Fermilab Physics Advisory Committee Report

29 June-2 July, 2020

Executive Summary:

The Fermilab Physics Advisory Committee (PAC) met 30 June-3 July, 2020 in a virtual forum to review the status of the Laboratory amidst the ongoing COVID-19 pandemic. Despite the inevitable disruptions, the Laboratory continues to advance on critical elements of the 2014 "Building for Discovery Report" from the Particle Physics Planning and Prioritization Panel, while adjusting and planning for the effects of the pandemic.

The meeting began with an overview from the Director on the status of the laboratory. The Laboratory is assessing the impact of COVID-19 on projects in three impact scenarios: low (optimistic/best case), medium (realistic/ best guess), and high (pessimistic/worst case). For operations, 20% less protons were delivered in FY20 and new experiments are ramping up more slowly. The test beam program, which requires significant on-site presence, has been seriously impacted, while data analysis has been largely unaffected with uninterrupted computing support. The pandemic raises longer term demographic issues regarding the reduced presence of university and international users, and the impact of financial pressures on universities. The Laboratory plans to start operations on the pre-COVID target date of 1 November for an eight month run and is investigating starting the new Irradiation Test Area earlier.

The Laboratory has made new hires in neutrino-nucleus interaction theory and lattice QCD, while two other members have earned DOE Early Career Awards. It is actively investigating systemic racism in hiring at Laboratory by examining its past record and ongoing efforts. The Committee would like to hear updates in future meetings about further findings and initiatives, and has made comments and recommendations on this issue in this report for the topics that were discussed in this meeting.

Recent changes in the work visa program, particularly related to the H1-B visa and the limited availability of consular services outside the US, are a serious risk to future hiring and the overall mission of the Laboratory, which requires attracting the best talent globally to the United States. Fermilab is working with other DOE laboratories to respond to this situation.

A transition is underway for the International Linear Collider, where the Linear Collider Board and Linear Collider Committee are expected to give way to an international development team to facilitate transition into the preparatory phase for the construction in Japan. The Committee notes that FNAL is in a strong position to contribute to the accelerator through its vibrant Superconducting RF Cavities (SCRF) program and encourages it to consider strengthening its engagement with the detectors and physics given the continued global support for a next generation electron-positron collider.

For LBNF, the next major step is a review to proceed on excavation activities for the next 54 months. Fermilab is in close contact with DOE management to maintain the scope of the experiment as value engineering proceeds.

The status of scientific computing at Fermilab was reported by the CIO. The first meeting of the new Fermilab Computing Resource Scrutiny Group (FCRSG) was held. Prioritization of R&D activities within the Scientific Computing Division has identified storage and modernization of

HEP physics software as high priority areas. The Laboratory is also planning to respond jointly with NCSA to a FOA to host the LSST data facility.

The Laboratory continues to rapidly develop its Quantum Information Science (QIS) effort. Superconducting RF Cavities have already yielded results on dark matter searches and quantum non-demolition detection, while Fermilab is building facilities to serve as a testbed for quantum processors produced elsewhere. FNAL scientists have developed an instruction module in quantum computing for high school students. FNAL has submitted an application to host a national quantum center; the outcome is expected soon. The committee continues to support reinforcing its QIS efforts through the one or more (associate) scientist hires.

In the Cosmic Frontier, the Laboratory has partnered with ANL and the University of Chicago in a proposal to lead CMB-S4, with ANL as lead Laboratory. SuperCDMS-SNOLAB will have a rebaselining review following a reduction of its cryostat capacity. The Laboratory also is leading operations and testing for ADMX. The Committee believes that with its long history in sky surveys and expertise in large scale computing, Fermilab is in a strong position to host the LSST Data Facility. The broad range of activities also offer opportunities for cross-programmatic synergies.

The Committee heard about recent developments in Detector R&D at FNAL, including a new competitive process ("New Initiatives") for awards. Exciting new initiatives in ASIC development, LGADs, Skipper-CCD, and pixelated LArTPC readout were discussed, and the Laboratory is in a strong position to lead initiatives in the Snowmass planning process.

FNAL continues to play a central role in CMS efforts, with leadership efforts in the HL-LHC CMS upgrades, operations, software development, hosting of a Tier 1 facility, and the LHC Physics Center (LPC). The collaboration recently reached a milestone of its 1000th publication overall. In FY2020, eleven of these publications were led by the FNAL group in FY2020. The Laboratory has made effective efforts to strengthen the program despite the constrained resources. The Committee continues to support the reinforcement of its HL-LHC activities through additional hires, the replacement of end-of-life Tier-1 hardware as the Laboratory plans a long term transition, and to maintain the LPC Distinguished Researcher program, particularly in engaging with the Snowmass activities and machine learning-related projects.

The Committee heard reports on the Accelerator Upgrade Program (AUP), which coordinates US HL-LHC contributions, and IOTA, a storage ring dedicated to accelerator and beam physics studies. AUP is delivering ten cryo-assemblies for twenty dipole magnets along with ten RF cavities for the crab cavity system. Overall, the project has been on track and an assessment of potential impacts due to COVID-19 are in progress. IOTA was commissioned in 2018 with a first run in 2019. Construction of the proton injector was started in 2019 with the goal of operating a proton beam in 2021. An optical stochastic cooling study has been postponed to Fall 2020 due to COVID-19. High priority studies for the future are related to beam loss studies for high intensity/brightness beams and cooling for next generation colliders. The dedicated environment has allowed non-FNAL collaborators to perform experiments efficiently.

The muon g-2 experiment started its third run at the end of 2019, accumulating 3.3 times the statistics of the BNL experiment until operations were stopped due to COVID-19. The Committee heard about the result of improvements to temperature variations in the experiment hall and the kicker magnets, which has resulted in increases in efficiency and stability. Analysis of the Run 1 data, which requires a careful treatment of the varying run conditions, continues. The Committee looks forward to these first results from the experiment.

The Committee was updated on recent developments at MicroBooNE, including the deployment of a new software and simulation framework (MCC9) that is the basis for significant across-the-

board improvements, including recent results presented at Neutrino 2020. The flagship low energy electron excess analysis is in its final stages with results expected soon.

The NOvA experiment maintained high data-taking efficiency in FY20 despite COVID-19 and presented new, high impact results on both neutrino-nucleus interactions and neutrino oscillation parameters at Neutrino 2020. The Committee considers continued prioritization of operation and computing resources for the experiment to be crucial, particularly in delivering the full planned exposure before the long shutdown for LBNF.

The ICARUS experiment has achieved important milestones on the path towards operations, including commissioning of the cryogenic system and filling of the detector with LAr, which continued through the curtailment of Laboratory activities due to COVID-19. Work is continuing on commissioning the high voltage and PMT systems. The Committee encourages the collaboration to prepare for continued potential disruptions, particularly with regard to travel, due to COVID-19.

SBND reported its progress on detector construction, with most components now available from collaborating institutions and arriving at Fermilab for assembly. The cryostat construction is on the critical path, with delivery expected at the end of 2020. The project schedule was recently reviewed prior to COVID-19 and another review is scheduled for the Fall.

