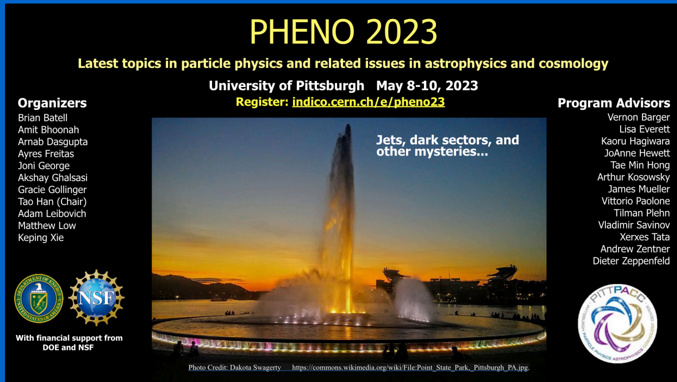


Visions on Particle Physics After Snowmass/2021 – during P5/2023

Joel Butler, Fermilab

Talk presented at Pheno 2023

May 10, 2023

Plan for getting a vision:

Unfortunately, the weather was too nice, so …

Outline

- The US Planning Process and Outcome of 2013/14 Exercise
- The Snowmass 2021 Process
- The High Energy Physics Landscape in 2023
- Some Outcomes of Snowmass 2021
- Summing Up and Looking Ahead

Disclaimer

These are my personal views based on my experiences in the recent Snowmass process and P5 townhalls.

Acknowledgements

The Snowmass Steering Committee, all the Frontier Conveners and Topical Group leaders, and all participants. Special thanks to Tao Han who guided us through the worst days of the pandemic.

Thanks (I think)

to the conference organizers of Pheno 2023 for asking me to give this talk

The US Planning Process and Outcome of 2013/14 Exercise

History: US HEP Community Planning Exercise, a.k.a. Snowmass

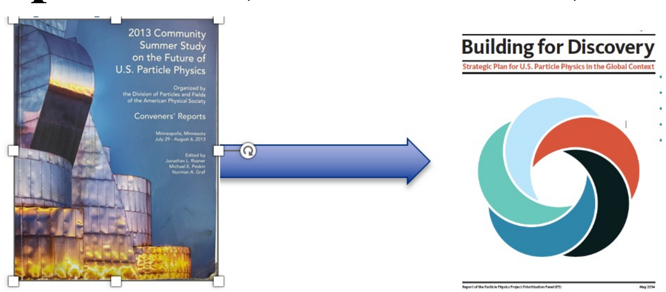
- **Snowmass, the DPF-hosted Community Planning Exercises, started in 1982**
  - The then DPF chair Charles Baltay said: "The 1982 DPF Summer Study was the first attempt in recent years to bring together physicists from the whole country to consider the future of our field from the point of view of the best overall national program. The DPF Executive Committee feels that this summer study was sufficiently useful in this last respect to hold similar summer studies at appropriate times in future years."
    - **The study lasted several months and culminated in a 3-week-long workshop in Snowmass, Colorado**
- **Goal (then and now): To identify the most important questions in HEP and the tools and infrastructure required to address them**
    - To achieve a broader and deeper understanding of the science in our field
    - To engage junior scientists and foster our community development
    - To reach a compelling vision for the field moving forward
- The previous edition, Snowmass 2013, was moved outside of Snowmass, Colorado to the University of Minnesota
- Community Planning Process has became increasingly international and interdisciplinary

Snowmass and P5

- **Snowmass** is the DPF-sponsored "Community Planning Exercise" to get all ideas, projects, and issues on the table **for the next decade, with an eye to the one following that.**
- **P5** is charged by the funding agencies and given a few specific budget scenarios and it recommends which projects should have priority for funding under each scenario.
  - The work and reports from Snowmass are an important input to P5, but it also acquires other inputs from the community through Town Meetings and written submissions and usually requests and reviews information on project costs.
- This two-phase process is undertaken every 7-10 years, as one batch of projects begins to complete and resources, i.e., people and funds, become available for the next round of research

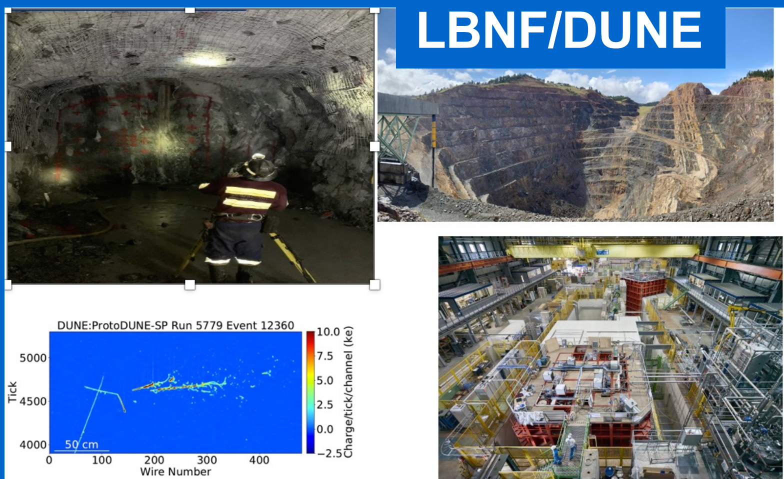
P5/2014 Science Drivers

- **From the 2014 P5 report:** "Snowmass, the yearlong community-wide study, preceded the formation of our new P5. A vast number of scientific opportunities were investigated, discussed, and summarized in Snowmass reports. **We distilled those essential inputs into five intertwined science Drivers for the field:**
  - 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**"



Project Outcome, P5 2014

LBNF/DUNE



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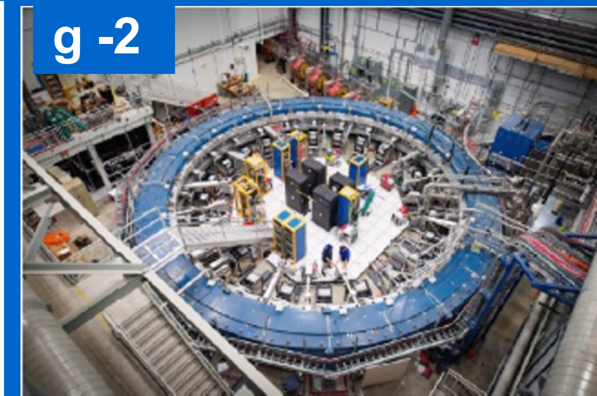
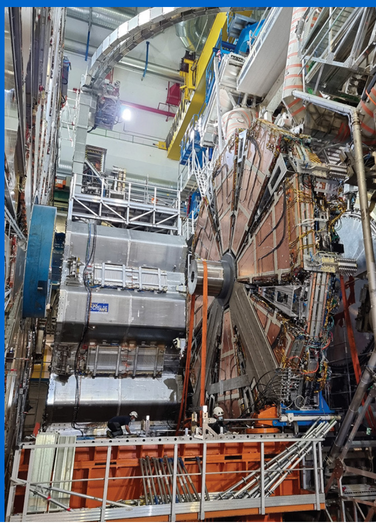
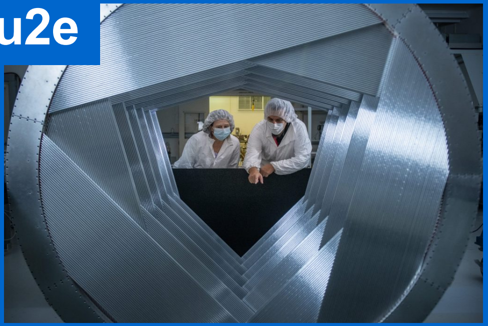


ATLAS Upgrade



CMS Upgrade

Mu2e



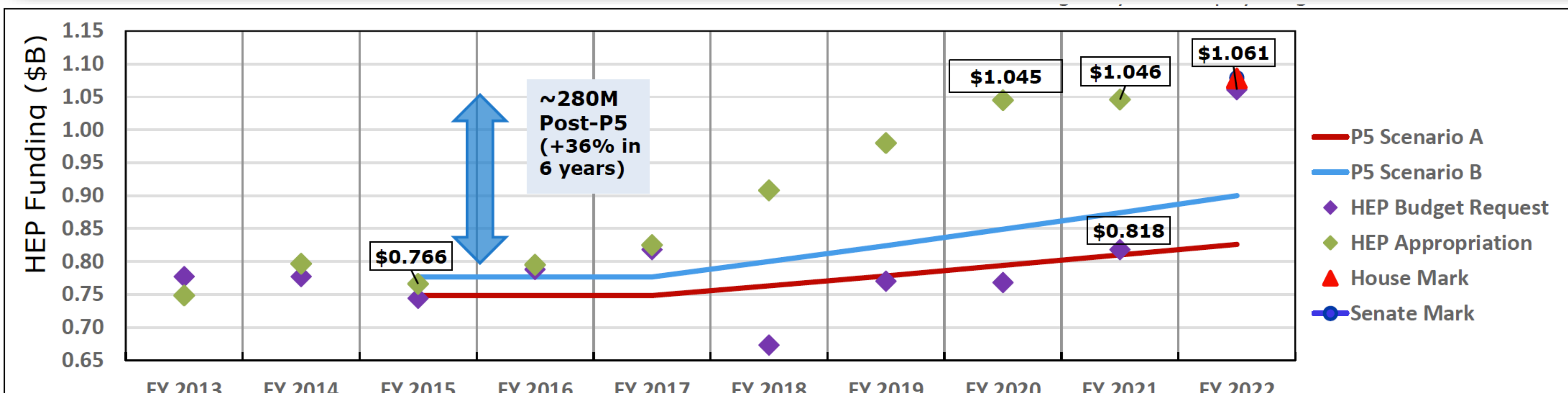
Vera
Rubin
LSST

and many other projects, large and small

Snowmass 2013 and P5 2014 Impact on Funding

- The U.S. particle physics community enthusiastically supported the P5 plan.
  - 2,331 community members signed a letter of support to DOE and NSF (organized by DPF)

