Fermilab Physics Advisory Committee Report July 2024

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Scientific Secretary: Sergo Jindariani

Directorate: Lia Merminga, Bonnie Fleming

Executive summary

The PAC meeting took place during July 8 to July 11, 2024 and most of the members were present in person. The meeting was co-chaired by Prof. Allen Caldwell while the PAC chair, Prof. Halina Abramowicz, exceptionally attended the meeting remotely.

At the start of the meeting, the lab Director Lia Merminga outlined a vision for FNAL encompassing scientific goals as well as a focus on a culture of excellence in all activities. The difficult budget situation in FY24 and its impact on the laboratory and staff was also presented. The PAC commends the lab leadership for putting together a compelling vision, well aligned with P5 recommendations and the expertise of the lab. The PAC took note of the fact that in spite of the budget strictures, the lab management strives to ensure a successful realization of the high priority projects.

As usual, the chair of the LBNC, Niki Saoulidou, summarized for the PAC the latest progress in the preparations of the DUNE experiment, in particular the progress made in completion of the caverns and in planning the Near Site construction to begin in 2025. She also pointed out that DUNE is entering a phase of finalizing many aspects of the construction of the Far Detectors, of the design of the Near Detectors and of the beamline TDR, as well as converging on the future software framework.

As far as the status and plans for the accelerator complex, the PAC was pleased to hear that the Accelerator Safety Documentation to comply with the updated DOE Order 420.2D "Safety of Accelerators" has been updated and approved. The PAC commended the accelerator team for the upgrade of the main injector and reaching a 1.018 MW power record in June 2024. The PAC also expressed concern about the decrease in reliability in accelerator operation and expressed support for the campaign of upgrades, modernization, and investments into spare parts of the accelerator complex. The PAC was informed that the long shutdown of the accelerator complex, required to tie-in elements of PIP-II and LBNF beamlines, is now planned to start in January 2028 instead of January 2027. The revised schedule is effective in optimizing the physics program, providing at least as much beam-time to experiments as previously planned, without compromising the schedule of LBNF/DUNE.

The PAC was asked to review how the Test Beam Facility (FTBF) enables progress in physics around the globe and to comment on the benefits of proposed evolution of this facility. The FNAL accelerator complex also offers users a unique Irradiation facility (ITA). The FTBF/ITA is the only facility of its type on US soil, serving a wide array of users, including experiments from the CMS, ATLAS, EIC, neutrino, and general detector R&D communities. The FTBF beamline is aging, affecting the reliability of the operations, while the ITA will end when the LINAC shuts down (planned for 2028). Since the combination of an irradiation area and test beam onsite is only available at FNAL (or at CERN), the PAC encourages the lab to consider a future planning exercise on the long-term evolution of the FTBF/ITA.

A preliminary strategy for the FNAL cosmic program was presented to the PAC. The PAC commended the Cosmic Group for concurrently operating cosmic experiments, producing scientific papers and engaging in innovative R&D for future experiments. The group is repositioning itself to engage only in efforts where FNAL's unique and emerging strengths provide substantial value, while maintaining a comprehensive and impactful cosmic program. The PAC supports this approach as well as the proposed focusing of their survey effort on Rubin/DESC operations and science.

Fermilab has a long tradition of providing unique input to deciphering the structure of the proton through measurements of the Drell-Yan process in fixed target experiments. In the quest for the origin of the nucleon spin crisis, the SpinQuest experiment aims to provide information about the sea-quarks motion by extracting the so-called Sivers function. The PAC commended the SpinQuest collaboration for the tremendous progress made towards the commissioning of the polarized targets, the implementation and testing of the safety procedures, and the successful collection of the first data set. The PAC encourages SpinQuest to collaborate closely with the accelerator group to develop a scenario where, together with improvements in data-taking efficiency, its target of 1.4*10^18 POTs before the long shutdown can be achieved.

The PAC was presented with the update on the Strategic Plan for Software and Computing Program at the lab. Presently, progress in the various areas of the CSAID activities is affected by budget reductions. CSAID had to put on hold a long-term strategy of targeted expansion, and to focus on providing core services. On the previous recommendation of the PAC, a Computing Resources Evolution Strategy group was formed to develop a complete model of FNAL long-term resource needs, including infrastructure, compute, tape, disk, and networking. A draft computing model report shows that resource needs through 2032 are dominated by CMS. No major shortage is projected. The model does not yet include GPU resource projections. These will be added as usage of GPU by Fermi-supported experiments becomes significant. The PAC was pleased to hear that if budget levels return to normal within two years and the planning for a new or extended data center comes to fruition, there should be no major disruptions to FNAL computing strategy.

