ROADMAP OF PARTICLE PHYSICS

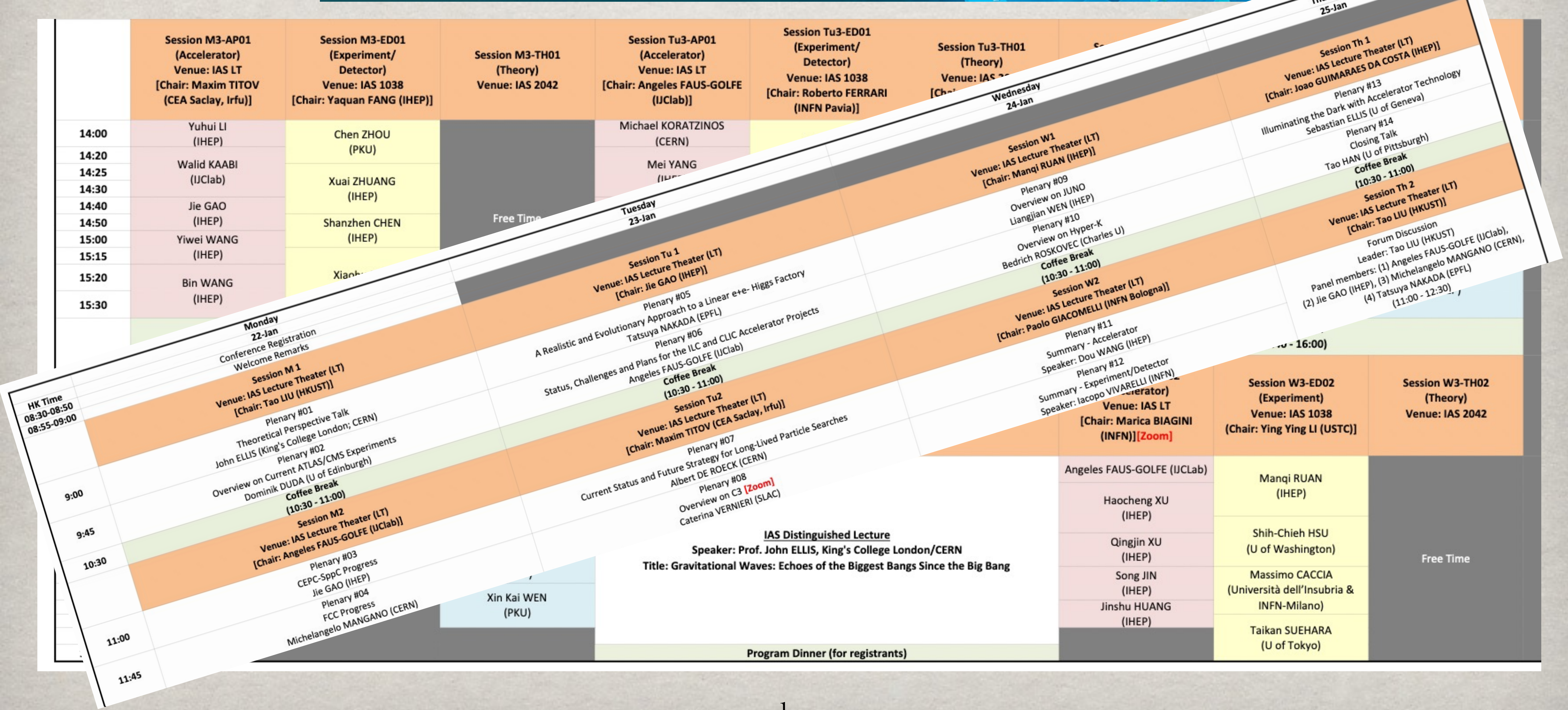
In light of the 2023 P5 Report

韩涛 Tao Han

University of Pittsburgh

IAS Program, HEP 2024
HKUST IAS, Jan. 25, 2024

Highly successful workshop & a conference!
Congratulations to the organizers & participants!



Session M3-AP01 (Accelerator) Venue: IAS LT [Chair: Maxim TITOV (CEA Saclay, Irfu)]
Session M3-ED01 (Experiment/ Detector) Venue: IAS 1038 [Chair: Yaquan FANG (IHEP)]
Session M3-TH01 (Theory) Venue: IAS 2042
Session Tu3-AP01 (Accelerator) Venue: IAS LT [Chair: Angeles FAUS-GOLFE (IJClab)]
Session Tu3-ED01 (Experiment/ Detector) Venue: IAS 1038 [Chair: Roberto FERRARI (INFN Pavia)]
Session Tu3-TH01 (Theory) Venue: IAS 2

14:00
14:20
14:25
14:30
14:40
14:50
15:00
15:15
15:20
15:30

Yuhui LI (IHEP)
Walid KAABI (IJClab)
Jie GAO (IHEP)
Yiwei WANG (IHEP)
Bin WANG (IHEP)

Chen ZHOU (PKU)
Xuai ZHUANG (IHEP)
Shanzhen CHEN (IHEP)
Xiaoh

Free Time

Michael KORATZINOS (CERN)
Mei YANG (IH

Xin Kai WEN (PKU)

IAS Distinguished Lecture
Speaker: Prof. John ELLIS, King's College London/CERN
Title: Gravitational Waves: Echoes of the Biggest Bangs Since the Big Bang

Program Dinner (for registrants)

Ac
celerator)
Venue: IAS LT
[Chair: Marica BIAGINI (INFN)][Zoom]

Session W3-ED02 (Experiment) Venue: IAS 1038 (Chair: Ying Ying LI (USTC)]
Session W3-TH02 (Theory) Venue: IAS 2042

Angeles FAUS-GOLFE (IJCLab)
Haocheng XU (IHEP)
Qingjin XU (IHEP)
Song JIN (IHEP)
Jinshu HUANG (IHEP)

Manqi RUAN (IHEP)
Shih-Chieh HSU (U of Washington)
Massimo CACCIA (Università dell'Insubria & INFN-Milano)
Taikan SUEHARA (U of Tokyo)

Free Time

0 - 16:00)

HK Time
08:30-08:50
08:55-09:00
9:00
9:45
10:30
11:00
11:45

Monday
22-Jan
Conference Registration
Welcome Remarks
Session M 1
Venue: IAS Lecture Theater (LT)
[Chair: Tao LIU (HKUST)]
Plenary #01
Theoretical Perspective Talk
John ELLIS (King's College London; CERN)
Plenary #02
Overview on Current ATLAS/CMS Experiments
Dominik DUDA (U of Edinburgh)
Coffee Break
(10:30 - 11:00)
Session M2
Venue: IAS Lecture Theater (LT)
[Chair: Angeles FAUS-GOLFE (IJClab)]
Plenary #03
CEPC-SppC Progress
Jie GAO (IHEP)
Plenary #04
FCC Progress
Michelangelo MANGANO (CERN)

Tuesday
23-Jan
Session Tu 1
Venue: IAS Lecture Theater (LT)
[Chair: Jie GAO (IHEP)]
Plenary #05
A Realistic and Evolutionary Approach to a Linear e+e- Higgs Factory
Tatsuya NAKADA (EPFL)
Plenary #06
Status, Challenges and Plans for the ILC and CLIC Accelerator Projects
Angeles FAUS-GOLFE (IJClab)
Coffee Break
(10:30 - 11:00)
Session Tu2
Venue: IAS Lecture Theater (LT)
[Chair: Maxim TITOV (CEA Saclay, Irfu)]
Plenary #07
Current Status and Future Strategy for Long-Lived Particle Searches
Albert DE ROECK (CERN)
Plenary #08
Overview on C3 [Zoom]
Caterina VERNIERI (SLAC)

Wednesday
24-Jan
Session W1
Venue: IAS Lecture Theater (LT)
[Chair: Manqi RUAN (IHEP)]
Plenary #09
Overview on JUNO
Liangjian WEN (IHEP)
Plenary #10
Overview on Hyper-K
Bedrich ROSKOVEC (Charles U)
Coffee Break
(10:30 - 11:00)
Session W2
Venue: IAS Lecture Theater (LT)
[Chair: Paolo GIACOMELLI (INFN Bologna)]
Plenary #11
Summary - Accelerator
Speaker: Dou WANG (IHEP)
Plenary #12
Summary - Experiment/Detector
Speaker: Iacopo VIVARELLI (INFN)

Thursday
25-Jan
Session Th 1
Venue: IAS Lecture Theater (LT)
[Chair: Joao GUIMARAES DA COSTA (IHEP)]
Plenary #13
Illuminating the Dark with Accelerator Technology
Sebastian ELLIS (U of Geneva)
Plenary #14
Closing Talk
Tao HAN (U of Pittsburgh)
Coffee Break
(10:30 - 11:00)
Session Th 2
Venue: IAS Lecture Theater (LT)
[Chair: Tao LIU (HKUST)]
Forum Discussion
Leader: Tao LIU (HKUST)
Panel members: (1) Angeles FAUS-GOLFE (IJClab), (2) Jie GAO (IHEP), (3) Michelangelo MANGANO (CERN), (4) Tatsuya NAKADA (EPFL)
(11:00 - 12:30)

OPPORTUNITIES IN PARTICLE PHYSICS

Tao Han
University of Pittsburgh

IAS, HKUST
February 16, 2023


shutterstock.com - 1061946965

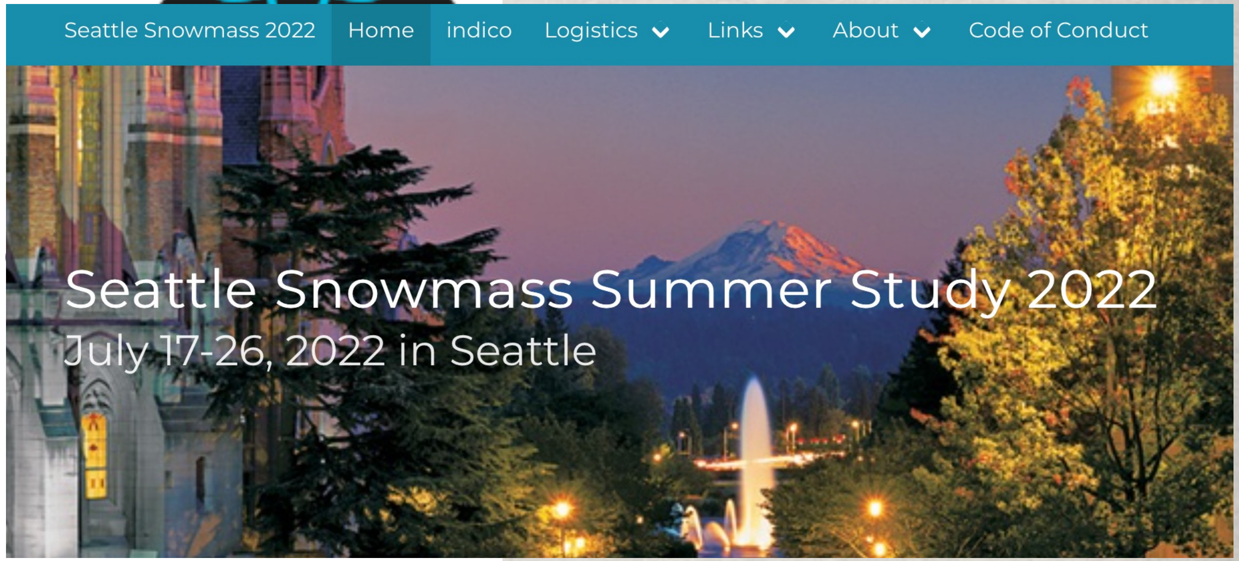
Snowmass
2021

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

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

(Snowmass 2021)

organized by the APS Division of Particles and Fields



The field of HEP is vibrant, dynamic & exciting!

Summary & Frontmatter

Cosmic Frontier

Rare Processes Frontier

Accelerator Frontier

Energy Frontier

Theory Frontier

Community Engagement Frontier

Instrumentation Frontier

Underground Facilities Frontier

Computational Frontier

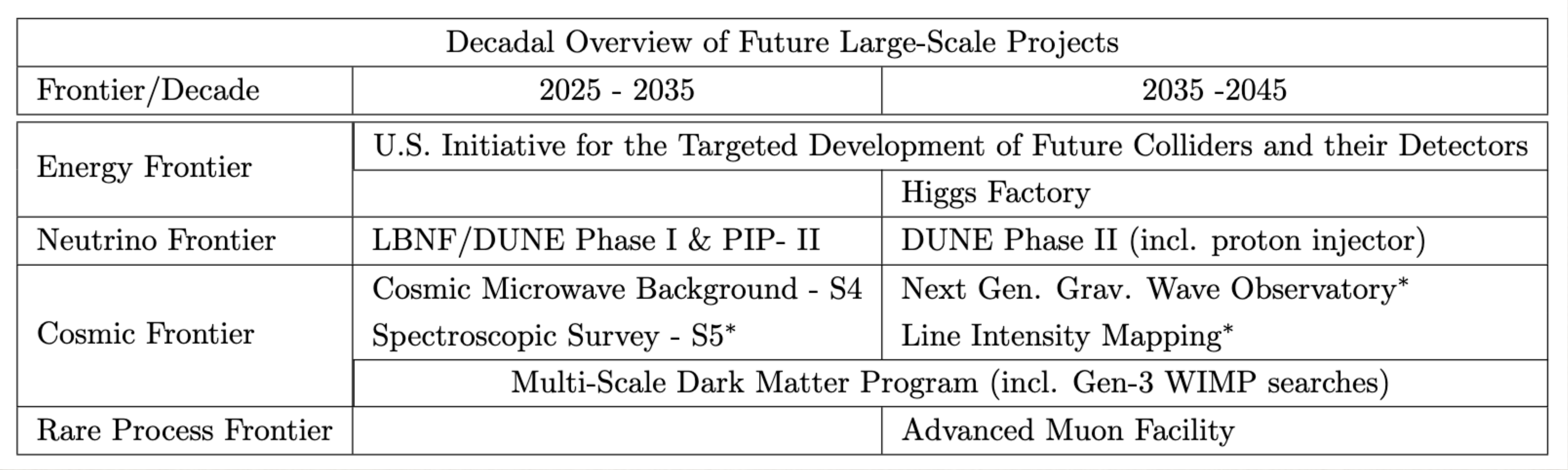
Neutrino Frontier

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	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

Medium- and Small-Scale Future Experiments and Projects:

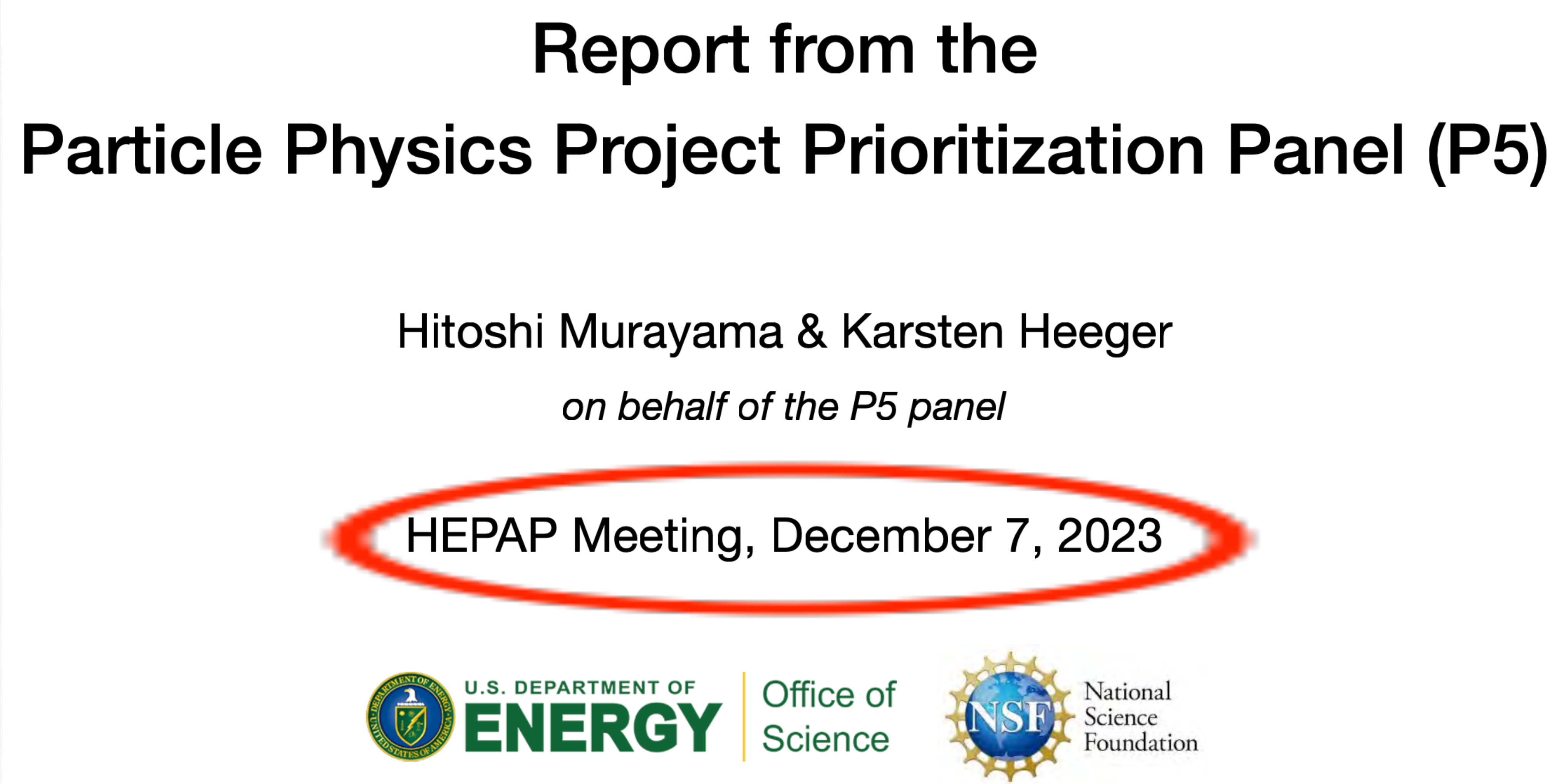
(see the full frontier reports)

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

National Science Foundation

Explore the Quantum Universe

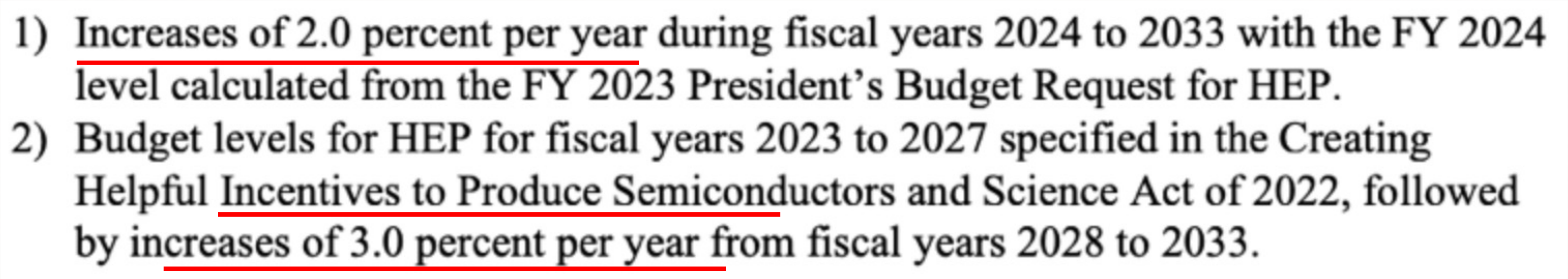
https://www.usparticlephysics.org/2023-p5-report/

Decipher the Quantum Realm

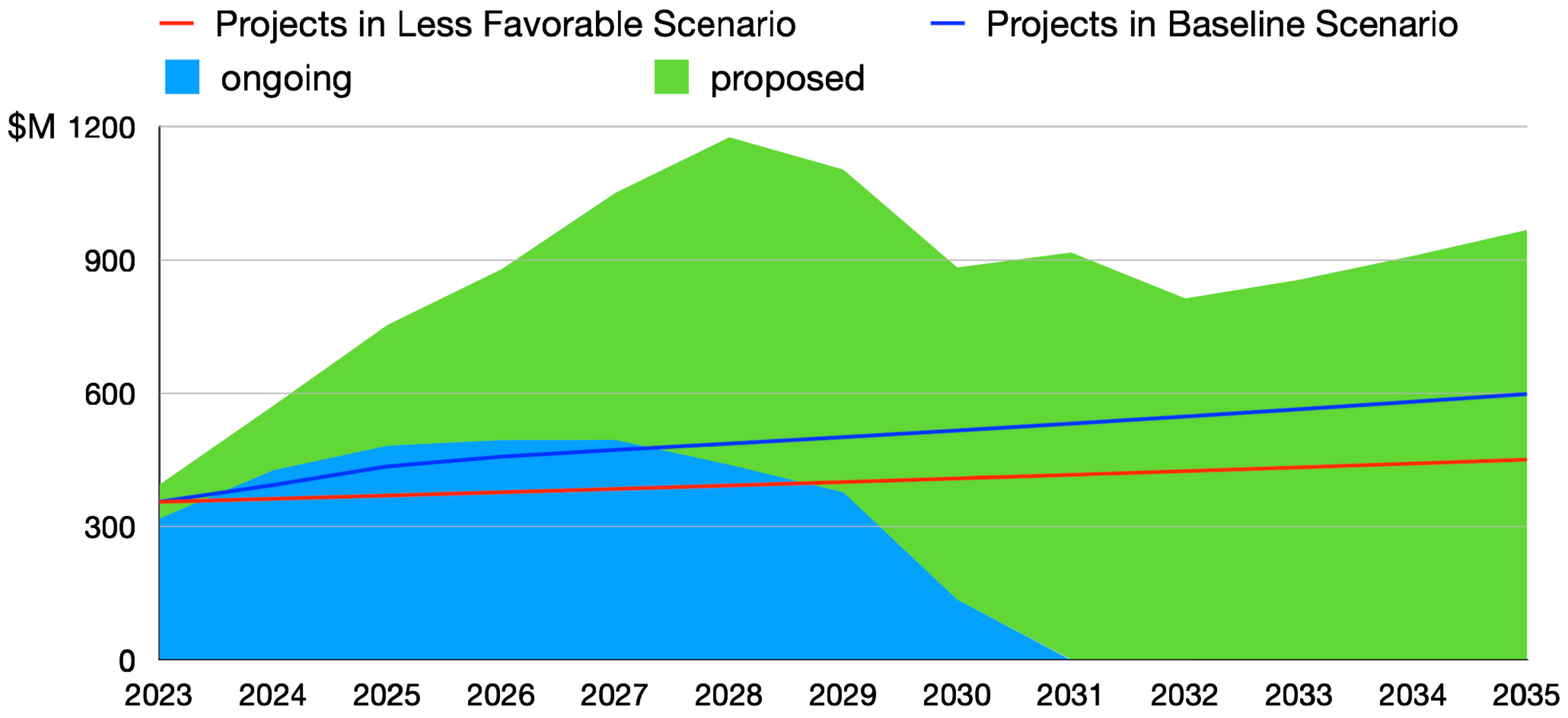
Explore New Paradigms in Physics

Illuminate the Hidden Universe

Budget Scenarios and Projects



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.



not including on-shore Higgs factory

DOE only

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.

Principles for Deliberation

Everything was on the table, nothing was off the table

- including ongoing projects

Everyone listened to each other with respect

- talked through all concerns avoiding preconceptions
- tried to optimize the overall particle physics portfolio, thinking beyond individual interest

Lots of difficult conversations

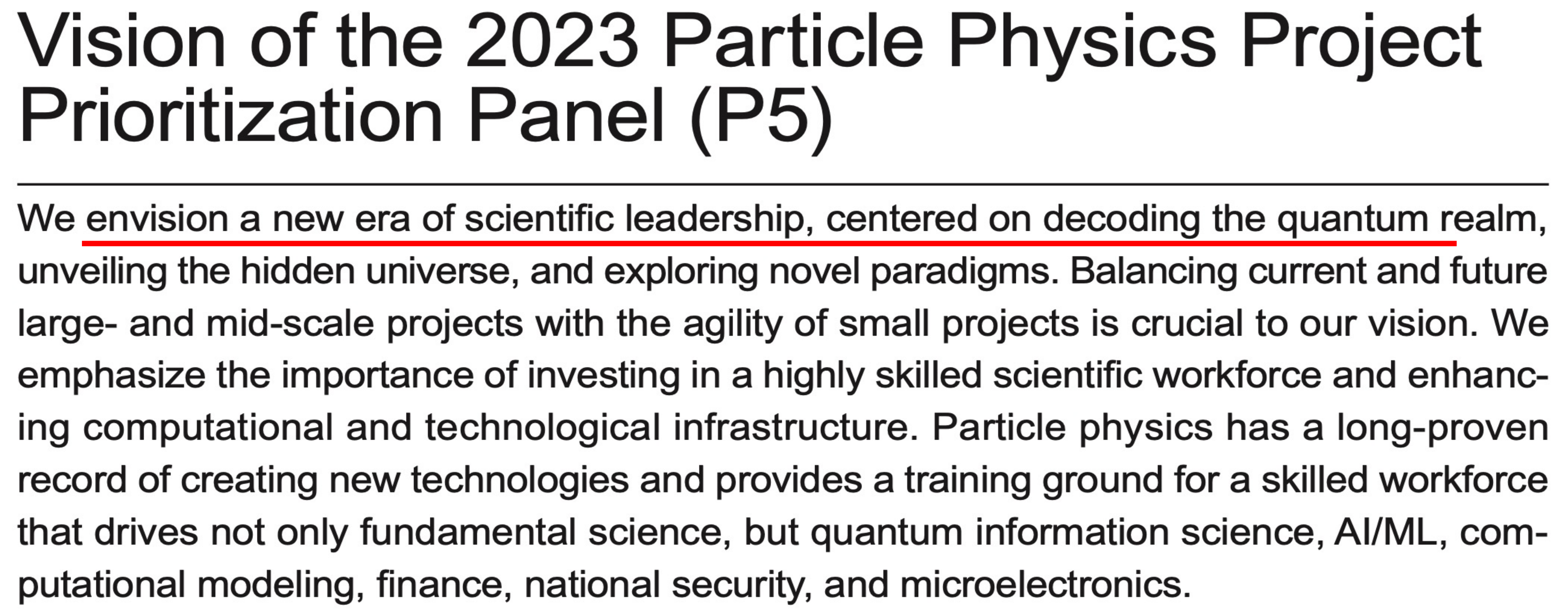
- necessary to understand issues
- long discussions really paid off

Decisions by consensus

- we never made decisions based on voting
- If 30 members can't agree, how can we expect support from thousands of physicists

Conflict of Interest (COI)

- Everyone recorded their COI, stated their COI during discussions
- If CoI, can make factual statements but not express opinions during deliverations



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:

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:

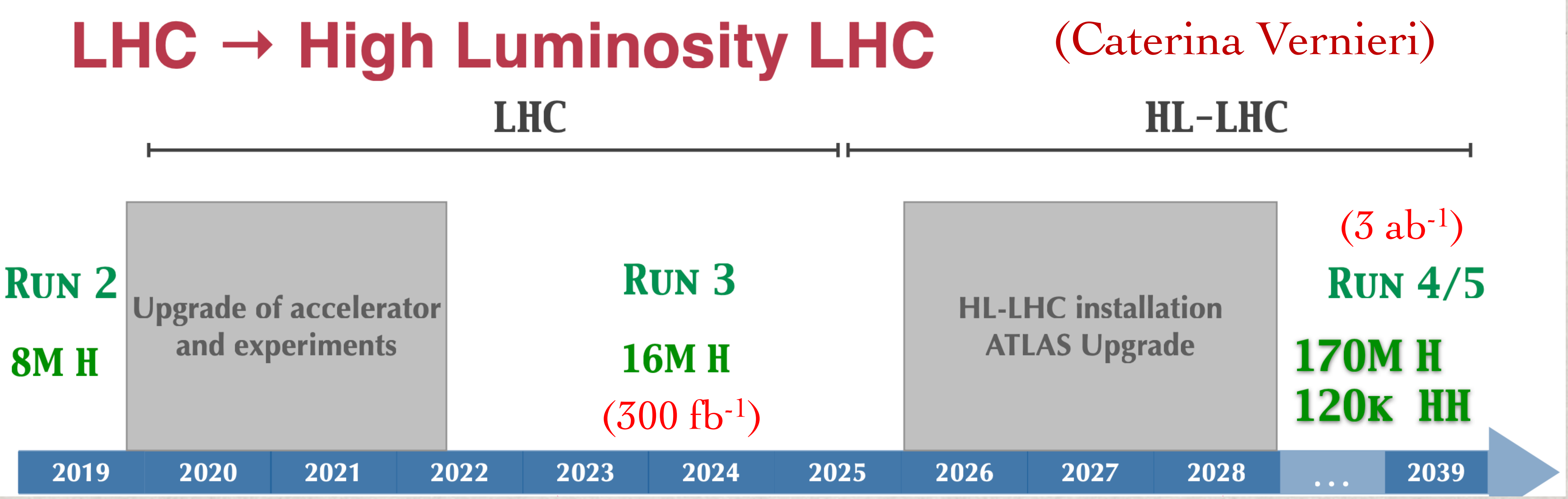
Including:

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:

NOvA, SBN, T2K, IceCube (neutrino physics)
DarkSide, LZ, SuperCDMS, XENONnT (DM direct searches)
DESI (DM, inflation)
Belle-2, LHCb, Mu2e (flavor physics at higher scales)

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



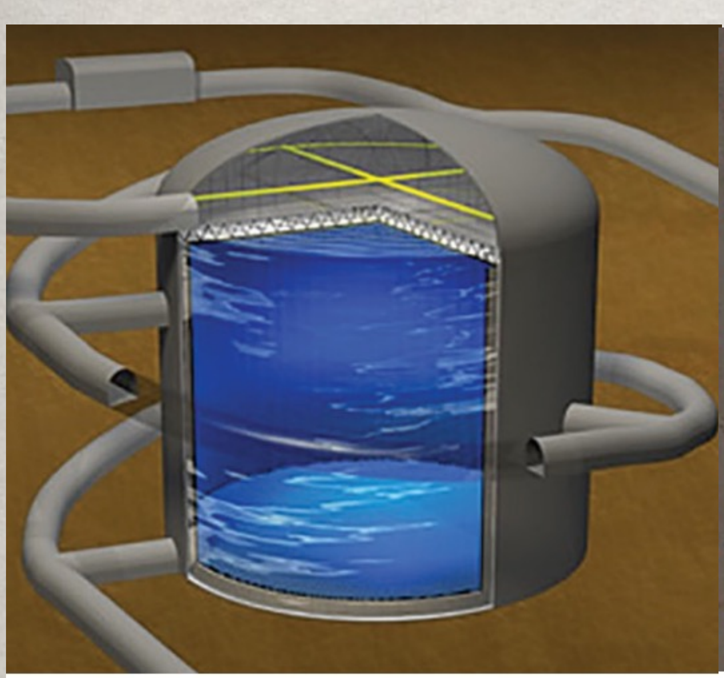
LHC → High Luminosity LHC (Caterina Vernieri)

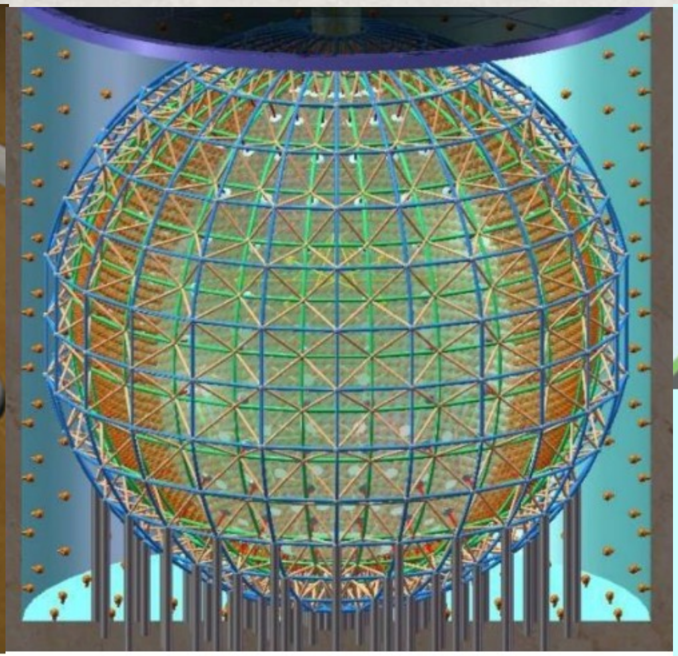
H couplings to:	**O(5-10)%**
H self-coupling to:	**O(50)%**

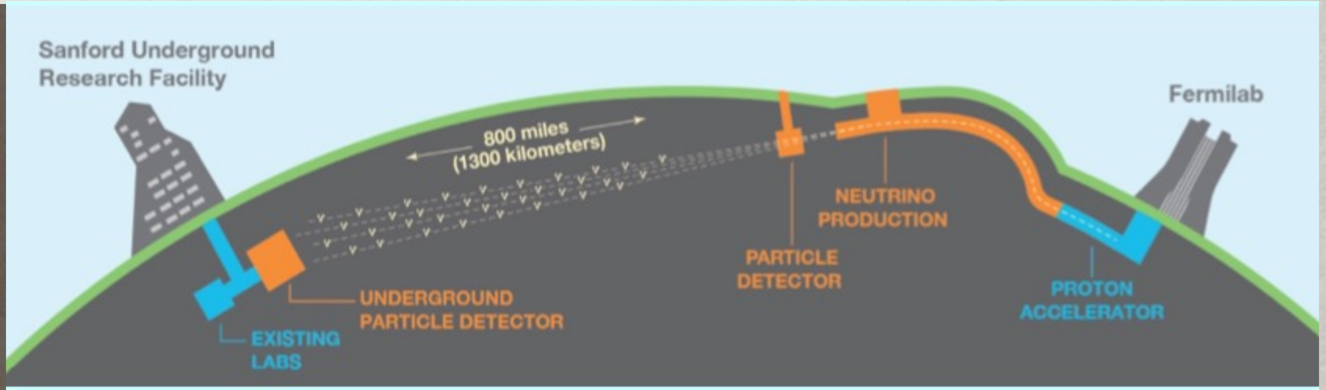
New physics reach:

M, Λ ~ O(a few TeV)

b. Next generation of Neutrino Experiments/SN detection







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

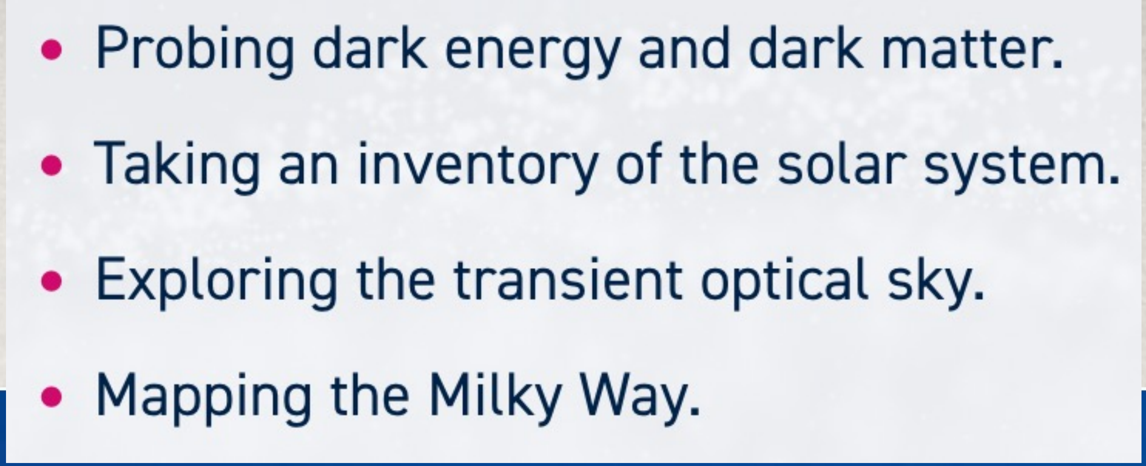
Hyper-Kamiokande
260 kton water

JUNO
20 kton scintillator
(hydrocarbon)

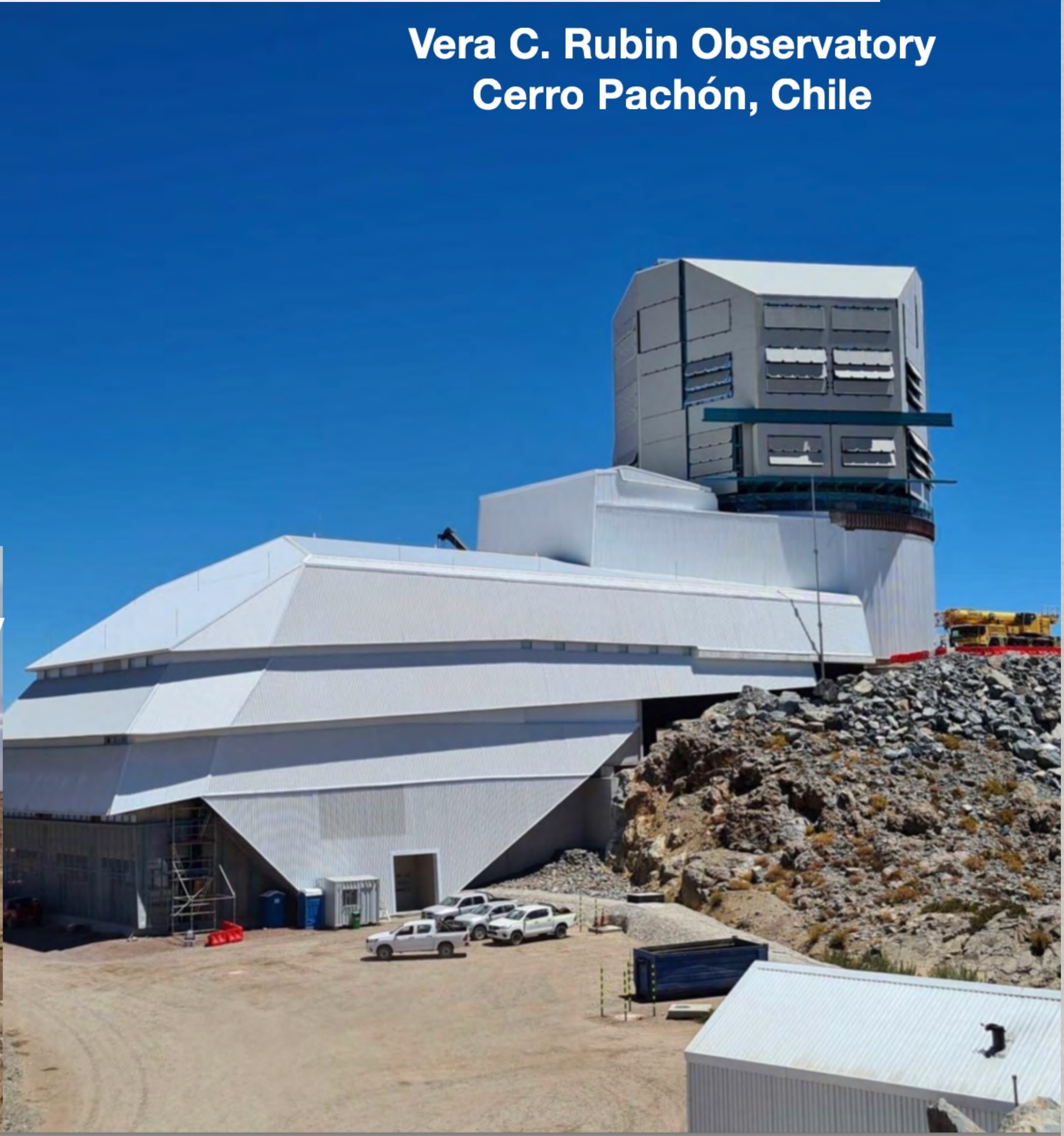
(Lianjian Wen)

Exp.	Time	**Mass ordering**	**CP phases**	**Precision Meas.**	**CCSN burst @ 10 kpc**	**DSNB**	**Geo-v**	**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

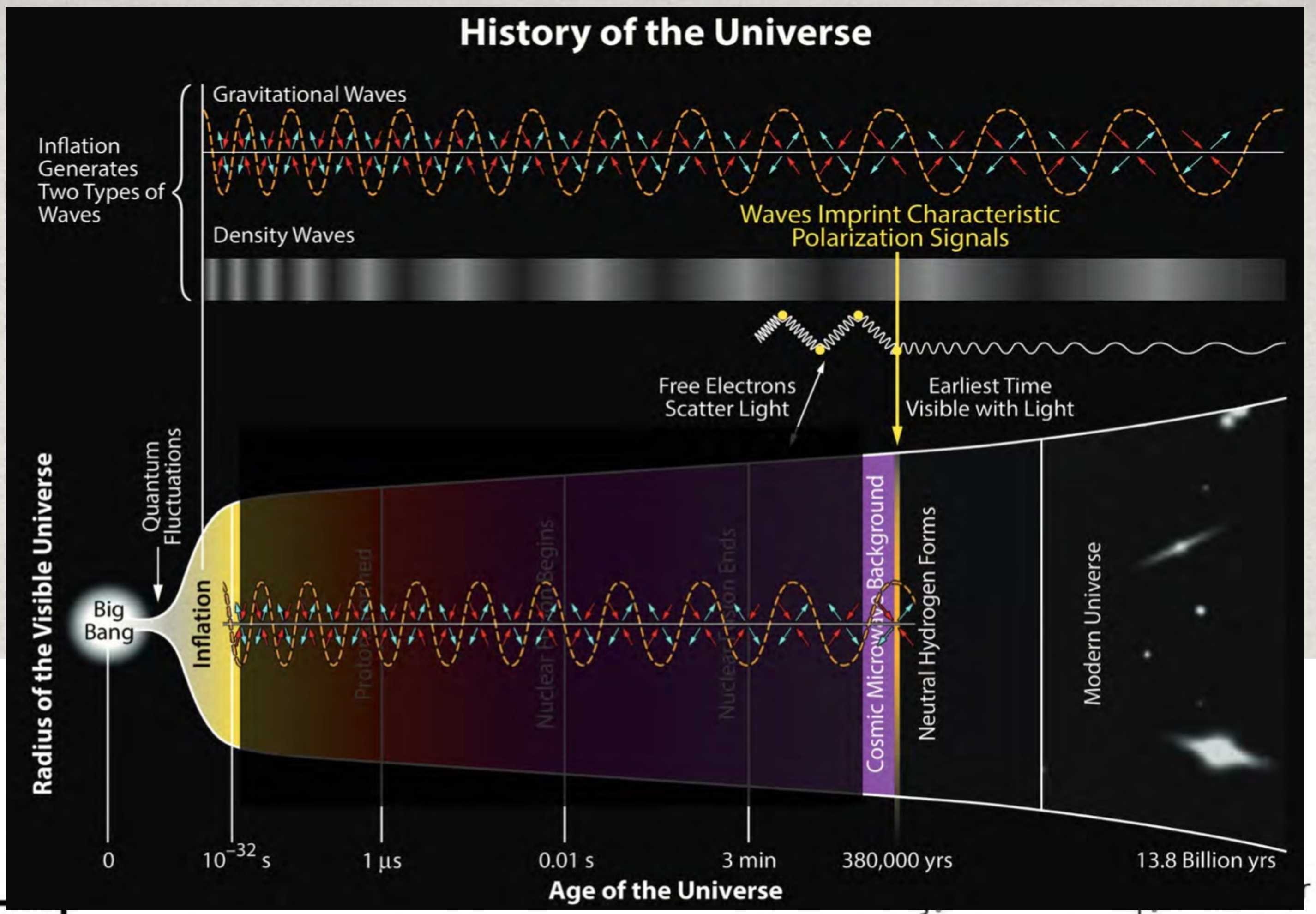
a. **CMB-S4**, which looks back at the earliest moments of the universe to probe physics at the highest energy scales. It is critical to install telescopes at and observe from both the South Pole and Chile sites to achieve the science goals (section 4.2).

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).

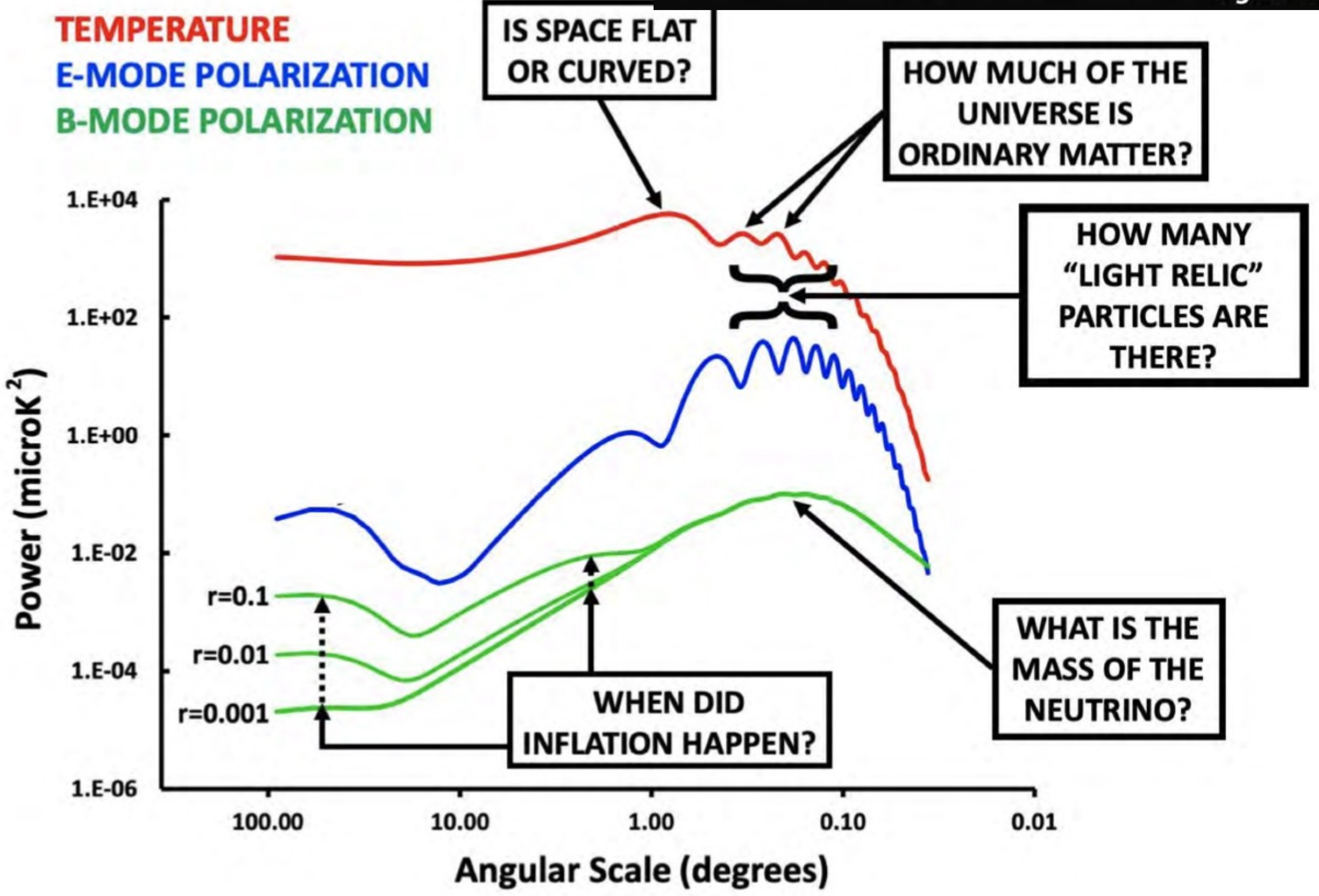
c. **An off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. Once a specific project 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).

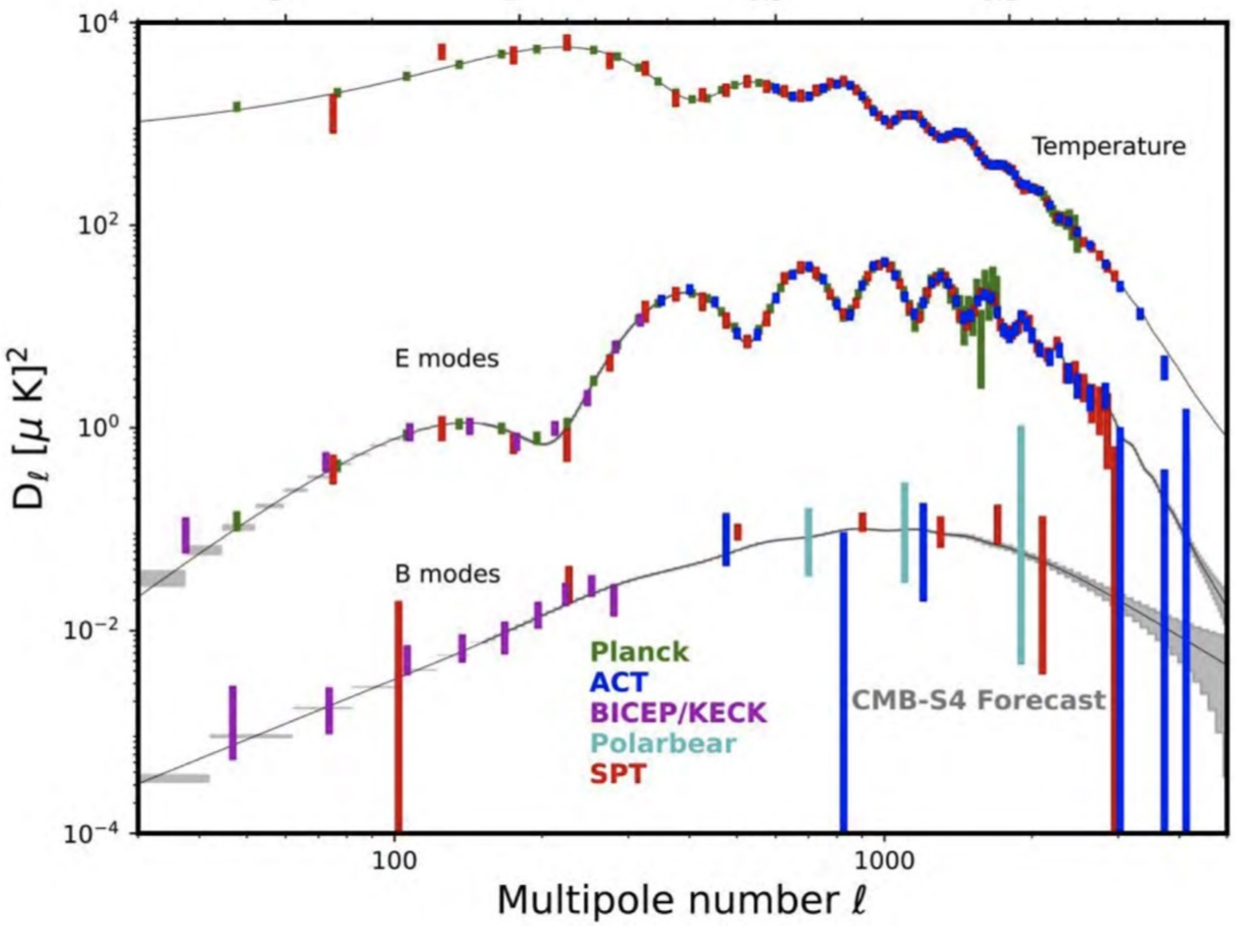
d. **An ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog, in coordination with international partners and preferably sited in the US (section 4.1).

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).


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
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

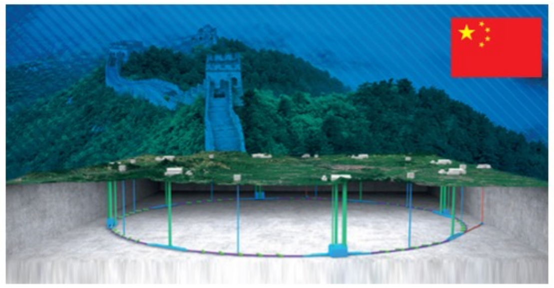
a. CMB S4


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)


3°
1°
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

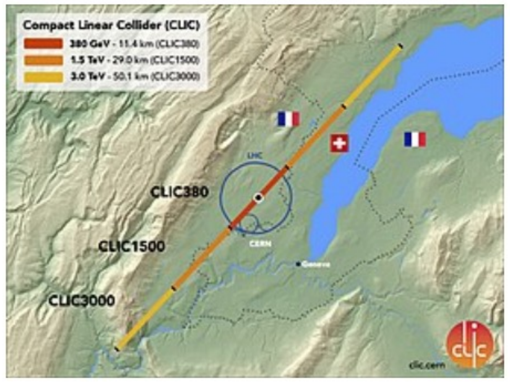
c. Off-shore Higgs Factories

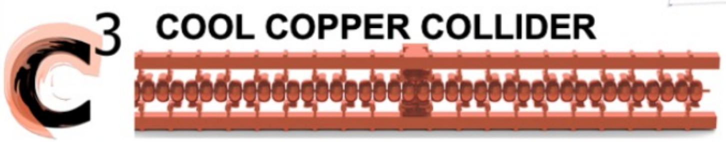
250/500 GeV



CEPC 240 GeV

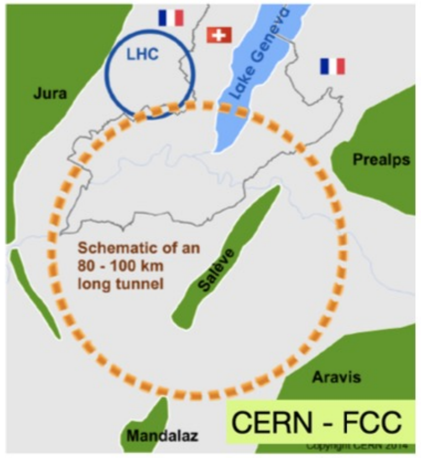
CLIC 380/1500/3000 GeV





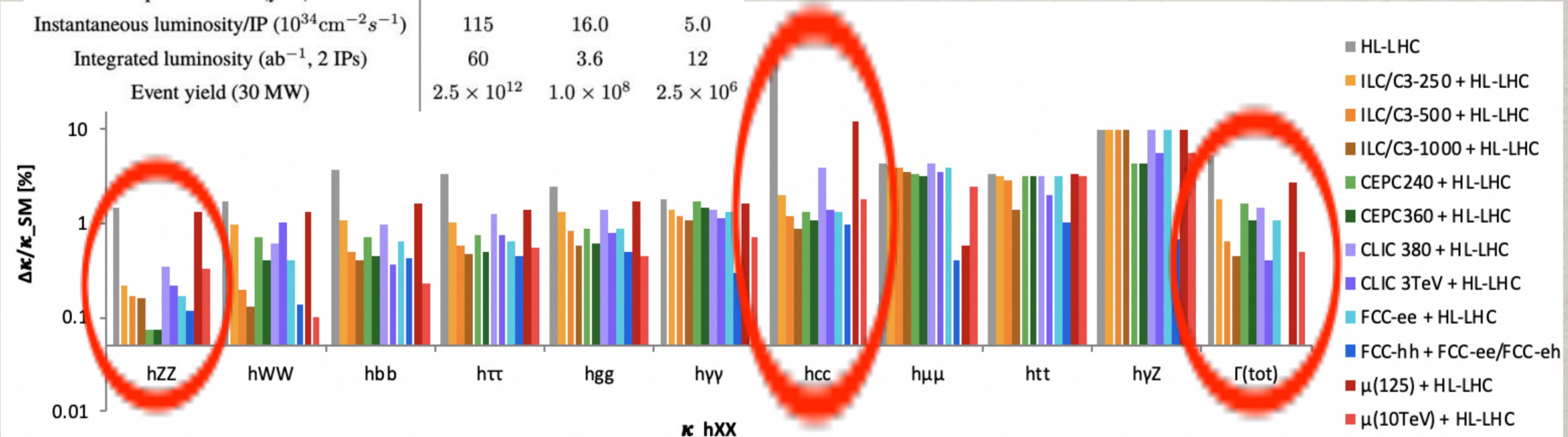
250/550 GeV

… > TeV



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

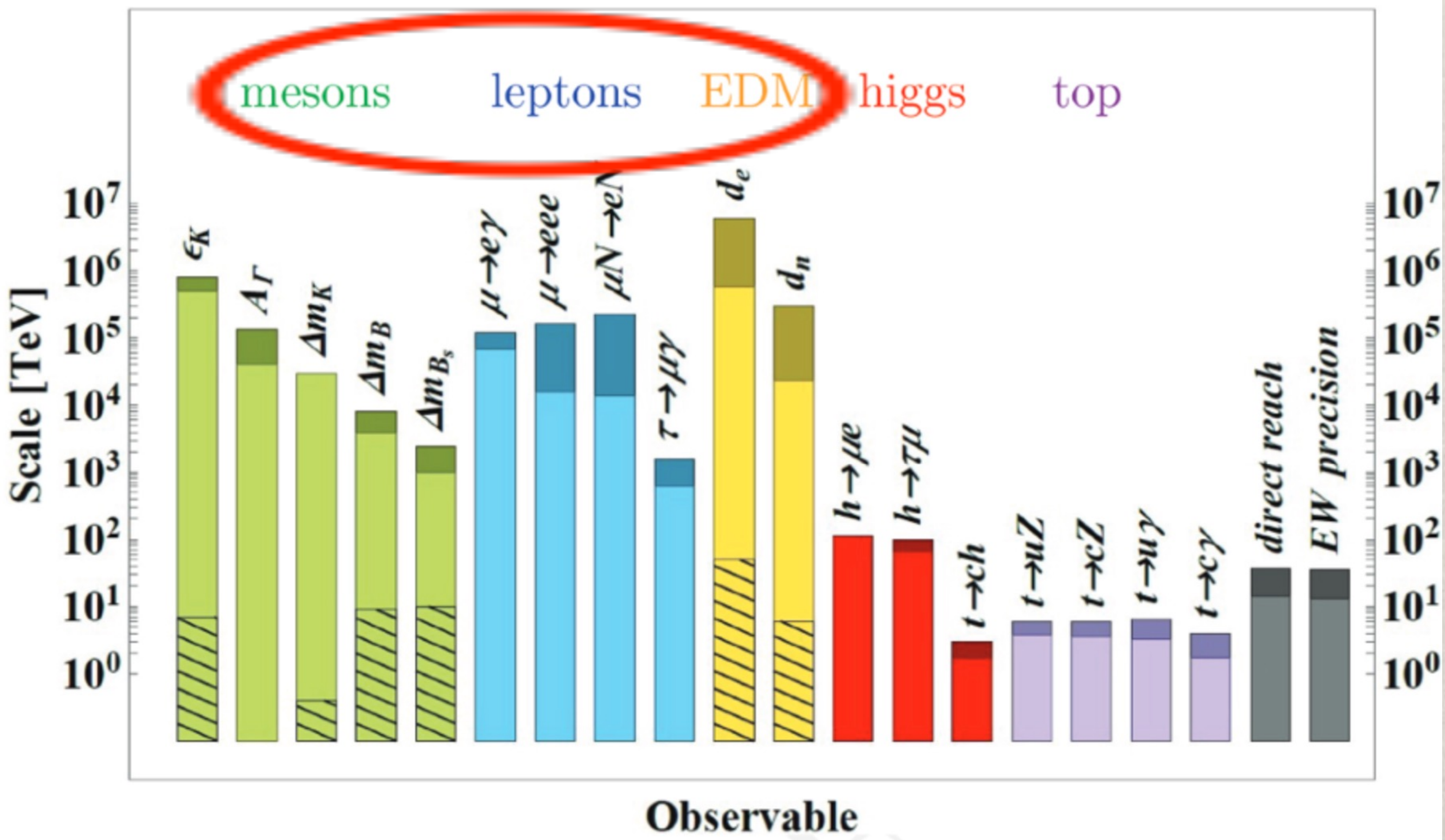
Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

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:



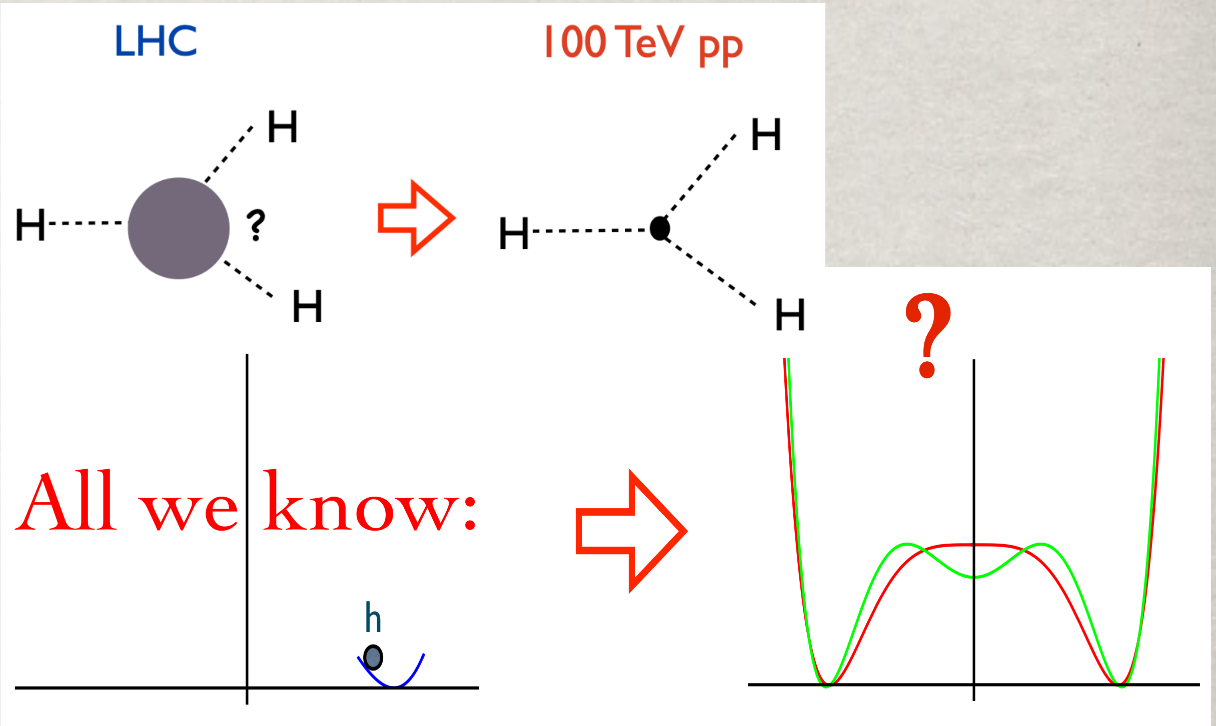
Recommendation 4

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?