"Four years into executing the P5, the Committee commends the Office of Science and the high energy physics community for achieving significant accomplishments and meeting the milestones and goals set forth in the strategic plan…"



The Snowmass 2021 Process

Quick Summary of Snowmass 2021

- Two-year, 2021-2022, community study (lengthened because of COVID)
- Organized into 10 **working groups**, called "Frontiers" because of their cutting-edge nature
  - Accelerator, Cosmic, Community Engagement, Computing, Energy, Instrumentation, Neutrino, Rare Processes and Precision Measurements, Theory, Underground
    - Each with three conveners and
      - each with ~8 Topical Groups (also three conveners each)
  - In addition, **Snowmass Early Career** – treated as an ~full Frontier
- About 2500 people involved
- Many meetings, workshops, lecture series, etc.
- Many documents
  - Two-page Letters of Interest (April 1 – August 31, 2020)
    - >1500 submitted
  - These resulted in the creation of >540 contributed papers (white papers)

Final "Community Summer Study"

- A ten-day meeting at University of Washington in Seattle, July 17-26, 2022
  - To bring it all together and into perspective and organize for writing final reports
  - **Participation**
    - Number of in-person participants: 743
    - Number of virtual participants: 654
    - Local Organizing Committee/Volunteer/Press: 58
    - **Total number of participants: 1397**

Snowmass Proceedings Website

https://www.slac.stanford.edu/econf/C210711/

Snowmass 2021

Snowmass 2021

Proceedings of the 2021 US Community Study on the Future of Particle Physics

(Snowmass 2021)

organized by the APS Division of Particles and Fields

These proceedings are dedicated to the memory of Meenakshi Narain (1964-2023), in honor of her many contributions to Snowmass 2021.

The US Community Study on the Future of Particle Physics (Snowmass 2021) was a grassroots study to plan for US particle physics in the decade 2025-2035 with an eye towards the following decade. Snowmass 2021 was organized by the APS Division of Particles and Fields, with input and collaboration from the Divisions of the Physics of Beams, Astrophysics, Nuclear Physics, and Gravitational Physics. It began with a kick-off meeting at the 2020 APS April Meeting and a Community-wide Planning Meeting in October of 2020. Because of the COVID pandemic, the study was paused between January and September 2021. The study finally concluded at the Community Summer Study meeting at the University of Washington, July 17-26, 2022.

Full Report: 750 pages;

Executive Summary: 8 pages

Report Summary: 70 pages

All of the Frontier Summaries and Early Career

Examples of cross-cutting research

The ... ersion of the Snowmass Book.

We h... future of our field over the next decade.

Peskin

Frontier Summaries

Summary & Frontmatter	Cosmic Frontier	Rare Processes Frontier
Accelerator Frontier	Energy Frontier	Theory Frontier
Community Engagement Frontier	Instrumentation Frontier	Underground Facilities Frontier
Computational Frontier	Neutrino Frontier	Snowmass Early Career

Home

Topical Group Reports:

- Higgs Boson Physics — arXiv:2209.07510
  Conveners: Sally Dawson, Patrick Meade, Isobel Ojalvo, Caterina Vernieri
- Heavy Flavor and Top Quark Physics — arXiv:2209.11267
  Conveners: Reinhard Schwienhorst, Doreen Wackeroth
- Electroweak Precision Physics and Constraining New Physics — arXiv:2209.08078
  Conveners: Alberto Belloni, Ayres Freitas, Junping Tian
- Quantum Chromodynamics — arXiv:2209.14872
  Conveners: Michael Begel, Stefan Hoeche, Yen-Jie Lee Huey-Wen Lin, Swagato Mukherjee, Pavel M. Nadolsky Christophe Royon, Michael Schmidt
- Beyond the Standard Model — arXiv:2209.13128
  Conveners: Tulika Bose, Antonio Boveia, Caterina Doglioni, Simone Pagan Griso, James Hirschauer, Elliot Lipeles, Zhen Liu, Nausheen R. Shah, Lian-Tao Wang

Cross-Frontier Reports:

T. Roser et al.	*Report of the Snowmass 2021 Collider Implementation Task Force*	arXiv:2208.06030
K. M. Black et al.	*Report of the Snowmass 2021 Muon Collider Forum*	arXiv:2209.01318
M. Chamizo Llatas et al.	*Report of the Snowmass 2021 Electron-Positron Collider Forum*	arXiv:2209.03472
A. Boveia et al.	*Snowmass 2021 Dark Matter Complementarity Report*	arXiv:2210.01770

Contributed Papers:

General - centered on this frontier

A. Blondel et al.	*FCC-ee: Your Questions Answered*	arXiv:1906.02693
A. Blondel, P. Janot.	*Circular and Linear e+e− Colliders: Another Story of Complementarity*	arXiv:1912.11871
L. A. Anchordoqui et al.	*The Forward Physics Facility: Sites, Experiments, and Physics Potential Modern and Future Colliders*	arXiv:2109.10905

P5 2023

- **Chairpersons: Hitoshi Murayama, Berkeley Karsten Heeger: Yale**
- **Website: https://www.usparticlephysics.org/p5/**
- **Open Town Halls**
  - LBNL: Feb 22-24, 2023, focus - Cosmic Frontier (except HE Astrophysics)
  - Fermilab/Argonne: March 21-23, 2023, focus - Neutrino, Rare Processes, HE Astrophysics
  - Brookhaven: April 12-14, focus - Energy, Instrumentation, Computational
  - SLAC: May 3-5, focus - Underground, Accelerator, Theory, Community Engagement
- DPF session on P5 (April 15)
- Costs/Risks/Schedule committee to understand maturity of cost estimates
- Virtual Town Halls (additional opportunities for university engagement)
  - week of May 15
  - week of June 5
  - week of June 26

  UPCOMING!
- Closed meetings
- Preliminary recommendations in August
- Final report due in October

From charge: Develop an updated strategic plan for U.S. high-energy physics that can be executed over a 10-year timeframe in the context of a 20-year, globally aware strategy for the field.

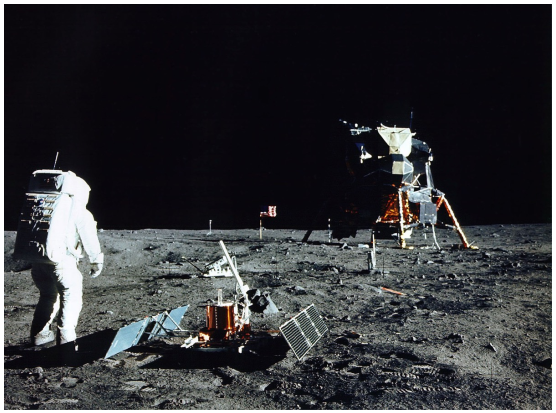
Charge also for first time includes request for advice on DEI and workforce development.

The High Energy Physics Landscape in 2023

Current Status and Outlook

- Many of the projects prioritized by P4/2014 are either just coming online or are still being built
- Given the length of time needed to get projects funded in the US, it was necessary to start planning the next round of projects ➔ Snowmass 2021
- **In the work done in the last decade using facilities then in place or since completed, no mass/energy scale for BSM physics has been identified**
  - **Some hints exist that may point us in a particular direction, e.g. g-2, flavor anomalies(?), neutrino anomalies, W mass**
- Many new ideas have expanded the search space, e.g. for Dark Matter, but also in other topics as well
  - For DM, huge mass range recognized: **perhaps 90 orders of magnitude**
- Calls for a new strategy
  - More diverse, with large, medium, and perhaps more small experiments
  - More interconnected/interdisciplinary – use all available information from all Frontiers, scales of experiments, theory, …

Campaigns vs Investigations

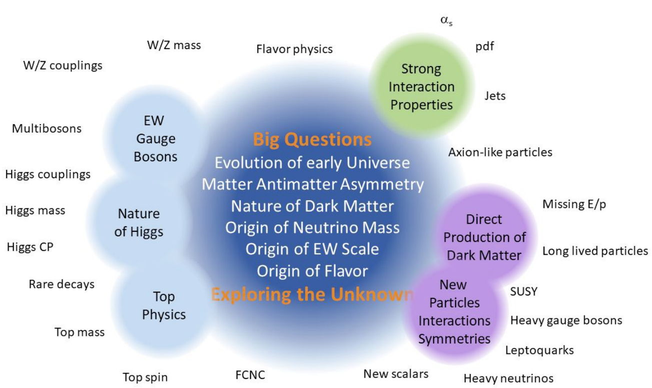


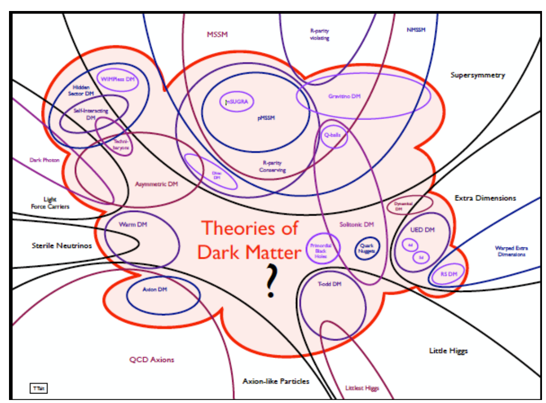
For a campaign:

1. Have a goal that you know is achievable
2. Have the means to carry it out
3. Have the determination and support to do it

The W, Z, Top, and Higgs are examples

In 2013/2014 with the Higgs newly discovered and the first 13 TeV run at the LHC coming up, it was possible to imagine we would soon identify specific targets and mass scales for BSM to aim for that were accessible. **This has not happened yet!**

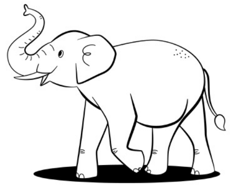




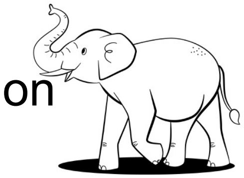
1. We now must do a broad **investigation** to look for experimental guidance. The key idea or technique may not yet have been invented. R&D, theory, and an interdisciplinary approach are crucial.

