

## Fermilab Physics Advisory Committee Report - January 2023

January 17-20, 2023

Executive Summary	2
Plans for Users and Affiliates Engagement	5
Status of the DEI program at the laboratory	6
Status of the AI/ML program at the laboratory	7
The head of the AI/ML Project office presented the status of AI/ML efforts and planning at Fermilab	7
<b>Findings:</b>	7
<b>Comments:</b>	8
<b>Recommendations:</b>	8
Status of the MicroElectronics program at the laboratory	8
Status of the SQMS center	10
Status of the FQI program at the laboratory	11
Status of the CMS experiment	12
Updated Cosmic Frontier strategy at the laboratory	13
Report on the Mu2e experiment	14
Stage 1 approval for the Spin quest upgrade	15
Status of the ICARUS detector	16
Status of the SBND	17
<b>Findings:</b>	17
<b>Comments:</b>	18
<b>Recommendations:</b>	18
Status of the SBN Analysis Working group	18
Muonium R&D/Physics Program at the MTA	19

---

## Executive Summary

The Fermilab Physics Advisory Committee (PAC) met 17-20 January at Fermilab (“the Laboratory”) in its second in-person meeting since the start of the COVID-19 pandemic. The meeting occurred in a period of transition for the US High Energy Physics (HEP) community, with the conclusion of the Snowmass 2021 Community Planning Exercise and the start of the Particle Physics Project Prioritization Panel (P5) which will prioritize the activities of the US HEP community over the next ten years in a twenty year context. Regina Rameika was appointed as the new Associate Director for the DOE Office of High Energy Physics in October 2022 and Fermilab Director Merminga has reorganized and filled many key positions at the Laboratory since her appointment on 18 April 2022.

The Committee heard several presentations regarding ongoing initiatives and activities at the Laboratory. The new Deputy Director for Research presented Fermilab’s plans for user and affiliate engagement, where a plan to reinvigorate the process and environment is in development, with an eye to supporting a larger community from the neutrino physics program. A Site Access Task Force is in place to streamline the onboarding processes with solutions to be deployed in the next 12 months. The Committee noted the significant challenges for site access and endorsed the current initiatives with a recommendation to identify metrics to evaluate and monitor the user “welcoming” capabilities of the Laboratory.

The Chief Diversity Office reported on a number of new initiatives underway at Fermilab, including new fellowships for underrepresented minorities, a new summer school exchange program in collaboration with BNL, and the Fermilab Alumni Network to track the trajectory of past participants in Fermilab’s programs. For 2023, DEI factors will be included in employee reviews and a lab-wide climate survey. The Committee commends the Laboratory for its efforts, and recommends developing metrics to track progress and hearing further about efforts on accessibility in a future meeting.

The PAC heard an overview of the AI/ML group, and the coordination efforts of the AI Project Office. The Committee noted Fermilab’s strengths in Fast AI/ML and FPGA/ASIC-based AI/ML and its development of hls4ml, a widely used package. It would be useful to clarify the mandate of the Project Office in balancing fundamental AI/ML research and engagement with Fermilab experiments, where other experience (e.g. CMS AI/ML efforts at the LPC) may provide models. While the Committee was charged with evaluating a possible bid to host an AI/ML Center, it recommends formulating a strategy to respond more generally to potential AI/ML funding opportunities.

The status and strategy of the Microelectronics group in supporting the scientific mission of the Laboratory was presented, highlighting several projects, ranging from electronics for QSC to chip design for CMS upgrades (ETROC, ECON-D/T). The ASIC PMG group provides oversight in prioritization. In preparation for a potential call for DOE Microelectronics centers, the group is investigating joining DOD and DOC coalitions/projects where its specific know-how provides strong synergies. The Committee endorses these goals and recommends prioritizing areas in which Fermilab has leadership and developing a strategic plan to prepare for upcoming bids. The Committee also recommends that Fermilab continue its support for completing its deliverables for the HL-LHC upgrades.

The SQMS Center has grown to 55 FTE at Fermilab with 420 collaborators and produced 115 preprints/publications since its inception in 2020. Its accomplishments include achieving a 200  $\mu$ s coherence time in a transmon qubit and coupling the qubits to SRCF cavities. The Committee would be interested to hear more about the physics program at the next meeting, and to understand which of the proposed activities are planned to be explored further, and to hear further details on the plans for the colossus cryostat. It recommends that the Laboratory streamline the procurement process for the Center as part of its overall effort, and that the Center explore collaborations with other groups at FNAL, particularly on quantum sensors.

The Fermilab Quantum Institute, separate from the SQMS center, spans a wide range of quantum activities at Fermilab including FQnet, the Quantum Science Center, QuantiSED, theoretical quantum simulation, MAGIS-100 and (micro)electronics for quantum efforts. The Committee commends Fermilab for this wide range of activity. With uncertainty in support for some projects in the near future, the PAC recommends that the Laboratory coordinates with the DOE to review the current portfolio in time for upcoming funding opportunities and develop a long term strategy towards quantum science and its integration with HEP goals.

Since its 2018-19 strategic plan, which consolidated its dark matter program and identified CMB-S4 as its highest priority, the Fermilab Cosmic Frontier (CF) effort has expanded its axion program, becoming lead lab for ADMX-G2, while the SENSEI won the 2021 Breakthrough Prize New Horizon Award. Fermilab was strongly engaged in Snowmass with five scientists participating as convenors in CF. The program is well aligned with the 2014 P5 report and the vision articulated in Snowmass 2021, heavily leverages local quantum science efforts, but faces challenges with declining research funding. Nonetheless, the group has established well-defined roles on CMB-S4 and in LSST/DESC operations and science. The Committee recommends that Fermilab develop a strategic approach to light dark matter searches that leverage laboratory capabilities, update their strategic plan, and work with DOE to secure adequate support for its CF effort based on this strategy.

