Fermilab Physics Advisory Committee Report

November 16-18th, 2021

Executive Summary:

The Fermilab Physics Advisory Committee (PAC) met 16-19 November 2021 in a virtual format. The meeting took place as Snowmass 2021, the US particle physics community's Planning Exercise, restarted following a hiatus resulting from the ongoing COVID-19 pandemic. The process is expected to lead to another Particle Physics Project Prioritization Panel (P5) process in late 2022. In the meanwhile, the Laboratory continues to execute critical elements of the 2014 P5 plan ("Building for Discovery"), with several important status reports presented at this meeting.

Throughout the meeting, the continuing impact of COVID-19 on scientific activities at both the Laboratory and throughout the community was omnipresent. As we approach the end of the second year of the pandemic, site access at Fermilab remains highly curtailed relative to universities and peer institutions. This has had disproportionately negative effects on the early career members of the community who by this time may have spent a majority (in some cases all) of their current term at Fermilab in remote work conditions. With the continued uncertainty in the evolution of the pandemic, we urge the Laboratory to continue to work with the various stakeholders to enhance community and mentorship activities that are essential for continued scientific productivity. Site and travel restrictions to the Laboratory are also impacting projects and operations.

The meeting started with an overview from the Director. The DUNE collaboration now has nearly 1500 members. The excavation of the far site cavern has started and the process to baseline all far site excavation activities is underway, while the full project proceeds to another CD1RR to produce a new point estimate. Costs have remained stable with the maturation of major elements and DOE and international support (including the CERN Neutrino Platform) is strong. A new funding profile to support the new estimate has been provided by DOE. Establishing the cost range is a priority.

For PIP-II, the new cryogenic plant building is 80% complete. A CD-2/3a review to baseline and start long lead procurements is underway, with a CD3 review expected in March 2022. The contract for Indian contributions to the cryogenic plant from DAE/BARC is being executed. Additional FY2022 milestones include completion of the cryogenic plant building and the first prototype cryomodule.

The SQMS center held a successful Year 1 DOE review. The Center now has nearly 300 members, with seventy new hires, including twenty from underrepresented groups, and has produced 33 publications.

The High Luminosity LHC (HL-LHC) FY2022 budget requests were lower than expected with the expectation that a reconciliation bill would fully fund these efforts. A strategy was developed with CERN to mitigate the worst impacts in FY2022 which is still pending approval from DOE SC and Congress. The strategy, however, will impact DUNE funding in FY2023.

In advance of the meeting, Fermilab announced the search for a new Director to succeed Nigel Lockyer in 2022. The Fermilab Research Alliance has formed a search committee headed by Walter Massey. Other leadership changes include the appointment of Kevin Burkett as the head of Particle Physics Division and Marcela Carena as head of the newly formed Theory Division. In the LBNF/DUNE project, Ron Ray has been appointed as Deputy Project Director and Mary Convery as Deputy Project Director for Facilities.

Following the overview, the PAC heard presentations related to its charge for the meeting.

The NOvA collaboration presented a status update on its recent physics results and projections for its sensitivity to neutrino oscillation parameters with further running. After its update to the flagship oscillation measurements in 2020, the Collaboration has published on a wide range of physics including

neutrino cross sections, exotic physics, and astrophysical searches. As the experiment matures, the Collaboration is improving workflow to facilitate future results.

In the months prior to the meeting, the MicroBooNE collaboration released its first major results on the MiniBooNE low energy excess, a major milestone for the experiment. The Committee heard a report on these results from the Collaboration along with a perspective on its implications for the Short Baseline Neutrino program from Pedro Machado. It is still too early to propose any concrete strategic changes but it is becoming clearer that the SBN program has a broader reach that should be refined, and the Committee recommends a workshop on the physics potential of SBN experiments to engage the theory and experimental community.

The Committee also heard a report from SBND, which recently successfully completed a Director's Review. With the successful delivery and assembly of key components, the critical path lies with the cryostat, with the aim to start cryogenic operations in early CY2023. It is particularly important to ensure that international travel does not cause further delays and the PAC recommends mitigation strategies for travel difficulties to be considered. We received an offline report from ICARUS which reported on continued developments in the commissioning of the detector, such as the ongoing detector performance studies and the application of the fully automated reconstruction algorithms to the neutrino data.

