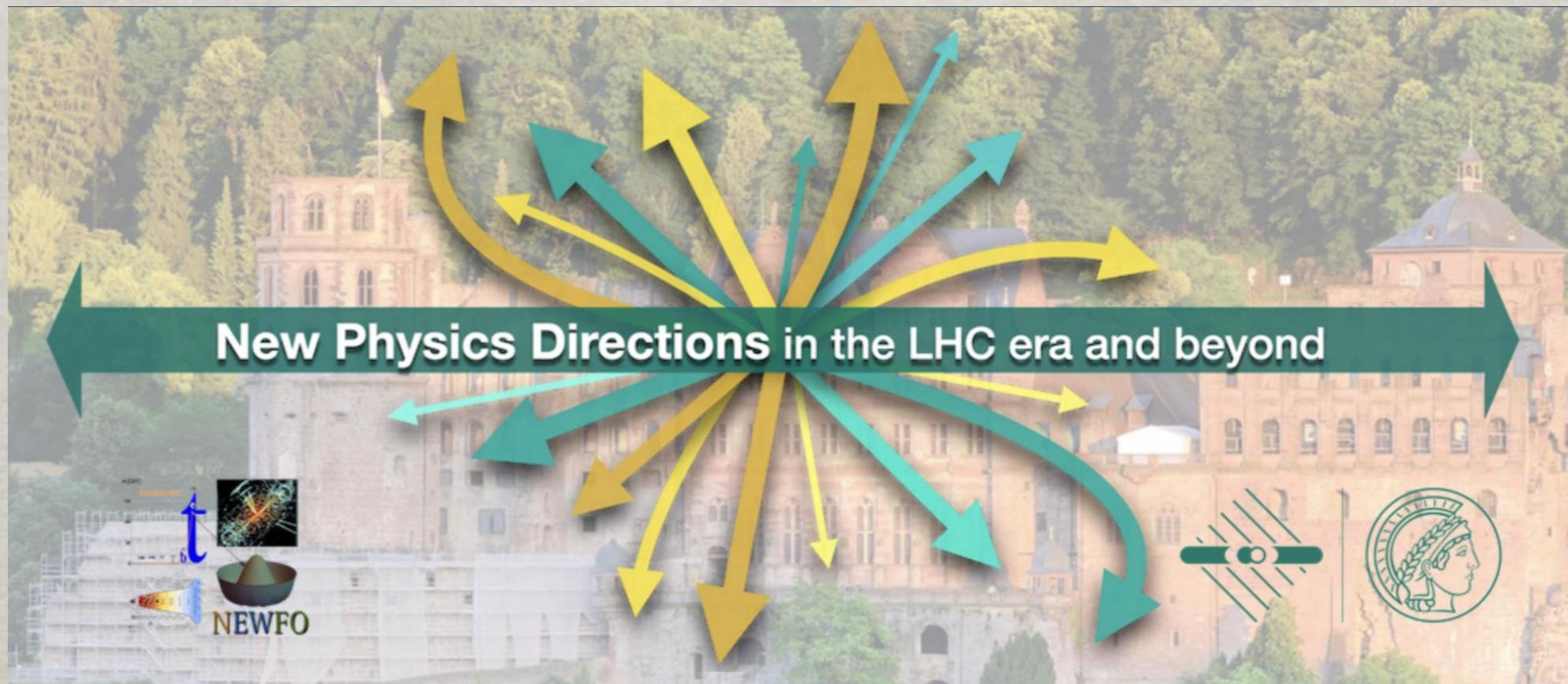# Standard Model & Beyond:
The lessons, puzzles & the way forward

Tao Han

University of Pittsburgh

Max Planck Institute for Nuclear Physics
Heidelberg, April 26, 2024

The Standard Model: Triumph in science!

With the Higgs discovery, completion of the SM:

- A relativistic & quantum-mechanical
- Perturbative & unitary
- Renormalizable & ultra-violet (UV) complete

→ **potentially valid up to an exponentially high scale, perhaps to the Planck scale!**

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 quantum mechanics spacetime gravity strong & matter Higgs
understanding electroweak

An eminent physicist remarked:

"... most of the grand underlying principles have been firmly established. The future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

Michelson–Morley experiment (1887):
"the moving-off point for the theoretical aspects of the second scientific revolution"

Will History repeat itself (soon)?

The Standard Model in the making: Lesson 1: "UV completion"

- QED is UV complete, but doesn't go beyond O(GeV)

  e.g. (g-2)$_e$ versus (g-2)$_\mu$

- QCD is UV complete, could be dynamically extrapolated to an exponentially high scale Q

$$\alpha_s(Q^2) \approx 1/\ln(Q^2/\Lambda_{QCD}^2) \Rightarrow \Lambda_{QCD} \approx Q\exp(-1/2\alpha_s)$$

  But new physics comes in at $v \sim 250 \text{ GeV}$

- The SM with the Higgs IS UV complete,

  but what confidence do we have to extrapolate it to O(M$_{PL}$)?

  (talk by Daniel Litim)

→ **UV completion needs NOT to be a completion!**
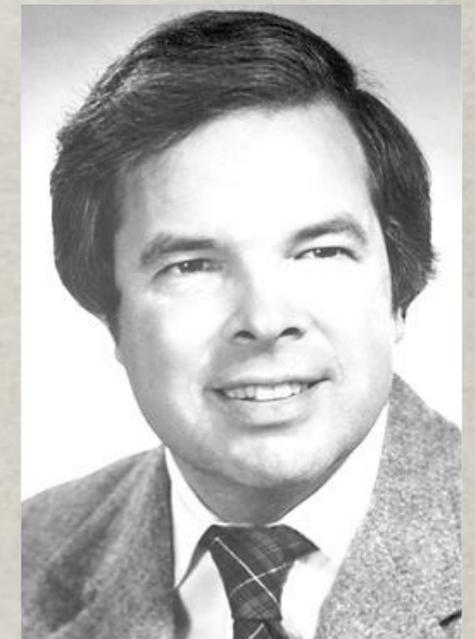*i.e.* **Go for BSM!**

Lesson 2: EFT

"The present educated view of the standard model, and of general relativity, is again that these are the leading terms in effective field theories."   S. Weinberg, hep-th/9702027

"We are all Wilsonians now."

- J. Preskill, Quantum Frontier (2013)

In terms of a new physical scale Λ, below which the theory is valid:

(relevant operators)

$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = \underline{c_0 \Lambda^4 + c_2 \Lambda^2 \mathcal{O}_{\dim 2} + c_3 \Lambda \mathcal{O}_{\dim 3}}$$

$$+ \underline{c_4 \mathcal{O}_{\dim 4}} + \underline{\frac{c_6}{\Lambda^2} \mathcal{O}_{\dim 6}} + ...$$

(marginal operators)   (irrelevant operators)

The 1st (most) "relevant operator": $\quad c_0 \Lambda^4$

Known physics scales and the observation:

$$(M_{PL}/\Lambda_{cosm})^4 \sim 10^{120} \; ! \quad (\Lambda_{QCD}/\Lambda_{cosm})^4 \sim 10^{44} \; !$$

Wilsonian argument failed (badly)!

"… I do not understand (quantum) gravity" --- William Bardeen

The 2nd "relevant operator": the Higgs boson mass

$$V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

$$c_2 \Lambda^2 \sim m_h^2 : \; \lambda v^2 \sim \mu^2 \sim (100 \; \text{GeV})^2 \sim (10^{-16} M_{\text{Planck}})^2$$

"… scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." Ken Wilson, 1970

→**We are only in command with "marginal & irrelevant operators"! Think outside of the box …**

6 (talks by James Wells, Gia Dvali)

Lesson 3: Unification

- Newtonian universal gravitation unified the terrestrial & celestial forces & motion
- Maxwell equations unified the electricity & magnetism
- Dirac eq. unified Schrodinger eq. & Special rel.
  → electron + positron
- The SM unifies the electromagnetism (γ) & weak force ($W^{\pm}$, Z^0) to "electroweak"
  → New vacuum structure

→"Unification" reveals deep principles!

Lesson 4: Symmetry principles

- Time translation → energy conservation
- Spatial translation → momentum conservation
- 3D rotation → angular momentum conservation
- Poincare invariance → mass & spin of states
- "higher symmetry" of space-time & S-matrix
  Supersymmetry? Bosons ←→ Fermions

→Symmetry governs dynamics;
Symmetry breaking specifies the Nature!

- We have LEARNED A LOT about Nature!
- We have ACCOMPLISHED A LOT in the SM making!
- We have been lucky to have WITNESSED the history, and CONTRIBUTED to it!

Still, there are many PUZZLES to contemplate on;

and PROBLEMS that need a solution!

Problem 1: Neutrinos ARE massive

ν's: the most elusive/least known particle in the SM:

- How many species: 3 ν_L 's + N_R?
- Absolute mass scale: $m_\nu \sim y_\nu v < 1$ eV?

  or a new physics scale via "see-saw": $\quad m_\nu \sim \kappa \dfrac{\langle H^0 \rangle^2}{M}$

- Flavor oscillations & CP violation?
- Mixing with sterile/Majorana ν's?
- Portal to dark sector?

