Universal Extra Dimension: A Challenging Higgs Sector at LHC

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Based on:

Biplob Bhattacherjee and AK, PLB 653, 300 (2007) [arXiv:0704.3340]

UED at a glance

Minimal UED : Only one extra dimension (x^μ, y)

(Appelquist, Cheng and Dobrescu, PRD 64, 035002, 2001)

The fifth dimension, y, is compactified on a circle of radius R :

$y \equiv y + 2\pi R \quad (S^1)$

(Breaks 5d Lorentz invariance: y different from x^μ).

In 4d, tower for every SM particle : equispaced ($\sim 1/R$)

$$m_n^2 = m_0^2 + \frac{n^2}{R^2}$$

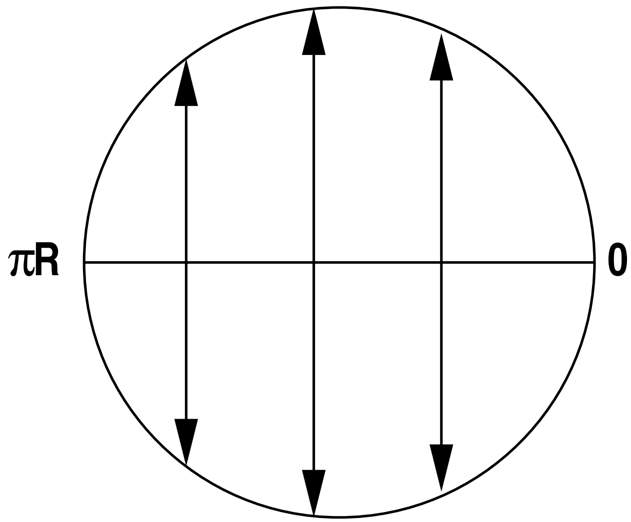
where n is the Kaluza-Klein number

UED at a glance

Orbifolding: Necessary to get chiral fermions of the SM

$y \equiv -y$ ($\mathcal{Z}_2$ symmetry)

$y = 0, \pi R$ are *fixed points* under $\mathcal{Z}_2$



(This breaks translational invariance in the fifth direction.)

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  Need counterterms, symmetrically located at two fixed points $y = 0$ and $y = \pi R \quad \sim \log \Lambda^2/\mu^2$; Λ is the cutoff
- They violate n, but due to their symmetric nature, another $\mathcal{Z}_2$ ($y \to y + \pi R$) is still present:
  $(-1)^n$, KK-parity

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  Collider signals are soft SM particles plus large $\not{E}$
- Seems to mimic SUSY, but angular analysis discriminates

UED at a glance

Limits on R^{-1}:

- ~ 250 - 300 GeV from $g_\mu - 2$, B^0-$\overline{B}^0$ mixing, $Z \to b\bar{b}$

  (Agashe, Deshpande, Wu; Chakraverty, Huitu, AK; Buras, Spranger, Weiler; Oliver, Papavassiliou, Santamaria)

- ~ 300 GeV from oblique parameters (depends on SM Higgs mass, 600 GeV for $m_h = 115$ GeV) (Gogoladze, Macesanu)

- ~ 600 GeV from $b \to s\gamma$ at NLO (Haisch, Weiler)

- Upper bound ~ 1 TeV from overclosure of the universe from LKP dark matter (Servant, Tait)

UED at a glance

- Scalar field

  Compactification: $\Phi(x^\mu, y) = \Phi(x^\mu, y + 2\pi R)$

  Orbifolding: $\Phi_\pm(x^\mu, y) = \pm\Phi_\pm(x^\mu, -y)$

  Kaluza-Klein states:

$$\Phi_+(y) = \sqrt{\frac{1}{\pi R}}\phi_+^{(0)} + \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\phi_+^{(n)}\cos\frac{ny}{R};$$

$$\Phi_-(y) = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty}\phi_-^{(n)}\sin\frac{ny}{R}$$

