Fermilab Physics Advisory Committee Report - June 2023

Executive Summary

The Fermilab Physics Advisory Committee (PAC) met 5-9 June 2023 at Fermilab ("the Lab"), with most of the members present in person. The PAC was charged with reviewing:

- strategic plans for the Software and Computing and the upcoming microelectronics center bids,
- readiness of the Lab for the upcoming DOE Comparative Review of its theoretical physics program,
- status of the various Lab centers: the LHC physics center (LPC), the Neutrino Physics Center (NPC) and the Cosmic Physics Center (CPC),
- status of the Mu2e experiment, plans for upgrade to Mu2eII and status of the SpinQuest experiment,
- address the plans for the proposed Accelerator Complex Evolution (ACE).

The agenda was very well structured and allowed ample time for discussions with the speakers, the laboratory Directorate as well as in camera, among the PAC members.

Prior to being presented with the material pertaining to the charges, the PAC heard the executive report by the Lab Director, Dr Lia Merminga. This was followed by reports from the LBNC by its chair, Dr Niki Saoulidou and on the Accelerator Directorate by Dr Alexander Valishev.

Report of the Lab Director

The report of the Director was very extensive, summarizing the progress of the Lab in its various strategic thrusts. Particularly noteworthy were:

- the completion of data taking by the muon g-2 experiment, with new results expected early August 2023;
- progress in the installation of the SBND detector, with LAr fill starting September/October;
- significant progress in the LBNF-DUNE project execution, with completed excavation of the central utility cavern and overall excavation completed at 66% level, establishment of the Dune Coordination Office to coordinate and integrate host lab support for the LBNF/DUNE project and DUNE experiment;
- completion of the PIP-II cryogenic plant building and of the HB650 prototype cryo-module, and in general good technical progress;
- good progress in the HL-LHC accelerator and CMS detector upgrades.

The PAC was also apprised of the efforts to develop an effective culture of safety and security on the Lab site, while trying to facilitate site access which remains a worry for most national and international users.

The Lab remains strongly engaged in the P5 process with the March P5 Town Hall hosted by the Lab and Argonne National Lab. The Lab vision for the US particle physics is:

- to realize the full scope of the DUNE experiment with international partners,
- to continue strong participation in the LHC and HL-LHC science programs,
- to lay foundations to an international Higgs factory and a next-generation multi-TeV collider,
- to exploit the accelerator complex for small and mid-scale experiments with high impact,
- to engage in enhanced accelerator and detector R&D, the strength of the Lab, to enable the advancement of science,
- uncover the mysteries of the Universe with CMB-S4,
- to excel in national initiatives in QIS, AI/ML and microelectronics.

All in all, the foundation of the Lab remains to engage, train, and retain a diverse workforce.

Report from the LBNC The committee is charged by the Lab Director to provide external scientific peer review and to monitor the technical progress of the international DUNE collaboration, and those aspects of the facility construction that have direct impact on the DUNE experiment. The chair reported that the LBNC was very impressed with the progress made by LBNF/DUNE both in the Far and the Near Site. Impressive progress was achieved on the FD-VD prototyping. Substantial progress was also achieved on reconstruction and analysis of oscillation, low energy physics and BSM searches. The computing CDR was completed. The DUNE collaboration initiated the formation of a "common fund" mechanism for commissioning and integration and later for experimental operations. The LBNC also welcomed the formation of a dedicated group that will investigate the strategy for achieving the Phase II physics goals. It noted however that the success of Phase I should remain DUNE's highest priority and all necessary resources should be identified and secured.

