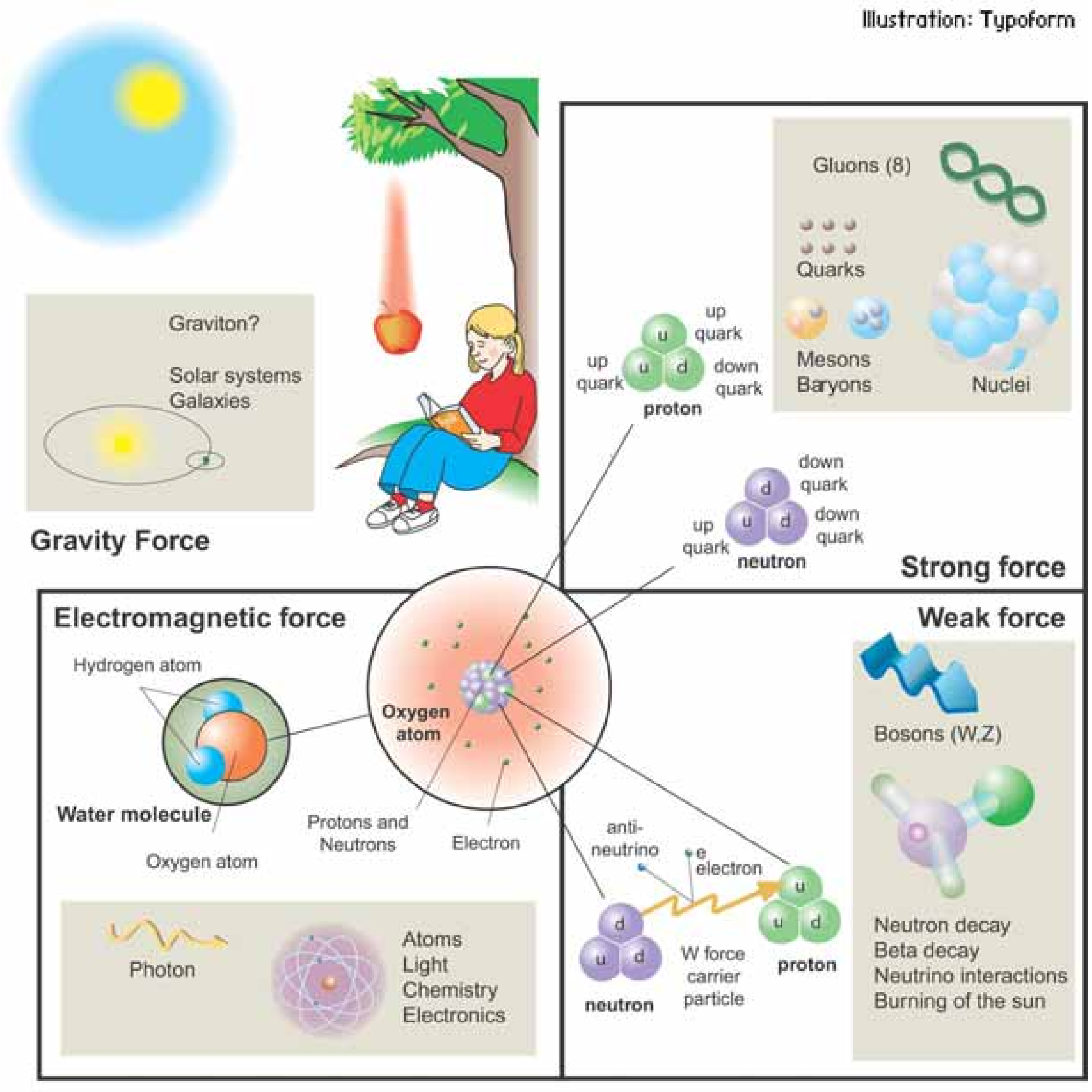
The hierarchy problem and Physics Beyond the Standard Model

