Signals of Universal Extra Dimensions at the ILC

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Based on: BB and A. Kundu,

hep-ph/0508170, PLB 627 (2005) 137

Plan of talk

- Universal Extra Dimensions
- Kaluza-Klein states and Spectrum
- Fermion Production at ILC
- Gauge Boson Production at ILC
- Summary

Extra Dimensions

- First motivated by Kaluza (1921) and Klein (1926) to interpret electromagnetism as a space-time property
- Later revived in the context of string theories, which need a number of compactified EDs
- Different models: Number of EDs, compactification manifold, and which particles can go into the bulk
- In Universal Extra Dimension type models, everything can go into the bulk, no need for branes

Universal Extra Dimensions

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

where $R \equiv$ Compactification Radius

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

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

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

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

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

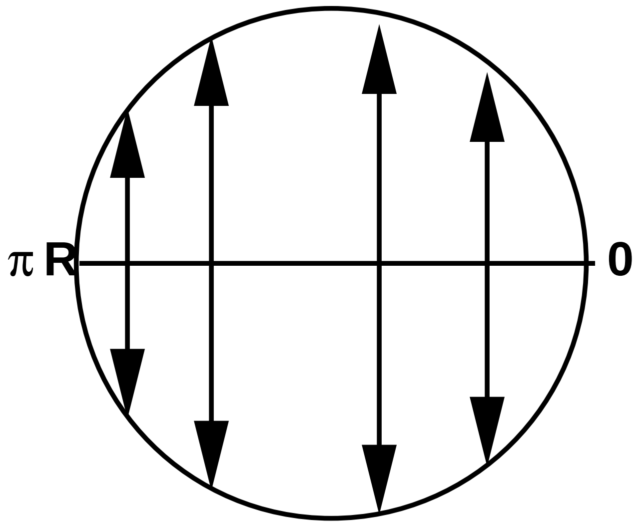
$$R^{-1} \geq 250 - 300 \text{ GeV} \qquad (g_\mu - 2, \text{ FCNC}, Z \to b\bar{b}, \rho)$$

UED (contd.)

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.)

Kaluza-Klein states

- 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:

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

Kaluza-Klein states (contd.)

- Fermion field

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

  Zero mode corresponds to chirality with even parity

  SM left-handed leptons: Left-chiral states of even parity:

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

  SM right-handed lepton: Right-chiral states of even parity

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

  KK excitations of fermions form vector multiplets

Kaluza-Klein states (contd.)

- 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 $B_1 \approx \gamma_1$

Kaluza-Klein states (contd.)

- Scalar field

  Scalar fields can appear as the excitation of Higgs bosons or as the 5th component of gauge bosons

  The latter is $\mathcal{Z}_2$-odd

  Higgs fields are always even to allow Yukawa couplings

  $n = 1$ Higgs spectrum: $H_1^{\pm}$, H_1^0, A_1^0

Momentum along the 5th dim. is conserved, so KK number is also conserved

UED Spectrum

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

- Bulk corrections: from breaking of 5D Lorentz invariance
  Finite and in general small
- Boundary corrections: Dominant effect due to loss of translational invariance, 'localized' at fixed points, (Divergent)

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

β some combination of Casimirs, Λ cutoff

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

UED Spectrum (contd.)