The Good News – There has to be BSM Physics!

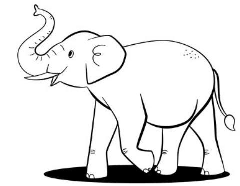
Flavor dynamics



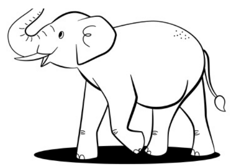
Inflation

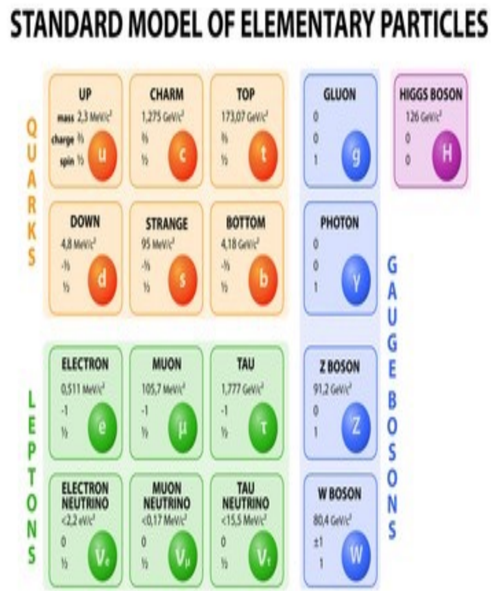


Dark matter

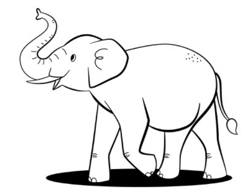


Electroweak scale,Higgs mass, hierarchy problem

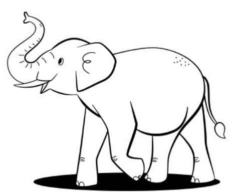




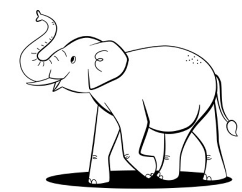
Dark Energy



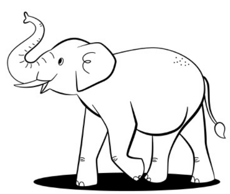
Neutrino masses and mixing



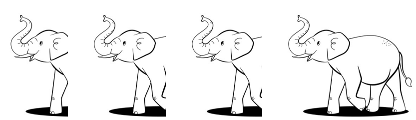
Matter-antimatter asymmetry



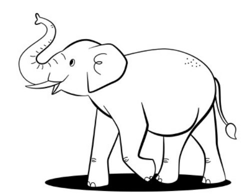
Strong CP violation



And more …



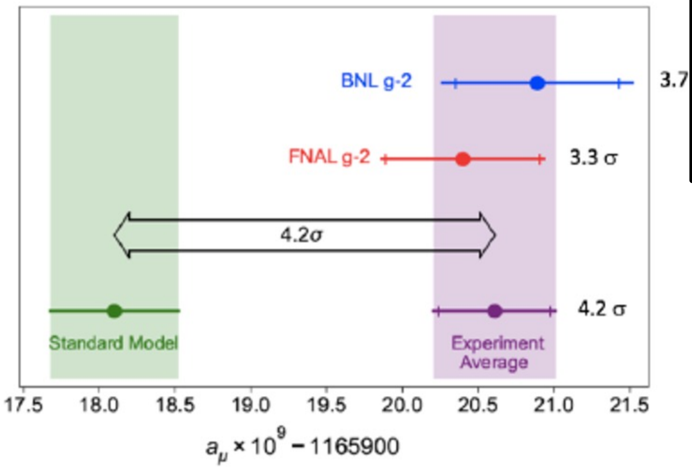
Gravity and Quantum



- Image by Freepik

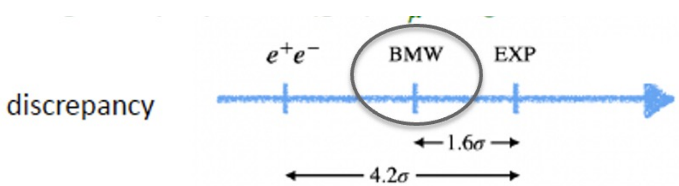
We know there is BSM Physics and there may be new Hints (or not)

$a_\mu = (g-2)/2$ with $\vec{\mu} = g\frac{e}{2m}\vec{s}$



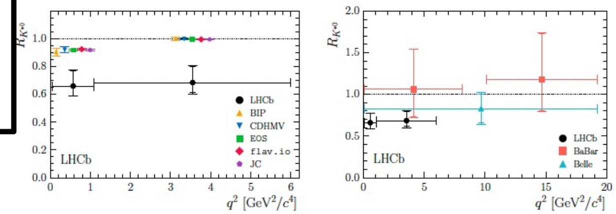
$a_\mu(\text{Theory}) = 116591810(43) \times 10^{-11}$

$a_\mu(\text{BMW}) = 116591954(55) \times 10^{-11}$

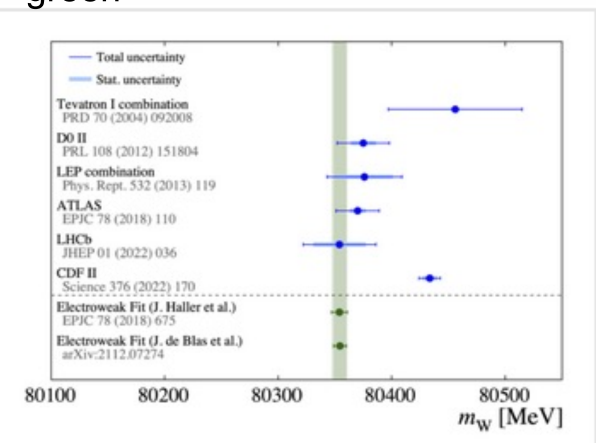


Evidence for BSM:
Dark matter
Dark energy
Neutrino masses, mixing
Baryon Asymmetry of Universe
Cosmic Inflation.

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]

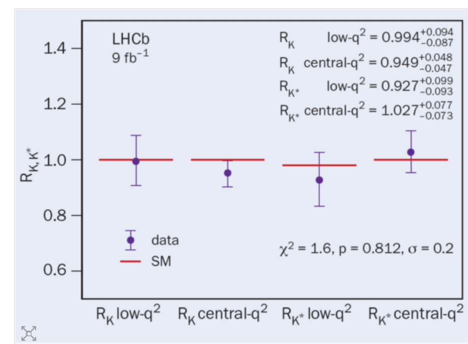


New CDF measurement of the W mass along with other results. SM prediction is in green



LHCb brings leptons into line

20 December 2022



Flatline Final measured values of lepton-flavour universality observables in $B \to K\mu^+\mu^-$ and $B \to Ke^+e^-$ decays with the full Run 1 and 2 data sample, and their overall compatibility with the Standard Model. Source: LHCb-PAPER-2022-045

The Challenge

- While the distinction may be largely semantic, we are no longer doing "campaigns" with one (or a few) very focused, identifiable objective(s), but much broader "investigations", at least until we find some new clues,
- For a scientist, this is an excellent and exciting challenge!
  - it may, however, be difficult to explain it to members the public and the political system in a way that motivates them to provide the necessary resources. They relate better to campaigns.

Expanded public outreach will be a requirement for future success

Some Outcomes of Snowmass 2023

An HEP Mission Statement from Snowmass 2021

"Lead the exploration of the fundamental nature of matter, energy, space and time, by using ground-breaking theoretical, observational, and experimental methods; developing state-of-the-art technology for fundamental science and for the benefit of society; training and employing a diverse and world-class workforce of physicists, engineers, technicians, and computer scientists from universities and laboratories across the nation; collaborating closely with our global partners and with colleagues in adjacent areas of science; and probing the boundaries of the Standard Model of particle physics to illuminate the exciting terrain beyond, and to address the deepest mysteries in the Universe."

Reviewing P5/2014 Drivers

- We were asked to review the 2014 P5 Science Drivers
- The science questions that HEP seeks to answer continue to be the ones identified in the 2013 Snowmass Report and so eloquently and succinctly summarized by P5 in the formulation of its Five HEP Science Drivers. These five drivers have guided US HEP for nearly a decade with great success. **There was a consensus in Snowmass that these drivers were still relevant for the next decade.**
  - There was a suggestion that the physics of flavor, currently included under the fifth driver, be more specifically recognized given the current tensions between recent results in this area and the Standard Model. An assessment of the current and projected status of HEP relative to the P5 Drivers is given below.
    - My personal opinion: this is still a valid request even though some of the BSM indications have faded.

