Fermilab Physics Advisory Committee Report

June 7th-11th, 2021

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Executive Summary:

The Fermilab Physics Advisory Committee (PAC) met virtually on 7-11 June 2021 amidst the ongoing COVID-19 pandemic. The pandemic continues to significantly impact activities in particle physics at Fermilab and beyond, including the US particle physics community study ("Snowmass") which has been paused for one year. Against this backdrop, Fermilab continues to execute key elements of the 2014 P5 report "Building for Discovery". A critical milestone was reached earlier this year when the FNAL g-2 experiment presented its first results, confirming the anomaly previously observed by the BNL experiment and attracting worldwide attention.

The meeting started with a report from the FNAL Director providing an overview of the status of the Laboratory. Fermilab's science and technology goals have been updated to incorporate advancement of large-scale data analysis, quantum computing, and quantum sensing. The Committee noted that cosmology, an area of strength for the Laboratory aligned with the science driver for the current P5 plan through dark energy and inflation, should continue to be visible within these goals.

In the flagship LBNF/DUNE program, pre-excavation work at the far site is approaching completion. With international support, the project is incorporating a second far detector module to the baseline scope. The Committee applauds the election of Regina Rameika as DUNE co-spokesperson and congratulates the Laboratory on the progress in PIP-II, which is now on track towards CD-3 following successful CD-2 and CD3a reviews.

Fermilab continues to expand its international engagement despite the pandemic. Recent events include the visit of the Consul General of Italy to the Laboratory, the signing of a FNAL-CERN MOU in relation to the HL LHC upgrade project, and an I-CRADA with Tel Aviv University for dark matter detector development with the Skipper-CCD technology.

The Laboratory has implemented a number of important organizational changes. Kevin Pitts, formerly vice provost at UIUC, was appointed as Chief Research Officer, where he will serve as the point of contact in the Laboratory for the DUNE Collaboration. An international search is underway for the head of the Particle Physics Division to replace Josh Frieman, who recently stepped down. To reflect the importance of theory efforts across many of the Laboratory's initiatives, the Theory Department has been reorganized as a Division led by Marcela Carena. Likewise, the importance of ASIC development has been reflected in a new ASIC R&D Department headed by Farah Fahim and Jim Hirschauer. To develop FNAL's engagement with future collider projects across the world, a new Future Colliders Group, headed by Pushpa Bhat and Sergo Jindariani, has been formed. The Committee congratulates Farah Fahim and Brian Nord for their recent Early Career Awards, where they join a cohort of past awardees, many of whom now occupy prominent positions. These include FNAL division head and experiment spokesperson appointments.

NuMI reached a record of 801 kW beam and a target station upgrade to accommodate 1 MW beam is to be completed during the shutdown. NOvA is running well, with nearly 30x1020 protons-on-target accumulated. Tension with results from T2K is attracting attention and joint analysis efforts are in progress. The new irradiation facility has been completed and first tests for CMS have been conducted. Mu2e has also achieved a number of important milestones, including the receipt and successful testing of 14 coil units for the Transport Solenoid, the prototype electrostatic septum, and calorimeter crystals. The production target and cryogenic feedboxes were delivered to Fermilab, and the first tracker planes were successfully built and tested with cosmic rays. The current plan for the muon campus would start a transition from g-2 to mu2e in FY23, with commissioning for mu2e starting in FY24.

The Committee heard a presentation from Sandra Charles, Fermilab's new Chief Officer for Equity, Diversity and Inclusion (EDI) about the Laboratory's many activities and initiatives in this area, including the new SQMS Carolyn B. Parker Fellowship, that builds upon a strong track record of outreach. We look forward to continued reports and discussions on this important topic.

Fermilab's efforts in QIS continue to grow with the successful hiring of over twenty new members of the new SQMS center, while the Quantum Internet Initiative has had its first publication on high fidelity teleportation and is expected to commission a site-based network as a step towards a Chicago area metropolitan network.

The Scientific Computing Division presented an overview of its strategic plan for software and computing, with a focus on storage and the use of HPC resources. Significant challenges are on the horizon due to the uncertainties in the ability to incorporate and exploit new

architectures. The Committee recommends further development of these plans based on milestones and decision points that consider the possible outcomes from these developments.

The Committee heard several reports regarding the experiments on the Booster Neutrino Beam line. Since its last report a year ago, MicroBooNE has produced twelve publications on a variety of topics, including several cross-section measurements, and is in the process of finalizing its low energy excess analyses. From the SBN analysis working group, in addition to general reports on analysis development and computing needs, a presentation on the impact of concrete overburden for the SBND and ICARUS detectors was presented. The ICARUS collaboration has made impressive progress on the commissioning of its detector, with the first neutrino events observed from the Booster and NuMI neutrino beams. The SBN institutional board continues to make progress in developing the by-laws and governance structures for the SBN organization that will be responsible for overseeing the joint effort of the multi-collaboration SBN program.

Additionally, the plans for the ArgonCube 2x2 system, which will serve as a technical demonstrator of a key component of the DUNE near detector system, was presented for the first time. The Committee recommends Stage 1 approval, noting that the schedule is tight. The Committee also heard plans from FNAL's Neutrino Division to make targeted contributions to the DUNE near detector and far detector prototypes.

