EWSB Beyond SM

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Questions that we ask

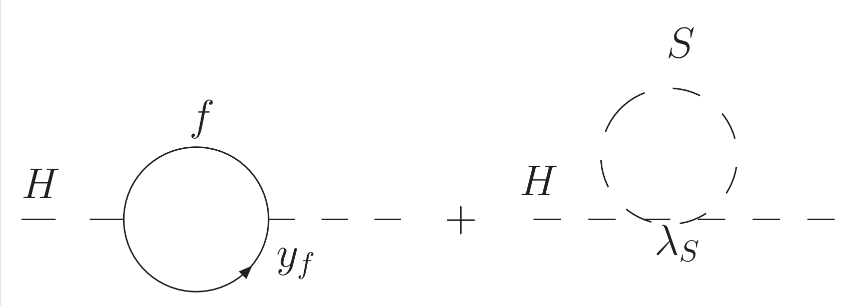
Higgs mechanism in SM is an effective description of EWSB. But how one can explain the dynamics behind EWSB? LHC may answer some of the following questions:

- Why weak scale $\ll$ Planck scale?
- What is the symmetry that controls particle physics at the TeV scale?
- Which solution of the hierarchy problem is correct?
- Is considering naturalness criterion as a guiding principle (or discriminator) a step in the right direction?
- Is Higgs elementary or composite?
- What if the Higgs is not there at all?

Reviews: Contino 1005.4269, Bhattacharyya 0910.5095, Grojean 0910.4976, Kaul 0803.0381, Giudice 0801.2562, Cheng 0710.3407, Rattazzi hep-ph/0607058, $\cdots$

Hierarchy problem

Gildener,Weinberg,Witten,Dimopoulos,Georgi,Sakai,Kaul,Majumdar (1976-1982)



- 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 $\left(\int d^4k/k^2\right)$

  $$\Delta m_h^2(f) = -\frac{y_f^2}{16\pi^2} 2\Lambda^2 \quad ; \quad \Delta m_h^2(S) = \frac{\lambda_S}{16\pi^2}\Lambda^2$$

- Quadratic divergence cancels if $\lambda_S = 2y_f^2$. Fine-tuning has to be done order by order in perturbation theory.

EWPT tells us $m_h < 200$ GeV, which means unnatural F.T $(1 \div 10^{26})$.

Can some symmetry tame this unruly quantum behavior?

Supersymmetry

Most studied BSM model offering explanation for a natural Fermi scale.

- Unification of gauge couplings.
- Large h_t drives $M^2_{H_u}$ negative triggering EWSB.
- Good compatability with EWPT.

EWSB condition: $$M_Z^2 = \frac{2\left(M^2_{H_d} - M^2_{H_u}\tan^2\beta\right)}{\tan^2\beta - 1} - 2|\mu|^2$$

CMSSM: $M_Z^2 \approx -2|\mu^2| + 0.2\, m_0^2 + 0.7\left(2.6\, M_{1/2}\right)^2$.

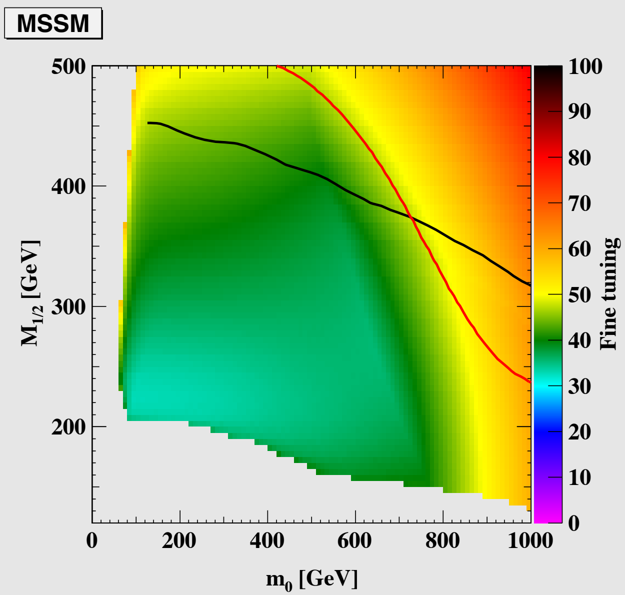
- Natural expectation $M_Z \sim \mu \sim m_0 \sim M_{1/2}$. Excluded by LEP/Tevatron.
- As a consequence of LHC bound, $m_{\tilde{g}}(\approx 2.6\, M_{1/2})$ contribution to M_Z^2 is about 50 times larger, so about 2% fine-tuning. LHC probing sparticles a loop factor above M_Z (Strumia 2011).