The DUNE collaboration presented the physics case for ND-GAr, a proposed element of the near detector complex which will provide measurements of neutrino-argon interactions beyond the capabilities of LArTPCs. Sensitivity studies show that while the ND-GAr measurements may not be necessary in the first year of running, it plays a crucial role in subsequent milestones. As a result, the PAC recommends the development of a plan that facilitates the inclusion of ND-GAr in DUNE.

The ANNIE collaboration reported on its recent progress, including the successful loading of the detector with gadolinium to enhance neutron detection while maintaining water transparency. The deployment of novel LAPPD photosensors was imminent. In view of the expected long term and increasing complexity of the effort, the Committee recommends that the Collaboration plan carefully for the long term needs of future operation and the analysis of the data, including personnel needs.

The NuBDX-DRIFT experiment reported on analysis developments, including estimates for NuMI beam-induced backgrounds with a comparison to measurements from COUPP. A range of physics topics, including the weak mixing angle, nuclear skin measurements, and coherent neutrino scattering was presented.

The PAC heard an update on Fermilab's CMS activities, with a focus on HL-LHC, where it is making important contributions in nearly all areas of the effort. The Committee recommends that Fermilab ensure that the level of postdocs is at least sustained (if not increased) so that the interesting physics analysis program can indeed be conducted, and given the COVID-19s situation, to revitalize the personal interactions between postdocs, staff within CMS and with scientists in other divisions (e.g. theory) to foster innovation and creativity as soon as this can be done safely. Given the recent budget challenges, it is also very important that the Laboratory continue to strongly advocate for the US contributions to the LHC and the cooperative agreements with its international partners in all areas.

The Committee heard three presentations related to the g-2 experiment. Aida El-Khadra reported on the ongoing collaboration to improve the calculation of the expected Standard Model value of the muon g-2, while Carlos Wagner presented on anomalies in the flavor sector (including muon g-2 and rare B decays). The g-2 collaboration presented its status and plans.

Following the release of its first results, the g-2 experiment is preparing for improved results with additional data. The Collaboration has proposed a run with μ^- for Run 6 which will allow sensitivity to Lorentz Violation and CPT violation scenarios that may explain the current anomaly, which the PAC recognizes as a unique physics opportunity. Given that analysis of significant additional μ^+ data is still pending, the Committee encourages SCD and the g-2 computing experts to further improve their level of collaboration, focusing on reducing the turnaround time in g-2 data processing. The Collaboration should investigate whether it is possible to make the final decision on whether to run μ^+ or μ^- in CY 2023 following an analysis of the full dataset in CY 2022.

Theory activities at Fermilab have been consolidated into a new Theory Division with three departments (particle physics, astrophysics, quantum). The Committee supports this reorganization and recommends that Fermilab provide the Theory Division with the requested support, and that the new Division maintain close connections to the university community and ensure that the programs it is offering are welcomed by the community given the continuing tight funding environment. As noted, COVID-related restrictions have a negative impact on the development of early career scientists, and we advocate for more aggressive return-to-in-person arrangements for those who desire them.

The new Microelectronics Department is the focal point for ASIC design needs and developments across Fermilab divisions. The Committee welcomed this development and recommended evaluating the balance and resource-loading of project and R&D activities in accordance with Lab priorities and to continue the pursuit of external collaborations to position itself for an anticipated call for proposals for DOE microelectronics centers.

The Committee heard an update on Fermilab's engagement with the Snowmass process. The Laboratory has been highly visible both through individuals leading discussions and groups and institutionally by hosting community-wide meetings. The Scientist Advisory Committee was established to identify the most promising future projects which are aligned with the community interests with the upcoming P5 process in mind. The Committee recommends that Fermilab fully support the involvement of its scientists in the Snowmass process with a bold vision for its future in mind. The Laboratory policy is to "let all flowers bloom. As the laboratory undergoes a leadership transition, it is essential that it maintains attention and focus on the Snowmass and P5 process.

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 virtual meeting.

The Physics Advisory Committee:

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

Scientific Secretary: Anadi Canepa

Directorate: Nigel Lockyer, Joseph Lykken, Kevin Pitts, Hema Ramamoorthi

Status of the NOvA experiment

Charge: We ask the committee to review the status of the NOvA experiment and to comment on the expected sensitivity for neutrino oscillations and neutrino mass hierarchy as a function of the PoT. The PAC will also be asked to review the status of the combination of the NOvA and T2K results as well as the status of the two recommendations made at the July 2020 PAC meeting:

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

Findings

The PAC heard about the recent developments in the NOvA Collaboration. Last year, 3 papers were published, 1 accepted, and 2 submitted - among them the 3-flavor oscillations paper. The Collaboration plans to run until the long shutdown, which starts in 2027, leveraging the increased POT delivery from the intermediate stages of PIP-II, though the accumulated POT will largely depend on the number of weeks per year of accelerator operations that is achieved. The Collaboration is therefore taking this period to improve production and calibration workflow in support of a broader physics program and more automated operations.