As noted above, a new Future Colliders Group (FGC) has been formed to develop the Laboratory's engagement in future collide projects. Following previous recommendations from the PAC, the exploratory phase of the Booster Replacement task force has finished, leading to a new Central Design Group to oversee the technology development towards CD0. These developments are timely as the Snowmass Community process restarts following its year long pause.

The Committee received offline reports on the Fermilab's LHC Physics Center, which continues its successful track record even as its funding support has resulted in a reduction of activity to a level that the Committee considers a bare minimum. Further details of Fermilab's plans for membership in JLAB's CLAS-12 experiment were provided, as well as a status of the analysis effort at ProtoDUNE.

In addition to the reports, the Committee heard presentations on Fermilab's wide-ranging program of dark sector searches and its contributions to recent results from the Dark Energy Survey.

The Committee is grateful for the informative presentations throughout the meeting, and to Anadi Canepa and Kalya Decker for the seamless management of logistics for this virtual meeting.

The Physics Advisory Committee:

Present: Halina Abramowicz, Ayana Arce, Franco Bedeschi, Alexander Friedland, Ines Gil-Botella, Beate Heinemann, Katrin Heitmann, Pedro Machado, Luca Malgeri, Kevin McFarland, Isabell Melzer-Pellmann, Hugh Montgomery (ex officio), Christoph Simon, Marcelle Soares-Santos, Hirohisa Tanaka (chair).

Regrets: Alex Szalay

Scientific Secretary: Anadi Canepa

Directorate: Nigel Lockyer, Joseph Lykken, Kevin Pitts, Hema Ramamoorthi

Report on the EDI activities at the laboratory

Charge: We ask the committee to review the EDI activities at the laboratory and the Fermilab's plans to lead the field in fostering equity, diversity, and inclusion.

Findings:

The PAC heard an update from the Equity, Diversity and Inclusion (EDI) effort at Fermilab, which aims to, among other goals, increase diversity and inclusion at the Laboratory, continuously assess the Laboratory's culture and climate, and engage diverse identities and communities. The committee heard about several activities towards improving EDI: a climate survey which took place in 2019, while another will take place in 2022; the Change-Now group which meets regularly; focus groups and so on. The EDI effort has successfully implemented several actions towards improving conduct and accountability: Fermilab Concerns Reporting System, the Code of Business Ethics and Conduct and the Lab-wide online harassment and discrimination training. The PAC also learned that the next topics the EDI effort will focus on are consequences for violations and Lab-wide reporting cadence; LDRD Review (to include EDI efforts); pay equity, promotion, and career progression; and pipeline program conversion.

Comments:

1. The PAC commends the EDI initiative, its role in facilitating recent recruitments and promotions from a diverse talent pool as well as in pursuing the successful outreach programs of FNAL.
2. The PAC commends the creation of the SQMS Carolyn B. Parker Fellowship.
3. The PAC commends the effort to assess the current status and future progress of the lab with respect to equity (via data related to hiring, promotion, recognition, and retention) and inclusion (via the data generated through periodic climate surveys and focus groups).
4. The PAC observes that interpreting this data and disseminating reports is essential for reviewing progress and could be bolstered with additional support to statistically analyze the data.
5. The PAC observes Fermilab's leadership role via its influence on the scientific community through, in particular its alumni. The PAC suggests that the lab tracks the career trajectories of URM and female alums in academia or industry, which can serve as a resource to obtain further funding and may facilitate progress in URM and female recruitment.
6. The PAC was pleased to hear that the EDI effort is coordinated with the University of Chicago and Argonne National Laboratory.

Recommendations:

1. The PAC recommends the Laboratory continue and expand its EDI effort, including the SQMS Carolyn B. Parker Fellowship.
2. The PAC recommends that the Laboratory provide resources to proceed with a systematic collection of EDI related data and their analysis. The PAC recommends the identification of measurable goals to be met regarding climate and inclusion, to assess success and to

guide future actions. A regular (e.g., every two years) report on EDI would be useful for tracking progress.

3. The PAC encourages/recommends the Laboratory to explore the possibility of different recruitment and hiring approaches, such as cohort or cluster recruitment, as tools to more effectively strengthen an inclusive culture.

Status of the SQMS Center

Charge: We ask the committee to review the status of the SQMS Center and of the recommendation made at the December 2020 PAC meeting:

- *"Given the very ambitious goals, aggressive schedule, and strong competition in this area overall, the project poses some major challenges and connected risks. For example, the hiring plan to fill ~20 positions by September 2021 is very important and could cause delays if this goal is not reached. We therefore recommend that risks and risk mitigation are evaluated frequently in the early phases of the project in order to enable the development of timely possible alternatives (e.g. finding staff within Fermilab that can be reassigned if the hiring plan does not proceed in the timeframe proposed".*

Findings:

The presentation briefly described the scale and scope of the center and highlighted key members of the leadership team. The total effort by the Laboratory is currently the equivalent of 33 FTE (with 100 different employees contributing) and is expected to reach 50 FTE. The team is currently designing a record-size dilution fridge (2m diameter).

Details (including a roadmap) were given on the quantum sensing efforts, in particular on dark photon and axion searches, along with an effort to develop a publication policy. Restrictions on foreign visitors are posing hiring challenges for SQMS's university partners.