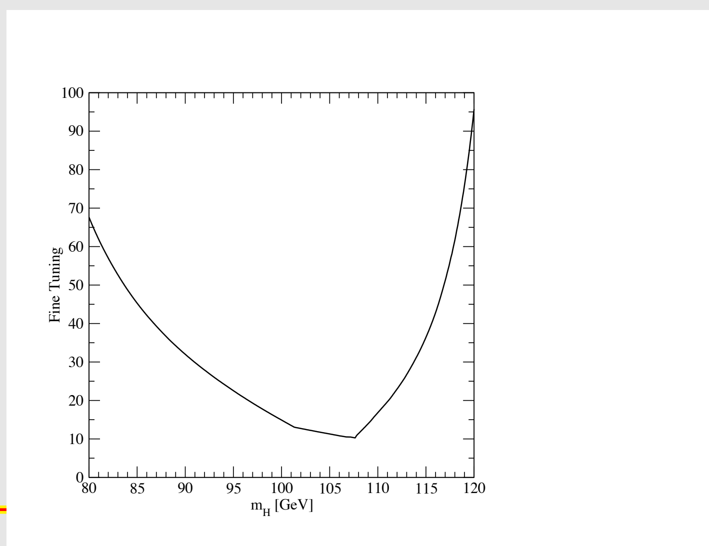
Higgs mass: $m_h^2 \simeq m_{h0}^2(\leq\ M_Z^2) + \frac{3h_t^2}{2\pi^2} m_t^2 \ln\left(\frac{m_{\tilde{t}}}{m_t}\right)$ $m_h > 114.4$ GeV $\Rightarrow m_{\tilde{t}} > 1$ TeV

Little hierarchy problem! Unless there is some symmetry!

Fine-tuning in Supersymmetry

(Ellwanger,Espitalier-Nöel,Hugonie, 2011)





Barbieri, Giudice criterion: $\Delta_i = \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2}{\partial a_i} \right|$

Fine-tuning in CMSSM

ATLAS (black) bounds with $\tan\beta = 3, A_0 = 0$, CMS (red) for $\tan\beta = 10, A_0 = 0$. White region ruled out. F.T. at best 3% (35 pb^{-1}), worse with 1.1 fb^{-1} data.

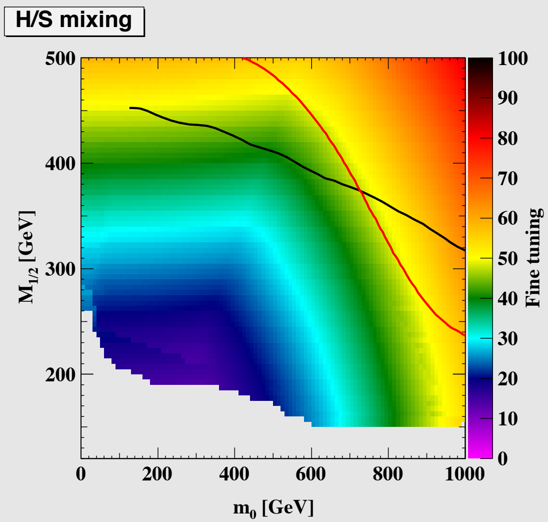
Cassel,Ghileancea,Kraml,Lessa,Ross, 2011: Complementarity of LHC and next generation direct search dark matter experiments.