A recurring theme throughout the discussion was the broad and intricate nature of the quantum effort at Fermilab and its interfaces to light dark matter searches. The Committee suggests having a dedicated discussion on Fermilab's strategy with respect to its overall quantum program and its light dark matter program, where the Laboratory's capabilities should be broadly taken into account.

Phase 1 upgrades for CMS were completed for Run 3 with FNAL commitments successfully delivered. Essential Fermilab capabilities and resources such as ASIC design, SiDet, scintillators, and the LPC were highlighted. Challenges arising from the war in Ukraine and a shortage of operational personnel were also discussed. The Committee recommends the Laboratory work with DOE to ensure adequate funding for the LHC Physics Center (LPC) to rebound from the COVID pandemic lull, and ensure the regular on-site presence of FNAL-based experts. To support operations, the Committee recommends investigating an expanded usage of the Fermilab Remote Operations Center (ROC) and ensuring a stable presence at CERN. Finally, FNAL site access for CMS collaborators should be streamlined so that they can readily access FNAL-based LPC and ROC.

The Mu2e experiment is undergoing a transition from construction to initial operations with a significant injection of resources by Fermilab via the Inflation Reduction Act with the goal of an initial physics run in 2026 before the long shutdown for PIP-II. A new technically limited schedule for the facilities was presented. While the Committee views the plan as challenging with little contingency, the value of even a small amount of data before the shutdown is very high. To track progress towards this goal, the PAC recommends the experiment monitor at a regular pace a resource loaded schedule for all items needed to be ready for data taking with clear "need by" dates.

The SpinQuest experiment is awaiting laboratory approvals to start operations/data taking and is planning an upgrade to enhance its physics program to include novel measurements of sea quark transverse momentum dependence and light dark matter models. Overall, the Committee found the physics case for the upgrades to be compelling, which would initiate a "beam dump" program at the Fermilab, but recommends that the Laboratory comprehensively review the operational readiness for SpinQuest and the resources required for the upgrade. The PAC endorses Stage 1 approval for the upgrade pending a successful outcome from these reviews.

ICARUS reported on the commencement of its first physics run, following the installation of the overburden. Over 90% data taking efficiency was achieved, and the collaboration showed preliminary

results of neutrino vertex reconstruction algorithms, where output from both Pandora and AI/ML-based algorithms were compared to hand-scanning results, and cosmic ray rejection with matching between cosmic ray tagging and the photosensor system.

SBND reached an important milestone with the completion and transport of the detector from the D0 Assembly Building to the SBND detector hall on 1 December 2022. Detailed commissioning plans and the physics plan taking advantage of the large statistics and the variation of neutrino flux across the detector were presented. The Collaboration aims to start taking physics data in Fall of this year.

The SBN Analysis working group has reproduced proposal-era sensitivities using truth-level information, with updates reflecting current performance estimates, and is working towards incorporating full event simulation/reconstruction, and detector systematics, with both disappearance and appearance channels. The PRISM concept exploiting the spectrum variation across the detectors and events from the NuMI beam will also be incorporated. Calibration and Analysis Infrastructure groups have been established to coordinate cross-detector calibration and software and computing needs across SBN. The PAC notes a five-year computing plan, including data preservation, is being developed with SBND and ICARUS.

The Committee noted a recurring thread throughout the SBN discussion on the need to continue close coordination between SBND and ICARUS, and to ensure that DUNE maximally benefits from this experience.

The Committee heard about a muonium (M, a muon-electron bound state) program that could be carried out at Fermilab. The program would extend limits on M-Mbar oscillations and perform spectroscopy measurements and antimatter gravity tests in a pure QED system (vis-a-vis antihydrogen). It would be based on a new target concept from PSI which could be deployed at FNAL with higher efficiency high-Z targets and a thicker superfluid He layer, for which the proponents envisage an R&D program at MTA. The Committee noted the value of the potential physics program and recommends that the proponents provide more details on the proposed studies and explore other measurements that could be competitive with the full PIP-II statistics, and that the implications for Laboratory support related to the R&D be clearly understood.

The Committee expresses its appreciation for the informative presentations throughout the meeting, and for the prompt and detailed followup to questions from the Committee. The Committee thanks Anadi Canepa and Kayla Decker for the seamless management of logistics for the meeting. We also express our thanks to Aaron Chou for his overview of the Quantum Science Center during the meeting.

#### **The Physics Advisory Committee:**

**Present:** H. Abramowicz, Z. Ahmed, F. Bedeschi, P. Calafiura, S. Dodelson (remote), P. Machado, L. Malgeri, I. Melzer-Pellmann, N. Saoulidou (remote, ex-officio) P. Schuster, M. Soares Santos (remote), H. A. Tanaka, E. Worcester

**Scientific Secretary:** Anadi Canepa

---

## Plans for Users and Affiliates Engagement

**Charge:** We ask the PAC to review the laboratory's plans for users and affiliates engagement in the context of Fermilab as host for both national and international collaborations.

The Director of Research presented the status and plan for Fermilab with regard to user/affiliate engagement and site access.