Comments:

1. The PAC commends the SQMS team for a very impressive start of the program, which is a major and exciting initiative for the Laboratory. The hiring plan is progressing well overall, with nearly a 100% success rate in accepted offers. There have been 22 hires, of which 2 were URMs (male) and 6 women. Other notable EDI efforts include new summer internships (30% URMs, 40% women) and the new Parker fellowship.
2. We commend SQMS on the success in hiring, and on achieving an appreciable level of diversity in the pool of new hires, as well as on the other EDI efforts.
3. The PAC anticipates that the transdisciplinary character of SQMS will pose some challenges for achieving consensus on a publication policy, given the very different traditions in the communities that are involved (e.g. quantum information science vs. high-energy physics). At the same time, maintaining science as open as possible will be important for the success of SQMS.
4. The presentation was very dense (40 slides in 20 minutes). Fewer slides targeted at the most important aspects might have been more impactful for the presentation. Additional backup slides are always welcome.

Recommendations:

1. We encourage SQMS to discuss publication policy with the other national quantum centers, which are likely to face similar issues in this area. There may be an opportunity to establish common standards that take into account the traditions and needs of the different disciplines, but that can nevertheless be applied in a consistent way. The PAC would appreciate an update on these discussions in the next meeting.
2. We encourage the SQMS leadership to continue to build strong ties to the core scientific program of the Laboratory, as this initiative has potential impact in priority areas of HEP research. The PAC looks forward to learning more about this in future meetings.

Status of the Quantum Internet Initiative

Charge: We ask the committee to review the status of the QIS program at the laboratory, the integrated plan with the SQMS Center, and the status of the recommendations made at the July 2020 PAC meeting:

- *"Fermilab should investigate developing the high-school quantum computing module as a part of its strategy for engaging underrepresented communities, as well as for outreach in general."*
- *"The Committee also recommends that the Laboratory continue to develop international partners and collaborations for its quantum internet activities"*

Findings:

FQNET/CQNET had a first publication on sustained high-fidelity teleportation, which was widely reported in the media. The IEQNET project (metropolitan quantum network testbed in the Chicago area) has started, the FNAL Q-LAN (which is a first important part) is expected to be commissioned this summer. There is a proposal to expand IEQNET to a regional testbed with partners, notably at UIUC who have excellent expertise in this area.

Comments:

1. We commend the Laboratory for its excellent work in this area and promising initial results.
2. Fermilab has played an active role in efforts towards a national quantum internet strategy. The Laboratory helped with organizing a national workshop and writing a white paper/roadmap. Discussions with other regional testbed projects are in progress (ORNL, LBNL). We support the Laboratory's effort to play a leading role in this area nationally.
3. The Laboratory is planning to organize an international workshop to start developing international partnerships and possibly an international quantum internet strategy. We support this plan. International partnerships are essential for the broader quantum internet effort.
4. The high-school quantum computing module is being used productively, *e.g.* in a summer school for minority-serving institutions. We commend the Laboratory for these activities.

Recommendations:

None.

Strategic Plan for Software and Computing at the Laboratory

Charge: We ask the committee to review the strategic plan for software and computing at the laboratory and the status of the recommendations made at the July 2020 PAC. meeting:

- *"SCD should start thinking about the data lifecycle and its relation to long term data management and update the Committee at the next meeting. This report should include all relevant aspects, e.g. data storage, transfer, and compression".*
- *"The PAC continues to recommend [...] the development of a long-term computing transition plan" (to HPC)*

Findings:
An overview of the strategic plan for software and computing at the Laboratory was presented to the PAC, describing the overall computing strategy, with a focus on storage, the use of HPC resources and related challenges as requested in the charge. The presentation also briefly described AI/ML at Fermilab.

Comments:

1. The PAC commends the SCD on a broad and interesting program and appreciates the overview of its wide-ranging activities.
2. There will be significant challenges for computing in the next five years and both ATLAS and CMS are working on possible solutions. Potential transition plans to HPC resources beyond describing the opportunities (exascale machines) and barriers for utilizing HPC systems remains unclear.
3. The presentation would have benefited from information on how the efforts at Fermilab are coordinated with the different experiments that are targeted. For example, CMS is a large, international collaboration and it would be important to understand how the Fermilab efforts fit into the overall CMS plans.
4. The presentation highlighted the HEP-CCE pilot program. Further details on how this will enable the desired large-scale off-loading of computing to HPC systems in a production environment would be welcome.
5. A detailed strategy on data transfer and compression (highlighted in the recommendations made at the July 2020 PAC meeting) and mass storage is needed to understand how projected requirements will be met. Across the program, the significant needs of smaller experiments for SCD support to effectively use central facilities, even if their CPU and storage requirements are small, needs to be clarified.

Recommendations:

1. The PAC recommends the development of a resource and computing plan including timelines, milestones and connected decision trees based on the progress on the GPU implementation and therefore possible off-loads to HPC resources. This should help to ensure that Fermilab computing resources can be optimally used to support the experiments.

