New Approaches in Electroweak Symmetry Breaking

Hsin-Chia Cheng
University of California, Davis

Pheno 2008, Madison, Wisconsin

Introduction

- Electroweak symmetry breaking (EWSB) is currently the most prominent question in particle physics.
- Finding the mechanism for EWSB is the major motivation for looking for new physics beyond the Standard Model (SM). Because of naturalness, It is widely believe that new physics should appear at the TeV scale.
- LHC is expected to fully explore the TeV scale and address the origin of EWSB. We need to be ready for any possibility that LHC will present to us.

What to expect at TeV scale?

- From a phenomenological point of view, we can ask what goes wrong if there is nothing beyond what we have discovered below 1 TeV. The answer is that the longitudinal $W_L W_L$ scattering amplitude will grow like E^2 and the (tree-level) unitarity will be violated.
- Therefore new physics needs to come in below the TeV scale to unitarize the longitudinal $W_L W_L$ scattering amplitude.

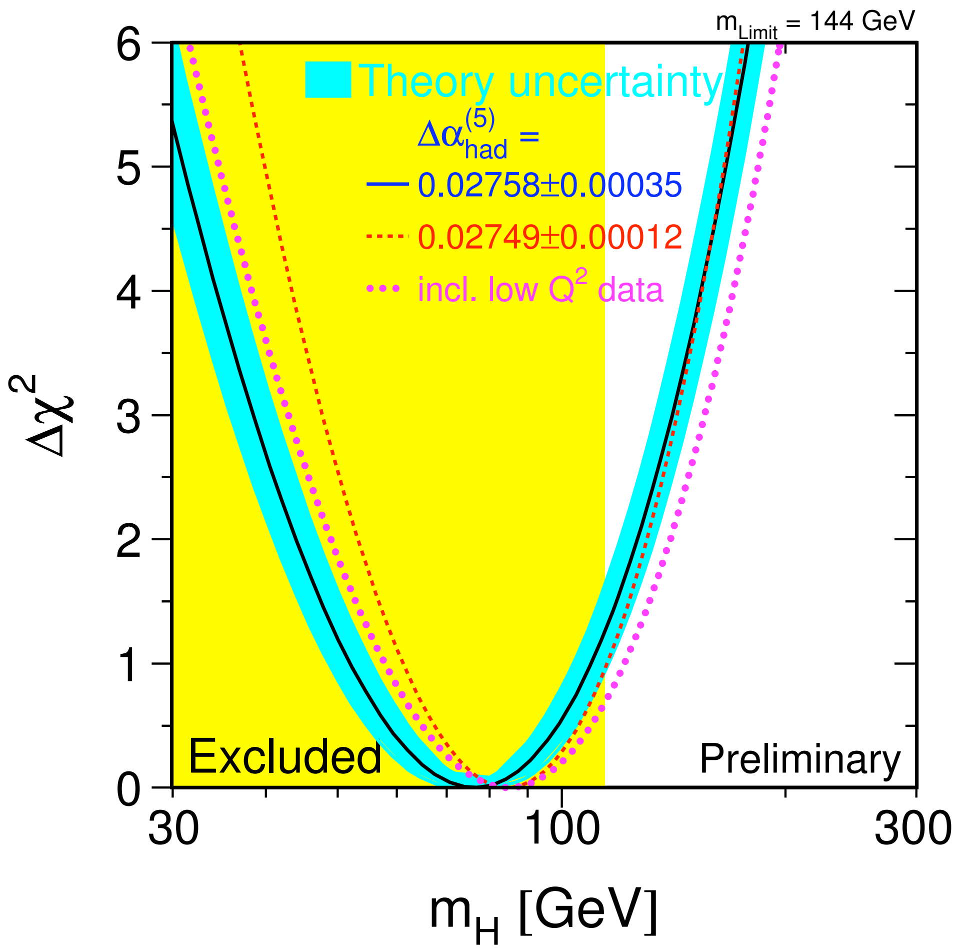
Unitarizing WW Scattering

- A scalar (Higgs) particle with appropriate couplings to the W and Z bosons: This is the simplest possibility, but suffers from the hierarchy problem.
- (A tower of) vector particles: Examples are the techni-rhos in technicolor theories and KK gauge bosons in extra dimensions.
- Something else which we don't understand yet.
- A combination of the above.

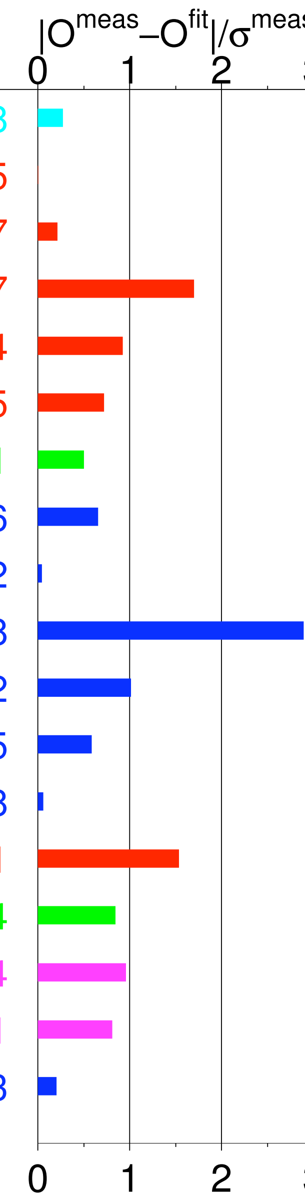
Challenge for New Models of EWSB

- Theoretical consistency and predictivity: If the new models are based on strong dynamics. How can we make claims and predictions with confidence?
- Experimental constraints: LEP, Tevatron and other low energy experiments have put stringent constraints on possible new physics beyond the Standard Model. How can we construct models which satisfy these constraints.

