Little Higgs, Non-standard Higgs, No Higgs and All That

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Introduction

- The mechanism of the electroweak symmetry breaking (EWSB) is currently the most prominent question in paricle physics.
- Because of the hierarchy problem of the Standard Model (SM) Higgs sector, it's 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.

Introduction

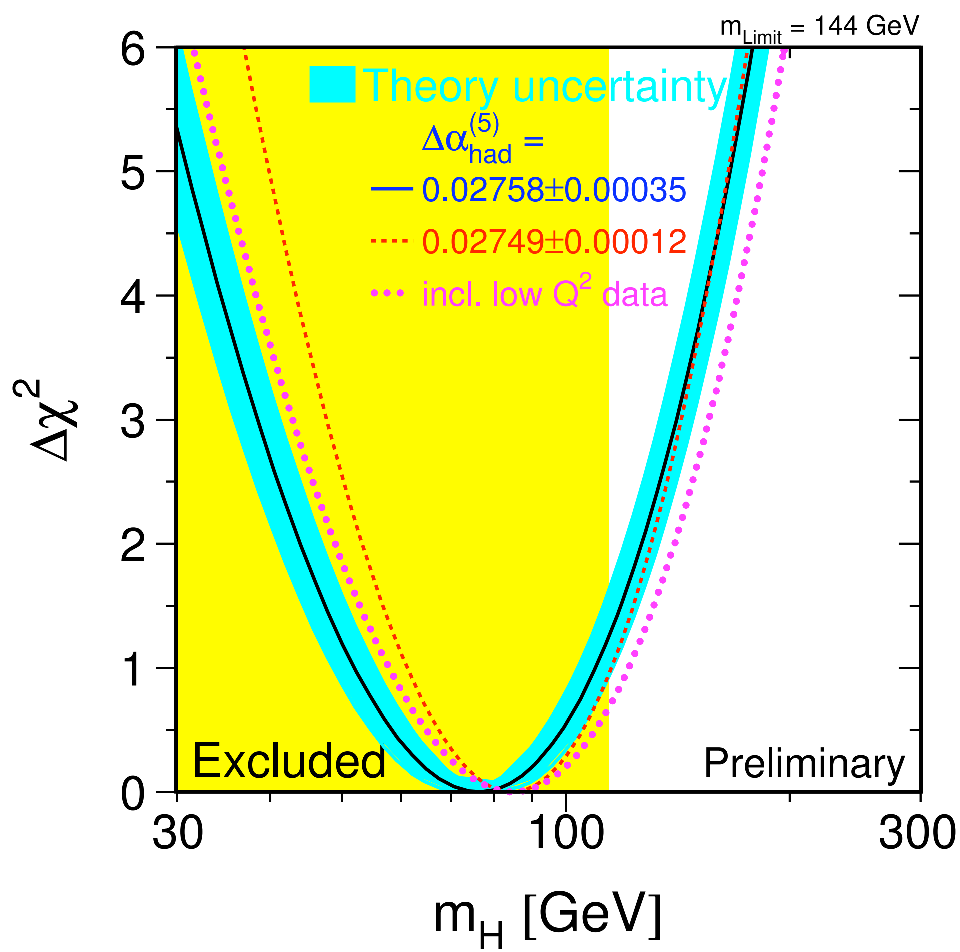
- Supersymmetry (SUSY) has been the leading candidate for physics beyond the SM. However, there have been a lot of progresses in alternative theories in recent years based on new ideas such as extra dimensions (flat, warped, or deconstructed), collective symmetry breaking (little Higgs mechanism). They allow us to construct new models or revive old ideas, calculate or estimate theoretical predictions, and finding new ways to satisfy experimental constraints.

Introduction

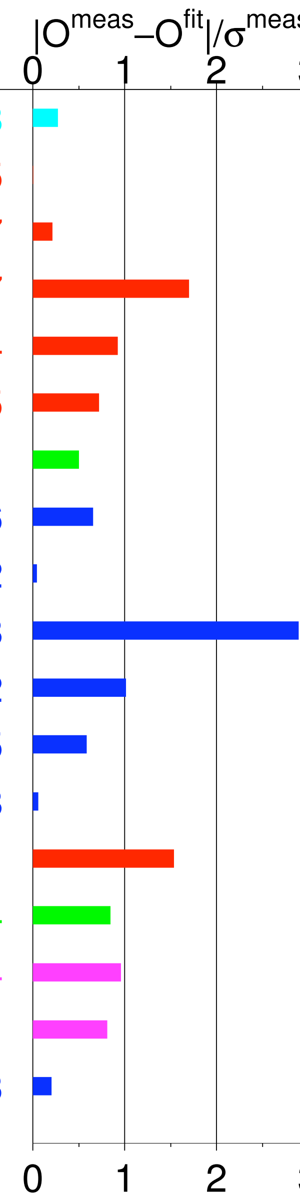
Challenges for alternative theories:

