Electroweak Symmetry Breaking and BSM Physics (A Review)

Gautam Bhattacharyya

Saha Institute of Nuclear Physics, Kolkata

Origin of Mass

- Newton: Weight is proportional to Mass
- Einstein: Energy is related to Mass
- Neither commented on the origin of Mass
- What is responsible for the origin of Mass ?
- Answer: Electroweak Symmetry Breaking sector

Many avenues open:

Higgs ? (SM, MSSM, Little Higgs, more than minimal set)

Extra dimension ? (G-H Unification ? Higgsless ?)

Will LHC be able to discriminate different scenarios?

Data $\longrightarrow$ Theory $\Rightarrow$ LHC Inverse Problem

The SM Lagrangian and M_h

$$
\begin{aligned}
&(1) \qquad \mathcal{L}_{\rm SM} &=& \ \overline{\Psi} \not{D} \Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
&(2) \qquad &+& \ \lambda \Psi \Psi \Phi + \frac{1}{M} L L \Phi \Phi \\
&(3) \qquad &+& \ |D_\mu \Phi|^2 - V(\Phi)
\end{aligned}
$$

- Gauge sector very accurately measured (per mille precision at LEP).
- Flavour sector (fermion masses & mixings known). But Symmetry ?
- EWSB sector: well kept secret! Most expensive!

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

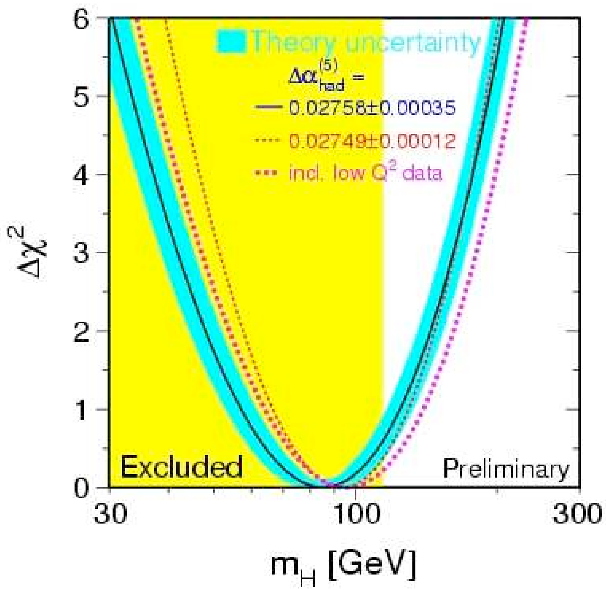
SSB and stability require: $\mu^2 < 0 \ , \ \lambda > 0 \ \rightsquigarrow \ v^2 = \frac{|\mu^2|}{\lambda}$

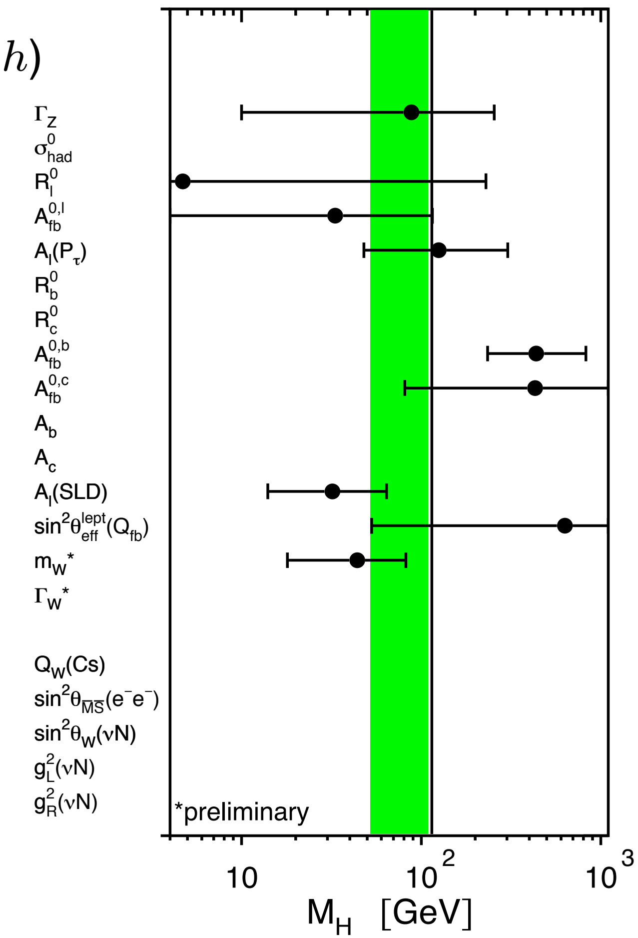
Masses: $M_W = \frac{1}{2} g v, \quad m_f = \frac{1}{\sqrt{2}} y_f v, \quad M_h = \sqrt{4\lambda}\, v$

Constraints ? Complaints ?