Report from the Accelerator Directorate On the Accelerator Directorate (AD) front, the committee heard an extensive analysis of the dynamics of the workforce through 2030 and the efforts that are being made to ensure continuity of expertise and timely delivery of projects. This was an explicit request of the PAC from previous meetings. Of the 405 employees half is expected to retire by FY30. Presently the total openings stand at 62 out of which 26 are in different stages of recruitment. The Lab is constantly improving hiring practices and has a workforce development liaison who assists in hiring managers, aids with outreach and headhunting, and oversees DEIA matters. The AD is developing a succession planning and is engaged with global accelerator workforce effort, aligned with nationwide campaign to develop accelerator expertise and the OHEP supported personnel development programs such as traineeships at Universities, US Particle Accelerator School (hosted by AD), summer internship programs as well as PhD program managed by AD, Peoples fellowship and joint appointments with universities. The PAC was also presented with some measures of the accelerator performance in the last 12 months, with uptime for FY22 of 69% dominated by MI magnet failures. On May 22, 2023, the maximum power of the machine of almost 1 MW was reached via MI cycle time reduction from 1.2 to 1.13 s, an increase of 7% compared to the nominal one.
In matters pertaining to the charges of PAC for the meeting, the findings and the recommendations, the latter preceded by the PAC comments, are presented in detail following the executive summary. Below is a short summary of the proceedings.

Strategic Plan for Software and Computing Program at the Laboratory The presentation delineated an ambitious strategy that combines R&D in HEP software with providing crucial computing resources and services to the experiments. The plan identifies the weak points of the present infrastructure as well as the aging elements which will need to be replaced. Despite potentially large uncertainties, the PAC recommends that CSAID develops a complete model of FNAL long-term resource needs, including infrastructure, compute, tape, disk, and networking. The PAC also recommends that CSAID continues to contribute to major community HEP software tools taking a leadership role for the Intensity Frontier aspects and focusing on the needs of FNAL Physics Centers.

Report from the Microelectronics Program at the Laboratory The ME group has a window of opportunity to develop expertise in new technologies and consolidate applications of the existing know-how after the successful completion of large projects for CMS and DUNE. The group is targeting calls for projects in several different areas overseen not only by DOE, but also by DOD and DOC. In all proposals, the objectives are aligned on two main strategic goals, maintaining existing and gaining new know-how and expertise to serve future HEP needs and ensure in-house prototype and packaging capabilities. The group has developed a solid strategic plan for upcoming microelectronics center bids. The PAC recommends that the group develops further capabilities in service of future HEP needs and that the Lab provides the ME group with adequate resources for developing strong bids.

Overview of the Theoretical Physics Program at the Laboratory The scientific focus areas for the Theory Division include neutrino physics, particularly neutrino interactions and generators, event generators for SM and BSM phenomenology at colliders, calculations of the muon anomalous magnetic moment, dark matter, cosmic history, quantum simulation, and lattice strong dynamics. The Theory Division is playing leadership roles in several theory community activities, notably the Neutrino Theory Network, the QuantISED Theory Consortium, the muon g-2 Theory Initiative, and the USQCD collaboration, all of which are collaborations with university groups. The theory community activities led by the division appear to be well suited to a laboratory group and the division reports that their programs are well regarded in the larger theory community.
The PAC was not presented with the strategy for presentations at the upcoming comparative review and therefore recommends that the laboratory perform an internal review.

Overview of the LHC, NPC and CPC centers Reviewing the three centers, one after the other, was very informative and generated long discussions. The LPC is recognized worldwide as an extremely successful endeavor. It integrates the USCMS academic community and facilitates networking and cooperation between various groups which leads to original ideas and prompt execution of proposed analyses. Naturally it serves as a model for other centers and the question arose whether as such it can serve the diverse neutrino or cosmic physics communities as well as it serves the USCMS. Presently, the NPC is an important asset for both the Fermilab and broad international neutrino communities, bringing together members of the different experiments as well as theorists, and should play an essential role interfacing the local and international community. Given that in about five years, DUNE will be the main focus of the Fermilab neutrino community, the organization of the NPC might be expected to evolve. The PAC recommends that the NPC clearly articulates its goals, stakeholders, methods, and needs to continue to promote a rich intellectual environment in the Fermilab and broader neutrino community of today, while keeping in mind the need for evolution to the DUNE era.
As for the CPC, the current rationale relies heavily on historical context and funding that is in danger of running out. Thus the justification and strategy for the Center would benefit from being updated to match the Lab's evolving activities and strategy.