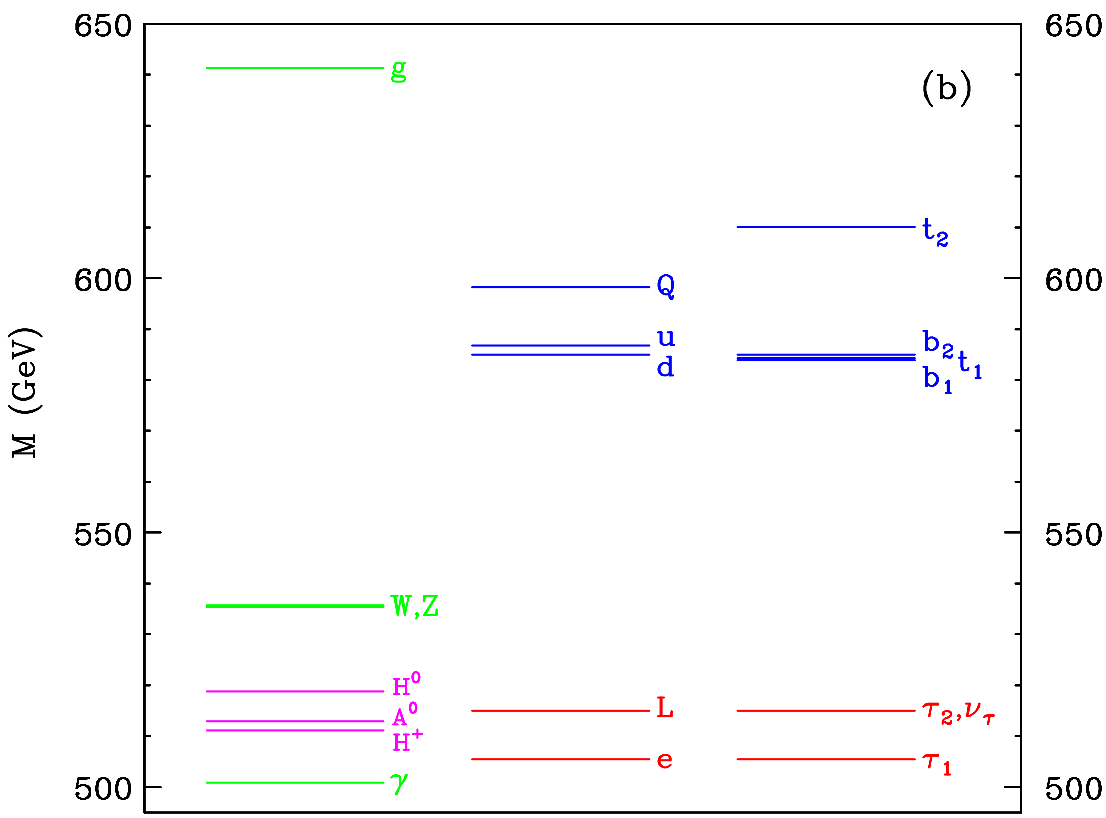


Figure 1: Spectrum for $R^{-1} = 500$ GeV, $\Lambda R = 20$. From Cheng, Matchev, Schmaltz, PRD 66, 036005, 2002

UED Spectrum (contd.)

- KK number is conserved by the bulk interactions (momentum conservation)
- Minimal UED: Symmetric fixed point terms $\Longrightarrow$ KK number violation by two units, conservation of KK-parity $(-1)^n$, analogous to R-parity
- $n = 1$ particles must be pair produced, and they must decay to γ_1 (LKP: Candidate for dark matter)
- All $n = 1$ states must be accompanied by large missing energy signal: mimic SUSY
- $n = 2$ EW gauge bosons can be produced alone as resonance in ILC

Fermion Production at ILC

Bhattacharyya et al., hep-ph/0502031, PLB 628, 141 (2005);
Battaglia et al., hep-ph/0502041, JHEP 0507, 033 (2005)

- Pair Production $e^+e^- \to \mathcal{E}_1^+\mathcal{E}_1^-, \quad \hat{\mathcal{E}}_1^+\hat{\mathcal{E}}_1^-$
- Need ILC at 1 TeV, with one year luminosity $\sim$ 300 fb^{-1}
- s channel mediated by γ/Z
- t channel by γ_1/Z_1 and γ_1^5/Z_1^5. Dominant
- Decay $\Rightarrow \mathcal{E}_1, \ \ \hat{\mathcal{E}}_1 \stackrel{100\%}{\longrightarrow} e\gamma_1$
- Signal: soft, acoplanar e^+e^- with large missing energy
- Cross section $\sim \mathcal{O}$(1pb)

Fermion Production (contd.)

- Same final state can be obtained from $e^+e^- \to W_1^+ W_1^-$
  s channel mediated by γ/Z, t channel by $\mathcal{N}_{1L}$
  Roughly, $\sigma(\mathcal{E}_1^\pm) \sim \sigma(W_1^\pm)$, but for the latter there is a BR suppression ($1/9$) into specific flavor.
- SM backgrounds can be removed by energy and acoplanarity cuts
- Angular distribution can discriminate UED and SUSY: slepton pair production

Consider different initial polarizations.

