Roadmap of Particle Physics in the Next Decade

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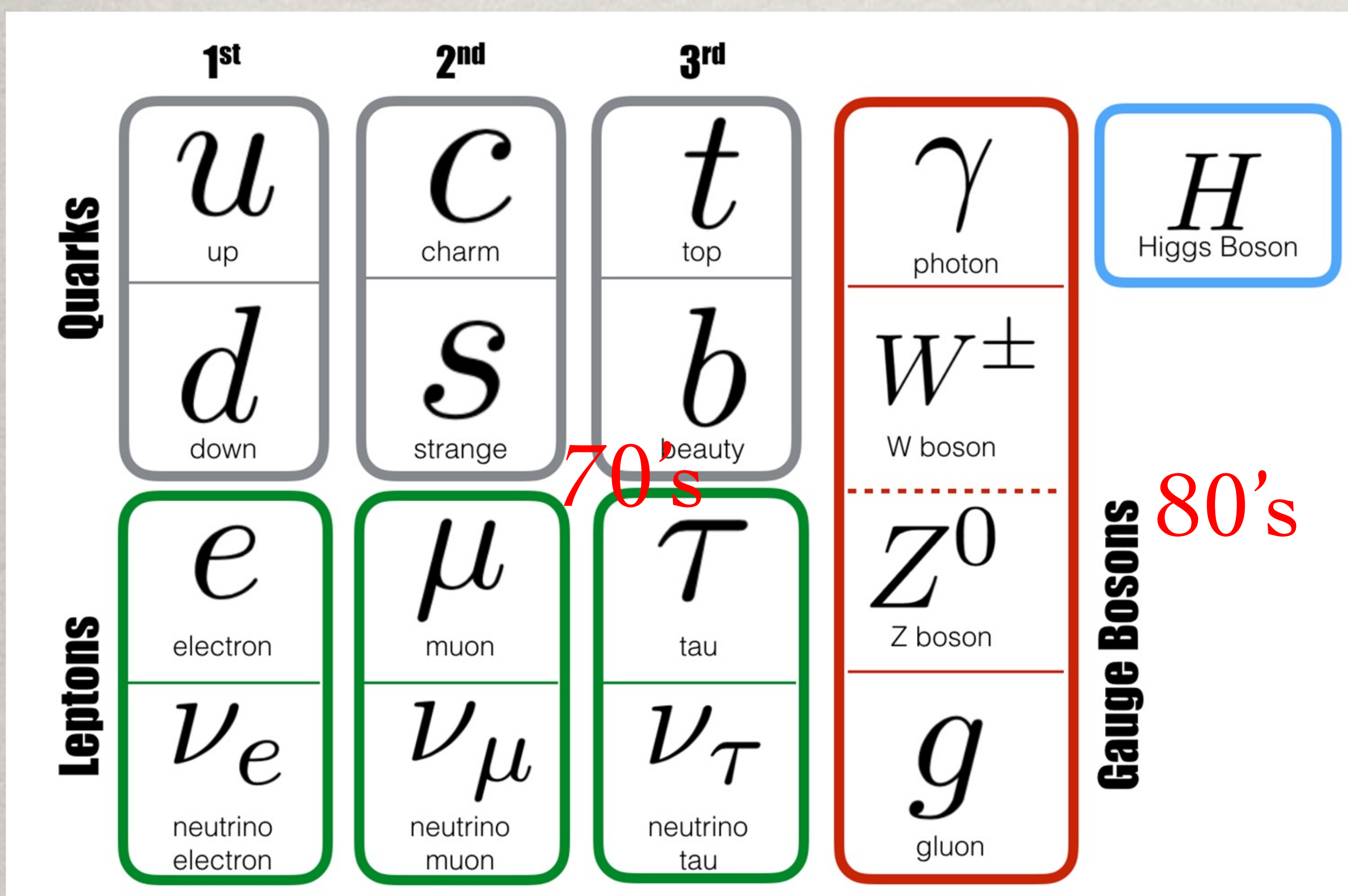
University of Pittsburgh

Nanjin Normal University,
March 13, 2024

高能物理是一个充满活力，激动人心的领域

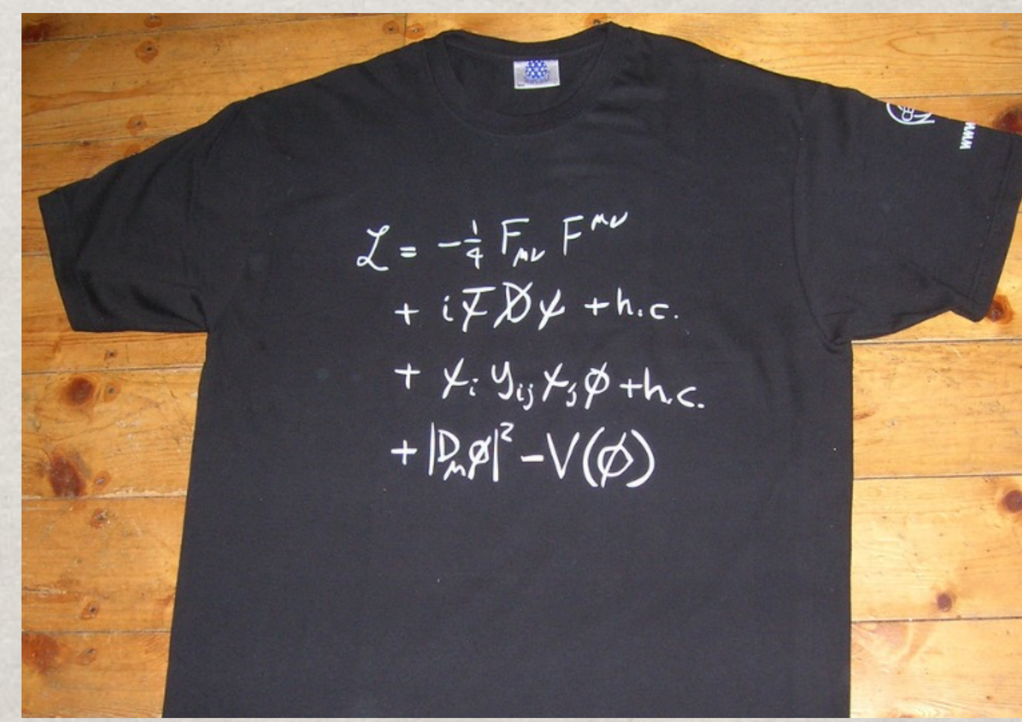
半个世纪以来,
高能物理经历了从无间断的重大发现和发展,
从 quarks 到 Higgs boson,
从理论到实验:

60's 70's 90's 2012



1930/1956 1962 2000

目前科学上最为成功的理论：
“标准模型”



Completion of the SM: 新的里程碑

First time ever, we have a self-consistent theory:

- quantum-mechanical,
- relativistic,
- unitary,
- renormalizable,
- vacuum (quasi) stable, valid up to an exponentially high scale, possible M_{Pl} (!?)

B-asymmetry?
CP violation?

Λ? Dark Matter?
Cosmic inflation?

All known physics

M_ν? Scale hierarchy …

$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \exp\left\{\frac{i}{\hbar}\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{4}F^2 + \bar{\psi}i\not{D}\psi - \lambda\phi\bar{\psi}\psi + |D\phi|^2 - V(\phi)\right]\right\}$$

amplitude
current understanding
quantum mechanics
spacetime
gravity
strong & electroweak
matter
Higgs

高能物理晴朗的天空上飘着几朵乌云

Questions that need an answer:

- Origin of neutrino masses & mixing
- Nature of dark matter
- Matter-antimatter asymmetry
- …

Puzzles that may/may not have an answer:

- Large hierarchy, "naturalness": $m_H / M_{PL} \sim 10^{16}$!
- Fermion mass hierarchy & mixing:

  $m_t : m_e : m_\nu = 1 : 0.3\text{x}10^{-5} : 10^{-11}$!
- Grand Unification of all forces:

  G_F & $\boldsymbol{\alpha} \rightarrow SU(2)_L \otimes U(1)_Y$. What about SU(3)c ?
- Quantum gravity & black holes ?
- Cosmic inflation & dark energy ?
- …

HEP at a Cross-Road: 遇到三岔路口

While there are many fundamental questions,
no clear argument for the next physics scale for discovery!

"Prediction is hard, especially about the future."
"When you come to a fork in the road, take it!"
– Yogi Berra

We must explore all directions!

In the Global Context: 国际状况

• Europe

European Strategy Process:

2020 Update of European Strategy for Particle Physics

HL-LHC; Fcc-ee, Fcc-hh; R&D in accl., detec, theo.

(Feb. 2, 2024: CERN Council midterm review on Fcc project)

• Asia

- Japan: 2017 JAHEP/KEK Roadmap:

  SuperKEKB; J-PARC; Hyper-K; ILC …
- China: BEPC-II; JUNO; PandaX; LHAASO; AliCPT, CEPC/SppC …

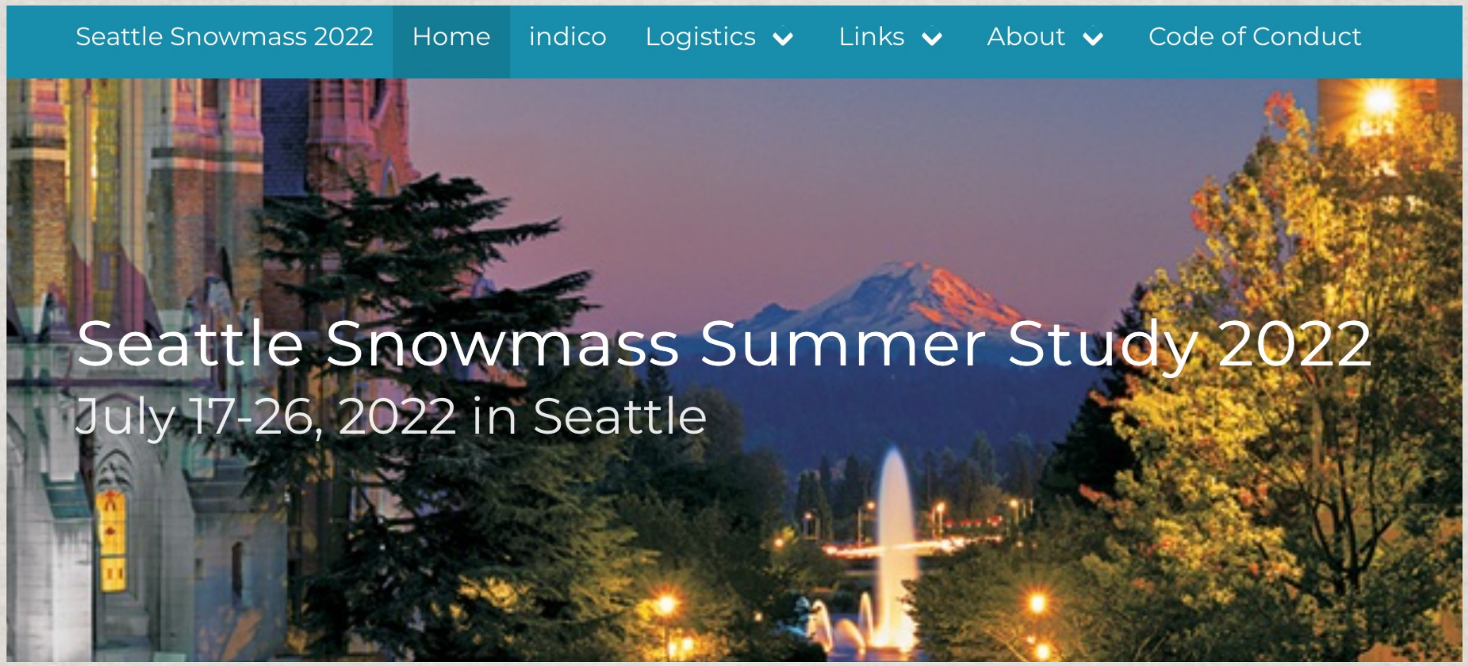
• United States

- NAS Decadal survey on Astronomy & Astrophysics (2021)
- NAS Decadal survey on Elementary Particle Physics (2023)
- Snowmass 2021 for a decadal study: two year work
- P5 (Particle Physics Project Prioritization Panel) final report