Electroweak Precision Fit



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



Electroweak Constraints

- Electroweak precision data put strong constraints on any TeV scale models.
- New particles at the TeV scale can induce too large corrections to the electroweak observables.

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H \rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2} (\bar{L} \gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i (H^+ D_\mu H)(\bar{L} \gamma_\mu L)$	14	8.0

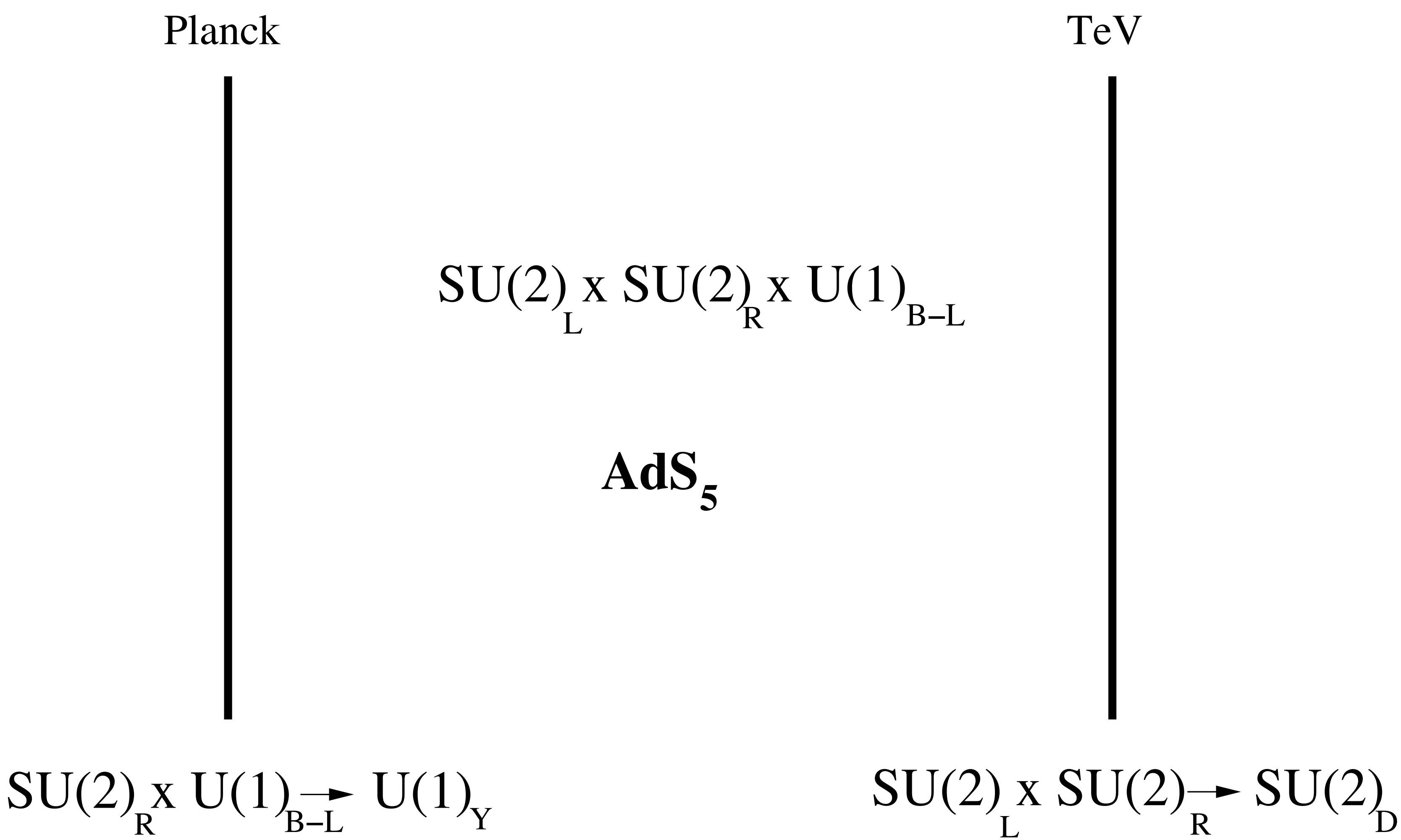
(Barbieri and Strumia '00)

- Strongest constraints come from *S*, *T*, 4-fermion interactions, and $Z \to b\bar{b}$

No Higgs Scenario

- Technicolor theories are the original models without Higgs. The $W_L W_L$ scattering is unitarized by techni-rhos.
- New approaches involve extra dimensions and the electroweak symmetry is broken by boundary conditions. $W_L W_L$ scattering is unitarized by KK gauge bosons. (Csaki, Grojean, Murayama, Pilo, Terning, ...)
- The Higgsless model in warped extra dimensions provides an alternative (dual) and calculable description of electroweak symmetry broken by strong (conformal) dynamics.

5D Higgsless Model in Warped Space



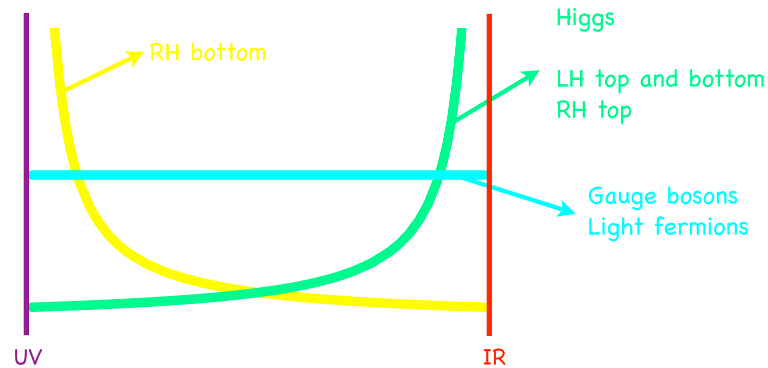
Electroweak Constraints

- *T* parameter can be suppressed by a custodial SU(2).
- *S* parameter is positive (and large) if the SM fermions are localized on the UV brane (fundamental), in agreement with the estimate in Technicolor models.
  - In Higgsless model, the KK gauge bosons have to be around 1 TeV because they are responsible for unitarizing $W_L W_L$ scattering. One can reduce their couplings to SM fermions by choosing a near-flat profile in the bulk for the light fermions.