The CMS experiment continues to have excellent operations performance, including good detector performance in 2024. The FNAL group is a big part of this success, with an increasing number of shifts performed at FNAL's Remote Operation Center (ROC), good performance of FNAL's computing center, and vibrant intellectual activity in the LHC physics center (LPC). The PAC congratulated the FNAL CMS group on their high-level leadership roles within the collaboration, as Patty McBride finishes her term as spokesperson and Anadi Canepa begins her term as deputy spokesperson, with many other leadership roles also held by group members. The PAC also commended the FNAL group for continued excellence as a hub for US-CMS, with the ROC and the LPC serving as models across the collaboration and the field. FNAL is responsible for a number of LHC high-luminosity upgrade projects, including design, fabrication, and assembly of outer tracker, HGCAL, MTD, and L1 trigger components, with US-CMS responsible for about 30% of the CMS upgrade. Upgrades are making good technical progress in spite of challenging staffing levels and administrative delays. Given the time-critical nature of the group's contributions to the upgrades, the PAC encourages the group and the lab

leadership to work together with the DOE HEP to ensure that the group has sufficient scientific resources, including postdoctoral researchers, to deliver on US commitments, despite the challenging budget.

The PAC has been following the development of the AI/ML activities at FNAL. To promote and support these activities across the lab, an AI Project Office (AIPO) was set up. The AIPO is developing a vision, strategy and near-term priorities for a coordinated effort to cross-fertilize HEP and AI research, build partnerships among HEP and AI researchers across FNAL and the broader AI community, and develop/train an AI workforce. The PAC was pleased to see that the strategy is coalescing along three areas: the FNAL core strength in real-time AI and intelligent sensing, infusion of AI techniques into FNAL research and operations, and development and maintenance of adequate tools. The PAC encourages AIPO to seek broad input from the FNAL community as the strategy develops.

The PAC was asked to review the future research program of the Theory Division and comment on its alignment with the P5 report. The PAC finds that the program aligns well with the P5 science drivers, covering each driver comprehensively. Some important research directions (i.e., generators to support experiments, lattice field theory, and theories that can be probed with quantum sensors) are rather unique to a laboratory setting; others are also carried out at universities (i.e., collider and dark matter / dark sector physics). The Theory Division successfully trains a diverse group of postdocs and students. The PAC commended the Theory Division for developing strong DEI efforts, and for developing mentoring programs for early career members. It also commended the Theory Division for successfully building up their Quantum Theory Department in just a few years. There is a need to identify a long term model to support the Quantum Theory Group. Residual difficulties in accessing the lab site continue to affect cooperation with external colleagues.

The PAC was asked to review the science goals and milestones, under different beam delivery scenarios provided by the laboratory, for the SBND, ICARUS, Nova and the 2x2 neutrino experiments. The PAC notes that FNAL has a highly successful neutrino program and a bright future in neutrino physics with the upcoming DUNE experiment. With NOvA, FNAL is today at the forefront of accelerator neutrino physics research with tantalizing results on the mass ordering of neutrinos, one of the key questions in neutrino physics. With the SBND and ICARUS experiments, the clarification of the MiniBooNe anomaly within the next few years will take place as well as a range of BSM physics searches. And with the 2x2 effort, the LAr technology that will be used in the DUNE experiment is being commissioned and understood today, giving DUNE a running start when it begins operation. The SBND, ICARUS, Nova and 2x2 collaborations were presented with various beam delivery scenarios in FY25, FY26, FY27, till

the long shutdown. The scenarios were expressed in terms of the number of weeks spent in running in different configurations of the neutrino beams, BNB (low energy) or NuMI (high energy). Not surprisingly, the best scenario to maximize the physics output for the wide range of neutrino experiments at FNAL is to provide the maximum 40 weeks of beam time for both the BNB and NuMI beams for each available FY (25,26 for NuMI and 25-27 for the BNB). As a minimum, the PAC recommends that the NUMI and BNB beams be operated for 24 weeks in each of FY25 and FY26, and that the BNB beam is operated for 40 weeks in FY27. This scenario was labeled as Option 3+ in the more detailed report below.

