Electroweak Symmetry Breaking and Dark Matter from Extra Dimensions

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IFAE, Aprile 2007

Based on hep-ph/0510373, hep-ph/0605292 and hep-ph/0612286
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Why Extra Dimensions (ED) ?

"Predicted" by String Theory

Depending on their scale, ED provide a promising arena for physics beyond the Standard Model. Focus on compact TeV–sized ED, in particular on the idea that the Higgs is the internal component of a higher-dimensional gauge field, Gauge–Higgs Unification (GHU) [Fairlie; Manton; ...]

We consider the GHU idea on flat extra dimensions (see Contino's talk for a model in warped space).

Interesting proposal because can

stabilize the electroweak scale

provide a natural explanation of the hierarchy of fermion masses

provide a natural DM candidate

Minimal and phenomenologically more interesting set-up: $D = 5$. In this case the Higgs VEV is a **Wilson line phase**

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Key points

Electroweak SB = Wilson Line SB

Higgs potential $V(H)$ is radiatively generated and non-local in the extra dimension $\Rightarrow$ $V(H)$ is finite to all orders in perturbation theory

Yukawa couplings are effective non-local couplings, exponentially sensitive to microscopic parameters of the model.

Reduction of fine-tuning in the model can be achieved by introducing a $\mathbf{Z}_2$ symmetry that at the same time gives rise to a stable massive particle, which is a good DM candidate

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Simplest GHU model and Its Problems

[Scrucca, M.S. and Silvestrini (2003)]

$$G = SU(3)_w \times U(1)'$$

Extra $U(1)'$ needed to fix the weak–mixing angle. Orbifold boundary conditions break $G \to SU(2)_L \times U(1)_Y$ ($U(1)_X$ is anomalous and gets a mass via Green-Schwarz mechanism.)

Massless 4D gauge fields:

- Gauge fields A_μ of $SU(2) \times U(1)_Y$
- Complex scalar A_5, doublet of $SU(2)$

Identify A_5 with Higgs field H: a VEV for $H = 2\alpha/(g_4 R)$ will induce an Electroweak Symmetry Breaking (EWSB) $SU(2) \times U(1)_Y \to U(1)_Q$

$\alpha \in [0, 1/2]$ is the value of the Wilson line phase and its values sets the scale of new physics, since

$$M_W = \frac{\alpha}{R}$$

Matter Lagrangian includes massive bulk and massless chiral boundary fermions, mixed with each other. Zero modes of the system are identified with SM fermions. They are not localized anymore and have a non-trivial profile in the extra dimensions, leading to non-local interactions between matter and the Higgs field.

At low energies, effective Yukawa couplings and fermion masses are generated. For large bulk–boundary mixing

$$m_q \simeq M_W \frac{\lambda}{\sinh \lambda}$$

$\lambda = \pi R M$ properly rescaled bulk fermion masses
$\Rightarrow$ Natural explanation of fermion mass hierarchy
All fermions OK, but the top, which is problematic
The Higgs effective potential $V(\alpha)$ can also be computed
This minimal model has all features to nicely include the SM, but it fails at the quantitative level

$V(\alpha)$ is all radiatively generated, Higgs quartic coupling small, Higgs too light

Top mass too low, $m_t \lesssim M_W$

$\alpha_{min} \gtrsim 0.1$, $\Rightarrow$ scale of new physics too low

These problems are not unrelated. Increasing the bulk fermion (gauge) Yukawa couplings would lead to an increase of both M_H and m_t. The symmetry which links the Yukawa and gauge couplings to be equal is 5D Lorentz symmetry.
We will solve first two problems by **breaking 5D Lorentz symmetry** and third one by imposing an extra $\mathbf{Z}_2$ symmetry in the model.

