Physics Beyond the SM
Under The Higgs Lamppost

Tao Han

Pitt PACC, Univ. of Pittsburgh

Herbstschule of High Energy Physics 2025

Bad Honnef, Sept. 8 – 11, 2025

François Englert and Peter W. Higgs

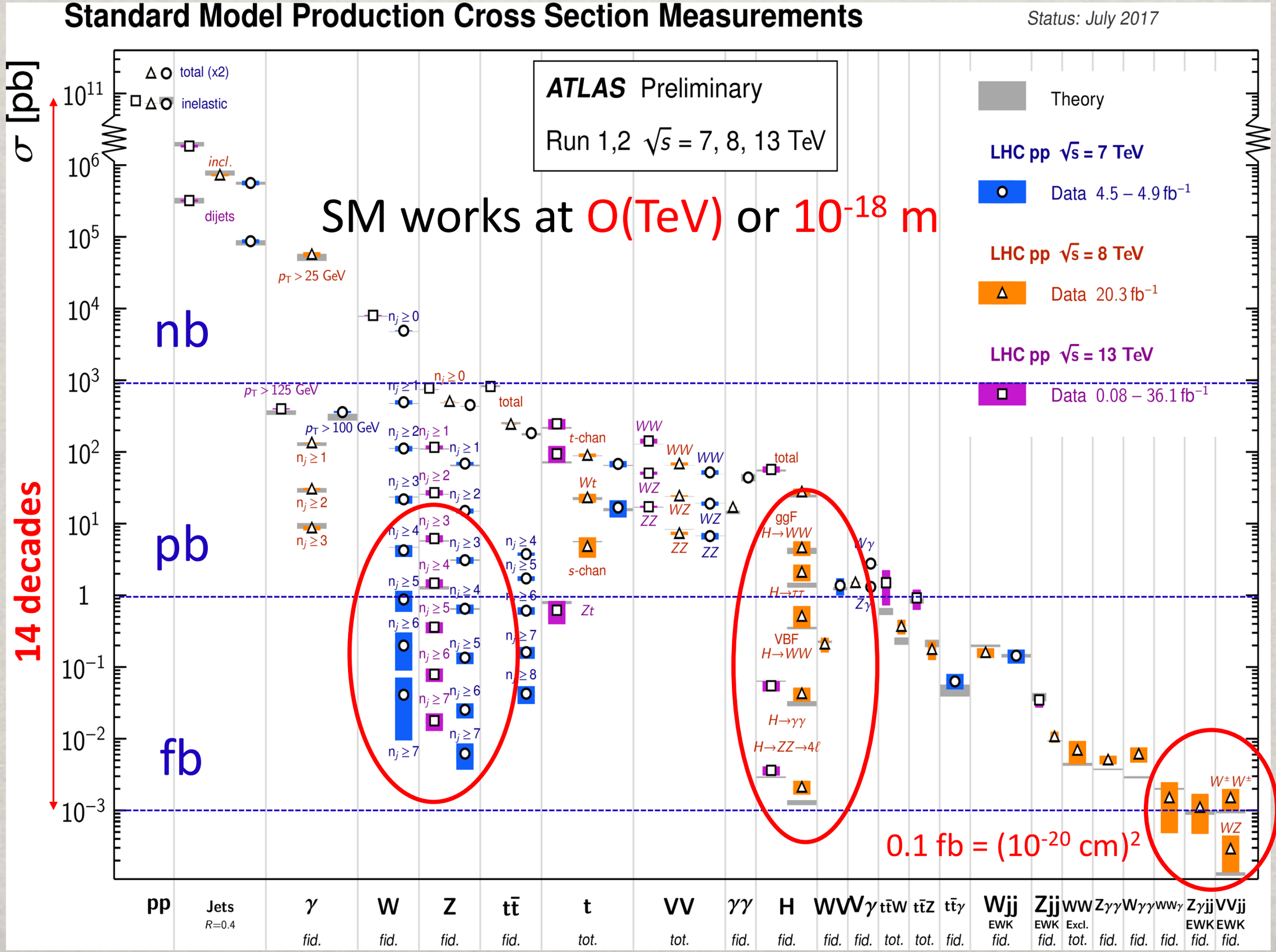
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

50 years theoretical work …

25 years experimental work …

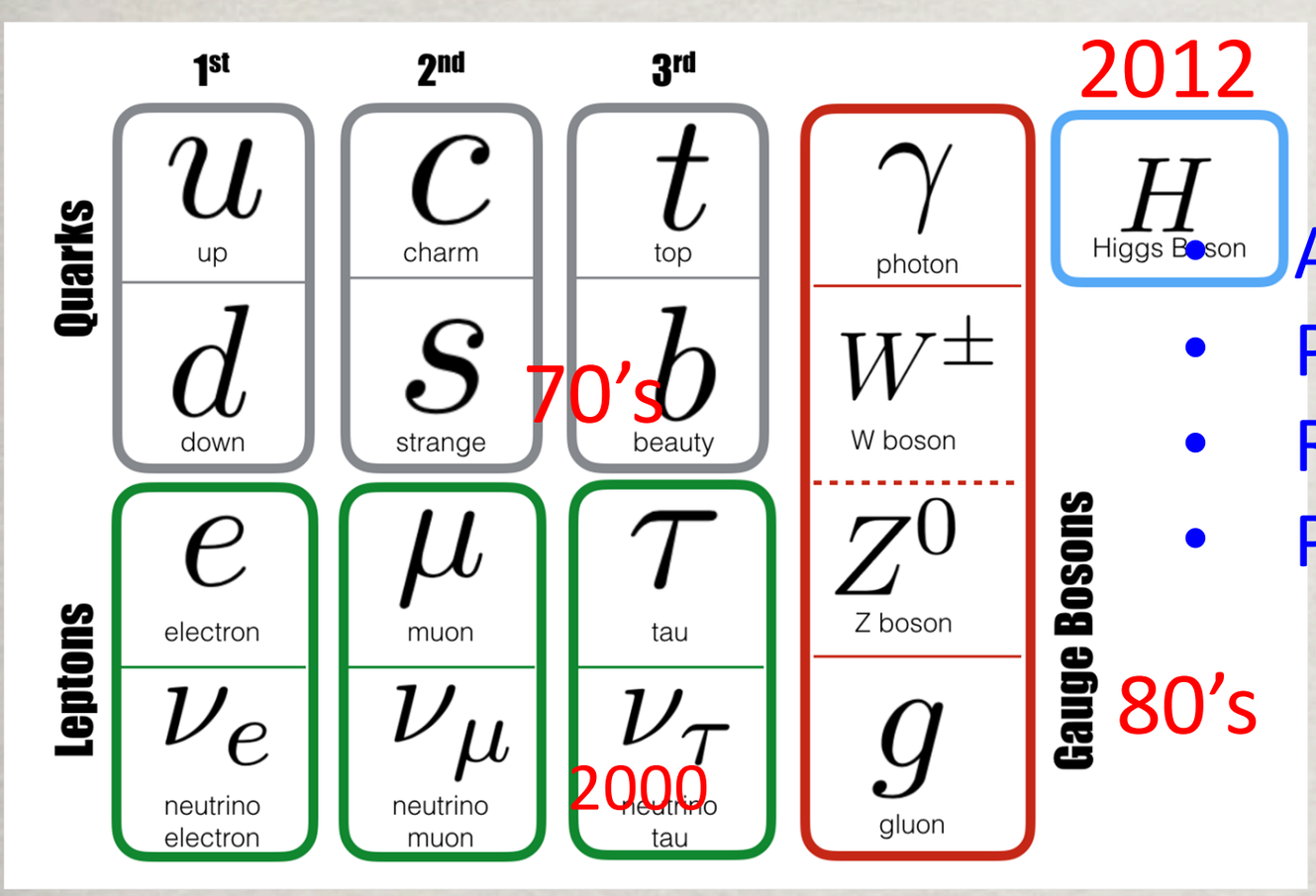
We Made It !