UED at a glance

- Fermion field

  Left- and right-chiral states have opposite $\mathcal{Z}_2$ parity

  Zero mode corresponds to chirality with even parity

  Doublet leptons: states of even/odd $\mathcal{Z}_2$ parity:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \mathcal{N}_n \\ \mathcal{E}_n \end{pmatrix}_L , \begin{pmatrix} \mathcal{N}_n \\ \mathcal{E}_n \end{pmatrix}_R$$

  Singlet leptons: states of even/odd $\mathcal{Z}_2$ parity

  e_R, $\hat{\mathcal{E}}_{nR}$, $\hat{\mathcal{E}}_{nL}$

  KK excitations of fermions form vector multiplets

UED at a glance

- Fermion field

  The SU(2) singlet and doublet fields at $n \neq 0$ are split due to radiative corrections

  Apart from top, mass and SU(2) eigenstates are the same

  For top, the mass eigenstates have a slight admixture:

$$\begin{pmatrix} \frac{n}{R} + \delta_2 & m_t \\ m_t & -\frac{n}{R} - \delta_1 \end{pmatrix}$$

UED at a glance

- Vector field

  Excited fields have 5 components, first 4 are even and the 5th is odd under $\mathcal{Z}_2$
  But a combination of that and the excited Higgs is eaten up by the excited gauge bosons, the other one remains in the spectrum

  $(W_3)_1$ and B_1 mix to give Z_1 and γ_1

  But the mixing is much smaller than that for $n = 0$ (radiative corrections), so $(W_3)_1 \approx Z_1$ and $B_1 \approx \gamma_1$

γ_1 is *always* the LKP

Radiative Corrections

(Cheng, Matchev and Schmaltz, PRD 66, 036005, 2002
Georgi, Grant and Hailu, PLB 506, 207, 2001)

- $\mathcal{L}_{\rm kin} = Z\partial_\mu\Phi\partial^\mu\Phi - Z_5\partial_5\Phi\partial^5\Phi$
  where, Z and Z_5 are wave function renormalizations.
- $\partial_5\Phi\partial^5\Phi \Rightarrow m_n = n/R$.
  If $Z = Z_5$, no corrections to KK masses.
- But, $Z \neq Z_5$ due to Lorentz violation $\Rightarrow \Delta m_n \propto (Z - Z_5)$.

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Compactification:

$$\int \frac{d^5k}{(2\pi)^5} \to \frac{1}{2\pi R} \sum_{k_5} \int \frac{d^4k}{(2\pi)^4}$$

Bulk Corrections (breaking of Lorentz invariance): When loops can sense compactification, (finite, zero for fermions) $\Delta m_n^2 \sim \beta_1/16\pi^4 R^2$. ($R \to \infty$, exact Lorentz symmetry).

β_1 some combination of Casimirs

Radiative Corrections

$Z \neq Z_5$ due to Lorentz violation $\Rightarrow \Delta m_n \propto (Z - Z_5)$.

Orbifold Corrections (breaking of translational invariance in 5th dim.): 'localized' at fixed points, (Divergent)