U.S. Community Summer Study: Snowmass 2021

July 17 – 26, 2022 @ UW – Seattle

http://seattlesnowmass2021.net



Participants

Number of in-person participants: 743

Number of virtual participants: 654

Local Organizing Committee/Volunteer/Press: 58

Total number of participants: 1397

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

- 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

Snowmass 2021 Succinct Summary:

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.

Opportunities in HEP for the decade & beyond

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 Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Medium- and Small-Scale Future Experiments and Projects:

(see the full frontier reports)

Medium- and small-size experiments and projects are an important component of the current and proposed program.

Because of their shorter timescale and smaller size, these experiments offer unique leadership and training opportunities for younger physicists and allow for greater diversity in the experimental particle physics ecosystem.

Such as SBND, CE**ν**NS; g-2, Mu2e, 0**νββ**, AMF, Belle II; DM …

Mostly science considerations.

Report from the
Particle Physics Project Prioritization Panel (P5)

Hitoshi Murayama & Karsten Heeger

on behalf of the P5 panel

HEPAP Meeting, December 7, 2023

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF National Science Foundation

Explore the Quantum Universe

https://www.usparticlephysics.org/2023-p5-report/

Prioritization Principles

In the process of prioritization, we considered **scientific opportunities, budgetary realism**, **and a balanced portfolio** as major decision drivers.

Large projects (>$250M)
- Paradigm-changing discovery potential
- World-leading
- Unique in the world

Medium projects ($50–250M)
- Excellent discovery potential or development of major tools
- World-class
- Competitive

Small projects (<$50M)
- Discovery potential, well-defined measurements, or outstanding technology development
- World-class
- Excellent training grounds

Prioritization Principles

Overall program should

- **enable US leadership** in core areas of particle physics
- leverage **unique US facilities and capabilities**
- engage with **core national initiatives** to develop key technologies,
- develop a **skilled workforce** for the future that draws on US talent
- realize **effective engagement, partnership, and leadership in international endeavors**

Balance of program in terms of

- Size and time scale of projects
- Inside or outside the US
- Project vs research
- Current vs future investment

Balance and Theory

Balance to the portfolio

- To support a healthy program, we aim for balance across the various project areas

Importance of theory

- While statements were made in support of theory in the previous P5 report, we've seen the funding – particularly at universities – erode, to the detriment of our potential for discover.

Vision of the 2023 Particle Physics Project Prioritization Panel (P5)

We envision a new era of scientific leadership, centered on decoding the quantum realm, unveiling the hidden universe, and exploring novel paradigms. Balancing current and future large- and mid-scale projects with the agility of small projects is crucial to our vision. We emphasize the importance of investing in a highly skilled scientific workforce and enhancing computational and technological infrastructure. Particle physics has a long-proven record of creating new technologies and provides a training ground for a skilled workforce that drives not only fundamental science, but quantum information science, AI/ML, computational modeling, finance, national security, and microelectronics.

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. This includes HL-LHC, the first phase of DUNE and PIP-II, the Rubin Observatory to carry out the Legacy Survey of Space and Time (LSST), and the LSST Dark Energy Science Collaboration.

Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

1. **CMB-S4**, which looks back at the earliest moments of the universe,
2. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam as the definitive long-baseline neutrino oscillation experiment,
3. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,
4. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,
5. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage. The proposed portfolio includes implementing the recommended program, Advancing Science and Technology using Agile Experiments (ASTAE).

Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV parton center-of-momentum (pCM) collider. In particular, the muon collider option builds on Fermilab strengths and capabilities and supports our aspiration to host a major collider facility in the US.

Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

Final report: (Dec. 7, 2023)

https://www.usparticlephysics.org/2023-p5-report/

6 Recommendations:

including 30 action items of ranked priorities,
ranging from particle physics,
astro-particle physics,
particle-cosmology;
balanced projects of O($M - $B) + R&D + theory

20 Area Recommendations:

including suggestions/advice to
agencies, national labs, university programs …

Recommendation 1

Not Rank-Ordered

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. We reaffirm the previous P5 recommendations on major initiatives:

Including:

a. HL-LHC (energy frontier)

b. 1st Phase DUNE & PIP-II (LBN neutrino)

c. The Vera Rubin Observatory (dark energy survey)

Plus smaller scale projects:

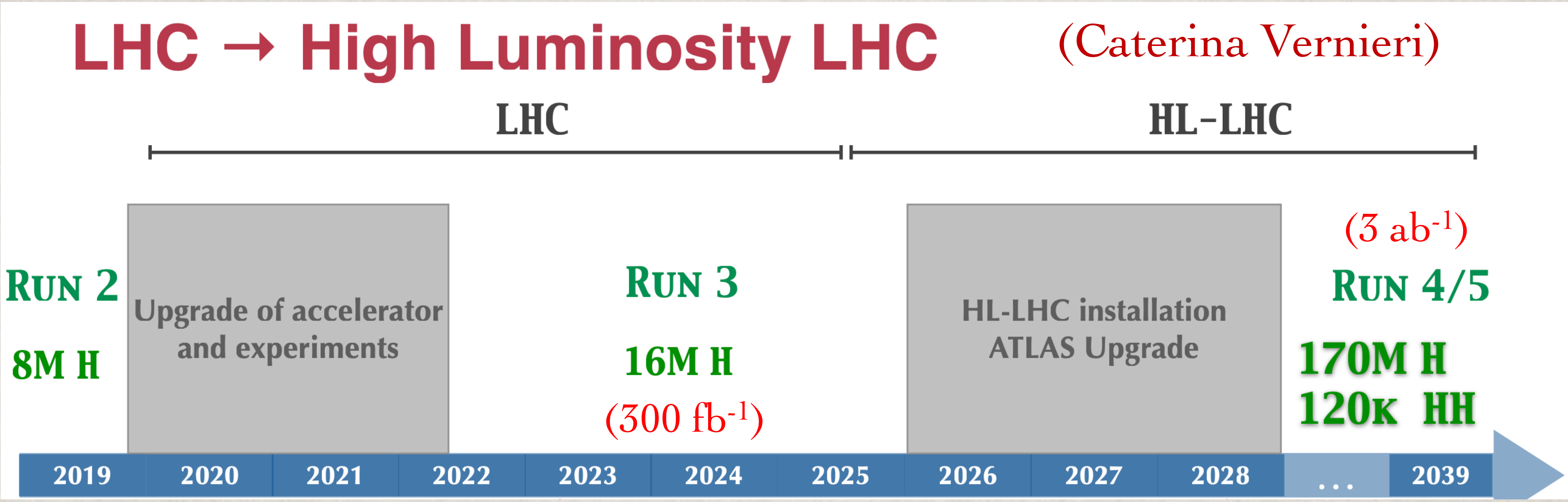
a. NOvA, SBN, T2K, IceCube (neutrino physics)

b. DarkSide, LZ, SuperCDMS, XENONnT (DM direct searches)

c. DESI (DM, inflation)

d. Belle-2, LHCb, Mu2e (flavor physics at higher scales)

a. LHC / HL-LHC:
Lead the energy frontier for the next 15 years!



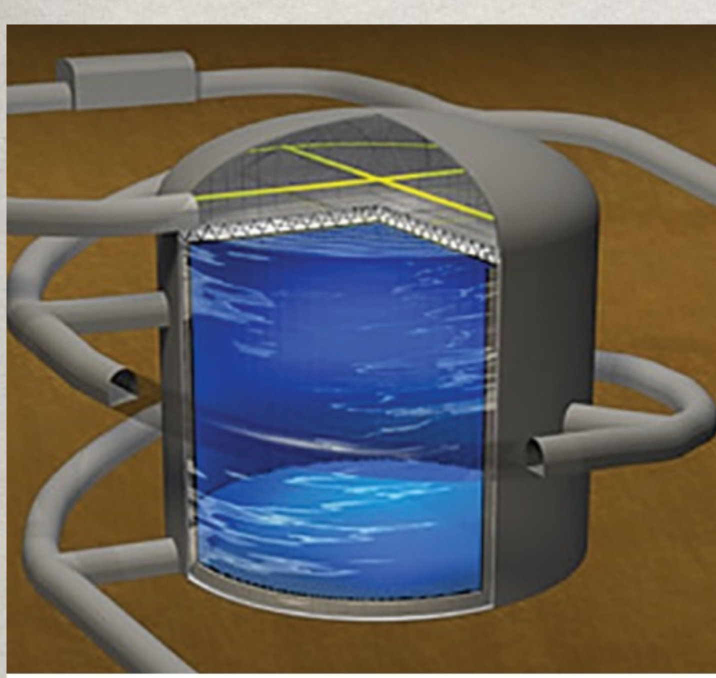
H couplings to:	**O(5-10)%**
H self-coupling to:	**O(50)%**

