The Higgs Boson & Beyond*

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PITT PACC, Univ. of Pittsburgh

International Symposium on Higgs & Beyond

August 15, 2016

* Beyond the SM & beyond the LHC.

N. Arkani-Hamed, TH, M. Mangano, L.T. Wang: arXiv:1511.06495 (Phys. Rept)

The 1st ISHP: Aug. 12 – 16, 2013

International Symposium on Higgs Physics

At the Institute of High Energy Physics (IHEP), Beijing
on August 12-16, 2013 to

Update our understanding of Higgs physics in SM & beyond
Address the impact for searches for new physics at LHC
Discuss the future planning for Higgs factories

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Discussions on Future Facilities for Higgs Physics

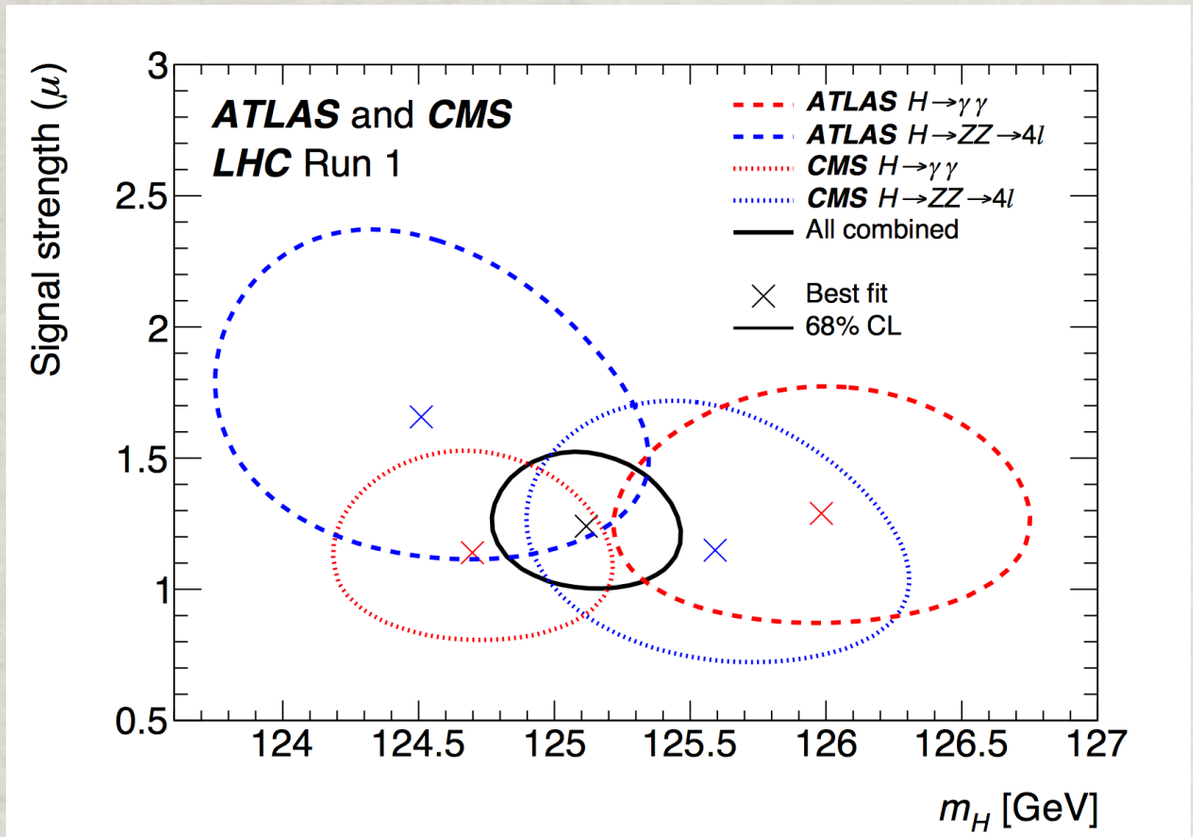
Tao Han,
Univ. of Pittsburgh/Tsinghua Univ.

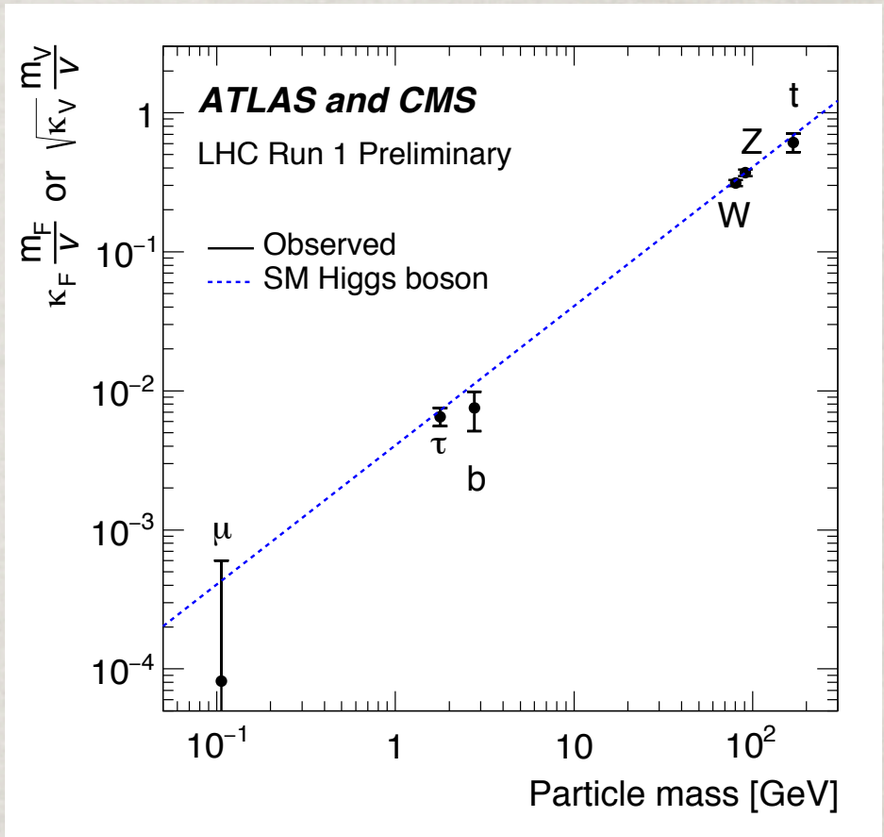
ISHP 2013, IHEP, Beijing, August 16, 2013

Today: Reiterate the need for new physics under the Higgs lamppost.

(For LHC updates, see: M. Solfaroli; A. Polini; G. Rakness; Y. Gao; etc. etc.)

Before ICHEP 2016:

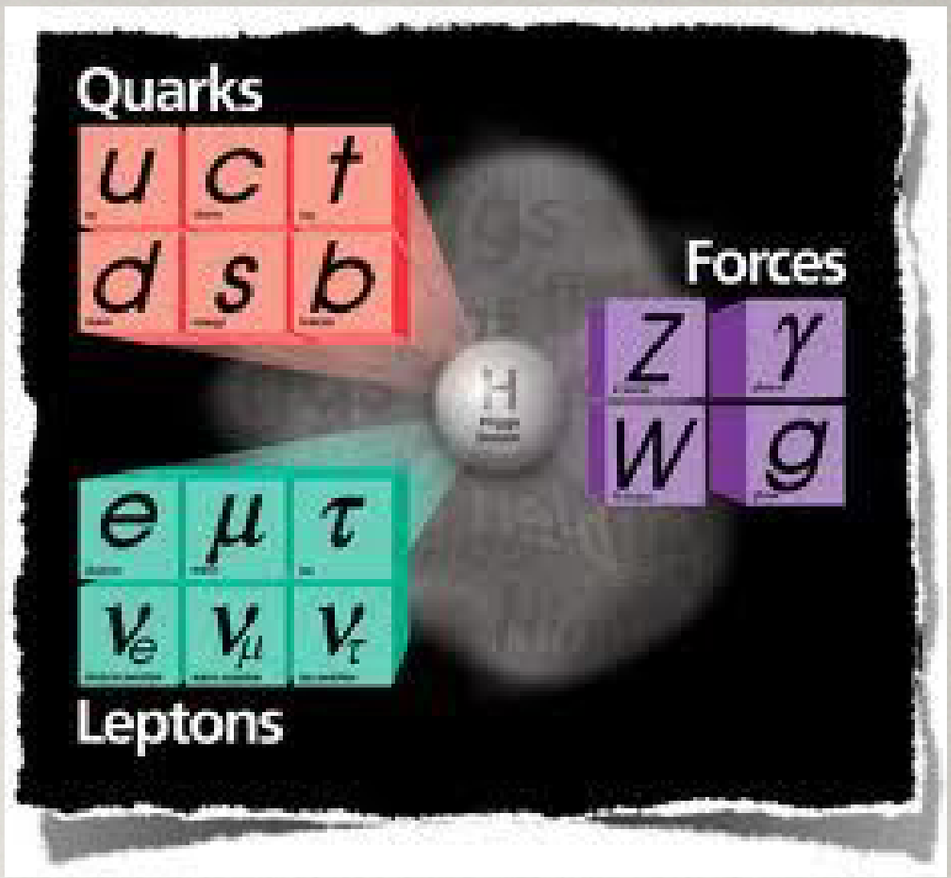




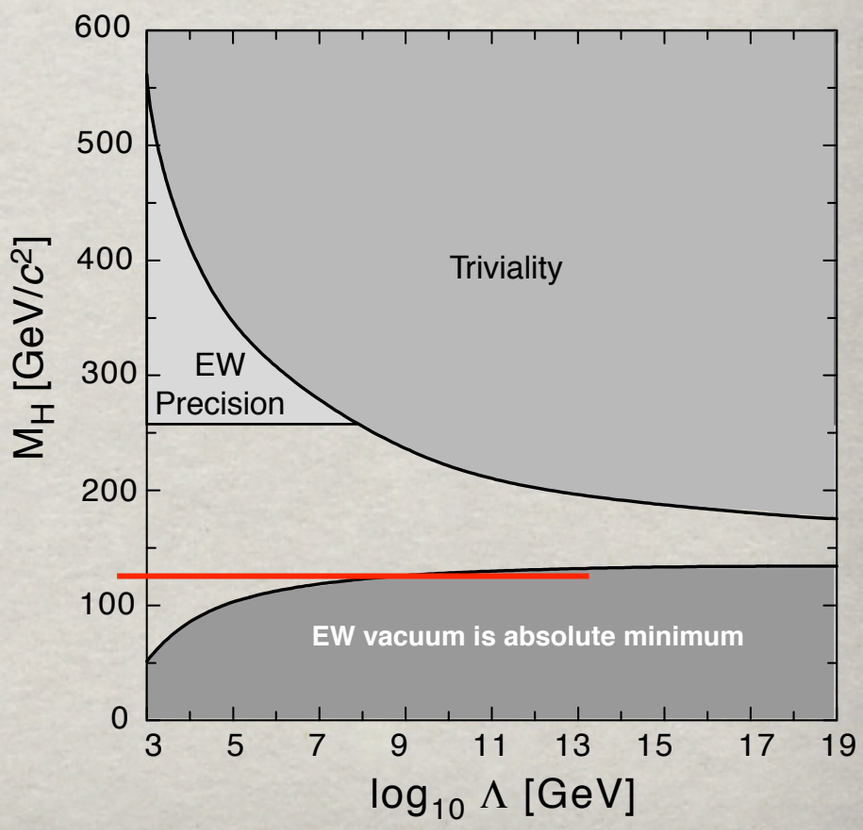
- **Mass accuracy 0.2%: 125.09±0.21±0.11 GeV**
- 5σ for both fermion coupling h → ττ
- & bosonic coupling WW→h
- Couplings proportional to mass

All indications point to a SM-like Higgs boson "elementary" at a scale Λ < O(1 TeV)

The completion of the SM: First time ever, we have a consistent relativistic/ quantum mechanical theory: weakly coupled, unitary, renormalizeable, vacuum (quasi?) stable.



Valid up to an exponentially high scale, perhaps to the Planck scale M_{Pl}!



"... most of the grand underlying principles have been firmly established. (An eminent physicist remarked that) the future truths of physical science are to be looked for in the sixth place of decimals. "

--- Albert Michelson (1894)

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

Will History repeat itself (soon)?

A Reminder

The Higgs mechanism ≠ a Higgs boson !

From theoretical point of view,
3 Nambu-Goldstone bosons were all we need!
(non-linear realization of the gauge symmetry)

With no Higgs, the theory is valid only
to a unitarity bound ~ 2 TeV

The existence of a light, weakly coupled Higgs boson carries important message for our understanding & theoretical formulation in & beyond the SM.

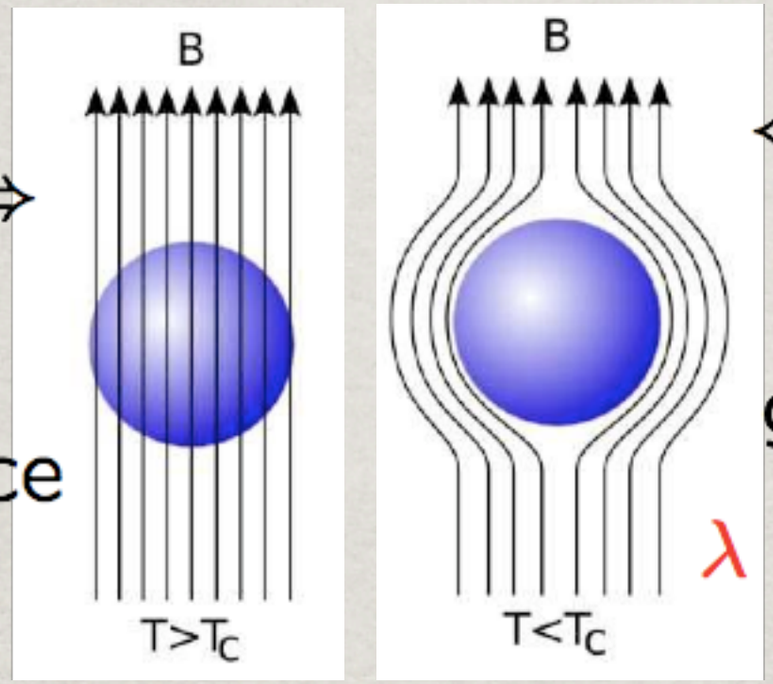
Observations & Questions

A. Electroweak Super-Conductivity

Normal phase⇒

$E^2 = p^2c^2$

Long-range force



⇐Superconducting phase

$E^2 = p^2c^2 + m^2c^4$

gap leads to $\sim exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

In "conventional" electro-magnetic superconductivity:

$m_\gamma \sim m_e/1000$, $T_c^{em} \sim \mathcal{O}(\text{few } K)$. BCS theory.

In "electro-weak superconductivity":

$m_w \sim G_F^{-\frac{1}{2}} \sim 100$ GeV, $T_c^w \sim 10^{15}K$!

We are living in a EW superconducting phase!

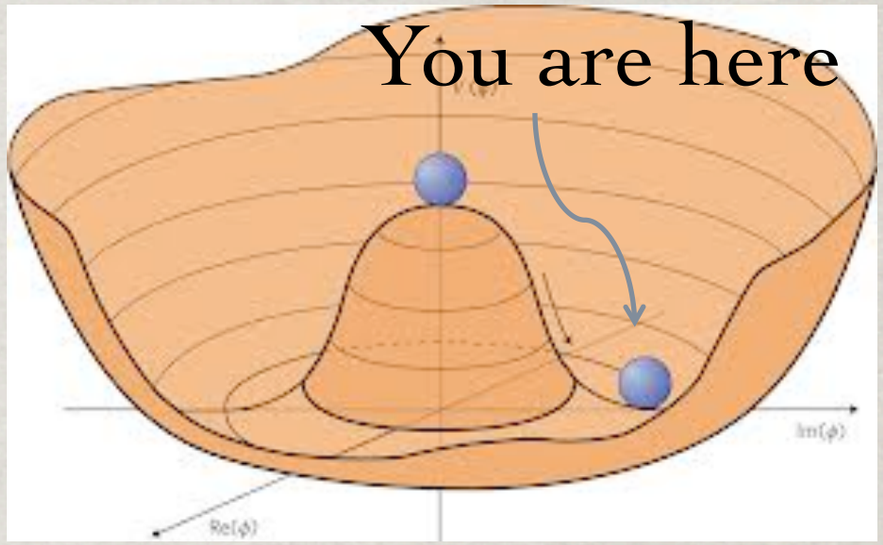
It's like Landau-Ginzburg
It's NOT Landau-Ginzburg