Status of the MicroBooNE Experiment

Charge: We ask the committee to review the status of the MicroBoone experiment and of the recommendation made at the July 2020 PAC meeting:

- *"We encourage MicroBooNE and SCD to continue to collaborate on developing a multi-year detailed resource plan for completing high priority MicroBooNE analyses. Such a plan should include planning for the desired use of MicroBooNE data in the SBN multi-detector analyses."*

Findings:

The PAC heard a detailed report on the significant progress achieved by the MicroBooNE collaboration since its last presentation to this committee. In total, twelve papers were released in this time window, spanning topics ranging from signal processing and charge diffusion in the detector to constraints on certain new physics scenarios with light force mediators. Additionally, the collaboration released twenty public notes, many of which deal with key physics issues for liquid argon TPC detectors, such as detector systematics and cross section uncertainties.

Some of the published work covers the three event reconstruction approaches pursued in MicroBooNE: Pandora, Deep Learning, and Wire-Cell. The last two, in particular, have demonstrated impressive recent progress and hold a lot of potential as techniques for future liquid argon TPCs.

The recent publication of various cross section results has provided valuable physics input for event generator improvements. Both inclusive and several exclusive cross sections have been measured, with two of the papers appearing in Physical Review Letters. Some of these results have already influenced the development of GENIE v3, the generator package used by all Fermilab-based neutrino experiments.

All these steps are also essential prerequisites for the examination of the physical origin of the low-energy excess reported by MiniBooNE. The Collaboration is considering several approaches for this problem, including looking for signatures of active-sterile oscillations, novel BSM physics, or a mismodeled hadronic effect. While the results of these analyses are not yet available, the collaboration envisions that at least some of them may be released in the near future.

A detector R&D program is being completed by the end of summer including efforts to understand the unexplained noise source in MicroBooNE, the high single-photoelectron rate in the detector, and the prospects of operating at the nominal voltage.

The Collaboration is working with SCD to develop a multi-year resource plan for completing the full 5 year data processing and next Monte Carlo campaigns.

Comments:

The PAC:

1. Commends the Collaboration for the impressive amount of work since the last PAC meeting, in particular, the strong record of publications and technical notes.
2. Encourages the Collaboration to investigate ways to quantify the relative performance of the three reconstruction techniques, on events of varying topology. The PAC further recommends the collaboration to incorporate, where appropriate, cross-checks between the reconstruction techniques in the analysis and publication of their results.

3. Encourages the Collaboration to quantitatively explore the impact of the cosmic ray tagger on the performance of the three reconstruction algorithms.
4. Encourages the Collaboration to continue the systematic work on sharing the tools and lessons learned with the upcoming experiments using liquid argon TPC technology. The PAC emphasizes the importance of data and analysis preservation for results comparisons with the other SBN experiments.

Recommendations:
The PAC:

1. Encourages the collaboration, in its upcoming results on the low-energy excess analysis, to take full advantage of the cross checks in selection and systematic strategies it has developed.
2. Encourages the collaboration to develop a prioritized plan for its future analyses. The plan should take into account the data-taking and analysis schedules from the other elements of the SBN program and the concomitant resource constraints from shared personnel and from computing. It should weigh the expected impact of the results against the likelihood of their success on the available time scale.
3. Recommends that efforts to validate and improve neutrino event generators remain the integral part of cross section studies as more exclusive reactions are analyzed.

Status of the SBN Analysis Working Group

Charge: We ask the committee to review the status of the SBN analysis group activity, the status of the recommendation from the December 2020 PAC meeting (see below) and the outcome of the studies of sensitivity for the SBND and ICARUS detector with the two possible overburden configurations.

- *"The PAC recommends the SBN analysis working group support the ICARUS collaboration in using the common tools developed in SBN to quantify the sensitivity of running ICARUS in the single- detector mode, as is planned in the current timeline, and to assess computing needs."*

Findings:
The PAC heard about the recent evaluation of the cosmic ray (CR) induced background at SBND and ICARUS with and without 2.8 meters of concrete overburden. A detailed simulation was performed, including accurate descriptions of the geometry and composition of the experimental setups. It is found that the overburden significantly reduces certain components of the CR background, particularly photons, protons and neutrons.
While the impact on SBND is negligible due to the large neutrino event rate, larger effects are found at ICARUS. In particular, the rate of cosmic induced π^0 background without overburden is higher than that from dirt production. The presence of overburden significantly reduces this background at ICARUS. This hints at an important role played by the overburden, although a definitive assessment of its impact on the physics reach of ICARUS would require a more thorough analysis.

Common software structure and computing optimization is being shared between the two experiments. The SBN analysis Working Group continues to organize workshops and tutorials, as well as to compare ICARUS data with Monte Carlo. The working group has also devoted efforts to event selection developments and the impact of different neutrino-argon cross section models on the event statistics (though not on the experimental sensitivity). Finally, SBN requested computing resources and is working with experiment and Laboratory experts to address computing bottlenecks. SBN is awaiting a final report from the Fermilab Computing Resource Scrutiny Group review.