Electroweak Constraints

- To have large enough top Yukawa coupling, top quark needs to be near the IR brane.

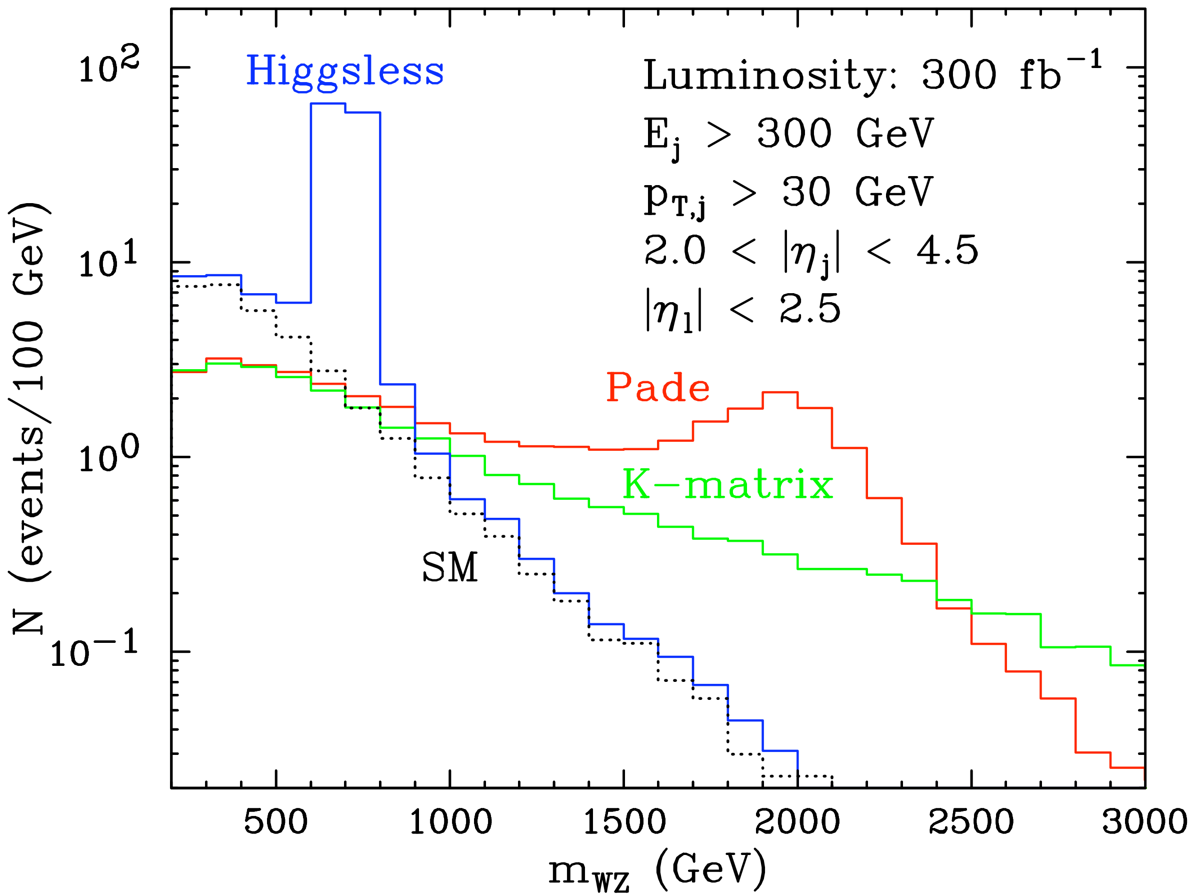
A Higgsless realization:



- In the traditional embedding, $(t_L, b_L) \sim (2, 1)$ under SU(2)L x SU(2)R , (t_L, b_L) mixes with KK states which transform as (1, 2), which induces large correction to $Z \to b\bar{b}$.

- A different embedding $(t_L, b_L) \sim (2, 2)$ with a custodial symmetry $SU(2)_L \times SU(2)_R \times P_{LR}$ can solve this problem. (Agashe, Contino, Da Rold, Pomarol '06) (Cacciapaglia, Csaki, Marandella, Terning '06)

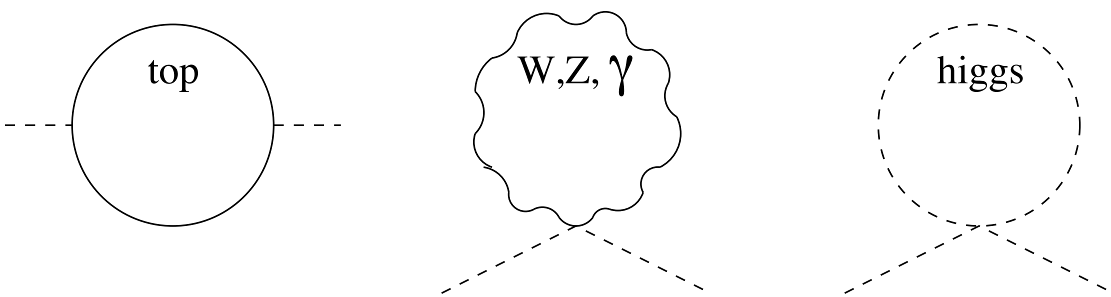
LHC Signal



Birkedal, Matchev, Perelstein hep-ph/0412278

Theories with a (light) Higgs

- The simplest way to unitarize the longitudinal WW scattering is to add a scalar Higgs particle (Standard Model). However, a fundamental scalar field suffers from the hierarchy problem.