EWPT Constraints on M_h in SM

- Electroweak precision tests
  $$\Delta\rho \simeq \frac{3G_F}{8\pi^2\sqrt{2}}\left[m_t^2 - (M_Z^2 - M_W^2)\ln(\frac{M_h^2}{M_Z^2})\right] \; , \; S = \frac{1}{6\pi}\ln\left(\frac{M_h}{M_Z}\right)$$
- Combined EW fit $M_h < 186$ GeV @ 95% C.L. LEPEWWG
- Direct search: $M_h > 114.4$ GeV (full strength ZZh)





Unitarity, Triviality, Vacuum Stability

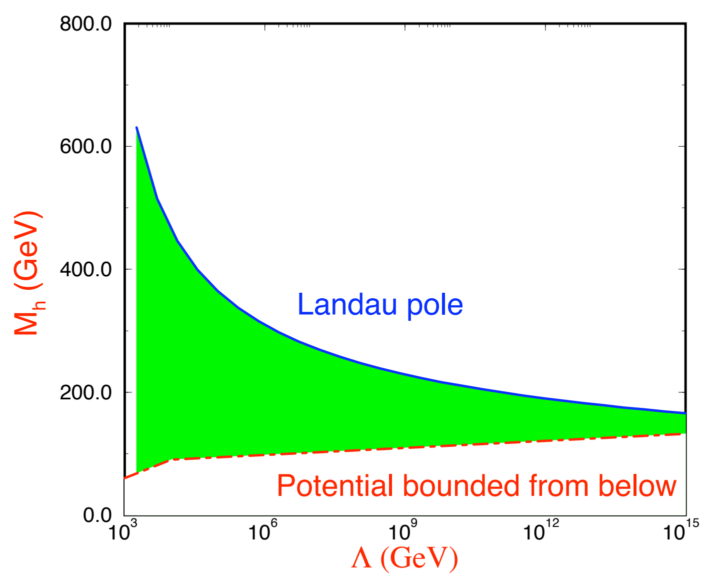
Unitarity: $W_L^+ W_L^- \to Z_L Z_L$ scattering $\rightsquigarrow$

$$a_{(J=0)} = \frac{s}{32\pi v^2} - \frac{s}{32\pi v^2}\left(\frac{s}{s-m_h^2}\right) \to \frac{m_h^2}{32\pi v^2} \Rightarrow M_h < 780 \text{ GeV.}$$

$$\boxed{d\lambda/dt = (16\pi^2)^{-1}\left[24\lambda^2 + 12\lambda y_t^2 - 6y_t^4 - ...\right]}$$

Triviality: Avoid Landau pole ($\lambda^{-1} > 0$) $\rightsquigarrow$ $M_h < 170$ GeV for $\Lambda = 10^{16}$ GeV.

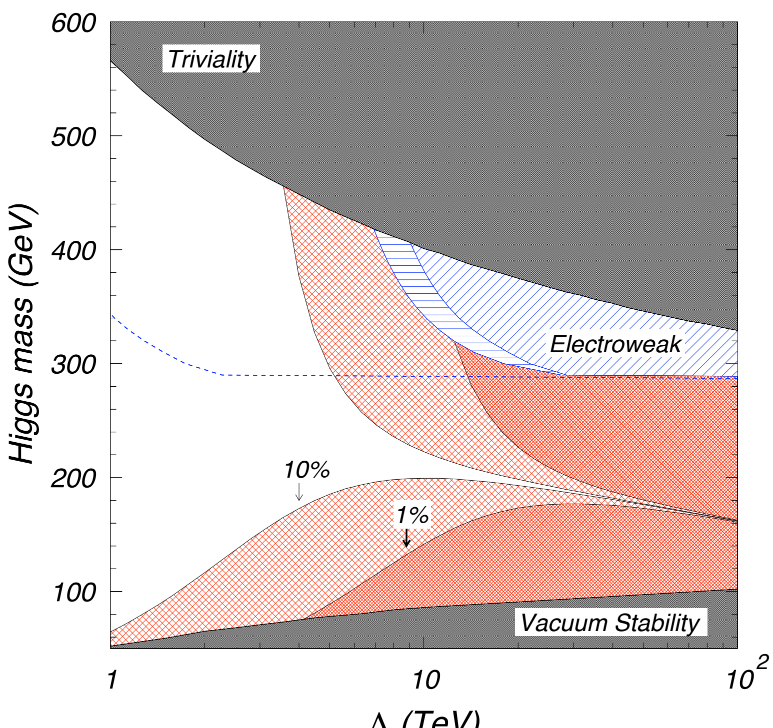
Vacuum stability: V bounded from below ($\lambda > 0$) $\rightsquigarrow$ $M_h > 130$ GeV for $\Lambda = 10^{16}$ GeV.