Comments:
The PAC:

1. Commends the on-going progress in the development of common tools for SBND and ICARUS.
2. Commends engagement with the Scientific Computing Division and is eager to see the response from the Fermilab Computing Resource Scrutiny Group review and the application of computing resources to actual data.
3. Commends the completion of the cosmic background study with and without overburden. While an assessment of the overburden impact on the experimental sensitivity was not completed, the studies presented hint at a possible important role played by the overburden in ICARUS.
4. Looks forward to sensitivity analyses including the systematic uncertainties, as noted in previous reports.
5. Notes that neutrino interactions from the NuMI beam in ICARUS will provide a timely opportunity to test/validate the common liquid argon TPC tools in the energy range relevant for DUNE. The comparison between the performance of Pandora, Machine Learning and Wire-Cell reconstruction techniques may spur further development of these tools. Likewise, cross section studies with the NuMI beam will allow probing the physics of the resonance-to-DIS transition with an Ar target. Benchmarking GENIE against the expected ICARUS measurements will be beneficial for the DUNE physics program.

Recommendations:

1. SBN should support the use of common tools to develop the ICARUS-only physics case. This should include sensitivity projections incorporating systematic uncertainties and backgrounds.
2. SBN should begin developing tools for cross section analysis that would help to leverage the unique characteristics of ICARUS. In particular, ICARUS will be sensitive to neutrinos from the (off-axis) NuMI beam, which has a large overlap in energy with the future DUNE neutrino spectrum, allowing for important neutrino-argon interaction studies.

Status of the ICARUS detector

Charge: We ask the committee to review the status of the ICARUS detector and the status of the recommendation from the December 2020 PAC meeting:

- *"The PAC recommends the collaboration to further develop the ICARUS-only physics goals using the common SBN simulation and analysis tools and present more details, including the computing needs, in the next PAC meeting."*

Findings:
The PAC heard about the commissioning of the ICARUS detector, which reported very stable operations, a significant improvement in LAr purity allowing the detector to achieve the nominal ~3 ms free electron lifetime, and data taking triggered by both Booster and NUMI beam spills. All of the side walls of the CRT are now installed and being commissioned, leaving only the top CRT which is planned to be installed during the summer shutdown. ICARUS has recently begun full-time operation collecting minimum-bias neutrino beam data, which will be used to tune reconstruction tools. The PAC congratulates the collaboration for these numerous achievements and on its preparation of the detector for the upcoming physics run.
Studies utilizing SBN common simulation tools were presented that demonstrate that, for ICARUS, an overburden significantly reduces backgrounds that cannot be tagged by the CRT, so the balance of available data suggests that the overburden is a well-motivated detector improvement. The Committee heard a presentation pointing out additional implications of cosmic ray induced background in the form of pion production that may have implications for analysis of ν_μ events. The Collaboration anticipates installation to begin late in 2021, contingent on both procurement and smooth installation and commissioning of the top CRT.
The goals of ICARUS early physics running are driven by a test of the NEUTRINO-4 anomaly. The experiment's sensitivity to this anomaly in light of the current detector status and the planned improvements has not been quantified.
The necessary resources for data storage and processing for 2021-2023 were presented.

Comments:
1. The PAC notes that activities planned for the summer shutdown depend on the presence of international collaborators on site and encourages the laboratory to continue to facilitate this process.

Recommendations:
1. The PAC recommends that the improvements in detector characterization from cosmic and neutrino beam running be incorporated into SBN common reconstruction/analysis tools as soon as possible to allow for detailed sensitivity studies including systematics, which may help in prioritizing detector and reconstruction software development tasks as well as the physics goals for the ICARUS-only data taking period.

Update on the SBN Organization

Charge: We ask the committee to review the status of the SBN organization.

Findings:
The PAC heard a report from the Chair of the SBN Institutional Board on the structures defined to oversee the completion of the SBND and ICARUS detectors, to develop plans and procedures

for their commissioning and operation, and to coordinate efforts toward combined physics analyses in the context of the SBN Program. Two main common boards are in place: the SBN Oversight Board and the SBN Institutional Board. In addition, there are several joint working groups mainly focused on SBN operations and physics analysis. MicroBooNE is not currently a participant in the data sharing, analysis, and publication agreement and does not participate in the Oversight or Institutional Boards.
The Institutional Board is making substantial progress in the preparation of by-laws and rules for a series of committees in charge of the approval of common scientific results, publications, presentations and computing resources.

Comments:

1. The PAC encourages the SBN Institutional Board to finish the writing and approval of organization and data-sharing agreements and have in place the committees in charge of managing the common tasks. The envisaged framework will be very important to maximize the impact of the SBN data.

Recommendations:
None.

Status and plans of the Argon Cube 2x2 demonstrator

Charge: We ask the committee to review the status and plans of the Argon Cube 2x2 demonstrator. In addition, the PAC is asked to evaluate the readiness of the demonstrator for a Stage 1 approval as a test technology experiment.

Findings:
The motivation of the 2x2 is to demonstrate the novel segmented LArTPC technology can be assembled and operated, and that the technology is able to be calibrated with throughgoing muons and is able to identify and reconstruct tracks from neutrino interactions.
The demonstrator is being constructed on a schedule which will enable it to inform the final design of the ND-LAr detector, with a large portion of the ND-LAr consortium directly engaged.
Significant funding for the 2x2 has been secured, but installation and operation at Fermilab will also require resources from FNAL.
The successful run of Module 0 is an encouraging demonstration of the project's feasibility.

Comments:

1. The 2x2 demonstrator project is very valuable because of its ability to demonstrate the novel technology for DUNE near detector before it is mission critical for DUNE physics.
2. Possible issues related to the timeline (full-scale modules installation underground, cryostat operation, use of cryocoolers, etc.) should be addressed carefully to be in time to inform the Final Design Review in late 2023. The schedule appears tight and the Committee suggests evaluating the risks there are to meeting that schedule and would reduce the usefulness for that review.