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Break the Lorentz symmetry in the bulk: $SO(4,1) \to SO(3,1)$

- Fermions: $\overline{\Psi}\left[i\,\not{D}_4 - kD_5\gamma^5\right]\Psi$
- Gauge fields: $-\frac{1}{2}\mathrm{Tr}\,F_{\mu\nu}F^{\mu\nu} - \rho^2\mathrm{Tr}\,F_{\mu5}F^{\mu5}$

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The $\mathbf{Z}_2$ "Mirror Symmetry"

Address the compactification scale problem

- Double part of the bulk fields: $\phi \to \phi_1,\ \phi_2$

  and impose twisted boundary conditions

  $$\phi_1(y \pm 2\pi R) = \phi_2(y), \quad \phi_1(-y) = \pm\phi_2(y)$$

- Require interchange symmetry: $\phi_1 \leftrightarrow \phi_2$

Twisted fields give periodic and antiperiodic fields $\phi_\pm = \phi_1 \pm \phi_2$ with charges ± 1 under $\mathbf{Z}_2$

- An order of magnitude hierarchy between the EW scale and $1/R$ is completely natural

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The Model

Gauge group $SU(3)_w \times G_1 \times G_2$. with $G_i = U(1)_i \times SU(3)_{i,s}$ ($SU(3)_s$ doubling is actually not needed, but changes the DM analysis)

SM gauge bosons and Higgs field are $\mathbf{Z}_2$ even. The $\mathbf{Z}_2$ odd fields are antiperiodic KK gluons and B–like gauge fields of G_-.
"Mirror" symmetry doubling

- $(\Psi_1, \widetilde{\Psi}_1)$ charged under G_1
- $(\Psi_2, \widetilde{\Psi}_2)$ charged under G_2

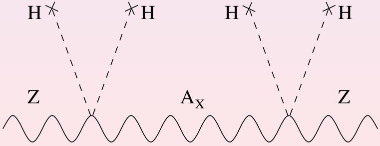
in $\overline{\mathbf{3}}$ and $\mathbf{6}$ representations of $SU(3)_w$, (fund. rep. of $SU(3)_{1,2,s}$) and $U(1)_{1,2}$ charge $+1/3$
Boundary fermions ($\mathbf{Z}_2$ even) at $y = 0$:
$Q_L = (t_L, \;\; b_L)^t$, t_R and b_R

All SM fields are $\mathbf{Z}_2$ even $\rightarrow$ lightest $\mathbf{Z}_2$ particle absolutely stable (DM candidate)

Flavor-conserving new physics effects are given by universal parameters only. Non–universal effects are sub–leading

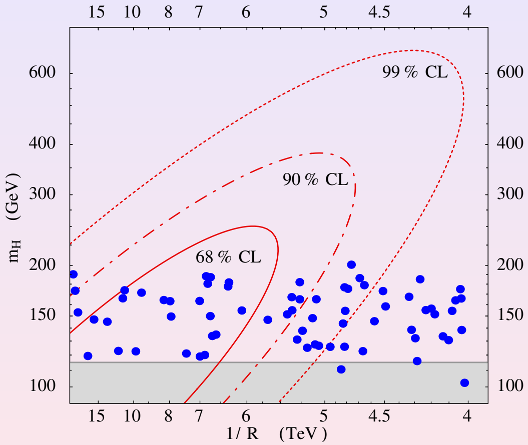
Relevant universal parameters in our model (compared to generic flat ED model [Barbieri et al.])

$$\begin{cases} \hat{S} = \frac{2}{3}\pi^2\alpha^2 \left(= \frac{2}{3}\pi^2\alpha^2 \right) \\ \hat{T} = \pi^2\alpha^2 \left(\gg \frac{1}{3}\tan^2(\theta_W)\pi^2\alpha^2 \right) \end{cases} \qquad \begin{cases} W = \frac{1}{3}\pi^2\alpha^2 \left(= \frac{1}{3}\pi^2\alpha^2 \right) \\ Y \simeq \frac{1}{3}\pi^2\alpha^2 \left(= \frac{1}{3}\pi^2\alpha^2 \right) \end{cases}$$



$\Rightarrow$ The large value of $\hat{T}$ is explained by the distortion of the ρ parameter

EWPT fit



- **Bounds**
  - Compactification scale $1/R \gtrsim 4 - 5$ TeV
  - Allowed Higgs masses up to 600 GeV
- **Predictions (blue dots)**
  - The bounds can be satisfied with some tuning $O(few\,\%)$
  - The Higgs mass is in the range $100 - 200$ GeV

Dark Matter and Relic Density

Two basic scenarii, depending on whether we have or not antiperiodic gluons on S^1 (i.e. we "double or not" $SU(3)_s$).