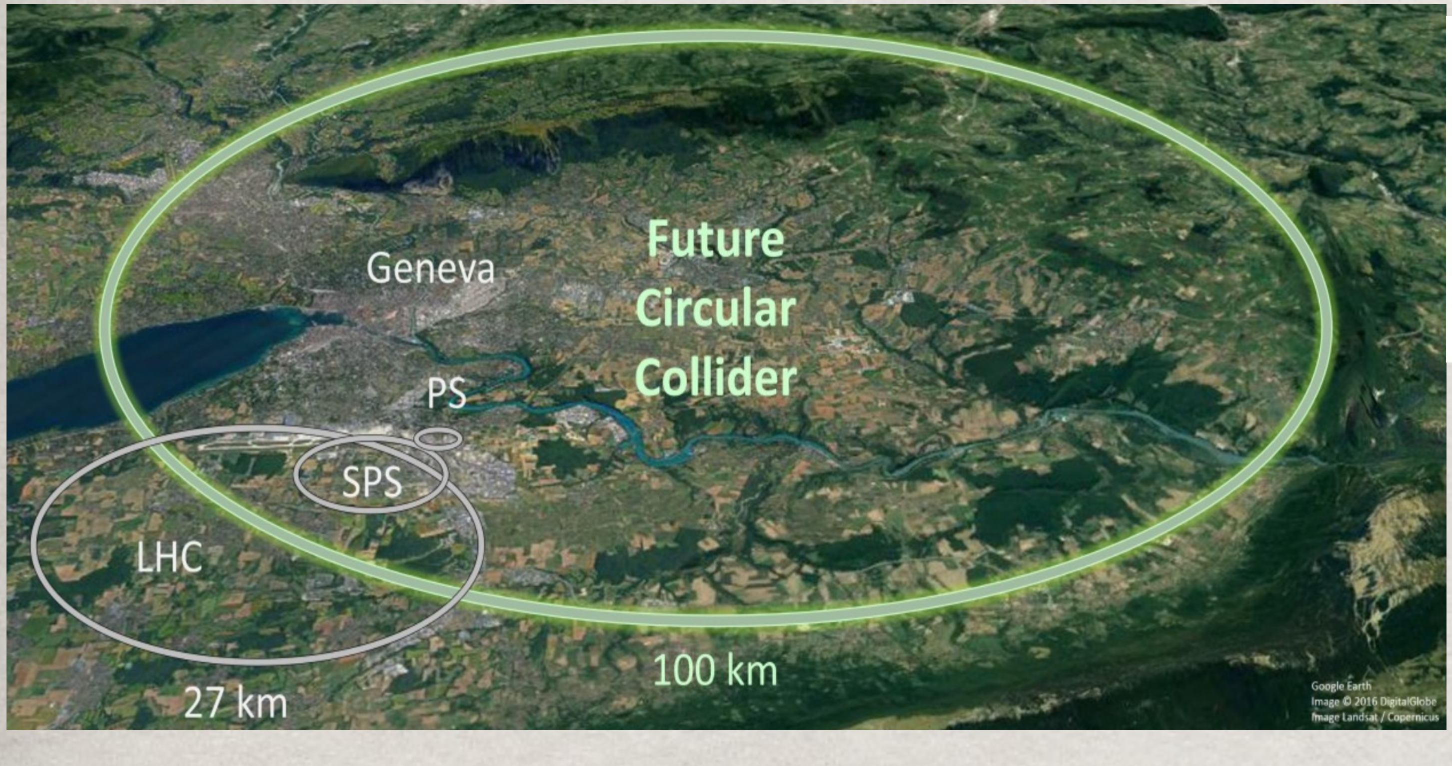
Open a new energy threshold:

- 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

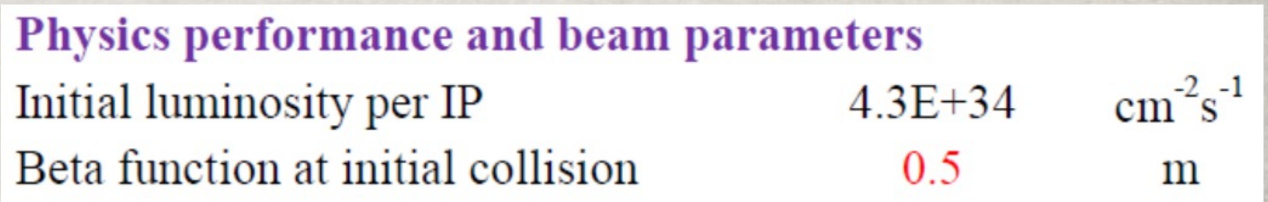
(see Michelangelo Mangano's talk)



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

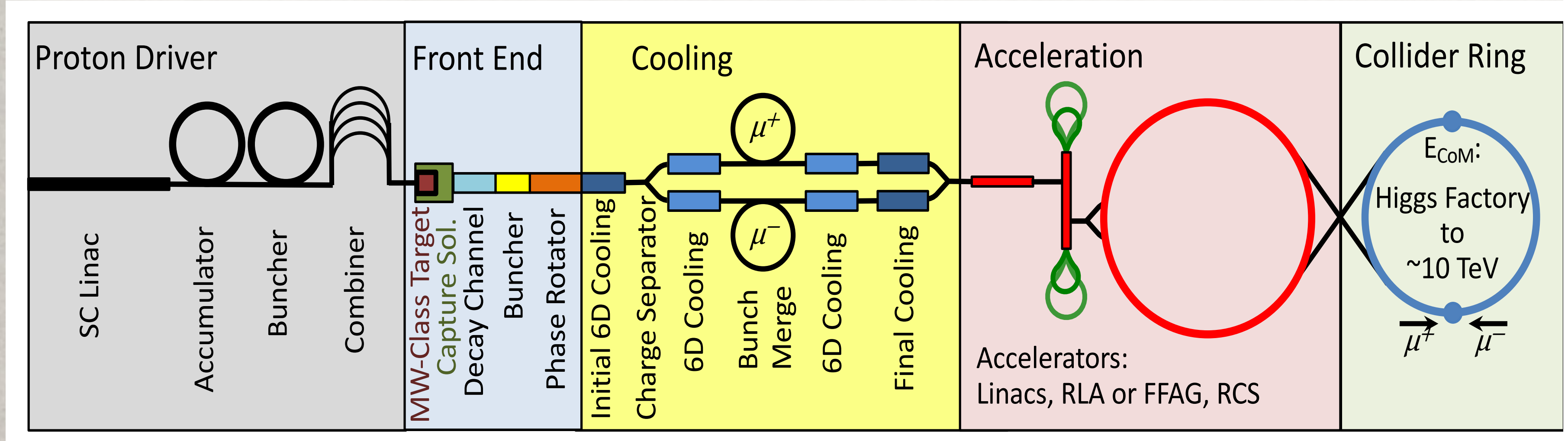


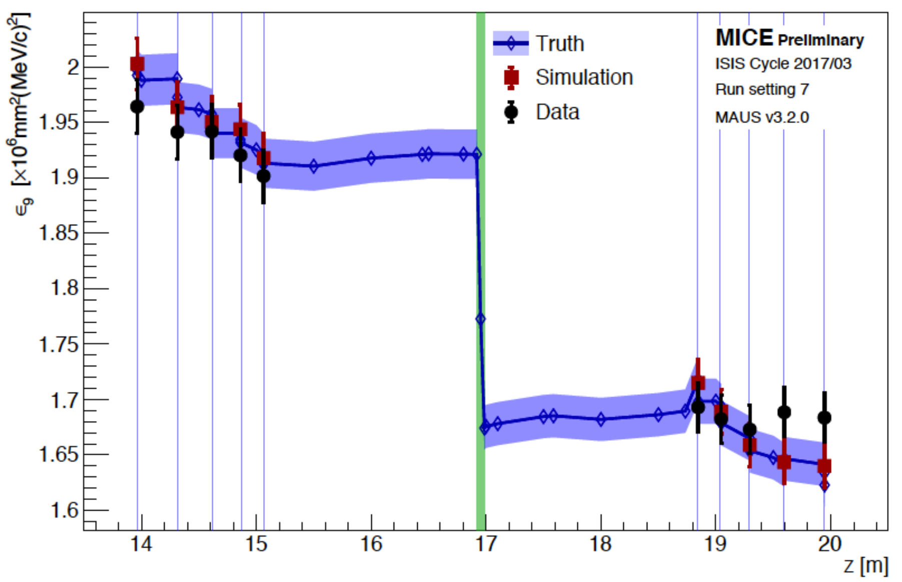
Physics performance and beam parameters		
Initial luminosity per IP	4.3E+34	$cm^{-2}s^{-1}$
Beta function at initial collision	0.5	m

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 Da

The international journal of science / 18 January 2024

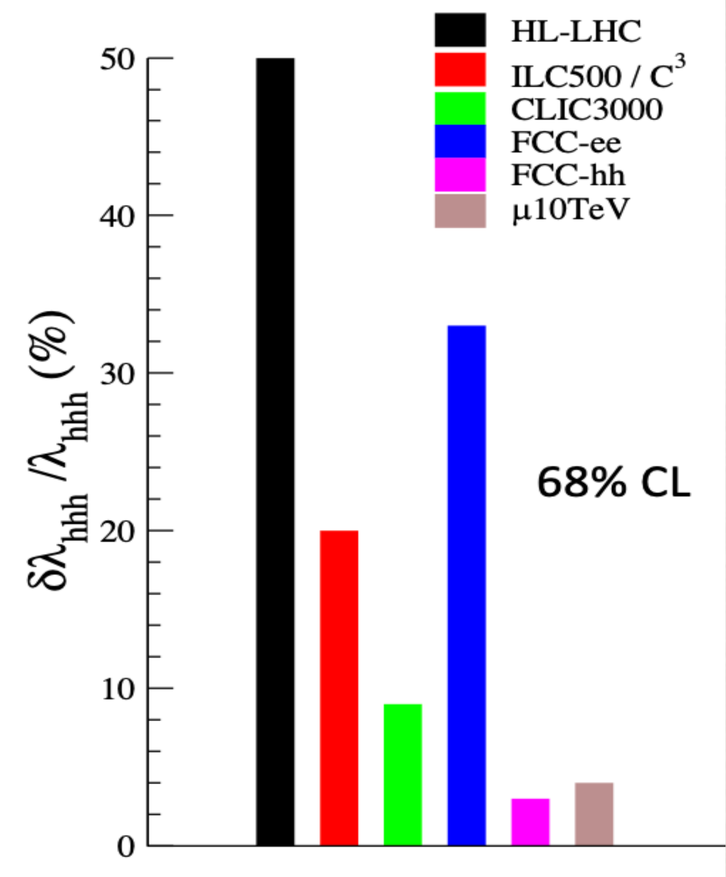
nature

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.

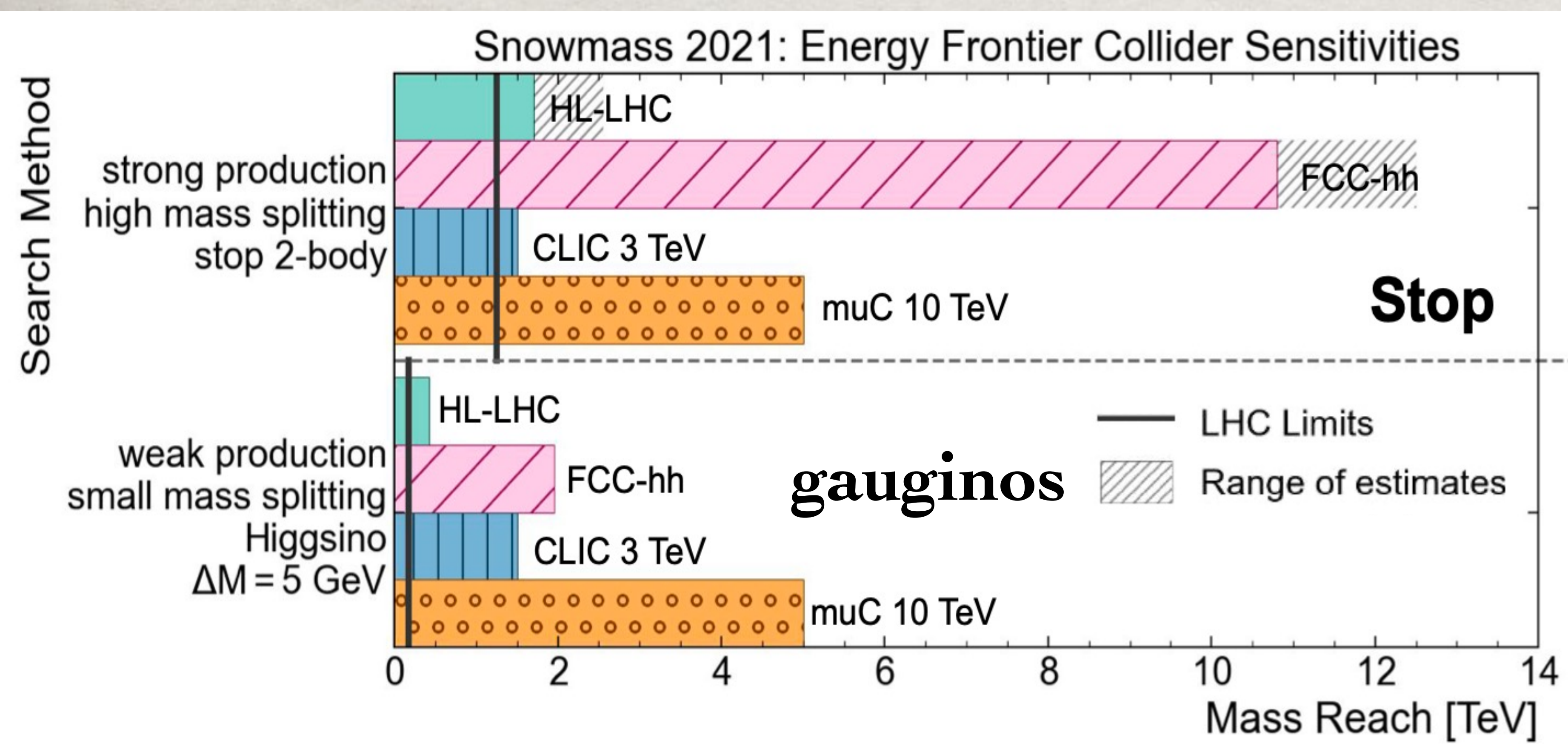
Reach at 10 TeV pCM energies

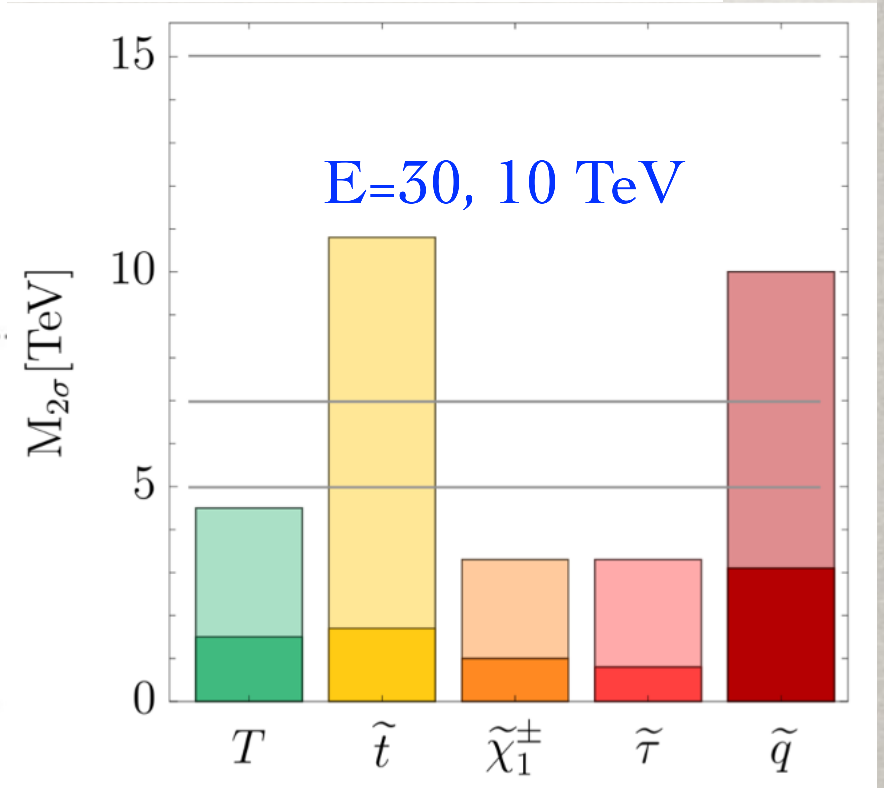
Higgs coupling reach for λ_{hhh}^{SM} →



Pushing the "Naturalness" limit:

The searches for top quark partners
& gluinos, gauginos …





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

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.

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.

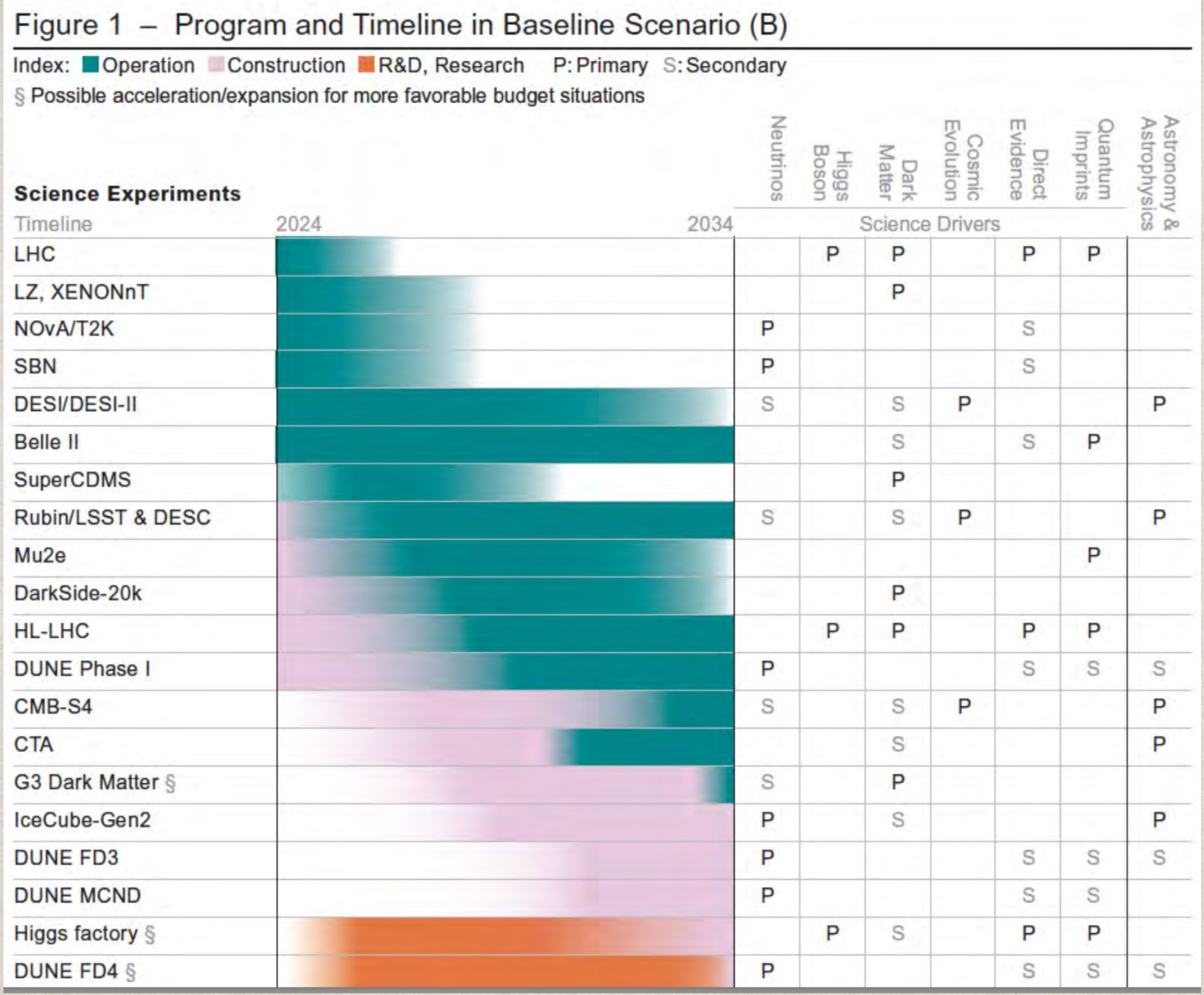


Figure 1 – Program and Timeline in Baseline Scenario (B)

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

§ Possible acceleration/expansion for more favorable budget situations

Science Experiments		Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
Timeline	2024 2034	Science Drivers						
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

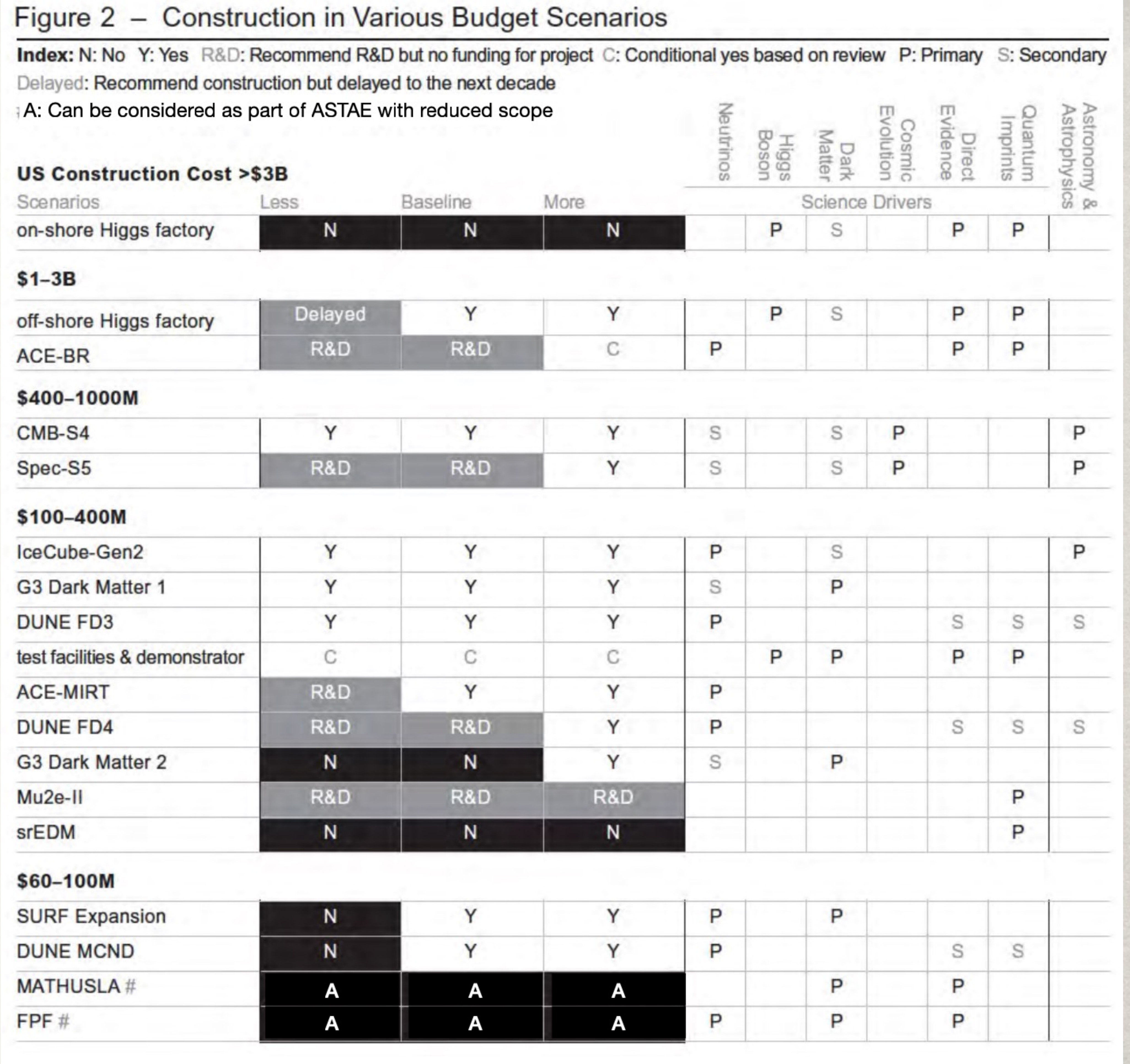


Figure 2 – Construction in Various Budget Scenarios

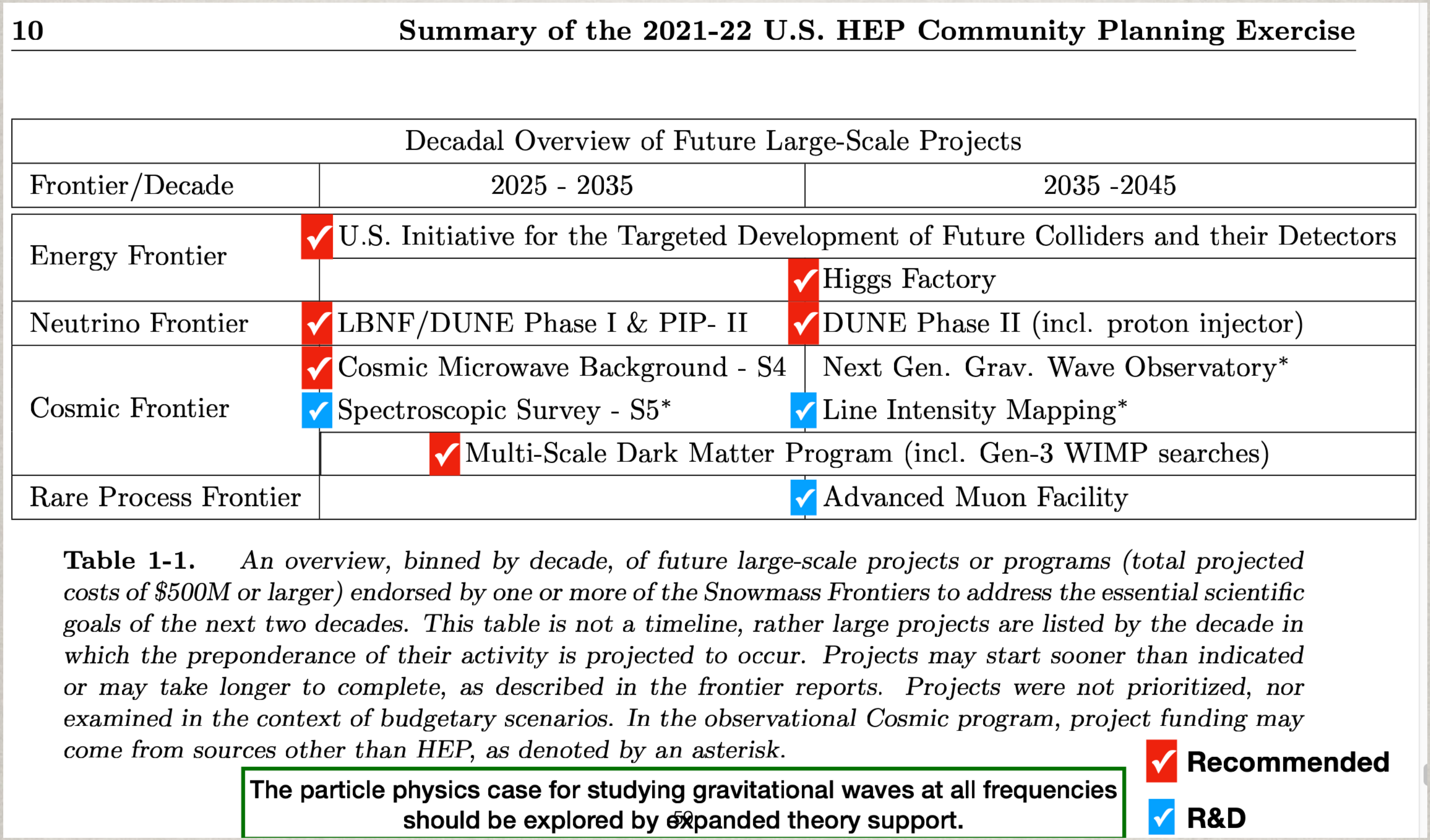
Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

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

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
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		

Science Drivers



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.*

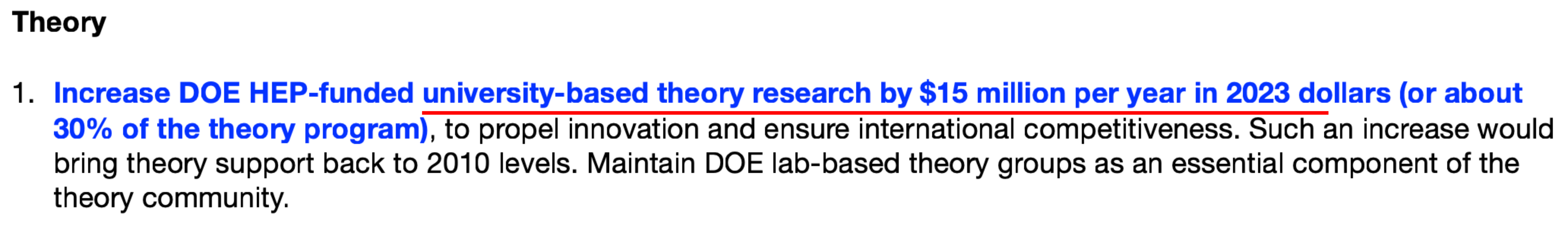
The particle physics case for studying gravitational waves at all frequencies should be explored by expanded theory support.

🟥✓ **Recommended**

🟦✓ **R&D**

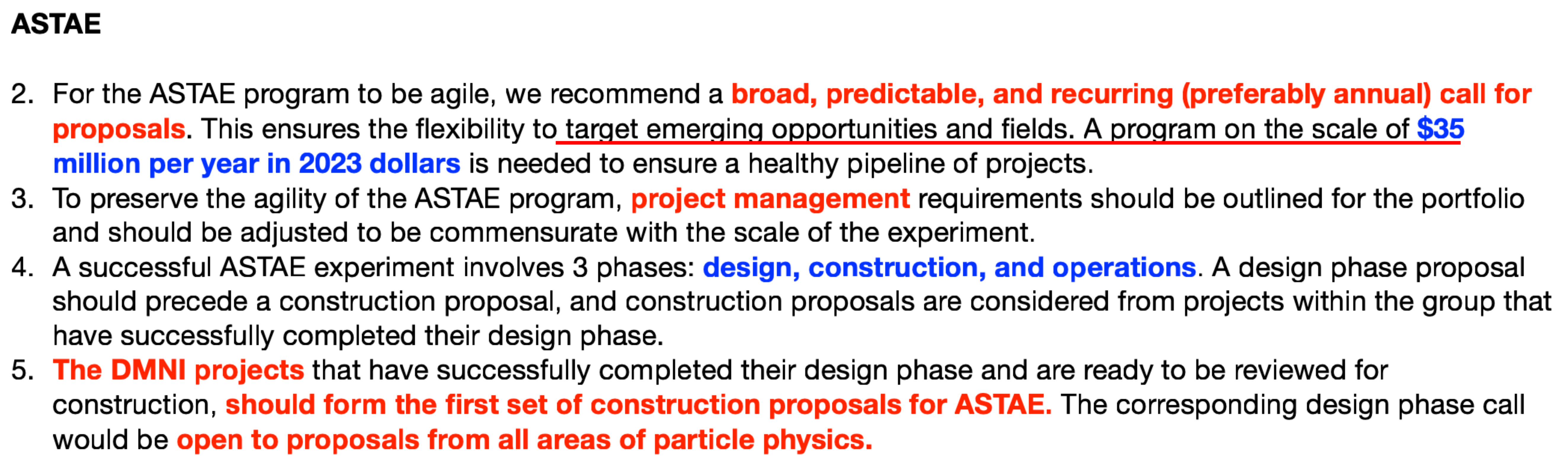
Area Recommendations

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



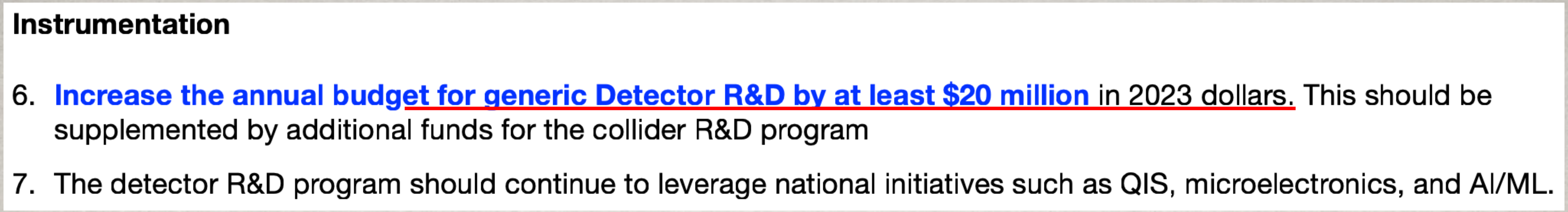
Theory

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.



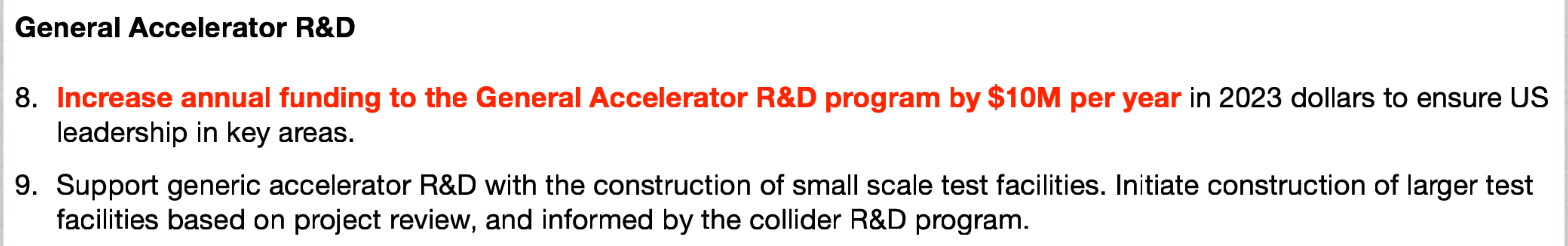
ASTAE

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.**



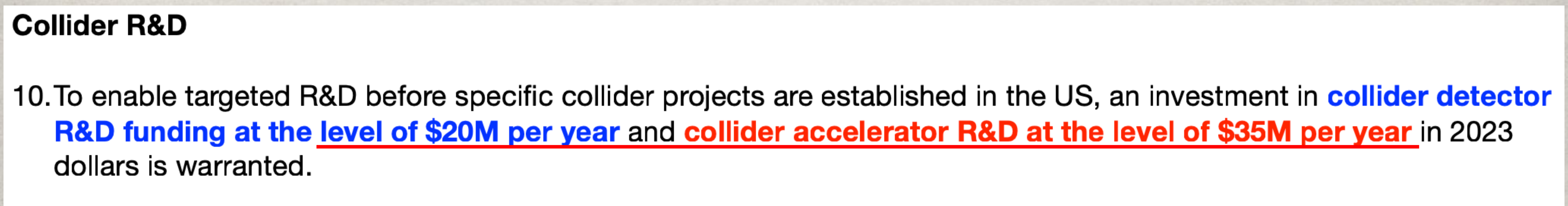
Instrumentation

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.



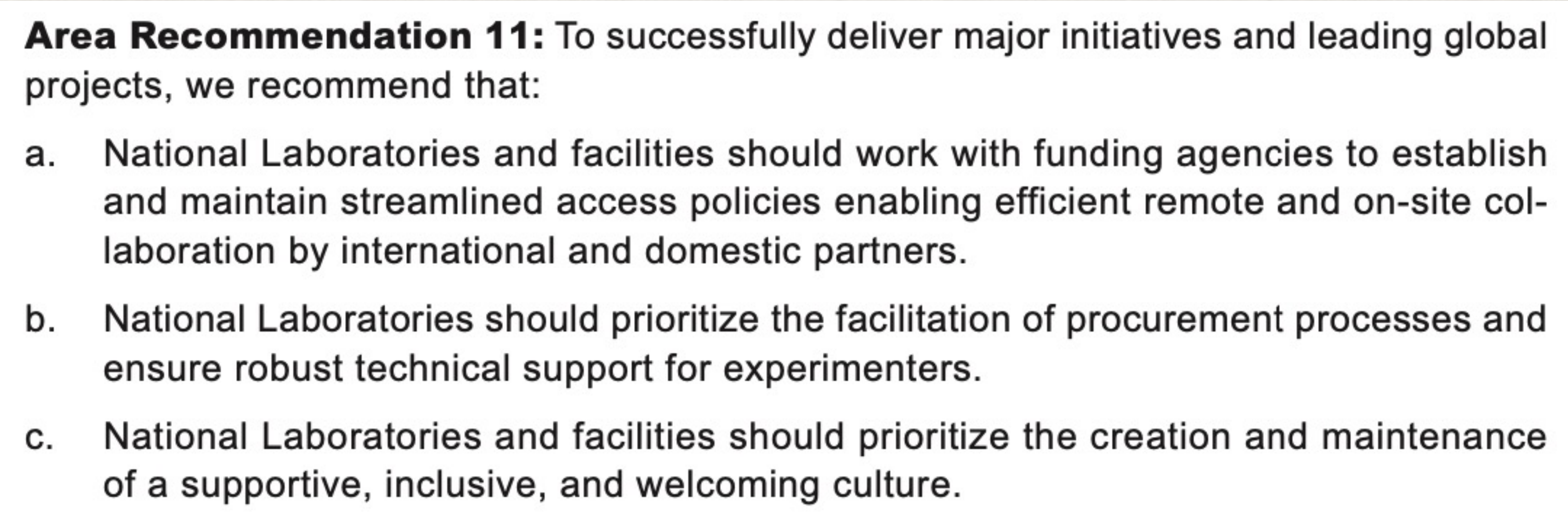
General Accelerator R&D

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.

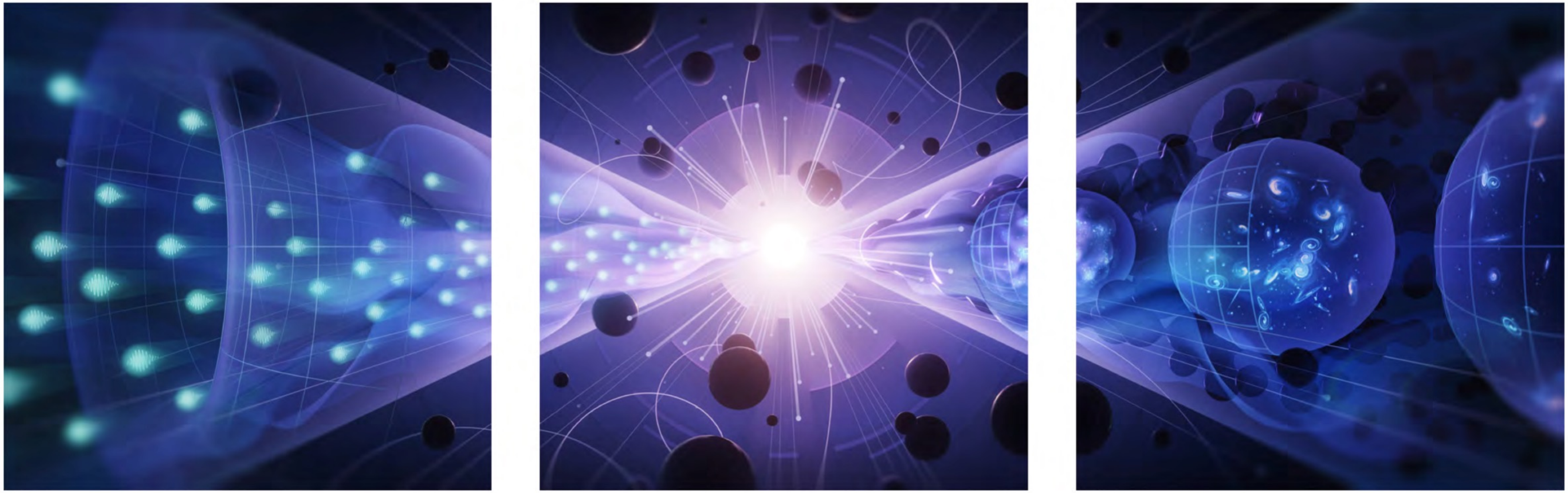
Area Recommendation 18: Through targeted investments at the level of $8M per year in 2023 dollars, ensure sustained support for key cyberinfrastructure components. This includes widely-used software packages, simulation tools, information resources such as the Particle Data Group and INSPIRE, as well 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!

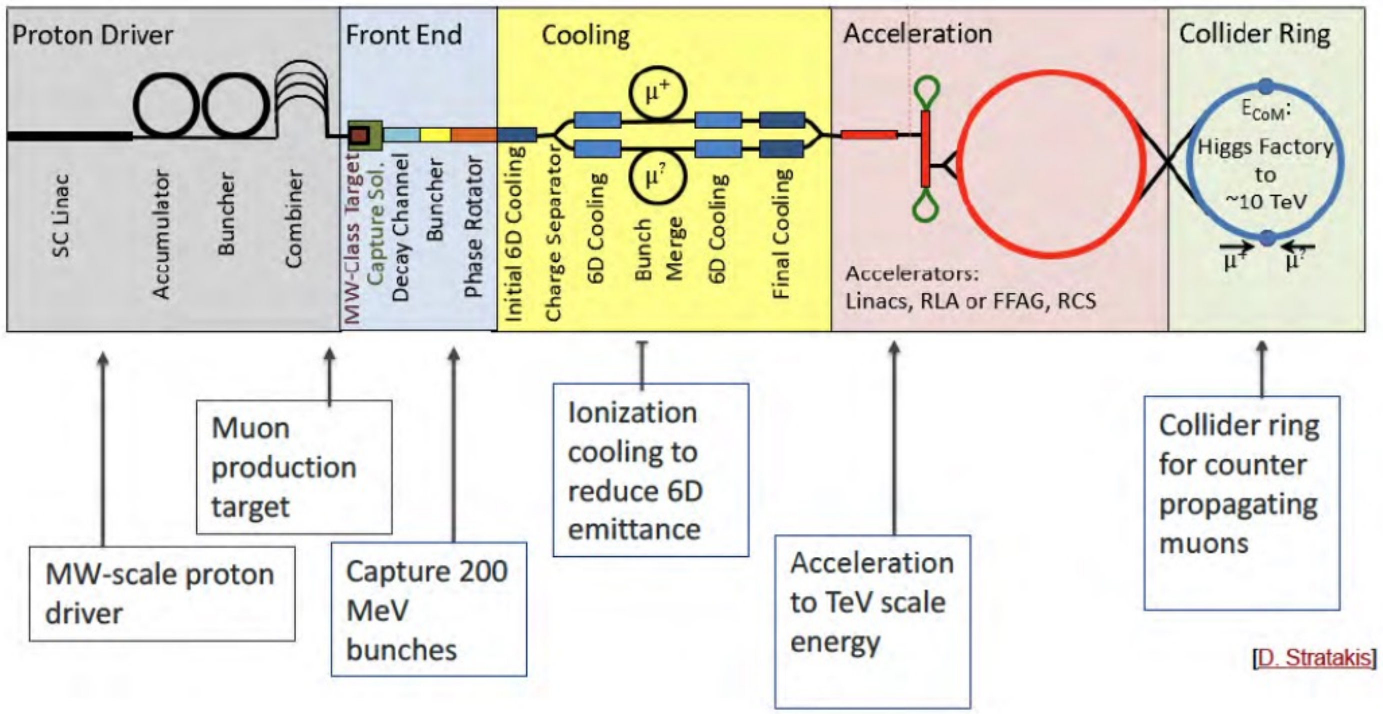
Backup slides

Muon Collider: The “Muon Shot”

- Best of both worlds: cleanness of leptons, no PDFs as in hadron collider
    - But muons decay! Considerable challenge to accelerate & build detectors
- P5 2.3: “This P5 plan outlines an aggressive R&D program… **for a muon collider test facility by the end of the decade**. This facility would test the feasibility of **developing a muon collider in the following decade**.”
- P5 2.5: “…synergies between muon and proton colliders, especially in the area of development of **high-field magnets**. R&D efforts in the next 5-year timescale → initiating demonstrator facilities within a 10-year timescale.”

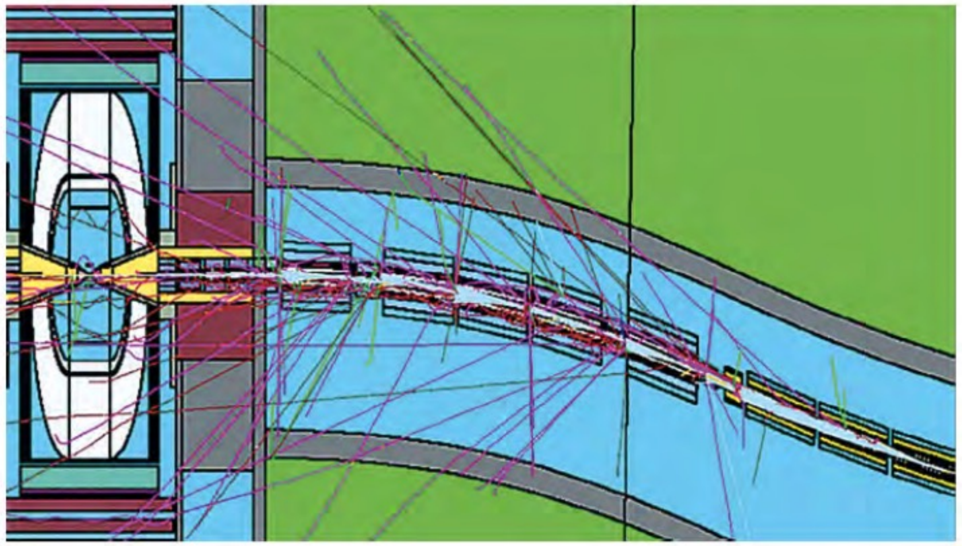
μC @ Fermilab

[2203.08088]

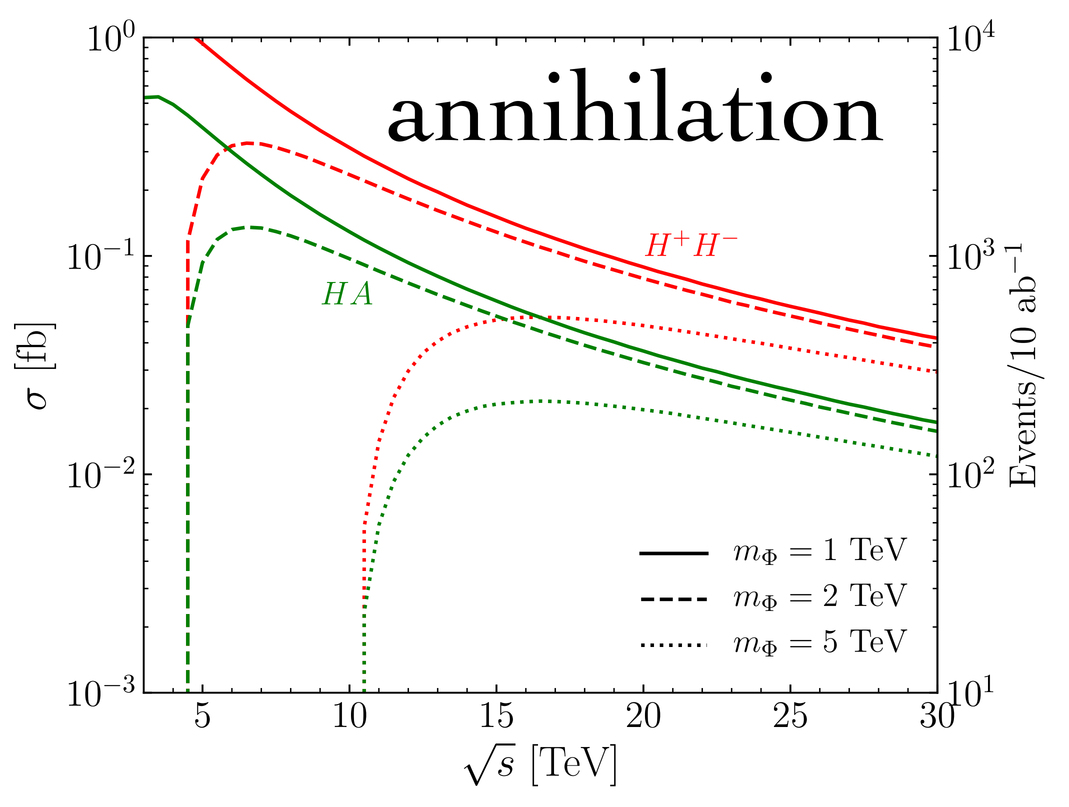


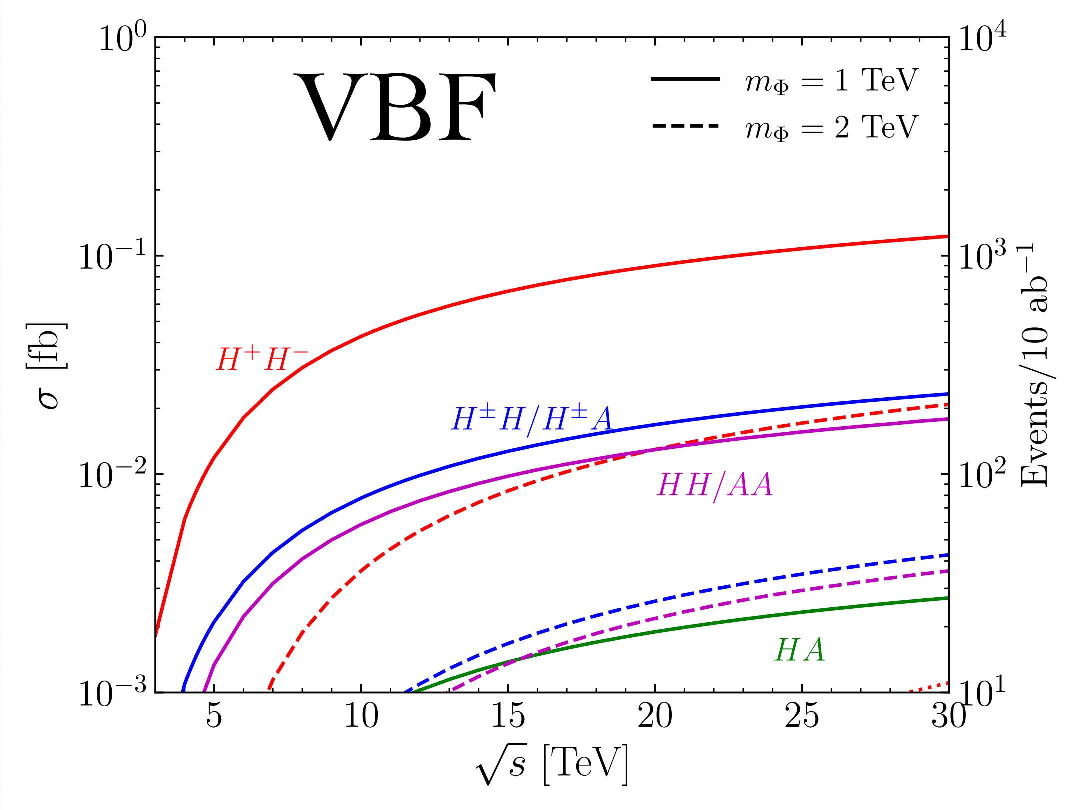
[D. Stratakis]

μC Beam- Induced Background



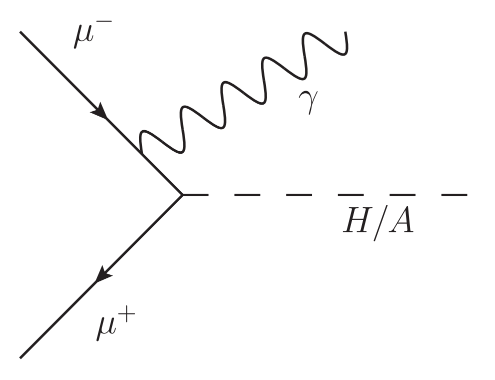
• Heavy Higgs Bosons Production

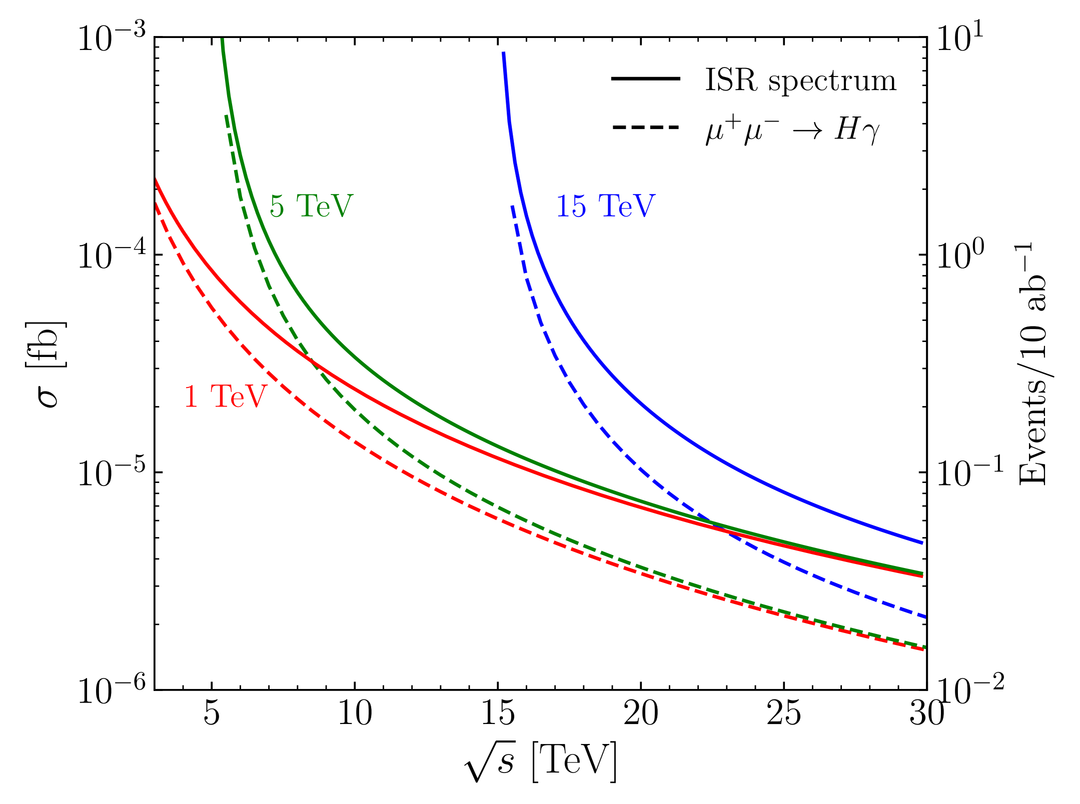




Radiative returns:

$$\hat{\sigma}(\mu^+\mu^- \to H) = \frac{\pi Y_\mu^2}{4}\delta(\hat{s} - m_H^2) = \frac{\pi Y_\mu^2}{4s}\delta(\tau - \frac{m_H^2}{s})$$



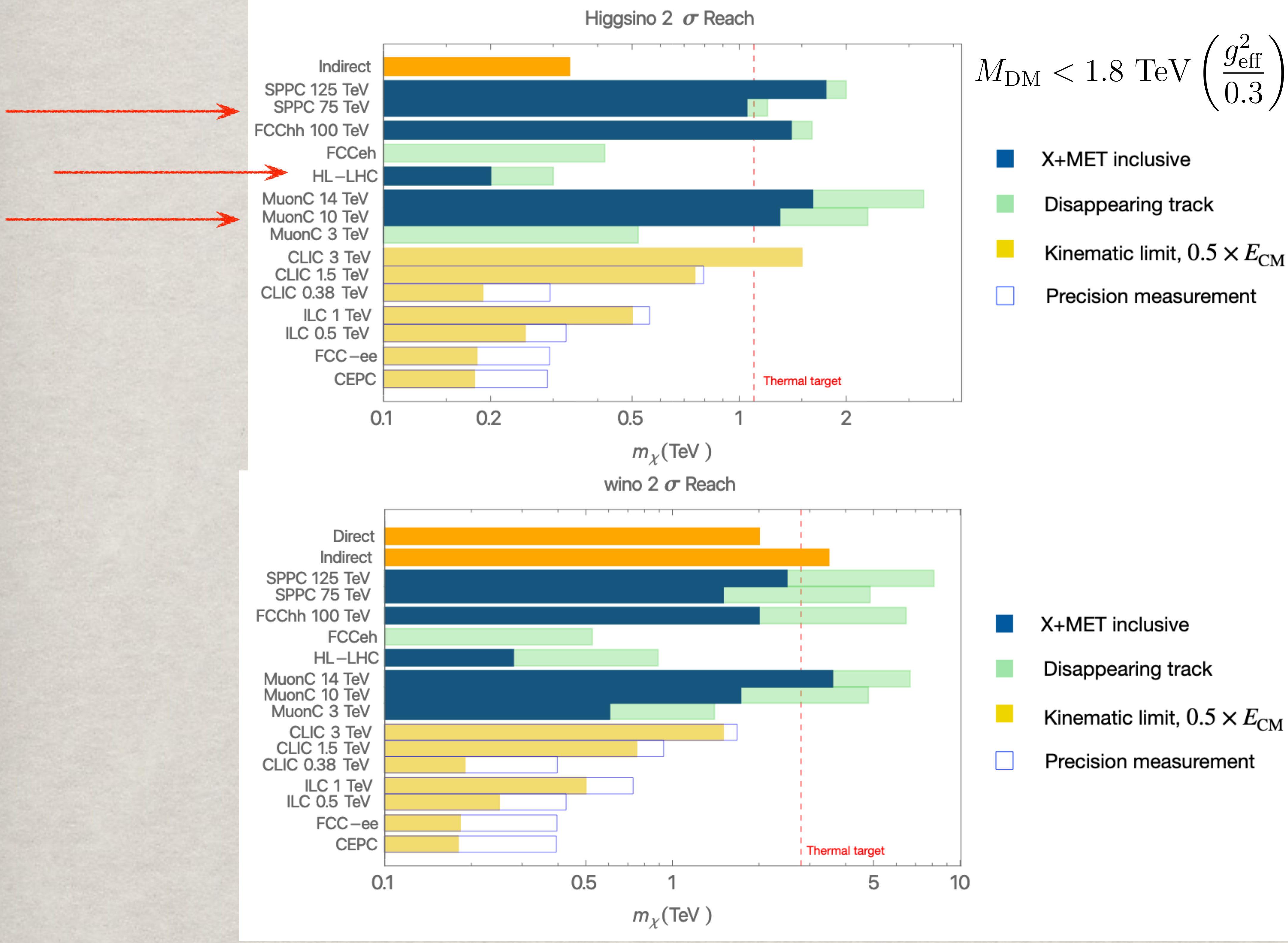


Reach M ~ E_{cm}!