- Theoretical consistency and predictivity: Alternative theories often 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 satify 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

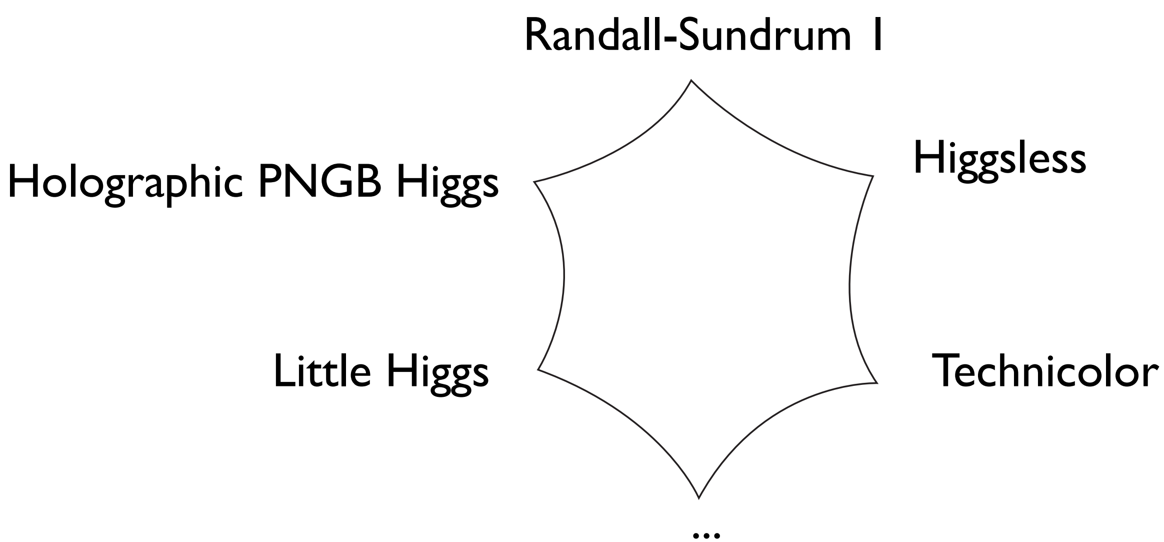


Categories (basesd on the Higgs sector)

- (Naturally) light (composite) Higgs: Higgs is light because of a (shift) symmetry. E.g., Higgs as a PNGB or A_5.
- Heavy (composite) Higgs: No symmetry to protect the Higgs mass, so it's heavy unless by fine-tuning. E.g., top condensate models, RS 1.
- No Higgs: $W_L W_L$ scattering is unitarized by some other states. E.g., Technicolor, Higgsless models.

Categories (basesd on the Higgs sector)

- The model space is continuous. There are scenarios interpolating among these categories.



- Different models often share some similar features and face similar challenges. It would be desirable to describe them and understand them in some universal way (at least for LHC phenomenology).

Light Higgs Scenarios

The idea that a light Higgs is a PNGB (Georgi-Kaplan '85) or A_5 (Fairlie '79, Manton '79, Hosotani '83) have been around for a long time.

Recent new models:

- Little Higgs models (Arkani-Hamed, Cohen, Georgi, ...)
- Gauge-Higgs unification based on flat or warped extra dimensions (Dvali, Randjbar-Daemi, Tabbash, and many others...)
- Twin Higgs models (Chacko, Goh, Harnik,...)

Little Higgs Theories

- Higgs field(s) are pseudo-Nambu-Goldstone bosons (PNGBs) of a spontaneouly broken global symmetry G $\rightarrow$ H.

- G is explicitly broken by 2 sets of interactions (for example, by gauging some subgroup F), with each set preserving a subset of the symmetry. The Higgs is an exact NGB when either set of the couplings is absent.

