Fermilab Physics Advisory Committee Report

December 7th-11th, 2020

Executive Summary:

The Fermilab Physics Advisory Committee (PAC) met virtually 7-11 December 2020 to review the status of the Fermilab program. Since the last meeting, a number of critical processes, events, circumstances have affected activity and planning at the Laboratory. This includes the ongoing US Community Planning Process (Snowmass), which recently held its Community Planning Meeting, and the COVID-19 pandemic, which continues to impact all aspects of the high energy physics program and community. There were also major developments in the Cosmic Frontier and Quantum Information Science. Under overall extraordinary circumstances, Fermilab continues to advance the goals of the 2014 Particle Physics Planning and Prioritization Panel's (P5) report across a number of fronts.

The Director presented an overview of the Laboratory on the first day starting with the status of LBNF/DUNE, where a number of major items for the pre-excavation at SURF are nearing completion. A milestone was achieved with the awarding of the contract for cavern excavation. At Fermilab, near site preparation work was completed on schedule and budget. The preliminary design effort for the near site conventional facilities has also completed and transitioned to final design, while the beam line is also progressing into the final design phase. In preparation for CD-2 in 2021, final decisions regarding the scope of the project are in progress.

For PIP-II, the cryoplant building construction is underway. Progress with international partners continues, with resources to cover the full scope of the project in place in advance of formal baselining. During the meeting, we received the very welcome news that the DOE has approved baselining for the project, a major milestone. Construction of the Integrated Engineering and Research Building (IERC), approved in September, has also started.

In the Cosmic Frontier, the Dark Energy Survey has constructed the largest map of the dark and luminous matter in the universe and is expecting first results on weak lensing and galaxy clustering with its first three years of data. In the Intensity Frontier, delays in Mu2e, partly arising from COVID-19, will necessitate a re-baselining of the project. ICARUS has progressed in commissioning, with two INFN personnel arriving at FNAL arriving to carry out critical tasks.

The Laboratory's quantum information science program, which has undergone continuous growth with a number of initiatives such as MAGIS-100, Dark SRF and the quantum networks project, received a significant boost with the success of Fermilab's proposal to host a national quantum center (SQMS) centered on superconducting quantum computing and sensing. Fermilab is also participating in the QSC national quantum center with Oak Ridge and Los Alamos, and the Deputy Director serves on the new National Quantum Initiative Advisory Committee.

Fermilab recently appointed a new Chief Equity, Diversity, and Inclusion Office, who leads a new Lab-wide task force towards ensuring that the Fermilab’s culture, climate, and practices are welcoming to all. The Committee looks forward to hearing about this and other equity, diversity, and inclusion initiatives in future meetings and strongly supports the laboratory's initiatives to lead in this area, which will be important to the particle physics community at large.

The Laboratory is preparing changes to site access, both physical and virtual, to improve security in advance of the eventual reopening of public access to the site. Fermilab successfully hosted the virtual Community Planning Meeting as part of the Snowmass process, which currently is considering a potential adjustment to its timeline.

The Committee heard a report on the new SQMS national quantum center hosted by Fermilab, which has the very exciting and ambitious goal of projecting Fermilab's core expertise in superconducting radio frequency cavities (SRF) into the realm of quantum computing and sensing in an extensive collaboration that includes commercial partners like Rigetti. The Committee congratulates Fermilab on this major achievement and for the appointment of its Director, and looks forward to future updates on the initiative. The scope and schedule require a rapid ramp up in hiring and organization in a highly competitive environment, and the Committee recommends that risks and risk mitigation are evaluated regularly in order to maintain progress.

The FNAL CMS group continues to represent a major resource for the CMS collaboration, with a wide range of important roles and impressive achievements in operations, analysis, and upgrades. The Committee is concerned about the steadily declining effort of the group, which has resulted in a significant decrease in its involvement in operations. A shortfall of funding for the highly successful LHC Physics Center (LPC) has significantly reduced its activities, which could be sustained at a viable level in 2020 only through support from the US-CMS operations program. This represents a chronic trend, and the Committee reiterates its strong support for increasing support to LPC.

The LPC is one of several visitor programs (such as the Cosmic Physics Program and the Neutrino Physics Program) within the FNAL research program, and a review of the structure, support, and community impact of these programs could provide additional context for future discussion.

The g-2 experiment presented their status, which included the start of Run 4 following a series of improvements that have significantly stabilized operations. Working with the Scientific Computing Division, the Collaboration has succeeded in processing nearly all of its Run 1 and 2 data, with Run 3 in production. While the lower currents in the lithium lens and the absence of the inflector magnets will result in a modest shortfall in data with respect to the TDR goals, the collaboration has prioritized stable running in the coming years. The Committee supports this strategy and commends the Collaboration for its excellent work on the operational improvements and evaluation of systematic uncertainties. We look forward to seeing the first results from the experiment in the coming months.

The commissioning of the ICARUS detector has made steady progress despite the complications due to COVID-19. Impressive results from the first data-taking with cosmic were shown by the collaboration, along with a program to probe the recent claims for short baseline oscillations by the NEUTRINO-4 collaboration in response to the Committee's request to identify physics goals prior to the operation of SBND. A few major installation and commissioning milestones remain. The Committee looks forward to the completion of the commissioning program and further development of the physics program.