Gautam Bhattacharyya

Saha Institute of Nuclear Physics, Kolkata

Fundamental interactions



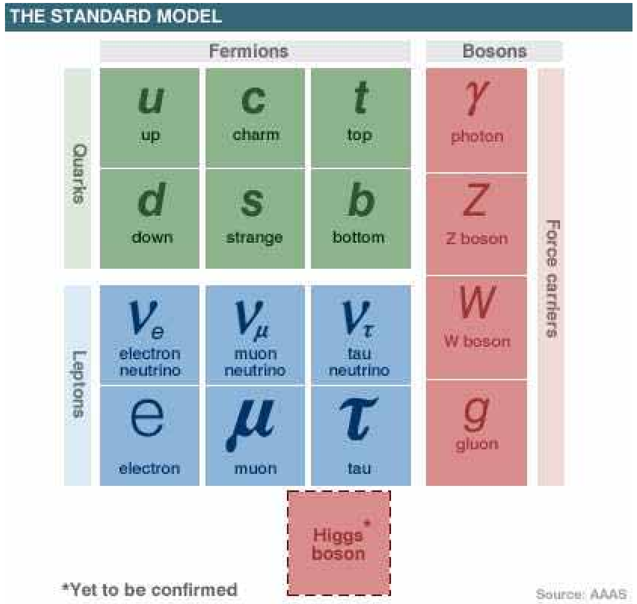
The Standard Model

$$\mathcal{L}_{\rm SM} = \overline{\Psi} \not{D} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + y \overline{\Psi} \Psi \Phi + |D_\mu \Phi|^2 - V(\Phi)$$

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

SSB and stability: $\mu^2 < 0, \lambda > 0 \quad \rightsquigarrow \quad v^2 = \frac{|\mu^2|}{\lambda}$

$$M_W = \tfrac{1}{2} g v, \quad m_f = \tfrac{1}{\sqrt{2}} y_f v, \quad m_h = \sqrt{4\lambda}\, v$$



- Gauge sector very accurately measured (per mille precision at LEP).
- Flavor sector (fermion masses & mixings known). But Symmetry ?
- Unlocking EWSB sector turned out MOST expensive!

The Higgs boson

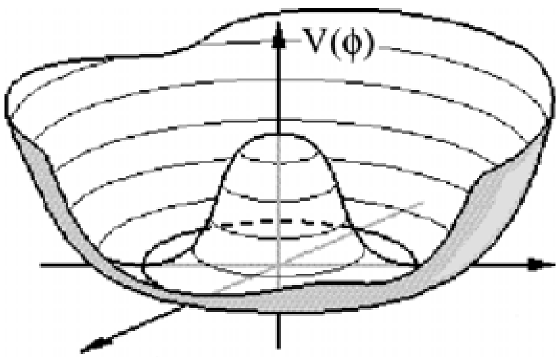
- Newton: Weight is proportional to Mass
- Einstein: Energy is related to Mass
- What is responsible for the origin of Mass ?

Main concept: Spontaneous symmetry breaking

Ex: Ferromagnet, Pions

Elementary particle mass is generated by Higgs mechanism. Gauge boson acquires mass by eating a massless Goldstone boson.

Potential is minimum on the orbit. Tangential mode is Goldstone boson, radial excitation is the Higgs boson. Without the Higgs, theory is not unitary.



Mass of Higgs boson

Precise knowledge of Z boson properties from LEP (Electroweak precision tests) $\Rightarrow$ $m_h < 200$ GeV

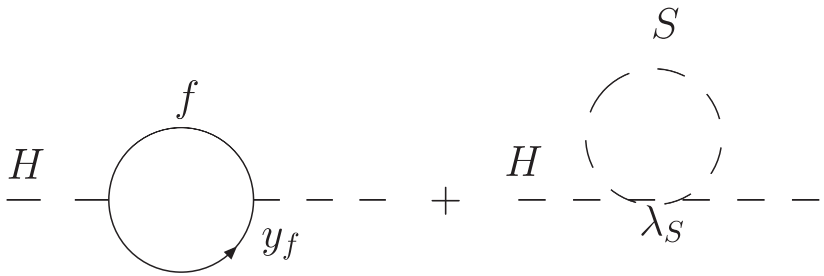
From non-observation at LEP2, $m_h > 114$ GeV

LHC (CMS and ATLAS)

$m_h = 125.09 \pm 0.21$ (stat) ± 0.11 (syst) GeV

$m_h \sim M_Z \ll M_{\mathrm{G,\ Pl}}$. Why the Higgs boson is so light?

