# Fermilab Physics Advisory Committee Report

**June 21-24, 2022**


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## Executive Summary

The Fermilab Physics Advisory Committee (PAC) met on 21-24 June 2022. It was the first meeting in a hybrid format since the start of the COVID-19 pandemic. The meeting occurred as many changes and developments are in progress in the US High Energy Physics (HEP) program. The Committee had the opportunity to congratulate the new FNAL director on her recent appointment. In the US HEP community, the Snowmass planning process is approaching its culmination in the Summer Meeting in Seattle and will be followed by the next Particle Physics Planning and Prioritization Panel (P5) process to set the US HEP plan and priorities for the coming decade.

Due to this juncture where the Laboratory continues to execute the 2014 P5 plan while preparing for the outcomes of the Snowmass process and its input to the next P5 process, the meeting examined the ongoing scientific activities at the Laboratory while receiving updates on the Snowmass process. The Committee also heard about the Laboratory's plan for providing input to the P5 process following the Summer Meeting, the status of its accelerator complex, and its planning for the future needs in software and computing. The Committee was also asked to evaluate the scientific case for an upgrade to the SpinQuest program, and received an update on the exciting developments in the SQMS Center.

The meeting started with an overview on the FNAL Science and Technology strategy from the new FNAL Director. In addition to two elements to deliver science and technology innovation and effective project execution, the strategic thrusts include important elements to diversify and empower the workforce, transform its business systems, and to forge alliances locally, nationally, and globally. The final thrust is to develop a strategic plan for the next twenty years. A leadership transition is in progress, which will include a restructuring of the organization that will directly connect critical projects (LBNE/DUNE, PIP-II, Mu2E, HL-LHC, AUP, and HL-LHC CMS) to the Directorate to ensure their successful execution.

The Committee heard about FNAL's plan to form two working groups, one focussed on the upgrade of the accelerator complex to 2.4 MW and the other on delivering a prioritized set of recommendations for FNAL's role in the US HEP program over the next decade. The Committee supports the proactivity of the Laboratory in the process and noted the importance for the overall community to achieve a healthy balance between projects, research, and operations, and to explore and identify specific activities in which the non-neutrino community will benefit from the success of DUNE.

The Chief Accelerator Officer presented the status of the FNAL accelerator complex, which is successfully supporting FNAL's wide-ranging program. However, a shortfall of resources is concerning, resulting in pressures in maintaining components and expertise, operational efficiency, and in supporting preparations for Mu2e. This highlights the need for continued succession planning.

The Committee heard a report from the Head of the Neutrino Division, which is now supporting a broad program with two neutrino beams (Booster and NuMI), while preparing for DUNE through both its ongoing program and R&D. Recent major milestones include the first low energy excess results from MicroBooNE and the first deployment of LAPPDs at ANNIE. Given the importance of recent, ongoing, and upcoming measurements in supporting DUNE, the Committee noted the importance of a data preservation program. The presentation was followed by a presentation from the Snowmass Neutrino Frontier.

The Head of the Particle Physics Division presented its diverse program, which includes a growing program in CMB, a focused program in Dark Matter, a Dark Energy program transitioning to operations, a world-class muon program, and many critical contributions to CMS, with many recent milestones and accomplishments in each area. The Committee discussed the portfolio of Physics Centers and Fellowships (LPC, CPC, and Neutrino) and R&D initiatives. Following this presentation, the Committee heard reports from the Cosmic, Precision, and Energy Frontiers of Snowmass.

The Strategic Plan for Software and Computing was presented by the Head of the Scientific Computing Division, providing an overview of the current and expected needs of FNAL's program in storage, computing, and software. The Committee noted the progress in utilizing accelerators like GPUs, support for modern data processing tools through the new Elastic Analysis Facility, as well as its support for scientific software such as event generators for both collider and neutrino experiments.

The Committee heard about the status of the SpinQuest experiment, which is upgrading its target for gluon spin tranvsersity studies, and the physics case for an upgrade (DarkQuest) to add an electromagnetic calorimeter to search for dark photon candidates in the mass range of 10-200 MeV. The Committee endorsed the physics case for the upgrade.

Throughout the meeting, the Committee noted the continued impact of COVID in impeding the restoration of a vibrant scientific community and environment at the Laboratory. Furthermore, increased security measures are also complicating and restricting access for visitors. We urge the Laboratory to work with all stakeholders to seek a solution even as the pandemic continues to evolve.