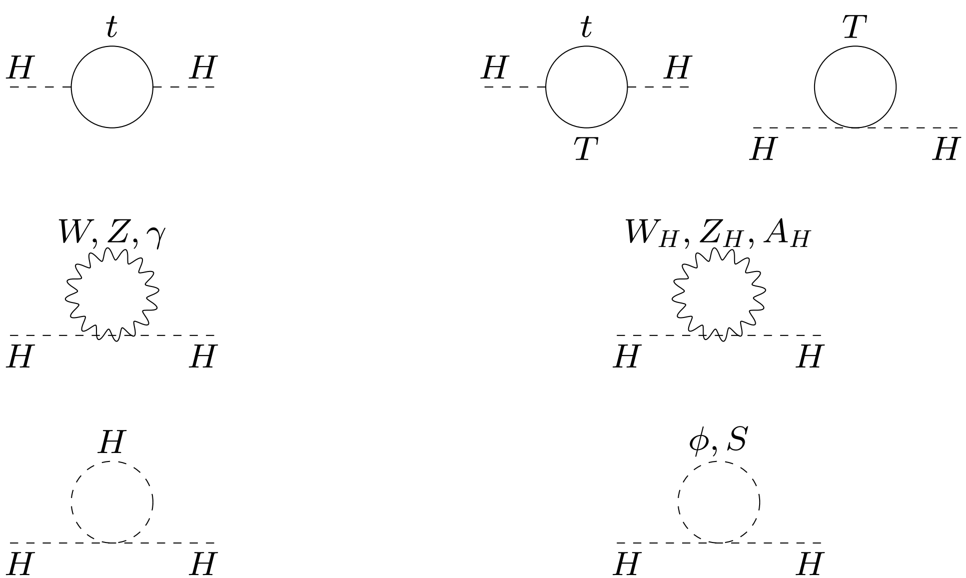
$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

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

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

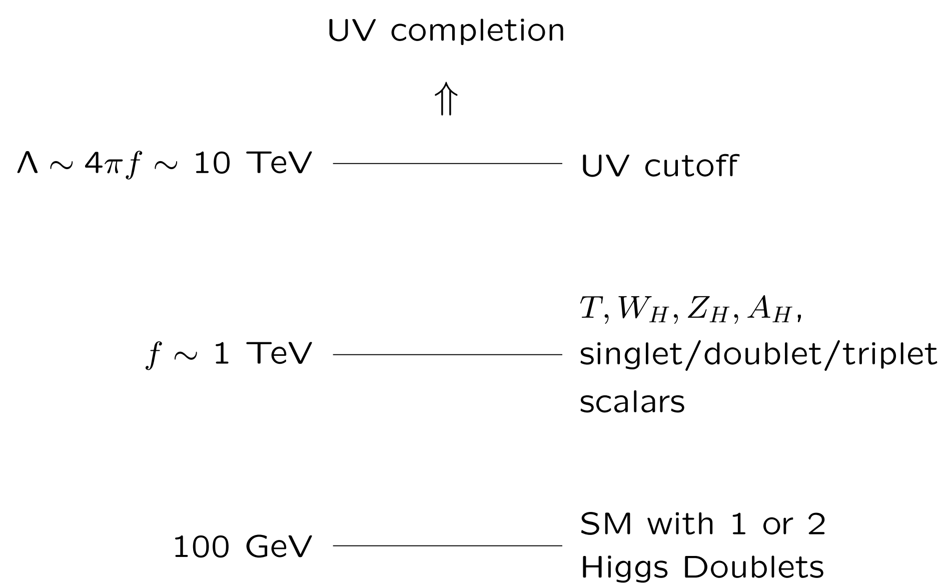
Little Higgs Theories

- The quadratic divergences are cancelled 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.



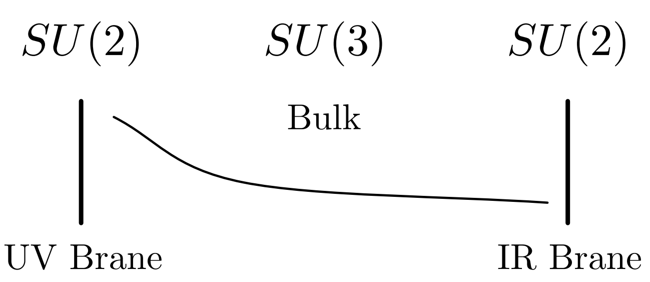
$m_{W_H} \sim gf,\ m_T \sim \lambda_t f, \ldots,\ f \sim 1$ TeV, $\Lambda \sim 4\pi f$

Generic spectrum for little Higgs theories:



Gauge-Higgs Unification

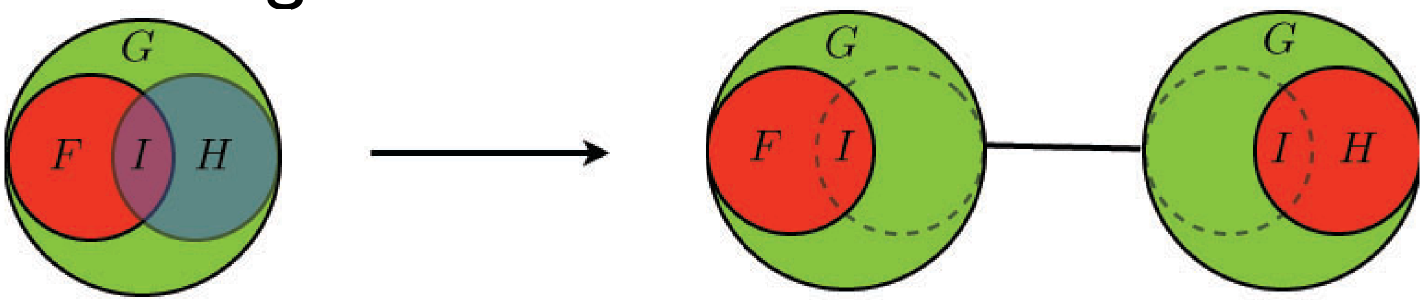
- A larger bulk gauge symmetry (containing the SM) in extra dimensions is broken (down to SM) by boundary conditions.
- Higgs is identified with the extra component of the bulk gauge fields, and hence its mass is protected by the bulk gauge symmetry.
- In the case of warped extra dimension, it has a 4D 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)



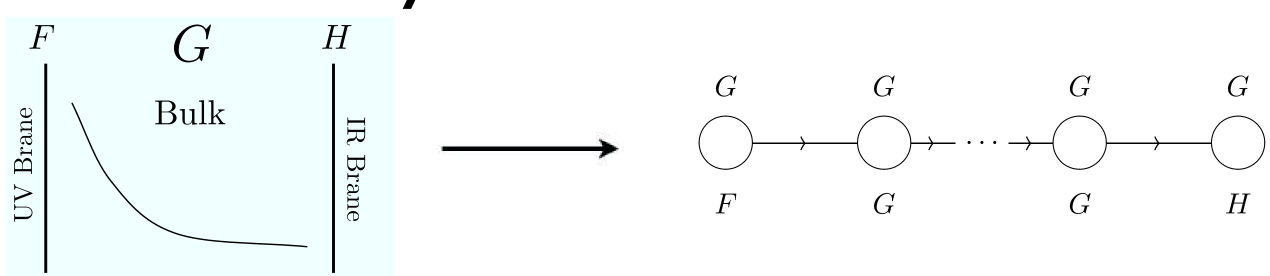
A Unified Approach: Little M-theory

HC, Thaler, Wang, hep-ph/0607205

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

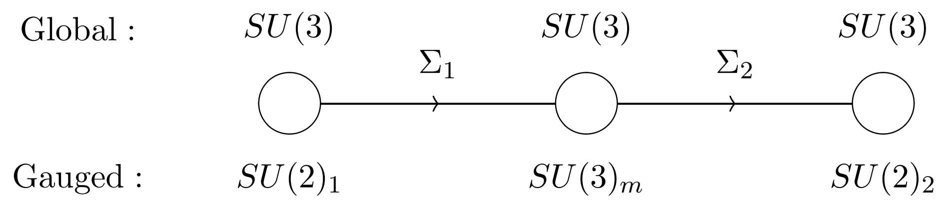


- Extra dimensional models can be converted into moose models by deconstruction.



- 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.

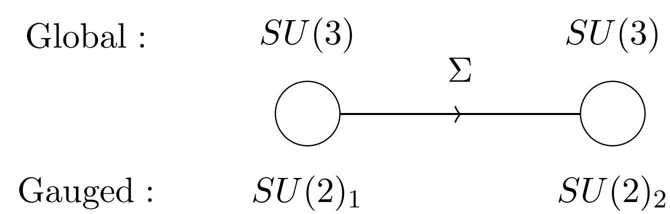
- Simple little Higgs: $g_{1,2}$ of $SU(2)_{1,2} \to \infty$

  Kaplan & Schmaltz, hep-ph/0302049

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

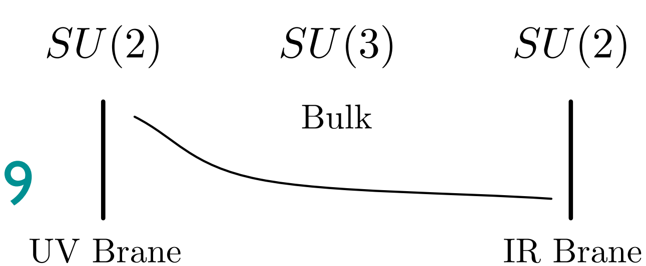
  Arkani-Hamed et al, hep-ph/0206020

  The middle site can be integrated out.



- Holographic PNGB Higgs

Contino, Nomura & Pomarol, hep-ph/0306259



Electroweak Constraints

- 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 (W and Y in Barbieri, Pomarol, Rattazzi, Strumia, hep/ph/0405040) , and $Z \to b\bar{b}$.