The Short Baseline Neutrino (SBN) analysis working group presented an array of recent progress in simulation, selection, and reconstruction. Initial comparisons of simulation with ICARUS data were also shown. We encourage the continued development of common analysis tools across the SBN effort and look forward to seeing further progress in the future.

The Committee heard a report on the CERN Neutrino Platform, which has facilitated contributions of the European neutrino community to a wide range of activities critical to the global neutrino program, including the refurbishment of ICARUS for SBN and the ProtoDUNE program for DUNE. Continuing on this impressive track record, the Committee strongly supports the ongoing and planned activities at the Neutrino Platform.

The possibility of deploying low pressure time projection chambers used in the DRIFT experiment into neutrino beams at FNAL, motivated by potential dark sector signatures, was presented. Relative to electron beams, the pulsed neutrino beams are favorable for reducing non-beam

related backgrounds. The committee requests further development of the physics motivation for this experiment and quantification of beam-induced backgrounds.

The MAGIS-100 experiment reported on several important developments in the effort, including the achievement of larger momentum transfers, which will improve the sensitivity of the experiment, and progress in design, planning, and funding, including a successful Director's Review in September. The experiment includes proponents of the AION effort, who aim to build a second system in the UK, leading to the intriguing possibility of a network of such detectors.

A proposal for FNAL physicists to join the CLAS-12 collaboration on a limited membership basis was presented. This would allow these physicists to access the CLAS-12 data at JLab towards performing electron-scattering analyses that would improve neutrino-nucleus scattering modeling to the benefit of the overall neutrino effort at FNAL. The Committee supports this proposal.

The Committee heard an update from the PIP-III task force, which is charged with an exploratory study of physics opportunities with the Booster replacement required to deliver 2.4 MW to LBNF, as recommended in the 2014 P5 report. The study includes a variety of accelerator configurations to deliver different beams and has categorized a large range of potential experiments according to science targets. The Committee looks forward to the white papers which will be submitted to the Snowmass process and, given the potential reexamination of the timeline for the Snowmass process, recommends extending the study into a second phase to define priorities for Fermilab with an eye towards maximizing synergies.

The Snowmass Community Planning Meeting (CPM) was hosted by the Fermilab Scientific Advisory Committee and Users Executive Committee as a week-long virtual event. Nearly 3000 community members participated and Fermilab scientists had a major presence in the organization, presentations, and discussions. Following on the success of this meeting and Fermilab's ambition to lead the field in fostering equity, diversity, and inclusion, the Committee notes an opportunity for the Laboratory to amplify the voices that are not being heard in this discussion due the disparate impact of the COVID-19 pandemic on members of the community.

The Committee expresses its gratitude and appreciation for the concise and highly informative presentations, and for the advance availability of some of the slides, which allowed for a more focussed discussion. The Committee also thanks K. Decker and the FNAL staff for arranging the virtual meeting environment, which allowed for a smooth and productive discussion.

The Physics Advisory Committee:

Present: E. Aprile, A. Arce, F. Canelli, A. Friedland, I. Gil-Botella, K. Heitmann, L. Malgeri, P. Machado, K. McFarland, I. Melzer-Pellmann, S. Miscetti, H. Montgomery, Christoph Simon, A. Szalay, H. A. Tanaka (chair)

Regrets: None

Scientific Secretary: A. Canepa

Directorate: G. Bock, L. Ristori, H. Ramamoorthi

Status of SQMS Center led by Fermilab

Charge: We ask the committee to review the status of the SQMS center at the laboratory.

Findings:

We learned about the establishment of the new SQMS quantum center, which is focused on integrating superconducting qubits with Fermilab's world-leading RF cavities. The Center has two main goals. On the one hand, it aims to improve the performance of superconducting quantum computers significantly relative to the state of the art, including scaling and integration. The Center involves a close partnership with Rigetti to facilitate commercialization of these advances. On the other hand, SQMS also aims to make significant contributions to high energy physics, in particular by improving the sensitivity of dark sector searches. In addition to these main goals, there will also be work towards networking superconducting quantum computers. There are substantial synergies between the quantum computing and high-energy physics goals, because they will rely on the same basic technology. We learned that there are already very promising results on the cavity lifetimes with integrated qubits. We also learned about impressive infrastructure efforts, including the construction of the world's largest dilution refrigerator. Fermilab has created a new SQMS division and is planning twenty strategic hires in this area.

Comments:

The PAC commends the team for successfully competing for this major project and building a strong collaboration. The SQMS leadership team has put forward an exciting vision and very ambitious goals. The center is led by a strong and enthusiastic director and the PAC commends the Laboratory for this excellent choice. The creation of a new division and the major hiring plan show strong commitment of the Laboratory in this area. The PAC also was happy to hear about commitment to EDI with regard to the new hires.

The goals in the area of quantum computing are ambitious, and competition in this area is global and fierce. But Fermilab has unique technological capabilities to offer, so there is definite potential for substantial contributions. Rigetti is a credible partner for technology development and commercialization. The Center has also been able to identify quantum sensing applications that are important for HEP research. The application of the qubits to HEP questions would probably not happen without such a direct DOE involvement, and this can be a very valuable contribution of this new center.