Report from the Mu2E experiment The Mu2e Project re-baselining is complete. The detailed commissioning and operations schedule are being updated to match the new Project dates. The highest priority of the Collaboration (both US and non-US), Project, and Program Coordinator continues to be

working to complete the Project by December 2025. The new Project schedule allows for one year between the early Project completion date and the beginning of the long LBNF/PIP-II shutdown. Several high-level milestones need to be accomplished after Project completion and before beam can be delivered to the experiment. An evaluation of the commissioning schedule will occur after updating the Project deliverable and LBNF/PIP-II shutdown dates. This new schedule will plan to retain the physics reach of a three-order-of-magnitude improvement over SINDRUM with the first data.
Based on experience from similar experiments, the collaboration expects to need 25 graduate students and 25 postdocs full-time to both commission and run the experiment. The Collaboration is currently evaluating the resource plans of all institutions and is devising a strategy to ramp up to the needed level. The Fermilab group has submitted their labor request to the Lab during the commissioning and running phases (FY24-FY26).
The PAC recommends that the collaboration works with FA to secure the needed person-power from non-FNAL institutions as soon as possible and that the Lab closely follows the readiness for the commissioning phase.

Overview of the physics for Mu2e II experiment and foreseen R&D needs The proposed upgrades to Mu2e (Mu2e-II) aims to improve the BR sensitivity by a factor 10 w.r.t to Mu2e, i.e. a factor 10^5 w.r.t. to the current best limit. In case of a hint of a signal in the current generation of experiments, Mu2e-II may be able to characterize the new physics signal by using different targets. R&D is needed in several areas on the experimental side. This upgrade is proposed before any experience with Mu2e running has been obtained and the Mu2eII design will rely on the experience acquired during the Mu2e running. The PAC recommends that the proponents carefully evaluate the person-power involved in the upgrade studies and avoid any diversion of Fermilab technical personnel or resources from Mu2e to Mu2e-II.

Summary of the Spin Quest ORR An Operational Readiness Review (ORR) was conducted for the Spin Quest experiment in April 2023 and its report shared with the PAC. The ORR report identifies a few areas of concern – improving maturity of SOPs, methodology for safe storage and handling of the polarized NH3 target, and personnel shortfalls on both the Fermilab side and the collaboration for commissioning. The ORR recommends focusing solely on the CH2 target for the commissioning run. Overall, timeline and resource needs for successful operation and science results from SpinQuest remain a risk. The lab acknowledges the need for additional engineering resources and has responded by committing more mechanical engineering support. The PAC endorses the ORR report and recommends approval for start of commissioning when the ORR and ARR approvals are granted, hopefully allowing some beam-time in FY23.

Overview of the proposed ACE at Fermilab A report from the Proton Intensity Upgrade Central Design Group has proposed the Accelerator Complex Evolution (ACE) to upgrade the accelerator complex in two phases.
First, a reduction of the Main Injector cycle time plus target R&D can take the Main Injector beam power up to 2 MW, with positive impact on the physics output of DUNE Phase I. Second, the Booster Replacement, would ensure long-term reliability for Fermilab's accelerator complex, and would lead to a large increase in beam continuous wave (CW) power, which can be used for physics program beyond

DUNE, such as dark sector searches, muon-based experiments, and muon collider R&D. Fermilab is organizing a series of ACE Workshops which will cover a broad spectrum of physics and technical topics, focusing on potential cross-pollination among several areas. The ACE Booster Replacement will be a breakthrough for Fermilab's accelerator science and physics capabilities. The PAC recommends the Lab to work with DOE to proceed with the ACE Main Injector and target upgrade and to start the Booster Replacement project in a timely manner.

The Physics Advisory Committee: Halina Abramowicz, Chair; Zeeshan Ahmed; Franco Bedeschi; Paolo Calafiura; Scott Dodelson; Pedro Machado; Luca Malgeri; Isabell Melzer-Pellmann; Niki Saoulidou, ex officio; David Schuster, Stanford; Elizabeth Worcester. Marcelle Soares-Santos, not present.

Scientific Secretary: Anadi Canepa

Directorate: Lia Mermina, Bonnie Fleming.