TH, S. Li, S. Su, W. Su, Y. Wu, arXiv:2102.08386.

WIMP Dark Matter

Covering the thermal target



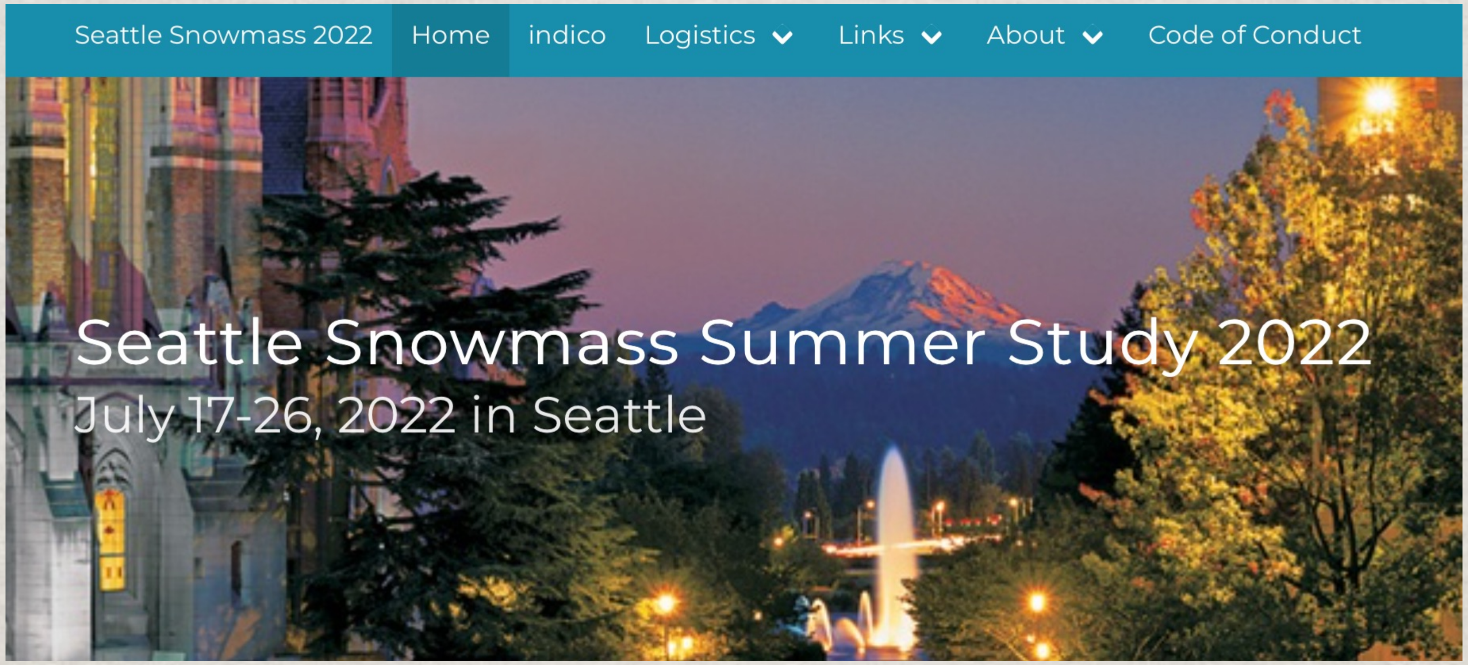
$$M_{\mathrm{DM}} < 1.8\ \mathrm{TeV} \left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$$

TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

U.S. Community Summer Study: Snowmass 2021

July 17 – 26, 2022 @ UW – Seattle

http://seattleshowmass2021.net



Seattle Snowmass Summer Study 2022

July 17-26, 2022 in Seattle

Participants

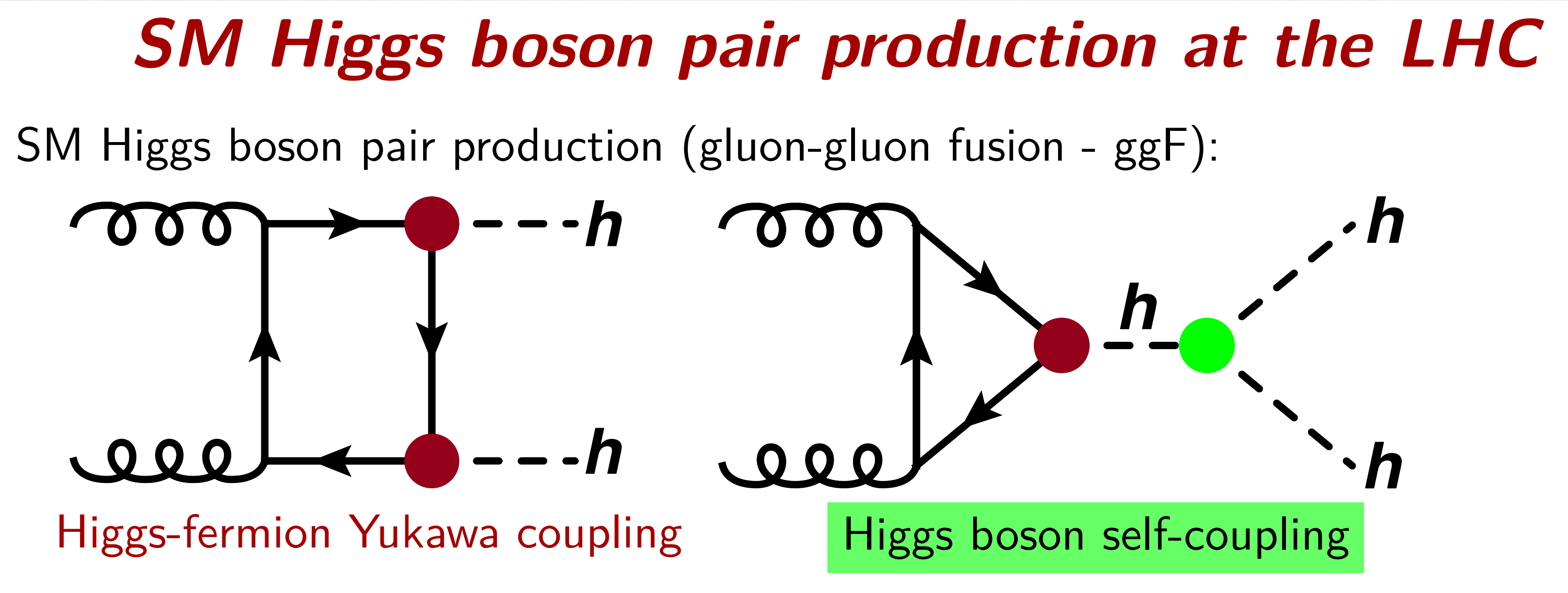
Number of in-person participants: 743

Number of virtual participants: 654

Local Organizing Committee/Volunteer/Press: 58

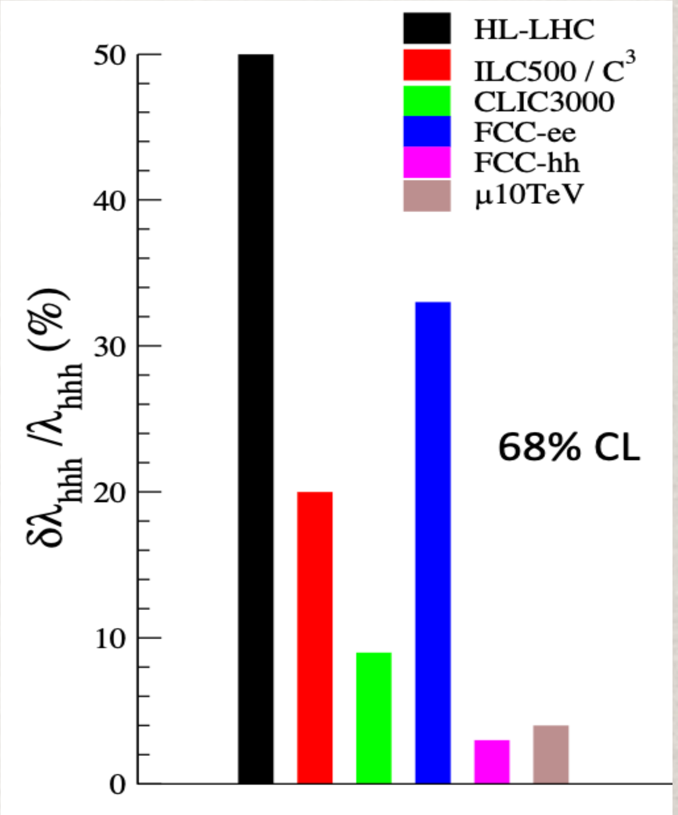
Total number of participants: 1397

Higgs pair production & triple coupling:



SM Higgs boson pair production at the LHC

SM Higgs boson pair production (gluon-gluon fusion - ggF):



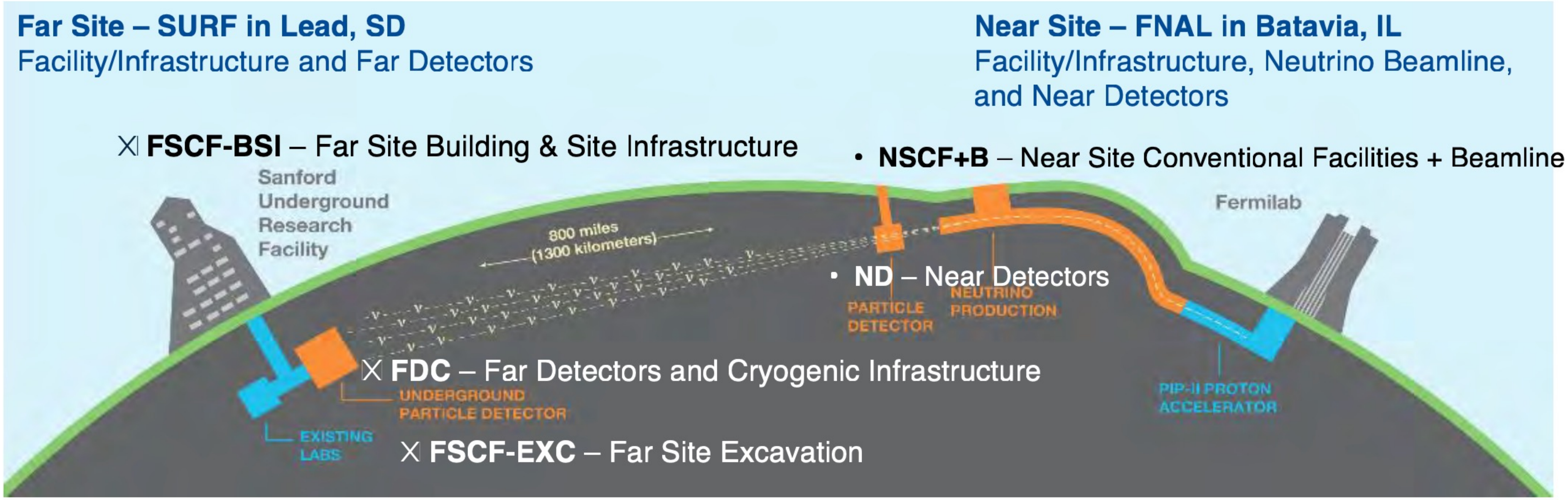
→dictate EW phase transition & impact on early universe cosmology!

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Table 7: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204

Long baseline neutrino facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)



Far Site – SURF in Lead, SD
Facility/Infrastructure and Far Detectors

Near Site – FNAL in Batavia, IL
Facility/Infrastructure, Neutrino Beamline, and Near Detectors

- **FSCF-BSI** – Far Site Building & Site Infrastructure
- **NSCF+B** – Near Site Conventional Facilities + Beamline
- **ND** – Near Detectors
- **FDC** – Far Detectors and Cryogenic Infrastructure
- **FSCF-EXC** – Far Site Excavation

- DUNE is an international science collaboration of more than 1300 scientists from 35 countries plus CERN
  - 50 – 50 split between U.S. and non- U.S. collaborators

Largest **DOMESTIC** project in Office of Science (TPC = $3.2B)
the first U.S.-hosted international particle physics mega-project

P5 Panel

Shoji Asai (University of Tokyo)
Amalia Ballarino (CERN)
Tulika Bose (Wisconsin–Madison)
Kyle Cranmer (Wisconsin–Madison)
Francis-Yan Cyr-Racine (New Mexico)
Sarah Demers (Yale)
Cameron Geddes (LBNL)
Yuri Gershtein (Rutgers)
Karsten Heeger (Yale) - *Deputy Chair*
Beate Heinemann (DESY)
JoAnne Hewett (SLAC) - HEPAP chair, ex officio until May 2023
Patrick Huber (Virginia Tech)
Kendall Mahn (Michigan State)
Rachel Mandelbaum (Carnegie Mellon)
Jelena Maricic (Hawaii)
Petra Merkel (Fermilab)
Christopher Monahan (William & Mary)
Hitoshi Murayama (Berkeley) - *Chair*
Peter Onyisi (Texas Austin)
Mark Palmer (BNL)
Tor Raubenheimer (SLAC/Stanford)
Mayly Sanchez (Florida State)
Richard Schnee (South Dakota School of Mines & Technology)
Sally Seidel (New Mexico) – interim HEPAP chair, ex officio since June 2023
Seon-Hee Seo (IBS Center for Underground Physics until Sep, Fermilab since Sep)
Jesse Thaler (MIT)
Christos Touramanis (Liverpool)
Abigail Vieregg (Chicago)
Amanda Weinstein (Iowa State)
Lindley Winslow (MIT)
Tien-Tien Yu (Oregon)
Robert Zwaska (Fermilab)

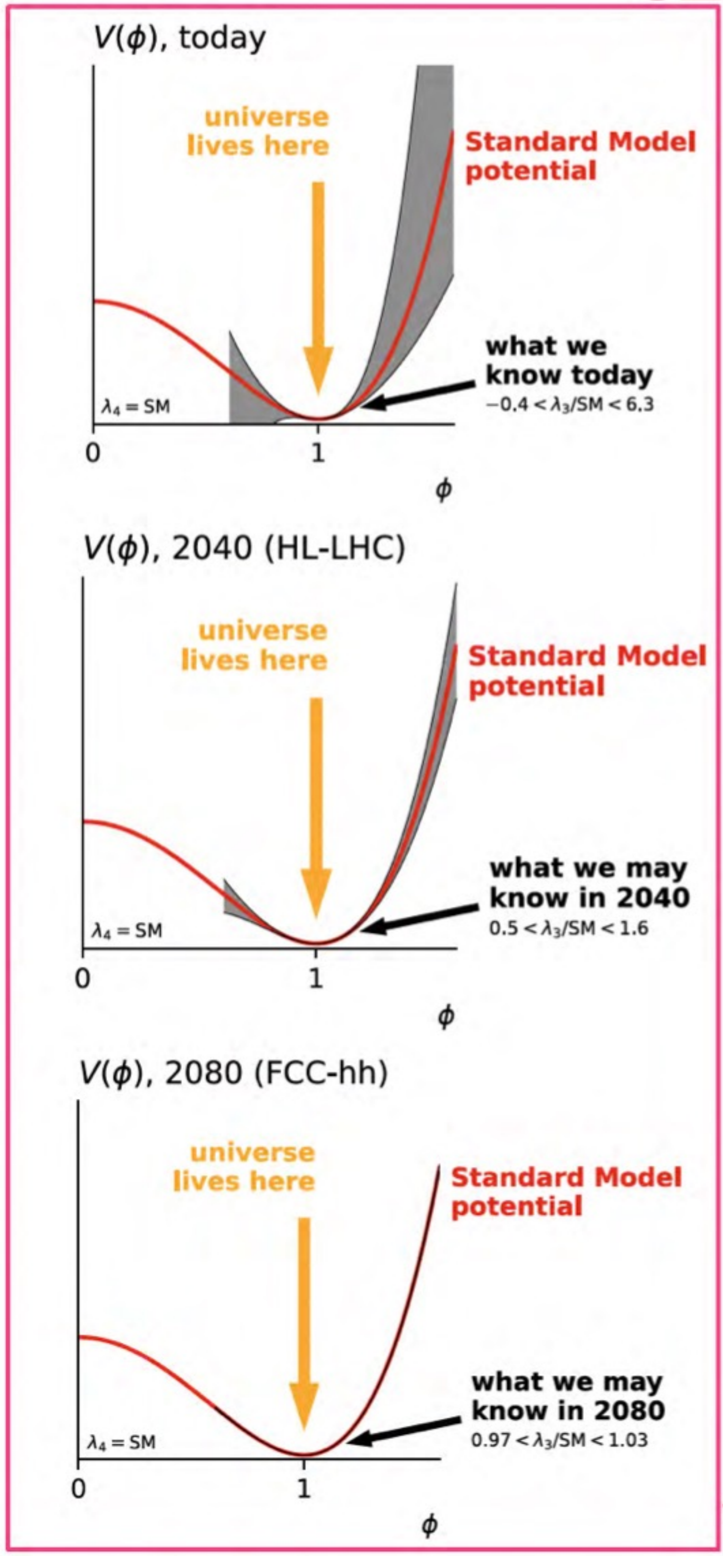
Towards 10 TeV pCM

SLAC

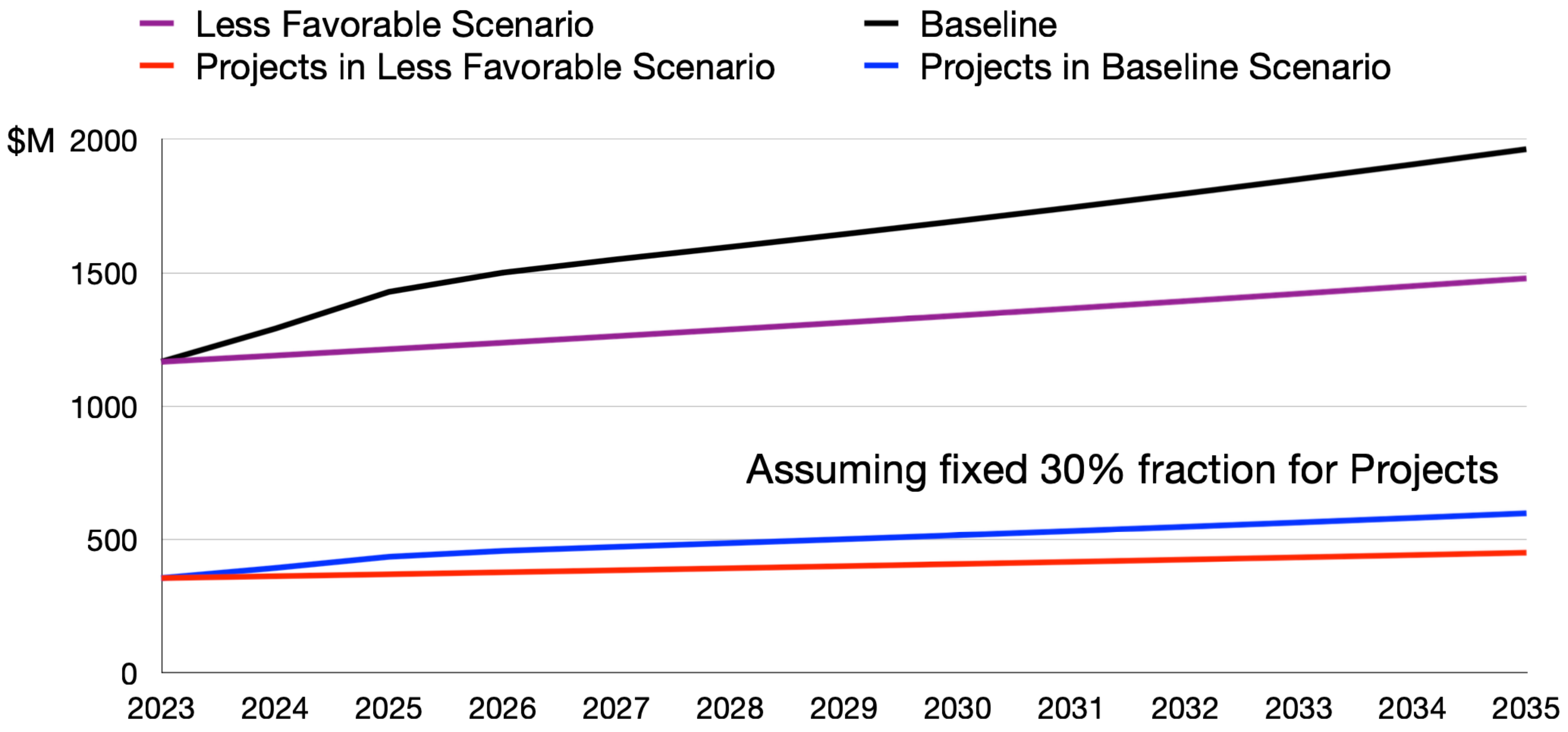
- Ultimate direct discovery reach of TeV scale phenomena
- Possible with hadron (FCC-hh @ 100 TeV) or muon colliders, but R&D is needed

- Higgs physics:
    - Probe the electroweak phase transition; Higgs self coupling measurements to 5% precision

- Direct beyond the SM searches:
    - Direct discovery of the particles responsible for any deviations observed in Higgs factory
    - Dark matter: “reach the thermal WIMP target for minimal WIMP candidates”



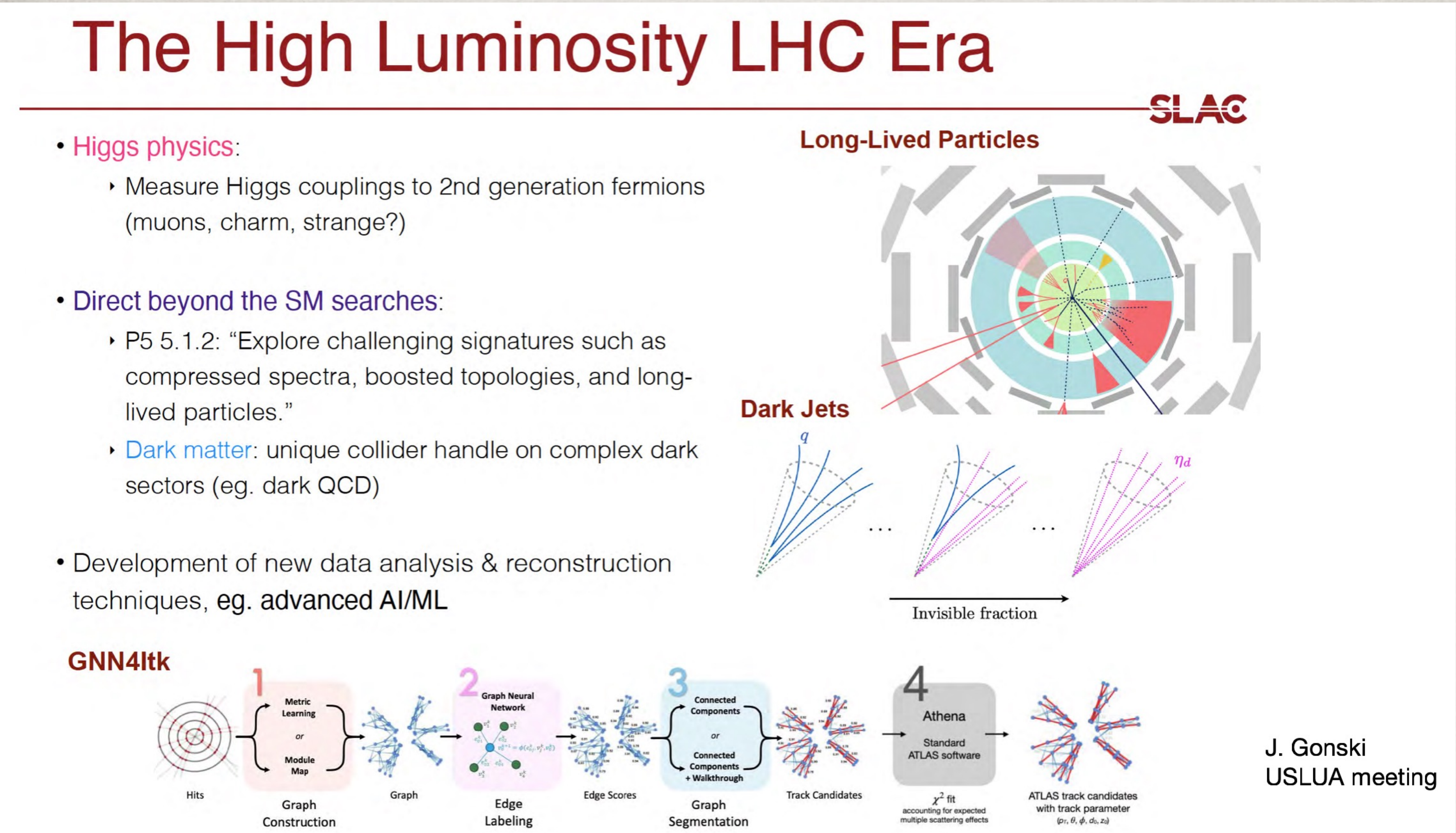
Budget Scenarios



Assuming fixed 30% fraction for Projects

DOE only

HL-LHC:



The High Luminosity LHC Era

- Higgs physics:
  - Measure Higgs couplings to 2nd generation fermions (muons, charm, strange?)

- Direct beyond the SM searches:
  - P5 5.1.2: "Explore challenging signatures such as compressed spectra, boosted topologies, and long-lived particles."
  - Dark matter: unique collider handle on complex dark sectors (eg. dark QCD)

- Development of new data analysis & reconstruction techniques, eg. advanced AI/ML

Long-Lived Particles

Dark Jets

GNN4Itk

J. Gonski
USLUA meeting

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 & $\alpha \rightarrow SU(2)_L \otimes U(1)_Y$. 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.

• Asia

- Japan: 2017 JAHEP/KEK Roadmap:
  -- SuperKEKB; J-PARC; Hyper-K; ILC …
- China: BEPC-II; JUNO; PandaX; LHAASO; CEPC/SppC …

• Latin America

Latin America: Strategy Forum for Research Infrastructure

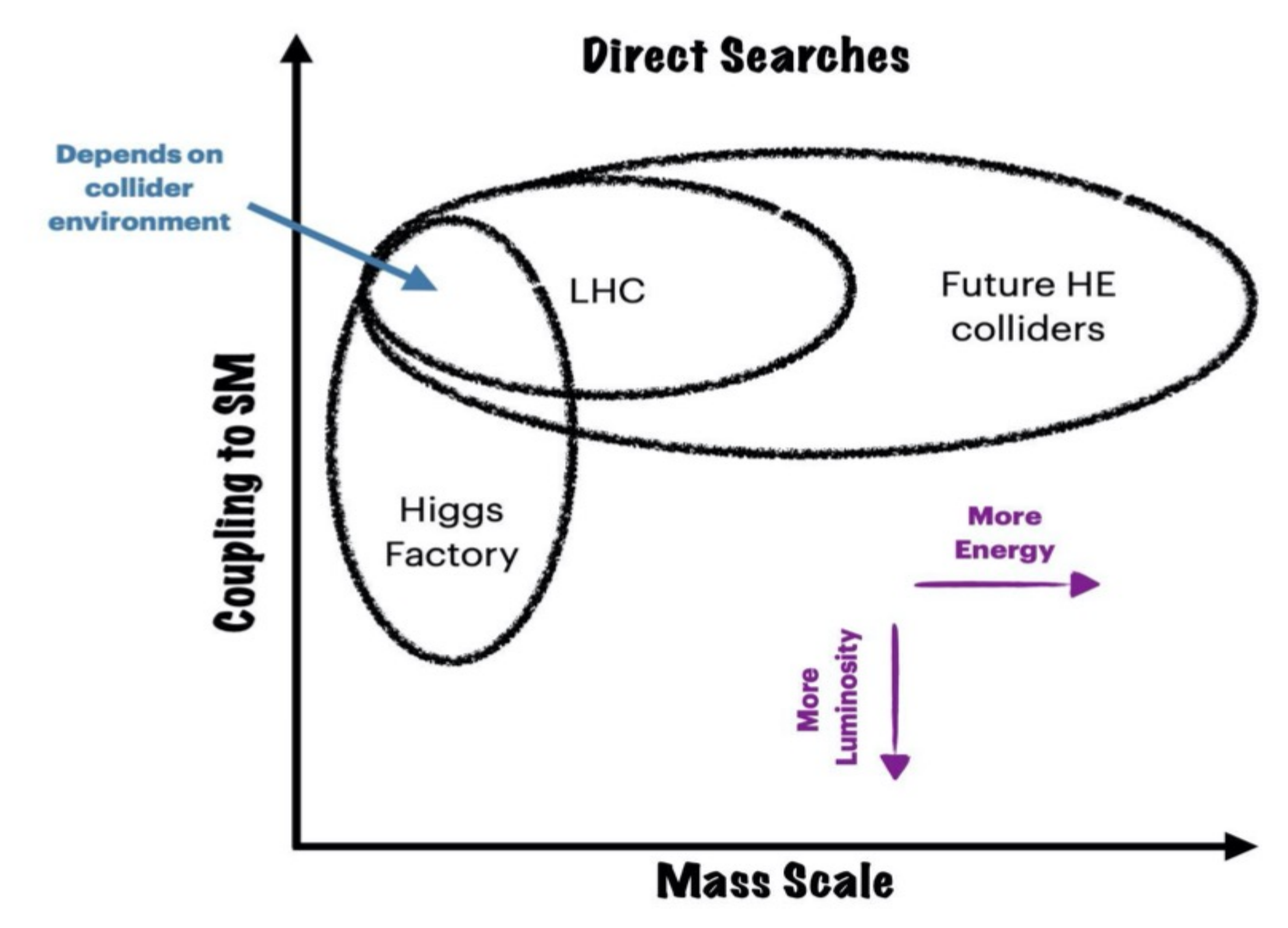
• United States

- NAS Decadal survey on Astronomy & Astrophysics (2021)
- NAS Decadal survey on Elementary Particle Physics (2023)
- Snowmass 2021 for a decadal study

(1). Energy Frontier: 高能前沿

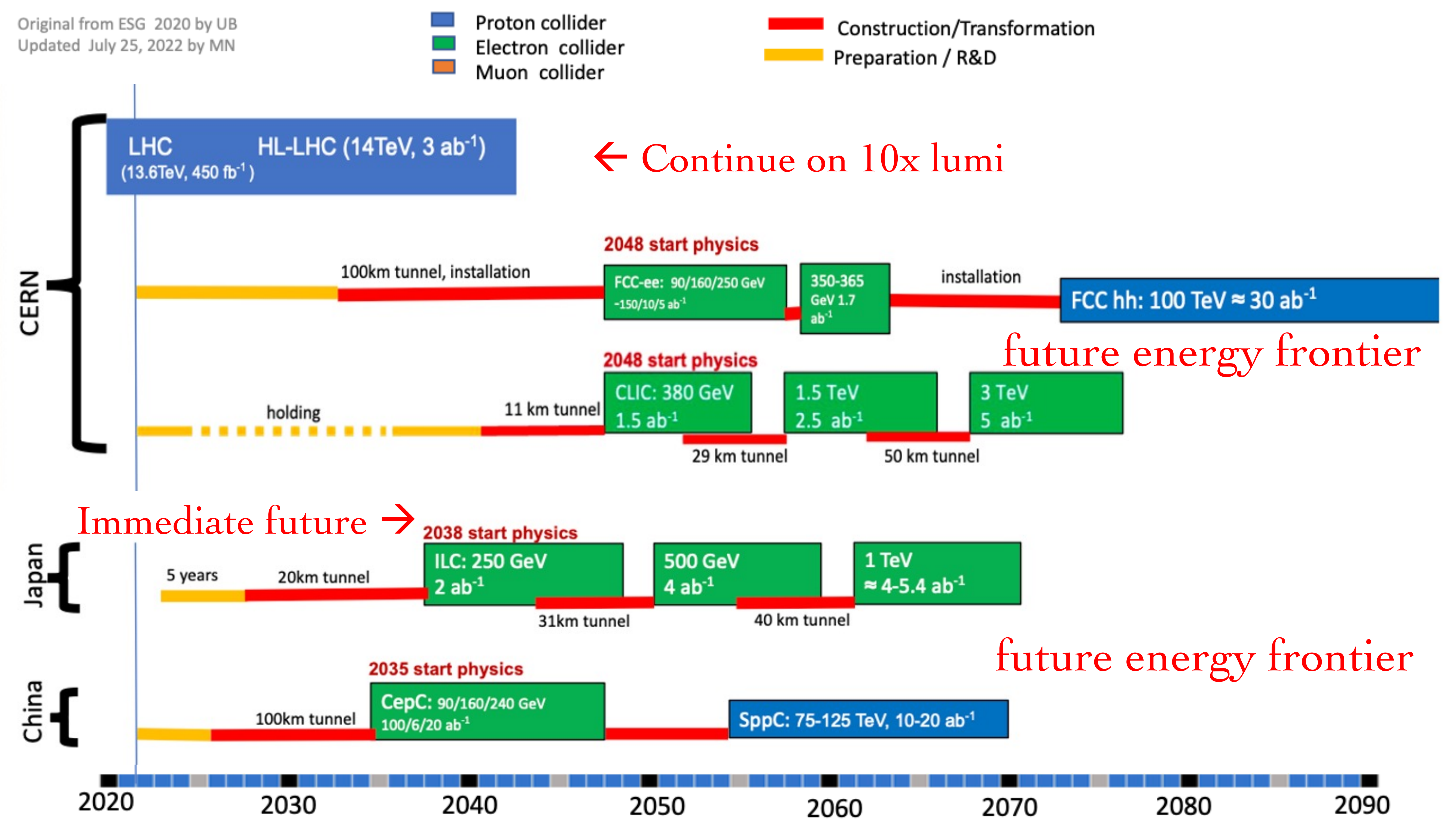
Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



The Energy Frontier Vision:

The energy frontier believes that it is essential to complete the HL-LHC program, to support construction of a Higgs factory, and to ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a Muon Collider or a hadron collider.



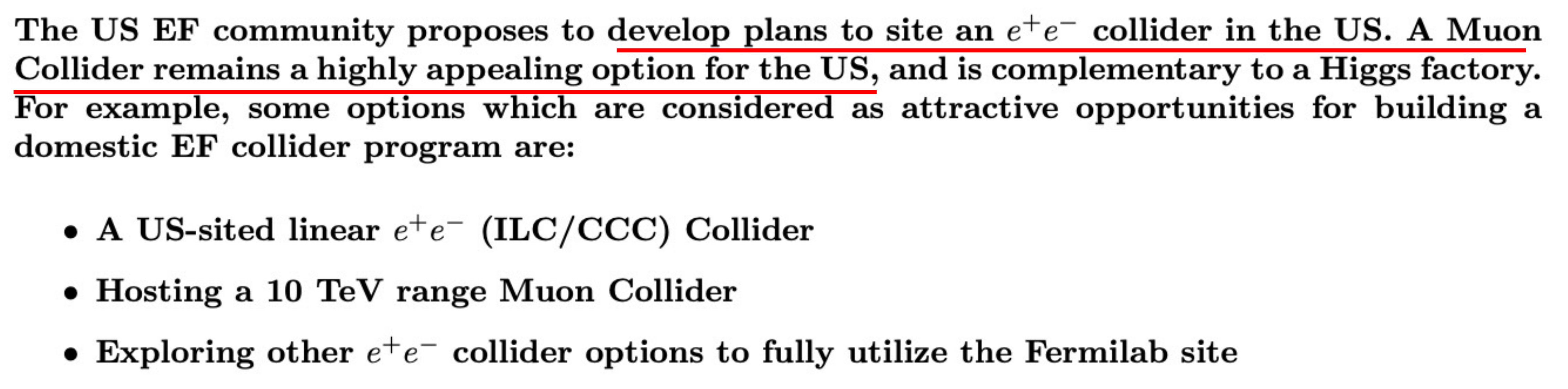
← Continue on 10x lumi

future energy frontier

Immediate future →

future energy frontier

Figure 6-40. *Projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options.*



The US EF community proposes to develop plans to site an e^+e^- collider in the US. A Muon Collider remains a highly appealing option for the US, and is complementary to a Higgs factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- **A US-sited linear e^+e^- (ILC/CCC) Collider**
- **Hosting a 10 TeV range Muon Collider**
- **Exploring other e^+e^- collider options to fully utilize the Fermilab site**

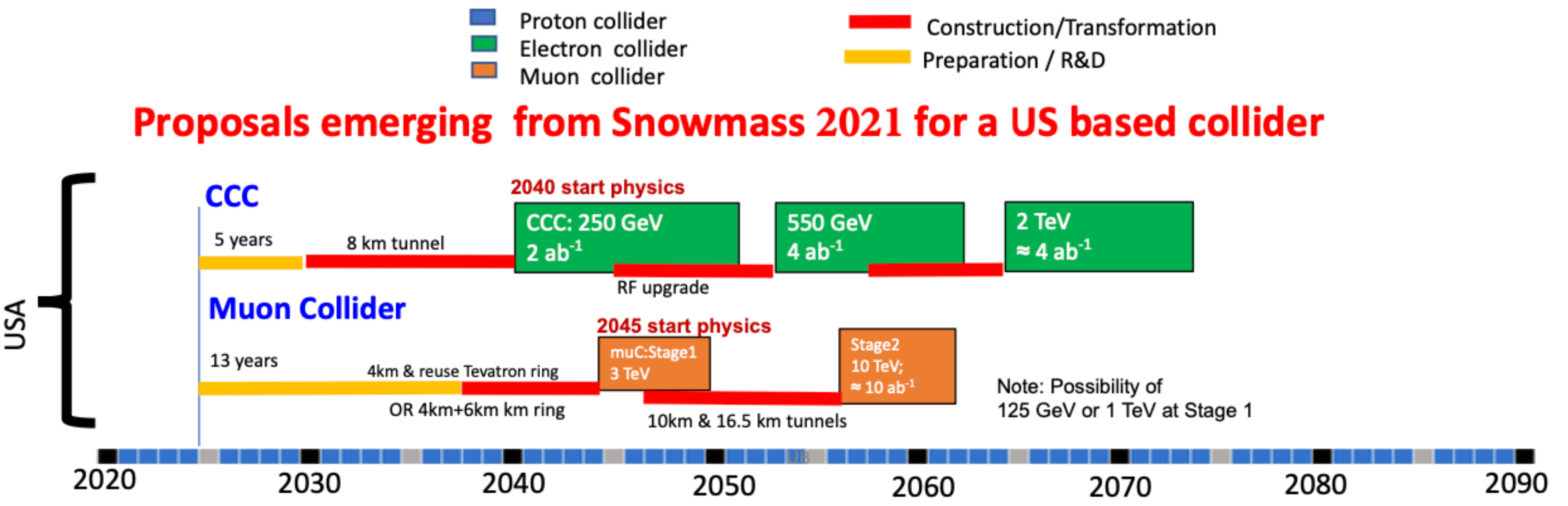
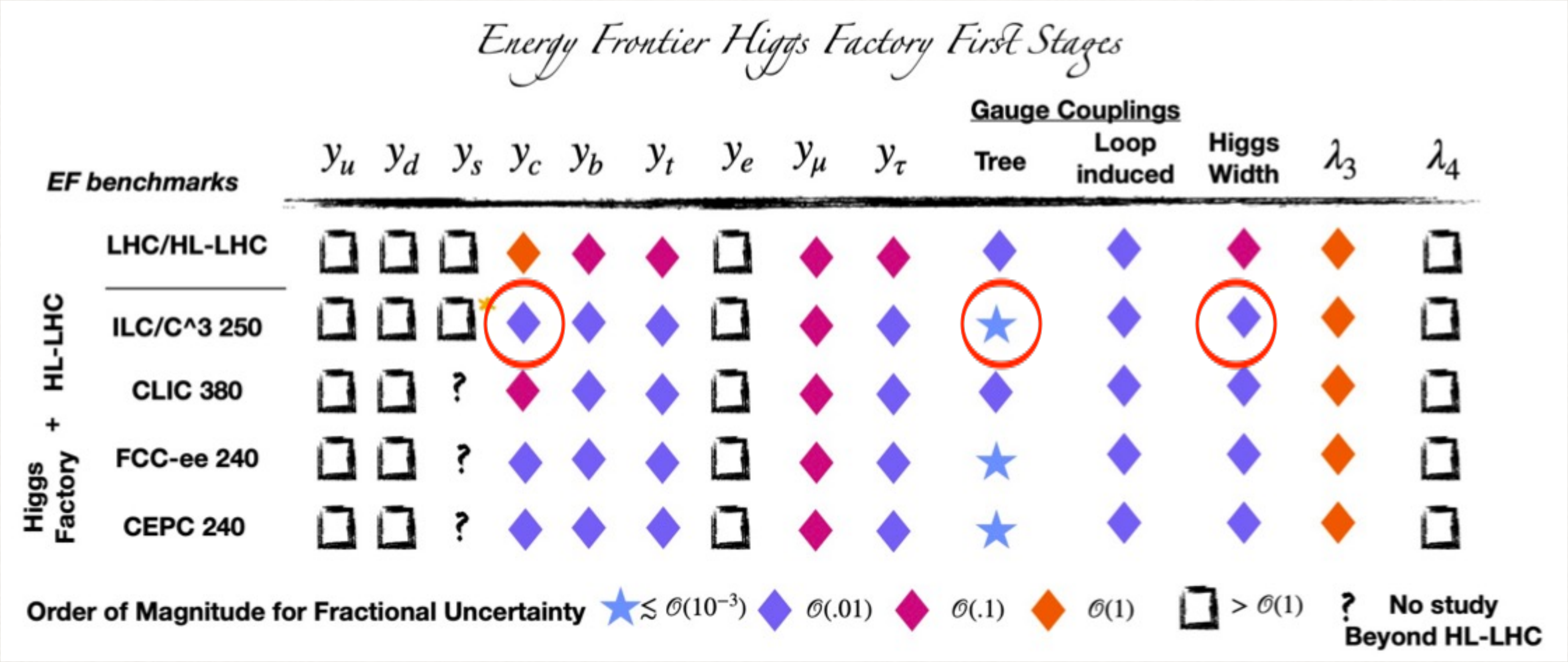


Figure 6-41. *Approximate timelines for proposals for ILC/CCC and Muon Collier emerging from Snowmass 2021 for a US based collider option.*

Physics example 1:

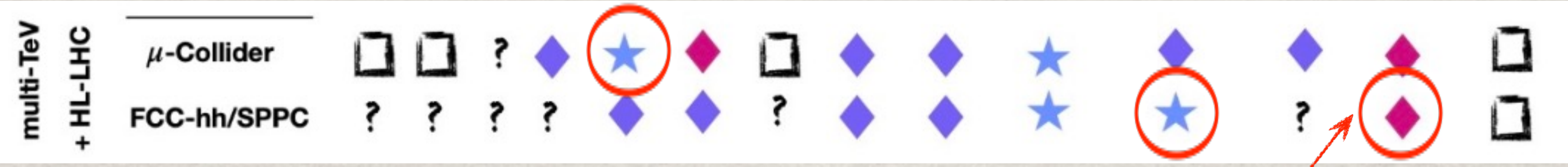
Sensitivity reach for Higgs couplings for Higgs factories and multi-TeV colliders



Energy Frontier Higgs Factory First Stages

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings Tree	 Loop induced	Higgs Width	λ_3	λ_4
	LHC/HL-LHC	☐	☐	☐	🔶	♦	♦	☐	♦	♦	🔷	🔷	♦	🔶	☐
Higgs Factory + HL-LHC	ILC/C^3 250	☐	☐	☐	🔷	🔷	🔷	☐	♦	🔷	★	🔷	🔷	🔶	☐
	CLIC 380	☐	☐	?	♦	🔷	🔷	☐	♦	🔷	🔷	🔷	🔷	🔶	☐
	FCC-ee 240	☐	☐	?	🔷	🔷	🔷	☐	♦	🔷	★	🔷	🔷	🔶	☐
	CEPC 240	☐	☐	?	🔷	🔷	🔷	☐	♦	🔷	★	🔷	🔷	🔶	☐

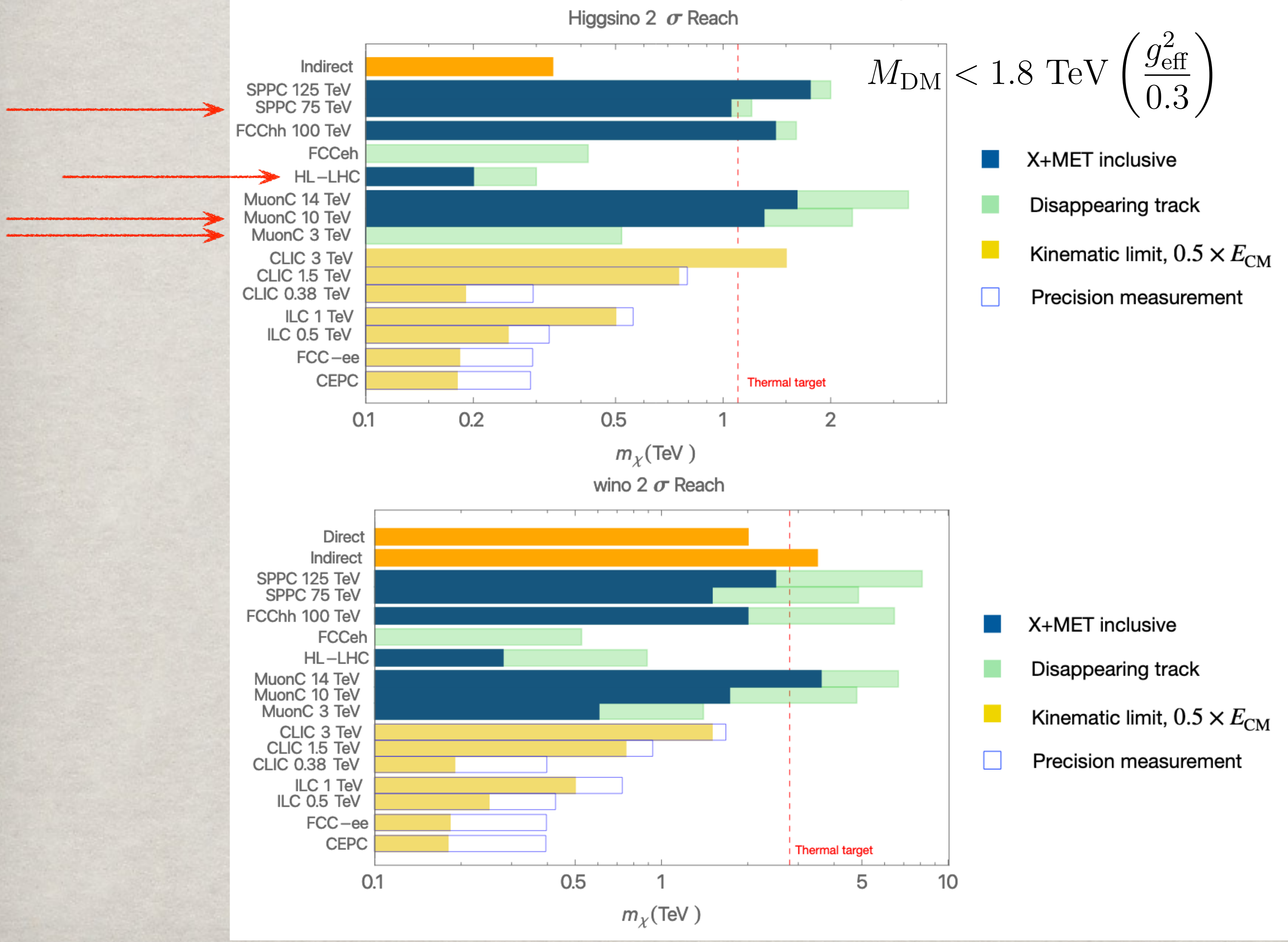
Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ 🔷 $\mathcal{O}(.01)$ ♦ $\mathcal{O}(.1)$ 🔶 $\mathcal{O}(1)$ ☐ $> \mathcal{O}(1)$? No study Beyond HL-LHC



	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Tree	Loop induced	Higgs Width	λ_3	λ_4
multi-TeV + HL-LHC	μ-Collider	☐	☐	?	🔷	★	♦	☐	🔷	🔷	★	🔷	🔷	♦	☐
	FCC-hh/SPPC	?	?	?	?	🔷	🔷	?	🔷	🔷	★	★	?	♦	☐

Most wanted in order to understand EWSB!

