Opportunities in Particle Physics

Tao Han
University of Pittsburgh

IAS, HKUST
February 16, 2023

A highly successful workshop & conference!

	Sunday		Monday	
	12-Feb		13-Feb	
	Experiment/Detector (1/F)	Theory (2/F)	Session M-ED1/ M-TH1 Venue: IAS LT [Chair: Jia LIU (Peking U)]	
08:30-08:50	Registration	Registration		
08:55-09:00	Welcome Remarks	Welcome Remarks		
	Session S-ED1 Venue: IAS1038 [Chair: Zhijun LIANG (IHEP)]	Session S-TH1 Venue: IAS2042 [Chair: Liming ZHANG (Tsinghua U)]		
9:00	Tianya WU (IHEP)	Jure ZUPAN [Zoom] (U of Cincinnati)	John ELLIS [Zoom] (CERN and King's College)	
9:20	Yiming LI (IHEP)		Shin-Chieh HSU (U of Washington)	
9:25		Lorenzo CALIBBI (Nankai U)	Ke LI (U of Washington)	
9:40	Sheng DONG (IHEP)		Keping XIE [Zoom] (U of Pittsburgh)	
9:50		Qin QIN (Huazhong U of Science and Technology)		
10:00	Yunyun FAN (IHEP)		Qiang LI (Peking U)	
10:15		Anson KWOK (HKUST)		
10:20	Chengxin ZHAO [Zoom] (Institute of Modern Physics)		Zhen LIU (U of Minnesota)	
	Coffee Break		Coffee Break	
	Session S-ED2 Venue: IAS1038 [Chair: Lorenzo CALIBBI (Nankai U)]	Session S-TH2 Venue: IAS2042 [Chair: Yu GAO (IHEP)]	Session M-ED2 Venue: IAS1038 [Chair: Gang LI (IHEP)]	Session M Venue: IAS [Chair: Xiaopi (Beihang
11:00	Shanzhen CHEN [Zoom] (IHEP)	Mengchao ZHANG (Jinan U)	Xingtao HUANG (Shandong U)	Ariel RC (HKUS
11:25	Zhen HU (Tsinghua U)	Yuichiro NAKAI (Shanghai Jiaotong U)	Weidong LI (IHEP)	Kento A (U of Tok
11:50	Kai YI (Nanjing Normal U)	Xiao-ping WANG (Beihang U)	Shengsen SUN (IHEP)	Shigeki MATSUM (U of Tok
12:15	Liming ZHANG (Tsinghua U)	Yong Chao ZHANG (Southeast U)	Xiaomei ZHANG (IHEP)	Suchita KULKAN (U of Gr
12:40	Lunch Break (Self-arranged)		Lunch Break (Self-arranged)	
	Session S-ED3 Venue: IAS1038 [Chair: Huaqiao ZHANG (IHEP)]	Session S-TH3 Venue: IAS2042 [Chair: Hao ZHANG (IHEP)]	Session M-ED3 Venue: IAS1038 [Chair: Mingyi DONG (IHEP)]	Session M Venue: IAS [Chair: Qin QIN (of Science and Technology)]
14:00	Yong LIU (IHEP)	Alessandro VICINI [Zoom] (U of Milan)	Huirong QI (IHEP)	Feng-Kun GUO (Institute of Theoretical Physics)[Zoom]
14:25	Sen QIAN (IHEP)	Bin YAN [Zoom] (IHEP)	Mingyi DONG (IHEP)	Alberto LUSIANI (Scuola Normale Superiore) [Zoom]
14:50	Roberto FERRARI (INFN Pavia)	Jiayin GU (Fudan U)	Peter KLUIT (NIKFHH) [Zoom]	Wei SU (Sun Yat Sen U)
15:15	Huilin QU (CERN)	Jean-Claude BRIENT [Zoom] (Ecole Polytechnique)	Brunella D'ANZI [Zoom] (INFN and U of Bari)	Luiz Vale SILVA [Zoom] (Universitat de Valencia)
15:40	Coffee Break		Coffee Break	
	Session S-ED4/ S-TH4 Venue: IAS LT [Chair: Jiayin GU (IHEP)]		Session M-ED4 Venue: IAS1038 [Chair: Mingshui CHEN (IHEP)]	Session M-TH4 Venue: IAS2042 [Chair: Zhen LIU (U of Minnesota)]
16:00	Manqi RUAN (IHEP)		Roberto FERRARI (INFN Pavia)	Rick S. GUPTA (Tata Institute of Fundamental Research)
16:25	Roman POESCHL [Zoom] (IJClab)		Huaxing ZHU (Zhejiang U)	Juraj KLARIC (Catholic University of Louvain) [Zoom]
16:50	Zhijun LIANG (IHEP)		Zhao LI (IHEP) [Zoom]	Shengdu CHAI (Fudan U)
17:15	Paul COLAS [Zoom] (CEA)		Siqi YANG (U of Science and Technology of China) [Zoom]	Zeren Simon WANG [Zoom] (National Tsinghua U)

	Tuesday			Wednesday			Thursday
HK Time	14-Feb			15-Feb			16-Feb
08:30-08:50	Conference Registration						
08:55-09:00	Welcome Remarks by Andrew COHEN (HKUST)						
	Session Tu 1 Venue: IAS Lecture Theater (LT) [Chair: Tao LIU (HKUST)]			Session W1 Venue: IAS Lecture Theater (LT) [Chair: Jie GAO (IHEP)]			Session Th 1 Venue: IAS Lecture Theater (LT) [Chair: Tao LIU (HKUST)]
9:00	Plenary #01 Perspective Talk [Zoom] ARKANI-HAMED Nima (Princeton U)			Plenary #05, ILC Progress [Zoom] (Akira YAMAMOTO/ KEK)			Plenary #10, New Approaches on DM Detection Tien-Tien YU (U of Oregon)
9:45	Plenary #02 New Physics Opportunities at ee Colliders Liantao WANG (U of Chicago)			Plenary #06 CLIC Progress (Andrea LATINA/ CERN)			Close Talk Tao HAN (U of Pittsburgh)
10:30	Coffee Break			Coffee Break			Coffee Break
	Session Tu2 Venue: IAS Lecture Theater (LT) [Chair: Joao GUIMARAES DA COSTA (IHEP)]			Session W2 Venue: IAS Lecture Theater (LT) [Chair: Manqi RUAN (IHEP)]			Session Th 2 Venue: IAS Lecture Theater (LT) [Chair: Tao LIU (HKUST)]
11:00	Plenary #03 CEPC Progress Haijun YANG (Shanghai Jiaotong U)			Plenary #7 Quantum Simulation for High Energy Physics Ying-Ying LI (U of Science and Technology of China)			Forum Discussion Leader: Tao LIU (HKUST) Panel members: (1) Tao HAN (U of Pittsburgh), (2) Michael HOFER (CERN), (3) Andrea LATINA (CERN), (4) Yifang WANG (IHEP), (5) Akira YAMAMOTO (KEK) (Zoom) (11:00 - 12:30)
11:30				Plenary #8 New Dark SHINE Exp Kun LIU (Shanghai Jiaotong U)			
11:45	Plenary #04 FCC Progress Michael HOFER (CERN)						
12:00				Plenary #9 Excesses at the LHC and Potential Implications for the HL-LHC and e+e- Colliders Bruce MELLADO (U of the Witwatersrand and iThemba LABS)			
12:30	Program Lunch for Registered Participants only			Self-arranged Lunch			Self-arranged Lunch
	Session Tu3-AP01 (Accelerator) Venue: IAS LT [Chair: Jie GAO (IHEP)]	Session Tu3-ED01 (Experiment/Detector) Venue: IAS 1038 [Chair: Hongbo ZHU (Zhejiang U)]	Session Tu3-TH01 (Theory) Venue: IAS 2042 [Chair: Yuichiro NAKAI (Shanghai Jiaotong U)]	Session W3-AP01 (Accelerator) Venue: IAS LT [Chair: Yuhui LI/ IHEP]	Session W3-ED01 (Experiment) Venue: IAS 1038 [Chair: Yaquan FANG]	Session W3-TH01 (Theory) Venue: IAS 2042 [Chair: Yongchao ZHANG (Southeast U)]	
14:00	Makato TOBIYAMA [Zoom] (KEK)	Michael K. SULLIVAN [Zoom] (SLAC)	Serguey PETCOV [Zoom] (SISSA)	Akira YAMAMOTO [Zoom] (KEK)	Xuai ZHUANG (IHEP)	Kingman CHEUNG [Zoom] (National Tsinghua U)	
14:20	Yiwei WANG (IHEP)			Jiyuan ZHAI (IHEP)	Jinfei WU (IHEP)		
14:25		Suen HOU (Institute of Physics)	Shun ZHOU (IHEP)			Haipeng AN (Tsinghua U)	
14:40	Dou WANG (IHEP)			Zusheng ZHOU (IHEP)	Junle PEI (IHEP)		
14:50		Haoyu SHI (IHEP)	Xuxiang LI (Peking U)			Bin GONG (IHEP)	
15:00	Cai MENG [Zoom] (IHEP)			Yingshun ZHU (IHEP)	Nilanjana KUMAR [Zoom] (SGT U)		
15:15		Guangyi TANG (IHEP)	Sungwoo HONG [Zoom] (KAIST)			Yusheng WU (U of Science and Technology of China)	
15:20	Sha BAI (IHEP)			Qingjin XU (IHEP)	Abdualazem Fadol Mohammed Ebrahim (IHEP)		
15:40	Coffee Break (15:40 - 16:00)			Coffee Break (15:40 - 16:00)			
	Session Tu3-AP02 (Accelerator) Venue: IAS LT [Chair: Marica BIAGINI (INFN) (Zoom)]	Session Tu3-ED02 (Experiment) Venue: IAS 1038 [Chair: Xuai ZHUANG (IHEP)]	Session Session Tu3-TH02 (Theory) Venue: IAS 2042 [Chair: Haipeng AN (Tsinghua U)]	Session W3-AP02 (Accelerator) Venue: IAS LT [Chair: Angeles FAUS-GOLFE/ IJClab (Zoom)]	Session W3-ED02 (Experiment) Venue: IAS 1038 [Chair: Hao ZHANG (IHEP)]	Session W3-TH02 (Theory) Venue: IAS 2042 [Chair: Qiang LI (Peking U)]	
16:00	Angeles FAUS-GOLFE [Zoom] (IJClab)	Yaquan FANG (IHEP)	Yu GAO (IHEP)	Frank ZIMMERMANN [Zoom] (CERN)	Junsong ZHANG (IHEP)	Desheng LI (Hunan Institute of Engineering)	
16:20	Yongsheng MA (IHEP)			Yuan ZHANG (IHEP)			
16:25		Mingshui CHEN (IHEP)	Wen YIN [Zoom] (Tohoku U)		Yongsheng HUANG (Zhongshan U)	Ning CHEN [Zoom] (Nankai U)	
16:40	Wen KANG (IHEP)			Na WANG (IHEP)			
16:50		Huaqiao ZHANG (IHEP)	Bo LIU (IHEP)		Serguei GANJOUR [Zoom] (CEA)	Yu ZHANG (Hefei U of Technology) [Zoom]	
17:00	Bin CHEN (IHEP)			Zhe DUAN [Zoom] (IHEP)			
17:15		Hao ZHANG (IHEP)	Sida LU (HKUST)		Huirong QI (IHEP)		
17:20	Jinhui CHEN (IHEP)			Dazhang LI (IHEP)			
17:40	Jingru ZHANG (IHEP)	Gang LI (IHEP)					

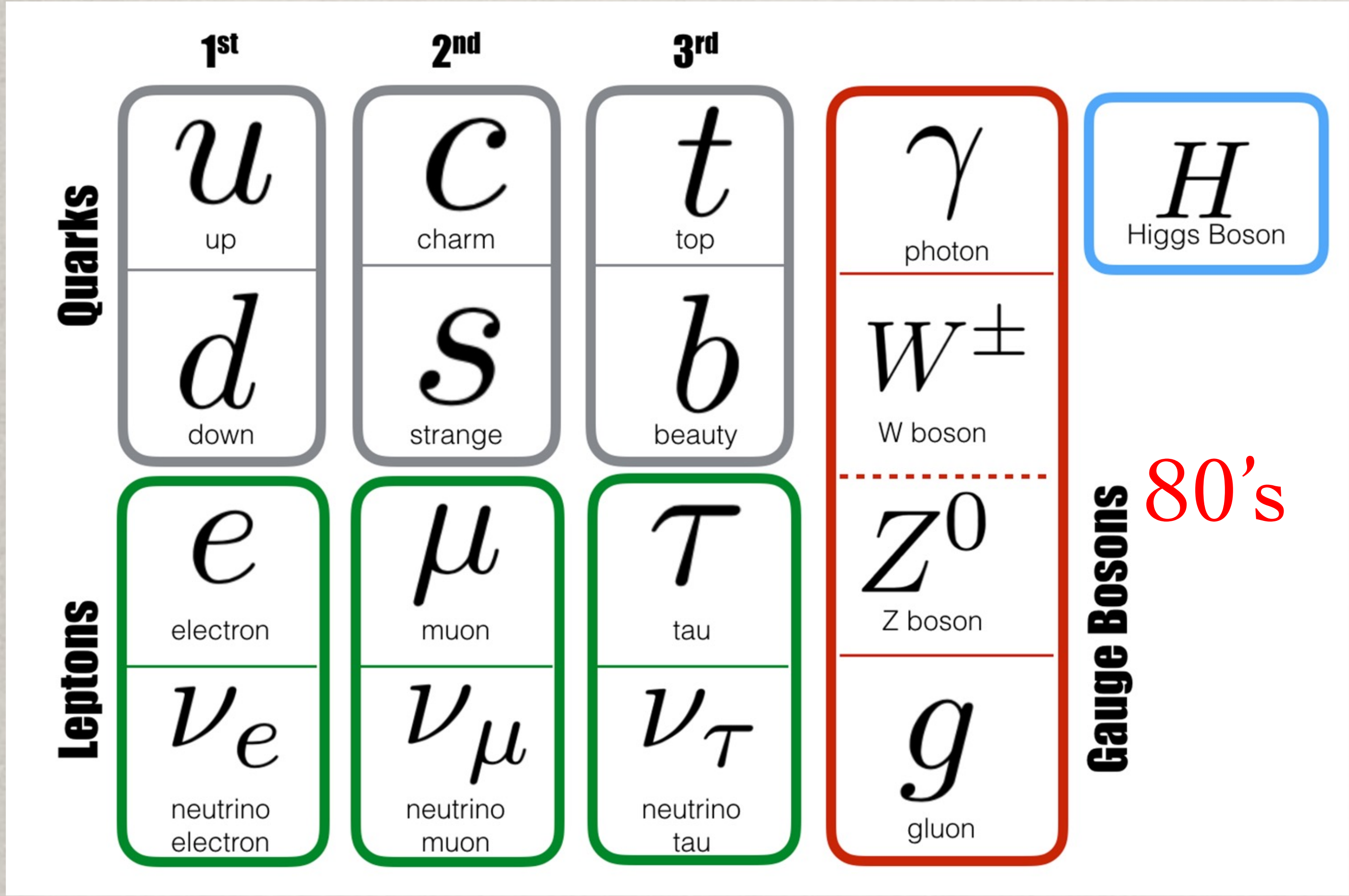
Congratulations to the organizers & all participants!