A working group on the potential physics program of a Booster replacement, the primary purpose of which is to deliver 2.4 MW to LBNF, has been formed and held a workshop exploring opportunities in dark sector, neutrino physics, charged lepton violation, precision tests, and R&D for future facilities. Through its Scientific Advisory Committee, FNAL has engaged in a lab-wide effort to exchange and develop ideas for Snowmass, and is strongly positioned to make contributions across a wide range of areas in this important process. The Committee notes that the Snowmass process requires significant commitment over a long period of time, and scientists participating in the process will require both support and recognition for their contributions.

The Committee received further reports from the Long Baseline Neutrino Committee (LBNC), ProtoDUNE-SP, and the Snowmass Community Study, and held an informal discussion on the recent update to the European Strategy for Particle Physics.

The Committee expresses its gratitude and appreciation for the concise and highly informative presentations, particularly given the challenges and time limitations arising from the new virtual format.

Attendance (all remote):

Physics Advisory Committee: E. Aprile, A. Arce, F. Canelli, A. Friedland, I. Gil-Botella, F. Halzen, K. Heitmann, P. Machado, L. Malgeri, K. McFarland, I. Melzer-Pellmann, H. Montgomery (*ex-officio*, LBNC), S. Miscetti, C. Simon, A. Szalay, H. A. Tanaka

Scientific Secretary: A. Canepa

Fermilab Directorate: G. Bock, J. Lykken, N. Lockyer, H. Ramamoorthi, L. Ristori

1. ***Status of Scientific Computing at the laboratory Charge: We ask the committee to review the status of Software and Computing at the laboratory and the status of the recommendations made at the January 2020 meeting.***

Findings:

The Committee heard a detailed and comprehensive report on the status of the scientific computing effort at Fermilab from the FNAL CIO.

The Scientific Computing Division (SCD) continues to effectively support hardware and middleware services for more than ten experiments with a wide range of resource needs. The largest, CMS, currently represents roughly as much processing and storage as the Intensity (IF) and Cosmic Frontier (CF) experiments combined.

The SCD presentation to the PAC included responses to the recommendations from the previous PAC meeting. Since the last review, the Fermilab Computing Resources Scrutiny Group (FCRSG) had its first meeting, which was delayed until May due to schedule changes related to the pandemic. This resulted in a detailed report that was made available to the PAC.

The SCD reported on two R&D priorities, storage and modernization of physics codes. Fermilab experiments were able to use 144M CPU hours at HPC centers and 33M CPU hours on OSG in addition to their local resources.

A budget request to DOE for computing resources was presented. The SCD is awaiting DOE's response. This request includes hardware replacements.

Fermilab is planning to respond to the FOA to become the LSST Data Facility together with NSCA. This plan is a good and timely opportunity to hire junior people that will be trained and in the future can then also contribute to the IF and EF experiments. Planning exercises for Mu2e, DUNE, HEP-ESNet and Snowmass were also discussed, along with investigations for funding and science opportunities in the area of AI/ML.

Comments:

The PAC thanks the SCD for preparing a detailed and informative presentation to address our recommendations from the last PAC meeting. We revisit the recommendations from the previous meeting:

Recommendation 1: Report on how the SCD plans to satisfy the needs of different experiments

The PAC would like to thank the CIO for providing a detailed report on the resource usage by the experiments. The information was very useful to understand in detail the Fermilab Service Model for computing. It appears that SCD is able to provide adequate computing resources to the different experiments that are currently running at Fermilab. Some experiments have also been able to utilize resources on HPC systems and the OSG. Facilitating the use of these additional systems in the future will be important to ensure adequate computing resources in the long term.

The PAC notes that the availability of storage may become a problem in the future. In particular the rapid growth of tape requests seemed to be a concern. SCD has started to work with the experiments to address this issue. We look forward to hearing more about the overall plans in the future, including storage management developments and advances by the experiments to make continued use of HPC systems and the OSG.

Recommendation 2: Report about the FCRSG process and its outcome

The PAC thanks the CIO for providing the FCRSG report in advance of the meeting. This detailed report demonstrates that the scrutiny mechanism is well-suited to ensuring that SCD can continue to forecast experiment resource needs and to proactively align its effort to match the challenges of growing needs. The report highlights a particular issue in storage R&D where there are clear challenges on the horizon. The PAC considers the SCD response, focusing on integrated data lifetime policies and models to effectively leverage different storage services across architectures, to be appropriate. The PAC supports the outcome from FCSRG regarding refinements to the scrutiny process, which will improve assessment and review of experiment requests, as well as the recommendations for investment of effort towards future challenges in processing and storage for the experiments.

Recommendation 3: Ranked list of high priority software R&D projects

The PAC appreciates the clear articulation of priorities in the presentation.

For the first priority, Storage R&D, the PAC encourages the SCD to explore more innovative solutions. It is clear that the growth of the cost of long-term (tape) storage without data lifetime management will become untenable in a few years. This requires more attention and broader and creative thinking before it is too late. An aggressive data lifecycle management combined with exploration of more advanced algorithms for data compression, such as those developed as part of the Exascale Program, may yield considerable savings. Also, exploring innovative uses of elastic overflows to commercial clouds may be an interesting possibility. As it was noted in the presentation, current commercial storage prices in the cloud are much too high. However, this may be the result of a few factors that may be overcome with some negotiations. For example, (a) egress fees are the result of using the commercial internet for data transfers - dedicated ESNET gateways to the commercial clouds may eliminate this cost, (b) the commercial service guarantees are more stringent than needed for science - one may be able to negotiate better rates with less redundancy, (c) longer term contracts could take into account Kryder's Law, the exponential drop in the cost of storage - this may result in substantial discounts over a decade-long timescale.

The Committee had concerns regarding plans to drop the use of Globus. The development and maintenance of custom software for e.g. data transfer is usually much higher over time than the cost of Globus. Given that other DOE facilities are using Globus very successfully it is not clear why Fermilab wants to invest resources into building their own software. A more detailed cost/benefit analysis is warranted.

The PAC would like to stress that a careful integration of the Fermilab/OLCF Geant4 efforts into the international Geant4 developments is important. The development work at Fermilab should therefore be regularly reviewed to ensure this integration is progressing well.

LSST Data Facility:

The possible award of the LSST Data Facility is an exciting but also very challenging opportunity for SCD. The LSST project is close to commissioning, which will be followed by a transition to operations. Compared to the status of the instrumentation and the observatory, the data management is less advanced, meaning that the Data Management (DM) group will play a critical role with little margin for error due to the timeline. Given these risks, the PAC encourages the Laboratory to proactively prepare for the formal decision about Fermilab's involvement. A small task force to plan for this transition could significantly reduce the time needed for the transition, and would enable the Laboratory to hit the ground running. Needless to say, the transition will involve many partners, but as the main responsibility will stay with the Fermilab, it is necessary to understand the LSST group's position within Fermilab, both physically and organizationally.