LHC Rocks!


Standard Model Production Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
SM works at O(TeV) or 10-18 m
σ [pb]
14 decades
nb
pb
fb
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb−1
LHC pp √s = 8 TeV
Data 20.3 fb−1
LHC pp √s = 13 TeV
Data 0.08 – 36.1 fb−1
0.1 fb = (10-20 cm)2
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
WVγ fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Wjj EWK fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
WWγ fid.
Zγjj EWK fid.
VVjj EWK fid.

Particle physics has enjoyed uninterrupted discoveries for several decades: from quarks to the Higgs boson

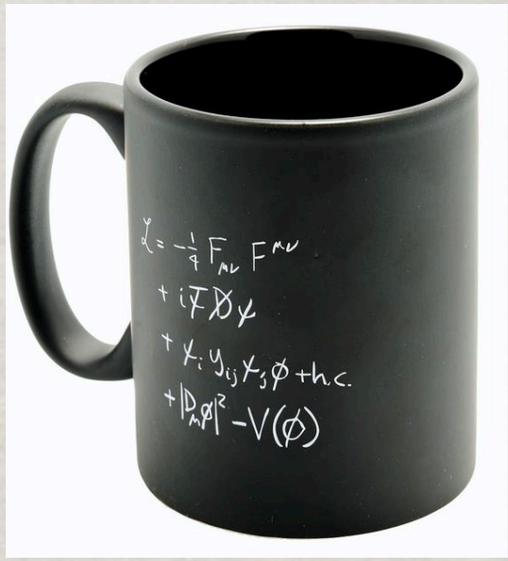
60's 70's 90's



The SM is a triumph in science!

The first theory:

- A relativistic & quantum-mechanical
- Perturbative & unitary
- Renormalizable & UV complete
- Potentially valid 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 understanding — quantum mechanics — spacetime — gravity — strong & electroweak — matter — Higgs

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

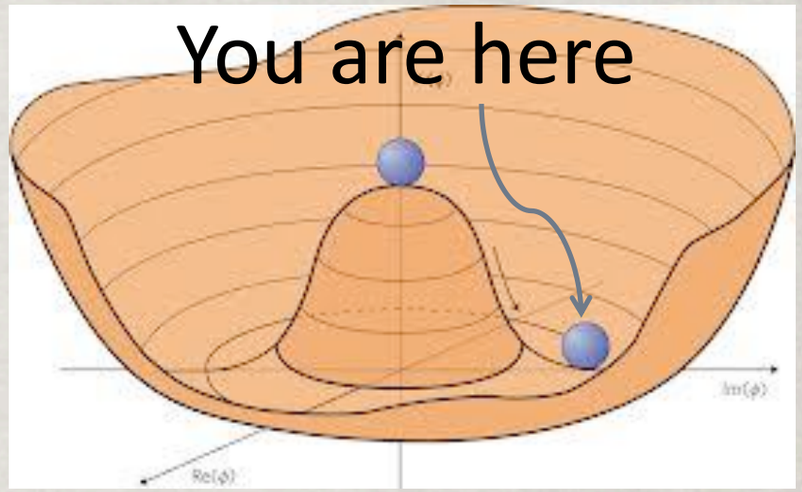
Will History repeat itself (soon)?

In these lectures:

1. The Quest for the SM & Beyond
2. A Strongly-coupled EW Sector
3. A Weakly-coupled Extension
4. Flavors of Matter Fields

Question 1:
Electroweak Superconductivity

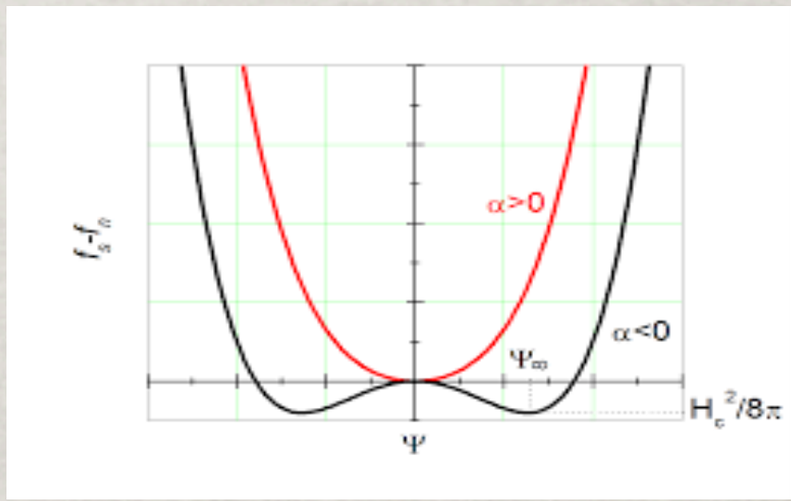
10^{-9} s after the Big Bang, when the Universe was as cold as 10^{15} K, the electro-weak phase transition took place.
Ever since, the Universe is in an EW super-conducting phase.



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)!**

SM NOT Landau-Ginzburg Theory

$V(|\Phi|) = -\mu^2 \Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$ $\quad m_H^2 = 2\mu^2 = 2\lambda v^2 \quad \Rightarrow \quad \mu \approx 89\ \mathrm{GeV}, \quad \lambda \approx \frac{1}{8}.$

- A consistent relativistic quantum mechanical scalar field theory, valid to high scales.
- The Higgs boson weakly coupled,
  a very narrow resonant particle: $\Gamma/m_h \approx 10^{-5}$!
- Elementary up to a scale >1000 GeV!
- The Universe underwent a slow cross-over phase transition at the EW scale ~ 100 GeV.
- The EW vacuum is a Type-2 superconductor.

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

Q1: What is the underlying theory / mechanism?

BCS-like, responsible for the EWSB?

→ Explain / calculate m_H, λ, ...

Question 2:
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

"We are all Wilsonians now."

