Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

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Large Infrastructures
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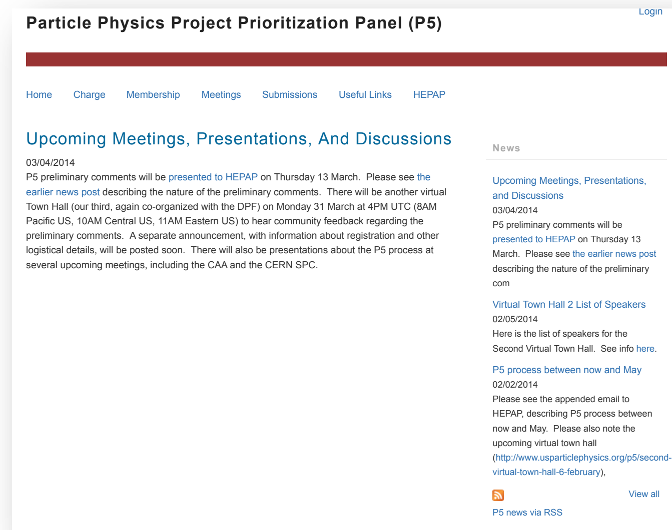
A very dedicated, hardworking panel!

Summary of P5 Process

- Continuous effort to maximize community interactions
- Three big, open, topical meetings.
  - Four additional panel face-to-face meetings.
  - Community Town Halls and Discussions. Input portal.
- Project data collection
- Peer review of report draft



http://interactions.org/p5

HEPAP unanimously accepted the report on 22 May 2014

- Internal deliberations worked by consensus.
- No topic or option was off the table. Every alternative we could imagine was considered.

Science Drivers

- We distilled the eleven groups of physics questions from Snowmass* into five compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years.
- The Science Drivers:
  - **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 Drivers are deliberately not prioritized because they are intertwined, probably more deeply than is currently understood.
- A selected set of different experimental approaches that reinforce each other is required. Projects are prioritized.
- The vision for addressing each of the Drivers using a selected set of experiments – their approximate timescales and how they fit together – is given in the report.

* See Appendix D and http://www.slac.stanford.edu/econf/C1307292/

Particle Physics is Global

- The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere.
  - Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a global vision.
- Strong foundations of international cooperation exist, with the Large Hadron Collider (LHC) at CERN serving as an example of a successful large international science project.
- Reliable partnerships are essential for the success of international projects. This global perspective is finding worldwide resonance in an intensely competitive field.
  - The 2013 *European Strategy for Particle Physics* report focuses at CERN on the Large Hadron Collider (LHC) program and envisions substantial participation at facilities in other regions.
  - Japan, following its 2012 *Report of the Subcommittee on Future Projects of High Energy Physics*, expresses interest in hosting the International Linear Collider (ILC), pursuing the Hyper-Kamiokande experiment, and collaborating on several other domestic and international projects.

Summary (1/2)

- A vision that starts from the science Drivers, driven by community discussions and inputs, with criteria to make tough choices and develop a program.
- The enormous physics potential of the LHC, entering a new era with its planned high-luminosity upgrades, should be fully exploited.
- The U.S. should host a world-leading neutrino program.
  - An optimized set of short- and long-baseline neutrino oscillation experiments, with the long-term focus on the Long Baseline Neutrino Facility (LBNF).
  - The Proton Improvement Plan (PIP-II) project at Fermilab would provide the needed neutrino physics capability.
- Large projects are ordered by peak construction time: the Mu2e experiment completion, the high-luminosity LHC upgrades, and LBNF.
  - Based on budget constraints, physics needs, and readiness.
- The interest expressed in Japan in hosting the International Linear Collider (ILC) is an exciting development.
  - Participation by the U.S. in project construction depends on a number of important factors, some of which are beyond the scope of P5 and some of which depend on budget Scenarios.
  - As the physics case is extremely strong, all Scenarios include ILC support at some level through a decision point within the next 5 years.

Summary (2/2)

- Medium and small projects in areas especially promising for near-term discoveries and in which the U.S. is in a leadership position, should move forward under all budget scenarios.
  - Second- and third-generation dark matter direct detection experiments, the particle physics components of the Large Synoptic Survey Telescope (LSST) and cosmic microwave background (CMB) experiments, and a portfolio of small neutrino experiments.
  - Another important project of this type, the Dark Energy Spectroscopic Instrument (DESI), would also move forward, except in the lowest budget Scenario.
- With a mix of large, medium, and small projects, important physics results will be produced continuously throughout the twenty-year P5 timeframe.
  - In our budget exercises, we maintained a small projects portfolio to preserve budgetary space for a set of projects whose costs individually are not large enough to come under direct P5 review but which are of great importance to the field.
  - This is in addition to the aforementioned small neutrino experiments portfolio, which is intended to be integrated into a coherent overall neutrino program.
- Specific investments should be made in essential accelerator R&D and instrumentation R&D. The field relies on its accelerators and instrumentation and on R&D and test facilities for these technologies.