Strategic Plan for Software and Computing Program at the Laboratory

Charge: We ask the PAC to review the strategic planning for Software and Computing at the laboratory: The committee is asked to review the plan in the context of Fermilab as host lab for large collaborations (DUNE and USCMS) and for its scientific and technological competitiveness. The PAC is also asked to review the status of the recommendations from previous reviews:

1. Following up on the recommendation from the last PAC, we recommend that the Laboratory develops a strategic computing plan based on the experiments' needs. The plan should project computing and storage resources that will be made available to the experiments, as well as central services like power and cooling. The plan should include a timeline and milestones for critical technology decision points e.g. the integration of heterogeneous computing resources provided by US HPCs and the role of commercial clouds.
2. [made to the g-2 Collaboration] We encourage SCD and the g-2 computing experts to further improve their level of collaboration, focusing on reducing the turnaround time in g-2 data processing.

Findings

- The presentation clearly delineated an ambitious strategy that combines R&D in HEP software with providing crucial computing resources and services to the experiments.
- Tape storage needs for the next two decades were presented, together with a discussion on two possible strategies to allocate mass storage: shared ("Public") or partitioned in three pools for CMS, DUNE, and the other experiments.
- The current mass storage system (Enstore) shows its age and does not provide the functionality needed by Fermilab, the ability to share tape drives with guaranteed QoS:
    - Viz the problem with g-2 data processing that was solved ad-hoc by moving resources out of the mass storage system.
- The projections for compute resources for DUNE and other experiments are too uncertain to be shown now. No projections for disk storage were shown either. The HL-LHC experience with resource modeling shows that projections become more precise and accurate when repeated multiple times.
- The facility infrastructure plans will be presented separately in 2023. The cooling system needs to be refreshed, and potentially replaced by a more powerful one. Power costs and infrastructure are less of a concern than at other DOE facilities as they are small compared to the accelerators'.
- The FNAL facility and computing services are the priority for CSAID and HEP software development is a core component of its mission. CSAID aims to increase its expertise in data sciences and heterogeneous computing through three new hires.
- CSAID HEPCloud helps experiments in running their workloads across multiple platforms (HPC, clouds, local).

Comments

1. We support the proposed plan to replace Enstore with the CERN Tape Archive system.
    a. In parallel it may be worth modeling costs and benefits of sharing tape drives (and robotics?) vs assigning them exclusively to the large experiments.

2. We support the CSAID plan to play a leading role in DUNE framework development as it is natural for the host lab. The proposed framework should be flexible and usable enough to be adopted by the next generation of small and medium-sized Fermilab IF experiments. Similarly the CMS experiment framework, co-developed by FNAL experts, could evolve to support more than one collision event-based experiment.
3. We support the proposed plan to expand the focus of FNAL software development beyond its traditional areas of strength (frameworks and infrastructure). This plan foresees supporting experiments in developing their algorithms and data models in the current heterogeneous computing landscape.
4. The new proposed hires would help CSAID grow in critical areas of modern computing. The scope of work of the new proposed hires should be evaluated in collaboration with the experiments to maximize the impact.
5. Besides framework development, Fermilab plays a major role in crucial community projects like GEANT4, ROOT, and generators. Fermilab is uniquely well-placed among DOE labs to continue to lead and contribute to strategic, cross-cutting HEP software projects. In this context, CSAID could help the neutrino experiments take a more prominent role in the HEP Software Foundation.
6. We commend the "all-of-the-above" approach taken by CSAID when it comes to diverse computing platforms. Care should be taken in evaluating costs and benefits of adding more and more supported resources. Collaborating with other experiments and groups in the development of a HEP-wide resource provisioning system like HEPCloud would share the burden of supporting an ever-growing variety of resources.
7. We commend CSAID for helping the experiments (particularly small and medium-sized ones) develop and refine their computing plans and optimize their software and workflows. We commend the role CSAID played in optimizing data processing and analysis campaigns for the g-2 experiment.
8. The PAC is pleased to see that CSAID has included DEI as an integral part of their strategic plan.
9. We commend CSAID plans to reach out beyond the traditional Computational HEP community. It will be important to continue coordinating with CERN and other national and international labs when developing its strategic plan.