- J. Preskill, Quantum Frontier (2013)

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

$$\mathcal{L} = \sum c_i \Lambda^n \mathcal{O}_n = \underbrace{c_0 \Lambda^4 + c_2 \Lambda^2 \mathcal{O}_{\text{dim } 2} + c_3 \Lambda \mathcal{O}_{\text{dim } 3}}_{\text{(relevant operators)}}$$

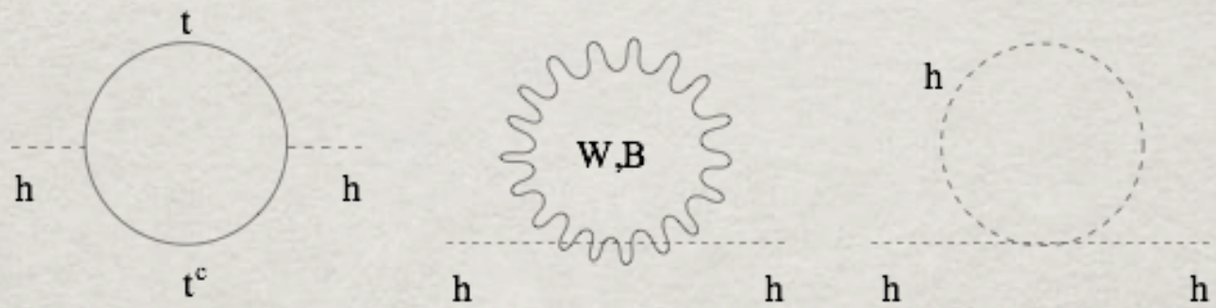
$$+ \underbrace{c_4 \mathcal{O}_{\text{dim } 4}}_{\text{(marginal operators)}} + \underbrace{\frac{c_6}{\Lambda^2} \mathcal{O}_{\text{dim } 6} + \cdots}_{\text{(irrelevant operators)}}$$

The Higgs mass as a "relevant operator": $-\mu^2 |\phi|^2$

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

"… 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

→ Any underlying theory at a scale Λ, quantum corrections ~ $g^2\Lambda^2$



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

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

Requiring less 90% cancellation → $\Lambda_t < 3$ TeV,

Or the Higgs mass is **fine-tuned.**

Q2: Where is the new scale? $\Lambda \sim 4\pi v \sim$ O(TeV)?

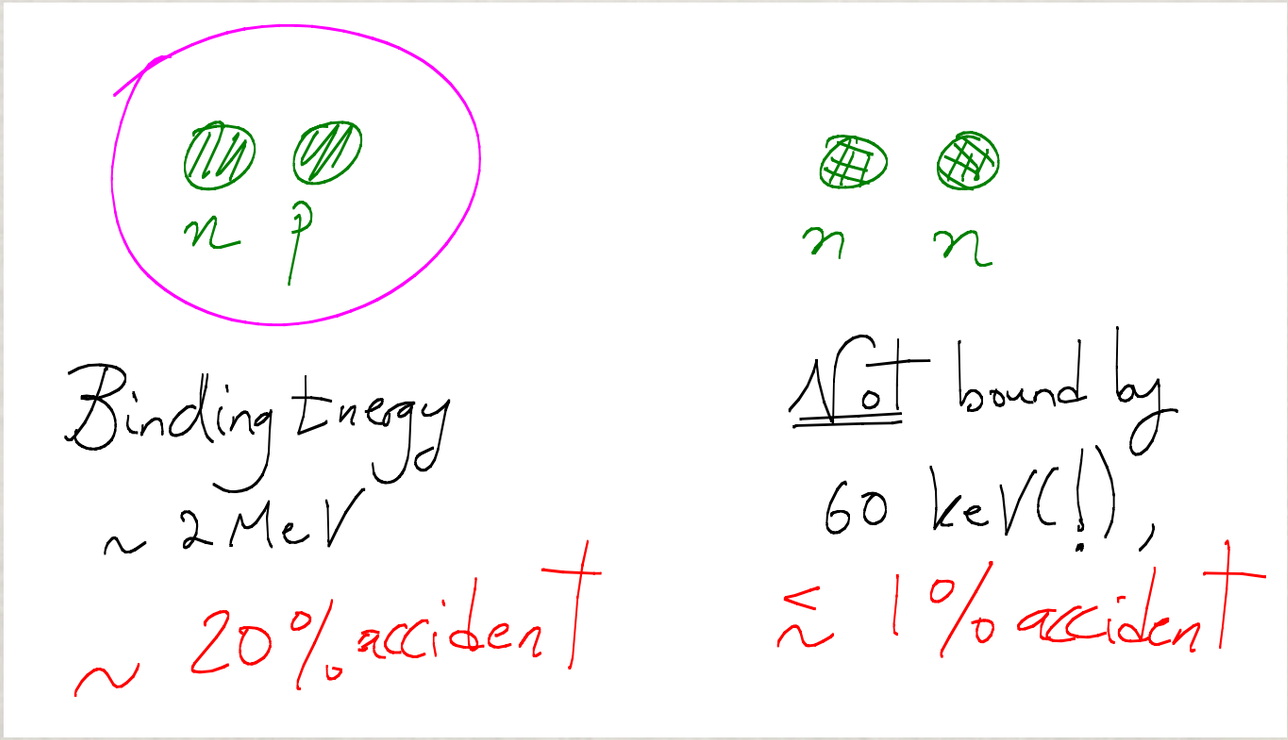
"Hierarchy problem" between m_h & M_{planck} !

How much "tuned" is fine-tuned?

Atomic physics:

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

Nuclear physics?



Solar eclipses:

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

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

Can you tolerate 10^{-32} ?!

Higgs boson analogue in CM:

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

Science

Home News Journals Topics Careers

Science Science Advances Science Immunology Science Robotics Science Signaling Science Tra

REPORT

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

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,*]

+ Author Affiliations

↵*Corresponding author. E-mail: matsunaga@thz.phys.s.u-tokyo.ac.jp (R.M.); shimano@phys.s.u-tokyo.ac.jp (R.S.)

↵† Present address: Terahertz Technology Research Center, National Institute of Information and Communications Technology, Tokyo 184-8795, Japan.

↵‡ Present address: Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China.

Science 05 Sep 2014:
Vol. 345, Issue 6201, pp. 1145-1149
DOI: 10.1126/science.1254697

Though not naturally existed, could be prepared, and thus **fine tuned,** to produced it,.

Some words about "naturalness"

There are many "unnaturally small" numbers around beyond our expectation from "naïve dimensional analysis":

- Cosmological constant: $\rho_\Lambda / M^4_{Pl} \sim 10^{-120}$
- Electroweak scale: $v^2 / M^2_{Pl} \sim 10^{-32}$
- QCD scale: $\Lambda^2_{QCD} / M^2_{Pl} \sim 10^{-38}$
- Electron mass: $y_e \sim m_e / v \sim 10^{-5}$
- Neutrino mass: $m_\nu / v \sim 10^{-13}$
- Strong CP problem: $|\theta| < 10^{-10}$
- … …

Dirac naturalness:

In a theory with a cut-off scale Λ, all properly normalize dimensionless parameters should be naturally of ~ O(1).

As such, all the parameters above are "unnatural", in the Dirac sense!

’t Hooft naturalness (technical naturalness):

The dimensionless parameters associated with an operator can be much smaller than the fundamental scale, if the absence of this operator enhances the symmetry.
The natural size is then ~ S x O(1),
where S is a parameter that violates the symmetry.