Recommendations:

Given the short time scale to the start of Vera Rubin/LSST operations and the host selection for the data facility, and considering the complexities in the data processing task, we recommend that Fermilab establish a small task force to plan for hosting the data facility as soon as possible. The task force should represent expertise in large-scale computation and storage and sky survey experience. The charge to this group would build upon the proposal presented in December 2019 and work out an internal transition plan, including preparing job descriptions for potential hires, considering various alternatives for hardware solutions, their placement, and levels of integration/sharing with other computing resources with the aim of optimizing economies of scale where possible. This plan should include the evaluation of the currently available software that will be delivered by the project in order to assess and prepare for any remaining risks. It should also include a detailed evaluation of the currently proposed approaches, e.g. qserv and possible short-comings. Finally, it should include computing resource estimates.

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.

2. ***Status of the QIS program at the laboratory Charge: We ask the committee to review the status of the QIS program at the laboratory (including MAGIS) and the status of the recommendations made at the January 2020 meeting.***

Findings:

The Committee received an informative update on the status of QIS activities at the Laboratory from the FNAL Deputy Director for Research.

The Committee learned about several publications as well as unpublished results in the quantum area. In particular, the SCRF-based dark matter search has already generated new results thanks to quantum technology development. There were also unpublished results on the quantum non-demolition detection of single photons in SCRF cavities and on high-fidelity quantum teleportation.

Fermilab serves as a testbed for superconducting quantum processors fabricated at other institutions such as NIST, and is developing a quantum network testbed (IEQNET) in the Chicago area. We learned about intensifying industrial collaborations with Rigetti and Google on quantum computing. FNAL postdocs have also developed a high school module on quantum computing.

MAGIS-100 is making good progress on laser system development, but is facing COVID-19 related challenges in other areas. We also heard brief updates on the development of a DOE quantum internet strategy and on Fermilab's involvement in proposals for national quantum centers.

Comments:

- It is remarkable that the quantum technology effort is already yielding results that are directly applicable to HEP goals such as the dark matter search.
- The unpublished results on quantum non-demolition detection of single photons and on high-fidelity quantum teleportation may also be significant for quantum technology development.

- The testbed efforts are valuable contributions to advance the maturity of quantum computing and quantum networks that seem well aligned with the role of a national lab in this space.
- The industrial collaborations sound promising.
- The high school module on quantum computing is an excellent initiative to strengthen talent development in this critical area.
- We were glad to hear that MAGIS-100 has been able to make progress on the laser system under the present challenging circumstances.
- We continue to support the Laboratory in playing a leading role in the development of a national quantum internet strategy and of national quantum centers.

Comments on previous recommendations:

One of our recommendations from January 2020 was to explore international collaborations regarding the quantum internet. Fermilab is waiting for guidance from DOE on this. The Committee iterates its view that international collaboration is critically important in this area.

The other recommendation was to strengthen the quantum area through one or more associate scientist/scientist hires. There have been discussions about this in the context of the national quantum center proposal. The Committee's perspective is that such hires continue to be a high priority. In particular, we think that the quantum networks area, which is critical for the Laboratory's plans to play a significant role in the development of a national quantum internet strategy, needs permanent leadership with experimental expertise.

Recommendations:

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.

3. ***Status of the Cosmic program at the laboratory Charge: We ask the committee to review the status and future perspectives of the Cosmic program at the lab, including expected contributions to LDMX and CMB-S4, and the status of the recommendations made at the January 2020 meeting.***

Findings:

The Committee heard an update from the head of the Particle Physics Division on the Cosmic Program priorities, the status of the ongoing experimental and theoretical efforts, and the long-term strategy for the program. The experimental program consists of three broad categories: large scale structure surveys, direct-detection dark matter searches, and CMB experiments. Fermilab has an impressive record with its decades-long involvement with sky surveys, starting with SDSS and continuing with DES and DESI. The Laboratory contributed to the construction of DESI and is presently playing a small but crucial role in DESI operations. Fermilab is preparing to respond to an expected DOE FOA for the LSST Data Facility.

For the dark matter program, a comprehensive approach includes direct, indirect, colliders, and astrophysical (surveys) probes of dark matter. Some of the R&D effort is resulting in its first science results, with SKIPPER@MINOS record-setting limits on MeV dark matter interactions with electrons.

CMB-S4 and SuperCDMS are passing major milestones in the near future. CMB-S4 is awaiting the decision on the choice of the leading laboratory and the result of the evaluation by the astronomy Decadal Review. Fermilab has partnered with ANL and the University of Chicago to develop a proposal to lead CMB-S4 in which ANL would be the host lab with Fermilab and the University of Chicago supporting institutions. SuperCDMS is heading for a rebaselining review. Fermilab has played an important role in SuperCDMS from the start and continues to do so. Despite the reduction of the cryostat capacity from 31 to 7 detector towers due to the redesign of the dilution refrigerator system, the potential for exploring a significant dark matter parameter space at low masses is still present.

The Laboratory involvement in LDMX at the moment is limited to one experimentalist and dark-sector model-building efforts by a small group of theorists. As for ADMX, FNAL is a lead laboratory responsible for operations and testing the hardware array for Run 2. Data taking continues despite the COVID-19 restrictions, with remote shifts and weekly site visits by a few essential personnel. Funding for designing the next-generation experiment has been provided by a Dark Matter New Initiatives grant.

Comments:

With its decades-long involvement with sky surveys, starting with SDSS and continuing with DES and DESI, and given the scale of LSST and the scope of the tasks of the data management, Fermilab is particularly well-placed to host the LSST Data Facility.

Several ongoing initiatives cut across the Laboratory organizational structures and would benefit from coordination between divisions and programs. For example, the technology of Skipper CCDs may have potential beyond advancing dark sector bounds. Its applications to quantum imaging and neutrino physics can develop into new, fruitful areas, if sufficiently supported. This calls for coordination between the Cosmic, QIS, and Neutrino Programs. Another example in the presented material is the possibility of using the LDMX detector to improve the physics of neutrino-nucleus scattering. This SLAC-led effort is presently joined by a single FNAL scientist. Engaging a team of experts in the Neutrino Division tasked with improving neutrino interaction modelling could bring considerable benefits.

Recommendations:

If Fermilab is chosen to host the LSST Data Facility, it needs to consider the science impact on research at the Laboratory and in coordination with the SCD they should develop an integrated plan for this opportunity. LSST would fit quite naturally with ongoing efforts, like the various cross-correlation projects, and it would be wise to consider potential hires into the Cosmic program related to LSST science.

There appear to be physics opportunities that cut across the existing group and division structure. Coordination between efforts in the areas such as sensor development or neutrino physics could have significant physics and institutional benefits.

4. Status of the Detector R&D at the laboratory Charge: We ask the committee to review the status of the detector R&D program at the laboratory, the long-term strategic plan, and the role of Fermilab within the community.

Findings:

The PAC heard a detailed and clear summary of the April 2020 Detector R&D strategic plan. It aims to align R&D activities with the science priorities of Fermilab, its technical expertise, and DOE basic research needs for detectors. The plan emphasizes two main directions for

expansion: liquid noble element detectors for neutrinos and picosecond timing detectors primarily for collider physics. The plan also supports increased funding for "blue sky" ideas, which may be high risk and not aligned with these foci, but could be transformative technologies.