Finally, the PAC was asked to review FNAL's plan to respond to the P5 recommendations and in particular if the proposed plan enables the laboratory to set the foundations for the ambitious physics program. Concerning the response to the P5 recommendations, the PAC noted that these are very well aligned with the priorities of FNAL so that no major reorientation of the program is necessary. Indeed, there are a number of ongoing projects which already have well-defined plans that are regularly evaluated by other means for their progress and alignment with P5 recommendation, so that the focus was on projects that would go beyond these. To define this more future oriented program plan, FNAL management has established a Steering Committee that will oversee six task forces to address: F2D2 (a beam dump facility at the end of PIP-II), Dark Wave Lab, DUNE 2, Off-Shore Higgs Factory, Muon Collider, and ACE-MIRT. These task forces will provide initial plans that will be used to respond to DOE PEMP notables due at the end of August. It is expected that these task forces will seed larger efforts that will integrate the broader community. The PAC endorses the plan proposed by FNAL management.

Status and plans for the Fermilab's accelerator complex

Charge: For information only

Findings:

1. The Accelerator Safety Documentation [Safety Assessment Document (SAD) and Accelerator Safety Envelope (ASE)] to comply with the updated DOE Order 420.2D "Safety of Accelerators" has been updated and approved.
2. The upgrade of the main injector to 1.068 s cycle operation has been completed.
3. A 1.018 MW power record has been demonstrated.
4. The AD has implemented measures to address the 12% personnel turnover in the last two years.
5. The AD team has more scope than the workforce can execute.
6. The accelerator operation uptime decreased from ~90% in 2019 to only ~40% in 2023. In 2024 the uptime is about 70%.

Comments:

1. The PAC commends the accelerator team for the upgrade of the main injector and reaching a 1.018 MW power record in June 2024.
2. The outlook for reaching >= 2MW beam power for LBNF/DUNE was presented and commended by the PAC.
3. The decrease in reliability in accelerator operation is a point of great concern. The very low efficiency in 2023 was due to the unexpected failure of an otherwise reliable accelerator component for which spares are not typically held at hand. Other reasons for the loss of beamtime have been investigated, but the findings have not yet been translated into an accelerator reliability performance plan.
4. The PAC supports the campaign of upgrades, modernization, and investments into spare parts of the accelerator complex.

Recommendations:

None (for information only)

Status and plans for the Fermilab Test Beam Facility (FTBF)

Charge: We ask the PAC to review how FTBF enables progress in physics around the globe and to comment on the benefits of proposed evolution of this facility.

Findings:

1. The Fermilab Test Beam Facility (FTBF) is unique to the US because it provides a high-energy hadron beam and a long running time of ~8 months each year. FTBF technical and scientific staff provide a high level of support, leveraging the technical expertise and infrastructure (SiDet, clean rooms, equipment pools, etc) from the Fermilab complex to get experiments running on short timescales.
2. FTBF supports a wide research and detector R&D program using two beamlines (MTest and MCenter) that provide 120 GeV protons and secondaries of ~200 MeV. FTBF offers a highly flexible space to accommodate a wide variety of experiment types at various locations in the beam line.
3. The Irradiation Test Area (ITA) uses Low energy (400 MeV protons) at a high rate of ~2.2e15 protons/hr.
4. The FTBF/ITA is the only facility of its type on US soil, serving a wide array of users, including experiments from the CMS, ATLAS, EIC, neutrino, and general R&D communities.
5. FTBF is in high demand for the 120 GeV beam and tracking to support collider needs, increased interest in high purity electron/muon beams from muon, dark matter, and neutrino communities, as well as emerging interest from APRA-E and NASA.

6. The ITA proton beam is uniquely fast at reaching HL-LHC fluences and has high beam availability. ITA has also received interest from private sector efforts and is working with Fermilab management to develop a charge model and agreements to support this type of effort.
7. The FTBF beam was the last to turn on in FY 2024 after completing the required DOE Safety Assessment Document (SAD) and Accelerator Safety Envelope (ASE) process, losing 3 additional weeks compared to the rest of the complex. The beam delivery was further impacted by two "low tempo" periods and unseasonal high temperatures in June.
8. The FTBF beamline is aging, affecting the reliability of the operations.
9. The ITA will end when the LINAC shuts down (planned for 2028).
10. Upcoming long shutdowns at FNAL, CERN, and DESY increase demands on operating test beam facilities over the remaining 2020s across all major projects.

