No Higgs Models

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Fermilab, April 12, 2007

Life without a Higgs:

- The Standard Model has been tested very accurately, however…
- we still don't know the origin of the Electroweak symmetry breaking (and masses…)
- The Higgs mechanism is a nice description of such phenomenon, but it suffers from theoretical prejudices (hierarchy problem), and the Higgs boson has not been discovered yet.
- What if we don't see the Higgs at the (early) LHC?

The role of the Higgs:

- Weakly coupled H = (h , $W_L^{\pm}$, Z_L)
- The same dof's can arise as composite states of a strongly interacting sector (Technicolor) → no fundamental scalar
- Can we decouple h from the theory? What would that imply?

$W_L W_L$ scattering violates Unitarity at ~ 1 TeV scale.

Strong coupling appears below 1 TeV → broad resonances (techni-ρ, …), theory out of control (precision EW tests, …)

We would like to keep the theory under control up to a safe scale of 10 TeV:

- Let's consider the contribution of the ρ-mesons to the W_L scattering:

➢ Expanding the scattering amplitude for large Energy:

$$\mathcal{A}\,(W_L\text{-}W_L) \sim A^{(4)}\,E^4 + A^{(2)}\,E^2 + \text{finite terms}.$$

➢ $A^{(4)}$ vanishes due to gauge invariance;

➢ $A^{(2)}$ receives contributions both from the vector resonances and the Higgs:

$$\mathcal{A}^{(2)} \sim g^2_{WWWW} - \frac{3}{4}\sum_k \frac{M^2_{Z^k}}{M^2_W} g^2_{WWZ^k} - \frac{1}{4}\sum_k g^2_{WWH^k}$$

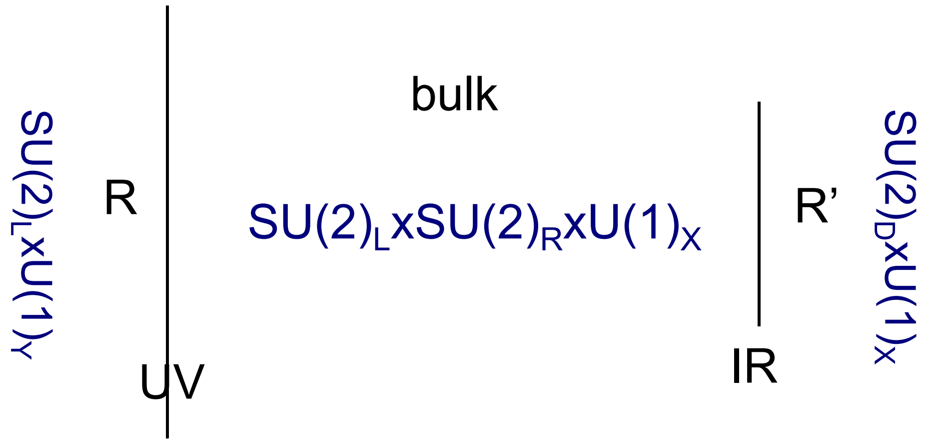
The violation of perturbative unitarity can be delayed up to 10 TeV!
We can smoothly go to a Higgsless model (gaugephobic Higgs model)
hep-ph/0611385

Extra dimensions: a holographic view into strongly coupled 4D theories

- conformal sector (strong)
- Mass gap
- CFT global symmetries
- Elementary sector
- Bound states

- Warped 5D
- IR brane
- Bulk gauge symmetries
- UV brane
- KK states

The model



- AdS_5 space: $$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

- UV brane at z=R, IR brane at z=R';
- $SU(2)_L \times SU(2)_R \times U(1)_X$ in the bulk;
- $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$ on the UV brane;
- $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$ on the IR brane.