top loop	$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$
$SU(2)$ gauge boson loops	$\frac{9}{64\pi^2}g^2\Lambda^2$
Higgs loop	$\frac{1}{16\pi^2}\lambda^2\Lambda^2$

For no more fine tuning than ~10%, it's required that

$$\Lambda_{top} \lesssim 2 \text{ TeV} \qquad \Lambda_{gauge} \lesssim 5 \text{ TeV} \qquad \Lambda_{Higgs} \lesssim 10 \text{ TeV}.$$

(Taken from M. Schmaltz, hep-ph/0210415)

How to Keep the Higgs Light?

- Supersymmetry (SUSY) has been the leading candidate for new physics at or below 1 TeV. In SUSY, the quadratically divergent contributions to the Higgs mass^2 from the SM fields are canceled by their superpartners with the opposite spins.
- Many new models have been proposed in recent years with the quadratic divergence canceled in various ways, including Little Higgs, Twin Higgs, Folded SUSY, ...

Higgs as a Pseudo-Goldstone Boson

- Higgs may be light because it's a pseudo-Nambu-Goldstone boson. It's an old idea (Georgi-Kaplan '85) but got revived recently with the help of the new ideas of collective symmetry breaking, (deconstructed) extra dimensions, and so on.
- Examples are Little Higgs models (Arkani-Hamed, Cohen, Georgi, ...), Gauge-Higgs unification (Dvali, Randjbar-Daemi, Tabbash, and many others...), Twin Higgs (Chacko, Goh, Harnik,...), etc.

Little Higgs Theories

- Higgs field(s) are pseudo-Nambu-Goldstone bosons (PNGBs) of a spontaneouly broken global symmetry G → H.
- G is explicitly broken by 2 sets of interactions, with each set preserving a subset of the symmetry. The Higgs is an exact NGB when either set of the couplings is absent.

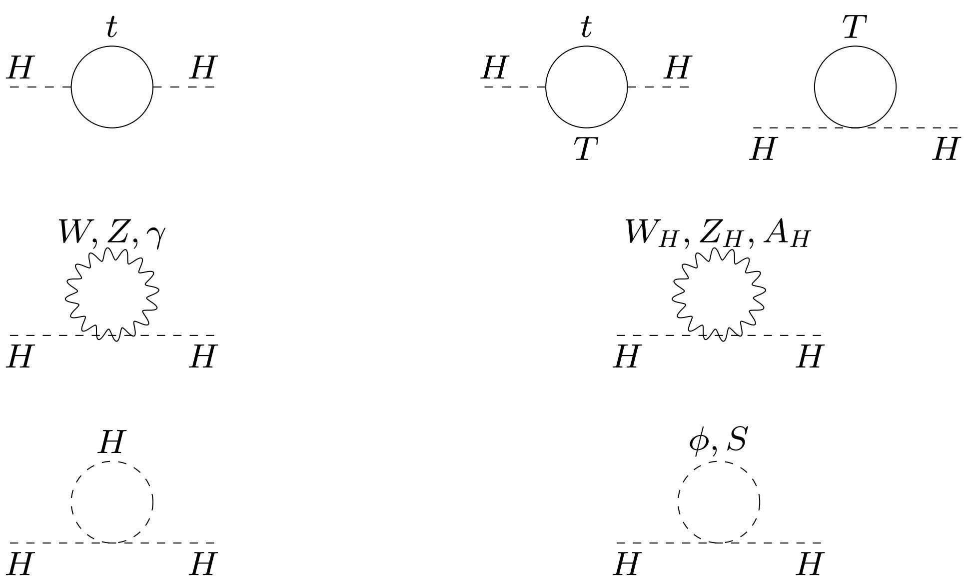
$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

- Higgs mass is protected from one-loop quadratic divergence so that the cutoff can be pushed up to ~10 TeV.

$$\delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2}\right)\left(\frac{\lambda_2^2}{16\pi^2}\right)\Lambda^2$$

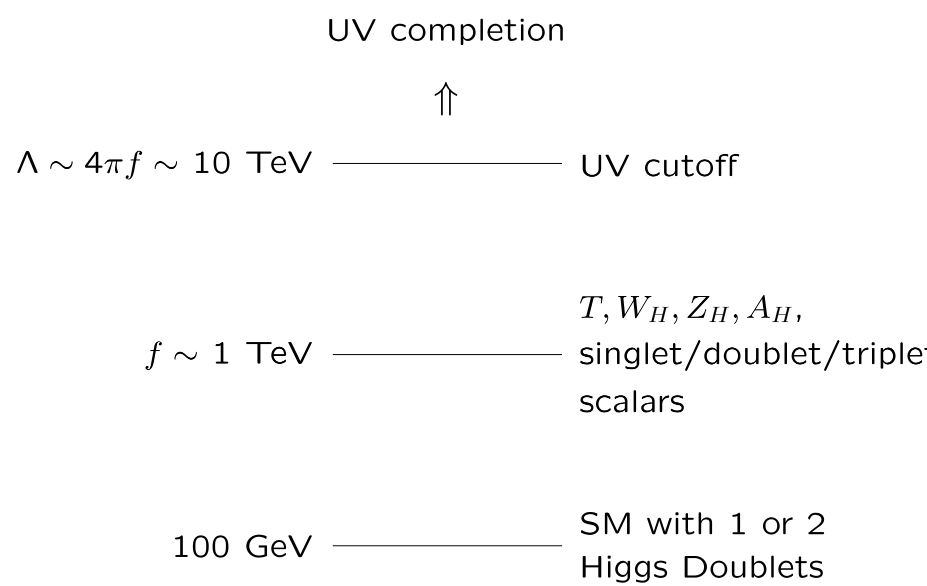
Little Higgs Theories

- The quadratic divergences are canceled by new particles which are partners of the SM top quark, gauge bosons and Higgs. Unlike SUSY, they have the same spins as the SM particles.



