Building for Discovery

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

Report of the Particle Physics Project Prioritization Panel (P5)

Nuclear Science Advisory Committee
30 June 2014

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Charge to P5

A strategic plan, executable over 10 years, in the context of a 20-year global vision

Contains 3 budget scenarios for consideration

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

A. **FY2013 budget baseline: flat for 3 years, then +2% per year** (728M)

B. **FY2014 President's budget request baseline: flat for 3 years, then +3% per year** (758M)

C. **"Unconstrained" budget scenario**

Beyond A and B, prioritize projects "… needed to mount a leadership program addressing the scientific opportunities identified by the research community."

Identify opportunities.

Panel Composition

Members chosen for their combination of expertise and broad view of field

- **Solicited nominations widely; ~800 nominations, for ~400 individuals**
- **Consulted widely, including with P5 Chair, agencies**

Composition intended to cover range of expertise & roughly reflect demographics of field

Size chosen as optimal for efficacy, considering above

Steve Ritz (UCSC) - **chair**
Marty Briedenbach (SLAC)
Bob Cousins (UCLA)
Andre de Gouvea (Northwestern)
Marcel Demarteau (ANL)
Scott Dodelson (FNAL/Chicago)
Jonathan Feng (UCI)
Bonnie Fleming (Yale)
Fabiola Gianotti (CERN)
Francis Halzen (Wisconsin)
JoAnne Hewett (SLAC)
Wim Leemans (LBNL)
Joe Lykken (FNAL)
Dan McKinsey (Yale)
Lia Merminga (TRIUMF)
Toshinori Mori (Tokyo)
Tatsuya Nakada (Lausanne)
Steve Peggs (BNL)
Saul Perlmutter (Berkeley)
Kevin Pitts (Illinois)
Kate Scholberg (Duke)
Rick van Kooten (Indiana)
Mark Wise (Caltech)
Andy Lankford (UCI) **– *ex officio***

A year-long community-wide study preceded P5

Community-driven (APS DPF)

Goal: Identify compelling HEP science opportunities over an approximately 20-yr time frame

Not a prioritization, but made some scientific judgments

Deliverables:

"White papers"

Input to working group write-ups

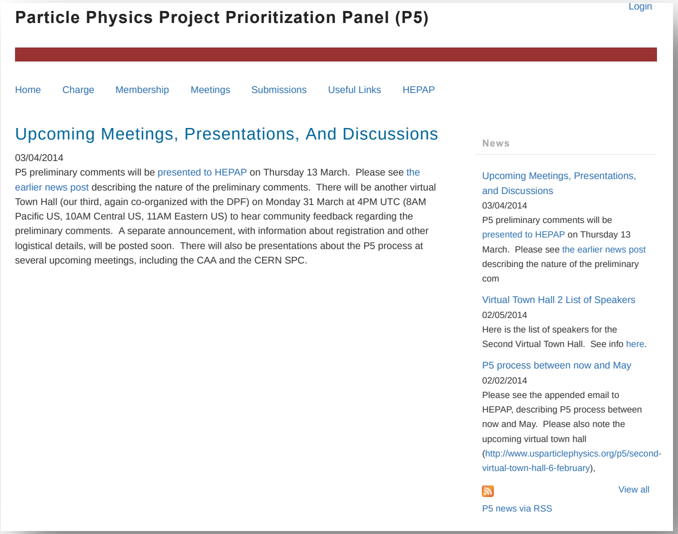
Report:

- ***7x* 30-page group write-ups**
  + theory report
  w/ executive summaries input to overview
- **30-page Overview**

Served as invaluable input, the departure point for P5

Summary of P5 Process

- All info available on P5 website, frequently updated with News (RSS and Twitter feeds)
- Meetings:
  - Face-to-face
    - 3 big open topical meetings
    - 4 additional P5 F2F's
  - Phone meetings ~ weekly
- Project data was collected
- Continuous effort to maximize community interactions, including:
  - Numerous emails, outreach to young physicists
  - Town halls at each open meeting
  - 3 "virtual town hall meetings"
  - Public submissions portal
  - Many discussions and consultations
- Peer review of report draft