New institutions have joined NOvA, primarily as a result of former students and postdocs moving to faculty positions. This has somewhat mitigated the natural contraction of the collaboration as some experimentalists move their focus to new and future neutrino experiments. NOvA is currently working on a joint fit with T2K to neutrino mass ordering and CP violation phase. The fit is particularly relevant since the different matter effects on these two experiments makes them complementary to each other.

The Collaboration presented the estimated future sensitivity to the mass ordering and the CP violation phase given the possibility of more than doubling the number of protons on target. The sensitivity strongly depends on the true value of the oscillation parameters, which is a natural consequence of neutrino oscillations. Regardless, for some regions of parameter space, NOvA could provide an early determination of the mass ordering. The Collaboration is entering the third year of test beam running and anticipates improvements in the detector response and energy calibration systematics from analysis of test beam data.

Finally, the PAC also heard about the computing needs of NOvA. The SAM file catalog may not fulfil NOvA's needs around 2030; the collaboration is working with Fermilab computing to pursue common solutions with DUNE. Rucio is expected to meet the file transfer needs, but other aspects of SAM's functionality also have to be developed.

Comments

1. The PAC commends the collaboration on the physics output this year and encourages they continue broadening their physics program

2. We look forward to the joint T2K-NOvA results and are encouraged by the possibility that first results might be available in the coming year.
3. Accumulation of the required statistics depends on the number of weeks/year of accelerator operations. Regardless of the parameters, NOvA and T2K, with their different baselines and resulting sensitivities to matter effects, will lead the field in these measurements until the next generation of experiments (LBNF/DUNE and Hyper-Kamiokande) start.
4. The Collaboration recognizes that NOvA will complete data taking this decade and is making preparations to facilitate more efficient operations and to maximize the physics output and legacy of the experiment, including data preservation.
5. We encourage the NOvA Collaboration to continue discussions with theorists and others to broaden the physics output of the experiment.
6. The PAC encourages the collaboration to continue working together with SCD to find solutions for the experiment data and file handling.

Recommendations

None.

Impact of the potential MicroBooNE results on the SBN program

Charge: We ask the committee to review the impact of the potential MicroBooNE results on the SBN program.

Findings

The MicroBooNE data confirm the superb performance of LAr TPC in the study of neutrino interactions and open the possibility of exploring a broad range of BSM physics with this exciting technology.

The recent result on the $\Delta \rightarrow \gamma + p$ process rules out one of the potential conventional physics explanations of the MiniBooNE low energy excess.

Currently the analysis of exclusive final states with one electron shows consistency with expectations based on Monte Carlo in the absence of non-standard effects.

The MicroBooNE analysis covers specific exclusive final states and does not overlap completely with the fully inclusive MiniBooNE analysis. Therefore, although the MicroBooNE results render the sterile neutrino explanation for example less plausible, the MiniBooNE low energy excess cannot be conclusively excluded. Several BSM models could explain both MiniBooNE and MicroBooNE data.

Comments

1. The MicroBooNE Collaboration is commended for exploiting the potential of LArTPCs in the analysis of the data. This is a substantial achievement for the Collaboration in fulfilling one of its flagship goals and in showcasing the capabilities of LArTPCs in general.
2. It is not possible to answer the question contained in the charge with the currently available information. While there are many BSM models still to be studied, no quantitative evaluation of the parameter space that can be explored by future SBN experiments and how that compares with that of past and planned experiments, has been shown to the PAC.

3. It is still too early to propose any concrete strategic changes and the miniBoone excess still warrants extensive follow-up. However, it is becoming clearer that the SBN program has a broader reach than simply following up on previous anomalies. Therefore, the Lab should work with the community to continuously refine the scientific case for the short baseline program.

Recommendations

1. The Committee recommends a workshop on the physics potential of SBN experiments to engage the theory and experimental community.