Recommendations:

1. The project is technically feasible and is needed as a key input for the DUNE ND program. The PAC recommends proceeding to stage 1 approval.

Fermilab's plans for contributing to the near and far detector prototypes, and the upgrade of ProtoDUNE experiment

Charge: We ask the committee to review Fermilab's plans for participation in the construction of the near (ArgonCube 2x2 demonstrator) and far (cold electronics test stand, HV test stand) detector prototypes. The PAC is also charged with reviewing the laboratory's involvement with the past and future phases of the ProtoDUNE experiment at CERN.

Findings:

The PAC heard an overview of the involvement of Fermilab in different prototypes and test stands in the context of DUNE. The resources are deployed where they can have the most impact leveraging other FNAL capabilities. The aim is to complement the effort from university collaborators.

At present 154 FNAL scientists are DUNE members contributing with 41.8 FTEs distributed in a variety of detector developments, collaboration services and physics simulations and analysis, including the prototyping and test stand efforts.

Fermilab scientific and technical staff played leading roles in the successful ProtoDUNE-SP first phase. We heard that Fermilab personnel will be available to play similar roles in the second phase of ProtoDUNE-SP.

FNAL is heavily involved in developing a photon detection solution for the DUNE Vertical Drift technology. The Laboratory is ready to take a major role in the Vertical Drift photon detection system prototyping and fabrication, but it is also ready to step aside or collaborate if other groups are interested to take leading roles in the detector construction.

FNAL has several important cryogenic test stands which have played major roles in LArTPC technology development, and are expected to be available for future studies as plans for DUNE detectors are finalized.

FNAL is preparing a neutrino test beam facility for DUNE detectors in the on-axis NuMI near hall. The first use will be in the 2x2 ArgonCube demonstrator. The facility could be available for future DUNE-ND tests until the beam ceases operations at the start of the long shutdown.

Comments:

1. The PAC recognizes the high level of engagement by FNAL with ProtoDUNE-SP in the detector integration, test and installation at CERN, DAQ system, cryogenics instrumentation, and data reconstruction and analysis. ProtoDUNE phase II (Module-0 for the first DUNE Far Detector) also needs a strong leadership at CERN which should normally come from the DUNE consortia. The committee appreciates FNAL is equally committed to make ProtoDUNE-II a success and it is ready to contribute where needed.
2. The PAC also supports the general strategy of FNAL to not compete with universities in areas where strong university partners are ready to take on responsibility, and instead to focus on the areas where the host laboratory has to take responsibility.

Recommendations:
None.

Strategic plan of the Future Colliders Organization

Charge: We ask the committee to review Fermilab's strategic plan for future colliders studies (accelerator, detector, physics) and allocated resources.

Findings:

- The PAC heard about the successful organization of the Future Collider Group (FCG), consisting of about fifteen representatives who devote a small fraction of their time, with the goal to develop Fermilab's engagement plans in future collider projects and to provide a forum to synergize efforts on future colliders/accelerators of interest to Fermilab.
- International projects, in which Fermilab is active and can take national leadership, are the ILC, the FCC (ee and hh options), and a Muon Collider. Fermilab has the opportunity to play key roles in the ILC accelerator (in particular the superconducting RF cavities for which activities have already started) as well as in detector development for the ILD. The DOE has signed an agreement in 2020 with CERN to continue the R&D for FCC, with focus on civil engineering, high-temperature superconducting magnet development, and beam physics studies. Fermilab scientists are active in the Muon Collider community, in the areas of magnets, muon cooling, radiation protection, and machine-detector interface.
- The FCG contributes strongly to the Snowmass process through White Papers.

Comments:

1. The PAC commends the current activities of the FCG, in particular, the short-term organization of the Snowmass contributions.
2. The PAC supports the strategy to use FNAL expertise and limited resources to support this process.
3. The structures created for Snowmass participation could be useful for developing infrastructure to support continued accelerator R&D and detector R&D when appropriate.
4. The PAC supports the strategy to participate in international collaborations to become a major player for the next big project on the Energy Frontier outside the U.S.
5. While the FCG is currently exploring a number of possible future projects, no decision can be taken until the Snowmass process is finished and a new P5 strategy released.

Recommendations:

1. In the Snowmass process, the FCG should consider carefully weighing in on the discussions of the US scientific community in order to allow the latter to make informed decisions on the potential contributions of the US in the global projects.
2. The PAC encourages the FCG to use this process also to identify a potential global accelerator project in line with FNAL expertise and development interests, in which FNAL would assume a leading role after the successful completion of the neutrino program.

Report on the Booster Replacement

Charge: We ask the committee to review the status of the Booster Replacement program and of the recommendation made at the December 2020 PAC meeting:
"The PAC recommends that the current task force complete this exploratory phase by Spring 2021 in order to give the necessary input for the second phase".