Studying neutrino physics has been rewarding:
6[+] Nobel Prizes related to ν's!

Great playground for theory & experimentation.

→ **Determine the masses & their generation mechanism!**

Problem 2: Dark Matter exists

Mounting evidences for DM, thus BSM

Dark Matter in theory: "embarrassment of riches"

axions, dark photons …   sterile ν's   WIMPs   WIMPzillas   PBH?

Dark Matter in practice:

Much more recent activities in light DM detection!

→ **Possible next breakthrough: WIMPs, ALPs …**

Problem 3: Baryogenesis & CPv

The observed baryon dominance → BSM

Sakharov conditions: Talks by Geraldine Servant, M. Muhlleinter

- Baryon # violation (EW sphalerons)
- C & CP violation (BSM)
- Out of equilibrium (1st order PT, BSM)

Many BSM theories to accommodate

- Affleck-Dine mechanism (primordial universe)
- Lepto-genesis (ΔB = ΔL via sphalerons)
- EW baryogenegis (1st order PT, BSM)

Observationally,

ΔB ≠ 0 → proton decay, $n - \bar{n}$ oscillation

ΔL ≠ 0 → Majorana neutrinos

Plus extra Higgs bosons to search for

Stochastic gravitational waves …

Puzzles
that we may not find a solution

- Mass hierarchy: "Naturalness"?

- Flavors: "minimal flavor violation"?

- New dynamics: "Composite"?

- Extended symmetry: SUSY?

- Unified forces: GUTs?

- Extra dimensions / Quantum gravity?

- … …

The Way forward: global context

- **Europe**

European Strategy Process:

2020 Update of European Strategy for Particle Physics

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

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

- **Asia**

- Japan: 2017 JAHEP/KEK Roadmap:

  SuperKEKB; J-PARC; Hyper-K; ILC …

- China: BEPC-II; JUNO; PandaX; LHAASO; AliCPT, CEPC/SppC …

- **United States**

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

Explore the Quantum Universe

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

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

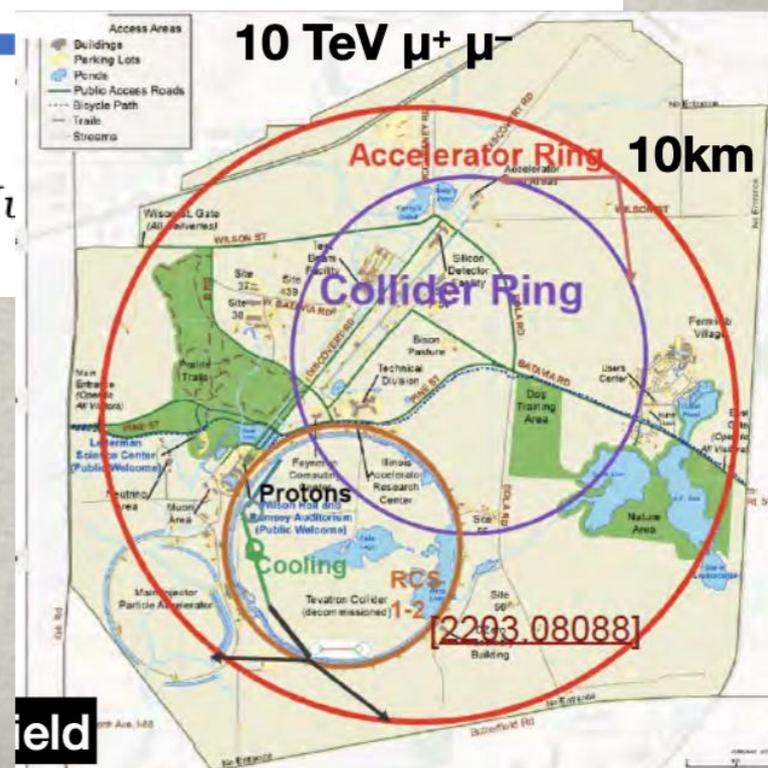- Exploring other e^+e^- collider options to fully utilize the Fermilab site

Proposals emerging from Snowmass 2021 for a US based collider

Approximate timelines for proposals for ILC/CCC and Mu[...] for a US based collider option.
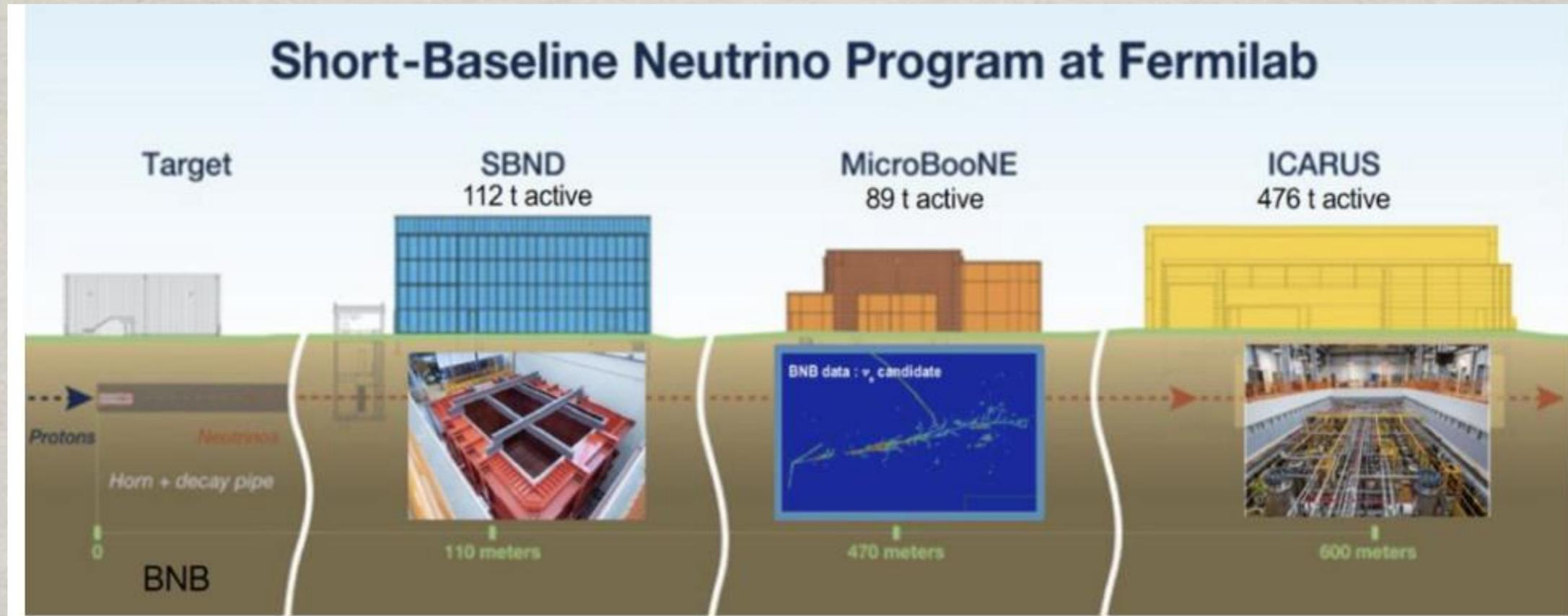
The "Muon Shot"

Most wanted coupling: hhh

collider	Indirect-h	hh	combined
HL-LHC [78]	100-200%	50%	50%
ILC$_{250}$/C^3-250 [51, 52]	49%	—	49%
ILC$_{500}$/C^3-550 [51, 52]	38%	20%	20%
CLIC$_{380}$ [54]	50%	—	50%
CLIC$_{1500}$ [54]	49%	36%	29%
CLIC$_{3000}$ [54]	49%	9%	9%
FCC-ee [55]	33%	—	33%
FCC-ee (4 IPs) [55]	24%	—	24%
FCC-hh [79]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [64]	-	15-30%	15-30%
μ(10 TeV) [64]	-	4%	4%

Conclusive test for the Higgs potential & EWPT

On-going & Upcoming neutrino Experiments

Future LBNE:

Exp.	Time	Mass ordering	CP phases	Precision Meas.
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*
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*
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*