In the SM:

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

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

$$m_H \approx 126 \text{ GeV}$$

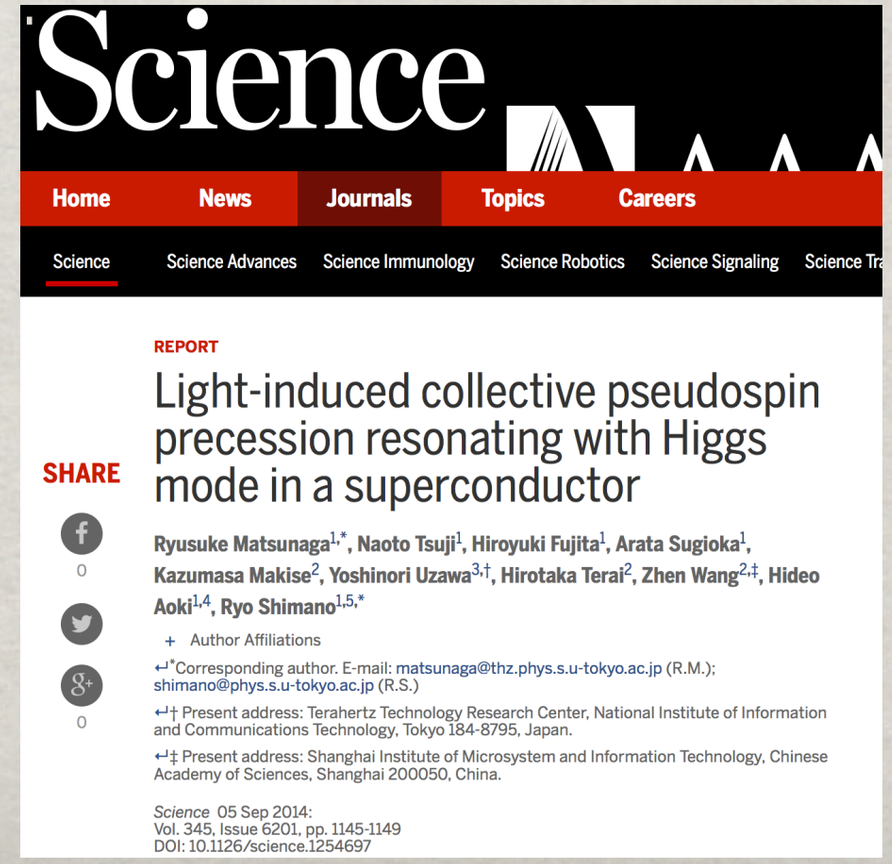


It is a weakly coupled, very narrow particle ($\Gamma/m \approx 10^{-5}$) elementary at a scale >1000 GeV!

Landau-Ginzburg:

Similar parameterization, but BCS as the underlying theory!

A collective mode of TeraHertz (10^{-3} eV) vibration observed!



B. λ: a "New Force"

The Higgs potential: $V = -\mu^2 |\phi|^2 + \lambda |\phi|^4$

It represents a weakly coupled new force (a 5th force):

- **In the SM, λ is a free parameter, now measured:**

$$\lambda = m_H^2 / 2v^2 \approx 0.13$$

Is it fundamental?
Or induced? Landau-Ginzburg? Van der Waals?

- **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**

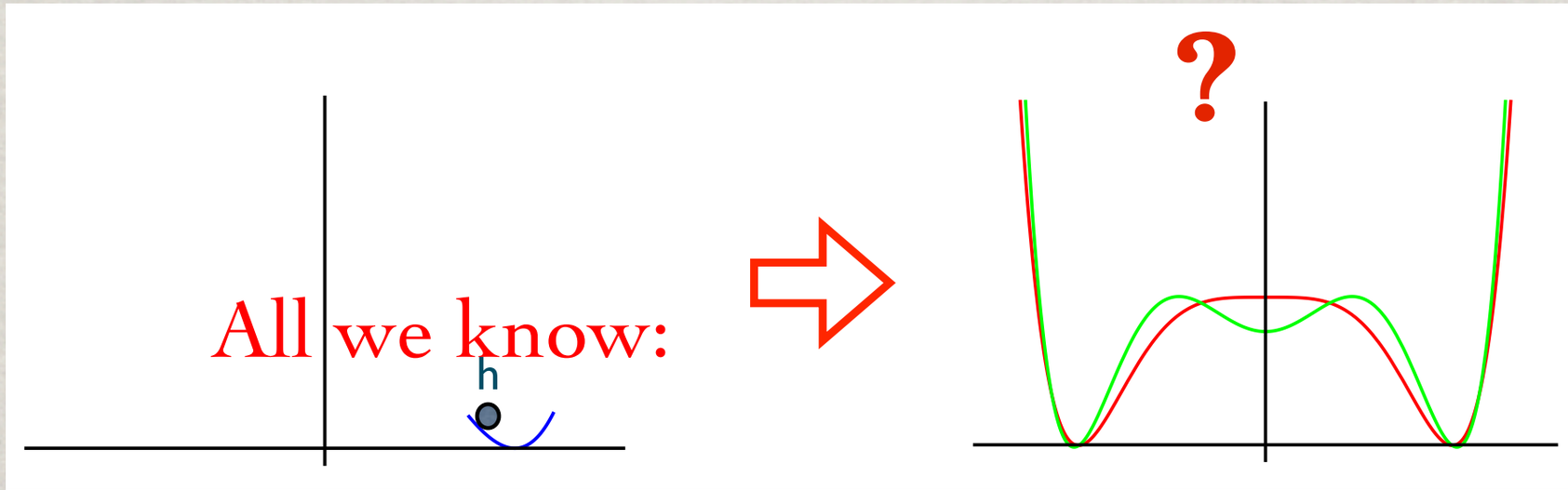
- **In composite/strong dynamics,**
  harder to make λ big enough.

(due to the loop suppression by design)

Measured m_H: *too light to be heavy (SUSY);*
too heavy to be light (new dynamics)

Question 1: The Nature of EWSB ?

In the SM, $m_H^2 = 2\mu^2 = 2\lambda v^2 \;\Rightarrow\; \mu \approx 89\ \mathrm{GeV}, \;\; \lambda \approx \frac{1}{8}.$
underwent a 2nd order phase transition! Really?



With new physics near the EW scale:

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

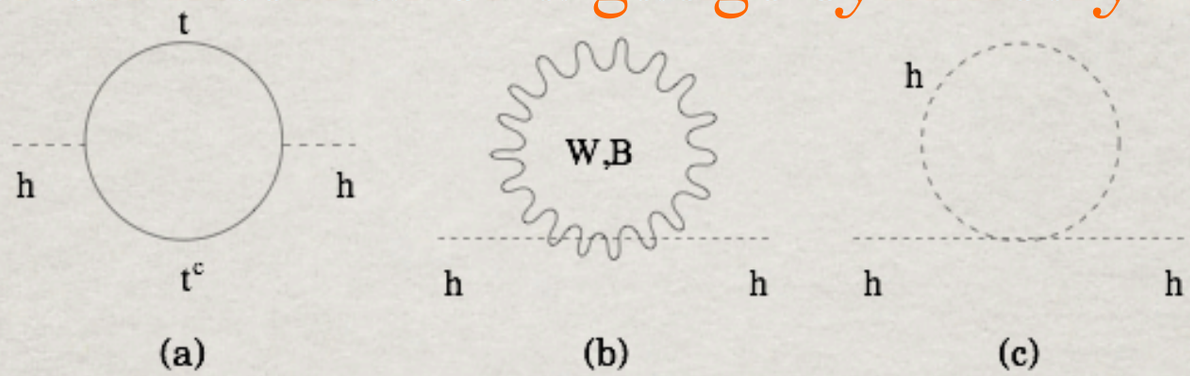
$$\to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right] \quad \rightarrow \lambda_{hhh} = (5/3)\lambda_{hhh}^{SM}$$

EW phase transition strong 1st order!

→ O(1) deviation on λ_{hhh}

Question 2: The "Naturalness"

"… 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



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

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

Cancelation in perspective:

m_H^2 = 36,127,890,984,789,307,394,520,932,878,928,933,023

–36,127,890,984,789,307,394,520,932,878,928,917,398

= $(125\ \text{GeV})^2$! ?

Natural: O(1 TeV) new physics, associated with ttH.
Unknown: Deep UV-IR correlations: gravity at UV?
Agnostic: Multiverse/anthropic?