Particle Physics Project Prioritization Panel (P5)

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Upcoming Meetings, Presentations, And Discussions

03/04/2014

P5 preliminary comments will be presented to HEPAP on Thursday 13 March. Please see the earlier news post describing the nature of the preliminary comments. There will be another virtual Town Hall (our third, again co-organized with the DPF) on Monday 31 March at 4PM UTC (8AM Pacific US, 10AM Central US, 11AM Eastern US) to hear community feedback regarding the preliminary comments. A separate announcement, with information about registration and other logistical details, will be posted soon. There will also be presentations about the P5 process at several upcoming meetings, including the CAA and the CERN SPC.

News

Upcoming Meetings, Presentations, and Discussions
03/04/2014
P5 preliminary comments will be presented to HEPAP on Thursday 13 March. Please see the earlier news post describing the nature of the preliminary com

Virtual Town Hall 2 List of Speakers
02/05/2014
Here is the list of speakers for the Second Virtual Town Hall. See info here.

P5 process between now and May
02/02/2014
Please see the appended email to HEPAP, describing P5 process between now and May. Please also note the upcoming virtual town hall (http://www.usparticlephysics.org/p5/second-virtual-town-hall-6-february),

View all

P5 news via RSS

http://interactions.org/p5

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

HEPAP unanimously accepted the report on 22 May 2014

Criteria

Criteria were established to guide the prioritization process.

Program optimization criteria

- Science
- International context
- Sustained productivity

Individual project criteria

- Science
- Timing
- Uniqueness
- Cost vs. value
- History and dependencies
- Feasibility
- Roles

Particle Physics is a Global Field for Discovery

- The scientific program required to address all of the most compelling questions of the field is beyond the finances and technical expertise of any one nation or region.
- 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 historically competitive field.
  - 2013 *European Strategy for Particle Physics* report
  - Japan, following its 2012 *Report of the Subcommittee on Future Projects of High Energy Physics*,
- **Recommendation 1: Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.**

The Science Drivers

- P5 distilled the 11 groups of physics questions from Snowmass into 5 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 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 is given in the report, along with their approximate timescales and how they fit together.

- **Recommendation 2: Pursue a program to address the 5 science Drivers.**

Pursue the physics associated with neutrino mass

The report recognizes the diversity of the neutrino research program.

It identifies 6 essential questions:

- **What is the origin of neutrino mass?**
- **How are the neutrino masses ordered?**
  - Oscillation experiments
- **What are the neutrino masses?**
  - Beta-decay spectrum
  - Cosmic surveys
- **Do neutrinos and anti-neutrinos oscillate differently?**
- **Are there additional neutrino types and interactions?**
  - Oscillation experiments
  - Cosmic surveys
- **Are neutrinos their own antiparticles?**
  - Neutrinoless double-beta decay

Explore the unknown:

New particles, interactions, and physical principles

Clear indicators of physics beyond the Standard Model invite exploration.

A broad-based strategy of search:

- **High energy colliders**
- **Precision physics and rare processes**
  - Baryon number violation
  - Lepton number violation
  - Muon anomalous magnet moment
  - Electric dipole moments
- **Cosmic particles**
  - Supernova neutrinos
- **Low-mass “hidden sector” particles**

examples

Principal features of the strategic plan (1/2)

- A vision that starts from the science Drivers, driven by community discussions and inputs, with criteria to guide project selection and develop a program.
- **Large projects are ordered by peak construction time:**
  - **Mu2e & g-2, high-luminosity LHC upgrades, LBNF**.
  - Order based on budget constraints, physics needs, and readiness.
  - **Enormous physics potential of the LHC should be fully exploited**, as it enters a new era with its planned high-luminosity upgrades,.
  - **U.S. should host an international 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.
  - **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.

Principal features of the strategic plan (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 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?

  (Note that neutrino cross-section measurements are important to oscillation program)
- 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.**

Neutrino Oscillation Program - Recommendations

Recommendation 12: **Neutrino oscillation program**

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

Recommendation 13: **Long-baseline neutrino facility**

- 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.

Recommendation 14: **Proton Improvement Plan II**

- 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.