G2 to G3 DM Direct Detection

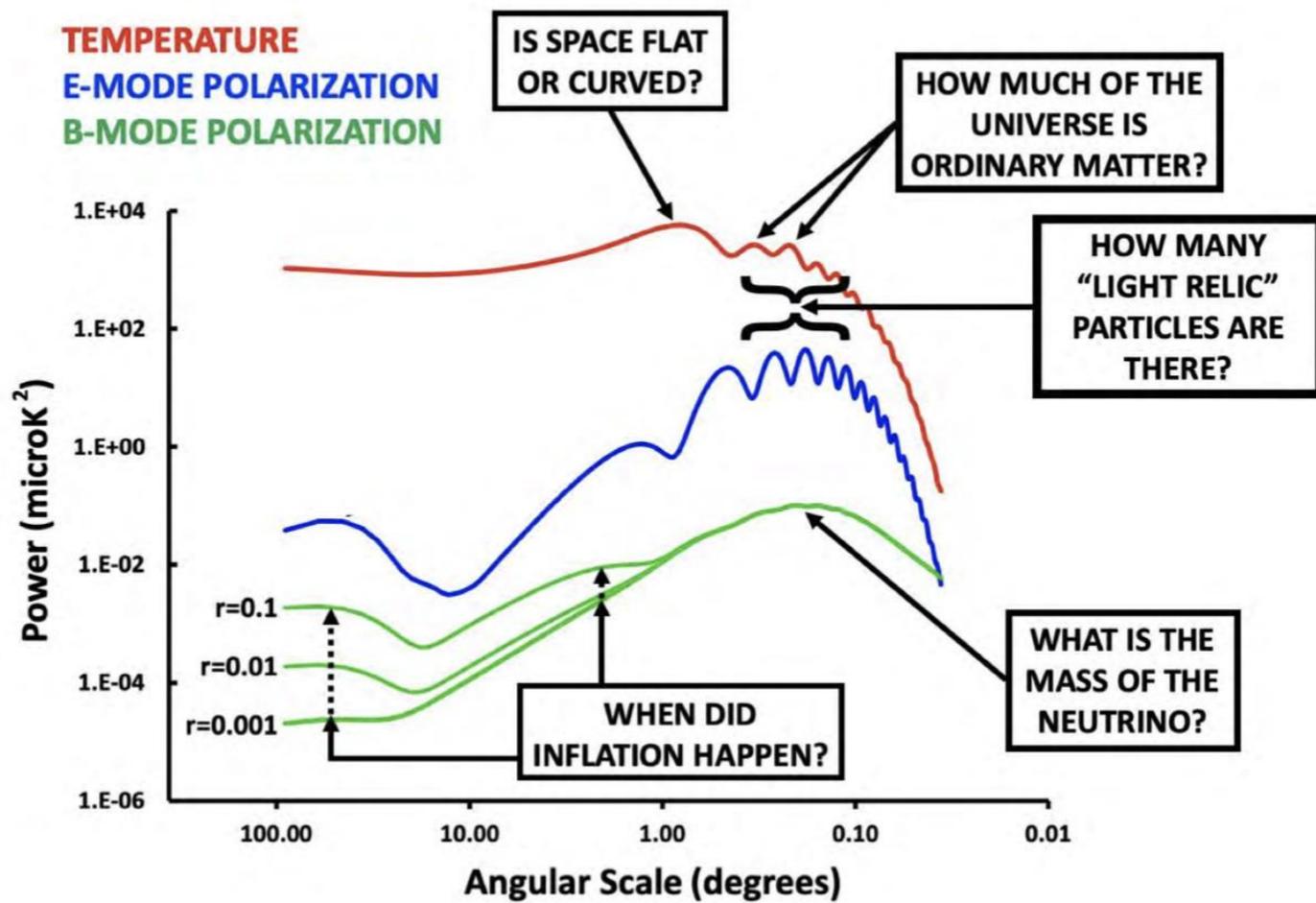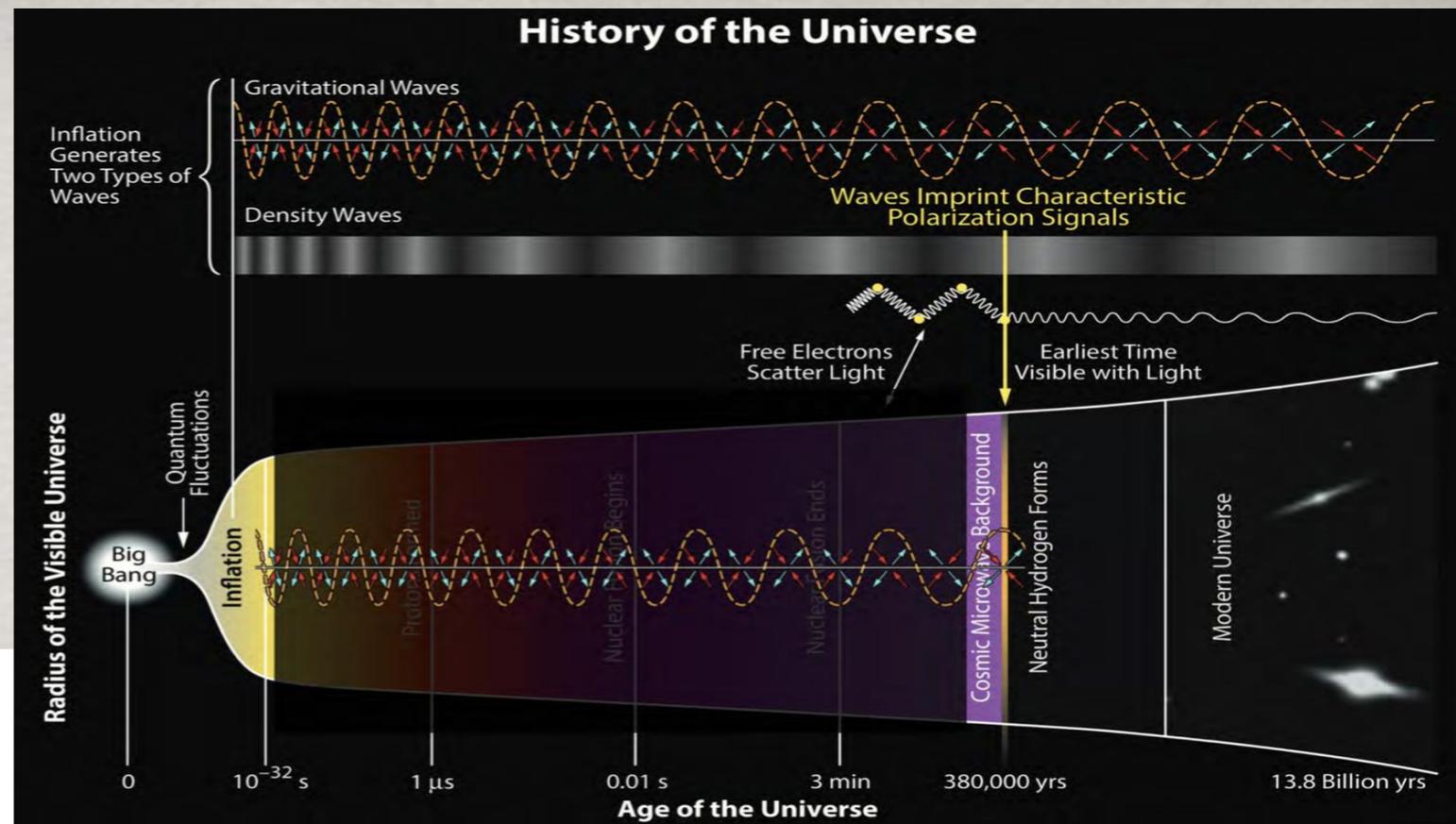Gradient of Xe discovery limit, $n = -(d \ln \sigma / d \ln MT)^{-1}$
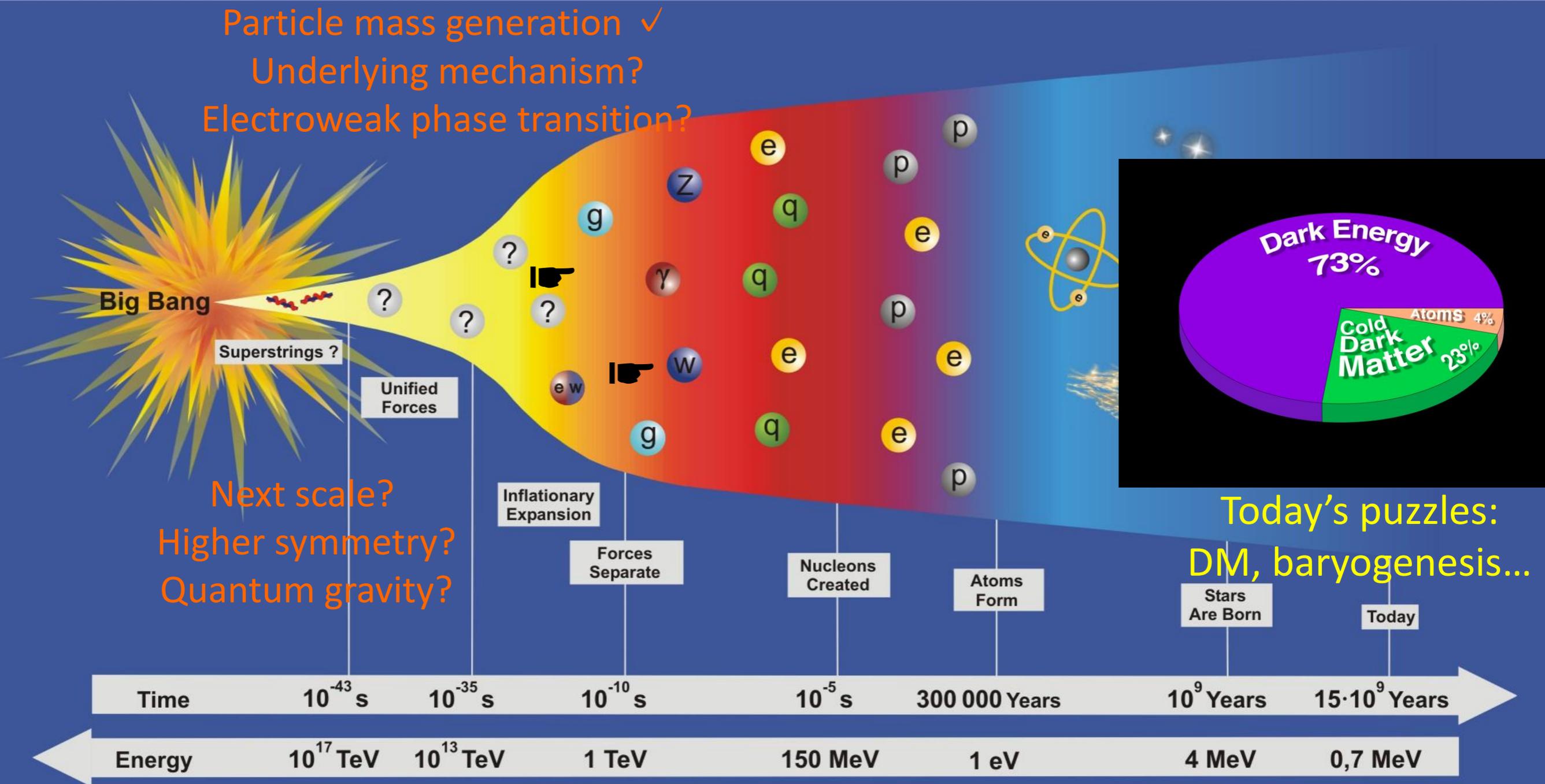
GeV low mass:
DD difficult;
Collider complementary