### Findings:

- The Lab is developing a plan to reinvigorate the welcoming of users and affiliates also in view of a potentially larger community joining the neutrino physics programme
- The plan needs to take into account several aspects:
  - Provide a safe working environment both physical and psychological. An essential component of this goal is the establishment of procedures for violations of code-of-conduct taking into account also user's institutes and Collaboration's procedures;
  - Manage host-lab responsibilities on all sites;
  - Cope with increased security levels to access the lab.
- In particular, the difficulties to access the lab facilities are well known by the management and they represent an unfortunate deterrent for newcomers even more so in a post-Covid period.
- A Site Access Task Force (SATF) has been established to address the issue and propose a streamlined process with deliverables/changes to be deployed in the next 12 months.
- A DUNE Host Lab Task Force has also been set up to ensure both the short and long term support to LBNF/DUNE in both sites. The support includes science, engineering, and business support. The report should be finalized by March 2023.

### Comments:

- FNAL user access formalities have become a serious issue that may discourage the engagement of external users. It is also a barrier to internal staff to organize events/conferences given the burden in the organization of accesses with all the consequences in terms of rebuilding communities.
- Supporting effort from the local staff is remarkable but there is a strong need to streamline the process, avoid duplication, and simplify the administrative steps. The establishment of the SATF is a very positive action. It is also noted that the efforts spent by the local staff in punctual help for external users and in leading responsibilities in the SATF and host lab task forces may affect their "physics delivery" efficiency and resulting Laboratory science output.
- The needs of the user and affiliate communities are bound to increase with the realization of the flagship DUNE project, with the development of an enhanced culture of safety and the administrative burden of the new access procedures. The PAC is concerned about the availability of sufficient and/or timely resources to follow up on all these aspects.
- A regular presence of scientific staff is an essential element of a welcoming environment.
- The PAC took note of the completion time of the Host Lab Task Force and looks forward to the report due in March 2023.

### Recommendations:

- The PAC endorses the current initiatives in order to solve an increasingly difficult and highly frustrating process to welcome users. Specifically the PAC supports the three layered approach foreseeing:
  - an assessment of the situation;
  - streamlining of all current procedures avoiding duplication and unnecessary, possibly self-created, administrative steps;
  - explore improvements together with the DOE site office (isolate critical areas, increase automatic checks, simplified access formalities for users from large partner laboratories/institutes/collaborations, etc.).
- The PAC recommends putting in place some metric to evaluate the user “welcoming” capabilities of the lab to be continuously monitored.

---

### Status of the DEI program at the laboratory

**Charge:** We ask the PAC to review the status of the DEI program at the laboratory and of the open recommendations made by the PAC in June 2021:

- The PAC recommends the Laboratory continue and expand its DEI effort, including the SQMS Carolyn B. Parker Fellowship.
- The PAC encourages/recommends the Laboratory to explore the possibility of different recruitment and hiring approaches, such as cohort or cluster recruitment, as tools to more effectively strengthen an inclusive culture.

The Committee heard a presentation from the Chief Diversity Officer on the current status and plans for DEI efforts at the Laboratory.

### Findings

- New DEI initiatives are underway at Fermilab:
  - Continuation and expansion of its broad outreach program, which includes several internship programs, aiming at domestic and international participants and serving high school students, teachers, undergraduates and graduate students, and veterans.
  - New, prestigious fellowships for underrepresented minorities, such as the ASPIRE, JTFI, Parker and Gates Fellowships; besides, several new initiatives and activities were highlighted.
  - The Summer School Exchange Program, a Fermilab-Brookhaven program for college freshmen, has received roughly \$600k of funding from the RENEW funding.
  - The *Fermilab Alumni Network* with the goal of tracking the trajectory of Fermilab alumni;
  - The VALOR program for veterans, with a DOE investment of \$4M over 5 years, which has already converted 2 participants to full-time hires;
- A lab-wide climate survey will take place in 2023, following the last climate survey in 2019.
- DEI factors are now included in Fermilab employee performance reviews.
- The PAC also heard about the timescale for some of these initiatives to yield substantial results.

- VALOR already has indication of successes with the hiring of two recent participants trained in the program.
- For the summer school, a five year period should provide a good indication of the applicant pool and how many students are retained in HEP.
- The Fermilab Alumni Network will be able to track the long-term impact of several internship programs at Fermilab.

### Comments and observations

- The PAC commends Fermilab on
  - The broad portfolio of DEI initiatives and activities, and the leveraging of funding opportunities to continue and further expand these efforts, including the named fellowships.
  - The impact of the DEI effort in hiring and recruitment, such as the impact of the VALOR program, and the cohort recruitment within the Summer School Exchange Program.
  - The 2023 climate survey initiative, in particular given the broad participation of 70% of lab employees in the 2019 climate survey.
  - Its coordination of DEI efforts with other laboratories, such as the Summer School Exchange Program together with Brookhaven. The PAC further encourages coordination of DEI efforts with labs and universities in order to disseminate successful models and to overcome institutional challenges on the implementation of efforts.
- The Fermilab Alumni Network can become a powerful tool to evaluate the long-term impact of Fermilab DEI and outreach programs, particularly if the network is publicized broadly and interfaced with existing social media platforms.
- Fermilab, as the main hub for US high energy physics, has an important role in diversity, equity and inclusion for the community.

### Recommendations

The PAC recommends that Laboratory

- Develops metrics on diversity to be shared in future PAC meetings.
- Present its efforts on accessibility in an upcoming PAC meeting.

---

### Status of the AI/ML program at the laboratory

**Charge:** We ask the PAC to review the status of the AI/ML program at the laboratory and to assess whether the laboratory is in position to make a compelling case to become an AI/ML center.

The head of the AI/ML Project office presented the status of AI/ML efforts and planning at Fermilab

#### Findings:

The PAC heard an overview over the vision and strategic drivers of the AI/ML group, the AI Project Office as link between the different groups working on AI/ML, and interesting highlight results. Unique and core capabilities were pointed out.