Light fermions

- Light fermions are doublets of the SU(2)'s:

  $\psi_L = (u_l, d_l) = (2, 1, 1/6)$ bulk mass c_L

  $\psi_R = (u_r, d_r) = (1, 2, 1/6)$ bulk mass c_R
- The bulk masses control the localization of the zero modes.
- Delocalizing the zero modes in the bulk ($c_L \sim 0.46$) it is possible to minimize the EWPTs ($S\sim0$).

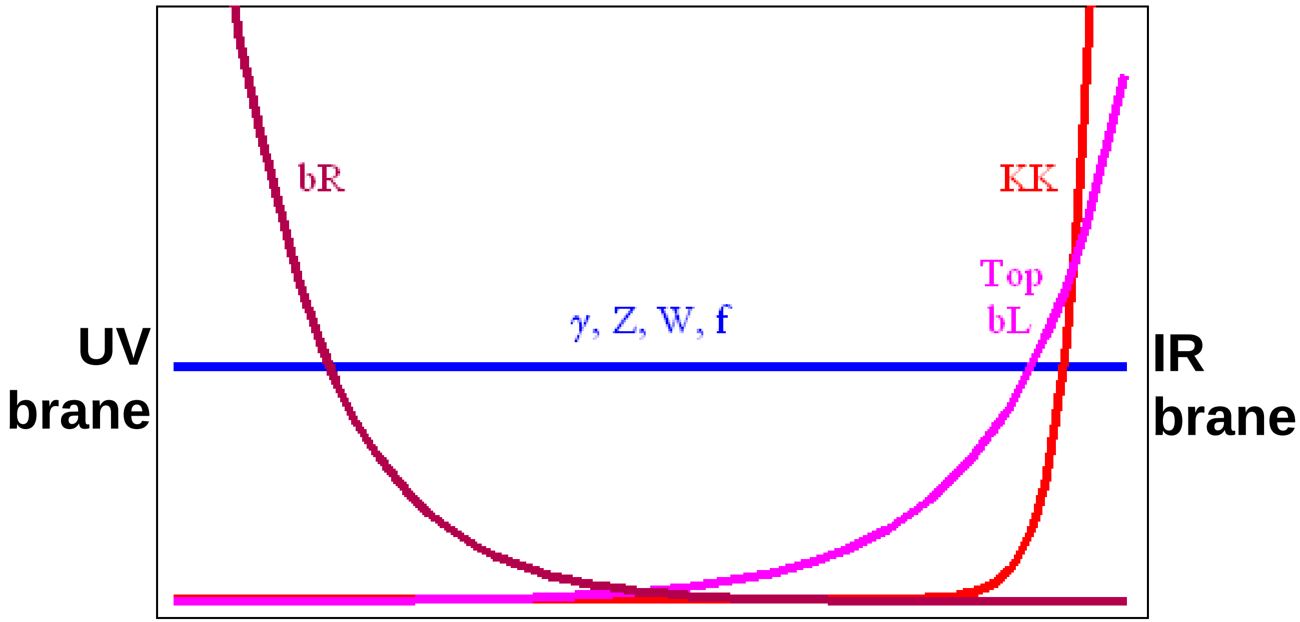
Both representations and localization are preferred by precision measurements!

Third generation: m_{top} vs Zbb

Csaki et al, hep-ph/0607146

- In Higgsless models it is a challenge to have a heavy top and small corrections to the Zbb coupling (below 1%).
- The top must be composite due to its heaviness: the b_L is also composite.
- The $SU(2)_R$ doublet ψ_R contains a left-handed b' that mixes with the b_l via the top Yukawa.
- If we extend the custodial symmetry to O(4) ~ $SU(2)_L x SU(2)_R x P_{LR}$, we can use P_{LR} to protect Zbb: need to use new representations that respect O(4). (Agashe, Contino, daRold, Pomarol)
- Or, we can exile top and bottom to a different AdS throat (like, we have two independent CFT sectors – Csaki et al, hep-ph/0505001 and 0604218)

Group portrait without the Lady:



- Gauge bosons and light fermions are flat
- Top, bL and KK resonances are localized near the IR brane -> highly composite
- bR is localized near the UV brane -> elementary

Summary of the models:

- The only free parameter is the mass of the KK states M_{KK}. (minimal model)
- All the other parameters are fixed by SM values (M_Z, G_F, α, …) or precision tests.
- Reasonable mass range (unitarity):

  $600\ \text{GeV} < M_{KK} < 1\ \text{TeV}$.