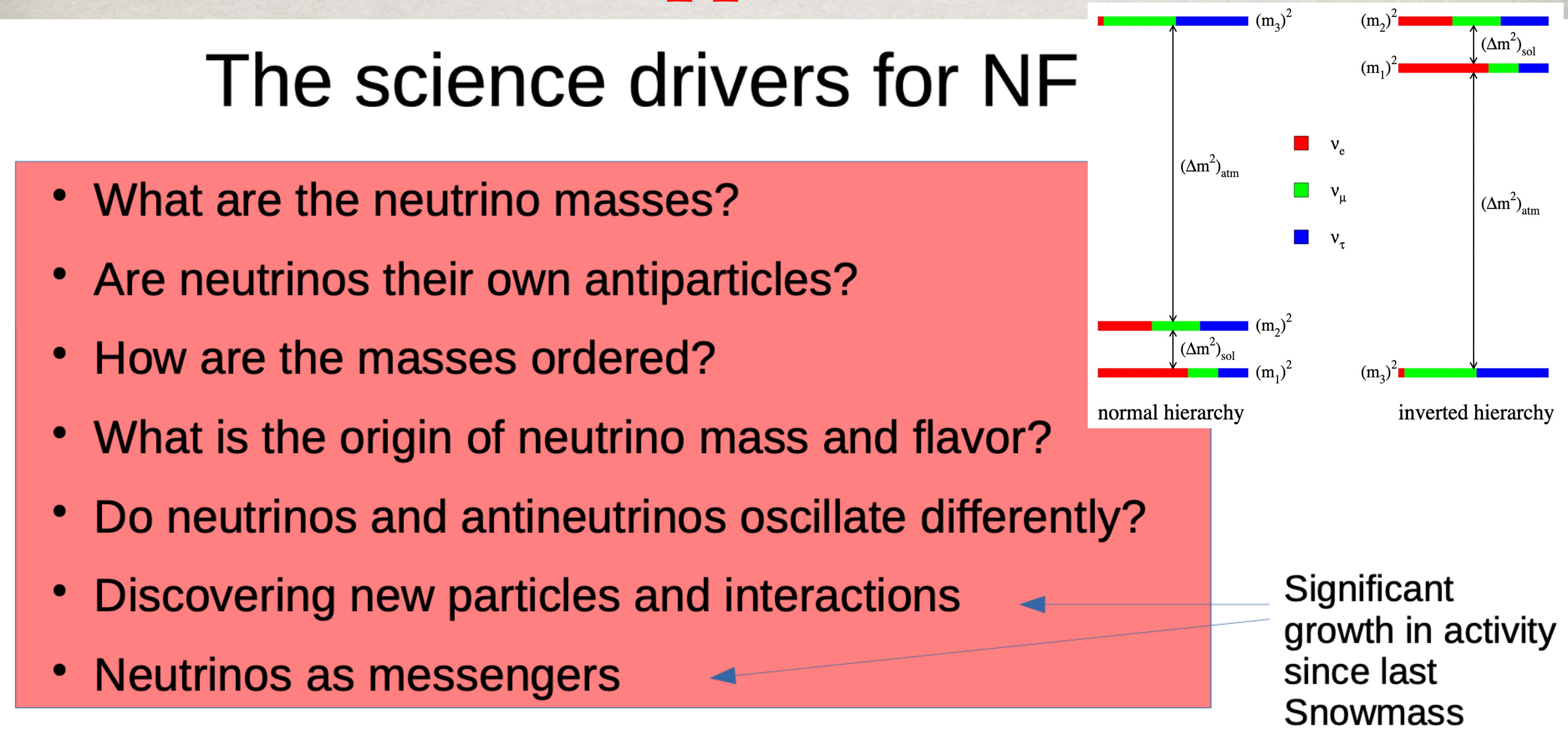
Physics example 2:
WIMP DM Searches: Covering the thermal target



$$M_{\rm DM} < 1.8\ {\rm TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$$

(2). Neutrino Frontier: 中微子前沿

ν Opportunities

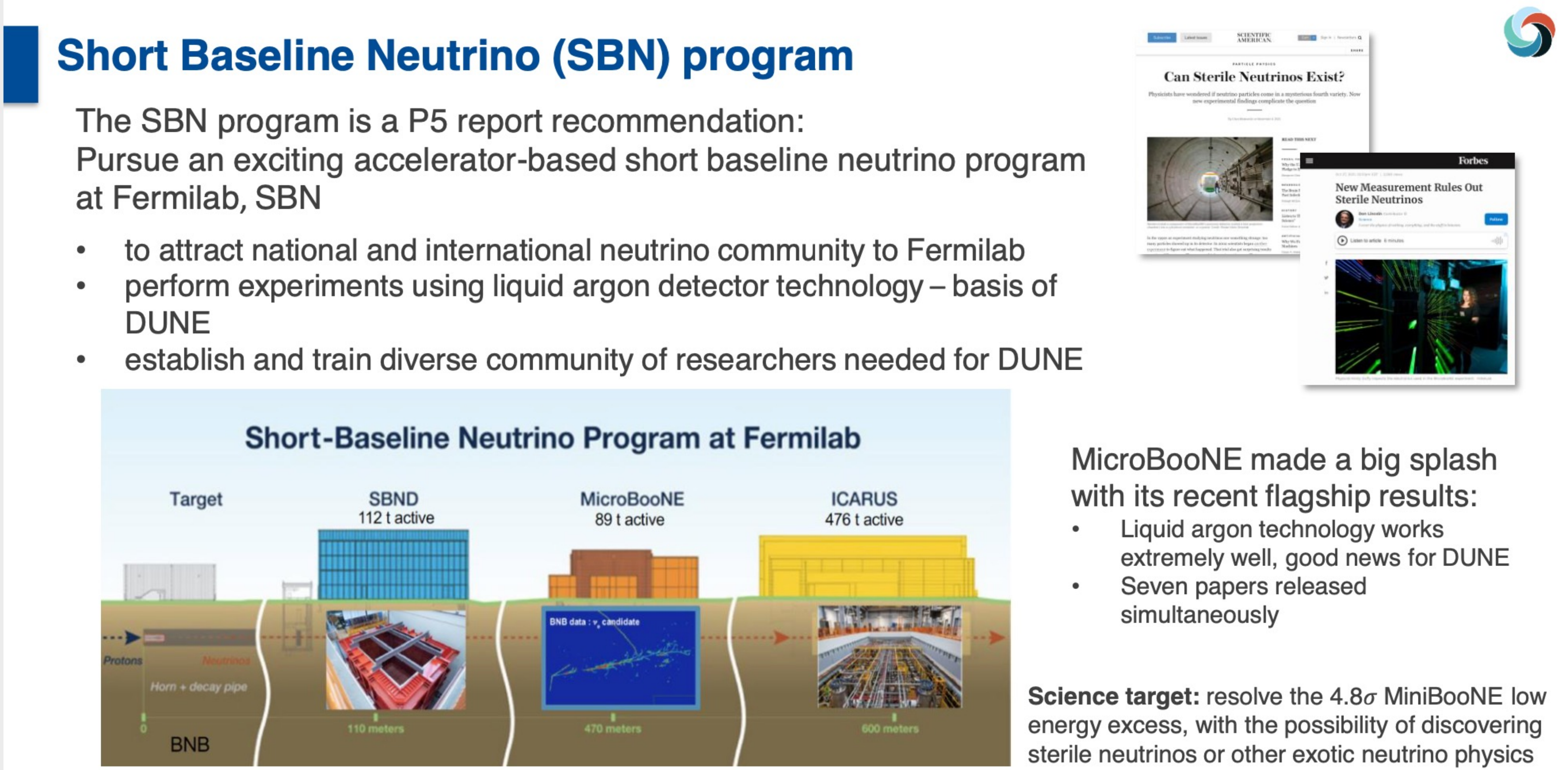


The science drivers for NF

- What are the neutrino masses?
- Are neutrinos their own antiparticles?
- How are the masses ordered?
- What is the origin of neutrino mass and flavor?
- Do neutrinos and antineutrinos oscillate differently?
- Discovering new particles and interactions
- Neutrinos as messengers

Significant growth in activity since last Snowmass

From Fermilab (Lia Merminga)



Short Baseline Neutrino (SBN) program

The SBN program is a P5 report recommendation:
Pursue an exciting accelerator-based short baseline neutrino program at Fermilab, SBN

- to attract national and international neutrino community to Fermilab
- perform experiments using liquid argon detector technology – basis of DUNE
- establish and train diverse community of researchers needed for DUNE

Short-Baseline Neutrino Program at Fermilab

SCIENTIFIC AMERICAN

PARTICLE PHYSICS

Can Sterile Neutrinos Exist?

Physicists have wondered if neutrino particles come in a mysterious fourth variety. Now new experimental findings complicate the question

Forbes

New Measurement Rules Out Sterile Neutrinos

MicroBooNE made a big splash with its recent flagship results:

- Liquid argon technology works extremely well, good news for DUNE
- Seven papers released simultaneously

Science target: resolve the 4.8σ MiniBooNE low energy excess, with the possibility of discovering sterile neutrinos or other exotic neutrino physics

coming complete operating

ORNL: COHERENT, PROSPECT, PROSPECT-II

From Fermilab (Lia Merminga)

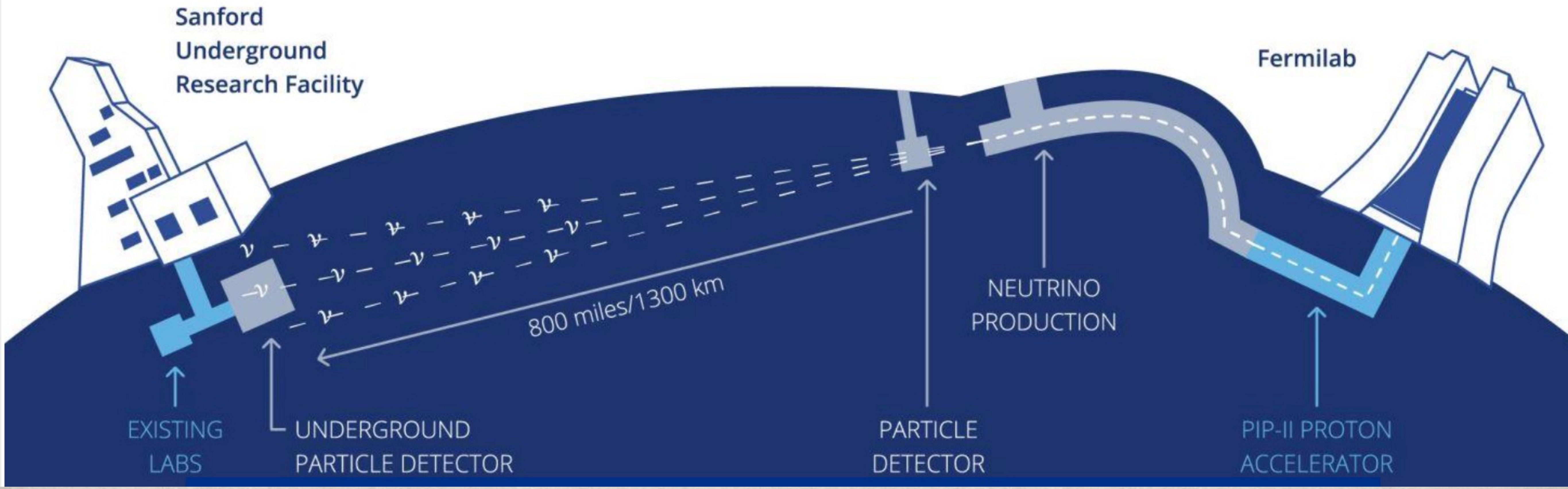
Delivering on LBNF/DUNE is Fermilab’s highest priority

S&T DUNE: The world’s most capable neutrino experiment, driven by LBNF and PIP-II

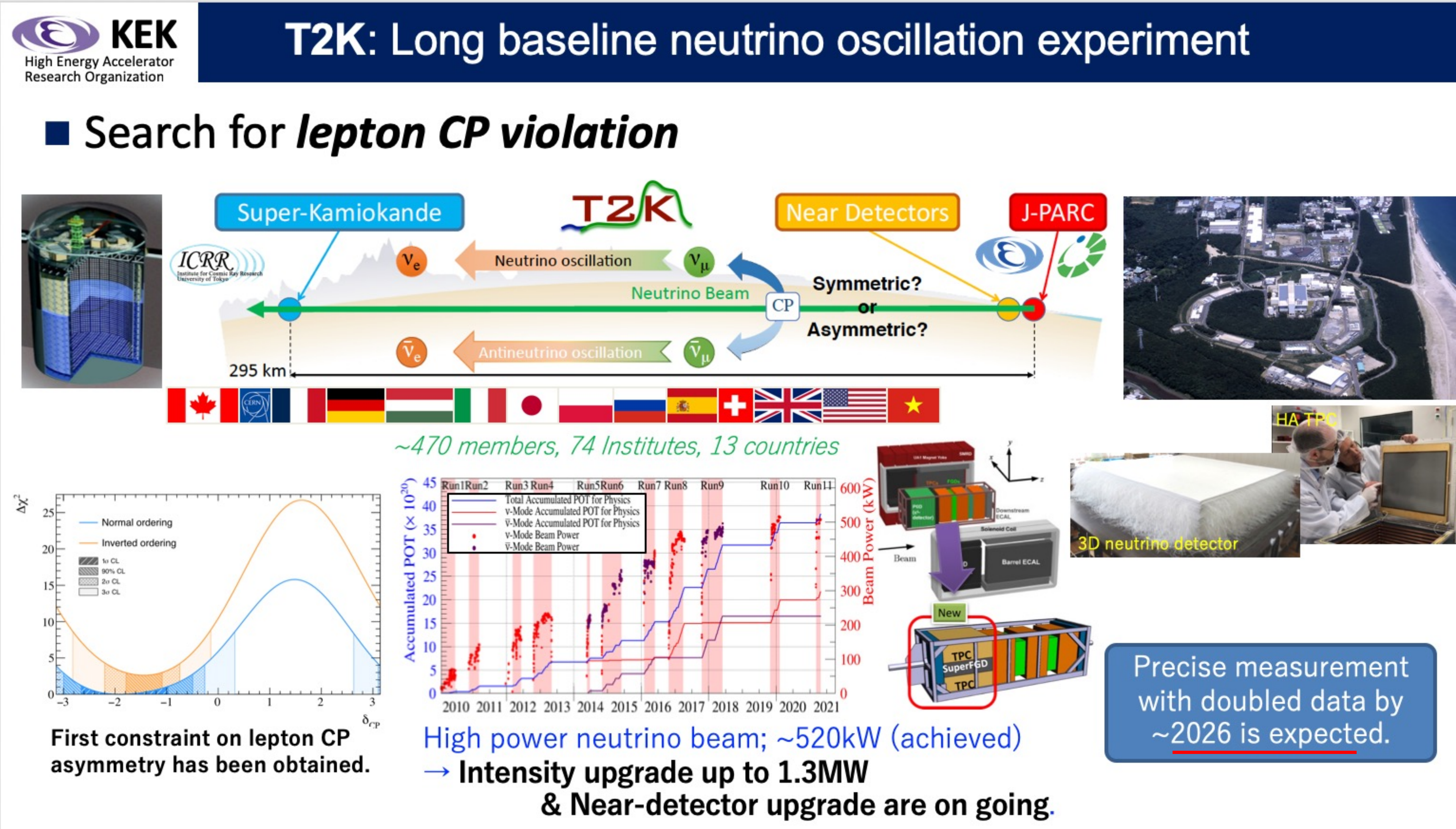
Gina Rameika Sergio Bertolucci

Vision for Neutrino Science

US/Fermilab is universally acknowledged as the world leader in neutrino science for decades to come



From KEK (Masa Yamauchi)



KEK High Energy Accelerator Research Organization

T2K: Long baseline neutrino oscillation experiment

- Search for ***lepton CP violation***

~470 members, 74 Institutes, 13 countries

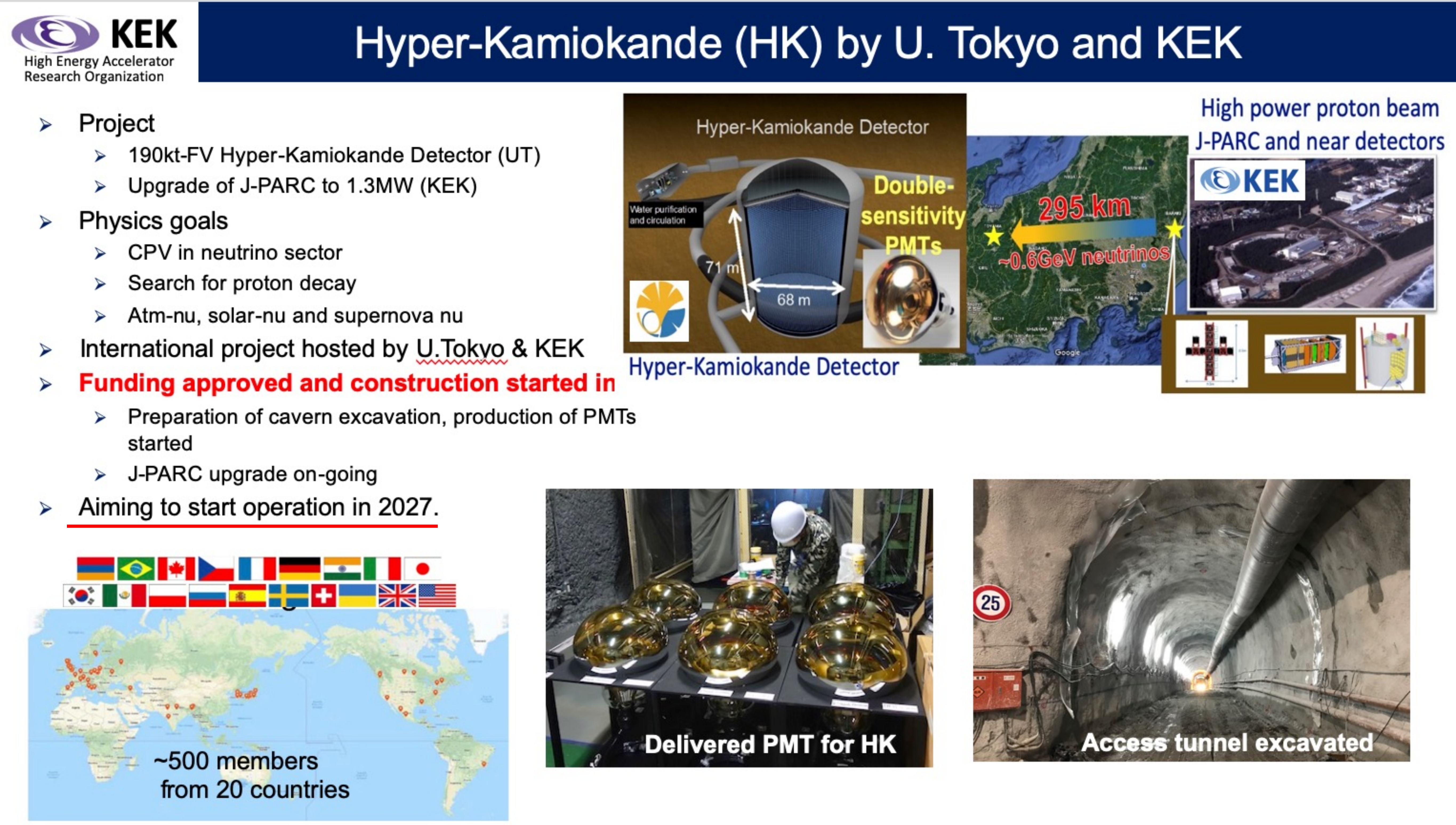
First constraint on lepton CP asymmetry has been obtained.

High power neutrino beam; ~520kW (achieved)

→ **Intensity upgrade up to 1.3MW & Near-detector upgrade are on going.**

Precise measurement with doubled data by ~2026 is expected.

From KEK (Masa Yamauchi)



KEK
High Energy Accelerator Research Organization

Hyper-Kamiokande (HK) by U. Tokyo and KEK

- Project
  - 190kt-FV Hyper-Kamiokande Detector (UT)
  - Upgrade of J-PARC to 1.3MW (KEK)
- Physics goals
  - CPV in neutrino sector
  - Search for proton decay
  - Atm-nu, solar-nu and supernova nu
- International project hosted by U.Tokyo & KEK
- **Funding approved and construction started in**
  - Preparation of cavern excavation, production of PMTs started
  - J-PARC upgrade on-going
- Aiming to start operation in 2027.

Hyper-Kamiokande Detector

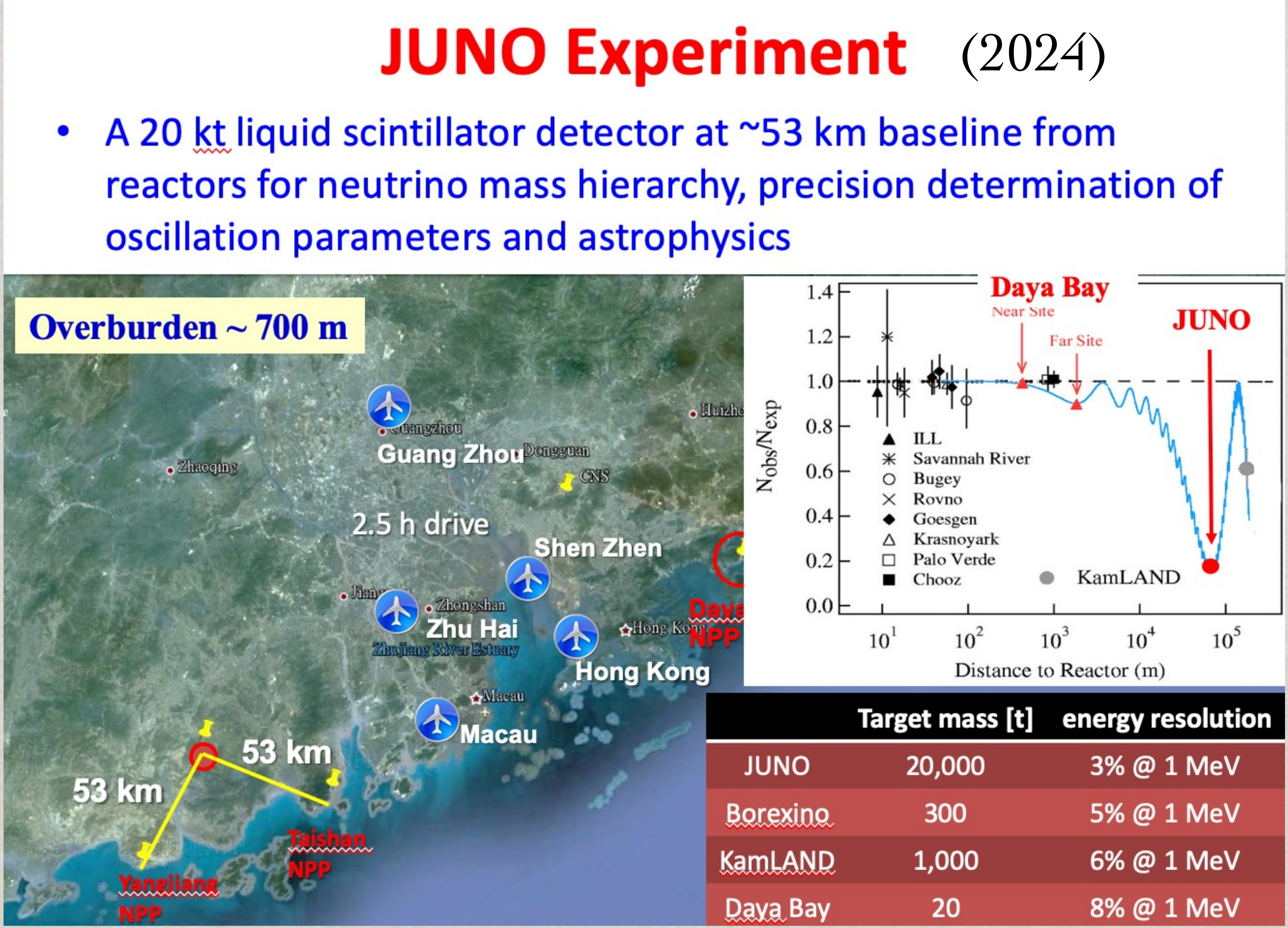
High power proton beam
J-PARC and near detectors

~500 members
from 20 countries

Delivered PMT for HK

Access tunnel excavated

From IHEP (Yifang Wang)



JUNO Experiment (2024)

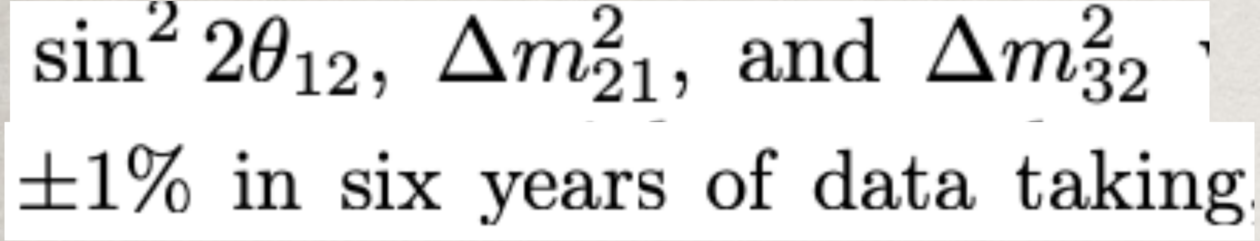
- A 20 kt liquid scintillator detector at ~53 km baseline from reactors for neutrino mass hierarchy, precision determination of oscillation parameters and astrophysics

Overburden ~ 700 m

	Target mass [t]	energy resolution
JUNO	20,000	3% @ 1 MeV
Borexino	300	5% @ 1 MeV
KamLAND	1,000	6% @ 1 MeV
Daya Bay	20	8% @ 1 MeV

Bread & butter ν physics:

JUNO (starting 2024):



$\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{32}

±1% in six years of data taking

Hyper-K (starting 2027):

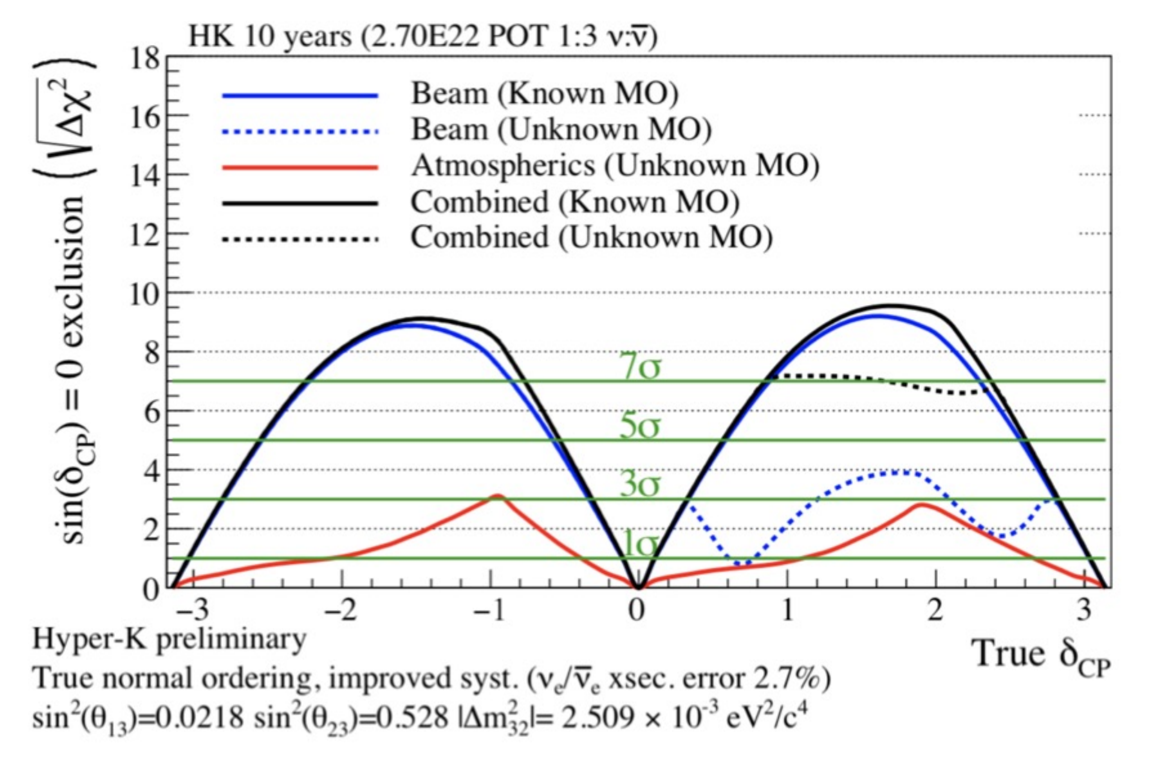


FIG. 4. HK sensitivity to exclude $\sin\delta(cp) = 0$, plotted as a function of the true value of δ_{CP}, assuming the mass ordering is unknown. A combined fit of HK beam and atmospheric neutrinos significantly enhances the HK sensitivity to δ_{CP}.

DUNE (starting 2032):

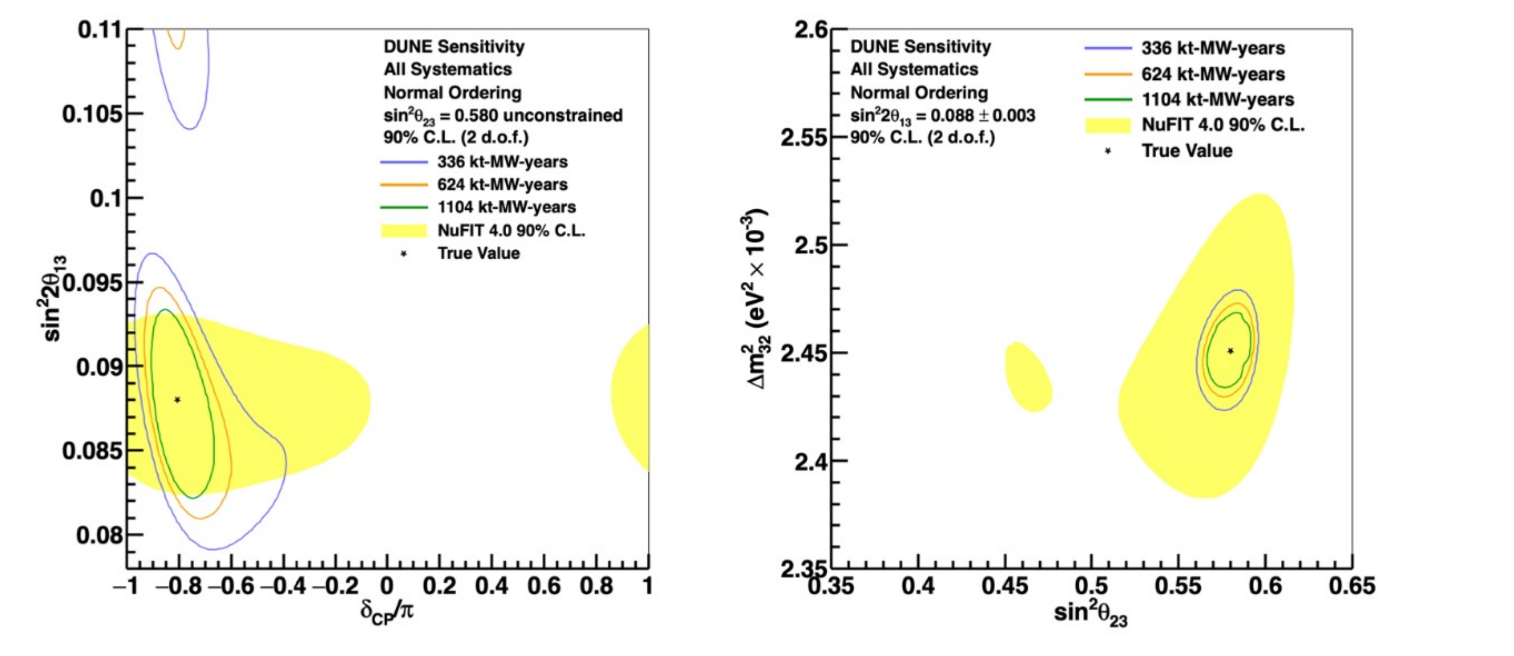
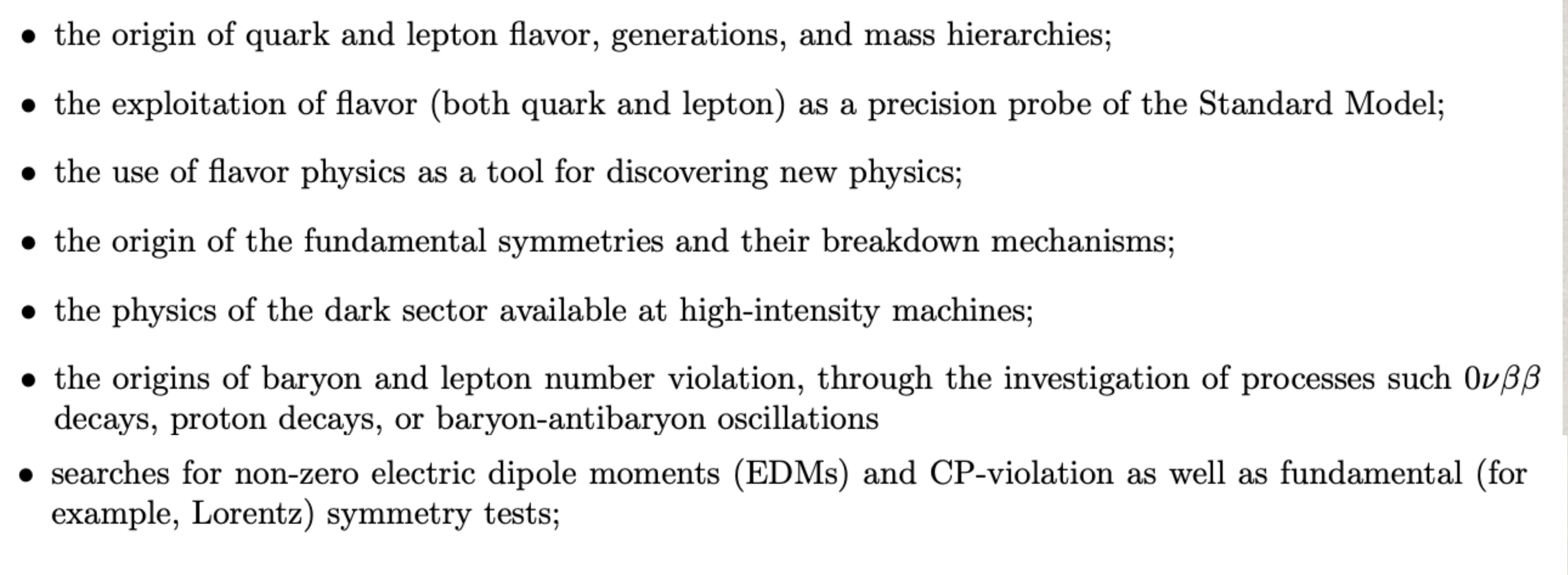


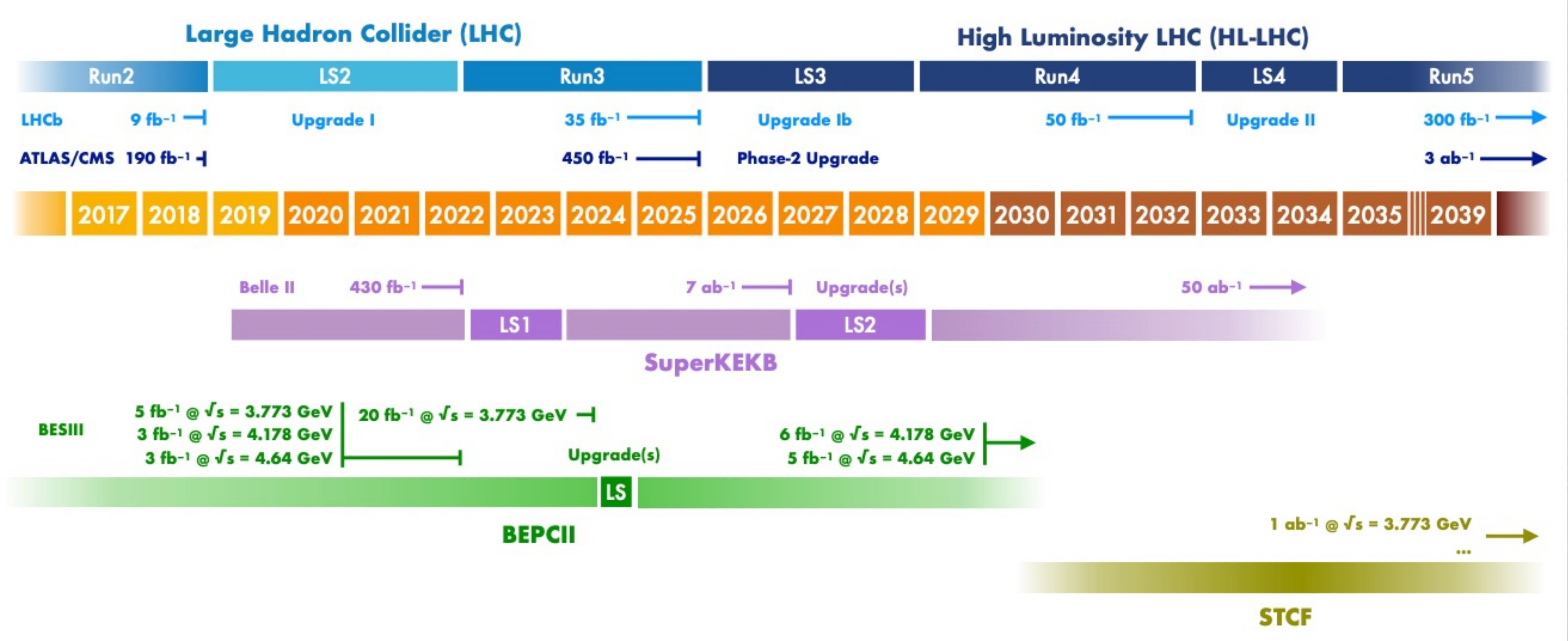
FIG. 3. 90% confidence intervals for $\sin^2 2\theta_{13} - \delta_{\text{CP}}$ (left), and $\sin^2 23 - \Delta m^2_{32}$ (right) after a range of exposures in kt-MW-years, for a projected measurement with assumed true parameter values near the current global best fit. Yellow regions indicate recent global fits from NuFIT 4.0.

Complementarity!

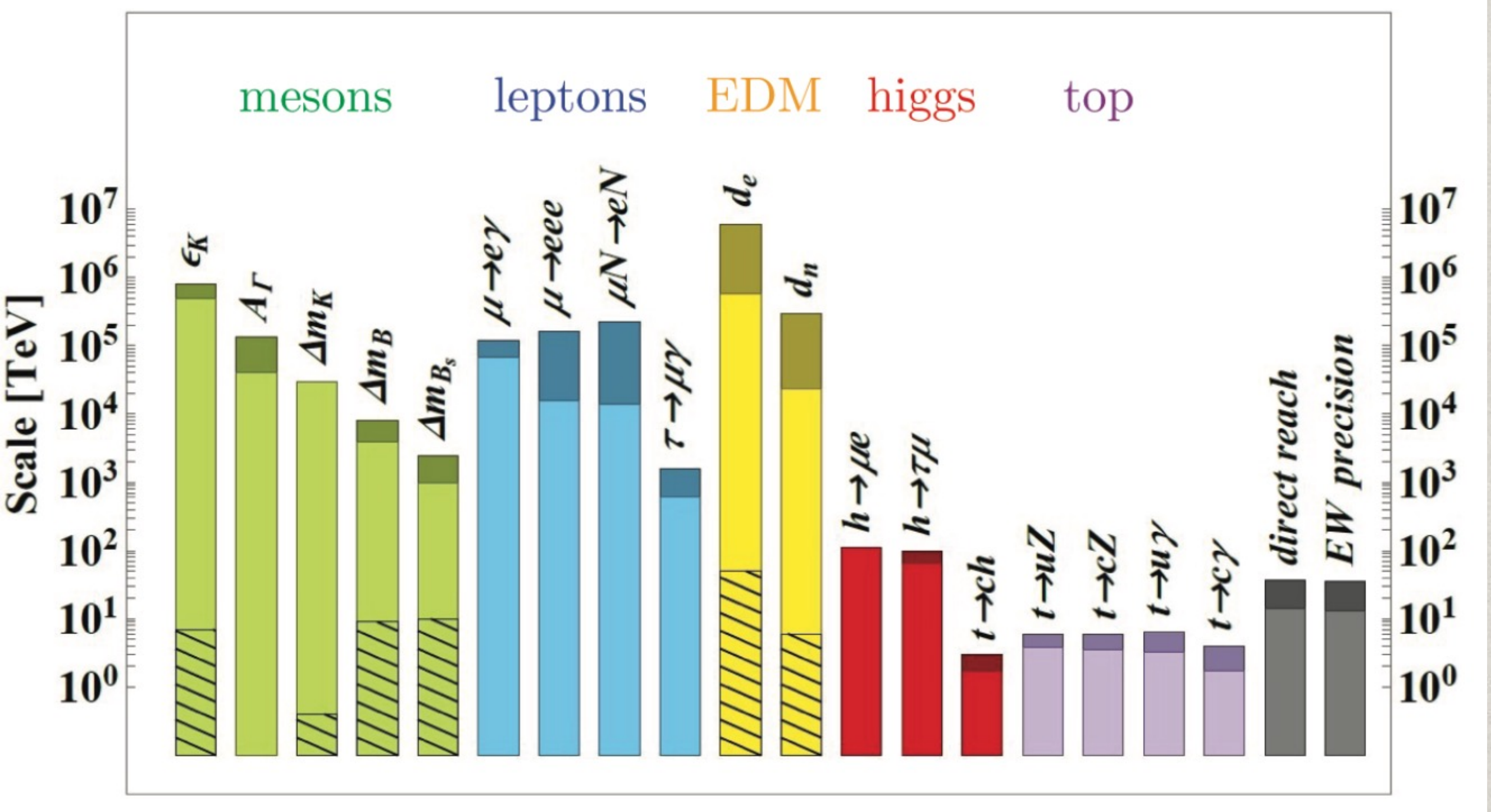
(3). Rare Process @ Precision



- the origin of quark and lepton flavor, generations, and mass hierarchies;
- the exploitation of flavor (both quark and lepton) as a precision probe of the Standard Model;
- the use of flavor physics as a tool for discovering new physics;
- the origin of the fundamental symmetries and their breakdown mechanisms;
- the physics of the dark sector available at high-intensity machines;
- the origins of baryon and lepton number violation, through the investigation of processes such $0\nu\beta\beta$ decays, proton decays, or baryon-antibaryon oscillations
- searches for non-zero electric dipole moments (EDMs) and CP-violation as well as fundamental (for example, Lorentz) symmetry tests;



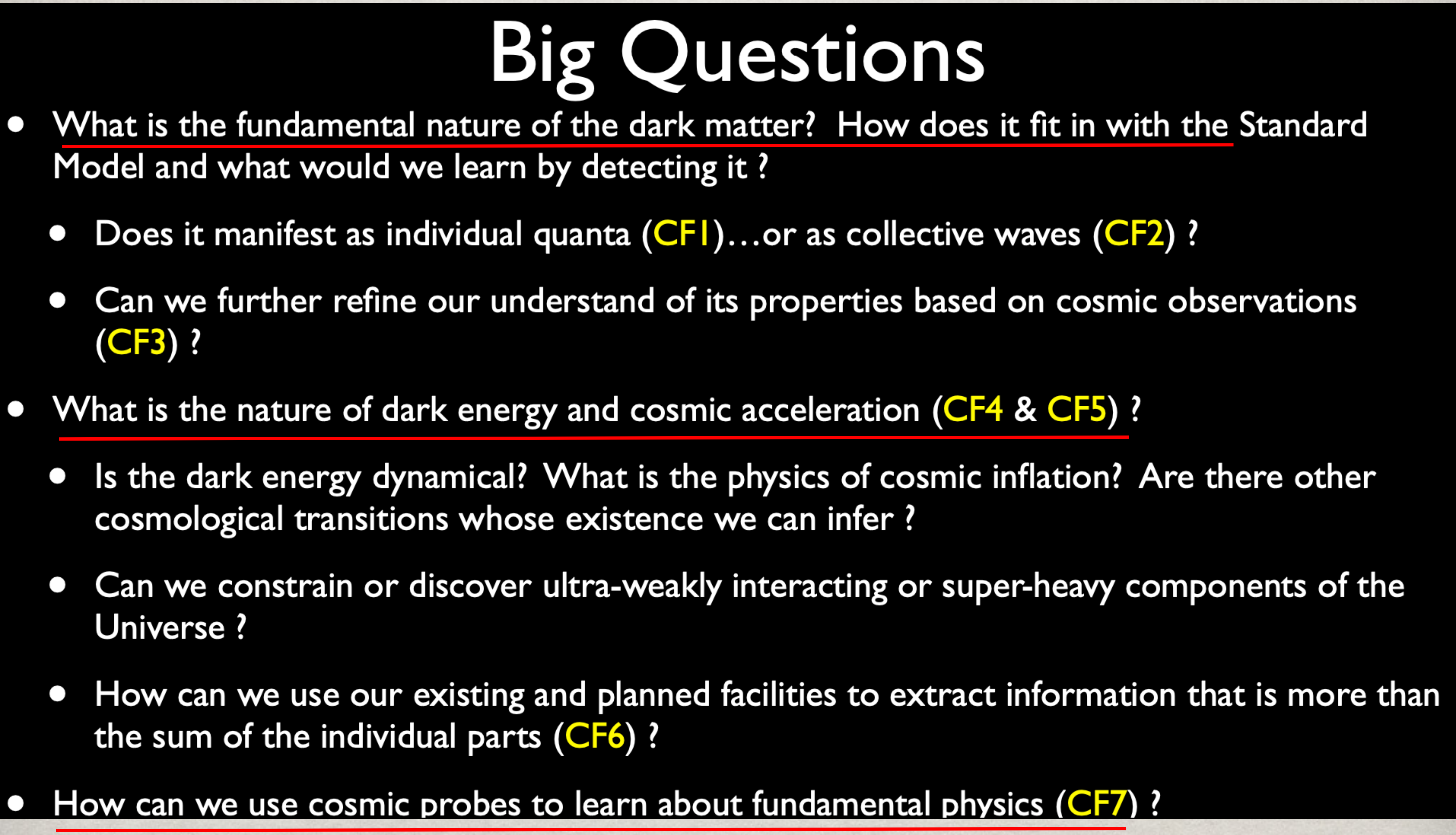
Low energy & high energy synergy: Sensitivity to dim-6 operators in EFT



Observed

Current/future bounds
e.g. HL-LHC

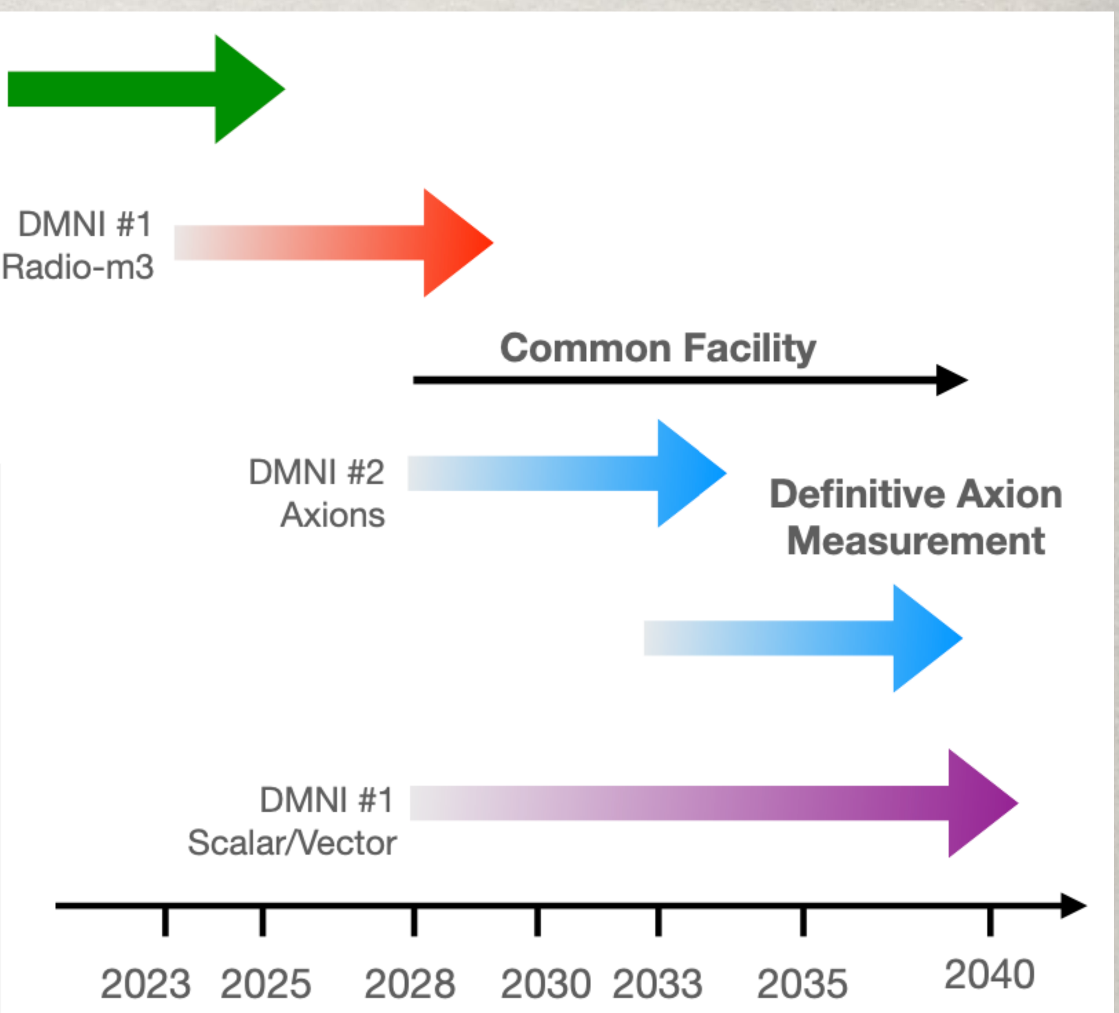
(4). Cosmic Frontier: 宇宙学前沿



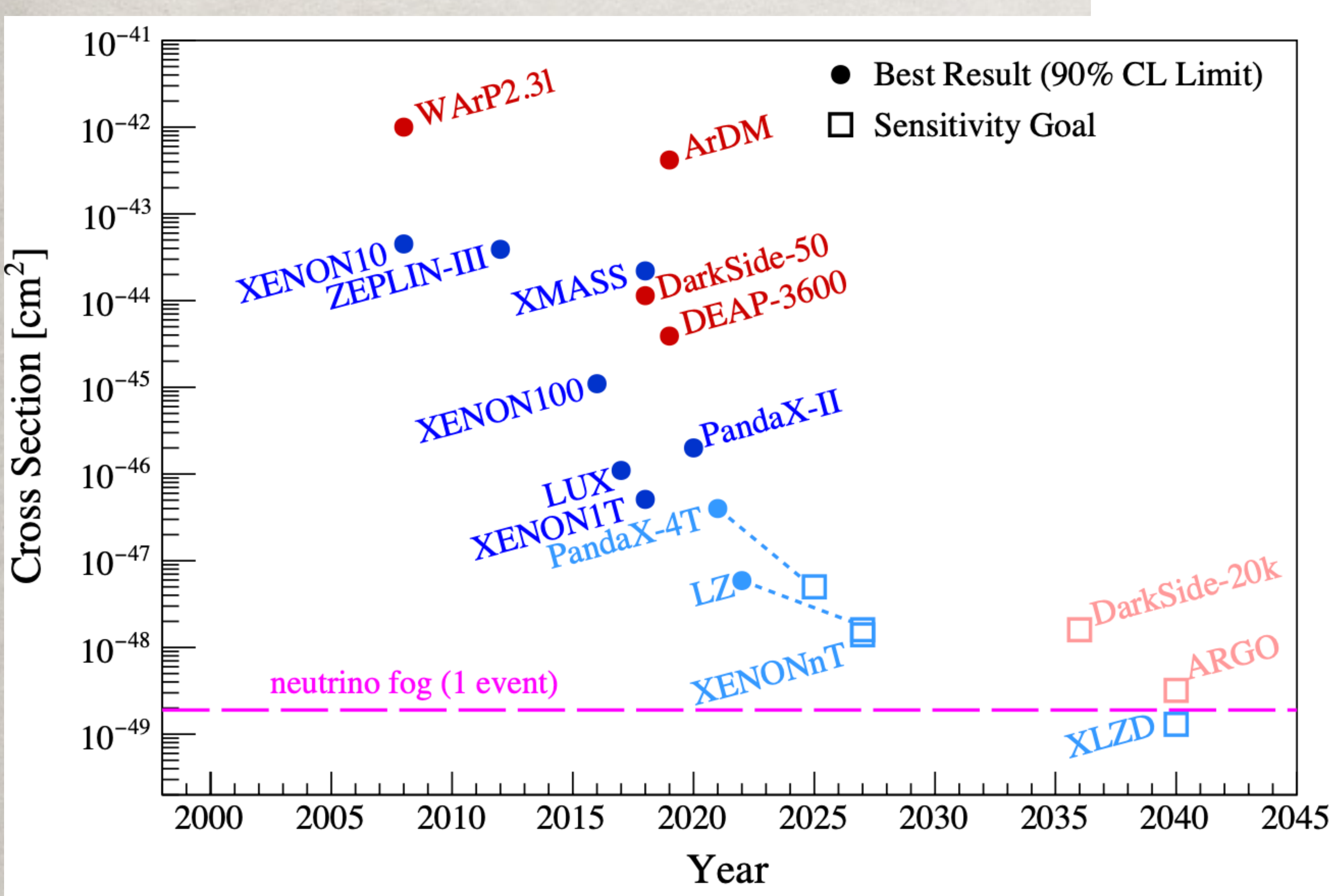
Big Questions

- What is the fundamental nature of the dark matter? How does it fit in with the Standard Model and what would we learn by detecting it ?
  - Does it manifest as individual quanta (CF1)…or as collective waves (CF2) ?
  - Can we further refine our understand of its properties based on cosmic observations (CF3) ?
- What is the nature of dark energy and cosmic acceleration (CF4 & CF5) ?
  - Is the dark energy dynamical? What is the physics of cosmic inflation? Are there other cosmological transitions whose existence we can infer ?
  - Can we constrain or discover ultra-weakly interacting or super-heavy components of the Universe ?
  - How can we use our existing and planned facilities to extract information that is more than the sum of the individual parts (CF6) ?
- How can we use cosmic probes to learn about fundamental physics (CF7) ?

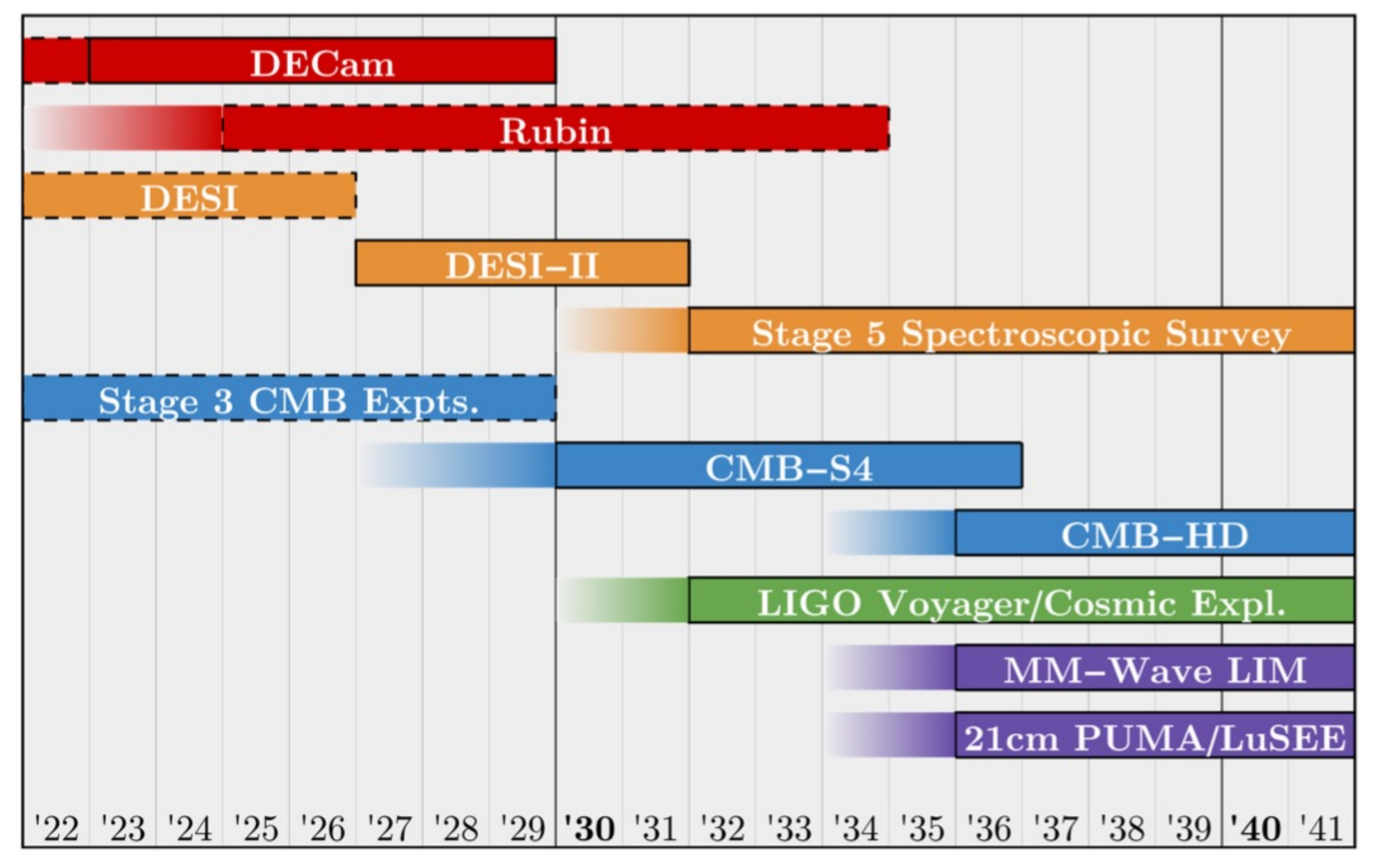
Axion search plans



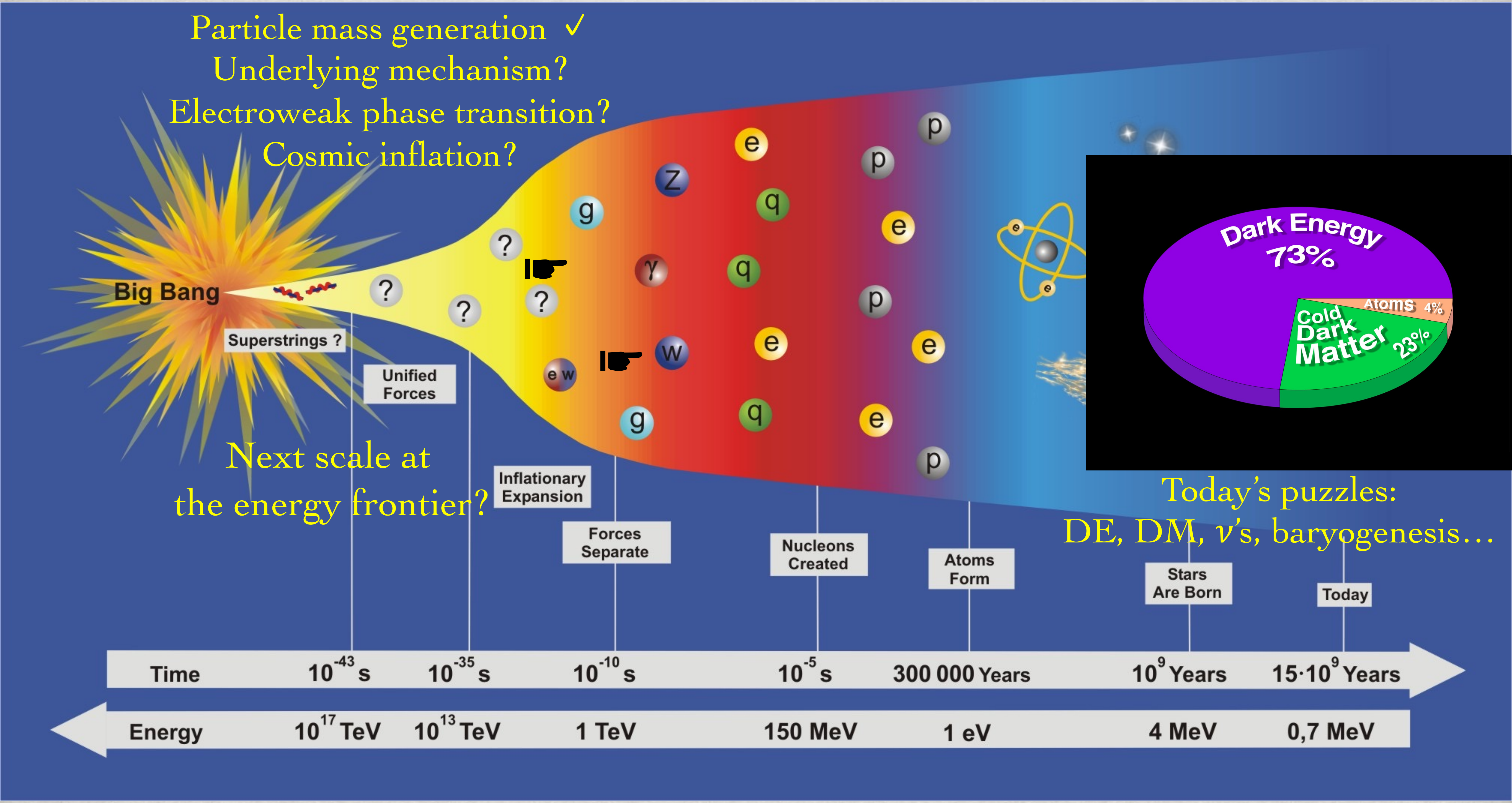
WIMP DM direct searches



Other cosmic probes



A GRAND PICTURE: 纵观全局



Particle mass generation ✓
Underlying mechanism?
Electroweak phase transition?
Cosmic inflation?

