Universal Extra Dimension

Anirban Kundu

University of Calcutta

Plan of talk

- UED: formulation
- UED: spectrum
- Indirect bounds
- Collider search: LHC, ILC
- Discrimination with SUSY
- UED and gravity
- 6D UED

What is UED?

- Flat metric, TeV^{-1} compactification radius
- Minimal: 4+1 with S^1 compactification.
  4+2 has also been studied
- All fields can go in the ED, so no need for branes
- Effectively, 4+1 SM, except
  (i) Lorentz invariance is gone
  (ii) 5-d fermions are *vectorial*

Motivations

- Excellent DM candidate with LHC-accessible spectrum
- Proton stability: in 4+2, effective 9-d operator

$$\tau_p(e^-\pi^+\pi^+\nu\nu) = 10^{35}\left(\frac{R^{-1}}{500}\right)^{12}\left(\frac{\Lambda R}{5}\right)^{22}\ yr$$

(Appelquist et al., PRL 87, 181802, 2001)

- Three generations: in 4+2, SU(2)$_L$ global anomaly exists unless $2_L - 2_R$ is a multiple of 6

(Dobrescu & Poppitz, PRL 87, 031801, 2001)

UED at a glance

Minimal UED : We consider a five-dimensional model (x^μ, y) (Appelquist, Cheng and Dobrescu, PRD 64, 035002, 2001)

The fifth dimension, y, is compactified: $y \equiv y + 2\pi R \quad (S^1)$

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

$m_n \approx n/R$, n is KK number

$\mathcal{L}_{\rm kin} = \partial_\mu \Phi \partial^\mu \Phi - \partial_5 \Phi \partial^5 \Phi$

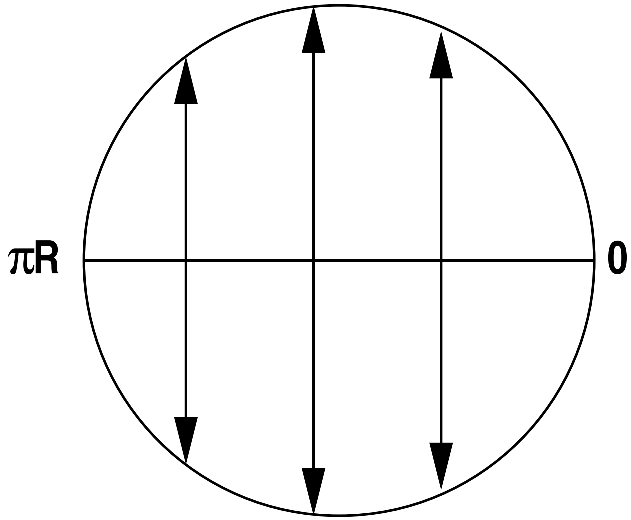
$\partial_5 \Phi \partial^5 \Phi \Rightarrow m_n = n/R$

UED at a glance

Orbifolding: Necessary to get chiral fermions of the SM

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

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



(This breaks translational invariance in the fifth direction.)

UED at a glance

- All fields can go into the 5th dimension

  Momentum along the 5-th dimension, and hence n, is *conserved* (to a good approx.)

UED at a glance

- All fields can go into the 5th dimension
  Momentum along the 5-th dimension, and hence n, is *conserved* (to a good approx.)
- Potentially log-divergent radiative contributions to KK-number violating processes (*e.g.*, $2 \to 00$)
  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

UED at a glance

- All fields can go into the 5th dimension
  Momentum along the 5-th dimension, and hence n, is *conserved* (to a good approx.)
- Potentially log-divergent radiative contributions to KK-number violating processes (*e.g.*, $2 \to 00$)
  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

UED at a glance

- $n = 1$ states must be produced in pairs

UED at a glance

- $n = 1$ states must be produced in pairs
- Lightest $n = 1$ is stable $\Rightarrow$ *LKP*

UED at a glance

- $n = 1$ states must be produced in pairs
- Lightest $n = 1$ is stable $\Rightarrow$ *LKP*
- All higher $n = 1$ states decay to LKP and corresponding $n = 0$
  Collider signals are soft SM particles plus large $\not{E}$

UED at a glance

- $n = 1$ states must be produced in pairs
- Lightest $n = 1$ is stable $\Rightarrow$ *LKP*
- All higher $n = 1$ states decay to LKP and corresponding $n = 0$
  Collider signals are soft SM particles plus large $\not{E}$
- Seems to mimic SUSY ... but discrimination possible

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:

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

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 $B_1 \approx \gamma_1$

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
  $\Rightarrow \Delta m_n \propto (Z - Z_5)$.

Radiative Corrections

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

Compactification:

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

Bulk Corrections (breaking of Lorentz invariance): When loops can sense compactification, (finite, zero for fermions)

$\Delta m_n^2 \sim \beta_1 / 16\pi^4 R^2$. ($R \rightarrow \infty$, 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)