- Perturbative and under control up to

~10 TeV (safe for EWPTs).

Benchmark points: two scenarios

$M_{KK} \sim 700$ GeV

- Scenario 1: topless
- The third generation decouples from the EWSB (i.e. “a brane on their own”, hep-ph/0505001)
- Top and bottom decouple from the (light) KK states

- Scenario 2: top
- “New custodian” to protect Zb_Lb_L: hep-ph/0607146
- KK states do couple to t, b
- KK states of the third generation (effects of the new custodian)

Phenomenology: Gauge Bosons

[GeV]	0	1	2	3
W	80.4	699	1105	1583
Z	91.2	694	1110	1578
γ (A)	0	718	-	1603
G	0	718	-	1603

Couplings, an example:

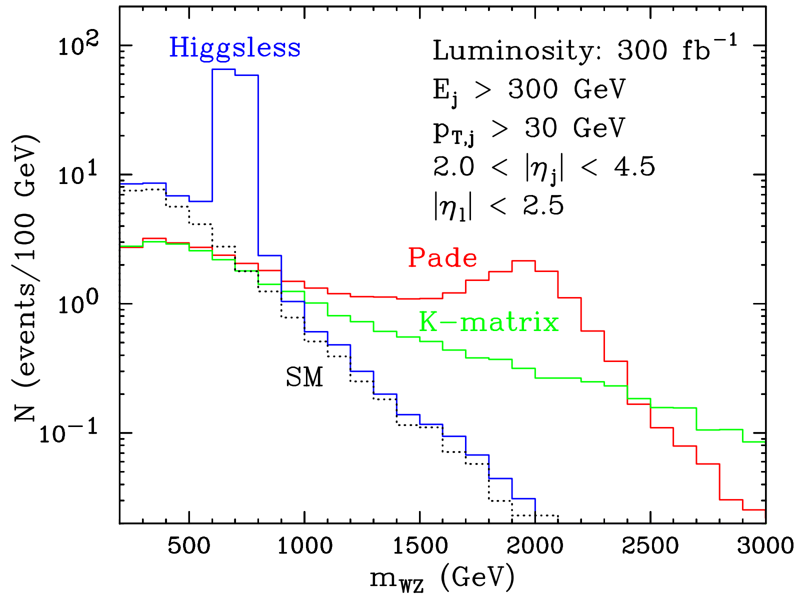
Z1 W W	0.034	~ 10% SM
Z1 f_L f_L	(-0.048) T_{3L} + (0.096) Y	~ 10% SM
Z1 t t	(0.46) P_L + (0.44) P_R	~ SM

	Scenario 1	Scenario 2
W1	Γ = 16 GeV	Γ = 54 GeV
	99% in ZW	30% in ZW
		34% in bt; 35% in heavy tops
	1% jets; 0.1% leptons	0.2% jets; 0.04% leptons
Z1	Γ = 9 GeV	Γ = 60 GeV
	97% in WW	15% in WW
		67% in bb; 18% in tt
	1% jets; 0.15% l^+l^-; 1.5% inv	0.02% jets; 0.025% l^+l^-; 0.3% inv
A1	Γ = 7 GeV	Γ = 21 GeV
	90% in WW	31% in WW
		59% in tt; 6% in bb
	5% jets; 2% l^+l^-	2% jets; 0.6% l^+l^-

Vector Boson Fusion

- Probes the couplings unitarizing longitudinal GB scattering, i.e. the core of the new EWSB mechanism!
- Studied in Perelstein-Matchev-Birkedal hep-ph/0412278 (assuming 100% BR in GBs)

  - $\sigma(pp \to W1\ jj) = 200$ fb
  - decay channel $W1 \to WZ \to jj + 3l +$ missing E_T
  - With 10 fb^{-1}, probe < 550 GeV
  - To probe up to 1 TeV mass, 60 fb^{-1} are needed!
  - BR in tb makes it worse!
  - $Z1, A1 \to WW$ is even more challenging.