Fermilab's RF cavities are promising also for quantum networks applications, e.g. for quantum memories and microwave-to-optical quantum transducers, which will be essential for networking superconducting quantum computers over long distances. Given that Fermilab already has significant ongoing activities in the quantum networks area (e.g. FQNET and IEQNET) and is aspiring to play a leading role in it nationally, it seems pertinent for SQMS to systematically explore these types of applications as well.

It will be nontrivial to run a ~200 member strong collaboration with many institutions involved, in particular given the extremely aggressive schedule. The organizational structure is complex and will require careful monitoring to guarantee success. Identifying and attracting suitable candidates for the 20 new positions will be a challenging task and will need careful tracking. There will also be unavoidable tension between the open science culture of HEP and the development of proprietary technology with an industrial partner in a highly competitive environment, which will need to be managed.

Quantum computing is likely to have major impacts on society, e.g. quantum computers will force a transformation of our techniques for secure communication and might disrupt various existing

industries. It may be appropriate for SQMS to also address this societal dimension in some way, *e.g.* by engaging appropriate social science partners.

The PAC is looking forward to updates on the progress of this major and exciting new venture in future meetings.

Recommendations:

Given the very ambitious goals, aggressive schedule, and strong competition in this area overall, the project poses some major challenges and connected risks. For example, the hiring plan to fill ~20 positions by September 2021 is very important and could cause delays if this goal is not reached. We therefore recommend that risks and risk mitigation are evaluated frequently in the early phases of the project in order to enable the development of timely possible alternatives (*e.g.* finding staff within Fermilab that can be reassigned if the hiring plan does not proceed in the timeframe proposed).

Status of CMS experiment

Charge: We ask the committee to review the status of the CMS experiment with focus on Fermilab's deliverables, as well as the status of the recommendations made at the January and July 2020 meetings.

Findings:

The Fermilab CMS Group continues to represent a major resource of the CMS collaboration, filling important roles and taking on essential commitments. The recognition of these contributions is evident in the many internal and external awards earned by the Fermilab CMS group and the successful placement of the group's postdocs.

The physics analysis portfolio of the Fermilab group is expanding to cover unexplored parameter space. New technologies are being developed to search for hadron-like dark matter (Dark QCD) and long-lived particle (LLP) signatures of New Physics from improvements in the trigger to advanced machine learning techniques.

The CMS Fermilab group has important commitments in the Phase-II CMS detector upgrades, specifically in the outer tracker, the High Granularity calorimeter, the timing layer, and the level-1 trigger. Despite COVID-related restrictions, activities on those fronts are proceeding at the expected pace.

Current operations activities are limited to two major aspects: Data Quality Monitoring and hadron calorimeter (HCAL) performance. This is a rather limited scope with respect to past involvements, dictated by optimization of the decreased funding available.

The CMS Fermilab group is one of the main contributors to CMS software and computing development. Because using HPC as a grid-like resource is sub-optimal, new routes, especially towards efficient exploitation of high-performance computing (HPC), are being explored with an advanced framework for “inference as a service” and with the portable parallelization strategy project. The availability of HPC resources will increase with time, but for CMS and other experiments to benefit from the heterogeneous architectures requires a set of new developments in software, and the funding to complete the R&D and deployment phases.

CMS is implementing the succession plan that the PAC supported in prior meetings. Nevertheless, the natural loss of expertise due to new responsibilities or retirements has outpaced the new hiring, resulting in a net reduction of FTEs in the group.

The LHC Physics Center (LPC) continues to be a formidable attractor for young physicists and an incubator for new ideas that are being developed with the help of Laboratory resources. The COVID lockdown has affected the program, but despite the restrictions and a significant funding shortfall, LPC activities continued in 2020 with a suite of “remote” Hands-on Advanced Tutorials (HATs), courses and the scheduled CMS Data Analysis School (CMSDAS).

The current level of financial support for the LPC can only sustain the program of junior and senior Distinguished Researches (DR) in 2021 because of partial support from the US CMS Operations Program. The PAC recommendation to strengthen ML/AI development and Snowmass studies with dedicated LPC fellowships could not be executed because of a lack of funding. It has been remarked that if the funding trend continues the whole program will be at critical risk.

Comments:

- The PAC commends the CMS Fermilab group for initiating new directions and approaches in physics analyses to explore new parameter spaces such as LLP and dark QCD. This is important preparation for both Run3 and the HL-LHC phase, and also essential for keeping young researchers motivated.
- The PAC also commends the way the LPC adapted to COVID travel restrictions, allowing important programs such as HATS, CMSDAS, seminars, and courses to continue in a fully virtual way.
- The PAC strongly supports the plan presented to hire one associate scientist who will fully focus on the tracker, and one senior scientist committed to the CMS upgrade (including the tracker) at the 50% level.
- The PAC is increasingly concerned about the funding situation of the LPC. The program of junior and senior DRs has proven to be an incubator of new ideas. The LPC coordinators*,* with the help of the CMS Fermilab group, maintained a minimum level of operation for 2021, but they could clearly not expand into programs to support Snowmass studies and AI/ML as recommended last time.
- The PAC is also concerned about the decreasing level of funding of the Fermilab CMS group, which has damaging consequences on the engagement in detector operations, especially now that Run3 is approaching. This group has historically been a pillar of CMS operation teams and this has proved time and again to be a worthy investment that has paid off in experience and expertise exploiting the physics output.
- The PAC appreciates the focused approach in CMS upgrade activities. The efforts on the ASICs front, strategically supported by new hirings, have clearly paid off and we have no particular concerns. The prioritization of upgrades tasks clearly has an impact on other efforts competing for resources (see operations point above).