A mechanism for seeding new ideas are the "New Initiative" awards in response to competitive initial stage R&D proposals. Three awards were made last year, in areas related to the priorities described above. The strategic plan recognizes the goals of workforce development and technology transfer. Collaborations with partners outside of Fermilab are valued, and examples of these are described in the strategic plan. Several examples of exciting new R&D initiatives, in areas such as ASIC development, Low Gain Avalanche Detectors, Skipper-CCDs, and Pixelated LArTPC Detector Readout were presented to the PAC.

The Laboratory continues to maintain and modernize facilities for detector R&D, and recognizes this infrastructure as critical for attracting FNAL scientist and user effort to Fermilab's detector R&D program. The Fermilab Detector R&D group is well positioned to lead initiatives in the Snowmass planning process. The PAC heard that more than thirty whitepapers with significant Fermilab involvement are already planned.

Comments:

"New Initiative" awards are only open to PIs who are Fermilab employees, although there is one example of a co-investigator currently at a university. As the strategic plan notes, bringing in more users from universities and other national laboratories is an effective way to broaden the impact of Fermilab's Detector R&D program, and to attract students into the area of Detector R&D. The Laboratory could consider a proposal-driven process along these lines.

Opportunities and mechanisms for technology transfer outside of HEP are briefly discussed in the strategic plan, but were not a focus of the discussion. These ideas could be developed further and discussed with Laboratory leadership and with the PAC in future meetings.

The Department of Energy recognizes Fermilab's ASIC group as a "core competency" and critical resource for the national HEP program.

Many areas of Detector R&D enjoy critical contributions from senior staff at Fermilab. Succession planning for these staff members will require active and careful collaboration from the Detector R&D leadership and Laboratory management.

Recommendations:

None

5. Status of the CMS Experiment Charge: We ask the committee to review the status of the CMS experiment including research, operations, and upgrades with focus on the Fermilab contributions and the management of the national programs.

Findings:

The PAC heard a comprehensive report on the status of the CMS experiment that included a summary of the impressive range of activities within Fermilab and US-CMS.

Fermilab continues to hold leadership roles in the international CMS collaboration and in addition leads, manages, and supports the US program with scientists serving as managers of the HL-LHC CMS Upgrade and US-CMS Operations Programs. The Fermilab group continues to lead in computing operations, development of simulation and reconstruction software, as well

as computing R&D. The Fermilab CMS members are active leaders and participants in the community planning process and are highly recognized for their contributions to cutting edge science and technology.

CMS continues its outstanding record of publications, reaching 1000 papers published based on LHC collision data. During FY20 the Fermilab group led the analysis for eleven publications/public notes and two review papers. Fermilab scientists contribute significantly to exploiting physics opportunities provided by the CMS data in many relevant areas. Fermilab members are involved in developing advanced analysis tools with AI/ML in different areas such as analysis, object reconstruction, identification, and triggering. This effort is synergetic with the Fermilab AI initiatives, whose scope extends labwide and beyond the needs of the CMS experiment.

The Fermilab Tier-1 center carries 40% of the CMS-Tier-1 capacity. It has been performing excellently and enabling physics data analysis. A needed refurbishment of equipment has been requested in the FY21 FWP. This would bring the Tier-1 facility back to a state where all equipment is within warranty and provides important redundancy in case of future possible procurement delays.

Fermilab plays a central role in the software modernization that is needed to cope with the anticipated large data rates expected in Run 3 and HL-LHC. In particular, Fermilab scientists contribute, in collaboration with the wider community, to the development of detector simulation, storage-effective data formats, fast analysis frameworks, and innovative algorithms and data structures such as AI/ML solutions to data reconstruction that are cost-effective and able to exploit modern HPC architectures.

Fermilab has strong participation in the HL-LHC upgrade of the CMS detector with core deliverables for the Outer Tracker, High Granularity Endcap Calorimeter (HGCAL), Endcap MIP Timing Detector (MTD), and the Trigger and Data Acquisition (TDAQ) systems. These upgrades take advantage of the unique on-site infrastructure at Fermilab such as the Silicon Detector lab (SiDet) and the planned Irradiation Test facility (ITA), as well as continued engineering and technical support from the ASIC group. Significant progress has been made on ITA, which is crucial for validating sensors for the Outer Tracker upgrade. Fermilab continues to engage junior scientists in detector development and upgrades. In the past year, several junior members have received awards for their outstanding contributions to detector design and development.

A significant decrease in the Fermilab CMS group is expected in the next few years due to career evolution and retirements, potentially impacting near-term Tracker deliverables for the CMS HL-LHC upgrade. The Laboratory has included the hire of an Associate Scientist and a Senior Scientist to oversee the HL-LHC upgrades in the guidance for the upcoming FYs. While the initial focus of these persons would be on Tracker activities at SiDet, they will play an important role in future detector R&D efforts.

Fermilab's LHC Physics Center (LPC), including its Distinguished Researchers (DR) program, continues to stimulate new analyses and developments and enables involvement in operations, upgrade, software and computing activities. Thanks to contributions from the US-CMS Operation program (Ops), in FY2020 LPC was able to support three senior DRs (travel only), fourteen junior DRs, and two Graduate Scholars. This is significantly lower than in previous years where twenty DRs and three Graduate Scholars were supported, but sufficient to keep core research and educational programs afloat. Through focused outreach towards underrepresented groups, the DR program has maintained a notably higher participation of women in the past four years. For FY2021, the LPC requested minimum funding at the same level as in FY2020 (from both Research and Operations), plus provide additional support to

establish an annual LPC AI/ML fellowship to get new ML-related projects off the ground and partial salary support for few senior DRs to lead Snowmass efforts at the LPC.

With COVID-19 access restrictions, the Center has continued to operate most of its regular events over video with a larger level of engagement and participation. Due to Fermilab access restrictions most users are unable to access hardware labs, test-beam facilities, *etc*. The full impact on the physics and operations/upgrade programs still needs to be quantified. The Center has initiated a survey to better understand the effectiveness of LPC programs and challenges faced by the community during this period.

Comments:

The PAC congratulates Fermilab's CMS group for its important role in the International CMS Collaboration's exceptionally proficient physics output, which reached a major milestone of 1000 publications.

The PAC commends the Laboratory for continuing reinforcing its ASIC group as well as support facilities. This support is of paramount importance for the HL-LHC core deliverables of the Fermilab CMS group. The Committee also strongly supports the Laboratory's commitment to engage junior scientists in detector development and operations.

The long lead time of the HL-LHC upgrade makes it urgent to plan for the replacement of departing scientists. The new hires requested are essential for Fermilab to deliver its commitments to the CMS HL-LHC upgrades. Without replacements, the Laboratory may lose core expertise and the ability to execute succession planning for its leadership in the HL-LHC upgrades.

The LPC is widely recognized as a unique asset to the Fermilab and CMS communities. In the past year, the LPC suffered a reduction in the research budget of 50%, which limited the DR program severely. The FY2021 request allows the LPC to maintain the current minimum funding scenario while enhancing the support for additional DRs and establishing a new ML/AI LPC fellowship initiative in line with national priorities. DRs are expected to be engaged in Snowmass preparation, possibly including the discussion of future colliders. The MLAI LPC fellowship is meant to consolidate ML/AI projects with the goal of improving impact on various aspects of CMS. The DR program has been proactive and successful at encouraging the participation and visibility of CMS members from underrepresented groups in physics and could play a supportive role in the Laboratory's planned activities against systemic racism in the field.