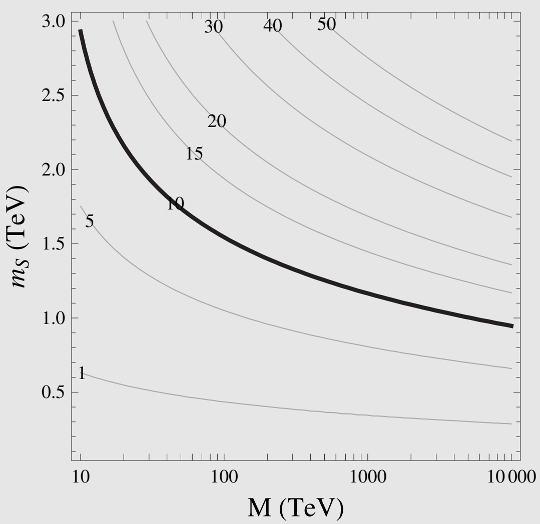
Fine-tuning w.r.t Higgs mass

LEP constraints not imposed. When m_H is small, F.T. is large as sparticle masses cannot be smaller than experimental limits. Minimum F.T for $m_h \approx 108$ GeV. For larger m_h, F.T. grows very fast.

Fine-tuning in NMSSM

F.T. is reduced in NMSSM (Bastero-Gil, Hugonie, King, Roy, Vempati 2000)





(Ellwanger,Espitalier-Nöel,Hugonie, 2011)

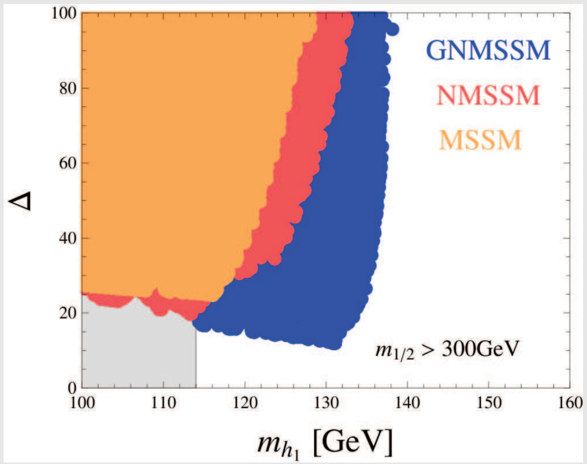
$$W_{\rm NMSSM} \supset \lambda S H_u H_d + \frac{1}{3}\kappa S^3$$

$$\boxed{m_h^2 \leq M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta}$$ Drees'89

F.T. as a function of dominantly singlet-like Higgs mass. NMSSM is less tuned than CMSSM.

λSUSY (Barbieri et al 2006, Lodone 2010)
Purpose: increase m_h significantly. $\lambda \sim 1$ at low scale. Set $\lambda(\Lambda) = \sqrt{4\pi}$. For $\Lambda = 10^4$ TeV (100 TeV), $m_h^{\rm max} = 2M_Z(3M_Z)$, consistent with naturalness and EWPT. Gain: heavy Higgs, less 'little hierarchy'. Loss: low cutoff, no unification. Signature: $H \to hh \to 4V \to \ell^+\ell^- 6j$ (Cavicchia et al 2007).

F.T. in G-NMSSM and GMSB

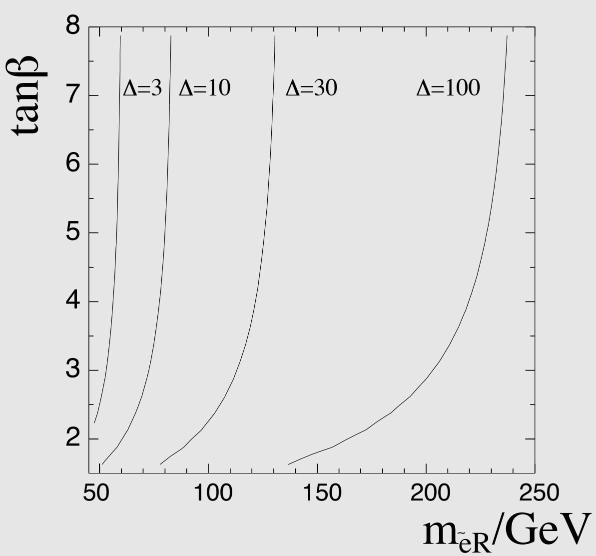


G-NMSSM

(Ross,Schmidt-Hoberg 2011)