Fine-tuning in the SM

$$
\begin{aligned}
V_1(\phi) &= \frac{1}{64\pi^2}\int d^4k \,\mathrm{STr}\ln\left(k^2+M^2(\phi)\right) = \frac{\Lambda^2}{32\pi^2}\,\mathrm{STr}M^2(\phi) + \ldots.. \\
\bar{\mu}^2 &= \mu^2 + \frac{\Lambda^2}{32\pi^2}\,\mathrm{STr}M^2(\phi) = \mu^2 + \frac{3\Lambda^2}{32\pi^2}\left(2M_W^2 + M_Z^2 + M_h^2 - 4m_t^2\right)
\end{aligned}
$$

Veltman: STr$(M^2) = 0$. But this cancels only 1-loop divergence.

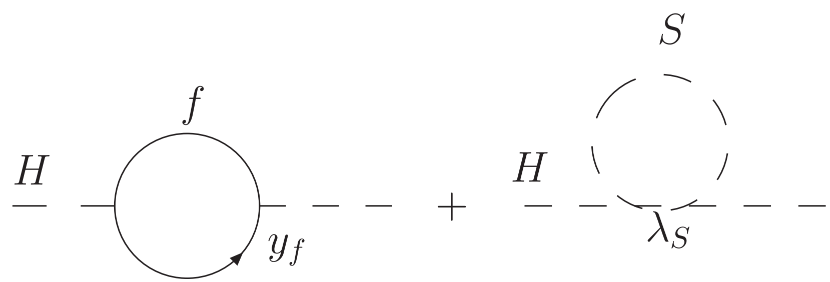


All order result:

$$
\begin{aligned}
\bar{\mu}^2 &= \mu^2 + \Lambda^2 \sum_{n=0}^{n_{\max}} c_n(\lambda_i)\ln^n(\Lambda/Q) \\
\Delta &= \left|\frac{\delta M_W^2}{M_W^2}\right| = \frac{2\Lambda^2}{M_h^2}\left|\sum_{n=0}^{n_{\max}} c_n(\lambda_i)\ln^n(\Lambda/I\right.
\end{aligned}
$$

Complaints on the SM Higgs

- Negative sign in front of μ^2 put in by hand!



- No symmetry protects the Higgs mass, unlike in QED: $\Delta m_e = m_e \frac{\alpha}{4\pi} \ln(\Lambda)$, where $m_e \to 0$ gives enhanced symmetry.
- ΔM_h^2 is quadratically divergent $\left(\int d^4k/k^2\right)$
  $\Delta M_h^2(f) = -\frac{y_f^2}{16\pi^2} 2\Lambda^2 \quad ; \quad \Delta M_h^2(S) = \frac{\lambda_S}{16\pi^2}\Lambda^2$
- Quad. div. cancels if $\lambda_S = 2y_f^2$. Fine-tuning has to be done order by order in perturbation theory.

What guarantees the stability of M_h against Q. corrections?

Gauge hierarchy problem $\Rightarrow$ Different scenarios

Supersymmetry

- Fermions $\leftrightarrow$ bosons; relates matter and force particles
- Symmetry protects the scalar mass. Quad. div. cancels between diagrams with different spin particles
- Two Higgs doublets. 5 physical scalars: $h, H, A, H^{\pm}$
- Quartic coupl related to gauge coupls $\Rightarrow M_h$ predictive

$$M_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left[\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{A_t^2}{M_S^2}\left(1 - \frac{1}{12}\frac{A_t^2}{M_S^2}\right)\right]$$

Relation valid irrespective of SUSY breaking mechanism.