Recommendation 15: **Short-baseline neutrino experiments**

- 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 FNAL.

Neutrinoless Double-Beta Decay

Are neutrinos their own antiparticles? – one of the essential questions associated with the physics of neutrino mass

The questions and experiments are of "the greatest interest to particle physics".

Included in Recommendations section of the report:

Experiments that can provide essential information to particle physics are sometimes hosted by U.S. agencies other than the U.S. particle physics funding agencies (DOE-HEP, NSF-PHY).

An important example is provided by neutrinoless double-beta decay experiments,

- **which address one of the most significant questions in the neutrino Driver and**
- **which are stewarded in the U.S. by the DOE Office of Nuclear Physics, with construction contributions also from NSF Particle Astrophysics.**

Modest levels of support by the U.S. particle physics funding agencies for particle physicist participation in such experiments, as well as in experiments hosted by other nations without major U.S. construction investments, can be of great mutual benefit.

Recommendation 9: Funding for participation of U.S. particle physicists in experiments hosted by other agencies and other countries is appropriate and important

- **but should be evaluated in the context of the Drivers and the P5 Criteria and**
- **should not compromise the success of prioritized and approved particle physics experiments.**

Small Projects Portfolio

Small-scale experiments can address many questions related to the Drivers.

These experiments combine timely physics with:

- opportunities for a broad exposure to new experimental techniques,
- leadership roles for young scientists,
- partnerships among universities and national labs.

In our budget exercises, we maintained **a small projects portfolio** to preserve budgetary space for a number of these important small projects,

- Costs typically less than $20M.
- Projects individually not large enough to come under direct P5 review.
- Not an explicit budget line!

Many “explore the unknown” experiments fall in the small projects portfolio.

Small investments in large, multidisciplinary projects, as well as early R&D for some project concepts, were also accounted for here.

Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.

Explore the unknown - 2

Baryon number violation

- Nucleon instability
  - Report calls for a significant improvement in discovery sensitivity over current searches for proton decay as a requirement for LBNF.

- Neutron-antineutron oscillation
  - NNbarX as an example – concept with large construction scope but small near-term R&D request -> small project portfolio

Charged lepton number violation

- Muon-to-electron conversion:
  - Mu2e project recommended for completion.

- Tau lepton decays: LHCb & Belle II -> small projects portfolio

Explore the unknown - 3

Muon anomalous magnetic moment (g-2)

- g-2 at Fermilab recommended for completion

Electric Dipole Moments (EDM's)

- Extremely sensitive probe of new physics that does not conserve CP
- Considerable discussion at Snowmass
- Storage Ring Proton EDM experiment (Fermilab) – concept with large construction scope but small near-term R&D request -> small project portfolio

Supernova neutrinos

- Report calls for a demonstrated capability to search for supernova bursts as a requirement for LBNF.
- (LBNF liquid-argon neutrino detector will be sensitive to neutrinos, as opposed to anti-neutrinos.)

Low-mass hidden-sector particles

- *E.g*. dark photons -> small project portfolio

Improvements to Fermilab proton complex will improve future capabilities.

Accelerator R&D

Advances in particle physics require advances in accelerator technology,
which demands an aggressive, sustained, and imaginative R&D program.
Experience suggests this R&D will also have large, positive impacts beyond particle physics.

Recommendation 23:
Support the discipline of accelerator science
through advanced accelerator facilities and
through funding for university programs.
Strengthen national laboratory-university R&D partnerships,
leveraging their diverse expertise and facilities.
(This recommendation has important workforce development implications.)

Recommendation 26:
Pursue accelerator R&D with high priority
at levels consistent with budget constraints.
Align the present R&D program with the P5 priorities and long-term vision,
with an appropriate balance among
generic R&D, directed R&D, and accelerator test facilities
and among short-, medium-, and long-term efforts.
Focus on outcomes and capabilities that will dramatically improve cost-effectiveness for mid-term and far-term accelerators.