$W_{\mathrm{GNMSSM}} \sim W_{\mathrm{NMSSM}} + m_{3/2}^2 S + m_{3/2} S^2$

G-NMSSM has discrete R symmetry. It is less tuned than NMSSM due to additional terms that enter V. F.T. minimum for heavy Higgs!



GMSB

(Bhattacharyya,Romanino'96)

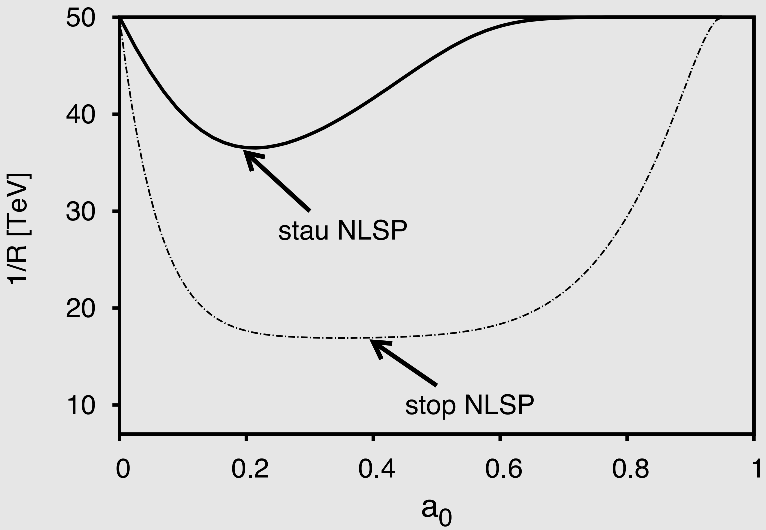
F.T. in GMSB is worse than in MSSM.

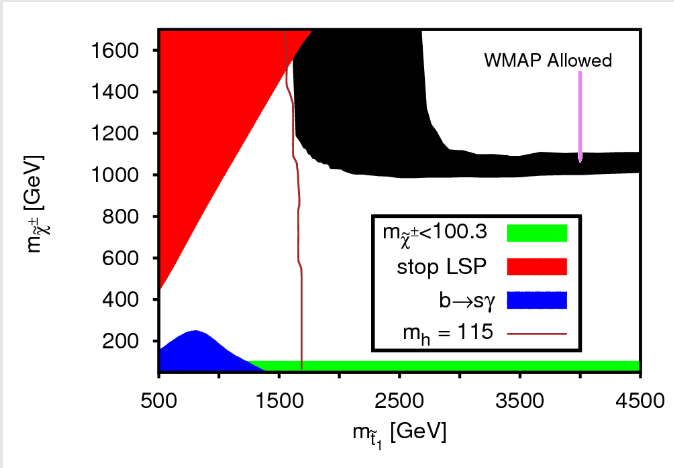
F.T. in low scale SUSY breaking

Bhattacharyya,Ray 2012 (to appear in JHEP)

Higher dimensional origin – Scherk-Schwarz supersymmetry breaking

- With $M_S \sim 10$ TeV, a gain of factor of ~ 7 in F.T. compared to mSUGRA.
- Spectrum: Higgsino around a TeV or slightly less, a stop around 1.5 TeV, and super-heavy multi-TeV gauginos. Nearly degenerate chargino-neutralino.
- Substantially lighter spectrum, maintaining the above hierarchy, possible by ignoring the lower limit of WMAP d.m. constraint, or by formulating NMSSM.
- Can evade easy detection at LHC-7, solve FCNC & CP problem, manifest at LHC-14.