Status of the SBND

Charge: We ask the committee to review the status of the SBND and to address the following recommendation made at the July 2020 PAC meeting:

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

Findings and Comments

The PAC heard an update on the detector construction progress of the SBND experiment.
Pandemic work stoppages and related supply chain issues have had a large impact on the schedule, pushing back projected milestone completion dates by over a year since projections made in June 2020. Nevertheless, progress is being made on the TPC construction, thanks in part to proactive management of the work schedule and to the contributions of students, scientists, and engineers who are now able to access the site more easily. The TPC assembly was most affected by the stoppage of on-site activity in 2020. Its Assembly and Transport Fixture was completed over the 2020-2021 period and the TPC is now progressing very well, with the first anode and cathode planes already installed, and is projected to be ready for transport in March of next year. All photon detection systems and ARAPUCA modules have been delivered. The cryostat and cryogenics are done in collaboration between FNAL and CERN, and membrane cryostat installation is now scheduled to take place in phases beginning in December 2021 with a schedule tightly constrained by the COVID delays of limited personnel mobility and delivery of materials. There are still several challenges ahead before the cryostat is ready to be filled in February 2023. Until this point, little can be said regarding the LAr purification system performance, but no problems are foreseen by the collaboration. TDAQ and offline data processing preparations for the commissioning phase are progressing well and will be ready well before commissioning commences in summer 2023.
The experiment underwent a Director's review in October 2021, scrutinizing both costs and progress towards installation and commissioning. The PAC commends the collaboration on the successful review, and the impressive progress in light of challenges from the pandemic.

Recommendations

1. For the membrane cryostat installation, it is particularly important to ensure that international travel does not cause further delays. Mitigation strategies for travel difficulties should be considered.

Status of physics case for the ND-GAr

Charge: We ask the committee to evaluate the physics case for ND-GAr and its role in supporting DUNE's ultimate neutrino oscillation goals, as well its potential to broaden DUNE's physics program.

Findings

The PAC heard about the role of ND-Gar, a magnetized high-pressure gas argon TPC surrounded by a calorimeter located in the Near Detector (ND) hall, on DUNE's physics goals. ND-GAr will play an important role in significantly reducing neutrino-argon interaction uncertainties. ND-GAr has lower particle detection thresholds and lower density than ND-LAr, which allows improved measurements of low energy protons and more detailed reconstruction of final states. This can be used to reduce the uncertainties coming from nuclear physics effects by reconstruction of samples of exclusive final states. Moreover, the ND-GAr detector has full angular coverage, in contrast to ND-LAr due to its small size relative to typical muon track lengths. Comparing the impact of the angular coverage in ND-GAr and ND-LAr can help mitigate systematic uncertainties due to different near and far detector geometry.
It was shown that the reduction of systematic uncertainties from ND-GAr data will have a significant impact on the determination of the CP violation phase, particularly when the measurement becomes systematics limited. ND-GAr can also play an important role in broadening the physics case of DUNE, particularly on BSM searches whose signatures come from decay of new particles as opposed to scattering in the detector, e.g. heavy neutral lepton scenarios. Besides, the lower thresholds for detecting hadronic activity may allow for more efficient cuts which boost signal to background ratios.

Comments

1. The PAC commends the analysis of the impact of ND-GAr on the determination of the CP violation phase. As shown, while ND-GAr may not be necessary in the first years of running, it plays a crucial role when the statistical uncertainty becomes comparable to the systematic uncertainties.
2. The PAC commends ongoing studies on possible measurements of final state neutron energy and angle using timing techniques, as those could be highly relevant for DUNE.

Recommendations

1. The PAC recommends the development of a plan that facilitates the inclusion of ND-Gar in DUNE, given its crucial impact on the main measurement of the experiment, the determination of the leptonic CP violation phase.

Status of the ANNIE experiment

Charge: We ask the committee to review the status of the ANNIE experiment, including the performance of the detector during the initial data taking period.

Findings

The PAC has heard about the current status of the ANNIE experiment. ANNIE is testing new technologies that could be used by other neutrino experiments such as LAPPDs for improved timing capabilities, Gd-loaded water for neutron detection and water-based liquid scintillator detection technology which could enhance neutrino energy reconstruction. The measurement of final state neutrons in neutrino interactions is highly relevant for neutrino experiments as they directly impact the systematic uncertainties on oscillation measurements and may impact supernova and diffuse supernova background measurements as well.