Recommendations:

- In order to mitigate the impact of having had several group members acquiring other major responsibilities, the PAC recommends the additional hire of one or two associate scientists. The new hires will ensure the successful delivery of the upgrades and in addition, reinforce the operational activities for the upcoming Run3.
- The PAC reiterates, yet again, its strong support for increased LPC funding, and also for dedicated resources to support an ML/AI researcher at the LPC. Not only is funding for junior DRs needed, but funding for senior DRs is also essential. These positions are crucial to foster new activities and collaborations which are especially important now in preparation for Snowmass.

Status of g-2 experiment

Charge: we ask the committee to review the status of the g-2 experiment, of the physics program, and of the recommendations made at the July 2020 meeting.

Findings

Operations

Run-3 of the g-2 experiment started in December 2019 with stable data-taking at a rate of approximately 1 "BNL" experiment statistical equivalent per month and accumulated a raw data sample of 3.3 x BNL statistics before early end in March 2020 due to the Covid-19 outbreak. The total “raw” statistics on tape is now 7 x BNL in Runs 1-3. At time of the meeting, the first Run-4 beam was put in the ring, and the collaboration expects to start stable data taking in the coming weeks.

The data quality is greatly improved and stable due to a long list of operational improvements in the past years. These include:

1. Cryogenics and PLC upgrades that were successful to avoid quenches. The last quench happened in Run-2 and was not at full field.
2. A successful campaign to control and reduce temperature variations in the hall and in the laser-hut helped to reduce electronic failure rate and muon losses and also improved stability for calorimeter gains, stored beam, and the uniformity of the magnetic field in the ring.
3. At the end of Run-3, the kicker HV was successfully raised to nominal value and the ramp time decreased after a number of upgrades. This resulted in the beam radial position being better centered than in the previous running.

Thanks to the prompt analysis of data, it is possible to project how these operations improvements will reduce systematic uncertainties in the analysis. Some new problems which are also becoming better understood and could become dominant systematics include field transients due to quadrupole vibrations and unexpected and unexplained field jumps.

Even with improvements, event rates are ~60% of TDR projections. The largest single factor in this is the reduced current in the Li lens being used to prolong the lifetime of the lens.

Production and Computing

Many changes happened during last year: (i) SCD increased the CPU quota to 5000 nodes improving reconstruction speed and (ii) structural changes were applied to the reconstruction path (configuration database, shift training, improved efficiency, data quality monitoring). As a result, production of Run1 is 100%, Run 2 is 98% and Run 3 is 15% complete.

Summary of Run-1 analysis

The collaboration is very close to completing its Run-1 analysis with a statistical uncertainty estimated to be 450 ppb and a systematic roughly half of the statistical uncertainty. The collaboration projects completion of this first Run-1 result in February or March 2021.

Many of the analyses methods and systematics have been presented and summarized in the previous PAC meetings. New evaluations of systematic uncertainties related to eddy currents from the kickers, quadrupole vibration, and the phase acceptance corrections from the Run-1

analysis were presented. Importantly, all of these systematics are forecast to decrease with the improved operating conditions after Run 2, or with studies currently being analyzed.

Plans for Run 2 and Run 3 analysis

98% of Run2 has been processed, and Run3 production is in early stages. Nevertheless, the similarity of data quality and systematics between Run 2 and Run 3 has led the collaboration to plan for a combined Run-2/Run-3 result.

Comments

- **The PAC commends the collaboration for the excellent work** done on the improvement of operations and on the evaluation of the analysis systematics. The PAC looks forward to seeing the Run-1 result released in the next few months.
- **Run 4 & Run 5:** Even though the experiment has run at lower Li lens current since April 2019, and no Li lens failures have been observed in Run-3, there is still a risk of catastrophic single failure from the Li lens. The experiment's emphasis is to complete Run-4 and Run-5 under current operating conditions to reach a 120 ppb statistical error, which is close to the 100 ppb TDR target. Assuming the quality of data taking to be similar to Run-3, the collaboration expects to reach or reduce the TDR goal for the systematic uncertainty. We concur with the collaboration's decision not to prioritize installation and operation of a new inflector because of the risks involved.
- Due to **Covid-19**, operations rely heavily on FNAL staff and remote shifts. The PAC encourages the experiment, and the Laboratory, to plan additional measures to increase personnel available for operations on site.
- **Computing resources:** Computing improvements in the last year were substantial. The PAC encourages development of plans for computing and analysis resources through the end of the experiment while Run-4 progresses.
- Focus of planning for **Opportunistic Running:** the collaboration already plans to keep the ring cold for studies, and there is a possibility of some running as Mu2e is commissioned. Such running will require significant resources, and the collaboration will want to detail the opportunities and costs of additional running as part of its plan to complete operations and analysis. The merits of μ^- vs μ^+ running should also be evaluated as part of this work.
- The collaboration has addressed **recommendations from the previous PAC:** "*The PAC recommends the collaboration keep pursuing the coordination with the Mu2e collaboration and the Laboratory to ensure a smooth transition from g-2 data taking to the startup of the Mu2e operations. In this respect, an overall coordination between usage of inflector, design and realisation of the new g-2 extraction kicker and data analysis progresses is vital for the future assessment of schedule, running priorities or beam sharing."*
    - As noted above, the collaboration's plan for risk management emphasizes smooth data taking over improvements, such as the installation of inflector or new extraction kickers to make future opportunistic running more efficient.
    - The collaboration presented its plan for releasing Run 1 result and has started planning the Run-2/Run-3 combined analysis.