$m_{W_H} \sim gf,\ m_T \sim \lambda_t f, \ldots,\ f \sim 1$ TeV, $\Lambda \sim 4\pi f$

Generic spectrum for little Higgs theories:

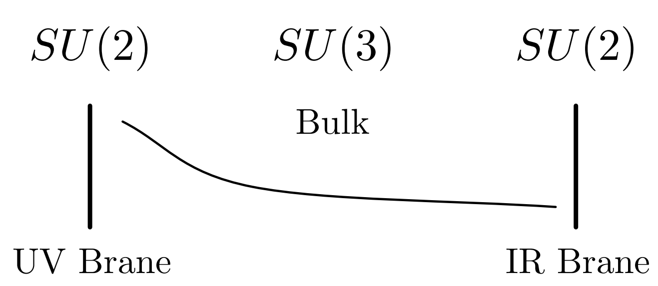


Gauge-Higgs Unification

- A larger bulk gauge symmetry (containing the SM) in extra dimensions is broken (down to SM) by boundary conditions.

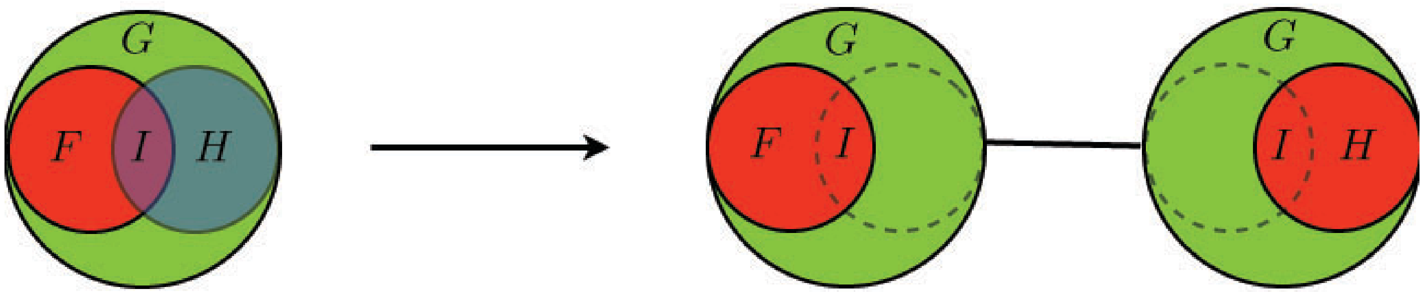
- Higgs is identified with the extra component of the bulk gauge fields, and hence its mass is protected by the bulk gauge symmetry.

- In the case of warped extra dimension, it has a dual description that the Higgs arises as the PNGB of a spontaneously broken global symmetry of the strongly coupled CFT. (Holographic PNGB Higgs, Contino, Nomura, Pomarol, '03)

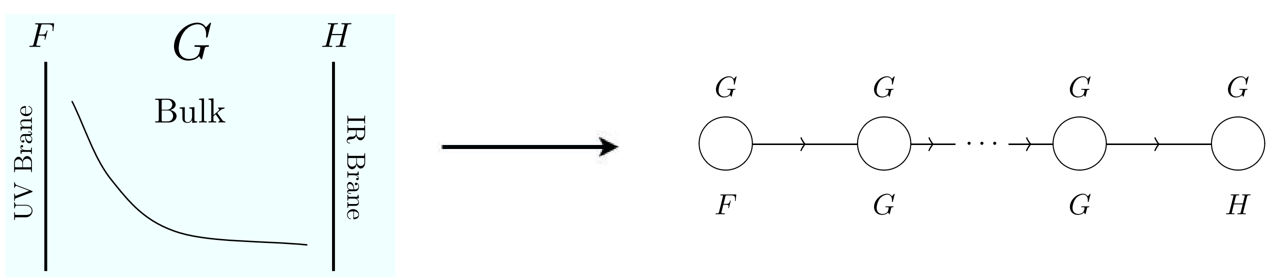


A Unified Approach: Little M-theory

- Almost all little Higgs models are either based on moose diagrams or can be converted into moose models using CCWZ.

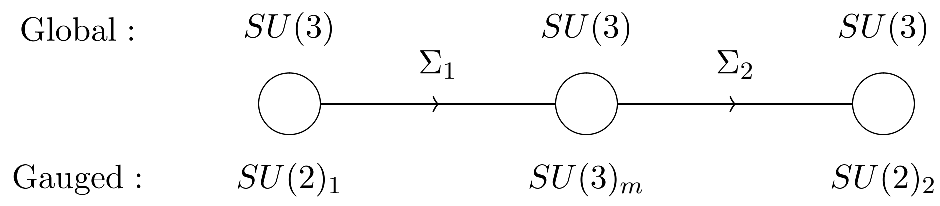


- Extra dimensional models can be converted into moose models by deconstruction.



- Many different models can be represented by the same moose diagram at low energies.

For example, the moose diagram



can describe several very different looking models by taking various limits.