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:

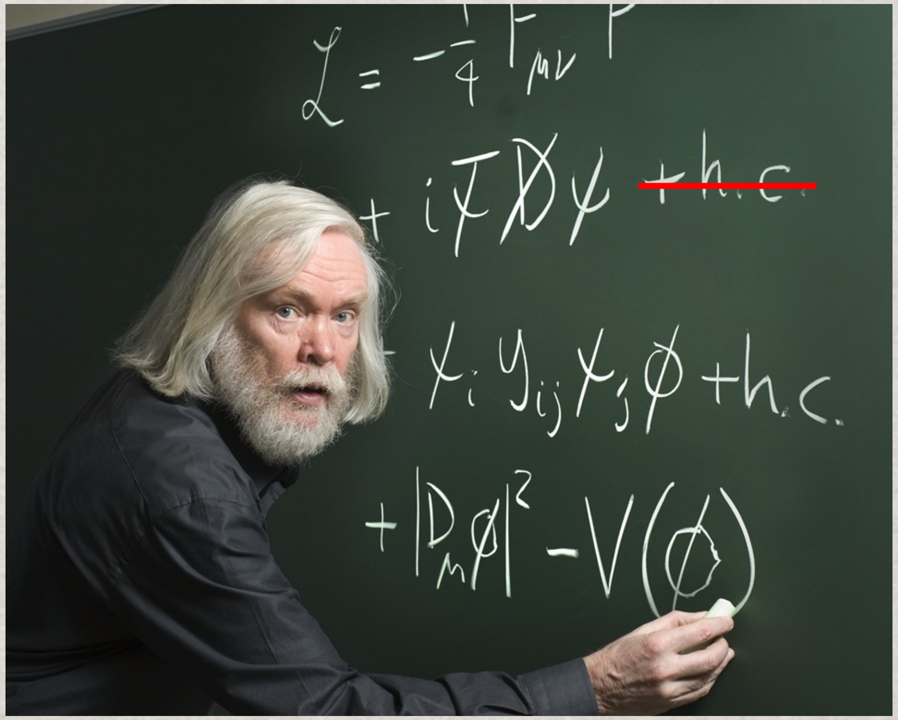
60's 70's 90's 2012



80's

1930/1956 1962 2000

A highly successful theory



Completion of the SM:

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

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

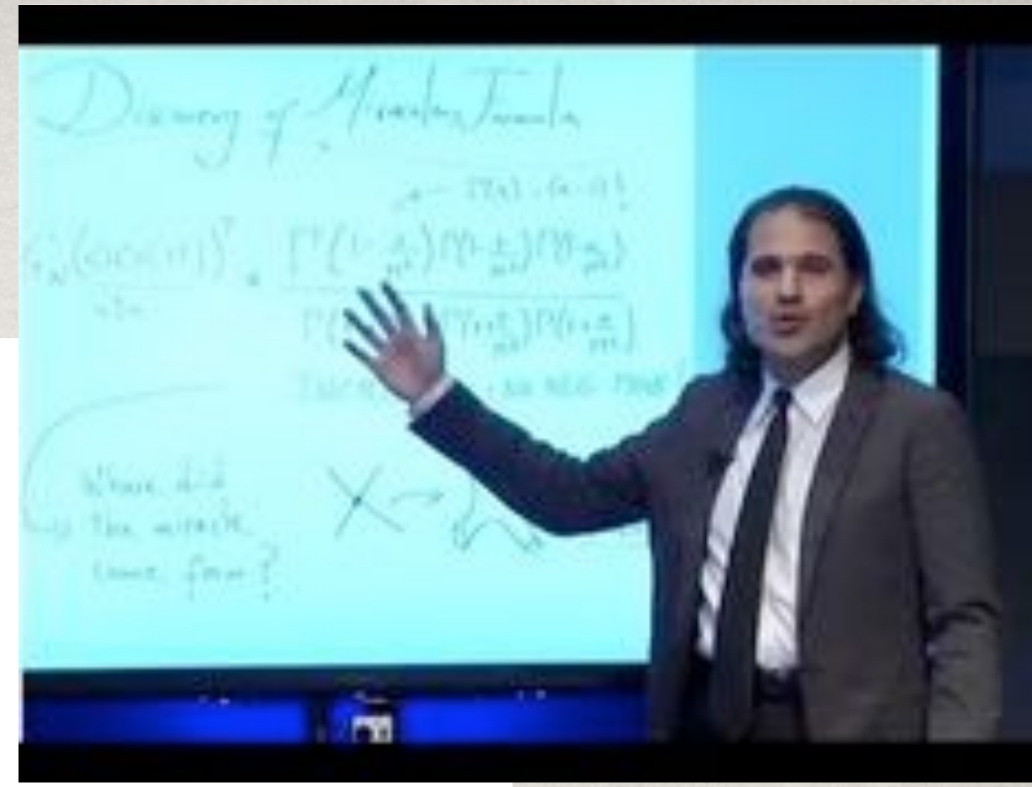
B-asymmetry?
CP violation?
Λ? Dark Matter?
Cosmic inflation?
M_ν? Scale hierarchy …

All known physics

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

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

Nima Arkani-Hamed



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

HEP at a Cross-Road

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

"When you come to a fork in the road, take it!"
– Yogi Berra

We must explore all directions!

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

Building for Discovery

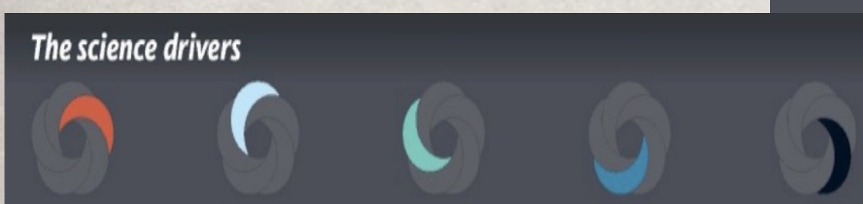
Strategic Plan for U.S. Particle Physics in the Global Context

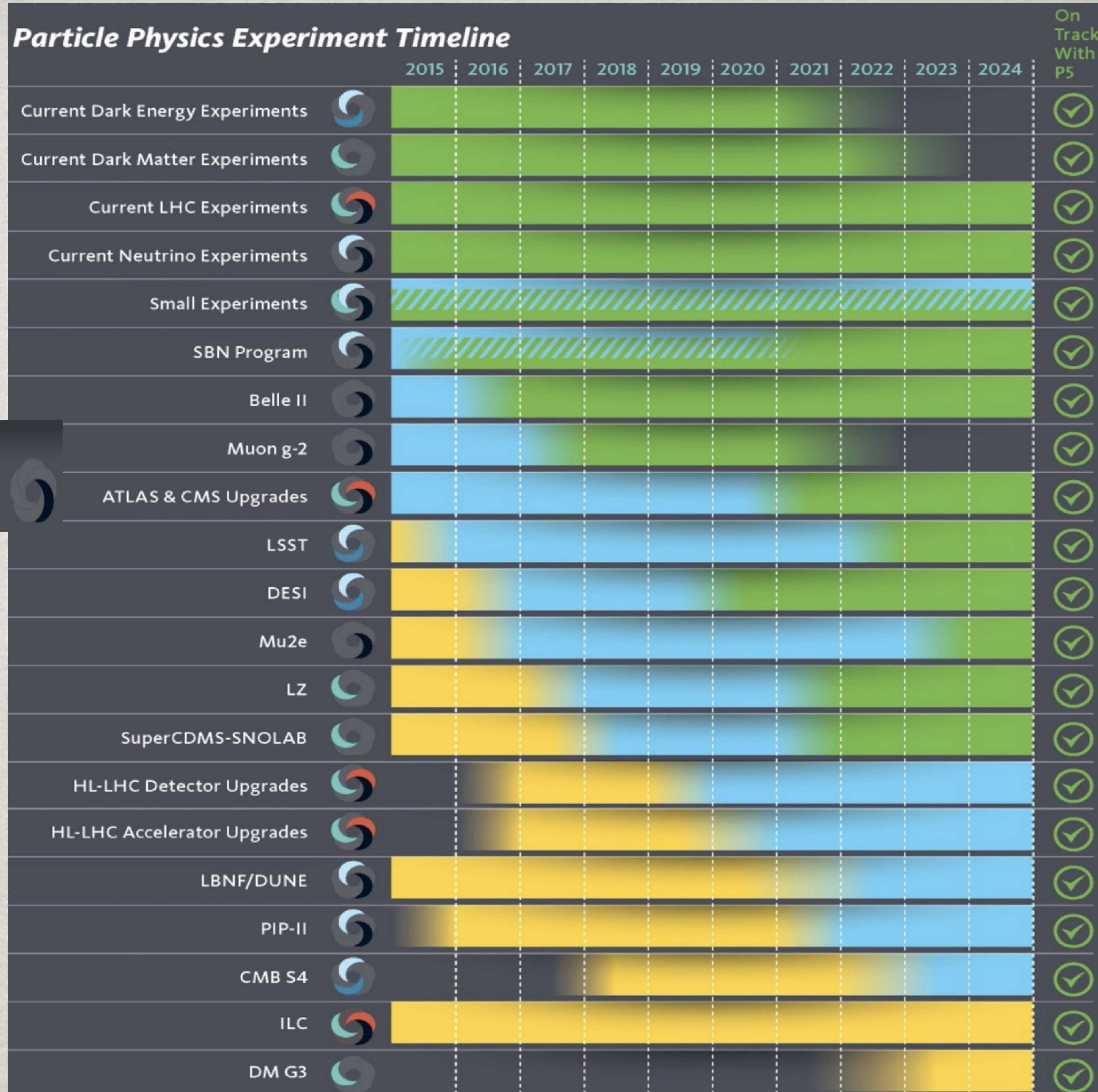
Report of the Particle Physics Project Prioritization Panel (P5) May 2014

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:





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, … 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… Physics, 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 S… …oscopy
Cosmic Frontier	Dark Matter: Particle-like, Dark Matter: Wave-like, D… …rgy & Cosmic Acceleration: The Modern Universe, Dark Energ… …awn & Before, Dark Energy & Cosmic Acceleration: Complementarity of P…
Theory Frontier	String theory, quantum gravity … …niques, CFT and formal QFT, Scattering amplitudes, Lattice gaug… …on physics, Collider phenomenology, BSM model building, Astro-pa… …n information science, Theory of Neutrino Physics
Accelerator Frontier	Beam P… …ccelerators for Neutrinos, Accelerators for Electroweak and Higgs P… …ators for Physics Beyond Colliders & Rare Processes, Advanced Accelerator … …ogy R&D: RF, Magnets, Targets/Sources
Instrumentation F…	…hoton Detectors, Solid State Detectors & Tracking, Trigger and DAQ, Micro Pattern Gas …lorimetry, Electronics/ASICS, Noble Elements, Cross Cutting and System Integration, Radio …ion
Computational Fron…	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.

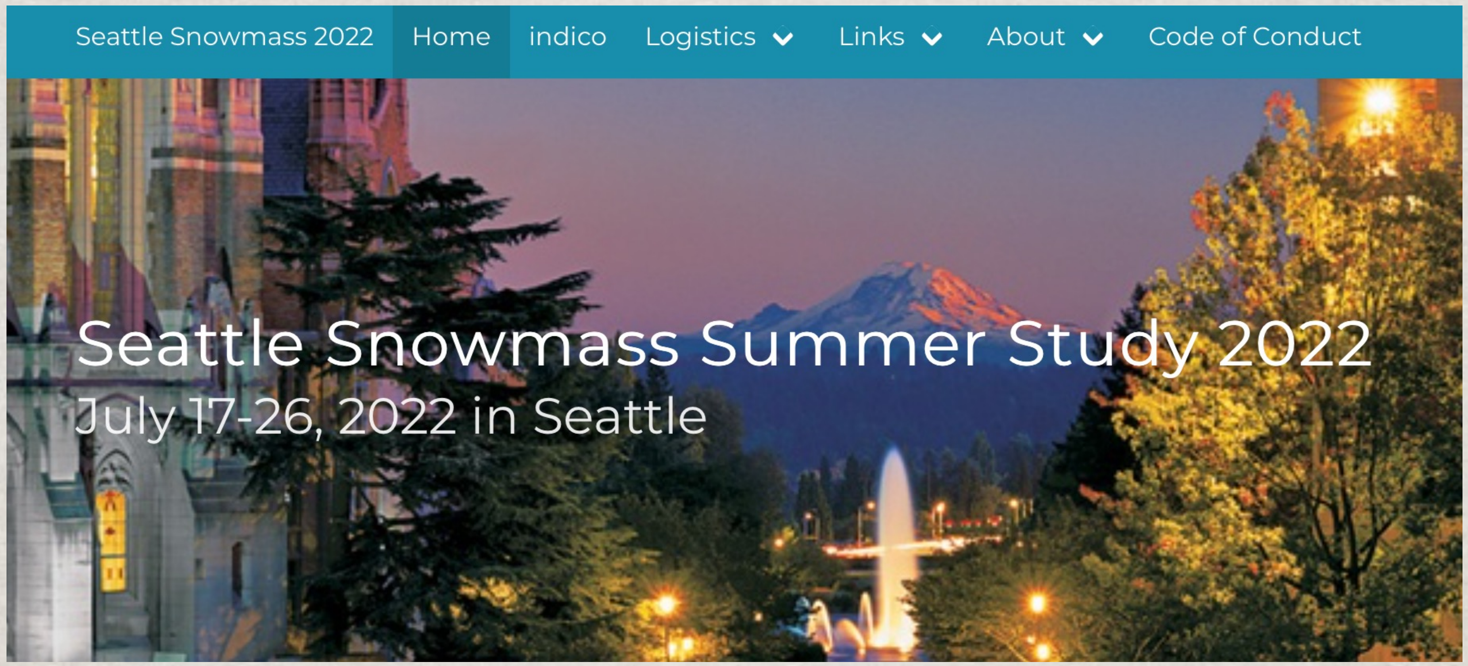
Snowmass Early Career to represent early career members and promote their engagement in the Snowmass 2021 process; to build a long-term HEP early career community

Broad coverage/connection in science and global community!

Community Summer Study: Snowmass 2021

July 17 – 26, 2022 @ UW – Seattle

http://seattlesnowmass2021.net



Participants

Number of in-person participants: 743

Number of virtual participants: 654

Local Organizing Committee/Volunteer/Press: 58

Total number of participants: 1397

Snowmass 2021

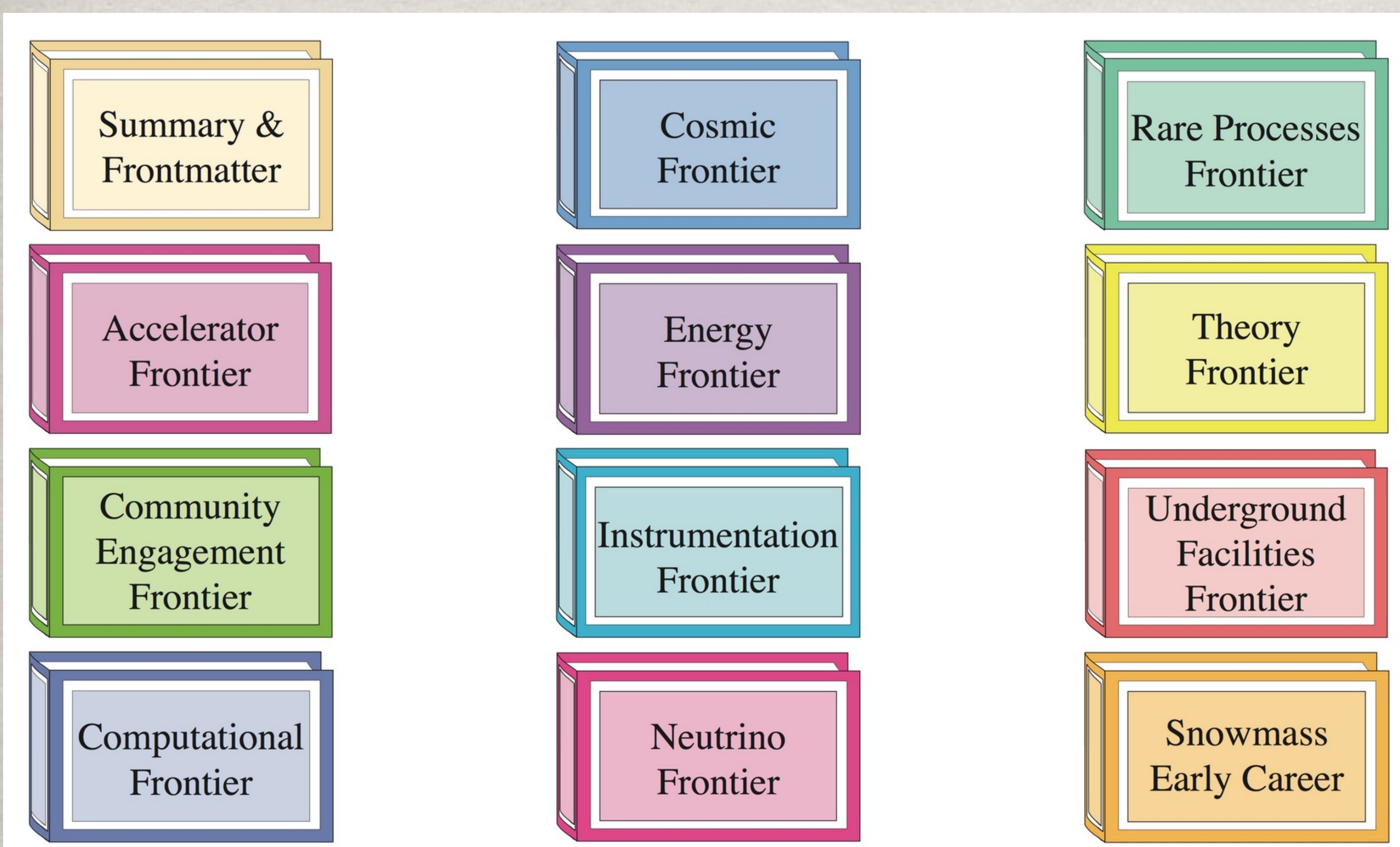
https://www.slac.stanford.edu/econf/C210711/

Snowmass 2021

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

(Snowmass 2021)

organized by the APS Division of Particles and Fields



Snowmass 2021 Succinct Summary:

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

Opportunities in HEP for the decade & beyond

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

Medium- and Small-Scale Future Experiments and Projects:

(see the full frontier reports)

Medium- and small-size experiments and projects are an important component of the current and proposed program. In the past, experiments with these scales have made significant measurements and important discoveries, opening up new areas of scientific exploration. Furthermore, because of their timescale and size, these experiments offer unique leadership and training opportunities for younger physicists and allow for greater diversity in the experimental particle physics ecosystem.