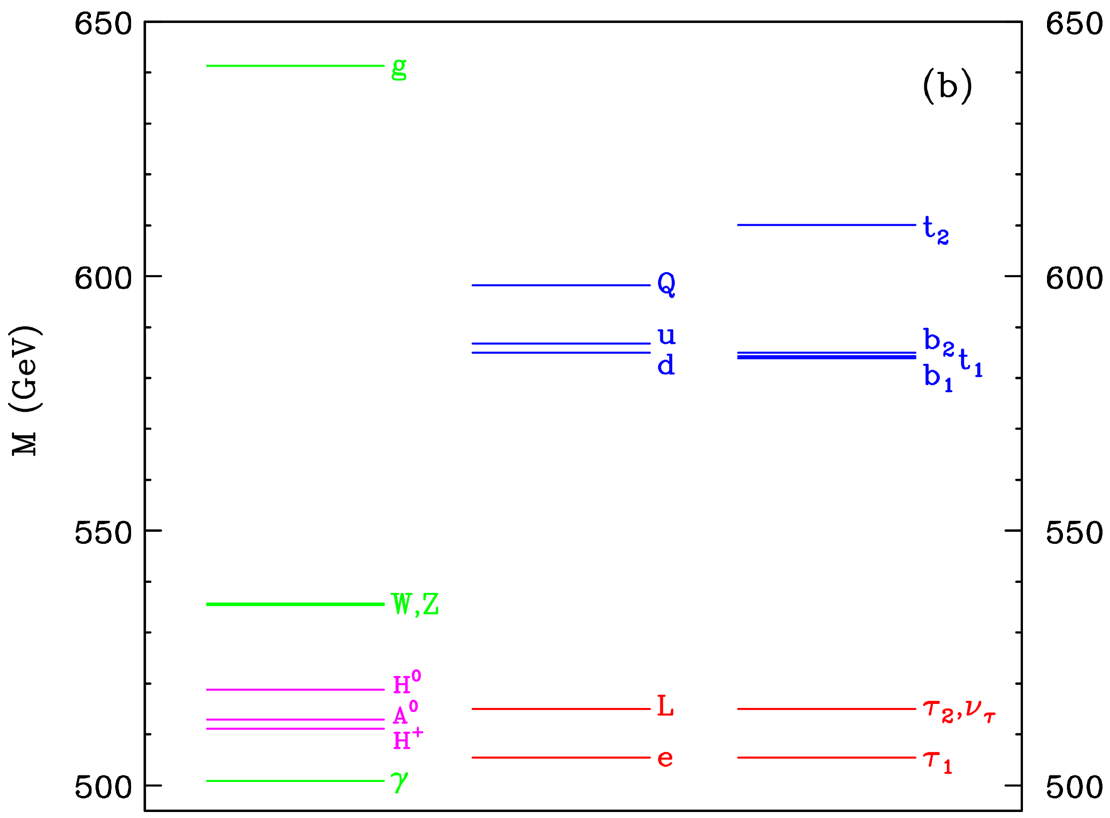
$$\Delta m_n = m_n(\beta_2/16\pi^2)\ln(\Lambda^2/\mu^2)$$

β_2 some combination of Casimirs, Λ cutoff

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

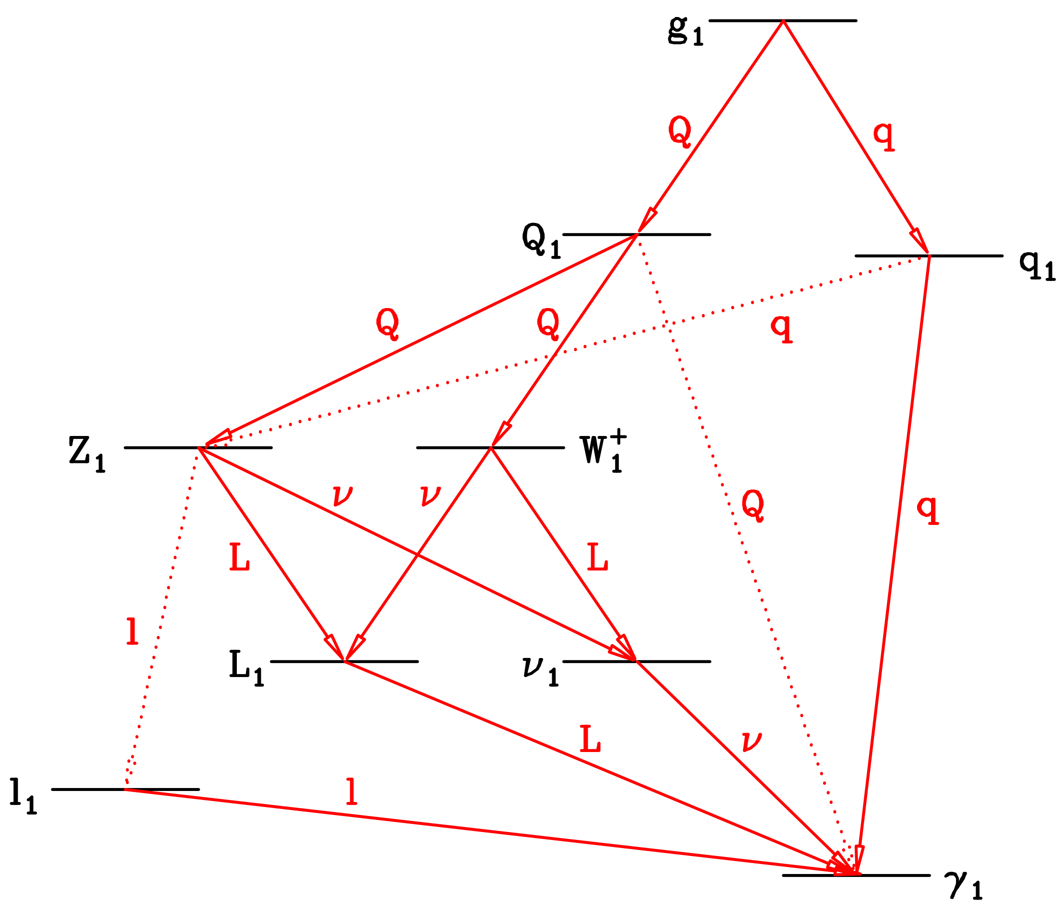
KK number conservation breaks down to KK parity, $(-1)^n$, which is conserved: $\mathcal{Z}_2$ of $y \to y + \pi R$

UED spectrum



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

UED Spectrum



- Allowed and suppressed transitions, from CMS

Indirect bounds

B^0-$\overline{B}^0$ mixing: 250-300 GeV

(Chakraverty, Huitu, AK: PLB 558, 173, 2003; Buras, Spranger, Weiler: NPB 660, 225, 2003)