Findings:
The PAC heard a presentation on the status of the Booster Replacement (BR) process. The replacement is required in order to reach 2.4 MW of beam power for DUNE, as specified in the P5 report. Two distinct options for the design of the beamline are under active consideration. The first involves using a new Rapid Cycling Synchrotron (RCS) to accelerate protons from 2 GeV to 8 GeV; the second envisions an extended LINAC capable of accelerating protons to 8 GeV. Whether the new accelerator should include a Recycler is also part of the design choice and, as stressed in the presentation, requires serious consideration. To meet the timeline of DUNE and the expected schedule for CD0 approval, the technology selection must be finalized by the next PAC meeting.
The Booster Replacement process offers an opportunity to develop one or more additional experiments that would take advantage of the high-luminosity proton beam. The exploratory phase of the physics opportunities for such experiments has been finalized with the completion of white papers and the submission of several Snowmass LOIs. The list identified by the task force is unchanged from the last presentation to the PAC. The presenter noted that, without major modifications in the beamline, the Booster design precludes the possibility of accelerating electrons with the same machine. This puts several of the proposed experiments listed in the table out of reach for this machine.
To select the design of the beamline and to prioritize the Booster physics program, the Booster Replacement Central Design Group (BR-CDG) will be formed. The presentation to the PAC did not describe the composition of the BR-CDG committee or its precise charge. The schedule for the committee's decisions is dictated by expected CD0 approval for the accelerator design by early 2022, as well as the need to prepare a draft of the Conceptual Design Report by Summer 2022, in coordination with the Snowmass process.

Comments:
1. The PAC commends the completion of the first, exploratory phase of the Booster Replacement Task Force via the publication of white papers and several contributions to Snowmass.
2. The PAC notes the tight planning schedule that must be adhered to in order to meet the timeline for obtaining CD0 for the accelerator design. The PAC looks forward to hearing the outcome of the selection process at its Winter meeting.

Recommendations:
The PAC recommends that:

1. The technology selection for the BR be driven by the overarching requirement to deliver a 2.4 MW beam for the DUNE experiment, which is the Laboratory's flagship physics program.
2. The prioritization of the additional Booster physics opportunities should take into account their suitability to the technology selection made for DUNE. The BR-CDG should ensure that there is no unintended interference between the additional experiments and the core goal of meeting the beam power requirements specified in the P5 report.
3. The BR-CDG set up a firm process to ensure the timely definition of the BR project.

Status of the LHC Physics Center

Charge: We ask the committee to review the status of the LHC Physics Center and the status of the recommendation from the December 2020 PAC meeting:

- *"The PAC reiterates, yet again, its strong support for increased LPC funding, and also for dedicated resources to support an ML/AI researcher at the LPC. Not only is funding for junior DRs needed, but funding for senior DRs is also essential. These positions are crucial to foster new activities and collaborations which are especially important now in preparation for Snowmass."*

Findings:

The LPC continues to be a flagship resource for the CMS collaboration and for US CMS, supporting a broad set of programs targeting in particular the education and further development of early career researchers. With over 500 users, the LPC's contributions to CMS physics results are substantial: LPC-affiliated physicists represent the majority of analyzers on nearly 30% of CMS publications in the past two years. While the LPC continues to operate virtually due to travel and laboratory access restrictions, training activities have continued, including the well-attended and received CMS Data Analysis Schools and Hands-On Tutorials, as well as a for-credit course in instrumentation.

The "distinguished researcher" (DR) program has especially enhanced the LPC's reputation for innovation and scientific excellence and has enabled more extensive programming than what could be accomplished by laboratory staff alone. DRs are seen as essential to the vibrancy of the LPC program because they are present on-site for at least half of their appointments, they propose and execute new physics analyses and technical developments, and they are responsible for educational and community building activities at the LPC.

The funding level for the LPC has declined by more than a factor of two since the start of the LHC. This has led to a significant constraint on the DR program, which typically provides travel support, some form of teaching relief for faculty, and half-time salary support for postdoctoral researchers. These cuts have been managed so far by reductions in the number of both faculty and early career researchers funded as DRs, as well as limited or carefully negotiated support for senior researchers. New components to the program, such as the recently initiated AI fellowship, were funded in FY 21 with redirected laboratory travel funds.

Comments:

The PAC:

1. Commends the Laboratory for the LPC's successful track record promoting excellence, professional diversity, and cooperation across institutions, and notes that the Center plays an essential role for US CMS universities, and a high-profile role in CMS as an incubator for new ideas for analyses.
2. Observes that the current level of funding appears to be the bare minimum for sustaining the broad range of activities it supports now, and that positive new directions such as the AI fellowship will require consistent support.
3. Encourages the LPC leadership to continue its current efforts to ensure a welcoming and inclusive workplace climate via surveys and other feedback mechanisms, and to engage with Laboratory-wide resources supporting equity, diversity, and inclusion.

Recommendations:
The PAC recommends that:

1. Essential facts about the structure of the LPC and its successes be disseminated in a concise document, which can be useful to the Center itself, and to other communities that may want to replicate the ideas.
2. Given the Center's unique role in training and in creating networks among CMS scientists, the LPC compile information about the degree of participation in and benefit from LPC programs among scientists from smaller US-CMS institutions, underrepresented demographic groups in the US, and nations with low representation in CMS.
3. The LPC management team continue its efforts on all fronts to maintain the operations of the Center, which requires that the budget is not further decreased, and is ideally increased to better serve more early career researchers.

