Resonances in Universal Extra Dimensions

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Fermilab

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Outline

- Minimal Universal Extra Dimension:
  - Level 1
  - Level 2: resonances in e^+e^- and $\mu^+\mu^-$ at Tevatron/LHC
- Two Universal Extra Dimensions:
  - (1,0) mode
  - (1,1) mode: resonances in $t\bar{t}$ at Tevatron/LHC
- Summary

Universal Extra Dimensions

(Appelquist, Cheng, Dobrescu,hep-ph/0012100)

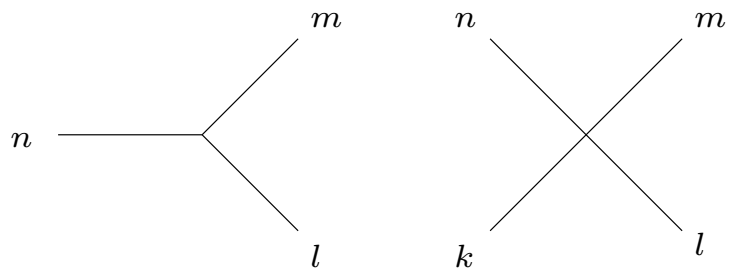
- Universal Extra Dimensions is an extra dimension theory with new bosonic coordinate y (spanning a circle of radius R):

$$\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \left(\phi^n(x^\mu) \cos\left(\frac{ny}{R}\right) + \chi^n(x^\mu) \sin\left(\frac{ny}{R}\right) \right)$$

- Each SM field ϕ (n=0) has an infinite tower of Kaluza-Klein (KK) partners ϕ^n and χ^n with identical spins, identical couplings and unknown masses of order of n/R:

$$S = \int d^4x dy \mathcal{L}_{SM} = \int d^4x \mathcal{L}_{eff}, \qquad E^2 = \vec{p}^2 + p_5^2 = \vec{p}^2 + \left(\tfrac{n}{R}\right)^2$$

- Bulk interactions: conserve KK number $\Leftarrow p_y$ conservation

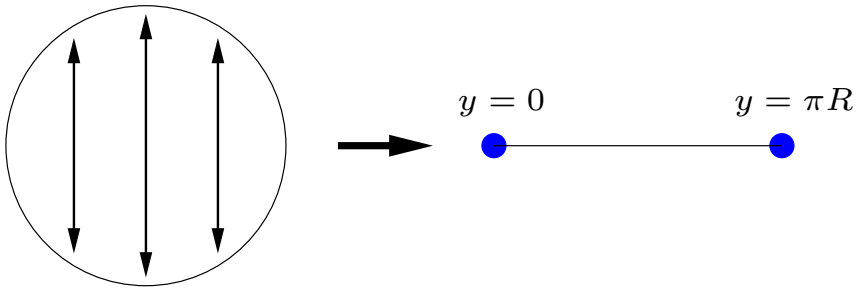


$n = m + l$ $\qquad$ $n + k = m + l$

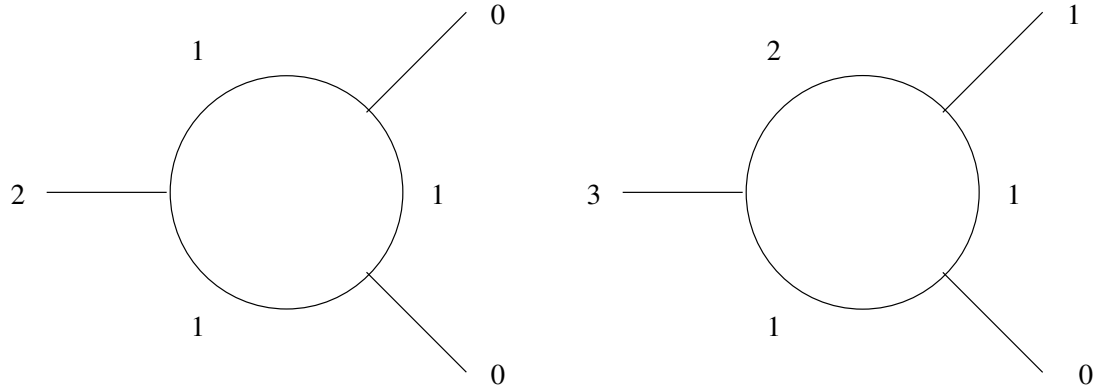
- Problem: chiral fermions?

