Recent Developments in Model Building

Anticipating physics at the TeV scale

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Model "Building"

⋆ **anticipates new phenomena** *(neutral currents, ...)*

⋆ **guides experimental searches** *(top-quark discovery, ...)*

⋆ **tries to explain:**

- **observed phenomena** *(dark matter, ν oscillations, ...)*
- **properties of observed particles** *(3 generations, $m_e \ll m_\mu \ll m_\tau$, proton stability, ...)*
- **fine-tuning** *($\langle H\rangle / M_{\rm Planck} \approx 10^{-17}$, $m_t \approx \langle H\rangle$, strong CP problem, ...)*

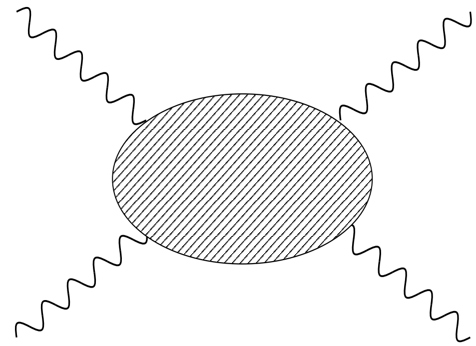
We know that:

- $SU(2)_C \times U(1)_Y \to U(1)_Q$
- The $W^{\pm}$ and Z have not only transverse polarizations, but also longitudinal ones: three spin-0 states have been eaten.

“What is the origin of electroweak symmetry breaking?”

... *a rather vague question* ...

$W_L^+ W_L^-$ scattering:



Perturbatively:

$$\sigma\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) \approx \frac{G_F^2\, s}{16\pi}$$

This makes sense only up to $\sqrt{s} \sim 1$ TeV.

At higher energy scales:

- ⋆ A new particle: Higgs boson

OR

- ⋆ New strong interactions (perturbative expansion breaks down)

OR

- ⋆ Quantum field theory description breaks down

In the context of the Standard Model,

"What is the origin of electroweak symmetry breaking?"

means:

- **Why is there a Higgs doublet?**
- **Why does the Higgs doublet have $M_H^2 < 0$?**
- **Does the Higgs boson have $M_h \lesssim 500$ GeV?**
- **(Is there a Higgs boson?)**

Why is there a Higgs doublet?

1. The A_4, A_5 components of higher-dim. gauge fields

5D $SU(3)_C \times SU(3)_W$ - *Burdman, Nomura, hep-ph/0210257*
AdS/CFT: composite pseudo-Goldstone boson -
Contino, Nomura, Pomarol, hep-ph/0306259

6D G_2 gauge theory - *Csaki, Grojean, Murayama, hep-ph/0210133*
...

4D version: "little Higgs" models *(see the talk by G. Kribs)*

Why is there a Higgs doublet?

2. A Bound state of Kaluza-Klein modes

gluons in the bulk: binding interaction - *hep-ph/9812349*
t_R **in the bulk: composite Higgs doublet, similar with "Top-seesaw"**
Cheng, Dobrescu, Hill, hep-ph/9912343

3rd generation in the bulk: "explains" Higgs quantum numbers, m_t
Arkani-Hamed, Cheng, Dobrescu, Hall, hep-ph/0006238

also in warped space - *Rius, Sanz, hep-ph/0103086*

strongly coupled SM gauge interactions in the UV
Is there a UV fixed point? - *Hashimoto, Tanabashi, Yamawaki, 2001-3*

Why is there a Higgs doublet?

3. Strongly coupled supersymmetric gauge interactions

Luty, Terning, Grant, hep-ph/0006224

Murayama, hep-ph/0307293

Supersymmetric “Fat Higgs” model

Harnik, Kribs, Larson, Murayama, hep-ph/0311349

$\rightarrow$ **below the scale of strong dynamics:**

version of NMSSM with $M_h = 200 - 450$ **GeV.**

Why does the Higgs doublet have $M_H^2 < 0$?

- Interactions with top-quark KK modes
  (similar with MSSM)

- Strong binding due to SM gauge interactions
in two extra dimensions

Bonus: infrared fixed point with $m_t \approx \langle H \rangle$

Is there a Higgs boson?

EWSB by boundary conditions

Csaki, Grojean, Pilo, Terning: hep-ph/0308038

One warped ED, bulk $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge group broken by boundary conditions.

AdS dual of a (walking) technicolor-like theory,
(the presence of the IR brane breaks electroweak symmetry)

$\rightarrow$ lightest W, Z and photon resonances around 1.2 TeV
$\rightarrow$ no fundamental (or composite) Higgs boson

What to look for

- **Vector-like fermions (KK modes)**

- **New gauge bosons**

(*e.g.*, unitarity restored by Z', W', ...)