$Z \to b\bar{b}$: $\sim$ 300 GeV

(Oliver, Papavassiliou, Santamaria: PRD 67, 056002, 2003)

$(g-2)_\mu$: No significant constraint

(Appelquist & Dobrescu, PLB 516, 85, 2001)

A negative result: $\ell_i \to \ell_j + \gamma$ is suppressed compared to SM by $(m_W/m_W^{(1)})^8$

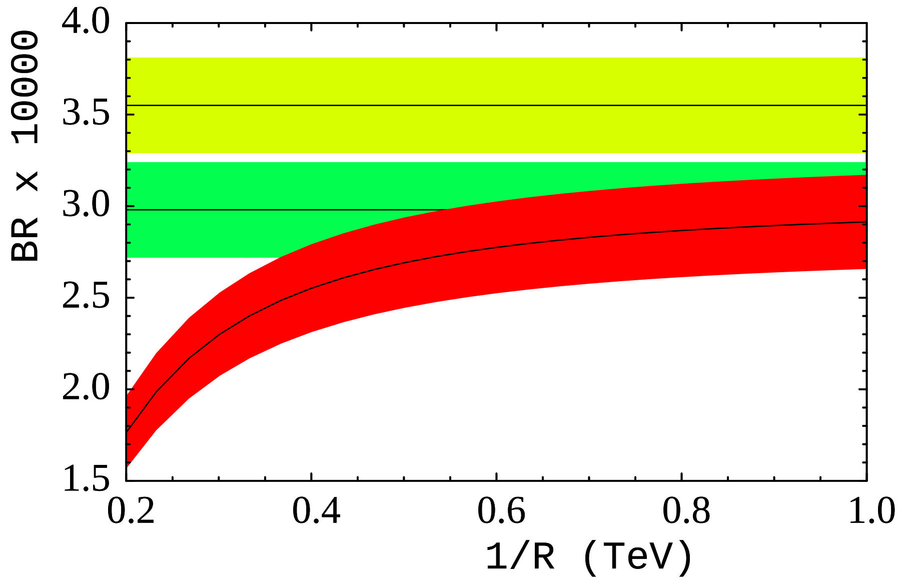
(Bigi et al., hep-ph/0603160

Indirect bounds

$b \longrightarrow s\gamma$ (Haisch & Weiler, PRD 76, 034014, 2007)

$$\mathcal{B}(B \to X_s\gamma)_{SM} = (2.98 \pm 0.26) \times 10^{-4} \quad (\text{NNLO})$$
$$\mathcal{B}(B \to X_s\gamma)_{exp} = (3.55 \pm 0.26) \times 10^{-4}$$

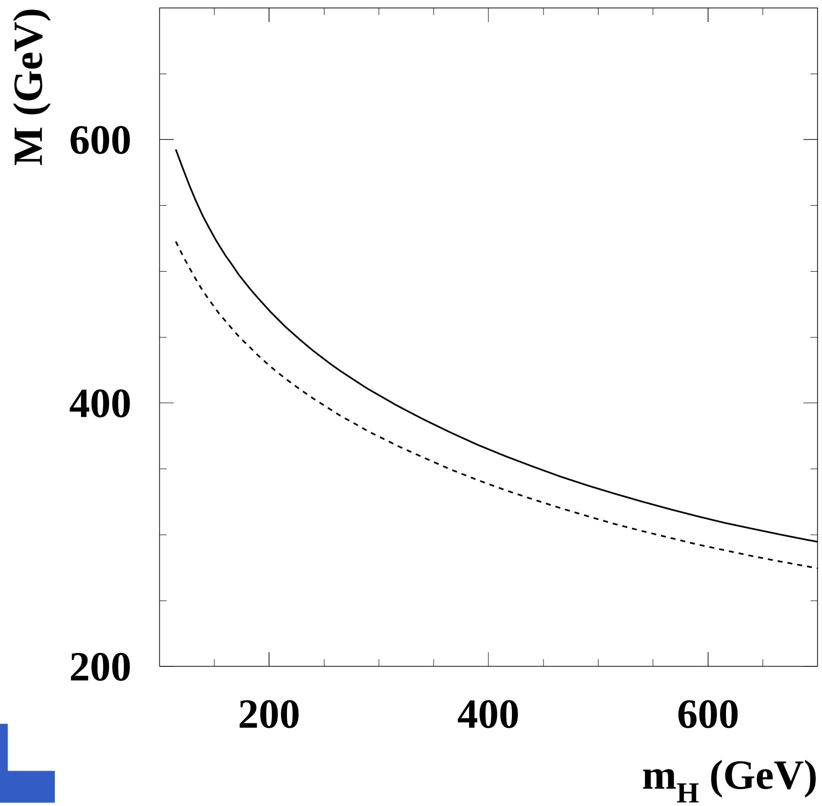
At 95% CL, the limit on 1/R is about 450 GeV