Next scale at
the energy frontier?

Today's puzzles:
DE, DM, ν's, baryogenesis…

THE FUTURE OF HEP IS BRIGHT!
EXCITING JOURNEY AHEAD!

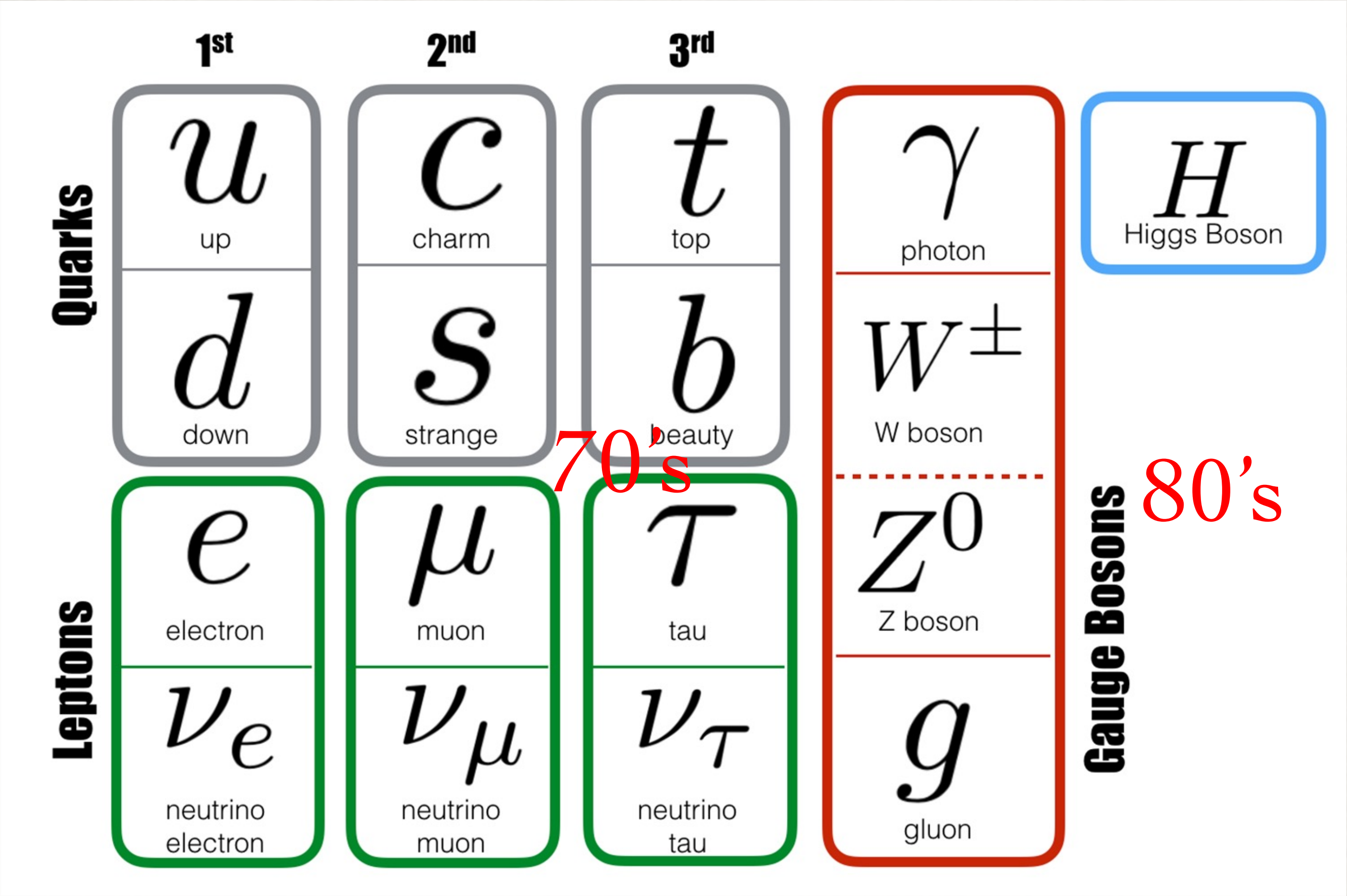
Backup slides

High-Energy Physics

is an exciting & dynamic field, uninterrupted discoveries over half a century

From the quarks to Higgs boson, together with Astrophysics/cosmological observations

60's 70's 90's 2012

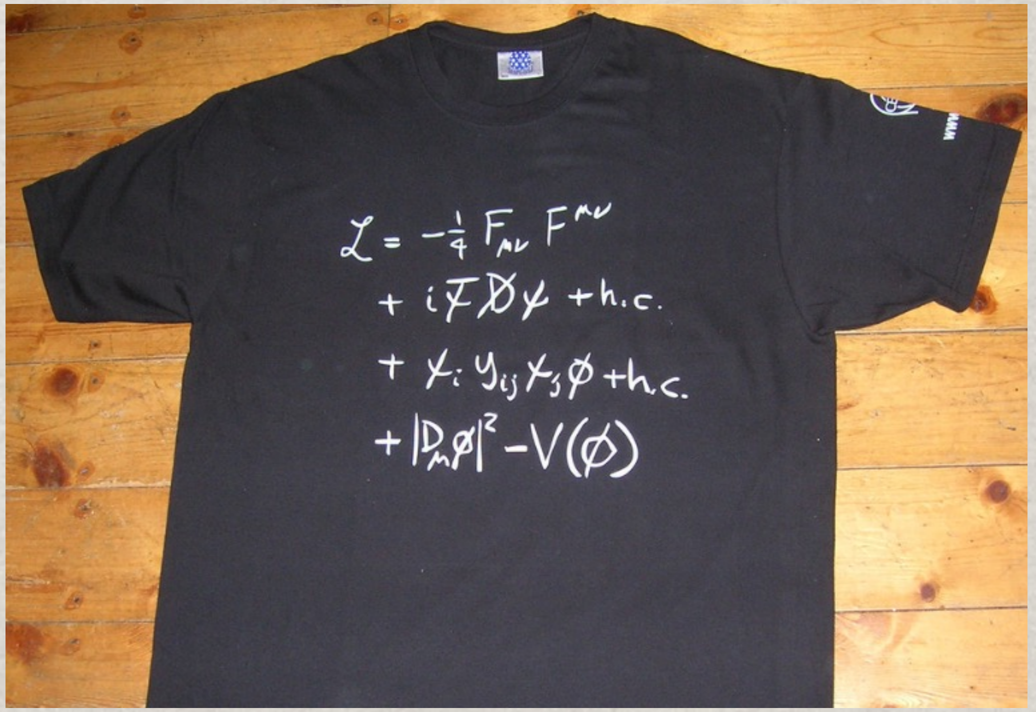


70's

80's

1930/1956 1962 2000

Highly successful theory



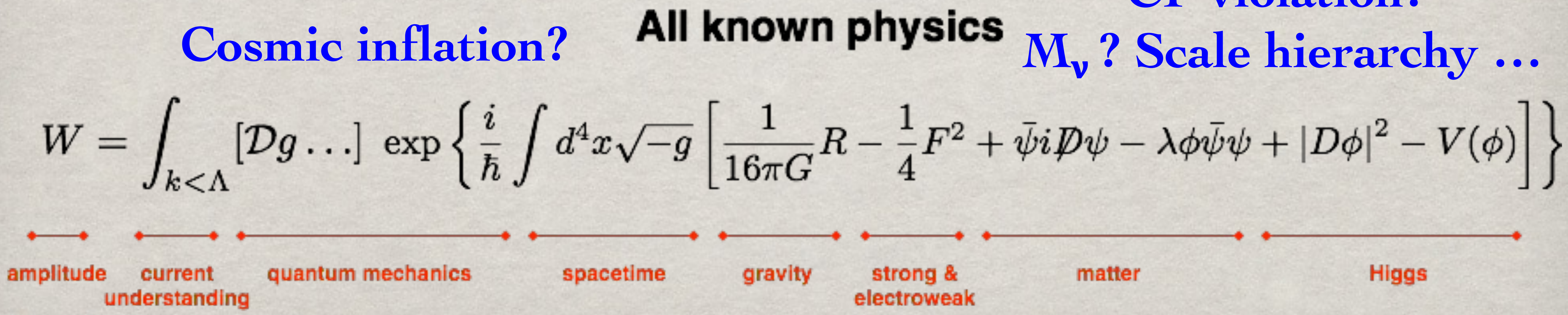
Completion of the SM: 新的里程碑

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?
M_ν ? Scale hierarchy …

***Λ*? Dark Matter?**
Cosmic inflation?

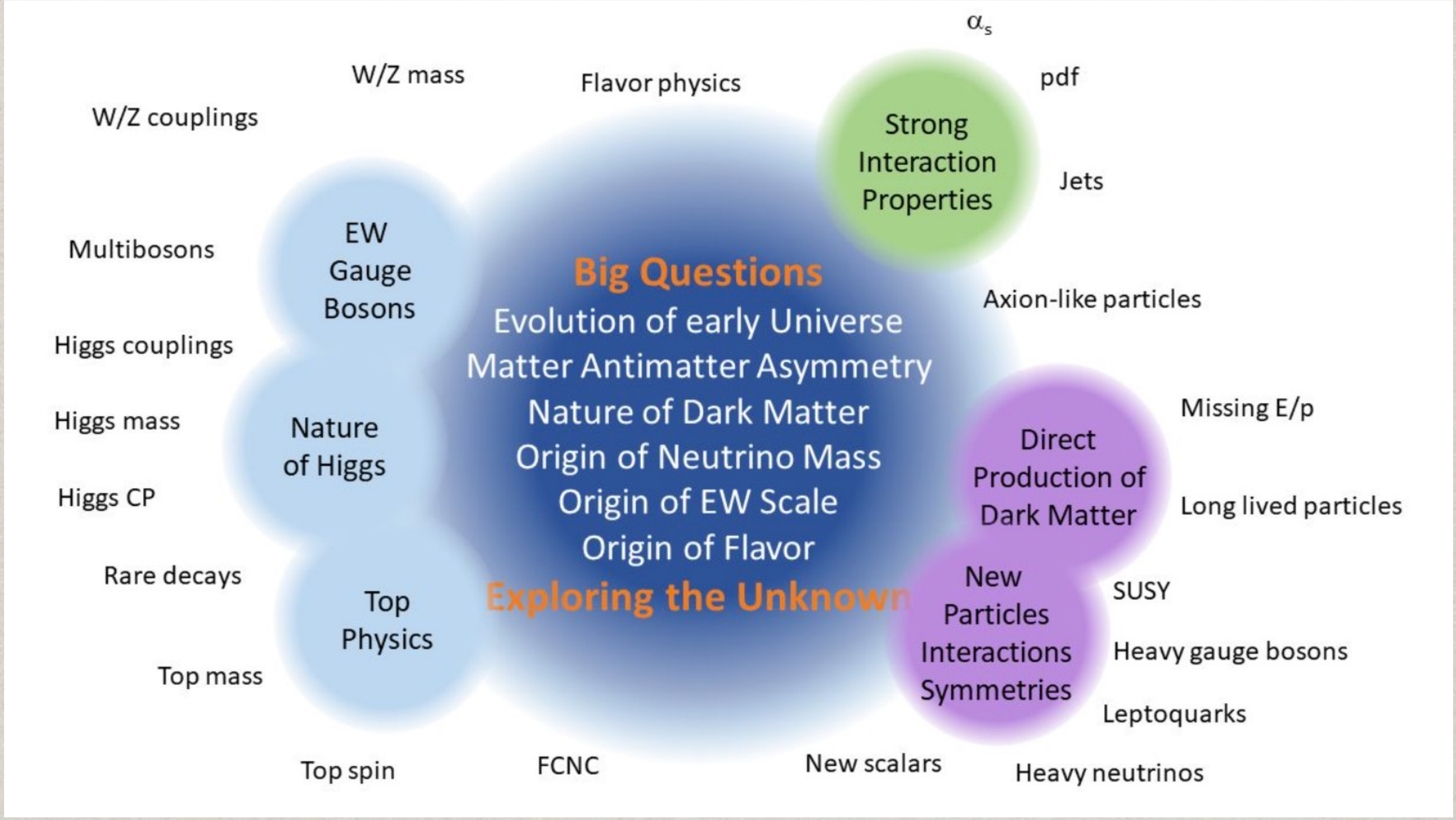


$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \exp\left\{\frac{i}{\hbar}\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{4}F^2 + \bar{\psi} i \not{D}\psi - \lambda\phi\bar{\psi}\psi + |D\phi|^2 - V(\phi)\right]\right\}$$

(1). Energy Frontier

Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Big Questions

Evolution of early Universe

Matter Antimatter Asymmetry

Nature of Dark Matter

Origin of Neutrino Mass

Origin of EW Scale

Origin of Flavor

Exploring the Unknown

EW Gauge Bosons

Nature of Higgs

Top Physics

Strong Interaction Properties

Direct Production of Dark Matter

New Particles Interactions Symmetries

W/Z mass

Flavor physics

α_s

pdf

W/Z couplings

Jets

Multibosons

Axion-like particles

Higgs couplings

Missing E/p

Higgs mass

Higgs CP

Long lived particles

Rare decays

SUSY

Heavy gauge bosons

Top mass

Leptoquarks

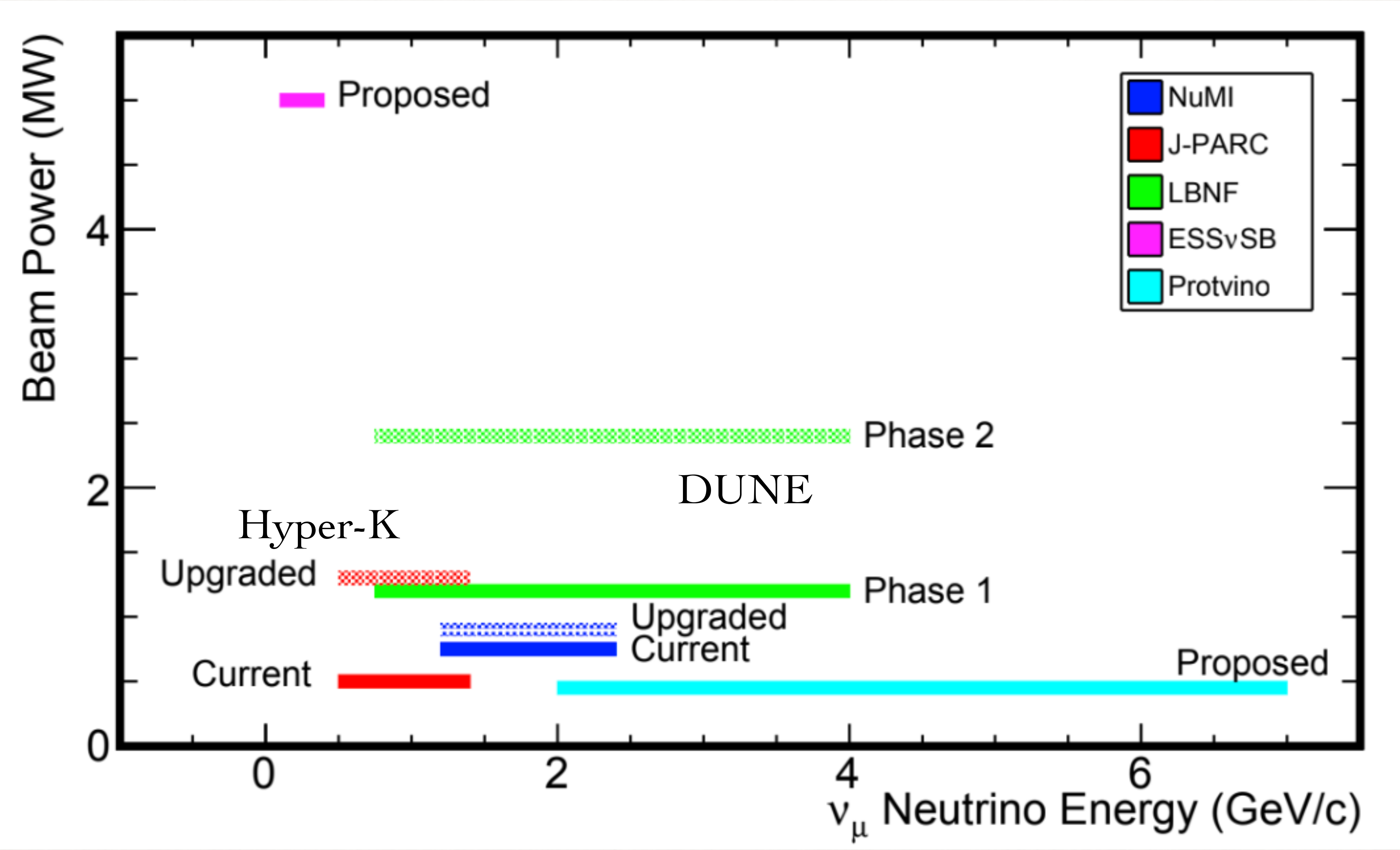
Top spin

FCNC

New scalars

Heavy neutrinos

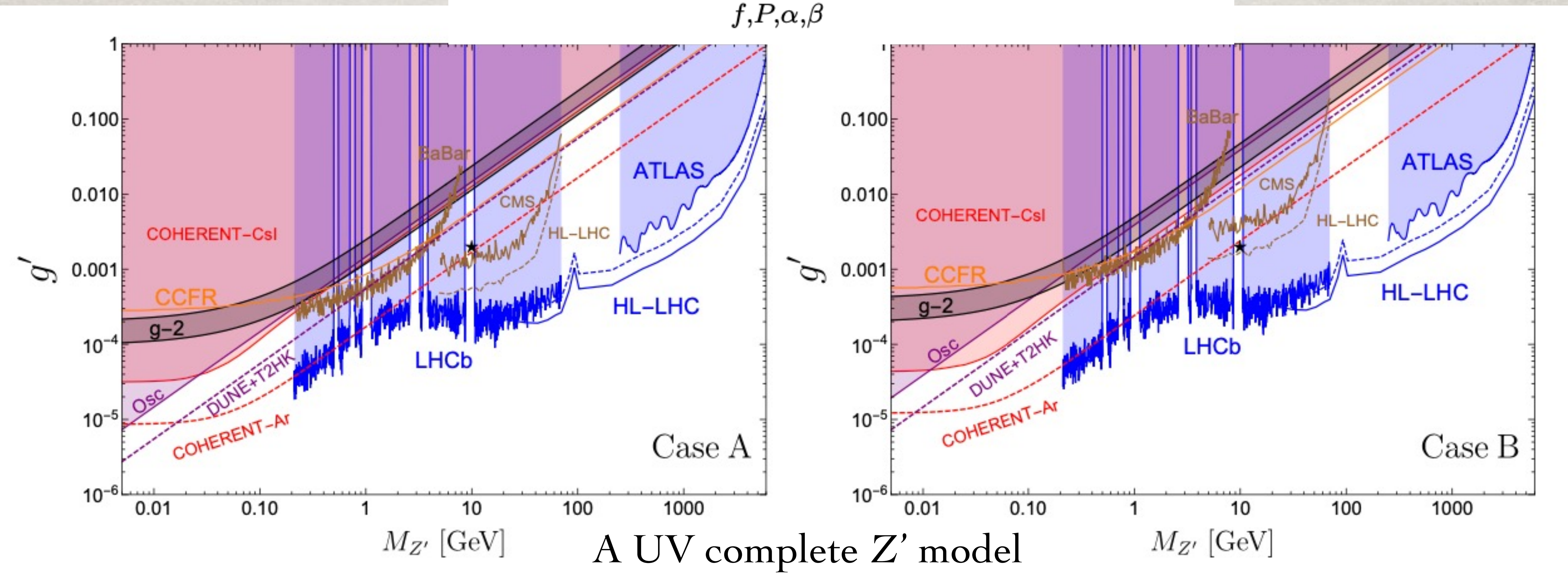
Accelerator-based neutrino sources



Physics example 1: Non-Standard Interactions, first introduced by Wolfenstein in 1978:

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P f),$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\bar{f}\gamma_\mu P f')$$

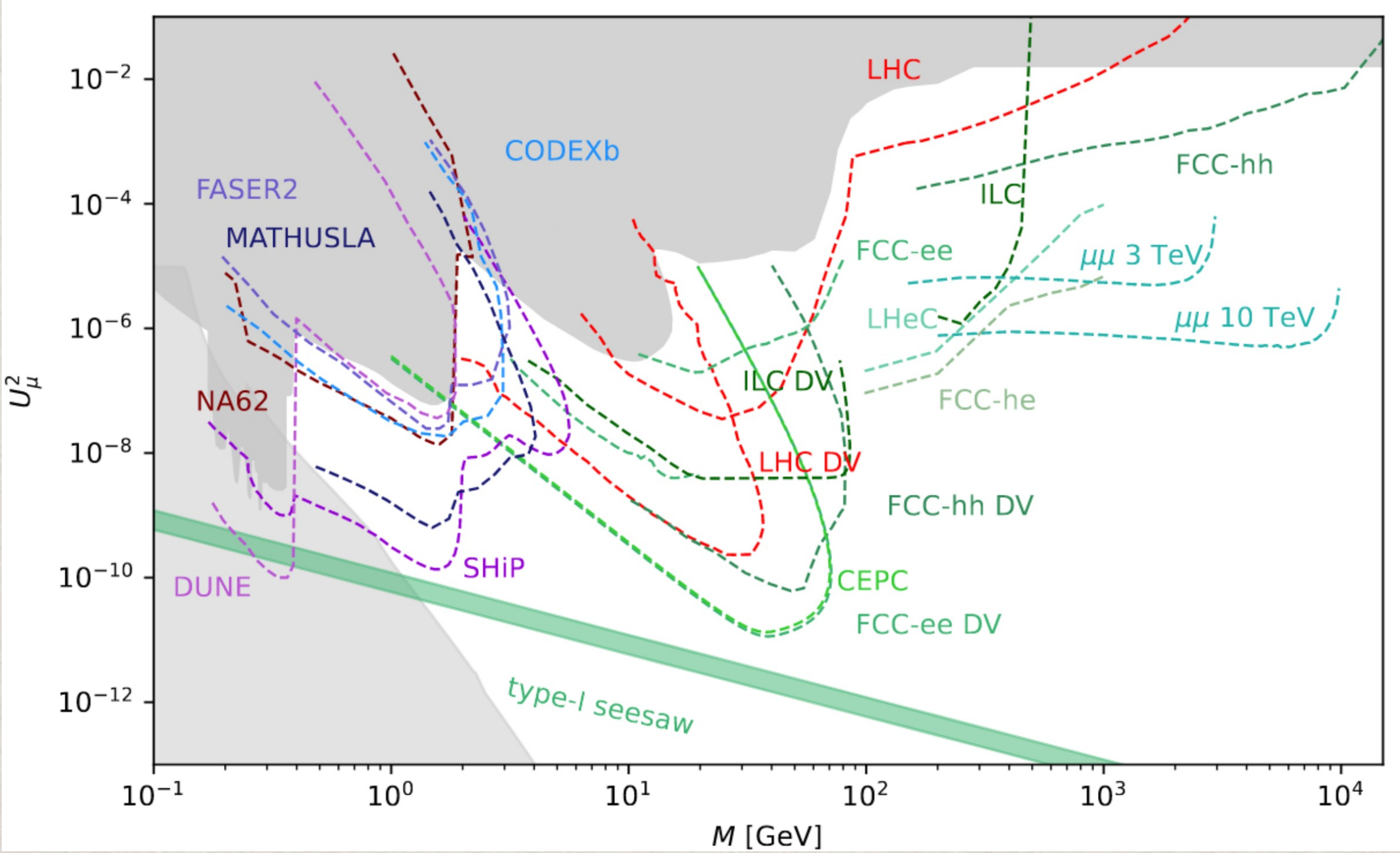


A UV complete Z' model

Complementary among a variety of searches:
Oscillation experiments: COHERENT, T2HK, DUNE, …
and collider searches: LHCb, ATLAS, CMS …

TH, Liao, Liu, Marfatia: arXiv:1910.03272; BSM ν Whitepaper: arXiv:2203.06131

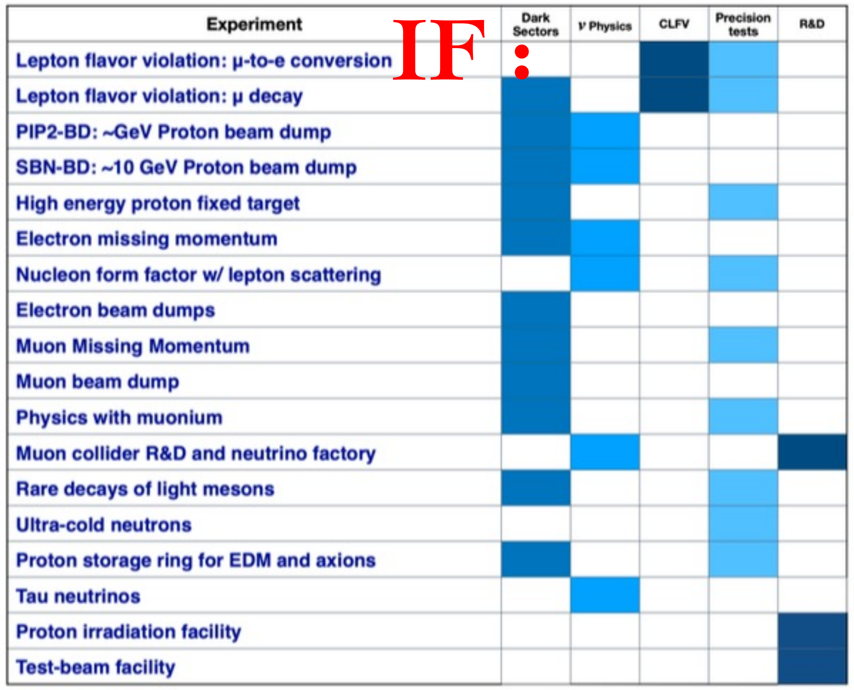
Physics example 2: Heavy Neutral Lepton (HNL, N_R, sterile neutrino)



Complementary among a variety of searches.

ν Synergistic aspects:

RPF & IF :

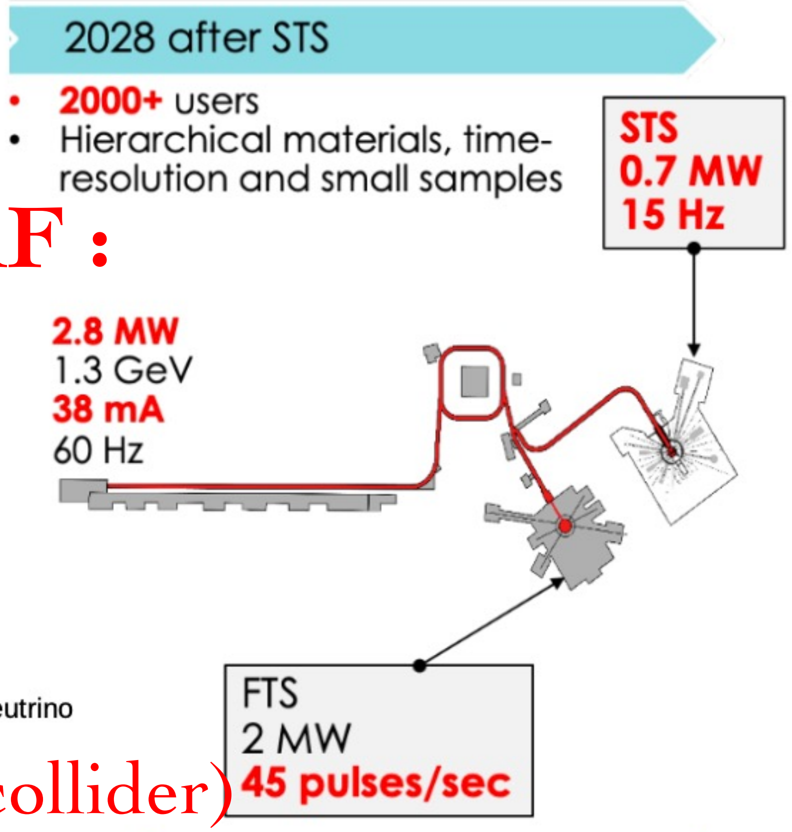


Experiment	Dark Sectors	ν Physics	CLFV	Precision tests	R&D
Lepton flavor violation: μ-to-e conversion			■	■	
Lepton flavor violation: μ decay	■		■	■	
PIP2-BD: ~GeV Proton beam dump	■	■			
SBN-BD: ~10 GeV Proton beam dump	■	■			
High energy proton fixed target	■			■	
Electron missing momentum	■	■			
Nucleon form factor w/ lepton scattering		■		■	
Electron beam dumps	■				
Muon Missing Momentum	■			■	
Muon beam dump	■				
Physics with muonium	■			■	
Muon collider R&D and neutrino factory		■			■
Rare decays of light mesons	■			■	
Ultra-cold neutrons				■	
Proton storage ring for EDM and axions	■			■	
Tau neutrinos		■			
Proton irradiation facility					■
Test-beam facility					■

Booster replacement (beam upgrade)

Synergies at the machine level as well as physics

AF :

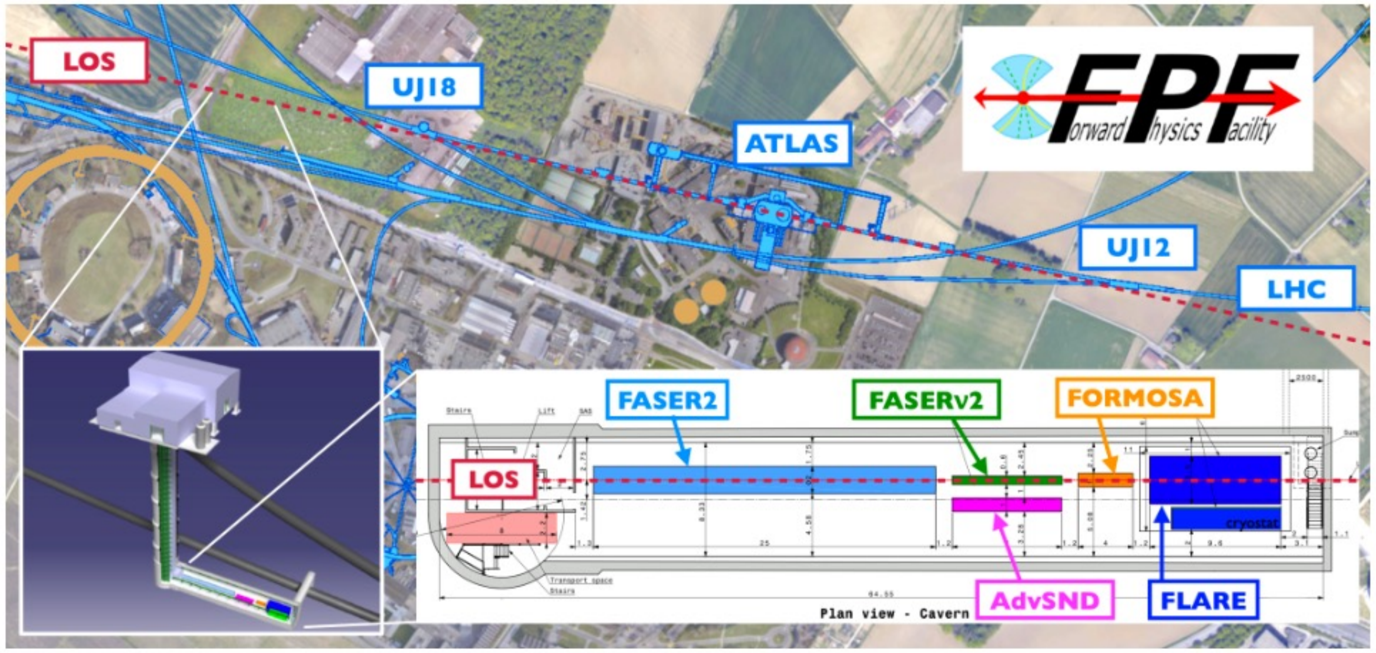


2028 after STS

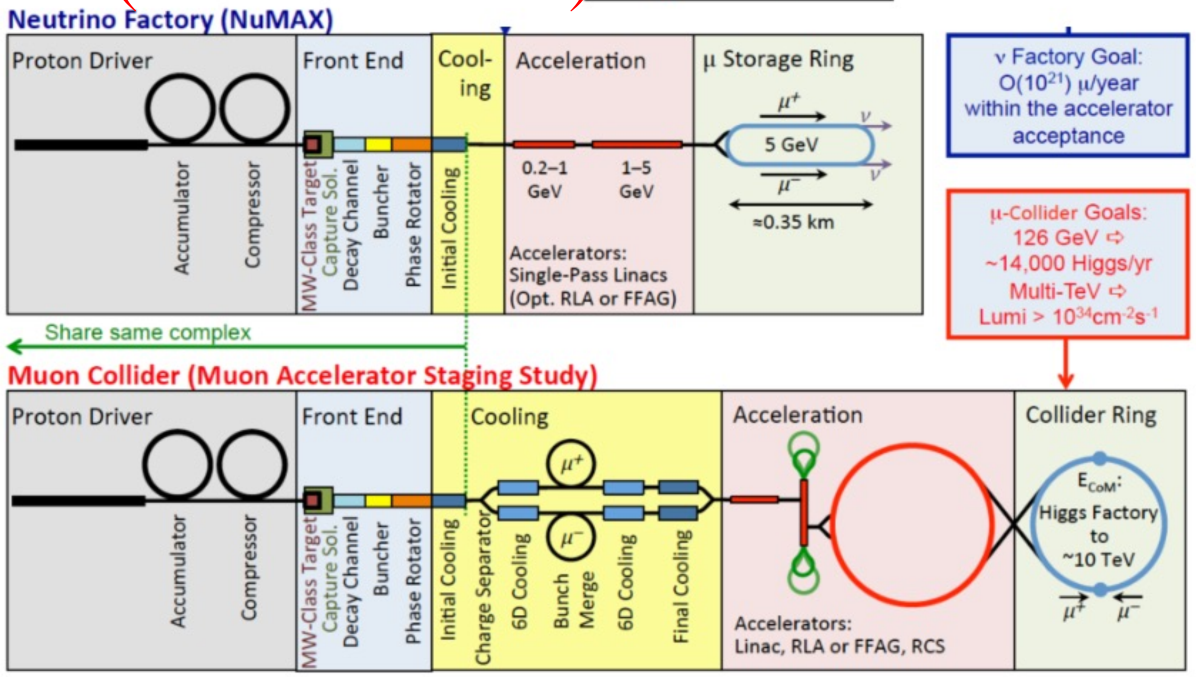
- **2000+** users
- Hierarchical materials, time-resolution and small samples

Figures from SNOWMASS neutrino colloquium by M. Toups

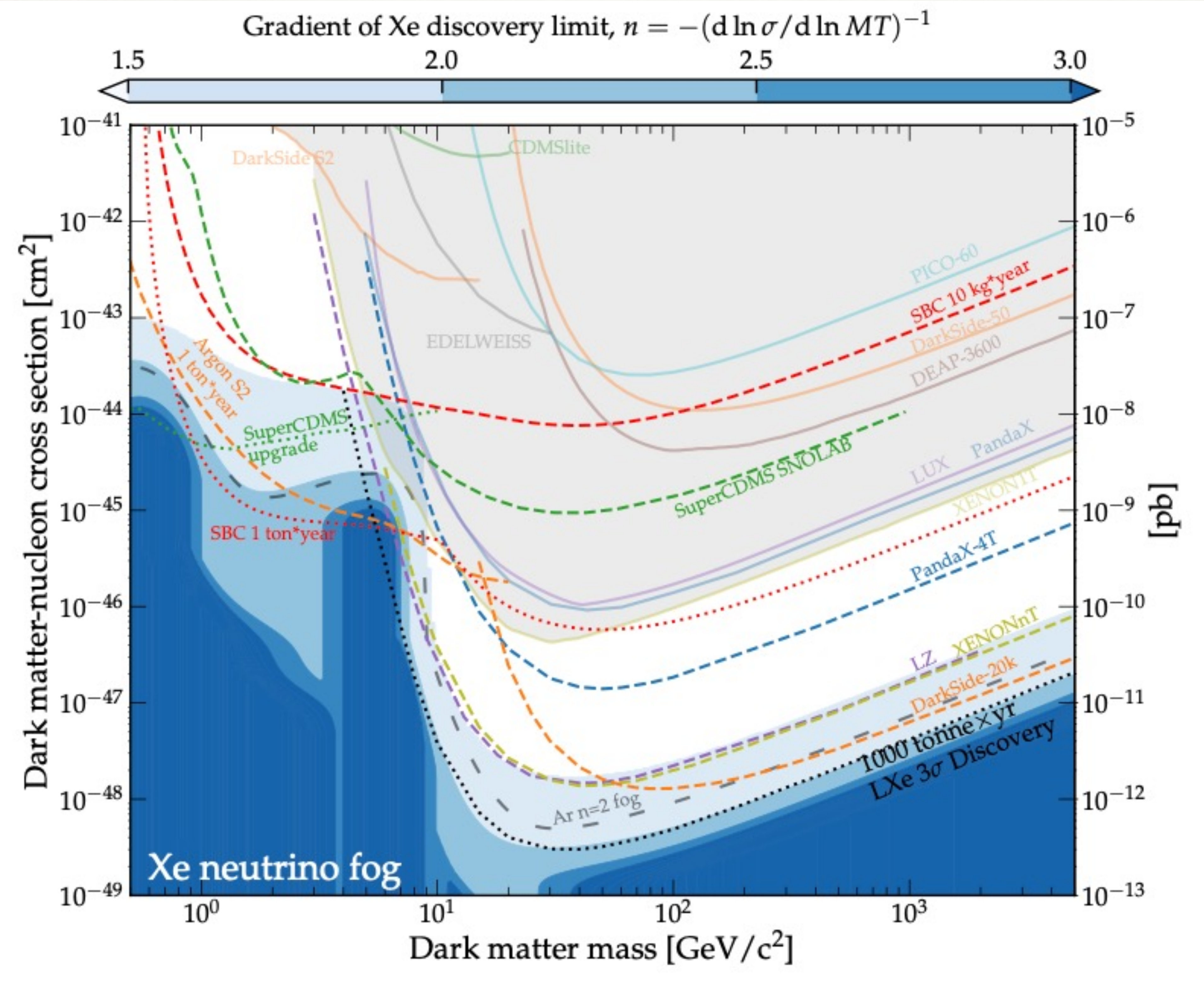
EF (HL-LHC)



AF (muon collider)

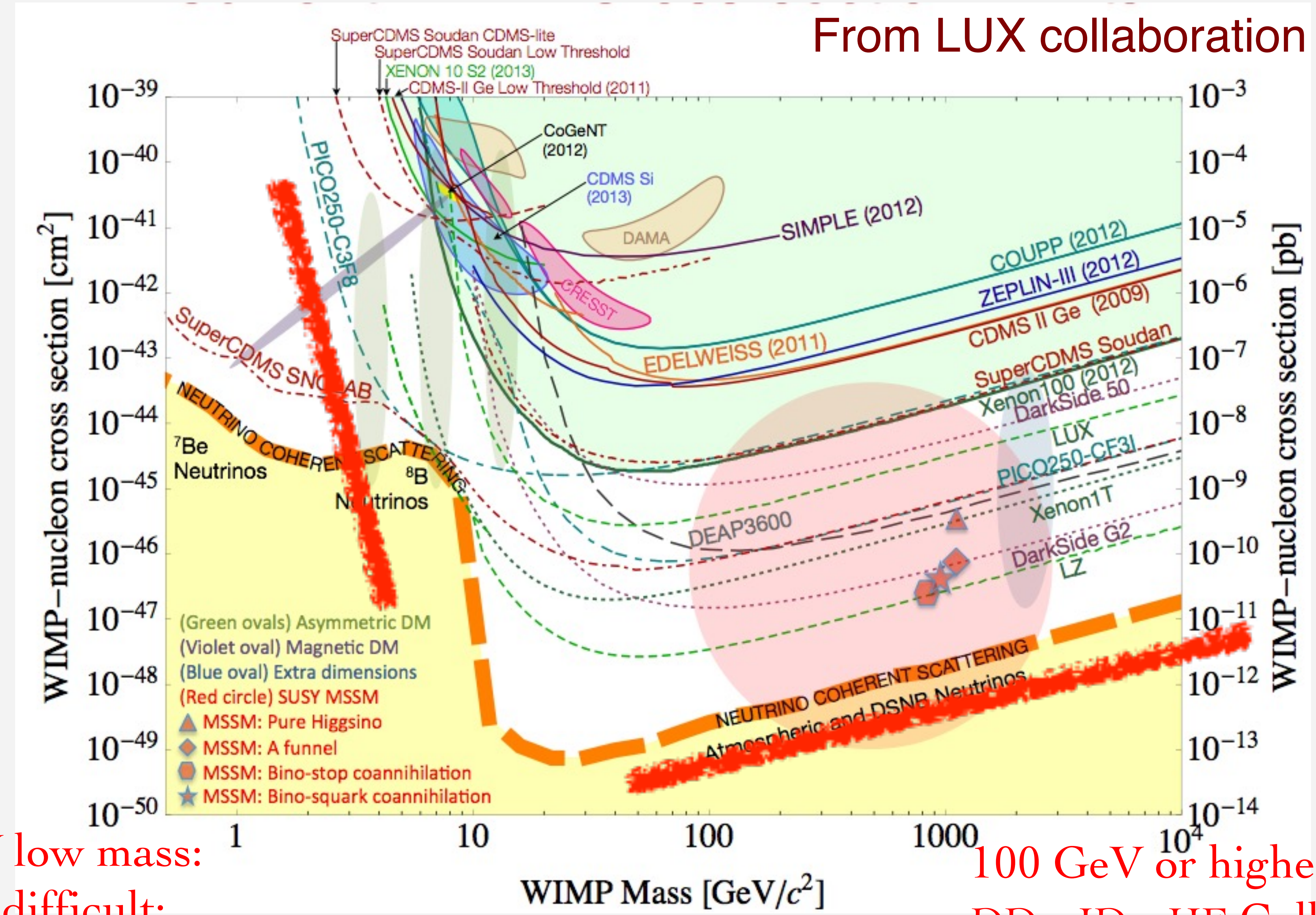


WIMP DM direct searches



Physics example 2:

WIMP DM Searches



GeV low mass:
DD difficult;
Collider complementary

100 GeV or higher mass:
DD + ID + HE Collider

Physics example: DM Searches in Cosmo

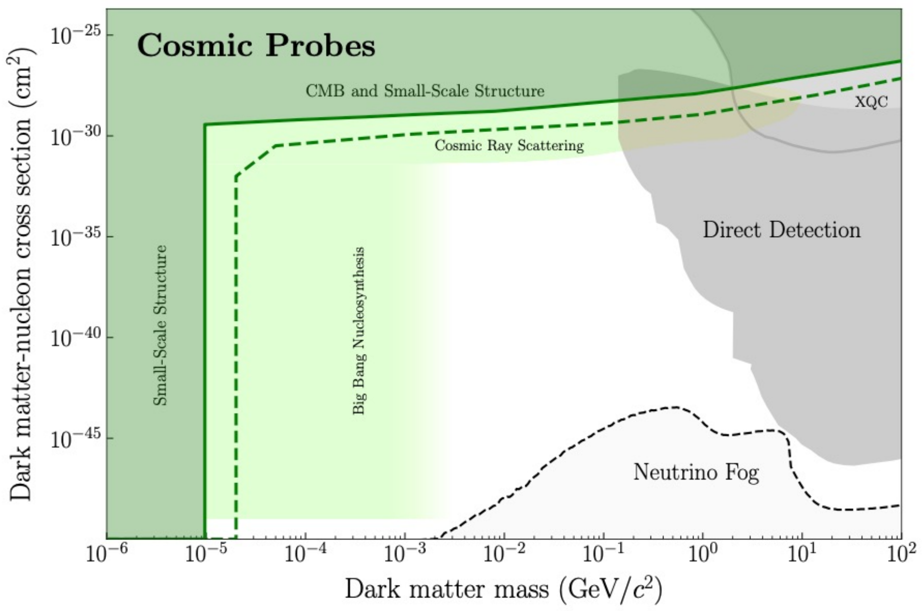


Figure 5-15. *Cosmic probes of the matter power spectrum, dark matter halos, Big Bang nucleosynthesis, and cosmic ray upscattering set strong constraints on the minimum thermal dark matter particle mass and spin-independent dark matter–nucleon scattering cross section (green regions). Projected improvements in sensitivity coming from future facilities and observations are indicated with a dashed green lines. These constraints are highly complementary to constraints from direct detection experiments (gray regions). The neutrino fog for xenon direct detection experiments is shown with dashed black line. From the CF3 report [3].*

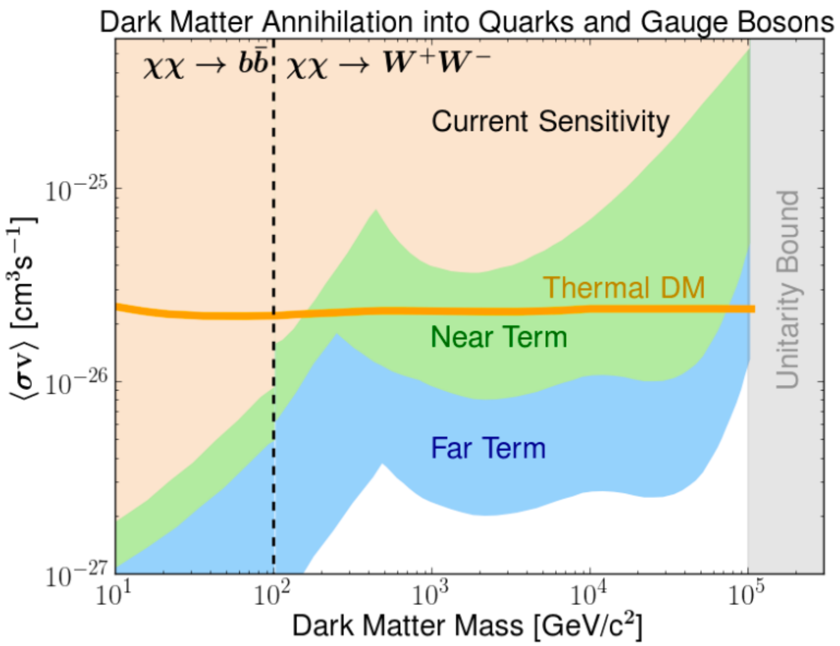
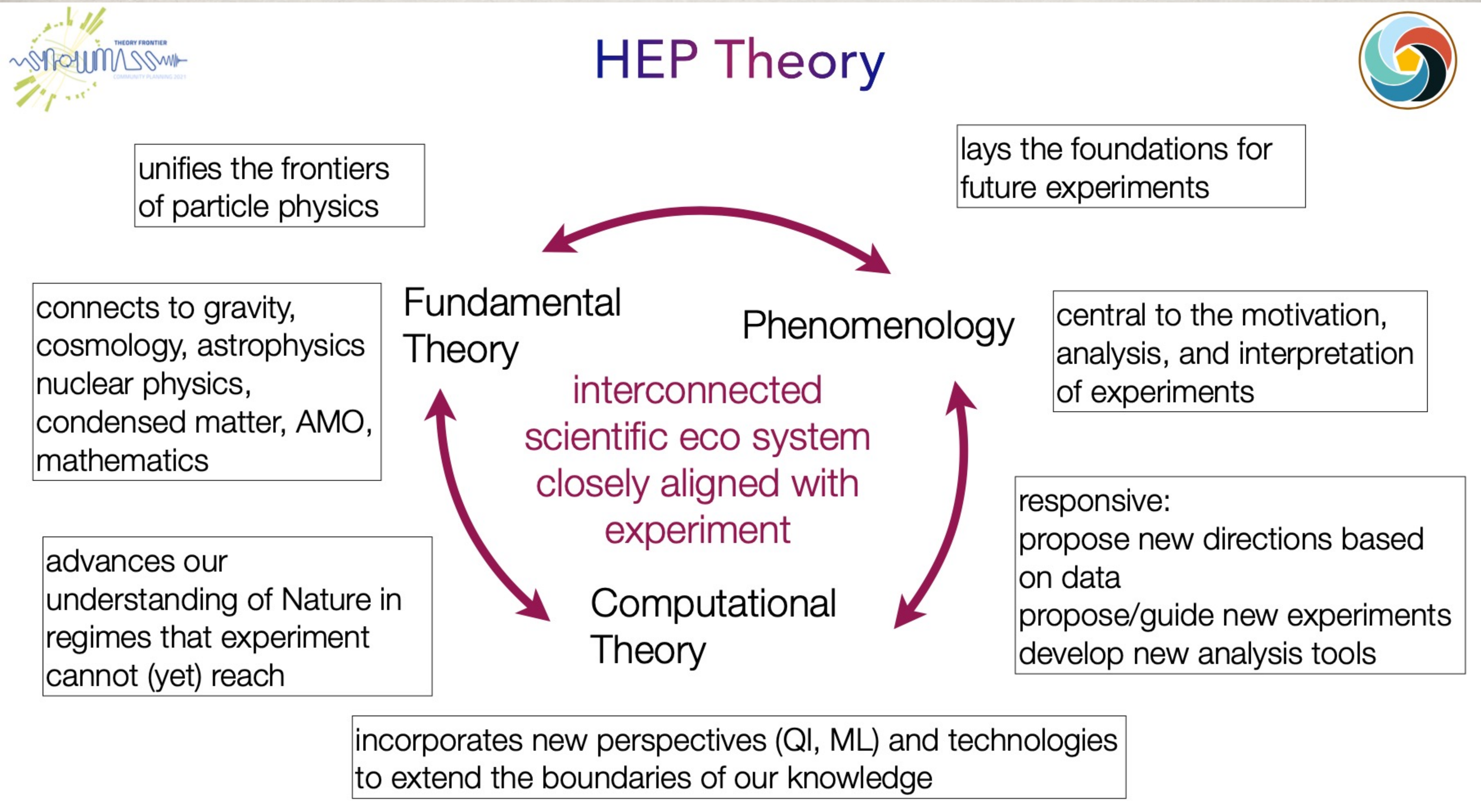


Figure 5-20. *Limits on WIMP annihilations into pairs of bottom quarks (for masses below ∼ 100 GeV and W bosons (for larger masses) based on null searches by gamma-ray observatories. The beige regions indicate the current limits for each mass, whereas the green shaded region indicates near future gains based on planned missions, and the blue shading indicates the reach that would be enabled by long term investments in ground- and space-based observatories. From the CF1 report [1].*

(5). Theory Frontier



HEP Theory

unifies the frontiers of particle physics

lays the foundations for future experiments

connects to gravity, cosmology, astrophysics nuclear physics, condensed matter, AMO, mathematics

Fundamental Theory

Phenomenology

central to the motivation, analysis, and interpretation of experiments

interconnected scientific eco system closely aligned with experiment

advances our understanding of Nature in regimes that experiment cannot (yet) reach

Computational Theory

responsive:
propose new directions based on data
propose/guide new experiments
develop new analysis tools

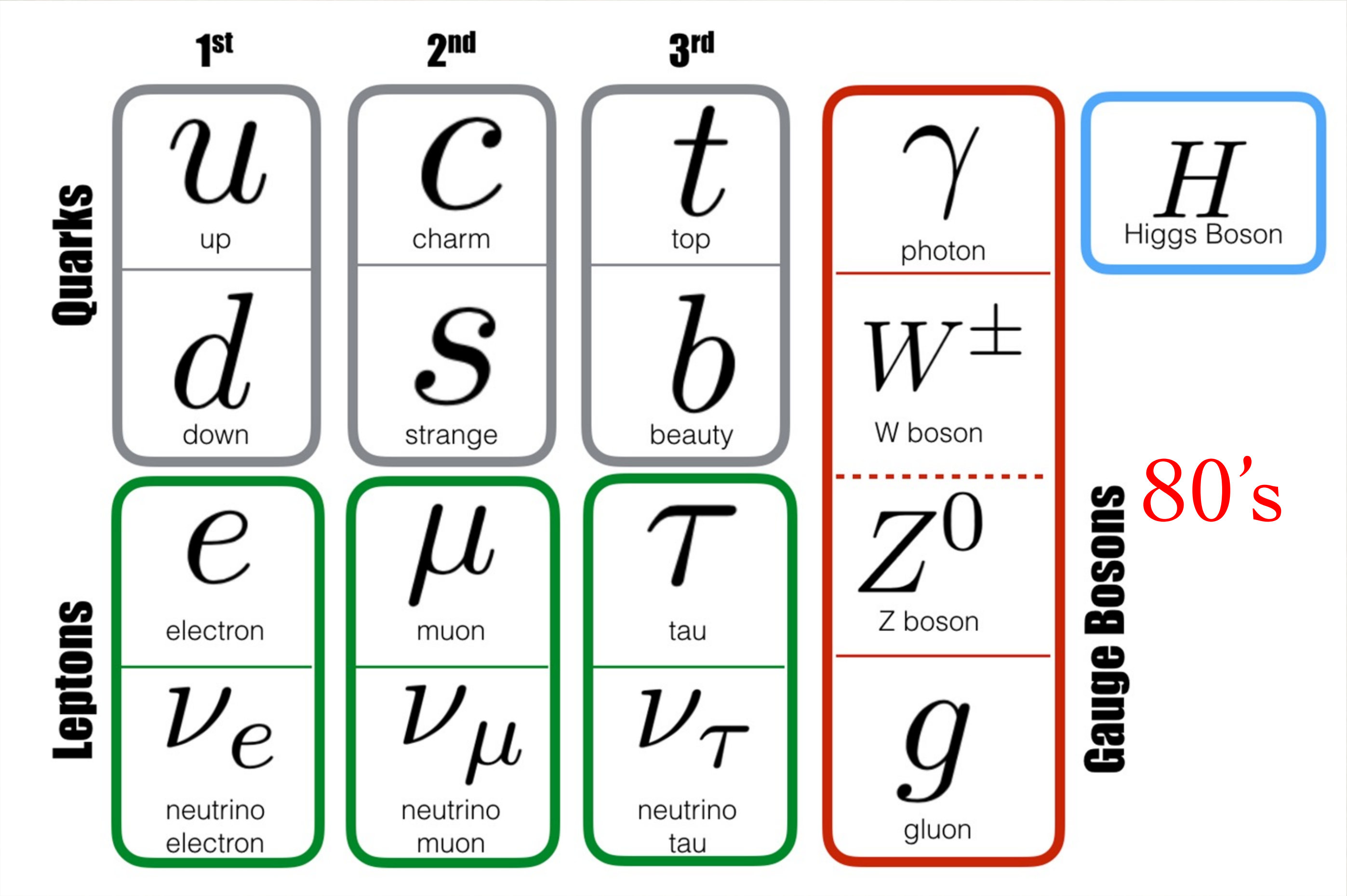
incorporates new perspectives (QI, ML) and technologies to extend the boundaries of our knowledge

The field of HEP has been vibrant & exciting!

HEP has enjoyed the remarkable achievement of 50^{+}-year uninterrupted discoveries!

