Theory Motivation for Future Colliders

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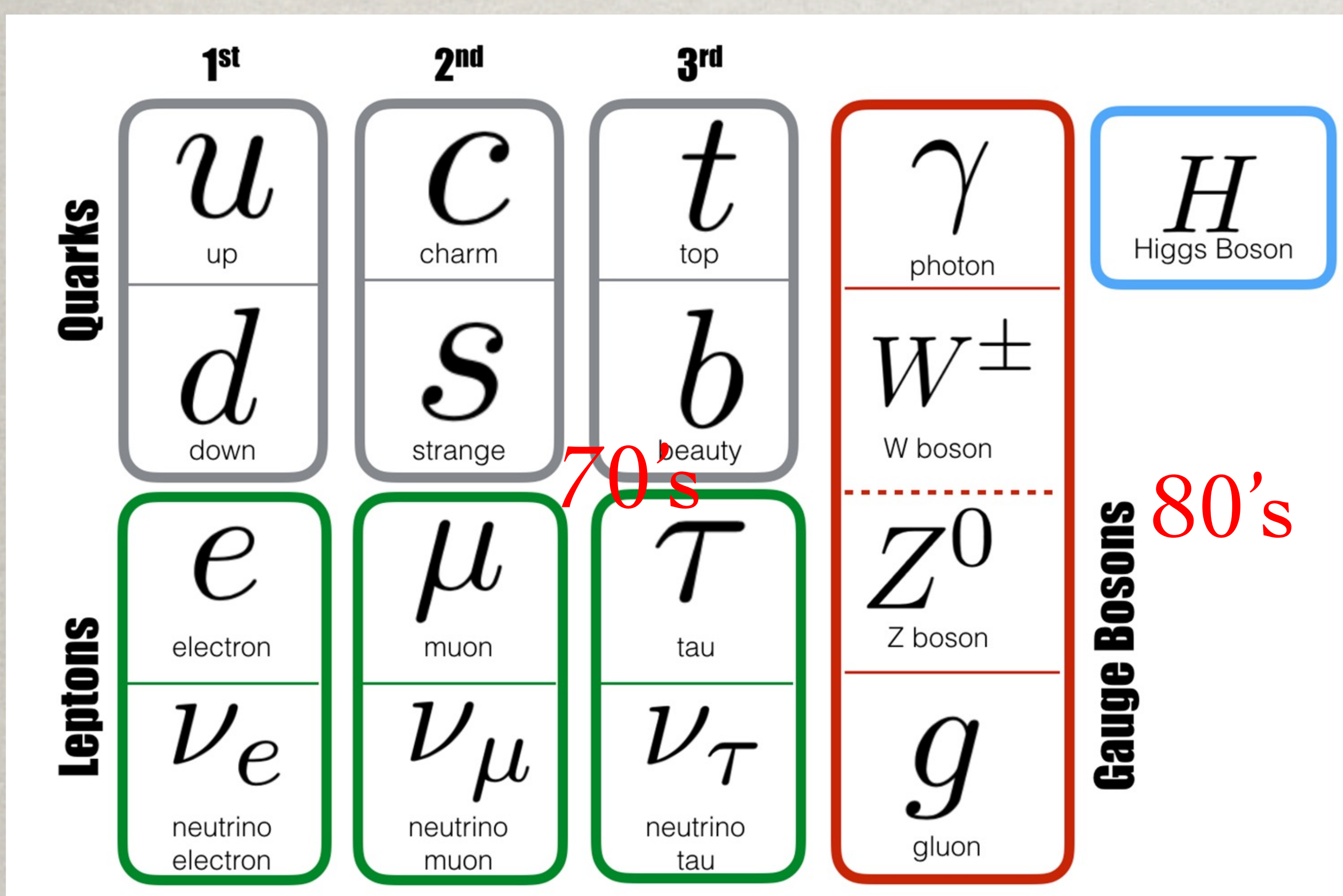
HEP: Uninterrupted discoveries for more than half a century!

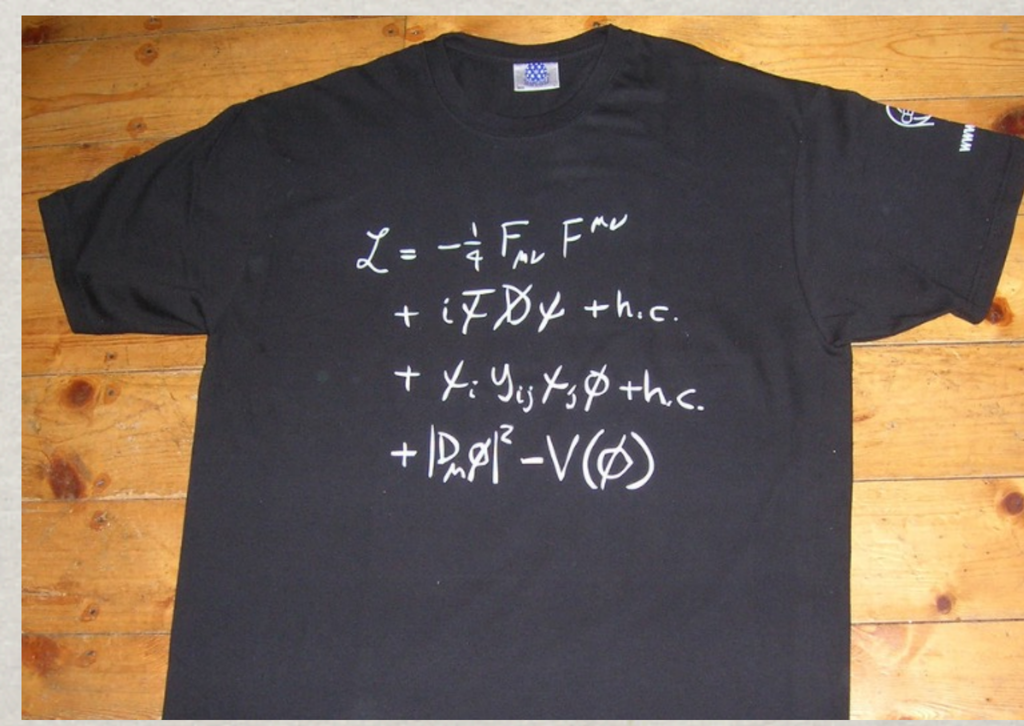
From quarks to the Higgs boson, with heroic efforts in theory and experiments:

60's 70's 90's 2012



ν's: 1930/1956 1962 2000

The Standard Model of particle physics



THE SM: Most precise theory in science

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} (!?)

Λ? Dark Matter?
Cosmic inflation?

All known physics

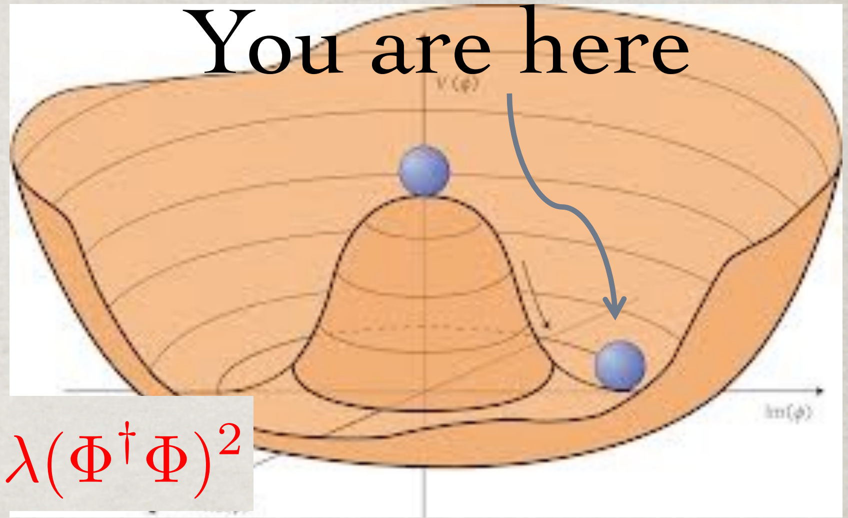
B-asymmetry?
CP violation?
M_ν ? Scale hierarchy …

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

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

Question 1. Electroweak Superconductivity

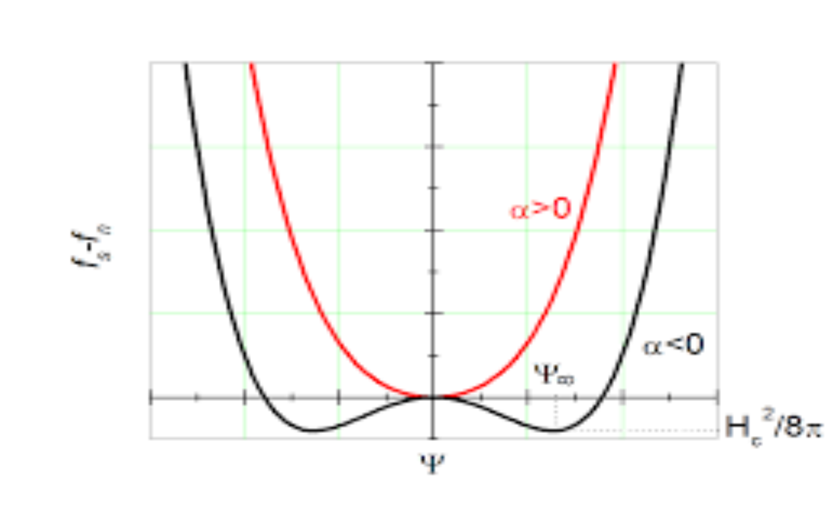
10^{-9} s after the Big Bang, when the Universe was as cold as 10^{15} K, the electro-weak phase transition took place.
Ever since, the Universe is in an EW super-conducting phase. $V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$



It's like Landau-Ginzburg Theory:

$$F = \alpha(T)|\psi|^2 + \frac{\beta(T)}{2}|\psi|^4$$

$$|\psi|^2 = -\frac{\alpha(T)}{\beta(T)}$$



- an effective phenomenological theory near the phase transition; an "order parameter" description.
- **BCS as the underlying theory to understand the dynamical mechanisms, to calculate *α*(T), *β*(T)!**

It's NOT Landau-Ginzburg Theory

The Higgs sector is a consistent scalar quantum field theory, valid to high scales.

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$<|\Phi|> = v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV} \qquad m_H = \sqrt{2\lambda}v = 125 \text{ GeV}$$

For such mass and coupling,
the Universe underwent a **slow crossover** EW phase change.

- The vacuum is a Type II EW superconductor:

$$\kappa \equiv \frac{\text{penetration depth}}{\text{coherence length}} = \frac{m_H}{M_W} \approx 1.5$$

- The Higgs boson is weakly coupled, $\lambda \sim 0.13$,
- Very narrow resonance: width/$m_h \approx 10^{-5}$.
- Elementary up to a scale ~1000 GeV!

The Higgs boson IS NEW PHYSICS!

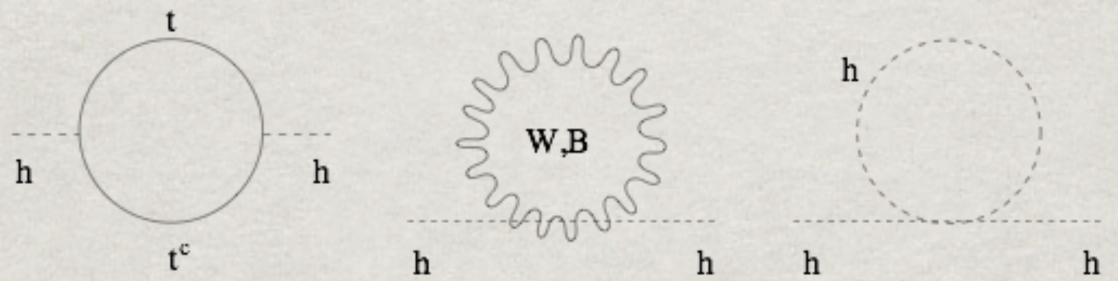
An underlying theory to calculate μ^2, λ?