Crucial test of MSSM: $M_h < 135$ GeV

- Add an extra bit of quartic coupling. $W_N = \lambda N H_u H_d + f(N)$

$\Rightarrow M_h^2(\text{tree}) = \mathrm{M_Z^2} \cos^2 2\beta \left(1 + \frac{2\lambda^2}{\mathrm{g^2+g'^2}} \tan^2 2\beta\right)$

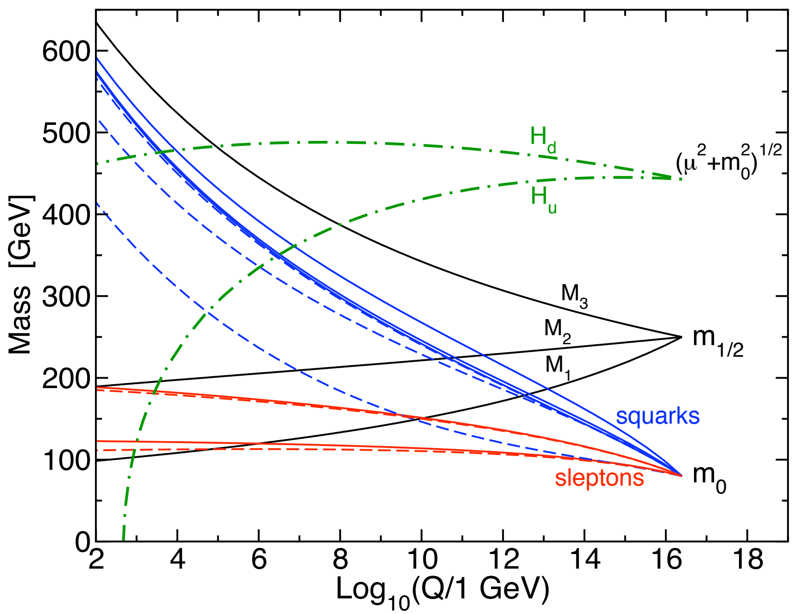
Low $\tan\beta$ can be revived

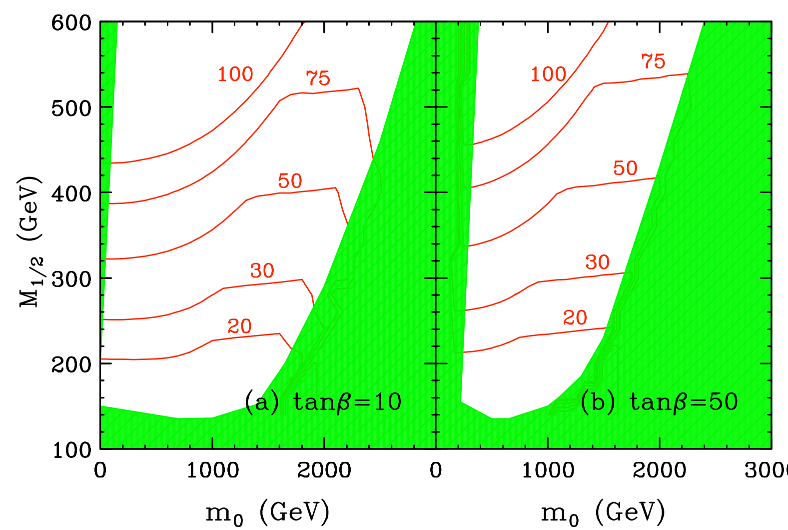
Radiative EWSB & Fine-tuning

$$\frac{1}{2}M_Z^2 \quad = \quad \frac{M_{H_d}^2 - M_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2$$

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

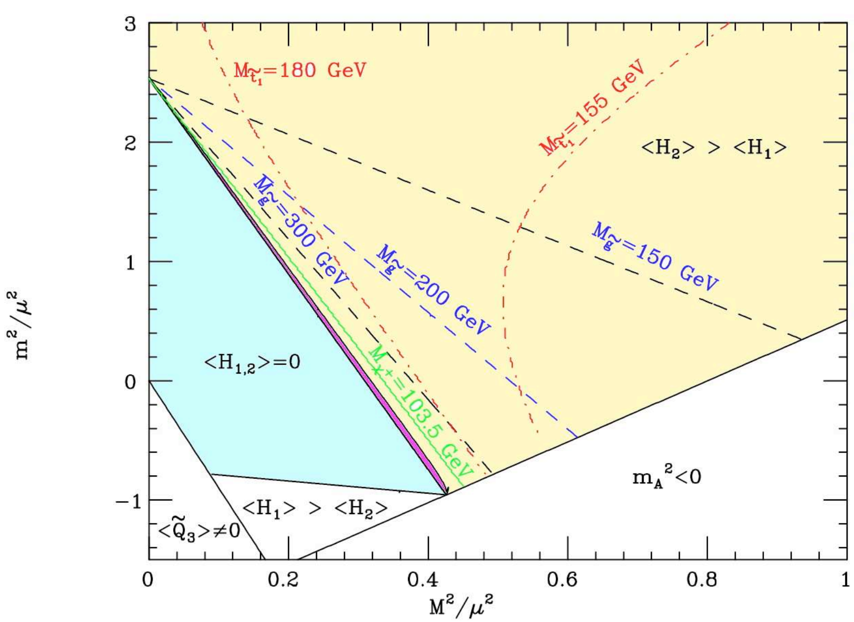
Improvement w.r.t. SM! Fine-tuning : $\Delta = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2}{\partial a_i} \right|$