The Committee is grateful for the informative presentations throughout the meeting, and to Anadi Canepa and Kayla Decker for the seamless management of logistics for this hybrid meeting in a rapidly changing environment. We also express our thanks to the Snowmass Frontier Conveners for a series of talks which provided a comprehensive view of the status in the weeks prior to the Summer Meeting.

**The Physics Advisory Committee:**

Present: Halina Abramowicz, Zeeshan Ahmed, Franco Bedeschi, Paolo Calafiura, Scott Dodelson, Luca Malgeri, Isabell Melzer-Pellmann, Hugh Montgomery (ex officio), Marcelle Soares-Santos, Hirohisa Tanaka (chair), Elizabeth Worcester.

**Scientific Secretary**: Anadi Canepa

**Directorate**: Lia Merminga, Joseph Lykken, Gregory Bock

### Process for defining the Fermilab's scientific program of the next decades

*Charge: We ask the PAC to review the process the laboratory is developing to define the Fermilab's scientific program of the next decades, how that program would leverage and enhance all laboratory's capabilities, how it would respond to the interest of the US HEP community, how it would integrate in and complement the international HEP programs.*

The PAC heard from the outgoing Chief Research Officer on Fermilab's preparations for engaging with and supporting the P5 process following the conclusion of the Snowmass process.

## Findings

1. The U.S. HEP community is in the middle of the Snowmass process, which will culminate in July, and feed into the P5 prioritization process. Further, the new Director has made it a priority to ensure a steady flow of scientific results and a long-term plan for the next 20 years. She also has made clear her intention to steer DUNE/LBNF to its full potential.
2. To facilitate this planning, the Laboratory has been working internally and with the larger community in Snowmass to identify exciting scientific opportunities that would leverage the Lab's capabilities. All scientists were given freedom to participate in the Snowmass process as their interests dictated, and many will be attending the final meeting in Seattle.
3. Most recently, the Director charged two working groups to provide input to P5: (i) one that will focus on the upgrade of the accelerator complex to 2.4MW and (ii) another that will deliver a prioritized set of recommendations for Fermilab's role in the U.S. particle physics program over the next decade.
4. The two working groups will be charged with gathering input from all Laboratory scientists about their priorities, and many of the scientists have been active in the Snowmass process so will communicate priorities from the broader community.
5. The working groups will work together to ensure that the full scientific potential of the accelerator upgrade will be articulated, examining new scientific opportunities that go beyond the baseline needs of the DUNE collaboration.
6. The Laboratory is considering its participation in future colliders in concert with its international partners.

## Comments

1. There is some uncertainty as to the timing of the P5 process, with an expected start date of order Fall, 2022.
2. The Committee supports the new Director's proactive process for providing input to P5 and bringing the Laboratory together to assess its priorities.
3. The current suite of DOE-HEP commitments to projects is quite large, leaving little room for new initiatives over at least the next five years. This follows on eight years of strong project support, which in turn has squeezed the research and operations budgets. This tension will likely continue.
4. The Snowmass exercise has uncovered many exciting (and potentially expensive) ideas, including those, such as gravitational waves, that expand the scope of High Energy Physics. There will likely be stiff competition for the remaining funds over the coming decade. While the Committee

understands that DUNE (including Phase 2) is the current Fermilab priority, there will likely be pressure to ensure a robust program across the Energy and Cosmic Frontiers.

### Recommendations

1. Input to P5 from the Laboratory should take into account the interests of the broader community as expressed at Snowmass and the pressure that the research community is experiencing in an era of large projects. The internal working groups should strive to provide input to P5 that maintains healthy research and operations budgets.
2. Given the expected pressure to start new projects, we recommend that the Laboratory explore and emphasize specific activities in which non-neutrino communities benefit from the success of DUNE. Two examples are the science capabilities of the 2.4 MW beam and the possibility that DUNE far detector modules in Phase II have capabilities for expanded physics scope, including potentially dark matter or neutrinoless double beta decay detection.

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## Overview of the performance and plans for the Operations of the Fermilab accelerator complex

*Charge: We ask the PAC to review the performance of the accelerator complex and the operations' plan in the context of the current and future projects and programs at the laboratory.*

The Chief Accelerator Officer provided an overview of the status of the FNAL accelerator complex.