ILC benchmark: 80% for electron, 50% for positron

Cross sections

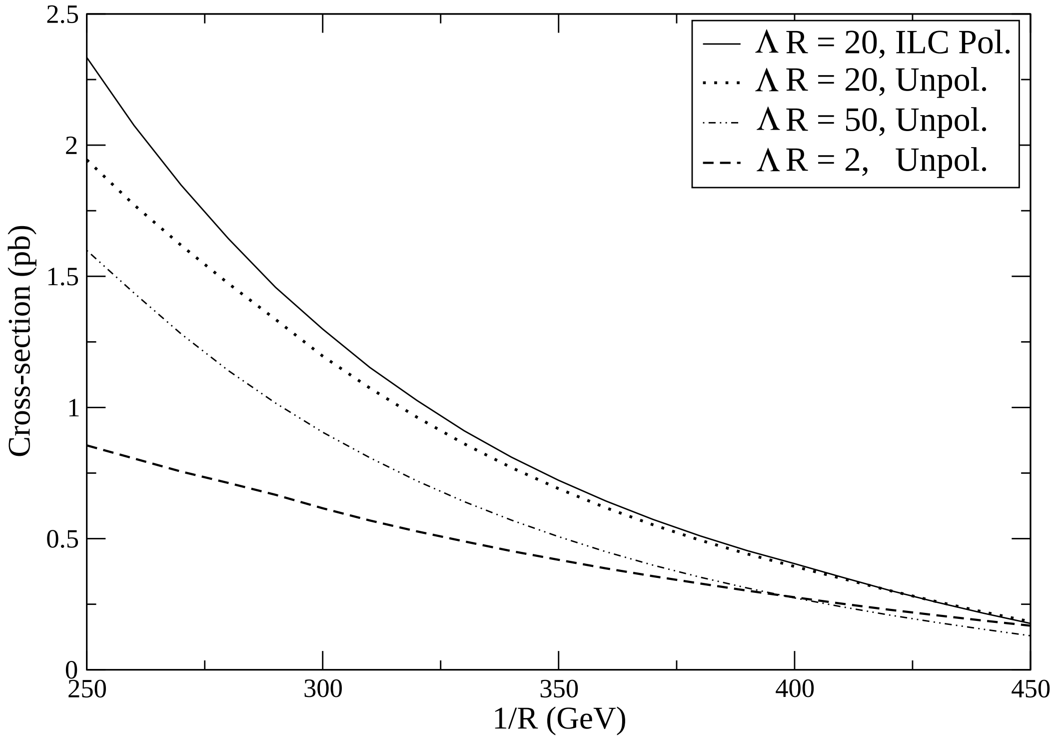


Figure 2: Cross-section for $e^+e^- \to e^+e^- + \not{E}$. From Bhattacharyya et al., PLB 628, 141 (2005)