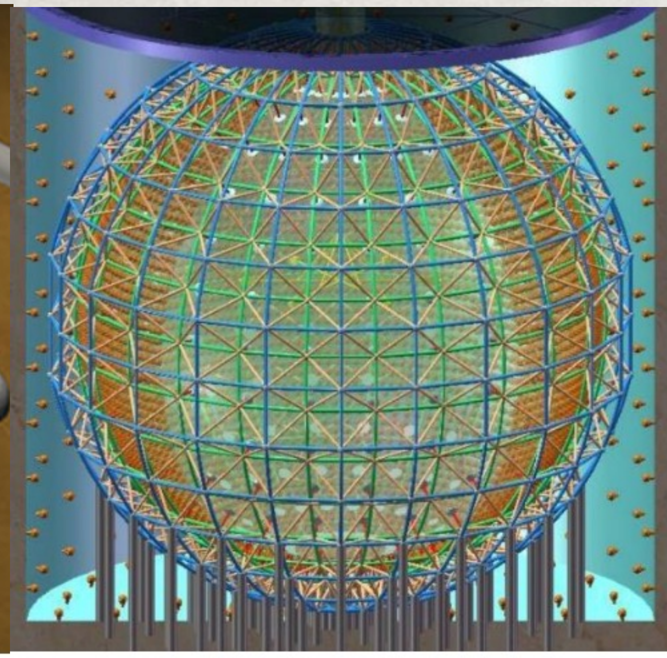
New physics reach:

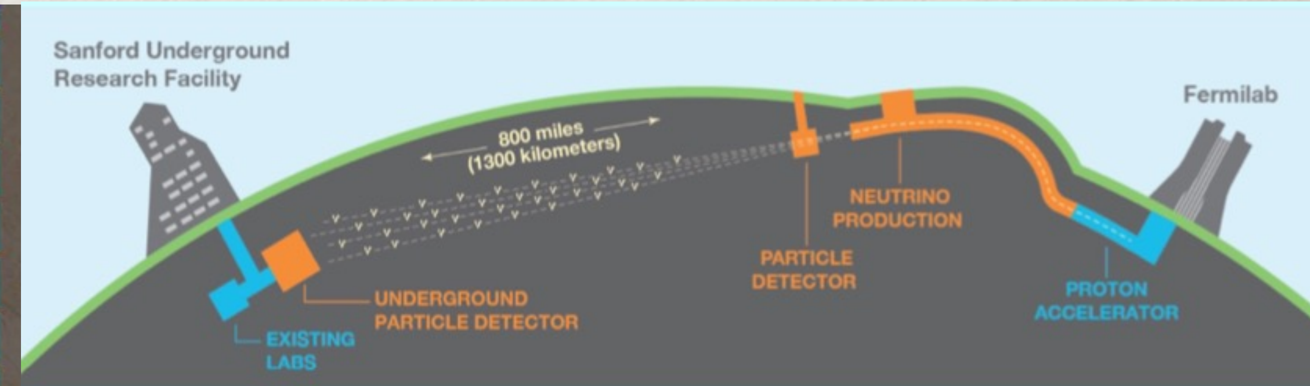
M, Λ ~ O(a few TeV)

just above the EW scale!

b. Next generation of Neutrino Experiments/SN detection







- 1300-km baseline
- 4 10-kton LArTPC modules
- 4850-ft depth

Hyper-Kamiokande
260 kton water

JUNO
20 kton scintillator (hydrocarbon)

(Lianjian Wen)

Exp.	Time	Mass ordering	CP phases	Precision Meas.	CCSN burst @ 10 kpc	DSNB	Geo-ν	Solar	Proton Decay (sensitivity@10 y)
JUNO (20 kt)	2024	**3-4 σ** *6 y*	—	**$\sin^2\theta_{12}$ (0.5%), Δm^2_{21} (0.3%), Δm^2_{31} (0.2%),** *6 y*	**all-flavor ν (IBD, eES, pES)**	**3σ**, *3 y*	**~400/y**	**^{7}Be, pep, CNO, ^{8}B**	> 9.6x10^{33} y ($\bar{\nu}K^+$)
DUNE (17 kt*4)	2030	**>5 σ** *1-3 y*	5σ (50%) *10 y*	Δm^2_{32} ~0.4%, $\sin^2\theta_{23}$~*1.1% *, 15 y*	**^{40}Ar CC & NC, eES**	^{40}Ar CC	—	^{8}B, hep	>8.7x10^{33} y ($e^+\pi^0$) >1.3x10^{34} y ($\bar{\nu}K^+$)
HyperK (260 kt)	2027	**3-5 σ** *10 y*	**5σ (60%)** *10 y*	Δm^2_{32} ~0.6%, $\sin^2\theta_{23}$~*1.6% *, 10 y*	**eES, IBD**	*3σ, 6 y*	—	^{8}B, hep	**>7.8x10^{34} y ($e^+\pi^0$) >3.2x10^{34} y ($\bar{\nu}K^+$)**

c. Vera Rubin Observatory

- Probing dark energy and dark matter.
- Taking an inventory of the solar system.
- Exploring the transient optical sky.
- Mapping the Milky Way.

Recommendation 2

Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

Rank-Ordered

a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

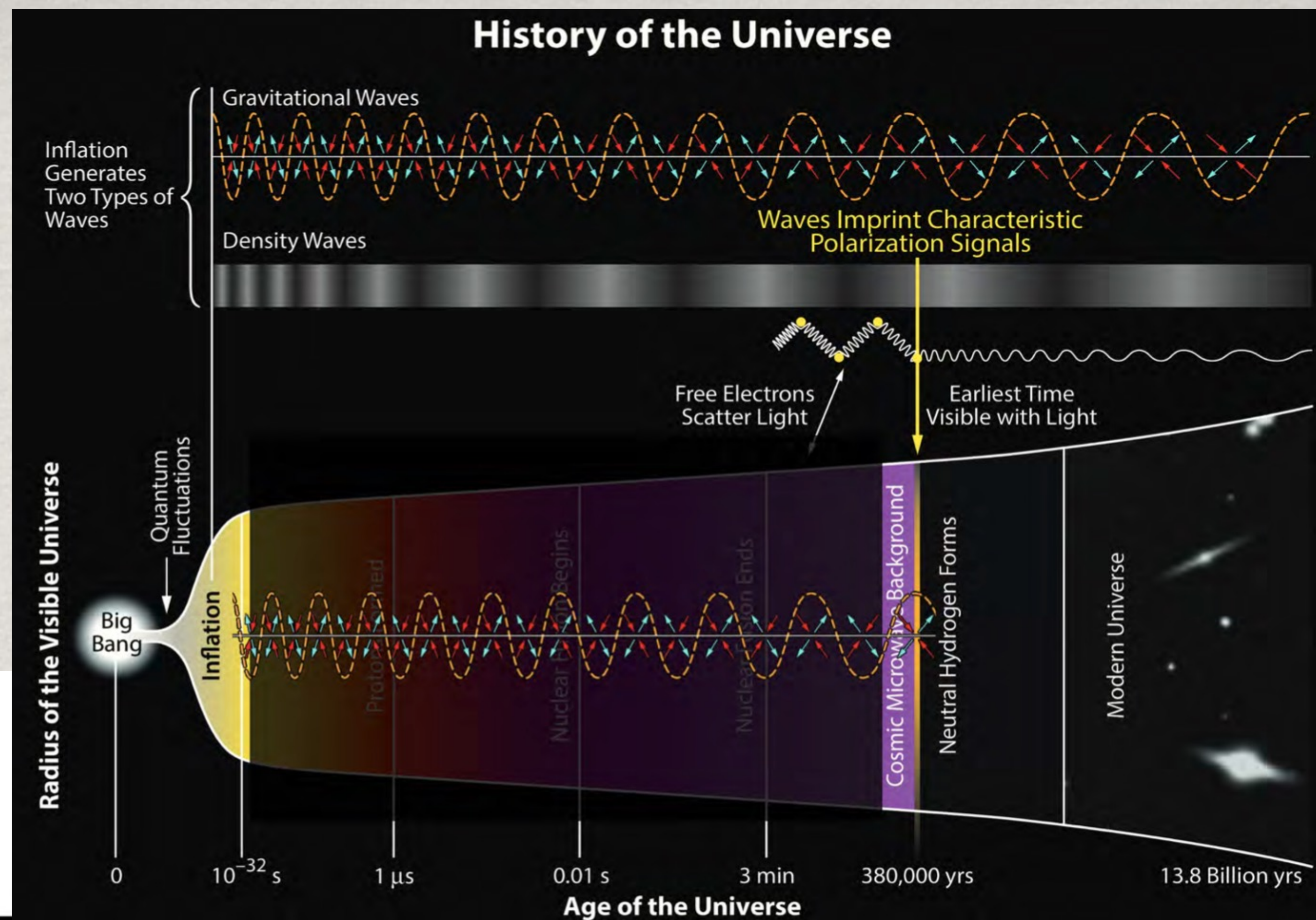
b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project is deemed feasible and well-defined (see also Recommendation 6), the US should aim for a contribution at funding levels commensurate to that of the US involvement in the LHC and HL-LHC, while maintaining a healthy US on-shore program in particle physics (section 3.2).

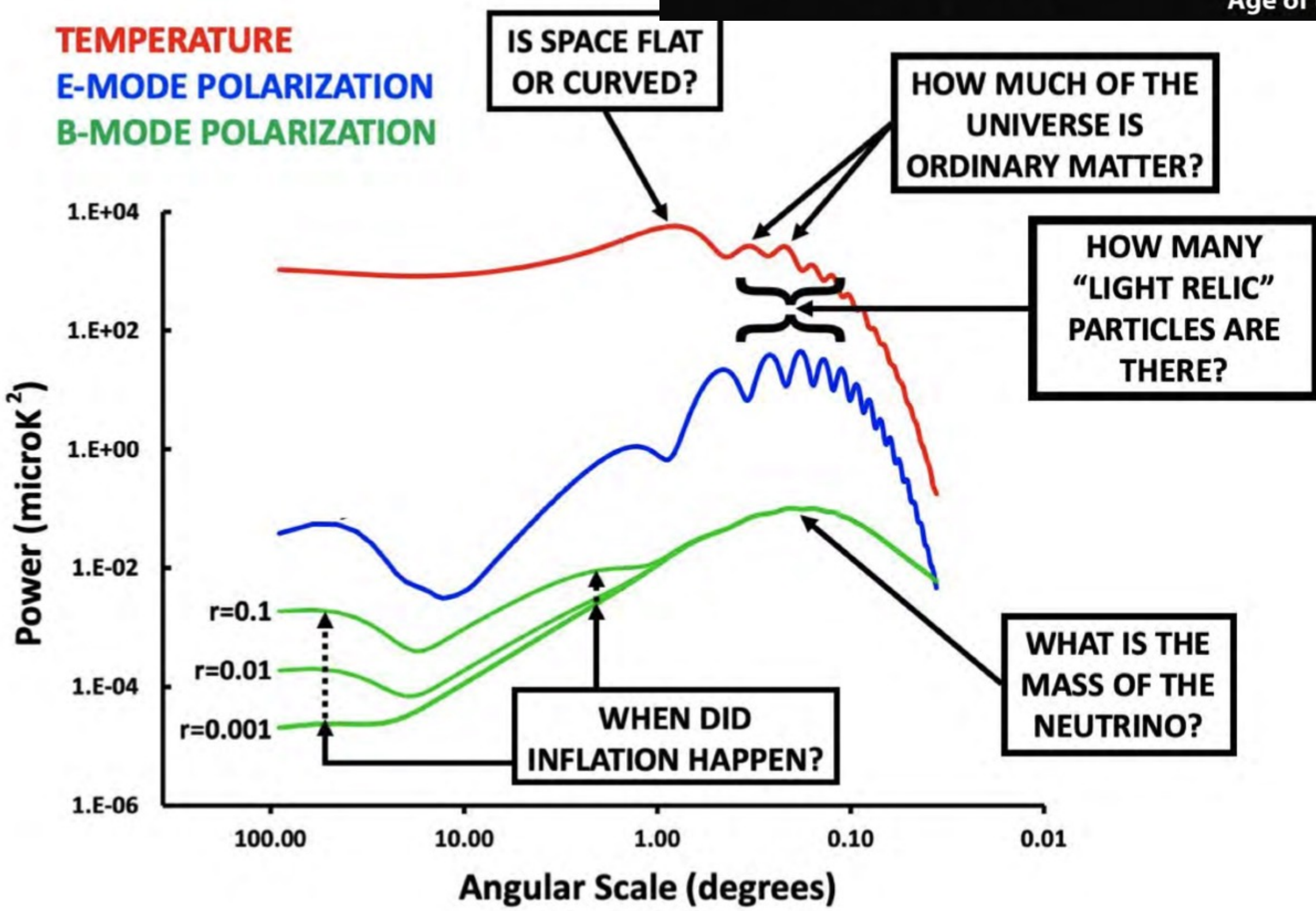
d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