Drell-Yan production

- Sensitive to couplings to light quarks (S=0)
- Channel ignored in the previous literature

$\sigma\,(p\,p \to W1^+) = 0.95$ pb
$\sigma\,(p\,p \to W1^-) = 0.48$ pb
$\sigma\,(p\,p \to Z1) = 0.7$ pb
$\sigma\,(p\,p \to A1) = 2.5$ pb

Compare with Higgs:
$\sigma\,(g\,g \to h) = 0.8$ pb
@ $m_H = 700$ GeV

- $\sigma\,(Z1, A1 \to W^+ W^-) = 2.9$ pb (0.9 pb): better discovery potential than a 700 GeV Higgs $\to$ discovery at 10 fb^{-1}! Impossible to distinguish Z1-A1.
- $\sigma\,(W1 \to W\,Z) = 1.4$ pb (0.4 pb): discovery at 10 fb^{-1}!
- top-bottom channels: swamped by gluon (see in a few slides)
- $\sigma\,(Z1, A1 \to l^+ l^-) = 43$ fb (15 fb): hundreds of dilepton events, easy to reconstruct the resonance!

Top-Bottom associated production

- Sensitive to couplings to the third generation (Scenario 2 only!)

$$\sigma\,(p\,p \to t\,\underline{b}\,W1^{+}) = 0.64\ \text{pb}$$
$$\sigma\,(p\,p \to b\,\underline{t}\,W1^{-}) = 0.64\ \text{pb}$$

$\sigma\,(p\,p \to t\,\underline{t}\,Z1) = 26$ fb　　$\sigma\,(p\,p \to t\,\underline{t}\,A1) = 26$ fb

$\sigma\,(p\,p \to b\,\underline{b}\,Z1) = 5.7$ pb　　$\sigma\,(p\,p \to b\,\underline{b}\,A1) = 0.2$ pb

- Large cross sections: good chance to be observed in W,Z!
- t, b channels swamped by the gluon.
- Other channels: pair production, associated production with gauge bosons, jets… (work in progress)

Gluon

- Large couplings to top-bottom, large production σ (strong interactions).
- Broad resonance: $\Gamma = 110$ GeV
- tt – 66%; bb – 30%; jj – 4%

$\sigma(pp \to G1) = 145$ pb $\sigma(pp \to G1\,G1) = 46$ pb

$\sigma(pp \to t\,t\,G1) = 75$ pb $\sigma(pp \to b\,b\,G1) = 3$ nb

➢ Discovery at > 5σ in tt channel (i.e. Barger, Han, Walker, hep-ph/0612016)

➢ Associated production: see Han, Valencia, Wang, hep-ph/0405055 ($pp \to tt\,G1 \to tt\,bb$ and $pp \to bb\,G1 \to bb\,tt$)

➢ Pollution for the Z1 and A1 decay channels in tt and bb!

➢ However, the gluon is not directly related to the EWSB…

- t t channel: Barger, Han, Walker, hep-ph/0612016

Semileptonic decay ($t\,t \rightarrow l\,\upsilon\,b + j\,j\,b$), small background;

at 10 fb^{-1}, for m_V = 800 – 1000 GeV, 5σ discovery if

$$\sigma \geq 1/5\ \sigma(\text{SM-Z'})$$

Not enough for our Z1, but yes for G1!

Interesting to study tb final state (no G1 pollution!)

- Associated production: Han, Valencia, Wang, hep-ph/0405055

For a Z' with SM couplings with t and b:

5σ discovery for m_V < 1200 GeV in $tt\,V \rightarrow tt\,bb$;

Discovery guaranteed for the G1, possible for Z1 and A1.

