

Office of Science

High Energy Physics Portfolio Review:

Report of the Main Subpanel

High Energy Physics Advisory Panel Transmittal Letter**FUNDAMENTAL PHYSICS DIRECTORATE**

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Dr. J. Stephen Binkley
Acting Director
Office of Science
U.S. Department of Energy

Dr. Anne L. Kinney
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

Dear Dr. Binkley and Dr. Kinney,

The report of the main HEPAP Subpanel for a portfolio review of DOE Office of High Energy Physics operating experiments was presented to HEPAP at its meeting on May 14, 2018. This subpanel was one of two formed to deliver reports addressing the charge in your letter of October 13, 2017 for HEPAP to assemble subpanels "to conduct an independent peer review of currently operating experiments supported by DOE Office of HEP," with a "focus on scientific impact and productivity of HEP-supported contributions to these experiments within the context of the overall DOE HEP portfolio."

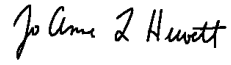
At the HEPAP meeting, the main Subpanel chair Dr. Paul Grannis summarized the major findings of the review. A draft of the written report had been circulated to HEPAP prior to, and in order to prepare for, the HEPAP meeting. The DOE General Counsel identified two categories of conflict of interest for the purpose of discussion and voting on this report: (i) Personal membership in one or more of the 13 collaborations reviewed in the report, and (ii) institutional membership in one of these collaborations. The second conflict of interest pertained to those HEPAP members whose home institutions held collaboration membership, regardless of whether the HEPAP member participated in that collaboration. All but five HEPAP members were thus conflicted for discussion. Of the five non-conflicted HEPAP members, only four were eligible to vote on the report. The five eligible HEPAP members discussed the report at the meeting, and the four eligible members voted to endorse the report without objection. Subsequent to the HEPAP meeting, the subpanel has prepared the final report, which is attached.

The review process was greatly aided by the extensive and detailed information provided in advance by the experimental collaborations under review. The review was expertly performed and documented by the subpanel and I thank the subpanel members on behalf of HEPAP.

With this letter, on behalf of the four eligible voting members of HEPAP, I respectfully submit for your consideration the final report of the HEPAP Main Subpanel for review of DOE U.S. operating experiments. In doing so, I note that the majority of HEPAP members have not discussed or endorsed the report.

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Sincerely,

A handwritten signature in black ink that reads "JoAnne L. Hewett". The signature is written in a cursive style with a large initial 'J' and 'H'.

JoAnne L. Hewett
Chair, High Energy Physics Advisory Panel

Report of the Main Subpanel
Portfolio Review of Operating Experiments

May 25, 2018

1. Overview

In this report we present an evaluation of 13 currently operating experiments that receive at least a portion of their funding from the DOE Office of High Energy Physics (HEP), based on the expected future scientific productivity and alignment with the strategic goals of HEP.

The experiments examined here vary widely in their scientific goals, location (in space, at telescopes, at power reactors, at particle accelerators, on mountain tops, or underground), size of collaboration, stage of operational life, and amount of DOE funding.

A recommendation is made for the future support of each experiment by placing it in one of four Groups, arranged in terms of the priority for funding.

The subpanel found that the scientific questions being addressed and the past performance of the experiments has been excellent. It recommends that in all cases, high priority be given to the analysis of data already acquired.

The experiments to be evaluated and the organization of the review are given in Section 2. The methodology used for the evaluation process is discussed in Section 3. Section 4 contains the Findings, Comments and Recommendations for each experiment. The Recommendations are summarized in Section 5.

2. Organization of the Review

In October 2017, the DOE Office of High Energy Physics charged the High Energy Physics Advisory Panel (HEPAP) to review currently operating experiments supported at least in part by HEP, with focus on their scientific impact and productivity. The charge is given in Appendix I. Two HEPAP subpanels were established to examine (a) the experiments at the Large Hadron Collider and (b) all other operating experiments. This report was prepared by the latter of these two subpanels. The review was intended to inform HEP in defining its programmatic plans for fiscal years 2019 to 2022. It is expected that HEP will use these recommendations to prioritize the set of experiments that have been operating for at least two years and are requesting significant DOE support in the years beyond FY 2018. The subpanel was charged to base its advice upon the scientific impact and the degree to which the future programs of these experiments are aligned with the recommendations of the Science Drivers in the 2014 report of the Particle Physics Project Prioritization Panel (P5)¹.

The five P5 Science Drivers are:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions and physical principles

The 13 experiments that were reviewed by this subpanel are:

- **AMS** (Alpha Magnetic Spectrometer) on the International Space Station
- **Daya Bay** Reactor Neutrino Experiment in Guangdong Province China
- **DES** (Dark Energy Survey), at the Cerro Tololo Inter-American Observatory, Chile
- **eBOSS** (extended Baryon Oscillation Spectrographic Survey), at the Apache Point Observatory in New Mexico
- **Fermi/LAT** (Fermi Large Area Telescope), in low earth orbit
- **HAWC** (High Altitude Water Cherenkov Observatory), on the Sierra Negra in Mexico
- **KOTO** ($K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$), at J-PARC in Japan
- **MicroBooNE**, on the Fermilab site in the Booster Neutrino Beam
- **MINERvA**, on the Fermilab site in the NUMI neutrino beam
- **NA61/SHINE**, at the Super Proton Synchrotron at CERN
- **NOvA**, on the Fermilab site and 810 km away in Ash River Minnesota in the off-axis NuMI beam
- **SuperK** (Super-Kamiokande Experiment), in the Kamioka mine in western Japan
- **T2K** (Tokai to Kamioka), in J-PARC in eastern Japan and 295 km away at SuperK

¹ “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context”, May 2014; <https://science.energy.gov/hep/hepap/reports/>.

DOE HEP supplied the subpanel with an estimate of funding (the sum of research and operating funds) for the 13 experiments in FY 2017. The funding levels in subsequent years may differ from those in FY2017. The table below shows the experiments falling into the indicated ranges of funding. The average (median) funding per experiment was \$2460 (\$1700).

Funding range	Experiments
> \$4M	AMS, DES, NOvA
\$2M to \$4M	Fermi/LAT, MicroBooNE
\$1M to \$2M	Daya Bay, eBOSS, HAWC, MINERvA, T2K
< \$1M	KOTO, NA61, SuperK

Table 1: Ranges of total (research plus operations) funding in FY 2017

The subpanel was formed at the end of 2017 with the membership shown in Appendix II. Each of 13 panelists was assigned to take the lead for the subpanel's discussion of one of the 13 experiments. On Feb. 1, 2018 the experimental proponents delivered documentation describing their scientific accomplishments, goals and plans for FY2019 – 2022, technical information, data management plans, young scientist mentoring and demographic information. Each experiment also provided estimates of DOE supported manpower for research and operations from the present to FY 2022.

The first full subpanel meeting was held in Rockville MD on Feb. 22, 23, 24 in which all 13 experiments made presentations and answered questions from the panelists. The agenda for Meeting 1 is shown in Appendix III. The subpanel divided into three groups to discuss sets of four or five experiments and make preliminary evaluations. These were then discussed by the full subpanel and arranged into a single coherent categorization within four groupings. In the interval between the first meeting and the second meeting on Mar. 28, 2018, again in Rockville, panelists prepared and circulated findings and comments aimed at explaining the evaluations. The second meeting was devoted to validating the grouping recommendations and finalizing the general and experiment-specific text for the report.

The subpanel commends all the experimental collaborations for their clear presentation of their results and goals, both in the written submissions and in the presentations. As expected for experiments that have been subjected to a long history of review by peers and funding agencies of the science goals, experiment design, operations and computing, the subpanel finds the scientific motivation for all 13 experiments to be very high. Those that have been operated for some time and produced results have added significantly to our knowledge. Those nearer to start of operations have already demonstrated their technical capability and shown that first rate science is on the way. The subpanel judges that the original decisions to invest in these experiments were very well justified. However, viewed through the somewhat narrower prism

of future impact and relevance to the Science Drivers articulated in the 2014 P5 Report, one can find gradations in their priority for continued funding by DOE.

The subpanel emphasizes the overall excellence and the strong contributions made by DOE-supported scientists in each of the 13 experiments that were scrutinized in this review. Although the evaluations for future operations support vary, we strongly believe that allocating the resources needed to analyze the data already acquired, thus maximizing the scientific impact, should be a very high priority. The return on taxpayers' money that went into construction and operation of these experiments would be diminished if the results from existing data are not finalized and put into the public domain.

3. Methodology of Evaluations

The 13 experiments under review vary widely in their past physics accomplishments, the nature of their physics goals and their relationship to the P5 drivers, the collaboration size, the duration and future prospects for operating the experiment, the mix of Research and Operations funding from DOE, and in the amount of DOE funding received. This variation made the evaluation process more difficult.

The evaluation criteria given to the subpanel by DOE HEP were:

- a) Science Merit and Productivity (including training and mentoring of junior researchers)
- b) Present and Anticipated Future Impact on the P5 Science Drivers
- c) Efficiency and Impact of DOE-supported contributions to the physics analysis efforts

In addition to these criteria, the subpanel and DOE HEP recognized that other considerations needed to be taken into account. These include the amount of DOE funding expected and the ‘physics bang for the buck’; variations in the leadership roles of the funding agencies involved; the impact of continued DOE funding on the full collaboration program; the expected impact on technology and methodology for future HEP-sponsored research; the extent to which the expected results from an experiment might be expected to be overtaken by newer experiments now in preparation; and the existence of valuable physics goals other than the P5 drivers.