Recommendations

None

Status of the ICARUS detector

Charge: We ask the committee to review the status of ICARUS and the status of the recommendations made at the July 2020 meeting.

Findings:

Since the last PAC meeting, the collaboration has completed the installation of all TPC and PMT components with the exception of the trigger system. The cryogenic system has been operating in a steady state since June 2020 with the exception of the South Gas Argon recirculation unit of the East module. The side CRT installation is in progress and the top CRT remains to be installed. The TPC wire planes and cathode HV were taken to nominal values and remained stable with the exception of a group of Induction-2 wires of West module that remain at 0 V. PMTs were calibrated with a laser and they are all operative except 3 out of 360.

Due to the COVID-19 travel restrictions, a good fraction of the collaboration is not able to access Fermilab for the completion of the preparatory phase. The collaboration is taking 24/7 remote-only shifts since February 14th.

The first data taking with cosmic-ray interactions in the detector has started and the first event samples were shown for a drift field of 500 V/cm. An electron-lifetime of ~1 ms is measured in both modules to be compared with the expected >3 ms goal. This is attributed to the saturation of gas recirculation filters operating at LAr temperature. GAr filters are being regenerated and new warm filters constructed to increase the filtering capacity.

Small space charge effects of the order of < 3 mm were already measured using anode-cathode crossing muon tracks, which is a bit smaller than previous ICARUS measurements. The results show a small dependence with time that needs to be understood. The maximum drift time of the charge associated with tracks was also estimated.

The collaboration proposed to verify with the initial ICARUS-only data the recent observation of the sterile neutrino oscillation claimed by the NEUTRINO-4 reactor neutrino experiment. Some estimations of the expected ICARUS Booster (ν_μCC QE) and NUMI (ν_eCC QE) event rates in a fiducial volume were shown together with the survival oscillation probability in the presence of the NEUTRINO-4 anomaly.

The early phase of ICARUS data taking will be dedicated to the detection of neutrino disappearance in the Booster and NUMI off-axis beams and the confirmation of the presence of a sterile neutrino.

Comments:

- The PAC congratulates the collaboration for the great progress in the detector installation, commissioning and acquisition of first cosmic data.
- The schedule for the installation of the overburden and top CRT should be clarified in view of the plan for physics data taking with the Booster and NUMI neutrino beams.
- The PAC would like to better understand if the collaboration has the needed resources to complete the commissioning plan in case of continuation of travel restrictions.
- The PAC found the prospect of confirming or disproving the NEUTRINO-4 result with early ICARUS running exciting. We would welcome further quantitative study on the impact of backgrounds and energy resolution on this analysis.
- The PAC commends the ICARUS study leveraging the NuMI off-axis neutrino flux. As identified by the collaboration, the NuMI off-axis flux provides several unique physics

opportunities, ranging from the ν_e disappearance study proposed by the collaboration to dark matter and kaon decay-at-rest physics.

Recommendations:

- PAC recommends the collaboration to further develop the ICARUS-only physics goals using the common SBN simulation and analysis tools and present more details, including the computing needs, in the next PAC meeting.

Status of the SBN analysis working group

We ask the committee to review the status of SBN analysis working group's activities and the status of the recommendations made at the January 2020 meeting.

Findings:

The PAC heard an update from the SBN analysis working group. The overarching goal of this group is to enable accurate comparison between the event spectra measured in different detectors located at different distances along the beam line. This is achieved by building a set of common reconstruction tools for efficient selection of the neutrino events and for background rejection in both near and far detectors (SBND and ICARUS), and simulation and analysis tools to extract the physics from the comparison of data at the two detectors

In calendar year 2020, despite the limitations imposed by the pandemic, the SBN analysis working group maintained regular meetings, organized two workshops on analysis and calorimetry, as well as tutorials on software tools. Additionally, it has put together a new working sub-group, SBN Analysis Infrastructure, tasked with coordinating the basic infrastructure and software organization across the detectors. Its goals include code sharing, a common analysis framework, large-scale event generation, and coordination of software package releases.

The Event Simulation, Selection and Reconstruction sub-group achieved significant improvements in detector description and event reconstruction. Modeling of physical effects, such as electron diffusion constants, space charge distribution, and optical model, were all significantly improved. The committee notes that some of these improvements were made possible thanks to the availability of ProtoDUNE measurements. Progress is also reported in the TPC and photon detection system modeling, as well as in the ability of the cosmic ray tagger system to reject cosmic background and improve the muon neutrino selection. Efforts to combine these systems are also underway. Electron-neutrino selection efficiency, a key ingredient for sterile neutrino appearance searches, was reported to be improved significantly, although still not reaching the level assumed in the SBN proposal. Plans for further improvements are outlined.

The Oscillation Sensitivities sub-group updated estimates of the sterile neutrino sensitivities breaking out the contributions of several exclusive final-state topologies.