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

Particle physics &
early universe cosmology

CMB S4

A Grand Picture: SM & BSM

Particle mass generation ✓
Underlying mechanism?
Electroweak phase transition?

Next scale?
Higher symmetry?
Quantum gravity?

Today's puzzles:
DM, baryogenesis…

Big Bang

Superstrings ?

Unified
Forces

Inflationary
Expansion

Forces
Separate

Nucleons
Created

Atoms
Form

Stars
Are Born

Today

| Time | 10^{-43} s | 10^{-35} s | 10^{-10} s | 10^{-5} s | 300 000 Years | 10^9 Years | $15 \cdot 10^9$ Years |

| Energy | 10^{17} TeV | 10^{13} TeV | 1 TeV | 150 MeV | 1 eV | 4 MeV | 0,7 MeV |

Dark Energy 73%
Cold Dark Matter 23%
Atoms 4%

exciting journey ahead!

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New Physics Directions in the LHC era and beyond

F. Goertz (chair)
A. Ahmed
A. Angelescu
A. Bally
Y. Chung
S. Fabian
M. Hager
S. Najjari
Á. Pastor-Gutiérrez
A. Tada
B. Schwarz (scientific secretary)

Backup slides

HEP at a Cross-Road

While there are many fundamental questions,
no clear argument for the next physics scale for discovery!
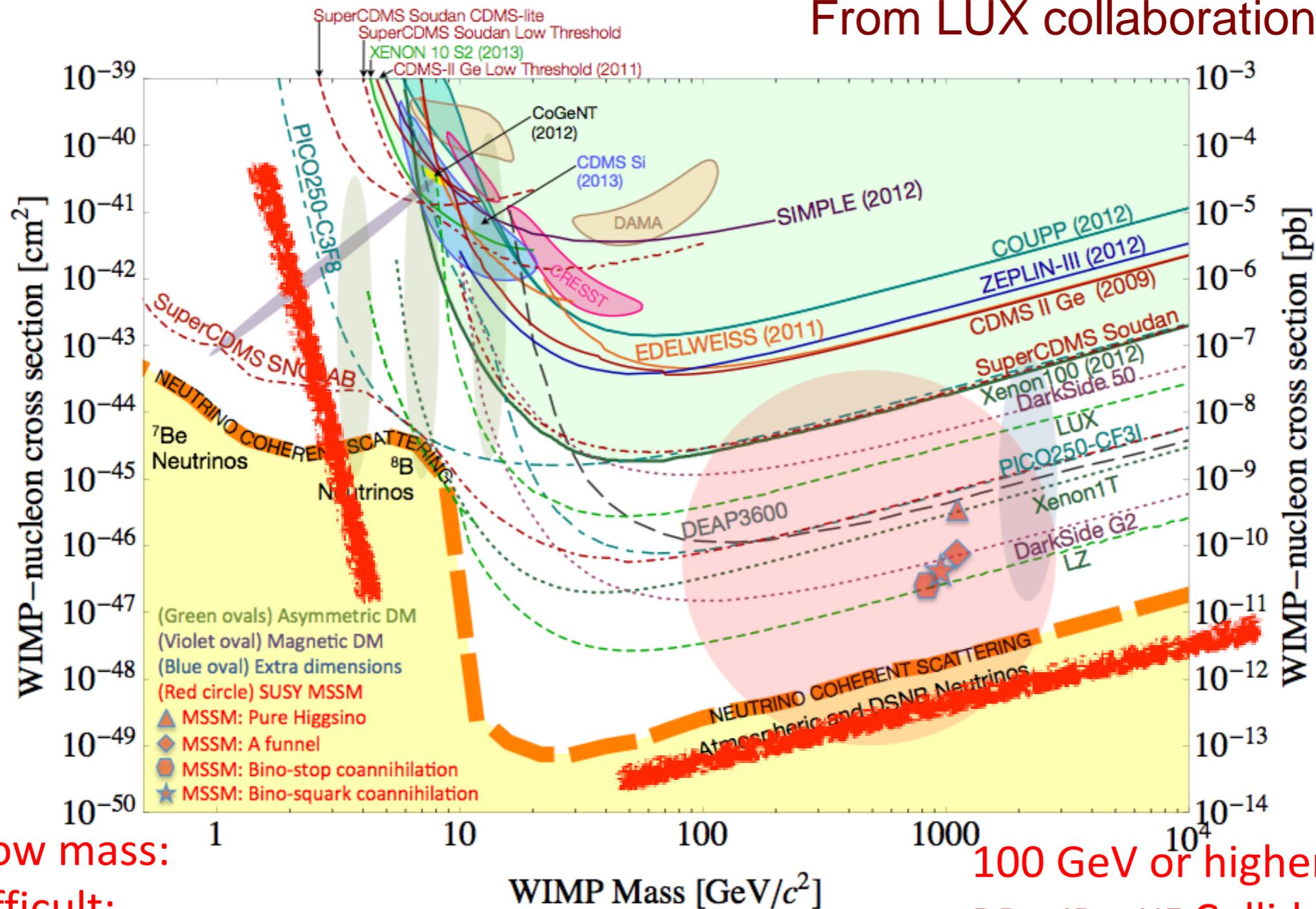
"Prediction is hard, especially about the future."
"When you come to a fork in the road, take it!"
— Yogi Berra

We must explore all directions!

From LUX collaboration

GeV low mass:
DD difficult;
Collider complementary

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

From Fermilab

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

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

Sanford Underground Research Facility

Fermilab

800 miles/1300 km

NEUTRINO PRODUCTION

EXISTING LABS — UNDERGROUND PARTICLE DETECTOR

PARTICLE DETECTOR

PIP-II PROTON ACCELERATOR

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

Puzzles
1. "Naturalness" facing the challenge

- In chemistry/AMO, m_e sets the scale, naturally :

$$a_{Bohr} = 1/\alpha m_e \sim 0.05 \text{ nm}, \quad E_{atom} \sim \alpha^2 m_e \sim 30 \text{ eV}$$

- Weak decay sets the scale: $1/\sqrt{G}_F \sim v \sim 250 \text{ GeV}$
  → the gauge boson mass, naturally:

$$M_W = \frac{1}{2}gv \approx 80 \text{ GeV}, \quad \Delta M_W^2 \sim M_W^2 \ln(\Lambda/M_W)$$

- But the Higgs mass fails our intuition, in the Wilsonian sense:

$$m_H = \sqrt{2}\ \mu = (2\lambda)^{1/2}\ v = 125 \text{ GeV} \qquad \delta m_H^2 \propto -\frac{k^2}{4\pi^2}\Lambda^2$$

What is Λ? $\Lambda \sim 4\pi v$, or M_{SUSY}, or M_{PL} ?

Dynamical scale generation is natural!

QCD inspired strong interacting theory:
Dynamical scale ("Technicolor") can be
generated by "dimensional transmutation":

$$\Lambda_{TC} \approx \Lambda \ \exp(-\frac{1}{2\alpha_{TC}}) \approx 4\pi v.$$

Observationally:

New dynamics not far from O(1 TeV)

Higgs composite $\rightarrow$ couplings, form factors?

and "partners": $T^{\pm}$, $\boldsymbol{\rho}^{\pm,0}$, $\boldsymbol{\Pi}^{\pm,0}$ ...