Comments:

1. The PAC notes that FTBF Beam is nominally available ~8 months a year (roughly November through June). However, only 5 weeks of beam were available to FTBF users in FY 24 due to the issues described before. This is a significant reduction from the minimum 12 weeks of stable beams recommended by the PAC in Jan 2024.
2. The combination of an irradiation area and test beam onsite is only possible at Fermilab and CERN.
3. Access to an irradiation facility in the US is essential to the global energy frontier community and the support to detector innovation and the US leadership in HEP instrumentation. The facility would be most impactful if it had the irradiation and test beam capabilities in the same location, allowing irradiated detector components to be tested in situ.
4. The PAC encourages the lab to consider a future planning exercise on the long-term evolution of the FTBF/ITA. Broad community input would facilitate the identification of synergistic uses with the proposed PIP-II beam dump facility (F2D2) for dark matter searches and the proposed 120 GeV dark matter program as part of the "Fixed Target Campus."

Recommendations:

1. The AD annual planning should aim to maintain predictable and reliable operations of the FTBF/ITA facilities.

Overview of the theory program at the laboratory

Charge: We ask the PAC to review future plans for the theory group at the laboratory and comment on whether they are aligned with the recent P5 report. The PAC is also asked to review the status of open recommendations from the previous reviews:

1. We recommend that the division develop a systematic method of evaluating the perception among the larger theory community of the added value of the DOE-funded programs led by the division.
2. The department should continue its activities, including the educational component, and develop a plan to secure funding after the completion of the QuantISED grant.

Findings:

1. The Theory Division comprises three departments: particle theory, astro theory, and quantum theory, the latter formed only about five years ago.
2. The division's research aligns well with the P5 science drivers, covering each driver comprehensively. Some important research directions (i.e., generators to support experiments, lattice field theory, and theories that can be probed with quantum sensors) are enhanced in the laboratory setting; others are also carried out at universities (i.e., collider and dark matter / dark sector physics).
3. Theorists are very well connected with local experiments and with experiments at other labs and drive new theory initiatives (neutrino theory network, QuantISED, …). Theorists develop and maintain software packages widely used by the HEP community.
4. The Theory Division successfully trains a diverse group of postdocs and students, for which they leverage outside funding sources, including joint appointments. Many of the postdocs of the past 5 years have secured a faculty/research position.
5. Regularly, in collaboration with experimental groups, the theory division organizes several summer programs for students (CERN-Fermilab Hadron Collider Physics Summer School, Quantum Computing School for Physics Undergraduates, International Neutrino Summer School, …).
6. The DOE comparative review in April 2024 was very positive. One of the recommendations was the restart of the Distinguished Fermilab Scholars' Program.
7. The Theory Division submitted three proposals to QuantISED 2.0, to continue supporting its Quantum Theory Department.

Comments:

1. As an example of added value, the Theory Division describes its leadership role in theory activities that are under-represented at Universities. Indeed, their research programs in areas such as lattice field theory, perturbative QCD, and event generators benefit from the large number of theorists dedicated to these efforts. Developing quantitative metrics in these and other areas would be useful long term.
2. The PAC commends the Theory Division for developing strong DEI efforts, for improving diversity of the division, and for developing mentoring programs for early career members.
3. Site accessibility issues continue to affect how short term visitors are hosted at the lab, and have a negative impact on community perception of Fermilab as a theory hub.
4. The PAC commends the Theory Division for successfully building up their Quantum Theory Department, in response to guidance from HEP and the directorate.

Recommendations:

1. The Theory Division should develop metrics to quantify the value added of the Division's programs to the larger community. Some possible examples include a running count of papers that use Division-produced software or the number of papers produced jointly with visiting scientists.
2. The PAC recommends that the Directorate and the Theory Division engage with DOE HEP to identify a long term model to support the successful Quantum Theory Department.

Update on the Strategic Plan for Software and Computing Program at the Laboratory

Charge**:** We ask the committee to review the strategic planning for S&C at Fermilab. The committee is also asked to review the status of the recommendations made at preview reviews:

1. Given the ambitious aspirations of the directorate, the PAC recommends showing the Computational Science and AI Directorate (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.