High Level Recommendations I

- The science questions that HEP seeks to answer continue to be the ones identified in the 2013 Snowmass Report …
- The portfolio of projects should continue to include a healthy breadth and balance of physics topics, experiment sizes and timescales, supported via a dedicated, robust, ongoing funding process.
- Completion of existing experiments and operation of DUNE and the HL-LHC programs, priorities of the 2014 P5, are critical for addressing the science drivers for the near term and for much of the next two decades.
- Strong, robust support for the research program is essential to analyze the data from the existing and planned experiments, plan upgrades and future programs and projects, and educate the next generations of researchers and technical experts.
- Strong and continued support for formal theory, phenomenology and computational theory is needed, as are stronger, targeted efforts connecting theory to experiment.

High Level Recommendations II

- Both R&D directed to specific future projects and generic research need to be supported in critical enabling technologies such as accelerators, instrumentation/detectors and computation, and in new ones such as quantum science and machine learning.
- An overall strategy, with overarching goals, for HEP engagement with five interrelated communities: HEP itself and the broader academic community, K-postdoc education, private industry, government policy makers, and the broader society, should be formulated. A structure for achieving these goals should be provided, along with the necessary resources, should be provided.
- The HEP community should institute a broad array of practices programs to reach and retain the diverse talent pool needed for success in achieving our scientific vision.
- A cohesive, strategic approach to promoting diversity, equity and inclusion in high-energy physics, and to improving community outreach and engagement, is required

Summary of the 2021-22 U.S. HEP Community Planning Exercise – Large Projects

Next Decade Next-Next Decade

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I& PIP - II	DUNE Phase II(incl proton injector)
Cosmic Frontier	Cosmic Microwave Background S4 Spectroscopic Survey - S5*	Next Gen. Grav. Wave Observatory* Line Intensity Mapping*
	Multi-Scale Dark Matter (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

From Hitoshi Murayama's talk at HEPAP in Dec 2022

Snowmass Input

10 **Summary of the 2021-22 U.S. HEP Community Planning Exercise**

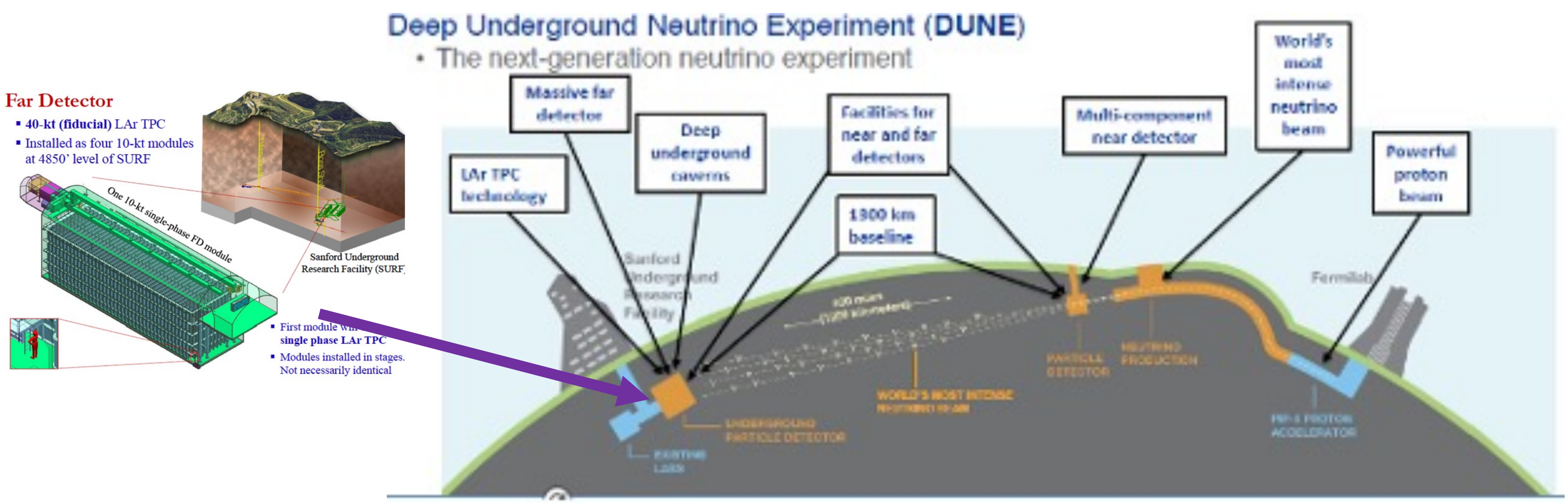
Decadal Overview of Future Large-Scale Projects

Frontier/Decade		
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
	US role?	Higgs Factory **Scope? Technology? Complementarity**
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4 Spectroscopic Survey - S5* **Scope?**	Next Gen. Grav. Wave Observatory* Line Intensity Mapping* **Do we embrace them?**
	Big, small, new? Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility **Scope? Other science?**

How do we develop enabling technology for long-term vision in a fashion executable in 20 years?

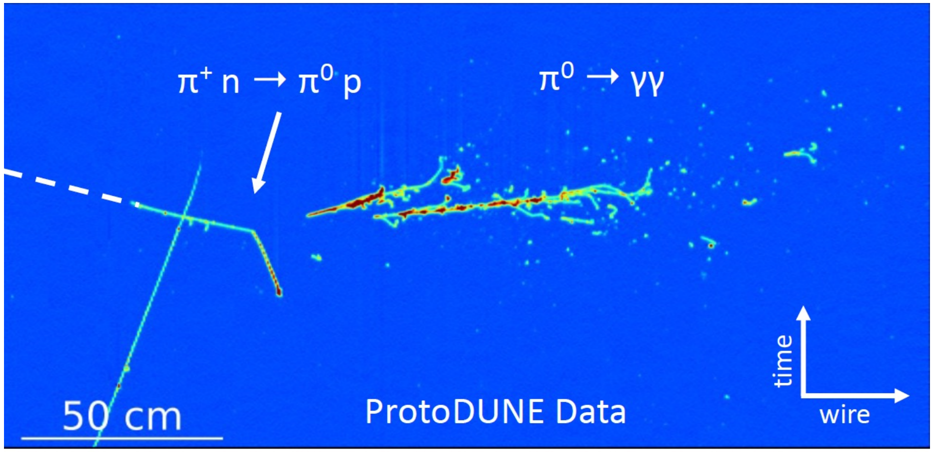
Neutrino Frontier

- A future program with a healthy breadth and balance of physics topics, experiment sizes, and timescales, supported via a dedicated, deliberate, and ongoing funding process, is highly desirable.
- Completion of existing experiments and execution **of DUNE in its full scope** are critical for addressing NF science drivers
- To exploit these new opportunities directed R&D needs to be supported.
- Strong and continued support for neutrino theory is needed.
- There are unique opportunities for NF to contribute to leadership of a cohesive, HEP-wide strategic approach to DEI and community engagement, which is urgently needed.



Dune

- Phase I (under construction):
  - Near (Fermilab) and Far (South Dakota) Infrastructure
  - 1.2 MW beam, upgradeable to 2.4 MW
  - Far detector (FD): 2 x 18kt (10 kt fiducial) liquid argon time-projection-chamber modules
  - Moveable Near Detector (ND), muon detector, on-axis ND
- Phase II (will be considered by P5):
  - Two more FD modules of ~ same mass
  - >2MW beam
  - Upgraded ND
- DUNE has joined search for BSM



LBNF-DUNE status

- Phase I Approval Critical Decision (CD) Status (CD-0 = mission need; CD-1=conceptual design; CD-2 = technical design; CD3 = construction start)
  - Far Site Excavation – CD3 Aug 19, 2022
  - Far site building and infrastructure CD2/3 Mar 23, 2023
  - Far site detectors and Cryo: CD3 expected Q1 2024
  - Near site conventional facilities and beamline: CD3 expected Q2 2024
  - Near detector: CD3 expected Q5 2025
- Schedule for start of experiment
  - Start science (beam, FD1) 2029
  - Beam checkout complete 2031
  - Near detector complete 2032

Phase II will give DUNE its full reach and allow it to do the definitive measurements of oscillation parameters in the three-flavor paradigm

Rare Processes and Precision Measurements Frontier

- B and Charm physics:
  - Strong support for US participation in LHCb and its Upgrade II.
  - Strong support for continued participation in BELLE in Japan
- Beam dump searches for Dark Matter
- Possible light quark physics experiments, e.g. REDTOP
- **Possible Muon Facility (AMF) at FNAL**
  - **Would employ PIP-II and additional machine upgrades, formerly called PIP III, now called ACE, to enable a world-leading versatile facility**
  - One goal: study **Charged Lepton Flavor Violation** in all three muon modes: $\mu^- N \rightarrow e^- N$; $\mu \rightarrow e\gamma$; and $\mu \rightarrow 3e$
    - Two new small rings for $\mu^- N \rightarrow e^- N$ and $\mu^- N \rightarrow e^+ N'$ and at high-Z and additional x100 in rate
    - x100-1000 more beam for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ than are possible at PSI
    - a possible DM experiment
  - possible muonium-antimuonium oscillation experiment
  - possible atomic physics studies with muonia
  - possible muon EDM experiment

RPF would like the PHYSICS of FLAVOR to be a SIXTH "DRIVER"

Accelerator Complex Evolution "ACE" at Fermilab

Previously referred to as PIP-III

- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the Complex
- Establish a project to build a Booster replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research, i.e. Muon Collider
  - **Fermilab is evaluating two options: Rapid Cycling Synchrotron or Linac**

We need to preserve an accelerator option in the US for new ideas, test beams for detector R&D, and radiation studies for electronics.