- The research is based on four pillars:

- Algorithms for HEP science, including physics-inspired models and data, robust models that can be adapted to other problems, solutions to quantify uncertainties and understanding of anomalies, and fast/efficient algorithms.
- Computing hardware and infrastructure.
- Accelerator operation and control.
- Real-time AI systems.
- Additional limited resources will be needed within the next year to complete projects. Support on the level of 2 FTE AI associates in addition to 1 FTE (split over several senior scientists and software engineers) are needed to build up new academic/industry engagement. These will help solidify cross-domain leadership and critical expertise in the field of real-time AI for sensing and complex control systems, as well as related core AI research on robustness, uncertainty quantification, and (physics-) constrained AI.

**Comments:**

- The PAC commends Fermilab on being unique in leading in Fast AI/ML and application of AI/ML on FPGA and ASIC, where the AI/ML effort has synergy with the Microelectronics group. The hls4ml code, developed at Fermilab, is an important package adopted by many other groups, including industry.
- The AI/ML project office is important for communication between the different groups and interchange of knowledge gained in the different pillars and provides a boost of the output.
- We encourage the group to clarify their mandate regarding the balance between fundamental AI/ML research and experimental engagement.
- In order to become an AI/ML center, more areas of AI/ML research, in which the center plans to become leading (besides the fast AI/ML), will have to be worked out. These areas should be tailored to Fermilab to make a unique case with a future vision. Depending on these fields more partners in science and industry would need to be identified.

**Recommendations:**

- Formulate a strategy to respond to future AI/ML calls, not necessarily just for AI/ML centers.

**Status of the MicroElectronics program at the laboratory**

**Charge:** We ask the PAC to review the status of the MicroElectronics program at the laboratory and the status of the open recommendations made by the PAC in November 2021:

- Evaluate the balance and resource-loading of project and R&D activities in accordance with Lab priorities, and report at an upcoming meeting.
- Continue to pursue external collaborations (industrial, commercial, and academic) to consolidate networks and be in a privileged position to become a DOE Microelectronics center.

The PAC heard from the head of the ASIC design department on the status of the FNAL Microelectronics group

**Findings:**

- The microelectronics group at Fermilab co-leads a major US co-design center supporting the major scientific goals of the laboratory. It provides cutting edge technology and IC design capability serving the Quantum initiatives, the AI program and electronics needs in extreme environments.



- While rapid prototyping cycles and relative freedom in R&D projects are elements that attract expertise in the field, the recruitment process remains difficult due to enormous competition from private companies.
- Fermilab microelectronics group, synergistically with PPD, is leading the implementation of fast inference for ML models on FPGA/ASICs through the hls4ml open-source project.
- The FNAL Microelectronics group is investigating the possibility to join DOD and DOC coalitions/projects where the specific know-how developed in the group is highly appreciated, especially in prototyping and scaling. The ultimate goal is to be well equipped to compete for the role of DOE microelectronics center (call foreseen in 2024).
- The microelectronics division organization was presented. It is noted that the ASIC PMG group provides oversight and sets the priorities for the group.
- The lab is highly supportive in terms of financial resources but the recruitment remains difficult with IC designers positions difficult to fill.
- Several projects were showcased, including chip design for CMS upgrades (ETROC, ECON-D and ECON-T), cryogenic electronics for QSC, portable optical atomic clocks, cryogenic quantum readout, scalable quantum controls, Skipper CCD and CMOS readout electronics, several AI/fast inference-on-chip projects.

**Comments:**

- The PAC endorses the current plan of the lab management that aims at becoming a DOE Microelectronics center.
- The PAC commends the wide spectrum of initiatives developed inside the group to support the physics program of the lab, and in particular, is pleased to see the advancement of flagship projects, such as the CMS HGCALECON-D/T chips design that were a source of serious concern at the last meeting. Concerns remain for the CMS ETROC chip that is on the critical path for the MIP Timing Detector.
- The broad portfolio remains a source of concern in terms of resources needed to fulfill all commitments but the PAC understands that the lab is fully supportive in the budget allocation even though it might be increasingly difficult to hire skilled engineers.
- Synergistically with the PPD and CSAID, the ASIC group is developing unique know-how in fast inference of AI/ML on chip. This is crucial expertise that will become increasingly important both in HEP future programs (HL-LHC/FCC) and in private/commercial applications.
- The PAC recognizes the importance of investing in co-design partnerships and coalitions that will ensure a sustained involvement of the current highly specialized workforce in cutting edge technology even when the needs from HEP will be reduced (for example when the chip design effort for HL-LHC will be ramping down).
- The PAC acknowledges the challenges faced by the microelectronics group in tool licensing and developing multi-party NDAs, and commends the efforts to overcome these issues.
- The PAC will like to hear in a future meeting how priorities will be set regarding the activities of the Microelectronics group.

**Recommendations:**

The PAC recommends that:

- Efforts in the area of fast-inference-on-chip, which Fermilab leads and is uniquely placed to follow early implementation in running experiments, are prioritized;

- The Laboratory management, ETD, and Microelectronics group develop a strategic plan for upcoming microelectronics center bids, including a forward vision for consolidating strengths and development of new thrusts unique to Fermilab. Such a plan should consider the option of incorporating the synergistic elements of the AI/ML program into the microelectronics center bid;
- The Laboratory continues its full support of the ASIC development group in completing its current commitments to the HL-LHC upgrade.