"Naturalness" in perspective:

Unbelievable!

$4\ mm^2 / 20\ cm^2 \sim 10^{-3}$ fine-tune.

"Naturalness" → TeV scale new physics:

SUSY? New strong dynamics QCD' ?

Question 3: The Dark Sector

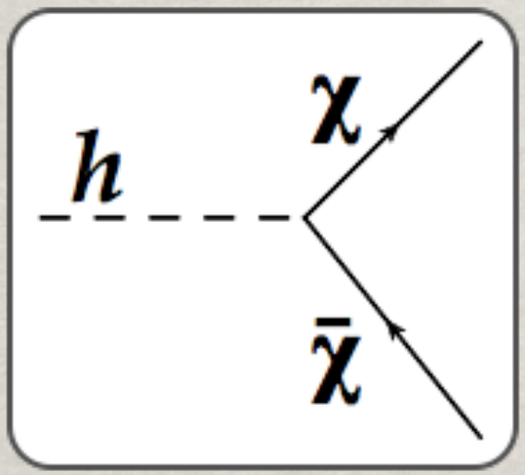
$H^\dagger H$ is the only bi-linear SM gauge singlet.

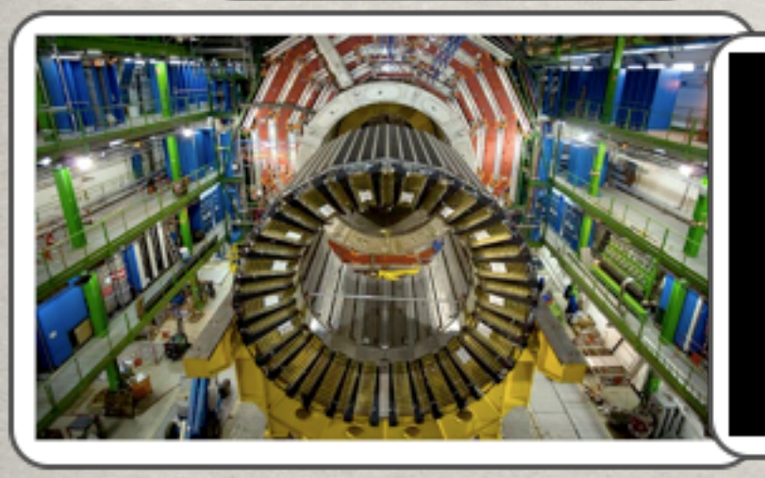
Bad: May lead to hierarchy problem with high-scale physics;

Good: May readily serve as a portal to the dark sector:

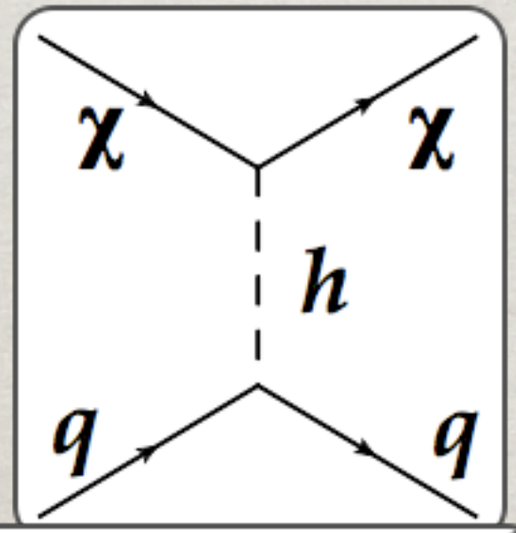
$$k_s H^\dagger H \; S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H \; \bar{\chi}\chi.$$