As such, all the parameters, except for ρ_Λ, m_H,
are “natural” in the ’t Hooft sense!

In other words, large quantum corrections are protected:

$$\delta m_w^2 \leftarrow m_w^2 \ln(\Lambda/m_w) \quad \text{(gauge symm)}$$
$$\delta m_f \leftarrow m_f \ln(\Lambda/m_w) \quad \text{(chiral symm)}$$

e.g. $m_e \sim m^0_e [1 + 3\alpha/4\pi \ln(\Lambda/m_e)]$

If m^0_e is turned off, the system possesses a chiral symmetry.

But not for $\delta m^2_H \sim g^2 \Lambda^2$

→ What protection mechanism at work?

A "measure" of fine-tune

Barbieri-Giudice (1988) fine-tune measure:

If an observable $\mathcal{O}$ runs with a high-energy scale $\boldsymbol{\Lambda}$, then the sensitivity of the observable to the high scale is defined by

$$\Delta_{BG} = |\frac{\partial \ln \mathcal{O}}{\partial \ln \Lambda}| = |\frac{\partial \mathcal{O}/\mathcal{O}}{\partial \Lambda/\Lambda}|$$

Which accounts for both scale ratio & slope ratio.

Originally, BG thought ~10 as "fine-tuned", corresponding to a 90%-cancellation.

$$m_H^2 = m_{H0}^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 \quad \Rightarrow \quad \Delta_{BG}(H) \approx \frac{1}{30}\frac{\Lambda^2}{m_H^2} \quad \text{(sensitive)}$$

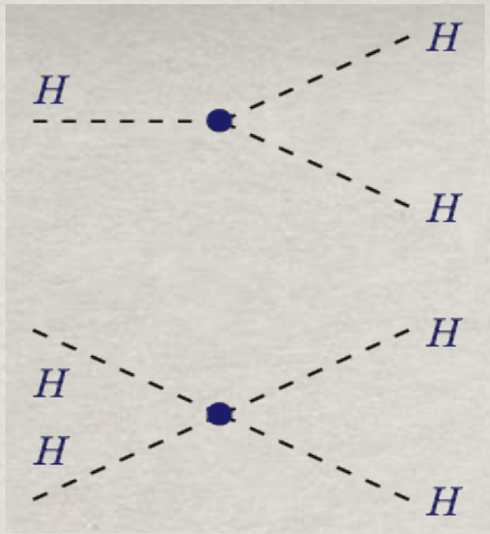
$$m_f = m_{f0}(1 + \frac{\alpha}{4\pi}\ln\frac{\Lambda}{m_f}) \quad \Rightarrow \quad \Delta_{BG}(f) \approx \frac{\alpha}{4\pi}\frac{1}{\ln\frac{\Lambda}{m_f}} \quad \text{(no tune)}$$

Question 3: The Nature of EWSB

$\lambda|\phi|^4$: a weakly coupled new force!

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

$$\Rightarrow \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$



A truly "self-interaction":

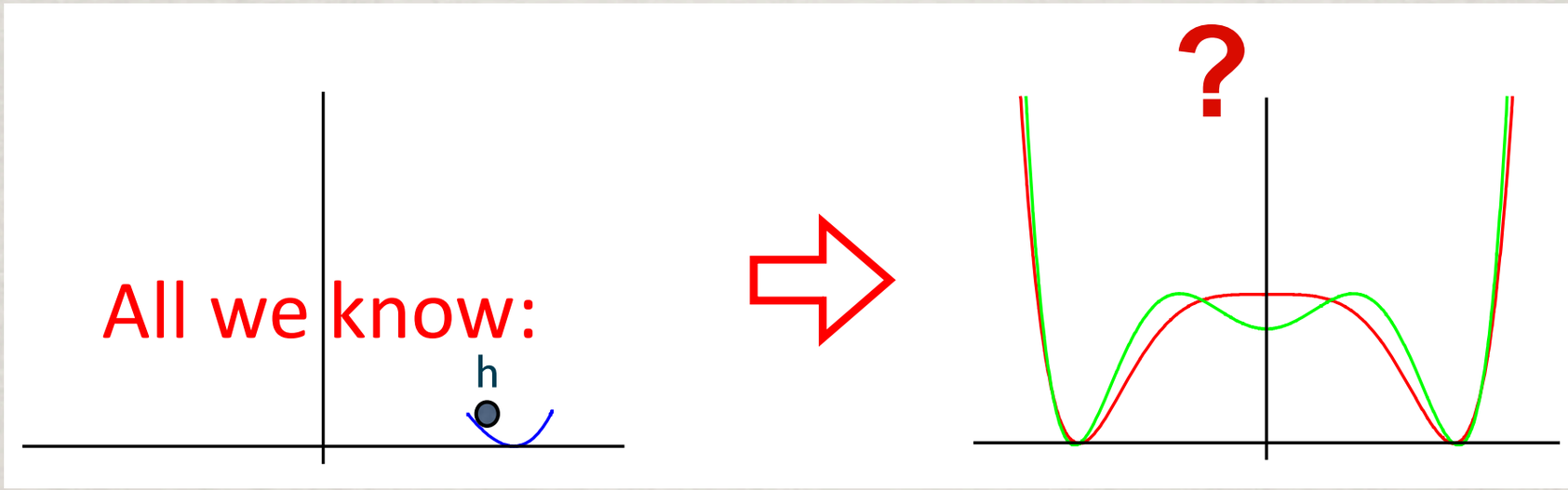
No charge/color, no spin, vacuum-quantum number!

In the SM, λ is a free parameter, now measured at the electroweak scale: $\lambda = m_H^2 / 2v^2 \approx 0.13$

Is it a "fundamental" 5th force? or "induced"

- Landau-Ginzburg <-> BCS?
- Van der Waals <-> Coulomb?
- Scalar <-> Fermion -- SUSY?

Triple Higgs coupling:



With new physics near the EW scale:

$$V(h) \to m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3 \; ! \; \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

→ $\lambda_{hhh} = (7/3)\lambda_{hhh}^{SM}$

→ $\lambda_{hhh} = (5/3)\lambda_{hhh}^{SM}$

$\lambda(h^+h)^2$ term could be modified (even "-"), leading to EW phase transition strong 1st order!

→ O(1) deviation on λ_{hhh}

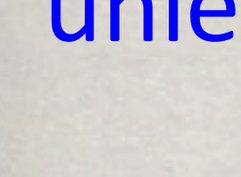
Significant impact on cosmology!