e. **IceCube-Gen2** for study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter covering higher mass ranges using neutrinos as a tool (section 4.1).

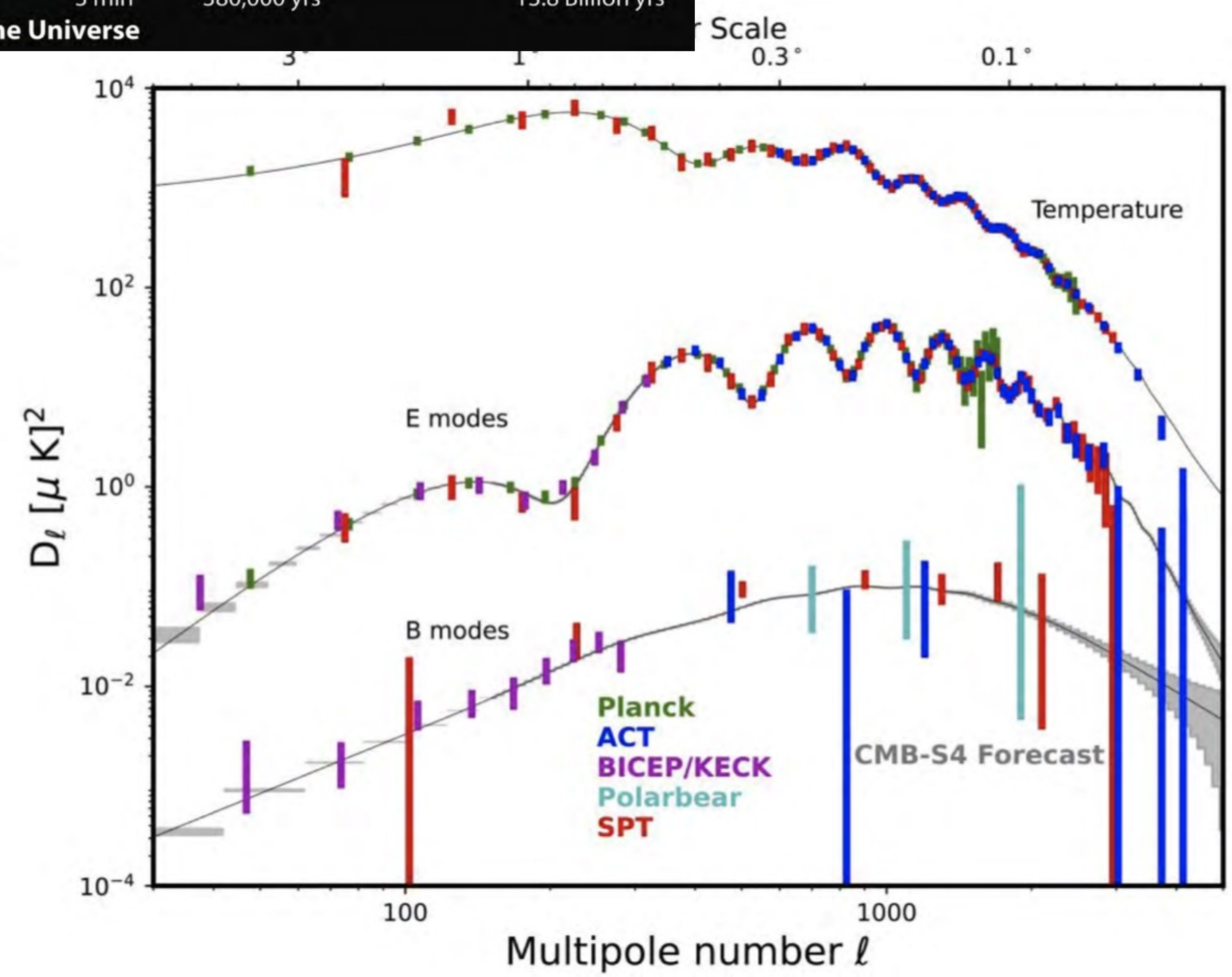
a. CMB S4



History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Quantum Fluctuations
Big Bang
Inflation
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
Radius of the Visible Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe



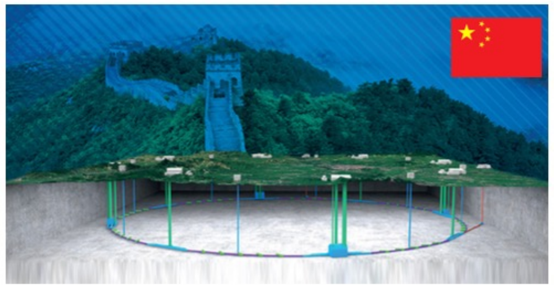
TEMPERATURE
E-MODE POLARIZATION
B-MODE POLARIZATION
IS SPACE FLAT OR CURVED?
HOW MUCH OF THE UNIVERSE IS ORDINARY MATTER?
HOW MANY “LIGHT RELIC” PARTICLES ARE THERE?
WHAT IS THE MASS OF THE NEUTRINO?
WHEN DID INFLATION HAPPEN?
r=0.1
r=0.01
r=0.001
1.E+04
1.E+02
1.E+00
1.E-02
1.E-04
1.E-06
Power (microK^2)
100.00
10.00
1.00
0.10
0.01
Angular Scale (degrees)



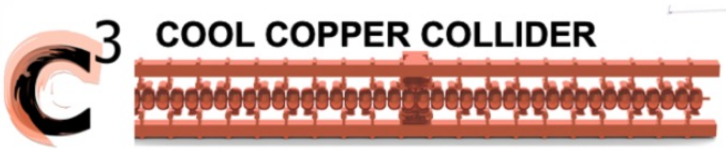
Scale
0.3°
0.1°
10^4
10^2
10^0
10^{-2}
10^{-4}
$D_\ell\ [\mu K]^2$
Temperature
E modes
B modes
Planck
ACT
BICEP/KECK
Polarbear
SPT
CMB-S4 Forecast
100
1000
Multipole number ℓ

c. Off-shore Higgs Factories

250/500 GeV

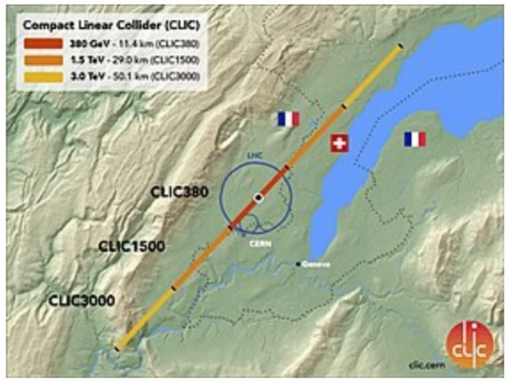


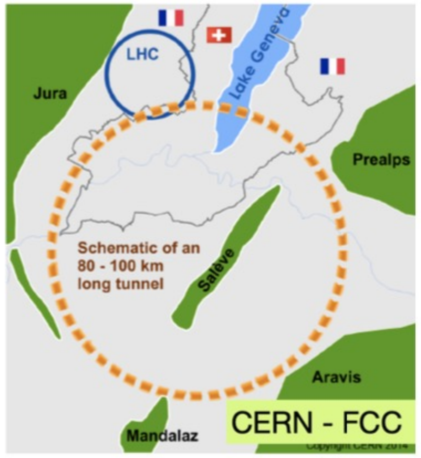
CEPC 240 GeV



250/550 GeV
… > TeV

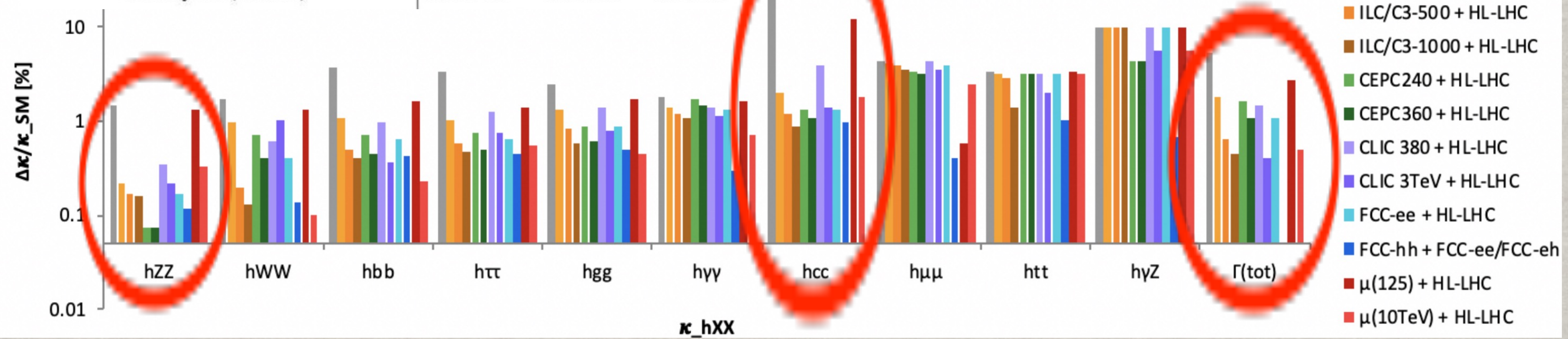
CLIC 380/1500/3000 GeV





FCC-ee
240/365 GeV

Operation mode	Z	W	Higgs
Center-of-mass energy (GeV)	91	160	240
Operation time (year)	2	1	10
Instantaneous luminosity/IP ($10^{34}\text{cm}^{-2}s^{-1}$)	115	16.0	5.0
Integrated luminosity (ab^{-1}, 2 IPs)	60	3.6	12
Event yield (30 MW)	2.5×10^{12}	1.0×10^{8}	2.5×10^{6}