ANNIE has loaded the water with gadolinium. Water transparency, which is crucial for Cherenkov light detection, has been successfully kept at high levels for two years now. LAPPDs exceed experimental requirements, and calibration measurements with AmBe source yield promising results. ANNIE has suffered delays by the COVID pandemic due to restricted site access. Recommissioning of the detector has started in early 2020 and neutrino beam data taking started in January 2021. The immediate next steps consist in deploying the LAPPDs and starting physics run. Water-based liquid scintillator is being produced for ANNIE and a potential test run could take place in 2022. Last, a proposal for a combined water/argon cross section study among ANNIE and SBND using the Booster Neutrino Beam has been awarded the NSF CAREER Award to Andy Mastbaum at Rutgers University.

Comments

1. The PAC commends the successful operations with Gd loading.
2. We are looking forward to hearing the results of the run with LAPPDs.
3. The experiment is planning to run for a long time with increased complexity in both operations and analysis. This needs a strong collaboration effort in data taking, maintenance and analysis.
4. The Collaboration plans on joint runs with SBND. This is a complex effort, which will likely require a dedicated task force. The PAC praises this additional initiative as it could have an important impact on the Fermilab neutrino program and encourages the Collaboration to plan ahead on tackling related issues.

Recommendations

1. We recommend that the Collaboration plan carefully for the long term needs of future operation and the analysis of the data, including personnel needs.

Proposal for the nuBDX-DRIFT Experiment

Charge: We ask the committee to review the proposal for the nuBDX-DRIFT experiment, the status of the two recommendations made at the January 2021 PAC meeting.

1. *The proposing team is encouraged to explore the full physics potential of this setup, including the sensitivity to CEvNS, a larger parameter space in boosted dark matter scenarios, and other beyond standard model scenarios.*
2. *Since backgrounds need to be estimated to evaluate experimental sensitivity to any physics case, the PAC recommends the collaboration to perform a quantitative investigation of the current knowledge on the rock neutrons background in NuMI, in order to estimate the physics reach of a pilot run with NuMI beam on-axis.*

Findings

The PAC has heard the responses to two previous PAC recommendations for nuBDX-DRIFT of exploring the full physics potential of the experiment and estimating the rock neutrons background in NuMI. Regarding the backgrounds, a simulation employing GENIE and GEANT4 was performed, assuming the NuMI low energy configuration, and benchmarked against background rates in the COUPP dark matter experiment. The simulation predicts 3.5 times less backgrounds than the COUPP measurement and there is ongoing work to understand this difference and improve the estimate. Multiplying the simulation background rates by 3.5 yields a large background at nuBDX-DRIFT above detection thresholds of 0.77 events per day. It was presented that these rates could in principle be reduced by adding a Gd-loaded scintillator around the detector. Since the rock neutron background is isotropic while the signal comes from the beam, the topology of events in the detector could also be used to further reduce the background rate.

Regarding the physics case, it was shown that nuBDX-DRIFT deployed off-axis from the DUNE beamline would yield a CEvNS event rate of 400 events in 7 years. Sensitivity studies were performed (not including backgrounds from rock neutrons) showing that the experiment could measure the weak mixing angle with an 8% precision and the neutron distribution in lead with a 5% precision. Other possible BSM searches were identified.

Comments

1. The PAC commends the efforts on background simulation and in particular the benchmarking against COUPP data.
2. The PAC appreciates the sensitivity studies on the weak mixing angle, non-standard neutrino interactions, and neutron skin performed by the collaboration, which focused on deploying the detector off-axis from the DUNE beamline. Nevertheless, the proposed sensitivities do not seem to significantly advance current knowledge, even if they are obtained neglecting the largest background component coming from rock neutrons.
3. Background suppression by leveraging event topology was mentioned, as well as by surrounding the detector with Gd-loaded scintillator. The committee had concerns with the effectiveness of this veto due to potentially large beam-related backgrounds, as well as the increase in size and complexity of the detector. Numbers were not given for either signal efficiencies nor background rejection.
4. For further consideration of the experiment, the collaboration would need to develop a substantially stronger physics case with a robust treatment of the background.

Status of the CMS experiment

Charge: We ask the committee to review the status of the CMS experiment focusing on the Fermilab's deliverables in the areas of detector and computing operations in preparation for Run 3. The PAC is also asked to review the plans for analysis of the Run 3 and HL-LHC data.