Recommendations:

We recommend the Laboratory, in coordination with DOE, to support the request to hire an Associate Scientist and Senior Scientist dedicated to supporting the HL-LHC activities,

The PAC continues to recommend the full replacement of end-of-life computing equipment of the Tier-1 computing resources for the CMS physics program, and that the Laboratory urgently proceed on development of a long-term computing transition plan as recommended at the last PAC meeting.

Even in this period of COVID-19 restrictions, the LPC has proven to be very effective in its role and in adapting to the circumstances. The LPC DR program is essential for Fermilab and the US-CMS participation in the Snowmass process. The PAC recommends the Laboratory coordinate with DOE to provide the necessary level of support for LPC activities, and strongly

endorses the request for additional funding for dedicated Snowmass activities and to strengthen their efforts in ML/AI-related projects.

6. Status of AUP Charge: We ask the committee to review the status of the AUP project including the potential impact of the Covid19 pandemic.

Findings:

An overview of the Accelerator Upgrade Project (AUP) was presented to the PAC for the first time. Despite the short time, the presentation provided the necessary information with additional useful material in the backup section. An update on IOTA was also provided; we provide comments separately below.

The AUP coordinates activities from several US Laboratories (FNAL, BNL, LBNL, with contributions from SLAC, JLAB, ODU & FSU) with the ultimate scope of delivering ten cryo-assemblies (twenty quadrupole magnets) and ten dressed RF cavities (crab cavities) for the High-Luminosity LHC (HL-LHC) project. AUP will contribute to increasing the peak magnetic field strength by around 50% compared with the current LHC dipoles, allowing the beams to be squeezed before collisions to reach a peak luminosity of $L_{peak} = 5\times10^{34}$ $cm^{-2}s^{-1}$. This is critical for the goal of accumulating an integrated luminosity of 3000-4000 fb^{-1}, a factor of at least ten beyond the LHC's design value, within twelve years after the upgrade.

The AUP project is currently in its CD-3b approval stage with the final CD-3 approval step planned for November 2020. The current schedule of the project foresees an 11-months float before the "needed-by-CERN" date (end of FY2025).

The cable fabrication for the magnet assemblies has a production yield better than anticipated while the coils production has a yield of 75% compared to the anticipated 85%. The first "deliverable" magnet is being tested at BNL. All field quality measurements meet the specifications. The production of the second "deliverable" magnet is delayed by COVID-19. The RFD cavity prototype exceeds HL-LHC requirements.

The COVID-19 pandemic has a direct impact on the assembly of magnets, which has stopped at the national laboratories. The design and procurements activities have continued in telework mode. The three month long Spring 2020 shutdown will reduce the eleven month float between planned completion and delivery dates. The activities in the laboratories are restarting and the efficiency is expected to be well below 100% due to COVID-19 precautions. "What-if" scenarios prepared by the OPSS at FNAL are constructed based on "low", "medium" and "high" impacts. Schedule delays in the "low" impact scenario, with no major second wave and no further lock-down, can be absorbed in the eleven month float. Other scenarios will need a reassessment. More data about production efficiencies under COVID-19 precautions will be ready by the CD-3 review in November.

Comments:

The project manager has shown full ownership and control of the activities. No individual cash-flow issues have been identified. In terms of schedule, the one year delay of LS3 communicated by CERN at the end of 2019, did not change the "needed-by-CERN" date. There may be the possibility for a (positive) increase of the eleven month float which could be discussed with CERN.

The committee commends the AUP project for the high quality of the "deliverable" first magnet assembly (MQXFA03) and of the first crab cavity prototype.

The production yield of the coils is a concern, though assuming a constant lower-than-expected yield, the project still seems to have margins to compensate. The current COVID-19 situation might slow down the understanding of the issue and contribute to additional inefficiencies. This item needs continuous monitoring.

It is difficult to assess at this stage the full impact of COVID-19. The data about the production efficiency will be essential. The current approach with three severity scenarios seems adequate. As of today, with the current contingencies both in schedule and costs, the PAC has no major concern about the timely delivery of the components. Clearly the situation needs to be revisited when new information is available. The PAC agrees that it is too early to decide if and when mitigation actions should be put in place. However, it is commendable that some potential actions are already being identified.

Recommendations:

The lower than expected yield in coil production is a reason for concern shared with the project management. While not yet on a critical path, the PAC recommends a detailed analysis of the situation and its possible consequences especially in view of a reduced efficiency due to COVID-19 restrictions.

IOTA

Findings:

The IOTA (Integrable Optics Test Accelerator) is a 40 m circumference storage ring commissioned to host dedicated beam experiments with both electrons and protons, to study frontier topics in accelerator and beam physics. The FAST (Fermilab Accelerator Science and Technology) facility consists of an electron LINAC, an experimental area, a proton injector, and the IOTA ring. As recognized by the latest GARD review, IOTA and FAST are top rank facilities for intensity frontier accelerator R&D. Although FAST is not a DOE user facility, it welcomes collaborators to conduct experiments at the electron LINAC and IOTA. Currently, thirty collaborating institutions participate in the FAST initiative.

The IOTA ring was commissioned with electrons in summer 2018, followed by 69 days of IOTA Run-1 in 2019. Work on the proton injector assembly started in 2019, followed by 85 days of IOTA Run-2. Originally, the FY2020 schedule included Optical Stochastic Cooling (OSC) studies and the completion of the proton injector assembly. The COVID-19 outbreak delayed the OSC tests to fall and studies with the proton beams are planned for 2021.

Among the priority items for accelerator and beam physics:

- Study and mitigation of beam losses, instabilities, and space charge effects for high intensity, high brightness beams. This includes non-linear optics, Landau damping, electron lenses, and space-charge compensation.
- Beam cooling studies for next generation colliders, such as OSC and EIC cooling R&D.

Collaboration-driven R&D is also carried out at IOTA/FAST such as EIC R&D in collaboration with other beam facilities (FACET, LCLS-II, PIP-II) and quantum science, as well as education and training programs. IOTA maintains a high efficiency for carrying out proof-of-principle experiments by providing a dedicated environment. During the 85 days of IOTA Run-2, nine experiments were carried out over 60 shifts with teams that included outside collaborators and six graduate students. IOTA has also demonstrated a unique capability by storing single electrons in a controlled and reproducible way, allowing to test fundamental principles of quantum science.

A proposal has been made to use IOTA to create a 1D crystal composed of 10^6 ions (~10 m length with 10 μm separation), adding a $^{171}Yb^+$ ion source and lasers for preparing and reading out the quantum states. A five year program is envisioned.

Comments:

The PAC discussed the possibility that IOTA could become a user facility. This would further enhance the participation of universities in the projects, increasing the participation of students and postdocs, thus bringing a new generation of scientists to the R&D and physics programs.

The suggested quantum initiatives are very interesting. In particular, it seems that the proposed ion trapping program could provide quite unique information regarding the scalability of ion-based quantum computing architectures.