Little Higgs

(Cohen, Arkani-Hamed, Georgi, Schmaltz, $\cdots$)

- Little Higgs is a pseudo-NGB of a spontaneously broken global symmetry ($\mathrm{G} \to \mathrm{H}$). Pions are pseudo-NGB of $\mathrm{SU(2)_L \times SU(2)_R / SU(2)_{Isospin}}$.

- Quark masses & electromagnetic interactions explicitly break chiral symmetry: $m_{\pi^+}^2 - m_{\pi^0}^2 \sim \frac{e^2}{16\pi^2}\Lambda_{\mathrm{QCD}}^2$.

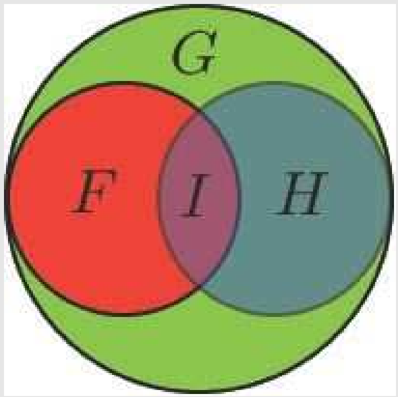
  Gauge/Yukawa interactions *explicitly* break G. $\boxed{m_h^2 \sim \frac{g^2}{16\pi^2}\Lambda^2 \rightsquigarrow \Lambda \sim 1 \text{ TeV}}$.

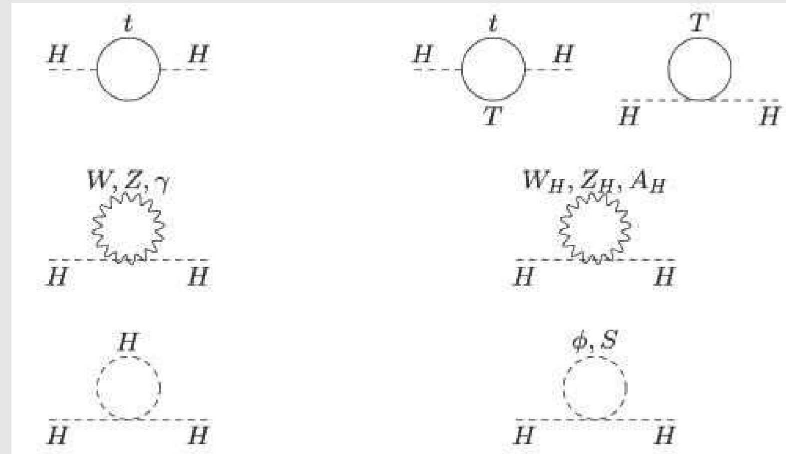
  Too low Λ, disfavored!!

- If we can arrange, $m_h^2 \sim \frac{g_1^2 g_2^2}{(16\pi^2)^2}\Lambda^2$, then $\Lambda \sim 10$ TeV. Little hierarchy problem is solved without paying the price of fine-tuning. The idea of little Higgs is all about achieving this extra suppression factor.

- *Collective* symmetry breaking ($g_1 \neq 0, g_2 \neq 0$) $\Rightarrow$ Cutoff *postponed* to 10 TeV. UV completions can be weakly OR strongly coupled (composite, like pions).