λ is NOT asymptotically free:

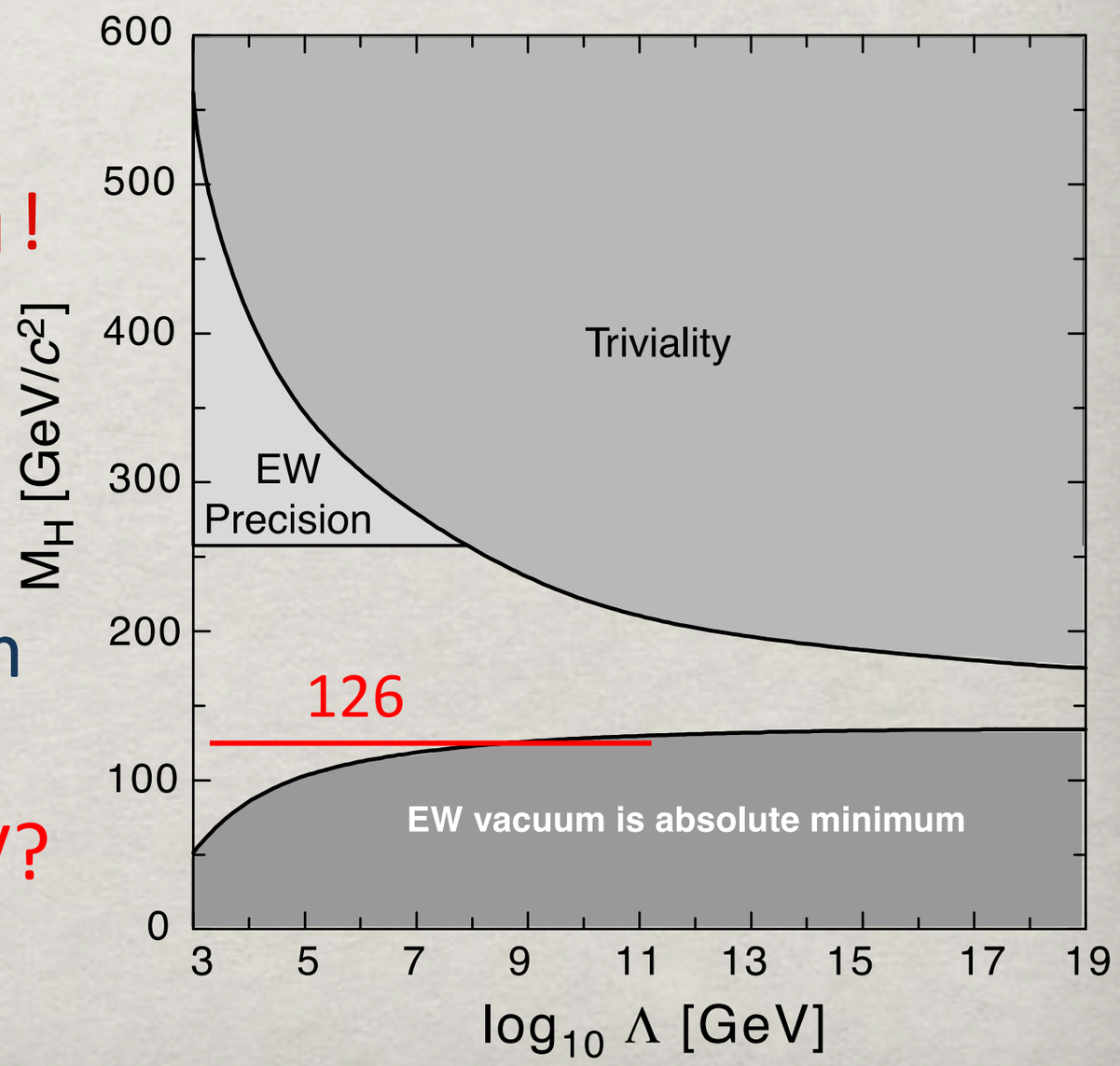
It blows up at a high-energy scale (the Landau pole), unless it starts from small (or zero → triviality).

For M_H = 125 GeV, rather light:

The SM can be a consistent perturbative theory up to M_{pl} !
allowing M_N, M_{GUT}, …



Top-Yukawa drags the vacuum meta-stable,
New physics below $10^{7\text{-}11}$ GeV?



Question 4: Physics of Flavors

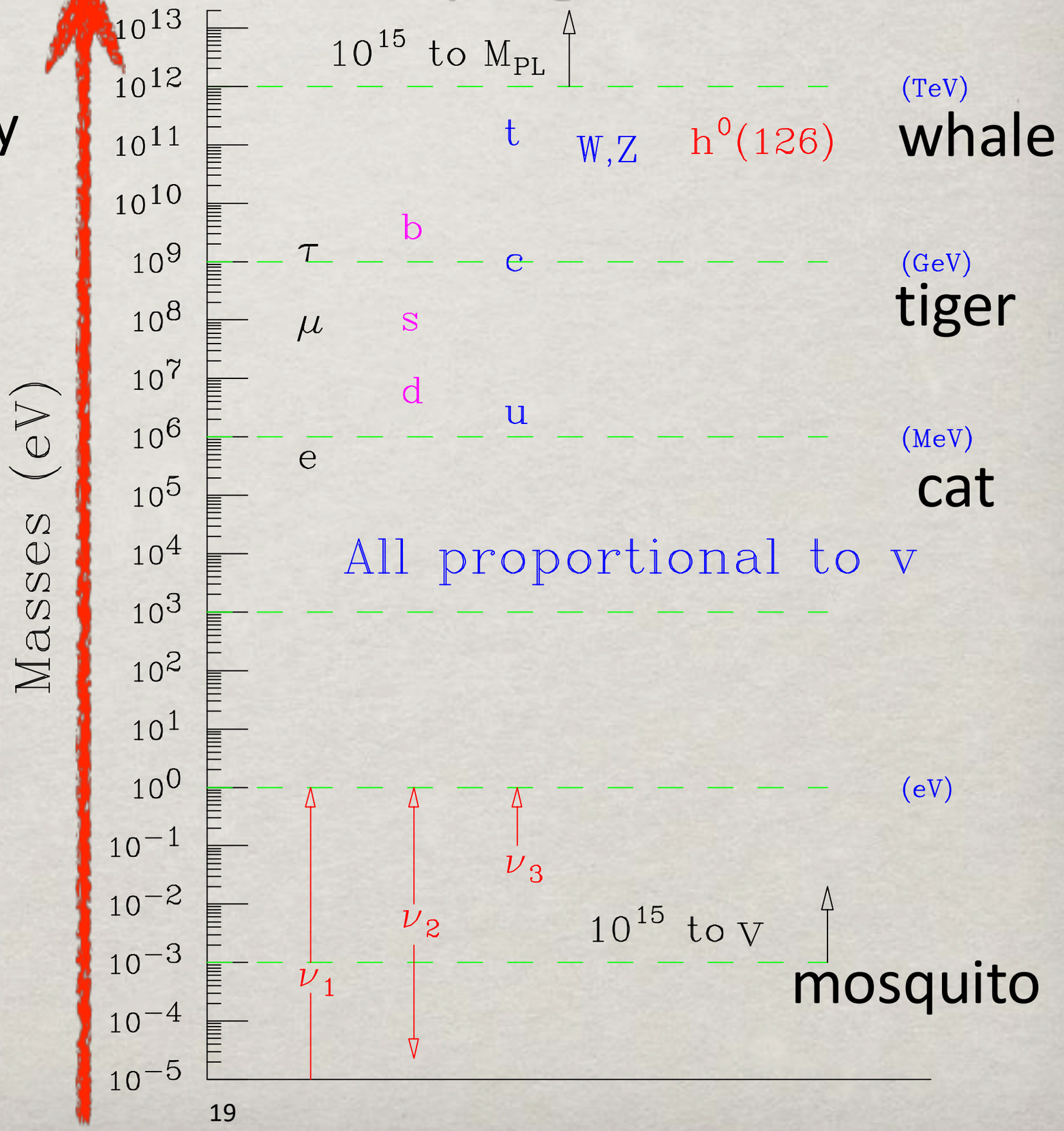
Flavor & Yukawa Couplings

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

Higgs Yukawa couplings as the pivot!