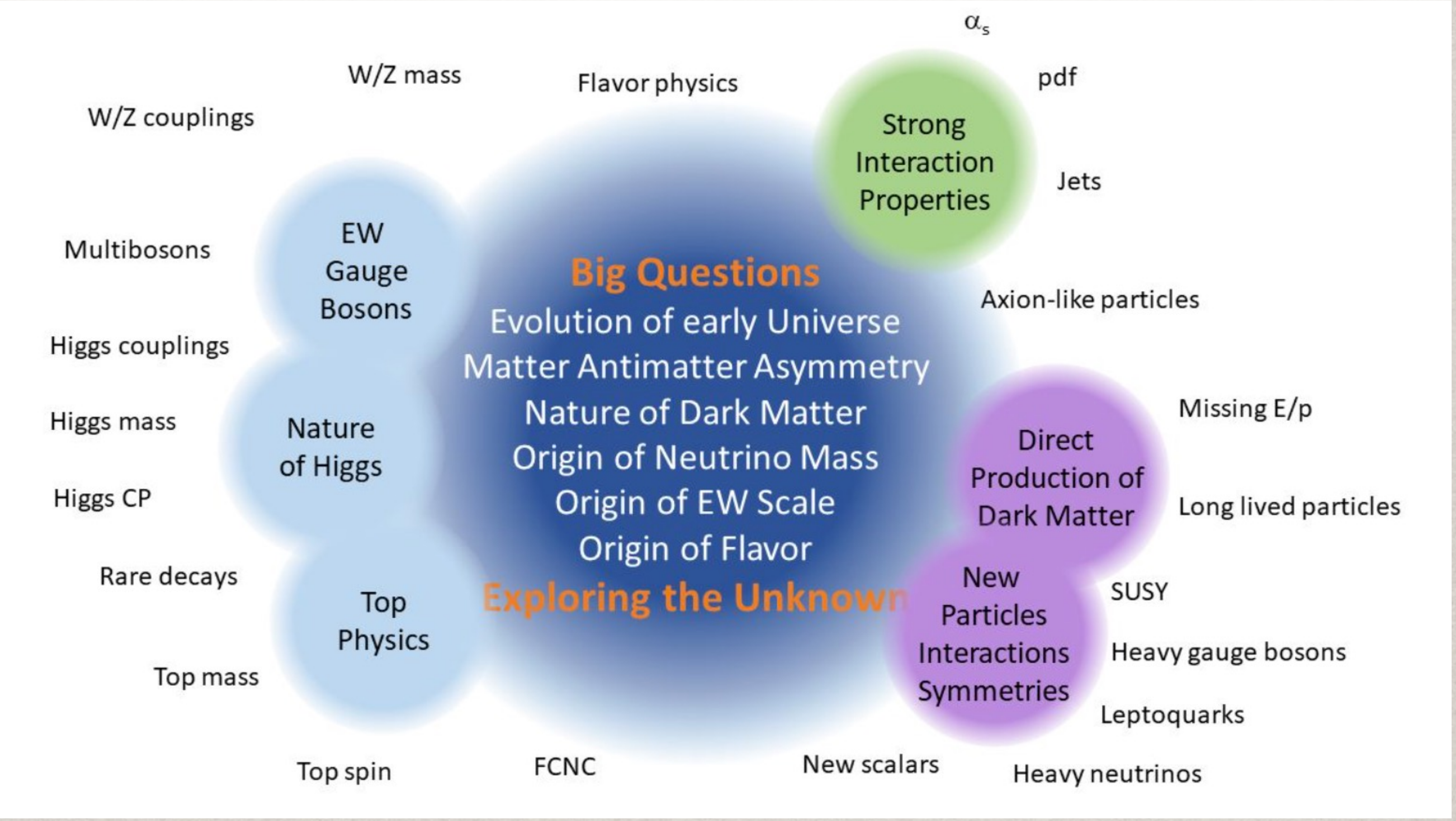
Such as SBND, CEνNS; g-2, Mu2e, $0\nu\beta\beta$, AMF, Belle II; DM …

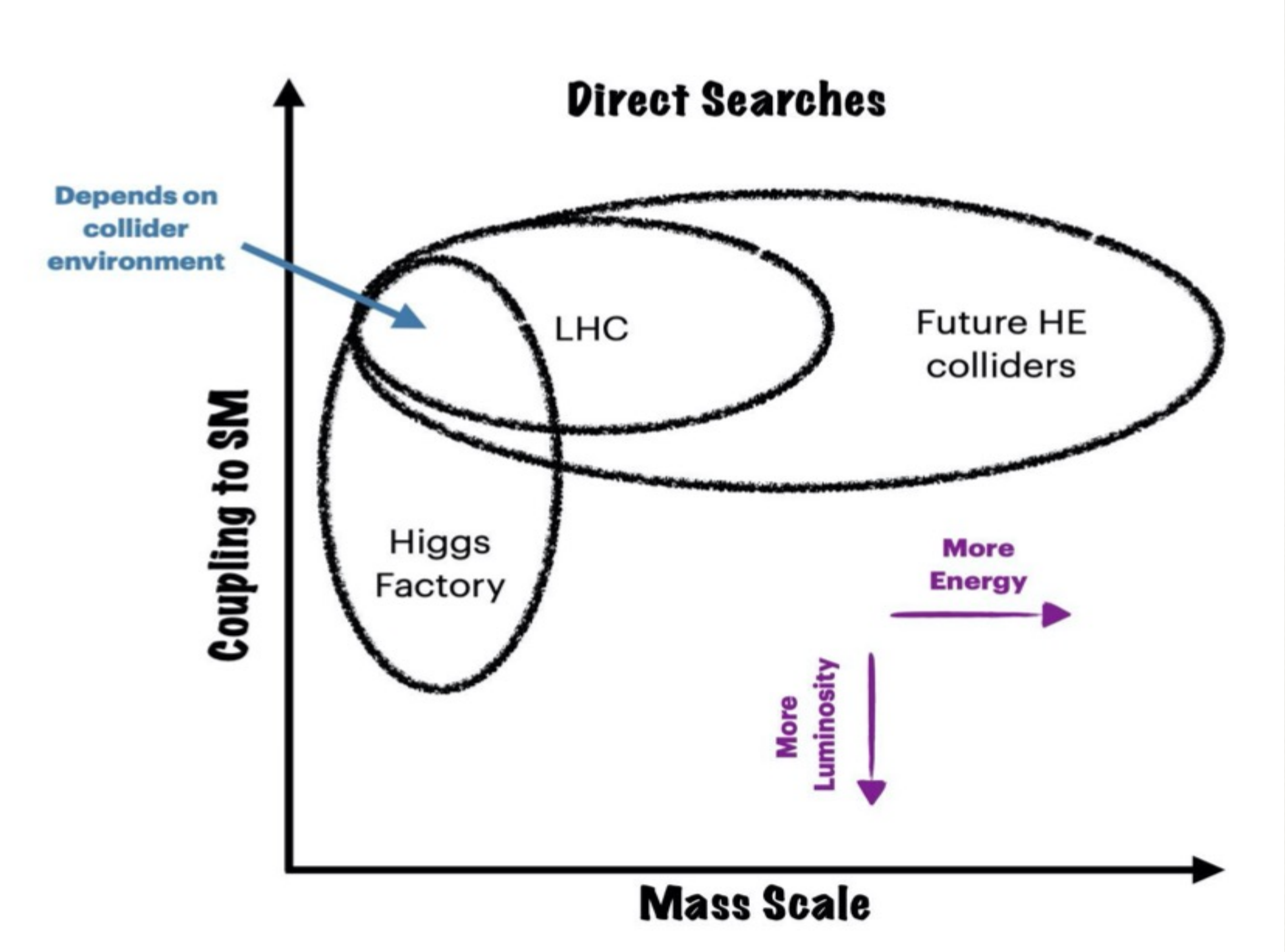
The field of HEP is vibrant, dynamic & exciting!

(1). Energy Frontier

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.

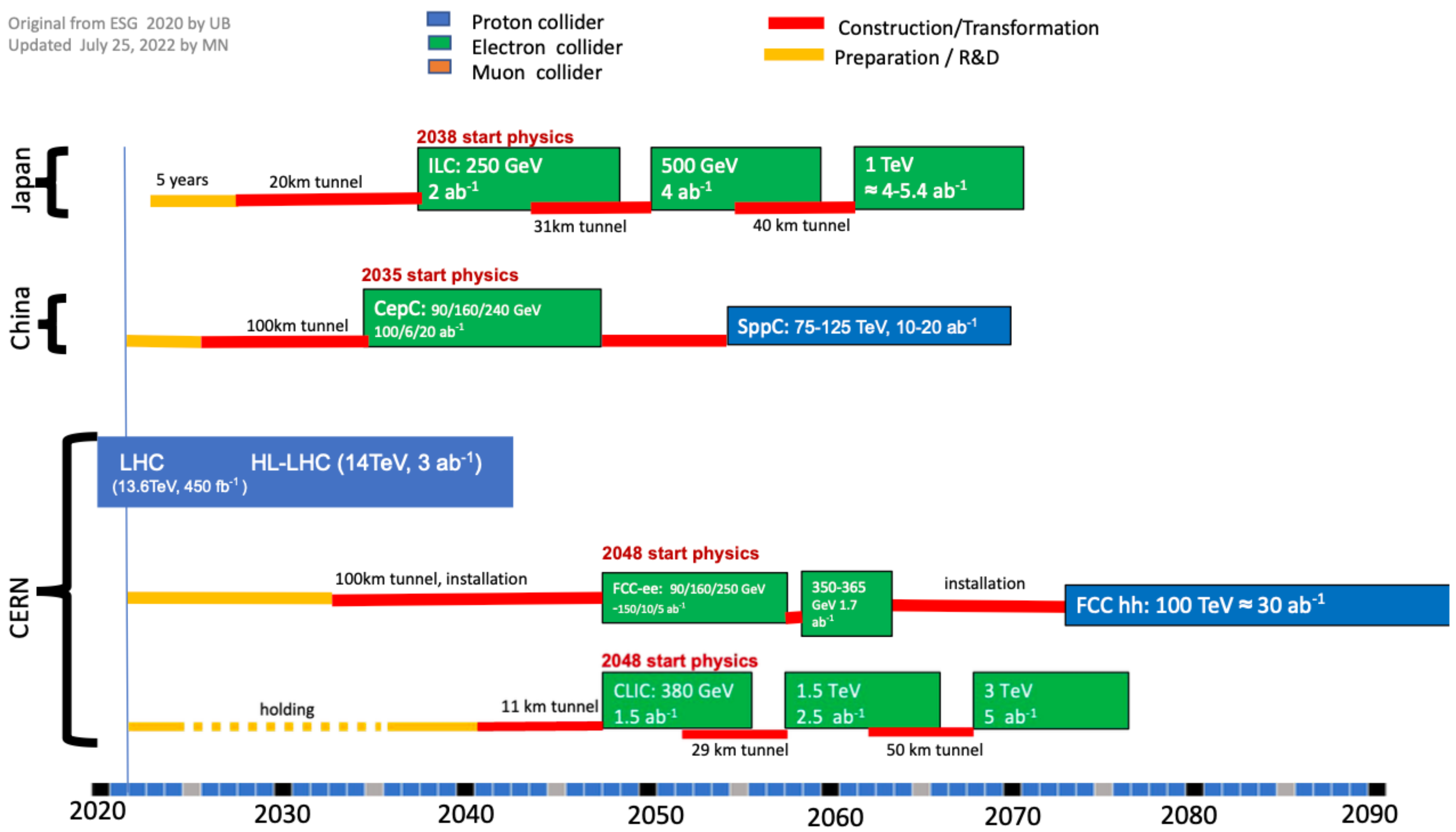


Figure 6-40. *Projected timelines for R&D, construction, and physics operations for some of the leading proposed future collider options.*

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**

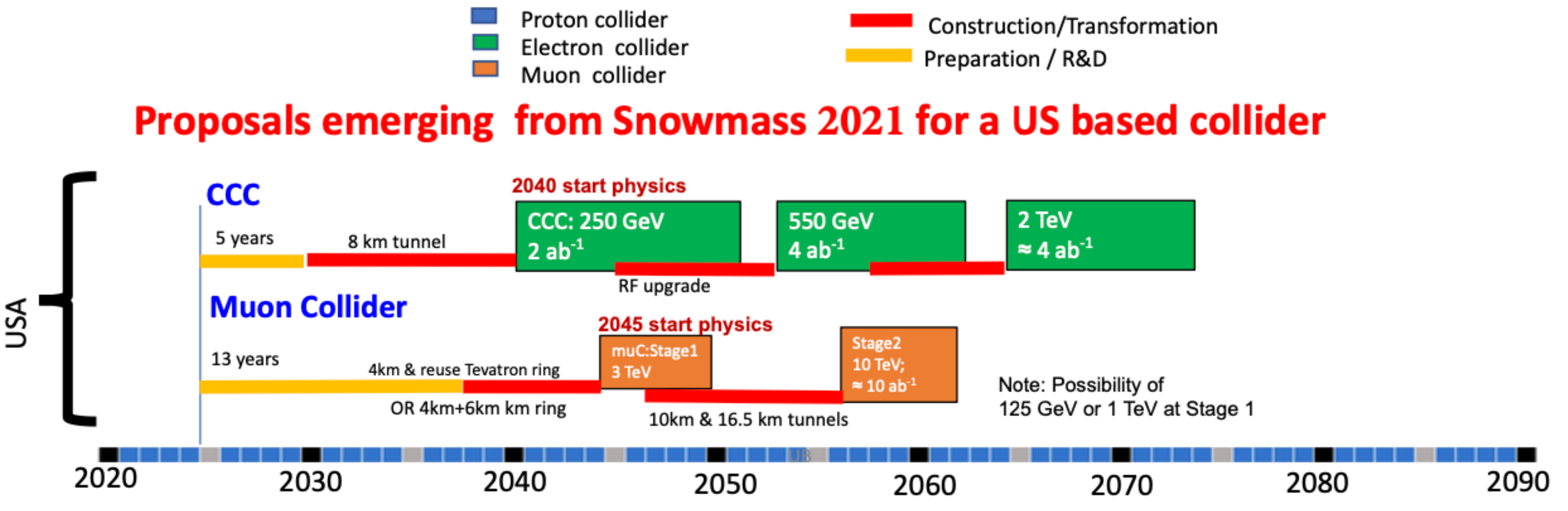
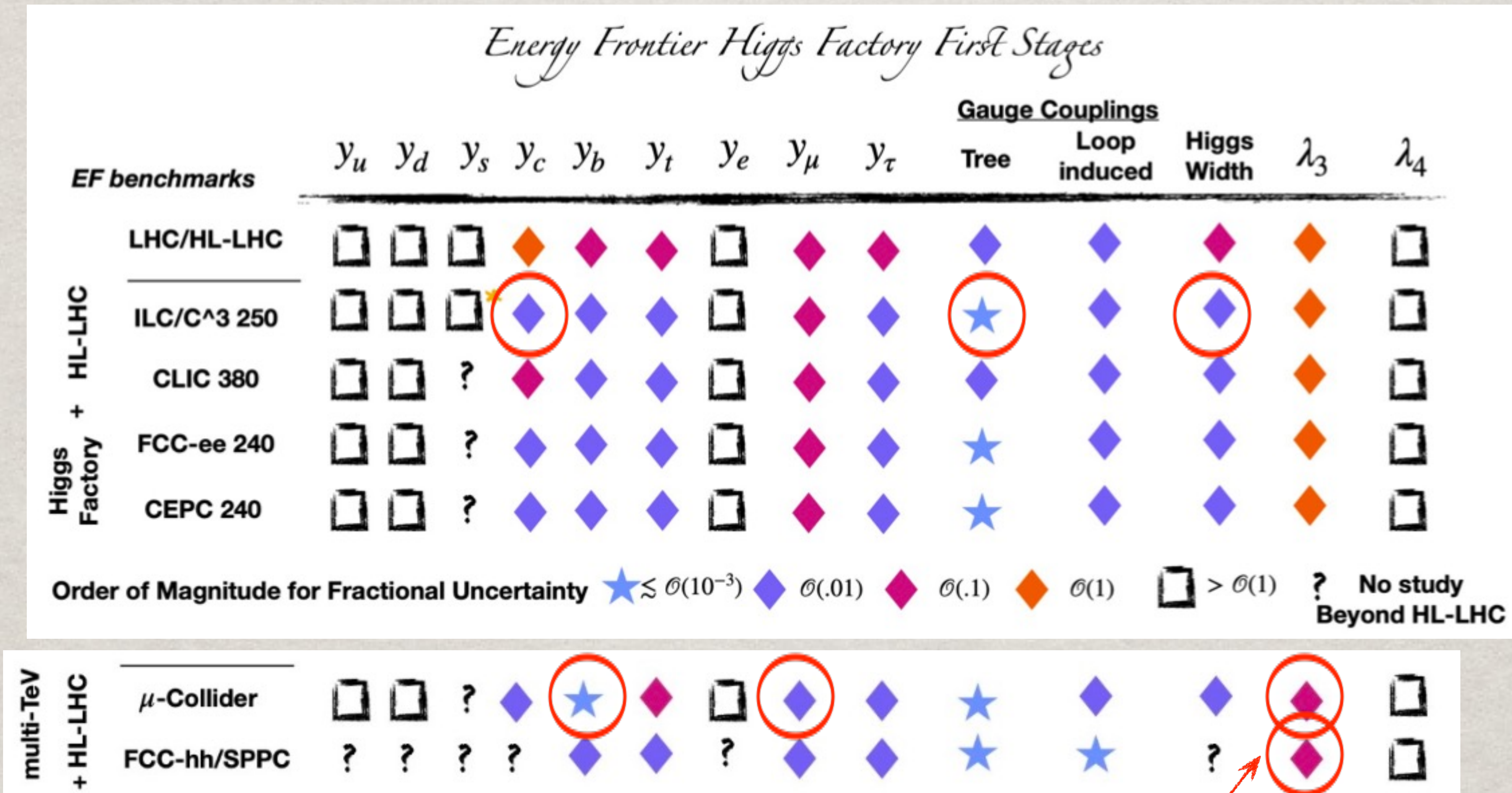