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

In Wilsonian EFT, the Higgs mass a "relevant operator":

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

"… 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



(a) (b) (c)

$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

As opposed to "technically natural": $\delta m_w^2 \sim m_w^2 \ln(\Lambda/m_w)$ (gauge symm) $\delta m_f \sim m_f \ln(\Lambda/m_w)$ (chiral symm)

The "Hierarchy problem" between m_h & M_{Planck}

- $\Lambda \sim 4\pi v$ near O(TeV) new dynamics?
- Or new principles: SUSY, extra dim, etc. ?
- Or accept "fine tune": **the anthropic principle?**

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

It represents a weakly coupled new force (a fifth force):

- **In the SM, λ is a free parameter, now measured at LHC energies $\lambda \approx 0.13$**
- **In SUSY, it is related to the gauge couplings tree-level: $\lambda = (g_L^2 + g_Y^2)/8 \approx 0.3/4$ ← a bit too small**
- **In composite/strong dynamics, harder to make λ big enough. (due to the loop suppression by design)**

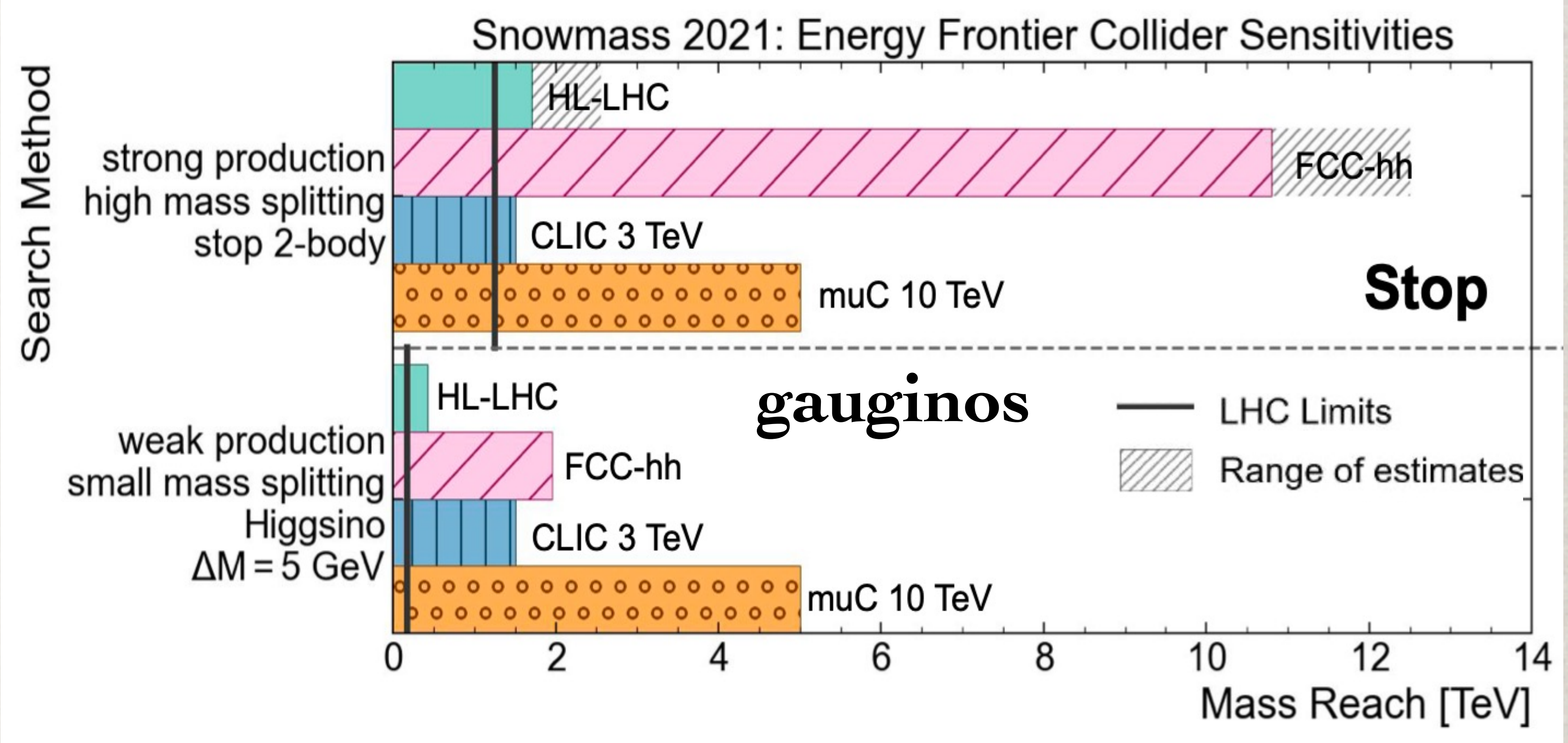
Already possess challenge to BSM theories.

(Strongest) Motivation for Future Colliders

~ 10 TeV pCM energies

Pushing the "Naturalness" limit:

The searches for top quark partners
& gluinos, gauginos, & heavy Higgses …



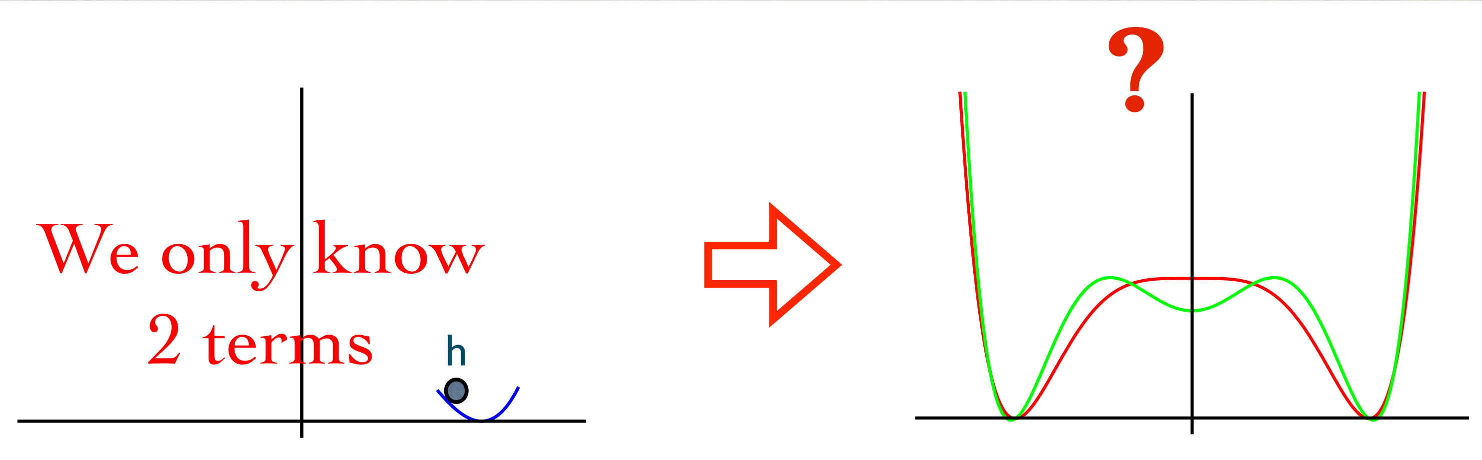
→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

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

Question 2: The Nature of EWSB ?

In the SM, $m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89 \text{ GeV}, \quad \lambda \approx \frac{1}{8}.$

slow cross-over phase change



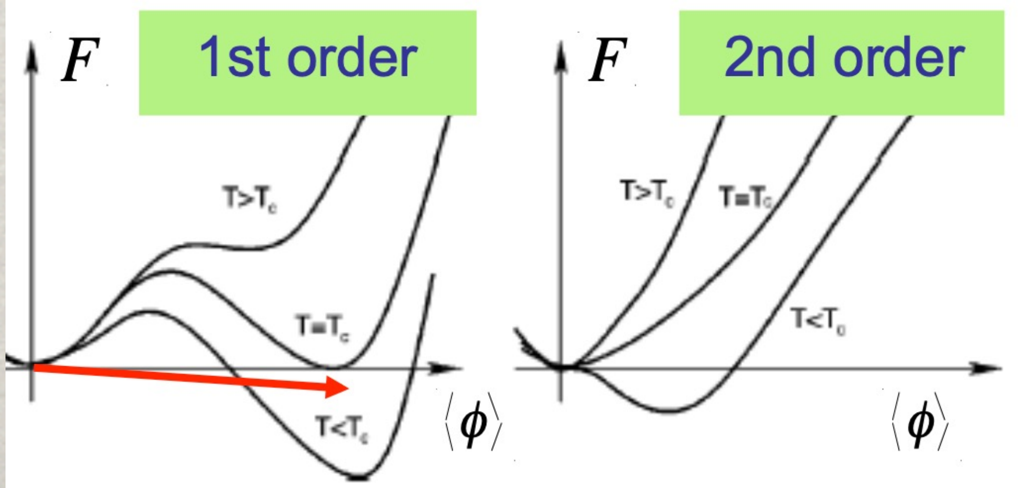
With new physics near the EW scale:

extended Higgs, Higgs portal to dark sector …

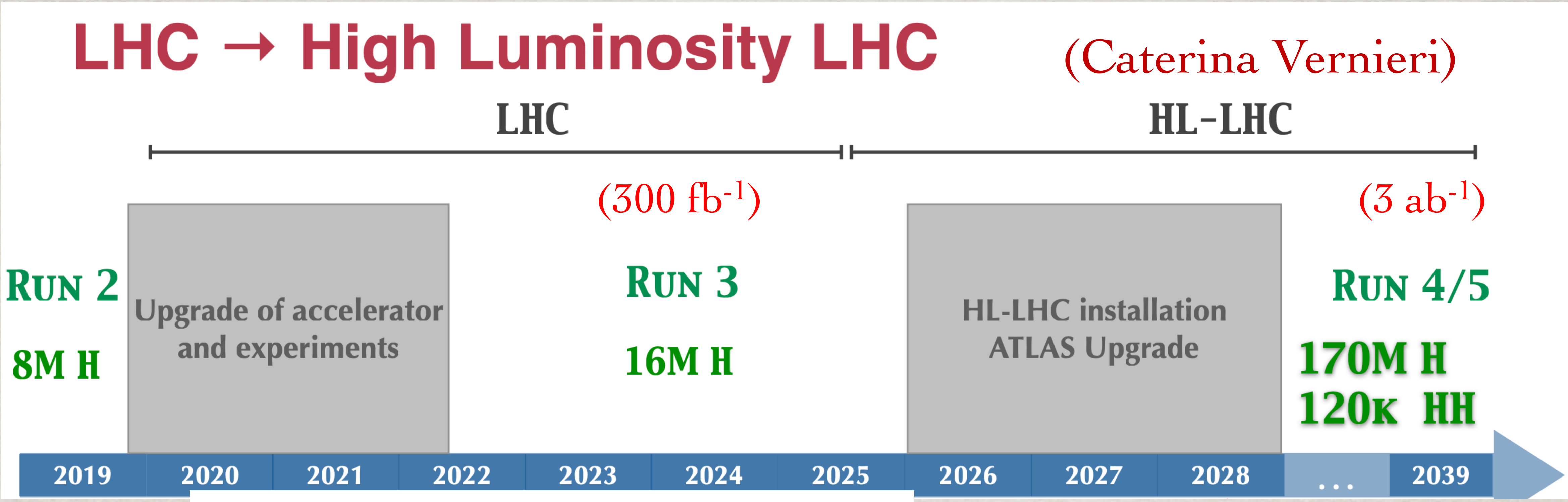
$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3; \quad \rightarrow \lambda_{hhh} = (7/3)\lambda_{hhh}^{SM}$$

$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right] \quad \rightarrow \lambda_{hhh} = (5/3)\lambda_{hhh}^{SM}$$

- May result in strong 1^{st} order EWPT!
- Possible EW baryogenesis
- Gravitational wave signals?