Cosmic Frontier/Dark Matter

- The Cosmic Frontier is focused on understanding how elementary particle physics shapes the behavior and evolution of the universe, and how observations of the universe inform our understanding of physics beyond the Standard Model. In the moments just after the Big Bang, fundamental physics governs the production of the particles and energy fluctuations that give rise to the current universe.

- Project timeline:
  - The next big project is CMB-S4
    - Endorsed as a “start” by P5 in 2014
    - **Has CD-0 from DOE**
  - 2022-2036: Build and operate CMB-S4 (current large project)
  - 2024: Target date for CD-0 for Spec-S5 (next large project)
  - 2029: Begin CD process for LIM, GWO (future large project)

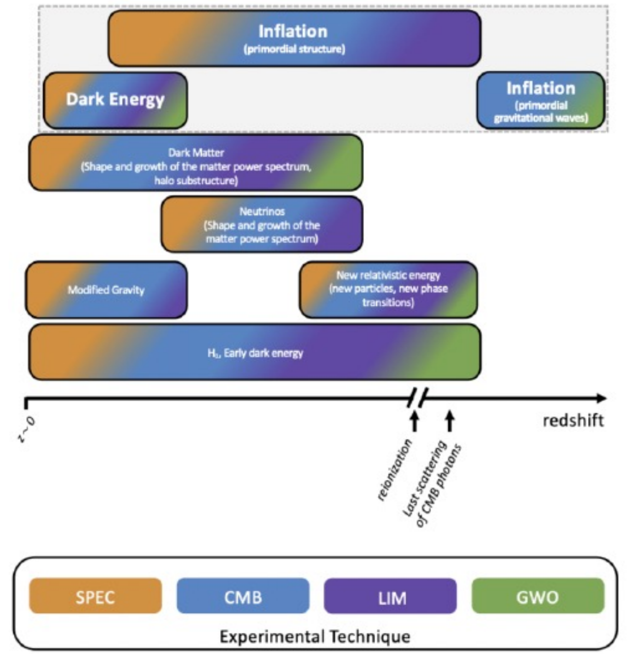


Figure 5-5. *A high-level summary of the key scientific opportunities. The horizontal extent of each box corresponds to the redshift-range of the tracer, while the coloring indicates the experimental technique used to measure the signal. The dashed grey box emphasizes dark energy and inflationary probes. From the CF6 report [6].*

Dark Matter

- Plan: '**Delve Deep, Search Wide, Aim High**' employs a range of direct searches for WIMPs interacting with targets on Earth, indirect searches for annihilation products, and cosmic probes based on structure, to scrutinize priority targets such as WIMPs and QCD axions, while broadly scanning parameter space, leaving no stone unturned.
- Multi-Scale Dark Matter (incl. Gen-3 WIMP searches)
  - Requests P5 to support R&D, pathfinders, and funding for a wide variety of experiments
    - In aggregate, this could be a significant cost, equivalent to a large project

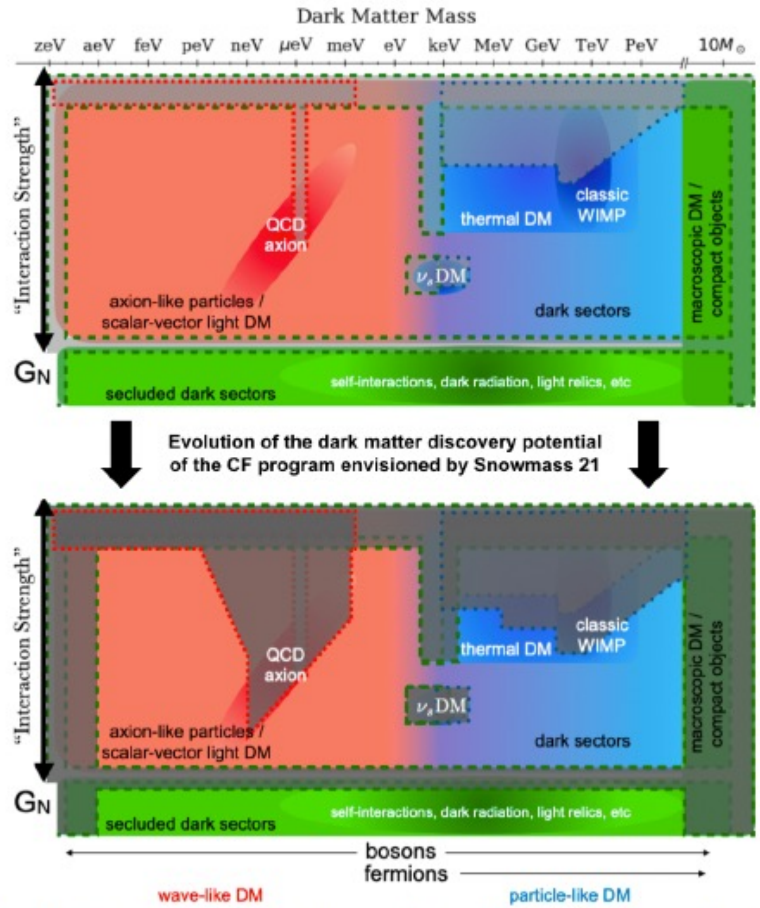


Figure 5-2. *Cartoon (not to scale) of the gains in sensitivity enabled by the search strategy outlined in this report (from light to dark gray shaded regions). Regions where dark matter typically manifests as a wave are shaded in red, whereas regions where it manifests as individual particles are blue. Broad, logarithmic gains in coverage are attainable through a range of newly developed techniques, which will require an ambitious and significantly expanded program of mid- and small-scale experiments as well as novel cosmic probes using existing and planned survey instruments (shaded green). See Section 5.5 for details.*

DM Research – An Example of Complementarity

- Advances in detector technology, analysis techniques, and theoretical modeling have enabled a new generation of searches while broadening the types of candidates we can pursue.
- In a cross-cutting contribution to the Snowmass process, participants across Frontiers collaborated to outline a road map for dark matter discovery, the Dark Matter Complementarity Report through summaries of the efforts across all Frontiers and four case studies of models generating significant interest in the Snowmass process: minimal WIMP DM, BSM and vector portal DM, sterile neutrino DM, and wave-like DM including QCD axions.
- The report proposes the following strategy:
  - Experiments at all scales are needed
  - Understanding the fundamental nature of DM is a worldwide endeavor. Coordination and cooperation across borders are critical for discovery.
  - A strong theory program is essential
  - Searches for DM benefit from cross-disciplinary expertise, with examples ranging from nuclear physics to metrology, and astrophysics to condensed matter and atomic physics. Mechanisms to support such interdisciplinary collaborations should be established.
  - Research funding is critical to enable discovery

Energy Frontier

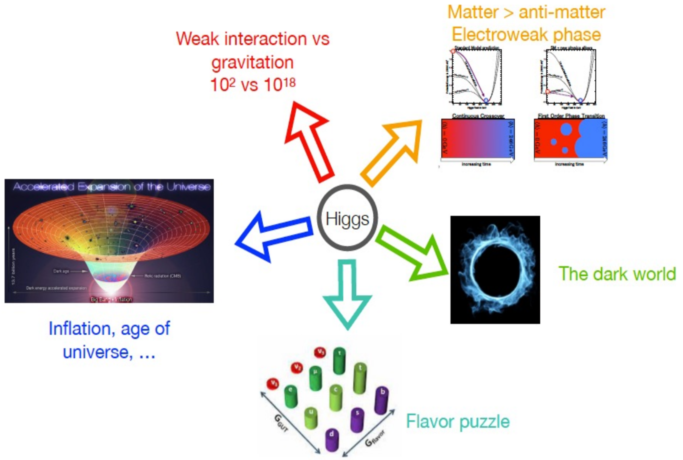
It is essential to

- Complete the LHC and HL-LHC program,
  - Instrumenting uncovered parts of phase space in ATLAS and CMS provides a "mid-scale" addition to the program and new opportunities for innovation and leadership
- Start now a targeted program for detector R&D for Higgs Factories
  - **Support a fast start of the construction of a Higgs factory somewhere in the world**
- Ensure the long-term viability of the field by developing **a multi-TeV energy frontier facility such as a muon or hadron collider.**

The US EF community has a renewed interest and ambition to bring back energy-frontier collider physics to US soil while maintaining its international collaborative partnerships and obligations, e.g. with CERN.