Forward-backward asymmetries

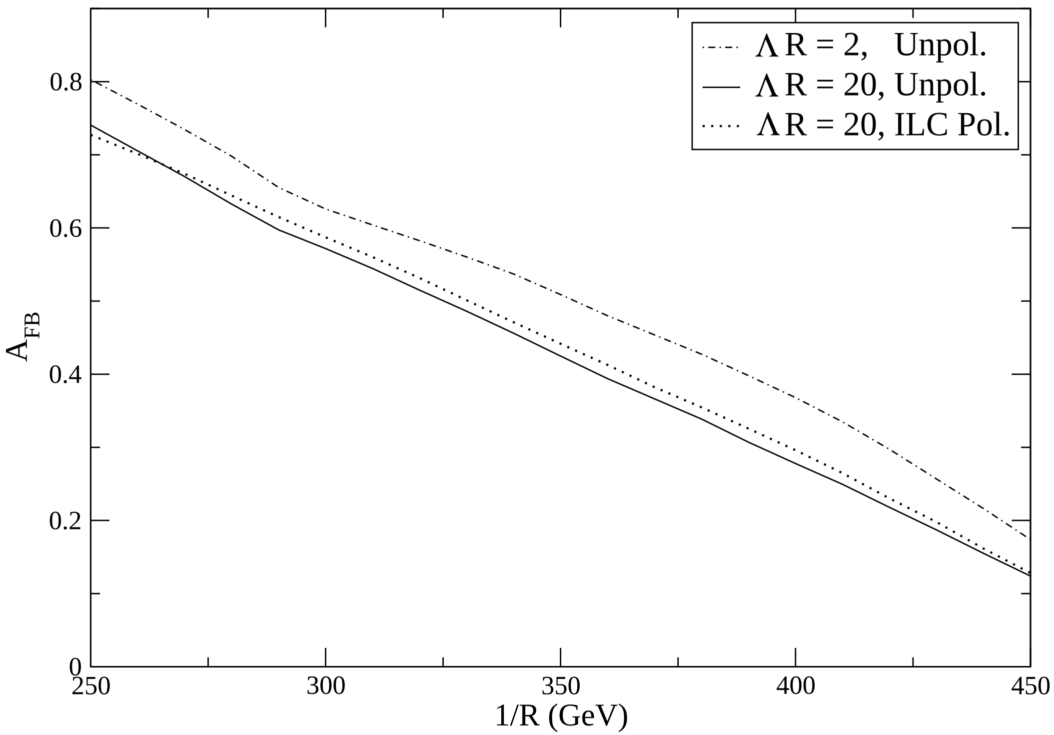


Figure 3: A_{FB} for $e^+e^- \to e^+e^- + \not{E}$. From Bhattacharyya et al., PLB 628, 141 (2005)

Standard Model background

- $e^+e^- \to (WW, ZZ, e\nu W, eeZ, \ \cdots) \to e^+e^- + \not{E}$
- $\sigma(e^+e^- \to WW, ZZ) \sim$ 2.81pb, 0.36pb
- Rapidity cuts: $15^\circ < \theta < 165^\circ$
  Energy cuts: 0.5 GeV $< E_e <$ 20 GeV.
- These backgrounds can be easily removed.
- Two-photon events constitute a serious background ($\sigma \sim 10^4$ pb).
  $e^+e^- \to e^+e^- (\rightsquigarrow \text{ Missing energy})$
  $\qquad + \ \gamma^*\gamma^* (\rightsquigarrow \text{ soft } e^+e^-)$
  This background can be reduced by studying FB asymmetry, and acoplanarity w.r.t. the beam direction.

n = 2 Gauge Boson at ILC

BB and Kundu, PLB 627, 137 (2005)

- $n = 2$ gauge bosons can be produced alone as s-channel resonances
- Need same energy to produce two $n = 1$ states or one $n = 2$ state
- The production goes through the coupling

$$(-ig\gamma^\mu T_a P_+)\,\frac{\sqrt{2}}{2}\left(\frac{\bar{\delta}(m_{V_2}^2)}{m_2^2} - 2\frac{\bar{\delta}(m_{f_2})}{m_2}\right)$$

where $m_2 = 2/R$, T_a is the group generator

Z_2/γ_2 Physics (contd.)

- Z_2 can decay to leptonic KK-conserving channels (kinematics) or KK-violating channels, but it is almost W_3, so couples only to left-chiral doublets ($\mathcal{Z}_2$-even)
- γ_2 can decay only through KK-number violating channels (two SM particles, no missing energy, impossible to see at LHC)
- ILC can precisely measure these resonances and *if it can sit on them, it can repeat LEP-1!*
- Positions of these two peaks should give Λ and R and should completely determine the fermionic UED spectrum