The subpanel endeavored to keep its primary focus on each experiment’s prospects to address the P5 Report’s Science Drivers, as informed by past accomplishments, the track record in effective mentoring of junior scientists, and the consideration of the other criteria mentioned above. The differences in recommendations arose due to the varying degree to which the experiments satisfied the criteria outlined above.

Preliminary evaluations of the experiments were performed in three subgroups: (a) experiments at accelerators (KOTO, MicroBooNE, MINERvA and NA61/SHINE), (b) neutrino oscillation experiments (Daya Bay, NOvA, SuperK and T2K), and (c) cosmic frontier experiments (AMS, DES, eBOSS, Fermi/LAT and HAWC). These preliminary evaluations were discussed and modified in subsequent discussions by the full panel in both of its meetings.

The subpanel found that in the short time available to evaluate the experiments, a detailed numerical ranking from 1 to 13 was not possible, and in view of their disparate nature, not advisable. Instead we have placed the experiments into four groups characterized as follows:

Group I: Experiments that should be pursued with highest priority.

Group II: Experiments with outstanding promise and relevance to the P5 Science Drivers, but whose funding could be reduced somewhat in the event of severe budget shortfalls.

Group III: Experiments that address the P5 Drivers in important ways, but for which a reduction in funding would cause less harm to the DOE/HEP program than in the case of Groups I or II.

Group IV: Experiments that require further demonstration of likely success, or whose future program is less effective in advancing the P5 Science Drivers.

The following section presents Findings summarizing the description of the experiments taken from the materials submitted to the subpanel, Comments that summarize the reasons for assigning the experiment to a particular group, and Recommendations for the assignment of the experiment to a group. In Section 5, we present a summary of the group categories for all experiments. Acronyms used in the report are defined in Appendix IV.

Our focus in this review has been to offer guidance to DOE on the potential for new results that can advance our understanding of the science related to the five P5 Drivers during FY 2019 – 2022. Due to the wide variations among the experiments and the differences in the factors that led to our recommendations, the comments associated with each experiment in Section 4 are essential for understanding the rationale for the grouping choices and for the special considerations for future support for each of them.

We emphasize that our categorizations are based mainly upon the importance of support in the FY 2019 – 2022 period, not the scientific merits or past accomplishments of an experiment. An outstanding experiment might not be ranked highly if its primary achievements have already been made.

4. Experiment evaluations

4.1 Alpha Magnetic Spectrometer (AMS)

Findings:

The AMS-02 project installed a high-precision mass spectrometer aboard the International Space Station (ISS) in 2011, with the capability of measuring the momentum and charge of cosmic rays above the earth's atmosphere, and to distinguish electrons and heavy particles. The instrument has produced very high-statistics measurements of the cosmic ray spectra of various species of charged particles and nuclei over a large energy range. This work was done through a partnership with a large international team that has succeeded in operating an accelerator-type spectrometer in a hostile space environment.

DOE funds support the lead AMS group at MIT consisting of 34 FTEs, roughly equally divided between research and operations. Under an Implementing Arrangement between NASA and DOE, NASA is responsible for operations of the ISS and DOE is responsible for operations of the AMS experiment itself, as well as management of the scientific program

The high precision cosmic ray flux measurements from AMS present challenges to our understanding of the nature of cosmic rays. The measured positron excess, also seen with high statistical significance by other experiments, has a shape that is compatible with the annihilation of weakly interacting massive particle (WIMP) dark matter candidates with a mass of about 1.2 TeV, although the large amplitude of the signal is more difficult to explain. The antiproton flux measurements are also relevant in this context.

AMS has collected eight candidate anti-Helium events. These include two anti-⁴He events for which the background of secondary production from known sources has been estimated to be very small.

AMS gives its top priority for future studies as the exploration of heavy antimatter nuclei in space. The second priority is measurement of positron, antiproton and anti-deuteron fluxes with which to confront models of dark matter. The third priority is further measurement of heavy nuclei in the range from helium to oxygen.

Four postdocs have participated in the research of the MIT group in the past four years and eight graduate students received their doctorate. However, the panel was provided with less evidence regarding mentoring and assignment of roles and responsibilities to junior collaborators in AMS than was supplied by other projects under review.

Comments:

The AMS measurements of cosmic ray spectra are of fundamental importance for deciphering the properties of Galactic cosmic rays. They reach a precision that is far superior to that of previous experiments and are unlikely to be matched or surpassed in the near term. The AMS collaboration is to be congratulated on this impressive technical and scientific accomplishment.

The extensive AMS results present challenges for our understanding of the nature of cosmic rays. The positron excess can be accommodated by the annihilation of massive dark matter particles but is subject to an ambiguity that is intrinsic to other searches for indirect signals of dark matter, namely distinguishing the signature of dark matter from that of astrophysical sources of the positrons. Models of the astrophysical sources of cosmic ray particles still have considerable uncertainty and remain a topic of intensive investigation.

The observation of anti-³He and anti-⁴He candidates directly challenge current cosmological models. They also challenge the stringent bounds on antimatter based on the absence of signatures for its annihilation with matter. The investigation of possible instrumental backgrounds has not been completed.

Although the legacy of this unique instrument to the field of cosmic ray physics is exceptional, it is the search for dark matter and antimatter that directly confront the P5 Science Drivers. The evidence for either one is at present inconclusive, but confirming the evidence for either would represent an historic achievement.

The key question facing the subpanel is whether the tantalizing signatures for dark matter could be significantly improved by continued data taking. The incremental gain in evidence for a possible dark matter signature in the positron spectra from additional run time is modest, as indicated by the comparison of the present and projected spectra shown in the material submitted by the AMS team.

With two candidate anti-⁴He events, additional running would still result in just a handful of events. The question is whether these candidate events could be produced at a very low level by instrumental background. The team is producing simulations of the detector with the required statistics to investigate the issue.

The subpanel believes that progress on the dark matter problem is best served by emphasizing the analysis of the data already collected. The curation and public availability of the unique AMS legacy data set should be the highest priority. It represents a valuable and unique resource that should be preserved for future analyses, with sufficient redundancy to ensure long-term access.

The data management plan did not describe a means for providing broad access that would allow for independent data analysis and exploitation. We encourage DOE and NASA to explore with AMS ways to bring this about.

The incremental gain on P5 goals from continued long-term data collection results in a lower priority than the continuation of most of the experiments reviewed here. However, we view the continued extraction of insights from the existing data as a higher priority.

Recommendation:

We assign AMS to Group IV.

4.2 Daya Bay

Findings:

The Daya Bay experiment consists of eight liquid scintillator detectors in three locations near six nuclear reactors in China. The experiment has been operated since 2011 with the primary objective of measuring the neutrino mixing angle θ_{13} . The Daya Bay mixing angle results are substantially more precise than those from any other experiment. If the experiment runs through 2020 as requested, and continues analysis of the data through 2022, they will acquire about 60% more antineutrino events, and can be expected to improve the $\sin^2(2\theta_{13})$ measurement by about 30%. The total uncertainty on the effective mass squared difference should be reduced by about 33%.

Recent Daya Bay measurements have shed new light on the comparison of the measured flux and spectrum of antineutrinos coming from reactors and models of the nuclear reactions in the cores, suggesting that the anomaly previously seen for positrons from inverse beta decay with energies near 5 MeV may be alleviated by modifications to the nuclear models. Further running should reduce uncertainties on the flux measurement by a factor of two, and reduce the uncertainties on the fraction of U^{235} in the fuel by about a third, and thus give further understanding of the ‘reactor antineutrino’ and ‘5 MeV bump’ anomalies.

Daya Bay will improve limits on the mixing angle between the first normal neutrino and a fourth ‘sterile’ neutrino in the mass range $0.0003 \leq (\Delta m_{14})^2 \leq 0.3 \text{ eV}^2$ by about a factor of three. In combination with other experiments, the full region of the LSND and MiniBooNE anomalies will then have been explored.

The international Daya Bay collaboration comprises 193 scientists corresponding to about 25 FTEs. The DOE supported collaborators contribute about 11 FTEs. The U.S. contribution to the common fund was terminated in 2017 and data-taking shifts can be done remotely from the U.S. Continuing support for data analysis in the U.S. is requested.

Comments:

The impact of the Daya Bay experiment has been dramatic since it was the first experiment to report a measurement of a relatively large non-zero value of θ_{13} . This large value of θ_{13} enables NOvA, T2K, DUNE and other electron-neutrino appearance experiments to have sensitivity to CP violation and also facilitates determination of the mass hierarchy using reactors. Daya Bay’s measurement of θ_{13} will not be surpassed in the foreseeable future.

Daya Bay’s determination of mixing parameters directly addresses the P5 Science Driver to explore the physics associated with neutrino mass. The current plan of data-taking into 2020 is well motivated, and the resulting improved precision on $\sin^2(2\theta_{13})$ to below the 3% level will be yet another impressive accomplishment. Since no data-taking beyond 2020 is foreseen, the

practical question reduces to supporting U.S participation in the data-taking until it is completed in 2020 and the U.S. participation in the analysis of the final Daya Bay dataset beyond 2020.

The U.S. role in Daya Bay has been critical in multiple respects, providing important scientific, technical and management expertise, significant hardware contributions, and key analysis contributions, including providing independent analysis cross checks. After the data-taking ends in 2020, it will be important for U.S. physicists to continue to participate in analysis, and especially to continue providing the cross checks that will help to maintain the high standards of quality and validity for which the experiment is recognized.

The Daya Bay experiment has demonstrated that it can contribute to testing the validity of models of nuclear reactions in reactor cores which are used to predict antineutrino flux. These studies may help elucidate the so-called reactor antineutrino anomaly. While these studies are important for understanding current and future reactor experiments, they are less connected to the P5 priorities.