Recommendations

1. Given the ambitious aspirations of the directorate, the PAC recommends showing the CSAID person power profile and planning at the next meeting.
2. We recommend the development of a complete model of FNAL long-term resource needs, including infrastructure, compute, tape, disk, and networking. Even if some experiments initially have order of magnitude uncertainties in their projections, the exercise will push them to think about their long-term needs.
3. The PAC recommends that CSAID help the experiments define and implement their data management and data preservation plans.
4. We recommend that CSAID continues to contribute to major community HEP software tools like ROOT, GEANT, taking a leadership role for the Intensity Frontier aspects, and focusing on the needs of FNAL Physics Centers.

5. The PAC recommends that the Directorate works with the Astrophysics department as it refines the Cosmic strategic plan, as software support can strengthen participation and leadership in cosmic experiments.

Overview of the Theoretical Physics Program at the Laboratory

Charge: We ask the PAC to review the status of the theoretical physics program and the readiness of the laboratory for the upcoming DOE Comparative Review. The PAC is also asked to review the status of the recommendations from previous reviews:

1. The PAC recommends that the Lab provide the Division with the requested support.
2. The Lab and the Theory Division should maintain close connections to the University community and ensure that the programs it is offering are welcomed by the community, as opposed to being seen as securing a larger piece of a small pie.

Findings

- The PAC was presented with details of the personnel and physics activities of three departments (particle theory, quantum theory, and astrophysics theory) that make up the theory division. There are about 40 scientists and postdocs in the division and several long-term visitors and students associated with the division.
- The presented scientific focus areas for the division include neutrino physics, particularly neutrino interactions and generators, event generators for SM and BSM phenomenology at colliders, calculations of the muon anomalous magnetic moment, dark matter, cosmic history, quantum simulation, and lattice strong dynamics. Members of the division have been active in the Snowmass process and in Fermilab's future planning process.
- The Theory Division is playing leadership roles in several theory community activities, notably the Neutrino Theory Network, which is managed by the Fermilab group but primarily funds university researchers, as well as the QuantISED Theory Consortium, the muon g-2 Theory Initiative, and the USQCD collaboration, all of which are collaborations with university groups. Fermilab is also hosting the Quantum Computing for Physics Undergraduates internship, an educational program aimed at an underserved community, which may merge with the DOE's RENEW program.
- The division has produced ~150 published papers over the last year as well as 30+ Snowmass contributions, more than 80% of which were co-authored with scientists outside the division. The division hosts a theory seminar series, coordinates the Fermilab Wine & Cheese seminar, and organizes several summer schools.
- The Theory Division hosts a large number of visitors, workshops, and in-person programs and thus have significant concerns that site access issues will affect their standing in the community and ability to continue to be a center of intellectual effort.

Comments

1. The PAC was not presented with the strategy for narrative or presentations at the upcoming comparative review. The PAC feels that the division may be well served by considering whether there are AI/ML efforts that could be highlighted. Additionally, it may be helpful to highlight the

impact of division activities on the wider Fermilab program, for example, dark matter and neutrino phenomenology, covering the full breadth of efforts within the Theory Division.

2. The PAC finds that the addition of the Quantum Theory department to the division demonstrates a forward-thinking vision that speaks to the health of the program.
3. The PAC notes that the division reports receiving adequate programmatic support, although additional support to reconfigure the division's physical space would be very welcome. The theory community activities led by the division appear to be well suited to a laboratory group and the division reports that their programs are well regarded in the larger theory community.

Recommendations

1. We recommend that the laboratory perform an internal review in preparation for the upcoming comparative review.
2. We recommend that the division develop a systematic method of evaluating perception among the larger theory community of the added value of the DOE-funded programs led by the division.

Overview of the LHC Physics Center

Charge: The PAC is asked to review the status of the LHC physics center (LPC) and of the recommendations from previous reviews:

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.