Recommendation 3

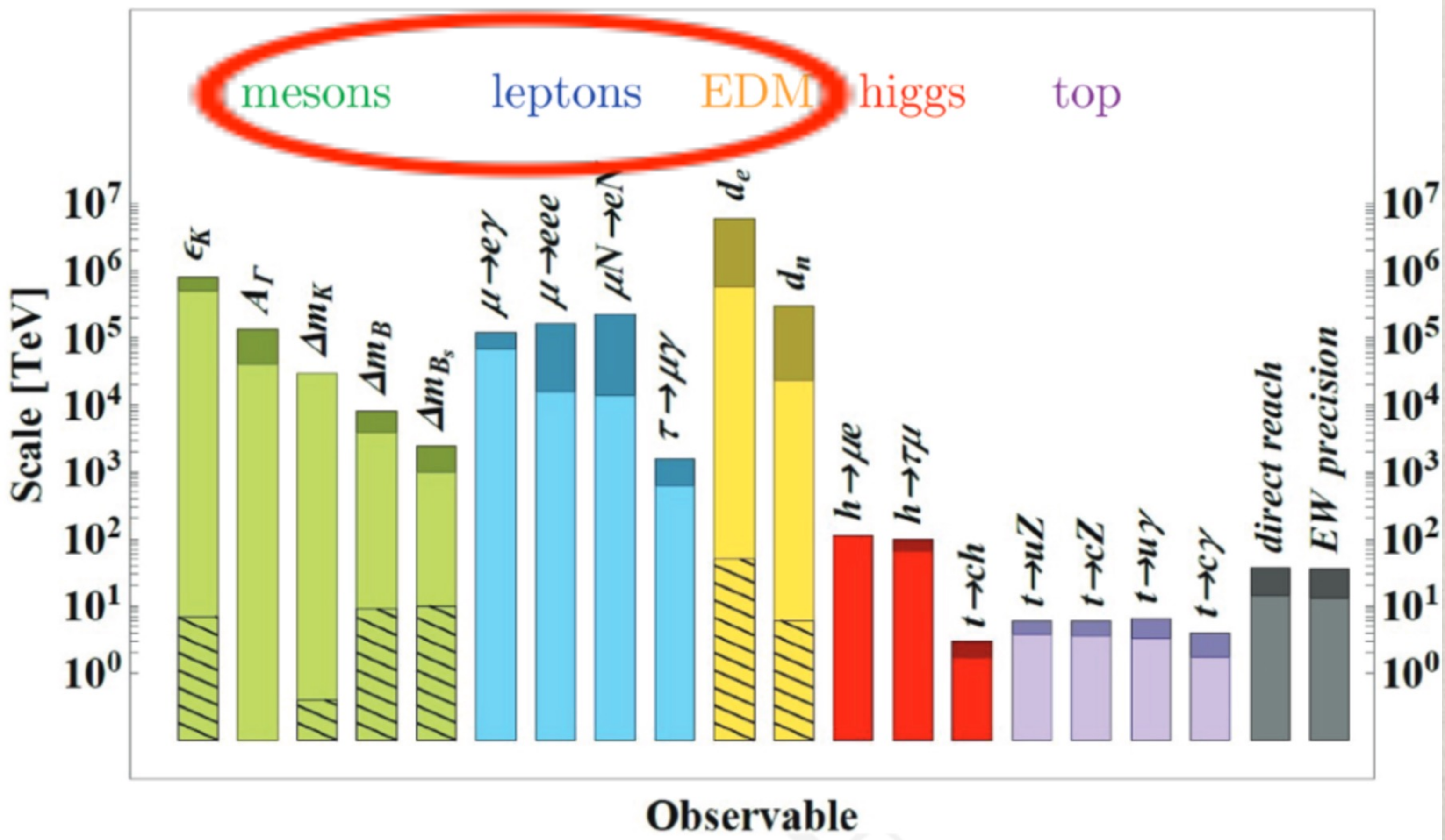
Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

a. Implement a new small-project portfolio at DOE, **Advancing Science and Technology through Agile Experiments (ASTAE)**, across science themes in particle physics with a competitive program and recurring funding opportunity announcements. This program should start with the construction of experiments from the Dark Matter New Initiatives (DMNI) by DOE-HEP (section 6.2).

b. Continue Mid-Scale Research Infrastructure (**MSRI**) and Major Research Instrumentation (**MRI**) programs as a critical component of the NSF research and project portfolio.

c. Support **DESI-II** for cosmic evolution, **LHCb upgrade II** and **Belle II upgrade** for quantum imprints, and **US contributions to the global CTA Observatory** for dark matter (sections 4.2, 5.2, and 4.1).

Precision flavor physics:



Recommendation 4

Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).
b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).
c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).
d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).
e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).
f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).
g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

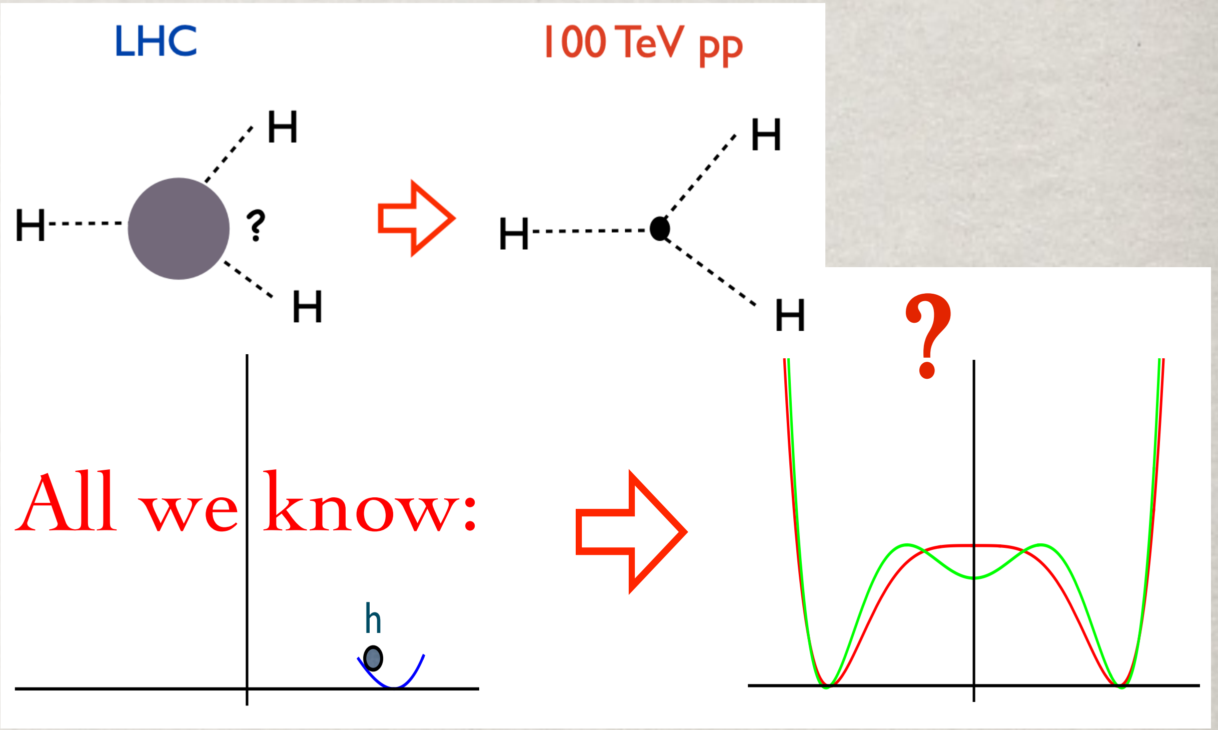
Toward 10 TeV partonic C.M. Energy (pCM)

fully explore the Higgs sector/mechanism & beyond

Precision Higgs physics:

O(1) modification from λ_{hhh}^{SM} →

- Strong 1st order EWPT!
- Possible EW baryogenesis
- Gravitational wave signals?



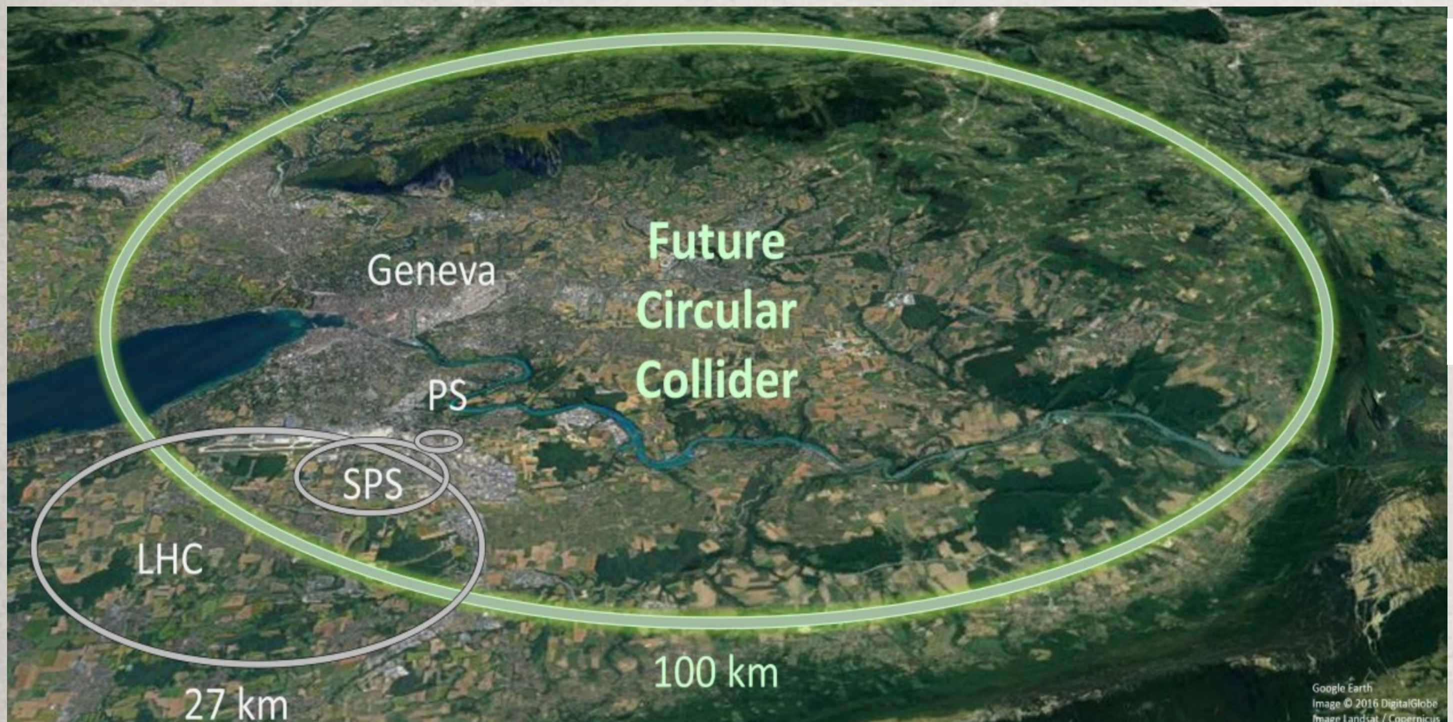
Open a new energy threshold:

- Direct new heavy state production:
  Higgs H^0A^0, H^+H^-; SUSY particles; quarks / leptons reaching $M > E_{cm}/2$.
- Indirect probe of contact interaction / composite scale ~ 100 TeV

proton+proton @ 100 TeV

FCC-hh @ CERN

(see Michelangelo Mangano's talk)



SppC in China

(see Jie Gao's talk)

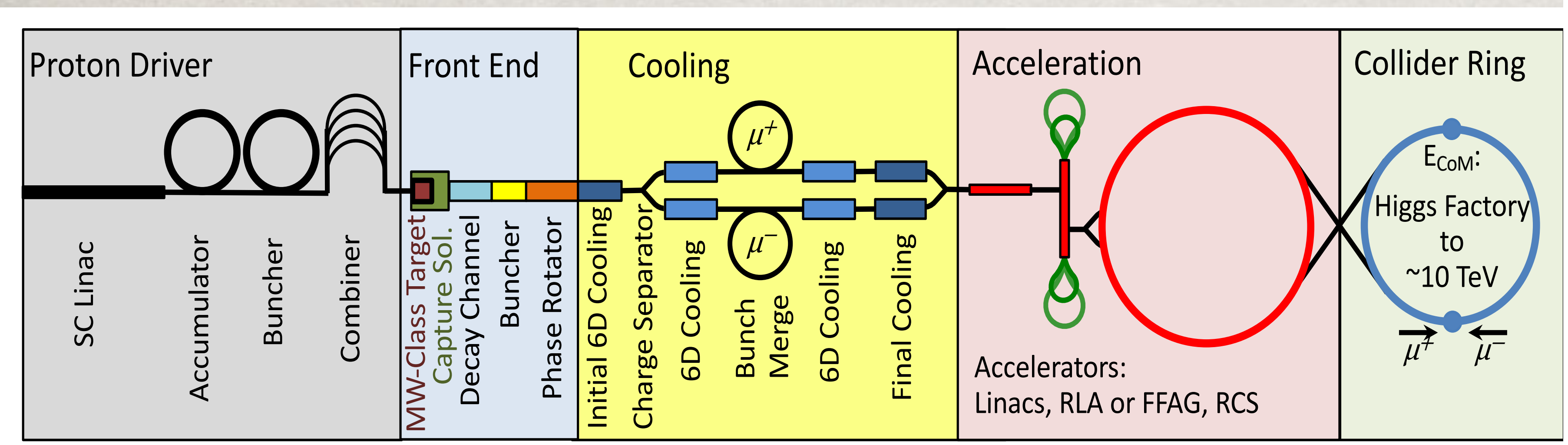
Main parameters		
Circumference	100	km
Beam energy	62.5	TeV
Lorentz gamma	66631	
Dipole field	20.00	T

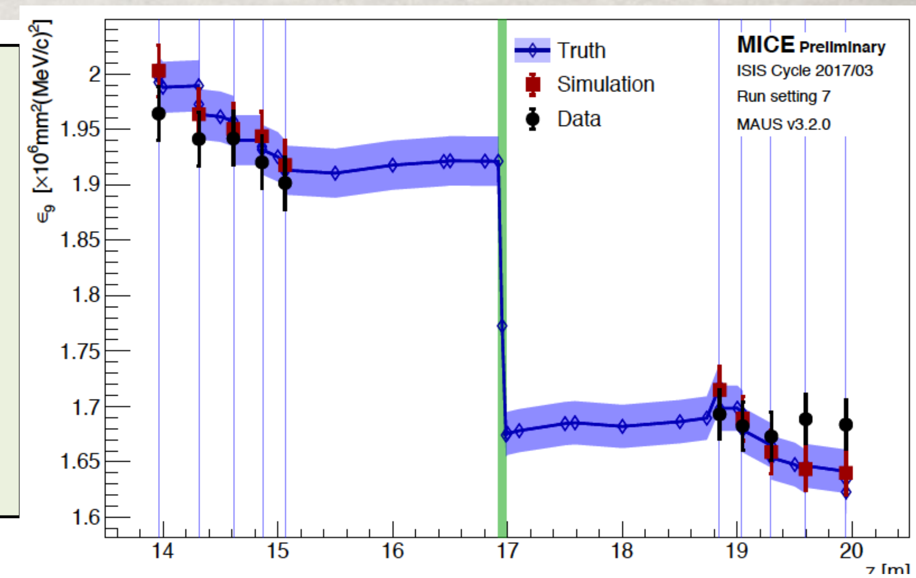
Physics performance and beam parameters		
Initial luminosity per IP	4.3E+34	$cm^{-2}s^{-1}$
Beta function at initial collision	0.5	m

The recent excitement: the "Muon Shot"

Muon Accelerator Project (MAP)

https://arxiv.org/abs/1907.08562, J.P. Delahauge et al., arXiv:1901.06150/





PARTICLE PHYSICS

Particle Physicists Dream of a Muon Collider

After years spent languishing in obscurity, proposals for a muon collider are regaining momentum among particle physicists

By Daniel Garisto on August 28, 2023

The international journal of science / 18 January 2024

nature

US and Europe should team up on muon collider

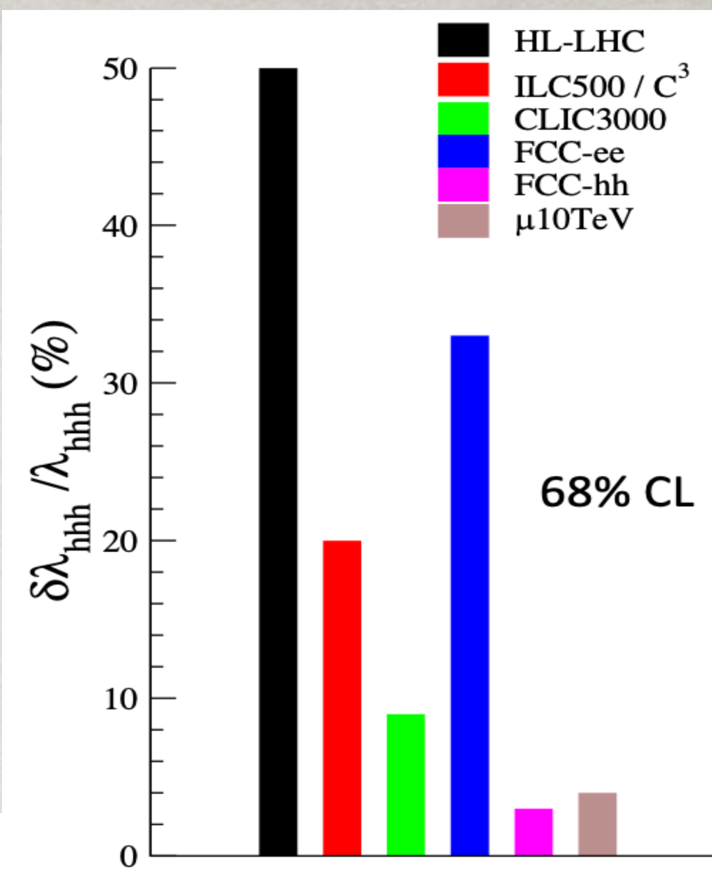
A feasibility study for a muon smasher in the United States could be an affordable way to maintain particle-physics unity.

P5: the path to 10 TeV pCM (partonic c.m. energy):