7. Status of the g-2 experiment Charge: We ask the committee to review the status of g-2 experiment and of the recommendations made at the July 2019 meeting.

The muon g-2 collaboration presented a comprehensive update of the status of the experiment and of the progresses on data taking and analyses.

Findings

The relevance of the experiment remains very high in the HEP community as proven by the number of citations of the previous measurement from BNL-E821, which has remained stable for many years. A world-wide update of the Standard Model (SM) prediction of a_μ was released in June 2020, placing the BNL-E821 measurement at 3.7 σ from the SM value.

Run-3 started in December 2019 with stable data-taking at a rate of O(1 BNL/month). A raw data sample of 3.3 x BNL statistics was accumulated before the run was stopped in March 2020 due to the COVID-19 outbreak. Including Run-1 and Run-2, the total statistics on tape is now 7xBNL.

The data quality of Run-3 is improved thanks to the following developments:

- The large temperature variations previously observed have been reduced to a negligible range due to the completion of the cooling system. The calorimeter gain corrections are much smaller and the magnet temperature variation is limited to an RMS of 0.04° C.
- The improved temperature stability resulted in much better B-Field stability as demonstrated by the NMR trolley mapping runs. The NMR trolley runs were more frequent thanks to remote operations.
- The problem of the kickers was solved and their high voltage was successfully raised to nominal values, resulting in the beam centered at the ideal radial position. This also increased the number of stored muons and reduced the size of the radial beam oscillations.
- The efficacy of RF focusing was demonstrated reducing the beam oscillations from O(± 10) to O(± 2) mm.
- The overall uptime (DAQ x Quads x Kickers) increased from 83 to 90%.

Progress on the Run-1 Analysis status was also presented:

The precession frequency (ω_a) is obtained by fitting the oscillation plot. Several analyses using different reconstruction algorithms and fitting methods have been implemented. Data have been double-blinded: the real clock-frequency is not known by the experiment and a random generated frequency offset is added to each analysis output. Statistical errors are of O(450 pb)

as expected. The relative offsets have been now removed and strategies for averaging the results between different reconstruction methods developed.

Overall systematics on the B-field analysis from the trolly runs and absolute calibration appear to be well under control. Larger transient fields are observed in the NMR fixed probes near the quadrupoles when they are pulsed. These may be related to vibrations, with an estimated effect on the B-field of approximately 70 ppb. Mitigations are being developed for the upcoming run by adding dampers.

A beam dynamics analysis showed that during Run-1, the failure of a few resistors in the quadrupole system caused beam movement during the fill, increasing the muon losses. This has been fixed after Run-1.

The final evaluation of the systematics is under way. Three detailed papers describing the systematics sources and their evaluation on ω_a, ω_P and beam dynamics corrections are in preparation. The collaboration plans to complete these papers first and then proceed to final unblinding and calculation of a_μ. Although 90% of Run 2 has been processed and reconstruction completion is expected for the Fall, the difference of data taking quality and systematics between the two running periods has led to the collaboration keeping the two samples separated. Results of Run-1 are expected in early 2021.

Comments:

The PAC was impressed by the progress made by the experiments and looks forward to the unblinding and release of the first results.

We turn to past recommendations from the PAC:

Recommendation 1: Status of Lithium Lens, usage of inflector before run-3 and impact on schedule with Mu2e

The experiment has run at lower lens current since April 2019 and no Li lens failures have been observed in Run-3. The usage of the inflector was delayed to the startup of Run-4, but the COVID-19 outbreak makes it impossible to install the new inflector in the current shutdown.

We commend the experiment for its work with the Mu2e collaboration and the FNAL Directorate to oversee the interferences between the two experiments in future running. Assuming no inflector is used, the goal of 100 ppb statistical error requires x20 BNL statistics corresponding to nine months of running in Run 5. The installation of Mu2e electrostatic septum in January 2022 will replace the g-2 extraction kicker, shortening Run 5 to about 6 months. The design of a new g-2 extraction kicker is underway to allow a fast switching between g-2 and Mu2e running and flexibility, and would allow the g-2 experiment to collect the necessary data while allowing the Mu2e experiment to start.

Recommendation 2: Make a solid plan with SCD for data storage and reconstruction

The PAC commends the positive interaction with SCD resulting in significant improvements in the software. The experiment now uses SCD database products and improved the DQM and calibration processes. A review by SCD led to an increase in assigned CPU slots. In the meanwhile, usage of external GRID resources (mainly in the UK) has started. For data storage, a request for increased tape storage, doubling the next few years is being discussed with SCD, along with a policy for deleting old reprocessed data.

The Committee commends the collaboration for the careful work done in the evaluation of systematic uncertainties. Given the relevance and interest in the measurements from the HEP community, we encourage the collaboration to complete the final stages of the analysis in a

timely fashion. For future publications, we suggest formulating a publication plan taking into account the different data taking stages, including milestones to improve tracking.

Recommendations:

The PAC recommends the collaboration to continue pursuing with the Mu2e collaboration and the Laboratory a smooth transition from g-2 running to the startup of Mu2e operations. In this respect, a well informed and timely reporting on usage of the inflector, design and realization of the new g-2 extraction kicker and data analysis is vital for the future assessment of schedule, running priorities or beam sharing.

8. Status of the MicroBooNE experiment Charge: We ask the committee to review the status of the MicroBooNE experiment and the status of the recommendations made at the July 2019 meeting.

Findings:

The Committee heard a detailed report on the significant progress obtained by the MicroBooNE collaboration on analysis, reconstruction techniques, and treatment of systematics. Of particular relevance is the development in MCC9, the latest software framework, of improvements to raw signal processing and noise filtering. MicroBooNE's better understanding of the detector allows them to improve several analyses. For instance, the collaboration has shown an eight-fold improvement on cosmic ray rejection and gains in signal efficiency and purity. Results on π^0 mass measurements, charged kaon reconstruction, and detection of sub-MeV energy depositions are encouraging. MicroBooNE has published its first double differential cross section result, showing that they also reached enough maturity to perform robust, high level analyses. The collaboration is on the cusp of opening runs 1-3 which will be an important step in understanding the nature of MiniBooNE's low energy excess.

Comments*:*

- MicroBooNE has not yet developed a detailed plan for preservation of their data or use of their data for a joint analysis of the SBN experiments. This reflects the focus on the current analyses that were necessary in order to realize the rapid progress of the last years.
- MicroBooNE has engaged with SCD in planning for the resources needed to complete analysis of their full data sets for oscillation analyses, new physics searches, and neutrino interaction measurements.
- The PAC is looking forward to MicroBooNE opening the box on the low energy excess, as well as future studies on neutrino-argon cross sections and liquid argon reconstruction techniques.
- The PAC encourages the collaboration to continue publication of results concerning the performance of the liquid argon time projection chamber technology – such as particle detection thresholds, efficiency of particle identification as a function of energy – and resulting energy resolution for different event topologies as the analysis software improves. Quantitative comparisons of the performance of the different reconstruction techniques will help guide future analyses at SBN and DUNE.
- The demonstrated capabilities should allow detailed investigations of exclusive hadronic final states, making possible cross section studies that will be crucial for testing the physics models in event generators. The PAC strongly encourages publication of the resulting cross section studies.