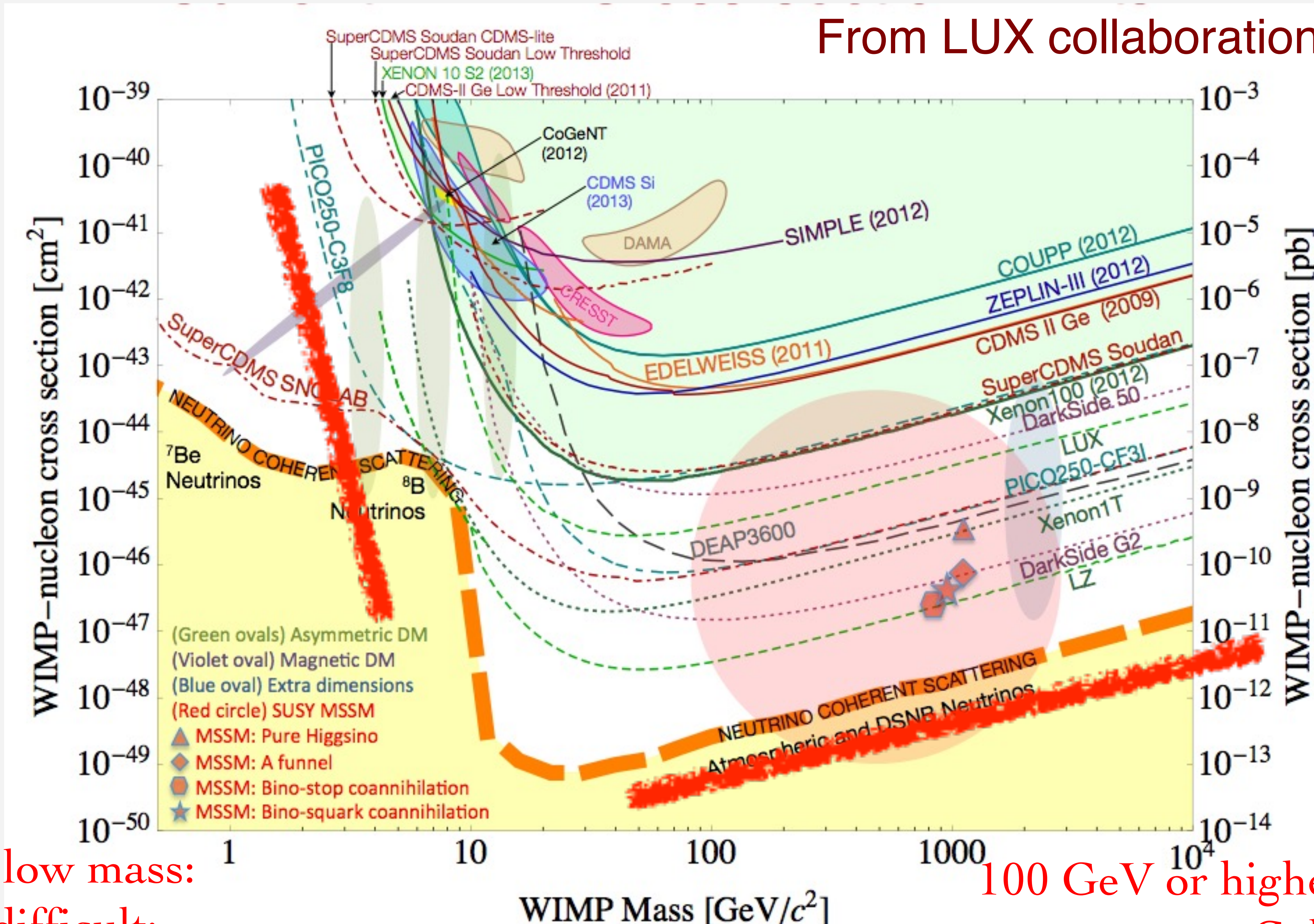
Figure 6-41. *Approximate timelines for proposals for ILC/CCC and Muon Collier emerging from Snowmass 2021 for a US based collider option.*

Physics example 1: Sensitivity reach for Higgs couplings for Higgs factories and multi-TeV colliders



Most wanted in order to understand EWSB!

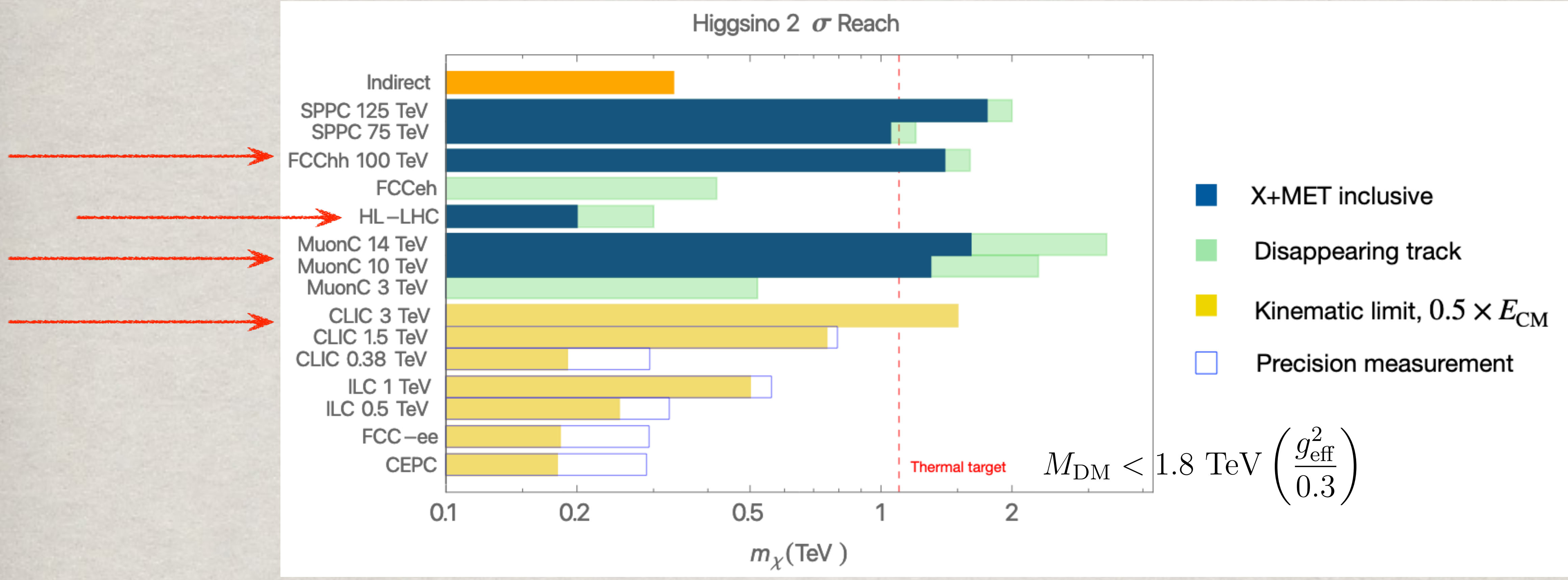
Physics example 2: WIMP DM Searches

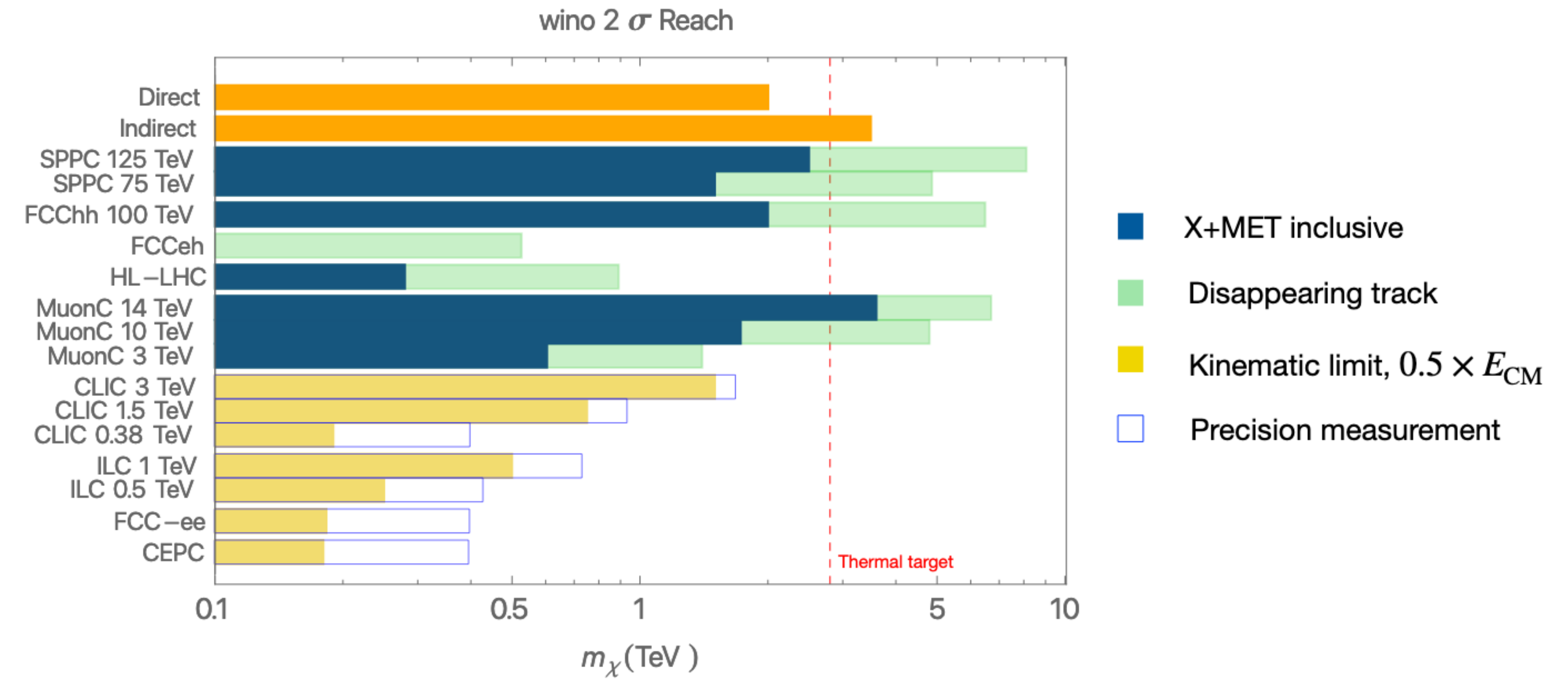


GeV low mass:
DD difficult;
Collider complementary

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

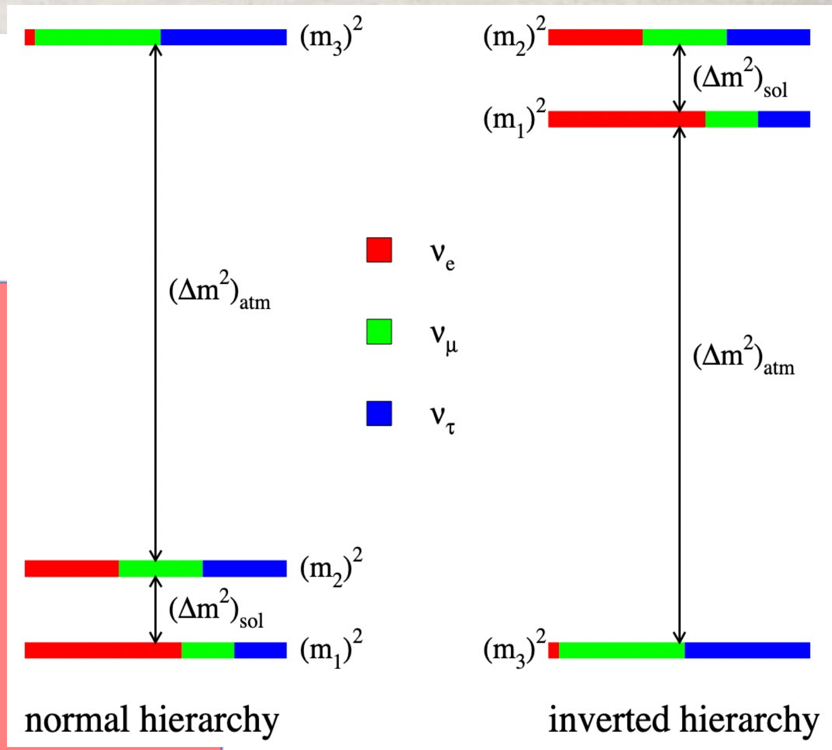
Covering the thermal target





(2). Neutrino Frontier
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

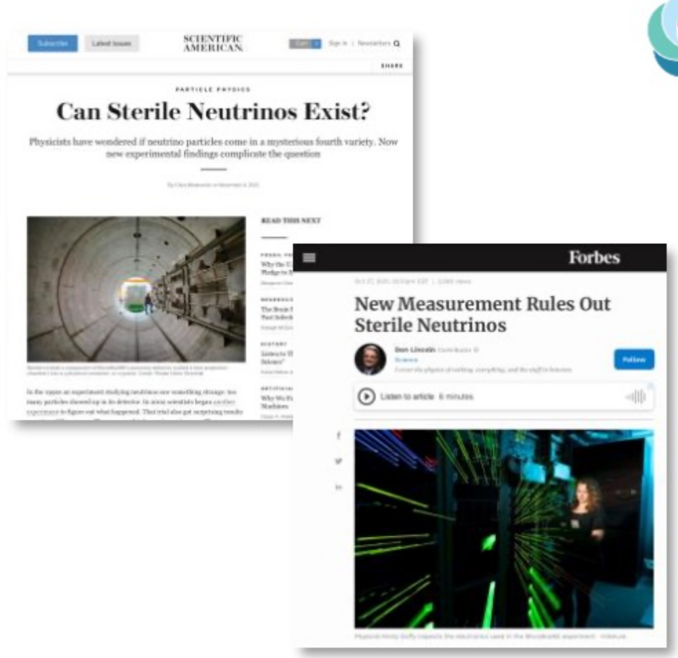
Significant growth in activity since last Snowmass