Findings

- The LHC Physics Center (LPC) presented a document outlining its history and contributions. Since 2004, the LPC has been providing a home for the USCMS and a wealth of resources for CMS collaborators from around the globe. It consists of
    - the Remote Operations Center (ROC) based at FNAL, to assist in the shifts operation of the CMS experiment at CERN and,
    - the center of excellence bringing together university students, postdocs and faculty to work together and with FNAL laboratory scientists and FNAL research associates on the CMS experiment.

  The LPC is led by two co-coordinators, one is a university faculty at a USCMS institution while the other is a FNAL staff scientist. The day-to-day activities at the LPC are facilitated by three support physicists based at FNAL, typically PhD research staff from USCMS institutions. They support physics activities, computing, and operations. They facilitate the formation of analysis collaborations and networks, lead the organization of training and education events.

- The primary users of the LPC are USCMS members, but the center also attracts visitors from outside the US, from countries under-represented in CMS.
  All active USCMS groups participate in LPC, including all 14 small groups (with less than 10 authors) and all four non-R1 university/college groups.
- The LPC manages research funding to bring users to FNAL for extended periods of time, such as the Distinguished Researcher (DR), Graduate Scholar, and Guest & Visitor (G&V) programs.
- The LPC provides training and education programs such as the CMS Data Analysis School (DAS), Hands on Advanced Tutorial Sessions (HATS), and graduate courses; advanced workshops; and a variety of physics seminars and journal clubs.
- LPC plays a key role in USCMS PURSUE (summer internship program for underserved minorities and women undergrads), hosting all interns for an initial two-week program and a significant fraction for the whole summer.
- The LPC presented some measures of its impact on CMS, with about 500 active LPC users, comprising 11% of primary analysis leaders, 60% of Analysis Review Committee members, and 23% CMS papers with majority LPC participants involved in the analysis.
- The programs hosted by the LPC are supported by the research funding (DRs) and by the USCMS operations funding (G&Vs, GS). Due to the overall decrease in research funding within HEP, the LPC research component was halved in FY18. It has been maintained "flat-flat" ever since. As a result, the number of senior DRs dropped from an average of 10 to 2 in 2019. The total number of DRs was maintained at about 15 per year by awarding more junior DRs and by securing matching funds from partner institutions. Exceptionally in 2023, a stopgap has enabled the LPC to award 17 DRs.
- After 2019, also the number of HATs (week-long training events) had to be reduced from 20 to 15, the number of workshops to 1-2 per year (prior to 2019, the center offered 5-10 per year).
- The LPC reported a loss of institutional presence during the COVID lockdown. The LPC resumed on-site in-person activities including topical workshops, CMS data analysis school (DAS), HATS tutorials, and graduate courses (also available remotely). Visitors have returned to LPC, and their number is now limited by funding.
- The LPC reported Fermilab user site access challenges.
- LPC summer programs are being impacted by limited Fermilab on-site housing.

Comments

1. The LPC plays the role of interface between the USCMS academic community and FNAL; this was highlighted in the presentation and is clearly reflected in the LPC leadership and management structure. The PAC compliments the LPC on the scope and organization of its DR program, G&V program, training activities and support for analysis and computing.
2. The visitor programs (junior and senior DRs and G&V) offer a unique opportunity to academics, otherwise busy with teaching and other university assignments, to focus on research for a period with adequate support to efficiently lead to physics results. For the younger generation, this offers in addition visibility that facilitates future career opportunities.
3. The DR program intersperses LPC residents with local researchers and brings together researchers focused on similar or complementary topics at the same time. This facilitates collaboration that might not otherwise happen and therefore adds value to the visit.

4. The DR program is critical to maintain cohesion in the USCMS effort. Senior researchers typically bring members of their groups to the LPC, lead workshops, and drive new research directions. All these benefits are lost with each cut in the number of DRs. The projected level of funding for the DRs (at the level of FY19) threatens the effectiveness of the LPC.

Recommendations

1. We recommend the Laboratory work with DOE to maintain the LPC at a successfully functioning level by fully supporting the required number of junior and senior Distinguished Researchers.