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 (Cheng & Low) which forbids couplings between the SM fermions and TeV scale particles. (Recently Hill & Hill ('07) showed that T-parity is can be broken by WZW terms. However, it's a UV completion question. One can easily find UV-complete theories in which T-parity is exact.)

Low-energy Effective Lagrangian for a Strongly-Interacting Light Higgs (SILH)

Giudice, Grojean, Pomarol, Rattazzi, hep-ph/0703164

- The strongly coupled sector can be characterized by 2 parameters, $g_\rho (\gtrsim g_{SM}),\ m_\rho,$ with $m_\rho = g_\rho f.$
- Integrating out the strong sector, the low-energy effective Lagrangian can be expressed in terms of the expansions, H/f and $\partial/m_\rho.$
- The higher-dimensional operators can be divided into
  - Genuine strong operators (sensitive to the scale *f*)
  - Form factor operators (sensitive to the scale m_ρ)

SILH Effective Lagrangian

- Genuine strong operators:

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D_\mu} H\right). \qquad \frac{c_y y_f}{f^2}H^\dagger H \bar{f}_L H f_R \qquad \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3$$

(fixed by the σ-model structure)

(custodial SU(2) breaking)

(from both the σ-model structure and the resonances at m_ρ)

c_H term rescales the Higgs kinetic term after plugging in the Higgs vev and modifies the Higgs couplings.

⇒Unitarity is not exactly restored by Higgs alone, but also the heavy resonances in the strong sector.

This is a model-independent test of the compositeness nature of the Higgs.

- Form factor operators:

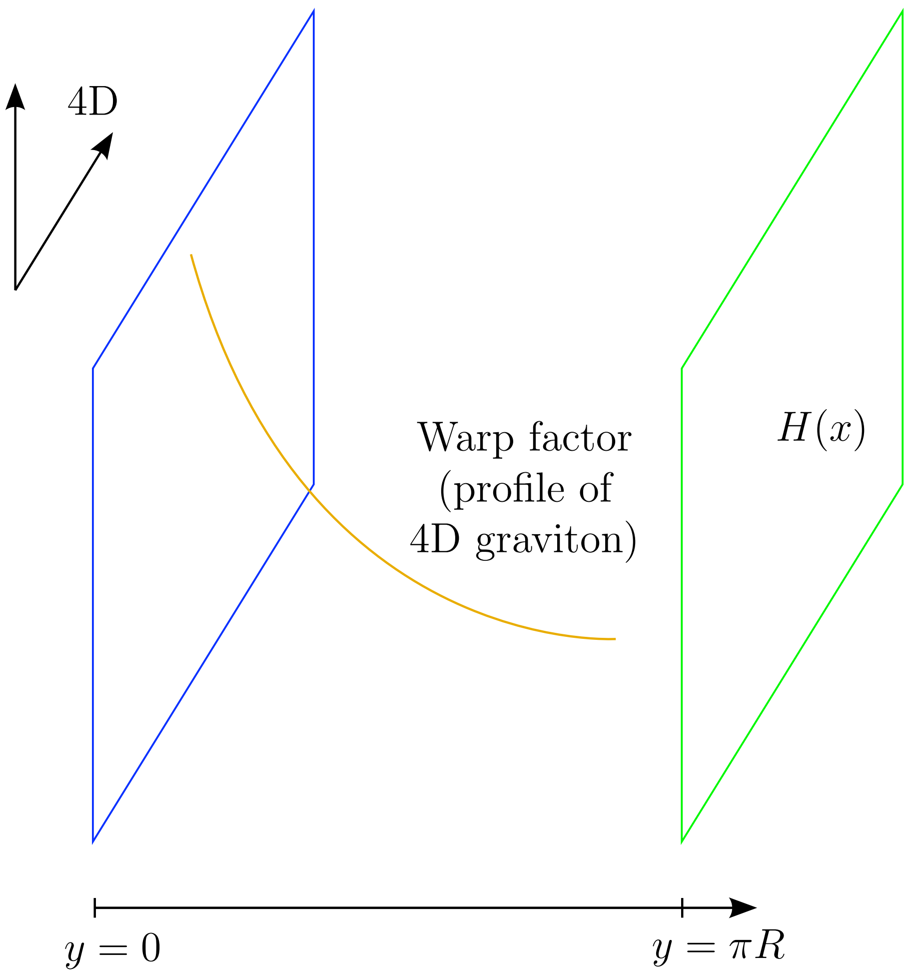
$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.$$

c_H and c_y are the most important ones for LHC studies

Heavy Composite (Fat) Higgs

- Higgs is a composite from some strong dynamics, but there is no symmetry to keep it light. (It may be possible to get a light Higgs by fine-tuning of the model parameters.) Old example: top condensate and its variations.
- Randall-Sundrum model (RS1) provides an extra-dimensional dual description of such a scenario with a strongly coupled CFT. Higgs localized at (or near) the IR brane is interpreted as the bound state of the (spontaneously broken) CFT in the 4D picture.