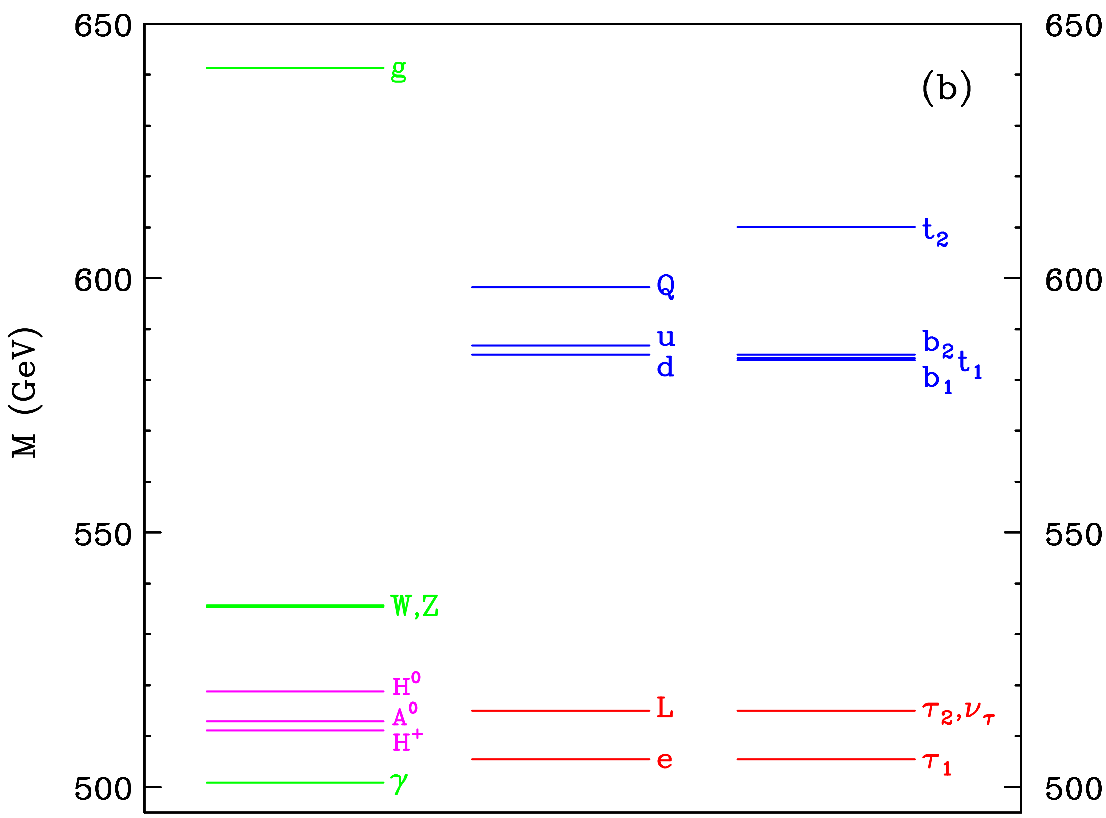
$$\Delta m_n = m_n(\beta_2/16\pi^2)\ln(\Lambda^2/\mu^2)$$

β_2 some combination of Casimirs, Λ cutoff

Splitting between $\mathcal{E}_1$ and γ_1 a few GeV

KK number conservation breaks down to KK parity, $(-1)^n$, which is conserved

UED spectrum



Spectrum for $R^{-1} = 500$ GeV, $\Lambda R = 20$. From Cheng, Matchev, Schmaltz, PRD 66, 036005, 2002