- **extended Higgs sectors**

(*e.g.*, radion-Higgs mixing, two composite H, ...)

$\Rightarrow$ **many possibilities!** *Will the experiments be able to differentiate between models?*

Vector-like quarks

$q_L\,,\,q_R$: same gauge charges

Predicted in many models:

- "Top-quark seesaw" model (Dobrescu, Hill, 1997)

  $\rightarrow$ Higgs doublet is composite

- "Little Higgs" models (Arkani-Hamed et al, 2002)

  $\rightarrow$ no quadratic divergences at 1-loop

- "Beautiful mirrors" (Choudhury, Tait, Wagner, 2001)

  $\rightarrow$ explains $A^b_{\rm FB}$;

  $\rightarrow$ signal in Run II: $b' \rightarrow bZ$ for $m_{b'} < 300$ GeV

Bosons in compact spatial dimensions

4D flat spacetime $\perp$ one dimension of size πR:

$$\text{Boundary conditions}: \ \frac{\partial}{\partial y}\phi(x,0) = \frac{\partial}{\partial y}\phi(x,\pi R) = 0$$

$$\text{KK decomposition}: \ \phi(x,y) = \frac{1}{\sqrt{\pi R}}\left[\phi^0(x) + \sqrt{2}\sum_{j\geq 1}\phi^j(x)\cos\left(\frac{jy}{R}\right)\right]$$

Zero-mode: ϕ^0 - wave function is flat along the extra dimension.

Kaluza-Klein modes, $\phi^j(x)$:

particles with momentum in extra dimensions,

or 4D point of view: a tower of massive particles:

$$m_j^2 = m_0^2 + \frac{j^2}{R^2}$$

Fermions in a compact dimension

Lorentz group in 5D ⇒ vector-like fermions:

$$\chi = \chi_L + \chi_R$$

Chiral boundary conditions:

$$\begin{aligned} \chi_L(x^\mu, 0) &= \chi_L(x^\mu, \pi R) = 0 \\ \frac{\partial}{\partial y}\chi_R(x^\mu, 0) &= \frac{\partial}{\partial y}\chi_R(x^\mu, \pi R) = 0 \end{aligned}$$

Kaluza-Klein decomposition:

$$\chi = \frac{1}{\sqrt{\pi R}}\left\{\chi_R^0(x^\mu) + \sqrt{2}\sum_{j\geq 1}\left[\chi_R^j(x^\mu)\cos\left(\frac{\pi j y}{L}\right) + \chi_L^j(x^\mu)\sin\left(\frac{\pi j y}{L}\right)\right]\right\}$$