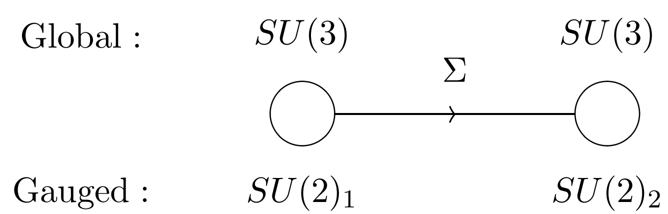
- Simple little Higgs: $g_{1,2}$ of $SU(2)_{1,2} \to \infty$

  Kaplan & Schmaltz, hep-ph/0302049

- Minimal moose: g_m of $SU(3)_m \to \infty$

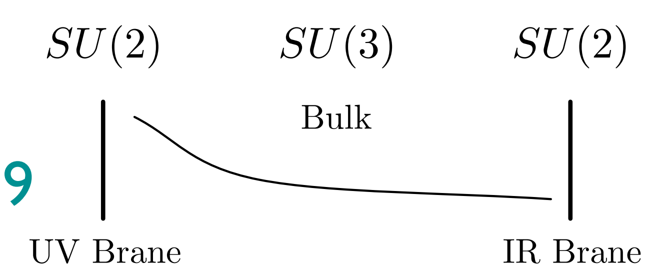
  Arkani-Hamed et al, hep-ph/0206020

  The middle site can be integrated out.



- Holographic PNGB Higgs

Contino, Nomura & Pomarol, hep-ph/0306259



Electroweak Constraints

- To avoid large corrections to *T*, the model should contain a custodial symmetry $SU(2)_L \times SU(2)_R$.
- *S* and 4-fermion interactions can be reduced by raising the masses of the TeV-scale particles (for the price of more fine-tuning), or reducing the couplings between SM fermions and the new TeV scale particles.

For example, in many little Higgs models one can impose a T-parity which forbids couplings between the SM fermions and TeV scale particles.
(Recently T-parity is claimed to be broken by anomalies, Hill & Hill '07. However, it's a UV completion question. One can easily find UV-complete theories in which T-parity is exact.)

Twin Higgs

Chacko, Goh, and Harnik, hep-ph/0506256, 0512088

- The accidental global symmetry is due to a discrete symmetry.
- The new particle responsible for canceling the top loop contribution to the Higgs mass needs not to be colored! It can be difficult to find at LHC.

Twin Higgs

- Consider a scalar field transforming as a fundamental rep. of a global SU(4). It gets a (TeV scale) vev f, breaking SU(4) to SU(3) => 7 Goldstone bosons
- Now gauge $SU(2)_A x SU(2)_B$ subgroup with a twin parity A⟺B (g_A=g_B).
- The quadratic corrections are SU(4) invariant,

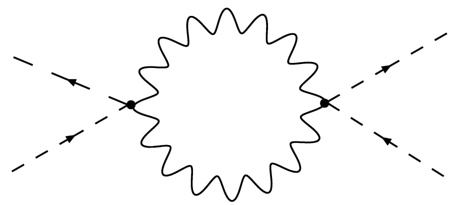
$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \quad \Delta V(H) = \frac{9g_A^2\Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9g_B^2\Lambda^2}{64\pi^2} H_B^\dagger H_B$$

$$= \frac{9g^2\Lambda^2}{64\pi^2}(H_A^\dagger H_A + H_B^\dagger H_B)$$

Does not give mass to the Goldstones.

Twin Higgs

- Higher order terms are not SU(4) invariant.



$$\Delta V = \kappa(|H_A|^4 + |H_B|^4)$$

with $$\kappa \sim \frac{g^4}{16\pi^2} \log \frac{\Lambda^2}{f^2}$$

- Correct EWSB (asymmetric vacuum, f_A~174 GeV << f_B) can be obtained by adding a soft Z_2 breaking mass,

$$V_{\rm soft}(H) = \mu^2 H_A^\dagger H_A$$

Twin Higgs

Two options:

- Mirror (twin) model: $SM_A \times SM_B \times Z_2$

  Top sector: $\mathcal{L} = y_t H_A q_L^A t_R^A + y_t H_B q_L^B t_R^B + \mathrm{h.c}$

  Top loop is canceled by the mirror top charged under the mirror gauge group => difficult to find at LHC.

  Top sector can be extended to remove the logarithmic sensitivity to the cutoff.

- Left-right model: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Folded SUSY

Burdman, Chacko, Goh, and Harnik, hep-ph/0609152

- Cancelation of quadratic divergence from the top loop:

	fermion	boson	
color	Little Higgs	SUSY	Global symmetry
Non-color	Twin Higgs - mirror	?????????	Discrete symmetry

- Can the top loop be canceled by uncolored bosons?

Yes,

$$t \;\overset{Q^{\alpha}}{\longleftrightarrow}\; \tilde{t}$$

Folded SUSY

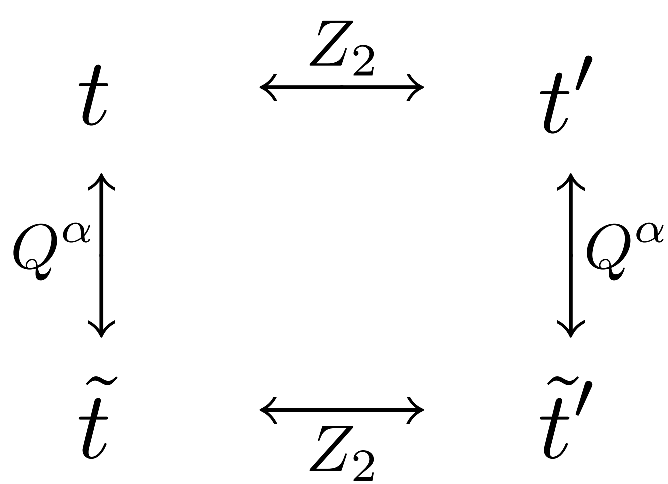
Burdman, Chacko, Goh, and Harnik, hep-ph/0609152

- Cancelation of quadratic divergence from the top loop:

	fermion	boson	
color	Little Higgs	SUSY	Global symmetry
Non-color	Twin Higgs - mirror	?????????	Discrete symmetry

- Can the top loop be canceled by uncolored bosons?