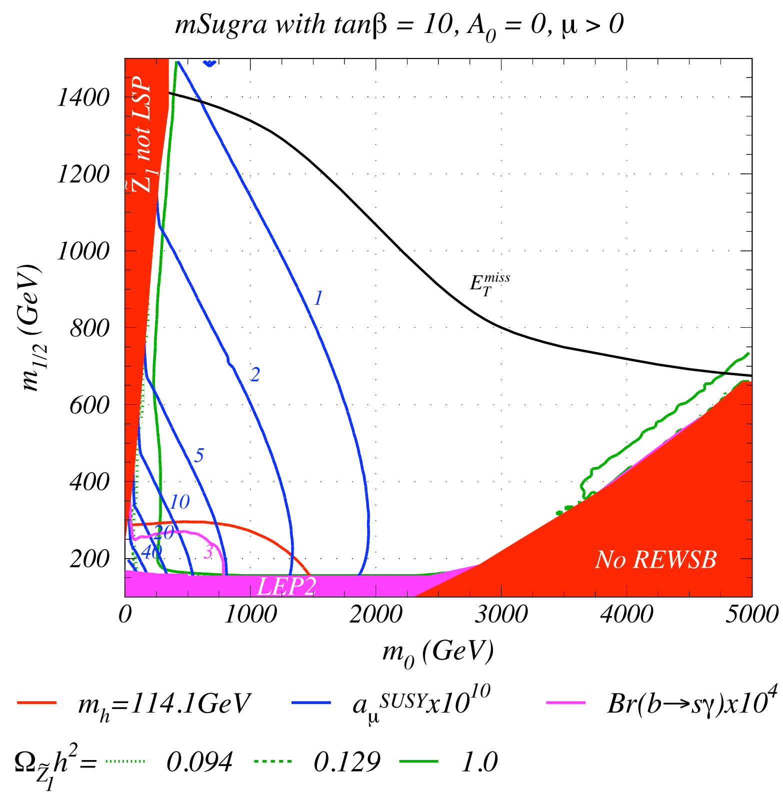




Fine-tuning: Explicit Example

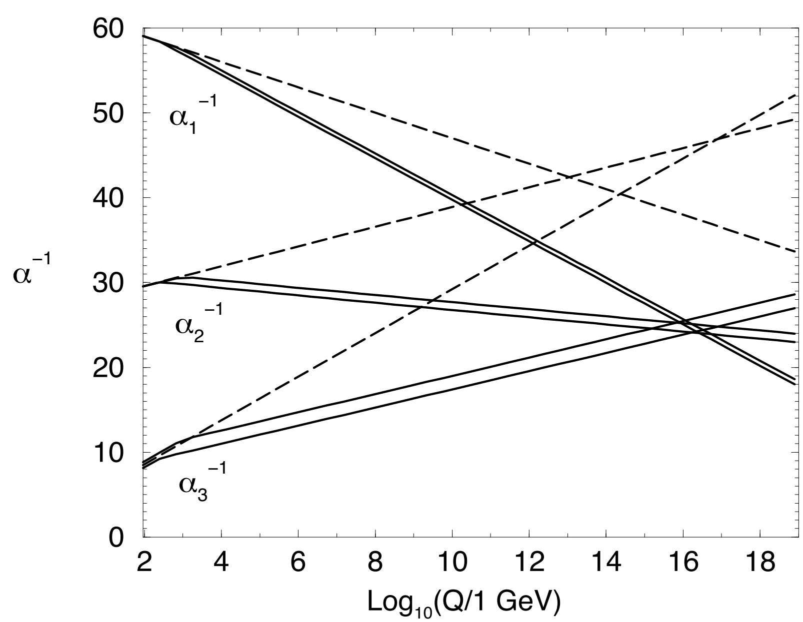
- $M_Z^2 \simeq -2|\mu^2| + \frac{3}{2\pi^2} h_t^2 m_{\tilde t}^2 \ln\left(\frac{M_{\rm Pl}}{m_{\tilde t}}\right) = -2|\mu^2| + \mathcal{O}(1)\, m_{\tilde t}^2.$
  Natural expectation $\boxed{M_Z \sim \mu \sim m_{\tilde t}}$.
- $M_h^2 \simeq M_Z^2 + \frac{3h_t^2}{2\pi^2} m_t^2 \ln\left(\frac{m_{\tilde t}}{m_t}\right)$. Now $M_h > 114.4$ GeV $\Rightarrow$ $\boxed{m_{\tilde t} > 1 \text{ TeV}}$.
- Cancellation of a few percent! Little hierarchy!