---

### Status of the SQMS center

**Charge:** We ask the PAC to review the status of the SQMS center and of the open recommendation made by the PAC in June 2021:

- We encourage SQMS to discuss publication policy with the other national quantum centers, which are likely to face similar issues in this area. There may be an opportunity to establish common standards that take into account the traditions and needs of the different disciplines, but that can nevertheless be applied in a consistent way. The PAC would appreciate an update on these discussions in the next meeting.

The director of the SQMS Center presented the status of the Center.

### Findings:

- The SQMS
  - is one of five NQI centers starting in 2020 and ending in 2025 with the possibility of extension to 2030. The center submitted its midterm report just prior to the PAC meeting. The PAC heard reports on the progress made during the first half of its first term, which was focused on material science developments.
  - The SQMS Center is making progress, having achieved many of the goals outlined in the initial proposal. The facility is almost complete, and the center is staffed with 55 FTEs at Fermilab. There are 420 collaborators from 26 institutions involved in SQMS.
- The SQMS Center has been able to leverage superconducting materials expertise at Fermilab from the SRF program and partner institutions, and has acquired expertise in qubits and quantum information systems, achieving state of the art, 200 microseconds coherence time in a transmon qubit. This complements their SRF-developed cavities which have shown world record ~1 second lifetimes. They have also recently coupled qubits to their cavities achieving some of the most important early milestones.
- The cryostat acquisition process has been hampered by procurement issues, but once the initial phase is complete (expected soon) the center should be less constrained by lack of measurement capability.
- The Center has crafted a publication policy addressing the previous recommendation of the PAC. They have published 115 preprints and publications.

### Comments/Observations:

- The Center addresses a critical need in superconducting based quantum computing, in developing materials for enhanced coherence.
- The Center has a range of relevant materials science experience that has been applied to Nb and which could also be applied to other materials.

- The SQMS dark matter thrust leverages Fermilab's unique capability in SRF cavities and has a lot of intellectual overlap with QSC and other cosmic frontier activities.
- As planned, the PAC would like to hear more about the physics program at the next meeting. There are already many interesting proposals and the Committee is interested to hear which are planned to be explored further as part of the Center, either in the first term or as part of the renewal. It would also be good to see proposed qubit/cavity experiments (beyond characterization) started. The PAC would also like to hear about the plans for the colossus cryostat.

**Recommendations:**

- The PAC recommends the Laboratory streamline procedures to improve the efficiency of the procurement process for SQMS Center in coordination with the overall lab efforts to improve procurement.
- The PAC recommends the SQMS center explore opportunities for collaboration with other groups at FNAL, particularly on quantum sensors.

**Status of the FQI program at the laboratory**

**Charge:** We ask the PAC to review the status of the FQI program at the laboratory.

The Associate Laboratory Director for Emerging Technologies presented the status of the Fermilab Quantum Institute, an organization under the Emerging Technologies Directorate that coordinates the FNAL Quantum Computing and Quantum Sensing R&D activities.

**Findings:**

- There are approximately 15 people involved in FQI activities. The research thrusts include HEP application of quantum computing, quantum sensors, foundational quantum science, and enabling technologies
- Presently, the following projects are part of FQI: FQnet Quantum network, Quantum Science Center + QuantiSED, theoretical quantum simulation, MAGIS-100, and cryogenic electronics/microelectronics for quantum (some supported through the quantum science centers).
- The SQMS center is independently managed.

**Comments/Observations:**

- Many quantum concepts and demonstrators are developed under the FQI umbrella. The PAC commends FNAL for supporting these efforts that prepare the Laboratory for upcoming opportunities.
- The QICK control electronics developed at FNAL finds use in several quantum projects at FNAL, as well as outside universities and companies. It was good to see the different centers collaborate and share control systems across organizations (SQMS, FQI, QSC, etc.).
- There is uncertainty around funding of some projects after next year.
- It was not clear how FQI interacts with Cosmic Frontier efforts given the utility of quantum sensors in light dark matter searches.

**Recommendations:**

The PAC recommends that the Laboratory

- Coordinates with DOE to have FQI projects reviewed and possibly extended to match timing of upcoming funding opportunities.
- Develops a long term strategy towards quantum science and how it integrates with HEP goals.

---

### Status of the CMS experiment

**Charge:** We ask the PAC to review the status of the CMS experiment and to address the impact of external factors on Fermilab and U.S. deliverables.

The Spokesperson of CMS presented the status of the CMS experiment, US CMS, and the FNAL CMS group.

#### Findings:

- CMS completed Phase 1 upgrades in time for Run 3. Additionally, several Phase 2 upgrades are being demonstrated in Run 3. Fermilab successfully delivered on their Run 3 commitments (HCAL upgrades, Computing, etc.)
- CMS had a successful first year of Run 3 running, collecting data at record rates, in spite of a shortage of operations personnel, including shifters.
- Encouraging results were presented for HGCALE and MTD electronics, a Fermilab contribution to Phase 2 upgrades. Specifically, the first submission of the HGCALE ECON-D chips is expected in February or March and the ECON-T P1 iteration is complete, with minor changes expected in the final iteration ECON-T. The MTD ETROC chip is a challenging design that may need more resources to mitigate risk. The recently submitted ETROC-2 was the first fully functional iteration. ETROC-3 is under development and expected to be the final prototype of the chip.
- There are significant external risks arising from cost inflation and the war in Ukraine. At this time, Russia/Belarus/JINR institutions still contribute to operations and M&O funds, but it is unclear if this will continue. CMS is updating its upgrade plans to make the contributions from Russian institutions optional to mitigate these external risks. The experiment created a detector upgrade fund, to which CMS institutions will contribute in-kind and financially. DOE allocated an additional extra \$10M to the Upgrade project. This will help Fermilab take on new scope in areas directly connected with its existing commitments, in particular HGCALE construction.
- It remains difficult to cover experiment shifts even post-pandemic. An uncovered core shift would halt data taking for several hours. To address this risk, US CMS is developing in collaboration with CMS new models to take remote shifts from Fermilab ROC.
- CMS data simulation, reconstruction and analysis, as well as trigger-level selection, provide fertile grounds for the development and validation of novel AI/ML methods in collaboration with the Fermilab AI/ML project office.
- The Fermilab CMS group plays a leading role in promoting DEI in the experiment, including founding the CMS diversity office and authoring its Code of Conduct.
- The Fermilab ROC is the 1st ROC in CMS to be qualified for DQM online remote shifts
- The Fermilab LPC is a critical service provided by Fermilab as US CMS host lab. During the COVID era it converted to virtual, and then hybrid, operations to continue serving the US CMS community.