Collider searches actively on-going ...
The absence of the signal signifies
the "Little hierarchy"

Puzzles
2. Flavors: masses & mixing

- Particle mass hierarchy

- Patterns of quark, neutrino mixings

- Tiny neutrino masses!

- New CP-violation sources?

Higgs Yukawa couplings as the pivot for all !

Masses (eV)

10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

10^{15} to M_{PL}

(TeV)

t   W,Z $h^0(126)$ whale

b

τ c   (GeV)

μ s   tiger

d

u

e   (MeV)

cat

All proportional to v

(eV)

ν_3

ν_2

10^{15} to V

ν_1 mosquito

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Flavor physics in theory: a serious challenge!

BSM: much harder to accommodate!

- Generate multiple mass scales
- Avoid FCNC
- Avoid Excessive CP violation

- Why the flavor mixing aligned with the SM Yukawa form?
  → Minimal Flavor Violation (MFV)

- Horizontal flavor symmetry: Froggatt-Nielson mechanism

$$(Y_u)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[u_j]}, \qquad (Y_d)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[d_j]}$$

- Warped extra-dimension: Couplings determined by the overlap with the EW brane.

- Radiative generation of m_f :

light generation masses loop suppressed ~ $1/16\pi^2$ ~ 10^{-2}.

Vibrant field in experimental explorations!

Lesson 4: s
4. "Symmetry" governs dynamics

- Time translation → energy conservation
- Spatial translation → momentum conservation
- 3D rotation → angular momentum conservation
- Poincare invariance → mass & spin of states
- "higher symmetry" of space-time & S-matrix
  Supersymmetry? Bosons ←→ Fermions

Observationally: hopefully near the EW scale O(100 GeV)

Talk by Margarete Muhlleitner

The known world of Standard Model particles

The hypothetical world of SUSY particles

- quarks
- leptons
- force carriers

- squarks
- sleptons
- SUSY force carriers

Supersymmetry in theory:

- SUSY unification
- Super-gravity
- Super-string/M theory
- Swampland

Supersymmetry in practice:

- Understanding Higgs scalars
- Predicting cold DM
- Baryogenesis & proton decay
- Neutrino mass & flavor physics
- Early universe cosmology

→ (arguably) most attractive theory for BSM

Recommendation 1

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

Including:

a. HL-LHC (energy frontier)

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

c. The Vera Rubin Observatory (dark energy survey)

Plus smaller scale projects:

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

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

c. DESI   (DM, inflation)

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

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

LHC → High Luminosity LHC
(Caterina Vernieri)

| LHC | | | | | | | HL-LHC | | | | |

RUN 2
8M H

Upgrade of accelerator and experiments

RUN 3
16M H
(300 fb⁻¹)

HL-LHC installation
ATLAS Upgrade

(3 ab⁻¹)
RUN 4/5
170M H
120K HH

| 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | . . . | 2039 |

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

New physics reach:
M, Λ ~ O(a few TeV)
just above the EW scale!

- 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	> 9.6×10^{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.

Camera

Vera C. Rubin Observatory
Cerro Pachón, Chile

Simons Observatory
Atacama Desert, Chile

Cerro Tololo Inter-American Observatory
Chile

U.S. Community Summer Study: Snowmass 2021
July 17 – 26, 2022 @ UW – Seattle
http://seattlesnowmass2021.net

Seattle Snowmass 2022 | Home | indico | Logistics ∨ | Links ∨ | About ∨ | Code of Conduct

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

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

Summary & Frontmatter
Accelerator Frontier
Community Engagement Frontier
Computational Frontier

Cosmic Frontier
Energy Frontier
Instrumentation Frontier
Neutrino Frontier

Rare Processes Frontier
Theory Frontier
Underground Facilities 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.

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SUSY in the Search @ LHC

Talks by C. Herwig,
Stefano Passagio,
Evan Carlson

...

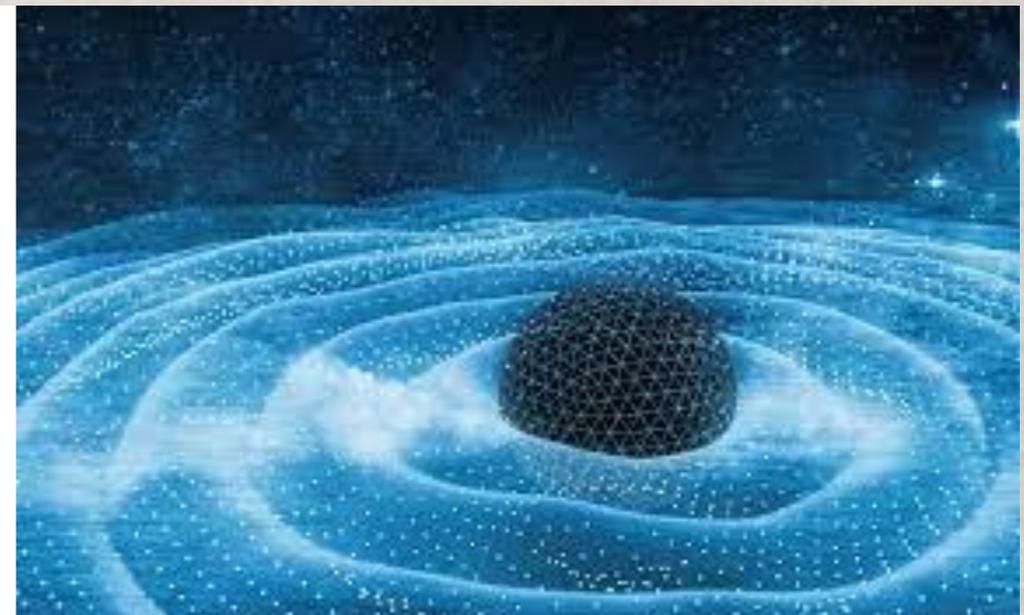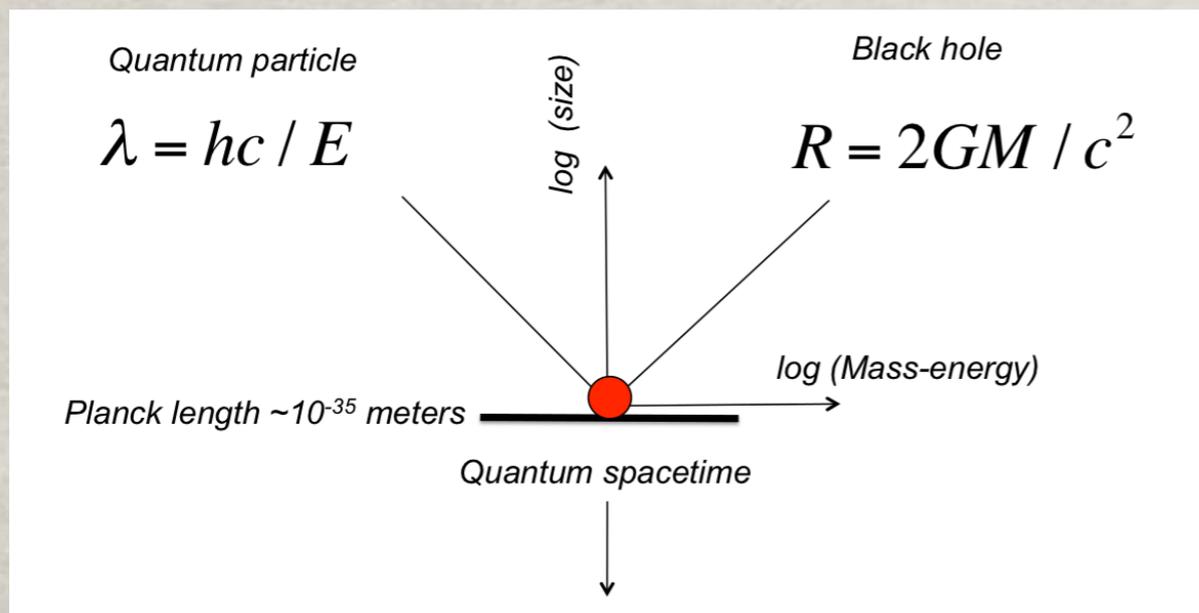Stringent mass bounds > 1 – 2 TeV!
The search continues at colliders as well as precision physics.

6. The marriage of Relativity & Quantum mechanics is the ultimate destiny

When approaching the Planck scale, the world is necessarily relativistic & Quantum-mechanical.