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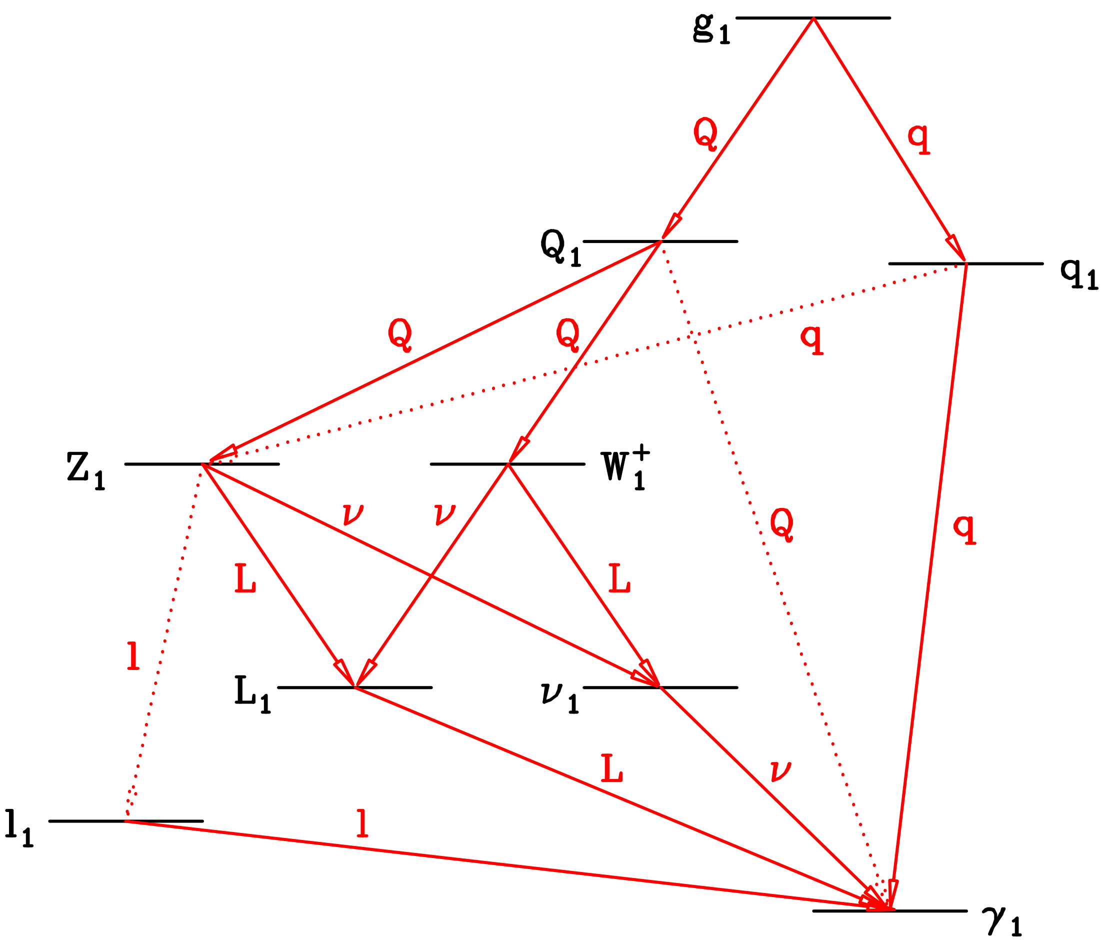

Allowed and suppressed transitions, from CMS

More on UED scalars

$$
\begin{aligned}
H_n &= \begin{pmatrix} \chi_n^+ \\ \frac{h_n - i\chi_n^0}{\sqrt{2}} \end{pmatrix} \\
G_n^0 &= \frac{1}{m_{Z_n}} \left[m_Z \chi_n^0 - \frac{n}{R} Z_n^5 \right] \\
G_n^\pm &= \frac{1}{m_{W_n}} \left[m_W \chi_n^\pm - \frac{n}{R} W_n^{5\pm} \right]
\end{aligned}
$$

Orthogonal combinations are physical scalars A_n^0, $H_n^\pm$

Excitation of SM Higgs is h_n

If $1/R \gg m_{W,Z}$, excited scalars are Goldstone excitations

More on UED scalars

At tree-level

$$m^2_{h_n, A^0_n, H^\pm_n} = \frac{n^2}{R^2} + m^2_{h,Z,W^\pm}$$

Radiative correction: adds universal δm^2_H:

$$\delta m^2_H = \frac{n^2}{R^2}\left[\frac{3}{2}g^2 + \frac{3}{4}g'^2 - \lambda\right]\frac{1}{16\pi^2}\ln\frac{\Lambda^2}{\mu^2} + \overline{m^2_h}$$

$\overline{m^2_h}$ is arbitrary and is not *a priori* calculable.