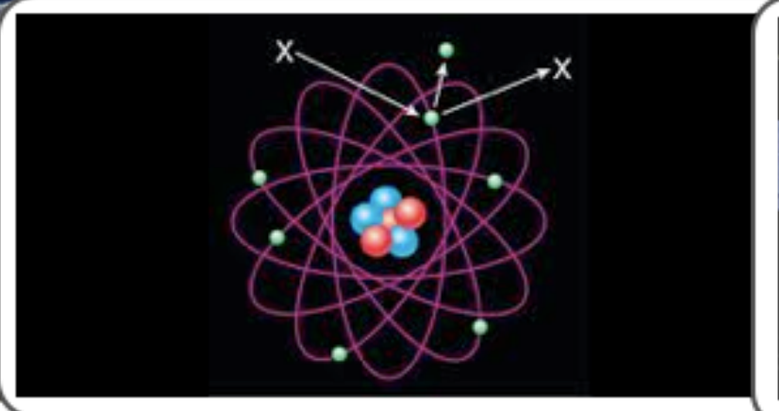
Missing energy at LHC



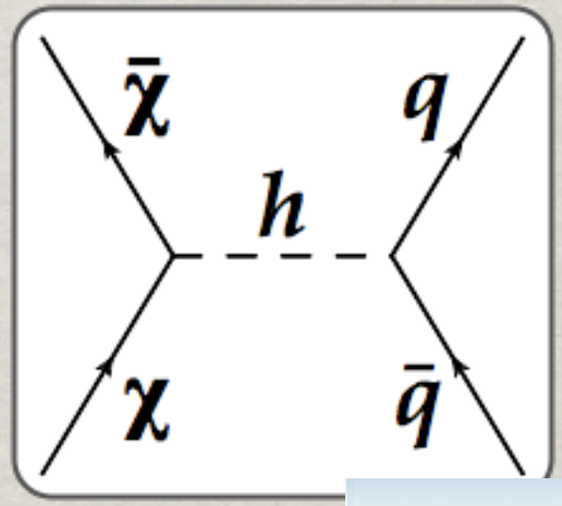


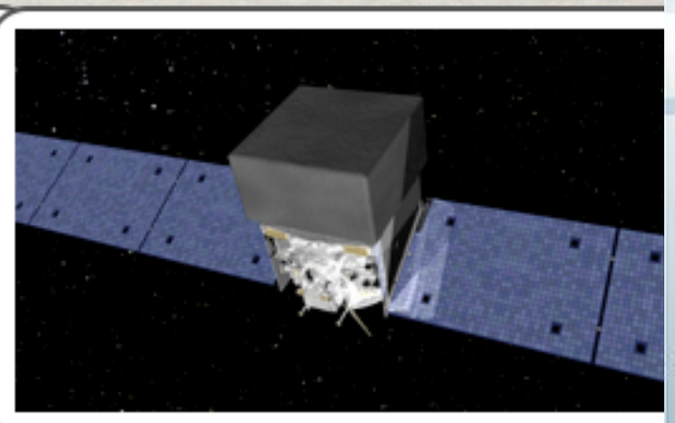
Direct detection

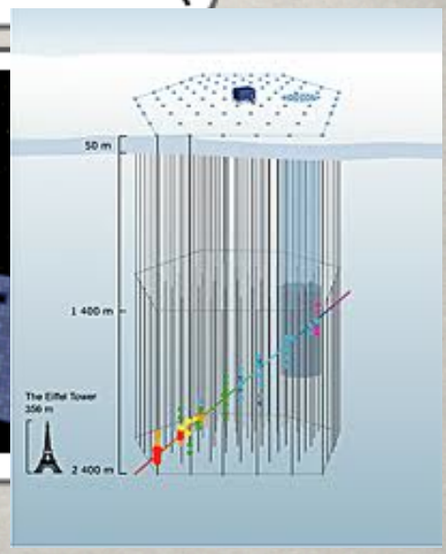




Indirect detection



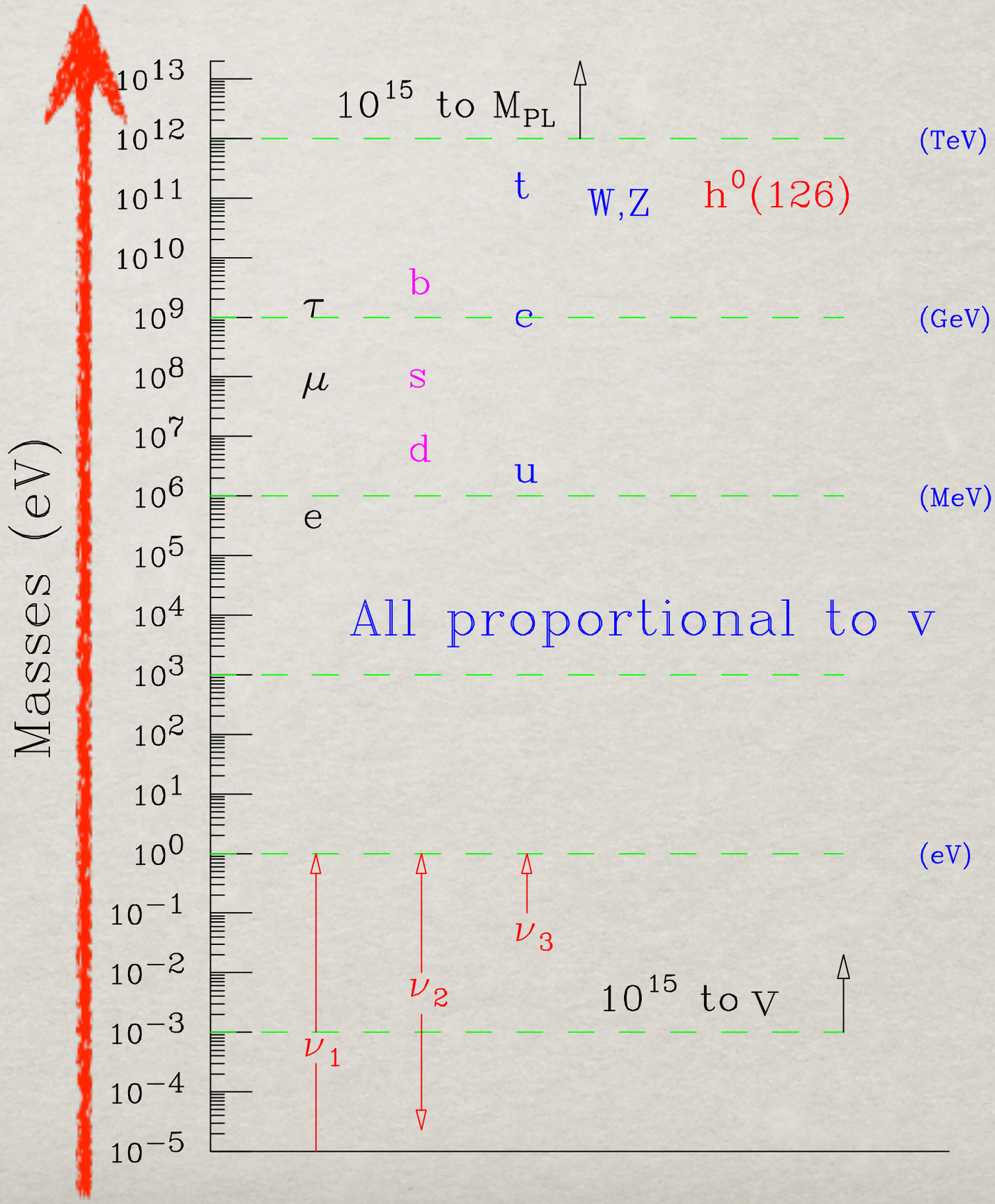




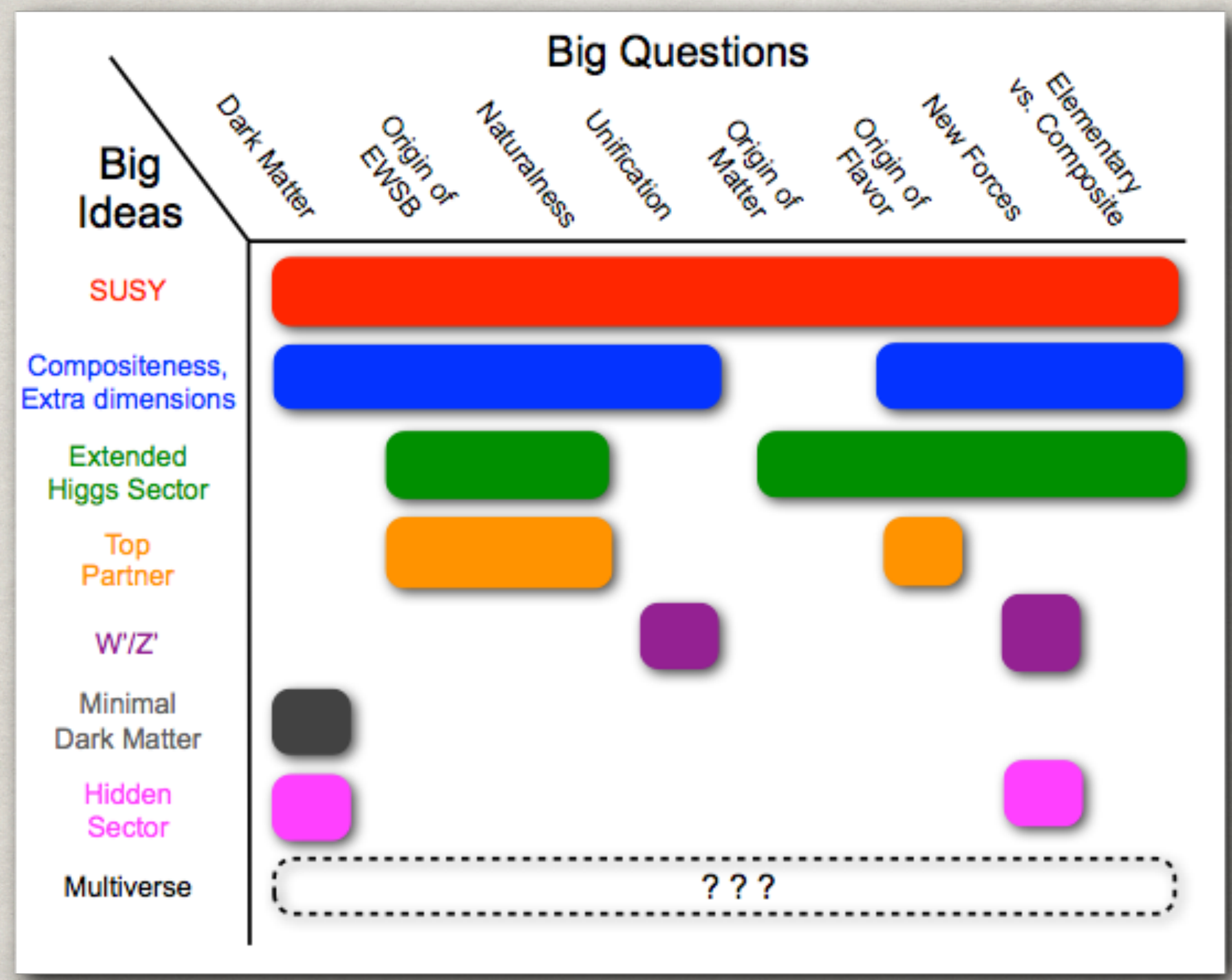
Question 4: The "Flavor Puzzle"

- Particle mass hierarchy
- Patterns of quark, neutrino mixings
- New CP-violation sources?

Higgs Yukawa couplings as the pivot!



Snowmass NP report, 1311.0299



Nature News, July '14

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.

LHC Leads the Way (2015-2030)

CERN's Large Hadron Collider
Circumference: 27 km
Energy: 14 TeV

US/European super proton collider
100 km; 100 TeV
e+e-&Z,240-350GeV

CEPC/SppC?

China's electron–positron collider
52 km; 240 GeV
China's super proton collider
52 km; ≤70 TeV

China-hosted international electron–positron collider
80 km; 240 GeV
China-hosted international super proton collider
80 km; ≤100 TeV

FCC?