Other aspects of Supersymmetry

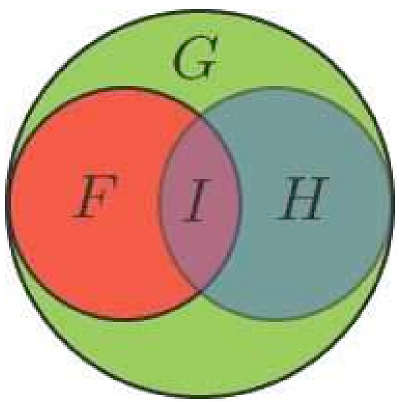
- In mSUGRA, $\frac{1}{2}M_Z^2 = c_0 m_0^2 + c_{1/2} M_{1/2}^2 - |\mu|^2$
  $|c_0| \ll |c_{1/2}| \Rightarrow$ Insensitivity w.r.t. $m_0 \Rightarrow$ Focus point
- Ggauginos few hundred GeV, Squarks/sleptons multi-TeV, are perfectly natural.
- Lightest neutralino is a dark matter candidate
- Big bonus! Modified beta functions make Gauge couplings unify



Little Higgs

Little Higgs is a p-NGB of a spontaneously broken global symmetry

$$\text{All order expression}\quad M_h^2 \;=\; \left(C_i\frac{\alpha_i}{4\pi} + C_iC_j\frac{\alpha_i\alpha_j}{(4\pi)^2} + \cdots\right)\Lambda^2$$



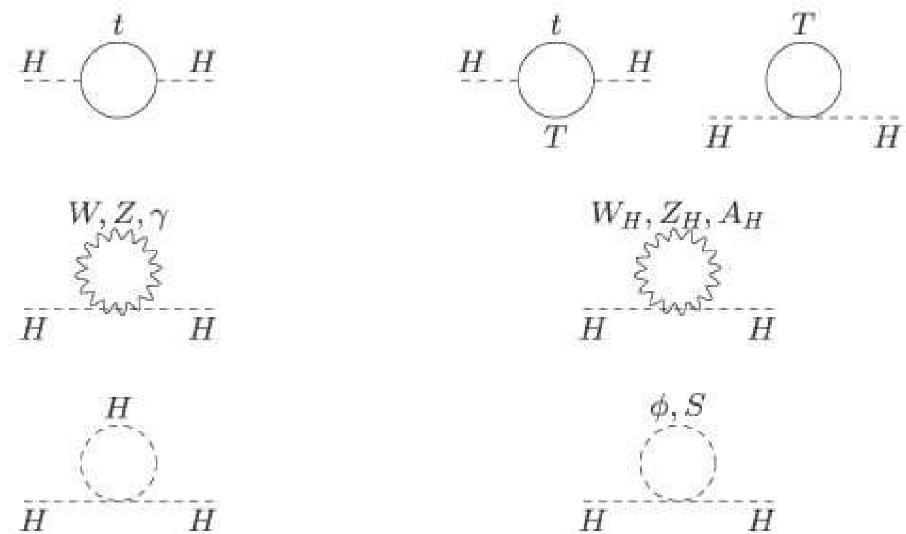
No of p-NGBS $= (N(G) - N(H)) - (N(F) - N(I))$. These are identified as Higgs ($I = F \cap H$ is the SM group).