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

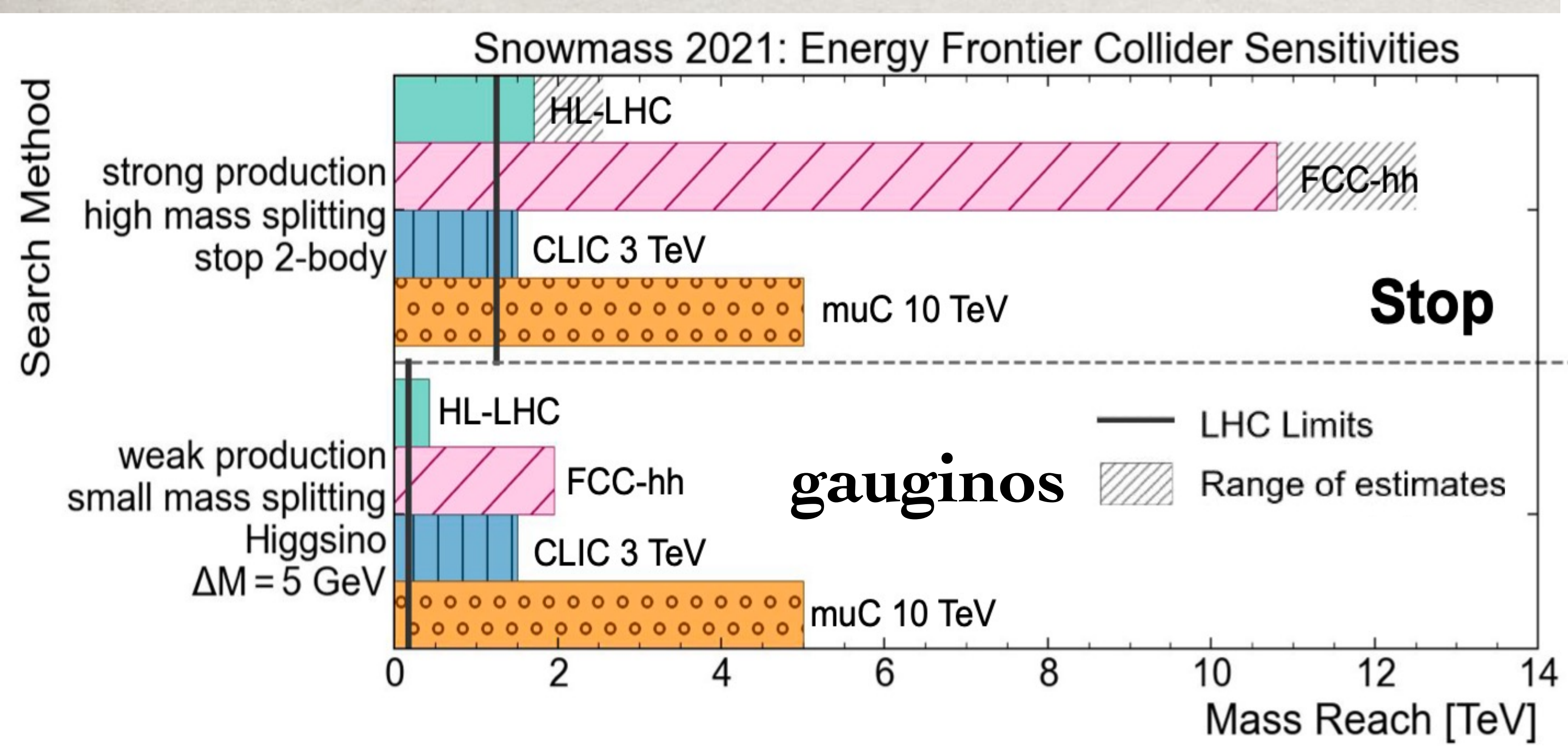
Reach at 10 TeV pCM energies

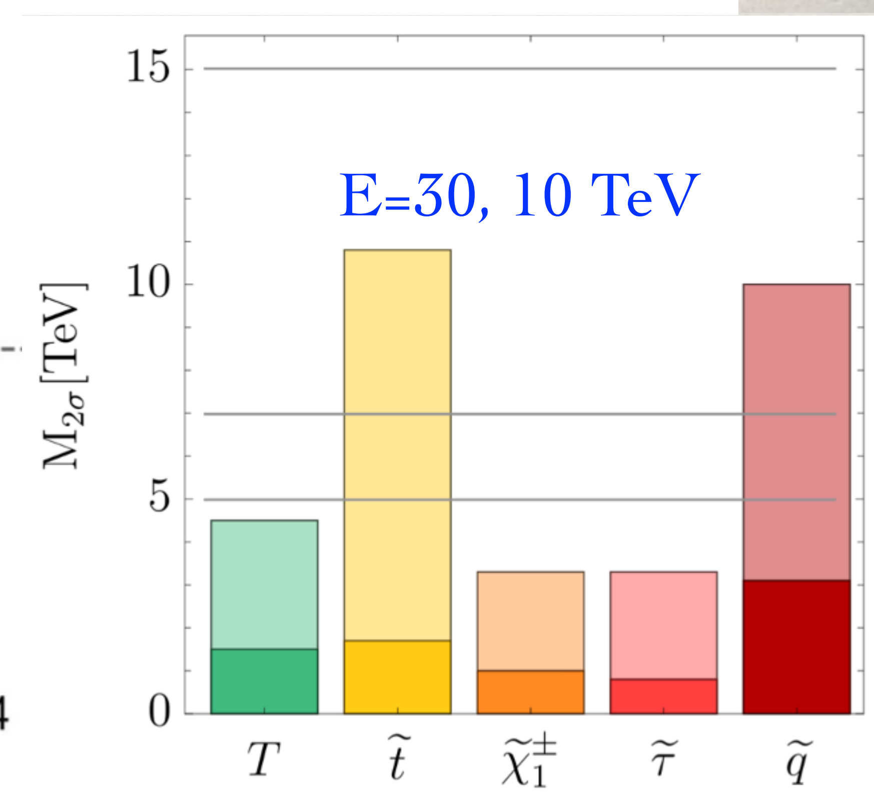
Higgs coupling reach for λ_{hhh}^{SM} →



Pushing the "Naturalness" limit:

The searches for top quark partners & gluinos, gauginos …





→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\%\ (1\ \mathrm{TeV}/\Lambda)^2$

Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

Recommendation 5

Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

a. All projects, workshops, conferences, and collaborations must incorporate ethics agreements that detail expectations for professional conduct and establish mechanisms for transparent reporting, response, and training. These mechanisms should be supported by laboratory and funding agency infrastructure. The efficacy and coverage of this infrastructure should be reviewed by a HEPAP subpanel.

b. Funding agencies should continue to support programs that broaden engagement in particle physics, including strategic academic partnership programs, traineeship programs, and programs in support of dependent care and accessibility. A systematic review of these programs should be used to identify and remove barriers.

c. Comprehensive work-climate studies should be conducted with the support of funding agencies. Large collaborations and national laboratories should consistently undertake such studies so that issues can be identified, addressed, and monitored. Professional associations should spearhead field-wide work-climate investigations to ensure that the unique experiences of individuals engaged in smaller collaborations and university settings are effectively captured.

d. Funding agencies should strategically increase support for research scientists, research hardware and software engineers, technicians, and other professionals at universities.

e. A plan for dissemination of scientific results to the public should be included in the proposed operations and research budgets of experiments. The funding agencies should include funding for the dissemination of results to the public in operation and research budgets.

Recommendation 6

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

1. The level and nature of **US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale **test and demonstrator facilities** in the accelerator and collider R&D portfolios.
3. A plan for the evolution of the **Fermilab accelerator complex** consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Science Experiments

Timeline 2024 – 2034

Science Experiments	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
LHC		P	P		P	P	
LZ, XENONnT			P				
NOvA/T2K	P				S		
SBN	P				S		
DESI/DESI-II	S		S	P			P
Belle II			S		S	P	
SuperCDMS			P				
Rubin/LSST & DESC	S		S	P			P
Mu2e						P	
DarkSide-20k			P				
HL-LHC		P	P		P	P	
DUNE Phase I	P				S	S	S
CMB-S4	S		S	P			P
CTA			S				P
G3 Dark Matter §	S		P				
IceCube-Gen2	P		S				P
DUNE FD3	P				S	S	S
DUNE MCND	P				S	S	
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S

Science Drivers: Neutrinos, Higgs Boson, Dark Matter, Cosmic Evolution, Direct Evidence, Quantum Imprints; Astronomy & Astrophysics

Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

A: Can be considered as part of ASTAE with reduced scope

				Science Drivers						
US Construction Cost >$3B				Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
Scenarios	Less	Baseline	More							
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	A	A	A			P		P		
FPF #	A	A	A	P		P		P		

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	Next Gen. Grav. Wave Observatory*
	✓ Spectroscopic Survey - S5*	✓ Line Intensity Mapping*
	✓ Multi-Scale Dark Matter Program (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.*

The particle physics case for studying gravitational waves at all frequencies should be explored by expanded theory support.

✓ **Recommended**

✓ **R&D**

Area Recommendations

20 in total, including suggestions/advice to agencies, national labs, university programs …

Theory

1. **Increase DOE HEP-funded university-based theory research by $15 million per year in 2023 dollars (or about 30% of the theory program)**, to propel innovation and ensure international competitiveness. Such an increase would bring theory support back to 2010 levels. Maintain DOE lab-based theory groups as an essential component of the theory community.

ASTAE

2. For the ASTAE program to be agile, we recommend a **broad, predictable, and recurring (preferably annual) call for proposals**. This ensures the flexibility to target emerging opportunities and fields. A program on the scale of **$35 million per year in 2023 dollars** is needed to ensure a healthy pipeline of projects.
3. To preserve the agility of the ASTAE program, **project management** requirements should be outlined for the portfolio and should be adjusted to be commensurate with the scale of the experiment.
4. A successful ASTAE experiment involves 3 phases: **design, construction, and operations**. A design phase proposal should precede a construction proposal, and construction proposals are considered from projects within the group that have successfully completed their design phase.
5. **The DMNI projects** that have successfully completed their design phase and are ready to be reviewed for construction, **should form the first set of construction proposals for ASTAE.** The corresponding design phase call would be **open to proposals from all areas of particle physics.**

Instrumentation

6. **Increase the annual budget for generic Detector R&D by at least $20 million** in 2023 dollars. This should be supplemented by additional funds for the collider R&D program
7. The detector R&D program should continue to leverage national initiatives such as QIS, microelectronics, and AI/ML.

General Accelerator R&D

8. **Increase annual funding to the General Accelerator R&D program by $10M per year** in 2023 dollars to ensure US leadership in key areas.
9. Support generic accelerator R&D with the construction of small scale test facilities. Initiate construction of larger test facilities based on project review, and informed by the collider R&D program.

Collider R&D

10. To enable targeted R&D before specific collider projects are established in the US, an investment in **collider detector R&D funding at the level of $20M per year** and **collider accelerator R&D at the level of $35M per year** in 2023 dollars is warranted.

Area Recommendation 11: To successfully deliver major initiatives and leading global projects, we recommend that:

a. National Laboratories and facilities should work with funding agencies to establish and maintain streamlined access policies enabling efficient remote and on-site collaboration by international and domestic partners.

b. National Laboratories should prioritize the facilitation of procurement processes and ensure robust technical support for experimenters.

c. National Laboratories and facilities should prioritize the creation and maintenance of a supportive, inclusive, and welcoming culture.

Area Recommendation 12: Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex within the next five years for consideration (Recommendation 6). Direct task force funding of up to $10M should be provided.

Area Recommendation 13: Assess the Booster synchrotron and related systems for reliability risks through the first decade of DUNE operation, and take measures to preemptively address these risks.

Area Recommendation 14: To provide infrastructure for neutrino and/or dark matter experiments, we recommend DOE fund the cavern outfitting of the SURF expansion.

Area Recommendation 15: Maintaining the capabilities of NSF's infrastructure at the South Pole, focused on enabling future world-leading scientific discoveries, is essential. We recommend continued direct coordination and planning between NSF-OPP and the CMB-S4 and IceCube-Gen2 projects, which is of critical importance to the field of particle physics.

Area Recommendation 16: Resources for national initiatives in AI/ML, quantum, computing, and microprocessors should be leveraged and incorporated into research and R&D efforts to maximize the physics reach of the program.

Area Recommendation 17: Add support for a sustained R&D effort at the level of $9M per year in 2023 dollars to adapt software and computing systems to emerging hardware, incorporate other advances in computing technologies, and fund directed efforts to transition those developments into systems used for operations of experiments and facilities.