Neutrino Oscillation Experiments (Program)

- Short- and long-baseline oscillation experiments directly probe three of the questions of the neutrino science Driver:
  - How are the neutrino masses ordered? Do neutrinos and antineutrinos oscillate differently? Are there additional neutrino types and interactions?
- There is a vibrant international neutrino community invested in pursuing the physics of neutrino oscillations.
- The U.S. has unique accelerator capabilities at Fermilab to provide neutrino beams for both short- and long-baseline experiments, with some experiments underway, and a long-baseline site is available at the Sanford Underground Research Facility in South Dakota.
- Many of these current and future experiments and projects share the same technical challenges. Interest and expertise in neutrino physics and detector development of groups from around the world combined with the opportunities for experiments at Fermilab provide the essentials for an international neutrino program.

- **Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.**

Long Baseline Neutrino Facility (LBNF)

- The long-baseline neutrino program plan has undergone multiple significant transformations since the 2008 P5 report. Formulated as a primarily domestic experiment, the minimal CD-1 configuration with a small, far detector on the surface has very limited capabilities.
- A more ambitious long-baseline neutrino facility has also been urged by the Snowmass community study and in expressions of interest from physicists in other regions.
- To address even the minimum requirements specified above, **<u>the expertise and resources of the international neutrino community are needed.</u>**

- **A change in approach is therefore required**: The activity should be reformulated under the auspices of a new international collaboration, as an internationally coordinated and internationally funded program, with Fermilab as host. There should be international participation in defining the program's scope and capabilities. The experiment should be designed, constructed, and operated by the international collaboration. The goal should be to achieve, and even exceed if physics eventually demands, the target requirements through the broadest possible international participation.

Neutrino Oscillation Experiments (LBNF Requirements)

- For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}.
  - By current estimates, this corresponds to an exposure of 600 kt*MW*y assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector.
- **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

These minimum requirements are not met by the current LBNE project's CD-1 minimum scope.

Neutrino Oscillation Experiments (LBNF Recommendation)

- Key preparatory activities will converge over the next few years: in addition to the international reformulation described above, PIP-II design and project definition will be nearing completion, as will the necessary refurbishments to the Sanford Underground Research Facility. Together, these will set the stage for the facility to move from the preparatory to the construction phase around 2018. The peak in LBNF construction would occur after HL-LHC peak construction.

- **Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.**

Budget Scenario C ("Unconstrained")

- The U.S. could move boldly toward development of transformational accelerator R&D.
  - Change the capability-cost curve of accelerators.
  - Newly formed HEPAP Subcommittee on Accelerator R&D to provide detailed roadmap.
  - As work proceeds worldwide on long-term future-generation accelerator concepts, the U.S. should be counted among the potential host nations.
- Should the ILC go forward, Scenario C would enable the U.S. to play major roles in the detector program as well as provide critical expertise and accelerator components.
- The U.S. could offer to host a large water Cherenkov neutrino detector to complement the LBNF liquid argon detector
  - Take full advantage of the world's highest intensity neutrino beam. This approach would be an excellent example of global cooperation and planning.

Thanks!

- Our community's passion, dedication, and entrepreneurial spirit have been inspirational.
- To our colleagues across our country and around the world, we say a heartfelt thank you. Every request we made received a thoughtful response, even when the requests were substantial and the schedules tight. A large number of you submitted inputs to the public portal, which we very much appreciated.

The report includes 29 recommendations. Only the main points can be summarized here, so please read the full report for the important details.

Discussion

Additional Slides

Table 1
Summary of Scenarios

Project/Activity	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
	Scenarios			Science Drivers					
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

Project/Activity	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
	Scenarios			**Science Drivers**					
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

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Figure 1
Construction and Physics Timeline

FIGURE 1 Approximate construction (blue; above line) and expected physics (green; below line) profiles for the recommended major projects, grouped by size (Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly.