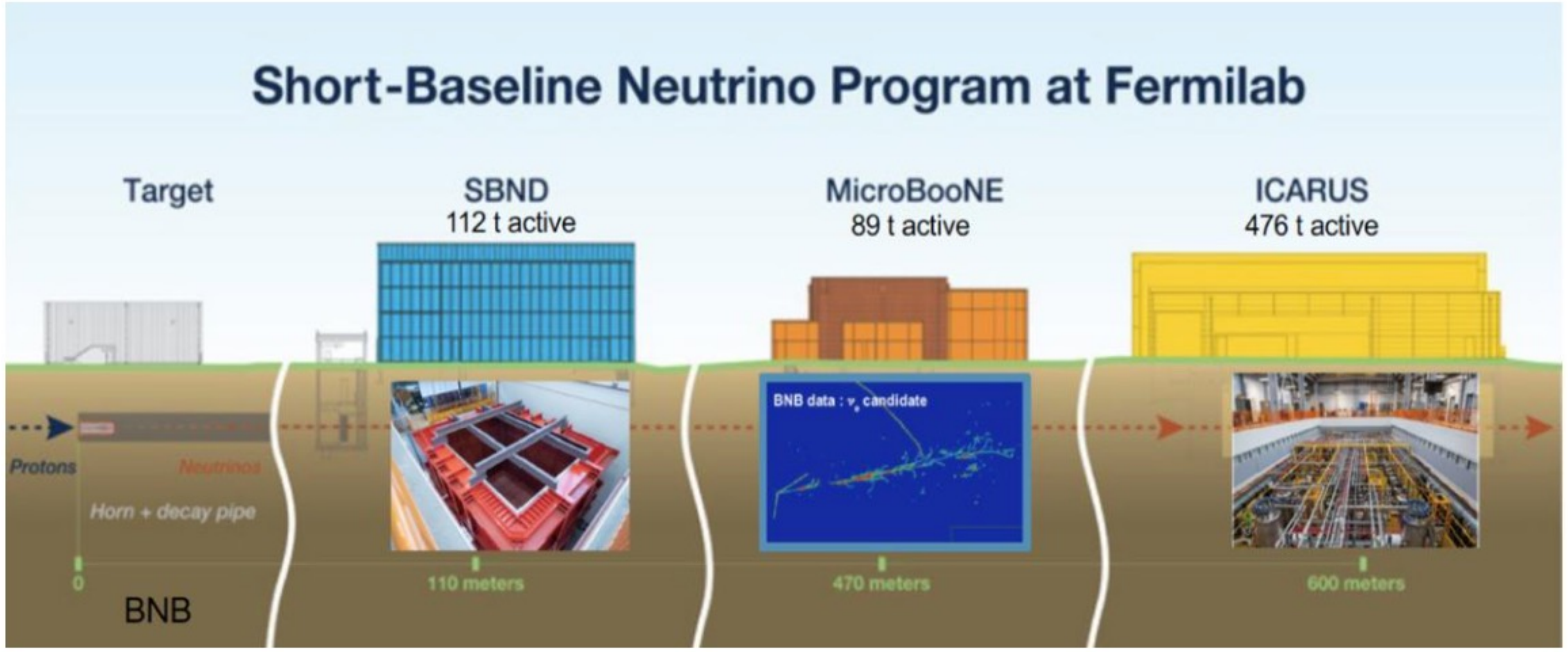
From Fermilab (Lia Merminga)

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





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

ORNL: COHERENT, PROSPECT, PROSPECT-II

From Fermilab (Lia Merminga)

Delivering on LBNF/DUNE is Fermilab's highest priority

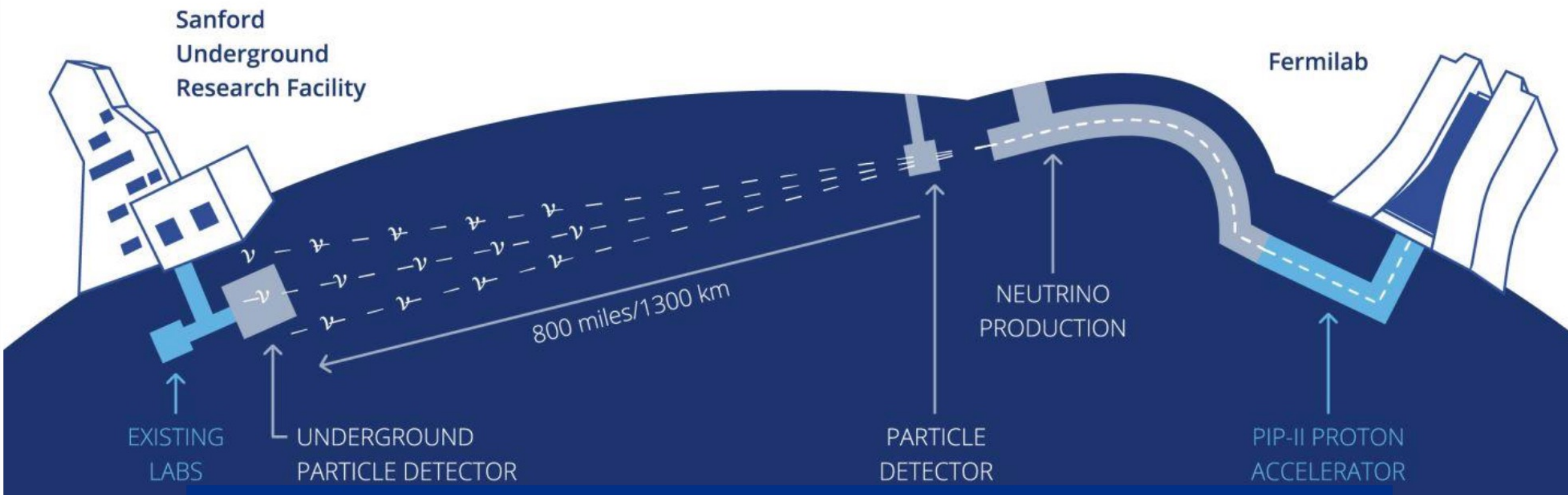
S&T **DUNE: The world's most capable neutrino experiment, driven by LBNF and PIP-II**

Gina Rameika

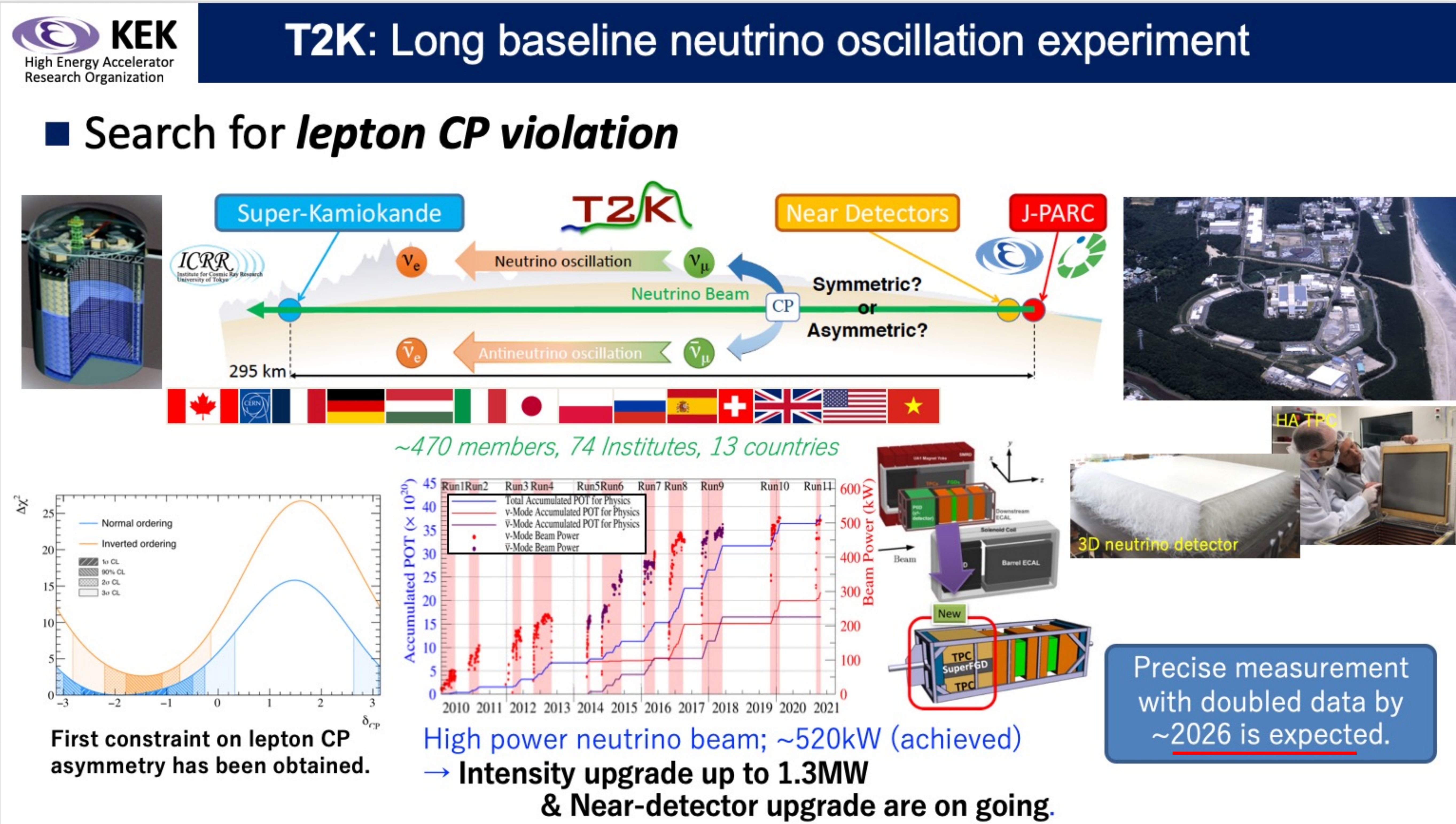
Sergio Bertolucci

Vision for Neutrino Science

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



From KEK (Masa Yamauchi)

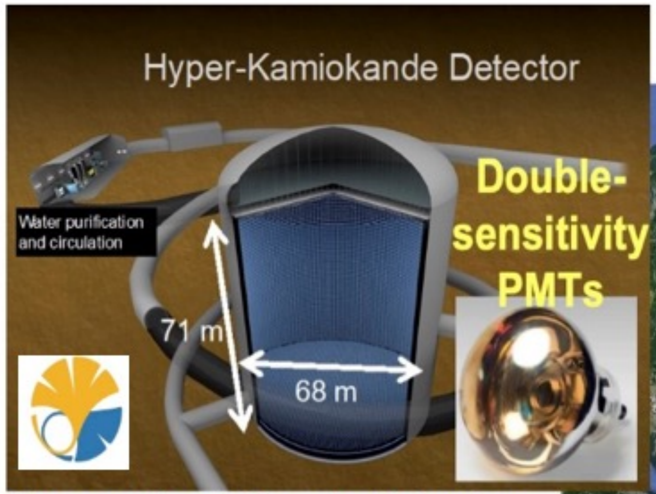


From KEK (Masa Yamauchi)

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

KEK High Energy Accelerator Research Organization

- 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.



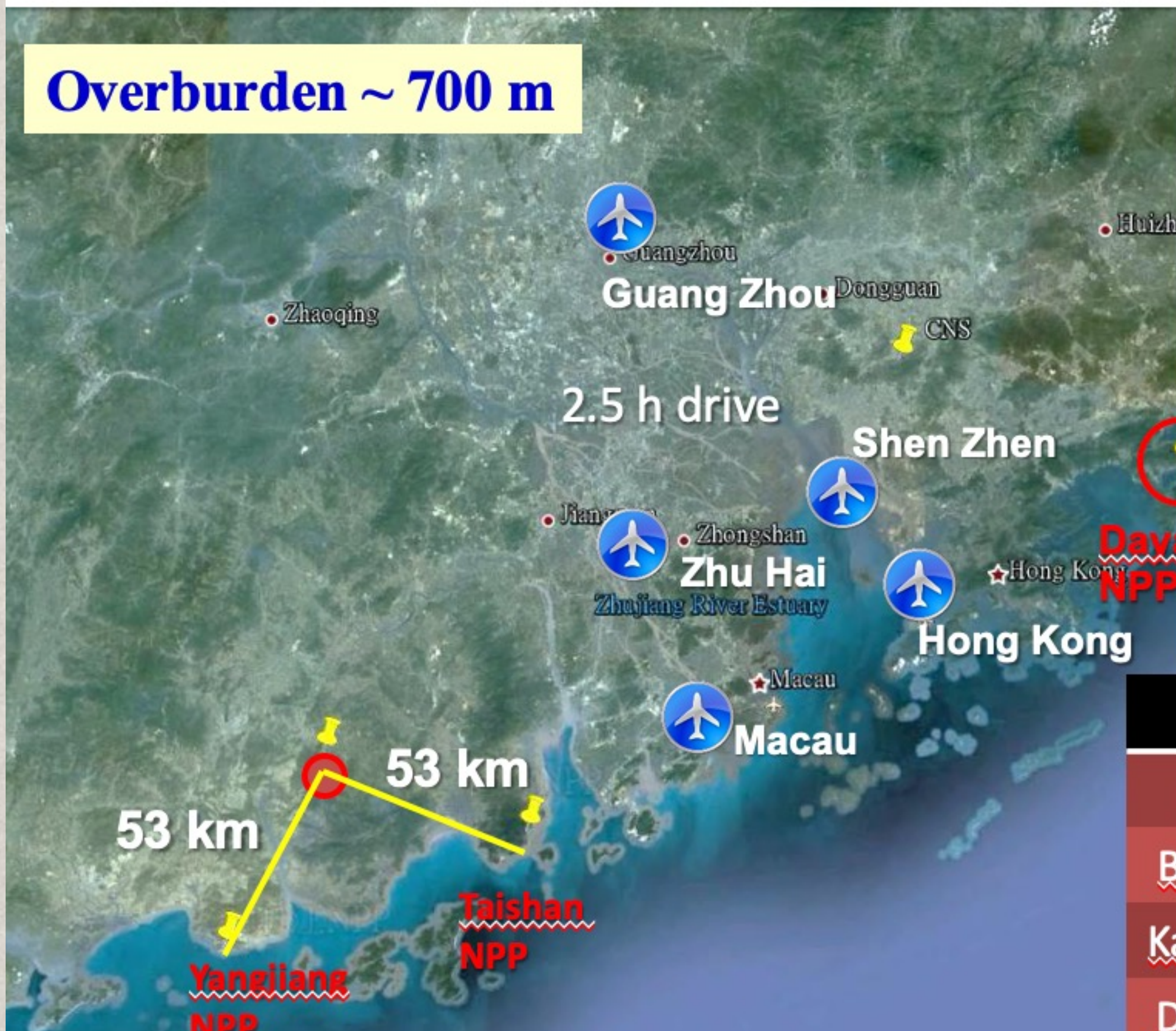
Hyper-Kamiokande Detector

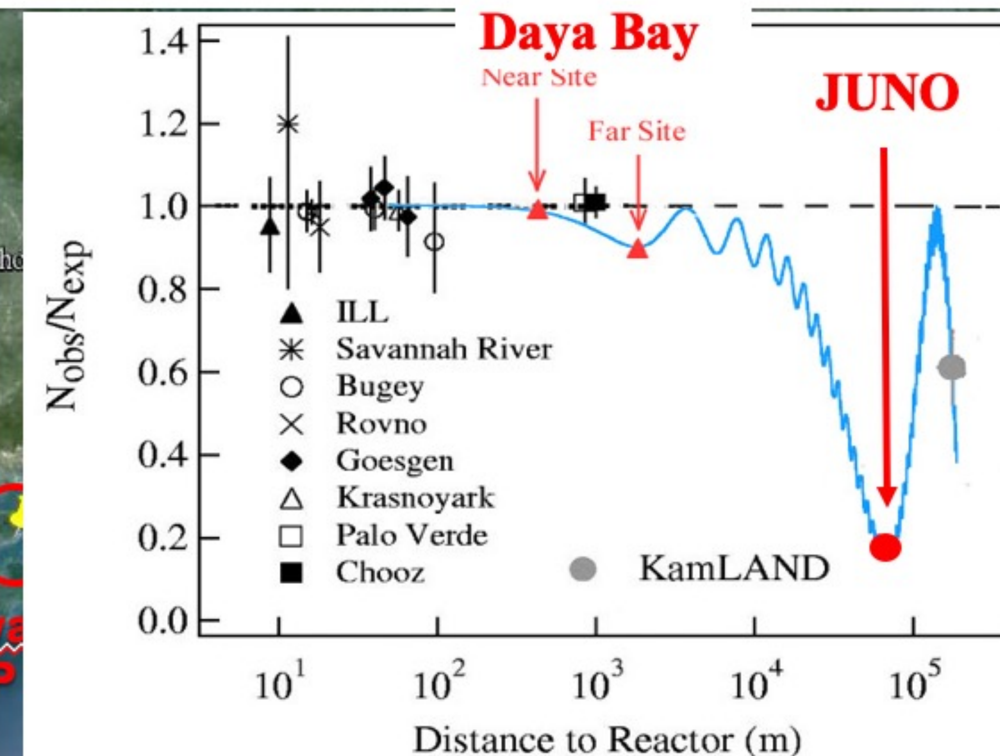
High power proton beam J-PARC and near detectors

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





	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}

$\pm 1\%$ in six years of data taking.