LH Trick: $M_h = 0$ when any of the $C_i = 0 \Leftrightarrow$ Collective breaking

$$\text{Ideally}\quad \mathrm{V(h)} \;=\; -\frac{g^4 f^2}{16\pi^2}(h^\dagger h) + g_{\mathrm{SM}}^2(h^\dagger h)^2 \quad (f \sim 1\ \mathrm{TeV},\ \Lambda = 4\pi f)$$

Little Higgs (contd..)

- G/H = SU(5)/SO(5), F = $[\mathrm{SU}(2) \times \mathrm{U}(1)]^2$ (Littlest Higgs) (with T parity very few constraints from EWPT).
- G/H = $[\mathrm{SU}(3) \times \mathrm{U}(1)]^2$ / $[\mathrm{SU}(2) \times \mathrm{U}(1)]^2$, F = $[\mathrm{SU}(3) \times \mathrm{U}(1)]$ (Simplest Little Higgs) (no large quartic).
- Quad div cancels between diagrams with same spin particles.



- $M_h \sim f/4\pi \sim 100$ GeV, $M_{V'} \sim m_T \sim f \sim 1$ TeV, $\Lambda \sim 4\pi f \sim 10$ TeV.

Supersymmetry vs Little Higgs

- Symmetry: In SUSY chiral symmetry protects Higgs mass (Quad Div cancels between F and B diags). LH is a pseudo-NGB (Quad div cancels between same spin).
- The minus sign: In SUSY large y_t drives H_u^2 negative triggering EWSB. In LH too large y_t generates negative sign.
- Fine tuning: $M_h > 114.4$ GeV requires large stop mass $\rightarrow$ Little Hierarchy. NMSSM helps to ease tension! In LH, suppression of bilinear term compared to quartic requires F.T. in a class of models. $V(h) = -\frac{g^4 f^2}{16\pi^2}(h^\dagger h) + g_{\rm SM}^2 (h^\dagger h)^2$
- Dark Matter: LSP is DM if R_p exact. A_H is DM if T is conserved.
- UV completion: $\Lambda_{\rm SUSY} = M_{\rm Pl}$, $\Lambda_{\rm LH} =$ 10 TeV (SUSY at 10 TeV!).

Gauge-Higgs Unification

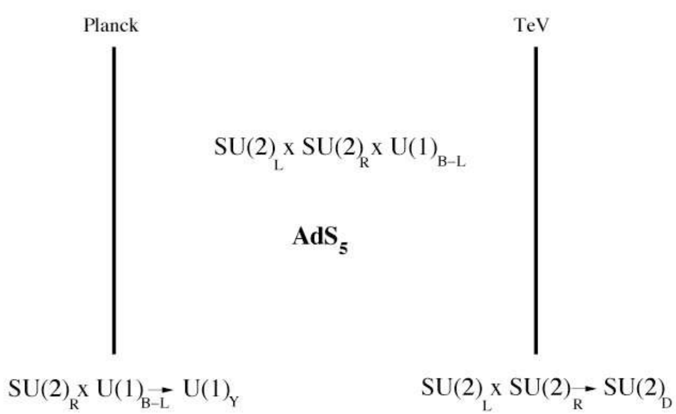
- Higgs $\equiv$ internal comp of higher dim gauge field (protected by higher dimensional gauge invariance)
- Wilson line phase $\theta_H = g \int_0^{2\pi R} dy W_5^0$ can acquire VEV
- SU(3) in S^1/Z_2: $PW_\mu P^\dagger = W_\mu$, $PW_5 P^\dagger = -W_5$, where $P =$ diag (-1,-1,1). Explicit: SU(3) $\rightarrow$ SU(2) $\times$ U(1)
- W_5^0 belongs to G/H and is a doublet under SU(2)
- Bilinear and quartic terms generated from KK loops
- SSB: SM $\rightarrow \mathrm{U(1)_{em}}$, $\quad M_W \sim \alpha/R$
- $M_h \sim (g_4/R)\sqrt{V''(\alpha)}$
- Problems: too small Higgs mass, too small top mass
- A possible way out: Break Lorentz symmetry in the bulk

$$L_g = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{a}{4} F_{\mu 5} F^{\mu 5} \quad ; \quad L_\Psi = \bar{\Psi} \left(i\gamma_\mu D^\mu - k D_5 \gamma^5 \right) \Psi$$