Significant Changes in Direction

- Increase investment in construction.
  - In constrained scenarios, this implies increased <u>fraction</u> of budget toward construction.
- Reformulate the long-baseline neutrino program as an internationally designed and funded program, with Fermilab as host.
- Upgrade the Fermilab proton accelerator complex to produce the world’s most powerful neutrino beam
  - redirecting Project-X activities & some existing accelerator R&D
- Proceed immediately with a broad second-generation (G2) dark matter direct detection program.
  - Invest at level significantly above that called for in 2012 joint agency announcement.
- Provide increased particle physics funding of CMB research & projects,
  - as part of the core particle physics program, in context of multiagency partnerships.
- Re-align activities in accelerator R&D, which is critical to enabling future discoveries, based on new physics information and on long-term needs.
  - Reassess the Muon Accelerator Program (MAP), and consult with international partners on the early termination of MICE (Muon Ionization Cooling Experiment).
  - In the general accelerator R&D program, focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid- and far-term accelerators.

The Report

Short (~60 pp)

- Science opportunities amply and ably documented in Snowmass reports

Outline

- Executive Summary (2.2 pp)
- Introduction (5 pp)
  - Particle Physics is Global
  - Summary of Drivers & Opportunities
  - Criteria
- Recommendations (14 pp)
  - Program-wide Recommendations (9)
  - Project-specific Recommendations (20)
  - Summary of changes in direction
  - Funding Scenarios (w/ table & timeline)
  - Enabling R&D recommendations
- The Science Drivers (17 pp)
  - 5 drivers
  - Enabling R&D and Computing
- Benefits & Broader Impacts (1.5 pp)
- Appendices (14 pp)

Strategic Plan for U.S. Particle Physics

- Charge: A strategic plan, executable over 10 years, in the context of a 20-year global vision
- US community has come together to make a plan
  - Driven by the science
  - Meets fiscal constraints
  - Considers the global context
  - Resolves key issues for the field
  - Provides a continuous flow of results while making essential investments for the future

- **The report includes 29 recommendations, please read the report for the important details.**

Discussion

Additional Slides

Program optimization criteria

– **Science**:
  - Based on the Drivers, assess where we want to go and how to get there, with a portfolio of the most promising approaches.

– **International context**:
  - Pursue the most important opportunities wherever they are, and host world-leading facilities that attract the worldwide scientific community;
  - Duplication should only occur when significant value is added or when competition helps propel the field in important directions.

– **Sustained productivity**:
  - Maintain a stream of science results while investing in future capabilities, which implies a balance of project sizes;
  - Maintain and develop critical technical and scientific expertise and infrastructure to enable future discoveries.

Individual project criteria

- **Science:**
  - How the project addresses key questions in particle physics,
  - The size and relevance of the discovery reach,
  - How the experiment might change the direction of the field
  - The value of null results.
- **Timing**:
  - When the project is needed,
  - How it fits into the larger picture.
- **Uniqueness**:
  - What the experiment adds that is unique and/or definitive, & where it might lead.
  - Consider the alternatives.
- **Cost vs. value**:
  - Scope should be well defined and match the physics case.
  - For multidisciplinary/agency projects, distribution of support should match the distribution of science.
- **History and dependencies**:
  - Previous prioritization, existing commitments, and impacts of changes in direction.
- **Feasibility**:
  - Consider the main technical, cost, and schedule risks of the proposed project.
- **Roles**:
  - U.S. particle physics leadership, or participation, criticality, as well as other benefits of the project.

Roles of P5, HEPAP, Agencies

- P5 provides the science drivers and recommended strategic priorities, particularly project priorities .
- HEPAP is the "keeper" of the plan and reviews implementation and progress.
- The agencies, as the stewards of the program, receive the advice and try to implement the plan as best they can with the actual budgets.

- I believe that the agencies understand our report and recommendations and are taking it on board.
- DOE is already taking steps to implement recommendations, which will affect FY2015 (starting in Oct 2014) allocation of funds.