Yes,



Folded SUSY

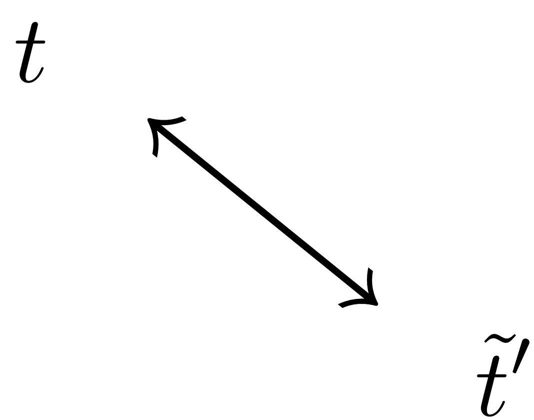
Burdman, Chacko, Goh, and Harnik, hep-ph/0609152

- Cancelation of quadratic divergence from the top loop:

	fermion	boson	
color	Little Higgs	SUSY	Global symmetry
Non-color	Twin Higgs - mirror	?????????	Discrete symmetry

- Can the top loop be canceled by uncolored bosons?

Yes,



The IR Model

- Below ~10 TeV we have the daughter of

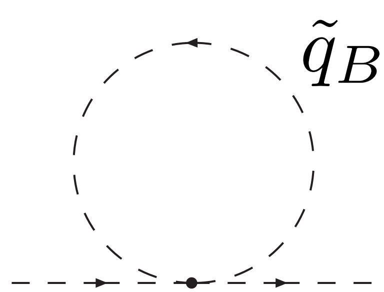
$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

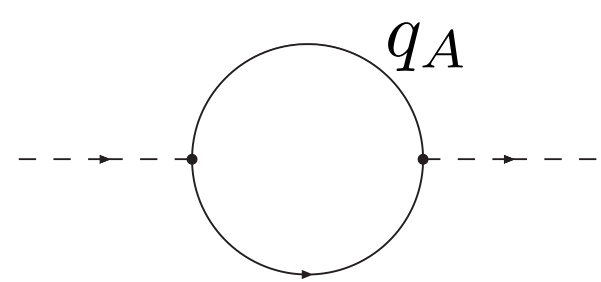
as orbifolded by $Z_{2\Gamma} \times Z_{2R}$:

$$\tilde{q} = \begin{pmatrix} \tilde{q}_A(-) \\ \tilde{q}_B(+) \end{pmatrix} \qquad q = \begin{pmatrix} q_A(+) \\ q_B(-) \end{pmatrix}$$

squarks

quarks





(Taken from R. Harnik's talk)

A Full Model

- A supersymmetric theory.

  SUSY is broken at 10 TeV by B.C.'s on 5D orbifold.

$$(SU(3)_A \times SU(3)_B \times Z_{AB}) \times SU(2)_L \times U(1)_Y$$

$\mathcal{N} = 1'$ (left brane) $\quad$ H, $\mathcal{N} = 1$ (right brane)

$$\begin{array}{llll} \hat{Q}_{iA} & (3,1,2,1/6) & \hat{Q}_{iB} & (1,3,2,1/6) \\ \hat{U}_{iA} & (\bar{3},1,1,-2/3) & \hat{U}_{iB} & (1,\bar{3},1,-2/3) \\ \hat{D}_{iA} & (\bar{3},1,1,1/3) & \hat{D}_{iB} & (1,\bar{3},1,1/3) \end{array}$$

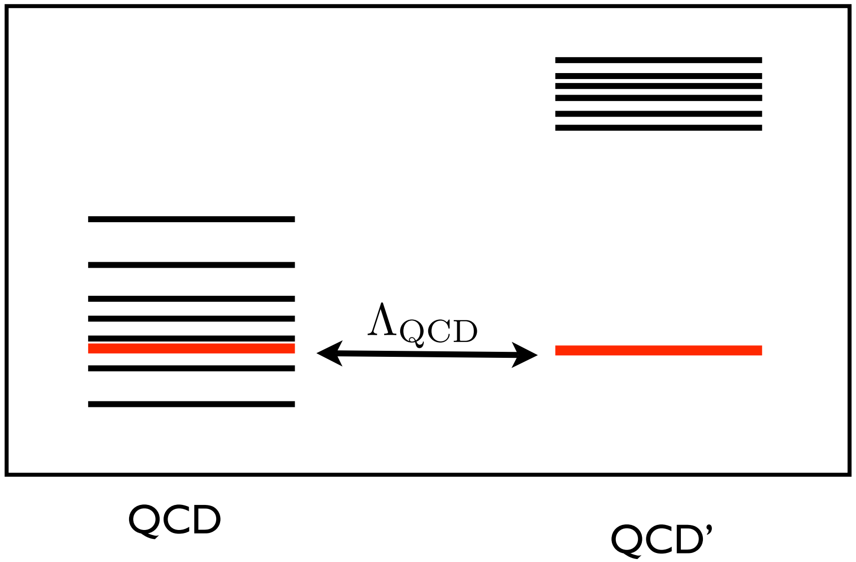
only have fermion zero modes

only have scalar zero modes

Technology by Quiros et al and Barbieri, Hall, Nomura et al.