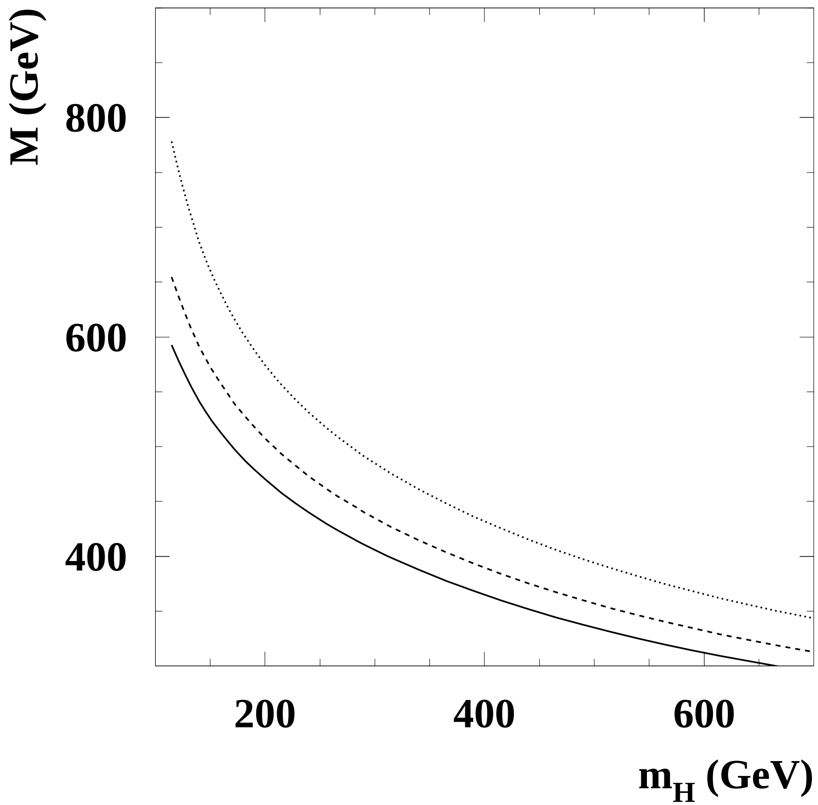


Indirect bounds

Oblique parameters (Gogoladze & Macesanu, PRD 74, 093012, 2006)

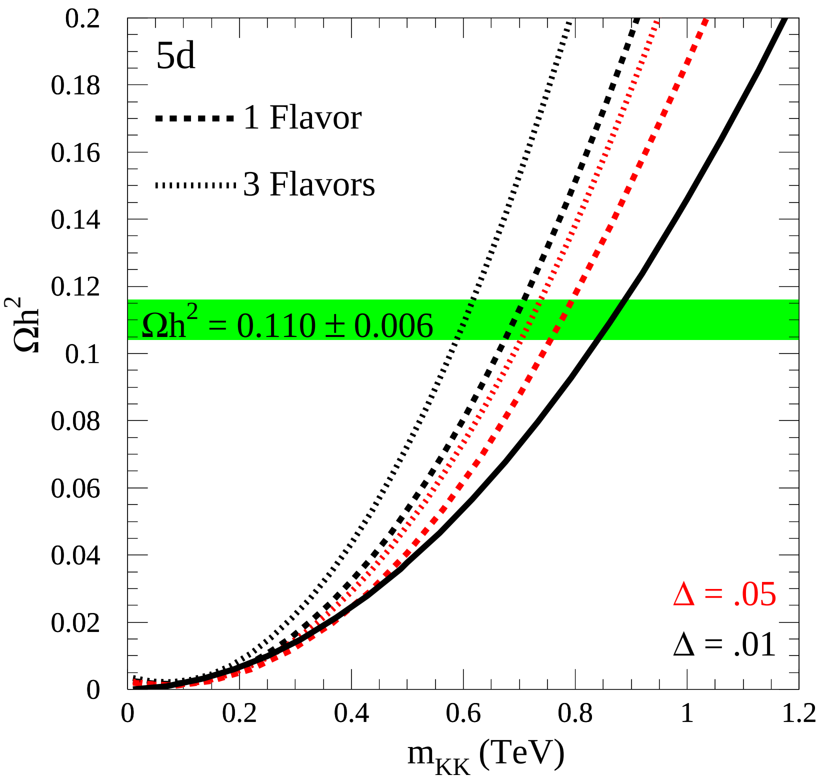
$1/R \sim 300$ GeV, but goes up for light Higgs, depends on m_t





Indirect bounds

Dark matter and overclosure (Servant & Tait, NPB 650, 391, 2003)