#### Comments:

- Overall the CMS Fermilab group does an excellent job contributing to Run 3 data-taking while preparing for the HL-LHC hardware and software upgrades.
- Replacing Russia/Belarus/JINR contributions to day-to-day operations of the detector would be hard and costly.
- US CMS relies on priority access to Fermilab expertise and facilities to deliver on their commitments:
  - SiDet (including CO<sub>2</sub> cooling) and Scintillator Development and Production Facility are needed for Phase 2 upgrades
  - ASIC designers from the microelectronics division are needed to complete the production of the ETROC chip for MTD front-end electronics and HGAL ECON-T and ECON-D chips.

### **Recommendations:**

The Committee recommends that:

- Fermilab streamline site access for US CMS collaborators so that they can easily access the LPC and ROC.
- Fermilab should work with DOE to restore adequate funding for the LPC to rebound from the COVID remote-work lull
- The LPC ensures regular on-site presence of Fermilab-based experts.
- US CMS investigates ways to expand the usage of the Fermilab ROC to help alleviate the current shortage of shifters at CERN.
- The Fermilab CMS group has a stable presence at CERN sufficient to contribute to data-taking operations with experts on shift and on call.

---

### **Updated Cosmic Frontier strategy at the laboratory**

**Charge:** We ask the PAC to review the status and plans of the cosmic program at the laboratory.

The head of Fermilab's Astrophysics Department presented the status of the Cosmic Frontier program at the Laboratory.

### **Findings:**

- The Cosmic Program developed a strategic plan in 2018-19, which had CMB-S4 as their highest priority and included cosmic surveys and dark matter searches.
- Since the strategic plan was developed, LBNL was selected as the Lead Laboratory for CMB-S4.
- Fermilab has established clear leadership in the Dark Energy Survey, the analysis of which will be tapering off in 2023-24.
- LSST/Rubin data-taking is projected to begin in 2024, and Fermilab scientists have roles in Rubin and DESC science and operations.
- Fermilab maintains roles in SuperCDMS.
- Fermilab is the Lead Lab for ADMX-G2 and has plans for axion searches extending to the end of the decade, and R&D initiatives that could probe a wide swath of the QCD axion dark matter parameter space.
- The SENSEI experiment that searches for light dark matter won the 2021 Breakthrough Prize New Horizon Award.

- There are several light dark matter searches spread throughout the lab, especially in groups applying quantum science.
- Five scientists were convenors in Snowmass and the Lab has joined the MegaMapper Design proposal.

### Comments

- The program is well-aligned with the DOE mission and the vision for the future articulated by the broader community at Snowmass 2021.
- The current program heavily leverages the increased funding for quantum science and the local expertise in quantum sensing for R&D.
- The program faces challenges with a decline in the research budget, DES ending, CMB-S4 being assigned to LBL as the lead lab, and SuperCDMS construction now primarily a SLAC effort that is winding down.
- The PAC commends the group, faced with these challenges, for responding proactively. DES survey scientists are successfully transitioning into operations and science roles in LSST/DESC. The group understands that establishing the kind of leadership they had in DES will be challenging and is working to carve out significant efforts.
- The PAC also commends the program on establishing a well-defined role in CMB-S4.
- Armed with two powerful capabilities – the accelerator and quantum sensing expertise – the Lab has an opportunity to play a major role in the search for light dark matter including axions.
- The dark matter detection efforts across the lab do not appear to be coordinated or developed in a strategic way.

### Recommendations

The PAC recommends that

- Fermilab develop a comprehensive strategic approach (that includes prioritization) to light dark matter searches that leverages laboratory capabilities
- In concert with this Lab planning, the Fermilab Cosmic Frontier group should update their strategic plan, including the vision and purpose of the Cosmic Physics Center.
- The Laboratory works with DOE to secure adequate funding to support its Cosmic Frontier program and strategy.

---

### Report on the Mu2e experiment

**Charge:** We ask the PAC to review the plan to transition from project to operations and for initial data taking.

#### Findings:

- The PAC heard an update on the status of the Mu2e experiment, after re-baselining.
- Fermilab is investing significant resources, obtained from the Inflation Reduction Act, in increasing Mu2e's priority in hopes of completing the transition to operations before the PIP-II complex. With this infusion of funds, the project schedule is now technically driven. Resources have been added for facilities, solenoids, detectors, and accelerator commissioning, and the schedule for accelerator commissioning has been advanced by one year.
- The goal is to take physics data in 2026. Projections are for collection of 10% of the full dataset before the shutdown, allowing order  $10^3$  improvement in  $R_{\mu e}$  over current best results.