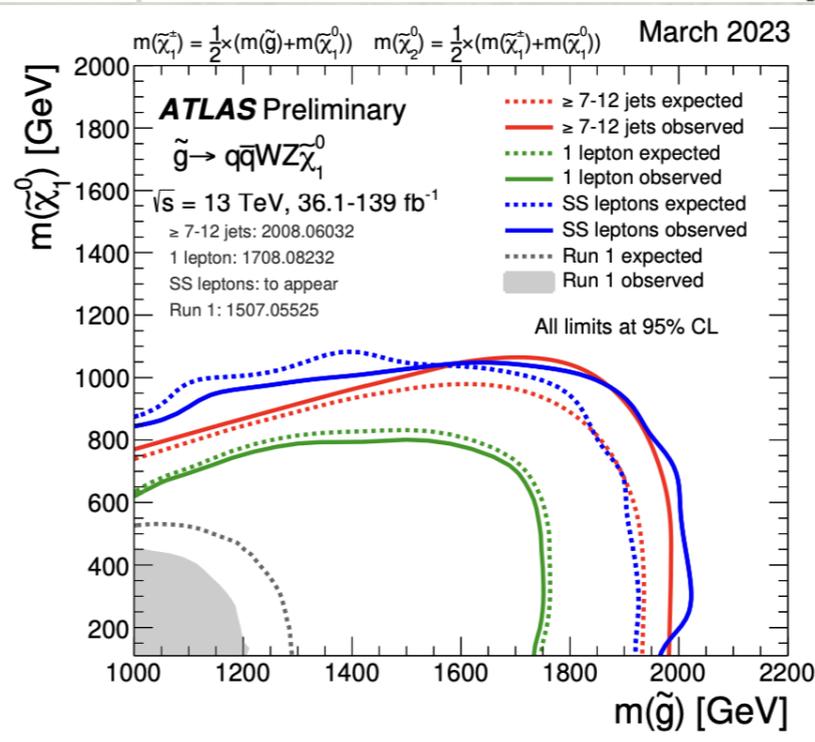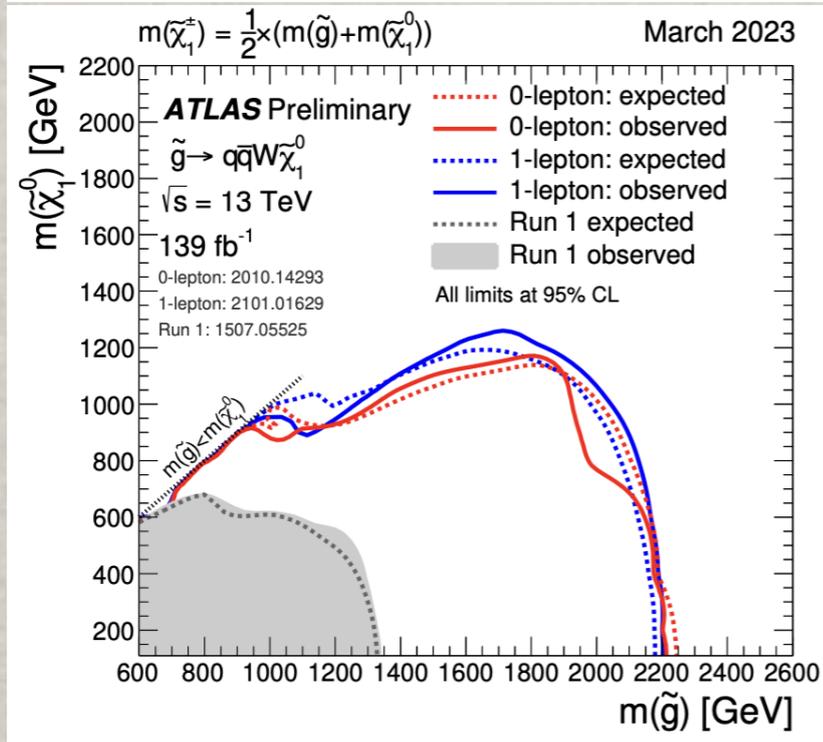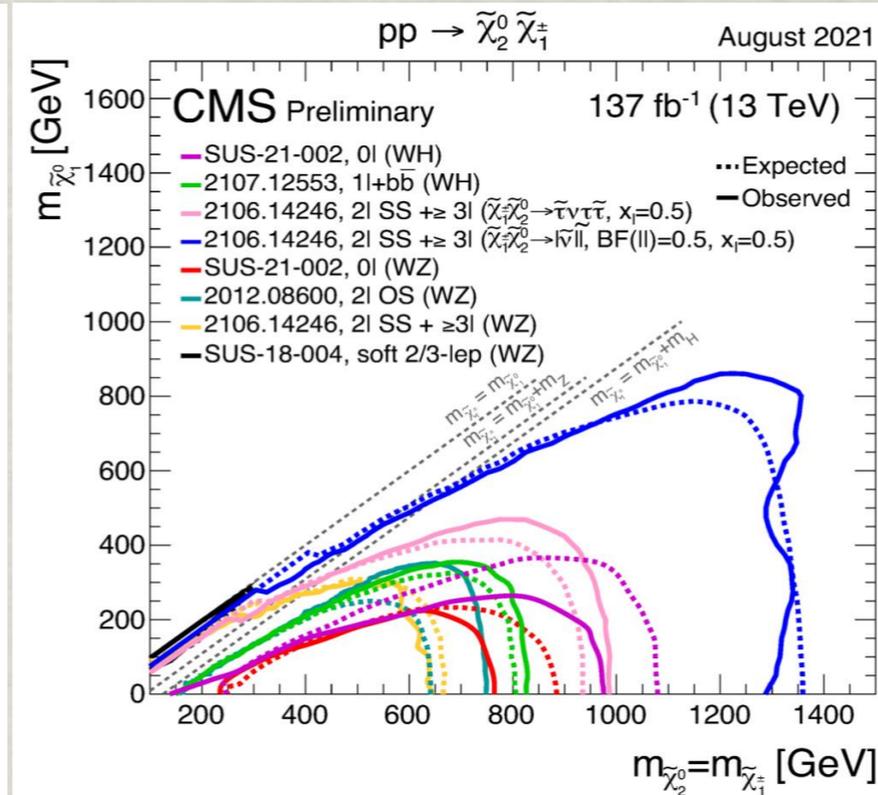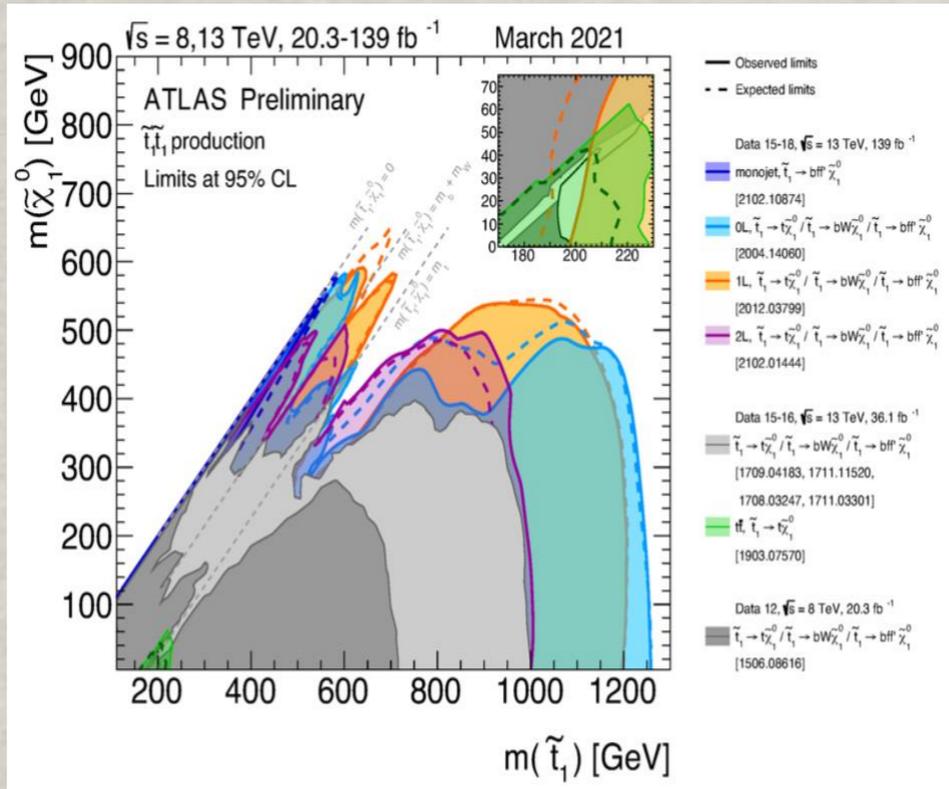$$l_p = \sqrt{\frac{G\hbar}{c^3}}$$
$$= 1.616 \times 10^{-35} \, meters$$

Quantum particle

$$\lambda = hc / E$$

log (size)

Black hole

$$R = 2GM / c^2$$

log (Mass-energy)

Planck length ~10^{-35} meters

Quantum spacetime

We do not have a unitary, renormalizable formulation ...
Perhaps string theory? but how to test?

Talk by David Kaplan, John Kovac

In practice,
primordial GW & BH observation may shed light on.

