Experimental Landscape

Snowmass Community Summer Study

Seattle Snowmass Summer Meeting 2022

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July 17, 2022

I thank all my colleagues who kindly provided material for my presentation, especially the program managers at DOE and at NSF.
P5 will be charged to develop a strategic plan for U.S. particle physics for future. The starting point for the plan will be the present program.

Outline of my presentation:

- General comments about the program
- Overview of experimental program, organized by P5 science driver
- Closing remarks

In this presentation, I would like to convey the diversity, richness, and balance of the current experimental program.

- Broad science scope, covering great range of different, but inter-related topics.
- Experiments with a diversity of scale, from small- to mega-
- Part of a global program of collaborative international efforts & shared facilities
- While P5 prioritizes projects, it does so in the context of the science drivers and of the program as a whole.

Recall that P5 = Particle Physics Project Prioritization Panel.
Strategic vision of 2014 P5: Particle physics is global

The current U.S. HEP program is guided by the 10-year strategic plan of 2014 P5 report:

“Pursue the most important opportunities wherever they are, and host unique, world-class facilities that engage the global scientific community.”

“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.”

The U.S. experimental program depends upon reliable partnerships.
2014 P5’s Science Drivers

2014 P5 distilled the compelling scientific questions developed by the 2012-2013 Snowmass community process into five topics that should drive the U.S. HEP program for the subsequent 10 years (within a 20-year vision):

- 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.

P5 emphasized that the 5 science drivers are intertwined, e.g. synergy between precision physics and direct production, or the insights that cosmic surveys shed on neutrino properties.

P5 then identified the highest priority projects for a balanced program that addresses these science drivers in constrained budget scenarios.
The experimental program is built upon the foundation of other critical research activities.

- Theory
- Technology R&D:
  - Accelerator R&D
    - See the 2015 HEPAP Accelerator R&D Subpanel report.
  - Detector R&D
    - See recent basic research needs (BRN) report.
    - Including microelectronics
- Software & Computing
  - Including AI/ML

DOE & NSF support theoretical + experimental Quantum Information Science.

The experimental program, and its foundation, cannot exist without its expert science & technology workforce.
Use the Higgs boson as a new tool for discovery.

- LHC and HL-LHC are the only means to produce and characterize the Higgs for the next decade or longer.
  - Precision measurements of Higgs properties leading to any deviations at the few %-level.
  - Access to rare processes, H decay to $\mu\mu$.
- ILC, FCC-ee, or other Higgs factory would eventually allow measurements of higher precision.
- A very high energy proton-proton collider (e.g. FCC-hh) would later allow other improved measurements, particularly Higgs self-coupling.
LHC has been one of the largest investments of U.S. in HEP, ever.

- **LHC accelerator** (DOE)
- **ATLAS** (DOE+NSF), **CMS** (DOE+NSF), **LHCb** (NSF, DOE NP), **ALICE** (DOE NP)

U.S. is single largest collaborating nation on both ATLAS & CMS.

- US-ATLAS: ~19% of ATLAS; US-CMS: ~27% of CMS

U.S. plays leading roles on LHCb (6 U.S. institutions)

**U.S. LHC Detectors Operations Program – DOE + NSF**

- Supports Maintenance & Operations and Software & Computing
- Spearheads HL-LHC Software & Computing planning + R&D
LHC and HL-LHC upgrades

“The LHC upgrades constitute our highest-priority near-term project.”

Phase-I upgrades were installed during LS2 for Run 3 started July 5th.


• **DOE: HL-LHC AUP**
  • Accelerator Upgrade Project
    • CD-3 – December 2020;
      (re-baseline in 2022: COVID & LS3 sched)

• **DOE & NSF: HL-LHC [Phase-II]**

  **ATLAS & CMS upgrades**
  • NSF MRFEC: Feb 2020
  • CD-2’s ATLAS + CMS in Fall 2022
  • Early start: CD-3’s:
    • ATLAS – CD3a 9/21
    • CMS – CD-3a 6/21, CD-3b 6/22

• **LHCb Upgrade I** – installed in LS2
• **LHCb Upgrade II** – for LS4
• **ESPPU** highlighted flavor physics at LHC & HL-HLC.
DOE contribution:
10 cold mass (Nb₃Sn) assemblies
• 4 each for ATLAS & CMS interaction regions
• 2 spares

DOE contribution:
- RFD Crab Cavities
  • 2 proto
  • 2 pre-series
  • 10 cavities
CMS HL-LHC Upgrade

• Upgrade for performance at high rate & high efficiency for LHC Run 4.
• NSF & DOE support large U.S. roles. NSF MREFC – Feb. 2020; DOE CD-2 in Fall 2022.