Recent P5 Activities

- (ongoing) many consultations and discussions with community members and leaders of projects and activities in other regions
- 27 May: 90-minute briefing at the Executive Office of the President (OSTP/OMB, including the examiners for NSF and DOE and agency representatives). They were very engaged and interested.
- 28 May: Secretary Moniz briefing (30 minutes)
- 29 May: briefing and discussion with the APS Physics Policy Council. Speakers were Ritz, Lankford, and Lockyer. APS President Mac Beasley sent testimony in support of HEP for our hearing on 10 June (see below).
- 2 June: Community presentation, followed by further discussions in various venues.
- 5 June: Senate Energy and Natural Resources briefing. Pushpa is writing a summary. There were also statements of support read by Jonathan Bagger, Drew Baden, and Bob Wilson. Joe Lykken was also there and talked with staffers and others.
- 6 June: LHCP panel and presentations. Fabiola gave a great talk on future colliders. Dennis Overbye moderated a panel discussion (Ritz, Arkani-Hamed, Blazey, Bertolucci, Muryama, Roe). Andy and Jim then summed up.
- 8 June: CMS meeting in Tahoe.
- 10 June: House Energy subcommittee hearing. Nigel Lockyer, Natalie Roe, Persis Drell, and Steve Ritz were invited to testify.
- 11 June: FNAL Users meeting
- 12 June: U. Chicago physics department presentation, as well as additional meetings.
- 16 June: DOE PI meeting presentation and discussion
- 16-17 June: Andy will present to the CERN SPC
- 23-24 June: P5 presentation at the international neutrino meeting in Paris

- Other presentations are being planned, including NSAC, ECFA, Advanced Accelerator Workshop in July, BPA, AAAC, …

- There are also strong letters of support from APS President Beasley and other community organizations.
- Still early days, but far enough along that we can now say so far so good! Suggestions always welcome and needed, as usual.

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.***"

Table 1
Summary of Scenarios

Project/Activity	Scenarios: Scenario A	Scenario B	Scenario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
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 contributions. 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	Scenarios			Science Drivers					Technique (Frontier)
	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	
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

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.

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.

Scenario C

- 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 world-leading 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.

Neutrino Oscillation 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 Program

- 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, **the expertise and resources of the international neutrino community are needed.**

- **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.

Requirements of a long-baseline neutrino facility

- **Goal**: P5 set as the goal:
  - **mean sensitivity to CP violation of >3σ over >75% of the δ_{CP} range**
  - Based on the science Driver and what is practically achievable in a major step forward
  - By current estimates, this goal 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 **>40 kilotons (kt) of liquid argon (LAr)** and a **suitable near detector**.

- **Minimum requirements:**
  - Identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe,
  - 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.
  - Demonstrated capability to search for:
    - supernova (SN) bursts and
    - proton decay,
      - providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

Long-Baseline Neutrino Facility (LBNF)

- Key preparatory activities will converge over the next few years:
  - International reformulation,
  - PIP-II design and project definition,
  - Necessary refurbishments to 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.**

Proton Improvement Plan II (PIP-II)

- The PIP-II project at Fermilab
  - 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,
  - 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.**

Short-Baseline Neutrino Oscillation Program

- 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 & international coordination toward LBNF.
  - The short-term short-baseline 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 FNAL.**

LHC (Near-term & Mid-term High-energy Colliders)

- The enormous physics potential of the LHC, entering a new era with its planned high-luminosity upgrades, should be fully exploited.
- LHC and its upgrades,
  - The nearest-term high-energy collider,
  - A core part of the U.S. particle physics program,
  - With unique physics opportunities addressing 3 of the 5 Drivers (Higgs, New Particles, Dark Matter).
- The Phase-2 luminosity upgrade (HL-LHC)
  - Encompasses both the general-purpose experiments (ATLAS and CMS) and the accelerator;
  - Required to fully exploit the physics opportunities offered by the ultimate energy and luminosity performance of the LHC.
- U.S. contributes unique technical capabilities to both experiments and the accelerator as well as vital resources.
- US participation in the LHC continues to be a successful example of U.S. reliability in international partnerships.
  - It can serve as a stimulus and model of the great mutual benefits while further partnerships are formulated, such as for the U.S.-hosted neutrino program.
- **The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program. It should move forward without significant delay to ensure that accelerator and experiments can continue to function effectively beyond the end of this decade and meet the project schedule.**
- **Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.**

ILC (Near-term & Mid-term High-energy Colliders)