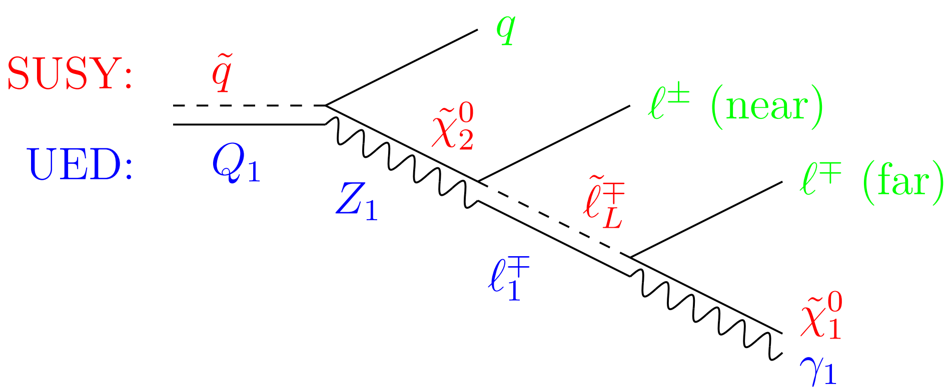


Collider signals

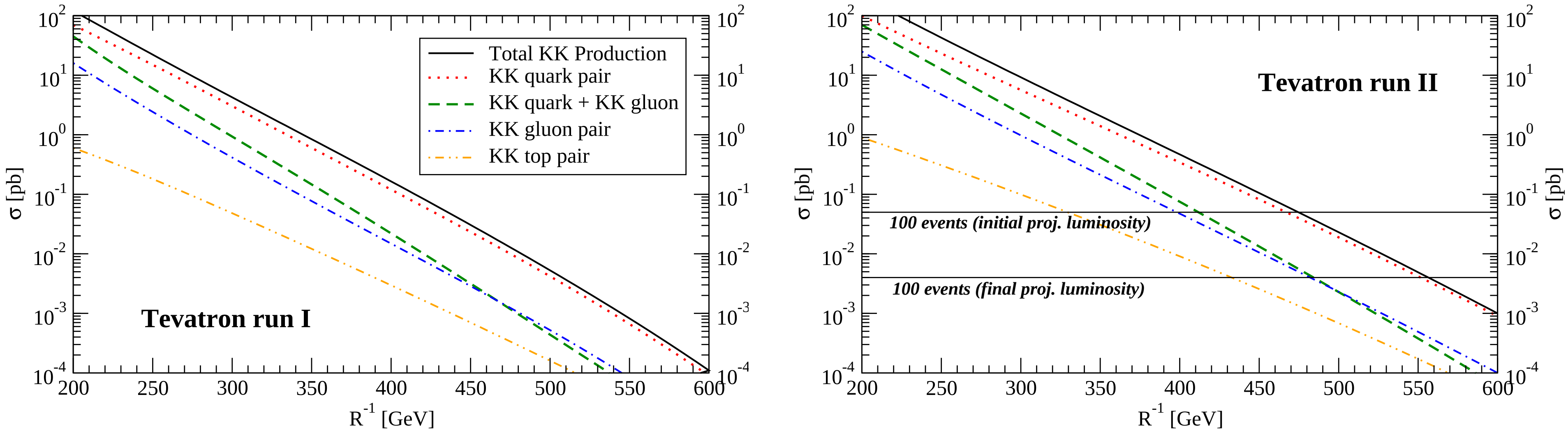
- KK number has to be conserved, apart from resonant production of $n = 2$ gauge bosons
- LKP gives a large missing $\not{E}_T$. The SM leptons and jets are expected to be soft
- The decay chain mimics SUSY

Collider signals

- KK number has to be conserved, apart from resonant production of $n = 2$ gauge bosons
- LKP gives a large missing E_T. The SM leptons and jets are expected to be soft
- The decay chain mimics SUSY



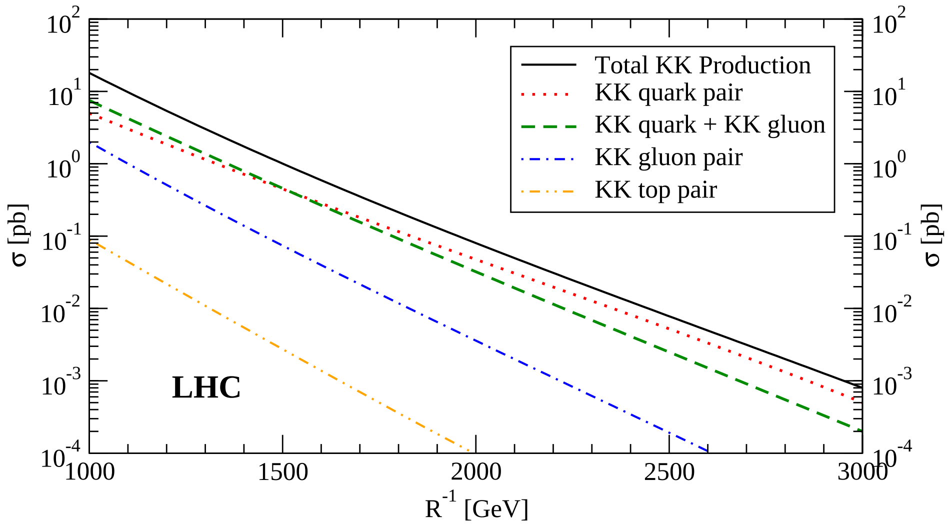
Collider signals



(Macesanu, McMullen, Nandi, PRD 66, 015009, 2002)

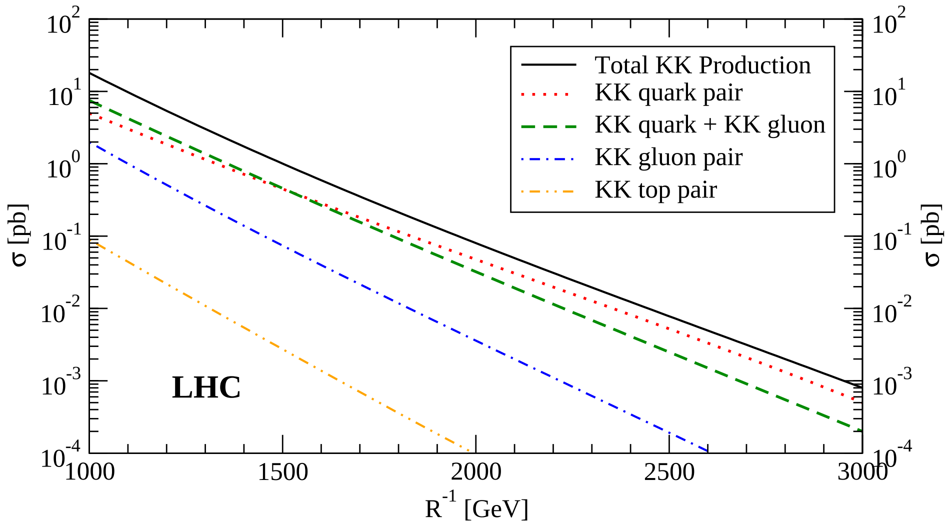
Collider signals

LHC can go all the way upto 1/R = 2.5-3 TeV for 100 fb^{-1} $\int$ lumi:



Collider signals

LHC can go all the way upto 1/R = 2.5-3 TeV for 100 fb^{-1} $\int$ lumi:



It can also produce γ_2, Z_2, or $n = 2$ quarks

(Datta, Kong, Matchev, PRD 72, 096006, 2005)

Collider signals

ILC for the study of $n = 2$ gauge resonances

(Bhattacherjee & AK, PLB 627, 137, 2005)

γ_2: 63 pb (300 GeV), 28 pb (450 GeV)

Z_2: 35-45 pb (300 GeV), 16-21 pb (450 GeV) [Λ-dep.]