The "seesaw" mechanism:

$$m_\nu \sim \kappa \frac{\langle H^0 \rangle^2}{M}$$



Question 5:
Portals to Cosmos?

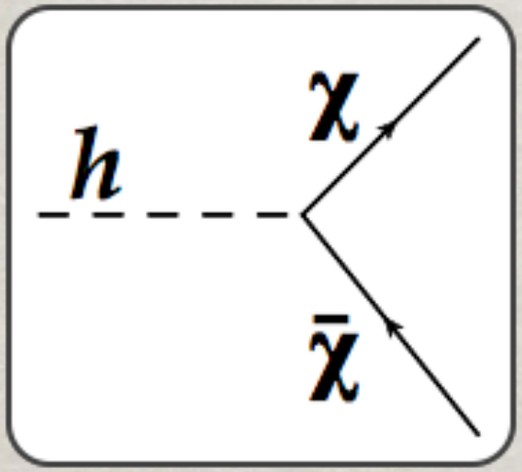
$H^\dagger H$ is the only bi-linear SM gauge singlet.

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

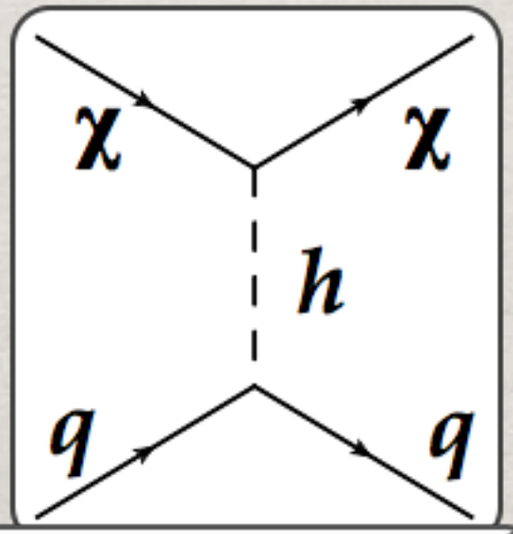
Good: May readily serve as a portal to the dark sector:

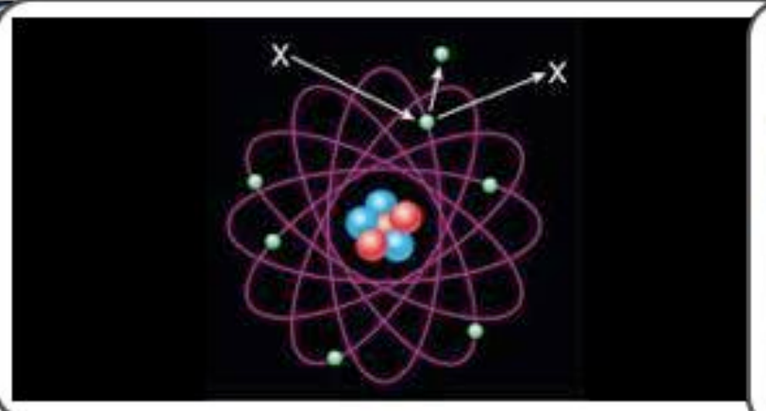
$$k_s H^\dagger H \; S^* S, \qquad \frac{k_\chi}{\Lambda} H^\dagger H \; \bar{\chi}\chi.$$