From quarks to the Higgs boson, with heroic efforts in theory and experiments:

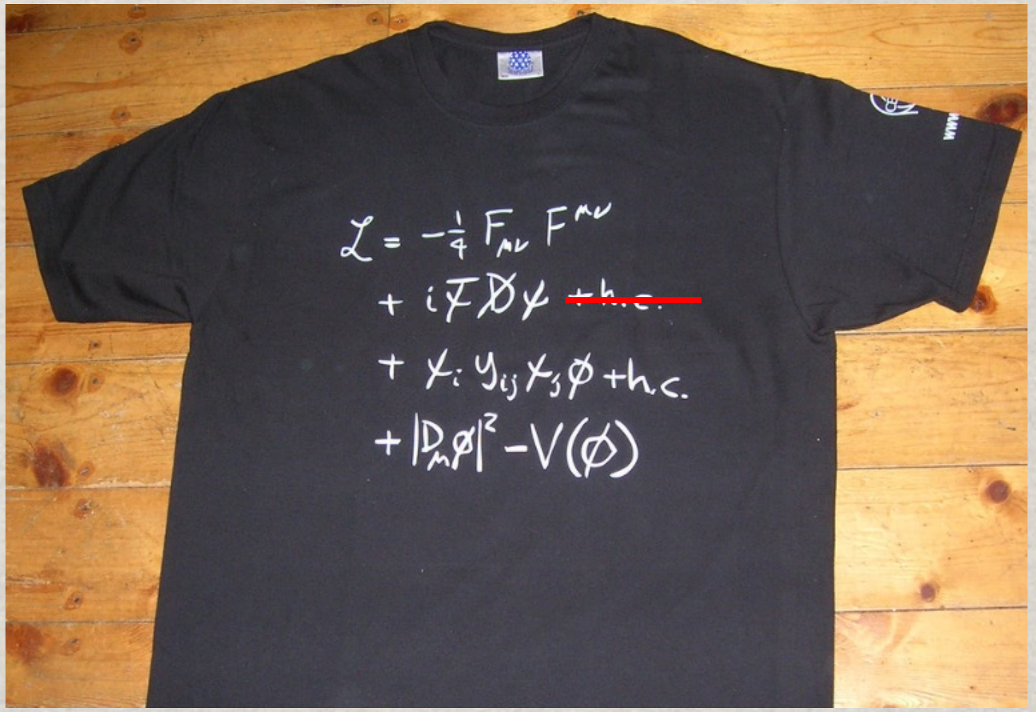
60's 70's 90's 2012



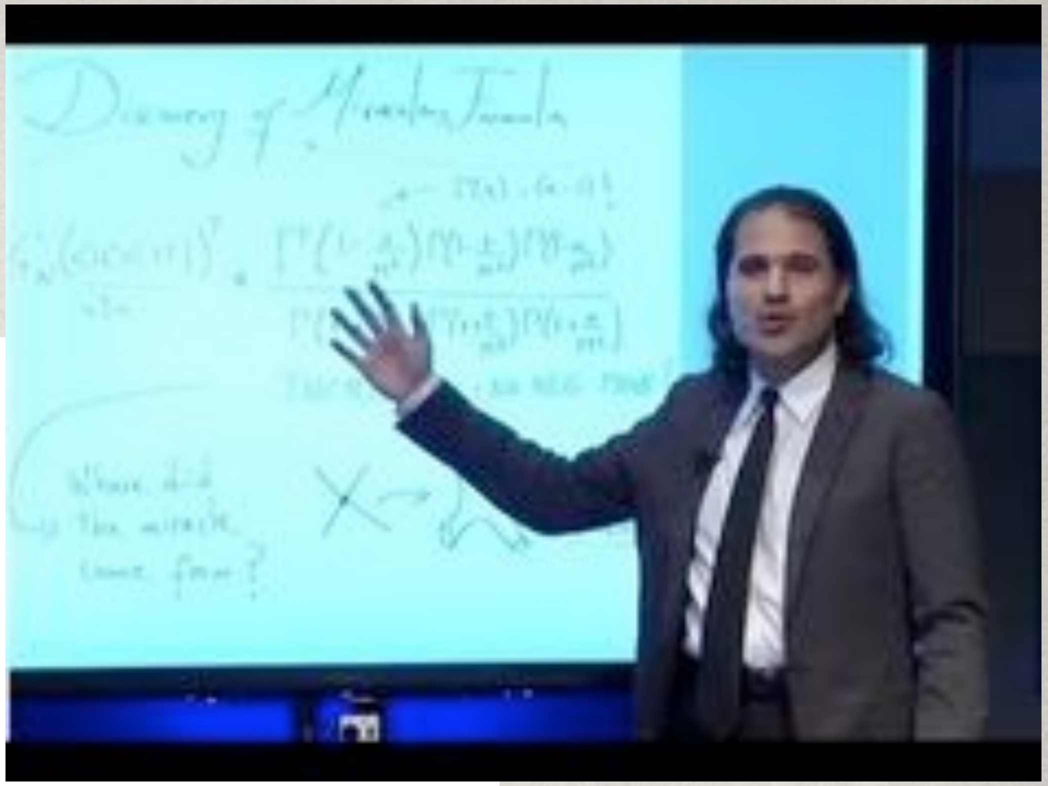
80's

1930/1956 1962 2000

A highly successful theory



Nima Arkani-Hamed



The central questions today are not details — but structural: origin of spacetime, UV/IR connection, standard model → real theory

Distilled from the Snowmass 2013 inputs, The "Particle Physics Projects Prioritization Panel" (P5) Report (May 2014)

Building for Discovery

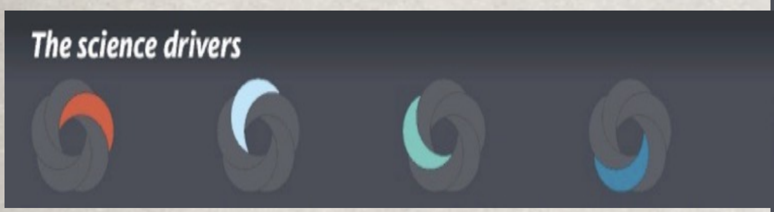
Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5) May 2014

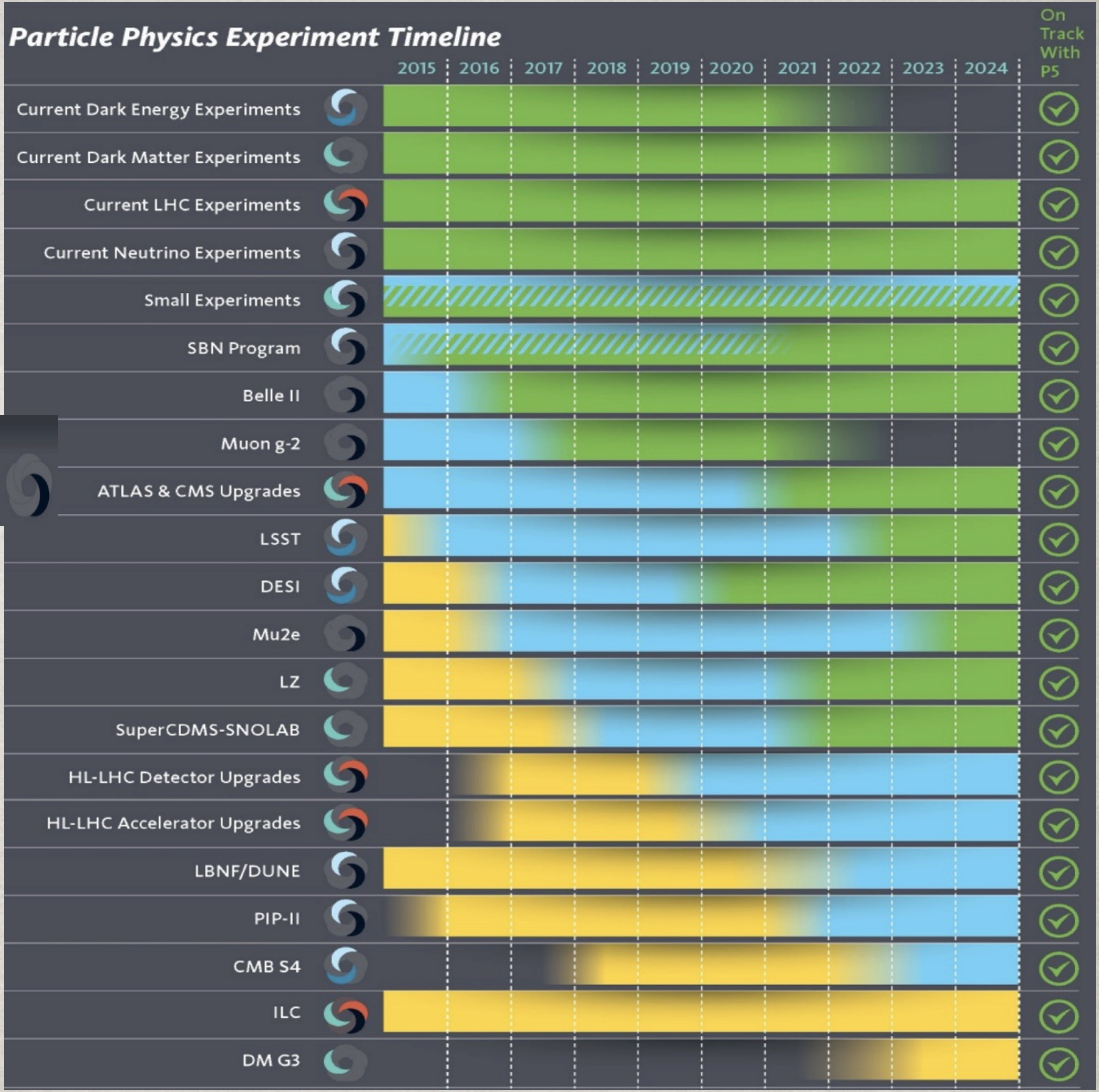
Five Science Drivers:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.

Exiting on-going projects:



- 🟩 Operation & Analysis
- 🟦 Fabrication/ Construction
- 🟨 Conceptual & Technical Design



Snowmass 2021 Process:

Snowmass 2021

DPF Community Planning Exercise

10 Frontiers	80 Topical Groups
Energy Frontier	Higgs Boson properties and couplings, Higgs Boson as a portal to new physics, H physics, EW Precision Phys. & constraining new phys., Precision QCD, Hadron Heavy Ions, Model specific explorations, More general explorations, Dark Matter at colliders
Frontiers in Neutrino Physics	NEUTRINO OSCILLATIONS, Sterile Neutrinos, Beyond the SM, Neutrinos from Natural Sources, Neutrino Properties, Neutrino Cross Sections, Nuclear Safeguards and Other Applications, Theory of Ne hysics, Artificial Neutrino Sources, Neutrino Detectors
Frontiers in Rare Processes & Precision Measurements	Weak Decays of b and c, Strange and Light Quarks, Fundamental Physics and Lepton Number Violation, Charged Lepton Flavor Violation, Dark roscopy
Cosmic Frontier	Dark Matter: Particle-like, Dark Matter: Wave-like, rgy & Cosmic Acceleration: The Modern Universe, Dark Ener wn & Before, Dark Energy & Cosmic Acceleration: Complementarity of
Theory Frontier	String theory, quantum gravity niques, CFT and formal QFT, Scattering amplitudes, Lattice gaug on physics, Collider phenomenology, BSM model building, Astro-pa information science, Theory of Neutrino Physics
Accelerator Frontier	Beam ccelerators for Neutrinos, Accelerators for Electroweak and Higgs ators for Physics Beyond Colliders & Rare Processes, Advanced Accelerator gy R&D: RF, Magnets, Targets/Sources
Instrumentation	oton Detectors, Solid State Detectors & Tracking, Trigger and DAQ, Micro Pattern Gas orimetry, Electronics/ASICS, Noble Elements, Cross Cutting and System Integration, Radio on
Computational Fro	Experimental Algorithm Parallelization, Theoretical Calculations and Simulation, Machine Learning, Storage and processing resource access (Facility and Infrastructure R&D), End user analysis
Underground Facilities and Infrastructure Frontier	Underground Facilities for Neutrinos, Underground Facilities for Cosmic Frontier, Underground Detectors
Community Engagement Frontier	Applications & Industry, Career Pipeline & Development, Diversity & Inclusion, Physics Education, Public Education & Outreach, Public Policy & Government Engagement

30 Frontier conveners, ~250 Topical Group conveners,
>40 Inter-Frontier Liaisons, ~25 Early Career Liaisons.

Snowmass Early Career to represent early career members and promote their engagement in the Snowmass 2021 process;
to build a long-term HEP early career community

Broad coverage/connection in science and global community!

(6). Community Engagement

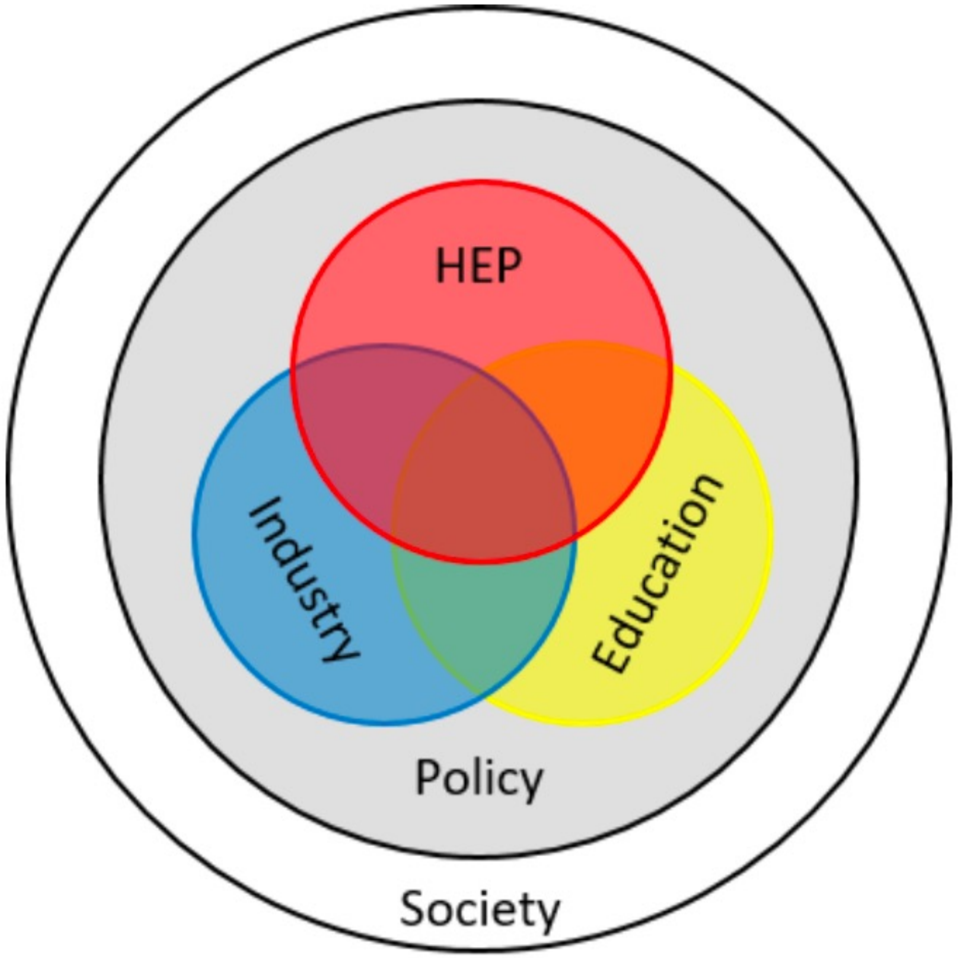
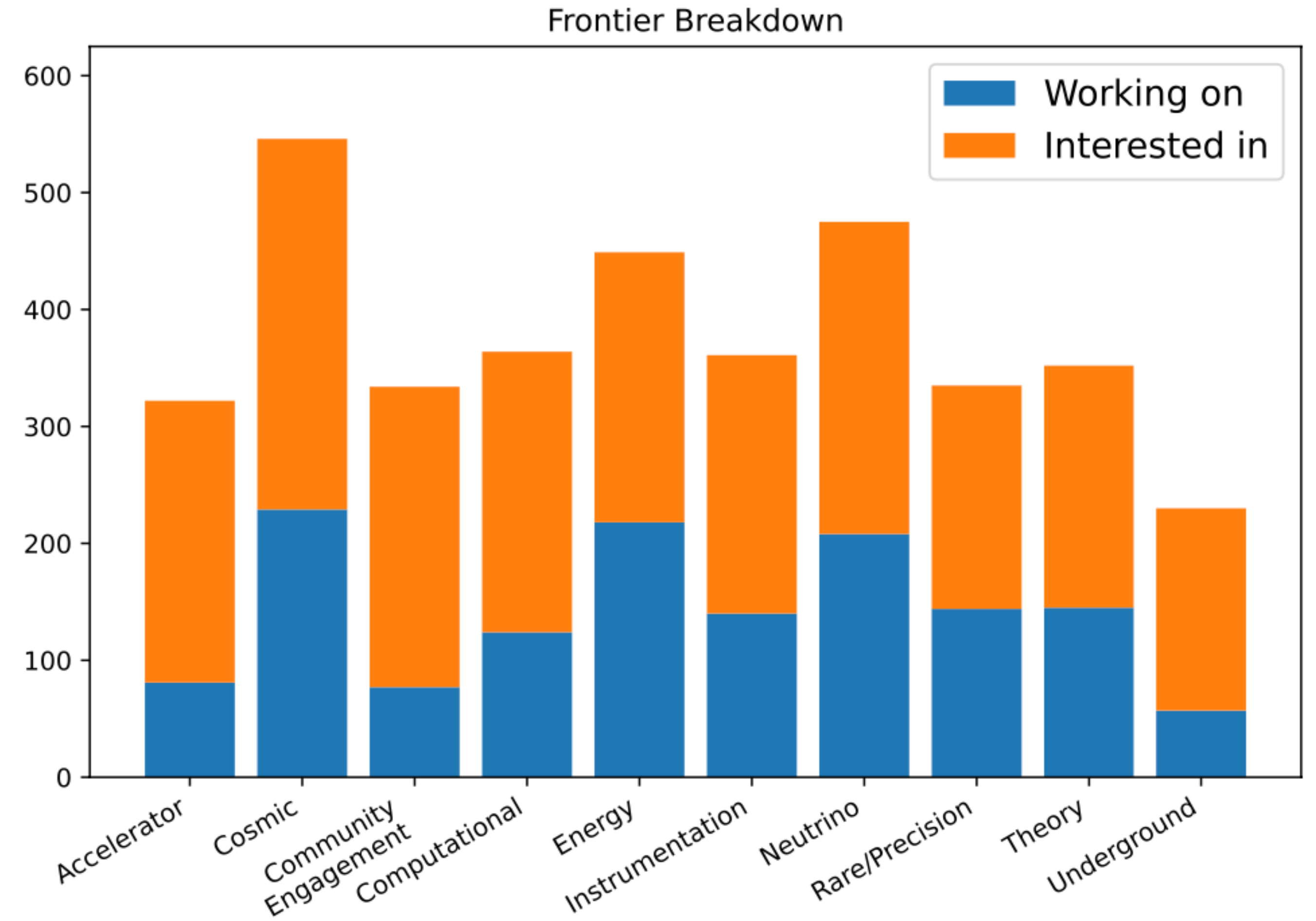


Figure 3-1. *Five interrelated communities targeted for HEP engagement.*

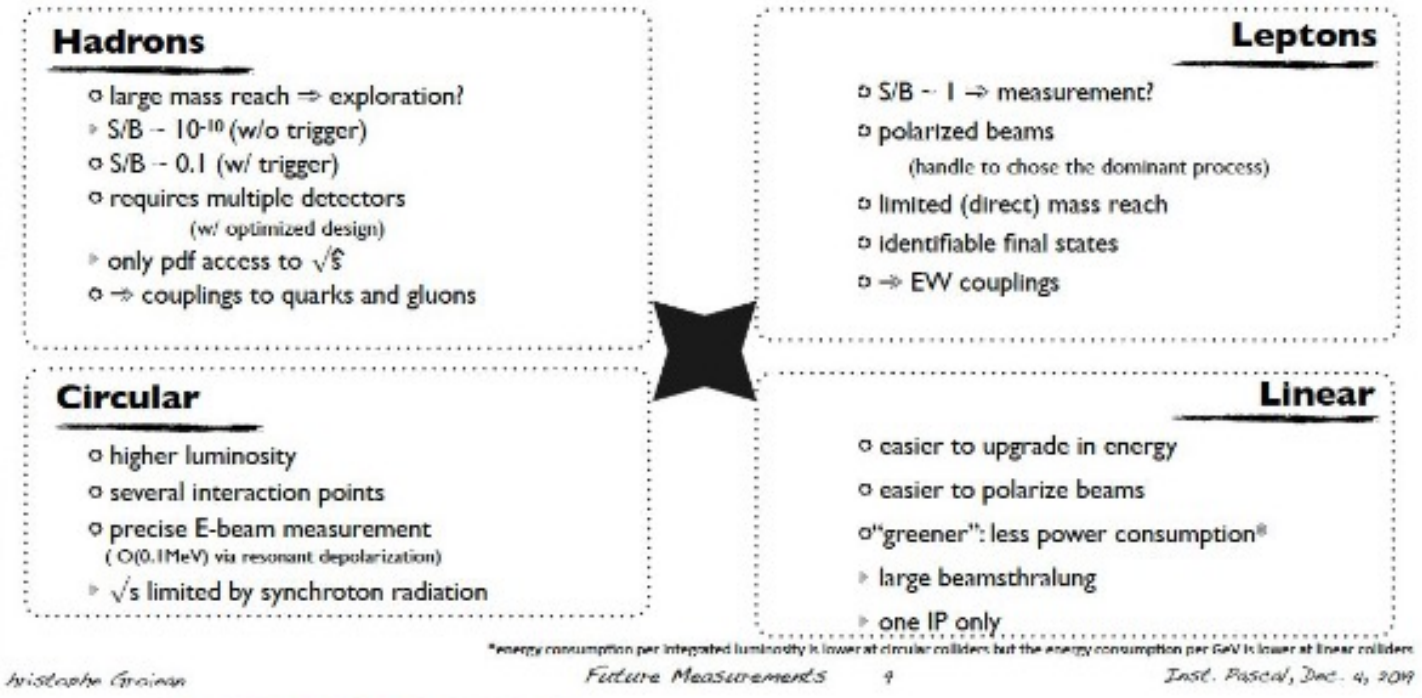
Equity, Diversity & Inclusion (EDI)

Early Career Physicists: Future of the field!

e.g. their interests in Snowmass 2021:



What Machine?



Hadrons

- large mass reach ⇒ exploration?
  - S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors (w/ optimized design)
  - only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

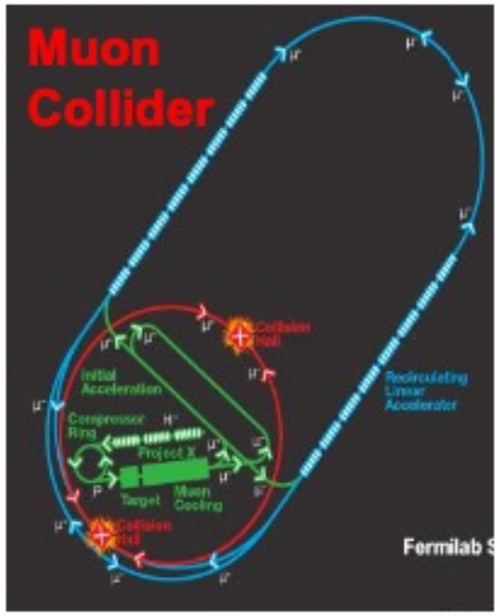
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
  - $\sqrt{s}$ limited by synchroton radiation

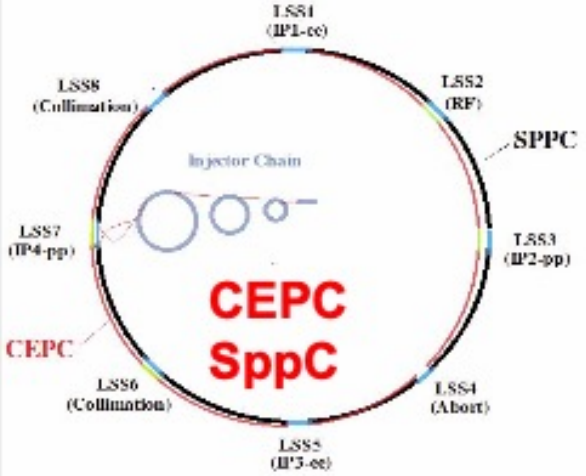
Linear

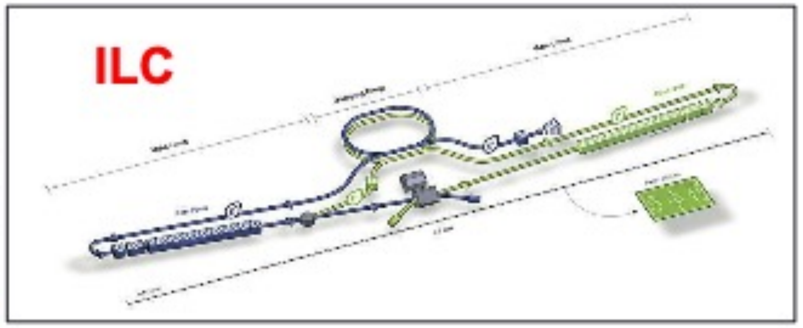
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
  - large beamsthralung
  - one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

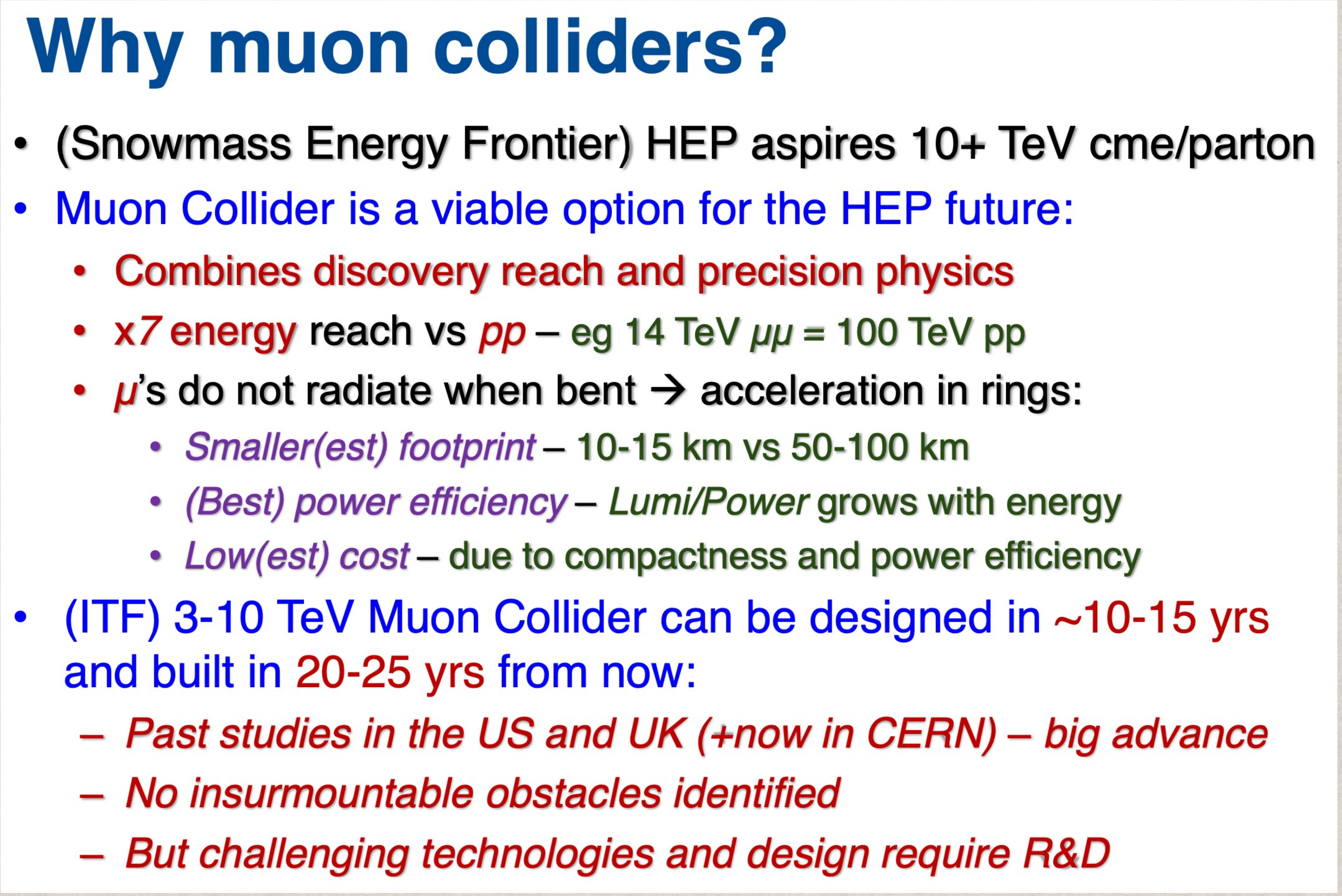
Christophe Grojean Future Measurements 9 Inst. Pascal, Dec. 4, 2019







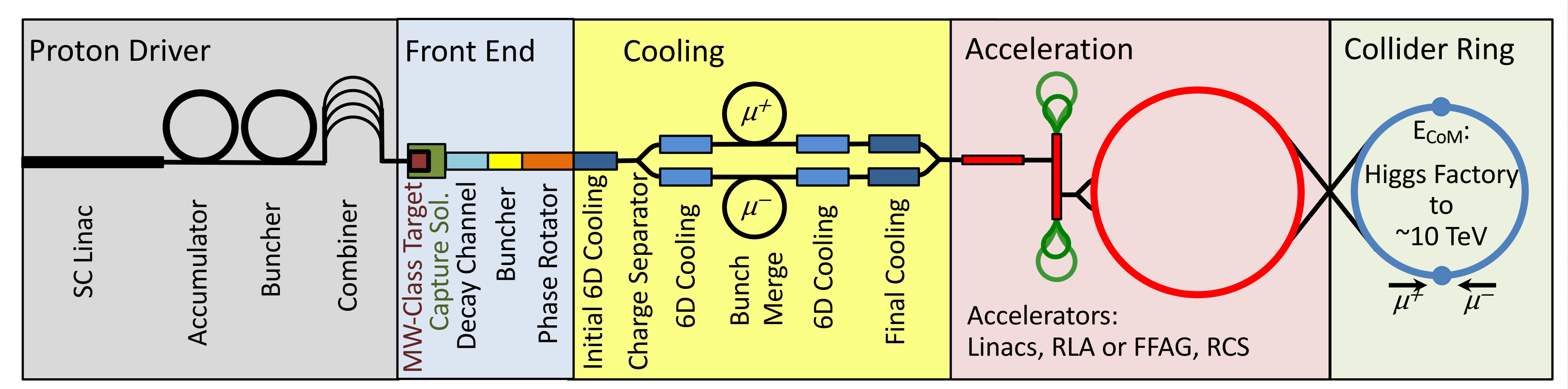
- Added C^3
- Gamma-gamma?
- Advanced colliders?



Why muon colliders?

- (Snowmass Energy Frontier) HEP aspires 10+ TeV cme/parton
- Muon Collider is a viable option for the HEP future:
  - Combines discovery reach and precision physics
  - x*7* energy reach vs *pp* – eg 14 TeV $\mu\mu$ = 100 TeV pp
  - μ's do not radiate when bent → acceleration in rings:
    - *Smaller(est) footprint* – 10-15 km vs 50-100 km
    - *(Best) power efficiency* – *Lumi/Power* grows with energy
    - *Low(est) cost* – due to compactness and power efficiency
- (ITF) 3-10 TeV Muon Collider can be designed in ~10-15 yrs and built in 20-25 yrs from now:
  - *Past studies in the US and UK (+now in CERN) – big advance*
  - *No insurmountable obstacles identified*
  - *But challenging technologies and design require R&D*

Recent technological breakthroughs:



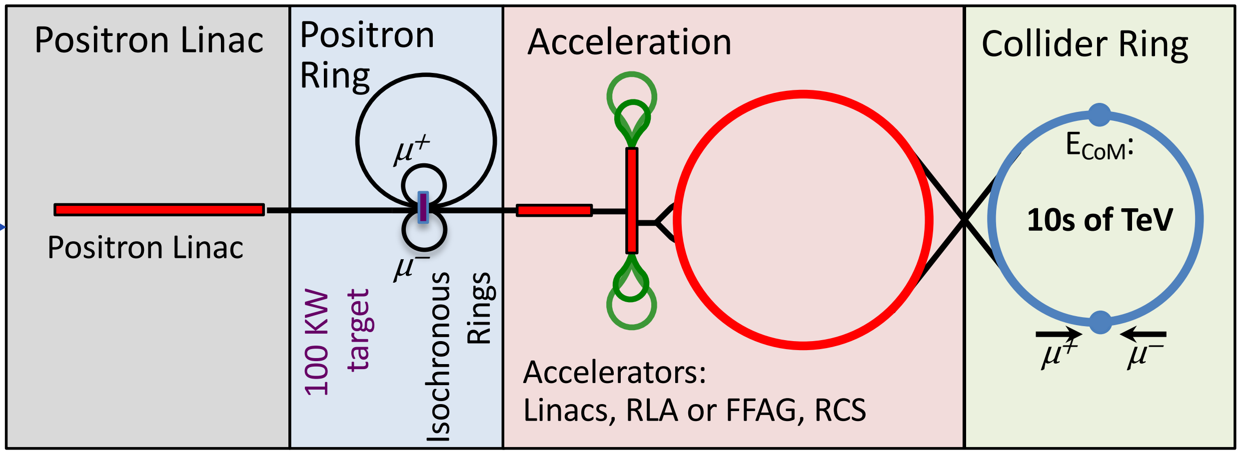
Proton-Driver:

Muon Accelerator Program
map.fnal.gov

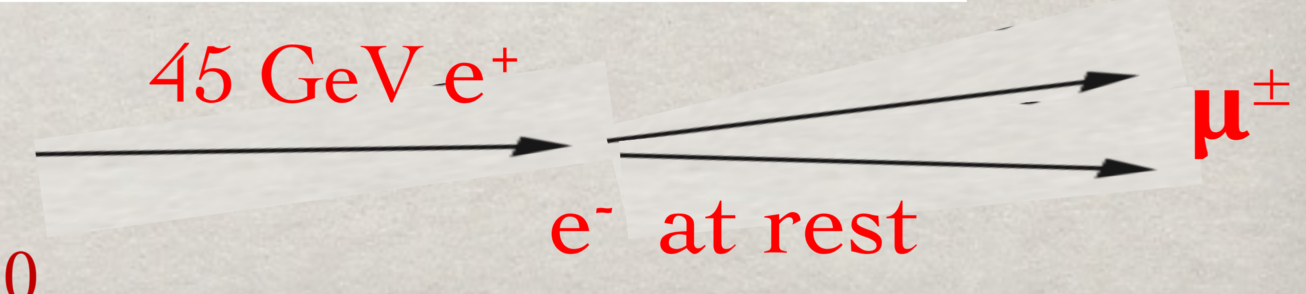
New results on μ cooling by MICE collaboration
Nature 508(2020)53

LEMMA: e^+e^- (at rest) → $\mu^+\mu^-$ (at threshold)

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Low EMittance Muon Accelerator
web.infn.it/LEMMA



J.P. Delahauge et al., arXiv:1901.06150

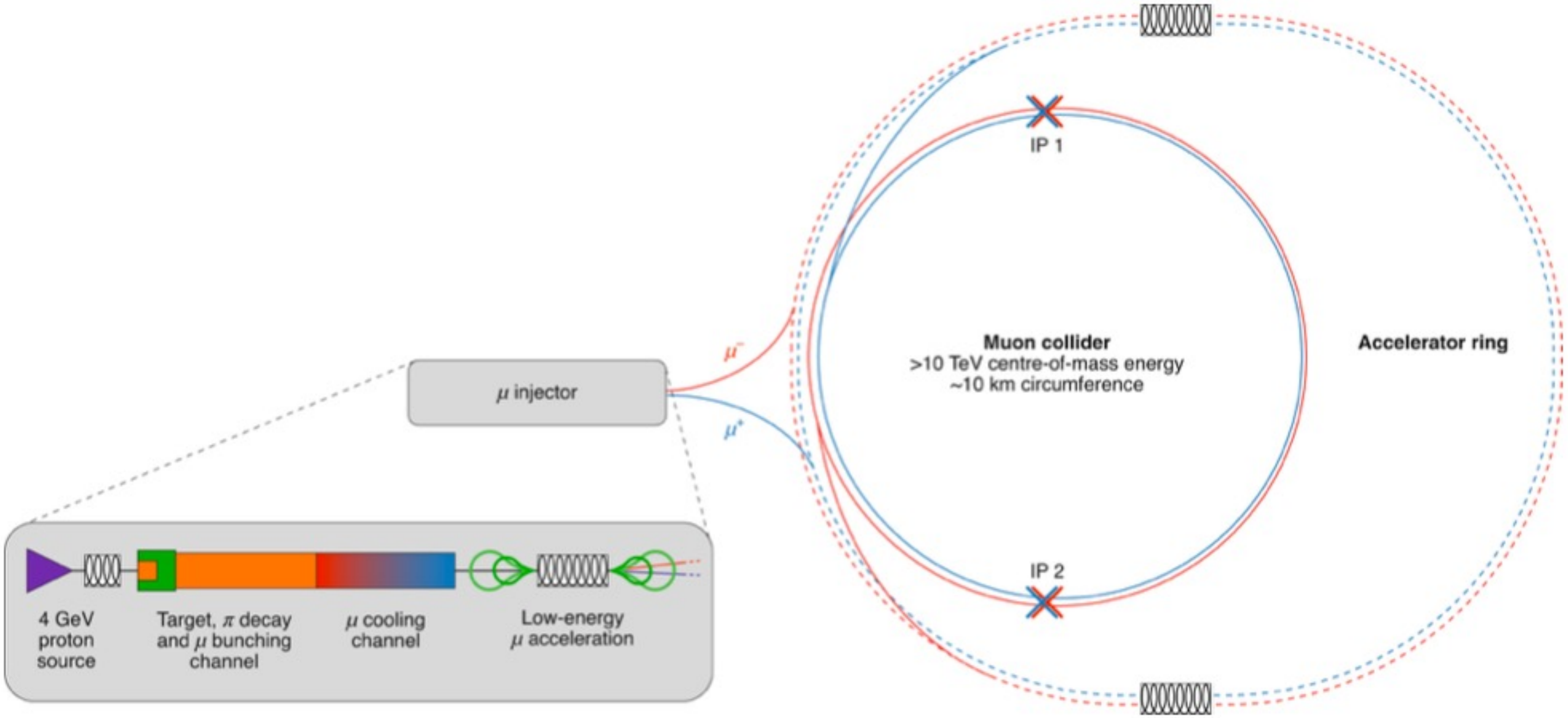
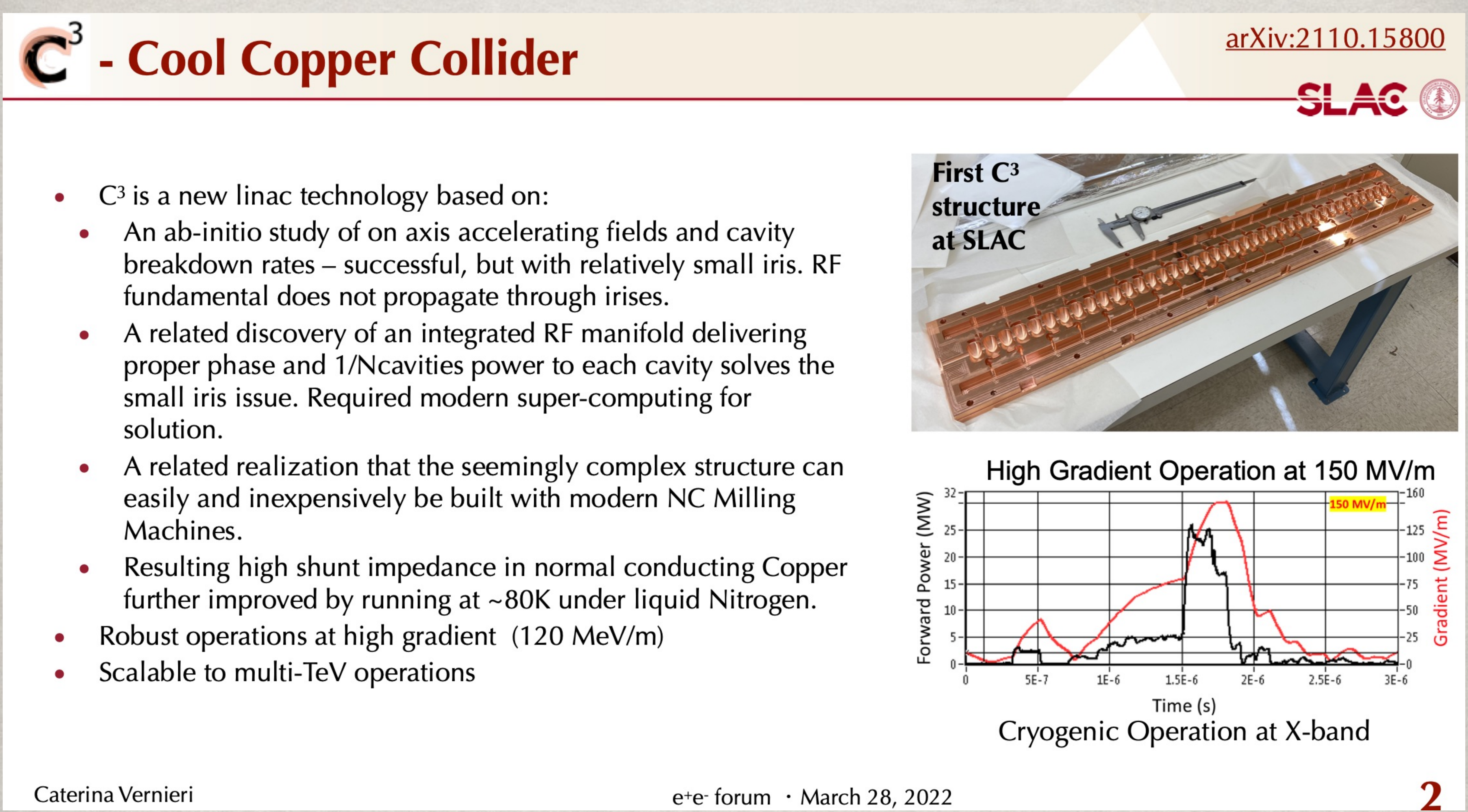


Figure 2-4. *A conceptual scheme for the muon collider (from Ref. [44])*

Backup slides …



C3 - Cool Copper Collider

arXiv:2110.15800

SLAC

- C^3 is a new linac technology based on:
  - An ab-initio study of on axis accelerating fields and cavity breakdown rates – successful, but with relatively small iris. RF fundamental does not propagate through irises.
  - A related discovery of an integrated RF manifold delivering proper phase and 1/Ncavities power to each cavity solves the small iris issue. Required modern super-computing for solution.
  - A related realization that the seemingly complex structure can easily and inexpensively be built with modern NC Milling Machines.
  - Resulting high shunt impedance in normal conducting Copper further improved by running at ~80K under liquid Nitrogen.
- Robust operations at high gradient (120 MeV/m)
- Scalable to multi-TeV operations

First C^3 structure at SLAC

High Gradient Operation at 150 MV/m

Cryogenic Operation at X-band

Caterina Vernieri

e^+e^- forum · March 28, 2022

2

PHYSICS POTENTIAL @ FUTURE COLLIDERS

Precision Higgs Physics: $(v/\Lambda)^2 < 6\%$

ILC: E_{cm} = 250 (500) GeV, 250 (500) fb^{-1}

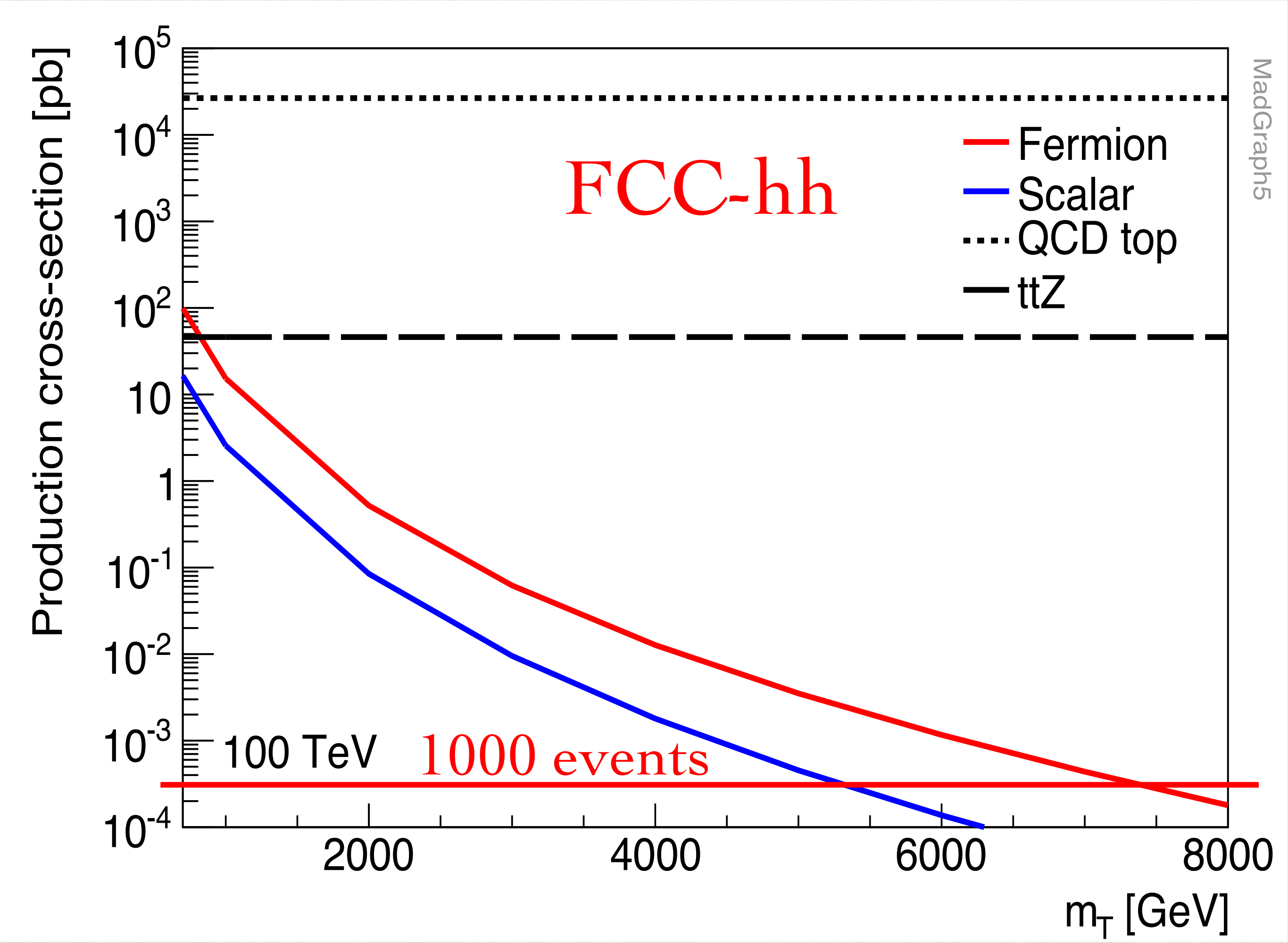
- Model-independent measurement:
  $\Gamma_H \sim 6\%$, $\Delta m_H \sim 30$ MeV, $\Delta k_{W,Z} < 1\%$
  (HL-LHC: assume SM, $\Gamma_H \sim 5\text{-}8\%$, $\Delta m_H \sim 50$ MeV)
- Higgs Factory: **10^6** Higgs: $\Gamma_H \sim 1\%$, $\Delta m_H \sim 5$ MeV.

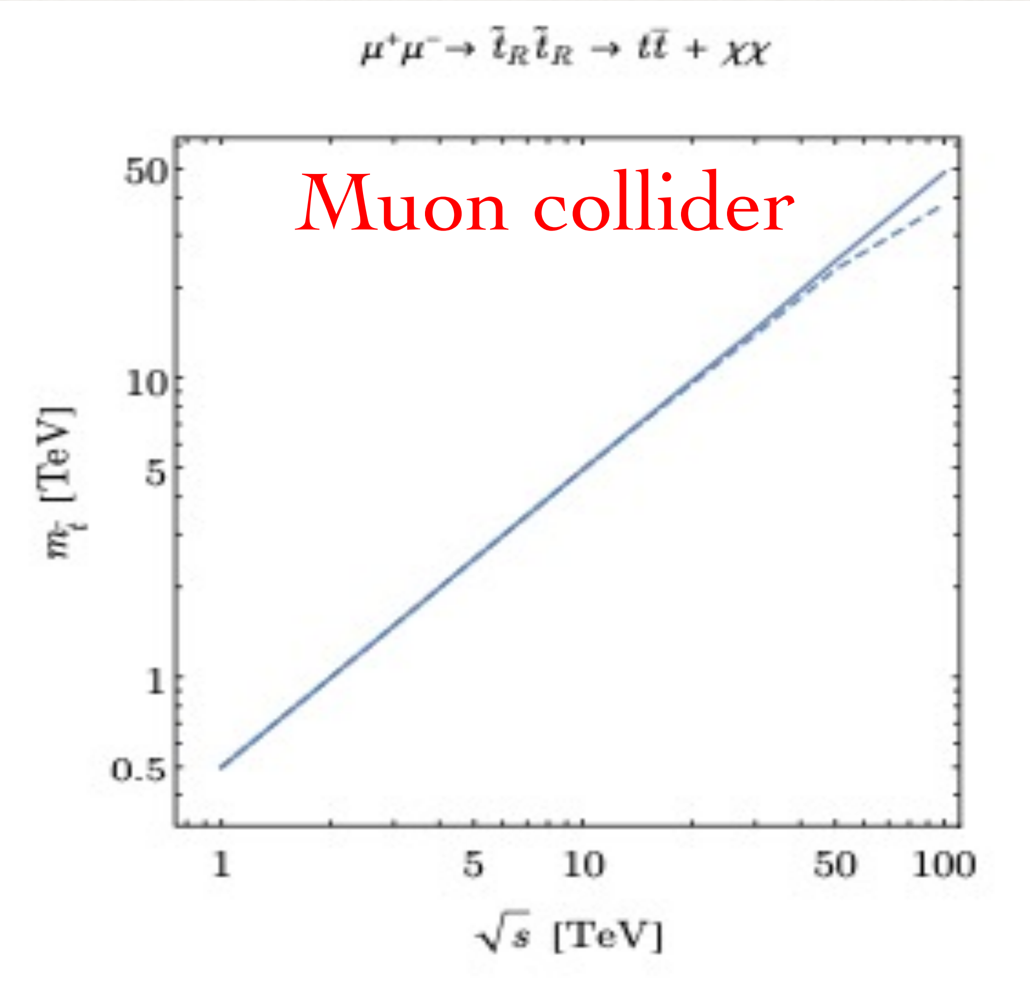
- FCC-hh / SPPC:
  $\Delta k_{HHH} \sim 5\%$
- 14 TeV muon collider:
  $\Delta k_{HHH} \sim 3\%$, $\Delta k_{W,Z} < 0.5\%$, $Y_\mu \sim 1\%$

Critically important to test the EW phase transition!

ILC: arXiv:1710.07621; TLEP Report: 1308.6176;
FCC: Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495;
muC: TH, D. Liu, I. Low, X. Wang, arXiv:2008.12204.

Pushing the “Naturalness” limit





Top quark partners searches:

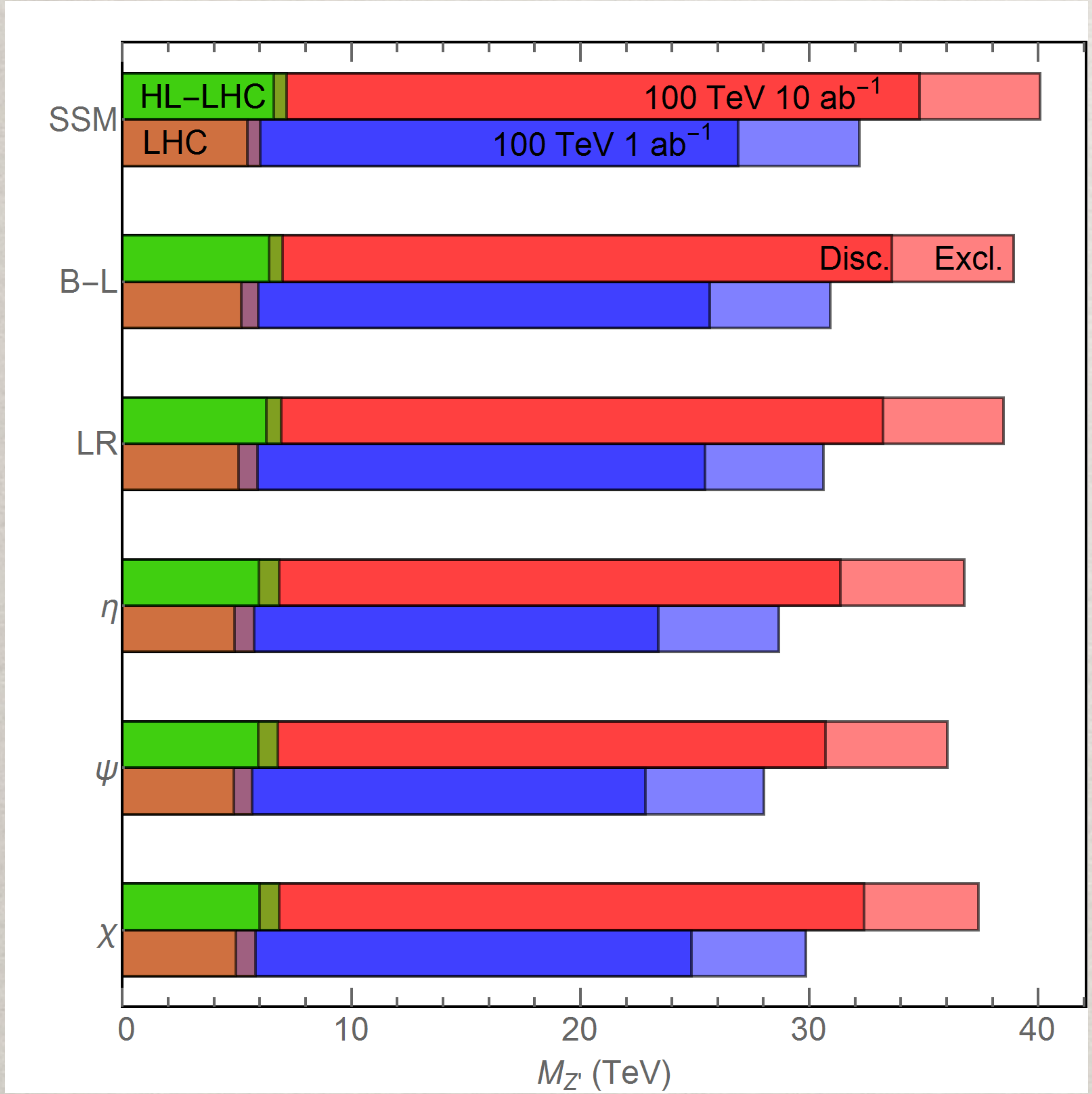
The Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \ (1\ \mathrm{TeV}/\Lambda)^2$

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

FCC: Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495;
muC: The Muon Smasher's Guide, https://arxiv.org/abs/2103.14043

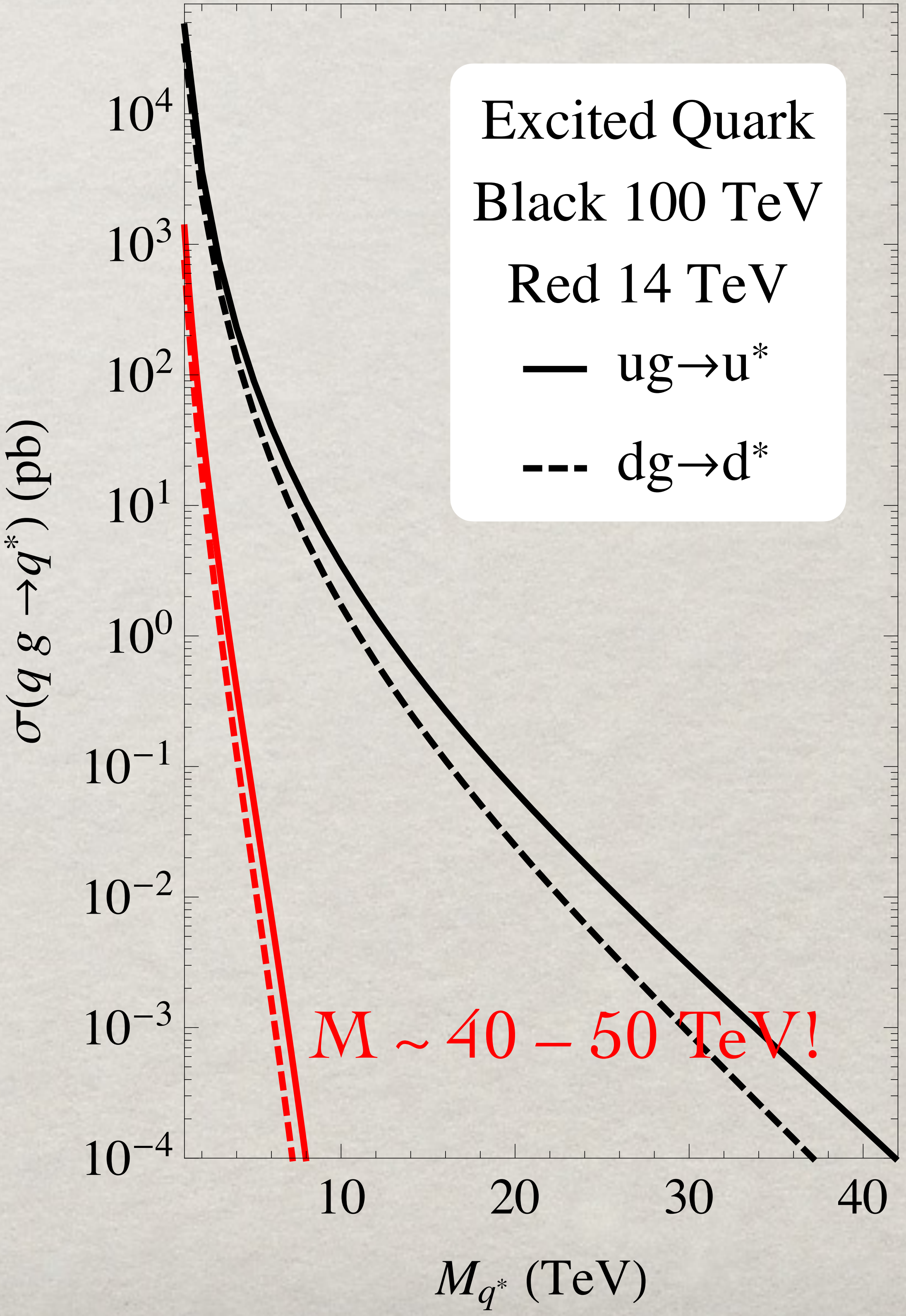
New Particle Searches

Electroweak Resonances: Z',W'



~ 6x over LHC

Colored Resonances:

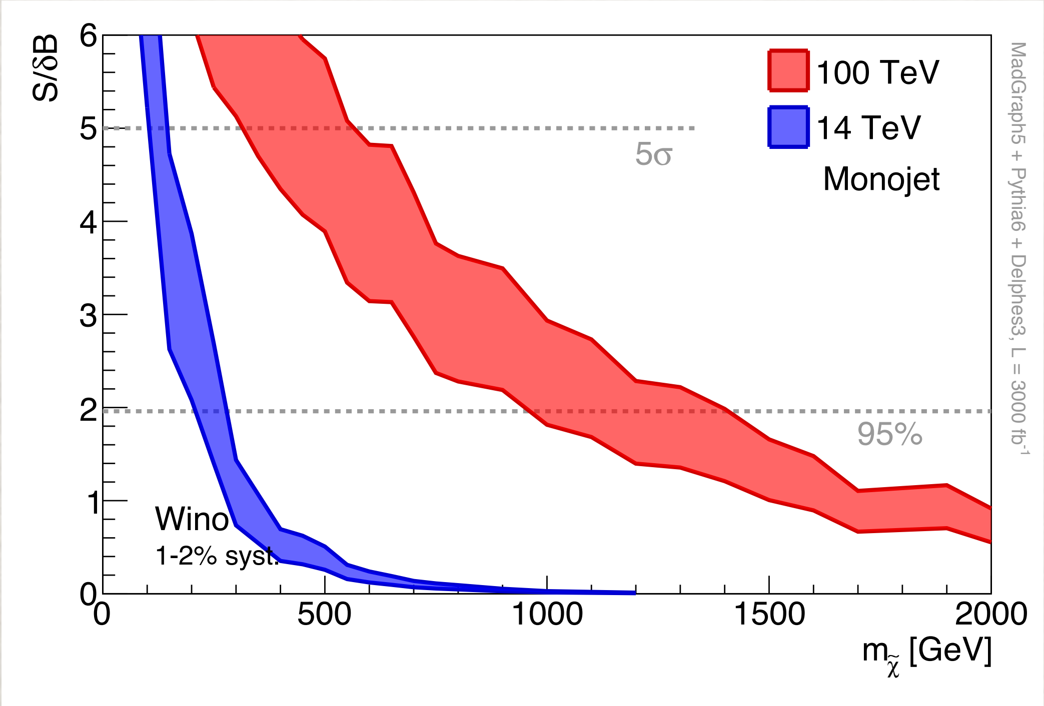


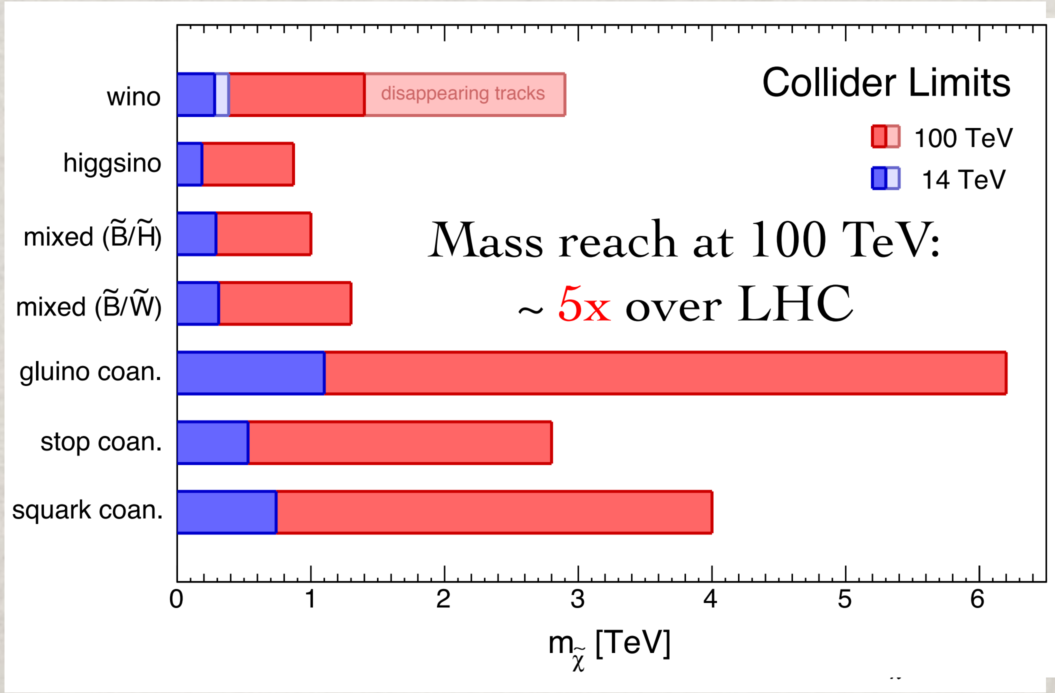
M ~ 40 – 50 TeV!

