects reduced a data/MC discrepancy in the hadronic energy that led to a large systematic uncertainty in the first results. A new algorithm has significantly improved the efficiency for electron neutrino selection. The experimental sensitivity has been further improved by

moving to a more sophisticated binned fitting framework. The Committee looks forward to NOvA presentations at Neutrino 2016, where results incorporating these developments with more than twice the exposure of the previous analyses will be shown.

The Committee supports the initiative to collaborate with the T2K experiment on common issues, such as neutrino event generator development, and is encouraged by the initial discussions on performing a joint analysis. We also note that the overlap of collaborators with MINERvA allowed the rapid progress in addressing the hadronic energy issue, illustrating the benefits of a rich and diverse neutrino program and interchange between collaborations.

NOvA plans to conclude FY16 operations with a short antineutrino run and start FY17 operations with 2×10^{20} POT in neutrino mode, with the rest in antineutrino mode. The PAC supports this run plan since it will give NOvA an early first look at antineutrino events. Furthermore, the plan will also allow the restart of the beam following the shutdown activities in neutrino mode and, if the accelerator complex performs as expected, it will provide a significant exposure of antineutrino data in FY17 for the next steps in the NOvA physics program.

MicroBooNE

The Committee congratulates the MicroBooNE Collaboration on the excellent operational performance of the detector, in particular the very high purity and electron lifetimes measured in their LAr target. The Committee was also very happy to see the successful development of a PMT trigger and mitigation techniques for electronics noise problems. The noise mitigation techniques may also be applied to other LAr-TPCs, and we enthusiastically welcome the Collaboration's creation of a "public notes" page that presents results like these. The outstanding performance of the cryogenic system and progress on readout should allow the Collaboration to fully exploit the unexpected bounty of proton delivery in FY2016, which has exceeded expectations. Numerous operational milestones and goals are being met, and in some cases significantly exceeded. Other aspects of the experiment, such as computing, analysis tools, and installation of a cosmic veto trigger, appear to be proceeding smoothly. The overall analysis strategy appears to be well structured to tackle the challenges expected in resolving the MiniBooNE low-energy excess. The PAC looks forward to exciting results to be presented at the upcoming Neutrino 2016 conference, which are anticipated to include first ν_μ CC results, π^0 reconstruction, and new and creative techniques for particle ID.

The Committee was also impressed to see automated reconstruction of Michel electron events. This is a major milestone in the development of LAr-TPC technology. It is clear that there is still some work to do to understand the overall

detector response, as evidenced by the data/Monte Carlo comparison of reconstructed Michel electron energy spectra. We expect that in the coming weeks and months the Collaboration will significantly refine their models and reconstruction methods, which will improve this agreement and allow them to move forward toward their ultimate physics goals. What is learned here by MicroBooNE will also certainly be important for future experiments using LAr-TPC technology.

In the future, the Committee would like to see further details on the performance of analysis tools (track finding, vertexing, particle identification, etc.), particularly on data, with comparison to simulation or other expectations. We also encourage the Collaboration to develop the tools necessary to quantitatively assess the impact of ongoing developments (operational issues/improvements, detector configuration changes, reconstruction improvements, etc.) for addressing the MiniBooNE low energy excess.

ANNIE

ANNIE (the Accelerator Neutrino Nucleon Interaction Experiment), which was granted Stage 1 approval in 2015, presented the status of their Phase I work. This is a highly leveraged experiment stationed at the Booster Neutrino Beamline that can measure the neutron emission cross section in neutrino interactions and therefore provide useful information for proton decay searches and the detection of supernova neutrinos. ANNIE can also study additional observables to constrain models of neutrino interactions. In addition, ANNIE provides a perfect experimental opportunity to deploy and test the ambitious LAPPD detector technology. Currently ANNIE is measuring neutron backgrounds with the water volume viewed by 60 8" PMTs. In the near future the Collaboration is planning to test LAPPDs fabricated by Incom Inc. and we expect that ANNIE will be ready to demonstrate LAPPD readiness in 2016-2017.