Findings:

1. CSAID strategy is centered around seven elements: Data Centers, Mass Storage, Compute Resources, Data Analysis, DEI&A, plus the newly introduced Engineering/Computing Interface.

2. CSAID discussed the steady progress made toward their strategic goal of expanding relationships with DOE ASCR.
3. The power capacity of the three data centers currently in production will saturate around 2027. Refurbishments may postpone the problem to 2029, but FNAL will need a new data center by then. The construction of a new data center is part of the lab strategy, and was presented to DOE. CSAID started planning discussions with the Infrastructure Services Division.
4. Software development is focused on a new framework targeting DUNE. Due to budget restrictions, CSAID had to pause the development and support of POMS, the FNAL production management system.
5. In response to budget reductions CSAID put on hold a long-term strategy of targeted expansion, and focused on providing core services. Over the last year, attrition and a hiring freeze reduced personnel from 157 FTE to 146. (charge question #1). There will be no hardware purchases in FY25/26. The plan is catch up with deferred purchases in FY27/28. Furthermore, the Wilson cluster will be decommissioned.
6. The impact of the upcoming lab closure on computing resource availability is still uncertain. Management at all levels indicates that preserving access to CMS T1 and other FNAL resources during the two weeks is a priority.
7. A new Computing Resources Evolution Strategy group was formed in response to PAC recommendation #2. A draft computing model report shows that resource needs through 2032 are dominated by CMS. No major shortage is projected. The PAC noticed that the computing model produced by CREST does not yet include GPU resource projections. These will be added as usage of GPU by Fermi-supported experiments in production workflows becomes significant. (charge question #2)
8. CSAID helps experiments define policies and implement them through the rucio data management system (charge question #3)
9. GEANT contributions of past years were significantly reduced due to the budget environment and DOE feedback. A P5 recommendation to support community software may change the situation longer term. (charge question #4)
10. CSAID and the Cosmology group are working to identify a software liason. Progress limited by budget reductions in both areas. (charge question #5)

Comments:

1. The PAC commends CSAID for their balanced and clearly presented strategy to deal with a significant budget shortfall.
2. If budget levels return to normal within two years and the planning for a new or extended data center comes to fruition, there should be no major disruptions to FNAL computing strategy.
3. CSAID should involve FNAL computing center stakeholders (CMS, LQCD, etc) when planning actions that may impact their science output and institutional commitments (for example, the upcoming summer closure).

4. The PAC encourages CSAID to discuss with DOE HEP how to restore and increase FNAL role in developing community software key to FNAL mission (accelerator and detector simulation, ROOT, rucio, etc.)

Recommendations:

None

Status of the CMS experiment operations and upgrades

Charge: We ask the PAC to review Fermilab CMS group's activities and scientific resources, with the emphasis on the Detector and S&C operations, as well as HL-LHC upgrades of the experiment.

Findings:

1. CMS continues to have excellent operations performance, including good detector performance in 2024. The FNAL group is a big part of this success, with increasing numbers of shifts performed at Fermilab's Remote Operation Center (ROC), good performance of Fermilab's computing center, vibrant intellectual activity in the LHC physics center, and high-level leadership roles for FNAL scientists within the collaboration.
2. The Fermilab group is leading a number of important physics initiatives, including Higgs and EW studies, and searches for long-lived particles, dark-sector physics, and other BSM phenomena.
3. There is additional burden on US-CMS operations to compensate for the departure of Russian collaborators.
4. The availability of Tier-1 computing services is essential while CMS processes data, regardless of Fermilab closures. Fermilab computing facilities will require significant upgrades in preparation for high-lumi LHC, including upgrades of the data storage facility and development of analysis facilities. These needs were also highlighted by FNAL computing.
5. Fermilab is responsible for a number of upgrade projects, including design, fabrication, and assembly of outer tracker, HGCAL, MTD, and L1 trigger components, with US-CMS responsible for ~30% of the CMS upgrade. Upgrades are making good technical progress in spite of challenging staffing levels and administrative delays.
6. CMS reports concerns going forward regarding subcritical staffing levels, increasing schedule risk, and potential loss of morale related to the challenging budget scenarios, increasing administrative challenges, particularly with respect to distribution of funds to collaborating partners, and communication regarding these issues.