Missing energy at LHC

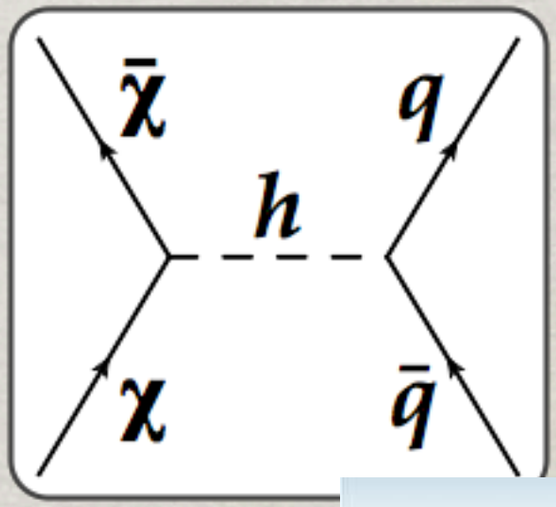


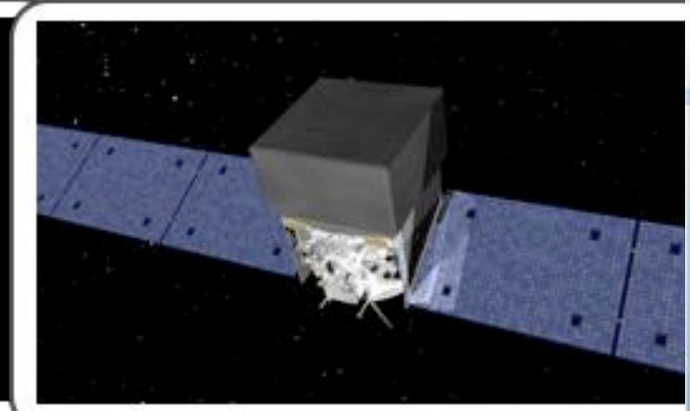
Direct detection

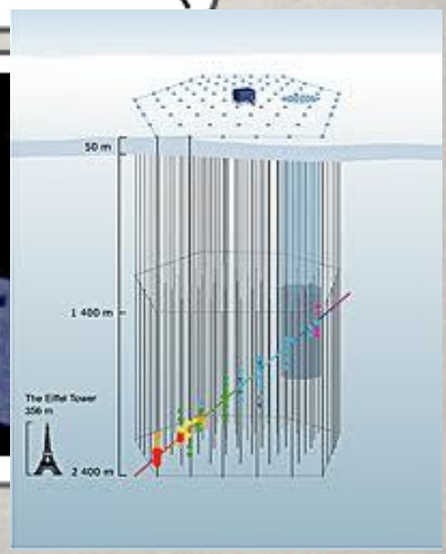




Indirect detection

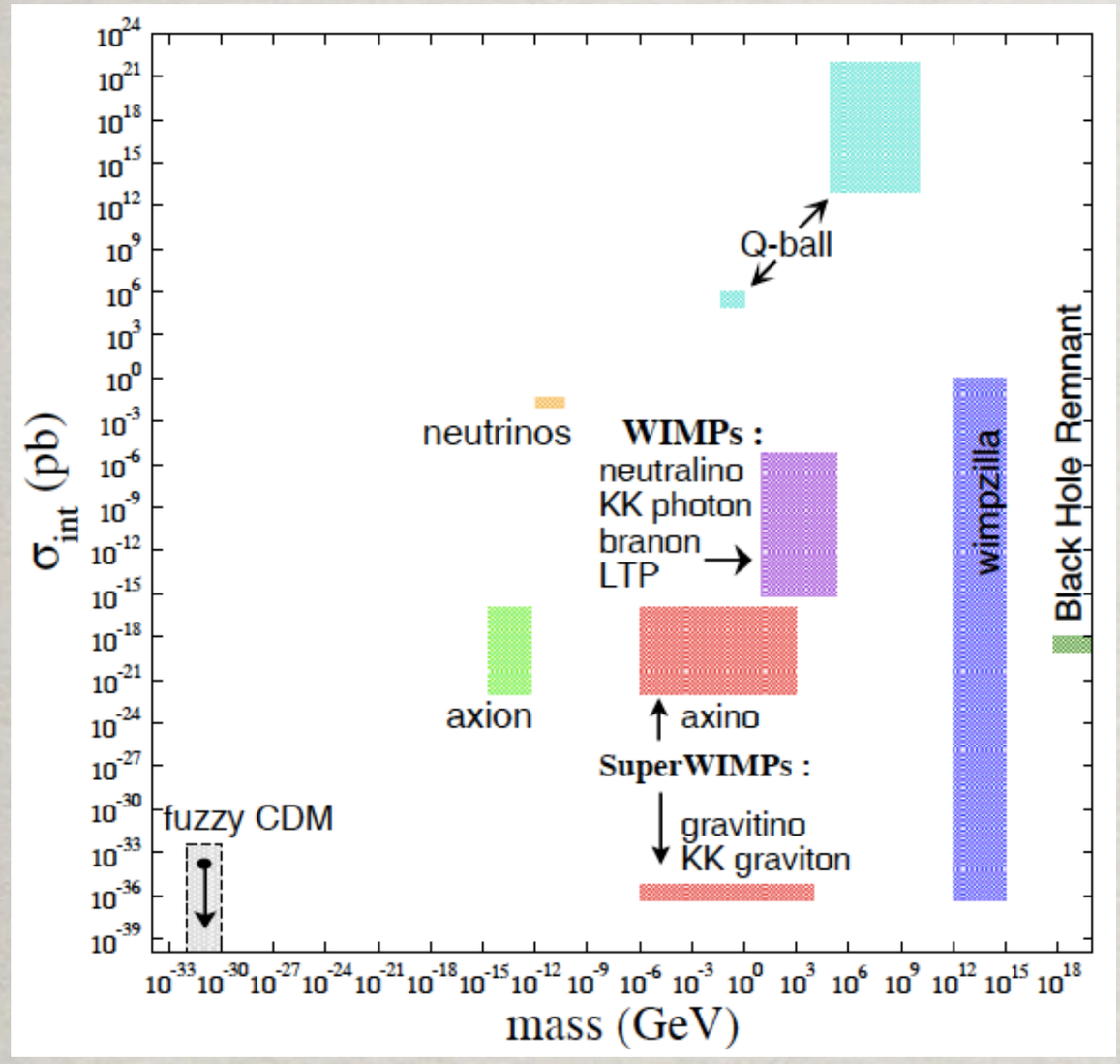


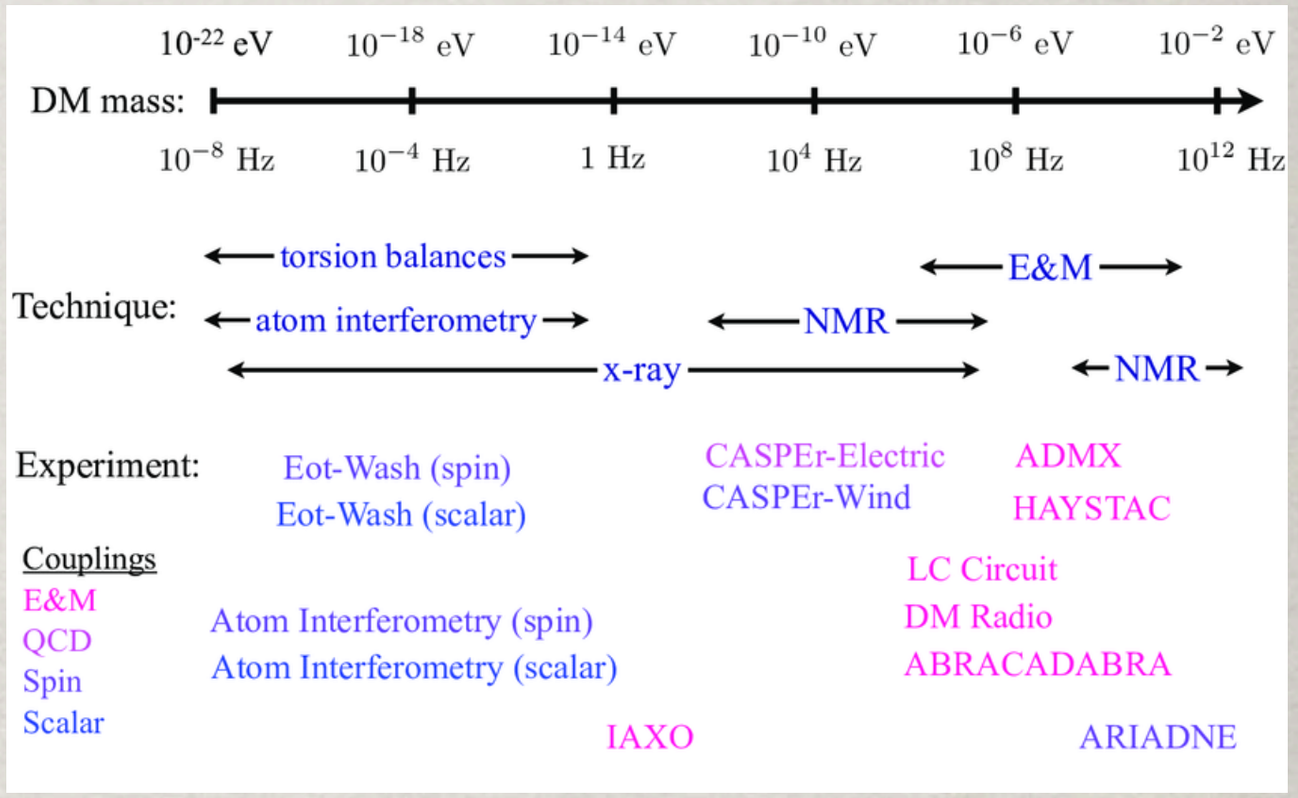




Be aware: DM Identity?