Little Higgs potential



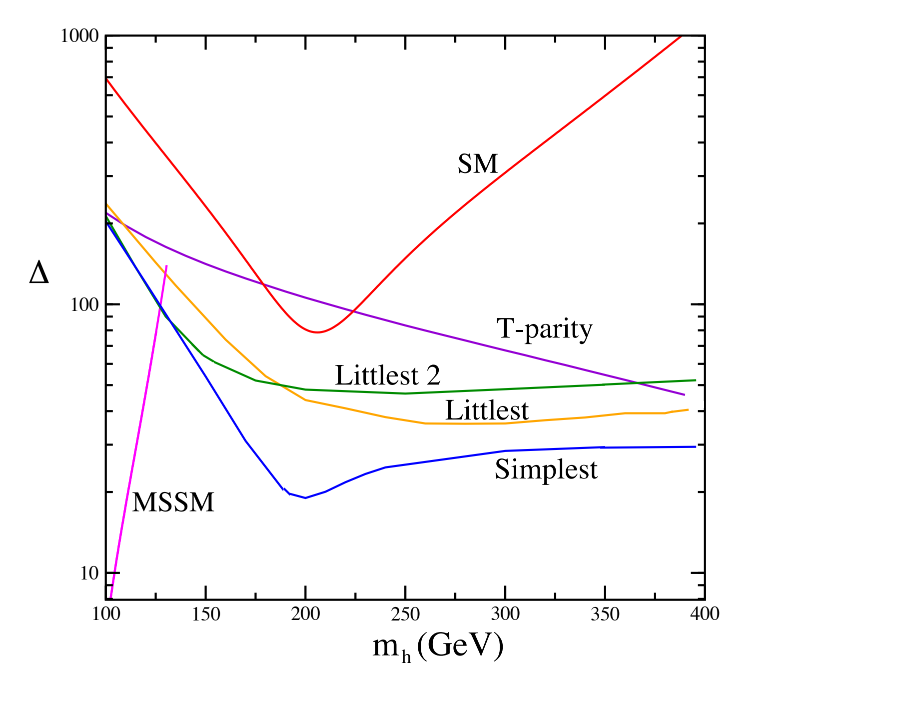


- $\mathrm{G} = \mathrm{SU}(5), \mathrm{H} = \mathrm{SO}(5), \mathrm{F} = [\mathrm{SU}(2) \times \mathrm{U}(1)]^2$: Littlest
  $G = [\mathrm{SU}(3) \times \mathrm{U}(1)]^2, \mathrm{H} = [\mathrm{SU}(2) \times \mathrm{U}(1)]^2, \mathrm{F} = \mathrm{SU}(3) \times \mathrm{U}(1)$: Simplest
- $V(h) = -\frac{g_{\mathrm{SM}}^4 f^2}{16\pi^2}(h^\dagger h) + g_{\mathrm{SM}}^2 (h^\dagger h)^2$.
  Large top quark Yukawa coupling responsible for generating the 'minus' sign.
- $m_h^2 \sim \frac{g_{\mathrm{SM}}^4}{16\pi^2} f^2 \ln\left(\frac{\Lambda^2}{f^2}\right), \quad f^2 \to F^2 = f^2 + \frac{\Lambda^2}{16\pi^2}$
- Same statistics cancellation of Λ^2 divergence in m_h^2 at one loop.

Little Higgs - EWPT & Fine-tuning

(Csaki,Hubisz,Kribs,Meade,Terning,Hewett,Petriello,Rizzo,Chen,Dawson, Noble,Perelstein)

- EWPT: $\mathcal{O}_T = \left|H^\dagger D_\mu H\right|^2$ and $\mathcal{O}_S = \left(H^\dagger \sigma^a H\right) W^a_{\mu\nu} B_{\mu\nu}$ are crucial operators.
- $f > (2-5)$ TeV in a general class of little Higgs models due to tree level mixing of SM particles with the new particles. In littlest Higgs model large contribution to $\mathcal{O}_T$ from $H^T \Phi H$, where Φ is a triplet.
- With T-parity ($H \to H$ but $\Phi \to -\Phi$), it is possible to allow $f \sim 500$ GeV. (Cheng,Low)



Casas, Espinosa, Hidalgo (2005)

EWPT vs Naturalness

- To keep the Higgs quartic coupling to be $\mathcal{O}(1)$ requires tuning.
- Fine-tuning in little Higgs larger than in MSSM.

Little Higgs - Collider signatures

- New scalars: Han et al (2003), Hektor et al (2007)
  Doubly charged scalar as a component of a complex triplet scalar, decaying into like-sign dileptons ($\Phi^{++} \to \ell^+\ell^+$).
  Resonant enhancement of $W_L W_L \to W_L W_L$ by Φ^{++} mediation. Search up to $m_{\Phi^{++}} \sim 1.5$ TeV with 300 fb^{-1}.