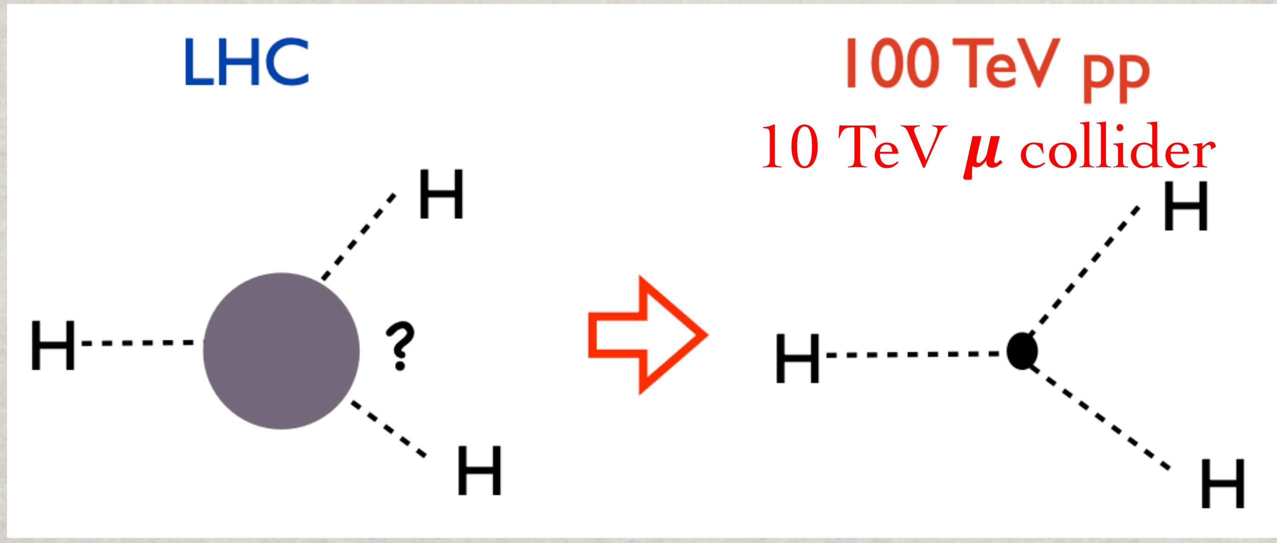


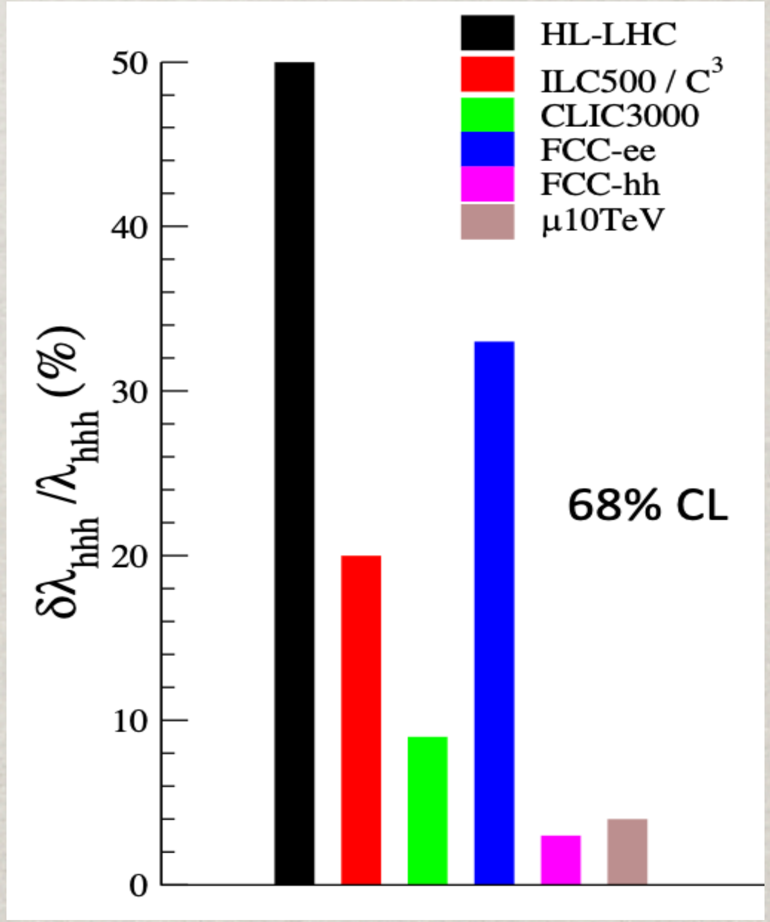
Determining the Higgs self-coupling λ_{hhh}



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

~ 10 TeV pCM energies





Conclusive test for SM EWPT!

Question 3. Particle Dark Matter
A generalized WIMP

Consider the "minimal EW dark matter": an EW multi-plet

- The lightest neutral component as DM
- Interactions well defined → pure gauge
- Mass upper limit predicted → thermal relic abundance

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	23 TeV
(1,7,ϵ)	Dirac	16 TeV

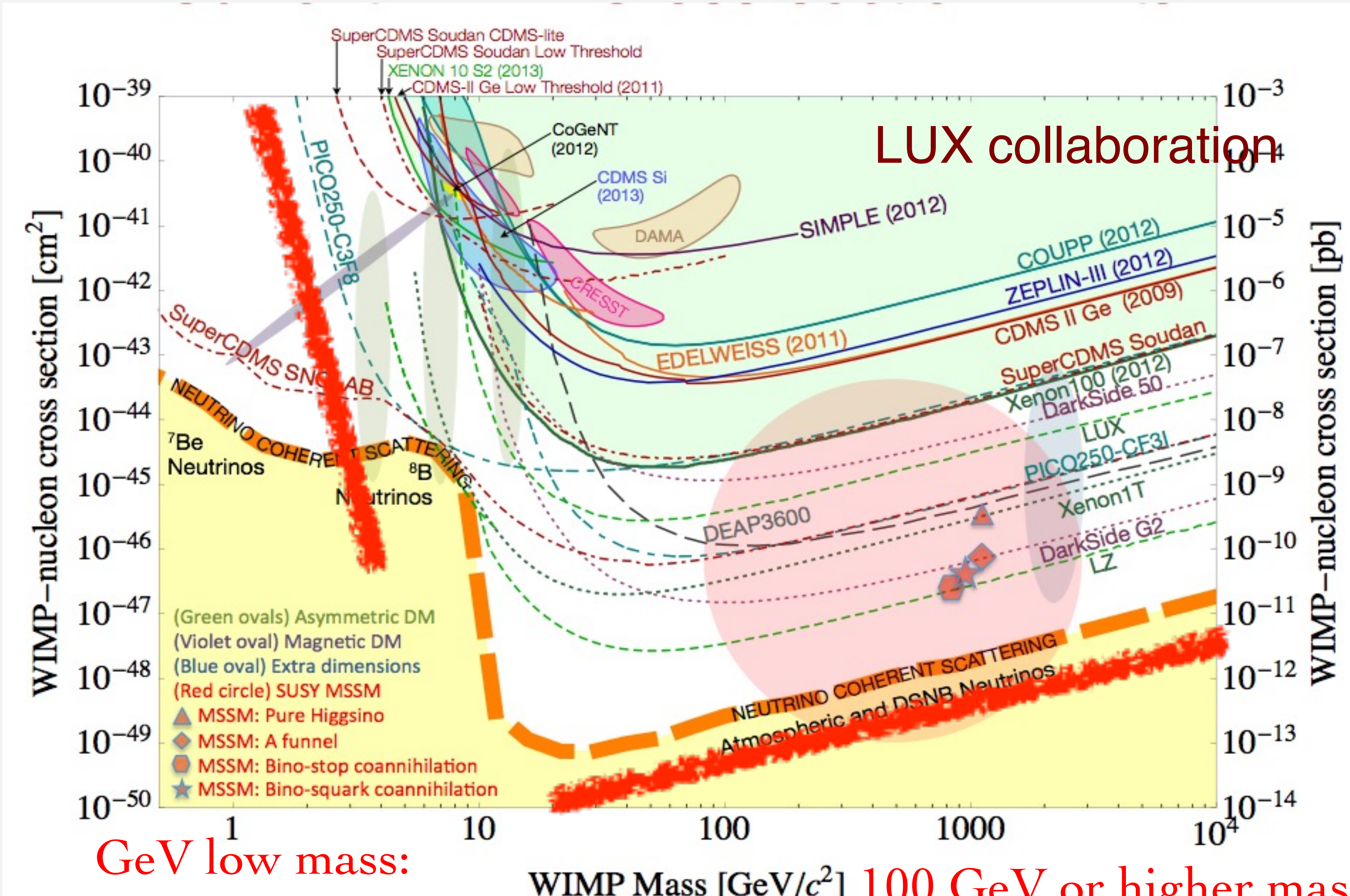
$$M_{\rm DM} < 1.8\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$

← Higgsino-like

← Wino-like

Cirelli, Fornengo and Strumia: hep-ph/0512090, 0903.3381;
TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287

Complementarity of Direct detection & Colliders



GeV low mass:
DD difficult;
Collider complementary

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

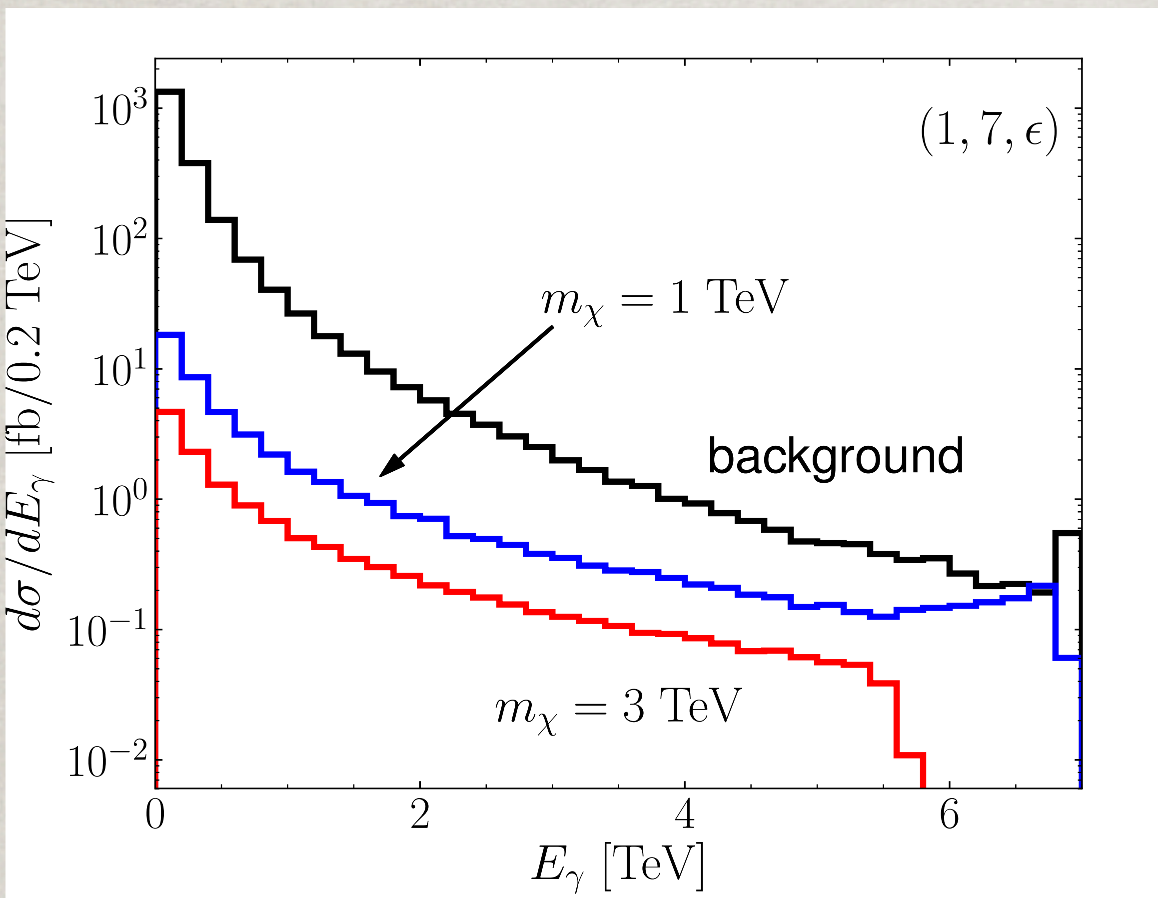
Advantage of HE lepton colliders:

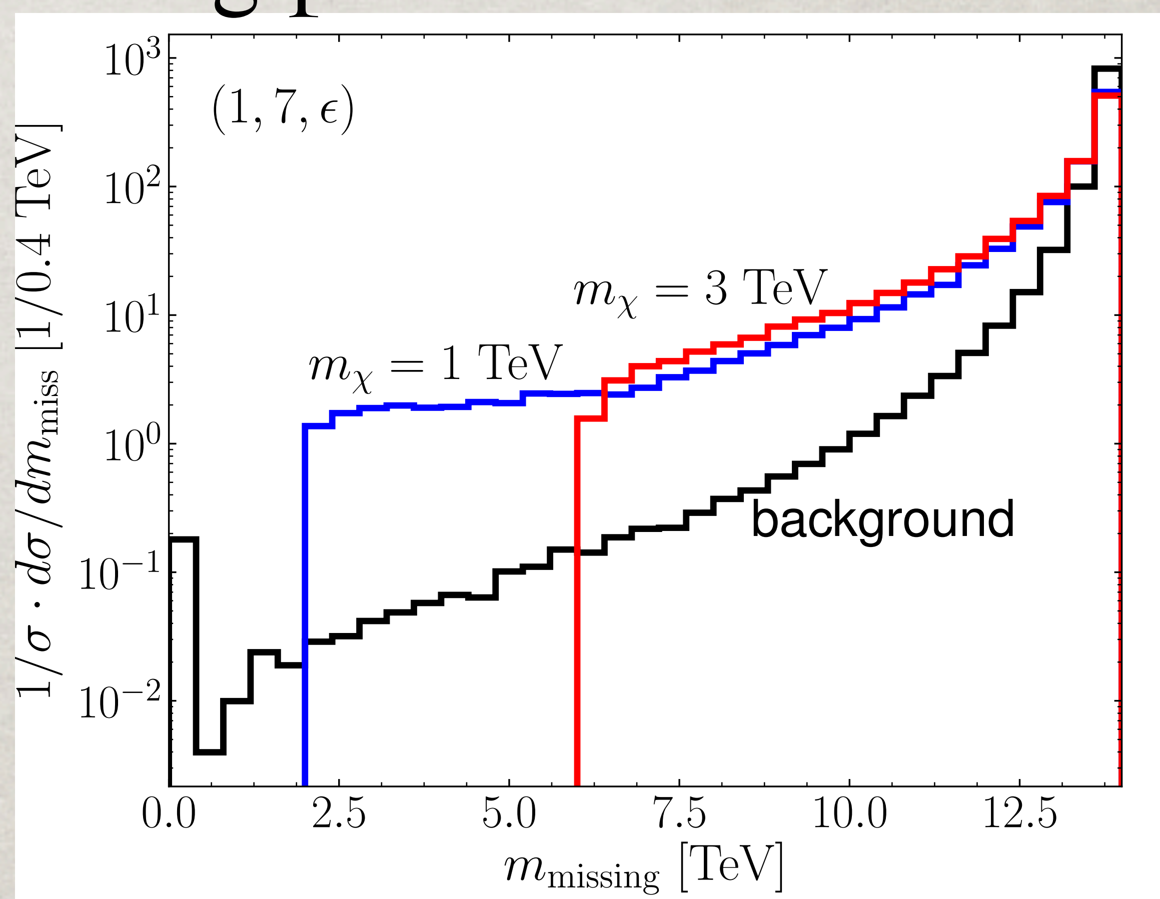
Key feature different from LHC: the "missing mass"

$$m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - \sum_i p_i^{\text{obs}})^2$$

$$E_\gamma < (s - 4m_\chi^2)/2\sqrt{s}, \qquad m^2_{\text{missing}} \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > 4m_\chi^2$$

Direct access to the missing particle mass!

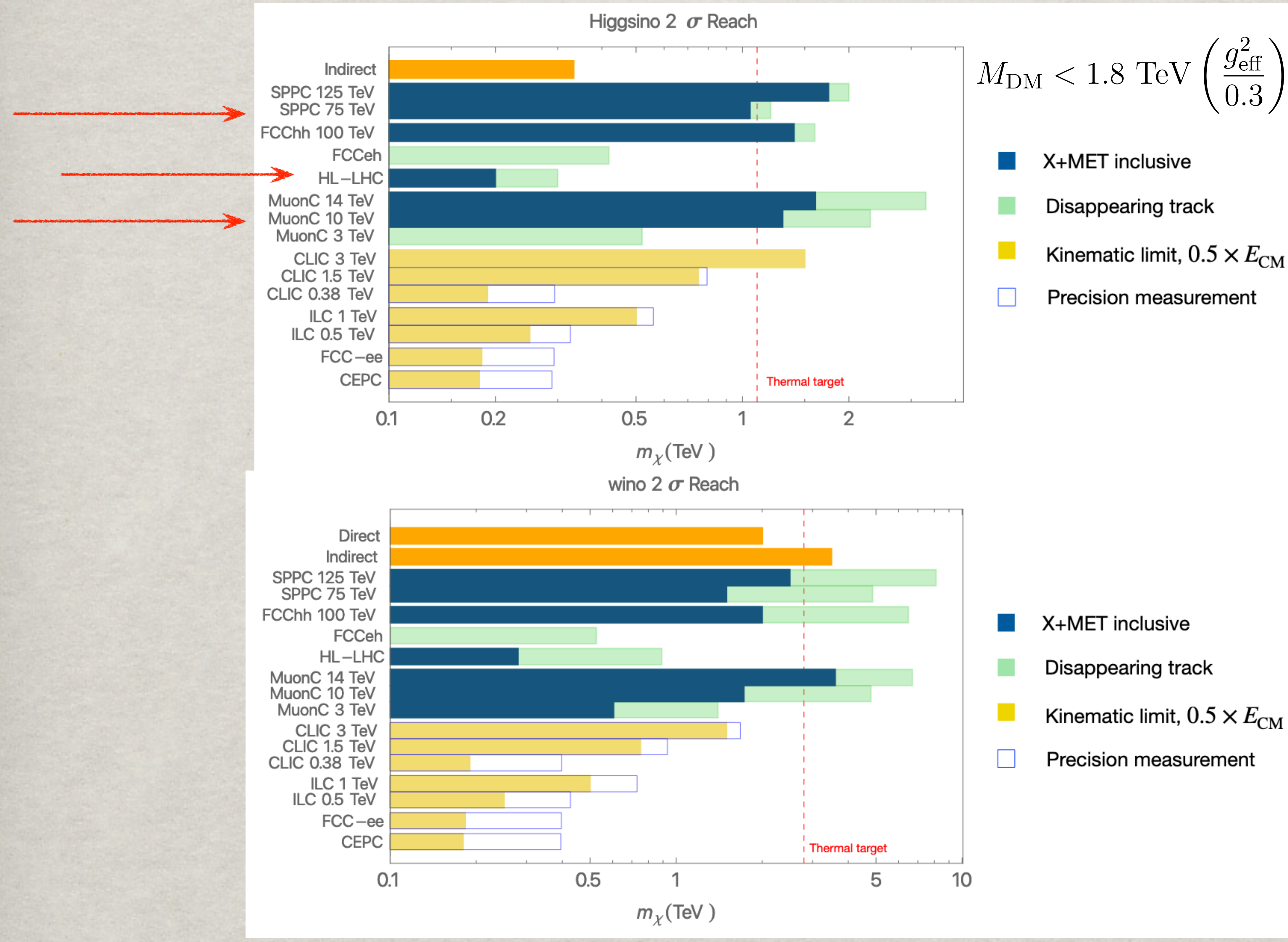




(a cone angle cut: $10^\circ < \theta < 170^\circ$)

WIMP Dark Matter coverage

Covering the thermal target

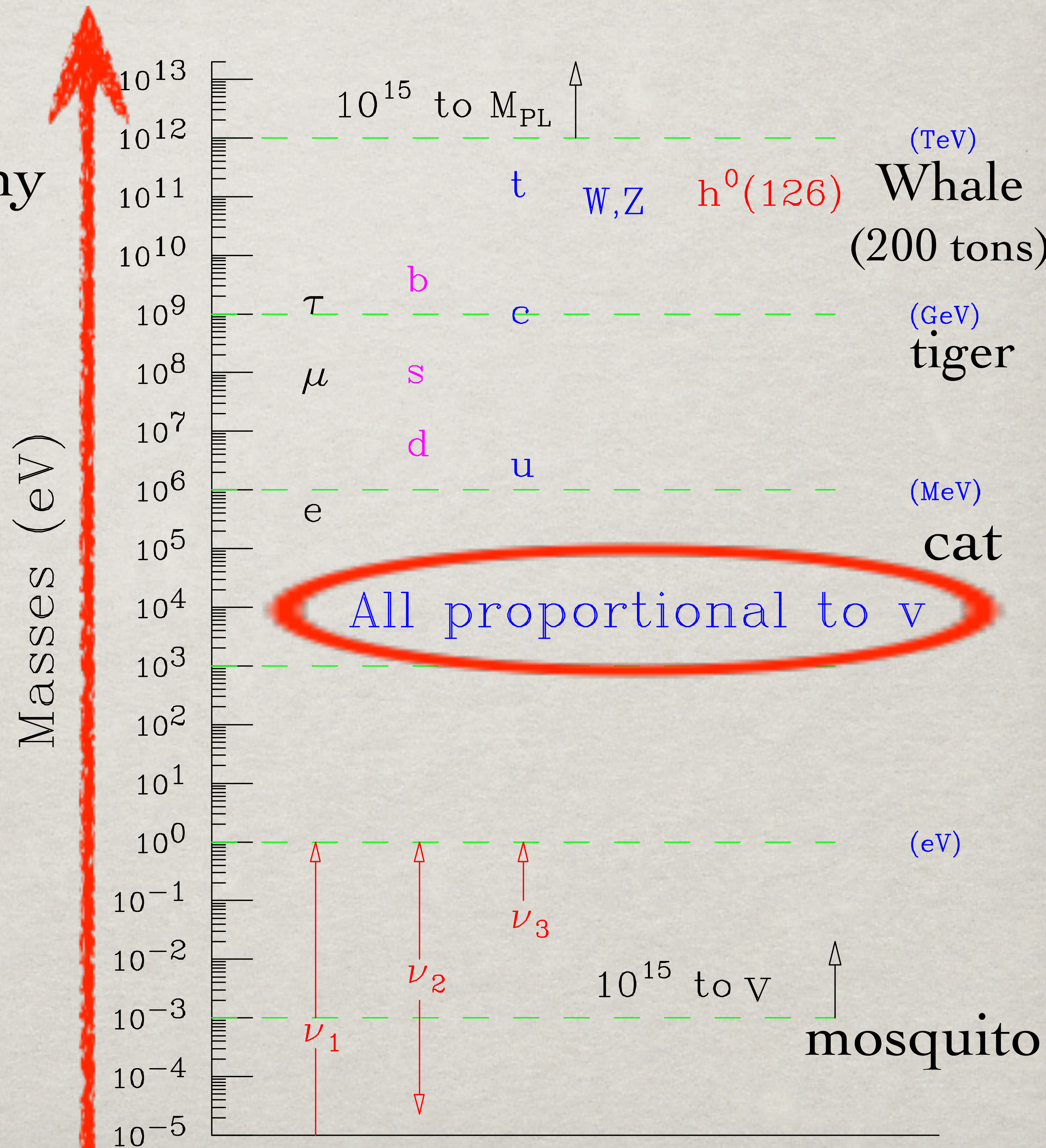


TH, Z. Liu, L.T. Wang, X. Wang: arXiv:2009.11287; arXiv:2203.07351

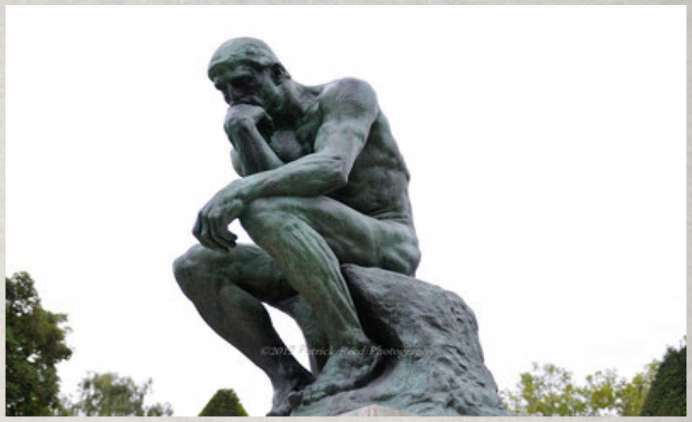
Question 4. The "Flavor Puzzle"

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- Neutrino mass generation (seesaw)
- New CP-violation sources

Higgs is in a pivotal position.