Findings

The PAC heard a report about the status of the CMS group, with focus on the preparations for HL-LHC.
Fermilab computing delivers very important contributions to the entire CMS collaboration, and is well-prepared for Run 3 with the recent Tier-1 and Tier-2 facility upgrades. Thanks to FNAL-led HEPCLOUD efforts, it can now easily use any allocations received, and the HPC Computing power utilized by CMS in 2021 was three times that of 2020, and the latter was already three times that of 2019.
The importance of the FNAL contribution to the CMS experiment is reflected in the number of FNAL people holding L2 management positions (four), as well as the co-coordinatorship of the newly formed Analysis Tool Task Force. An additional eight leadership positions are held by FNAL in US CMS.
FNAL delivered essential contributions to prepare CMS for Run 3. FNAL-led R&D in portability supports CMS in deploying GPUs in the High-Level Trigger for the first time, which led to an impressive 26% improvement over CPU baseline enabling a broader physics program for CMS.
The FNAL CMS group delivered key contributions to Data Quality Monitoring (DQM), part of the CMS Physics Performance and Datasets group, in which the Lab holds an L1 position, and to the migration of DQM, Trigger, and DAQ from the control room to remote operations during COVID-19 for cosmics runs and other commissioning activities which are very important for preparing for the 2022 data taking.
The responsibilities of the FNAL group in operations have been slightly reduced in Run 3 compared to Run 2, because of the very significant commitments of FNAL to the HL-LHC upgrade of the CMS detector. FNAL is a key player for many HL-LHC detector upgrades, with focus on HGCAL, MTD, and Tracker, and currently holds 14 leadership positions in CMS (and many additional ones in US-CMS).
For physics analyses, the group focuses on a list of topics that are essential for the scientific program of CMS, and develops novel techniques, like application of machine learning on FPGAs and ASICs, and at trigger level. The physics analysis topics span Higgs physics, electroweak SM measurements and searches for new physics, with a comprehensive program covering long-lived particles with displacement from O(mm) to 10 m.
A particular highlight is also the Fermilab engagement in the di-Higgs analysis efforts, where enormous progress has been made, and which is now considered to be among the most important LHC analyses in Runs 3 and 4 as it provides quasi-direct access to the shape of the electroweak potential.
Due to their large commitments to the upgrade projects, physics analyses are mostly conducted by the 14 postdocs, supported by the FNAL staff. Four postdocs hold L3 leadership positions in physics groups.
As a consequence of the pandemic, CMS group members and LPC visitors have had very few opportunities to work on site and meet each other in person for spontaneous informal interactions (which are important to foster innovation and new ideas).

Comments

1. The computing activities are particularly impressive, and world leading. Their significance cannot be overstated. They are essential for the whole of the CMS experiment.
2. The physics programme is very interesting and well selected for Run 3. With the relatively small amount of person power the group now has on physics analyses, it continues to make a significant impact in important ones and leverages its very strong expertise in the area of boosted objects. It is also commendable that the group leverages its expertise on detectors and innovations in the trigger for novel analyses opportunities, for example, by using the timing layer in HL-LHC. FNAL postdocs also impact the wider CMS physics program through their leadership positions.
3. A strong involvement in interesting physics analyses is crucial to be able to attract outstanding postdocs and staff to the FNAL CMS group. A return of the ability to interact in person on site would be beneficial to recapture the stimulating environment that existed at FNAL before the pandemic and continue the Lab's ability to attract and train first-rate postdocs.
4. FNAL and US CMS play a very important role in all areas of the CMS experiment. It is expected to deliver on its obligations to all the international partners involved in the project, in particular CERN. The recent budget reductions are a major concern for the CMS collaboration at large given the crucial role FNAL plays in many areas, particularly the HL-LHC upgrade and CMS computing.

Recommendations

1. The Lab should ensure that the level of postdocs is at least sustained (if not increased) so that the interesting physics analysis program can indeed be conducted.
2. It is important to revitalize the personal interactions between postdocs, staff within CMS and with scientists in other divisions (e.g. theory) to foster innovation and creativity as soon as this can be done safely.
3. It is very important that the Laboratory continue to strongly advocate for the US contributions to the LHC and the cooperative agreements with its international partners in all areas.

Status and plans of the g-2 experiment

Charge: We ask the committee to review the status of the g-2 experiment and plans for future data taking runs.