- Milestones for “facilities” - defined as any and all work that is off project but needed by the project - including “need by” dates were presented. Milestones for solenoids, detector, and the accelerator are tracked within the project and thus were not presented to the PAC at this meeting. Experiment milestones laying out the path from the present to first results are being developed.
- Updated sensitivity analysis has been performed and algorithm development is in good shape, but full development of the analysis framework making use of the Fermilab computing toolset remains to be done.

**Comments and Observations:**

- The schedule is extremely challenging for facilities, solenoids, and detectors and there is significant risk for commissioning the accelerator slow extraction. Significant resources are being used in hopes of being able to take data before the shutdown. While it may be challenging to succeed in this endeavor, the value of even a small amount of data before the shutdown is very high, and thus the attempt seems worthwhile.
- The PAC is concerned about many sub-projects being already on the critical path without any contingency. Many crucial components (production and detector magnets) are expected to arrive “just-in-time” with little time available to test/commission them. A detailed schedule with clearly identified milestones has been presented for the facilities items. The PAC understands that such a schedule exists within the project and is being developed for the experiment, and would appreciate in future meetings a high level summary of these schedules.
- The PAC supports the increase in resources dedicated by the Laboratory management for the completion of the Mu2e project given its unique physics capabilities.

**Recommendations:**

- The PAC recommends the experiment monitor at a regular pace a resource loaded schedule for all items needed to be ready for data taking with clear “need by” dates.

**Stage 1 approval for the Spin quest upgrade**

**Charge:** We ask the PAC to assess the readiness of the SpinQuest experiment for Stage 1 approval.

**Findings**

- The PAC heard about the status of the SpinQuest experiment, which aims to understand how the spin of the proton relates to the spin and angular momenta of sea-quarks and gluons. The experiment’s start of operations/science data taking awaits laboratory approvals including Accelerator Safety Envelope (ASE), Accelerator Readiness Review (ARR) and Target material review.
- The PAC also heard about the SpinQuest Upgrade, proposed as the next phase of the SpinQuest experiment. The physics case for the SpinQuest Upgrade can be summarized in novel measurements of transverse momentum dependence (TMD) of sea-quarks, and several competitive constraints on light dark matter scenarios.
- The proponents presented the experimental enhancements required for the upgrade and their proposed implementation, which include:
  - For dark sector searches, an EM calorimeter with good energy resolution and granularity at high beam repetition rate to identify and reconstruct displaced electromagnetic/hadronic signatures. They propose using the PHENIX EM calorimeter

currently located at BNL, with new readout electronics. A test stand has been developed at BU.

- For gluon transversity measurements, a new coil around the target cell and a new semi-saturating (SS)-RF modulating NMR system. A prototype has been built at the University of Virginia.
- For increased tracking acceptance and performance, an additional tracking layer between the FMAG and KMAG. They could use proportional chambers and readout from HyperCP.
- The cost of the SpinQuest upgrade as presented by the proponents is at the scale of \$565k for the EMcal upgrade and SS-RF NMR system, plus 2 FTEs for operation and analyses. Additionally, the impact statements from PPD and Accelerator Ops estimate \$1M and about 1.5 FTEs for the continued operation of the Neutrino Muon beamline beyond FY2024.

### Comments and observations

- The science goals and scientific impact of the proposed upgrade are compelling for both spin and dark matter physics.
  - The gluon spin physics measurements would be novel with possible impact on future experimental results.
  - On the dark matter sensitivity, the SpinQuest Upgrade would be competitive and complementary to the LDMX experiment and to the FASER2 proposal.
  - The PAC notes that while the completion of the upgrade before beam shutdown is desirable, an extended timeline may not diminish the competitiveness of the experiment.
- The proposed upgrade is in line with the laboratory's mission and utilizes its unique capabilities and facilities.
- The PAC recognizes interest in a beam dump program at Fermilab. The SpinQuest Upgrade would strategically serve as a start for such efforts.
- The SpinQuest experiment is not yet operational. Concerns were raised by stakeholders regarding safety, operational readiness of the experiment, and personnel available to start, conduct and analyze the SpinQuest science run. Unless resolved, these will impede progress on the SpinQuest Upgrade.

### Recommendations

- The PAC recommends that laboratory management comprehensively review the issues with respect to SpinQuest readiness for operation and resourcing for the SpinQuest Upgrade.
- The PAC endorses Stage 1 approval for the SpinQuest Upgrade pending a successful outcome of the aforementioned review.

---

### Status of the ICARUS detector

**Charge:** We ask the PAC to review the status of the ICARUS detector and the status of the open recommendation made by the PAC in June 2021:

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



## Findings

Since the last PAC meeting, the overburden has been installed, and ICARUS has completed a one-month-long physics run. Data acquisition had a high efficiency. Several important developments took place during the summer shutdown, such as improvements on trigger, reduction of TPC wire noise, PMT gain and timing calibration, and CRT calibration and timing. Although a fire incident interrupted work and data taking for several weeks, there was no permanent degradation of the detector. The start of the second physics run has been approved in late November, and currently physics data taking is ongoing with high efficiency (>90%).

On the reconstruction and analysis side, the ICARUS collaboration has made several developments, including vertex reconstruction algorithms that were validated by visual inspection of events; CRT-PMT time matching to improve cosmic ray muon rejection; TPC wire signal and calibration. The collaboration is pursuing two separate paths for analysis, one with LArSoft/Pandora and another using machine learning. The two groups pursuing these analyses work independently, but maintain communication. Last, the collaboration is pursuing its first analysis on events with one contained muon and one proton.