Z_2 and γ_2 Couplings

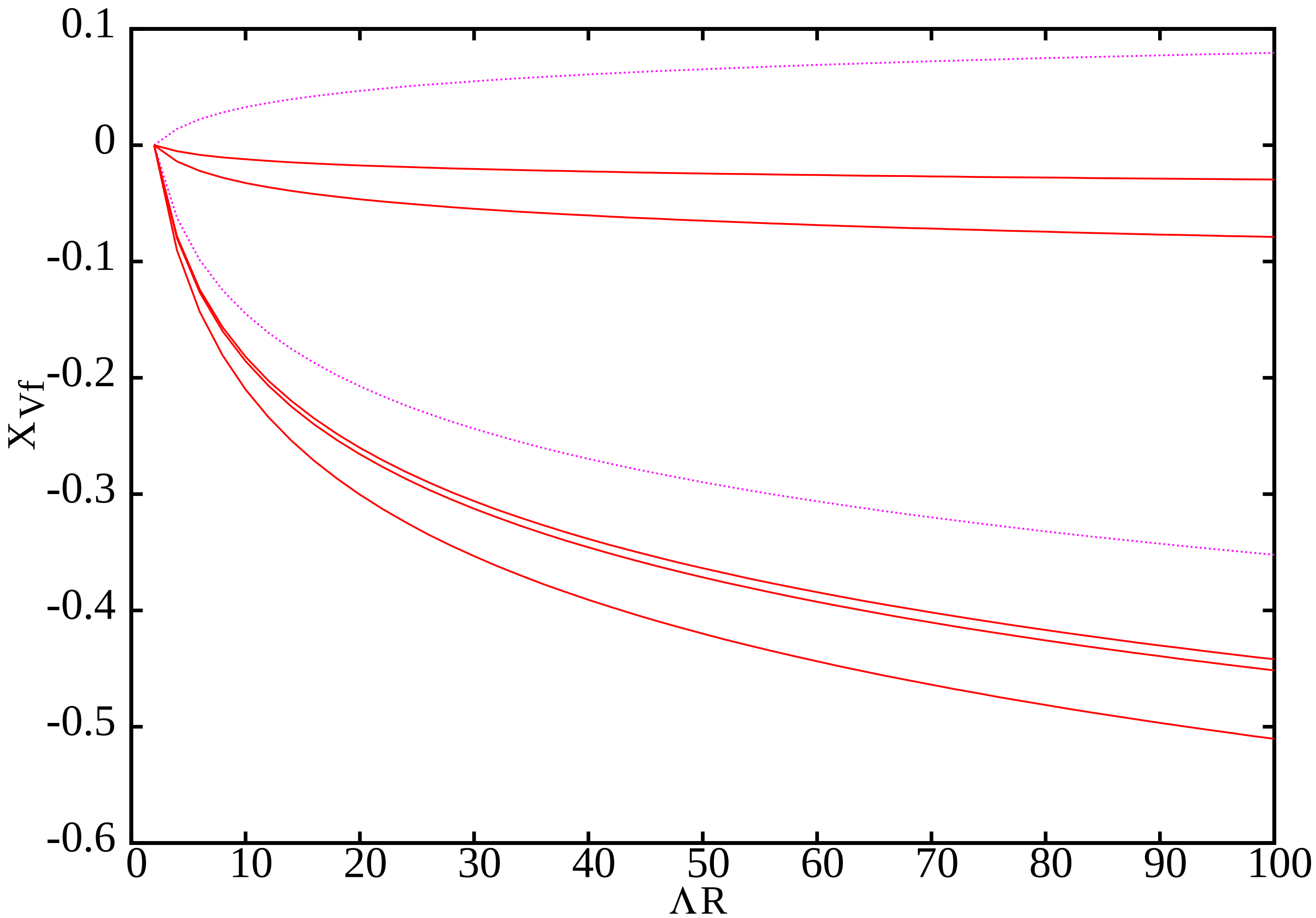


Figure 4: X_{Vf}, the KK number violating couplings, as a function of ΛR, for $R^{-1} = 300$ GeV (the values are independent of R). From top to bottom, the curves are for X_{ZL}, $X_{\gamma e}$, $X_{\gamma L}$, X_{ZQ}, $X_{\gamma d}$, $X_{\gamma u}$, and $X_{\gamma Q}$ respectively.