- Participation by the U.S. in ILC project construction depends on a number of key 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, we plan in all Scenarios for ILC support at some level through a decision point within the next five years.
  - If the ILC proceeds, there is a high-priority option in Scenario C to enable the U.S. to play world-leading roles.
  - Even if there are no additional funds available, some hardware contributions may be possible in Scenario B, depending on the status of international agreements at that time.
  - If the ILC does not proceed, then ILC work would terminate and those resources could be applied to accelerator R&D and advanced detector technology R&D.
- **Recommendation 11: Motivated by the strong scientific importance of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.**

Compelling scientific questions from Snowmass

1. **How do we understand the Higgs boson? What principle determines its couplings to quarks and leptons? Why does it condense and acquire a vacuum value throughout the universe? Is there one Higgs particle or many? Is the Higgs particle elementary or composite?**
2. **What principle determines the masses and mixings of quarks and leptons? Why is the mixing pattern apparently different for quarks and leptons? Why is the CKM CP phase nonzero? Is there CP violation in the lepton sector?**
3. **Why are neutrinos so light compared to other matter particles? Are neutrinos their own antiparticles? Are their small masses connected to the presence of a very high mass scale? Are there new interactions invisible except through their role in neutrino physics?**
4. **What mechanism produced the excess of matter over anti-matter that we see in the universe? Why are the interactions of particles and antiparticles not exactly mirror opposites?**
5. **Dark matter is the dominant component of mass in the universe. What is the dark matter made of? Is it composed of one type of new particle or several? What principle determined the current density of dark matter in the universe? Are the dark matter particles connected to the particles of the Standard Model, or are they part of an entirely new dark sector of particles?**
6. **What is dark energy? Is it a static energy per unit volume of the vacuum, or is it dynamical and evolving with the universe? What principle determines its value?**
7. **What did the universe look like in its earliest moments, and how did it evolve to contain the structures we observe today? The inflationary universe model requires new fields active in the early universe. Where did these come from, and how can we probe them today?**
8. **Are there additional forces that we have not yet observed? Are there additional quantum numbers associated with new fundamental symmetries? Are the four known forces unified at very short distances? What principles are involved in this unification?**
9. **Are there new particles at the TeV energy scale? Such particles are motivated by the problem of the Higgs boson, and by ideas about space-time symmetry such as supersymmetry and extra dimensions. If they exist, how do they acquire mass, and what is their mass spectrum? Do they carry new sources of quark and lepton mixing and CP violation.**
10. **Are there new particles that are light and extremely weakly interacting? Such particles are motivated by many issues, including the strong CP problem, dark matter, dark energy, inflation, and attempts to unify the microscopic forces with gravity. What experiments can be used to find evidence for these particles.**
11. **Are there extremely massive particles to which we can only couple indirectly at currently accessible energies? Examples of such particles are seesaw heavy neutrinos or GUT scale particles mediating proton decay.**

Use the Higgs boson as a new tool for discovery

- The recently discovered Higgs boson is a form of matter never before observed.
  - What principles determine its effects on other particles? How does it interact with neutrinos or with dark matter? Is there one Higgs particle or many? Is the new particle really fundamental, or is it composed of others?
  - The Higgs boson offers a unique portal into the laws of Nature, and it connects several areas of particle physics. Any small deviation in its expected properties would be a major breakthrough.

- The full discovery potential of the Higgs will be unleashed by percent-level precision studies of the Higgs properties. The measurement of these properties is a top priority in the physics program of high-energy colliders.
  - The Large Hadron Collider (**LHC)** will be the first laboratory to use the Higgs boson as a tool for discovery, initially with substantial higher energy running at 14 TeV, and then with ten times more data at the High-Luminosity LHC (**HL-LHC)**. The HL-LHC has a compelling and comprehensive program that includes essential measurements of the Higgs properties.
  - An e^+e^- collider can provide the next outstanding opportunity to investigate the properties of the Higgs in detail. The International Linear Collider (**ILC**) is the most mature in its design and readiness for construction. The ILC would greatly increase the sensitivity to the Higgs boson interactions with the Standard Model particles, with particles in the dark sector, and with other new physics. The ILC will reach the percent or sub-percent level in sensitivity.
  - Longer-term future-generation accelerators bring prospects for even better precision measurements of Higgs properties and discovery potential.