The list of questions continues …



5. Neutrino mass & mixing

seesaw mechanism & its scale

6. Matter–Antimatter asymmetry

Where is the anti-matter? New CP violation?

7. E&M + Weak + Strong → single force?

Grand Unification? proton instability?

8. Larger space-time symmetry?

Super-symmetry? Extra-dim/string theory?

9. Cosmology: inflation, dark energy …

Does the Higgs play a role?

10. Quantum gravity?

We need answers → colliders indispensable!

P5 report: 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).

Backup slides …

SM as an Effective Field Theory

"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

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\Psi}\not{D}\psi \\ &+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ &+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

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

(relevant operators)

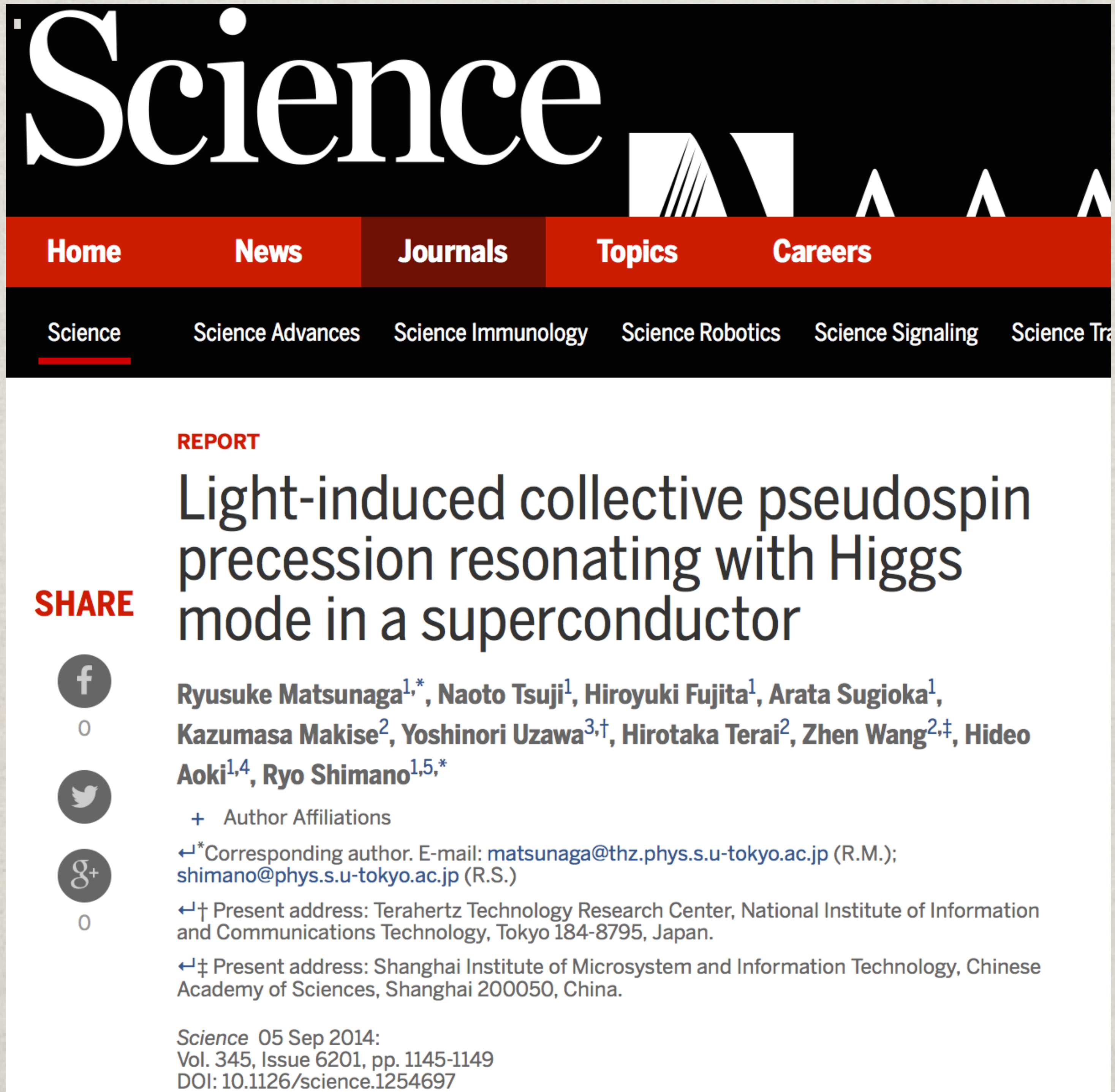
$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = \underline{c_0\Lambda^4 + c_2\Lambda^2\mathcal{O}_{\rm dim\ 2} + c_3\Lambda\mathcal{O}_{\rm dim\ 3}}$$

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

(marginal operators) (irrelevant operators)

Higgs boson analogue in CM:

In a 2014 report, a collective mode of Tera-Hertz (10^{-3} eV) vibration observed!



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REPORT

Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor

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Ryusuke Matsunaga[1,*], Naoto Tsuji[1], Hiroyuki Fujita[1], Arata Sugioka[1], Kazumasa Makise[2], Yoshinori Uzawa[3,†], Hirotaka Terai[2], Zhen Wang[2,‡], Hideo Aoki[1,4], Ryo Shimano[1,5,*]

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Science 05 Sep 2014:
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DOI: 10.1126/science.1254697

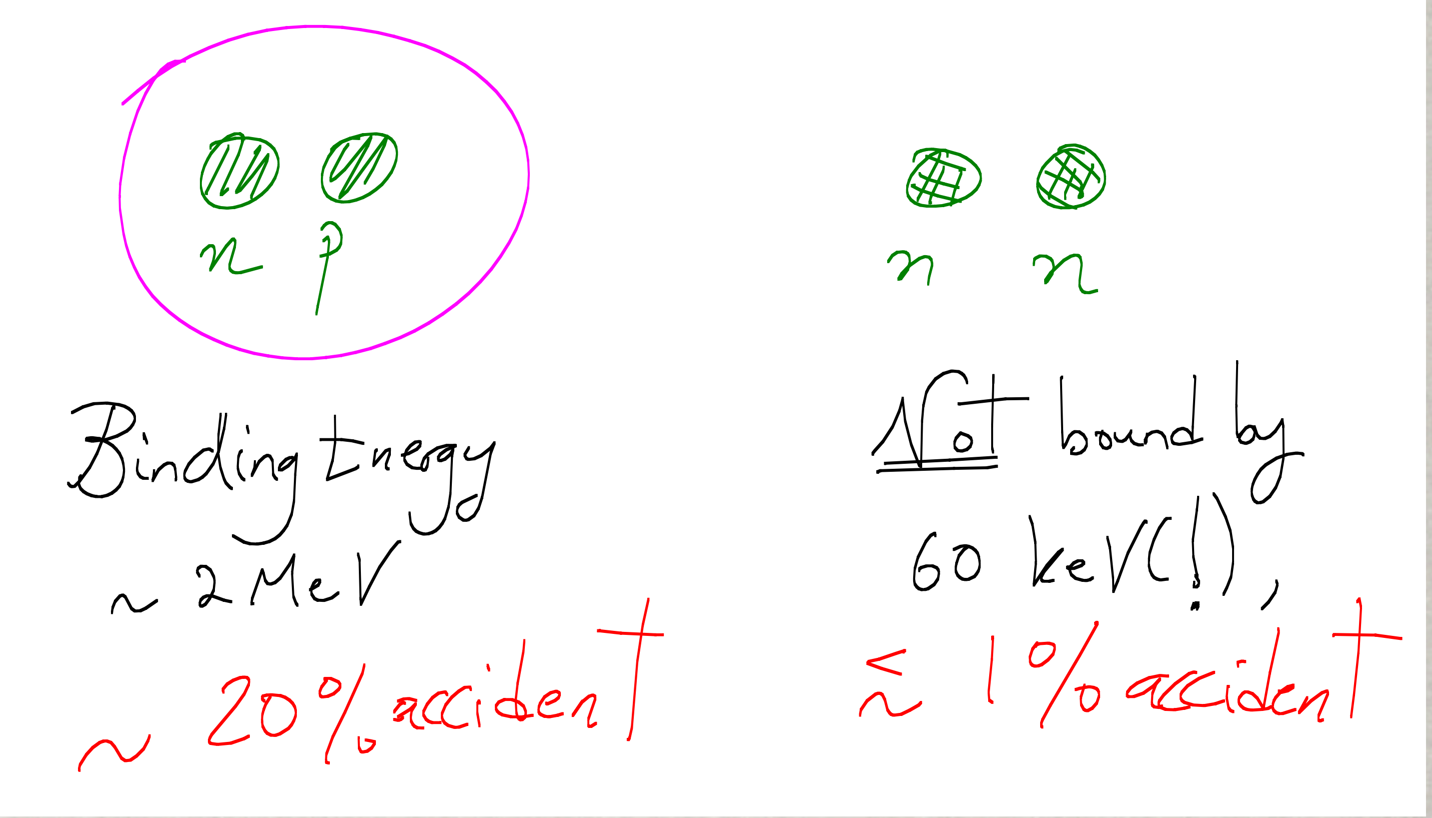
How much "tune" is fine-tuned?

Atomic physics:

Rydberg const. $E_0 \sim \alpha^2 m_e \rightarrow O(25\ \mathrm{eV})$, very natural!

Nuclear physics?