Z_2 and γ_2 Decay Widths

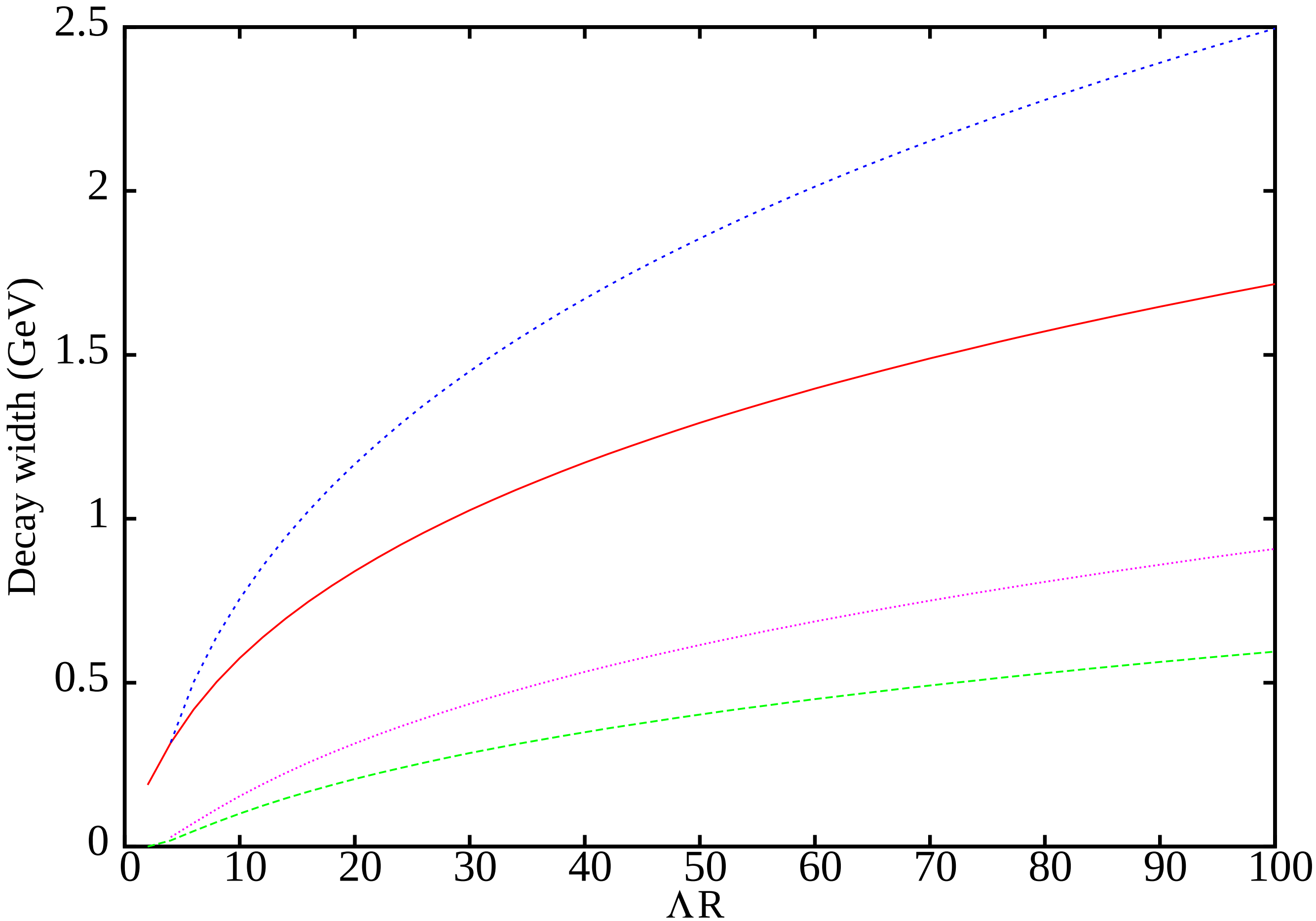


Figure 5: Decay widths of Z_2 (upper pair) and γ_2 (lower pair) as a function of ΛR, for $R^{-1} = 450$ GeV and 300 GeV (upper and lower curves in a pair).

Gauge Boson Decay (contd.)

- KK conserving and violating decays are equally important: either kinematic or phase-space suppression
- The peak x-sec is 35-45 pb (Z_2) and 63 pb (γ_2) for $1/R = 300$ GeV. Drops by half for $1/R = 450$ GeV
- The SM background is less than 10 pb and can be further reduced by cuts
- *Such $n = 2$ gauge bosons are 'smoking gun' signals of UED!*

Summary

- UED can mimic SUSY at LHC, spin correlation measurements possible but difficult
  (Smillie and Webber, JHEP 0510, 069, 2005)
- $gg \rightarrow h$ width at LHC enhances due to KK excitations in the loop (Petriello, JHEP 0205, 003 (2002), Datta and Rai, hep-ph/0509277)
- For $1/R \leq 450$ GeV, precision studies possible at ILC
- Angular distribution of leptons can discriminate between UED and SUSY
- Precision measurements at Z_2 and γ_2 can even discriminate between UED variants
- SM backgrounds are safely under control