- A US-sited linear e+e- collider (ILC/CCC) **(Cold Copper Collider)**
  - Exploring other e+e- collider options to fully utilize the Fermilab site
  - I sense that elements of the community at Snowmass are frustrated by a timeline which now appears to produce the next collider in ~25 years from now
- Hosting a 6-10 TeV range Muon Collider

Case for New Physics at Higgs Factories



The Higgs boson's unique role in the Standard Model connects it to numerous fundamental questions that can be investigated by studying it in detail

Sign of New Physics:

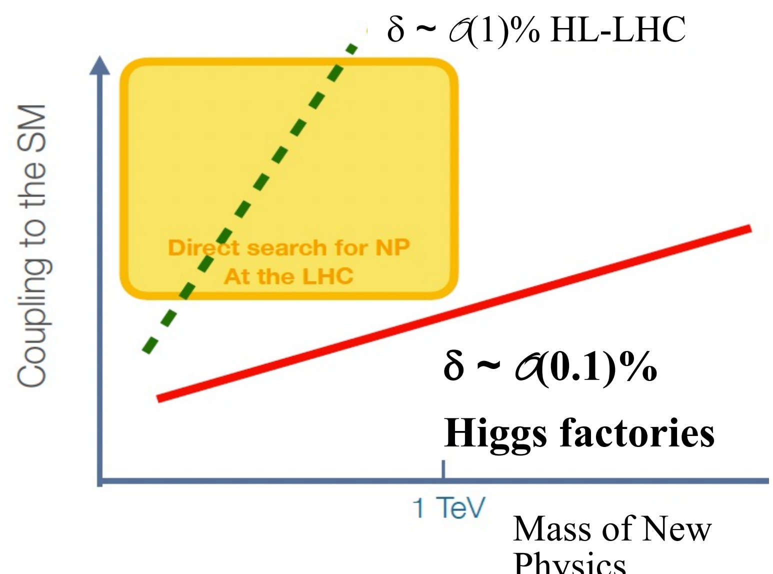
Coupling deviation from the Standard Model, $\delta \equiv \frac{g_{exp} - g_{SM}}{g_{SM}}$

Deviation generated by new physics: $\delta \sim g_{NP}^2 \frac{(100\ \mathrm{GeV})^2}{M_{new\ physics}^2}$

g_{NP} : coupling of new physics to the SM

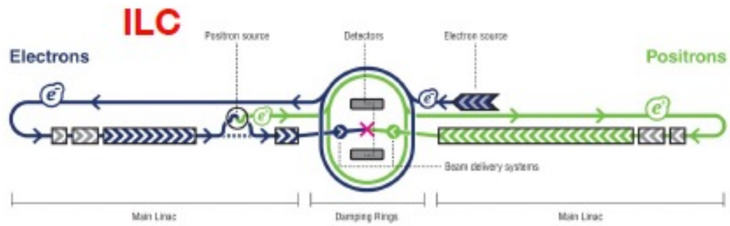
$M_{new\ physics}$: mass scale of new physics

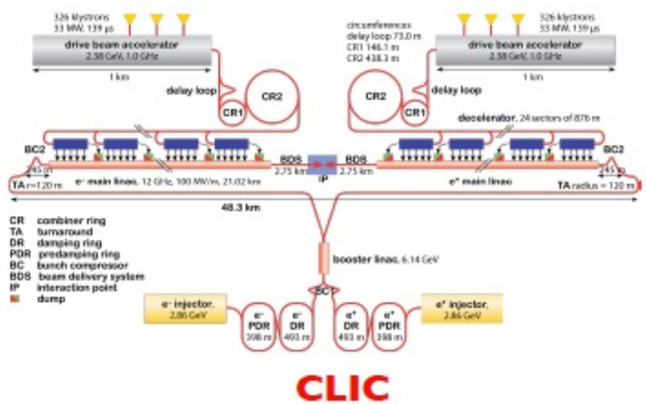
Measurement precision ⇒ sensitivity on δ ⇒ reach for NP

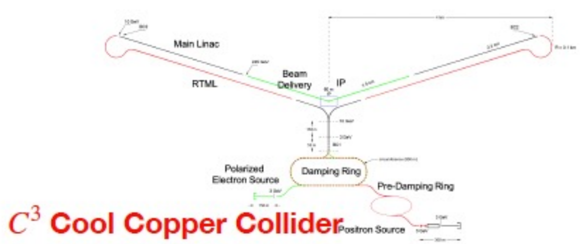


e⁺e⁻ Higgs Factories

Linear:

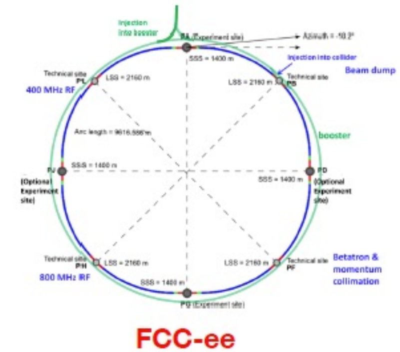


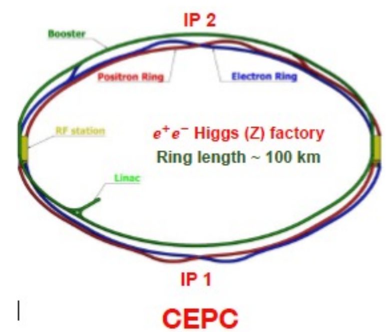




- Can go to higher energy – di-Higgs, with limited precision
- Polarization improves some precision measurements significantly

Circular:





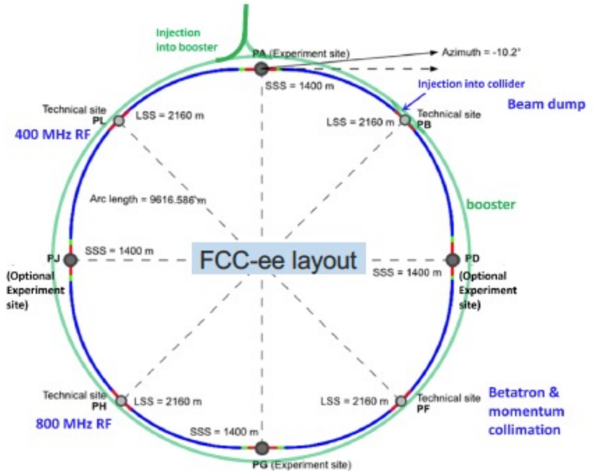
- Higher luminosity: can also do Z, WW, top
- Provides ring for future FCC-hh

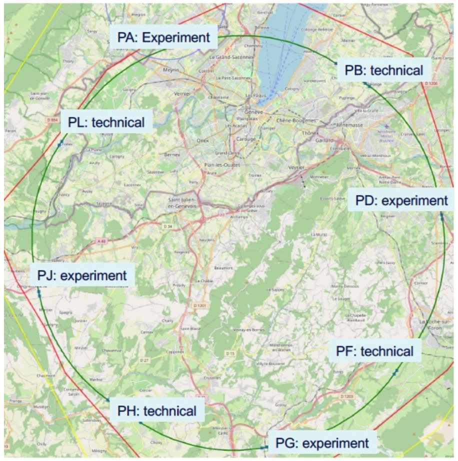
From the European Study on Particle Physics

- *"An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."*
- *"Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."*

FCC Feasibility Study (FS) started in 2021 and is scheduled for completion in 2025

(next slides based on presentation by F. Gianotti at BNL P5 Town Hall)



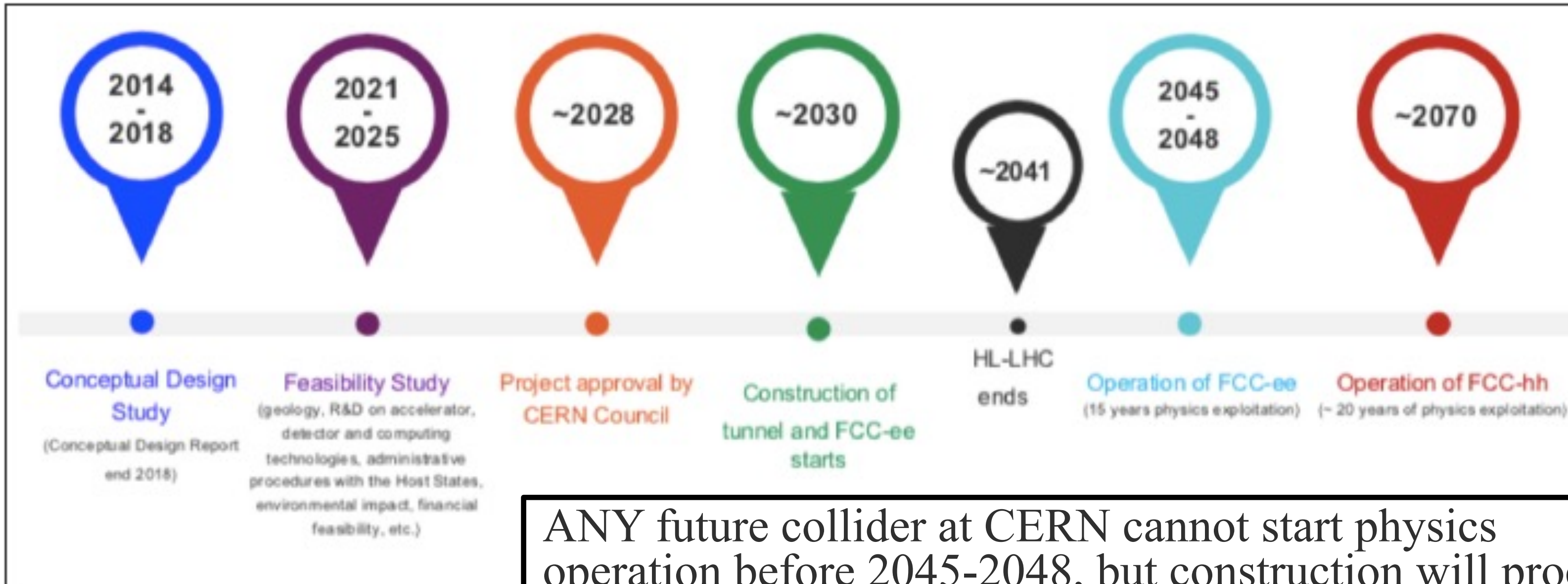


Circumference: 90.7 km

Surface points: 8

Operation: Z mass, WW, ZH, t-tbar (and others)