Status of the CLAS12 Membership

Charge: We ask the committee to review the Fermilab scope for the CLAS12 Membership.

Findings:
The PAC received slides on the proposed Fermilab involvement in CLAS12, which laid out the goals of the proposed involvement in CLAS12 and of the E4NU collaboration. The main goal is to use electron-nucleus interactions, in which the incoming electron energy can be tuned precisely, allowing for at-will selection of kinematical quantities, such as the momentum transfer, to inform neutrino-nucleus interaction models.
These goals are relevant to the current and future neutrino program at the Laboratory. Results of the analysis of CLAS12 data may be used to improve neutrino event generators, which currently fail to predict many aspects of exclusive cross sections. In particular, CLAS12 data will be able to measure electron-nucleus interactions in the resonance and deep inelastic scattering regime, which are the most difficult ones to describe theoretically.
The slides also presented a timeline for CLAS12 which includes a calibration and data taking phase starting at the end of 2021 and lasting approximately three years.
Fermilab personnel involved would be two associate scientists, one current research associate and another one who will be hired soon. A list of potential institutions which may provide external collaborations has been provided.

The proposed work spans theoretical predictions, analysis of data, and comparison of the two through implementation of theoretical predictions into the GENIE neutrino interaction generator.

Comments:

1. The materials make a general case for the value of comparing CLAS12 data to theoretical calculations implemented in the neutrino event generators.
2. Several areas of study with the data are proposed, and outputs of the work were described in responses to questions from the PAC. How these outputs would impact models in event generators is clear qualitatively, but not quantitatively.
3. The work is part of an extensive collaboration (E4NU) with many institutions. The value that the Fermilab scientists bring to the collaboration is largely through individual scientific expertise. It was not apparent whether the work leverages resources unique to FNAL and whether these proposed contributions from FNAL are critical to the work, even if it is likely that these contributions would be valuable.
4. It is not clear what value the collaborating Fermilab members would bring to the CLAS12 experiment proper, nor what benefit this formal involvement in CLAS12 brings that could not be realized by analysis of CLAS12 data as an outside contributor.

Recommendations:

1. If approval from the PAC is required for this work, the PAC should receive a report that addresses the comments above in a future meeting.

Status of the ProtoDUNE Experiment

Charge: We ask the committee to review the status of the ProtoDUNE experiment and the status of the following recommendation (July 2020 PAC meeting):

- *"The DUNE collaboration should continuously ensure that sufficient resources are in place to realize the publication of the physics analyses concerning energy reconstruction performance and cross section measurements".*

Findings:

The PAC received a written update on the ongoing activities of ProtoDUNE-SP. This year's update focuses on the status of various analyses and publications. A year ago, the DUNE collaboration posted its performance paper, which the PAC at the time commended for its high quality. The paper has since been published in JINST and has already gathered over 30 citations.

While no additional papers have since been released by ProtoDUNE-SP, the collaboration reports that the technical paper is currently under internal review and, moreover, as many as 22 ongoing studies are in various stages of completion.

The PAC got a glimpse of some of these ongoing analyses and is very encouraged by the scope of the work and by the preliminary results. These results demonstrate very high quality of detector and reconstruction performance and there is every reason to believe that the results, when released, will be very impressive.

Comments:

1. The results of the ProtoDUNE-SP analyses are expected to provide essential and urgently needed input for validating and improving the key capabilities and analysis tools of the future liquid argon detectors.
2. The energy loss rate measurements ("dE/dx") in ProtoDUNE-SP show excellent particle identification capabilities. The experiment easily discriminates between proton and muon tracks, as well as between electromagnetic showers created by gamma rays and by electrons. This capability is essential both for event selection in oscillation studies and for the accuracy of energy reconstruction.
3. Electron energy resolution is found to be excellent, at the level predicted by detector simulations.
4. Michel electron analysis gives valuable input for modeling the detector capabilities in the energy range relevant to supernova and solar neutrinos.
5. Studies of hadronic scattering and absorption provide important data for the validation of the GEANT4 modeling of particle propagation in liquid argon. This, ultimately, should lead to better understanding of hadronic energy resolution. The PAC encourages the collaboration to report its hadronic energy resolution and energy scale calibration, comparing the results to published simulation results, as appropriate.
6. The low-energy neutron source dataset could prove very useful both for understanding the energy resolution of supernova neutrinos and for full calorimetry of GeV-scale neutrino beam events. The PAC encourages the collaboration to advance the relevant analysis.
7. The PAC encourages the collaboration to use its data to establish the impact of finite volume effects on the accuracy of energy measurements. Doing so may help inform the near detector performance.
8. The PAC encourages the collaboration to use its test beam data for quantitative comparisons of the performance of the Pandora, Wire-Cell, and Machine Learning based reconstruction algorithms.
9. The PAC looks forward to physics/technical results from future ProtoDUNE operations.
10. As the material supplied to the PAC does not note any unforeseen difficulties with the analyses, this suggests that the publication rate could be accelerated with additional resources.

Recommendations:

1. The PAC reiterates its recommendation to the DUNE collaboration to ensure that sufficient resources are in place to realize the publication of the many ongoing physics analyses. Doing so would be very timely to improve the physics capabilities of the upcoming liquid argon detectors, both in the SBN program and DUNE.