Daya Bay results, especially when combined with other experiments, have the potential to strengthen constraints on light sterile neutrinos.

Daya Bay has done a good job of mentoring young colleagues.

In view of the low cost and the important role played by U.S. collaborators, DOE support for U.S. participation in the remainder of the Daya Bay experiment and the subsequent final analysis of the full dataset are well justified. Nonetheless, primarily as a reflection of Daya Bay's earlier success, the relatively small gains that will come from further running between now and 2020 do not place it in the highest evaluation groups.

Recommendation:

We assign Daya Bay to Group III.

4.3 Dark Energy Survey (DES)

Findings:

DES is a six year imaging survey of 5000 deg² of the Southern sky, with high-cadence monitoring of 27 deg². The wide-field mosaic CCD camera spans 3 deg² and is mounted on the Blanco 4-meter telescope in Chile. The DES team uses diverse techniques to better constrain our understanding of the nature of dark energy (DE), using weak gravitational lensing and the abundance of galaxy clusters vs mass and redshift to map out the evolution of large scale structure, and using type Ia supernovae (SNe1a) and photometric baryonic acoustic oscillations (BAO) to directly measure the history of cosmic expansion.

DES is in the final stages of data collection. No upgrades are planned and observations should end by the end of 2018. The team has produced initial science results using the survey data from the first year comprising 1800 of the eventual 5000 deg². The team asserts that the final cosmology constraints will scale much more favorably than the square root of the ratio of the imaging area, for two reasons. First, the shape of the surveyed area has a large impact on the results. Second, the team is developing increasingly refined analysis tools which, together with the increased data volume, will provide substantial improvements. An example of the anticipated performance using the full data set is the expectation of measuring the DE equation of state parameter, w , with a 3% statistical uncertainty using SNe1a combined with results from the Planck CMB mission.

With the impending completion of the data collection, the operations team is shifting its focus to the curation and effective public distribution of the data. The science analysis plan, supporting a diverse collection of cosmological probes, has five main aspects: (1) pushing the models of the evolution of structure to smaller angular scales, (2) improving the calibration of shape measurements for galaxies, (3) improving the de-blending stage of image processing, (4) improving the determination of photometric redshifts, and (5) measuring the detection efficiency for faint galaxies.

The DES team described a strong mentoring structure for junior scientists, with a track record of success in nurturing their careers. The team emphasized the importance of the evolution of methods, experience, and personnel from DES into the LSST project. The 47 FTEs with DOE support are about one third of the ~140 total FTEs on DES. The non-DOE-supported collaboration is split roughly equally between other U.S. participants and foreign scientists.

Comments:

DES is the world's leading optical imaging survey, and has been optimized for establishing cosmological constraints. An impressive suite of papers has been based on the analysis of the first year's data, and DES is in the process of winding down its data collection phase. The combination of the DES observations with other precision cosmology measurements (such as CMB data) provide an incisive probe of the competing effects of dark matter and dark energy on both the rate of cosmic expansion and on the growth of large scale structure.

The subpanel judges the likelihood of achieving important scientific results as very high, and in fact this is already happening. As DES progresses from analyzing the Year-1 data to digesting the entire 6-year data set, the team expects to gain by considerably more than the square root of the run time. The contiguity of the imaged area impacts the large-scale structure measurements, and the processing gain from improved algorithms should also pay significant dividends. The scientific merit and productivity of the DES project is impressive.

DES was motivated by the desire to better characterize and understand the nature of dark energy, and is consequently very well-aligned with that P5 objective. The DES experiment will be the leading imaging survey well into the initial era of LSST operations in the early 2020's. The combination of a wide field camera (designed and engineered by DOE-funded DES team members), dedicated time on a 4-meter-class telescope, reasonably good image quality, and a strong data analysis team will keep DES in the forefront of the field until the LSST era arrives. It is important that the experience, algorithms, and individuals engaged in DES migrate into the fabric of LSST. The subpanel was pleased to learn that this is occurring, and stresses the importance of the cross-pollination between these DOE-funded projects.

DES is advancing the state of the art in dark energy data analysis on many fronts. The subpanel viewed this as an essential precursor to the LSST project. The DOE support of the analysis team is essential to the success of the DES project. DOE-funded scientists provide intellectual leadership for the DES project. There is a healthy combination of national laboratory and university scientists, and a good balance of U.S. and foreign scientists' engagement in the experiment.

Although the DES team faces challenges in developing and exploiting analysis methods in order for DES to reach its full scientific potential, the subpanel felt that in comparison with other demands on HEP resources, the level of support for science analysis is appropriate to the task.

The periodic releases of DES data conform to current standards and expectations in the field, and we applaud the investment the team is making in that important aspect of the project.

The strong participation of graduate students and postdocs speaks to the attraction of DES as seen from the perspective of a junior Cosmic Frontier scientist. We judge the mentoring within DES to be excellent.

DES is well-aligned with the P5 Science Driver of understanding cosmic acceleration. The scientific merit and productivity of the DES project is impressive. Its likelihood of achieving important results is very high and it is advancing the state of the art in dark energy analyses.

Recommendation:

We assign DES to Group I.

4.4 Extended Baryon Oscillations Spectroscopic Survey (eBOSS)

Findings:

The eBOSS survey, one of four within the Sloan Digital Sky Survey (SDSS-IV), is doing spectroscopic studies of baryon acoustic oscillations (BAO) using four distinct astrophysical populations: luminous red galaxies (LRG), emission line galaxies, tracer quasars and the Lyman-alpha forest of quasars at high red shift. The measurement of redshift distortions (RSD) allows probes of modified models of gravity.

These measurements extend the period in cosmic history from that covered by the previous BOSS survey into the critical epoch of redshifts between 1 and 2 when the universe transitioned from deceleration to acceleration. eBOSS is measuring the excess in the two-point galaxy-galaxy correlation function at the radius of the sound horizon distance (150 Mpc today) due to the remnant overdense shell left by acoustic waves at the time of recombination. From this, eBOSS can extract the expansion history of the Universe. These measurements are performed for various redshifts.

eBOSS makes three primary contributions to science: (i) through spectroscopy, it provides a three-dimensional map of galaxies and quasars, wherein is coded both the cosmic expansion history and rate of structure growth; (ii) the suppression of power in the clustering of matter on small scales can constrain the sum of neutrino masses; and (iii) the data are potentially sensitive to the existence of non-Gaussian fluctuations in the initial density field which arise naturally in many inflationary models.

The eBOSS survey addresses topics related to three P5 Science Drivers:

The nature of Dark Energy: BAO is a precise and independent probe of cosmic distance; BAO measurements of distance as a function of redshift powerfully constrain the equation of state of dark energy. A key Figure-of-Merit will be improved by a factor of 2.5 over the previous BOSS measurements.

Seeking unknown physical phenomena: The RSD measurements encode the rate of structure formation, and allow a test of General Relativity (GR) at three different redshifts. Tests of GR through RSD are complementary to tests of GR through weak lensing.

Neutrino mass: If the power spectrum can be measured at the relatively short distance scales anticipated for RSD, the final eBOSS sample could allow a 95% confidence level upper limit on the sum of neutrino masses of 70 meV.

The eBOSS observing program has been accelerated so as to be complete by February 2019, 1.4 years ahead of schedule, with analysis extending through the following year.

Of the approximately 50 FTEs on eBOSS, about 13 are supported by DOE. DOE supported scientists provide key operational support including target selection, mountain operations,

pipeline software development, and final data release. The pipeline software development task is the most challenging one, and will benefit both eBOSS and the future DESI.

eBOSS has published or submitted 45 papers, with over 800 citations. Twenty high-impact papers feature a postdoc as a lead author and 15 have a student as lead author. DOE-supported co-authors appear on all but 7 of the papers.

Comments:

Based on the existing publications, the scientific merit and productivity of eBOSS is very high. With its full data set it will be on target to provide substantial improvement in the precision of cosmological parameters, and will pioneer new techniques that allow exploration of larger redshifts. The collaboration expects to submit all results for publication by the end of 2019, less than one year after the final observations.

The subpanel finds the potential impact on the P5 Science Drivers to be very high. eBOSS will fill in the redshift gap between LRG galaxies and quasars that was left by the BOSS survey, its direct predecessor.

In keeping with the tradition of the SDSS culture, there is an excellent mentoring effort within eBOSS to promote the careers of junior participants.

The subpanel finds the efficacy and impact of DOE-supported contributions to eBOSS to be exceptional. There is no other instrument doing the same science. It is preparing the techniques and the talent pipeline for the future DESI instrument.

Recommendation:

We assign eBOSS to Group I.

4.5 Fermi Large Area Telescope (Fermi/LAT)

Findings:

The Fermi/LAT is a primary instrument on the Fermi Gamma-Ray Telescope launched by NASA in 2008. The LAT is a pair-conversion detector comprising tracking and calorimeter systems, giving 2 steradian coverage over the γ ray energy range 20 MeV – 300 GeV with excellent angular resolution. The Fermi team proposes to continue operation for about five more years.

The LAT is sensitive to potential annihilations of dark matter (DM) particles in regions of high concentration such as Milky Way satellites, the galactic center, and dwarf spheroidal satellite galaxies. These annihilations, whether into hadrons or tau leptons, would generate photons (typically from π^0 s), which would travel in straight lines, unlike charged particles. Combining estimates of DM concentrations and cross-sections derived from standard cosmological pictures, expected fluxes of the gamma rays can be estimated as a function of the dark matter particle mass. Fermi/LAT has set limits on possible WIMP masses in the range 10 – 1000 GeV. The collaboration expects these to be significantly improved by analysis of existing data and by additional data from continued running. Fermi/LAT has also set limits on axions or axion-like particles in the mass range 0.5 to 20 neV.