Additional Project Concepts

- Concepts to address various aspects of neutrino oscillation physics via alternative approaches were considered, including
  - RADAR
  - CHIPS
  - DAEδALUS and IsoDAR
  - LAr1
  - PINGU
  - NuSTORM
- These cannot go forward as major projects at this time, due to concept maturity and/or program cost considerations. However, further development of PINGU is recommended, and IsoDAR (precursor to DAEδALUS) should be considered in the context of a short-baseline oscillation program.
- Similarly, P5 heard presentations about several other concepts for projects whose ultimate construction scope would be large but whose near-term request for R&D funding is small. These include the Storage Ring Proton EDM Experiment and NNbarX, both of which address P5 Drivers. Development has not yet advanced to a point at which it would be possible to consider recommendations to move forward with any of these projects. The R&D for these projects would fit as candidates in the small projects portfolio, with the path to eventual implementation presumably being among the evaluation criteria.

Neutrino Oscillation Experiments (Concepts)

- RADAR and CHIPS are both ideas for new detectors exploiting the existing NuMI beamline to improve knowledge of oscillation parameters. The RADAR proposal is to build a liquid argon TPC at the Ash River site, thereby offsetting R&D costs for LBNF. CHIPS proposes a large water Cherenkov detector in a water-filled mine pit, first at a NuMI off-axis location, and possibly later as an off-axis LBNF detector. Although one might gain some incremental sensitivity beyond NOvA and T2K in the shorter term with RADAR or CHIPS, the CP and mass hierarchy reach is reduced compared to that of the LBNF configuration, and these experiments are less capable for proton decay, atmospheric neutrinos, and SN burst neutrinos. A strategy focusing resources on moving ahead as fast as possible on LBNF is therefore favored.

- DAEδALUS is a different approach to the measurement of δ_{CP}, using multiple high-power cyclotrons to generate a large neutrino flux from pion decay-at-rest at a large water Cherenkov or liquid scintillator detector. The concept still requires significant development, and a suitable large-detector target has not yet been selected. IsoDAR is a proposed precursor phase to DAEδALUS with a well-defined short-baseline neutrino-oscillation physics program using cyclotron-produced ^{8}Li decay at rest. IsoDAR should be considered in the context of a short-baseline oscillation program.

MAP

- Neutrino factories based on muon storage rings could provide higher intensity and higher quality neutrino beams than conventional high power proton beams on targets. This concept would be attractive for an international long-baseline neutrino program offering more precise and complete studies of neutrino physics beyond short-term and mid-term facilities.
- Muon colliders can reach higher energies than e^+e^- accelerators, but have many technical challenges. Addressing all of the necessary challenges would require a very strong physics motivation based on results from ongoing or future accelerators.
- The **Muon Accelerator Program (MAP)** currently aims at technology feasibility studies for far-term muon storage rings for neutrino factories and for muon colliders, including the **Muon Ionization Cooling Experiment (MICE)** at the Rutherford Appleton Laboratory.
- The large value of $\sin^2(2\theta_{13})$ enables the next generation of oscillation experiments to use conventional neutrino beams, pushing the time frame when neutrino factories might be needed further into the future, and the small Higgs mass enables study at more technically ready e+e- colliders, reducing the near-term necessity of muon colliders.

- **Recommendation 25: Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.**

Neutrino Oscillation Experiments (Concepts)

- LAr1 is a mid-scale short-baseline accelerator-based experiment to address both the neutrino and anti-neutrino SBL anomalies. An appropriate combination of smaller near-term projects may accomplish most of these goals at much lower cost, so proceeding with LAr1 is not recommended at this time.

- PINGU, an infill array concept at the IceCube facility, may also have the interesting potential to determine the neutrino mass hierarchy using atmospheric neutrinos sooner than other competing methods, as well as have sensitivity to low-mass WIMP dark matter. The details of the experiment are still under development, and we encourage continued work to understand systematics. PINGU could play a very important role as part of a larger upgrade of IceCube, or as a separate upgrade, but more work is required.

- NuSTORM is a proposal for a small muon storage ring to produce ~GeV neutrinos and antineutrinos with the advantage of a precisely known flux. The facility would also serve as an intense source of low-energy muons and serve as a technology demonstrator for a future neutrino factory. The physics reach of this program includes sensitive sterile neutrino searches and precision neutrino cross-section measurements. Although the concept is attractive as a first step towards a neutrino factory and as a means to reduce the beam-related systematic errors for LBNF, the high cost makes it impossible to pursue at the same time as PIP-II and LBNF, which are the primary objectives.