### Findings

1. The current performance of the accelerator complex was reported. The PAC finds that the accelerator division adequately supports all existing programs at Fermilab, such as the NuMI, g-2 and SBN programs, with the caveat that the resources allocated yearly for the accelerator activities have always been less than needed. The insufficient resources led to a slow increase in the aging of critical components, which would have to be replaced to maintain good operational efficiency. This resulted in additional downtime and sometimes reduction of the length of programmed data taking runs of experiments. Furthermore, the ACNET control system is approaching obsolescence and will require a replacement to a modern system (ACORN), for which the timeline and overall impact to operations is being studied and planned. Concerns are also raised on the readiness for Mu2E operations.
2. Human resource needs in the accelerator division are expected to slightly rise once PIP-II starts operating. So far the hiring of new young accelerator personnel has been successful, however there have been some difficulties with continuity as experienced people retire, since hiring persons with experience is difficult due to competition with other laboratories and the private sectors. This applies in particular to electrical engineers.
3. Future activities are dependent on P5, following the Snowmass deliberations and output of the two working groups preparing input to P5.

### Comments

1. It is important for the two FNAL P5 working groups to provide the community with well-understood Booster replacement paths, including documentation of technical and resource needs. Accelerator Division input will be invaluable.

### Recommendations

1. The PAC encourages the Accelerator Division to continue regular hiring and succession planning to maintain needed expertise.

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## Overview of the Neutrino Science program

*Charge: We ask the PAC to review the status of the Neutrino Science Program at the laboratory including on-going experiments and experiments planned in response to the 2014 P5 recommendations.*

A presentation was given by the Head of the Neutrino Division on the status of the neutrino program at FNAL and the activities within the Division.

### Findings

1. Fermilab has a focused accelerator-based program in neutrino physics with the aim to address neutrino mixing, mass ordering and CP violation, and the potential to investigate beyond the standard model interactions.
2. Two experiments, MINERvA and MicroBooNE, completed data taking. Minerva has been a leading source of high-statistics neutrino interaction measurements and is developing an important data preservation project. MicroBooNE has released a high-profile result disfavoring several leading explanations for the MiniBooNE low-energy excess and will continue data analysis. There are three running experiments, NOvA, ICARUS, and ANNIE. The SBND experiment is expected to start data taking in late 2023. All these experiments are expected to finish data-taking before the long-shutdown in 2027. ANNIE achieved an important R&D milestone in 2022 - the deployment of a novel pico-second photon detection system (LAPPD) - and plans further deployments of LAPPDs and water-based liquid scintillators. NOvA expects to more than double the published dataset, which is sufficient for 3σ determination of the neutrino mass ordering if parameters are favorable. ICARUS and SBND expect to combine for 5σ sensitivity to sterile neutrino parameter space preferred by global fits.
3. On top of their own scientific program, current experiments will provide essential input for the future precision neutrino program at the LBNF/DUNE in terms of unprecedented control of systematic uncertainties, good understanding of the LAr TPC technology, operating high-power neutrino beams, and measurements of neutrino-argon interactions.
4. The experimental program is accompanied by a vibrant theoretical program covering standard and beyond standard physics with neutrinos, including support for developing event generators.

5. An extended “blue sky” detector R&D program is underway with potential applications to future neutrino experiments. A joint effort of the Neutrino and Scientific Computing Divisions promotes applications of Machine Learning to off-line and on-line processing.

### Comments

1. The MiniBooNE anomaly is still not fully resolved. Though MicroBooNE has analyzed only half of its available statistics, the expectation is that it will take ICARUS and potentially SBND to deal with it definitively.
2. The completion of the present scientific program is geared towards DUNE.
3. Fermilab plays a major role in beam design and delivery for DUNE Phase II. The priority of DUNE detector upgrades will be determined by the DUNE collaboration’s scientific strategy and available funding.
4. Much of the current R&D program may turn out to be of interest for future upgrades or phases of DUNE. At this stage, it is not driven by a formal top/down process but is coordinated with the DOE. It may be useful to think about higher level coordination as the DUNE program evolves.
5. The Committee would like to commend the Laboratory for establishing a broad, world-leading program in accelerator-based neutrino science.

### Recommendations

1. Given the value of the data collected by this program in particular for cross section measurements, the Laboratory should encourage the Collaborations to devise a process of data preservation.