The observation by the Fermi Gamma Burst Monitor of the recent neutron-star – neutron-star merger detected by LIGO has demonstrated the significant capability of the GBM for this newly opened area of fundamental research. The LAT, with its superior angular resolution, but higher energy threshold and smaller field of view, can play a complementary role in instances when it observes a merger.

The current DOE-supported program is a major reduction from that previously agreed upon, as responsibilities for support of operations, apart from those of the LAT instrument itself, will be transferred from SLAC to NASA and the LAT collaboration at the end of FY2018. However the hardware and computing infrastructure for LAT operations would remain as a DOE funded activity at SLAC. The future run plan for the Fermi mission will be reviewed by the NASA Senior Review in 2019.

Comments:

The capability of the Fermi-LAT makes it a unique instrument for observation of DM particles with masses in the range suggested by many models. The LAT program, originally proposed for five years, has already taken data for ten years and seeks an extension to 15 years. Results are currently available using data from about the first six years. Using conventional assumptions about the behavior of dark matter in the relevant mass range, limits have already been set for two typical final states of the annihilation, $b\bar{b}$ and $\tau^+ \tau^-$.

A common estimate for the anticipated flux from DM is $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. The limits that LAT can reach depend on the number of high quality dwarf spheroidal galaxies available for the analysis. Reanalysis of Fermi/LAT data to include newly observed sources should be possible,

even after termination of the mission. Using the $b\bar{b}$ channel and assuming just 15 dwarf satellite galaxies, a nominal limit on a WIMP DM mass of 125 GeV could be set with ten years of data, while 15 years of data would raise that to about 175 GeV. If instead 60 dwarf spheroidal galaxies are available, the corresponding limits would be about 330 GeV and 410 GeV. The limits from six years of data are significantly weaker.

The observation of the gamma ray burst associated with the neutron-star – neutron-star merger by the Fermi-GBM was an exciting development. The GBM has a lower energy threshold and wider field of view than LAT. Thus the LAT is likely to see fewer of these events, perhaps only 5-7% as many, but viewing the higher energy signal would provide very complementary information on the details of the merger process.

Fermi/LAT has a good record of training scientists. There have been ten P5-related PhDs in the LAT Collaboration since 2010, of which seven were in the US.

There is already an agreement between DOE and NASA to transfer many of the operations responsibilities away from SLAC. The proposal from SLAC for the 2019-2022 interval is for an annual level of 1.5 FTE for operations and 1.1 FTE for physics research.

It is the view of the subpanel that the highest priority should be given to analyzing the data already taken, that is, the ten-year data set.

Given that the incremental improvement from operating an additional five years is limited, operations should be continued only if the DOE budget can comfortably accommodate it. In any event, the DOE supported data analysis should focus on the P5-topic dark matter.

Recommendation:

We assign Fermi/LAT to Group III.

4.6 High Altitude Water Cherenkov Observatory (HAWC)

Findings:

HAWC is a close-packed array of 300 water Cherenkov tanks situated at 4100 meters above sea level in Mexico, designed to study air showers induced by very high energy gamma rays in the range 1 to 200 TeV, above that of existing gamma ray telescopes. Recently, smaller and more diffuse “outrigger” tanks were installed outside the main array to help pin down the center of high energy showers and substantially improve the direction and energy measurements.

HAWC has been operating for about three years. It has published or submitted 12 papers since June 2017 that give detailed studies of high energy gamma ray astrophysics. The collaboration aims to continue running through 2023.

HAWC seeks evidence for high energy gamma rays from dark matter (DM) annihilations or decays. The pulse amplitude and timing of Cherenkov light from relativistic particles passing through the tanks are used to estimate the energy and direction of the parent gamma ray. HAWC sees a large swath of sky and operates 24 hours per day. Thus it can investigate many possible source regions at higher energy than most other DM projects. It can also contribute to the understanding of the “positron excess” reported by lower-energy experiments and interpreted as a possible DM signature. Recently HAWC has measured the spatial extent and flux of gamma rays from two nearby pulsars and determined that these sources alone are unable to account for the positron excess observed by the AMS experiment.

HAWC measures gamma rays above several hundred GeV. Above about 10 TeV, their sensitivity exceeds that of the HESS, MAGIC and Veritas telescopes, but will be surpassed by the CTA arrays when they come online around 2025. Beyond about 50 TeV, HAWC will remain competitive with CTA.

HAWC proposes to extend the current DOE support through December 2020, one year beyond the date that DOE has said it will end its funding for the project. The proposed extension is motivated by the desire to make extended measurements using the newly installed outrigger array, and on the role played by DOE researchers in managing operations for the experiment. HAWC notes that in the absence of extended DOE funding, it is unclear if the particular DM studies described in its proposal will be carried out. Currently, the DOE partially supports four senior scientists and some students for data analysis, travel, and HAWC operations from among the 58 FTE on the experiment. The majority of the project support is from international agencies, NSF, and LANL discretionary funds.

Comments:

HAWC has relevance to the P5 goal of investigating dark matter. HAWC may be limited, as are many other searches, by presently unknown astrophysical backgrounds. However, HAWC brings unique qualities to this work, particularly the sensitivity to gamma rays at very high energies. No other projects study this energy regime so well. Although the proposed work

probes DM masses that are higher than in the most popular WIMP models, such very massive DM particles arise in some interesting models.

HAWC has large acceptance, continuous operation, effective gamma-ray identification, and good angular resolution. These attributes are valuable when seeking coincidences with LIGO, IceCube, Fermi, or other observatories. They also enhance HAWC's ability to search for sources. One particular set of targets is dwarf spheroidal galaxies; these are thought likely to harbor a great deal of dark matter and have very low background gamma ray emission.

The subpanel was impressed with how quickly HAWC came online and delivered high-quality scientific results in the realm of high energy gamma ray astronomy. Their results on the morphology of gamma ray emission from nearby pulsars have been widely noted by other experiments studying the "positron excess". The analysis work described in the report appears to be well understood and developed. As a young experiment, the next few years will noticeably improve the statistical power of their observations.

The subpanel was pleased to note the project's excellent history of mentoring students and postdocs. In just the last four years, the LANL group has hosted 14 students and supervised 4 postdocs. A majority were women and under-represented groups. Among previous LANL postdocs on HAWC, three women now are tenure-track faculty or hold senior positions at other major laboratories. LANL holds a special place in this pipeline as most postdocs and students, both undergraduate and graduate, have had extended stays at Los Alamos.

The cost of the proposed extended support is quite modest. The LANL group also has leveraged its DOE/HEP support well so far, for example in obtaining discretionary funding from their laboratory. The subpanel is concerned that when DOE support ends, the specific P5-related projects described in the proposal also will end. The subpanel believes that the potential return on continued support is worth the investment.

The subpanel concludes that the P5 goal of identifying the nature of dark-matter will be furthered if DOE support for HAWC is extended by another year. We do not place the proposal in the highest priority group because of the above-mentioned astrophysical uncertainties and because the targeted high mass range is rather speculative. Nevertheless, the window of allowed possibilities could be narrowed by the proposed work.

Recommendation:

We assign HAWC to Group II.

4.7 KOTO

Findings:

The KOTO experiment at J-PARC in Japan has the ultimate goal of recording about 100 events of the extremely rare decay $K_L \rightarrow \pi^0 \nu \nu$, with signal to background ratio (S/B) of about 4.8. The measured branching ratio (BR) can be interpreted as a measurement of the CP-violating parameter η with precision of about 5%, and compared with the value measured in the B meson system as a consistency test of the standard model (SM). Such a measurement aligns with the P5 Driver on exploring the unknown through the ‘quantum influence of new particles’.

Obtaining a few events at the SM BR of $(2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$ will require three orders of magnitude improvement in sensitivity over that of previous experiments. This ‘Step 1’ milestone was expected to have $S/B = 1.4$. Since the only visible particles in the decay are the two photons from the π^0 , precise photon measurements and very efficient vetos are required. The dominant background was expected to be $K_L \rightarrow 2\pi^0$ with two unseen photons.

The initial 100 hour run in 2013 showed unexpectedly large backgrounds from neutrons in the beam halo. The data set collected in 2015 is expected to have 0.02 events for the SM BR, or a single event sensitivity (SES) of 1.2×10^{-9} . Results from this run are expected in mid-2018. Further runs in 2016 and 2017 more than doubled the 2015 data set. The background in the 2015 data set is about ten times that expected from $K_L \rightarrow 2\pi^0$, apparently due to contributions from $K_L \rightarrow \pi^+ \pi^- \pi^0$ and sequential scatterings of background neutrons. Work continues on reducing all sources of backgrounds at the analysis level. In the meantime, crucial detector upgrades were performed for the 2016 and 2017 data sets, and another is planned for 2018.

Using reasonable assumptions for the J-PARC run plans, the proponents’ current projections for running through 2022 do not reach the SES of the Step 1 goal, and the subpanel was not presented with predictions for the accompanying background levels. Thus it is not yet known when Step 1 will be deemed complete. A new detector and beamline, referred to as Step 2, will be needed to obtain the additional two orders of magnitude further improvement in SES to reach 100 expected signal events, while improving the background rejection. The design for Step 2 is at a preliminary conceptual level.

The DOE supported U.S. groups provide 12 FTE out of a total of 44 and are heavily involved in all aspects of the experiment, including important leading roles. They have provided trigger and data acquisition systems that have advanced the state of the art and made dead-time negligible, and continue to be improved in response to what is learned from data-taking experience.