International Linear Collider
Length: 31 km
≤1 TeV

ILC as Higgs Factory & beyond

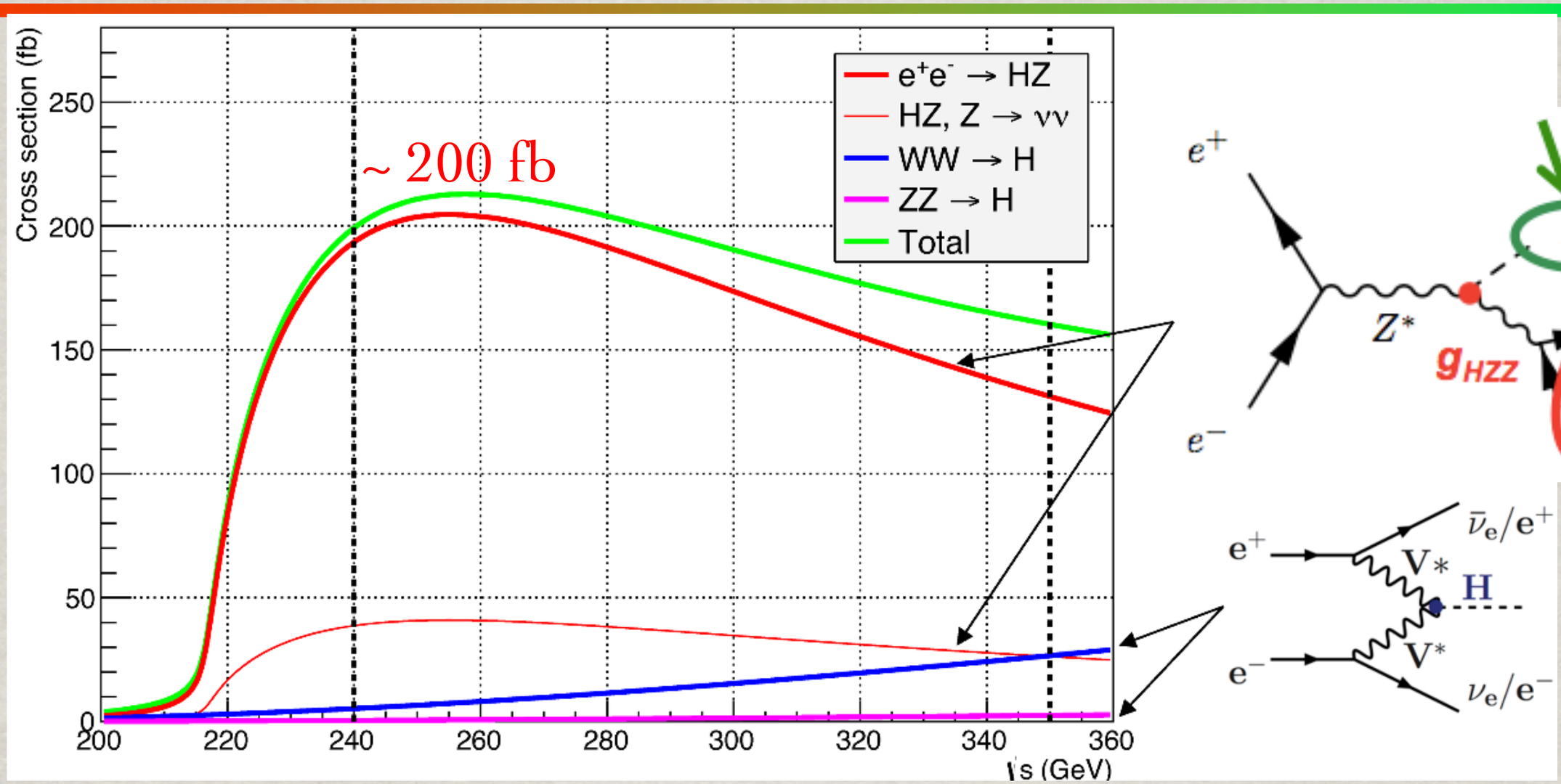
oposed
GeV, gigaelectronvolt

Table 1-1. *Proposed running periods and integrated luminosities at each of the center-of-mass energies for each facility.*

Snowmass 1310.8361

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\overline{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
dt (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

Higgs-Factory: Mega (10^6) Higgs Physics @ 5 ab^{-1}



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

- Model-independent measurement: ILC Report: 1308.6176

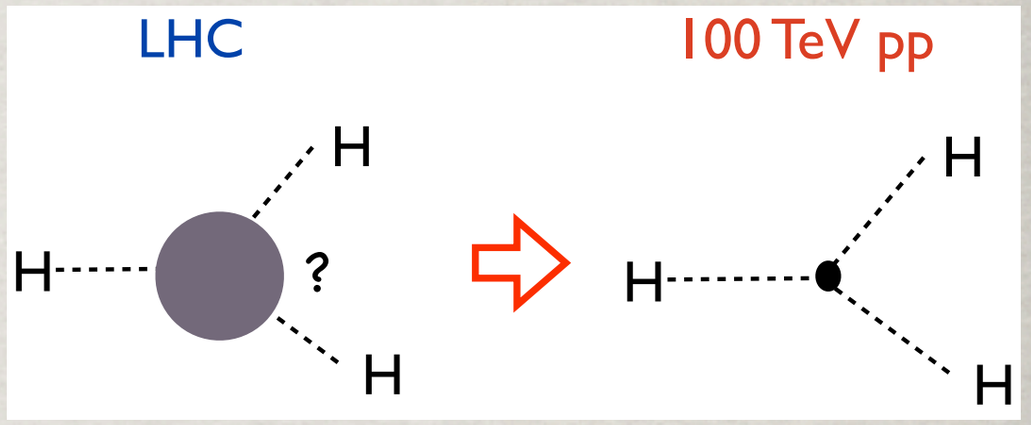
  Γ_H ~ 6%, Δm_H ~ 30 MeV

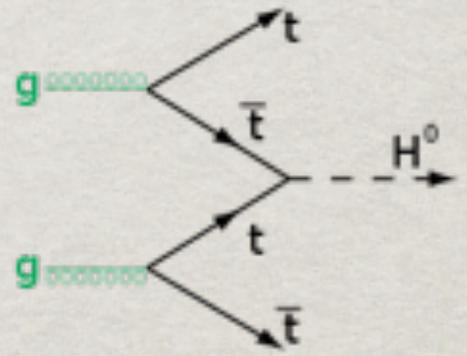
  (HL-LHC: assume SM, Γ_H~ 5-8%, Δm_H ~ 50 MeV)
- TLEP 10^6 Higgs: Γ_H ~ 1%, Δm_H ~ 5 MeV.

  TLEP Report: 1308.6176

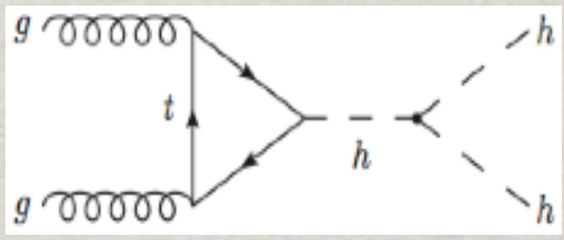
The Next Energy Frontier:
100 TeV Hadron Collider

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3





λ_t : 1%



λ : 8%

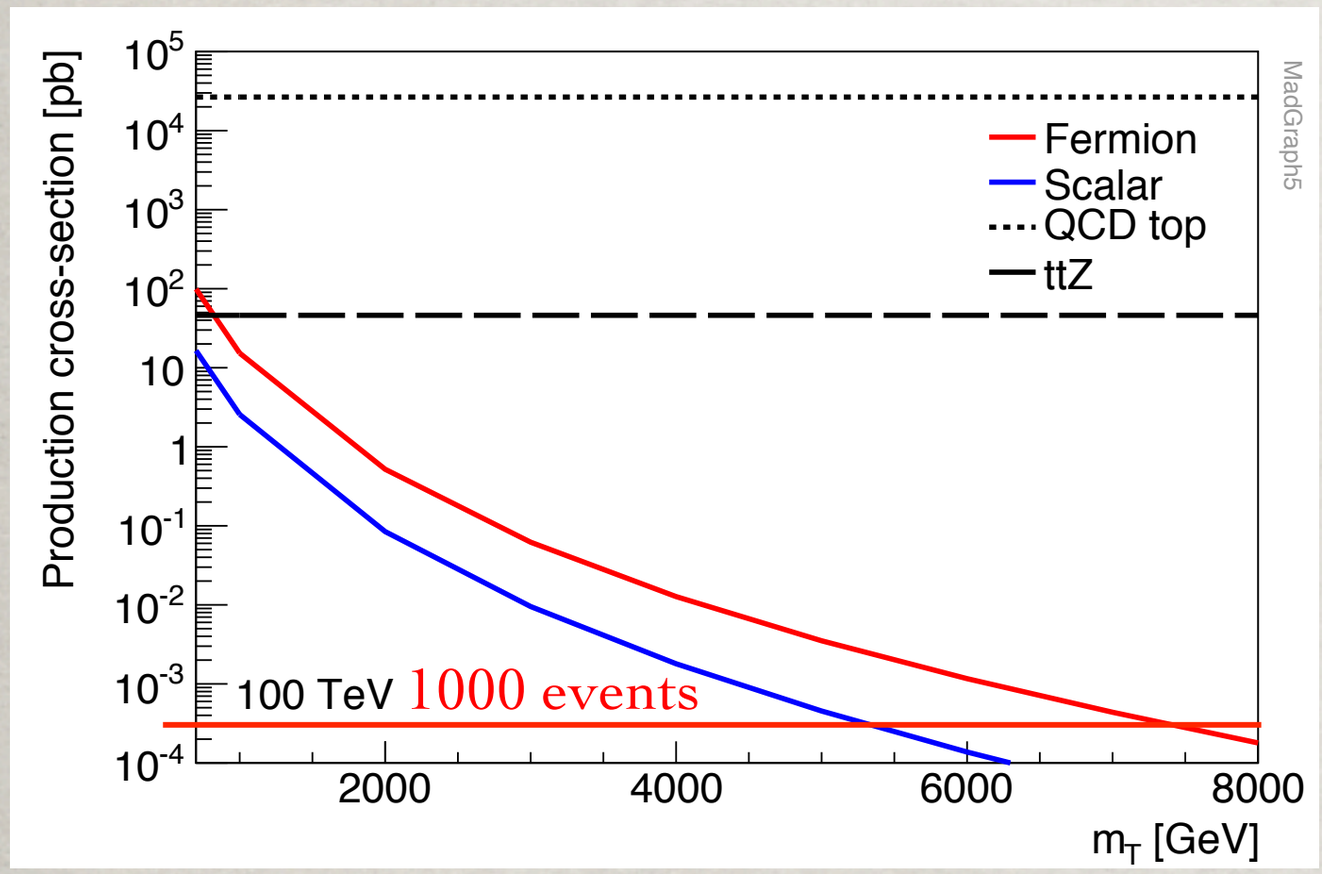
EW phase transition strong 1st order:

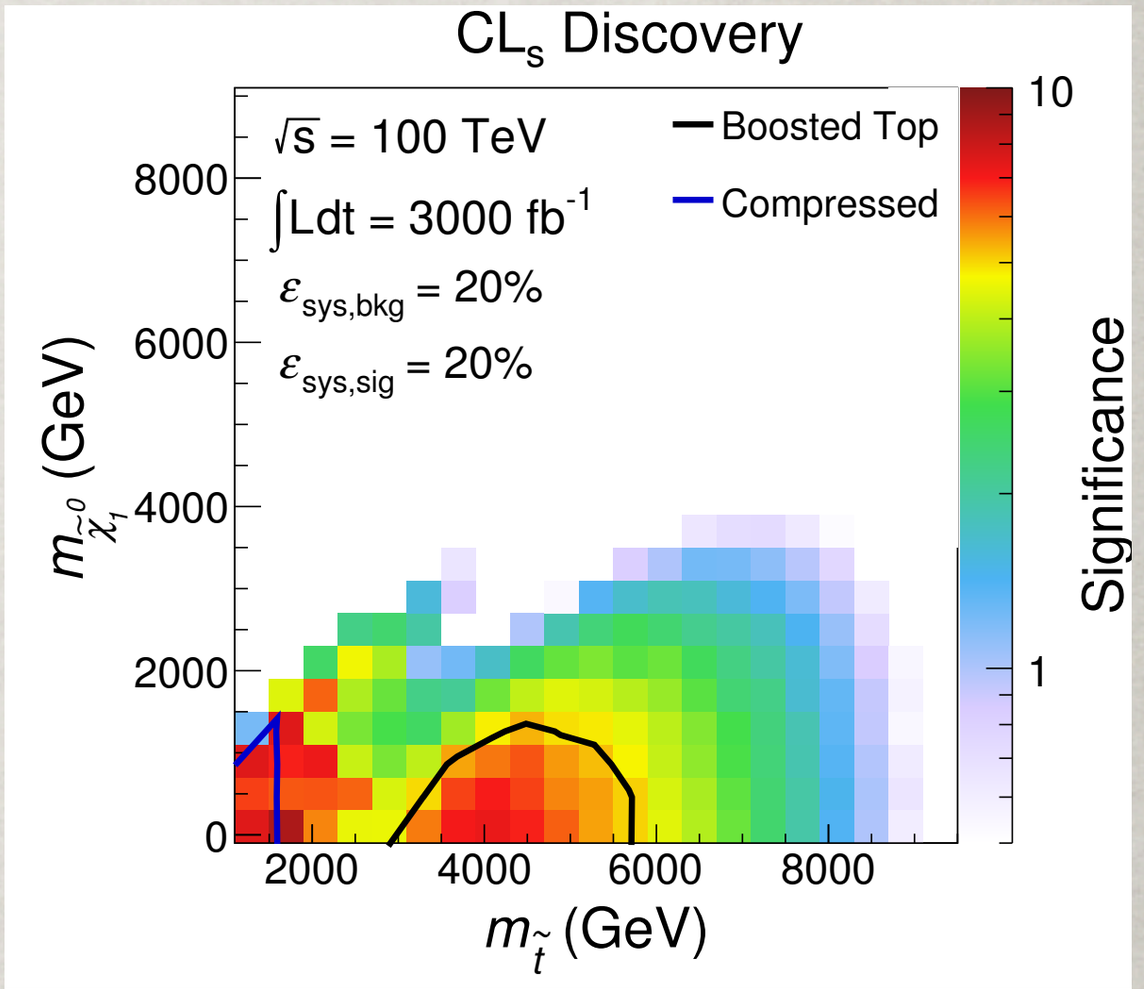
→ O(1) deviation on λ_{hhh}

Snowmass QCD Working Group: 1310.5189

Arkani-Hamed, TH, Mangano, LT Wang, 1511.06495, to appear in Phys Report

Pushing the “Naturalness” limit





Top quark partners searches:

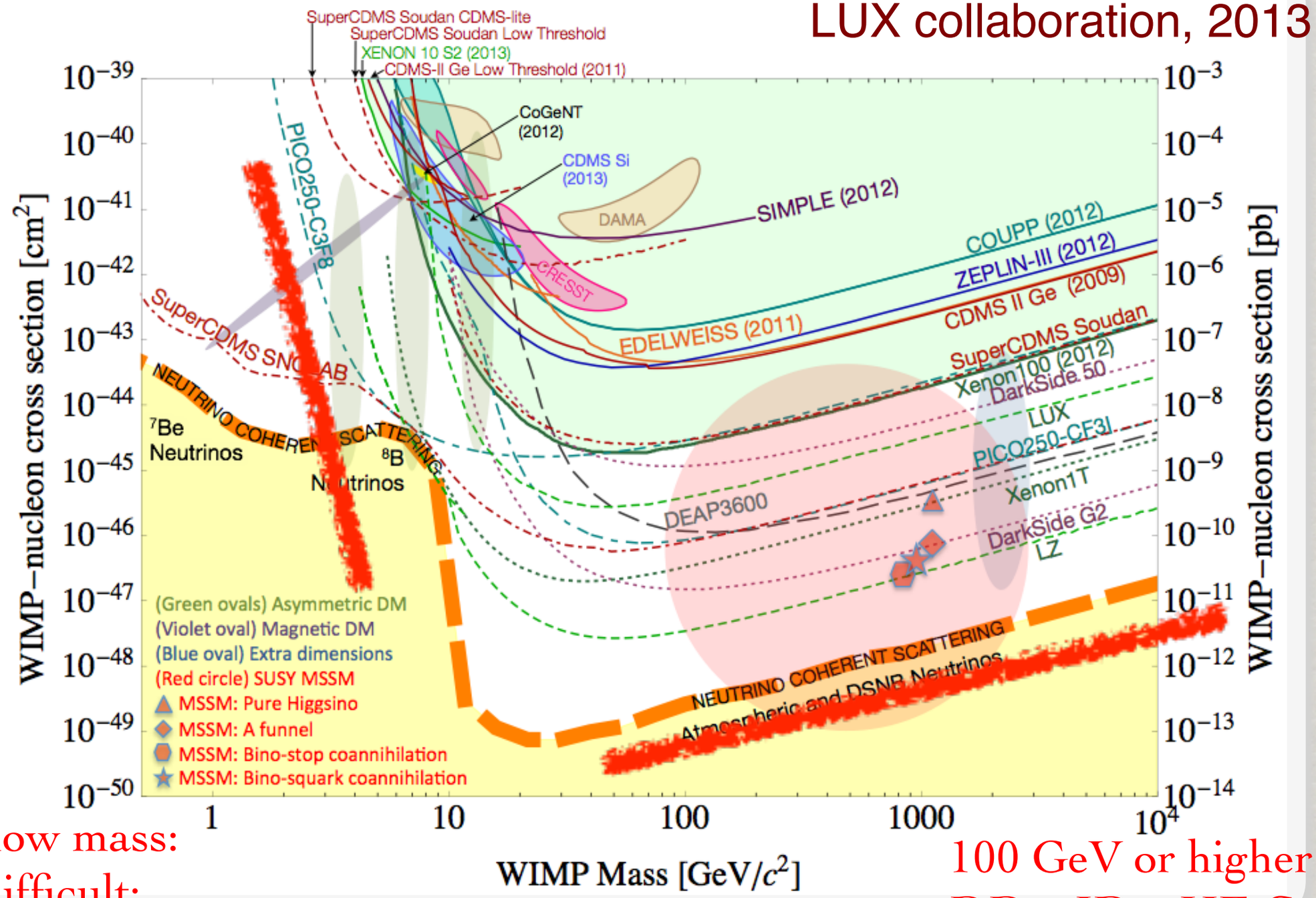
The Higgs mass fine-tune: $\delta m_H/m_H \sim 1\% \ (1 \text{ TeV}/\Lambda)^2$