Findings

- Various developments before Run 5 should further reduce systematic errors.
- Offline data processing has an unusually long turnaround time. We followed up with the collaboration and received a detailed write-up in response.
- Testing LV/CPT invariance is a unique opportunity offered by the Run 6 μ^- run. No other planned facility can do this measurement at this time, while in the future JPARC should run in μ^+ mode. The alternative would be to use Run 6 to increase μ^+ statistics by ~20%.
- The full dataset should be processed by early CY 2022, while the results of the Run 2-3 analysis should be published towards the end of CY 2022.

Comments

1. We commend the Collaboration on the excellent work and exciting results from the analysis of the Run 1 sample and look forward to next year's results.
2. Improvements in the analysis infrastructure to reduce the time between data taking and publication of results are warranted in order to maximize its impact.
3. The upcoming SCD/g-2 workshop and the F-CRSG provide an excellent opportunity to review the computing issues that are slowing the production and analysis of the data. We look forward to the outcome of that process, and a discussion in one of the upcoming PAC meetings.
4. An evaluation of the cost-benefits of Run 6 may change when the full Run 2-5 analysis (or even the Run 2-3 paper) will be out. Switching to mu- in Run 6 might cause a delay in the commissioning of mu2e.

Recommendations

- We encourage SCD and the g-2 computing experts to further improve their level of collaboration, focusing on reducing the turnaround time in g-2 data processing.
- Unique physics potential for mu- run justifies making an effort to pursue this measurement. We recommend investigating whether it is possible to make the final decision on whether to run μ^+ or μ^- in CY 2023 following an analysis of the full dataset in CY 2022.

Overview of the theoretical physics program at the laboratory

Charge: We ask the PAC to review the theoretical physics program at the laboratory, to comment on the role of the new division, and to assess whether the laboratory integrates in and contributes effectively to community efforts including (but not limited to) the Neutrino Network, Lattice, g-2 Theory Initiative.

Findings

- The Lab formed a new Division with 3 Departments.
- The new Division encompasses a broad range of activity, from lattice to cosmology to quantum.
- The Division is working with university partners with programs such as joint postdocs; visiting students and faculty; and prize fellowships targeting women and URMs.
- The three Departments within the Division are led by long-standing members of the Theory groups; together with the appointment of Fox as the Deputy Head of the Division, this expands the groups of scientists that have assumed leadership roles in this area.

Comments

1. As the field of high energy physics matures, it is timely to create a structure dedicated to generating novel ideas that would lead to new experiments. Including the Quantum Initiative in the Division is an excellent step along these lines.
2. It is increasingly a challenge to maintain a vibrant theory program in the current funding environment. This impacts theorists at the Lab and universities.

3. Given the tightness of the DOE theory budget, it is laudable that the Division has been proactive in securing other sources of funding and the Committee commends the Division for its success and strong engagement with EDI.
4. COVID has hit young scientists in the theory Division hard and keeping them from coming to work in person is detrimental to their careers, and therefore to the stated goals of developing the next generation of theorists.

Recommendations

1. The PAC recommends that the Lab provide the Theory Division with the requested support.
2. The Lab and the Theory Division should maintain close connections to the University community and ensure that the programs it is offering are welcomed by the community, as opposed to being seen as securing a larger piece of a small pie.
3. Management should inform the DOE that current COVID policies have a negative impact on the development of early career scientists and advocate for more aggressive return-to-in-person arrangements for those who desire them.

Overview of the microelectronics program at the laboratory

Charge: We ask the PAC to review the newly launched microelectronics initiative, how it contributes to and how it integrates in the core mission of the laboratory.

Findings

The Microelectronics Department at FNAL contributes to three main areas: Academic Research, Advanced Scientific Instrumentations, and Industrial products support.
It is the focal point for ASIC design needs and developments across Fermilab divisions (Quantum Initiative, PPD, SCD, etc.).
It spans from blue-sky/R&D projects to support for existing needs in the Lab and outside, including:

- CMS (ETROC and ECON chips for HL-LHC upgrades subsystems)
- DUNE (COLDATA/COLDADC) data concentrator and ADC chip
- QUANTUM (Deep Cryogenic electronics)
- AI (inside and outside previous projects)
- Co-lead of Snowmass' Application and Industry section

Collaboration with industrial partners has started with interests in R&D for quantum and AI technologies. The team is also involved in technology transfer initiatives, e.g. the University of Chicago's Polsky programs, with dedicated resources (one fellow).

Comments

1. The PAC commends the Microelectronics Initiative (and the related ASIC R&D Department) for the broad portfolio of activities that are aimed to support the core mission of the lab and to give ample space for R&D programs. These programs are crucial to creating attraction points for new generations of engineers/physicists from academia and industry that will lead future projects. In

the short term, though, and with the currently available resources, it needs careful management in terms of balancing lab core mission goals.