Pursue the physics associated with neutrino mass

- Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades, with a promising future of continued discovery.
- Many aspects of neutrino physics are puzzling. Powerful new facilities are needed to move forward, addressing:
  - What is the origin of neutrino mass? How are the masses ordered (referred to as mass hierarchy)? What are the masses? Do neutrinos and anti-neutrinos oscillate differently? Are there additional neutrino types or interactions? Are neutrinos their own antiparticles?
- The U.S. is well positioned to host a world-leading neutrino physics program, which includes an optimized set of short- and long-baseline neutrino oscillation experiments
  - The long-term focus is a reformulated venture referred to here as the Long Baseline Neutrino Facility (**LBNF**), an internationally designed, coordinated, and funded program with Fermilab as host.
  - LBNF would combine a high-intensity neutrino beam and a large-volume precision detector sited underground a long distance away to make accurate measurements of the oscillated neutrino properties. This large detector would also search for proton decay and neutrinos from supernova bursts.
- A powerful, wideband neutrino beam would be realized with Fermilab's **PIP-II** upgrade project, which provides very high intensities in the Fermilab accelerator complex.
- Cosmic surveys and a variety of other small experiments will also make important progress in answering these questions.

Identify the new physics of dark matter

- Astrophysical observations imply that the known particles make up only about one-sixth of the total matter in the Universe. The rest is dark matter (DM). The properties of dark matter particles, which are all around us, are largely unknown.
- Experiments are poised to reveal the identity of dark matter, a discovery that would transform the field of particle physics, advancing the understanding of the basic building blocks of the Universe. There are many well-motivated ideas for what dark matter could be, including
  - weakly interacting massive particles (WIMPs), axions, and new kinds of neutrinos.

- Direct detection experiments are sensitive to dark matter interactions with ordinary particles in the laboratory and will follow a progression from currently proposed second-generation (**DM G2**) experiments to much larger third-generation (**DM G3**) experiments.
- Indirect detection experiments, such as the **CTA** gamma-ray observatory, can spot the particle debris from interactions of relic dark matter particles in space. Cosmic surveys are sensitive to dark matter properties through their effects on the structures of galaxies.
- Experiments now at the LHC and eventually at future colliders seek to make dark matter particles in the laboratory for detailed studies.

Understand cosmic acceleration: dark energy and inflation

- With the telescopes that peer back in time and high-energy accelerators that study elementary particles, scientists have pieced together a story of the origin and evolution of the Universe. An important part of this story is the existence of two periods during which the expansion of the Universe accelerated.
    - A primordial epoch of acceleration, called inflation, occurred during the first fraction of a second of existence. The cause is unknown -- fundamentally new physics at ultra-high energies. A second distinct epoch of accelerated expansion began more recently and continues today, presumed to be driven by some kind of dark energy, which could be related to Einstein's cosmological constant, or driven by a different type of dark energy that evolves with time.

- Understanding inflation is possible by measuring the characteristics of two sets of primordial ripples: those that grew into the galaxies observed today, and gravitational waves, undulations in space and time that may have been observed just months ago by the BICEP2 telescope looking at the cosmic microwave background (CMB). Current CMB probes will lead to a **Stage 4 Cosmic Microwave Background (CMB-S4)** experiment, with the potential for important insights into the ultra-high energy physics that drove inflation.

- Understanding the second epoch requires better measurements:
    - The Dark Energy Spectroscopic Instrument (**DESI**) can determine the properties of dark energy to the percent level over the course of billions of years. The Large Synoptic Survey Telescope (**LSST**), measuring the positions, shapes, and distances of billions of galaxies, will perform many separate tests of the properties of dark energy.
    - Together, they can also probe the possibility that, instead of dark energy, new laws beyond those introduced by Einstein are responsible for the recent cosmic acceleration.

Explore the unknown: new particles, interactions, and physical principles

- There are clear signs of new phenomena awaiting discovery beyond those of the other four Drivers. Particle physics is a discovery science defined by the search for new particles and new interactions, and by tests of physical principles.