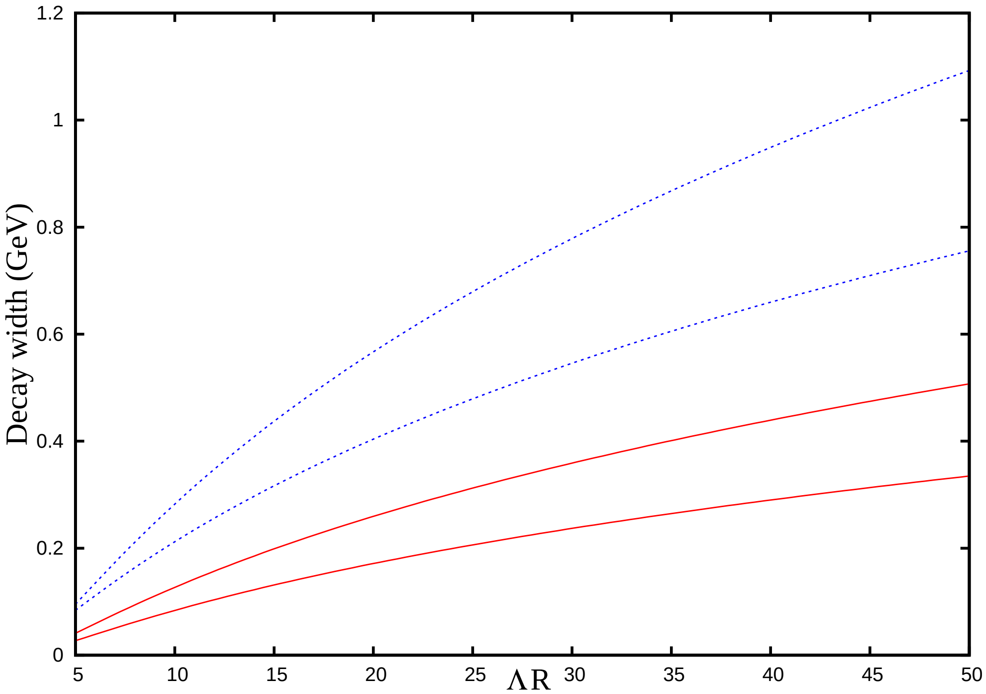
Collider signals

ILC for the study of $n = 2$ gauge resonances

(Bhattacherjee & AK, PLB 627, 137, 2005)

γ_2: 63 pb (300 GeV), 28 pb (450 GeV)

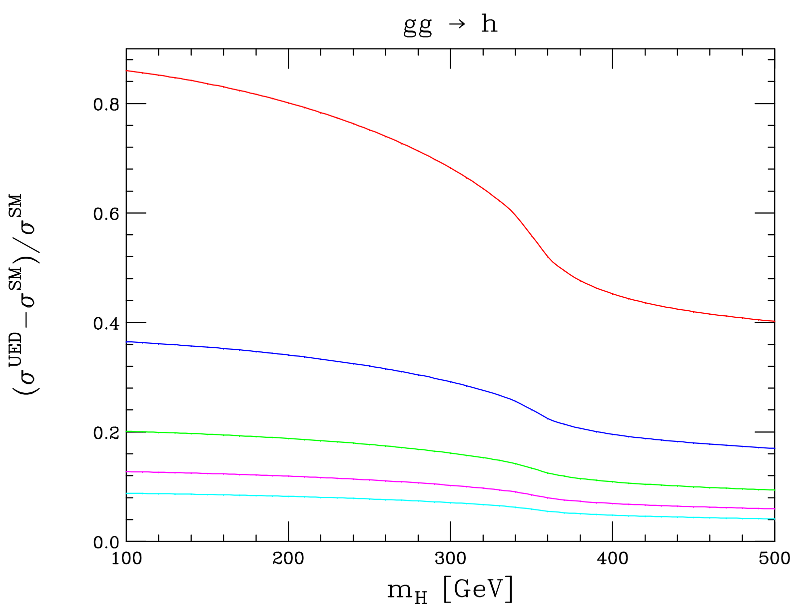
Z_2: 35-45 pb (300 GeV), 16-21 pb (450 GeV) [Λ-dep.]

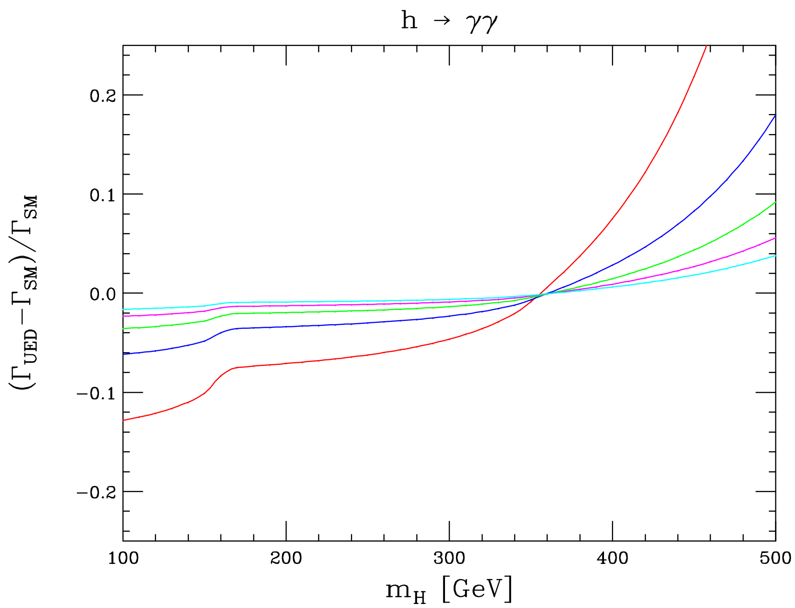


Higgs in UED

$gg \to h$ goes up and $h \to \gamma\gamma$ goes down

(Petriello, JHEP 05, 003, 2002)