The PAC commends the ANNIE Collaboration's success in commissioning its detector and with their first detection of events. The plans for Phase Ib, which is an opportunity afforded by the success of their proposal to the Intermediate Neutrino Research Program, is compelling and cost effective. The Committee believes this should proceed. To move beyond Phase Ib to Phase II, the Committee expects that a formal proposal will be submitted at an appropriate time determined by Fermilab.

The inflector for g-2

The PAC heard about the development of a new open-ended inflector magnet that reduces the risk of a single point failure that could bring the experiment to a halt for

a significant time (up to 2 years). In addition, the inflector increases injection efficiency by 60%, pushing the experiment to the systematic limit, and allowing the Collaboration to achieve the measurement of the anomalous magnetic dipole moment with a precision of < 140 ppm faster.

The PAC notes that several review committees recommended proceeding with the inflector if unspent contingency is available. The PAC fully endorses the request to proceed with the Stage 1 prototype.

Accelerator

The Committee heard the progress made by the accelerator team. The Main Injector beam power is ramping up, and has even briefly exceeded 700 kW for NOvA. The Committee recognizes that this is an important achievement and commends the accelerator division. The plan to reach 700 kW in normal operations is clear. The Proton Improvement Plan, which improves the performance and reliability of the Linac and Booster, has made significant progress. The Muon Campus Accelerator Improvement Plan is on schedule. Upgrades of NuMI and Booster Neutrino Beam horns are under study. The Committee congratulates the accelerator team for its successful operation. It also recognizes the need for a longer summer shutdown, but recommends the Lab to keep the future shutdowns as short as possible.

MINERvA

The MINERvA Collaboration presented the status of its efforts, including its overall analysis strategy with different beam configurations and nuclear targets. As a dedicated experiment to study neutrino-nucleus interaction properties, the Collaboration is making substantial contributions to the world neutrino community in producing not only measurements, but also model-tuning and improvements that are already making significant impact on ongoing neutrino oscillation experiments like NOvA and T2K. The Committee congratulates the Collaboration on its scientific output. The demonstration of an effective interface between the experimental measurements and the theoretical and modelling effort illustrates the importance of a well-integrated effort; it underlines the importance of continued progress in theory, modelling, and coordination with related activities such as NuSTEC and the Laboratory's new neutrino cross section working group. The Committee noted that the Collaboration appears to have weathered the cancellation of Captain-MINERvA; nevertheless, the broader LAr-TPC physics program will inevitably be affected by the absence of early direct measurements on argon. Such measurements would have provided an important test of the interpolation across different nuclear targets.

The Committee looks forward to the timely publication of results from the medium energy data.

MINERvA has requested an anti-neutrino exposure of $12x10^{20}$ POT. The Committee reiterates its support for an anti-neutrino exposure of at least $6x10^{20}$ POT in the medium energy beam configuration to allow sufficient statistics for the various antineutrino analyses. With the end of MINOS operations and the transfer of the operational responsibilities for the near detector, we encourage the Laboratory and Collaboration to work towards minimizing the overall operation burden.

Particle Astrophysics

The PAC congratulates the leadership of the Particle Astrophysics effort at Fermilab in presenting a coherent and compelling program, which is both diverse and balanced. The Fermilab Particle Astrophysics group provides key contributions to a large number of high-profile experiments in the national and international portfolio, which are expected to facilitate fundamental measurements and, possibly, new discoveries. These contributions exploit Fermilab's infrastructure and know-how, and provide elements central to the success of these experiments. The PAC also noted that the planned transition from G1 to G2 dark matter searches is now under way. The future transition between DES/DESI and LSST is under planning and was clearly articulated.

The PAC remarks that the Particle Astrophysics program remains central to the scientific vitality of Fermilab, and advises the Particle Astrophysics group to identify, among possible future directions, potential Fermilab flagship efforts.