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
• Tracks in L1-Trigger at 40 MHz
• PFlow-like selection 750 kHz output
• HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
• New FE/BE electronics for full granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
• ECAL and HCAL new Back-End boards

New Calorimeter Endcap
https://cds.cern.ch/record/2293646
• Referred to as HGCAL, EC, CE
• 3D showers and precise timing
• Si, Scint+SiPM in Pb/W-SS

Muon systems
https://cds.cern.ch/record/2283189
• DT & CSC new FE/BE readout
• RPC back-end electronics
• New GEM/RPC 1.6 < η < 2.4
• Extended coverage to η ≈ 3

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
• Barrel layer: Crystals + SiPMs
• Endcap layer: Low Gain Avalanche Diodes

Tracker
https://cds.cern.ch/record/2272264
• Si-Strip and Pixels increased granularity
• Design for tracking in L1-Trigger
• Extended coverage to η ≈ 3.8

= U.S. contributions to CMS HL-LHC Upgrade Scope
ATLAS HL-LHC Upgrade

• Upgrade for performance at high rate & high efficiency for LHC Run 4.
• NSF & DOE support large U.S. roles. NSF MREFC – Feb. 2020; DOE CD-2 in Fall 2022

DOE Scope:
- Barrel Inner Tracker (pixel & strip detector)
- LAr Calorimeter front-end analog chip development
- DAQ hardware (data flow elements)
- Common systems and infrastructure projects

NSF Scope:
- ‘Triggering’ at high luminosities
- Readout electronics for LAr, Tile, Muons
- Common systems and infrastructure projects

Electronics Upgrade for LAr and Tile Calorimeters; muon system
Upgraded Trigger & DAQ: L0: 1 MHz; improved HLT
Infrastructure and Common Projects

New muon chambers in the inner barrel region
New inner tracking detector (all silicon tracker, up to $|\eta|=4$
High granularity timing detector (forward region)
High-$\eta$ muon tagger
LHCb Upgrades I & II

### Upgrade I
- $\mathcal{L}_{\text{peak}} = 2.0 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$
- $\mathcal{L}_{\text{int}} = 50 \text{ fb}^{-1}$

### Upgrade II
- $\mathcal{L}_{\text{peak}} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- $\mathcal{L}_{\text{int}} = 300 \text{ fb}^{-1}$

**U.S. contributions:**
- GPU trigger application
- Triggers for inclusive heavy flavor & dark sector

**U.S. leadership in:**
- Upstream tracker detector
- Low-momentum tracker stations in magnet

**Upgrade Ib:**
- U.S. leadership in low-momentum tracker stations in magnet

**Upgrade II – Key features:**
- 4D vertex detector
- 5D calorimeter
- U.S. R&D
Seeding the future: Energy Frontier planning

Future collider strategy in the 2014 P5 plan:
- Support development & realization of ILC
  - Focus on SRF R&D, high gradient & high Q
- R&D towards a very high-energy pp collider
  - Focus on next-generation high-field dipoles through U.S. Magnet Development Program.

Advancing colliders of the proposed size, scale & complexity requires intergovernmental discussion & global coordination.
- Concerted U.S. Govt. interagency effort during the last ~5-6 years to support moving forwards with a proposed ILC in Japan and to collaborate with CERN on a proposed FCC.

DOE coordinates with ILC International Development Team to prepare ILC for its “Pre-Lab” phase.
- DOE plans to participate in any future intergovernmental discussion with Japan & global partners.

2020: DOE & CERN signed a FCC agreement to continue R&D & participate in the FCC Feasibility Study

Current efforts for ILC and/or FCC focus primarily on accelerator R&D, but DOE grants for the LHC experiments may apply up to 25% funds for development and physics studies for experiments for future colliders.

Other collider concepts are being considered during Snowmass/P5 process, which will guide future U.S. R&D and investments
Pursue the physics associated with neutrino mass.