2. The Committee would have benefited from further details on how the sharing of resources among the various projects is managed and what is the process of prioritization in case of competing requests.
3. The current staff is composed of 19 FTE with the vast majority in the form of ASIC designers. We welcome and support the consolidation plan for staffing that foresees three new hirings in the near future.
4. The potential of becoming a DOE Microelectronics center is an exciting possibility that might open paths for additional resources and opportunities.

Recommendations

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

Overview of the preparation for the Snowmass process at the laboratory

Charge: We ask the PAC to comment on the effectiveness of the internal organization, on the participation of the laboratory's scientists in the re-start of the process, and on the role the laboratory may play.

Findings

FNAL put in place the Scientist Advisory Committee with the goal of identifying future projects that Fermilab's scientists are most interested in pursuing and are aligned with the community interests, and to *develop a strategy for having them included in the P5 report*.

The Laboratory has taken the role of facilitator in the development of the Snowmass activities, for example, hosting community-wide meetings, which were productive and effective.

Scientific personnel are engaged in the progress, leading study groups in diverse areas including future colliders, energy frontier, cosmic frontier, and neutrino physics.

The FNAL scientists would like to see clearer guidance regarding the appropriate level of involvement in the months ahead, as the lab plans to further engage in the process.

Comments

1. Current major thrusts for FNAL are defined in accordance with the priorities described in the previous P5 report. New major thrusts for the future, however, are yet to be defined and will be based on the output of the ongoing Snowmass process and the P5 report that will follow. It is therefore critical that the Lab takes this opportunity to identify *new major thrusts* that its scientists and the broader community, both, would like FNAL to pursue.

2. It is commendable that the Laboratory is trying to balance the interests of the lab scientists with its role as facilitator for the community at large. The fact that the lab itself is a major part of the community cannot be overlooked. Lab scientists are the ones who know its strengths and weaknesses the best, and therefore are in a unique position to help the community identify ways to leverage FNAL resources to maximize the scientific impact of the US HEP program.
3. As the Laboratory undergoes a leadership transition, it will be essential to maintain attention and focus to the Snowmass and P5 process.

Recommendations

1. We encourage the Laboratory to fully support the involvement of its scientists in the Snowmass process with a bold vision for its future in mind.

Status of the ICARUS detector

Charge: We ask the PAC to review the status of the ICARUS detector and of the recommendation made at the January 2021 PAC meeting:

1. *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

The PAC received a report about the status of the ICARUS detector, highlighting what was learned from the first data taking run (Run 0), and about subsequent installation and commissioning activities. Run 0 has provided a good dataset for understanding detector and reconstruction software issues, with a 95% data taking efficiency for both BNB and NuMI beams and good detector performance with free electron lifetimes in both cryostats above 3 ms. TPC noise was present but stable in the Run 0 data taking and has since been reduced substantially, although not entirely, through a series of expert interventions. A difference in about 1 ms between the electron lifetime in the two cryostats is observed. ICARUS has confronted challenges in the LAr purification system, including LAr loss due to periodic venting, and the top CRT installation preventing regeneration of the activated copper internal filters. Warm filters were installed, and the electron lifetime is now improved over the Run 0 conditions.

The run ended in June 2021, providing over 60k of events triggered by the high threshold PMT majority trigger, from which a calibration sample of both ν_μ and ν_e CC events were visually identified and extracted for tuning purposes.

Personnel access to the site has delayed the top CRT installation, with major efforts beginning only in late September 2021 after the arrival of work crews. Currently about half of the modules and power lines, and all I-beams have been installed, and successful powering tests have been completed. The delay in

CRT and TPC noise mitigation activities, along with others, will reduce the detector availability during upcoming beam operations by as much as 45%.
Most of the reconstruction and simulation tuning to date has used cosmic muons recorded in ICARUS, such as the TPC response calibration. Neutrino events are also being used in several places, such as in understanding the reconstruction software, which is very much under development, and to verify the TPC event timing association.

Comments

The Committee congratulates the Collaboration for the continued progress in commissioning the detector and confronting the challenges of LAr purity and electronics noise. Likewise, we commend the substantial progress in understanding the detector performance and developing the analysis tools for identifying and reconstructing neutrino events.

Recommendations

None.