Higgsless Scenario

- S^1/Z_2: fixed points $[0, \pi R]$
- B.C.: $\partial_5 W_5 = V W_5$ ($V = 0$ (Neumann), $V \to \infty$ (Dirichlet))
- Gauge symmetry in bulk: $\mathrm{SU(2)_L \times SU(2)_R \times U(1)}$
  $y = 0$: $\mathrm{SU(2)_L \times SU(2)_R \to SU(2)_D}$
  $y = \pi R$: $\mathrm{SU(2)_R \times U(1)_R \to U(1)_Y}$
- $M_\gamma = 0$, $M_W = (4R)^{-1}$, $M_Z = (\pi R)^{-1} \tan^{-1} \sqrt{1 + 2g'^2/g^2}$
  $\Delta\rho \sim 0.1$ (flat space! Better in warped space)

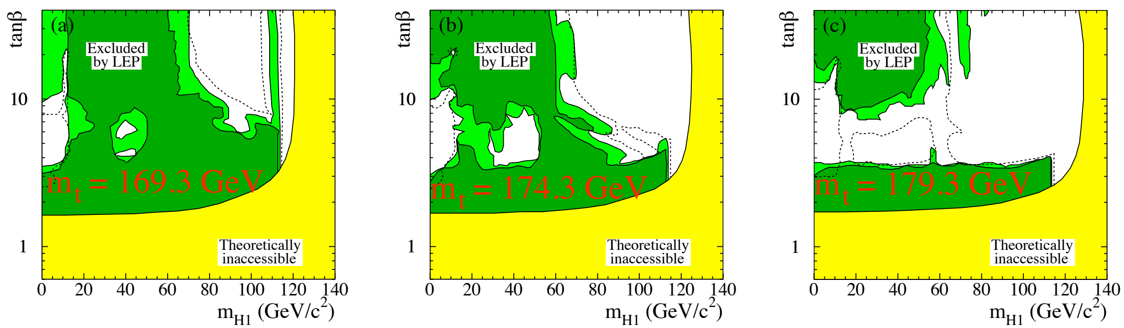
5D Higgsless Model in Warped Space

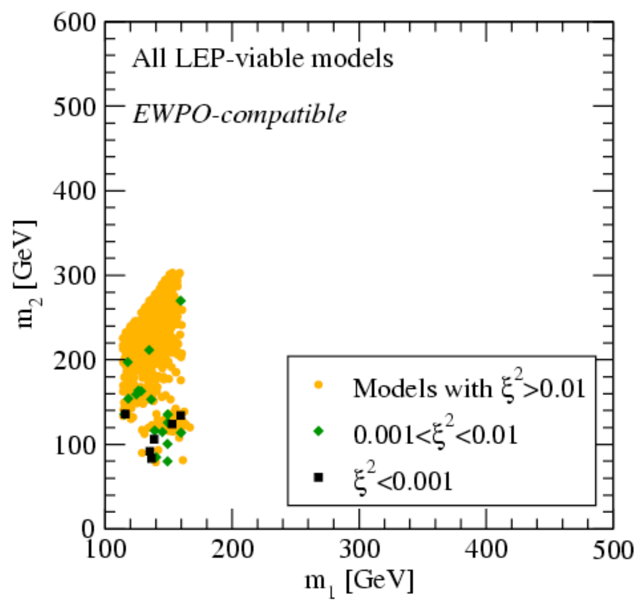


Saturation of 'unitarity' of VV scattering can be postponed in a calculable way beyond the SM limit of $\sim$ 1 - 1.5 TeV.

Why Not ? Evading the bounds!

- CP-violating Higgs sector: Phases in CPV Higgs sector can reduce ZZh coupling!



- 

Mixing with gauge singlet helps evade SM bounds (good for BAU, DM)!

Outlook

- All models based on calculability $\Rightarrow$ $\boxed{M_Z = \Lambda_{\rm NP} f(a_i)}$ where $f(a_i)$ are calculable functions of physical params. SUSY ($\Lambda_{\rm NP} = M_S, \mu$), LH ($\Lambda_{\rm NP} = f$), GHU ($\Lambda_{\rm NP} = R^{-1}$).
- Symmetry protects M_h! Chiral (SUSY), NGB (LH), gauge (GHU).
- Revival of interest in strongly interacting light Higgs models. ‘Usually’ they don’t work well with EWPT. Their UV completion is an open question! New theoretical tools provide calculability.
- Why should Nature care about calculability?
- Naturalness or the EWPT? Tension!
- LHC Win-Win situation! Either new physics for naturalness, or, new resonances to restore unitarity in W_L–W_L scattering!
- Whatever happens, we still need a LC for precision studies!
- Future agenda will be set by LHC.