Comments:

While the KOTO measurement is well-motivated to test an important aspect of the standard model, it is exceptionally difficult experimentally. Compared to the rare charged kaon decay $K^+ \rightarrow \pi^+ \nu \nu$, (already extremely difficult, and for which 100 events have not yet been observed),

the initial state of a well-characterized K^+ is replaced by an unseen K_L from a population with a broad momentum spectrum and direction defined only by collimators, and the final state of a precisely measured π^+ is replaced by a π^0 that decays immediately to two photons whose energies and locations in the precision electromagnetic calorimeter are measured.

In rare decay experiments that aim to improve the BR reach by several orders of magnitude, it is normal to encounter unforeseen backgrounds, and to need detector upgrades to improve SES for signal and/or to reduce backgrounds. However, KOTO has experienced both unforeseen backgrounds and the need for upgrades relatively early in the running (during the extension of its reach by about an order of magnitude.)

Thus the proponents have not yet demonstrated that Step 1 has a high probability of success, either in the SES for the signal or in the background suppression needed to see the signal above background. The information on SES and background levels after optimizing the analysis of the existing 2016 and 2017 data sets is crucial for both J-PARC and the DOE to evaluate the future priority for KOTO. (Since the 2015 data set was taken prior to detector upgrades, it is not sufficient for making that determination.) This subpanel is not in a position to make a technical review of KOTO and to fully evaluate its prospects for success.

The contributions of the U.S. groups are crucial to the KOTO experiment. Any reduction in the U.S.-supported effort would have a direct negative impact on KOTO; a complete withdrawal would risk lasting damage to the experiment. The senior physicists appear to be doing a good job of mentoring graduate students and postdocs. Notably, they have also involved 10 – 20 undergraduates, the majority of whom have worked on the experiment at J-PARC, resulting in multiple senior-thesis-winning departmental awards.

The subpanel believes that the focus of the proponents should be to optimize the analysis of the 2016 and 2017 data and obtain the resulting estimates of the SES and background levels. This is a prerequisite for projections of the required duration and probability of success of Step 1, and hence for determinations by the DOE for priority and resource allocation. The subpanel notes that similar opinions were expressed by the J-PARC PAC in the minutes of its July 2017 meeting (http://j-parc.jp/researcher/Hadron/en/pac_1707/PAC24thMinutes_final_draft.pdf).

Work on design and R&D for Step 2 should be put on hold until significant further progress is made on Step 1.

Overall, the experiment is in one of the defining situations for Group IV evaluations, namely that further demonstration of likely success is required. The subpanel encourages the DOE to work with other stake-holders, particularly in Japan, to perform a more detailed systematic review of this experiment.

Recommendation:

We assign KOTO to Group IV.

4.8 MicroBooNE

Findings:

MicroBooNE, the first phase of the Short Baseline Fermilab Neutrino program, is an experiment located on axis in Fermilab's Booster Neutrino beam at 470 m from the production target. The detector is an 85 ton active mass LAr TPC with dimensions: 2.3 m (height) x 2.6 m (drift) x 10.4 m (length). Three stereo wire planes (8,256 channels) read out the ionization and 35 PMTs collect the scintillation light produced by charged particles traversing the LAr.

MicroBooNE's primary physics measurement will look for the unexplained low energy excess of events with either electrons or photons in the final state observed by the previous MiniBooNE experiment. A secondary goal is the first cross section measurements of low energy neutrinos on Argon. The experiment responds to the P5 recommendation to perform a set of small-scale experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm, with some of the experiments using LAr to advance the technology.

Eventually the combination of MicroBooNE and the SBND and ICARUS detectors, sited at 110 and 600 m respectively, is expected to resolve the puzzles seen in short-baseline neutrino experiments. The MicroBooNE experiment is approved to collect 1.32×10^{21} protons on target, of which 7.4×10^{20} have been acquired. The full data set is projected to be complete by sometime in FY 2020. A cosmic ray tagger system, important for background rejection, was installed in March 2017 and ~20% of the existing data has been collected with the system in place. The experiment has produced 19 public notes and 7 publications, but the publication reporting on the MiniBooNE excess is only expected in 2020.

On the hardware side, the experiment has achieved argon purity 6 times better than the design goal but can only run at about 60% of the design voltage. Approximately 10% of the TPC channels appear to be cross-connected to other channels in a way not understood, making reconstruction and cosmic ray rejection more difficult.

A large number of former postdocs have moved on to good positions in the field leading to a number of requests to DOE for support of new groups. There are about 39 DOE-supported FTEs and another 11 FTEs whose DOE grants are being sought, out of 93 FTEs on the experiment.

Comments:

MicroBooNE combines the useful physics goal of checking the MiniBooNE low energy excess of e^+e^- or photons with the development of a LAr TPC, along with the software for event reconstruction and analysis. The combination of a clear physics goal and the LAr development goals is a good way to drive progress on the use of a LAr TPC. They have implemented continuous TPC readout and data handling and the simulation of the TPC waveforms, which proved to be challenging. Since much of the initial data was collected without a cosmic ray veto shield, it is important to achieve the experiment's goal of 1.32×10^{21} protons on target to have a

chance of providing definitive results on the MiniBooNE excess. Data are being analyzed using four different approaches. The MicroBooNE report did not quantitatively indicate how well each approach is doing in suppressing the important backgrounds to the low energy excess measurement and maintaining good reconstruction efficiency. The analysis is expected to be complete sometime in 2020, with perhaps an earlier report in 2019.

If the low energy anomaly is not verified by MicroBooNE, the experiment should shift from data taking to understanding the LAr TPC hardware. This would eventually require opening the TPC cryostat, possibly precluding further data taking. The problems that have been found, including a high single photo-electron rate, the difficulty of reaching the design voltage and drift field for the TPC, as well as a significant number of non-functioning, cross-connected, wires, need to be diagnosed for future LAr TPC experiments such as DUNE. Relative to continued operation, this effort would require a smaller group of more specialized personnel.

If the MiniBooNE excess is seen by MicroBooNE, a re-examination of the priority for further running would be needed.

MicroBooNE deserves significant credit for an excellent job of mentoring its graduate students and postdoctoral scientists.

MicroBooNE is well-aligned with the P5 Science Driver of pursuing the physics associated with neutrino mass. It also addresses the P5 recommendation for a set of short-baseline experiments to resolve existing anomalies such as the MiniBooNE low energy excess, and at the same time to advance LAr TPC technology for use in DUNE. The technical problems encountered by MicroBooNE threaten to lessen its scientific impact.

Recommendation:

We assign MicroBooNE to Group III.

4.9 MINERvA

Findings:

MINERvA is a dedicated cross-section measurement experiment running in the Fermilab NuMI beam of neutrinos and antineutrinos with energies near 3 or 6 GeV. The neutrinos are incident on He, C, Fe, Pb, CH, and H₂O (but not Ar) targets and the reaction products are observed in a scintillating strip tracker, electromagnetic and hadronic calorimeters, and the MINOS near detector for muon measurements. The simultaneous cross section measurements on multiple nuclear targets are needed for modeling nuclear effects and reducing systematic uncertainties in flux determinations for neutrino oscillation experiments. MINERvA measurements have already benefited the NOvA and T2K oscillation measurements and are well suited to provide the data needed by DUNE. MINERvA supports studies of the P5 Science Driver to pursue the physics associated with neutrino mass.

The top science and technology goals identified by the experiment are: hadron final state interactions and nuclear mass dependence; neutron content of neutrino interactions and their impact on neutrino energy reconstruction; nuclear effects in deep inelastic scattering; a Monte Carlo neutrino production tune for oscillation experiments and the determination of the NuMI beam flux. A data preservation program is planned for implementation during FY 2020-2021.

Data taking will be completed in FY 2019 and data analysis would be completed by FY 2022, with a significant ramp down over this period (from 52 to 29 FTE, half of which are supported by DOE). The experiment has 21 publications so far, with at least as many expected before the FY 2022 completion of the program. DOE supported groups (about half of the collaboration) provide a large fraction of the leadership for the experiment. The MINERvA experiment has trained a large number of students and postdoctoral researchers.

Comments:

MINERvA provides valuable and unique cross section measurements for neutrinos impinging on several nuclear targets in two energy ranges, including the high energy and large momentum transfer range appropriate for the future DUNE experiment.

MINERvA data are necessary for understanding collective nuclear effects and other sources of uncertainties affecting interaction rates in present and future neutrino oscillation experiments. NOvA and T2K are already using information from the MINERvA measurements to improve the models they use in their oscillation analyses. The higher energy and momentum transfer range is very relevant for DUNE which will have significant event rates in this region and will need a good understanding of the neutrino energy reconstruction in order to achieve the required precision for its oscillation measurements. Neutrino interactions on nuclei can occur through many processes and each of these leads to a different visible energy in the detector for the same incoming neutrino energy. Because the relative rates of the various processes depend on energy and are different for neutrinos and antineutrinos, it is very valuable to have cross-

section measurements for each, for both neutrinos and antineutrinos and in the different energy ranges.

MINERvA, is currently running in antineutrino mode in the 6 GeV beam and will need to take data through FY 2019 to accumulate an antineutrino sample that matches that for neutrinos, thus allowing for useful comparisons of neutrino and antineutrino rates.

The science and technology goals listed in the Findings section above are only the top of a prioritized list, to which many other interaction cross-section measurements will be added, each relevant to understanding the full picture of neutrino interactions in the appropriate energy range (e.g. electron neutrino interactions and shallow inelastic scattering).