Comments:

1. The PAC congratulates the FNAL CMS group on their high-level leadership roles within the collaboration, as Patty McBride finishes her term as spokesperson and Anadi Canepa begins her term as deputy spokesperson, with many other leadership roles also held by group members. The PAC also congratulates the FNAL CMS group on the success of their postdoctoral researchers in the next steps of their careers.
2. The PAC commends the FNAL group for continued excellence as a hub for US-CMS, with the ROC and the LHC physics center serving as models across the collaboration and the field.

Recommendations:

1. The PAC notes that the budget challenges faced by CMS are similar to those reported labwide and nationwide. Still, given the time-critical nature of the group's contributions to the upgrades, we encourage the group and the lab leadership to work together with the DOE to ensure that the group has sufficient scientific resources, including postdoctoral researchers, to deliver on US commitments to the CMS upgrade, despite the challenging budget.
2. We recommend the lab continue to explore more efficient methods for the distribution of funds to university and lab partners.

Status of the SpinQuest commissioning and first data

Charge: We ask the PAC to review the status of the SpinQuest experiment.

Findings:

1. SpinQuest accesses information about the sea-quarks motion using proton-proton Drell Yan di-muon production, in a kinematic range uniquely available using the 120GeV proton beam.
2. SpinQuest uses the MI beam on a polarized target. It is housed in the NM4 cavern with an existing Spectrometer that needs some repair that will be done this summer. The major construction of a new Polarized Target Cave in NM3 was completed.
3. SpinQuest collected ~10^15 POTs in 10 days of running this year and aims to collect 1.4*10^18 POT before the long shutdown. This luminosity would enable the measurement of the Sivers function.
4. Experimental uncertainties stem directly from runtime and scale of polarization for the statistical component. The systematic component is suppressed by scale of polarization and number of flips.

5. Daytime operation during the hottest months of the year is impacted by insufficient capacity of the Low Conductivity Water system.

Comments:

1. The PAC commends the SpinQuest collaboration for the tremendous progress made towards the commissioning of the target, including the beam-target alignment, the polarization for both CH2 and NH3, the implementation and testing of the safety procedures, and the collection of the first data set. Uneven, slow extraction (low beam duty factor) continues to be a concern as it causes loss of useful POT.
2. DarkQuest received Stage 1 approval by PAC pending a successful outcome of SpinQuest. In light of CERN's approval for the SHiP experiment, which shares several of DarkQuest's physics goals and is set to begin data collection in 2031, the PAC invites the collaboration to work with the directorate to develop updated upgrade plans for taking data with SpinQuest/Darkquest, possibly before the long shutdown.

Recommendations:

1. The PAC encourages SpinQuest to collaborate closely with the accelerator group to develop a scenario where, together with improvements in data-taking efficiency, the target 1.4*10^18 POTs can be achieved.

Report on the long shutdown planning

Charge: for information only

Findings:

1. A long (>2y) shutdown of the accelerator complex is required to tie-in elements of PIP-II and LBNF

   Beamlines. The schedule was planned in 2019 and has been recently revised to account for changes in the project schedules.
2. Schedule evolutions are decided by the lab director in consultation with the CRO, Deputy CRO, CPO, AD ALD, and representatives from LBNF/DUNE, PIP-II, and UIP.
3. The anticipated start of the long shutdown is January 2028. This scenario provides at least as much beamtime to experiments before shutdown as the previous plan. The new schedule eliminates the need for a separate 6-month shutdown for LBNF tie-in to MI while maintaining the beam startup for DUNE unchanged.

Comments:

1. The revised schedule is effective in optimizing the physics program without compromising the schedule of LBNF/DUNE.
2. There is no room to further delay the start of the long shutdown without impacting the end of the PIP-II upgrade.