CMB

The PAC heard a presentation on the ambitious physics goals of CMB-S4 (Stage 4). CMB-S4 expects to significantly increase sensitivity to B-mode polarization from inflationary tensor modes (gravitational waves) by measuring the tensor to scalar ratio (r) to the level of 10^{-3}, distinguish classes of models of slow roll inflation, determine the sum of neutrino masses down to 15 meV, severely limit N_{eff} beyond the known neutrino contributions and more (cluster science, CMB-galaxy cross-correlations, CMB lensing, etc.). The PAC is strongly supportive of the Fermilab activities in this area.

The CMB effort at Fermilab has provided significant support for the near-future SPT-3G experiment including detector packaging, mechanical assembly, wire

bonding, detector testing, and camera assembly. In addition, the associated science program is also strong. This effort focuses on cluster cosmology and has excellent synergy with DES and with a number of ongoing and new projects. The planned future growth of the CMB group is relatively modest compared to a previous plan that was presented earlier to the PAC, but appears reasonable considering that CMB-S4 is still evolving and is yet to be launched, and keeping in mind the balance of other activities in the overall Cosmic Frontier program.

Neutrinoless Double Beta Decay Searches

The PAC appreciated the very clear presentation on the national and international program of searches for Neutrinoless Double Beta Decay. This is an extremely rare nuclear decay, whose search provides the sole and unique opportunity to tackle what is perhaps the most fundamental open question on neutrinos, i.e., if the nature of these particles is that of Dirac or Majorana fermions. The search for neutrinoless double beta decay is complementary to the search for CP violation in neutrino oscillations, which is the primary goal of DUNE -- together, they could provide vital information for our understanding of the baryon asymmetry in the Universe.

The search for Neutrinoless Double Beta Decay is a national priority stewarded by the DOE and NSF Nuclear Physics programs. It is expected that in a few years the field will be shaped by the selection of one U.S.-led experiment and one experiment with U.S.-participation reaching a minimum sensitivity equivalent to $m_{\beta\beta}$ of 15 meV, which would enable a complete exploration of Neutrinoless Double Beta Decay under the assumption of an Inverted Hierarchy scenario. This requires operation of experiments collecting an exposure of a few ton-years, with an exquisite control of backgrounds.

The PAC advises that Fermilab pay close attention to developments in this field. Should opportunities present themselves to leverage Fermilab's unique infrastructure and know-how to advance this field, it would be appropriate for Fermilab to start planning specific actions that could enable the Laboratory to take the lead in one of the projects and/or take the lead in the development of innovative and very promising ideas.

Large Liquid Scintillator and Water Cherenkov

The PAC heard a presentation on the physics potential of a large scintillator-based detector installed at the Sanford Underground Research Facility. The FROST

workshop hosted at Fermilab in March 2016 attracted experts and leaders of scintillator detectors from around the world to discuss the potential for this type of experiment. In addition to performing neutrino oscillation measurements using the LBNF beam, such a detector has the potential to address a broad range of other physics topics including neutrinoless double beta decay, solar neutrinos, geoneutrinos, diffuse supernova background, Supernova burst neutrinos, and nucleon decay. The exploitation of this technology and the associated enhanced physics program might enhance the community of physicists served by the Laboratory, and could also attract different funding sources (e.g., nuclear physics).

We encourage Fermilab to support groups developing detector concepts to take full advantage of the unique opportunities that LBNF presents, without distracting effort from DUNE, which is the main priority. The development of such concepts is consistent with the P5 recommendation that the US "host a large water Cherenkov neutrino detector to complement the LBNF large liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam at Fermilab."

CMS

The PAC heard a presentation of the range of activities of Fermilab scientists on CMS. The Fermilab CMS group includes about 60 scientists (50 FTEs), of which 15 are postdocs. It is the largest U.S. group on CMS, and the 2nd largest group in all of CMS. With such a large group, and with unique technical resources, Fermilab continues to play a special role in CMS. Fermilab scientists hold many leadership roles in the U.S.-CMS organization (e.g., the U.S. CMS Operations Program and Upgrade Project Managers are Fermilab scientists) and Joel Butler is the next CMS Spokesperson.