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### Overview of the Collider, Cosmic, Precision Science programs

*Charge: We ask the PAC to review the status of the Collider, Cosmic, Precision Science Program at the laboratory including on-going experiments and experiments planned in response to the 2014 P5 recommendations.*

The Head of the Particle Physics Division presented the ongoing activities in the Division, which span the Cosmic, Energy, and Intensity Frontiers.

### Findings

1. The Cosmic Frontier program leverages a diversity of funding sources and utilizes the Laboratory’s core capabilities/facilities. Effort is being grown in CMB (in SPT-3G and CMB-S4), consolidated in Dark Matter (ADMX and Sensei) and transitioned from project to operations in Dark Energy.
2. Early career scientists are at the forefront of scientific results, innovative AI/ML techniques, detector R&D, and operations. They have won numerous awards and the Committee commends them for their success.
3. The Cosmic Physics Center receives no funding from DOE and is supported by a small amount of external funding only.

4. The Precision Science program is advancing strongly with updates on the important results of g-2 expected from the additional statistics collected, as well as progress towards mu2e.
5. The Energy Frontier program is thriving in the science exploitation of the LHC. The FNAL CMS group continues its leading role in physics analyses, with several major publications on a number of topics within the past few months. An FNAL scientist has served as collaboration spokesperson and another scientist is spokesperson-elect. Its contributions to the CMS upgrades are well-defined and executed effectively. The LHC Physics Center, supported by DOE, is an asset providing a stable attraction point for the community, leading to a substantial number of CMS publications and unique training opportunities. FNAL also maintains an R&D program for future colliders targeting wider use of AI/ML technologies and effective utilization of HPC resources.

## Comments

1. As noted by the Committee in the past, the LHC Physics Center is a very effective tool to ensure long term leadership of Fermilab in the Energy Frontier. Initiatives such as visiting programs, fellowships, data analysis schools and graduate level courses bring early career scientists together and encourage community engagement. Another example of a successful Physics Center at the laboratory is the Neutrino Physics Center.
2. There is concern that funding for the Physics Centers (CPC, LPC, NPC) is in tension with research support in other areas.
3. Concerns were expressed at the last PAC meeting regarding the schedule of the Fermilab deliverables for the Phase 1 CMS upgrades. We acknowledge and commend that additional resources are now associated with the project keeping it on track with the updated schedule of the experiment.
4. The R&D efforts for Future Colliders have grown and span many areas including picosecond level timing, solid state detectors, real time processing, and ASICs development, scintillator forming technology and silicon photonics.
5. The Future Colliders group is helping in defining a roadmap for the continuation of studies of future colliders based on the available options.
6. The Committee notes the significant success of the Particle Physics Division in delivering the CMS Phase I upgrades on time. The Division is currently working on the CMS Phase II upgrade and providing g-2 support.
7. The Committee notes a past recommendation to collect “essential facts about the structure of the LPC and its successes be disseminated in a concise document” and noted “a review of the structure, support, and community impact of [the Centers] could provide additional context for future discussion.”

## Recommendations

1. We recommend the laboratory to carry out a review of its Physics Centers to understand the structure, support, and impact of each in supporting their respective communities.
2. We recommend Fermilab to continue to support the R&D initiatives that are vital to define the future programs of the lab and educate the future generation of scientists.

### Strategic Plan for Software and Computing at the Laboratory

*Charge: We ask the PAC to review the strategic plan for software and computing, including AI/ML, at the laboratory and the status of the recommendation made at the July 2021 PAC meeting: "The PAC recommends the development of a resource and computing plan including timelines, milestones and connected decision trees based on the progress on the GPU implementation and therefore possible off-loads to HPC resources. This should help to ensure that Fermilab computing resources can be optimally used to support the experiments".*

The Committee heard an overview on the status of Software and Computer activities at FNAL from the Head of the Scientific Computing Division.