Universal Extra Dimensions

T. Appelquist, H.-C. Cheng, B. Dobrescu, Phys.Rev.D64 (2001)

All Standard Model particles propagate in $D \geq 5$

Momentum conservation $\Rightarrow$ KK parity is conserved

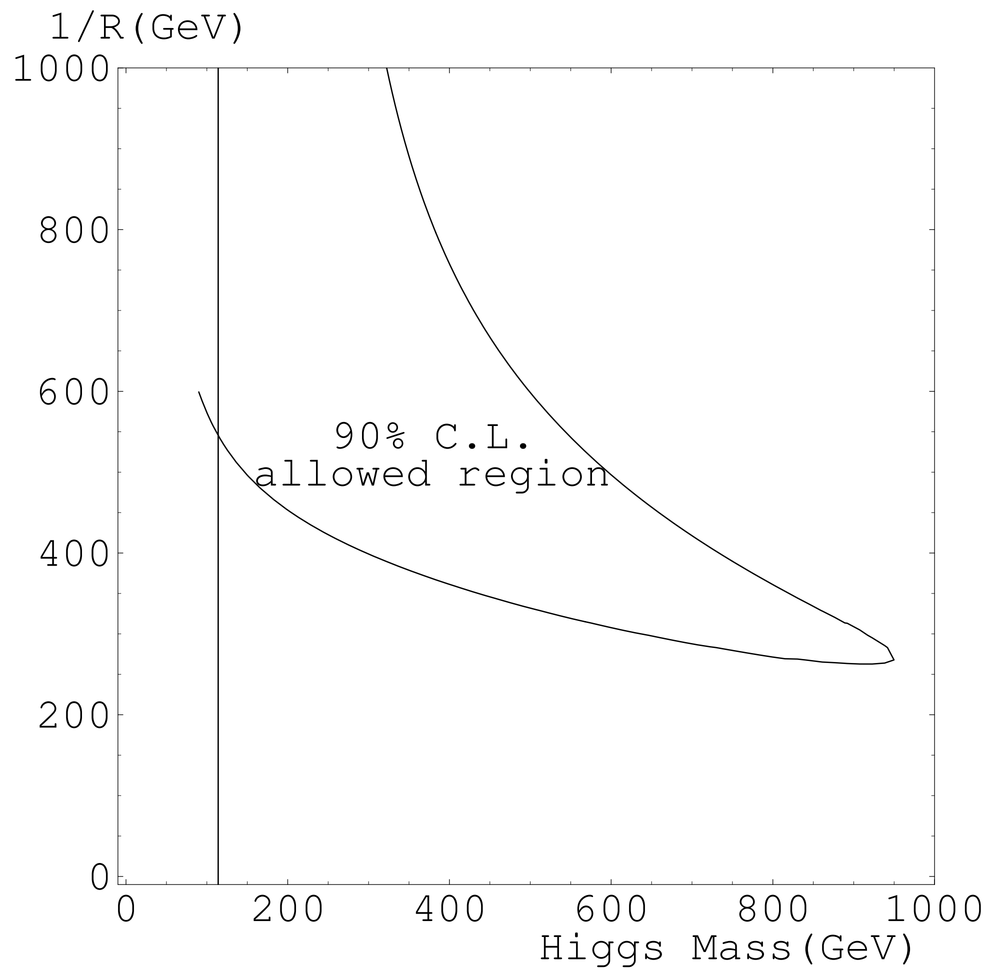
- **Bounds from one-loop shifts in M_W/M_Z and other observables:** $$\frac{1}{R} \gtrsim 300 \text{ GeV}$$
- **Pair production of Kaluza-Klein modes at colliders: could be discovered soon!**

(Cheng, Matchev, Schmaltz, hep-ph/0205314)

Does the Higgs boson have $M_h \lesssim 500$ GeV?

Contributions to the T parameter from top KK modes may compensate for the effect of a heavy Higgs boson on the electroweak fits.