While the WIMP DM is attractive, it can be ANYTHING,
from black holes, to particles, to waves





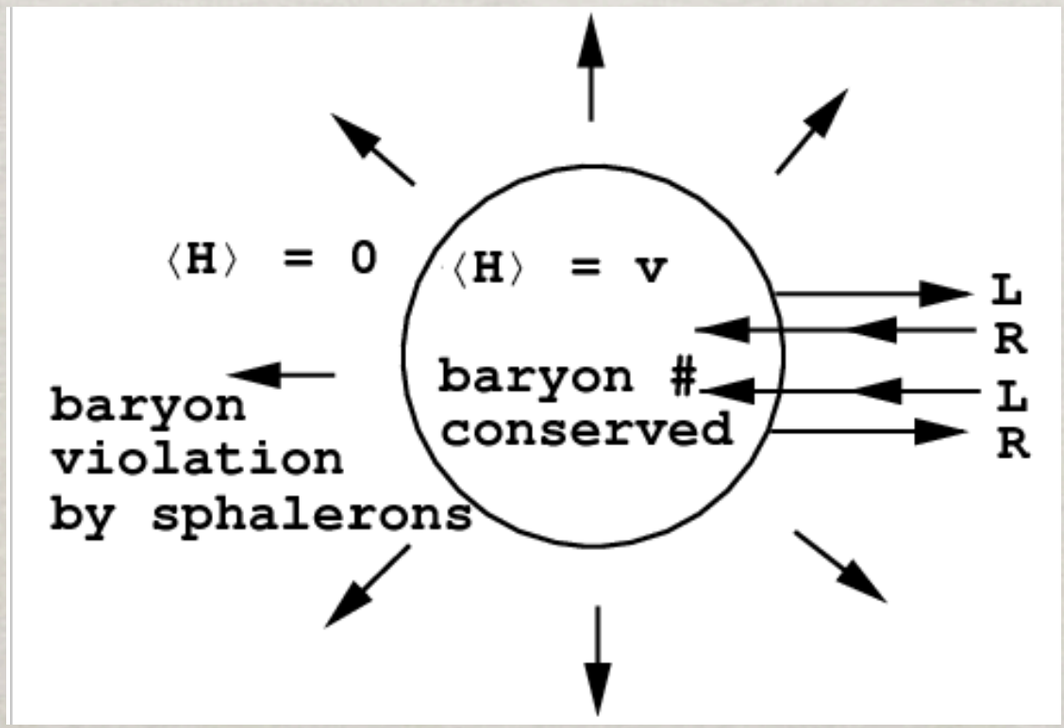
Open mind
for any new search techniques

Question 6:
Baryon & Anti-baryon Asymmetry

- The current observation: $n_{\bar{p}}/n_p \sim 10^{-4}$!
  consistent with the cosmic ray creation.

Dirac invented particle/anti-particle symmetry.

Baryogenesis is a mechanism to generate the imbalance:
p & $\bar{p}$ can annihilate very efficiently via strong interaction.
A tiny asymmetry at the early Universe could result in the observed matter-dominance.



Sakharov conditions for baryogenesis:

1. Baryo-number violation:

   YES in the SM: B,L anomalous.

   "sphaleron" process near $E_{sph} \sim 8\pi v/g_w$

$$\Delta B = \Delta L = 3, \quad \Delta(B-L) = 0$$

2. C- & CP-violation:

   YES in the SM: CKM, but not large enough!

   Perhaps from the neutrino sector:

   → "leptogenesis"

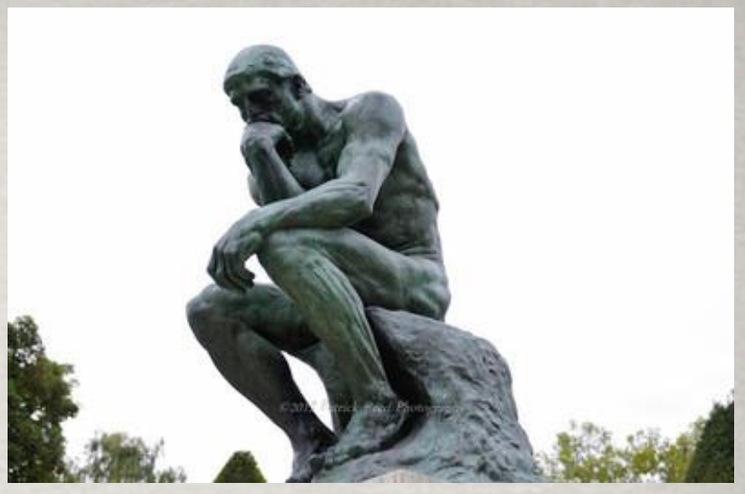
3. Non-equilibrium:

   No in the SM: SM EWPT is a cross-over,

   not a sharp 1st order phase transition.

Need BSM physics !

There are other fundamental questions:



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

Coupling unification? Quark-lepton unification?

8. Larger space-time symmetry?

Super-symmetry at EW scale?

9. Cosmology: inflation, dark energy …

Does the Higgs play a role?

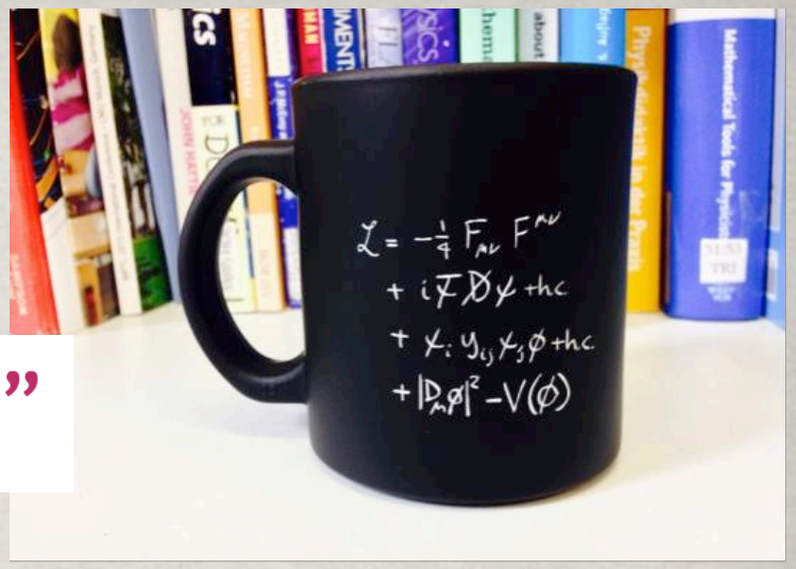
10. BH & Quantum gravity?

Beyond QFT, string theory? … …

→ **Continue to challenge our intelligence !**

In summary: SM solidly established

$$\mathcal{L} \propto \mu^2 H^2 - \lambda H^4 + \sum_i c_i \mathcal{O}_i(\mathrm{BSM})$$



"Higgs isn't everything. It's the only thing."

M. E. Peskin Lepton-Photon 2025

Questions that we need the answers

1. Nature of EW Superconductivity: BCS?
2. Large hierarchy problem: the next scale?
3. Nature of EW phase transition?
4. Flavor physics: fermion mixing/neutrino mass*
5. Dark matter*: WIMP & Higgs portal?
6. Matter – antimatter asymmetry*: baryogenesis
7. … …

All demands new physics BSM!