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity $[10^{11}]$	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
luminosity per IP $[10^{34}\ cm^{-2}s^{-1}]$	182	19.4	7.3	1.33
total integrated luminosity / year $[ab^{-1}/yr]$ 4 IPs	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10
	4 years 5×10^{12} Z LEP x 10^5	2 years $> 10^8$ WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 tt pairs



ANY future collider at CERN cannot start physics operation before 2045-2048, but construction will proceed in parallel to HL-LHC operation

Notional timeline for US/DOE decision to participate:
CD0: 2029; CD1: 2030/31; CD4: 2046/47
FCC-ee has a willing host and seems to have the most well-defined time-line of any of the Higgs factories, but final approval is still at least 5 years away

Even with this ambitious schedule, there would be a gap between the end of the HL-LHC and the next collider. EF experimenters will have a lot of work to do on this schedule. **But, if we cannot get a construction start around 2030, the gap may become unacceptably long, a point made by our younger physicists.**

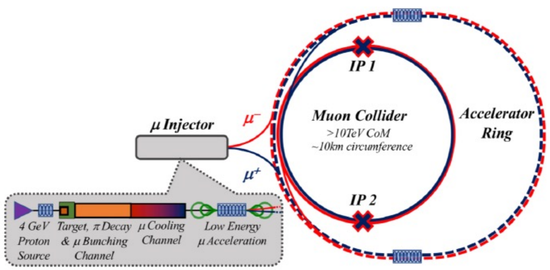
My Personal Take on e^+e^- situation now

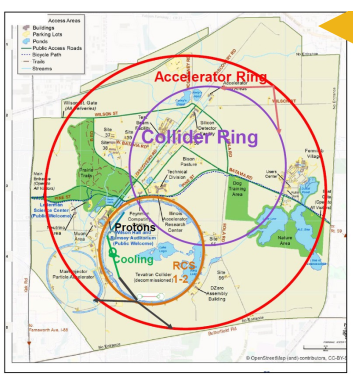
- It should be possible to confirm the Snowmass EF view that all the proposed e^+e^- colliders would be acceptable choices for a Higgs factory
- It should be possible for DOE and NSF to begin to develop their plans for validating the FCC-ee proposal in ~2025, focusing on cost and schedule
  - **This is expected to be a 10-12B$ project.** With such a high initial estimate, the project could not survive a factor of 1.5 or 2 cost increase, as has happened to several "big-science" projects lately.
  - US contribution might be in the 10-25% range
- Alternatives among the linear colliders should arrive at the same level of design and technical maturity in time to meet the FCC-ee decision timeline
  - If R&D is required to get the most promising alternatives ready for a decision, adequate funding should be provided
    - CLIC: *"Project Readiness Report" by end 2025 (as input to next ESPP)*
  - **Hosting and funding issues will have also to be resolved on that time frame**

If the FCC-ee should not prove to be feasible, then one of the other $e+e^-$ proposals must be developed to the point that it can be approved.

Multi-TeV Scale colliders

- Proton-proton colliders would benefit from tunnel for a circular Higgs factory. Significant magnet development and cost reduction is necessary, so this is considered to follow a Higgs factory, > 2070
- Muon colliders - Can do Higgs and precision EW, but also is a Multi-TeV boson-boson collider with parton CM energy >10 TeV





- A Muon Collider of 6-8 TeV center of mass energy is compatible with Fermilab accelerator complex and site. With ACE, the complex can provide a great platform for Muon Collider component R&D and a demonstrator project, and provide the foundation to host the collider.
  - Has synergy with potential future Fermilab program in neutrino physics, muon physics and dark matter searches, and an Advanced Muon Facility.

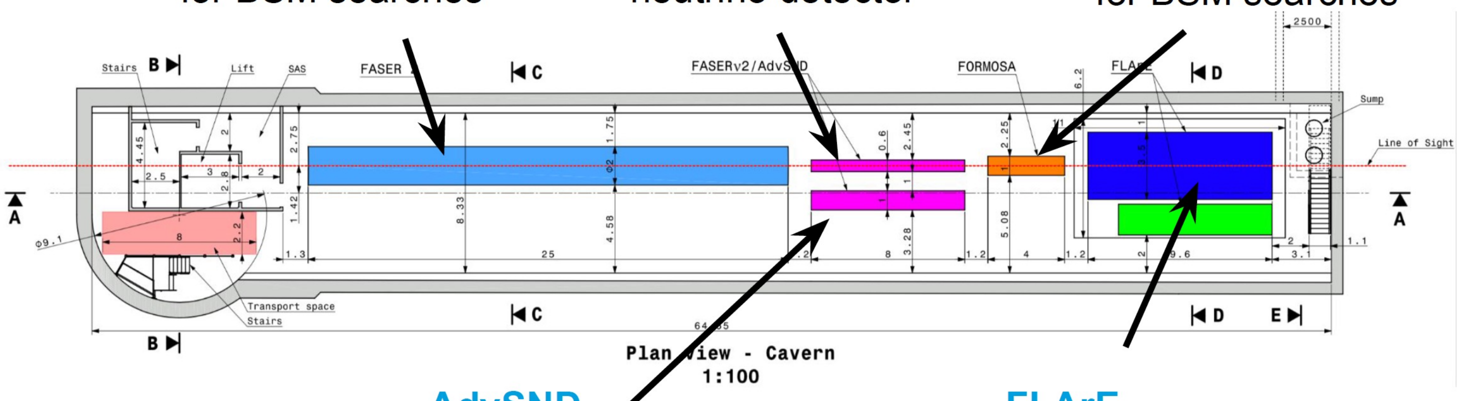
Forward Physics Facility (FPF) Experiments

- At present there are 5 experiments being designed for the FPF at LHC Interaction Point 1 (ATLAS) with diverse technologies optimized for particular SM and BSM topics. FPF covers $\eta > 5.5$, experiments on Line Of Sight cover $\eta \gtrsim 7$.

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

- There are also experiments being designed for CMS (Mathusla, Milliquin, FACET), LHCb (CODEX-b), and ALICE.

> These experiments can provide new phase space for LHC physics and new variety and opportunities for leadership.

Theory Frontier at Snowmass

- The Theory community was very active in the Snowmass process
  - Working to understand and explain the roles of all sectors of the theory community
  - Working with all other frontiers to help them develop their ideas during Snowmass
- There are numerous examples of how progress in theory is as important to overall progress as accumulation of more data, e.g. g-2
  - Many areas are dominated by systematic uncertainties, among which the theory uncertainties may be large. This will become more common as datasets grow.
- Theorists have embraced new opportunities to contribute
  - Inventing and proposing new experiments
  - Participating in the use of ML/AI to improve event generators and simulation tools
  - Beginning to take advantage of public HEP data to study event samples themselves
- Major conclusions:
  - Support the essential role of theory similar to (and at least as strong as) recommended by the European Strategy Update, both in relation to projects and in its own right.
  - **Support for a balanced program of Projects and Research, as both are essential to the health of the field.**
  - **Support for people, especially early career, who are the key "infrastructure" of Research.**
  - **Support for targeted funding advancing the physics goals.** (E.g. LQCD Project, LHC Theory Initiative, Neutrino Theory Network, QIS, AI/ML, Exascale Computing Project, SciDAC…)

Every Frontier expressed strong support for a vibrant theory program

Summing Up and Looking Ahead

The Game is Afoot!

- If we can finish the agenda set forth by the 2014 P5 and embark on the exciting projects that this P5 will prioritize, we will have an exciting future.
  - The "investigation" ahead of us will provide more collaboration and more opportunity to work across disciplines
  - We will be aided by many new tools and techniques, including ML/AI, new sensors, instrumentation, and computing
- As in any investigation
  - Patience, care, and time is required
  - Many good leads will prove to be false
  - Success is not guaranteed, and, at any point, the prospects may seem poor
    - Persistence and skill are both required

From The Hound of the Baskervilles:

"But we hold several threads in our hands, and the odds are that one or other of them guides us to the truth. We may waste time following the wrong one, but sooner or later, we must come upon the right."

A Hoped-for Good Outcome

With our international partners, I hope we will emerge from this P5 with

- An exciting program of new instruments, CMB-S, Spec-S5, and eventually new Gravity Wave Detectors to probe the mysteries of the universe
- A broad, well-supported, investigation of Dark Matter
- A best-in-class DUNE experiment
- Strong participation in the LHC and HL-LHC
- Progress towards a construction start for an international Higgs factory
- R&D towards a next-generation multi-TeV collider
- A program to upgrade to the Fermilab accelerator complex to probe the unknown with a broad, balanced, diverse, discovery program, with a possible emphasis on muons
- Strong, well-supported progrsms of Accelerator and Detector R&D, and Theory efforts to enable the science
- Strong programs in National Initiatives in Microelectronics, QIS, and AI/ML

Concluding remarks

- Thank you for your attention!
- I want to thank the organizers for a most congenial and productive environment and all the speakers for their excellent presentations.

For our field of HEP , we are embarked on an exciting exploration, filled with mysteries and promise, with more interactions with other disciplines, and with mind-blowing new tools and strategies. We can look ahead to an exciting few decades with lots of important work to do!