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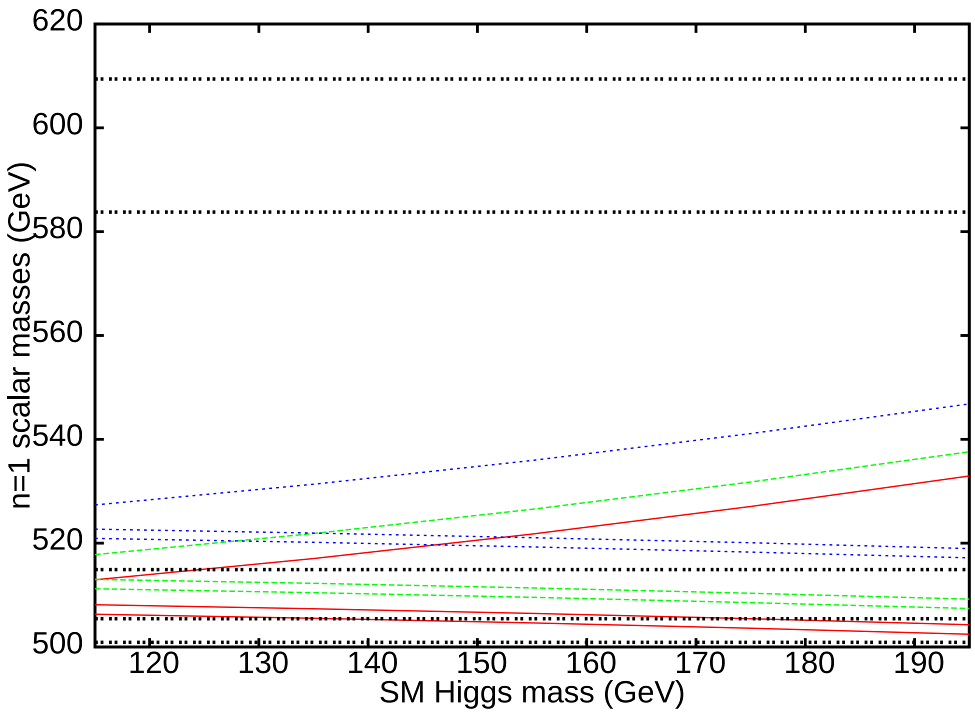

n=1 scalars in a nutshell

- 3 physical scalars: H_1^+, A_1^0, h_1

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- Two-body decays:

$$H_1^+ \longrightarrow \tau_1^+ \nu_{\tau 0}, \tau_0^+ \nu_{\tau 1}$$
$$h_1, A_1^0 \longrightarrow \tau_1^{\pm} \tau_0^{\mp}$$

(Two-body channels may be closed: $H_1^+ \rightarrow \bar{f} f' + LKP$. The SM fermions will be too soft for detection. Invisible decay)

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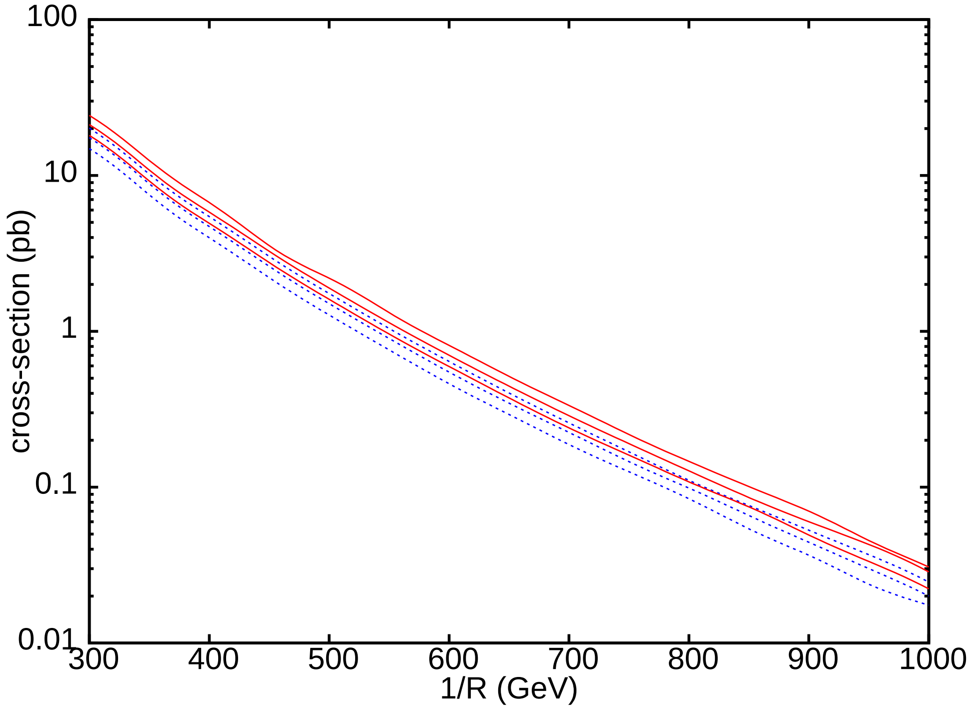
- *Challenge: Detection of soft τs!!*