- New fermions: Hubisz et al (2006)
  Colored vector-like T quarks: $\Gamma(T \to th) \approx \Gamma(T \to tZ) \approx \frac{1}{2}\Gamma(T \to bW)$.
  When T-parity is conserved, both $t_+ \equiv T$ and t_- exist.
  $\sigma(gg \to t_- t_-) \approx 0.3$ pb for $m_{t_-} = 800$ GeV. Decay $t_- \to A_H t$, where A_H is stable and a DM candidate.

- New gauge bosons: Han et al (2003), Burdman et al (2003)
  Heavy gauge bosons would decay as $Z_H \to W_L^+ W_L^-, W_H \to W_L Z_L, Z_H \to Z_L h$.
  Brs will follow definite pattern. About 30000 Z_H can produced with 100 fb^{-1} data.

Composite Higgs

(Agashe,Contino,Pomarol,Nomura,Barbieri,Rattazzi,Grojean,Espinosa, Muehlleitner,$\cdots$)
Better realization of little Higgs: Composite bound state from a strongly interacting sector.

- Strong sector: $\mathrm{G} \to \mathrm{H}$ at a scale $f(> v)$. $\mathrm{G/H}$ contains Higgs. Ex: $\mathrm{SO(5)/SO(4)}$.
- Holographic description: $A_5^{(0)}$ of a 5d warped model can be the Higgs, which is massless at tree level and acquires finite mass at one-loop (Serone 2009).

Collider test of compositeness

- $g_{hff} = g_{hff}^{\mathrm{SM}} \left(1 - C_f \xi\right), \quad g_{hVV} = g_{hVV}^{\mathrm{SM}} \left(1 - C_V \xi\right)$,

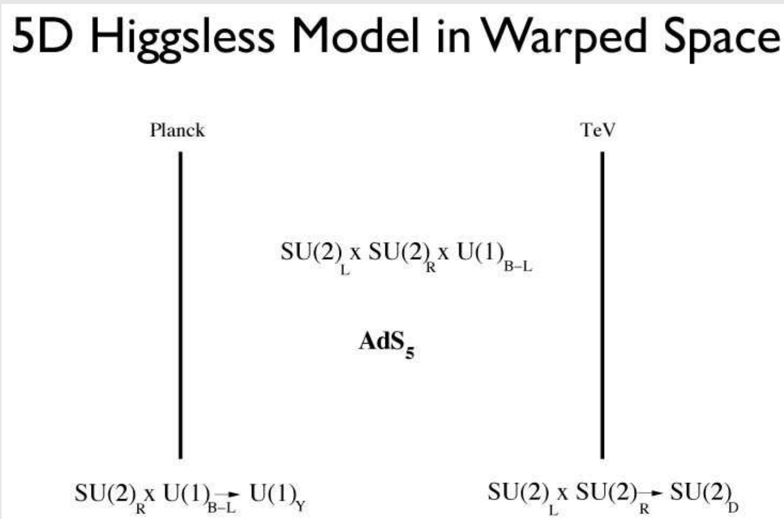
  where $\boxed{\xi \equiv \frac{v^2}{f^2}}$. $\xi \sim (20 - 30)\%$ (from EWPT).

  $\sigma_h \times (\mathrm{Br})_h$ can be measured with 20% precision at LHC (Duhrssen et al).
- Scattering amplitude $A(VV) \sim \frac{s}{f^2} \Rightarrow$ Excess events in $V_L V_L \to V_L V_L$ scattering.
- $q\bar{q}, gg \to q^*_{5/3} \bar{q}^*_{5/3} \to W^+ t W^+ t \to W^+ W^+ b W^- W^- \bar{b}$. Highly energetic same sign leptons, plus 6 jets two of which two are tagged b jets.

$$\boxed{\textbf{SM}} \xleftarrow{0 \leftarrow \xi} \boxed{\textbf{Composite}} \xrightarrow{\xi \to 1} \boxed{\textbf{Higgsless/TC}}$$