Randall-Sundrum I



Heavy Composite Higgs

- To satisfy the EW precision constraints and to address the fermion mass hierarchy, it's desirable to have gauge fields propagating in the bulk too.
  - Bulk gauge group should contains $SU(2)_L \times SU(2)_R$ (custodial symmetry of the CFT).
  - SM fermion masses may be explained by the localizations of the fermions in the extra dimension. Light generations are localized toward the UV brane (fundamental). (Right-handed) top should be localized near the IR brane (composite) to accommodate the large top Yukawa coupling.

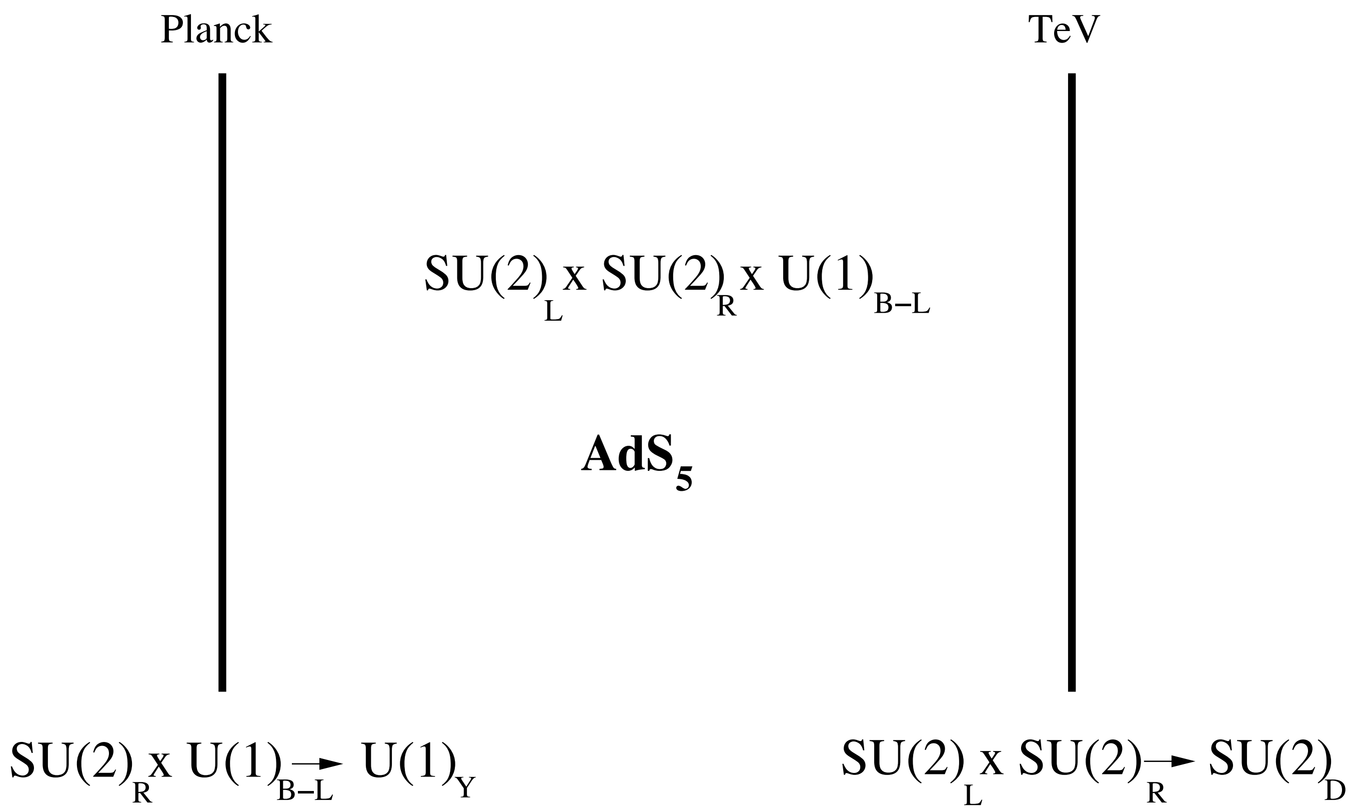
The localization of a field in the warped extra dimension just corresponds to the compositness content of the particle in the dual 4D picture (UV=more fundamental, IR=more composite). The 5D zero mode is in general a mixture of a fundamental field and the resonances produced by the CFT in the dual 4D picture.