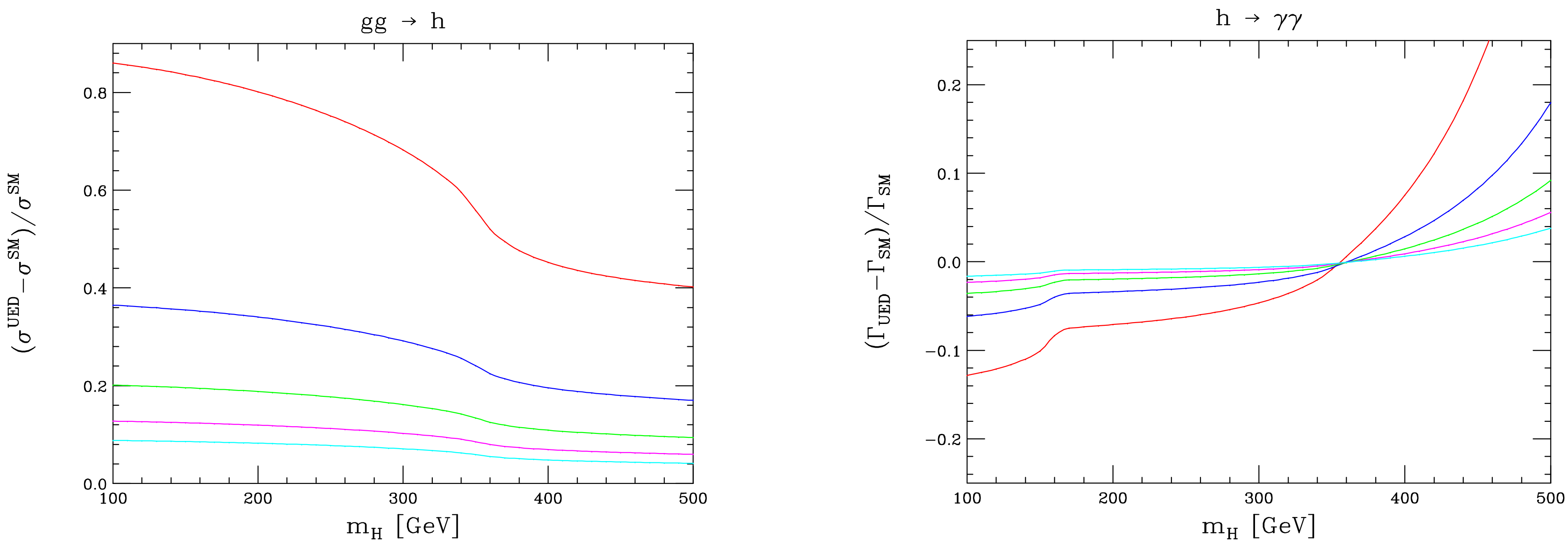


1/R = 500, 750, 1000, 1250, 1500 GeV

Higgs in UED

$gg \to h$ goes up and $h \to \gamma\gamma$ goes down

(Petriello, JHEP 05, 003, 2002)



1/R = 500, 750, 1000, 1250, 1500 GeV

n = 1 Higgs sector: Biplob to cover in detail

UED vs SUSY

γ_2 and Z_2 are the smoking guns

$e^+e^- \rightarrow e^+e^-$ + missing E_T: higher rate for UED (3-5), angular distribution different

(Bhattacharyya, Dey, AK, Raychaudhuri, PLB 628, 141, 2005)

Similar for $\mu^+\mu^-$ + missing E_T final state

(Battaglia et al., JHEP 07, 033 (2005))

UED vs SUSY

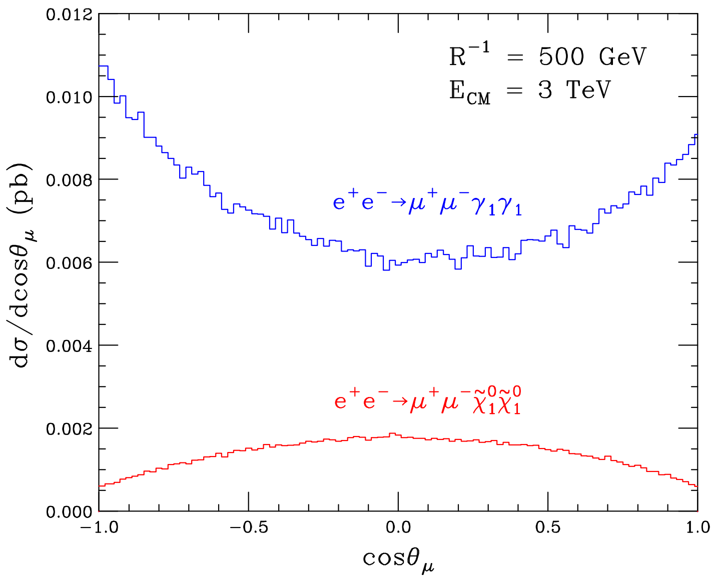
γ_2 and Z_2 are the smoking guns

$e^+e^- \rightarrow e^+e^-$ + missing E_T: higher rate for UED (3-5), angular distribution different

(Bhattacharyya, Dey, AK, Raychaudhuri, PLB 628, 141, 2005)