Recommendations:

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.

9. Status of the NOvA experiment Charge: We ask the committee to review the status of the NOvA experiment.

Findings:

The PAC heard a report from the NOvA collaboration, which continues to publish world-leading, high-impact neutrino oscillation results. COVID-19 had some impact on the beam delivered this year, but NOvA maintained high data-taking efficiency (97%) in FY2020. The PAC was shown new preliminary results on both interaction cross sections and neutrino oscillation parameters. The collaboration has grown modestly through NOvA physicists joining new institutions

Comments:

The Committee recognizes and commends the impressive efforts of the collaboration to integrate a new GENIE tune, new reconstruction software, and other key developments in order to produce the array of physics results shown. The PAC commends the Collaboration for the initial publication of its phenomenological cross section tune and encourages further systematic studies using its near detector data, which would provide better understanding of cross section uncertainties on the NOvA oscillation results and improve models for future endeavors like DUNE. Beyond the flagship oscillation analysis, the NC coherent and ν_e results demonstrate the strong physics potential of NOvA in electromagnetic final states. The PAC is also encouraged by the continued efforts to combine results with the T2K collaboration and considers the combination of oscillation parameter results to be a crucial exercise, with important consequence for the broader physics community. The Committee also recognizes the potential in the NOvA datasets for many measurements and searches that may require effort beyond the scale of the existing collaboration.

Recommendations:

The Laboratory should continue to prioritize operations and computing resources required for the NOvA collaboration to produce its oscillation results on the full planned dataset before the planned long shutdown for LBNF. Maintaining and even increasing the strength of the NOvA collaboration to exploit this data should be a high priority. The Collaboration should consider ways to engage scientists outside the collaboration who may be able to bring new effort to analysis of the NOvA data for studies of neutrino interactions or BSM physics topics.

10. Report on the ICARUS Experiment Charge: We ask the committee to review the status of the recommendations made at the January 2020 meeting and of the preparatory work towards the SBN operations.

The PAC received a comprehensive report on ICARUS and commends the collaboration for the impressive amount of work done since the last meeting, in spite of the unexpected COVID-19 outbreak.

Findings:

The cryogenic commissioning of ICARUS started in February, 2020 with cool-down beginning on 14 February and filling completed on 19 April. Since 21 April, the liquid recirculation has

been in operation. The work has been conducted as a common effort of CERN and FNAL cryogenics teams. The impact of COVID-19 was greatly reduced by having the CERN experts working remotely and the FNAL team working on-site.

During the cryogenic commissioning, the wire readout electronics, the PMTs, and the CRTs were continuously monitored to detect effects related to the cryogenic commissioning. In the meanwhile, software development for slow control, trigger, data analysis and event reconstruction was continued with high intensity;

Since the start of the cool-down, 24/7 shifts have been taken by ICARUS collaborators. These shifts were carried out first on the main Fermilab Control Room, but were moved to remote shifts after 17 March. Several collaboration members are now set up to take shifts remotely, with significant long-term benefits.

On-site commissioning activities are restarting since Illinois has entered Phase-3, allowing additional on-site work, and are carried out with organized teams following COVID-19 restrictions and safety rules. Work has been carried out on grounding, HV installation for the drift, and activation of PMTs. The next near-term activities will be to raise the cathode HV to half of its nominal voltage to begin a first set of verification on TPC functionality, including the measurement of the LAr purity and track detection.

There are still some remaining activities to be completed before starting data taking with the neutrino beam, including: the cabling of wire chambers electronics, the commissioning of trigger and slow control systems, the commissioning of the bias to the wires, the calibration of PMT and wires readout, and the installation and commissioning of the remaining CRT counters. As a consequence of COVID-19, these activities are delayed due to the difficulty in traveling and constraints on the on-site presence and operations. Assuming a restart of traveling in September 2020, an overall delay of ~4 months is foreseen, shifting the startup of operations with neutrino beam to mid-February 2021.

Comments:

The PAC congratulates the collaboration for achieving the major milestone of Lar filling completed even in a period of lockdown.

Due to the difficulty of assessing a stable date for re-establishing the traveling between Europe and US, we encourage the collaboration to prepare a contingency plan accounting for possible scenarios to complete the commissioning. The PAC suggests the collaboration evaluate the possibility to rely on Fermilab (or US) resources to maintain a steady pace on the work for the remaining commissioning activities.

Recommendations:

Regarding recommendation of previous meeting: if the presented schedule is maintained, ICARUS will be operating and acquiring neutrino data without the near detector for some time. Due to the unexpected COVID-19 outbreak, the collaboration has been focusing its efforts on the commissioning and did not discuss the science goals of ICARUS-only running. In addition, the SBND schedule is also fluid, which further motivates a reevaluation. The PAC iterates the request to present the ICARUS-only science goals and related computing needs to the next PAC meeting.

In case travel restrictions are maintained, or activities otherwise restricted due to possible sequential pandemic waves, the PAC would like to see a contingency plan at the next meeting.

11. Status of the SBND Charge: We ask the committee to review the status of the SBND.

Findings:

The SBND experiment presented the progress on the construction and assembly of its detector systems and the three main components of its science program: light sterile neutrinos, beyond-the-Standard Model searches, and GeV-scale neutrino interactions on argon. SBND will record beam data at approximately 7 times the rate of ICARUS and 24 times the rate of MicroBooNE starting in 2022.

Most of the detector components are constructed at collaborating institutions with some already at Fermilab for assembly. The anode plane assemblies were built in the UK and the US and are now aligned and connected in a clean tent at the DZero Assembly Building (DAB). The cathode is assembled at DAB and the HV and field cage follow the same design as ProtoDUNE-SP. The TPC cold electronics are ready for installation and the warm readout is already installed at the SBND hall. The photon detection system is being built, with 120 PMTs being tested at LANL and ARAPUCAs and X-ARAPUCAs in production in Brazil. The Assembly Transport Frame represented an important engineering effort in 2019-2020. In March, 2020 COVID-19 paused all on-site activities at Fermilab. The TPC assembly was the most impacted but is being resumed now and is expected to be completed soon. The cosmic ray taggers are also being finalized.

The cold cryostat construction is on the critical path of the experiment. The membrane materials were ordered in March 2020 and the delivery to Fermilab is expected by the end of December 2020. The cryostat top cap fabrication at CERN was paused due to COVID-19.

The major SBND upcoming milestones are:

- TPC assembly scheduled complete in early 2021 (including cold electronics installation).
- Detector ready-to-fill projected for October 2021.
- Detector commissioning and operation in the first half of 2022.

The project schedule has been evaluated in February 2020 at a Director's Review. Another review is planned for the fall. The current schedule does not include the impact of COVID-19 on the completion of the major milestones.

Comments:

The PAC congratulates SBND for their great progress in the detector construction and assembly in the last year. The Committee is looking forward to the continuation of the installation activities.

The Committee is pleased to see the first two SBND publications on the construction of the wire readout planes and the use of Deep Neural Networks in SBND and the first two PhD theses.

Recommendations:

The PAC suggests that the collaboration prepare a realistic schedule including the impact of the COVID-19 in view of the running time needed to complete the physics goals before the long shutdown planned for FY2025.