Hyper-K (starting 2027):

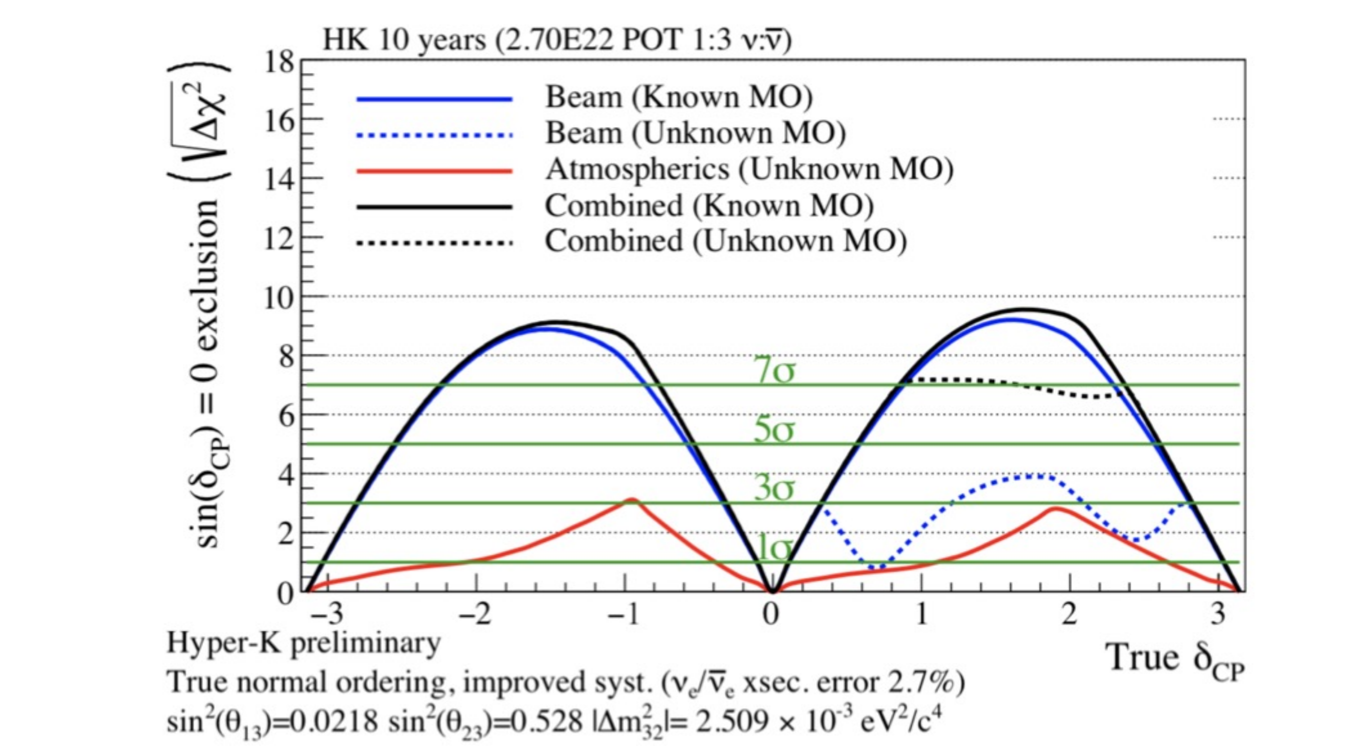


FIG. 4. HK sensitivity to exclude $\sin\delta(cp) = 0$, plotted as a function of the true value of δ_{CP}, assuming the mass ordering is unknown. A combined fit of HK beam and atmospheric neutrinos significantly enhances the HK sensitivity to δ_{CP}.

DUNE (starting 2032):

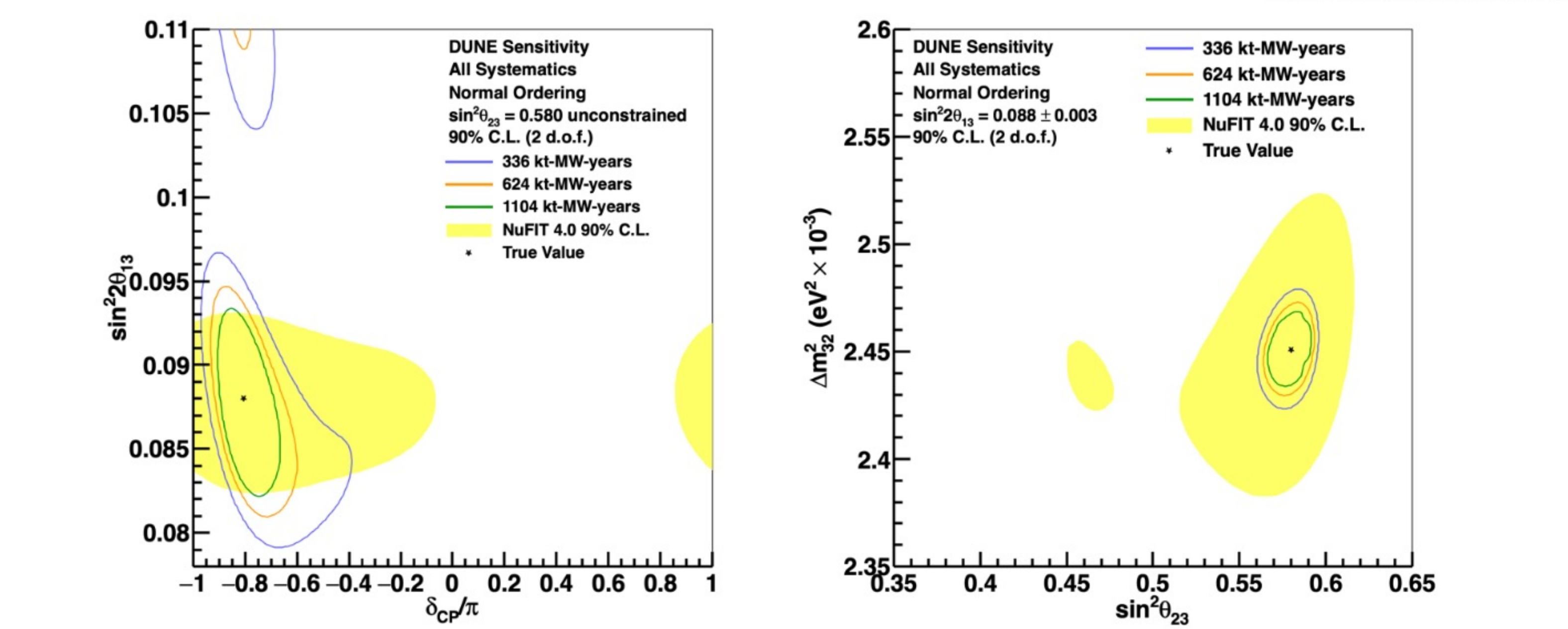
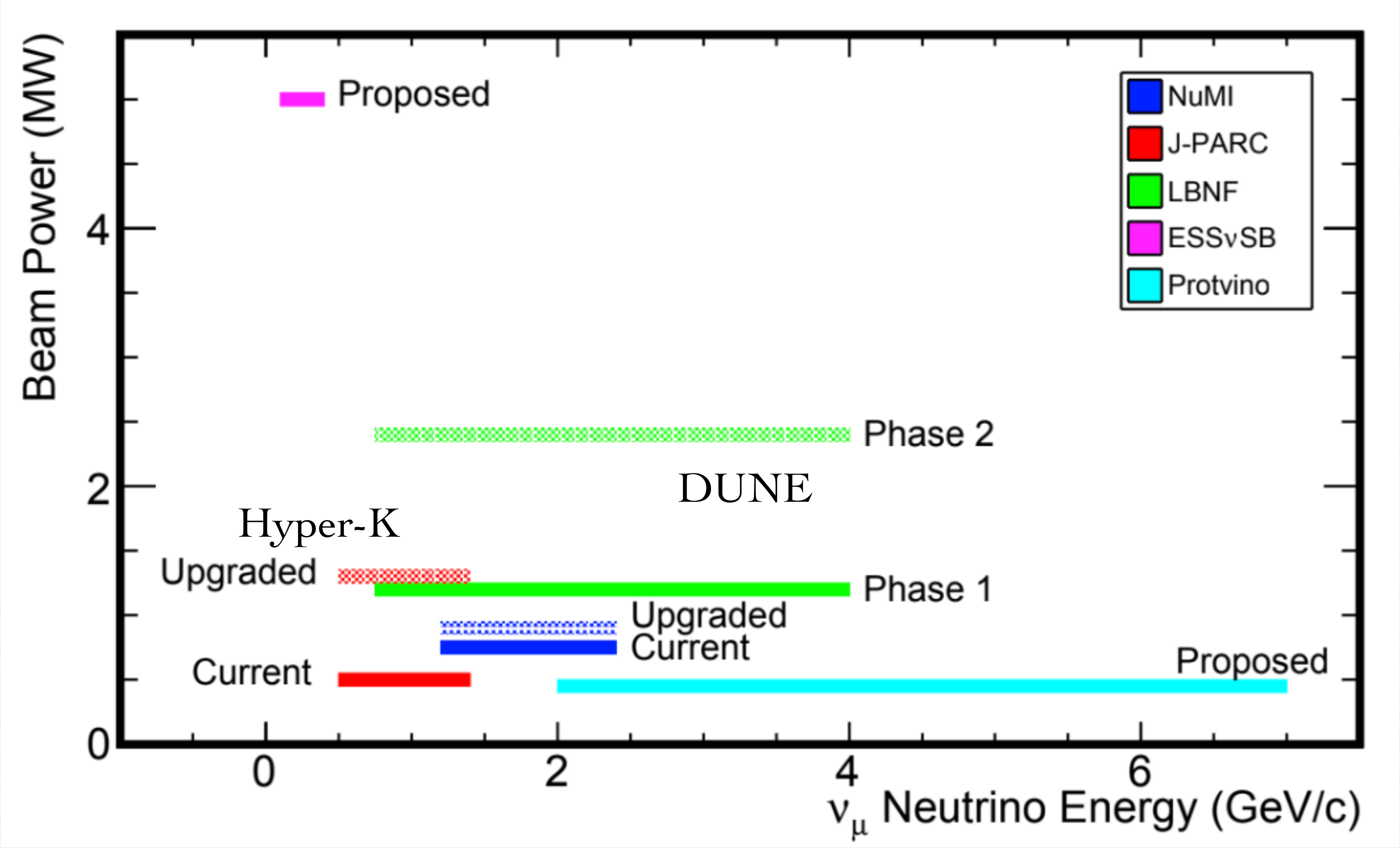


FIG. 3. 90% confidence intervals for $\sin^2 2\theta_{13} - \delta_{CP}$ (left), and $\sin^2 23 - \Delta m^2_{32}$ (right) after a range of exposures in kt-MW-years, for a projected measurement with assumed true parameter values near the current global best fit. Yellow regions indicate recent global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

Complementarity!

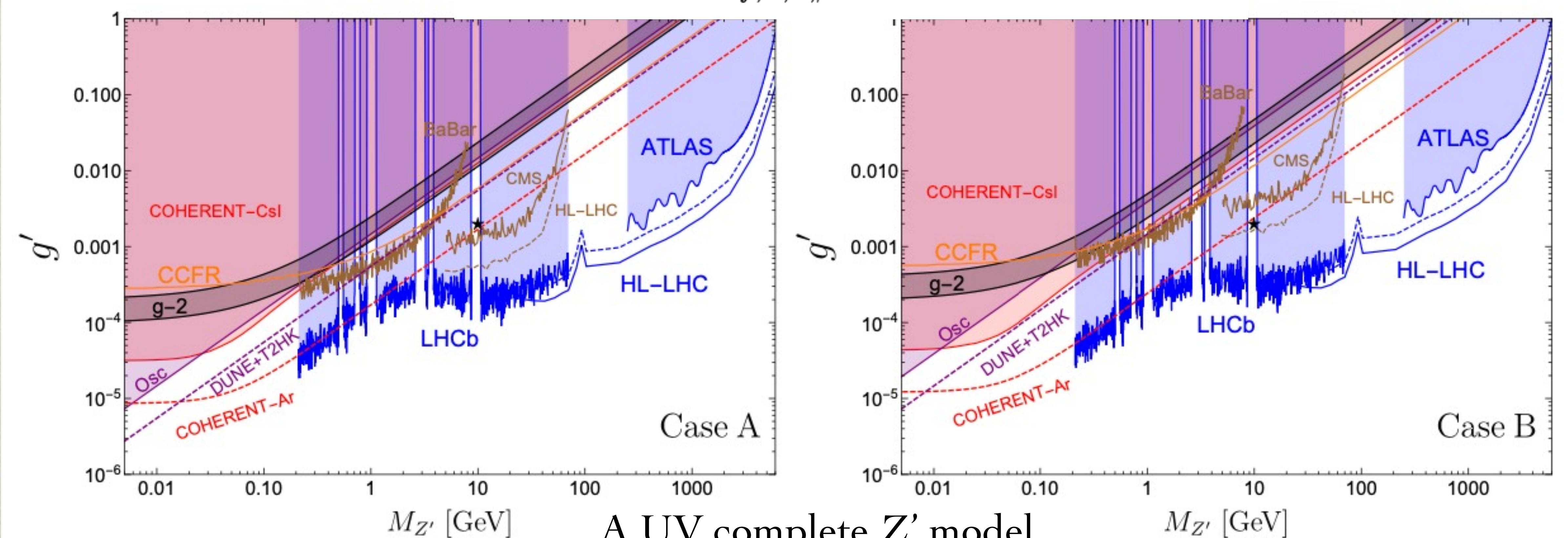
Accelerator-based neutrino sources



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

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

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

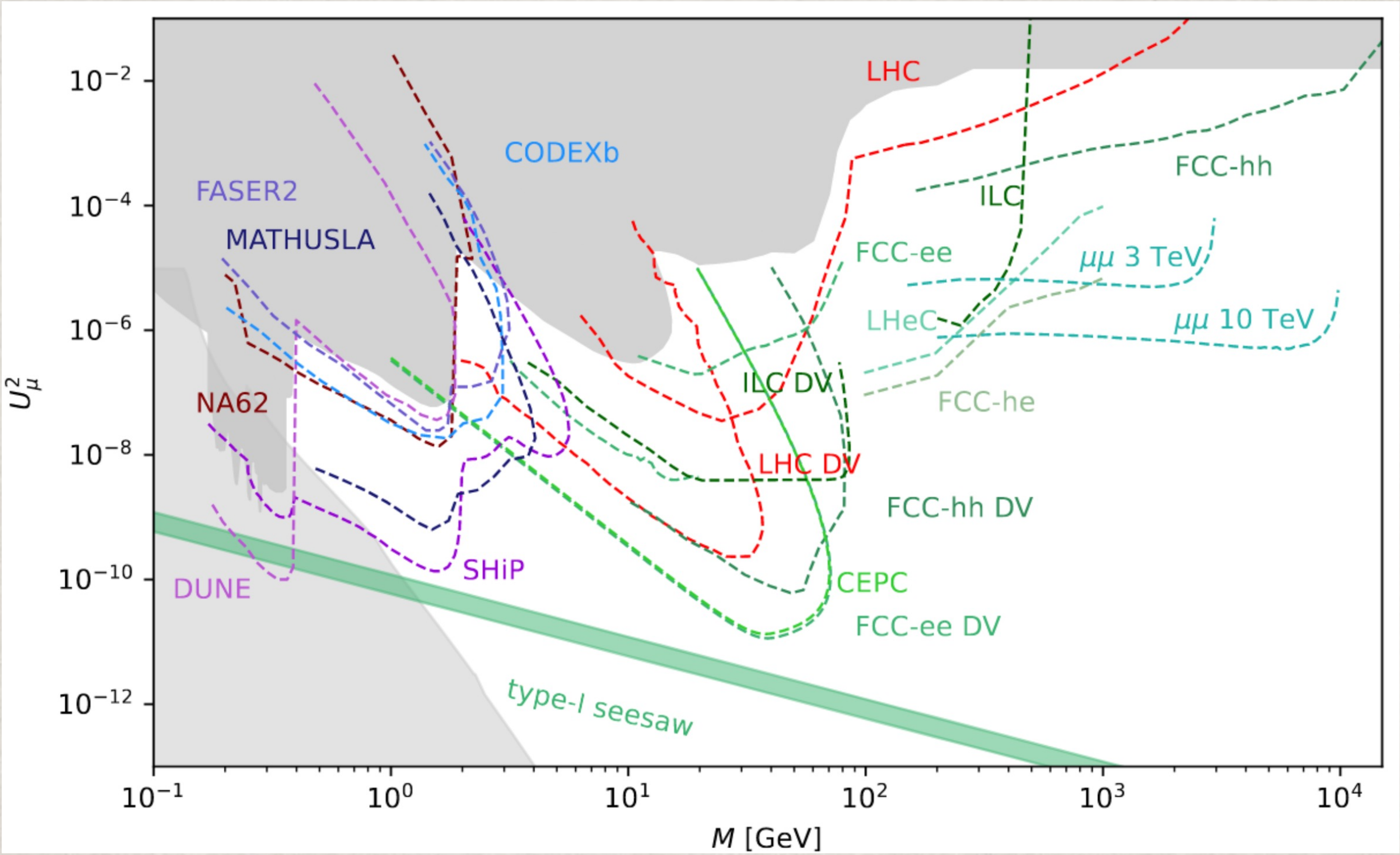


A UV complete Z' model

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 $\boldsymbol{\nu}$ Whitepaper: arXiv:2203.06131

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



Complementary among a variety of searches.