SUSY in the Search @ LHC

Talks by C. Herwig,
Stefano Passagio,
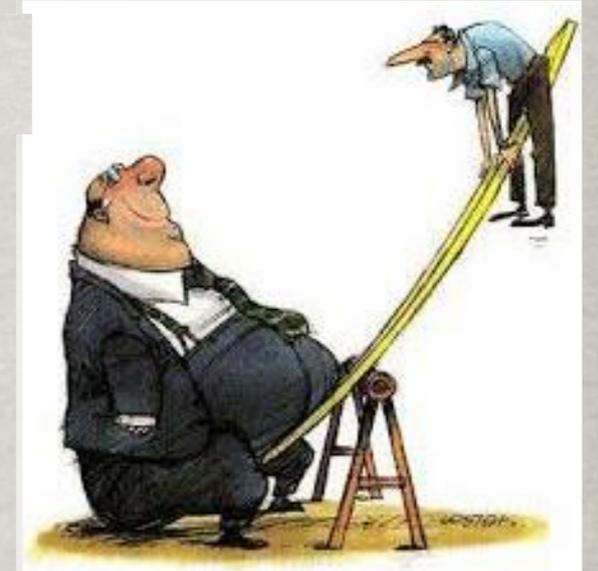Evan Carlson

...

Stringent mass bounds > 1 – 2 TeV!
The search continues at colliders as well as precision physics.

SM → **ν** SM: the seesaw spirit

The leading SM gauge invariant operator is at dim-5:[*]

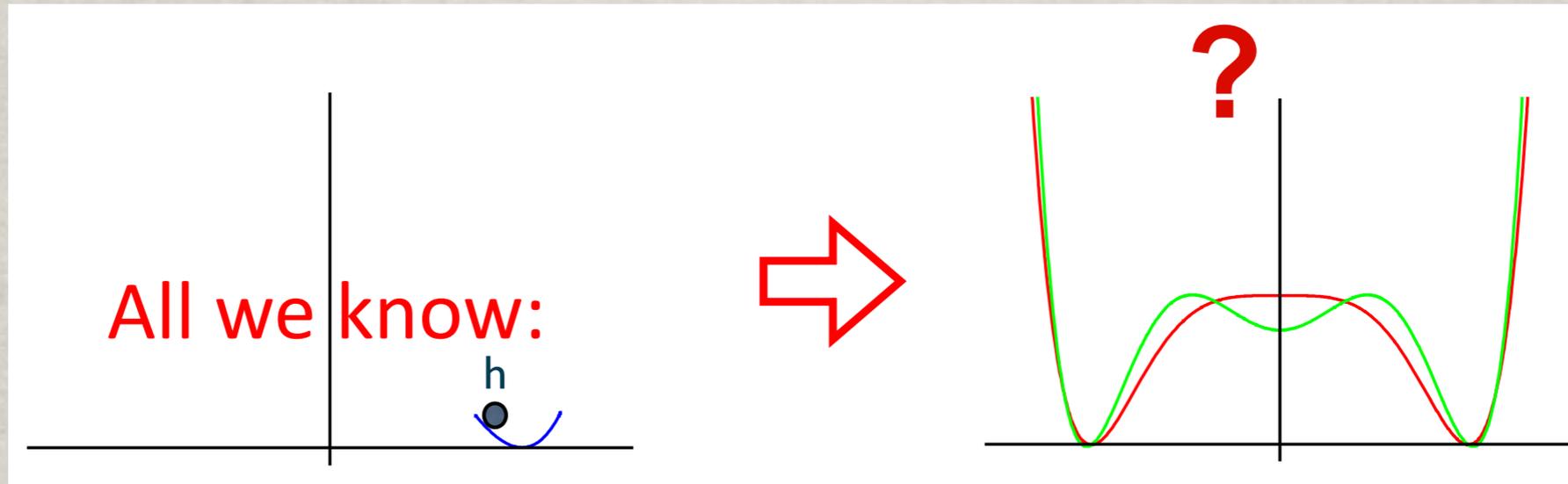$$\frac{1}{\Lambda}\,(y_\nu L H)(y_\nu L H) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\,\overline{\nu_L}\,v_R^c.$$

[*]S. Weinberg, Phys. Rev. Lett. 1566 (1979)

- Theoretical: **Λ** → new scale / particles, implies an underlying (UV) theory!

→ There are three possibilities @ tree-level:
- Type I: New fermion singlets N ⊗(L H)$_S$
- Type II: New scalar triplet **Φ** ⊗(L L)$_T$
- Type III: New fermion triplets T ⊗(L H)$_T$

- Observational: Talks by Mikhail Danilov, Ruben Saakyan
  ΔL=2 → Majorana mass (Majorana neutrinos)
  → much activity on-going:
  $0\nu 2\beta$ decay, meson decays, collider searches …

Quests for SM
The Nature of EWSB ?

All we know:

h

?

With new physics near the EW scale:

$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3$$

→λ_{hhh}= (7/3)λ_{hhh}^{SM}

$$\left. + \frac{1}{2}\lambda(h^\dagger h)^2 \log \frac{(h^\dagger h)}{m^2} \right]$$

→λ_{hhh}= (5/3)λ_{hhh}^{SM}

$\lambda(h^+h)^2$ term could be made "-":
leading to EW phase transition strong 1st order!
→ O(1) deviation on λ_{hhh}

Snowmass on Future Colliders:
Energy Frontier / Accelerator Frontier

Physics interests

e-collider 25 TeV
μ-collider 30 TeV

FCC-hh

μ-collider 14 TeV

CLIC

FCC-ee   ILC C^3 μ-collider 125

Technology challenge

Renewed interests:

- Muon colliders
- C^3: Cool Copper Collider (Linear e^+e^-)

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: Covering the thermal target

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

Bread & butter ν physics:

JUNO (starting 2024):

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

$\pm 1\%$ in six years of data taking.
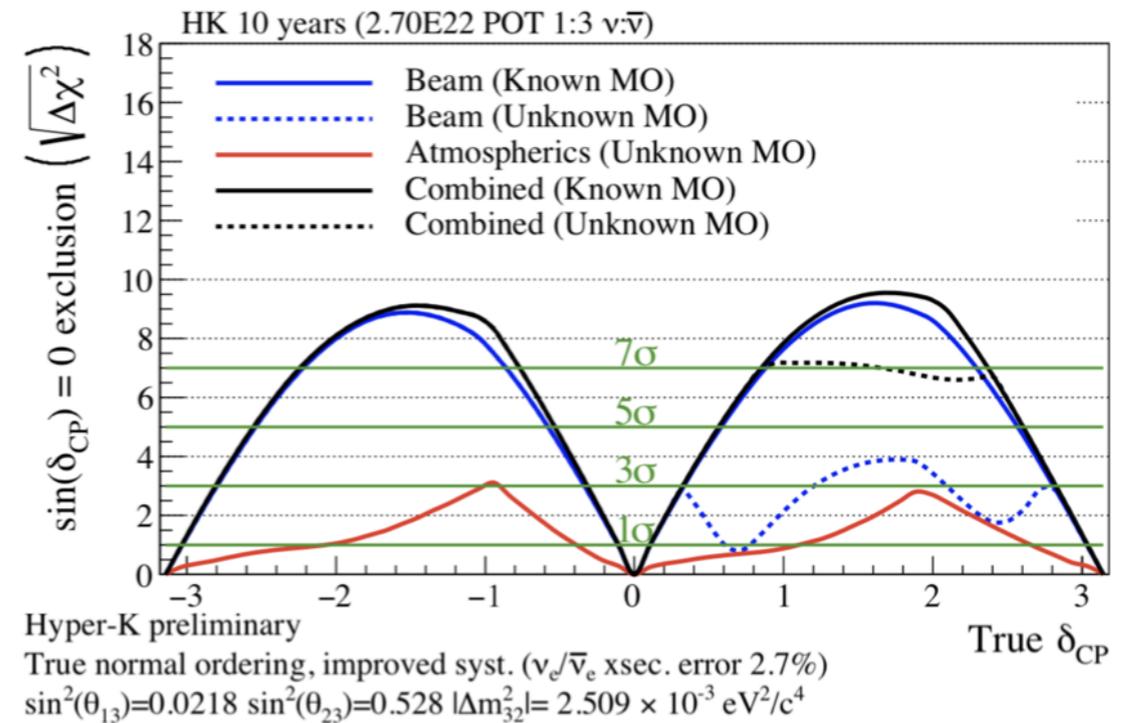
Hyper-K (starting 2027):