The Committee would like to hear more details about the cryogenics and LAr purification systems progress, schedule and commissioning plans, including the technical teams involved in these activities at the next PAC meeting.

12. Status of the workshop "Physics Opportunities at Fermilab's Booster Replacement" Charge: We ask the committee to review the scope and impact of the physics program being developed for the Booster Replacement.

Findings:

The PAC heard a status report on physics opportunities of a potential future accelerator upgrade with the primary goal to deliver 2.4 megawatts to LBNF. Such a capability would require a replacement of the Booster which could take the form of an extension of the PIP-II LINAC or a new rapid cycling synchrotron, or a combination of the two, which would impact the injection energy into the Main Injector. In addition to supplying protons to LBNF, such a facility could provide 8 GeV protons at 80 kW and 800 MeV protons at 100 kW, which could enable extensions of the current muon and short baseline neutrino program. A physics working group was formed to identify additional physics opportunities, guide the accelerator design, and solicit community input, including a workshop in May.

A document in preparation will summarize nearly twenty physics opportunities organized broadly in several categories: neutrino physics, dark sectors searches, charged lepton violation, precision tests of the Standard Model, and R&D for future facilities. Among the highlighted possibilities are light dark matter searches in meson decays with a stopped pion source produced from a 1 GeV proton beam. The same facility could provide a low energy neutrino source for studying neutrino-nucleus scattering and exotic neutrino properties . A higher energy proton beam would enable beam dump experiments to search for long-lived dark sector particles, while electron and muon beams could be used for missing momentum-based searches, flavor violating processes, and measurements to improve modelling of lepton-nucleus scattering.

The working group is also exploring the possibility of going beyond 2.4 MW, as well as potential paths to 2.4 MW beams at LBNF that may change the primary beam properties (e.g. lower energies, different time structures, etc.).

Comments:

The Committee was encouraged by the breadth of the studies under consideration at the workshop and by the working group, as well as the engagement of the wider community in the process. The importance of this exercise is difficult to overstate in understanding and planning for the future program. In evaluating potential experiments, it will be important to consider the capabilities of existing or other planned facilities, along with other experiments and facilities that are being developed.

13. Overview of the Snowmass LOIs planned by Fermilab Scientists and Engineers Charge: We ask the committee to review the scope of the LOIs proposed by Fermilab Scientists and Engineers.

Findings:

The Fermilab process for collecting LOIs and preparing for white papers for the Snowmass Community Study across all frontiers was presented.

Comments:

The SAC has collected an impressive number of ideas for LOIs across all areas. Some of these appropriately leverage existing community-wide efforts, with Fermilab scientists contributing expertise. Through the SAC organization, Fermilab is well-positioned to bring together teams across the Laboratory around key contributions as the Snowmass process continues.

The PAC would like to stress the need for the theory community to make a strong case for increased support. Strong contributions in this area are essential. We hope that Fermilab will take a lead role in this area in the current Snowmass process.

The PAC acknowledges that the Snowmass process is very time consuming, and that the scientists involved in the Snowmass process have important responsibilities in detector operations, computing and analyses. The load represented by the preparation of the Snowmass LOI should be recognized and accounted for.

Additional Reports and Discussions

Plans for the Snowmass Community Planning Meeting

The PAC heard a report from the DPF Chair regarding the plans for the upcoming Snowmass Community Planning meeting. The overall Snowmass process is now well underway, with nearly thirty frontier conveners managing ten frontiers and over two hundred topical conveners. Liaisons are also assigned in order to facilitate cross-frontier discussion. An early career group is being formed following the nomination of more than 250 nominations for representatives. To ensure safety and support for all community members throughout the discussions, an Ethics Task Force was formed, which has formulated core principles and guidelines for DPF activities, including Snowmass. The Community Planning Meeting is scheduled for 4-7 November, 2020. A local organization committee has been formed with the formation of the program committee underway.

European Strategy Update

The Committee held a discussion on the recent update to the European Strategy for Particle Physics led by L. Malgeri. Among the noteworthy statements include strong support for DUNE and LBNF and the investigation of the technical feasibility of a new hadron collider at CERN with center-of-mass energy of at least 100 TeV as a global endeavor, possibly with an initial phase as an electron-positron collider serving as a Higgs/Electroweak factory.

The Committee recommends further discussion on this topic, in connection to the Snowmass process in the US, at the next PAC meeting. In response to the planning efforts for a global collider, the PAC recommends that FNAL initiate discussions with DOE HEP to investigate potential major US contributions to the accelerator and detectors for such a program.

ProtoDUNE

Findings:

The Committee received a written update on current ProtoDUNE-SP activities, status of its ongoing physics analyses and plans for Phase II running. New dedicated photodetectors were installed in January. A campaign of xenon doping was started on February 13 and completed on May 20, with a total of 13.5 kg of xenon injected into the cryostat. Regular data-taking continued during this process and is expected to end by mid-July. The ARAPUCA systems confirmed the increase of the total collected light with increasing xenon concentration.

Overall, the detector has demonstrated outstanding operational stability over the 1.5 years of running. The drift voltage of 500 kV, the electron lifetime of 20 ms, and the photodetector light yield of 1.9 photons per MeV are all significantly better than the corresponding design specifications. Dead channels make up only 0.23% of the total, with the specifications of 1% or less. The first paper documenting the detector design and basic performance has been released. The analysis of the beam data is ongoing. Data-taking with a pulsed neutron generator is planned for the end of Run I.

Comments:

The PAC congratulates the DUNE collaboration on the outstanding performance of the ProtoDUNE-SP detector and on contributing crucial validation data to the DUNE TDR that was

released in February. The paper with the first results is of high quality and demonstrates the effectiveness of the single-phase far detector design for DUNE. Analysis and publication of the ProtoDUNE-SP physics results should remain a high priority for the DUNE collaboration, including the data taken with a pulsed neutron source. For this to succeed, it is important to keep personnel focused on analysis.

Recommendations:

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.

The Committee asks ProtoDUNE-SP to clarify its technical and scientific goals for Phase II, and its updated timeline in light of the delay necessitated by the response to the Covid-19 pandemic, in a future presentation to the PAC.

LBNC:

The PAC received a written report and slides summarizing the status of the Long Baseline Neutrino Committee, which provides the Fermilab Director with international oversight on DUNE, from its Chair. Among its critical tasks is evaluating conceptual and technical design reports and monitoring the project for the Resource Review Board in coordination with the Neutrino Cost Group which in turn will inform international funding agencies. Four TDR volumes were approved by the Director in early 2020, and a review of the Dual Phase TDR is underway. As of the meeting, submission of the Near Detector CDR was imminent.

LBNC has met twice since the previous PAC meeting. In the March 2020 meeting, it noted significant progress in many areas, including the potential to advance the construction of the beamline, the computing consortium, the planning for the construction and installation of the first far detector modules, and in ProtoDUNE-DP. While noting several issues, LBNC endorsed moving towards baselining the project and launching construction. At the April 2020 meeting, LBNC reviewed the baselining plan, technical developments in the ProtoDUNE program, and set forth a plan for reviewing the near detector CDR.