Charged Higgs production

$pp \longrightarrow t^{(1)}\bar{t}^{(1)}, t^{(2)}\bar{t}^{(2)}$

$t^{(1)} \longrightarrow b_0 H_1^+$, $t^{(2)} \longrightarrow b_0 W_1^+$



$n = 1$ top production cross-section at LHC. Red solid for $t^{(1)}$, blue dotted for $t^{(2)}$. $\Lambda R = 20$. NLO, with MRST PDF. The lines for $\mu_R = \mu_F = 0.5R^{-1}, R^{-1}, 2R^{-1}$. K-factors taken same as SM

Charged Higgs production

Dominant production: $gg \to t^{(1)}\bar{t}^{(1)}$ (except for large R^{-1})

Subdominant: vector boson fusion, $gg \to H_1^+ H_1^-$ through quark box, smaller than inherent QCD uncertainty of gg fusion

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Signal: *Two hard b jets, at least one τ with $p_T < 30$ GeV, large missing energy*

Charged Higgs production

Cuts: missing energy $\Rightarrow$ 150 to 300 GeV (lower cut removes SM background, upper cut reduces background from other UED processes)

$p_T^\tau < 30$ GeV to remove hard SM/UED τs

R^{-1}	Signal	BG1a	BG1b	BG1c	BG2a	BG2b	BG2c	Total
500	42	77	170	188	92	265	136	928
600	67	68	93	161	26	351	90	789
800	60	24	23	46	12	178	19	302
1000	54	6	6	12	4	56	5	89

Signal and dominant backgrounds, with at least one τ in the fi nal state, coming from gluon-gluon fusion. There are also R-independent 417 SM events.

1a: $W_1 \to \tau_1$ pair; 1b: $W_1 \to \tau_0$ pair; 1c: $W_1^+ W_1^- \to \tau_1^\pm \tau_0^\mp$;

2a: b_1 pair production, $b_1 \to b_0 Z_1 \to \tau_1 \tau_0$, $\bar{b}_1 \to \bar{b}+$ LKP;

2b: b_1 pair to Z_1 pair, $Z_1 \to \tau_1 \tau_0$, $Z_1 \to \nu_1 \nu_0$

2c: Z_1 pair to 4 τs, 2 or 3 missed

Neutral Higgs (n=1) production

- Production through:

  Bjorken $V_0^* \longrightarrow V_1 h_1$ (s-channel suppressed)

  Vector boson fusion (suppressed as two $n = 1$ states are to be produced in tandem)

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- How about using τ-polarisation?

  Can in principle discriminate τs coming from Higgs and gauge bosons, but not known if the analysis holds for soft τs

Summarising ...

- UED, as a model,
  (i) has a viable DM candidate;
  (ii) is of minimal flavour violation type, so strong constraints on flavour sector;
  (iii) has a particle spectrum which is accessible at LHC, with a characteristic large $\not{E}$ signature, and can be discriminated from SUSY (if not at LHC, then definitely at ILC/CLIC)

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- To complete the model, we need to get the scalars too, but there are problems:
  (i) Scalars can decay only to leptons, hence we must look for τs in the final state
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- But *this is a preliminary study and one needs to do a full detector simulation* — no final words before that!

Thank you