Overview of the Neutrino Physics Center

Charge: The PAC is asked to review the status of the Neutrino Physics Center (NPC), its function as center of the host laboratory for LBNF/DUNE, its role and impact within the domestic and international neutrino community. We ask the PAC to also evaluate whether the NPC could serve as a platform to coordinate and prioritize software and computing efforts, including those in data preservation.

Findings

- The PAC heard about the activities of the Neutrino Physics Center, which include the Neutrino Seminar Series, the Neutrino University, the International Neutrino Summer School, and a Fellowship (visitor) program. The latter depends strongly on the funding. Before 2018, the NPC was funded at the level of $475k annually. Between 2018 to 2022 there were no funds available for the NPC. In 2023, the NPC received $150k, allowing for a smaller Fellowship program. Overall, the NPC Fellowship program has brought 135 scientists to visit the lab since its inception.
- The onboarding of new users including computing accounts is currently done on the level of each experiment independently.
- The PAC also heard that current campus access policy has presented a challenge for the NPC to accomplish its mission.
- For the future the NPC plans to hold software workshops. Physical meeting space would be desirable for NPC's "brand recognition."

Comments

1. The NPC is an important asset for both the Fermilab and broad international neutrino communities, bringing together members of the different experiments as well as theorists, and should play an essential role interfacing the local and international community.
2. While reproducing the successes of the LPC model is attractive, the LPC structure (a center that serves a single experiment) may not be the most appropriate for the NPC today, which serves the neutrino community at the lab, currently including multiple international experiments with diverse needs.
3. In about 5 years, DUNE will be the focus of the Fermilab neutrino community. Therefore the purpose, goals and organization of the NPC might be expected to evolve accordingly, while continuing to offer an intellectual and collaborative environment for the broader national and international neutrino community.
4. The NPC could be a place to initiate discussions about data preservation.

5. The PAC agrees that a dedicated physical space (including a social meeting place) would enable the identification of the (visiting) community with the NPC. This includes centralized onboarding for everyone arriving at Fermilab who will be connected to neutrino science, experimental as well as theory.
6. Increased funding would increase the effectiveness of the NPC.

Recommendations

1. The NPC should clearly articulate its goals, stakeholders, methods, and needs to continue to promote a rich intellectual environment in the Fermilab and broader neutrino community of today, while keeping in mind the need for evolution to the DUNE era in about 5 years.
2. The PAC would like to see a short document describing the strategic plans of the NPC.

Overview of the Cosmic Physics Center

Charge: The PAC is asked to review the status of the Cosmic Physics Center (CPC), its role and impact within the domestic and international community.

Findings

- The Cosmic Physics Center at Fermilab was founded around the same time as the LPC and has a history of promoting and defining the cosmic program at the Lab and beyond.
- The Center was part of the Cosmic Strategic Plan developed in 2018-19. That plan included: growing in CMB, consolidating in direct dark matter experiments, and refocusing in dark energy survey science.
- The Lab has between 15-20 FTE's working on Cosmic Science. Several of them have won prestigious awards. They are in the process of updating the cosmic strategic plan.
- Funding for the cosmic frontier effort has decreased by 30% over the past N years, and the Cosmic Center no longer enjoys its own funding.

Comments

1. The effort to update the cosmic strategic plan is timely, especially given the opportunities due to progress in quantum sensing and accelerator-based searches for dark matter.
2. A vibrant visitors program would stimulate the intellectual environment.
3. The current rationale for the Center relies heavily on historical context and funding that is in danger of running out. The justification and strategy for the Center would benefit from being updated to match the lab's evolving activities and strategy.

Recommendations

1. Lab and Cosmic leaders should refine the overall strategy for the cosmic frontier and in the context of this strategy, reassess the vision for the CPC.

Overview of the physics for Mu2e II experiment and foreseen R&D needs

Charge: The PAC is asked to review the physics case for the Mu2e II experiment and the foreseen R&D needs.