The Detector Systematics working group carried out important initial comparisons of its Monte Carlo simulations with the first ICARUS data. The results allow to tune the space charge distribution, electron drift velocity, and electron diffusion in the model.

Comments:

- The development of the common analysis framework is essential for reaching the core science goals of the SBN program, which relies on accurate comparisons between the event

spectra in the SBND and ICARUS detectors. The PAC reaffirms its strong support for this effort.

- The PAC commends the SBN analysis effort for incorporating the inputs from ProtoDUNE-SP and the first ICARUS data into simulations of diffusion, space charge effects, and electron drift velocity.
- The PAC strongly encourages SBN to develop a scheme for incorporating the latest understanding of detector effects into modeling of projected oscillation sensitivity. This work involves close synergies among all working groups within SBN.
- The PAC encourages SBN to continue incorporating lessons learned on LArTPCs from MicroBooNE and ProtoDUNE.
- Given the large discrepancies in the predicted event rates reported by the collaboration when using different versions of GENIE, the PAC encourages the collaboration to quantify the impact of cross section uncertainties on the SBN physics program, particularly on the sterile neutrino search.
- SBN has been exploring the use of SciDAC resources, namely the HPC facilities at NERSC. It would be good to summarize the status of these efforts to date -- how much work it was to port the code, the resulting speedup, and the lessons learned.
- In some cases, there are three independent approaches to the same problem. While at the initial stage having redundancies is probably good, at some point it might lead to less than optimal efficiency. Accordingly, this should be periodically revisited.

Recommendations:

- The PAC recommends the SBN analysis working group support the ICARUS collaboration in using the common tools developed in SBN to quantify the sensitivity of running ICARUS in the single-detector mode, as is planned in the current timeline, and to assess computing needs.

Status of the CERN Neutrino Platform

Charge: We ask the committee to review the status of the CERN Neutrino Platform.

Findings

The CERN Neutrino Platform has successfully and effectively supported a large number of experiments, leading to a significant number of publications. The platform assists various groups in their component or integrated detector R&D phase through the development of demonstrators and providing charged particle test beams. This work has supported detector development for SBN and for current and future long baseline experiments, including DUNE.

Substantial CERN resources have been provided to support this initiative.

The CERN Neutrino Platform offers the opportunity to develop new ideas that are not driven only by CERN, but by the world wide neutrino community. Users, including those not already working at CERN, gain access to CERN infrastructure and the scientific staff working with the platform, which includes ~10 CERN staff members and 15 CERN Fellows and graduate students. These projects offer ways to start new collaborations and for CERN to join as a collaborating partner on work which will continue outside of CERN.

The CERN Neutrino platform has made crucial contributions to DUNE detector technologies through NP04 and NP02.

Comments

The PAC congratulates CERN for the highly successful Neutrino Platform and recognizes its importance for the worldwide neutrino program.

DUNE benefits greatly from ongoing Neutrino Platform efforts (NP04 and NP02), and it is important that the planned work continues.

The CERN Neutrino Platform facilitates contributions of the European Neutrino Community to the international neutrino program. In the US, it has had a profound impact on Fermilab's program. Examples include the ICARUS refurbishment and large-scale detector R&D and testing of different DUNE technologies. The Japanese neutrino program has also profited from detector studies, prototypes and test beams for several T2K near detectors.

Recommendations

The CERN Neutrino Platform has clearly had a major impact on a broad range of neutrino programs at Fermilab and Japan and has demonstrated its importance over several years. We urge all stakeholders to continue to support the effort and ensure that all needed resources are available.

A new experiment to study the Coherent Elastic Neutrino Nucleus Scattering and physics beyond the Standard Model

Charge: We ask the committee to review the physics case of the proposed experiment

Findings:

The PAC heard a presentation proposing deploying a DRIFT detector in a beam dump experiment at FNAL. Two possible science targets were outlined: (a) searching for light dark matter in an LBNF beam off-axis run and/or (b) detecting CEvNS events with on-axis NUMI beam.

The existing DRIFT detector is a $1m^3$ TPC filled with CS_2 and CF_4 gases at low pressure (typically 40 Torr) built to search for dark matter or measure neutrino interactions by means of recoiling nucleus. The nucleus will recoil in the direction perpendicular to the incoming beam thus providing an interesting reconstruction signature.

DRIFT is expected not to be affected by direct cosmic rays (CR) and γ backgrounds but does suffer from neutrons, either from CR interacting on surrounding materials, or directly from the beam. Although the drift is very slow, of order milliseconds, timing resolution of 10 μsec is achievable thus allowing to eliminate the beam-unrelated background.

Initially proposed as BDX at JLab, the proponents are now exploring NuMI and LBNF beams due to the slower beam window (10 μsec) and smaller duty factor that can better adapt to their timing resolution.

The most critical beam-related background is the one due to rock-neutrons. No estimate of this background has been shown either for the estimate of dark matter sensitivity or for measurement of CEvNS.

Different configurations of the detector were presented: (i) from 1 to 10 m^3 active volume, (ii) exposure to on-axis/off-axis beams, (iii) running at low pressure (40 Torr) when tuning for dark matter search/reducing the CEvNS background or (iv) running at high pressure (400 Torr) to measure the CEvNS spectrum.