The partial compositeness is also not a new ideal. It was propose by D. B. Kaplan (1991) as a mechanism to generate fermion masses in Technicolor theories. (A related idea: Top-seasaw mechanism, Dobrescu & Hill, '98)

No Higgs Scenario

- Technicolor theories are the original models without Higgs. The $W_L W_L$ scattering is unitarized by techni-rhos.
- Warped extra dimensions allows an alternative and calculable description of such a scenario -- Higgsless models. (Csaki, Grojean, Murayama, Pilo, Terning, ...)
- It's similar to RS1, except that there is no Higgs. Electroweak gauge symmetry is broken by the combination of the boundary conditions at the UV and IR branes. $W_L W_L$ scattering is unitarized by KK gauge bosons.

5D Higgsless Model in Warped Space



Compactification scale is fixed by the unitarity constraint (W' ~ 1.2 TeV), unlike the case with a Higgs where the compactification scale can be raised if one is willing to accept more fine-tuning.

- There can be models interpolating between the heavy Higgs and Higgsless scenarios: There is a Higgs, but unitarization of $W_L W_L$ scattering is shared by the Higgs boson and the KK gauge bosons (techni-rhos).

The couplings between the Higgs boson and SM gauge fields (and/or fermions) are reduced -- Gaugephobic Higgs. (Cacciapaglia, Csaki, Marandella, Terning)

Old realizatons: Bosonic Technicolor (Carone & Simmons, '92), Topcolor assisted Technicolor (Hill '94), ...

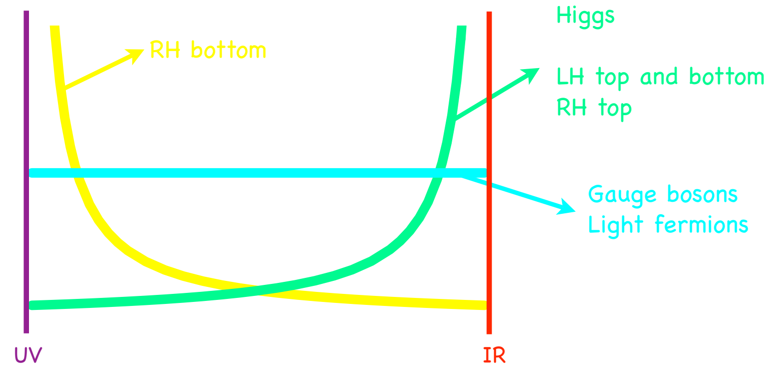
Electroweak Constraints

- 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.
  - If there is a Higgs, one can push up the KK gauge boson masses (the compositeness scale) at the expense of more fine-tuning.
  - In Higgsless limit, the KK gauge bosons have to be around 1 TeV . One can reduce their couplings to SM fermions by choosing a near-flat profile in the bulk for the light fermions (Cacciapaglia, Csaki, Grojean & Terning, '04, Foadi, Gopalakrishna & Schmidt, '04).

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 $Z \to b\bar{b}$.

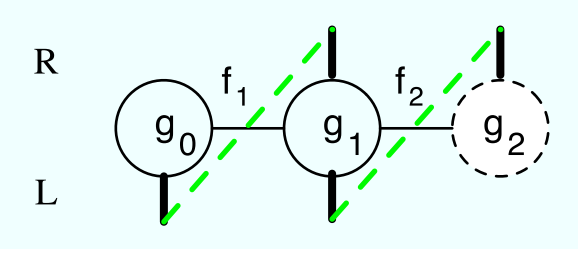
- A different embedding $(t_L, b_L) \sim (2,2)$ with a custodial symmetry $SU(2)_L \times SU(2)_R \times P_{LR}$ can solve this problem. (Agashe, Contino, Da Rold, Pomarol '06)
(Loop contributions should still be checked for specific models.)