Quantum fluctuations



- No symmetry protects the Higgs mass, unlike in QED:
  $\Delta m_e = m_e \frac{\alpha}{4\pi} \ln(\Lambda)$, as $m_e \to 0$ gives enhanced symmetry (chiral).
  Photon mass is zero due to EM gauge symmetry.
- A quantity is naturally small if is setting it to zero increases the symmetry of the theory.
- $\Delta M_h^2(f) = -\frac{y_f^2}{16\pi^2} 2\Lambda^2 \quad ; \quad \Delta M_h^2(S) = \frac{\lambda_S}{16\pi^2}\Lambda^2$. Here Λ is the highest scale of the theory.
- Thus physics at several orders of magnitude shorter distances is influencing weak scale dynamics.

Unnatural cancellation

- Since Higgs mass is not protected, the order parameter v is also not protected, which destabilizes the entire theory.
- Quad. div. cancels if $\lambda_S = 2y_f^2$. Fine-tuning has to be done order by order in perturbation theory.

Hierarchy problem

What guarantees the stability of v against quantum fluctuations?
$\Rightarrow$ Physics Beyond the Standard Model

Experimental side: Dark matter, neutrino mass, matter-antimatter asymmetry, ...

Supersymmetry

- Fermions $\leftrightarrow$ bosons; relates matter and force particles.
- Symmetry protects the scalar mass. Quad. div. cancels between diagrams with different spin particles even when SUSY is broken.
- The three gauge couplings unify at $M_G \sim 10^{16}$ GeV.
- Two Higgs doublets. 5 physical scalars: $h, H, A, H^{\pm}$
- Characteristic signature: Missing Energy.

Quartic coupl related to gauge coupls $\Rightarrow m_h$ predictive

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{\sqrt{2}\pi^2 v^2} \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

Relation valid irrespective of SUSY breaking mechanism.

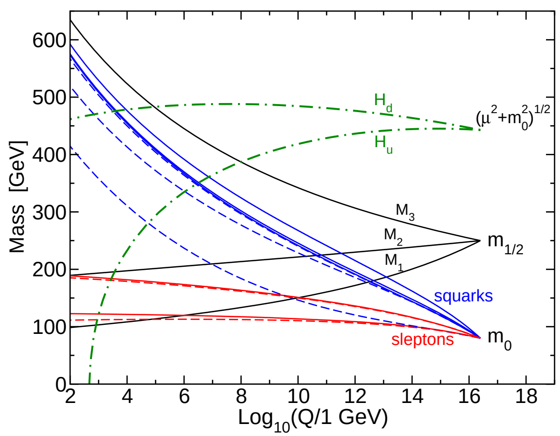
$m_h \simeq 125$ GeV requires the stop mass in TeV range.

Radiative EWSB & Fine-tuning

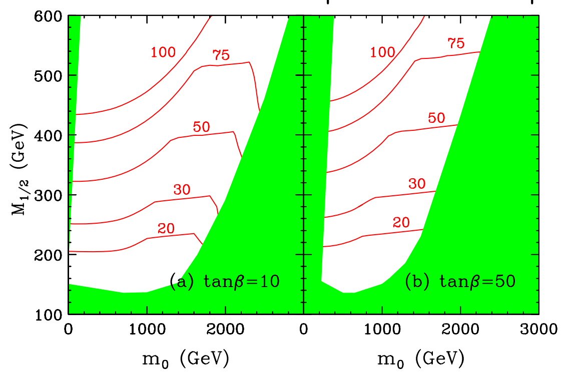
$$0.5\ M_Z^2 \simeq -|\mu|^2 - M_{H_u}^2 \simeq -|\mu^2| + \mathcal{O}(1)\ m_{\tilde{t}}^2$$

$m_h \simeq 125$ GeV $\Rightarrow m_{\tilde{t}} \sim$ few TeV $\Rightarrow$ large cancellation $\Rightarrow$
little hierarchy problem.