Comments:

- The physics case described in the presentation is quite limited, consisting of one new physics model with a specific choice of parameters.
- Even neglecting the contribution from the "rock neutrons" background, the maximum rate achievable for CEvNS events is of O(45 events/year) i.e. much less than other experiments such as COHERENT in its initial data release (159 ± 3 CEvNS events).
- Conversely, if the pressure is lowered and the detector is deployed off axis, the residual CEvNS events still have to be accounted for as a background in the estimate of the dark-matter sensitivity.

Recommendations:

- 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.
- 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.

Status of the MAGIS experiment

Charge: We ask the committee to review the status of the MAGIS experiment and to report on the director's review.

Findings

The PAC heard about the latest progress on MAGIS-100. The experiment is now approved as E-1101 with a nominal 5 year timescale, three for construction, commissioning and early science, and two for data taking and key results.

The Project is structured as a DOE project with a preliminary resource loaded schedule and is organized in a work breakdown structure well-separated between DOE and in-kind scope. Funding is based on two sources: DOE QuantiSED ($2.5 M) and in-kind contribution from the collaboration via the GBMF ($5.8 M). Other in-kind contributions from UK collaborators are under discussion. COVID-19 poses some challenges for the schedule and costs.

The Director's Review successfully held on 9/2020 recognized the importance of the experiment and the quality of the project team. The need for additional QuantiSED funding was recognized. The review also identified the need for a strengthening of the project team and the establishment of formal agreements among Fermilab departments and between MAGIS partners and institutions.

On the physics side, there was an impressive demonstration of clock atom interferometry with large momentum transfer that was recently published in PRL. MAGIS will use a similar technique with the objective to reach quantum superposition over several meters and seconds using an interferometer with a 100 m baseline. Experimental simulations are also being developed.

From the technical and construction side, the delivery of the optical frequency comb system is imminent. On the engineering side, we learned about the considerations related to achieving ultrahigh vacuum for such a long (by AMO physics standards) baseline. Work on this item from the Fermilab Accelerator Division has proven to be extremely valuable. Civil engineering aspects are being studied (*e.g.* the use of a mobile crane). We also learned about steps taken to eliminate beam pointing jitter (including sending the laser through a fiber).

We also learned about a very interesting companion effort in the UK (AION), with the goal of establishing a LIGO/VIRGO style collaboration for gravitational wave and dark matter detection.

We learned that some of the MAGIS-100 partners are part of SQMS (the new quantum center) in the context of research on optimal quantum control. Some of the collaboration's work related to spin-squeezed atom sources might also be relevant for other QIS applications, including quantum networks.

Comments

This is an impressive project, a great example for collaboration between AMO/QIS and HEP experts in order to accomplish something that neither side would be able to do on their own. We note for example the contributions made by the Fermilab Accelerator Division. The various aspects of the project (physics, engineering, construction) seem to be progressing well. We hope that the lab will continue to provide the needed support for this excellent venture.

The prospect of a LIGO/VIRGO type collaboration with the UK that would exploit the advantage of having two geographically separated detectors also seems exciting.

It may be worthwhile for the MAGIS-100 partners to explore possible synergies with the lab's efforts related to quantum networks, *e.g.* the use of spin-squeezed atoms as quantum memories.

Proposal to join the CLAS12 Collaboration through limited authorship:

Charge: We ask the committee to review the scientific opportunities and unique contributions that may emerge by joining the CLAS12 Collaboration through limited membership.

Findings:

The PAC heard the proposal of some Fermilab members to join the CLAS12 collaboration through limited membership. Fermilab is already a partner of the e4v collaboration with members from the neutrino and electron scattering communities. The current involvement of the Fermilab group in e4v is focused on the upgrade of models and parameters in event generators and understanding the implications for neutrino physics. In order to participate in the analysis of CLAS12 data, it is required to join CLAS as a limited member. Although the current level of involvement by Fermilab is rather low, this represents a long-term effort expected to continue for the next 5-10 years.

The physics of electron-nucleus scattering is relevant to both current and future neutrino experiments. There is growing recognition in the neutrino community that electron scattering data is highly relevant for obtaining a correct description of neutrino-nucleus interactions. Currently, neutrino event generators, when benchmarked against available electron-nucleus scattering data, reveal large discrepancies. Mismodeling of neutrino-nucleus cross sections could have an impact

on the determination of neutrino oscillation parameters at NOvA and DUNE. The CLAS12 experiment offers a wealth of electron scattering data that could be leveraged to better understand neutrino-nucleus interaction.

Comments:

- The PAC recognizes the high importance of leveraging electron scattering data on the NOvA, SBN and DUNE physics programs.
- The proposed level of involvement, of about 0.5 FTE divided among three people is appropriate for starting this new effort.
- The PAC would like to hear from this effort in the future. We suggest that the proponents, in consultation with the FNAL Neutrino and Theory groups, present an analysis plan at the next PAC meeting that should include:

1. What modeling issues will be targeted and how they will be addressed and incorporated into neutrino interaction modeling.
2. What measurements will be made (i.e. what energies, nuclear targets, final states, kinematic quantities) to this end.
3. A timeline for the analysis developments that outlines the activity of each member.
4. Potential external collaborators and experts.

Recommendations:

- The PAC supports the participation of Fermilab in CLAS12 through limited membership.

Proposed Booster Upgrade: plans for the machine and physics potential

Charge: We ask the committee to review the status of studies of beyond-neutrino physics case of the Booster Upgrade.