Exotic Phenomenology at LHC

- Spectrum of QCD' ($SU(3)_B$):



- No light particle charged under QCD'. The string of QCD' doesn't break. The pair-produced "squirks" will come back and oscillate before they eventually annihilate. The collider signals can be very exotic. Currently being studied by M .Luty; Burdman, Chacko, Goh, and Harnik; Harnik and Wizansky

Other possibilities?

- For example, can a spin-1 particle cancel the top loop?

  Yes, if top is a gaugino. SU(5) contains X/Y gauge bosons which transform as (3,2). They can be the superpartner of the left-handed top quark.

A spin-1 top partner

H. Cai, HC, and J Terning, work in progress

- SU(5)xSU(3)xSU(2)xU(1) => SU(3)xSU(2)xU(1)

	$SU(3)_C$	$SU(2)_L$	$U(1)_X$	$SU(5)$	$U(1)_X + aT_{24}$
Q_i	$\Box$	$\Box$	$\frac{1}{6}$	$\mathbf{1}$	$\frac{1}{6}$
$\overline{u}_i$	$\overline{\Box}$	$\mathbf{1}$	$-\frac{2}{3}$	$\mathbf{1}$	$-\frac{2}{3}$
$\overline{d}_i$	$\overline{\Box}$	$\mathbf{1}$	$\frac{1}{3}$	$\mathbf{1}$	$\frac{1}{3}$
L_i	$\mathbf{1}$	$\Box$	$-\frac{1}{2}$	$\mathbf{1}$	$-\frac{1}{2}$
$\overline{e}_i$	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{1}$	1
H	$\mathbf{1}$	$\mathbf{1}$	$\frac{3}{5}$	$\Box$	$(\frac{2}{3}, \frac{1}{2})$
$\overline{H}$	$\mathbf{1}$	$\mathbf{1}$	$-\frac{3}{5}$	$\overline{\Box}$	$(-\frac{2}{3}, -\frac{1}{2})$
Φ_3	$\overline{\Box}$	$\mathbf{1}$	$-\frac{1}{15}$	$\Box$	$(0, -\frac{1}{6})$
Φ_2	$\mathbf{1}$	$\overline{\Box}$	$\frac{1}{10}$	$\Box$	$(\frac{1}{6}, 0)$
$\overline{\Phi}_3$	$\Box$	$\mathbf{1}$	$\frac{1}{2}$	$\overline{\Box}$	$(0, \frac{1}{6})$
$\overline{\Phi}_2$	$\mathbf{1}$	$\Box$	$\frac{1}{2}$	$\overline{\Box}$	$(-\frac{1}{6}, 0)$

$$\overline{H} = (T^c, H_1)$$
$$H = (\overline{T}^c, H_2)$$

$$\langle\Phi_3\rangle = \begin{pmatrix} f_3 & 0 & 0 & 0 & 0 \\ 0 & f_3 & 0 & 0 & 0 \\ 0 & 0 & f_3 & 0 & 0 \end{pmatrix} \quad , \quad \langle\overline{\Phi}_3\rangle = \begin{pmatrix} \overline{f}_3 & 0 & 0 \\ 0 & \overline{f}_3 & 0 \\ 0 & 0 & \overline{f}_3 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\langle\Phi_2\rangle = \begin{pmatrix} 0 & 0 & 0 & f_2 & 0 \\ 0 & 0 & 0 & 0 & f_2 \end{pmatrix} \quad , \quad \langle\overline{\Phi}_2\rangle = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \overline{f}_2 & 0 \\ 0 & \overline{f}_2 \end{pmatrix}$$

$$\begin{aligned} W &= Y_u\, Q\, \overline{u}\, \overline{\Phi}_2 H + Y_d\, Q\, \overline{d} \Phi_2 \overline{H} + Y_e\, L\, \overline{e} \Phi_2 \overline{H} + Q_3 \Phi_3 \overline{\Phi}_2 + \overline{u}_3 H \overline{\Phi}_3 \\ &\quad + \mu_3 \Phi_3 \overline{\Phi}_3 + \mu_2 \Phi_2 \overline{\Phi}_2 + \mu H \overline{H} \end{aligned}$$

A spin-1 top partner

- Q_3 mixes with $(3,\ 2)$ states in $\Phi_2,\ \bar{\Phi}_3,$ and SU(5) gaugino, $\bar{u}_3$ mixes with the $(\bar{3},\ 1)$ state in $\bar{H}$, through $\Phi_{2,3},\ \bar{\Phi}_{2,3}$ vevs and μ terms.
- The parameters can be chosen such that our top lies mostly in the SU(5) gaugino and $\bar{H}$, then the top Yukawa coupling comes from the SU(5) gaugino coupling.
- The superpartner of the left-handed top quark is the spin-1 X/Y gauge boson in SU(5).

Conclusions

- For a long time, SUSY and Technicolor are the only candidates beyond SM to explain the electroweak symmetry breaking and the hierarchy problem.
- In recent years there is a flood of new theories for the electroweak symmetry breaking and the hierarchy problem with the help of many new ideas such as extra dimensions, decontruction, AdS/CFT correspondence, collective symmetry breaking, and so on.

Conclusions

- For theories with Higgs, the quadratically divergent contributions to the Higgs mass^2 from the SM fields can be canceled by a variety of new particles with same or different spins, and charged under SM or new gauge groups. They give a wide range of possible phenomenologies at LHC and other future experiments.

- No single model stands out as they all face the challenge of current tight experimental constraints. We don't know what we will discover and we need to be ready for any possibility.

- There can be other possible new theories waiting for us to discover.