Interesting to look at a resonance in tb channel (W1)!

Light fermions KK states

- $SU(2)_L$ doublet is flat → KK state degenerate with A1:
  m_{fL} = 720 GeV.
- Flatness is required by EWPTs (S=0)
- General facts (common to leptons and light quarks):
  - Γ = 1.2 GeV
  - BR (W) ~ 2/3; BR (Z) ~ 1/3

- Leptons: single production via a W or Z → tens of ab!
  Not enough at 10 fb^{-1}.
- Pair production: few fb. Not enough at 10 fb^{-1},
  but discovery guaranteed at higher luminosity!
  (multi-lepton events!)

Good chances to be studied at ILC.

KK quarks

$\sigma\,(pp \rightarrow q\,q1) = 310\text{ fb}$ (W,Z)

$\sigma\,(pp \rightarrow q1\,q1) = 3.3\text{ pb}$ (strong)

- Signatures in Wj, Zj
- Similar studies in Little Higgs models: good chances for discovery at 10 fb^{-1}.
- See for example, Azuelos et al, hep-ph/0402037
- Need of a detailed study at those lower masses!

The new custodian for the bottom.

$$\begin{array}{lll} \Psi_L & \sim (\mathbf{2},\mathbf{2})_{2/3} & \supset (t_\ell, b_\ell) \\ t_R & \sim (\mathbf{1},\mathbf{1})_{2/3} & \supset t_r \\ \Psi_R & \sim (\mathbf{1},\mathbf{3})_{2/3} & \supset b_r \end{array}$$

They will contain extra (heavy) degrees of freedom:

$$\Psi_L = \begin{pmatrix} q_L & Q_L \end{pmatrix} = \begin{pmatrix} t_L & X_L \\ b_L & T_L \end{pmatrix}, \qquad \Psi_R = \begin{pmatrix} X_R \\ T_R \\ b_R \end{pmatrix}, \qquad t_R$$

The top Yukawa (M1) does not involve the bottom!
The dangerous mixing is absent.

$$\mathcal{L}_{IR} = M_3 \left[\frac{1}{\sqrt{2}} T_R \left(t_L + T_L \right) + b_R b_L + X_R X_L \right] + \frac{M_1}{\sqrt{2}} t_R \left(t_L - T_L \right) + h.c.$$

$Q(b_L, b_R) = -1/3$; $Q(t_L, t_R, T_L, T_R) = 2/3$; $Q(X_L, X_R) = 5/3$.

B(-1/3)	4.5	-	670	943
T(2/3)	172.5	450	622	835
X(5/3)	-	435	-	812

X1) Γ = 6 GeV; W t – 100%
T1) Γ = 1.5 GeV; Z t – 76% W b – 24%

σ (pp -> X1 X1) = 11.3 pb σ (pp -> T1 T1) = 9.3 pb (strong)

- Interesting decay chain X1 -> W^+ t -> W^+ W^+ b
- Final state: 4W+2b-jet
- Studied in Dennis, Unel, Servant, Tseng, hep-ph/0701158: discovery >5σ guaranteed, looked at 1 leptonic decay of Ws.
- Interesting channel: 2 same sign W's decaying leptonically.

It allows to reconstruct a peak in the 4j+b channel!

Conclusions and outlook

- EWSB via a strong sector is a viable alternative to the (weakly coupled) Higgs mechanism.
- Extra dimensions are a new handle on the strong sector: perturbative control up to 10 TeV.
- Realistic No-Higgs models are now available.
- Rich phenomenology: $>5\sigma$ discovery at 10 fb^{-1} for W1, Z1, A1, q1, X1, T1, G1…and more!
- “Indirect” probes: Z t t, W t b (~ 10% deviation) [single top production], WWZ (~2% deviation)
- ILC necessary to study the couplings, and discover other particles (like L1).
- More detailed studies are necessary! (work in progress)