## Comments and observations

- The PAC commends the collaboration for a very successful start and data-taking with high efficiency.
- The PAC commends the improvements on vertex reconstruction with first data, and the cross check with visual inspection. The PAC looks forward to even further improvements on vertex reconstruction with new techniques as, for example, machine learning.
- The PAC commends the use of AI/ML and encourages further exploration of these techniques.
- The PAC acknowledges and encourages the ongoing efforts on sharing common tools between ICARUS and SBND

## Recommendations

None

---

## Status of the SBND

**Charge:** We ask the PAC to review the status of the SBND.

### Findings:

- The SBND detector was completed and transported from the DAB to the SBND detector hall on 1 December 2022.
- The readout & server rack installation is progressing well, integration and commissioning have already begun for the DAQ and the trigger.
- The group is developing cryogenics & detector commissioning plans [pre-LAr and post-LAr filling], with the focus on completing as much of the DAQ and trigger commissioning as possible in the months before filling with liquid argon.
- Main physics plans were presented:
- eV-scale sterile neutrinos: single detector searches taking advantage of the off axis variations of the beam
- New physics scenarios with many ideas for new searches emerging from collaboration with theory colleagues.

- Neutrino-argon interactions with an order of magnitude more data than is currently available.
- The SBND collaboration aims to start taking with physics quality data in Fall 2023.

**Comments:**

- The PAC commends the SBND collaboration on successfully reaching an important milestone.
- The PAC acknowledges and encourages the ongoing efforts on sharing common tools between ICARUS and SBND

**Recommendations:**

None

---

**Status of the SBN Analysis Working group**

**Charge:** We ask the PAC to review the status of the SBN analysis working group and the status of the open recommendations made by the PAC in June 2021:

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

**Findings**

The SBN Analysis working group is an effort devoted to developing common tools for joint SBN analyses, composed by members of both SBND and ICARUS collaborations. Currently, the working group is strongly focused on the main goal of the SBN program, the sterile neutrino search to probe the MiniBooNE/LSND anomaly using near and far detectors. Two important milestones have been met: reproducing proposal-era oscillation sensitivities using truth-level information; and updating the oscillation sensitivities using truth-level information with updated inputs for efficiencies, backgrounds, and systematic effects. The next milestone is to evaluate the SBN oscillation sensitivity with full event simulation and reconstruction, as well as detector systematics, with the goal of establishing a complete oscillation analysis pipeline to be used in the joint fit.

The oscillation analysis under development accounts for sterile neutrino oscillations fully consistently, that is, considering the presence of oscillations in both muon and electron samples. The near-term priorities include the incorporation of full event reconstruction, the inclusion of detector systematics, the development of analysis strategies, and the use of the SBND-PRISM concept to improve the sensitivity to sterile neutrinos. The SBN Analysis WG has organized a SBN Calibration Workshop, where relevant issues for the joint analysis were addressed, such as cross-detector calibration, as well as training of junior collaboration members. The SBN Analysis Working Group also communicates and works closely with the SBN Analysis Infrastructure Working Group in coordinating and addressing data and software infrastructure and computing resource needs across SBN.

Lastly, the future plans of the SBN Analysis WG include the incorporation of more refined analyses, for example leveraging the SBND-PRISM concept, NuMI event samples, and multiple event sample selection.

**Comments and observations**

- The PAC commends and further encourages the development of common software tools and analysis choices, such as neutrino-nucleus interaction modeling, by the SBN Analysis WG
- The PAC commends the consistent treatment of short baseline oscillation physics, which is quantitatively relevant to the sensitivity of SBN.
- The SBN Analysis WG is developing tools for the joint analyses that may also be used in single-detector analyses.
- The PAC notes that the SBN Analysis working group is currently preparing a five-year computing plan, including data preservation in coordination with SBND and ICARUS.

### Recommendations

None

---

### Muonium R&D/Physics Program at the MTA

**Charge:** We ask the PAC to review the physics case of the proposed muonium experiment at the Fermilab MTA and the potential of the muonium physics program at the PIP-II.

### Findings:

- Muonium (M) physics studies address three main topics:
  - M/M-bar oscillations complementary to Mu2E
    - potential to improve MAC limit (PSI 1999)
  - M energy level spectroscopy in pure QED system
    - Current measurements are 20 year old
    - New experiments in progress: MuMass (PSI), MUSEUM (JPARC)
  - Antimatter gravity with point-like massive particles
    - No direct tests available yet
    - ALPHA, AEGIS and GBAR experiments at CERN are currently targeting 1% measurement with anti-hydrogen
- Novel muonium production method under study at PSI can significantly improve the Muonium production
  - It could be used at FNAL with higher efficiency with high Z targets
  - The proponents plan to explore improvement of this technique with thicker superfluid He layer (100  $\mu\text{m}$  vs  $\sim 1 \mu\text{m}$ )
  - The current proposal calls for R&D on a limited scale at MTA with prospects for high rate measurements later at PIP-II.
- The work on R&D at MTA can occur parasitically to other lab activities
  - A simple experiment to measure M gravity at MTA has potential for 10% measurement resolution
  - Main costs are expected to be covered by sources outside FNAL

### Comments:

- The physics of M-Mbar oscillations are complementary to

- the current FNAL activities on Mu2E
  - anti-hydrogen gravity experiments since only point-like massive particles are involved
- There is strong competition from PSI, where this line of research has been active for some time already
- Reaching the projected muonium production rates will likely require a long R&D with significant risk involved
- The physics case is valuable and could most likely be expanded if the full potential of this experimental technique is achieved

**Recommendations:**

The PAC recommends that

- The proponents provide more depth and details on the studies that are currently proposed and explore other potential measurements that could be competitive with the full PIP-II statistics.
- The implications for Laboratory support related to the R&D work at MTA should be clearly understood.