The experiment has a very good record of publications and has provided excellent mentoring of students and postdocs. Half of the 21 published papers are in Physical Review Letters. These are mostly analyses of the 3 GeV beam data; more low energy results and analyses of the 6 GeV data are still to come.

At the moment there is no general phenomenological model that describes all neutrino interactions in the few GeV energy range. While multiple neutrino event generators exist for interactions with single nucleons, none of them accommodates all existing neutrino interaction data; further models for including nuclear physics effects are also needed. It is therefore clear that a more comprehensive framework is necessary. Ideally, this framework should be sufficiently flexible to allow updates demanded by future experiments or by novel theoretical ideas. The subpanel encourages MINERvA collaborators to continue their important role in developing such models.

Verification of the consistency of such future updates with MINERvA data demands that this data be carefully preserved. Implementation of a data preservation plan is scheduled for FY 2020 – 2021. The subpanel strongly encourages a dedicated effort so that efficient access to the data and the necessary analysis tools are available long after the completion of the MINERvA experiment. This goal is very important for the larger community in the long term.

The MINERvA results are important inputs for other experiments that measure neutrino properties, but they are themselves not among the primary P5 Science Drivers.

Recommendation:

We assign MINERvA to Group II.

4.10 NA61/SHINE

Findings:

NA61/SHINE addresses a broad range of goals in hadron, heavy ion and neutrino programs. The neutrino-related goals that mainly concern the DOE-supported groups are the measurements of differential cross sections for proton, pion and kaon interactions on production targets used in neutrino oscillation experiments, so that the neutrino fluxes in the near and far detectors can be more accurately predicted. These experiments require measurements of primary beam particle interactions, as well as of those of secondary and tertiary particles, in both the primary target and nearby materials.

NA61/SHINE results have helped improve the uncertainty in neutrino oscillation experiment fluxes; for example, using NA61/SHINE data as a constraint, T2K was able to lower the uncertainty in the ratio of near to far fluxes to about 2%. For DUNE, the NA61/SHINE goal is to limit the uncertainty in the incident neutrino flux due to hadron interactions to 3% which is needed to determine the CP-violating phase. The NA61/SHINE work therefore supports the P5 Science Driver to pursue the physics associated with neutrino mass.

Since joining as full-fledged members in 2014, the DOE groups have added forward TPC detectors that allow access to the kinematic range of interest for NOvA and DUNE. They have also contributed to an upgrade of the readout system for the TOF system. They are leading the modernization of the tracking code that is necessary to incorporate data from the forward TPCs, and the migration of the simulation software to GEANT4 needed to incorporate the vertex detector and forward TPCs into the detector description. Future requests may be made for hardware upgrades to allow for long targets.

Near-term analysis goals include measurements using existing data of production cross sections of pions and kaons on carbon and aluminum, the 60 GeV pion-carbon spectrum, and 120 GeV proton-carbon spectra, as well as the long NuMI target using 2018 data. A workshop was held to identify potential data samples for neutrinos following the 2019 – 2020 shutdown. Part of the NA61/SHINE program is directed at cosmic ray physics, and in particular determining the cross sections for anti-deuteron production, relevant to measurements by the AMS experiment. A non-DOE supported U.S. group is participating in this work. NA61/SHINE has 45 FTEs, mostly from CERN member states, with 5 to 6 supported by DOE. Students comprise half of the DOE FTEs, but the subpanel was not presented with mentoring activities or outcomes.

Comments:

The investigation of neutrino physics by T2K, NOvA, and DUNE is a key part of the world HEP program, and will involve searching for subtle signals of CP violation and other phenomena. Given the challenge of funding and building these experiments, their results are likely to shape our understanding of neutrino phenomenology for years to come. Under these circumstances, constraining dominant systematic uncertainties with data from other sources will be valuable. NA61/SHINE's measurements that can constrain the neutrino flux for a

relatively modest investment will be important for maximizing the potential of the long baseline oscillation experiments.

For NA61/SHINE to have its maximum impact, the collaboration needs to determine the associated systematic uncertainties in detail and quantify their correlations over the kinematic range, and from one data sample to another. Since DUNE is likely to run into the far future, all relevant NA61/SHINE results must be archived and documented in such a way that they may be used reliably throughout that period. The NA61/SHINE experimental team needs to provide detailed, quantitative, archived and well-documented results.

NA61/SHINE's publication of results has sometimes lagged data collection significantly, in some cases by many years. The lag has the distinct drawback that details of the running conditions can be lost, and can raise questions about the validity of the results and their uncertainties. Given the importance of the T2K, NOvA and DUNE measurements and the enormous scientific cost of anomalies arising from misunderstood conventional sources rather than from neutrino properties, it is hard to overstate the importance of NA61/SHINE's delivery of robust results. Analyzing the data promptly is necessary in order to meet this standard.

The DOE groups are leaders of the neutrino-related part of the program and have led in building detectors, modernizing software infrastructure and analyzing the data needed for understanding neutrino production.

Further upgrades would require a compelling case based on the potential to improve the precision or reliability of the neutrino flux constraints.

Given the benefits of NA61/SHINE's measurements to the neutrino program and cosmic ray physics, these should be completed if possible. The experiment could, however, cope with a modest reduction in funding by confining its measurements to those benefiting the neutrino program at the expense of those directed at cosmic rays. The subpanel recommends against larger cuts that would require sacrificing measurements important for one or more of the long baseline neutrino oscillation experiments.

Recommendation:

We assign NA61/SHINE to Group II.

4.11 NOvA

Findings:

The NOvA experiment uses the evolution of the neutrino flavor states as they propagate from Fermilab to northern Minnesota to make precision measurements of the neutrino oscillation parameters (mass differences and mixing angles), to investigate the neutrino mass hierarchy, and to search for violation of CP conservation in the neutrino sector. NOvA's physics program is well aligned with the P5 Science Driver "Pursue the physics associated with neutrino mass".

The experiment uses beams of predominantly (at birth) muon neutrinos or muon antineutrinos. After three years of running, 9.0×10^{20} protons on target (POT) have been delivered in neutrino mode and 3.9×10^{20} POT have been delivered in antineutrino mode. The plan is to achieve 24.4×10^{20} POT in each mode by the end of 2022.

Important physics has already been produced. New measurements of the mixing parameter, $\sin^2\theta_{23}$, and the mass difference squared, $(\Delta m_{23})^2$, have been obtained. These critical measurements are currently limited by statistical uncertainties. The team however seeks improvements to the systematic uncertainties, since by 2022 the systematic and statistical uncertainties will become comparable for the mass measurement. A program to improve the systematic errors by a factor of two is in place.

There are about 120 FTE physicists in the collaboration, of which about 60 are supported by DOE. To date, NOvA has produced 18 PhDs, mostly in the last 2 years. The proponents emphasize the key role they play as a training ground for the future DUNE project.

Comments:

NOvA is a central part of the Fermilab neutrino program that has already produced results for the oscillation parameters in the $[\nu_2, \nu_3]$ sector that are comparable with the best in the world. The systematic uncertainties are well controlled and the statistical uncertainties dominate the results. Substantial improvement is thus expected with continued running. The work has already led to several publications in leading journals. The project has the longest baseline of the current generation of experiments and this gives it the best sensitivity to the mass hierarchy. A 2σ preference for the normal hierarchy has been demonstrated and this should reach 3σ by 2020 if the present parameter values persist. This is of intrinsic interest as well as important in guiding the search for neutrinoless double beta decay. There are some indications of CP violation but these are unlikely to exceed a 2σ significance with running until 2022.

The NOvA program is similar to that of T2K, but they have significant differences in detector technology, baseline length and beam energy. These differences allow for complementary and independent measurements that strengthen the overall program. The planned program to combine NOvA and T2K results would add significant gains in physics understanding. The subpanel welcomes the plans for a joint analysis with T2K to exploit the complementarity between the two experiments.

The NOvA project focuses squarely on the P5 Science Driver related to understanding the physics of neutrino mass. It is having, and should continue to have, a major scientific impact.

NOvA is the only currently operating long baseline neutrino oscillation project based in the U.S. It plays an important role in training the next generation of physicists who will play critical roles in DUNE. The high efficiency of getting the data analyzed and published, and the high impact of the project as a whole, stems directly from the contributions of DOE-supported physicists. Although the cost to continue this DOE-dominated project is large, the high productivity and good potential for scientific payback make the investment worthwhile.

Recommendation:

We assign NOvA to Group I.

4.12 SuperKamiokande (SuperK)

Findings:

SuperK consists of a 50 kton tank of water that serves as a target and detection medium for neutrino interactions. Cherenkov light from high velocity particles emitted in the collisions is detected by an array of photomultipliers. The experiment has been in operation in an underground cavern in western Japan since 1996 and has made seminal contributions to our understanding of neutrino mass and mixing, based on the studies of neutrinos created in the earth's atmosphere and in the sun. It has set stringent lower limits on the rate of proton decay. In addition to its role as a stand-alone experiment, SuperK serves as the far detector for the T2K long baseline experiment studying neutrinos from the J-PARC accelerator in eastern Japan.

SuperK identifies five operations goals for FY 2019 – 2022. The first is based on the addition of Gd salts dissolved in the water that will give observable signals for neutrons produced in neutrino interactions. Neutron tagging will improve recognition of the inverse beta decay reactions typical of supernova antineutrinos, advance the study of supernova relic neutrinos, and provide more efficient discrimination between anti-neutrinos and neutrinos in the T2K beams.