WIMP DM:

mass bounded by the thermal relic

$$M_{\mathrm{DM}} < 1.8\ \mathrm{TeV}\left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$$





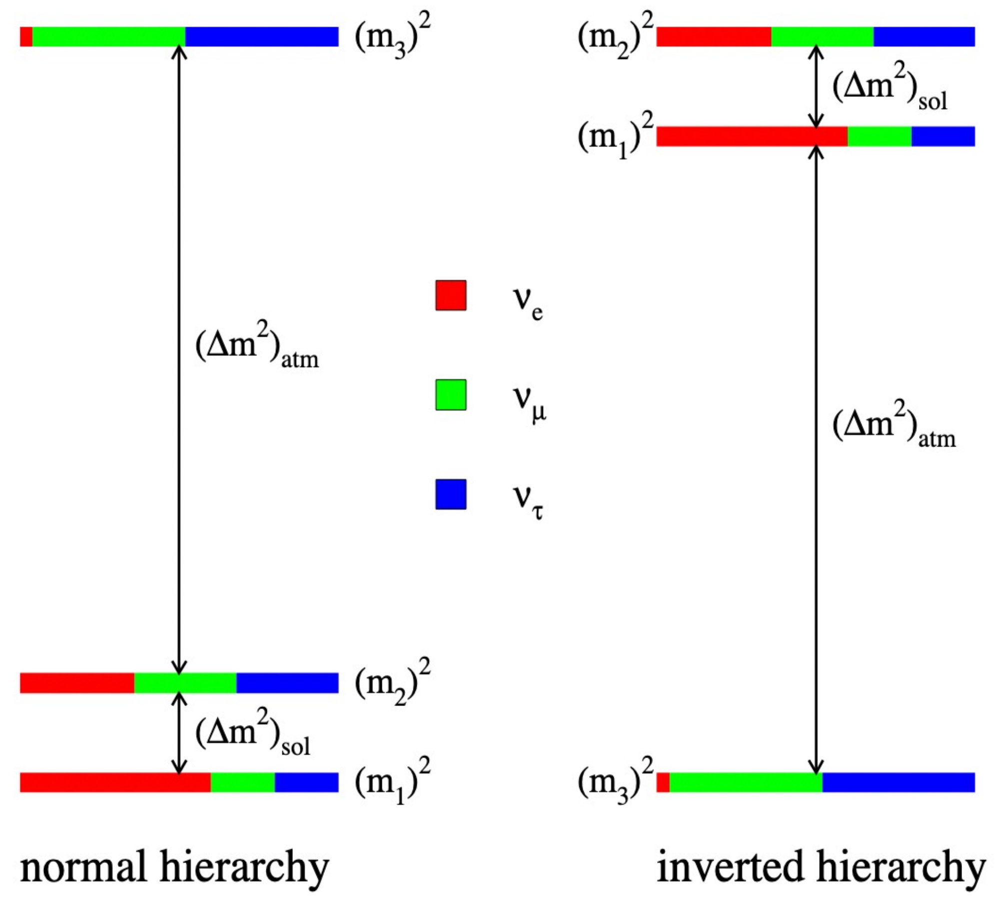
Mass reach at 100 TeV:
~ 5x over LHC

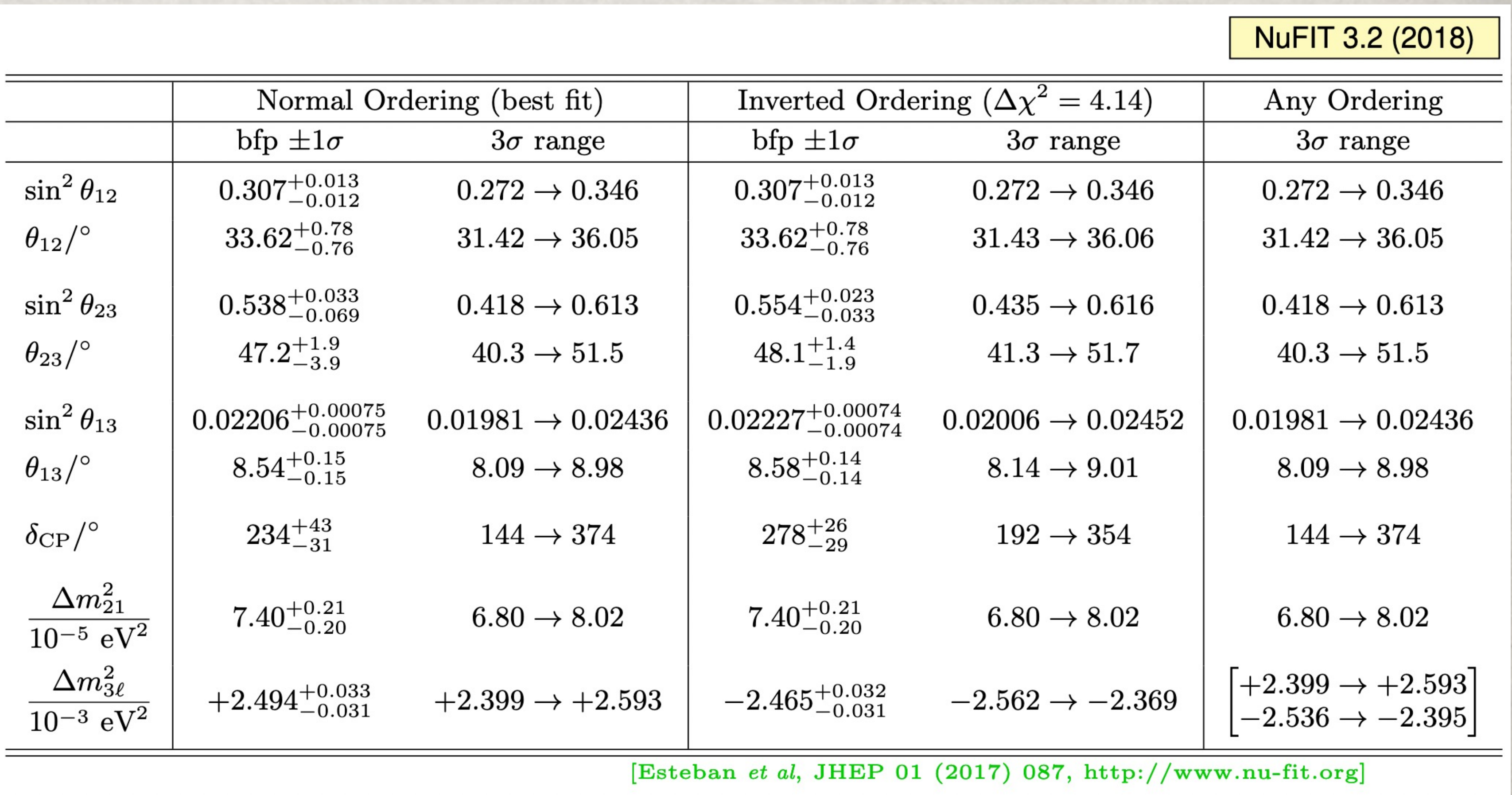
SM ν-physics on one page

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,c_{23} \end{pmatrix}.$$

This matrix is often called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix.





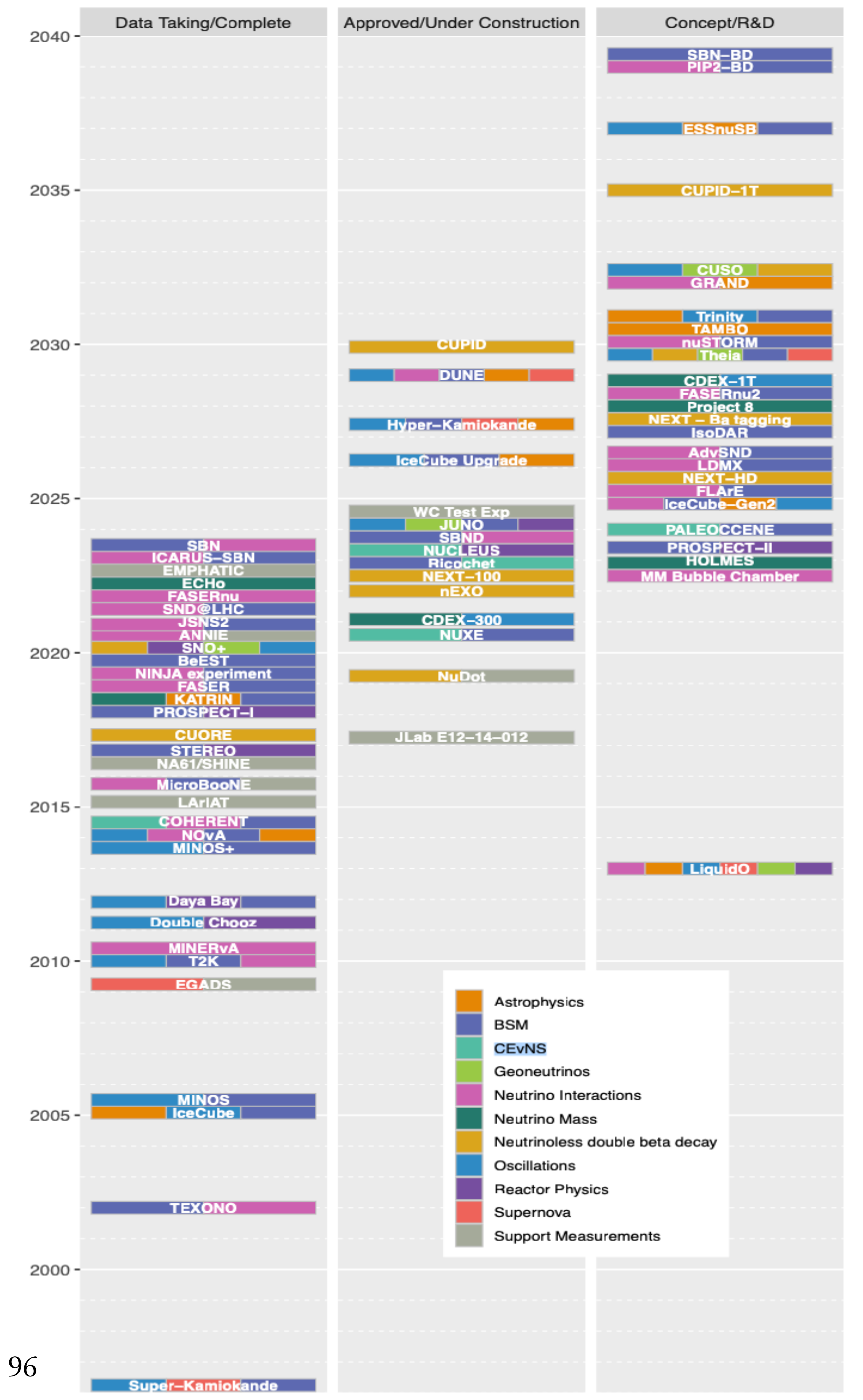
NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp ±1σ	3σ range	bfp ±1σ	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	0.272 → 0.346	$0.307^{+0.013}_{-0.012}$	0.272 → 0.346	0.272 → 0.346
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	31.42 → 36.05	$33.62^{+0.78}_{-0.76}$	31.43 → 36.06	31.42 → 36.05
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	0.418 → 0.613	$0.554^{+0.023}_{-0.033}$	0.435 → 0.616	0.418 → 0.613
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	40.3 → 51.5	$48.1^{+1.4}_{-1.9}$	41.3 → 51.7	40.3 → 51.5
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	0.01981 → 0.02436	$0.02227^{+0.00074}_{-0.00074}$	0.02006 → 0.02452	0.01981 → 0.02436
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	8.09 → 8.98	$8.58^{+0.14}_{-0.14}$	8.14 → 9.01	8.09 → 8.98
$\delta_{\mathrm{CP}}/^\circ$	234^{+43}_{-31}	144 → 374	278^{+26}_{-29}	192 → 354	144 → 374
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	6.80 → 8.02	$7.40^{+0.21}_{-0.20}$	6.80 → 8.02	6.80 → 8.02
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	+2.399 → +2.593	$-2.465^{+0.032}_{-0.031}$	−2.562 → −2.369	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

[Esteban *et al*, JHEP 01 (2017) 087, http://www.nu-fit.org]

Snowmass NF Report:
P. Huber, K. Scholberg,
Elizabeth Worcester:
arXiv:2211.08241

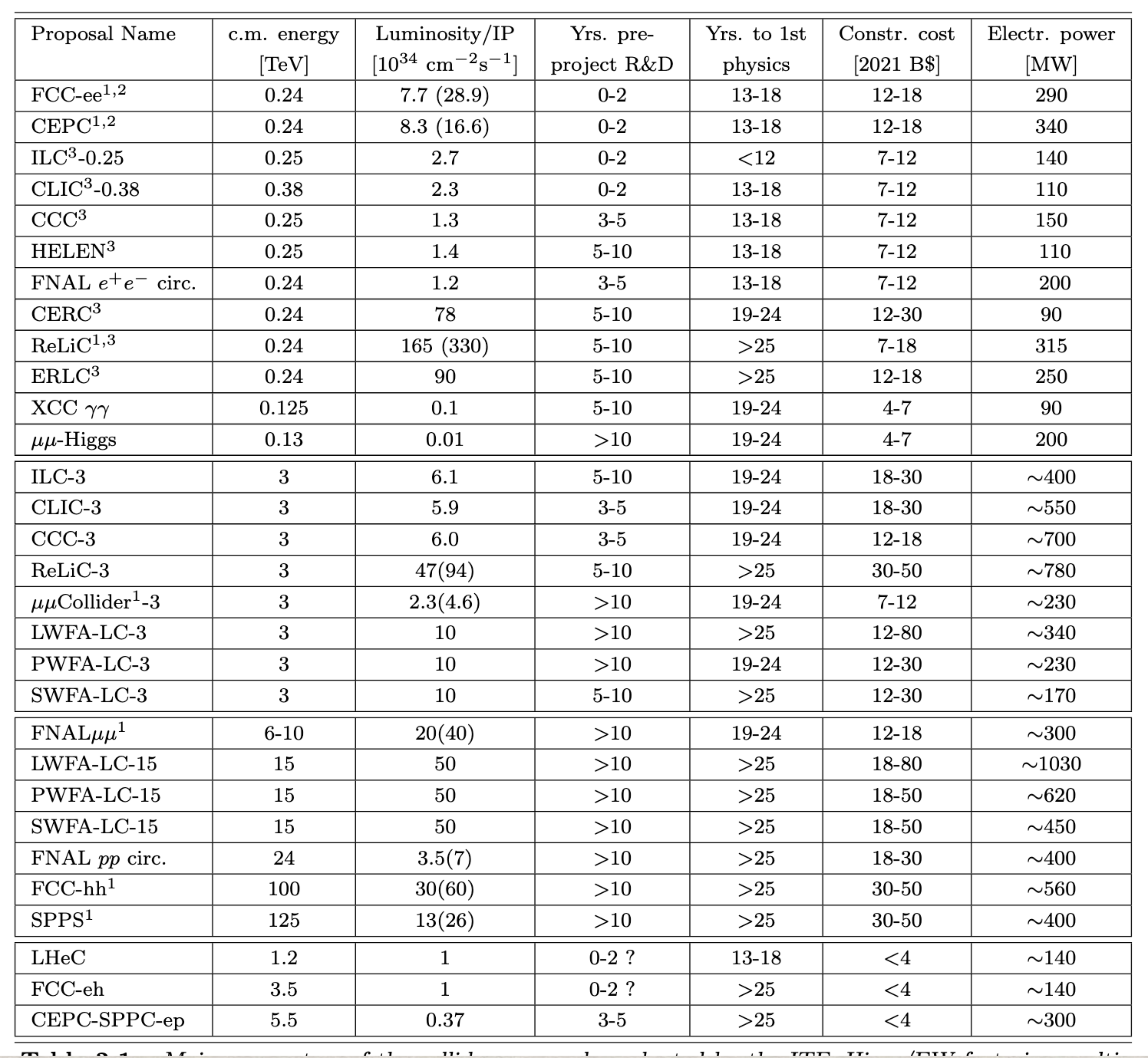
Summary table for the current and future neutrino facilities & the time lines



Many Proposed Experiments For Rare Processes

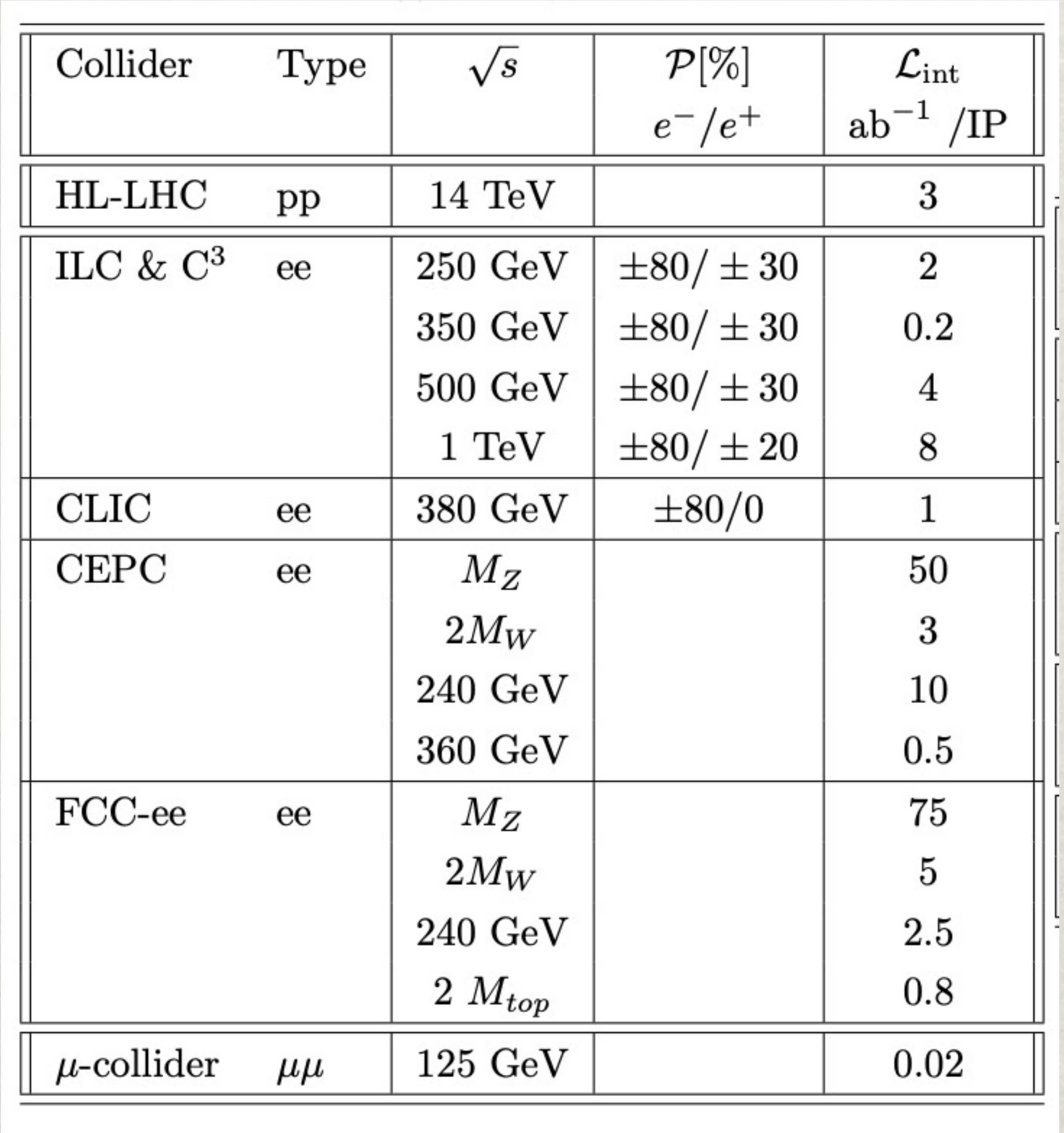
Searches for DM, axions, EDMs, CLFV experiments, muons, light mesons, beam dump experiments…

Experiment	Experiment type	Primary beam particle	Beam Energy [GeV]	Beam power [kW]	Beam time structure	Uses existing or under construction beamline?
Proton Storage Ring: EDM and Axion Searches	Precision tests, Dark Matter	proton	0.7 GeV/c beam momentum	1e11 polarized protons per fill	Fill the ring every 1000s	no
Physics with Muonium	Precision tests	proton (producing surface muons)	0.8 GeV	1e13pm1 POT per second	CW	no
Nucleon Electromagnetic Form Factors from Lepton Scattering	Neutrino	electron or proton (producing muons)	0.85 GeV to 2 GeV	1 nA to 10 microA for electrons, 10^7 to 10^8 per second for muons	A continuous or pulsed structure (ideally with a duty factor of 1% or larger) should be sufficient	no
Rare Decays of Light Mesons (REDTOP)	Precision tests	proton	1.8-2.2 GeV (Run I), 0.8-0.92 (Run II), 1.7 (Run III)	0.03-0.05 (Run I), 200 (Runs II and III)	CW, slow extraction for Run I	no
Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations	Precision tests	proton	0.8-2	1,000	quasi-continuous	no
CLFV with Muon Decays	CLFV	proton	Not critical 0.8 to a few GeV	100 or more	continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better	Muon Campus
Mu2e II	CLFV	proton	1 to 3	100	pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation	no
Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	0.8 to 1.5 GeV	100 or more	<O(1 micro s) pulse width for neutrino measurements, <O(30 ns) pulse width for dark matter searches, 10^{-5} or better duty factor	no
PRISM-like Charged Lepton Flavor Violation	CLFV	proton	1-3 GeV	up to 2 MW	15ns pulses at a rep rate of about 1 kHz	no
Electron Missing Momentum (LDMX)	Dark Sector	electron	~3 GeV to ~20 GeV	O(1 electron per RF bucket at 53 MHz)	CW-ish	no
Electron Beam Dumps	Dark Sector	electron	few GeV	10^{20} electrons on target over the experiment al runtime	Pulsed beam (duty factor not specified)	no
Proton Irradiation Facility	R&D	proton	Energy is not very important	1e18 protons in a few hours	Pulsed beam (duty factor not specified)	no
SBN	Neutrino	proton	8	32	20Hz	BNB
Mu2e	CLFV	proton	8	8	<10^{-10} extinction	Muon Campus
Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump	Dark Sector, Neutrino	proton	8	up to 115	Beam spills less than a few microsec with separation between spills greater than 50 microsec	BNB
Muon beam dump	Dark Sector	proton (producing muons)	3 GeV muons	3e14 muons in total on target for the whole run	CW	Muon Campus
Muon Collider R&D and Neutrino Factory	R&D	proton	5 - 30GeV	1e12 to 1e13 protons per bunch	10 - 50 Hz rep rate and bunch length 1-3 ns	no
Muon Missing Momentum	Dark Sector	proton (producing muons)	few 10s of GeV	10^{10} muons per experimental runtime	Pulsed beam (duty factor not specified)	no
High Energy Proton Fixed Target	Dark Sector, Neutrino	proton	O(100 GeV)	1e12 POT/s therefore ~20 kW	CW via resonant extraction. "If we could up the duty factor that woul dbe even better"(?)	Switchyard
Test-Beam Facility	R&D	proton	120, lower energies would also be beneficial	10 to 100 kHz on the testing apparatus	Pulsed beam (duty factor not specified)	no
Tau Neutrinos	Neutrino	proton	120	1200 or higher	MI time structure	LBNF

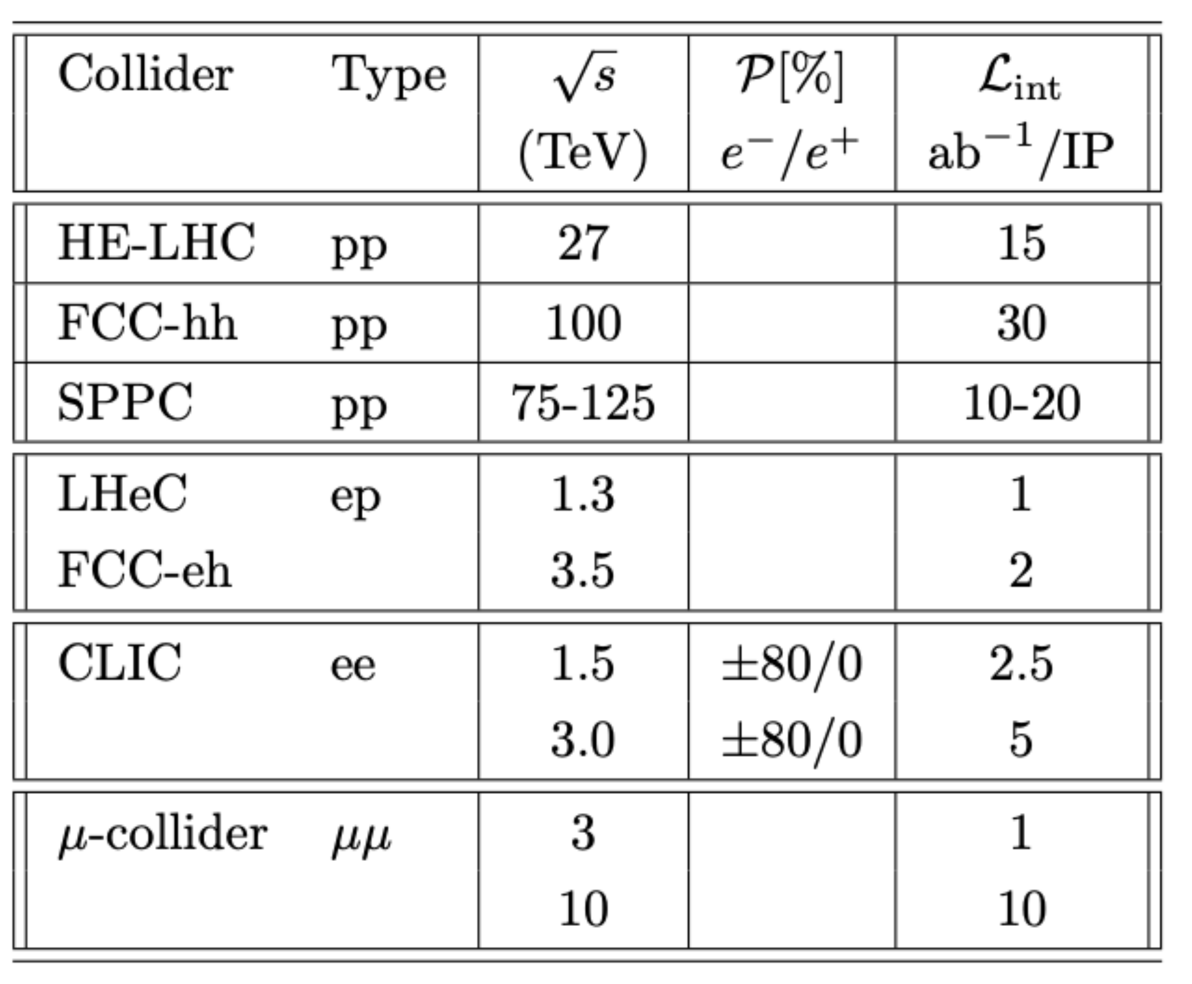


Proposal Name	c.m. energy [TeV]	Luminosity/IP [10^{34} cm^{-2}s^{-1}]	Yrs. pre-project R&D	Yrs. to 1st physics	Constr. cost [2021 B$]	Electr. power [MW]
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3]-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC[3]-0.38	0.38	2.3	0-2	13-18	7-12	110
CCC[3]	0.25	1.3	3-5	13-18	7-12	150
HELEN[3]	0.25	1.4	5-10	13-18	7-12	110
FNAL e^+e^- circ.	0.24	1.2	3-5	13-18	7-12	200
CERC[3]	0.24	78	5-10	19-24	12-30	90
ReLiC[1,3]	0.24	165 (330)	5-10	>25	7-18	315
ERLC[3]	0.24	90	5-10	>25	12-18	250
XCC $\gamma\gamma$	0.125	0.1	5-10	19-24	4-7	90
$\mu\mu$-Higgs	0.13	0.01	>10	19-24	4-7	200
ILC-3	3	6.1	5-10	19-24	18-30	∼400
CLIC-3	3	5.9	3-5	19-24	18-30	∼550
CCC-3	3	6.0	3-5	19-24	12-18	∼700
ReLiC-3	3	47(94)	5-10	>25	30-50	∼780
$\mu\mu$Collider[1]-3	3	2.3(4.6)	>10	19-24	7-12	∼230
LWFA-LC-3	3	10	>10	>25	12-80	∼340
PWFA-LC-3	3	10	>10	19-24	12-30	∼230
SWFA-LC-3	3	10	5-10	>25	12-30	∼170
FNAL$\mu\mu$[1]	6-10	20(40)	>10	19-24	12-18	∼300
LWFA-LC-15	15	50	>10	>25	18-80	∼1030
PWFA-LC-15	15	50	>10	>25	18-50	∼620
SWFA-LC-15	15	50	>10	>25	18-50	∼450
FNAL pp circ.	24	3.5(7)	>10	>25	18-30	∼400
FCC-hh[1]	100	30(60)	>10	>25	30-50	∼560
SPPS[1]	125	13(26)	>10	>25	30-50	∼400
LHeC	1.2	1	0-2 ?	13-18	<4	∼140
FCC-eh	3.5	1	0-2 ?	>25	<4	∼140
CEPC-SPPC-ep	5.5	0.37	3-5	>25	<4	∼300

Benchmark scenarios for Higgs factories, and multi-TeV colliders

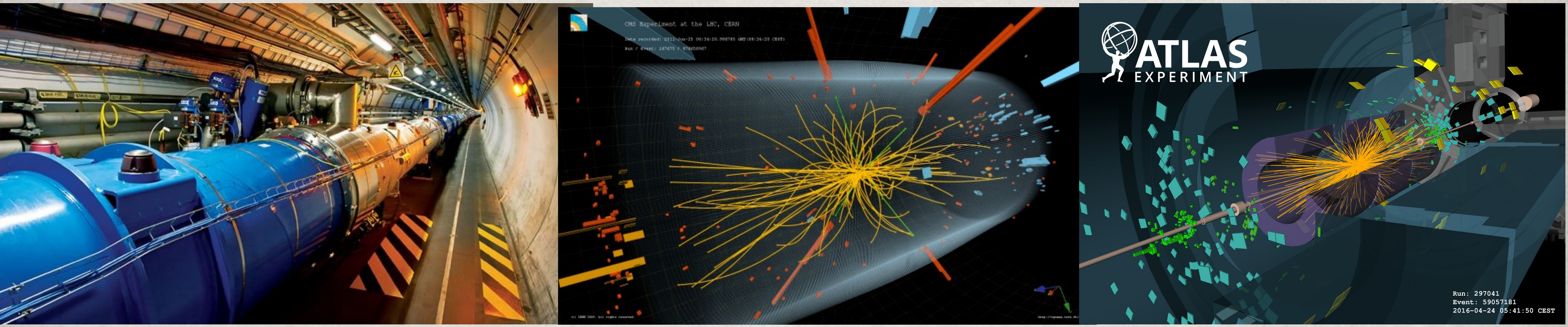


Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02



Collider	Type	$\sqrt{s}$ (TeV)	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HE-LHC	pp	27		15
FCC-hh	pp	100		30
SPPC	pp	75-125		10-20
LHeC	ep	1.3		1
FCC-eh		3.5		2
CLIC	ee	1.5	$\pm 80/0$	2.5
		3.0	$\pm 80/0$	5
μ-collider	$\mu\mu$	3		1
		10		10

LHC will continue at the energy frontier



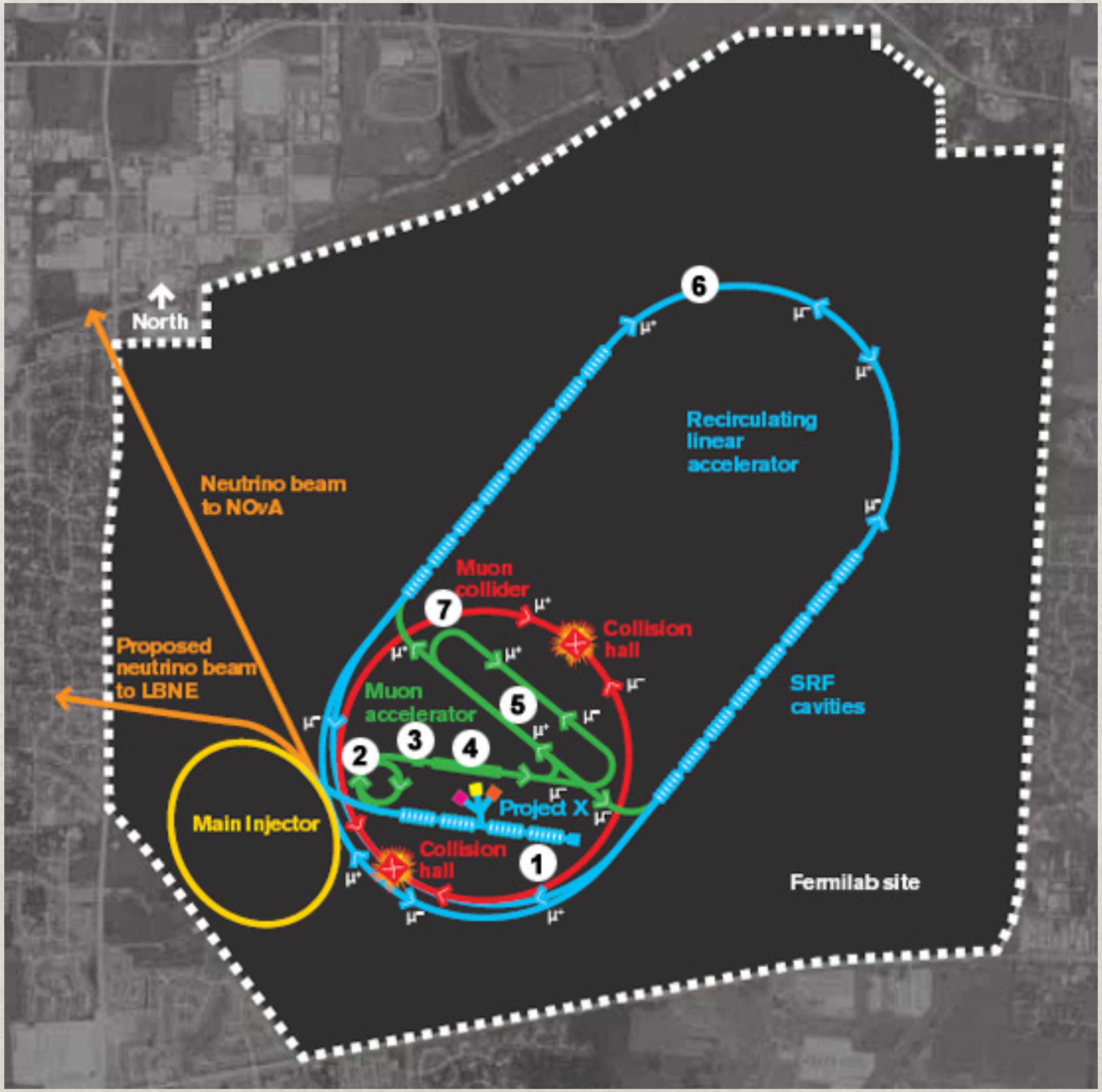
- Already ~ O(140 fb^{-1}) @ ATLAS/CMS
- Run 3 up-coming: 300 fb^{-1}
- HL-LHC: 3000 fb^{-1}

  → lead the energy/precision frontier!

Further searches at the LHC will be limited by

- Backgrounds
- Systematics
- New physics threshold

Muon collider on FNAL site: It may reach ~ m_h – 10 TeV



(Curtesy of Pushpa Bhat)

Snowmass Day: https://indico.fnal.gov/event/50538

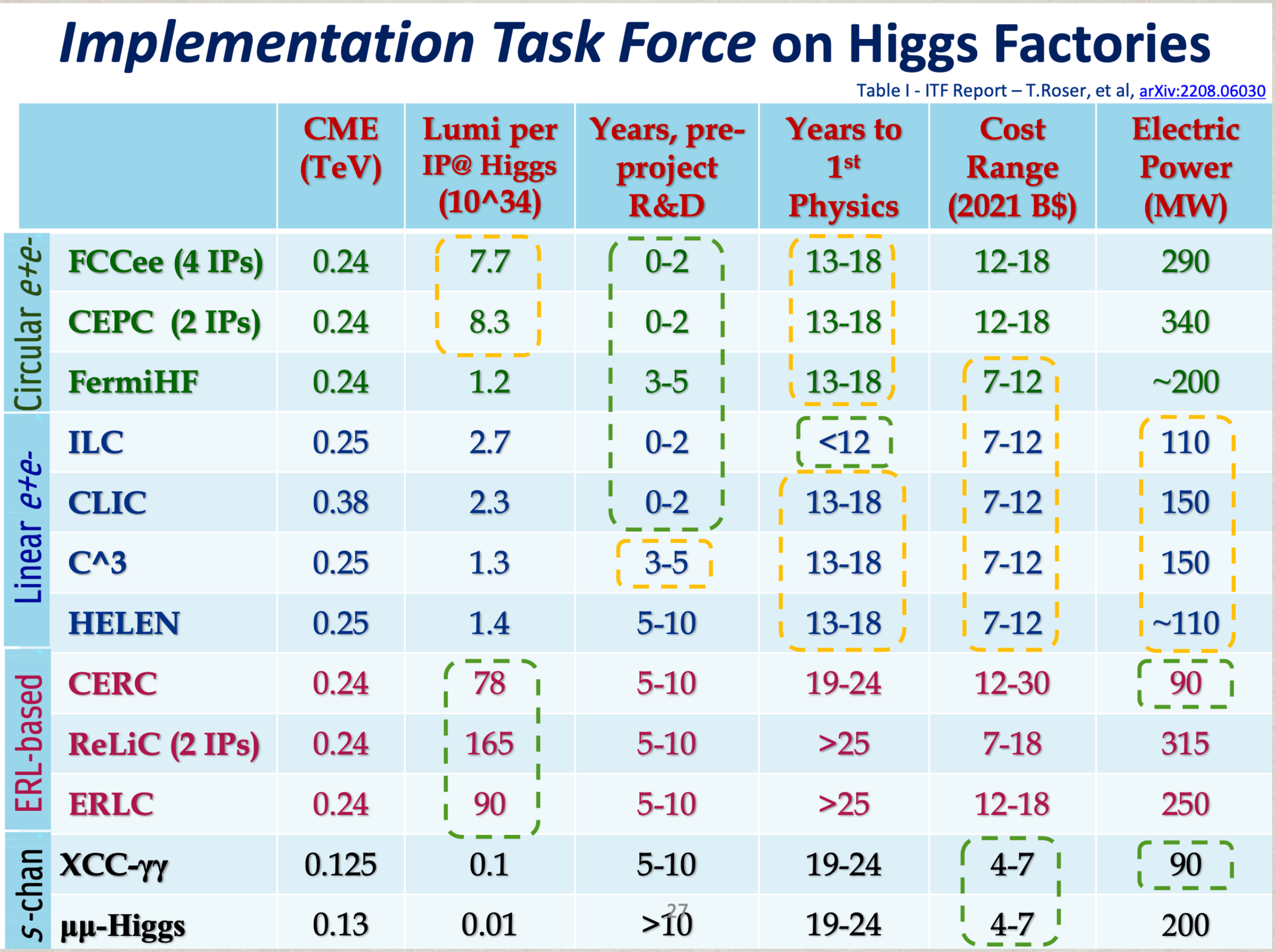
MAJOR THEMES IN NEUTRINO FRONTIER

P. Huber, K. Scholberg, Elizabeth Worcester: arXiv:2211.08241

- A defining and somewhat unique aspect of NF is breadth and balance of effort across a wide range of physics topics, timescales, sizes, and costs, with significant need for collaboration with other frontiers and across boundaries of what is typically considered particle physics
- Physics beyond the (3-neutrino) Standard Model is emerging as a major focus of NF – this includes investigation of anomalies in neutrino oscillation measurements, precision measurements of neutrino oscillation that are sensitive to new particles and interactions, and use of neutrino experiments to search for other new physics, such as dark matter
- Use of neutrinos as messengers carrying information about otherwise inaccessible systems, particularly as participants in multi-messenger astronomy, is a growing area of interest in NF

MAJOR THEMES IN NEUTRINO FRONTIER

- DUNE/LBNF is the largest project in the NF portfolio, with extensive investment from the US and international partners to make precision neutrino oscillation measurements as well as a broad program of astrophysics topics and BSM searches. Snowmass/P5 will be particularly focused on the 2nd phase of DUNE, which is necessary to achieve the full DUNE physics scope, and which also offers opportunities to expand the physics scope beyond that initially envisioned
- There is significant synergy with other frontiers/fields in detector, accelerator, and computing development
- Community engagement is critical for the success of NF
- Early career scientists are central to all of the ongoing and planned research in NF



Implementation Task Force on Higgs Factories

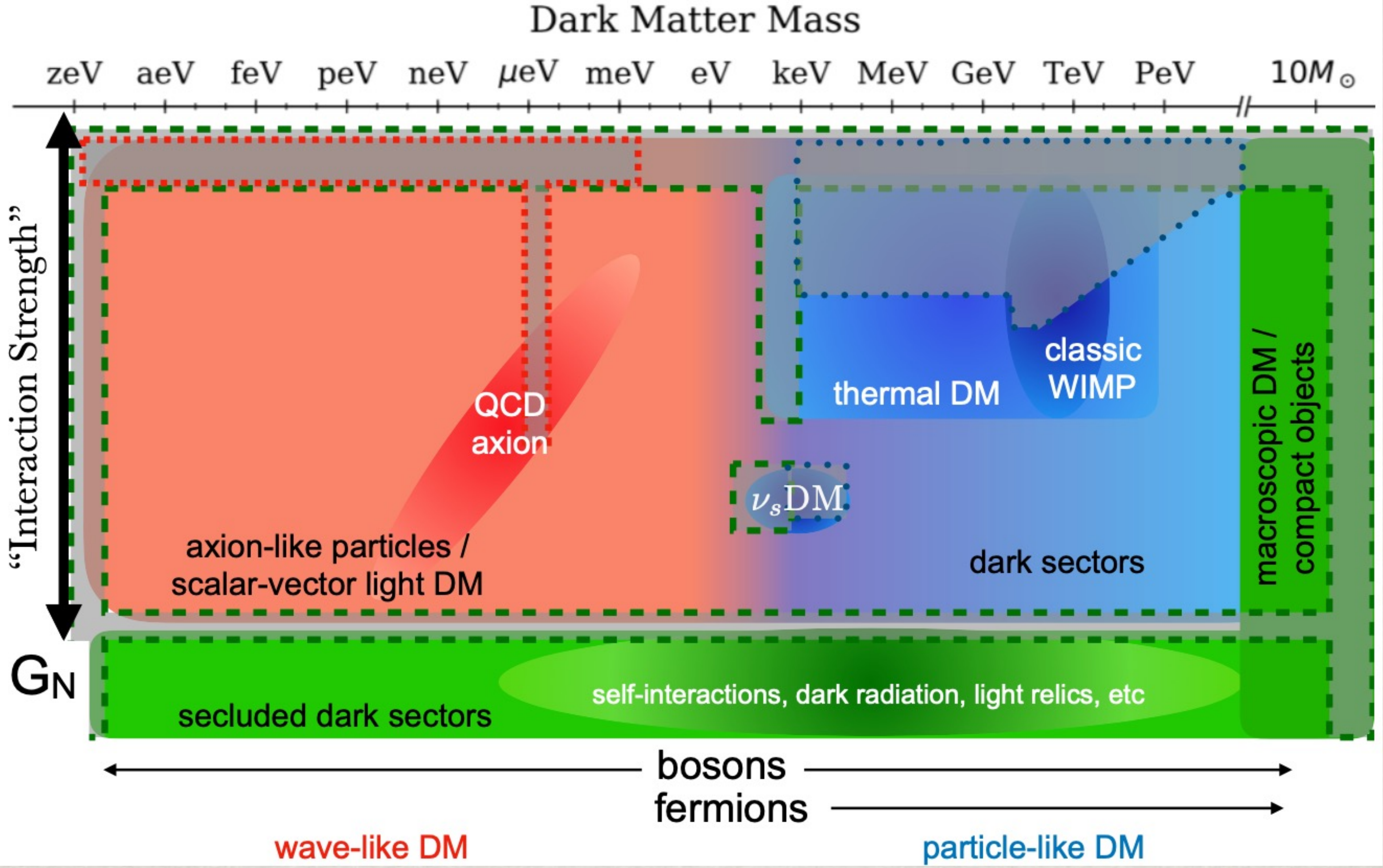
Table I - ITF Report – T.Roser, et al, arXiv:2208.06030

		CME (TeV)	Lumi per IP@ Higgs (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
Circular *e+e-*	FCCee (4 IPs)	0.24	7.7	0-2	13-18	12-18	290
	CEPC (2 IPs)	0.24	8.3	0-2	13-18	12-18	340
	FermiHF	0.24	1.2	3-5	13-18	7-12	~200
Linear *e+e-*	ILC	0.25	2.7	0-2	<12	7-12	110
	CLIC	0.38	2.3	0-2	13-18	7-12	150
	C^3	0.25	1.3	3-5	13-18	7-12	150
	HELEN	0.25	1.4	5-10	13-18	7-12	~110
ERL-based	CERC	0.24	78	5-10	19-24	12-30	90
	ReLiC (2 IPs)	0.24	165	5-10	>25	7-18	315
	ERLC	0.24	90	5-10	>25	12-18	250
s-chan	XCC-γγ	0.125	0.1	5-10	19-24	4-7	90
	μμ-Higgs	0.13	0.01	>10	19-24	4-7	200

ITF’s Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	*O*(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

ITF Report – T.Roser, et al, arXiv:2208.06030

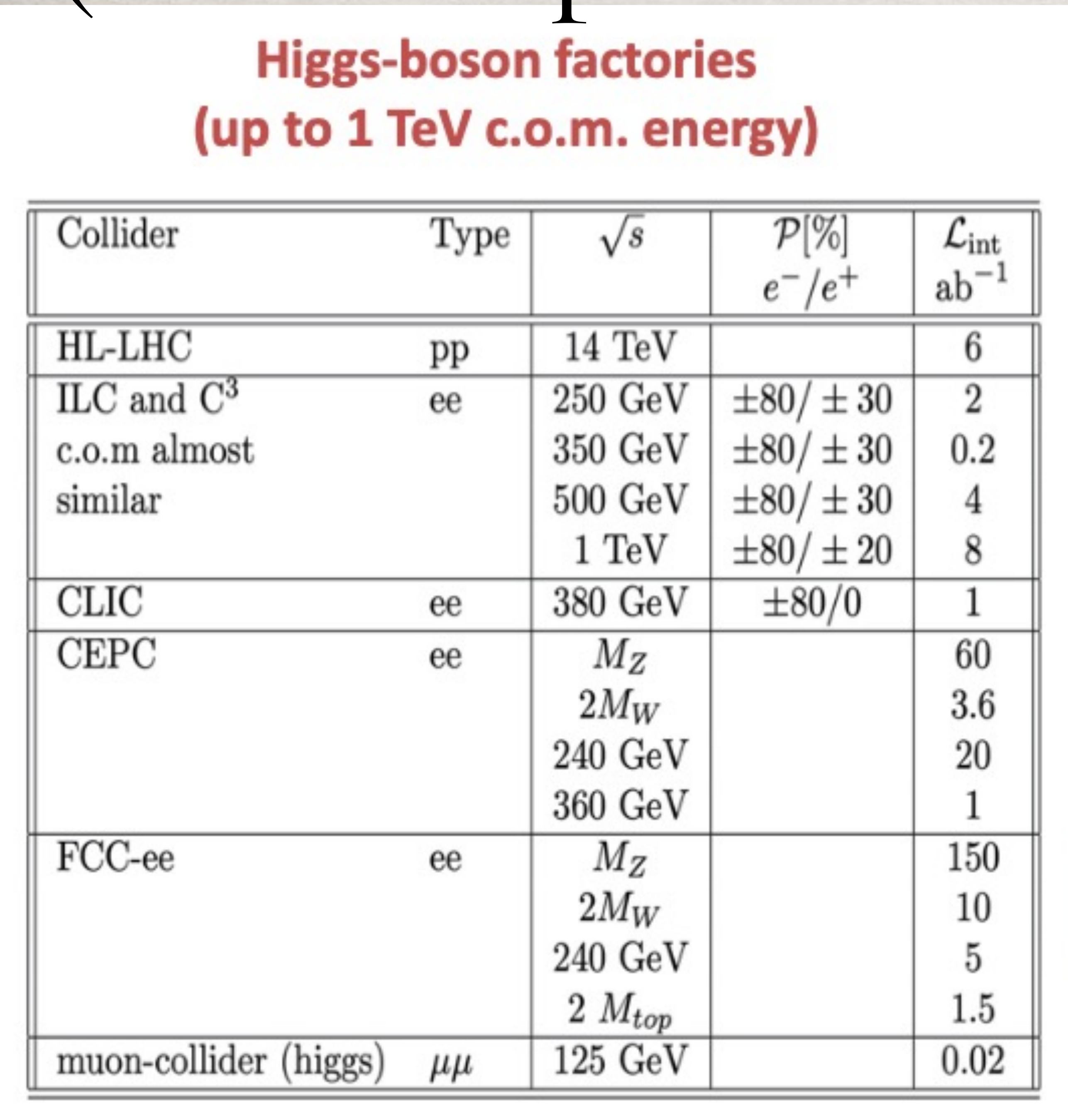


'Delve Deep, Search Wide' employs a range of direct searches for WIMPs interacting with targets on Earth, indirect searches for annihilation products, and cosmic probes based on structure, to scrutinize priority targets such as WIMPs and QCD axions, while broadly scanning parameter space, leaving no stone unturned.

The next 10 years, including future Generation 3 direct searches for WIMPs and axions, combined with future indirect observatories, a program of smaller scale searches, and key inputs from cosmic probes, results in broad coverage.

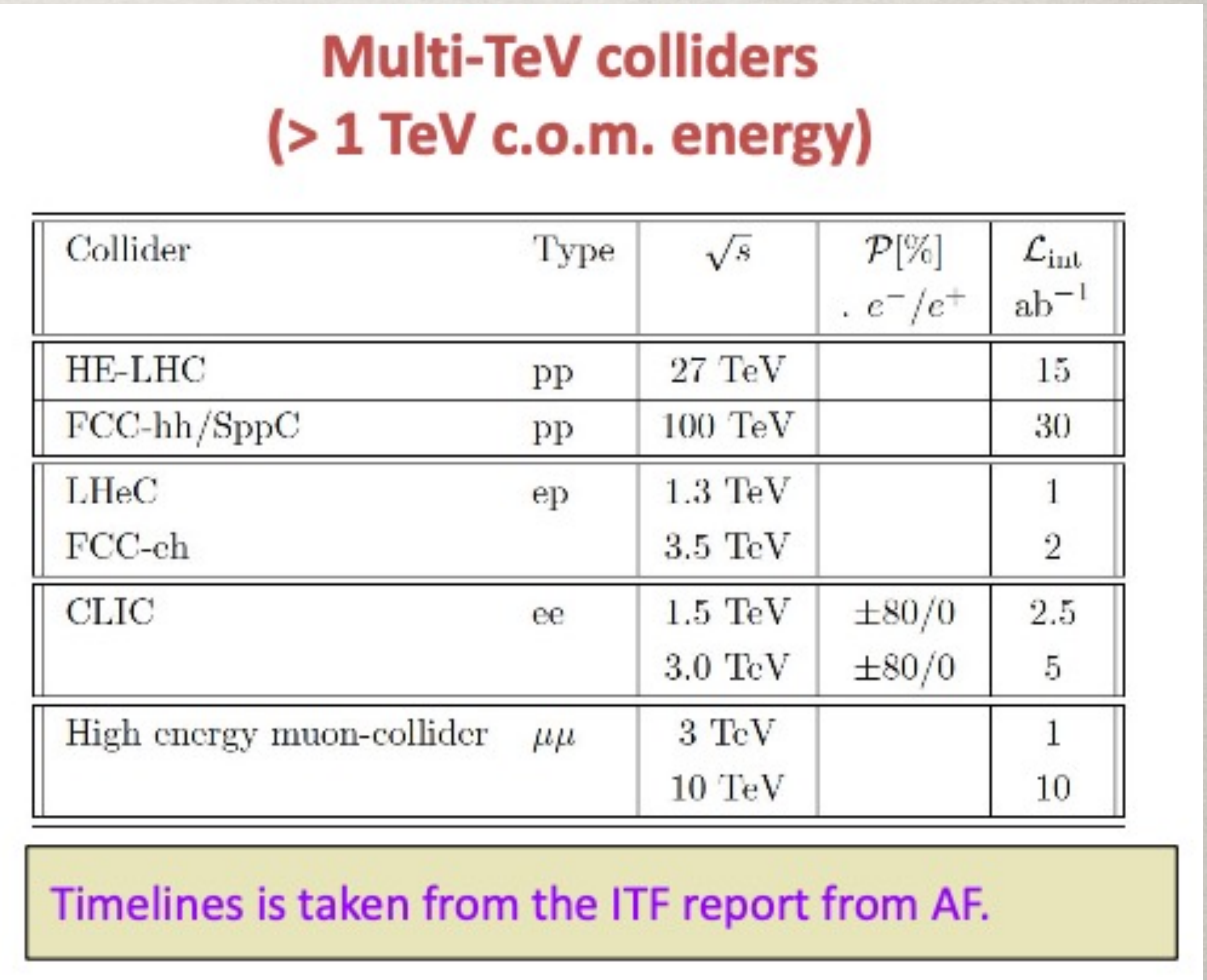
ITF report:

(ITF = Implementation Task Force @ AF)



Higgs-boson factories
(up to 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3 c.o.m almost similar	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

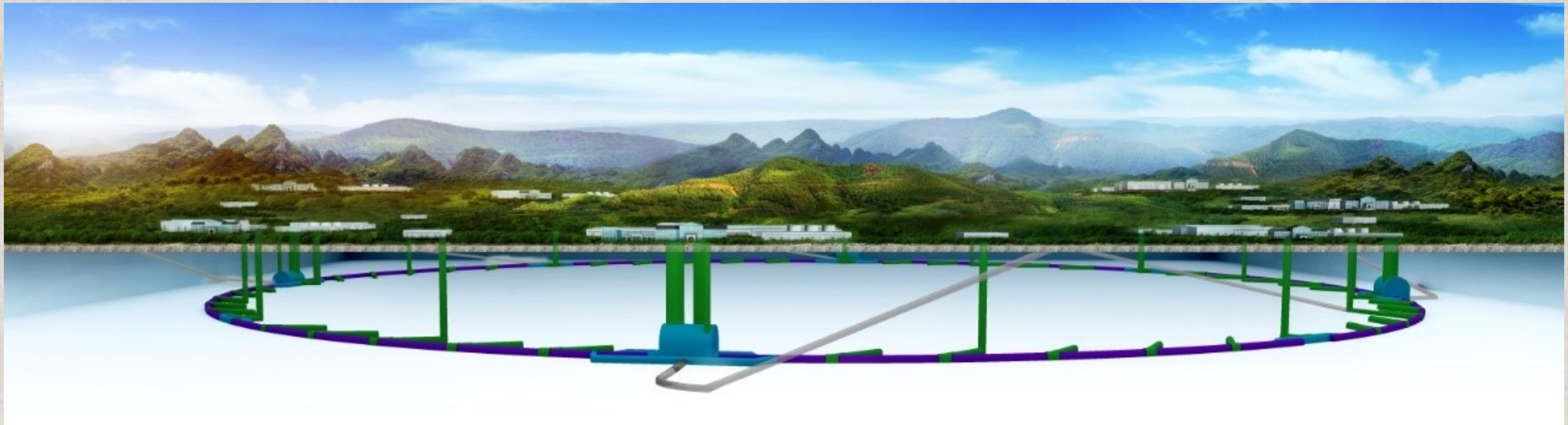


Multi-TeV colliders
(> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh/SppC	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Timelines is taken from the ITF report from AF.