Higgsless Scenario

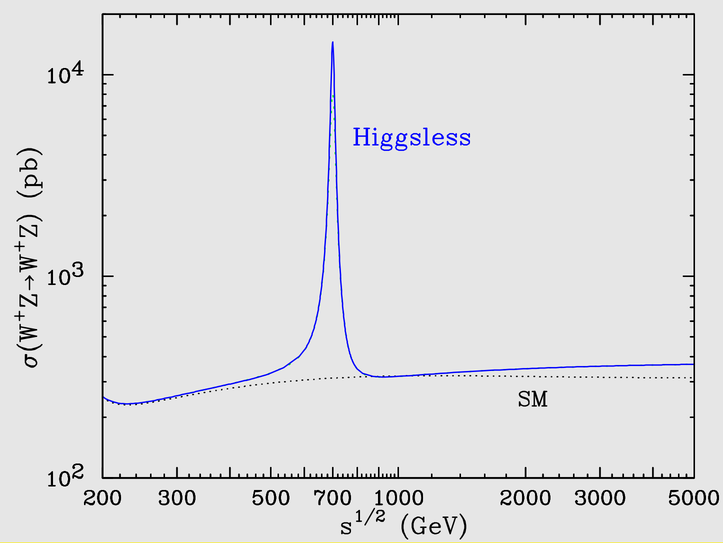
(Csaki, Grojean, Murayama, Pilo, Terning, $\cdots$) Compositeness scale $\sim$ weak scale



Tension between unitarity and EWPT

$$\Lambda \sim \frac{3\pi^4 M_W^2}{g^2 M_W^{(1)}} \sim 4 \text{ TeV for } M_W^{(1)} \sim 1 \text{ TeV.}$$

Unitarity is postponed. Increasing Λ means decreasing $M_W^{(1)}$ which, in turn, means increasing the T parameter.



LHC signature (Birkedal et al 2005)

$WZ \xrightarrow{W^{(1)}} WZ$ scattering channel: If $M_1^{\pm} \approx 700$ GeV, the coupling $g_{WZV^1} \sim 0.04$. Sharp resonance can be seen due s channel mediation. Striking feature is the narrow width (~ 13 GeV) of the resonance.

Little Higgs/Composite/Higgsless

- Composite models are UV-completed versions of LH models and relatively less fine-tuned. Also, unlike in LH models, there is a *clear separation* between *elementary* and *composite* sectors in Composite Higgs models.

- Composite: Strong sector does *not directly* break EW symmetry, but provides a composite pseudo-GB, the Higgs. Higgs potential is then generated at one loop. Two-stage breaking generates $\xi = \frac{v^2}{f^2}$, a measure of F.T.

  Higgsless/TC: QCD-like strong dynamics breaks EW symmetry *directly*.

  - $S_{\text{Composite}} \div S_{\text{Higgsless}} \sim \xi \sim 0.2 - 0.3$, where $v = \sqrt{2} M_W / g$.

  - Composite: $\mathcal{A}(W_L W_L) \sim \frac{s}{f^2}$. Higgsless: $\mathcal{A}(W_L W_L) \sim \frac{s}{v^2}$.

  - Composite: $M_{V'} \sim g_S\, f$. Higgsless: $M_{V'} \sim g_S\, v$.

Conclusions

- All models based on calculability $\Rightarrow$ $\boxed{M_Z = \Lambda_{\rm NP} f(a_i)}$ where $f(a_i)$ are calculable functions of physical parameters. The amount of F.T. is encoded in this relation.
- Different symmetries protect the Higgs mass – Supersymmetry, shift symmetry of Goldstone boson, higher dimensional gauge symmetry. OR, no Higgs at all!
- Heaviness of new particles do not *necessarily* mean large F.T. Symmetry may be responsible for cancellation. Feldman et al 2011
- SUSY models are comfortable with EWPT, while Technicolor-inspired models receive stronger constraints.
- Goal: 3-fold. (i) Unitarize, (ii) check EWPT, (iii) Naturalness.
  Tension between naturalness and EWPT.
- A light Higgs does not have to be necessarily elementary, it can be composite as well! Measurements of the Higgs couplings are crucial.