Neutrino Oscillation Experiments (PIP-II)

- The PIP-II project at Fermilab is a necessary investment in physics capability, enabling the world's most intense neutrino beam, providing the wideband capability for LBNF, as well as high proton intensities for other opportunities, and it is also an investment in national accelerator laboratory infrastructure. The project has already attracted interest from several potential international partners.
- **Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.**

Neutrino Oscillation Experiments (Short Baseline)

- Hints from short-baseline experiments suggest possible new non-interacting neutrino types or non-standard interactions of ordinary neutrinos. These anomalies can be addressed by proposed experiments with neutrinos from radioactive sources, pion decay-at-rest beams, pion and kaon decay-in-flight beams, muon-decay beams, or nuclear reactors.
- A judiciously selected subset of experiments can definitively address the sterile-neutrino interpretation of the anomalies and potentially provide a platform for detector development and international coordination toward LBNF.
    - These small-scale experiments are in addition to the small projects portfolio described above.
    - The short-term short-baseline (SBL) science and detector development program and the long-term LBNF program should be made as coherent as possible in an optimized neutrino program.
- **Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.**

Program-wide Recommendations (Building)

- Unlike other regions in the world, in recent years the U.S. particle physics program has not invested substantially in construction of experimental facilities. Addressing the Drivers in the coming and subsequent decades requires renewed investment in projects. In constant or near-constant budgets, this implies an increase in the fraction of the budget that is invested in new projects, which is currently approximately 16% (and was even lower before).

- **Recommendation 5: Increase the budget fraction invested in construction of projects to the 20%–25% range.**

- This represents a large commitment to building new experiments, which we see as essential. Increasing the project fraction would necessarily entail judicious reductions in the fractions of the budget invested in the research program and operations. (The three main budget categories are project construction, the research program, and operations.)

- In addition, for the research program, which has seen reductions in recent years, flat-flat budgets are substantially detrimental over time due to escalation of real costs. To limit reductions in research program funding, we adopted a guideline that its budget fraction should be >40% in our budget planning exercises.

March Preliminary Comments Presentation

Topics

- Review of the key elements of the charge; summary of P5 processes and activities since September
- Context:
  - The evolution of our field since the previous P5 report
  - Big scientific questions and drivers
  - The global nature of our field
- Key elements of strategic planning:
  - Opportunities to address the big scientific questions and how they fit together
  - Budgetary constraints compared with proposed programs
  - National planning in the global context
  - Balancing investments
- Discussion of prioritization criteria
- Steps to completion, and communication planning

March 2014 2

Discussed at length:

- **The 5 Science Drivers**
- **Global vision**
- **Criteria**
- **Budget scenario challenges**
- **Ongoing community interactions**

Recall, the Charge specifies three budget scenarios, with ten-year profiles:

A. *FY2013 budget baseline: flat for 3 years, then +2% per year.*
B. *FY2014 President's budget request baseline: flat for 3 years, then +3% per year.*
C. *Unconstrained:* projects *"…needed to mount a leadership program addressing the scientific opportunities…"*

Difference between scenarios integrated over the decade is ~$0.5B.

"…consider these scenarios not as literal budget guidance but as an opportunity to identify priorities and make high-level recommendations."

Scenarios B and A

- Scenario B allows for a balanced program
- The two constrained budget Scenarios differ by approximately $30M per year until FY2018, and thereafter have a one percent escalation difference. The return on the incremental investment would be very large:
  - DESI would yield scientific returns with high impact.
  - World-leading accelerator and instrumentation development research would be retained.
  - US. research capability would be maintained, including a thriving theory program.
  - The Muon-to-electron Experiment (Mu2e) at Fermilab would be completed on time.
  - The long-baseline neutrino program would proceed without delays.
  - Third-generation dark matter direct detection capabilities would be fully developed on time.
- As valuable as each of these items is, they simply do not fit in Scenario A.

Scenario A

- The lowest budget Scenario is precarious: it approaches the point beyond which hosting a large ($1B scale) project in the U.S. would not be possible while maintaining the other elements necessary for mission success.
- Without the capability to host a large project, the U.S. would lose its position as a global leader in this field, and the international relationships that have been so productive would be fundamentally altered.

Multidisciplinary Aspects

- Multidisciplinary connections are of great importance to particle physics. For example, the study of the particle physics of dark energy and inflation is performed by astrophysical techniques employing the detector technologies and computing techniques of particle physics. The research can also provide information on neutrino properties.
- In a different manner, studies traditionally carried out by nuclear physics to determine if the neutrino is its own antiparticle inform the particle physics campaign to address the neutrino science Driver.
- The support from different agencies, linked by the multidisciplinary nature of the science, enables new capabilities of mutual benefit.
- For multidisciplinary projects that receive particle physics funding, our criteria include a check that the distribution of support reflects the distribution of anticipated science topics and that particle physicist participation is necessary for project success. Similar criteria were developed and used by the 2009 PASAG panel.