	Mass (amu)	Binding Energy (J)	
		Total	Per Nucleon
$^{2}_{1}H$	2.01410	3.57×10^{-13}	1.78×10^{-13}
$^{3}_{2}He$	3.01603	1.24×10^{-12}	4.13×10^{-13}
$^{4}_{2}He$	4.00260	4.52×10^{-12}	1.13×10^{-12}
$^{16}_{8}O$	15.99491	2.04×10^{-11}	1.28×10^{-12}
$^{17}_{8}O$	16.999131	2.10×10^{-11}	1.24×10^{-12}
$^{56}_{26}Fe$	55.934939	7.90×10^{-11}	1.41×10^{-12}
$^{238}_{92}U$	238.0508	2.89×10^{-10}	1.22×10^{-12}

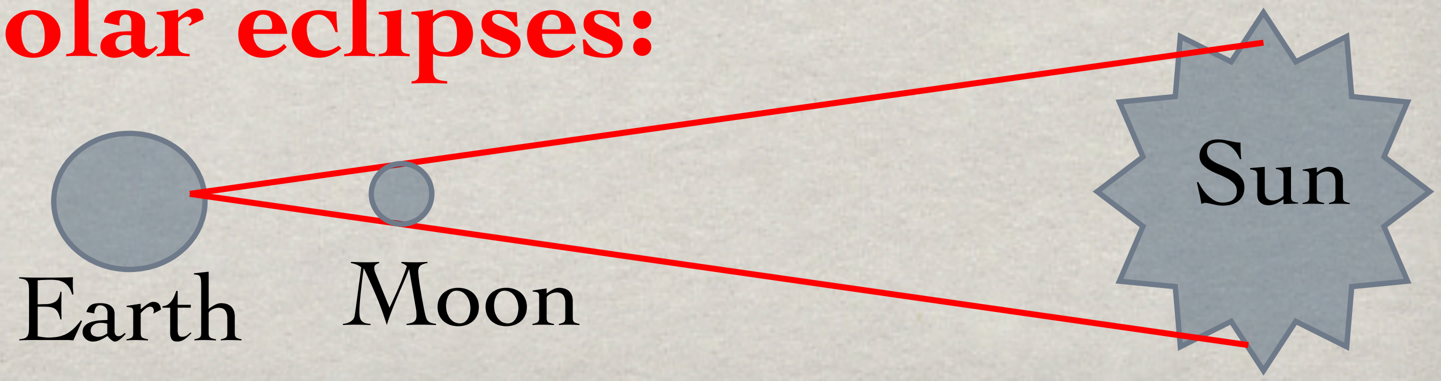


$r_m/d_m = 0.5583$; $r_s/d_s = 0.5450$ at perigee

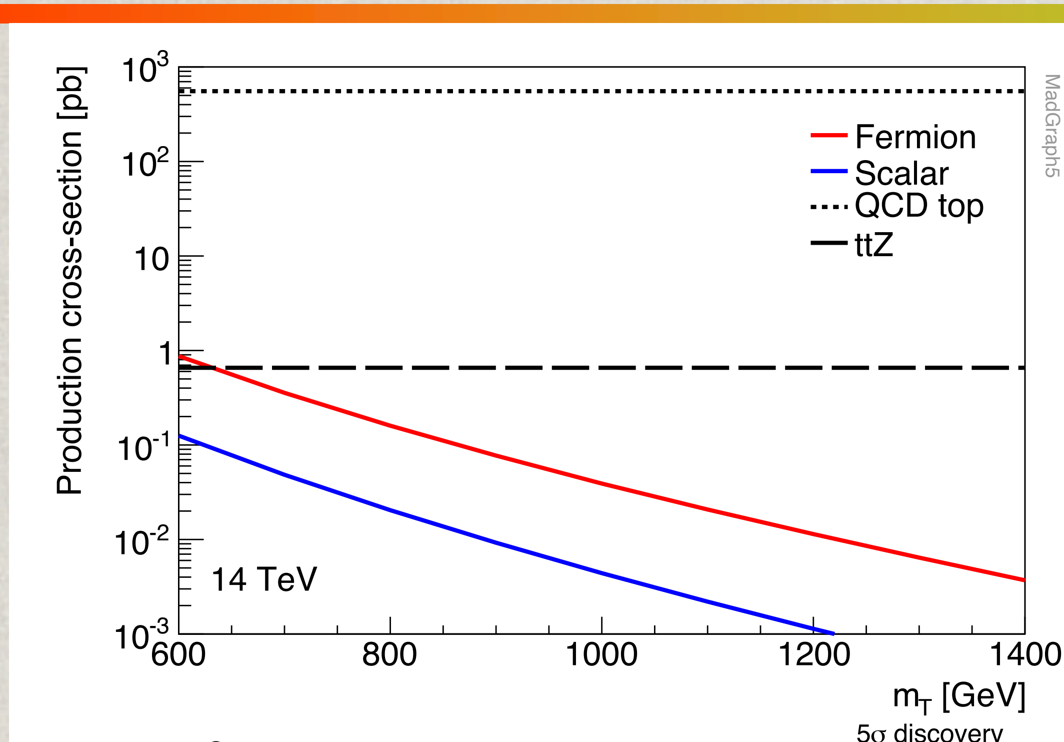
$\rightarrow \delta\theta/\theta \sim 2.10^{-2}$

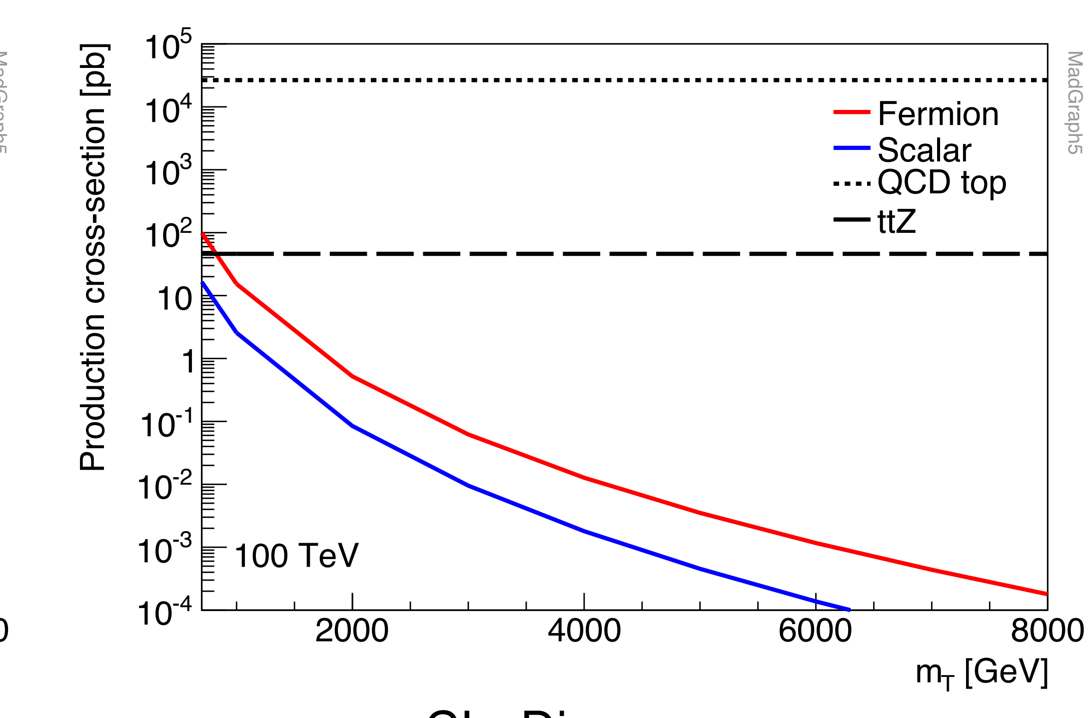
rather unnatural!

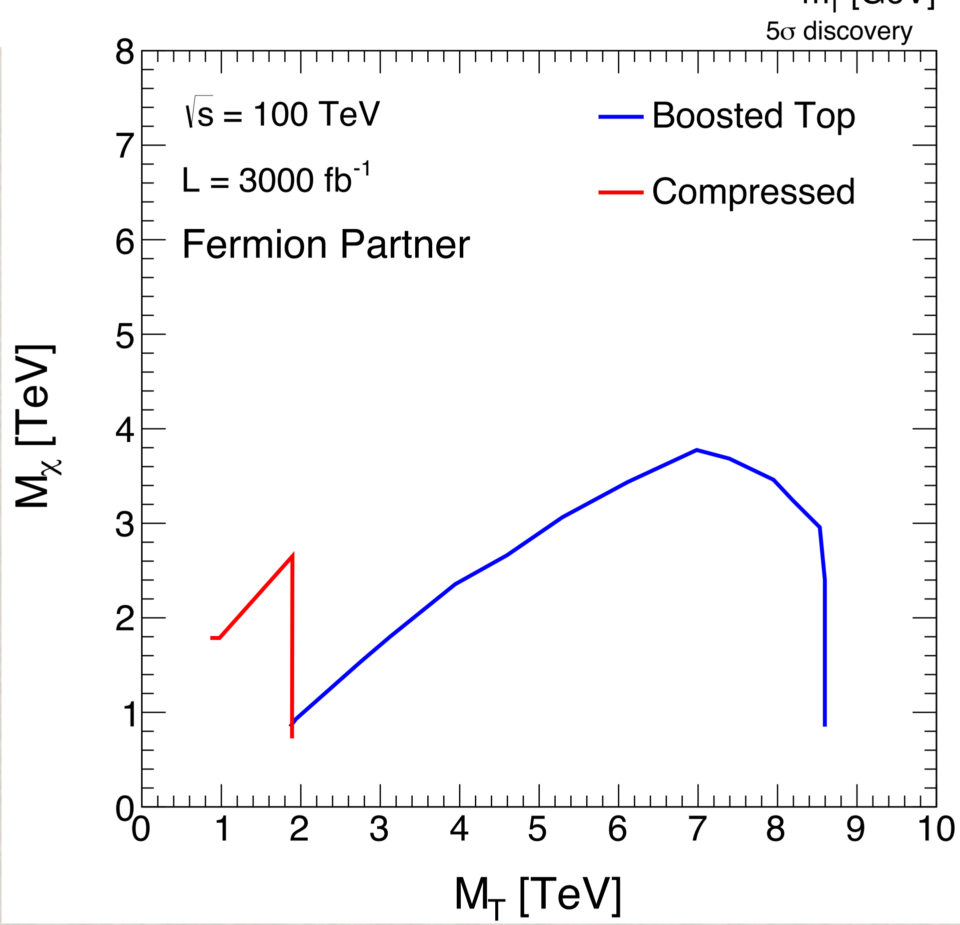
Solar eclipses:

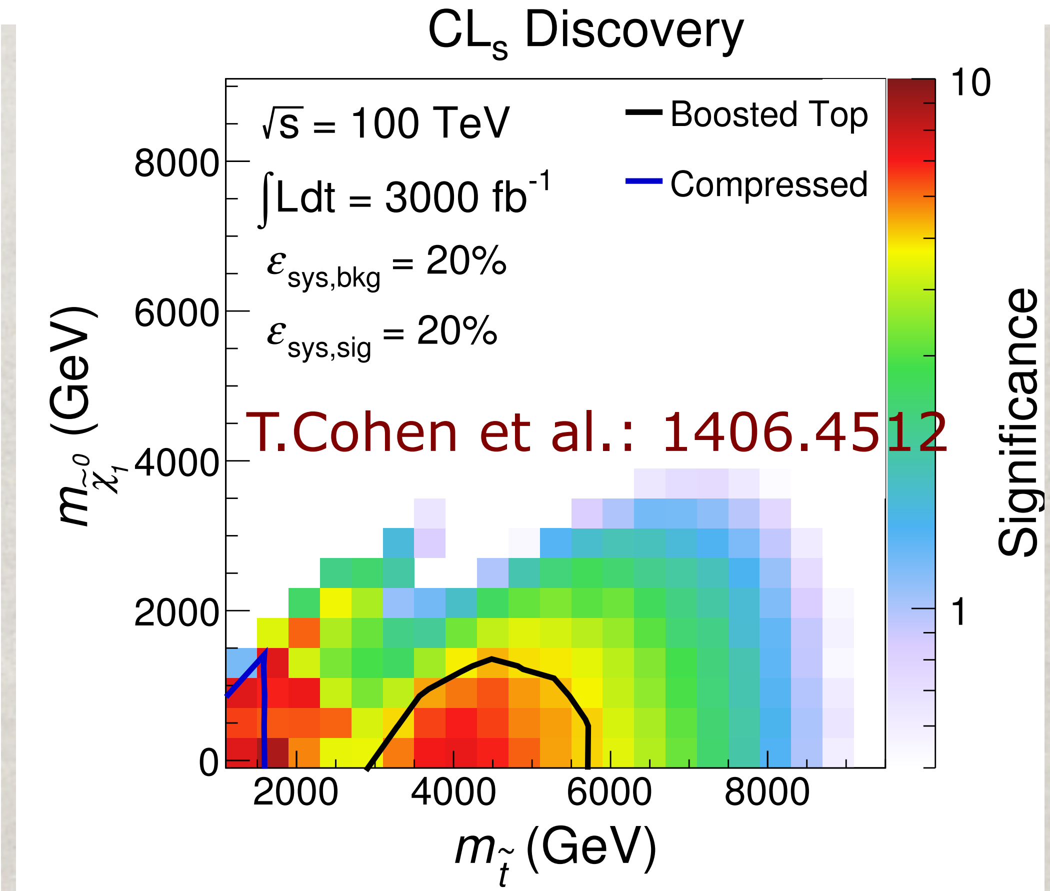


Pushing the “Naturalness” limit







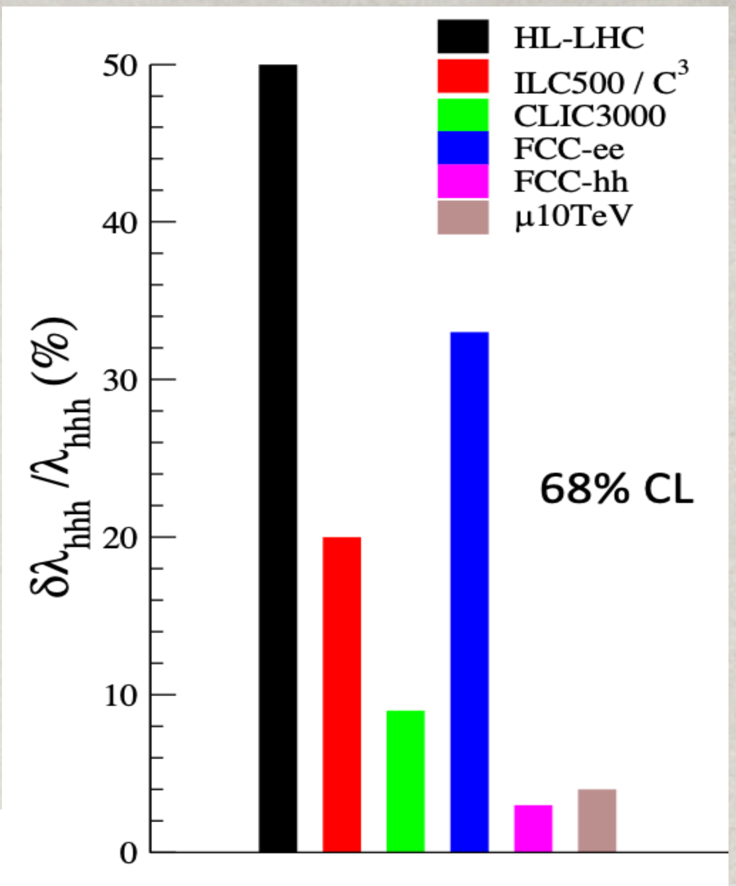


The Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \, (1 \text{ TeV}/\Lambda)^2$

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

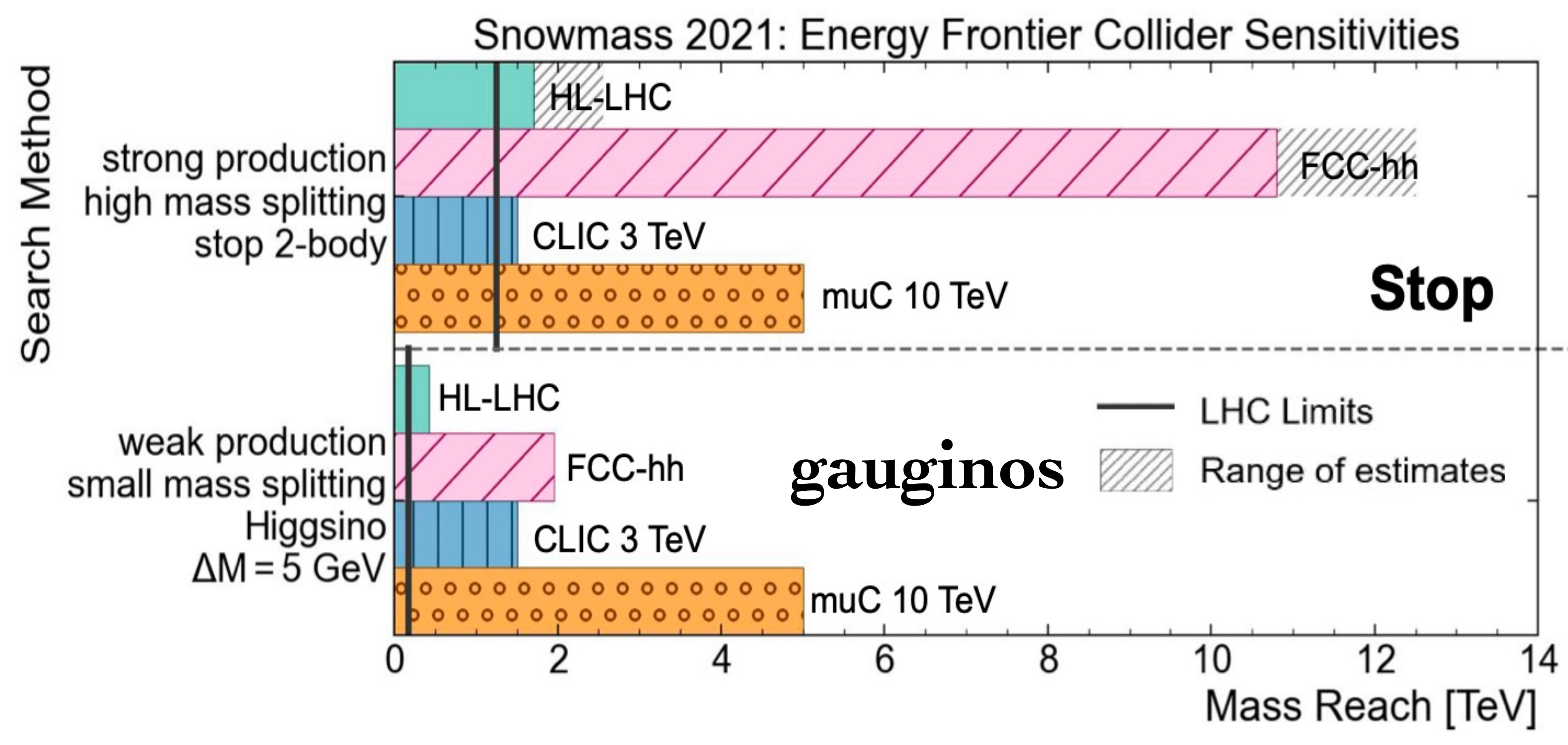
Reach at 10 TeV pCM energies

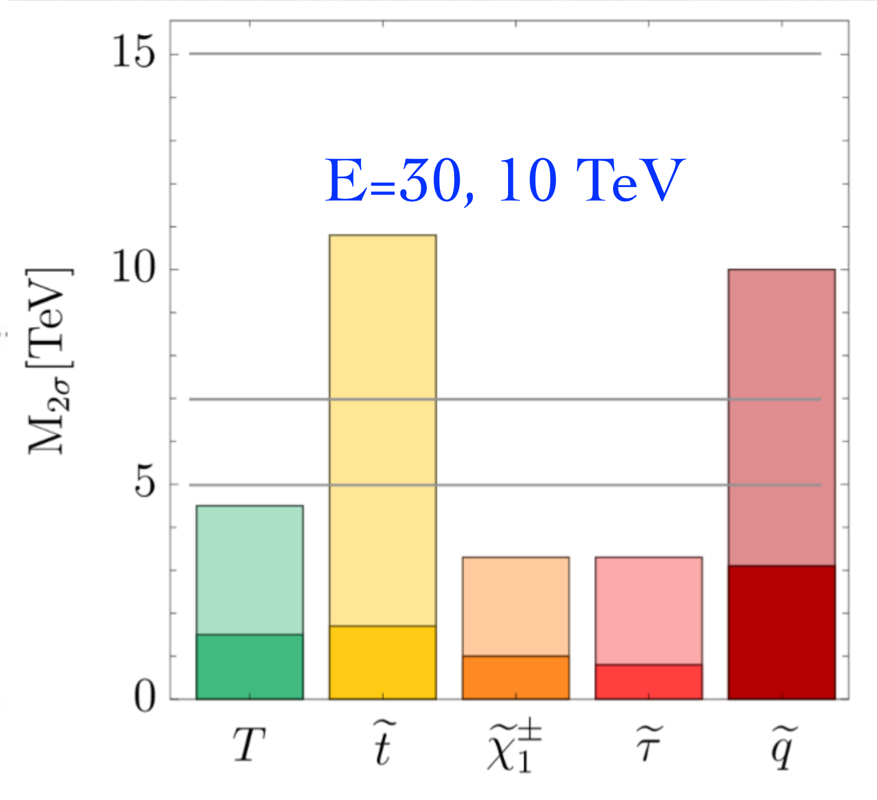
Higgs coupling reach for λ_{hhh}^{SM} →



Pushing the "Naturalness" limit:

The searches for top quark partners & gluinos, gauginos …





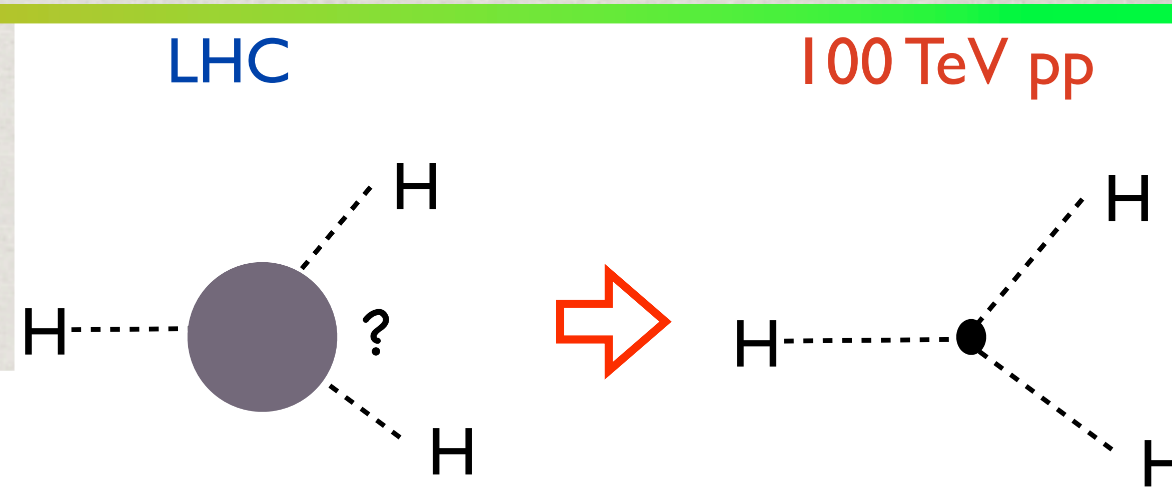
→ Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \,(1\text{ TeV}/\Lambda)^2$