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}.
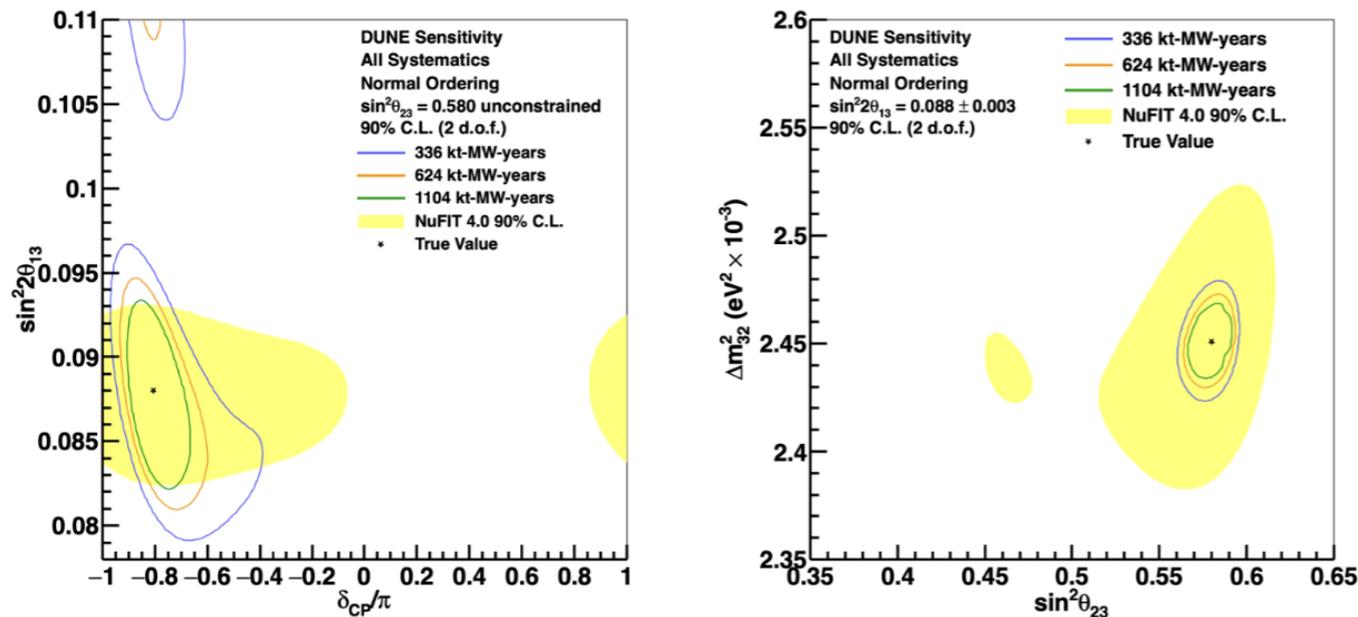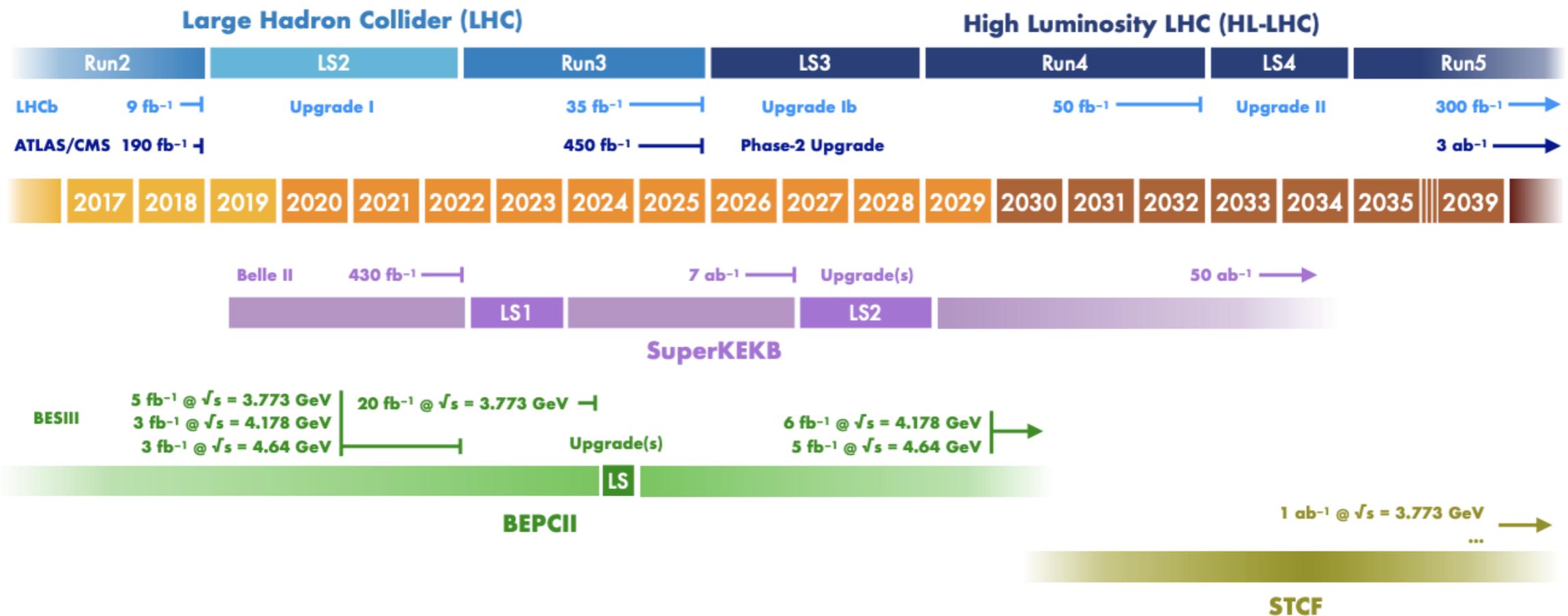
DUNE (starting 2032):

FIG. 3. 90% confidence intervals for $\sin^2 2\theta_{13} - \delta_{CP}$ (left), and $\sin^2 23 - \Delta m_{32}^2$ (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.
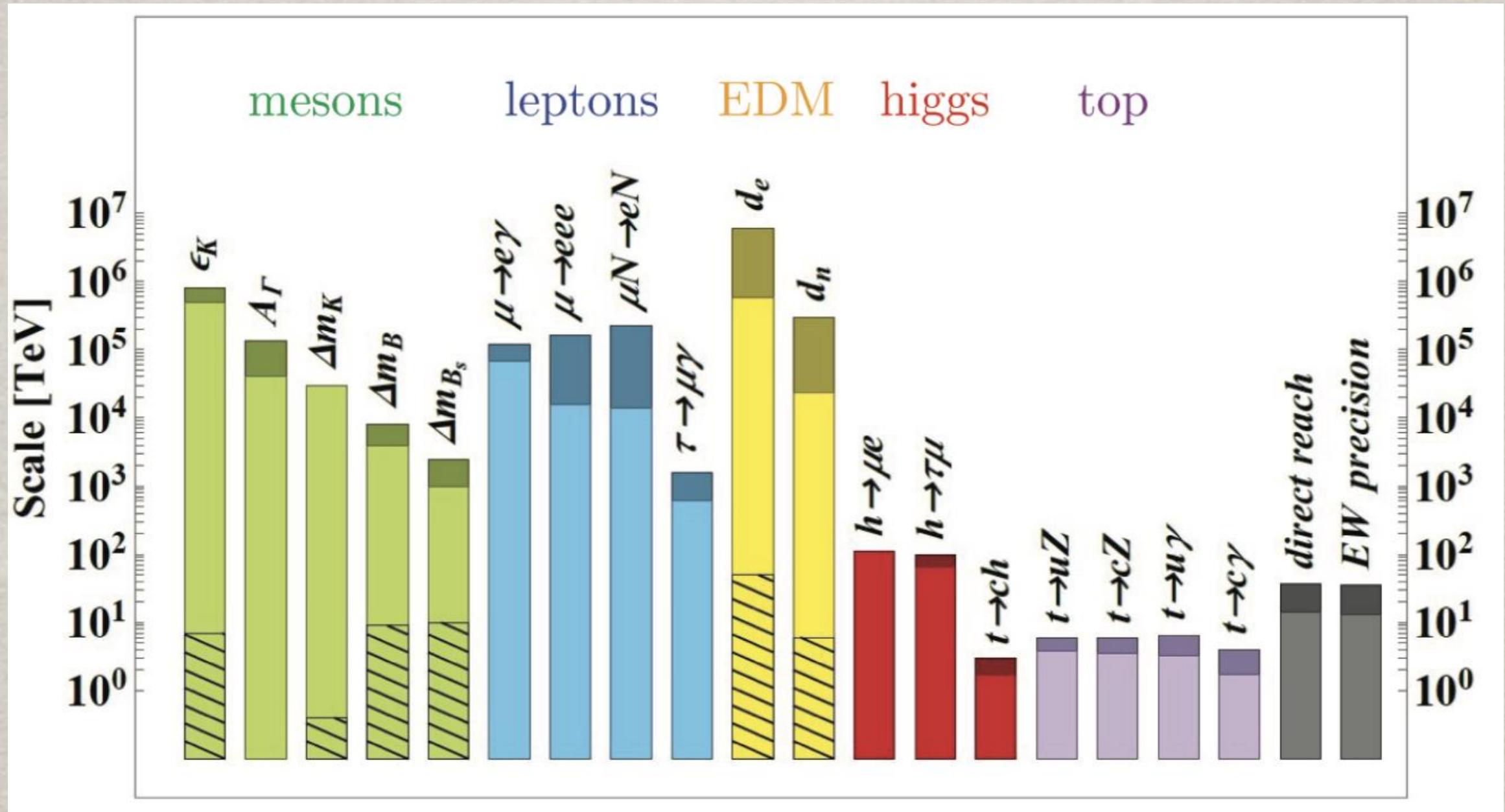
Complementarity!

(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

Axion search plans

WIMP DM direct searches