CEPC (Circular e^-e^+) / SppC (Super pp), China



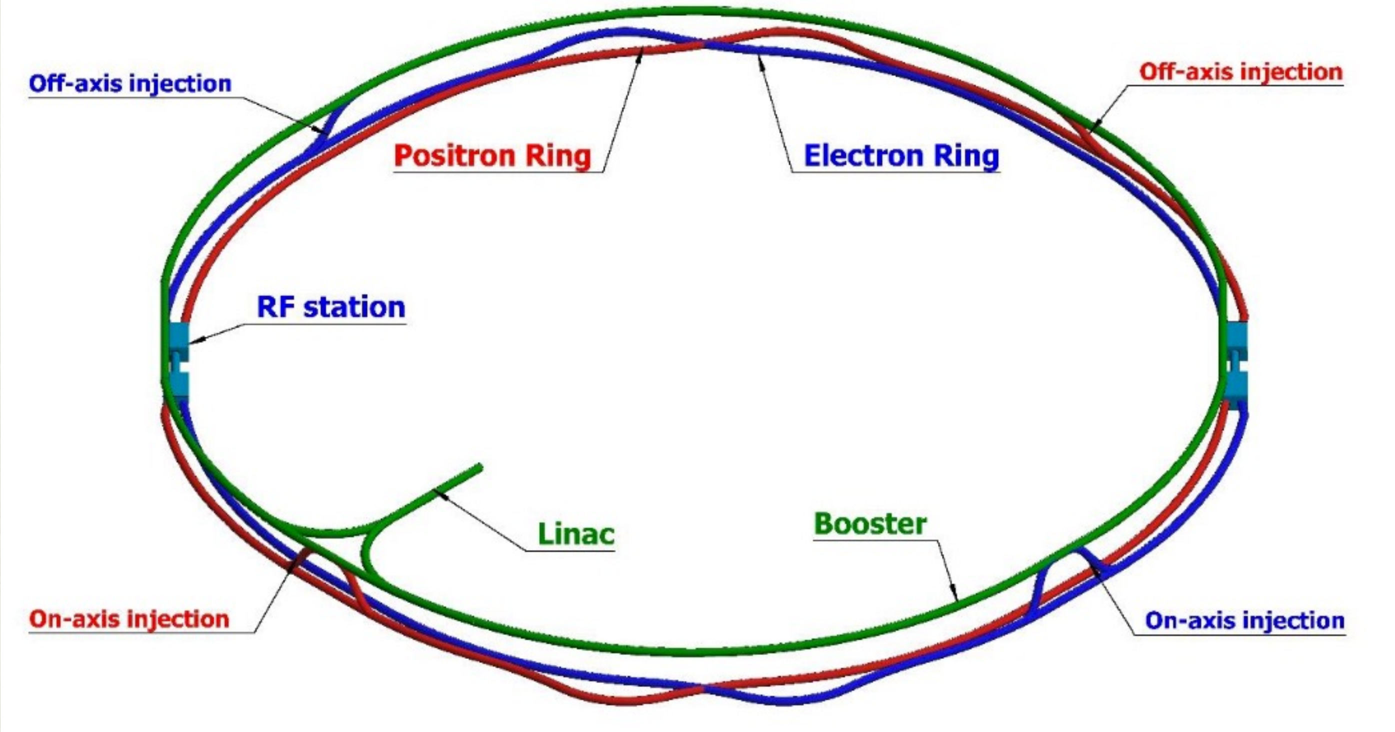


Figure 2.2: CEPC layout

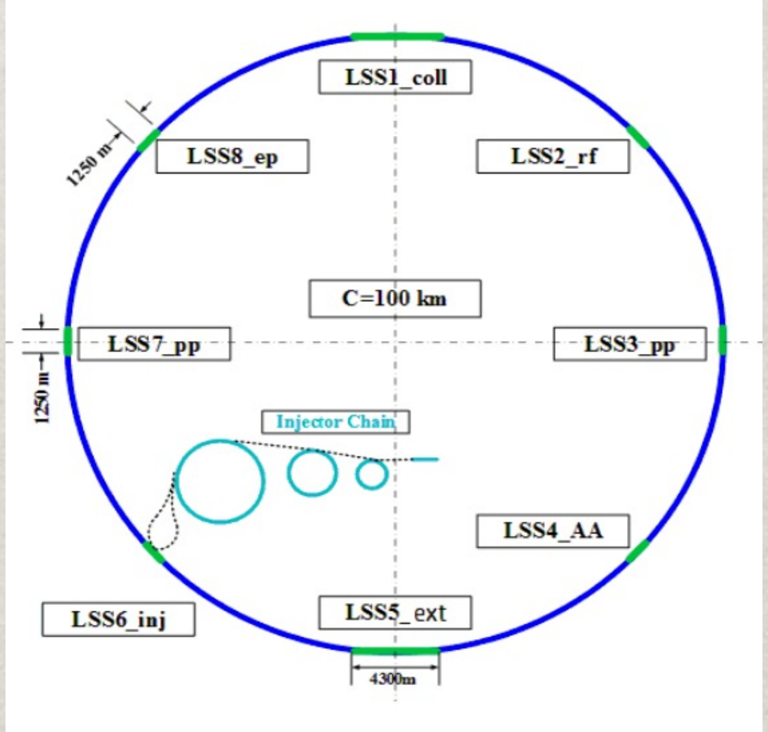
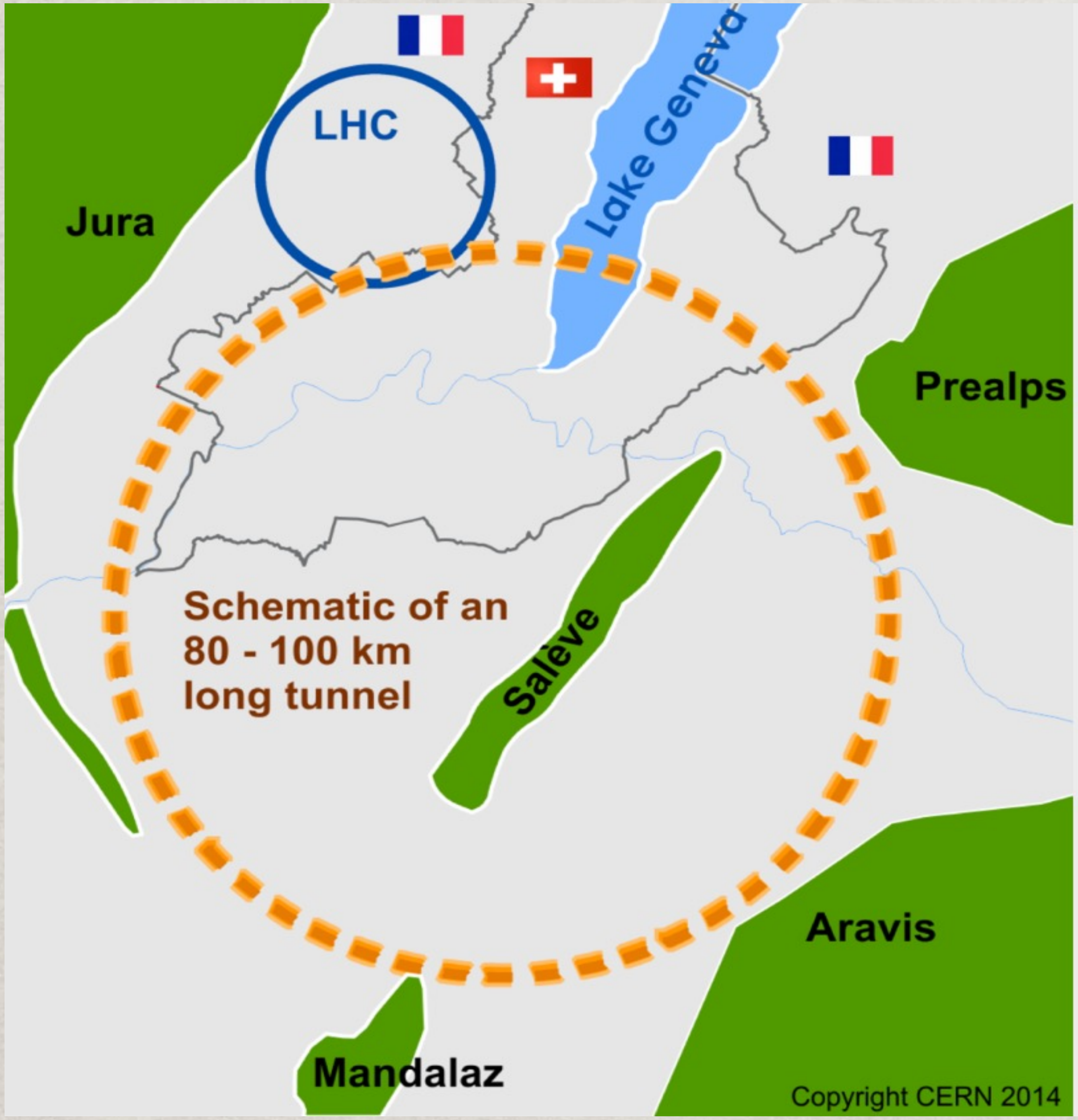


Figure 8.1.1: SPPC accelerator complex

Similar physics goals to FCC-ee, FCC-hh !

https://arxiv.org/abs/1811.10545

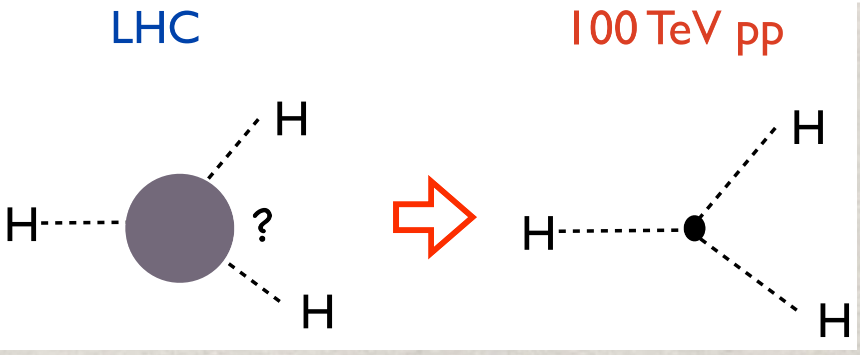
FCC (future circular collider): CERN



FCC-ee
80/100 km
90 - 400 GeV

10^{12} Z; 10^6 Higgs bosons;
10^6 top quark pairs

FCC-hh
80 /100 km, 16/20T
100 TeV



Open new energy frontier!

https://arxiv.org/abs/1607.01831, https://arxiv.org/abs/1606.00947;
Arkani-Hamed, TH, Mangano, LT Wang, Phys. Rept. 1511.06495.

ν-Physics Opportunities

Accelerator ν exp'ts are a flagship program in US & Japan

Short Baseline/Near Detector

SB/ND (100s m)

- SBND
- MicroBooNE
- ICARUS
- DUNE ND
- NOvA ND
- T2K ND280
- JSNS^2

Long Baseline/Far Detector

LB/FD (100s-1000s km)

- DUNE
- NoVA
- Super-K
- Hyper-K

High beam power, large detector mass + highly capable, precision near and far detectors with low E thresholds make BSM physics viable

From the ITF Report Draft: Higgs factories

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	110
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)

FCCee: 2-4 IPs
all LCs: 1 IP

Estimated
Total Project Cost
No escalation
No contingency

NB: HELEN, C^3 m.b. 85% of ILC but in the same range category

luminosity and power consumption
have not been reviewed by ITF

From the ITF Report: HE colliders

luminosity and power consumption

s have not been reviewed by ITF

all LCs: 1 IP

MC-3/14: 2 IPs

FCChh: 2-4 IPs

Estimated

Total Project Cost

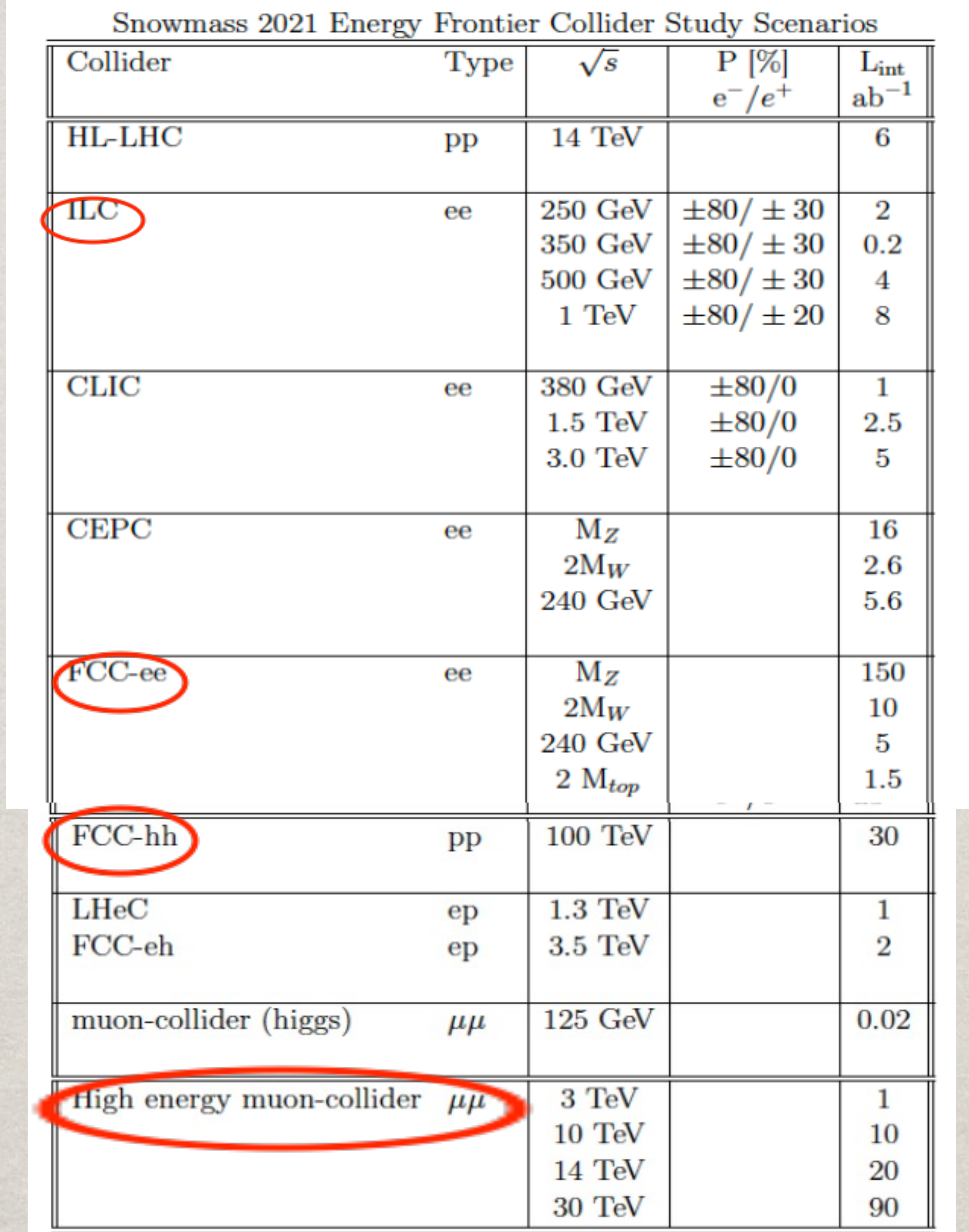
No escalation

No contingency

NB: broad ranges

	CME (TeV)	Lumi per IP	Years, pre-	Years to 1st	Cost Range	Electric Power
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	078	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-FNAL	6-10	20	>10	19-24	12-18	O(300)
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)

FUTURE COLLIDERS UNDER DISCUSSIONS*



Snowmass 2021 Energy Frontier Collider Study Scenarios

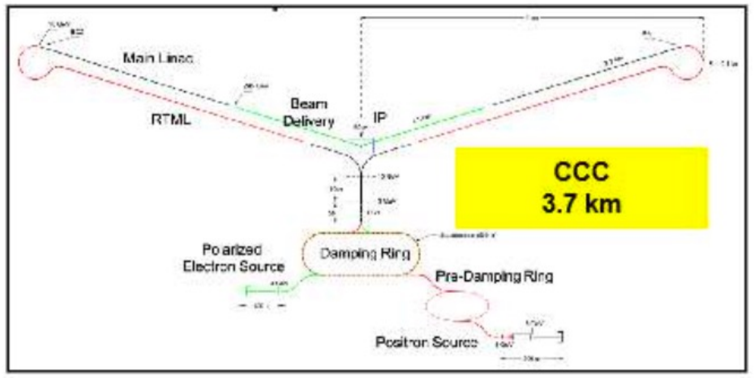
Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
CLIC	ee	380 GeV 1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	ee	M_Z $2M_W$ 240 GeV		16 2.6 5.6
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\,M_{top}$		150 10 5 1.5
FCC-hh	pp	100 TeV		30
LHeC FCC-eh	ep ep	1.3 TeV 3.5 TeV		1 2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV 10 TeV 14 TeV 30 TeV		1 10 20 90

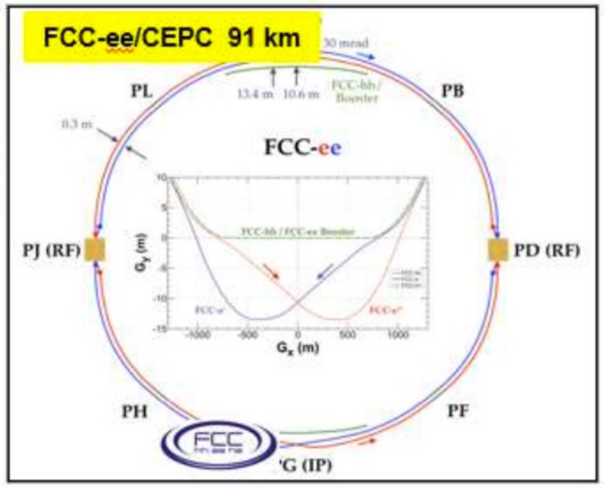
* Snowmass Energy Frontier: https://snowmass21.org

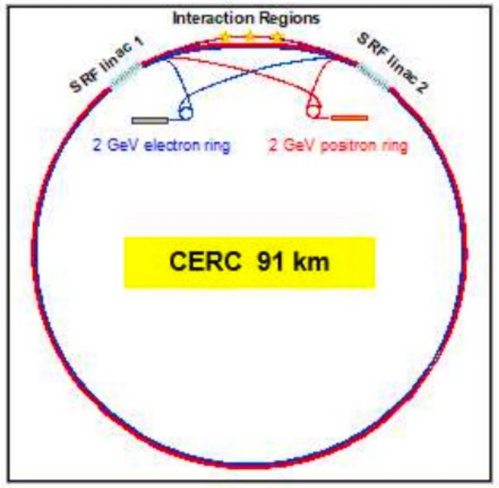
Proposals – Higgs/EW Physics

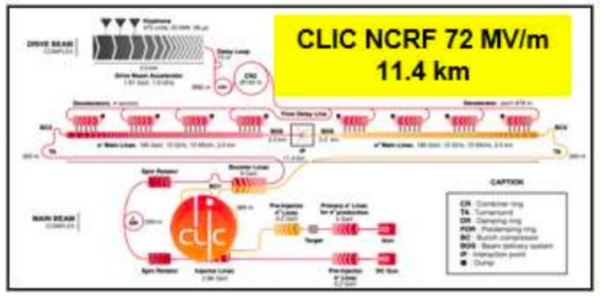
Higgs factory concepts (10)

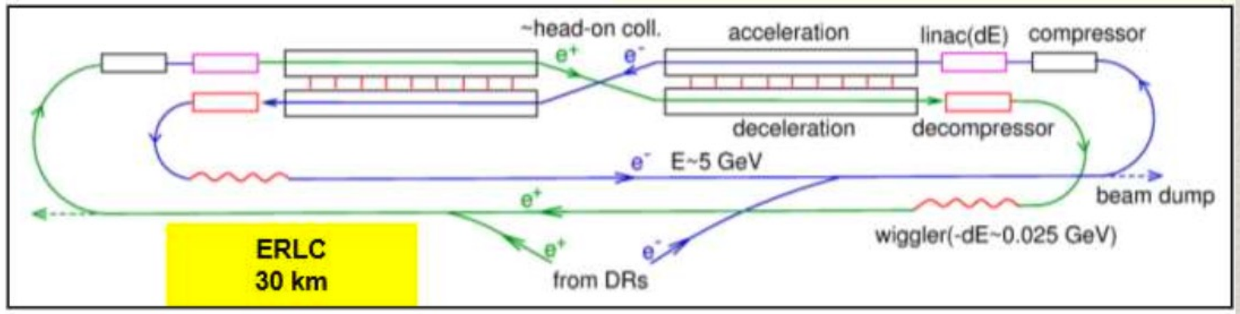
Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ TeV
ReLiC (Recycling Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 1$ TeV
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 0.50$ TeV
XCC (FEL-based $\gamma\gamma$ collider)	ee ($\gamma\gamma$),$\sqrt{s} = 0.125 - 0.14$ TeV
MC (Higgs factory)	μ+μ−, $\sqrt{s} = 0.13$ TeV

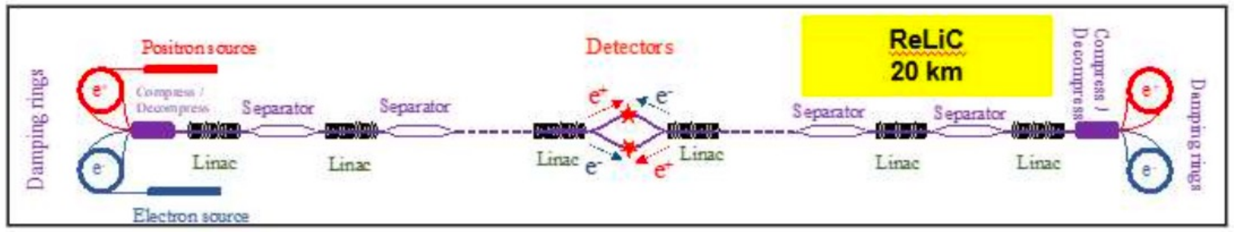








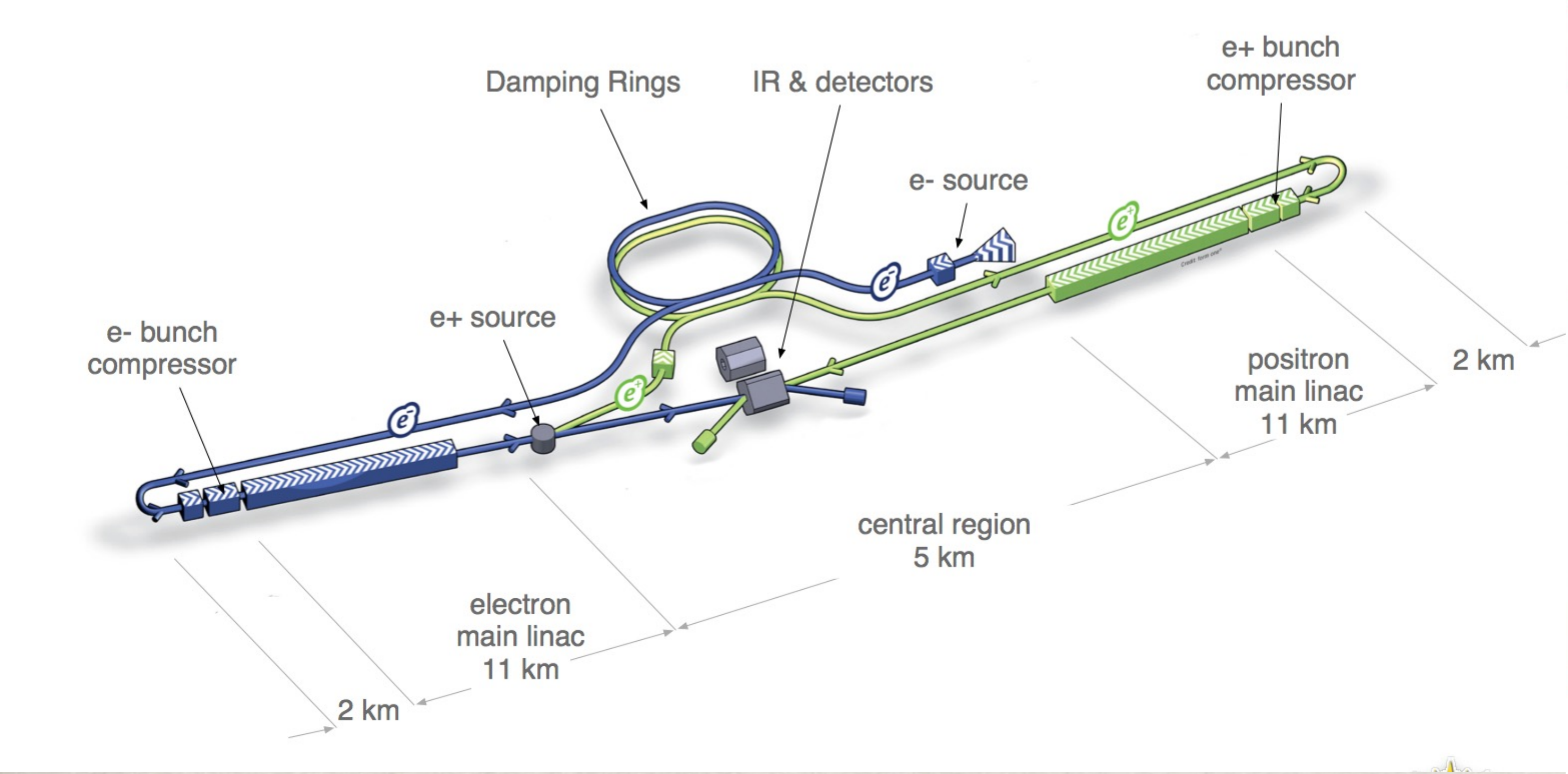


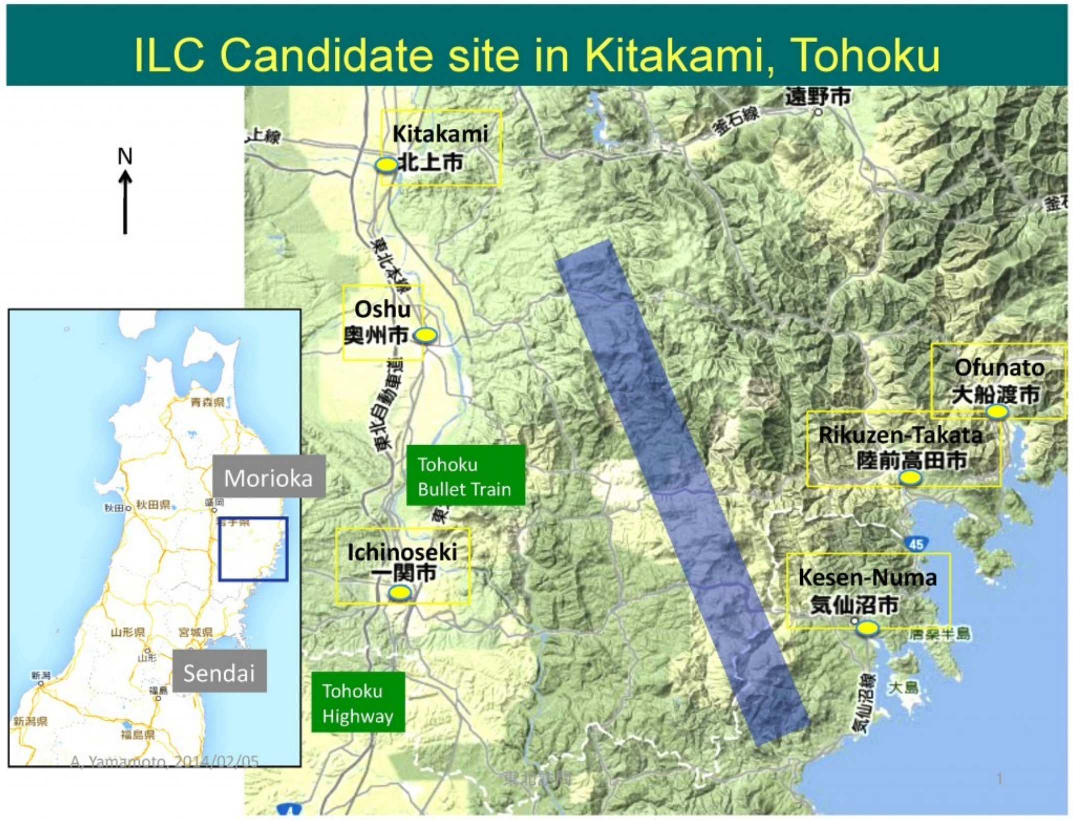


ILC (International Linear Collider) as a Higgs Factory & beyond

Under serious consideration in Japan

https://arxiv.org/abs/1901.09829



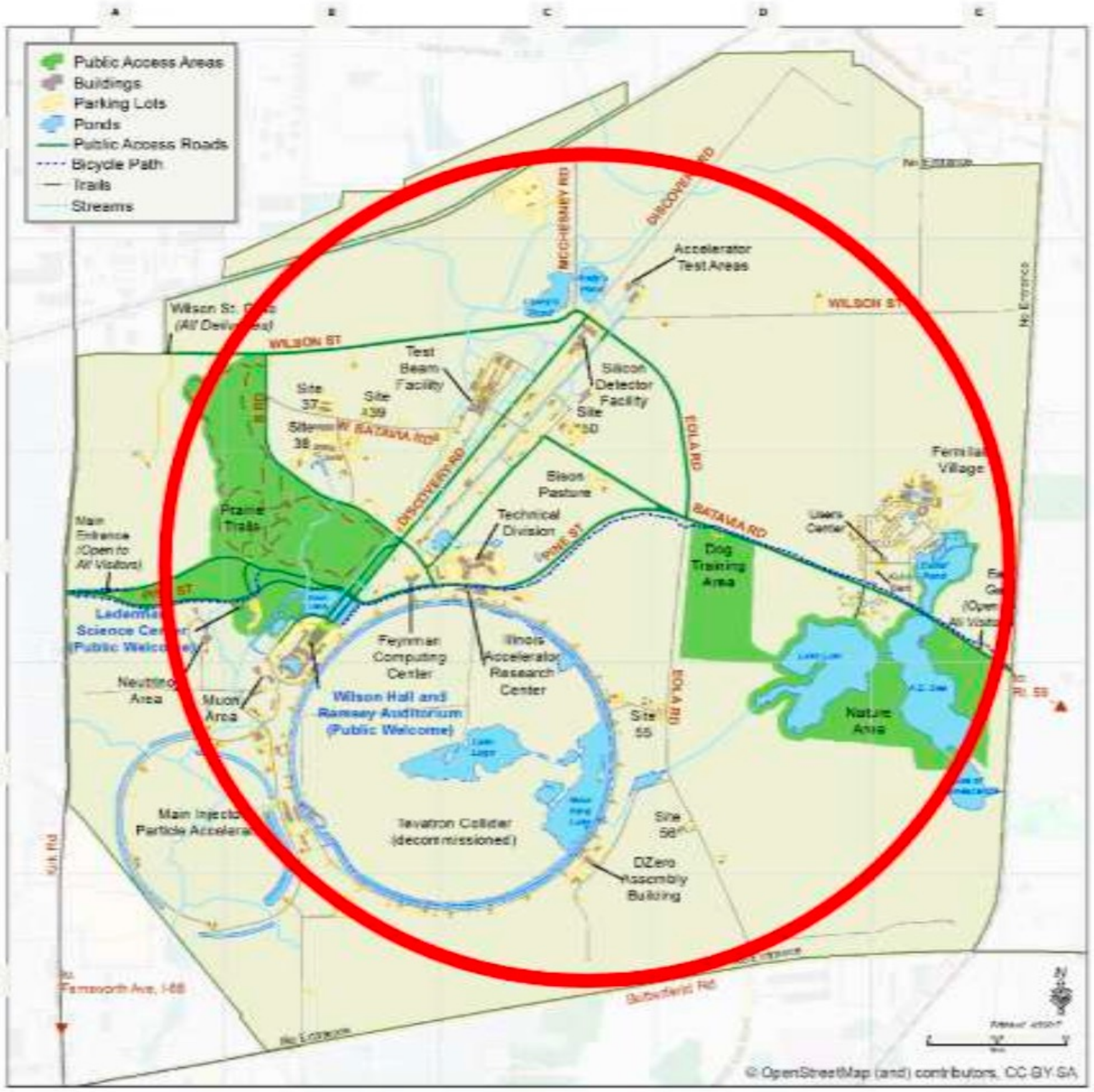


Ecm = 250 GeV / 2 ab^{-1} /yr: a Higgs factory

= 500 GeV / 4 ab^{-1} /yr: a top-quark factory

= 1000 GeV / 8 ab^{-1} /yr: new particle threshold

250 GeV cme Fermilab Site-Fillers

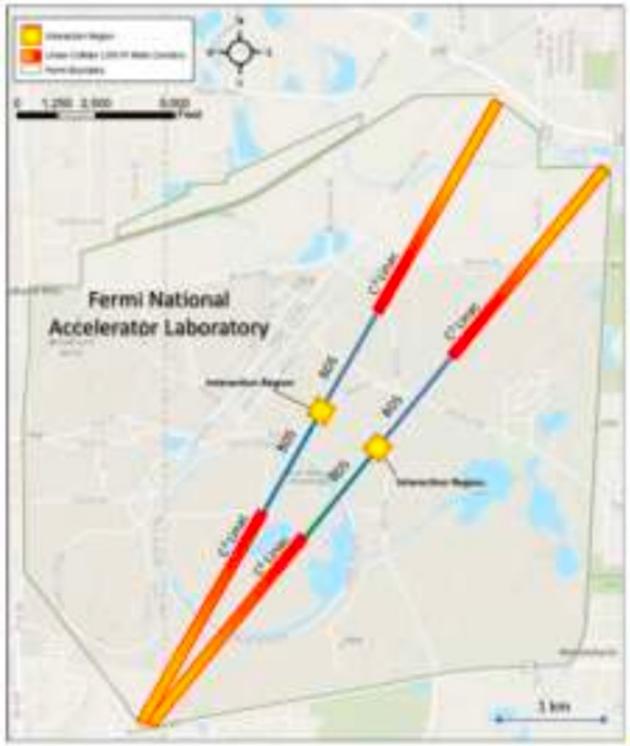


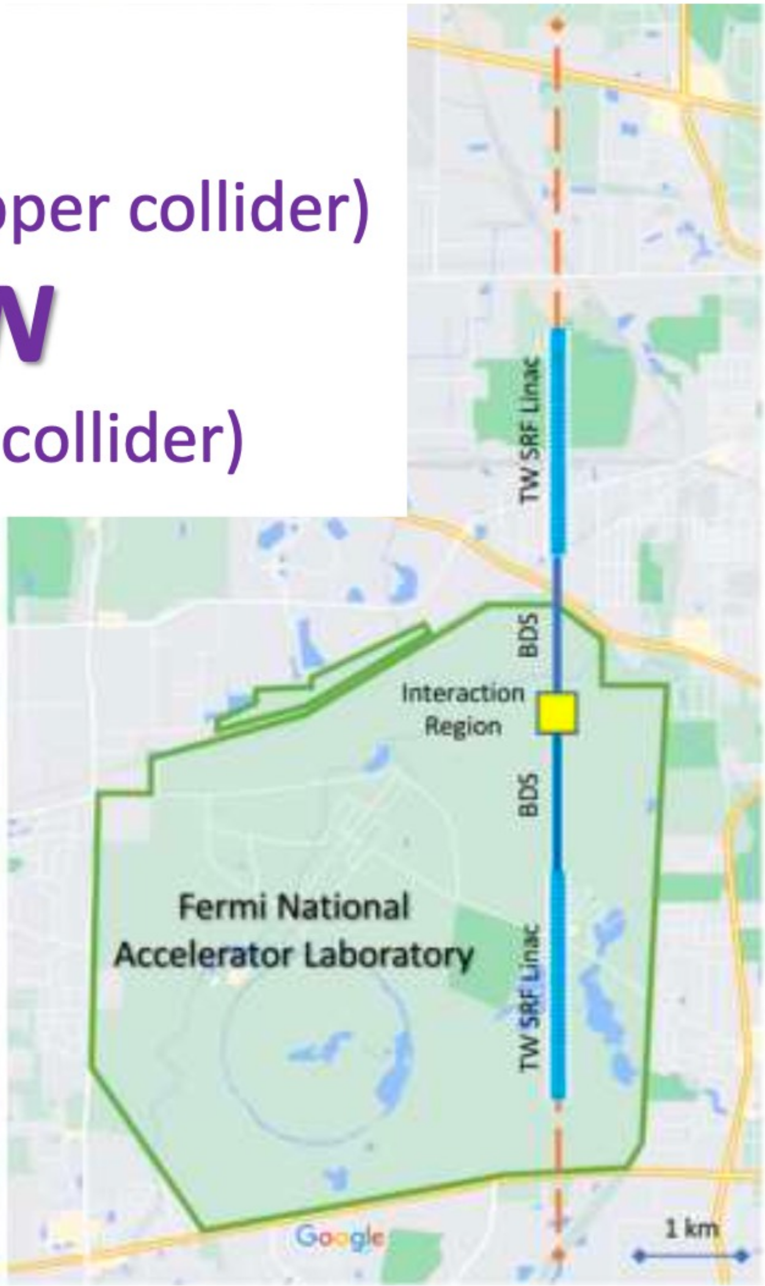
CCC

(cool copper collider)

HELEN

(TW SRF collider)





16-km collider e+e- ring

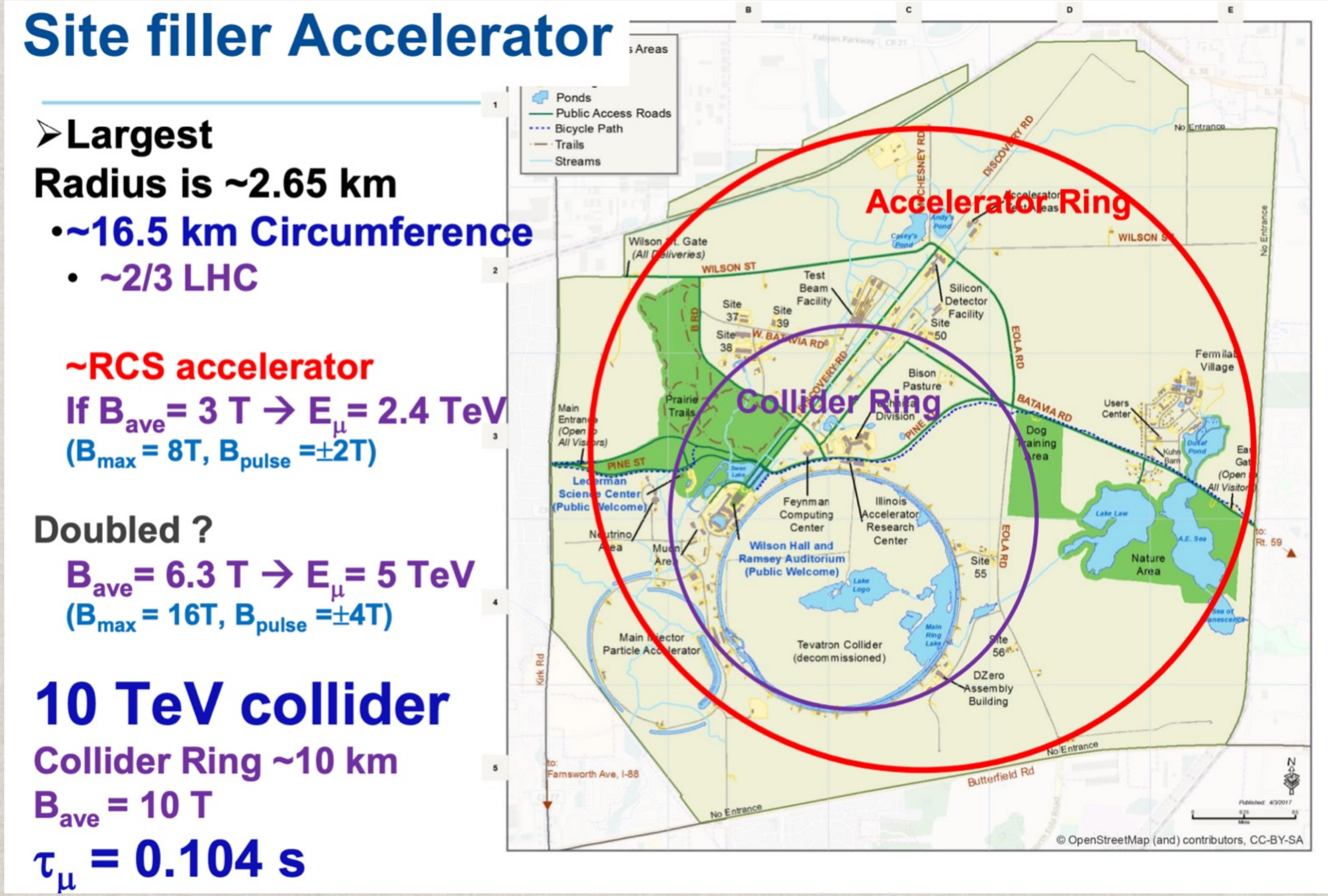
https://arxiv.org/abs/2203.08088

cool- or *SC-RF* e+e- linear colliders
7-km for 250 GeV, 12-km 0.5+ TeV

International Muon Collider Collaboration

https://muoncollider.web.cern.ch

Fermilab on site:



Site filler Accelerator

- **Largest**

Radius is ~2.65 km
- **~16.5 km Circumference**
  - **~2/3 LHC**

~RCS accelerator

If $B_{ave} = 3$ T → $E_\mu = 2.4$ TeV

($B_{max} = 8$T, $B_{pulse} = \pm 2$T)

Doubled ?

$B_{ave} = 6.3$ T → $E_\mu = 5$ TeV

($B_{max} = 16$T, $B_{pulse} = \pm 4$T)

10 TeV collider

Collider Ring ~10 km

$B_{ave} = 10$ T

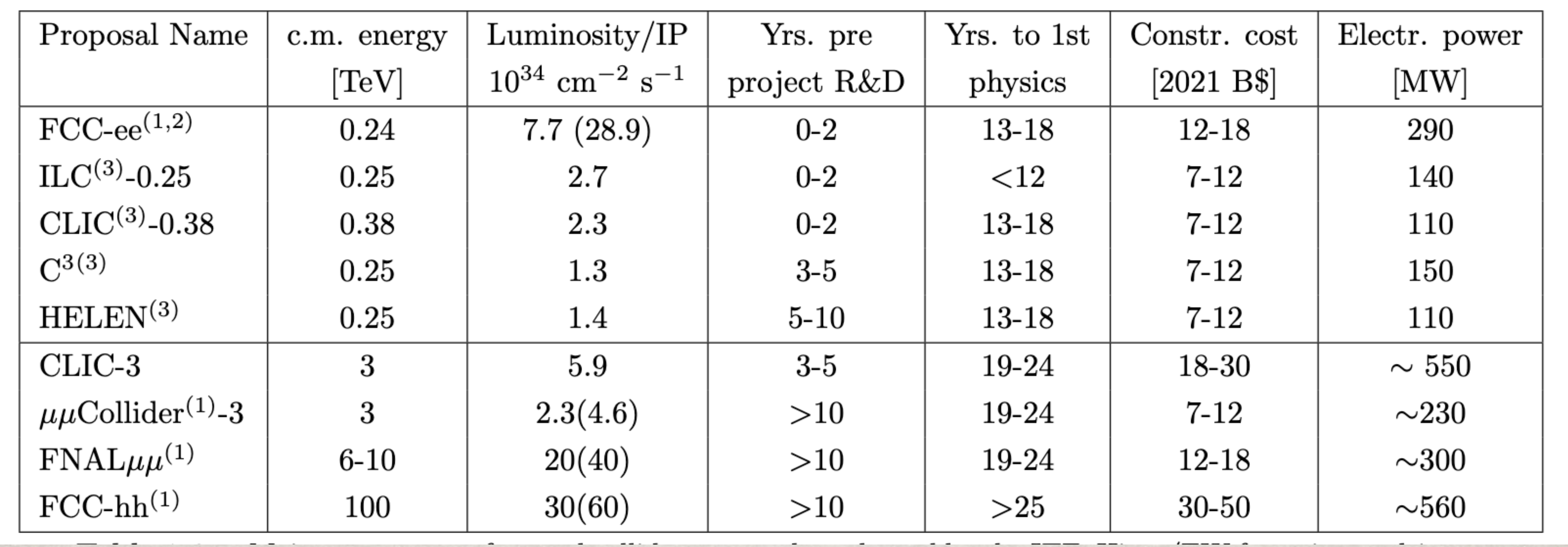
$\tau_\mu = 0.104$ s

Daniel Schulte; Mark Palmer; Katsuya Yonehara talk, March 2022

Accelerator Frontier Recommendation (to P5)

On Colliders: We need an integrated future collider R&D program to engage in the design and to coordinate the development of the next generation collider projects:

- to address in an integrated fashion the technical challenges of promising future collider concepts, that are not covered by the existing *General Accelerator R&D* (GARD) program.
- to enable synergistic U.S. engagement in ongoing global efforts (e.g., FCC, ILC, IMCC)
- to develop collider concepts and proposals for options feasible to be hosted in the U.S. (e.g., CCC, HELEN, Muon Collider, etc)



Proposal Name	c.m. energy [TeV]	Luminosity/IP 10^{34} cm^{-2} s^{-1}	Yrs. pre project R&D	Yrs. to 1st physics	Constr. cost [2021 B$]	Electr. power [MW]
FCC-ee$^{(1,2)}$	0.24	7.7 (28.9)	0-2	13-18	12-18	290
ILC$^{(3)}$-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC$^{(3)}$-0.38	0.38	2.3	0-2	13-18	7-12	110
$C^{3(3)}$	0.25	1.3	3-5	13-18	7-12	150
HELEN$^{(3)}$	0.25	1.4	5-10	13-18	7-12	110
CLIC-3	3	5.9	3-5	19-24	18-30	~ 550
$\mu\mu$Collider$^{(1)}$-3	3	2.3(4.6)	>10	19-24	7-12	~230
FNAL$\mu\mu^{(1)}$	6-10	20(40)	>10	19-24	12-18	~300
FCC-hh$^{(1)}$	100	30(60)	>10	>25	30-50	~560

Several Useful References:

1. Overview of accelerators – V.Shiltsev, Physics Today **73**, 4, 32 (2020).
2. RMP colliders – V.Shiltsev, F.Zimmermann, Rev.Mod.Phys. **93**, 015006 (2021).
3. Ultimate limits of colliders – V.Shiltsev, Proc. IPAC’21, WEPAB017 (2021).
4. Snowmass Accelerator Frontier report – arxiv:2209.14136
5. ITF Report – T.Roser, V.Shiltsev, et al, arXiv:2208.06030
6. *αβγ* cost model – V.Shiltsev, JINST **9** T07002 (2014).
7. Crystal collider – V.Shiltsev, Physics Uspekhi, **55** (10), 1033 (2012).
8. *CPT*-theorem – V.Shiltsev, Mod. Phys. Lett. *A*, **26**, 11, 761 (2011)

Conclusions

- Neutrinos are (arguably) the most elusive particles in the SM, thus hold promise to reveal BSM physics.
- Current and near-future neutrino facilities provide great opportunities for discoveries of BSM physics:

SBNE: MicroBooNE, ICARUS, SBND;
LBNE: JUNO, Hyper-K, DUNE;
CEνNS: COHERENT …

- They are complementary to collider searches.
- Three examples showed for the BSM signals:

- Non-Standard ν-Interactions (SNI)
- Leptonic scalar
- tau appearance at the SBND

Exciting journey ahead!

HEP: A highly dynamic field

Many fundamental questions to address

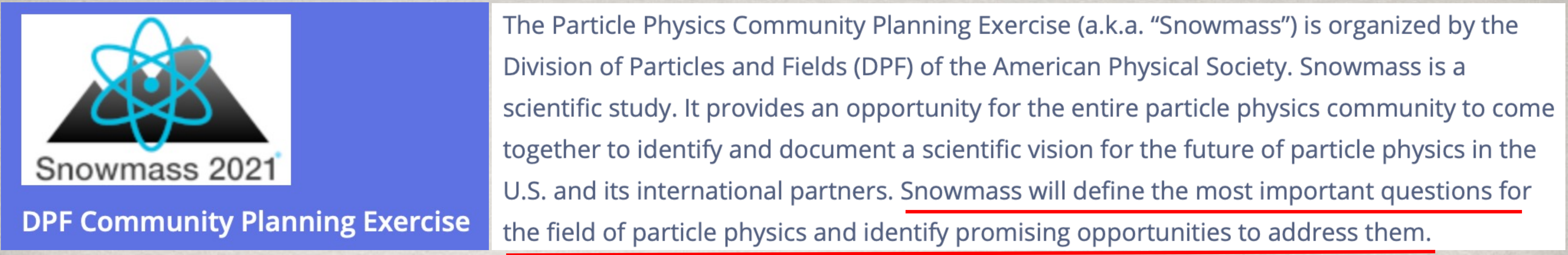
Both in theory & experimental observations:

xperimental,
bservational

Conceptual,
intellectual

- **The underlying theory of Electroweak symmetry breaking**
- **The nature of EW phase transition**
- **Quark & lepton flavor mixing**
- **The nature of neutrino mass**
- **New sources of CP violation**
- **Baryon-antibaryon asymmetry**

The pursuits of the fundamental questions drive the field:
Intellectual culture, technology and society

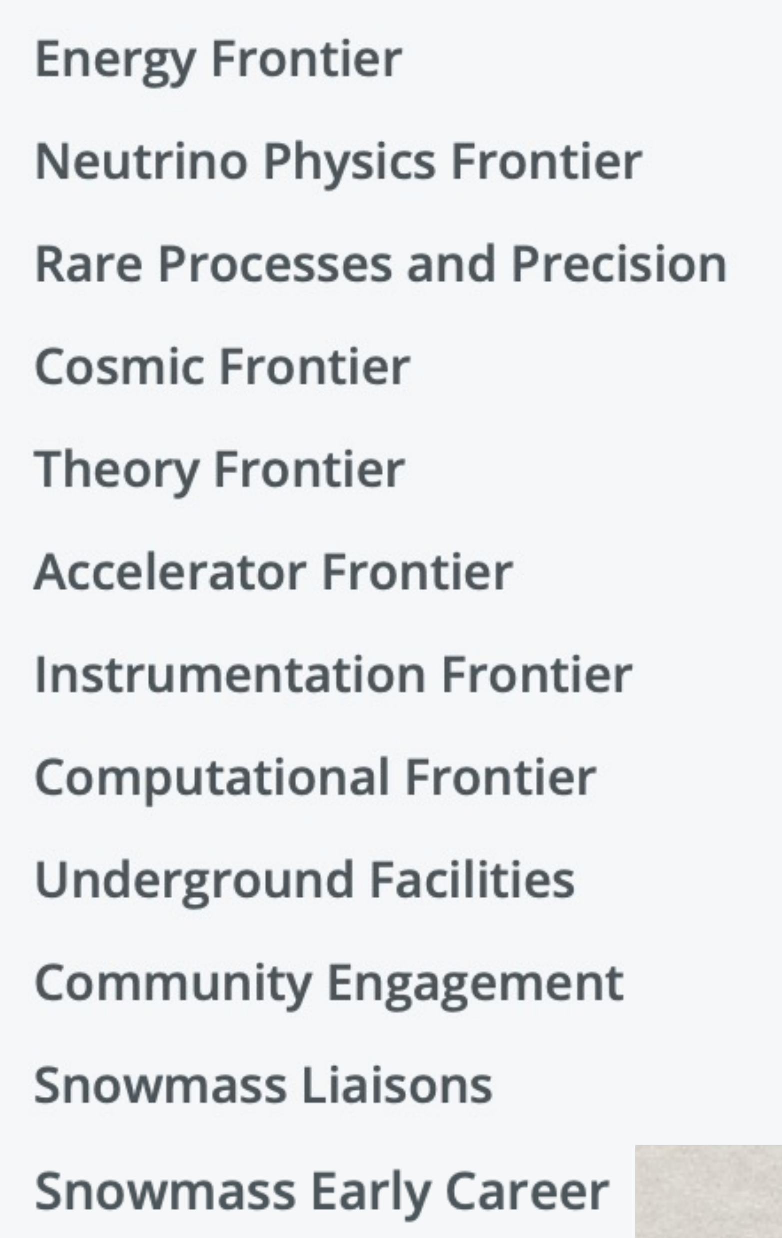


Snowmass 2021

DPF Community Planning Exercise

The Particle Physics Community Planning Exercise (a.k.a. “Snowmass”) is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them.

Snowmass frontiers:



- Energy Frontier
- Neutrino Physics Frontier
- Rare Processes and Precision
- Cosmic Frontier
- Theory Frontier
- Accelerator Frontier
- Instrumentation Frontier
- Computational Frontier
- Underground Facilities
- Community Engagement
- Snowmass Liaisons

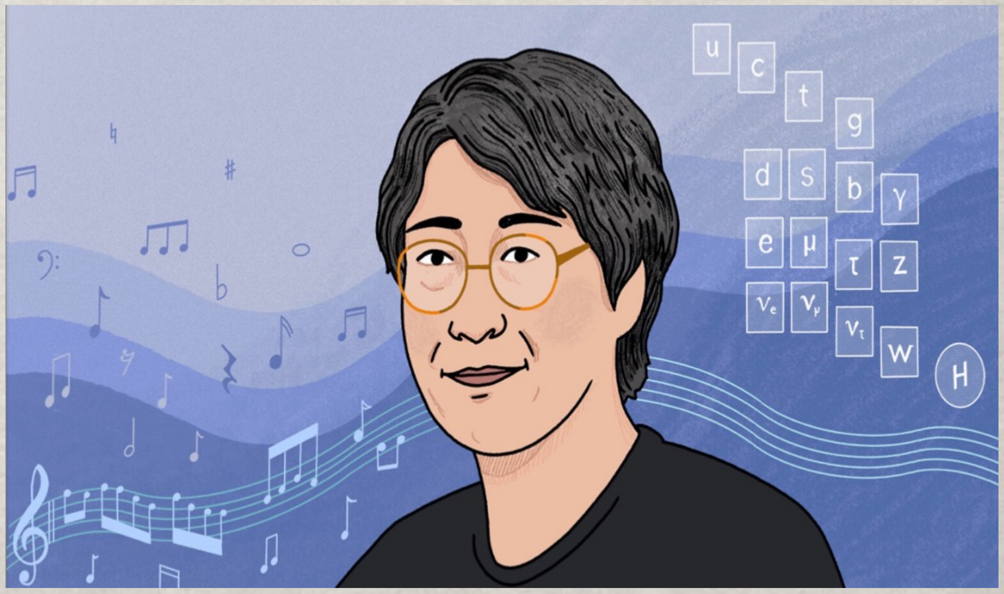
and Snowmass Early Career

https://snowmass21.org

With this year-long study,
the Snowmass output will
provide inputs for the prioritization of
the research directions of the field
in the decade to come: the “P5” process

(Particle Physics Project Prioritization Panel).

The P5 chair:
Prof. Hitoshi
Murayama



Collider benchmark points:

- The Higgs factory:

$E_{cm} = m_H$

$L \sim 1\ \mathrm{fb}^{-1}/\mathrm{yr}$

$\Delta E_{cm} \sim 5\ \mathrm{MeV}$

Parameter	**Units**	**Higgs**
CoM Energy	TeV	0.126
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.008
Beam Energy Spread	%	0.004
Higgs Production/10^7 sec		13’500
Circumference	km	0.3

Current Snowmass 2021 point: 4 fb^{-1}/ yr

- Multi-TeV colliders:

Lumi-scaling scheme: $\sigma\, L \sim$ const.

$$L \gtrsim \frac{5\text{ years}}{\text{time}} \left(\frac{\sqrt{s}_\mu}{10\text{ TeV}} \right)^2 2 \cdot 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

1 ab^{-1} /yr

The aggressive choices:

$$\sqrt{s} = 3,\ 6,\ 10,\ 14,\ 30 \text{ and } 100 \text{ TeV}, \quad \mathcal{L} = 1,\ 4,\ 10,\ 20,\ 90, \text{ and } 1000 \text{ ab}^{-1}$$

European Strategy, arXiv:1910.11775; arXiv:1901.06150; arXiv:2007.15684.