Recommendations:

None (for information only)

Status of the SBND experiment

Charge: The status and plans of the SBND experiment will be presented. We ask the PAC to review the science goals and milestones under different beam delivery scenarios provided by the laboratory. We are also asking the PAC to review the scientific resources and activities on SBND with the emphasis on the Detector and S&C operations

Findings:

1. The SBND detector is now successfully operating in a configuration appropriate for collection of high-quality physics data, overcoming an initial commissioning issue with instability in the high-voltage system.
2. With data collected in July 2024, SBND has demonstrated excellent signal-to-noise performance in the TPC, has observed an excess in PMT and CRT rates due to neutrinos during the beam spill relative to off-beam data, and has identified neutrino interaction candidates in event displays.
3. SBND plans to complete commissioning using already collected beam data and cosmic ray data collected over the coming summer and expects to be ready for physics data when the beam returns in fall 2024.
4. Regarding the various beam scenarios, the needs of the SBN oscillation physics program, for which SBND serves as the near detector, are driven by statistics in the far detector, so SBND refers us to the presentation from ICARUS. For the standalone SBND physics program, important goals for neutrino interaction measurements are multi-dimensional differential cross-sections and measurements of electron neutrino interactions and higher-energy interactions, all of which require large statistics. These interaction measurements will help constrain uncertainty in DUNE and thus have great value for the broader neutrino program. SBND's BSM searches typically have sensitivity that scales with statistics.
5. Software and computing needs for SBN are non-negligible, with SBND and ICARUS both requiring significant and concurrent use of disk, tape, and CPU resources and extensive

ongoing software development. SBN is coordinating shared resources between SBND and ICARUS.

Comments:

1. The PAC congratulates SBND on the successful operation of the experiment and collection of high-quality neutrino data and commends SBND on their readiness for beam in fall 2024.
2. While SBND does expect very large rates of neutrino interactions relative to other experiments, they would nonetheless be impacted by reduced beam delivery, as it will impact the oscillation physics program, the ability to perform important neutrino-argon interaction measurements, and the sensitivity of BSM searches.
3. FNAL computing hardware resources and technical support are critical for the success of the SBN program.

Recommendations:

1. We recommend a minimum of 6.6E20 POT in the BNB to ensure sufficient far detector (ICARUS) statistics in SBN. As described in the Executive Summary, we recommend at least Option 3+, which would provide enough beam time to meet this POT goal. Option 4 would provide a quicker path to high statistics physics results.

Status of the ICARUS experiment

Charge: The status and plans of the ICARUS experiment will be presented. We ask the PAC to review the science goals and milestones under different beam delivery scenarios provided by the laboratory. We are also asking the PAC to review the scientific resources and activities on ICARUS with the emphasis on the Detector and S&C operations.

Findings:

1. ICARUS Neutrino RUN 3 officially started on March 13th 2024 and continues to operate with good stability and performance of all major subcomponents.
2. Significant progress was made on calibration, reconstruction, event selection, data management and so on. Preliminary BNB 1muNp distributions were shown with the conventional Pandora-based analysis and ML based analysis both with ~50 % or higher efficiency. Search for BSM scalar decays in di-muon was conducted and a preliminary exclusion contour was shown.

3. It was reported that the proposal value of 80 % for the electron neutrino event selection efficiency is difficult to achieve. Difficulty comes from the low-energy shower reconstruction and background resulting from cosmic rays. Expected number of events was reduced by ~20% due to cross section model evolution from the time of proposal.
4. To fulfill the original proposed sterile-neutrino oscillation -parameters coverage, which provides ~5 sigma rejection of the LSND allowed region, additional BNB 9.7x10^20 POT would give sufficient statistics even for 50% efficiency and 6.6x10^20 POT would be sufficient if 65% efficiency is achieved, assuming concurrent running with SBND is not required. NuMI data would potentially contribute to resolving degeneracy in sterile-neutrino search.

Comments:

1. The PAC commends the collaboration on continued successful operations and first results shown at Neutrino 2024.
2. The PAC considers that reaching a definitive conclusion on the LSND anomaly by the SBN program is highly important.
3. Given possible limitations on accelerator operation, it is important to continue to develop strategies to improve the event selection efficiency. To maximize the physics output and reach the target sensitivity with additional 6.6x10^20 POT it is desirable to reach 65% or higher.

Recommendations:

1. The PAC would like to see the performance of the electron neutrino event selection in the coming meetings.
2. We recommend a minimum of 6.6E20 additional POT in the BNB to ensure sufficient far detector (ICARUS) statistics in SBN. As described in the Executive Summary, we recommend at least Option 3+, which would meet this POT goal. Option 4 would provide a quicker path to high statistics physics results.

Status of the NOvA experiment

Charge: The status and plans of the NOvA experiment will be presented. We ask the PAC to review the science goals and milestones under different beam delivery scenarios provided by the laboratory. We are also asking the PAC to review the scientific resources and activities on NOvA with the emphasis on the Detector and S&C operations.