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

DM Searches

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

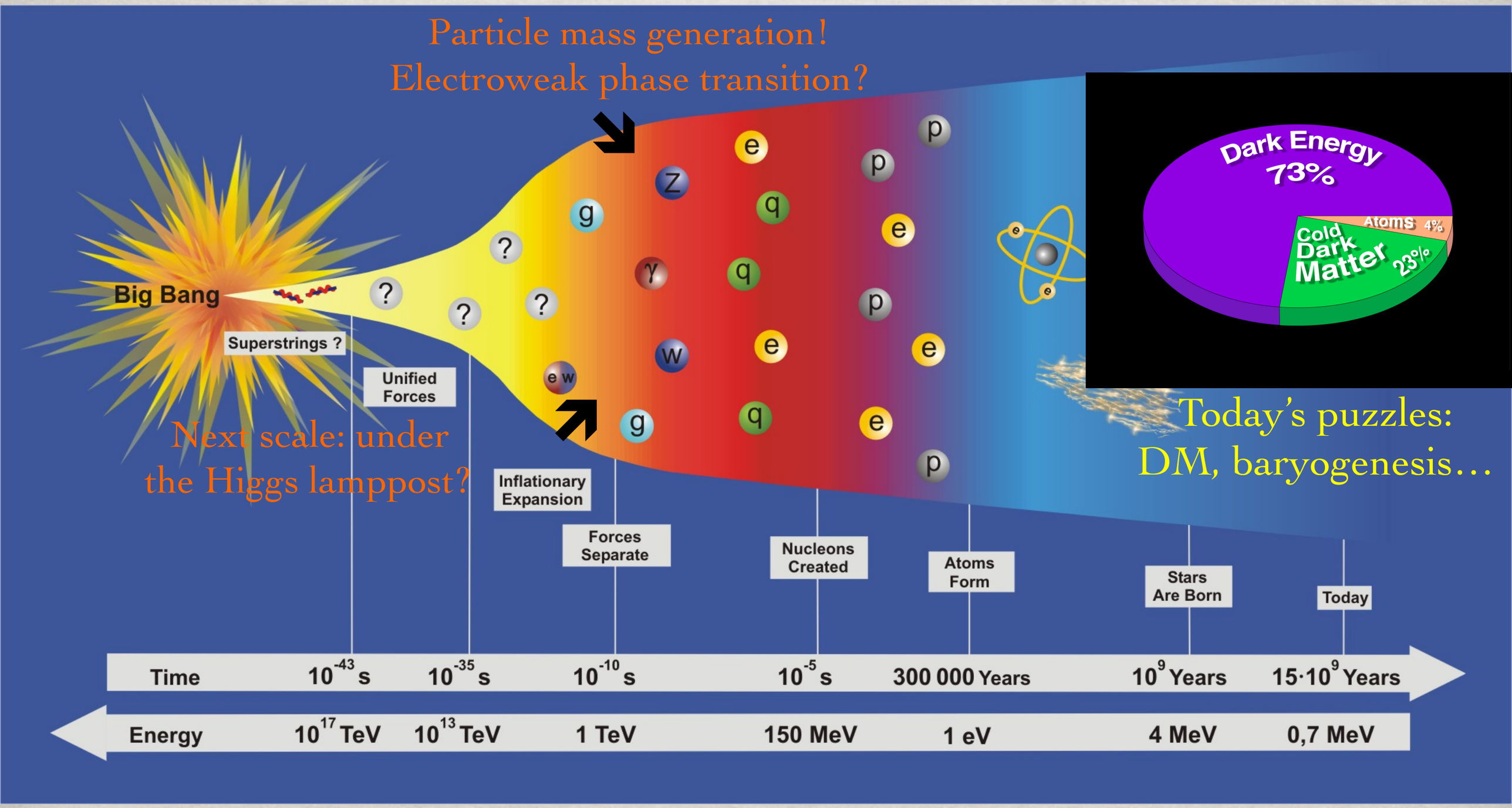
LUX collaboration, 2013



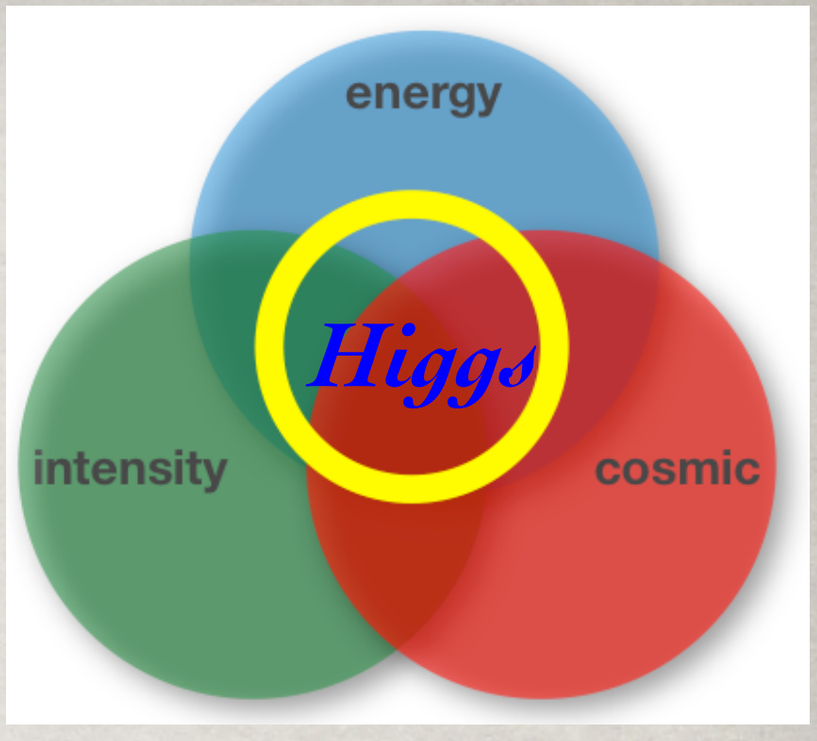
GeV low mass:
DD difficult;
Collider complementary

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

A Grand Picture:



Summary:



- The Higgs boson is a new class, at a pivotal point of energy, intensity, cosmic frontiers.

"Naturally speaking":

- It should not be a lonely solitary particle; has an "interactive friend circle": t, $W^{\pm}$, Z **An exciting**
"relatives": $\tilde{H}^{0,\pm}$, $\tilde{t}$, $\tilde{b}$, $(\tilde{g})$; S, $\tilde{S}$... **journey ahead!**
"siblings": H^0, A^0, $H^{\pm}$, $H^{\pm\pm}$, S...

- Precision Higgs physics:
  LHC lights the way: g~10%; λ_{HHH} ~ 50%; $Br_{inv.}$~ 20%
  CEPC/SppC: g~1%; λ_{HHH} < 10%; $Br_{inv.}$ ~ 2%; Γ_{tot} < 6%
- 6x LHC reach: 10 – 30 TeV → fine-tune < 10^{-4}
  WIPM DM mass ~ 1 – 5 TeV