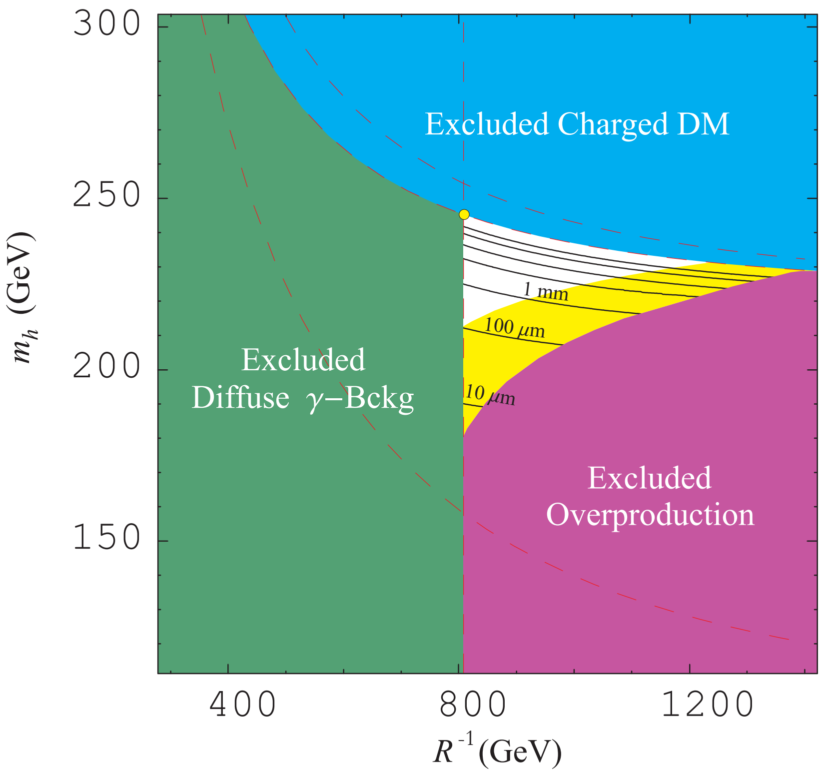
Similar for $\mu^+\mu^-$ + missing E_T final state

(Battaglia et al., JHEP 07, 033 (2005)



Gravity in UED

n = 1 graviton mass is 1/R and can be the LKP for $R^{-1} < 810$ GeV



(Cembranos, Feng, Strigari, PRD 75, 036004, 2007)

6D UED

(Burdman, Dobrescu, Ponton, PRD 74, 075008, 2006; Ghosh & Datta, arXiv:0801.0943[hep-ph])

Compactification on a square with two opposite sides identified to get chiral fermions

6D UED

(Burdman, Dobrescu, Ponton, PRD 74, 075008, 2006; Ghosh & Datta, arXiv:0801.0943[hep-ph])

Compactification on a square with two opposite sides identified to get chiral fermions

Each state marked by two KK numbers:

$$m_{j,k} = R^{-1}\sqrt{j^2 + k^2}$$

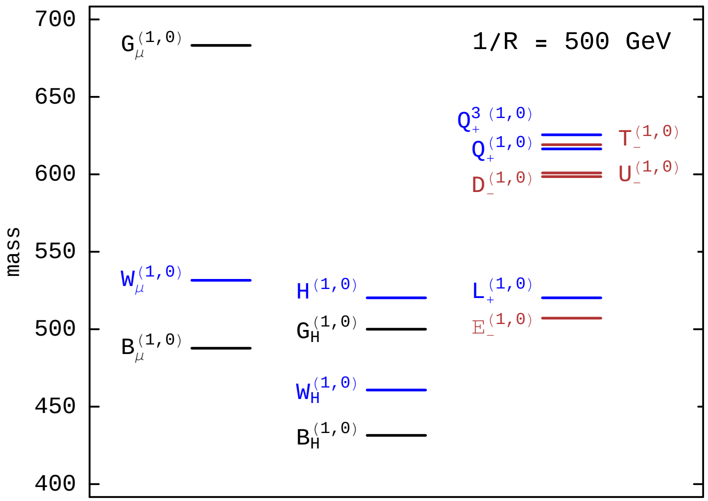
6D UED

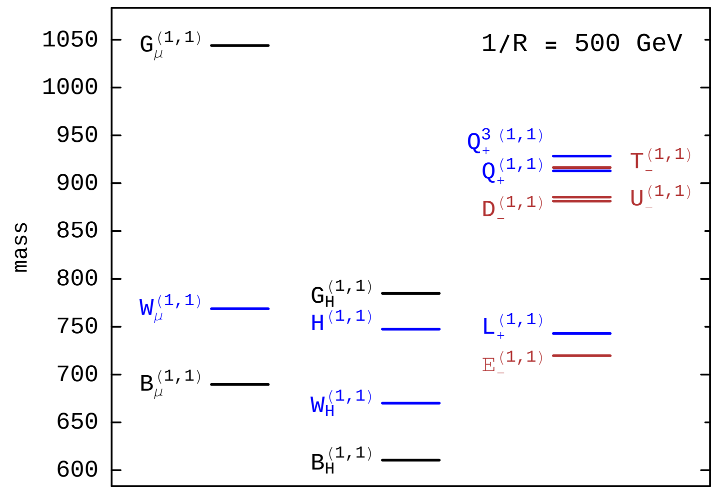
(Burdman, Dobrescu, Ponton, PRD 74, 075008, 2006; Ghosh & Datta, arXiv:0801.0943[hep-ph])

Compactification on a square with two opposite sides identified to get chiral fermions

Each state marked by two KK numbers:

$$m_{j,k} = R^{-1}\sqrt{j^2 + k^2}$$





Summary

- UED is a small-R flat metric theory where all SM fields can go in the ED
- R^{-1} is expected to lie between 300 GeV and 1 TeV, which is ideal for LHC
- Chiral fermions are obtained by a further $\mathcal{Z}_2$ orbifolding
- The symmetric fixed points on the ED provides another $\mathcal{Z}_2$. This conserves KK number; the LKP is stable and is an excellent WIMP DM candidate

Summary

- Collider signal is missing energy plus soft SM particle; LHC can probe the entire parameter space
- Discrimination with SUSY is possible even at LHC, but ILC will do better
- Once gravitons are included, G^1 is the LKP for $R^{-1} >$ 800 GeV and ruled out from diffuse photon background
- Extensions like 4+2 have interesting spin-offs like proton stability and explanation of generations

Thank you!