Key points in both cases

DM candidate is identified as the $n = 1/2$ KK mode of the $U(1)_-$ bulk gauge field A_-

Its annihilation rate too small for correct relic density (too massive: $M_A \gtrsim 2.3$ TeV), **BUT** coannihilations (resonance) effects present, because typically several $\mathbf{Z}_2$ odd states are close in mass. They are **colored** particles and greatly enhance annihilation rate, giving realistic relic densities

Fine-tuning needed for coannihilations and resonance effects is $O(5\%)$ in both cases.

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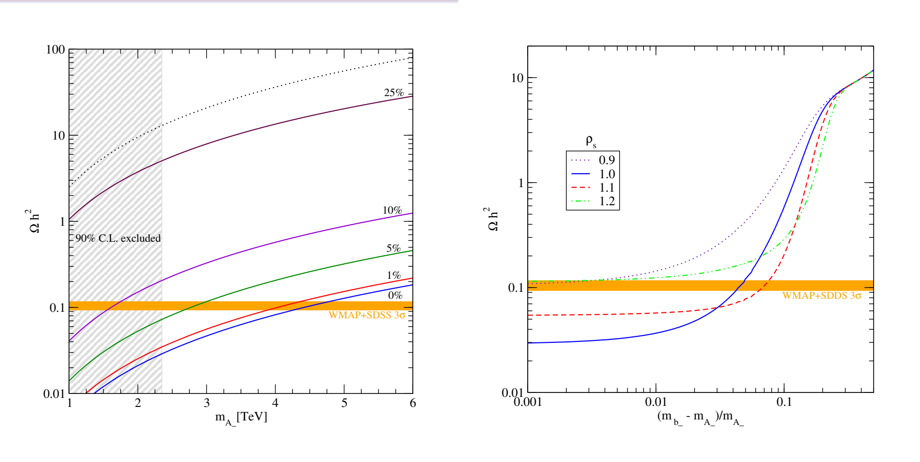
Roughly speaking,

$$\Omega h^2 \propto \frac{1}{\langle \sigma_{\rm eff} v \rangle}$$

For A_- alone, $\langle \sigma_{\rm eff} v \rangle$ very small, Ωh^2 very large. Important to increase $\langle \sigma_{\rm eff} v \rangle$

Gluons Periodic on S^1

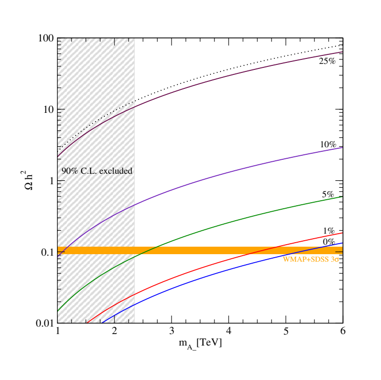
The NLKP in this case is generally the $n = 1/2$ mode of the bottom quark (**6** of $SU(3)_w$). Coannihilations with A_-, however, are not sufficient to get correct Ωh^2. If $M_g = 2M_b$ ($n = 1$ KK gluon), there is a resonance effect, giving further enhancement to annihilation rate.



(Left) Ωh^2 vs m_A for $m_A - m_B$ with g_+ on resonance in b_- pair annihilations.
(Right) Ωh^2 vs $m_A - m_B$ for ρ_s and assuming $1/R = 4.7$ TeV.

Gluons Periodic and Antiperiodic on S^1

The NLKP is generally the $n = 1/2$ KK mode of the gluon. Coannihilations with A_- are now sufficient to get correct Ωh^2.



Ωh^2 vs m_A, for $m_g - m_A$. Antiperiodic fermions decoupled assuming have a mass splitting larger than 50%.

Summary

- Typical problems of GHU models on $5D$ flat spaces can be solved by:
  - breaking the $SO(4,1)$ Lorentz symmetry in the bulk,
  - introducing a $\mathbf{Z}_2$ "mirror" symmetry.

- In this way a realistic model has been constructed which is compatible with the EW experimental measurements for $1/R \gtrsim 4-5\ \mathrm{TeV}$ and automatically provides a DM candidate

- Higgs mass is predicted in the range $100-200\ \mathrm{GeV}$. Lightest exotic particles are colored fermions with mass $\simeq 1-2\ \mathrm{TeV}$

Outlook

- Some amount of fine-tuning is required to satisfy the EW precision tests. Is it possible to do better?
- Analyze the flavour structure of the model
- Study collider signatures