Backup

Resources

- **Some Resources for Snowmass 2021:**
  - **Link Snowmass Proceedings: https://www.slac.stanford.edu/econf/C210711**
  - **Link to conference homepage for Community Summer Study:** http://seattlesnowmass2021.net/
  - Link to CSS agenda
    - **List : https://indico.fnal.gov/event/22303/timetable/?view=standard**
    - **Block: https://indico.fnal.gov/event/22303/timetable/#20220726.detailed**
  - **CSS SLACK: snowmass2021 – snowmass2021.slack.com**
  - **Link to Snowmass 2021 portal twiki**: https://snowmass21.org/
  - **Link to Contributed papers:** https://snowmass21.org/submissions/
  - **Snowmass Early Career 2021:** https://snowmass21.org/start/young
- **Historical overview – Snowmass 2013/P5 2014**
    - "How to Snowmass (article by C. Quigg)": https://indico.fnal.gov/event/45207/attachments/133652/164937/How_to_Snowmass-final-links.pdf
  - **Snowmass 2013 Book:** https://tinyurl.com/ypfd679z
  - **Link to material and report of P5, 2014**: http://usparticlephysics.org/p5/

Energy Frontier Collider Plans

During Snowmass, several new or modified colliders were proposed driven by (at least) two considerations

- Time to collisions – there was concern that there would be a big gap between the end of the HL-LHC and the beginning of the Higgs factor
  - This has produced a constructive focus on realistic costs and schedules
    - The new collider ideas and their proposed R&D plans were in part intended to address the concerns of costs and schedule
- The U.S. EF community has expressed renewed interest and ambition to develop options for an energy-frontier collider that could be sited in the U.S., while maintaining its international collaborative partnerships and obligations with, for example, CERN.
  - If there are less expensive options that are feasible, they should be considered
  - However, R&D to establish technical feasibility for Higgs factory alternatives would need to be completed by 2028 to match FCC decision timelines
  - **Options to address a multi-TeV collider can have a longer R&D period**
    - **For example, a 6 TeV COM Muon Collider on the FNAL site could fill a gap between FCC-ee and FCC-hh and enable other physics**

The Good News –
There has to be BSM Physics

The quest for BSM physics, which has always been on the agenda, is now more than ever the motivating force in particle physics, leading to many proposals

- experiments to directly search for and observe new phenomena directly.
- Precision measurements of SM processes continue to reveal discrepancies between theory and experiment that can indicate BSM physics, potentially at even higher mass or energy scales than can be observed directly
- Topics whose answers to these questions must lie in physics beyond the SM (BSM physics). include:
  - details of the evolution of the early universe,
  - the origin of the matter-antimatter asymmetry of the universe,
  - the nature of dark matter and dark energy,
  - the origin of neutrino masses,
  - The origin of the electroweak scale and the nature of the Higgs
  - and the origin of flavor dynamics,
  - …

Introduction - I

- We are engaged in an investigation to solve a mystery of how the physical world works, how the universe is put together, and how it began
  - It is one of the most challenging and exciting mysteries humankind has tried to solve
  - We are privileged to live in a time when it has become possible to acquire vast quantities of information **from many sources** to help us make progress in our investigation
  - As with all investigations, certain general strategies apply

Introduction - II

- While it may have started out differently, HEP is now a multidisciplinary investigation using a wide variety of techniques and some special platforms
  - For particle physics,
    - accelerators including both the high energy colliders and intense sources of particles designed for specialized studies, and other facilities
    - Special instruments to address specific problems
  - For astrophysics and cosmology,
    - the universe and especially
    - the Cosmic Microwave background, and
    - Great instruments to observe them

Con

- Direct observation of the new phenomena is the best outcome, but …
- Indirect observation may be all that we can achieve:
  - "How often have I said, when you have eliminated all which is impossible, whatever remains, however improbable, must be the truth" (Sherlock Holmes, The Sign of the Four
- There is no "no lose" theorem – we may not be able to discover the key information that will lead to success
- However, there may be a "no lose" theorem for trying.

Introduction - IV

- We had hoped to be discussing exciting new BSM results from the recent run, but such results have not emerged YET.
- Taking Stock of Our Investigation
  - This meeting brought together these "several threads" in a collegial environment, enabling us to assess where we are in our investigation.
  - We now briefly review these threads and at the end of the talk return to where we go next.

A brief introduction to Axion Searches

- The random initial axial **theta angle θ_0** $=a_0/f_a$ determines the available potential energy to be converted into axion dark matter.
- VEV $f_0 > 10^9$ GeV
- Mass range between 1μeV and 10^{-2} eV
- Density can be very high 10^{16}/liter
- Coupling to photon with strength $g_{a\gamma\gamma}$
- Can resonantly convert a monochromatic microwave signal in a high-Q cavity permeated by a strong B field
- Signal depends on B field strength, cavity volume, Q of cavity
- Frequency is $h\nu=M_aC^2$
- Fine-grained scan over frequency spectrum

Strong CP: Elephant in the room or **Elephant** in the living **room** is an English metaphorical idiom for an obvious problem or risk no one wants to discuss, or a condition of groupthink no one wants to challenge.

Taking Stock of Our Investigation

- We have not found anything new in the first ~40 fb^{-1} at th e LHC
- We expect to double this amount of data in 1 year
- Some may say that our investigation has stalled
- We have spent much of this meeting and similar ones discussing this in one form or another
- Of course, a new result could emerge in the near future, i.e. this spring/summer, as we continue to look at the data already taken
  - That is what will make the next few months very exciting

What to do

- Is it just a matter of taking more data – could the new physics have larger mass than expected or weaker coupling?
- Check the coverage (do a gap analysis) to see if we have left any corner unexplored
  - Similar to identifying the gaps In SUSY coverage from compressed spectra
- Did we introduce, intentionally or not, some assumptions that resulted in our overestimating the sensitivity. Are we oversimplifying?
- Are we taking advantage of all associated fields

What to do

- We need new ideas to try out
  - We have extended our focus to light objects
  - DM was not so much on our horizon when the LHC started
  - We have extended our focus to long-lived objects
- We need new tools and new techniques that will make the data we have and the data we plan to get go farther
  - You saw examples in advanced statistical methods, boosted techniques, improved flavor tagging, and machine learning

A Project Ready to "Approve"

- **Is there a collider construction project ready to be presented for approval?**
  - Physics Case
  - Demonstrated Technical Design
  - Host organization
  - Cost Estimate
  - Plausible demonstration of funding
  - Understanding of how risk will be "shared"
- Until something like this exists, it is not likely a project can move forward in the US

We have done a superb job of developing projects through the first two steps , as seen in this Agora series, but have not done so well at the remaining four tasks.

EF PLAN

The proposed plans in five-year periods starting in 2025 are given below.

- For the five-year period starting in 2025:
  1. Prioritize the HL-LHC physics program, including auxiliary experiments,
  2. Establish a targeted e+e   Higgs Factory Detector R&D program,
  3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
  4. Support critical Detector R&D towards EF multi-TeV colliders.
- For the five-year period starting in 2030:
  1. Continue strong support for the HL-LHC physics program,
  2. Support the construction of an e+e   Higgs Factory,
  3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.
- Plan after 2035:
  1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
  2. Support completing construction and establishing the physics program of the Higgs factory,
  3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
  4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

P5 Members

Panel Members

- *Shoji Asai (University of Tokyo)*
- *Tulika Bose (Wisconsin)*
- *Francis-Yan Cyr-Racine (New Mexico)*
- *Cameron Geddes (LBNL)*
- *Karsten Heeger (Yale) - Deputy Chair*
- *JoAnne Hewett (SLAC) - HEPAP chair, ex officio*
- *Kendall Mahn (Michigan State)*
- *Jelena Maricic (Hawaii)*
- *Christopher Monahan (William & Mary)*
- *Peter Onyisi (Texas Austin)*
- *Tor Raubenheimer (SLAC)*
- *Richard Schnee (South Dakota School of Mines and Technology)*
- *Jesse Thaler (MIT)*
- *Abigail Vieregg (Chicago)*
- *Lindley Winslow (MIT)*
- *Bob Zwaska (Fermilab)*
- *Amalia Ballarino (CERN)*
- *Kyle Cranmer (Wisconsin)*
- *Sarah Demers (Yale)*
- *Yuri Gershtein (Rutgers)*
- *Beate Heinemann (DESY)*
- *Patrick Huber (Virginia Tech)*
- *Rachel Mandelbaum (Carnegie Mellon)*
- *Petra Merkel (Fermilab)*
- *Hitoshi Murayama (Berkeley) - Chair*
- *Mark Palmer (Brookhaven)*
- *Mayly Sanchez (Florida State)*
- *Seon-Hee (Sunny) Seo (IBS Center for Underground Physics)*
- *Christos Touramanis (Liverpool)*
- *Amanda Weinstein (Iowa State)*
- *Tien-Tien Yu (Oregon)*

P5 Scenarios

The panel's report should identify priorities and make recommendations for an optimized particle physics program over 10 years, FY 2024–FY 2033, under the following budget scenarios:

1) Increases of 2.0 percent per year during fiscal years 2024 to 2033 with the FY 2024 level calculated from the FY 2023 President's Budget Request for HEP.

2) Budget levels for HEP for fiscal years 2023 to 2027 specified in the Creating Helpful Incentives to Produce Semiconductors and Science Act of 2022, followed by increases of 3.0 percent per year from fiscal years 2028 to 2033.

P5 charge Signatories

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