- Producing new particles at colliders:
  - Well-motivated extensions of the Standard Model predict that a number of such particles should be within reach of LHC. HL-LHC will extend the reach for new particles that could be missed by LHC. In the event that one or more new particles are already discovered during LHC running, HL-LHC experiments will be essential to reveal the identities and underlying physics of these particles.

- Detecting the quantum influence of new particles:
  - The existence of new particles that are too heavy to be produced directly at high-energy colliders can be inferred by looking for quantum influences in lower energy phenomena, using different kinds of particles as probes that are sensitive to different types of new particles and interactions. Some notable examples are a revolutionary increase in sensitivity for the transition of a muon to an electron in the presence of a nucleus **Mu2e** (Fermilab) and **COMET** (J-PARC), further studies of rare processes involving heavy quarks or tau leptons at **Belle II** (KEK) and **LHCb** (LHC), and a search for proton decay using the large neutrino detectors of the **LBNF** and proposed **Hyper-K** experiments.

- Future Opportunities:
  - In the longer term, **very high-energy e^+e^- colliders** and **very high-energy proton colliders** could extend the search for new particles and interactions, as well as enable precision studies of the Higgs boson and top quark properties . Upgrades at Fermilab (**PIP-II** and additional improvements) will offer further opportunities to detect the influence of new particles in rare processes.

Accelerator R&D – in Scenario C

- Scenario C presents 3 options. One focuses on accelerator R&D.
- The U.S. could move boldly toward development of transformational accelerator R&D.
  - There are profound questions to answer in particle physics, and recent discoveries reconfirm the value of continued investments.
  - Going much further, however, requires changing the capability-cost curve of accelerators, which can only happen with an aggressive, sustained, and imaginative R&D program.
    - A primary goal, therefore, is the ability to build the future-generation accelerators at dramatically lower cost.
    - For example, the primary enabling technology for pp colliders is high-field accelerator magnets, possibly with more advanced superconductors.
    - For e^+e^- colliders, primary goals are improving the accelerating gradient and lowering the power consumption.
    - Although these topics are R&D priorities in the constrained budget scenarios, larger investments could make these far-future accelerators technically and financially feasible on much shorter timescales.
  - A detailed vision and roadmap should be articulated by the upcoming HEPAP Subcommittee on Accelerator R&D.
  - As work proceeds worldwide on long-term future-generation accelerator concepts, the U.S. should be counted among the potential host nations.
  - Experience suggests this effort will also have large, positive impacts beyond particle physics.

Rolling out the report

- **Report presented publicly and approved by HEPAP on May 22nd.**
- **Roll out in Washington: Reception has been good.**
  - From Secretary of Energy to DOE Office of HEP
  - Executive Office of the President
    - Office of Management & Budget (OMB) & Office of Science & Technology Policy (OSTP)
    - FY16 budget in preparation
  - Congress (relevant committees of both House and Senate)
  - Seems to be positively affecting Congressional FY15 appropriation
  - Common Washington questions: international collaboration
- **Roll out in community: Reception has been good.**
  - HEPAP, Virtual Town Hall, conferences & workshops
  - APS Physics Policy Committee
  - Laboratory Directors
  - Influential physics leaders
  - Common community questions:
    - Internationalization of neutrino program, Muon Accelerator Program (MAP), impact on research groups, prospects for future machines in US.
  - International community

P5 Panel Perspective

- This is a challenging time for particle physics. The science is deeply exciting and its endeavors have been extremely successful, yet funding in the U.S. is declining in real terms. The report offers important opportunities for U.S. investment in science, prioritized under the tightly constrained budget scenarios in the Charge.
- We had the responsibility to make the tough choices for a world-class program under each of these scenarios, which we have done. At the same time, we felt the responsibility to aspire to an even bolder future.
- Wondrous projects that address profound questions inspire and invigorate far beyond their specific fields, and they lay the foundations for next-century technologies we can only begin to imagine. Particle physics is an excellent candidate for such investments.
- With foundations set by decades of hard work and support, U.S. particle physics is poised to move forward into a new era of discovery.

- More generally, we strongly affirm the essential importance of fundamental research in all areas of science.

- Our field is ready to move forward.

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.