Findings:

The PAC heard an update from the PIP-III task force charged with identifying physics opportunities of this proposed accelerator upgrade whose primary goal is to deliver 2.4 megawatts to LBNF. The task force at present consists of about a dozen Fermilab scientists and has been meeting regularly since last Spring. A heuristic map identifying compelling physics goals and the corresponding accelerator options on the path to PIP-III is being prepared and documented. A white paper summarizing the full breadth of the physics opportunities that could be pursued in the next 50 years is being developed, targeting submission to Snowmass. At this stage, the task force is not aiming to evaluate or prioritize the experiments.

The growing menu of physics is categorized according to their science targets. It spans the Standard Model and beyond-standard neutrino physics, dark matter and dark sectors searches, charged lepton flavor violation, precision tests of the standard model, and R&D for future facilities. In total, about twenty distinct opportunities have so far been identified by this effort. Several of the setups considered were noted to be capable of supporting multiple physics goals. A survey of other facilities worldwide with overlapping and potentially competing capabilities, as previously requested by the PAC, was presented.

Comments:

- The PAC commends the ongoing exploratory effort, which has led to the identification of a large number of physics opportunities, with several notable examples of well-developed individual physics cases.
- Furthermore, a variety of possible designs for the accelerator upgrades has been studied in response to the physics opportunities at the conceptual level.
- The PAC appreciates the difficulty in coordinating theory, experimental and accelerator efforts and commends the information exchange and synergies among all these efforts.
- The work of this task force has the potential to greatly enhance the physics output of the new accelerator complex to be built at Fermilab.
- The PIP-III task force is close to completing its original goal of identifying physics opportunities and producing a document to contribute to the Snowmass process.
- If the Snowmass process is delayed by one year, there is the possibility of further developments that would strengthen the case for this program.

Recommendations:

- The PAC recommends strengthening the current task force to ensure successful delivery of the white papers into the Snowmass process and to expand the task force in a second phase to include experimentalists and theorists, and experts on projects and budgets.
- The PAC recommends that the current task force complete this exploratory phase by Spring 2021 in order to give the necessary input for the second phase
- The Committee recommends that the second phase define the priorities for Fermilab and review the uniqueness, competitiveness, feasibility, and breadth of possible Standard Model measurements and searches for new physics. Identifying designs which maximize synergies between different physics goals and are cost-effective is especially of interest.

Report on the Snowmass CPM

Charge: We ask the committee to review the contributions made by Fermilab staff at the CPM, and to assess their impact and breath.

Findings:

The Committee heard a report on the October 2020 Snowmass Community Planning Meeting, hosted by the Fermilab SAC and User's Executive Committee, with extensive participation by Fermilab scientists. The local organization adapted the planned 2.5 day meeting to a longer, virtual format, using experience from other recent conferences to make the format as accessible and engaging as possible. Nearly 3000 community members connected during the workshop, far exceeding the number of participants that could have been expected in an in-person format. The meeting afforded the first opportunity for broad participation in cross-frontier discussions after the submission deadline for Letters of Intent.

The extent and breadth of Laboratory participation in all areas of the preparatory process, including the CPM organization, is impressive. Among the approximately 1500 letters of intent received, Fermilab scientists contributed to 279, on subjects distributed across all 10 Snowmass frontiers, with some concentration on the accelerator, cosmic, neutrino, and energy frontiers. The

Laboratory was well represented not only in the CPM planning committee but also among the session co-conveners, selected abstracts, and speakers.

The talks and LOIs with FNAL contributions reflect enthusiasm for fully exploiting the ongoing program across all frontiers, and for developing new capabilities through upgrades, new facilities and novel technology approaches. Cross-frontier themes such as quantum science emerged among Fermilab contributions in many areas. On the community frontier, Laboratory contributions spanned topics of community-building, outreach, and societal impact.

The pandemic circumstances were recognized by CPM organizers as a challenge. Because COVID-related delays across particle physics activities warrant revisiting the timescale for concluding the Snowmass process, a proposal to extend this timeline is under discussion. The SAC is currently launching a survey to get a sense of how laboratory scientists' ability to engage in the Snowmass process so far was affected.

Comments:

The PAC commends Fermilab for its key role organizing the CPM and for creating not only the infrastructure for a productive space for cross-frontier discussion, but also an impressive fraction of the intellectual contributions to this stage of the Snowmass process, under challenging circumstances.

The high level of engagement between Fermilab and the Snowmass process is an opportunity to bring in comprehensive community input about salient questions for the Laboratory such as the possibilities enabled by different Booster upgrade scenarios.

Fermilab is also well-positioned to take a leading role in developing a long-term package of science opportunities that includes accelerator and detector R&D for future facilities, dark matter searches, and in planning the exploration of the physics landscape after results from g-2, mu2e and DUNE, for the P5 report.

The disparate impact of the pandemic on some members of the particle physics community is a particular concern for Snowmass, and as noted above, the timeline is being reconsidered to address the inefficiencies of collaborating under COVID restrictions, and especially, the barriers to access and engagement in studies and conversations. Because of this, Fermilab, with its large role in the organization and in the participating community, and its ambition to lead the field in fostering equity, diversity, and inclusion, may have a unique opportunity to amplify the voices that are not being heard.