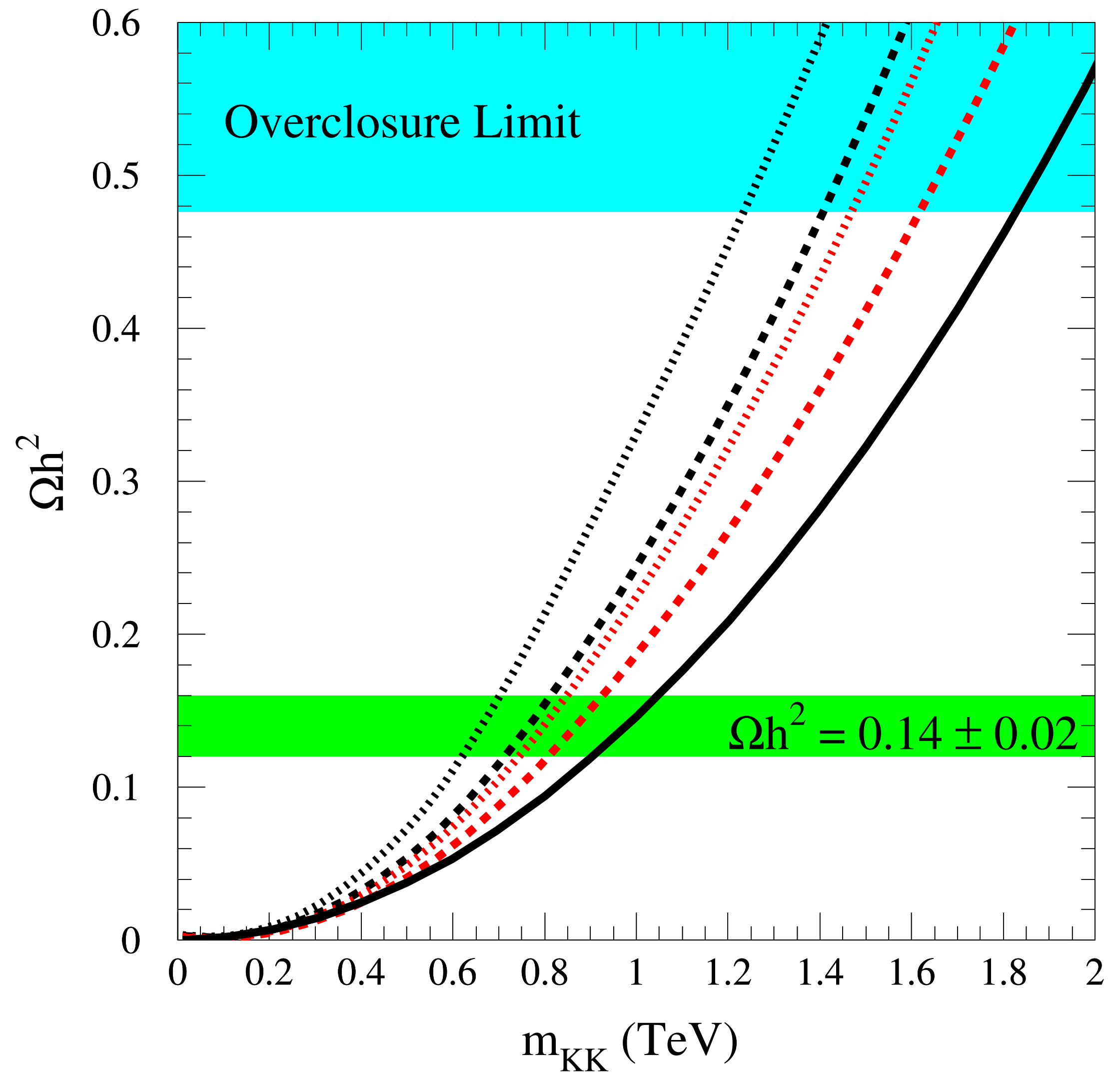
Appelquist, Yee,
hep-ph/0211023



Lightest KK particle is stable in UED:

$\gamma^{(1)}$ is a viable dark matter candidate

(from Servant, Tait, hep-ph/0206071)



Many other models in extra dimensions:

e.g., "Opaque branes" - localized operators

(Carena, Tait, Wagner, Ponton, 2002)

Six-Dimensional Standard Model

work with
T. Appelquist, G. Burdman, E. Ponton, E. Poppitz, H.-U. Yee

6D is special...

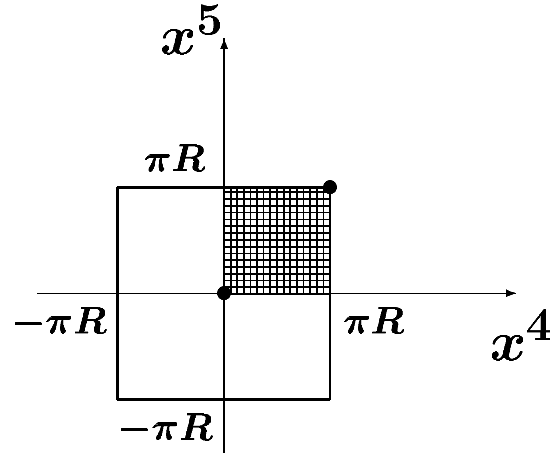
- **Global $SU(2)_W$ anomaly cancellation requires $3 \bmod 3$ generations!**

- **Gravitational anomaly cancellation in 6D requires one right-handed neutrino per generation.**

- **6D Lorentz symmetry allows ν masses only of the Dirac type.**

Compactification of two extra dimensions

Square torus of radius R:



6D Lorentz symmetry broken by compactification:

$$SO(5,1) \rightarrow SO(3,1) \times Z_8$$

Dominant baryon-number violating processes:

$p \rightarrow e^-\pi^+\pi^+\nu\nu$ and $n \rightarrow e^-\pi^+\nu\nu$

$$\tau_p \approx \frac{10^{35}\text{yr}}{C_{17}^2} \left[\frac{(4\pi)^{-7}10^{-4}}{\Phi_5 F(\pi\pi)}\right] \left[\frac{1/R}{0.5\ \text{TeV}}\right]^{12} \left[\frac{RM_s}{5}\right]^{22}$$

Long-live the proton!

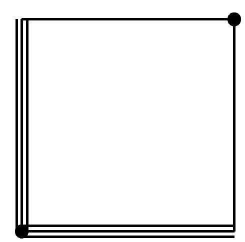
Chiral boundary conditions on a square

(Dobrescu, Ponton, hep-ph/0401032; work with G. Burdman and E. Ponton)

$\Phi(y, 0) = e^{i\theta}\Phi(0, y)$, ...

$\Rightarrow \ \theta = n\pi/2$

Symmetry: $Z_8 \times Z_2$



Signals at colliders: **4 leptons (pair production of KK modes),**
l^+l^- **(**s**-channel production of a (1,1) mode)**

Conclusions

- Electroweak symmetry breaking is the gateway towards beyond the Standard Model.

  But other observed phenomena (proton stability, the evidence for dark matter, ...) already provide information regarding the physics at the TeV scale.

- Extra dimensions allow tantalizingly new scenarios.

- Competing with the Standard Model is tough, but instructive!