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

** CURRENTLY AT FNAL:**
- **Short-baseline:**
  - MINERvA
  - MicroBooNE*
  - ICARUS

- **Long-baseline:**
  - NOvA

**FUTURE OUTLOOK AT FNAL:**
- **Short-baseline:**
  - SBN
  - SBND
  - ICARUS

- **Long-baseline:**
  - LBNF/DUNE

**U.S. working abroad:**
- **Long-baseline:**
  - T2K

- **Atmospheric/solar:**
  - SuperK

- **Reactor:**
  - Daya Bay
  - JUNO

- **Short-baseline:**
  - IsoDar

**OTHERS IN U.S.:**
- **Short-baseline:**
  - COHERENT (ORNL)
  - ANNIE (R&D; FNAL)
  - CCM (LANL)

- **Reactor:**
  - PROSPECT* (ORNL)

- **Atmospheric:**
  - IceCube

- **0ν2β:**
  - EXO-200
  - (0ν2β is now DOE NP)

- **Neutrino mass:**
  - Project-8

Cosmic surveys also shed light on neutrino properties.
Two principal goals:
• Resolve experimental anomalies in measured $\nu$-spectrum, including search for sterile neutrinos.
• Demonstrate the liquid argon TPC detector technology for DUNE.

Three detectors:
• MicroBooNE - *physics running complete; first results published on ½ data set;* 47 papers, ½ physics + ½ R&D
• ICARUS – brought from Gran Sasso, Italy via refurbishment at CERN – *operating*
• SBND – Short-Baseline Near Detector – *under construction*
Long-Baseline Neutrino Program – LBNF/DUNE


- Identified by P5 as the **highest priority large project in its time frame**.
- Centerpiece of a U.S.-hosted, international neutrino program.
- The 1st international science facility hosted in the U.S.

>1100 collab.
198 inst.
32 nations

Strong support for international collaboration within U.S. Govt.

UK-U.S. S&T Agreement
20 Sept 2017

US DOE – India DAE S&T Agreement for neutrino physics - 16 April 2018
1.2 MW proton beam on target; beam ready when LBNF ready (2031); upgradeable
Will also support other research goals by providing increased beam power and high reliability to future Fermilab experiments.

Replace existing 50-year-old linac with a high-power, 800-MeV SRF linac.
Based on LCLS-II experience (and ILC R&D)

Being built with international partners: India, Italy, UK, France, Poland.

Ultimate goal for upgrade of proton complex is >2 MW to LBNF w/ Booster upgrade.
Identify the new physics of dark matter.

P5: “It is imperative to search for dark matter along every feasible avenue.”

4 complementary experimental approaches, each providing essential clues:
- direct detection,
- indirect detection,
- observation of large-scale astrophysical effects,
- dark matter production at accelerators.

**Indirect detection:**
- Research continuing with Fermi-LAT & AMS-02.
- HAWC sensitive to very heavy DM particles.
- DOE has no new initiatives planned.

**Large-scale astrophysical effects:**

Evidence for Dark Matter M33 (galaxy rotation curve Wikipedia)
Direct detection searches for dark matter

DM-G2 program: 3 complementary experiments

**ADMx**

Axion search
Operating since 2017

at Univ. of Washington

**LZ**

WIMP search
LXe
First results this year

at SURF (South Dakota)

**DOE + NSF-PHY partnership**

WIMP search
Si/Ge at SNOLab

Fabrication complete - 2022
Operations – 2024

NSF supports numerous searches:
ABRACADABRA, ALPS-II, ARIADNE, COSINE, DAMIC-M, DarkSide, HAYSTAC, SABRE, SENSEI, XENONnT, R&D

Looking further forward, 2014 P5 also recommended one or more DM-G3 experiments.
Dark matter production at accelerators

Dark matter production with particle colliders

- Many DM searches at the LHC in ATLAS + CMS + LHCb & FASER
  - “invisible signatures” (mono-X; h->invisible, etc.)
  - “visible signatures” (e.g. mediator to dijets)
  - searches in the SUSY context

This active program will continue at HL-LHC.

Results also from BABAR, BELLE & BELLE-II.

Dark matter production in intense particle beams

- JLab: Heavy Photon Search (HPS); APEX in electron/positron beam
- LANL: Coherent CAPTAIN-Mills (CCM10) in neutron beam

New concepts under study in context of DMNI: e.g. CCM200, LDMX

Dark matter future planning via:

- All experimental techniques were explored at workshop on Dark Matter in 2017.
- Dark Matter New Initiatives funds development of 6 small project concepts
  4 in Cosmic Frontier, 2 in Intensity Frontier
Understand cosmic acceleration: dark energy & inflation

Dark energy: complementary imaging & spectroscopic surveys

Transitioning from Stage III:

- eBOSS – Extended Baryon Oscillation Spectroscopic Survey – final results 2020
- DES – Dark Energy Survey – survey complete; data processing nearing completion

to Stage IV:

DESI

Dark Energy Spectroscopic Instrument

Data taking started 2021
Fire has interrupted

Vera C Rubin Observatory

Legacy Survey of Space and Time (LSST)

aka Large Synoptic Survey Telescope

LSSTCam completed in 2021; to Chile in 2023
DOE + NSF MREFC
Dark Energy Science Collaboration (DESC) planning
Data taking to start late 2024.
Understand cosmic acceleration: dark energy & inflation

Inflation: Cosmic Microwave Background (CMB)

Operating Stage 3:
South Pole Telescope
Survey started in 2018
DOE-NSF partnership
1st science results - 2021

Planning for next generation:

CMB Stage 4 (CMB-S4)
Recommended by 2014 P5 + ASTRO2020; DOE-NSF partnership
CMB-S4 Concept Definition Taskforce Report approved in 2017; CD-0 - 2019
science goals, technical requirements, strawman concept
Learned in 2022 that must reduce footprint to fit South Pole infrastructure.
A note: P5 suggested international collaboration and coordination on Stage 4.

Dark Ages initiative (w/NASA): LuSEE-Night – Pathfinder mission to search for Dark Ages signal on lunar farside; MIE started FY22; launch 2025.
Measure low-frequency radio sky; sensitive to 21-cm emission from hydrogen at high redshift (z>30)
Explore the unknown.

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

Some approaches to exploring the unknown as outlined by P5:

- **High energy colliders** – ATLAS + CMS
- **Precision physics & rare processes**
  - Heavy quarks & tau leptons – LHCb, Belle-II
  - Rare kaon decays – KOTO, NA62
  - Rare muon decays and processes – Mu2e, MuonE
  - Muon magnetic moment – Muon g-2
  - Baryon number violation – LHCb
  - Electric dipole moments - ACME
  - CPT* - CeNTREX
  - Monopoles* - MoEDAL
- **Cosmic particles** – AMS-02, HAWC, Pierre Auger, VERITAS, BEACON, pSCT, ARA, IceCube, Radar Echo Telescope, RNO-G, SNEWS (synergy w/ multi-messenger astro)
- **New low-mass particles (e.g. hadron spectroscopy)** – LHCb
Searches at high-energy colliders are one approach to exploring the unknown.

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>( t \gamma )</th>
<th>Jets</th>
<th>( E_{\text{T}}^{\text{miss}} )</th>
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<td>( \gamma )</td>
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<td>HL-LHC</td>
<td>=&gt;</td>
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<td>Up to 40% larger discovery potential for new physics than prior to upgrades</td>
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</table>

HL-LHC => Up to 40% larger discovery potential for new physics than prior to upgrades.
Explore the “unknown” thru precision measurements

**Ongoing precision experiments:**
- Collaboration with Japan on $K$ meson studies with K0T0 and on heavy quark and $\tau$ lepton precision studies with Belle II.
- LHCb at LHC
  - Highlights in semi-leptonic $B$ decays, hadronic $B$ decays, CKM matrix, charm mixing & CPV

**The FNAL Muon Program**
- **Muon g-2**
  - Results from 1st year running published
  - Now has 19x data of BNL predecessor from 5 years under analysis
- **Mu2e**
  - Under construction (CD-3 – 2016)
  - Re-baseline planned in 2022
  - 1st run in 2026
<table>
<thead>
<tr>
<th>Subprogram</th>
<th>TPC ($M)</th>
<th>CD Status</th>
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<td><strong>INTENSITY FRONTIER</strong></td>
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<td>LBNF/DUNE</td>
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<td>CD-3a</td>
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<td>Proton Improvement Project (PIP-II)</td>
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<td><strong>ENERGY FRONTIER</strong></td>
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<td>LHC ATLAS Detector Upgrade</td>
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COVID seriously impacted numerous projects.
Closing remarks

The U.S. experimental particle physics program has been guided for the last several years by the strategic plan presented in the 2014 P5 report. It is time for an update.

The 2014 P5 plan is motivated by intertwined 5 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 2014 P5 strategic plan is:

- science driven.
- broad, covering a great range of different, but inter-related questions.
- a balanced program (not a strict prioritization).
- part of a global program of international collaborations & shared facilities.

The 2023 P5 strategic plan will build upon today’s experimental program and upon the projects that will soon complete. This Snowmass Community Summer Study will provide the new information upon which the 2023 P5 strategic plan will be built.

=> Let’s assemble a plan that shares the strong characteristics of the 2014 plan.
Thank you.