The activities of Fermilab scientists are divided among data analysis, operation, construction of phase 1 upgrades and R&D for HL-LHC, computing, and software. The range of activities takes good advantage of the Lab's resources. The Lab's involvement is crucial to the success of current and future upgrades. The PAC believes that the computing challenge of the coming years presents a particular opportunity for Fermilab to increase its role in scientific computing. Postdocs currently spend about half of their time on analysis, while this fraction is closer to 30% for other scientists. Although this balance seems reasonable, the PAC did not have sufficient information to assess the costs/benefits of changing the balance between physics analysis and other activities.

The Theory Strategic Plan

The PAC again commends the Fermilab theory groups, both particle physics and particle astrophysics, for their high visibility, their ability to attract and guide some of the best theory postdocs in the country, their support of the experimental program at the Lab and worldwide, and their essential role in fostering a vibrant intellectual environment in the Laboratory. We would like to echo all the comments and recommendations made in the last PAC report.

The particle theory group has made good progress in implementing its strategic plan to better align itself with the current particle physics experimental program in the Laboratory. The recruitment of an excellent, new associate scientist who dedicates most of her research efforts to neutrino oscillation phenomenology was a very positive step in the direction of strengthening the group's effort in neutrino oscillation physics. We look forward to seeing the result of the ongoing search for a new associate with concentrated research effort on perturbative QCD.

The particle theory group continues to increase its support to the neutrino experimental effort at the Lab and the U.S. neutrino theory community. We are encouraged to see that members of the group are playing a role in understanding the multi-layered complex problems and faithfully modeling neutrino-nucleus scattering. We expect this effort to take shape and strengthen in the near future with increasing involvement of other members of the group. This effort will also profit from the newly-created Neutrino Physics Center, whose leadership includes members of the particle theory group.

The Fermilab Distinguished Scholars Program (FDS) was successfully launched, and a strong list of recipients have already been announced. It aligns itself very well with the on-going efforts in the theory group and the Lab's experimental program. The FDS program is expected to play a role in shaping and strengthening the relationship of the Fermilab theory group with the theory groups at other National Laboratories and U.S. universities. We were also encouraged by the fact that the theory group has highlighted the subcritical current research effort in neutrino theory in the U.S., especially in light of the current experimental effort in neutrino physics research, and is invested in playing a role in facilitating a solution to this deficiency.

We were disappointed to learn that the Fermilab graduate student research program has ended. The program allowed theory graduate students at universities to spend one year at the Lab interacting with the theory and experimental groups. It

provided an excellent opportunity for students, was a resource for the U.S. theory community as a whole, and was virtually the only way through which Fermilab theorists could attract and support graduate students. The Office of Science Graduate Fellowship program could offer an alternative means of attracting graduate students, except that the program is restricted to U.S. citizens and green card holders. We urge Fermilab management to work with the Office of High Energy Physics to remove this very unfortunate restriction. We note that both University and Laboratory theory is currently under an inordinate amount of funding-pressure.

We believe the Fermilab theory group—and Lab theory groups in general—play an essential and unique role in the U.S. particle physics community, both in the theoretical physics effort and in support of the experimental effort. This was also emphasized in a presentation of the SLAC theory effort. When it comes to the Fermilab theory groups, their main assets are (i) critical mass and (ii) direct interactions with a vibrant and diverse experimental community. The critical mass attracts the best postdocs who are exposed to a broad theory effort. The access to the experimental community, and vice versa, is unique to the Labs since no university group mimics this environment. We believe the case made by the Fermilab theory group is strong and well-articulated, but it can be refined and sharpened further, especially when it comes to clearly identifying its unique capabilities.