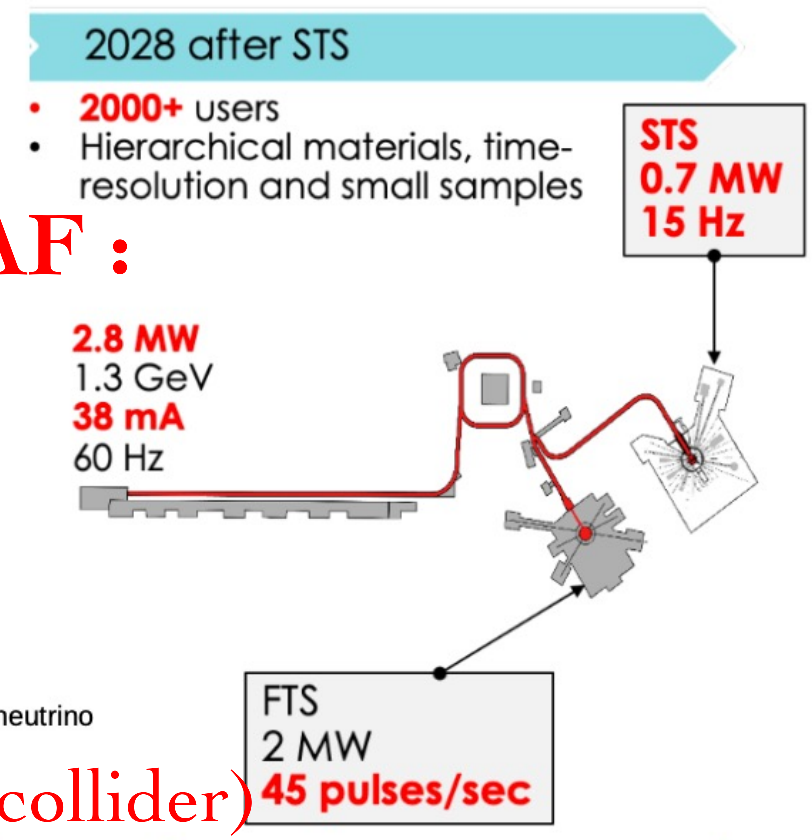
ν Synergistic aspects:

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)

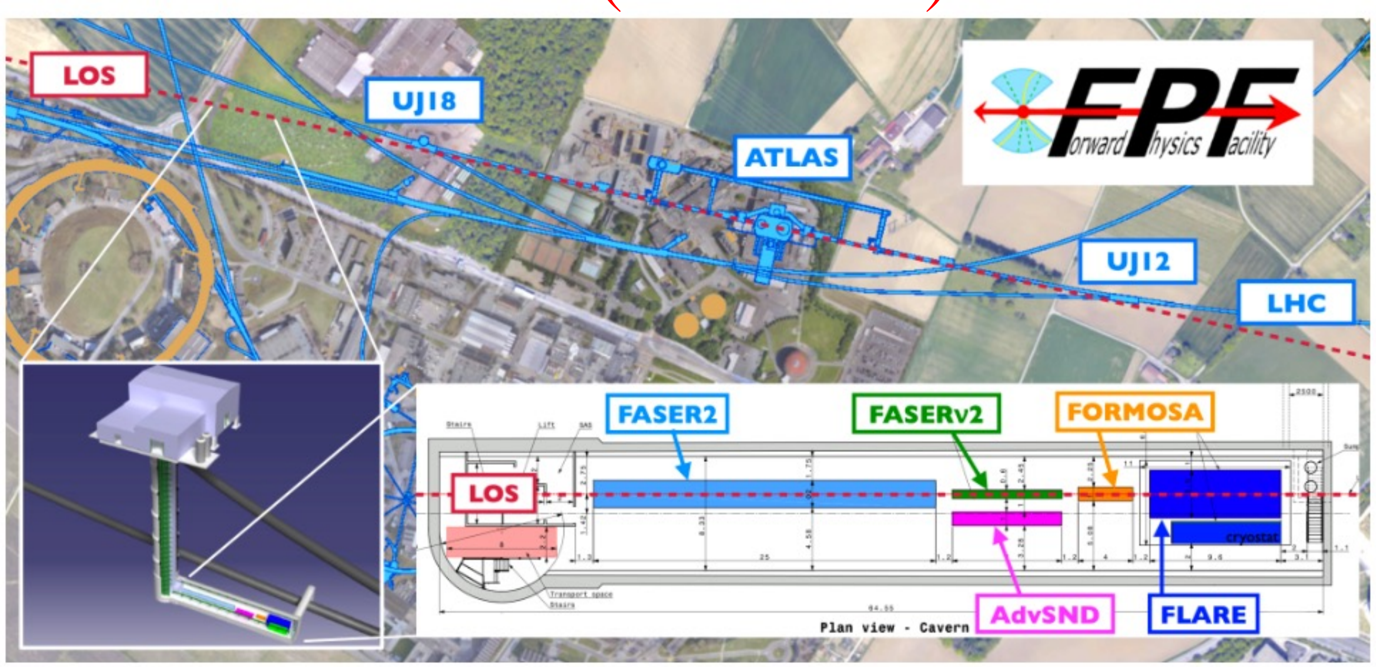
AF :



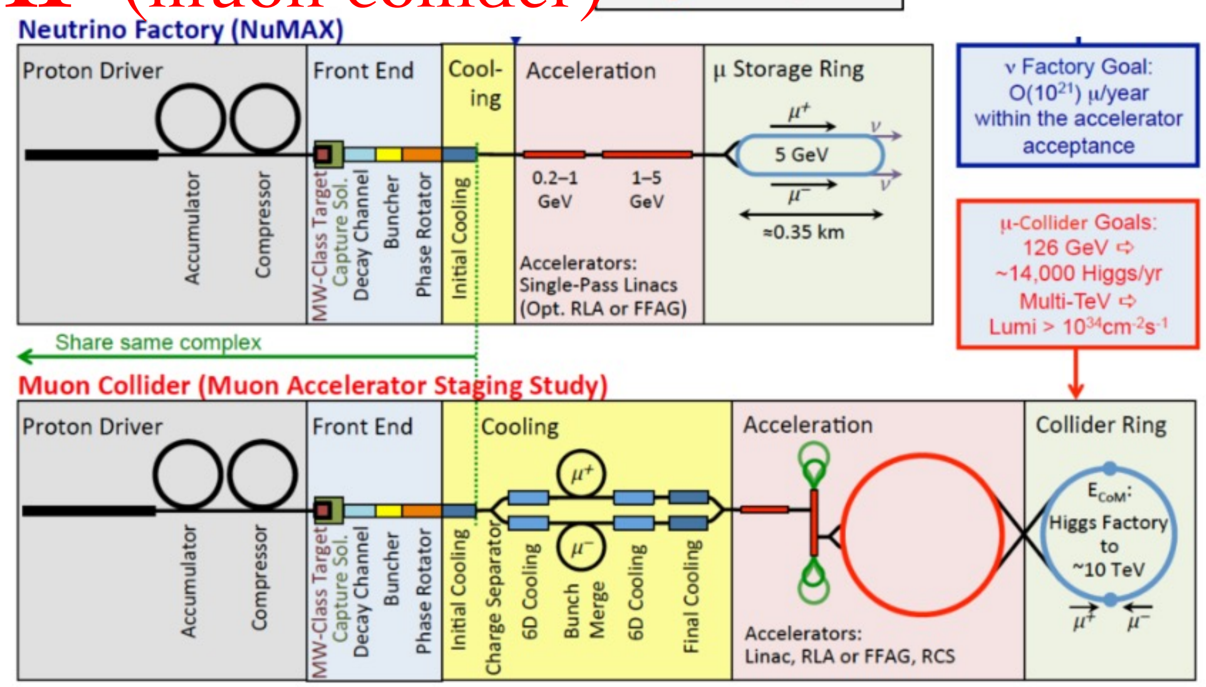
Synergies at the machine level as well as physics

Figures from SNOWMASS neutrino colloquium by M. Toups

EF (HL-LHC)

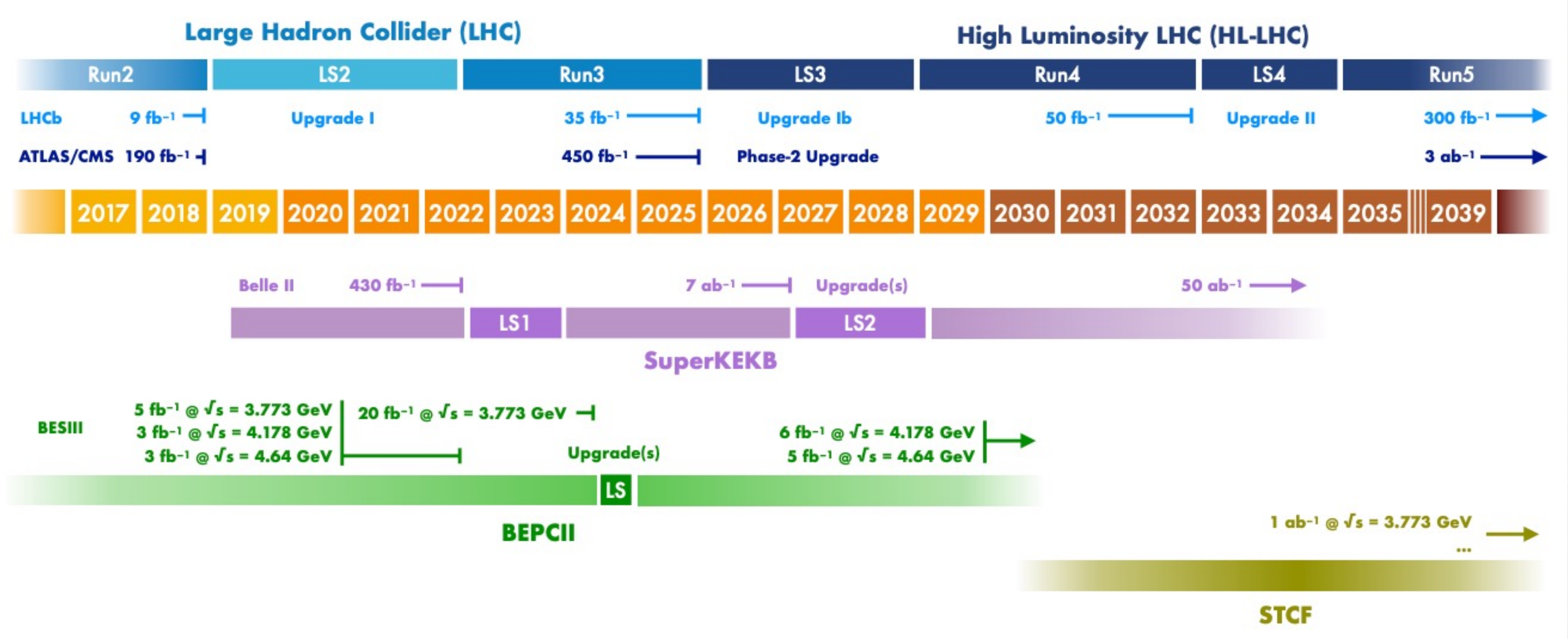


AF (muon collider)

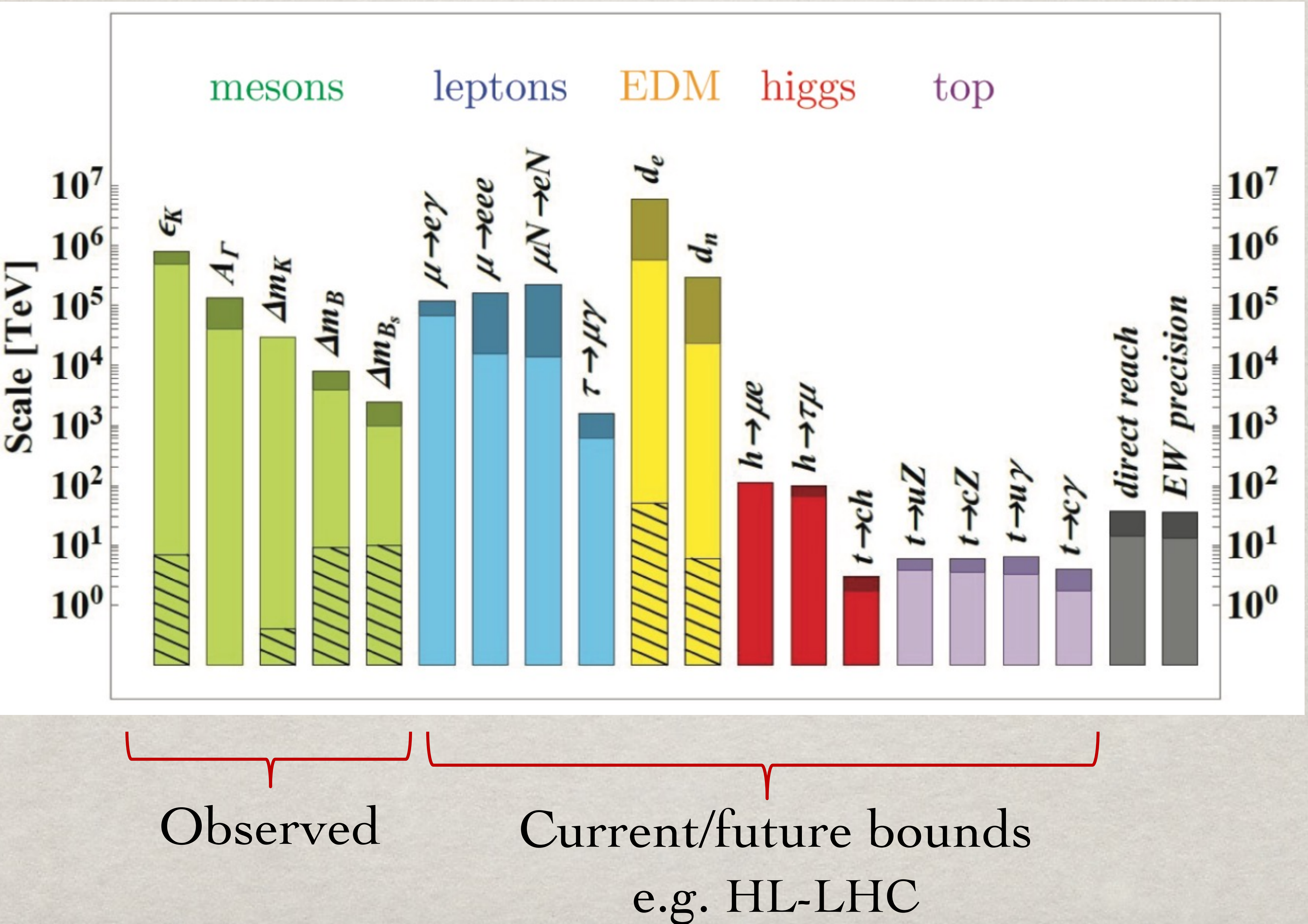


(3). Rare Process @ Precision

- 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



(4). Cosmic Frontier

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) ?

Physics example: DM Searches in Cosmo

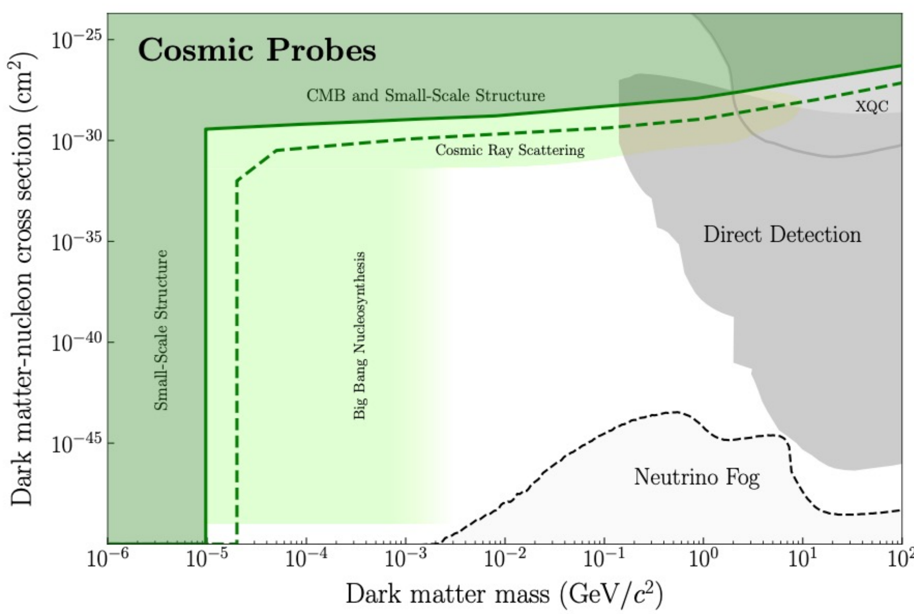


Figure 5-15. *Cosmic probes of the matter power spectrum, dark matter halos, Big Bang nucleosynthesis, and cosmic ray upscattering set strong constraints on the minimum thermal dark matter particle mass and spin-independent dark matter–nucleon scattering cross section (green regions). Projected improvements 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].*