The second SuperK goal is the study of the supernova neutrinos to provide new understanding of core collapse supernova explosions and to help resolve the neutrino mass hierarchy. The third goal is the continuation of the atmospheric neutrino oscillation studies to improve the knowledge of the octant of θ_{23} and mass hierarchy parameters, and to add information on possible CP-violation in the neutrino sector. The final goals aim to improve limits on nucleon decay and to continue the study of solar neutrino oscillations.

SuperK reports 11.5 FTEs who are receiving DOE support. The DOE-supported contingent in SuperK is 25% of the total collaboration.

Comments:

SuperK serves two purposes: it is both a stand-alone experiment and also the far detector for the T2K experiment. Our comments here are restricted to the first purpose. This includes studying naturally produced atmospheric and solar neutrinos, detecting the burst of neutrinos that would come from a nearby supernova event, and serving as the largest and most effective detector currently searching for nucleon decay.

The Gd upgrade of the SuperK detector that will provide neutron tagging and thus discrimination of inverse beta decay events and elastic scatters has been approved for the next stage of running. This will improve the study of supernova neutrinos as well as reduce backgrounds involving neutrons in proton decay searches. The performance of SuperK will help decide whether Gd doping is useful for possible future detectors such as HyperK.

Measurements of neutrinos from supernova SN1987A provided new knowledge about neutrinos. However the subsequent progress in accelerator and reactor experiments has overtaken SuperK's ability to add significantly to our knowledge of key neutrino properties if a new supernova were to occur. Nevertheless SuperK's contribution to supernova physics would be large. SuperK would be sensitive to matter effects and $\nu\nu$ interactions in extreme astrophysical environments, although the interpretation would be made difficult by uncertainties in supernova dynamics. The subpanel recognizes that there could be significant value for astrophysics from measurements of supernova neutrino energies and arrival times, but these would not directly address the P5 Science Drivers. In particular, the study of supernova core collapse dynamics would be greatly aided by neutrino detection at SuperK.

Although SuperK made pioneering measurements of neutrino properties and has continued to develop new analysis tools, improvements in our knowledge of neutrino mass scale, hierarchy, quadrant of θ_{23} and CP violation will be dominated by experiments using terrestrial neutrinos. The addition of the well-understood SuperK data will be useful, but its impact will be limited by the slow fractional growth of its statistical samples.

SuperK has the world's leading limits on nucleon decay. These limits and searches have been crucial to the field, since the quantum numbers of the fermions fit nicely within higher dimensional multiplets of a unified theory, suggesting the possibility of nucleon decay at measurable levels. The Gd upgrade will help reduce neutron-rich backgrounds. However, the improved limits after another ten years of running will be modest (less than a factor of two), especially in comparison to anticipated qualitative improvements of sensitivity in the future by DUNE and HyperK. The modest improvements in lifetime limits translate to even more modest limits in the sensitivity to the high mass scale that generates these decays.

Historically SuperK has mentored junior colleagues well, although in recent years the number of students has declined.

The multi-faceted SuperK physics program includes measurements of neutrino properties and searches for nucleon decay that are well-aligned with the P5 Science Drivers concerning the physics associated with neutrino mass and exploring the unknown. However, SuperK is a mature experiment and the prospect for statistical improvement of many measurements is limited.

Recommendation:

We assign SuperK to Group III, but note its role as the far detector for T2K, which is placed in Group I.

4.13 Tokai to Kamioka (T2K)

Findings:

T2K is a long baseline neutrino experiment that uses the 30 GeV proton beam at J-PARC. The experiment has a near detector 280 m from the target that is used to characterize the neutrino beam and SuperK, 295 km away in western Japan, as the far detector. The energy of the off-axis neutrino beam peaks at 0.6 GeV, which places SuperK at a ν_μ oscillation minimum. The current sample sizes, expressed in units of 10^{20} protons on target, are 15 for neutrinos and 8 for antineutrinos. These are expected to grow to 53 for each flavor during the period under consideration.

The U.S. contributed about \$5M to the construction of T2K, providing beam line components and the π^0 detector and side muon detector in the near detector location. The U.S. groups in T2K focus on operations of the near detector. U.S. groups contribute broadly to the analysis. These contributions to T2K physics include: measurement of the neutrino flux, including an analysis of the effects of secondary nucleons; neutrino cross section measurements; near-detector measurements of ν_e contamination in the beam; development of neutrino interaction models; and development of an improved SuperK event reconstruction algorithm.

T2K scientific goals include: 3σ exclusion of $\sin\delta_{CP} = 0$ for approximately 50% of the range of true CP values; 3σ evidence for anti- ν_e appearance; significant shrinkage of the allowed region in the $\sin^2\theta_{23} - (\Delta m_{23})^2$ plane; and further improvements in neutrino cross section measurements and interaction models.

In addition to physics analysis, the T2K-U.S. groups propose to carry out various detector upgrades and to embark with Japan on jointly funded detector R&D for a 3-dimensional detector, comprising 1-cm scintillator cubes read out by x-y-z fibers.

The 10 U.S. institutions comprise about 8% of the 500-member international T2K collaboration. The DOE supports 26 FTEs out of the 211 total FTEs in the collaboration.

Comments:

T2K has carried out a highly successful series of oscillation measurements resulting in significantly improved precision on $\sin^2\theta_{23}$ and $(\Delta m_{32})^2$. Both of these measurements are important ingredients for the P5 Science Driver to pursue the physics associated with neutrino mass.

T2K's current results show some sensitivity to the neutrino mass hierarchy and to CP violating effects and are thus further addressing the P5 Science Driver. These current results are statistically limited and one can expect significant improvements during the period under consideration that will further constrain parameters that are relevant to P5 Science Drivers.

The T2K program is similar to that of NOvA, but they have significant differences in detector technology, baseline length and beam energy. These differences allow for complementary and

independent measurements that strengthen the overall program. The subpanel strongly endorses the planned program to combine T2K and NOvA results, which would add significant gains in physics understanding.

T2K's relatively short baseline makes it less sensitive to matter effects than NOvA but it is more sensitive to CP violation effects, and is therefore complementary to NOvA (and DUNE). Moreover, the lower T2K beam energy allows measurements of cross sections that are potentially important to DUNE but not available from other experiments.

The SuperK collaboration is approved to introduce Gd salts into the water of the T2K far detector in summer 2018 to provide neutron tagging for improved identification of various signal and background reactions. Test data thus far indicate that the Gd-loading will not harm the far detector performance, but T2K should remain vigilant so as to ensure that there is no damage to its neutrino efficiency and identification capabilities.

U.S. scientists are important players in the T2K physics analysis and have made contributions that have had major impact on the T2K physics program. DOE-supported scientists have played significant leadership roles in T2K. With 20 U.S. Ph.D.'s completed to date and 10 more in progress, T2K is doing well in terms of training the next generation of neutrino physicists. The mentoring of young U.S. T2K physicists has been excellent.

T2K is a successful experiment addressing the P5 Science Driver to pursue the physics associated with neutrino mass. Its current results show that it has some sensitivity to the CP violation and to a lesser extent, the neutrino mass hierarchy. In these regards, T2K is complementary to NOvA.

Recommendation:

We assign T2K to Group I.

5. Summary

We summarize the definitions of the groups and the subpanel's recommendations for the 13 experiments. The ordering within a group is alphabetical.

Group I (*Experiments that should be pursued with highest priority*):

DES, eBOSS, NOvA, T2K

Group II (*Experiments with outstanding promise and relevance to the P5 Science Drivers, but whose funding could be reduced somewhat in the event of severe budget shortfalls*):

HAWC, MINERvA, NA61/SHINE

Group III (*Experiments that address the P5 Drivers in important ways, but for which a reduction in funding would cause less harm to the DOE/HEP program than in the case of Groups I or II*):

Daya Bay, Fermi/LAT, MicroBooNE, SuperK

Group IV (*Experiments that require further demonstration of likely success, or whose future program is less effective in advancing the P5 Science Drivers*):

AMS, KOTO

Appendix I Charge to HEPAP



U.S. Department of Energy
and the
National Science Foundation

OCT 13 2017



Dr. Andrew Lankford
Chair, HEPAP
University of California, Irvine
4129H Frederick Reines Hall
Irvine, California 92697

Dear Dr. Lankford:

The Department of Energy (DOE) Office of High Energy Physics (HEP) requests that the High Energy Physics Advisory Panel (HEPAP) charge subpanels to conduct an independent peer review of currently operating experiments supported by HEP [hereafter generically referred to as “HEP experiments”]. This review should focus on the scientific impact and productivity of HEP-supported contributions to these experiments within the context of the overall HEP portfolio. HEP will use the findings and recommendations from this review to help further define a detailed implementation plan for the strategic vision laid out in the Particle Physics Project Prioritization Panel (“P5”) Report, as recommended by the recent HEP Committee of Visitors.

This review process is modelled in part on similar “Senior Review” or “Portfolio Review” processes employed by the National Aeronautics and Space Administration and the National Science Foundation to maximize the scientific productivity of their respective mission or facility portfolios within realistic budget constraints, with modifications as needed and appropriate for the DOE mission and experimental portfolio. Therefore, this independent review will serve primarily as advice to HEP. Specifically, HEP will use the outcomes from this process to:

- Prioritize the currently operating HEP portfolio of experiments (including contributions to HEP experiments at off-shore facilities);
- Define an implementation approach to best achieve the goals of the P5 science drivers; and
- Provide programmatic guidance to the HEP experiments concerned for FY 2019 and beyond.