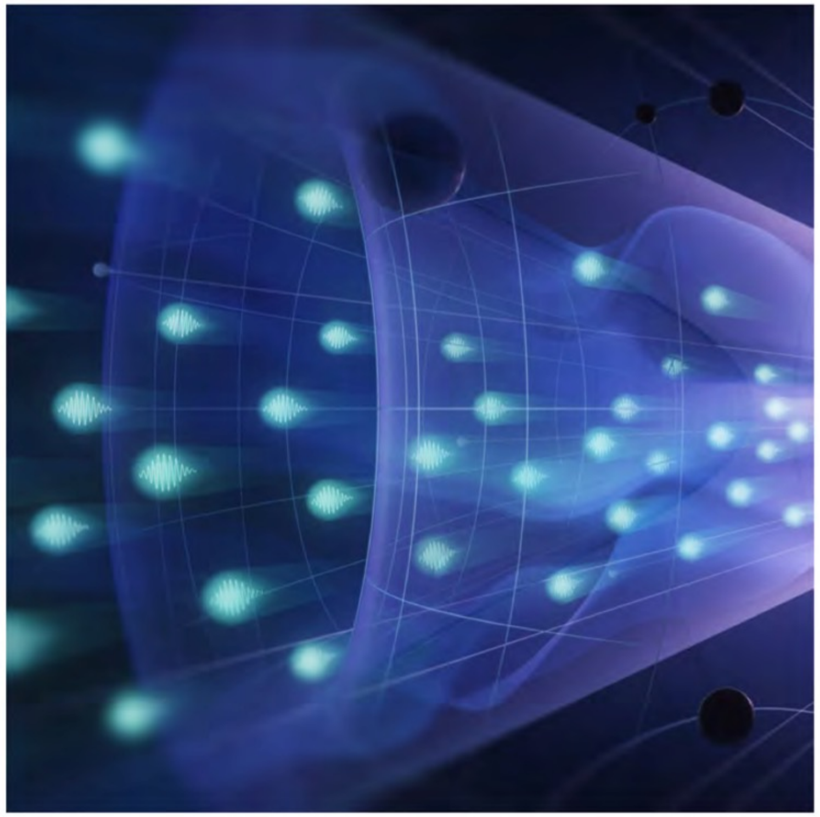
Area Recommendation 18: Through targeted investments at the level of $8M per year in 2023 dollars, ensure sustained support for key cyberinfrastructure components. This includes widely-used software packages, simulation tools, information resources such as the Particle Data Group and INSPIRE, as well as the shared infrastructure for preservation, dissemination, and analysis of the unique data collected by various experiments and surveys in order to realize their full scientific impact.

Area Recommendation 19: Research software engineers and other professionals at universities and labs are key to realizing the vision of the field and are critical for maintaining a technologically advanced workforce. We recommend that the funding agencies embrace these roles as a critical component of the workforce when investing in software, computing, and cyberinfrastructure.

Area Recommendation 20: HEPAP, potentially in collaboration with international partners, should conduct a dedicated study aiming at developing a sustainability strategy for particle physics.

Conclusion:

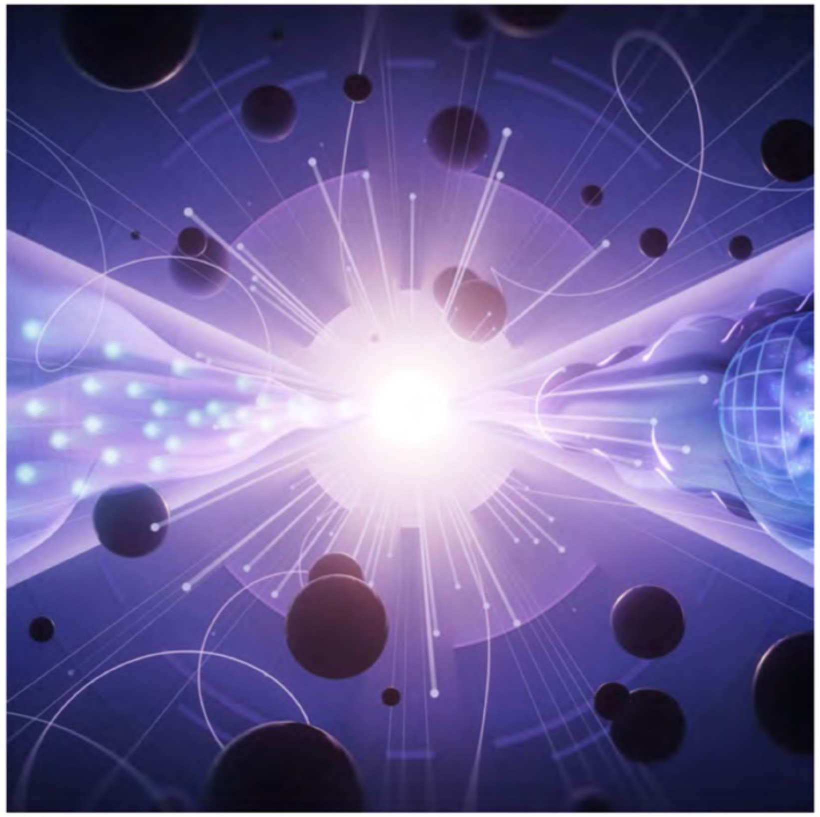
Pathways to Innovation & Discovery in Particle Physics in the next Decade & Beyond



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

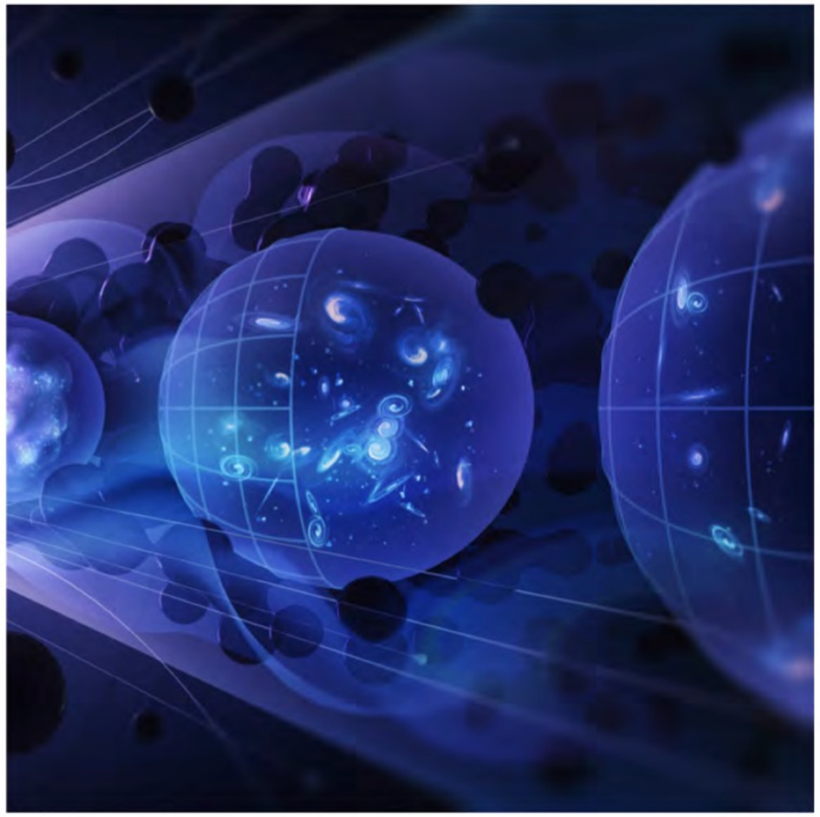
Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena



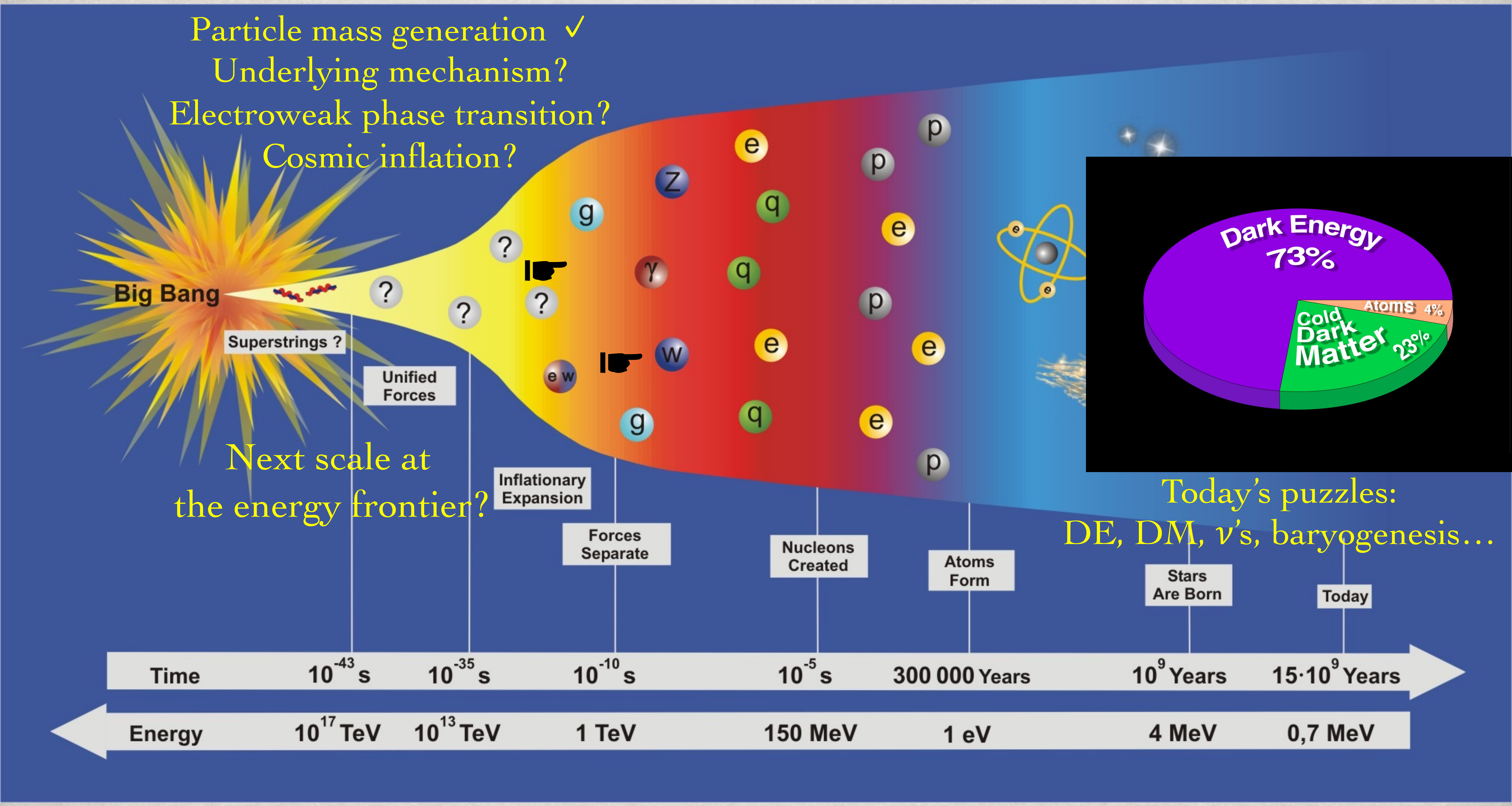
Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Exciting roadmap ahead!

A GRAND PICTURE: 纵观全局



THE FUTURE OF HEP IS BRIGHT!
EXCITING JOURNEY AHEAD!