Findings:

1. New results based on 10 years of NOvA data were shown at the Neutrino 2024 conference and the data are compatible with both Normal and Inverted mass ordering (MO).

2. NOvA provides the best single measurement of Delta(m^2_32), in good agreement with the other experiments.
3. Normal MO prefers CP conserving values of the phase delta_CP, while Inverted MO prefers maximal CP violation. By combining with Daya Bay data, normal MO is slightly preferred.
4. In comparison to T2K, in normal MO T2K and NOvA prefer different regions in delta_CP, while they overlap if Inverted MO is assumed. This intriguing tension in the normal MO could point to the inverted MO or possible BSM physics.
5. Assuming the normal MO, among the running scenarios, Options 2-4 give around > 2 sigma mass ordering resolution for the most favorable range in delta_CP. In the case of their best fit mass point a 2 sigma resolution can be achieved with option 4. Option 4 also allows to exclude the maximum asymmetry (Normal MO and delta_CP=+3/2pi) at 3 sigma level.
6. An additional 9E20 POT in RHC mode would allow NOvA to double their antineutrino dataset.
7. NOvA will provide the best dataset on mass ordering before JUNO's 6 years dataset, which is expected in 2030.

Comments:

1. The PAC commends NOvA for their significant scientific output, including highly cited papers, and a large number of PhD theses.
2. The PAC commends the NuMi power record above 1 MW and the >96% uptime of the far detector.
3. The PAC agrees with NOvA to stay with antineutrino beam until the end of NuMi, in order to increase the antineutrino sample and decrease its statistical uncertainty.
4. Maximizing POTs for NOvA is important for investigations of the tension with T2K and for the potential to rule out \delta_CP=3\pi/2 in the normal MO.
5. The PAC commends the combined analysis of T2K and NOvA data. By further investigating the intriguing tension in the case of normal MO, possible correlations of systematic uncertainties may have to be taken into account, as it may become relevant with a higher statistical sample.

Recommendation:

1. We recommend at least option 3+, which would provide a substantial additional data set, although would not meet the NOvA POT goal to double the antineutrino dataset. Option 4 would meet the NOvA POT goal.

Status of the 2x2 experiment

Charge: The status and plans of the 2x2 experiment will be presented. We ask the PAC to review the science goals and milestones under different beam delivery scenarios provided by the laboratory.

Findings:

1. The DUNE ND-LAr 2x2 Experiment is a key demonstrator for the full-scale DUNE near detector, ND-LAr. It consists of 4 TPC modules exposed to the NuMI neutrino beam.
2. The 2x2 represents a high-level physics demonstration of what is expected at DUNE, particularly with respect to reconstructing complex neutrino topologies as expected with liquid argon TPCs. This includes using a combination of light detectors and charge detectors for event reconstruction.
3. Installation of all 4 modules started in 2021 and was completed in 2023.
4. After a pause due to hall access from March to May 2024, cool down began on May 20. Cooldown was achieved faster than expected and the experiment achieved full HV ramp on July 1st. It has been running since July 8th, 2024.
5. The system is fully commissioned, with 97% of its 330,000 pixels active and first events have been recorded, with event displays of first events now being shown.
6. The collaboration has defined two benchmark analyses for the 2x2: Track multiplicity and Charge-to-light matching.
7. The collaboration has also been meeting milestones for analysis, data flow, and combined analyses with Minerva.

Comments:

1. The 2x2 collaboration has achieved a major milestone in commissioning its detector and observing first events from the NuMI neutrino beam. The collaboration has made excellent strides in preparing for data acquisition and analysis. The PAC commends the collaboration for this achievement.
2. The input from 2x2 will be crucial in upcoming reviews of the DUNE project.
3. To achieve its goals, the collaboration requests NuMI operations as early as possible in FY25. A minimum of 1.5E20 POT is required to perform studies needed for the upcoming near detector design review. However, something more like 4.7E20 (option 2) in FY25 would facilitate reconstruction, analysis, and preparation for DUNE physics.

Recommendations:

1. We recommend that a minimum of 1.5E20 POT of NuMI beam early in FY25 is provided for the 2x2 to perform critical work for development of DUNE. Option 1 is therefore

precluded by this requirement. As described in the Executive Summary, we recommend at least Option 3+, which would satisfy the needs of the 2x2.