Additional outcomes or programmatic guidance for future years may be provided to the experiments at the discretion of HEP management. Actions resulting from this review process could include changes to research support; extending the planned running of a particular experiment; maintaining the status quo; significantly restructuring the run plan; or terminating HEP support for experimental operations. **All currently-supported HEP experiments that have taken physics data for at least two years, and are expected to request significant DOE support for operations, or related activities (e.g., computing) beyond FY 2018 are subject to this review.**

This letter describes the general objectives and process to be used for this review. Separately, HEP will issue a call for proposals to the lead Principal Investigators, Spokespersons, and/or Institutional Boards for the relevant experiments listed below so that they can address the elements of this charge and the relevant review criteria in a common format. For international collaborations, the appropriate DOE-supported institutional lead(s) should prepare a response, in coordination with international collaboration management, which focuses on the DOE science deliverables as outlined below.

Each experiment that is invited to the HEP Portfolio Review will submit a proposal outlining its primary science goals for the next four years and describing how its research program will benefit the HEP science drivers described in the P5 Report. Performance factors to be assessed will include:

- Science merit and productivity (including training and mentoring of junior researchers),
- Present and anticipated future impact on the P5 science drivers, and
- Efficiency and impact of DOE-supported contributions to the research efforts.

Operations budgets and schedule information will be requested from proposers but will not be an explicit review criteria. DOE will provide additional information about DOE responsibilities and budget scenarios to the review panels.

All operating experiments (as defined above) should be comparatively assessed by a single subpanel, with suitable exceptions for the highest priority items identified in the P5 plan. Therefore, we request two subpanels be formed as follows:


1. The main subpanel: This comparative review panel will assess the scientific merits and impact of DOE-supported contributions to the following operating experiments (in alphabetical order): AMS, Daya Bay, DES, eBOSS, Fermi/GLAST, HAWC, KOTO, MicroBooNE, Minerva, NA61/SHINE, NOvA, SuperK, T2K.
2. The LHC Detectors (ATLAS, CMS) subpanel: This review panel will assess the scientific merits and impact of DOE-supported contributions to the multipurpose LHC detectors ATLAS and CMS. These detectors have been successfully operating since 2008, and other than recent modest upgrades, there have been no major changes to the initial detector configurations. Major detector upgrades for the High Luminosity phase of the LHC program (HL-LHC) are in the advanced planning stages, and U.S. groups have taken important roles in the detector upgrade projects. Given its centrality in the global HEP vision enunciated in the P5 Report, and the high priority placed on this program by HEPAP, DOE intends to support LHC operations and research through the HL-LHC era. U.S. contributions to LHC detector operations are regularly reviewed by the DOE and the NSF in a separate process. Therefore, this subpanel will focus primarily on the efficiency and impact of DOE-supported contributions to ATLAS and CMS research efforts.

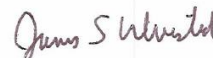
A call will be issued in parallel with this charge, along with the specific review criteria for each subpanel to consider, and proposals are expected to be due in November. The subpanels should meet expeditiously so that their final reports can be delivered to HEPAP no later than April 2018. HEPAP will review these reports and communicate its findings and recommendations to DOE.

After HEPAP makes its recommendations, DOE/HEP will contact each of the experiments and communicate guidance resulting from the HEP Portfolio Review. This direction may include new budget guidelines and other specific instructions resulting from the Portfolio Review process, possibly including notices of intent to terminate DOE involvement. DOE/HEP will also post the HEPAP subpanel reports and its response to the HEPAP website. Each of the experiments will submit back to DOE/HEP their plan for complying with the new guidance and instructions. HEP management will ensure that key officials in institutions or agencies that are partners in operating experiments are apprised of DOE's decisions resulting from the HEP Portfolio Review.

We anticipate that this review process will allow DOE the ability to periodically rebalance its HEP experimental portfolio, and adapt as needed to different budget scenarios. We feel the participation of HEPAP is critical in this important process and very much appreciate your timely consideration of these proposals. We look forward to lively and fruitful discussions of this topic at future HEPAP meetings.

Sincerely,


J. Stephen Binkley
Acting Director
Office of Science


James S. Ulvestad
Assistant Director (Acting)
Mathematical and Physical Sciences
National Science Foundation

Appendix II Subpanel membership

Robert Cahn	Lawrence Berkeley National Laboratory
Robert Cousins	University of California, Los Angeles
Paul Grannis (chair)	Stony Brook University
Francis Halzen	University of Wisconsin
Daniel Marlow	Princeton University
James Matthews	Louisiana State University
Irina Mocioiu	Pennsylvania State University
Ritchie Patterson	Cornell University
Jack Ritchie	University of Texas, Austin
Abraham Seiden	University of California, Santa Cruz
David Sinclair	Carleton University
Christopher Stubbs	Harvard University
Karl van Bibber	University of California, Berkeley
James Wells	University of Michigan
Andrew Lankford	University of California, Irvine (HEPAP chair, ex officio)

Appendix III Meeting 1 Agenda

duration	start	
0:15	8:30	Introduction
0:45	8:45	Guidance from HEP
0:45	9:30	Discussion of subpanel process
0:30	10:15	break
0:45	10:45	NOvA
0:45	11:30	T2K
1:00	12:15	lunch
0:45	13:15	SuperK
0:45	14:00	Daya Bay
0:45	14:45	MicroBoone
0:30	15:30	break
0:45	16:00	Minerva
0:45	16:45	NA61/Shine
0:45	17:30	KOTO
0:30	18:15	Executive session
	18:45	adjourn

Friday Feb. 23

duration	start	
0:45	8:15	DES
0:45	9:00	eBOSS/SDSS4
0:45	9:45	AMS
0:30	10:30	break
0:45	11:00	Fermi/Glast
0:45	11:45	HAWC
1:00	12:30	lunch
3:00	13:30	subgroup meetings
0:15	16:30	break
1:30	16:45	full subpanel meeting
	18:15	adjourn

Saturday Feb. 24

duration	start	
2:00	8:00	full subpanel meeting
0:30	10:00	break
2:00	10:30	full subpanel meeting
0:30	12:30	lunch
1:30	13:00	adjourn

Appendix IV Acronyms

BAO – Baryon Acoustic Oscillations (a cosmological distance ruler)

BOSS - Baryon Oscillation Spectroscopic Survey (predecessor to eBOSS in the SDSS project)

BR – branching ratio

C – Carbon

CCD – charge coupled device

CH – Carbon Hydrogen (the approximate chemical composition of plastic scintillator)

CKM – Cabibbo Kobayashi Maskawa matrix describing the transformation of the weak and strong interaction quark states

CMB – Cosmic Microwave Background

CP – the combined symmetry transformations of C=charge conjugation (particles to antiparticles) and P=parity (reflection of spatial coordinates)

CTA – Cherenkov Telescope Array (a future large telescope project to detect high energy cosmic gamma rays)

DAQ – data acquisition

DE – dark energy

deg – degrees

DESI – Dark Energy Spectroscopic Instrument (a future spectroscopic telescope project to probe distant galaxies)

DM – dark matter

DUNE – Deep Underground Neutrino Experiment (a future experiment to study oscillations of neutrinos travelling from Fermilab to South Dakota)

eV – electron volt (the energy gained by an electron falling through a 1V potential difference)

Fe – Iron

FTE – full time equivalents

GBM – Gamma Burst Monitor on the Fermi/Glast satellite

Gd – Gadolinium

GEANT4 – A Monte Carlo program used for simulating physical processes in detectors

GeV – 1 billion eV

GR – general relativity

He – Helium

HEP – the Office of High Energy Physics within the DOE Office of Science

HEPAP – High Energy Physics Advisory Panel to DOE and NSF

HESS – the High Energy Stereoscopic System (telescope array for high energy cosmic gamma rays in Namibia)

HyperK – A proposed large water Cherenkov detector to follow SuperK in Japan

ICARUS – the first LAr TPC detector, originally operated in the Gran Sasso Lab in Italy, now moved to the Fermilab Booster Neutrino Beam

ISS – International Space Station

J-PARC – Japan Proton Accelerator Research Complex in Tokai Japan

LAr – liquid Argon

Λ CDM – a favored model of the big bang cosmology with Cold Dark Matter and a cosmological constant (Λ)

LIGO - Laser Interferometer Gravitational-Wave Observatory (two gravity wave detectors in Louisiana and Washington states)

LRG – luminous red galaxies

LSND - Liquid Scintillation Neutrino Detector (a previous low energy neutrino detector at Los Alamos National Lab)

LSST – Large Synoptic Survey Telescope (a future project in Chile that will study DE)

MAGIC - Major Atmospheric Gamma Imaging Cherenkov Telescope (operating in the Canary Islands)

meV – 1 thousandth of an eV

MeV – 1 million eV

MiniBooNE – neutrino experiment in Fermilab, predecessor of MicroBooNE

Mpc – mega parsec (about 3.26 million light years)

neV – 1 billionth of an eV

NuMI – the Neutrinos from the Main Injector beam line at Fermilab

P5 - Particle Physics Project Prioritization Panel (subpanel of HEPAP)

PAC – Program Advisory Committee

Pb – Lead

Planck – European Space Agency project to study the cosmic microwave background

POT – protons on target

RSD – redshift distortions

S/B – signal to background ratio

SBND – Short Baseline Near Detector (to be installed in the Booster Neutrino Beam at Fermilab)

SDSS – Sloan Digital Sky Survey at Apache Point, Arizona

SES - single event sensitivity

SM – Standard Model of particle physics

SNe1a – supernovae type 1a

TeV – 1 trillion eV

TOF – time of flight

TPC – time projection chamber

U – Uranium (the fissile U^{235} isotope is used as reactor fuel)

Veritas - Very Energetic Radiation Imaging Telescope Array System for cosmic gamma ray observations in Arizona

WIMP – weakly interacting massive particle, a favored class of DM particles