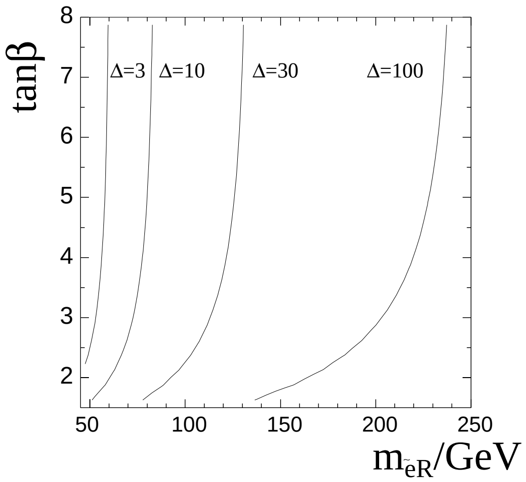
Large m_t drives $M_{H_u}^2$ negative. EWSB dynamically triggered by RG.

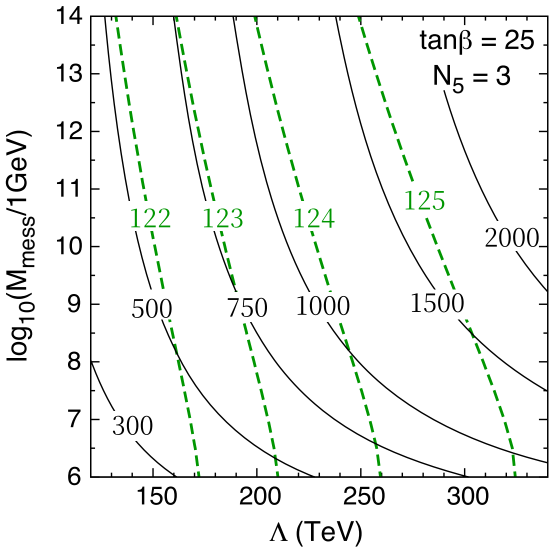


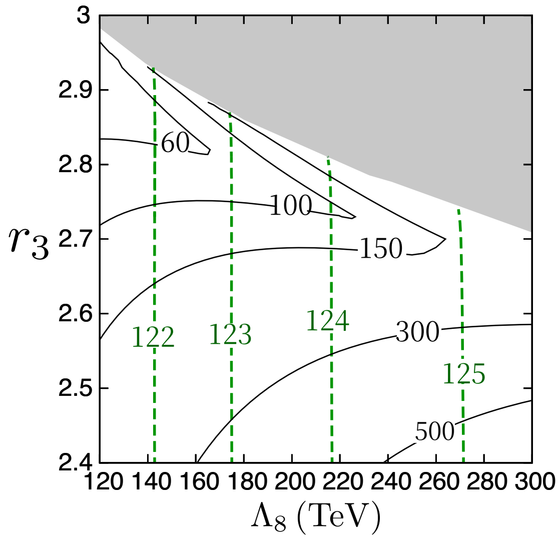
Fine-tuning : $\Delta = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2}{\partial a_i} \right|$



F.T. ‘then’ and ‘now’







- Years ago, $\Delta \sim 50$ for $M \sim 10^5$ TeV in minimal GMSB. It was worse than mSUGRA then (GB, Romanino 1997) than now. It can be substantially improved by choosing an unconventional set of messengers (GB, Yanagida, Yokozaki 2015).
- In 20 years it has gone up by a factor of ~ 20.

Model building

- Which symmetry protects m_h? Fermion-boson symmetry in SUSY. Higgs may be a (pseudo) Nambu-Goldstone boson, or a component of higher dimensional gauge field.
- Is Higgs strictly 'elementary' or 'composite'? SUSY vs Extra-dim?
- Ideally, BSM scenario should contain dark matter candidate, explain matter-antimatter asymmetry, account for the neutrino mass, ...
- Goal: 3-fold. (i) Unitarize, (ii) check EWPT, (iii) Naturalness?
- Naturalness or observability vs EWPT? Tension!
- Future agenda will be set by the next few years of LHC run.

'A Pedagogical Review of Electroweak Symmetry Breaking Scenarios', GB, Rept. Prog. Phys. 74 (2011) 026201

'Scalar sector of Two-Higgs-Doublet models: A mini-review', GB & Dipankar Das, arXiv:1507.06424 [hep-ph], to appear in the 'theme: Higgs' issue of PRAMANA