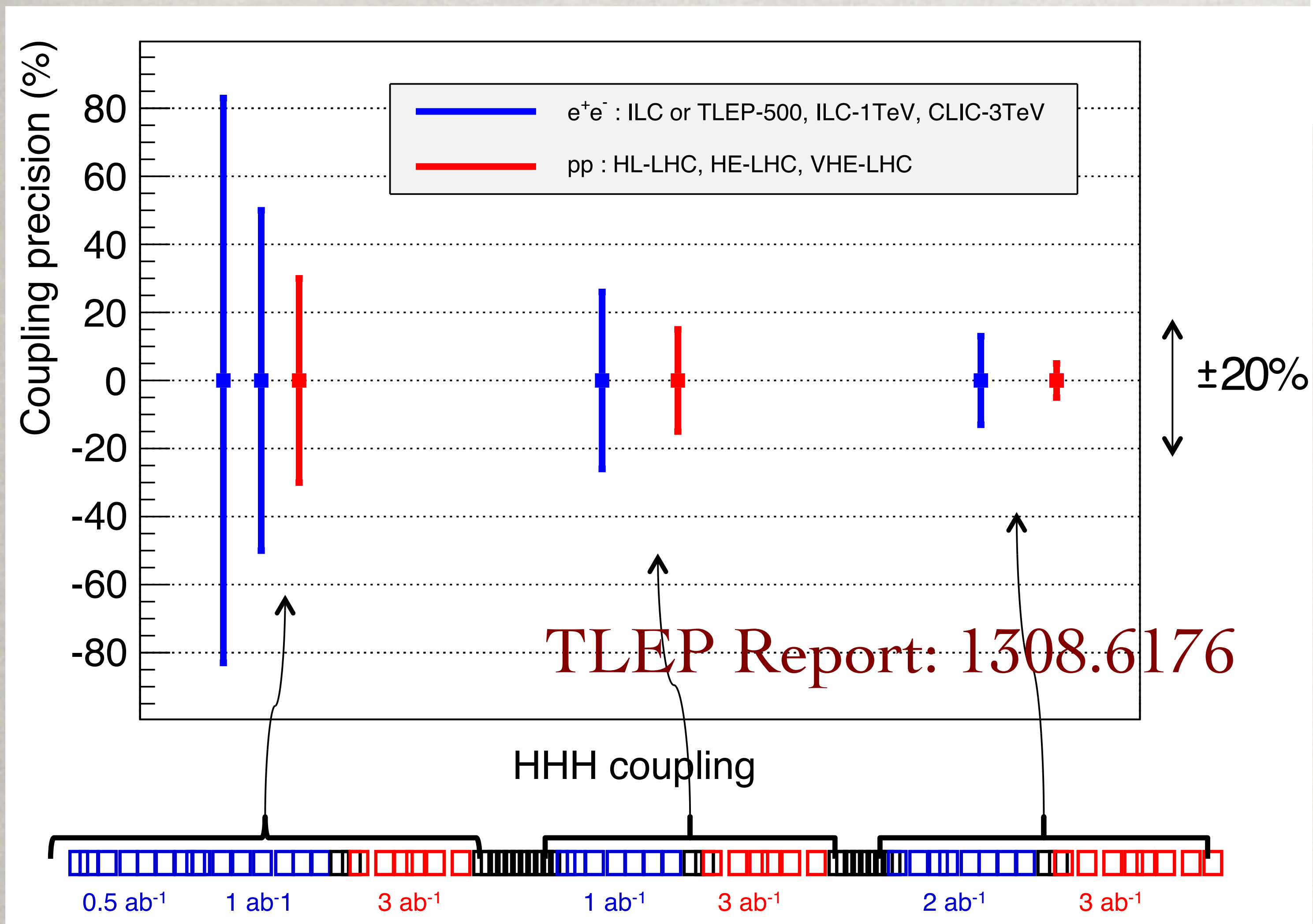
Thus, $m_{stop} > 8$ TeV → 10^{-4} fine-tune!

Higgs Self-couplings:

$$\mathcal{L} = -\frac{1}{2} m_H^2 H^2 - \frac{g_{HHH}}{3!} H^3 - \frac{g_{HHHH}}{4!} H^4$$

$$g_{HHH} = 6 \ \ v = \frac{3m_H^2}{v}, \qquad g_{HHHH} = 6 \ \ = \frac{3m_H^2}{v^2}.$$





TLEP Report: 1308.6176

Triple coupling sensitivity:

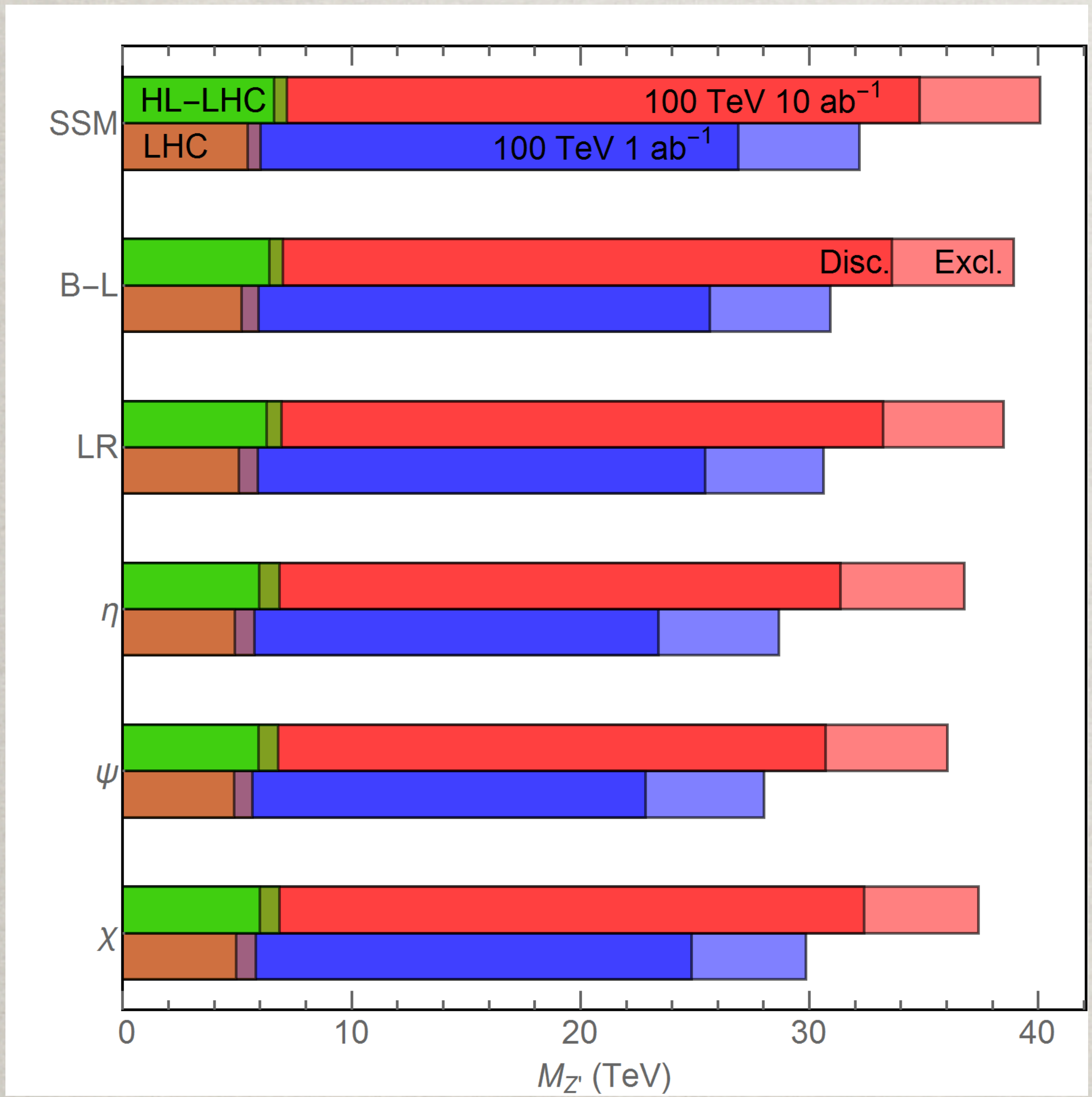
Test the shape of the Higgs potential, and the fate of the EW-phase transition!

Snowmass 1310.8361

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

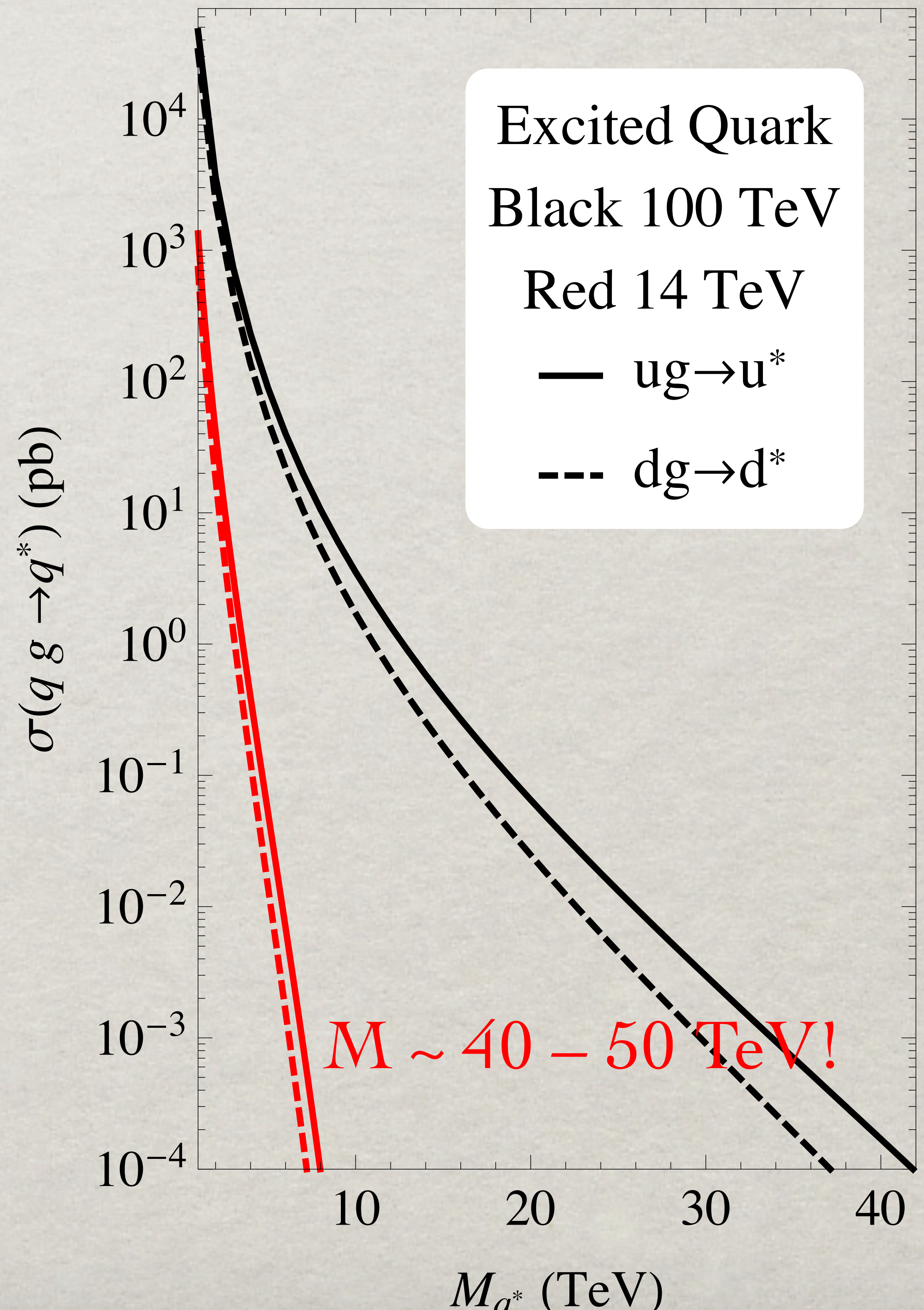
New Particle Searches

Electroweak Resonances: Z',W'



~ 6x over LHC

Colored Resonances:



Conclusions

- With ~ 50 year's un-interrupted success, the field remains vibrant.
- The future collider program promises definitive answers to some key questions.

- Precision Higgs@LHC: couplings~10%; λ_{HHH} ~ (20-50)%

  Future Higgs factory/SppC:

  Couplings~0.1%; $\lambda_{HHH} < 10\%$ → the **EW phase transition!**

  Dark matter coupling ~ 2% Search for the dark sector

- FCC_{hh} / SppC New physics reach:

  New particles~10 – 30 TeV → **probe fine-tune < 10^{-4}**

  (WIMP) DM mass reach ~ 1 – 5 TeV !

- Neutrino, flavor physics / Dark matter searches complementary.

An exciting journey ahead!