## Findings

1. Mass storage is a core responsibility of the FNAL Scientific Computing Division.
2. There is active R&D to update and improve the tape layer and disk layer of the storage system, emphasizing the role of Rucio as a layer. Preliminary timeline to migrate to new tape layer technology were provided.
3. CPU resources match requests from experiments, with actual usage approximately 10% below capacity.
4. HPC and Cloud resources are made accessible through SCD-developed HEPCloud. On average, over 20K cores are provided by HPC resources.
5. SCD recently made available 12 NVIDIA A100 GPUs. Some will be dedicated to analysis, some to R&D. SCD will measure utilization to decide on future purchases.
6. There is an AI/ML initiative across divisions with a structure to keep it coherent. Development is mainly driven by experiment software, partly due to lack of dedicated funding. SCD's purchase of A100 GPUs supports this initiative.
7. SCD reported progress in enabling the usage of computing accelerators, specifically GPUs. Most of the work that remains to be done is in common software like detector simulation and event generators, and in experiment-specific software, like frameworks and physics algorithms. SCD is contributing to this work directly through projects like Celeritas that is prototyping a parallel, GPU-friendly, detector simulation toolkit, and HEP-CCE that is developing common solutions to port experiment software, data stores, and workflows to new computing architectures.
8. SCD presented scenarios for the case GPU/HPC resources can not be exploited. The impact on CMS would be substantial, but the risk is low given current progress in GPU R&D. Impact on IF would be limited and could be handled with a limited increase in funding or a corresponding reduction in staffing.
9. A Fermilab Analysis Facility (AF) is a strategic priority for FNAL computing. The AF will support modern data processing tools like Jupyter, Dask, Coffea, and Ceph.

10. Simulation is a traditional area of expertise at FNAL, with significant contributions to Geant4 and collider generators. A new hire in support of theorists developing neutrino generators just started.

**Comments**

1. We commend the new resource allocation process through the scrutiny group. We suggest developing a mechanism to have requests better match the actual usage.
2. Real-time "FastML" is a unique FNAL AI/ML program capability obviously relevant to the FNAL mission.
3. We are concerned about the declining role of FNAL (and US HEP in general) in the development of detector simulation.
4. The Committee supports FNAL's increased effort towards the development of neutrino generators, and suggests it explore additional ways to support these endeavors.

**Recommendations**

1. Following up on the recommendation from the last PAC, we recommend that the Laboratory develops a strategic computing plan based on the experiments' needs. The plan should project computing and storage resources that will be made available to the experiments, as well as central services like power and cooling. The plan should include a timeline and milestones for critical technology decision points e.g. the integration of heterogeneous computing resources provided by US HPCs and the role of commercial clouds.

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## Science programs Status of the Spin Quest experiment and proposal of the Dark Quest upgrade

*Charge: We ask the PAC to review the status of the Spin Quest experiment and the proposal for its upgrade, referred to as Dark Quest.*

N. Tran presented the status of the SpinQuest experiment and its proposed upgrades, which involve an ongoing target upgrade to expand the transversity program and a electromagnetic calorimeter to enhance searches for dark sector particles (DarkQuest).

**Findings**

1. The PAC heard about the status of the SpinQuest experiment, which is planning to start data taking in November. The experiment is approved to run for two years.
2. Two upgrades are planned after the two years of running: The replacement of the original target by a new dedicated target to measure gluon transversity with SpinQuest, and the addition of an electromagnetic calorimeter (EMCal) to expand to DM searches (DarkQuest).
3. The new target for SpinQuest would allow it to expand the transversity physics program, which gained large attention in the community. It would require very minimal modification to the target system, by adding an RF-circuit and a target coil to RF-modulate across the domain of the Larmor frequency to manipulate the solid-state target spin population densities.
4. The addition of the EMCal enables DarkQuest to perform vertexing, invariant mass and energy measurements, and test Dark Matter masses from 10 to 200 MeV. This offers the opportunity to search for Dark Matter in regions that are not fully covered by other experiments. DarkQuest will

have sensitivity to the dark photon phase space not probed by past experiments, within a shorter time scale than other planned experiments. For example, with $10^{20}$ POT DarkQuest would extend sensitivity beyond the reach of the proposed FASER experiment at CERN after the ultimate collection of the High-Luminosity LHC data.

5. Furthermore, DarkQuest is sensitive to light (sub-GeV scale) solutions to the g-2 anomaly in displaced electron and photon final states as well as prompt dimuon final states, which originate from the end of the FMag beam dump. It is also sensitive to SIMPs, Higgs portal scalars, and ALPs.
6. Preliminary simulation-based energy and mass resolution as well as trigger efficiencies have been shown.

**Comments**

1. The DarkQuest proposal yields access to a range of dark matter searches for relatively small effort compared to other experiments, given that the EMCal already exists and just needs to be equipped with a new readout.

**Recommendations**

1. The PAC endorses the physics case for the DarkQuest upgrade and is looking forward to a presentation for the first approval step in the next PAC meeting.