Deconstructions

- At energy scales accessible to the LHC, it sufficient to approximate these models by a deconstruction with only a few sites.
  - At lowest truncation, the warped/composite phenomenology can be approximated by a two-site model with one site representing the composite sector, (Contino, Kramer, Son, Sundrum, '06, and see also Contino's talk in this conference)

$$\mathcal{L} = \mathcal{L}_{elementary} + \mathcal{L}_{composite} + \mathcal{L}_{mixing} \,.$$

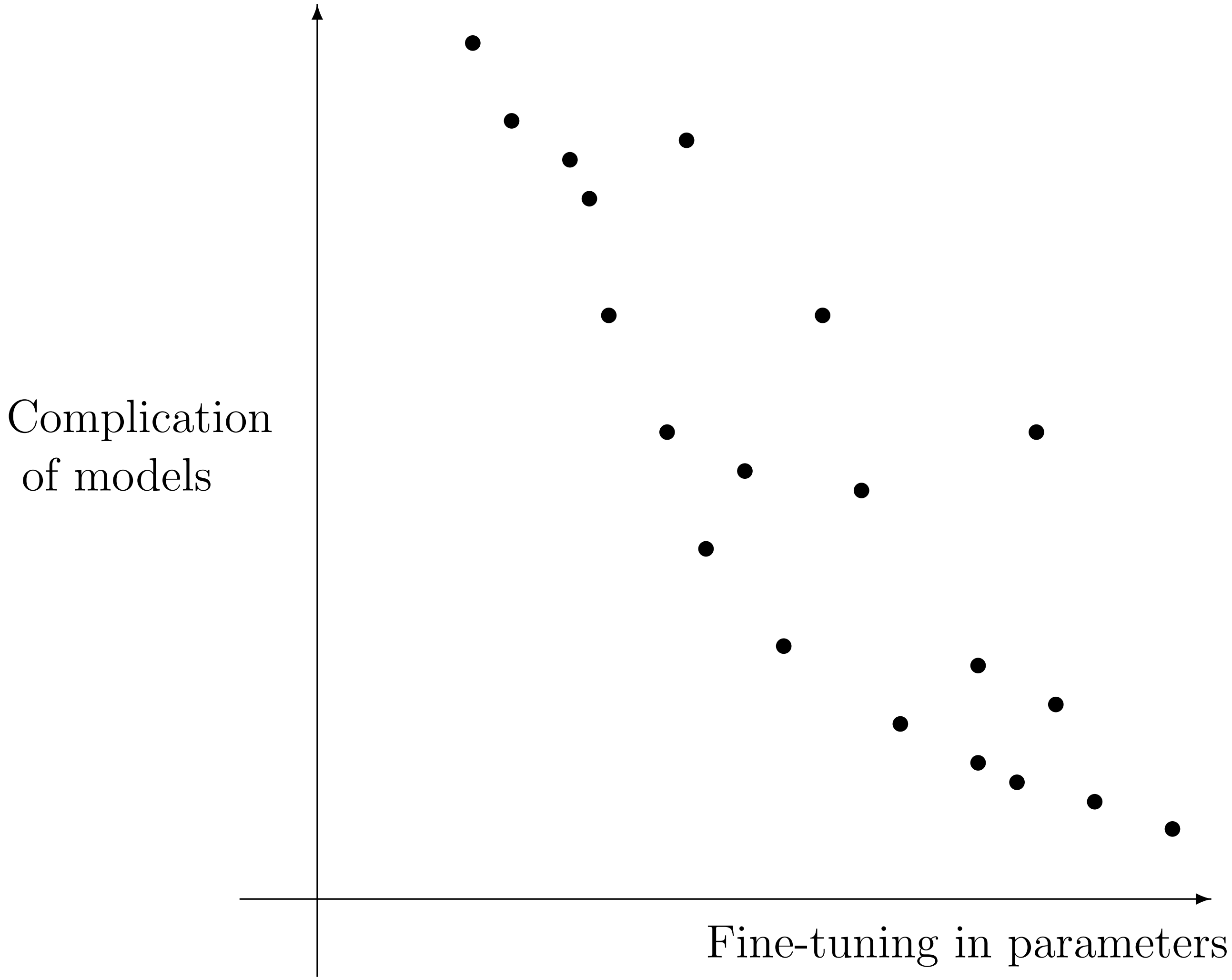
  - A three-site deconstruction of Higgsless model: (Chivukula et al '06 and see also Belyaev's talk)



Conclusions

- Recent new ideas such as extra dimensions, AdS/CFT correspondence, collective symmetry breaking have provided us new tools for model building.
  - Many new models of electroweak symmetry breaking have been built, including little Higgs, fat Higgs, Higgsless..., and the model space is continuous.
  - New and uniform way to understand and implement various (old) ideas.
- No single model stands out (due to the tight constraints of EW precision data).

Beyond the SM model space



Conclusions

- Given the large number of models, some unified approach for LHC phenomenology is desirable. This is possible by effective Lagrangian and deconstruction.
- Most of the models predicts new vector particles (KK gauge bosons or techi-rhos) and new fermions associated with the 3rd generation (and/or new scalars beyond the Higgs) which can be represented by some moose diagrams. If such new states are discovered, constructing a moose model can be a useful first step towards figuring out the underlying theory.