Findings

- The proposed upgrades to Mu2e (Mu2e-II) aims to improve the BR sensitivity (SES, 90% CL, and 5σ discovery limit) by a factor 10 w.r.t to Mu2e (and COMET Phase 2), i.e. a factor 10^5 w.r.t. the current best limit.
- In case of a hint of a signal in the current generation of experiments, Mu2e-II may be able to characterize the new physics signal by using different targets.
- PIP-II is well designed to provide the statistics needed to reach the physics goal of Mu2e-II, but R&D is needed in several areas on the experimental side: cooling, radiation in solenoids, improved shielding. In addition, a new tracker and calorimeter will be needed. Some LDRD has been already financed for the target and tracker studies. Several more are needed for a total projected funding of more than $10M. It is acknowledged that the R&D on high-temperature superconductors for the production solenoid will have synergies with R&D for future colliders. The projected total cost of the upgrades is in the ballpark of $120M, compared to the current cost of the Mu2e experiment of ~$300M.

Comments

1. The possibility of improving the muon conversion limit by an order magnitude w.r.t. the projected sensitivity of the current generation of experiments is clearly interesting, but the physics output should be weighed against the needed resources (person power and financial).
2. This upgrade is proposed before any experience from Mu2e running is obtained and therefore may not optimally target the upgrade needs COPY EXEC. Furthermore, without this experience, it is hard to predict with a high degree of confidence the expected improvement factor relative to Mu2e. This uncertainty makes unclear how much the projected result will surpass Mu2e and COMET.
3. There are concerns that the current efforts on the upgrades of the subsystems might compete with the finalization of the Mu2e experiment, which should be the highest priority. Detector FNAL R&D having synergies with other applications at FNAL could proceed, provided they do not have any impact on the successful execution of Mu2e.

Recommendations

1. The PAC recommends the proponents carefully evaluate the person power involved in the upgrades studies and avoid any diversion of FNAL technical personnel or resources from Mu2e to Mu2e-II.

Overview of the proposed ACE at Fermilab

Charge: The PAC will be asked to review the process for community engagement, identification of the science goals, development of alternative concepts and functional requirements.

Findings

- A report from the Proton Intensity Upgrade Central Design Group has proposed the Accelerator Complex Evolution (ACE) to upgrade PIP-II in two phases.
    - First, a reduction of the Main Injector cycle time plus target R&D which can take the Main Injector beam power up to 2 MW.

    - Second, the Booster Replacement, which would be necessary to ensure long-term reliability for Fermilab's accelerator complex and would lead to a large increase in beam continuous wave (CW) power.
- The ACE Main Injector and target upgrade will positively impact the physics output of DUNE Phase-I, as it leads to increased statistics.
- Two main options for the Booster Replacement were identified: a Rapid Cycling Synchrotron or an 8-GeV Linac.
- The ACE Booster Replacement will lead to an increase in beam CW power which can be used for a physics program beyond DUNE.
- Several physics opportunities have been identified for this improved beam, broadly within the context of dark sector searches, muon-based experiments, and muon collider R&D.
- The PAC also heard that Fermilab is organizing a series of ACE Workshops with the goal of co-designing physics case and technical design, with strong participation from the broad community and early career scientists. These workshops will cover a broad spectrum of topics, focusing on potential cross-pollination among several areas.

Comments

1. The PAC commends Fermilab for proposing the ACE Main Injector and target upgrade, which will enable faster determination of the neutrino mass ordering and improve the reach for leptonic CP violation.
2. The current Booster cannot provide additional beam power beyond the needs of DUNE. Without its replacement, Fermilab would be faced with a reduced scientific portfolio.
3. The Booster is 50 years old, and its replacement would ensure the long-term facility reliability and undisrupted DUNE operations.
4. The ACE Booster Replacement will be a breakthrough for Fermilab's accelerator science and physics capabilities, enabling a diverse scientific portfolio and setting the stage for a future collider on-site in the post DUNE era.
5. The PAC commends the initiative to start a workshop series to build a vibrant physics program around the Accelerator Complex Evolution, which will further expand the science goals with input from the broad community.

Recommendations

1. The PAC recommends the lab to work with DOE to proceed with the ACE Main Injector and target upgrade and to start the Booster Replacement project in a timely manner.
2. The PAC recommends Fermilab to be ambitious in the design of the ACE Booster Replacement, to advance accelerator science and expand scientific opportunities in the coming decades.