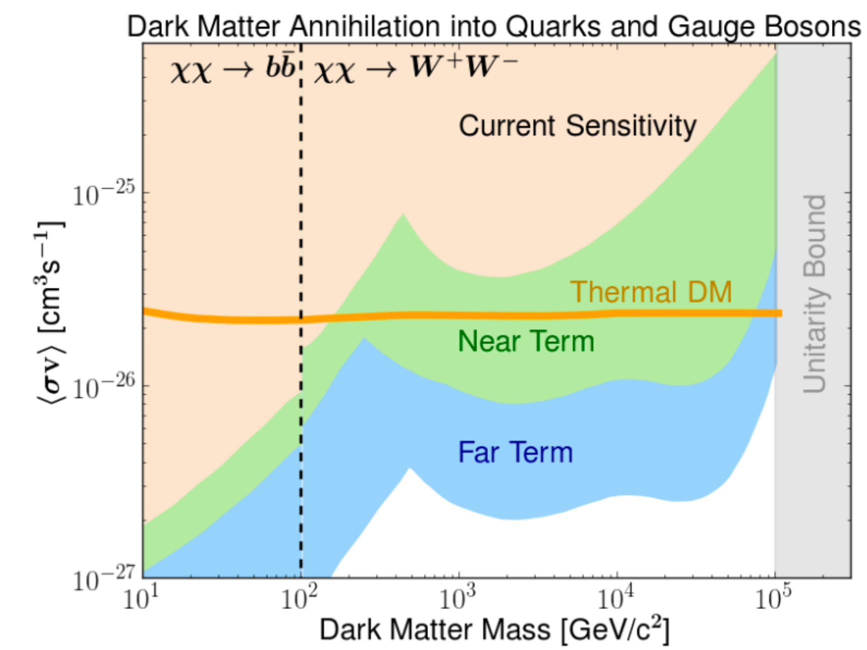


Figure 5-20. *Limits on WIMP annihilations into pairs of bottom quarks (for masses below ~ 100 GeV and W bosons (for larger masses) based on null searches by gamma-ray observatories. The beige regions indicate the current limits for each mass, whereas the green shaded region indicates near future gains 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

(6). Community Engagement

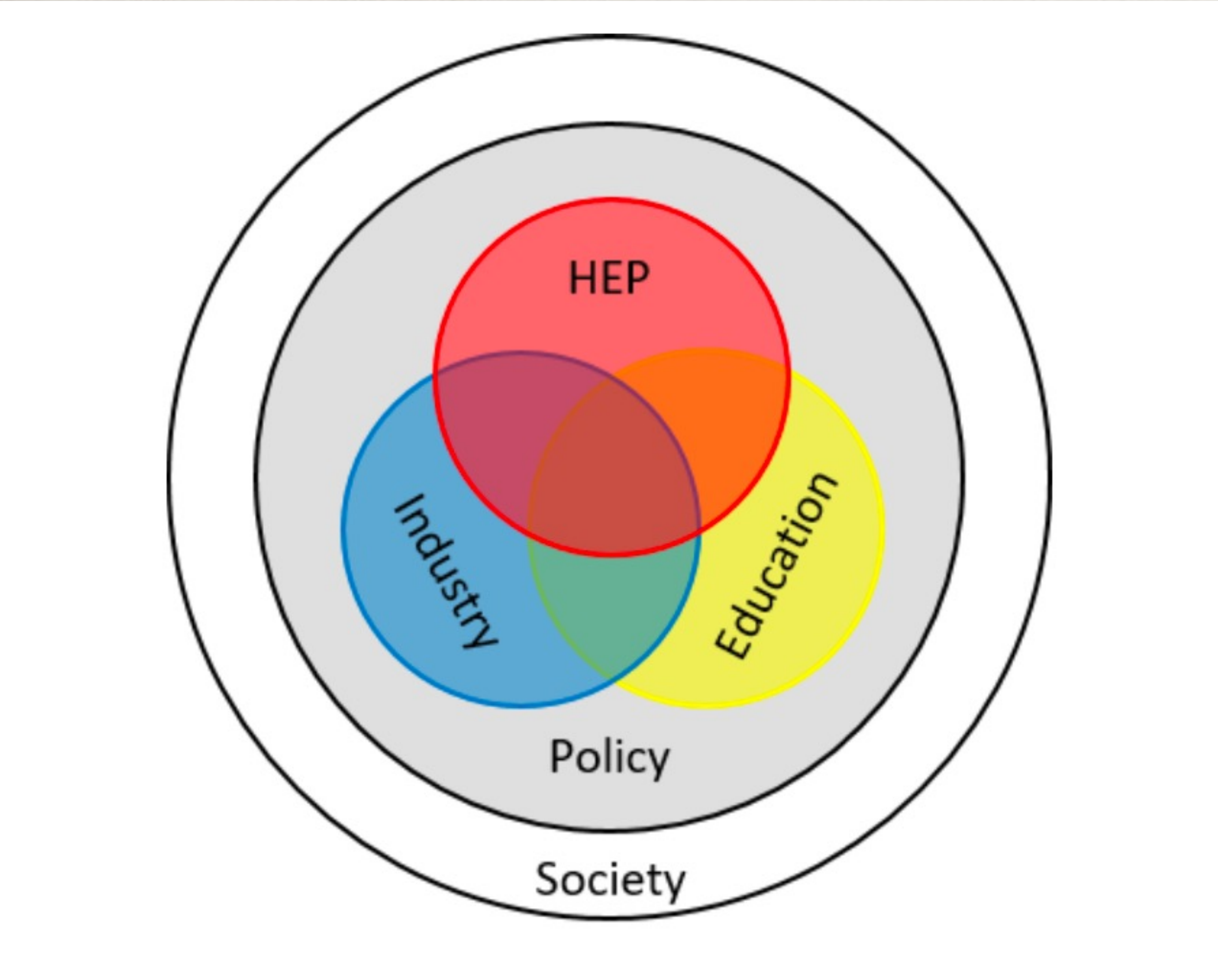
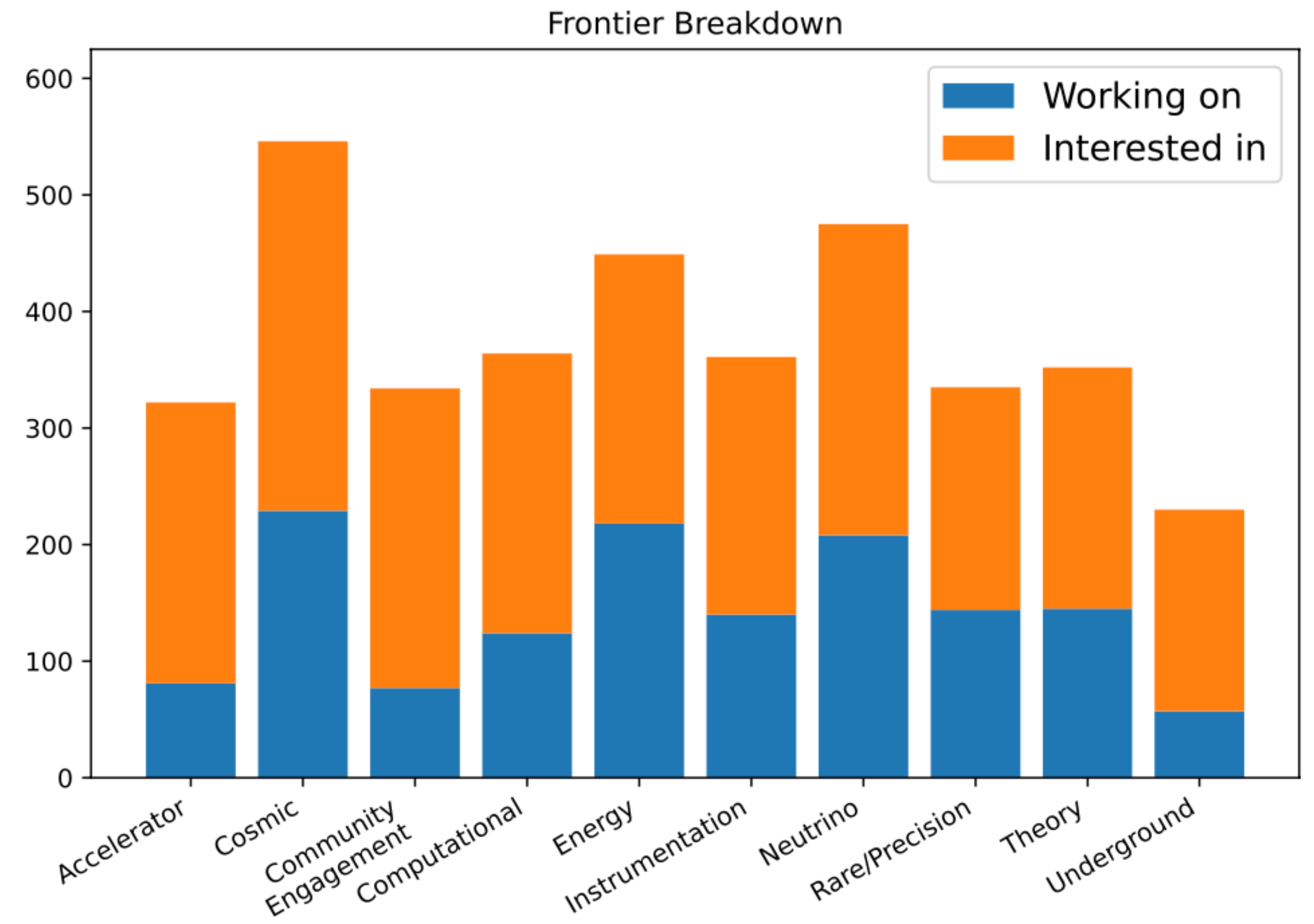


Figure 3-1. *Five interrelated communities targeted for HEP engagement.*

Equity, Diversity & Inclusion (EDI)

Early Career Physicists: Future of the field!

e.g. their interests in Snowmass 2021:



2023 P5 members:

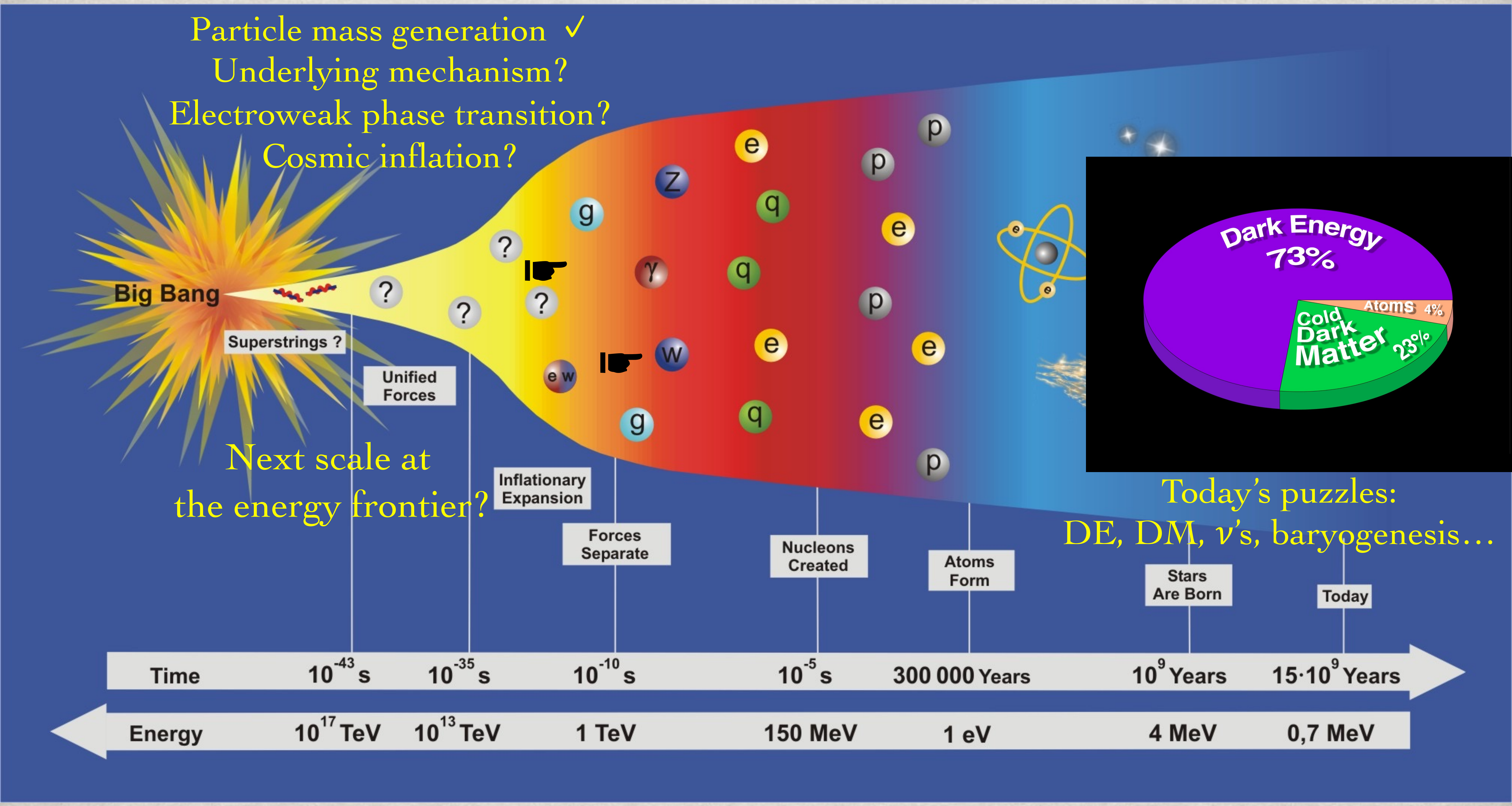
U.S. Department of Energy
and the
National Science Foundation
November 2, 2022

As the landscape of high-energy physics continues to evolve and the decadal timeframe addressed in the 2014 P5 report nears its end, we believe it is timely to initiate the next long-range planning guidance to the DOE and NSF. To that end, we ask that you constitute a new P5 panel to develop an updated strategic plan for U.S. high-energy physics that can be executed over a 10-year timeframe in the context of a 20-year, globally aware strategy for the field.

A critical element of this charge is to assess the continued importance of the science drivers identified by the 2014 P5 report and, if necessary, to identify new science drivers that have the potential to enable compelling new avenues of pursuit for particle physics. Specifically, we request that HEPAP 1) evaluate ongoing projects and identify potential new projects to address these science drivers; 2) make the science case for new facilities and capabilities that will advance the field and enhance U.S. leadership and global partnership roles; and 3) recommend a program portfolio that the agencies should pursue in this timeframe, along with any other strategic actions needed to ensure the broad success of the program in the coming decades.

- Shoji Asai (University of Tokyo)
- Amalia Ballarino (CERN)
- Tulika Bose (Wisconsin)
- Kyle Cranmer (Wisconsin)
- 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
- 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 (Brookhaven)
- Tor Raubenheimer (SLAC)
- Mayly Sanchez (Florida State)
- Richard Schnee (South Dakota School of Mines and Technology)
- Seon-Hee (Sunny) Seo (IBS Center for Underground Physics)
- Jesse Thaler (MIT)
- Christos Touramanis (Liverpool)
- Abigail Vieregg (Chicago)
- Amanda Weinstein (Iowa State)
- Lindley Winslow (MIT)
- Tien-Tien Yu (Oregon)
- Bob Zwaska (Fermilab)

A Grand Picture:

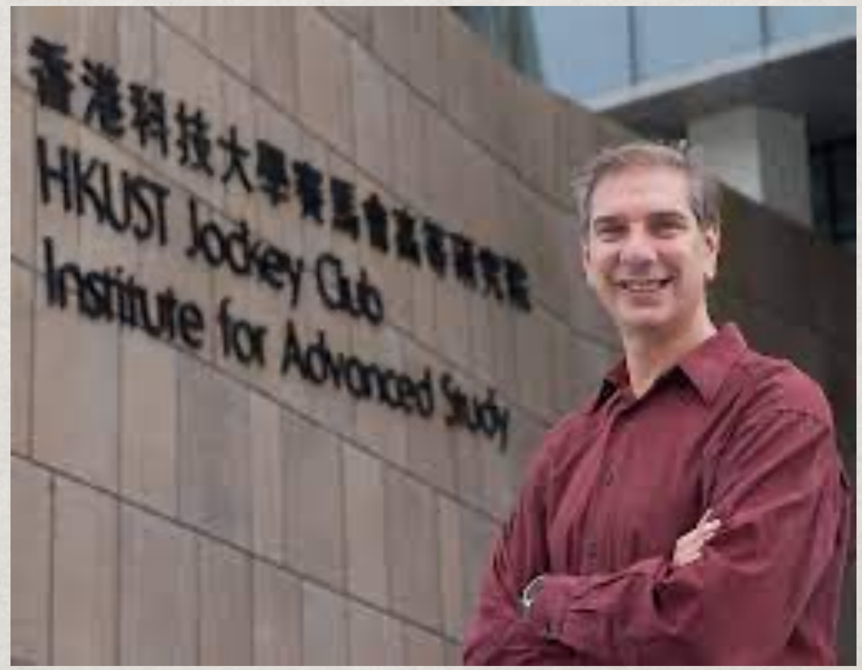


EXCITING JOURNEY AHEAD FOR DISCOVERIES!

Thank you very much for organizing the wonderful meeting, and for the great hospitality!

Tao (Jr.)

Andy



Prudence

plus many other HKUST IAS colleagues!