KK number versus KK parity

- The ED is not really a circle, but orbifold S_1/Z_2:



- Loop corrections generate boundary terms which break KK number n down to KK parity $(-1)^n$



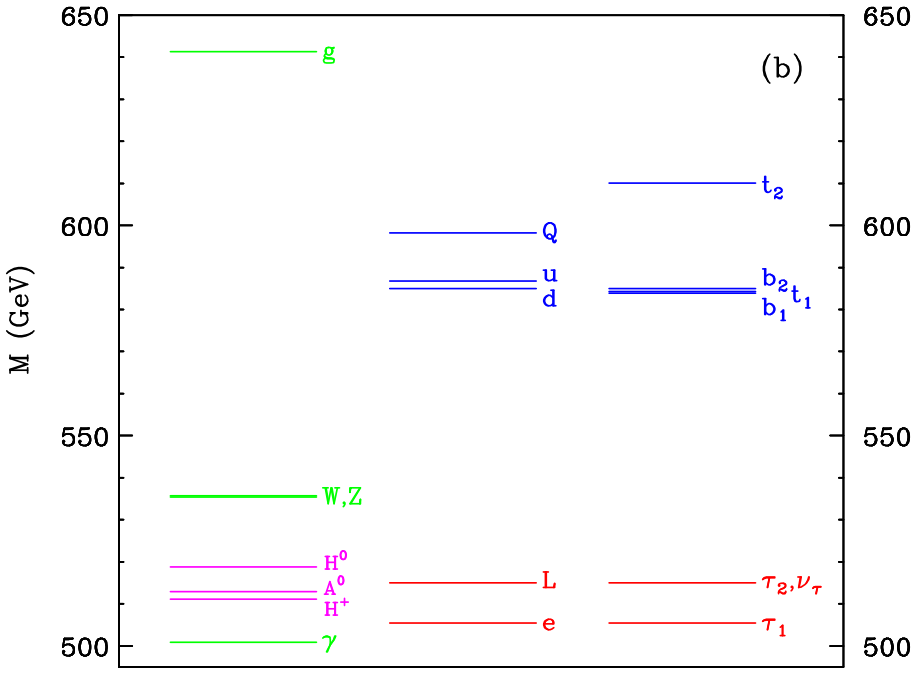
- Additional allowed decays: $2 \longrightarrow 00$, $3 \longrightarrow 10$, $\cdots$
- The lightest KK partner at level 1 (LKP) is stable $\Rightarrow$ DM ?
- No tree-level contributions to precision EW observables/need to pair-produce

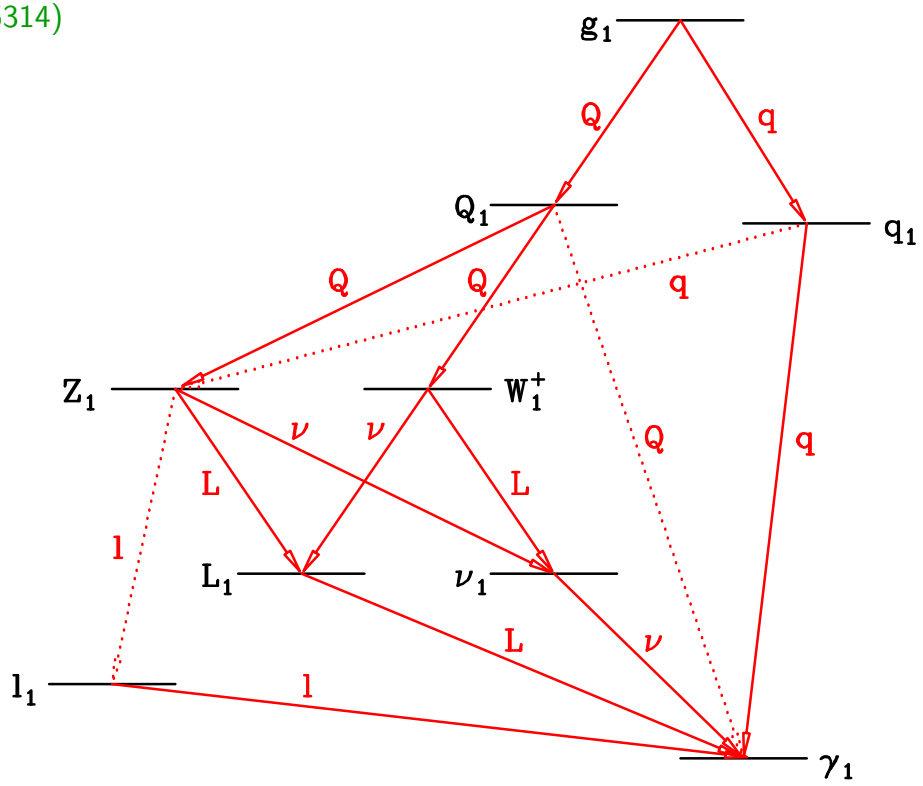
UED phenomenology

- EW precision constraints: $R^{-1} \geq 300$ GeV (Appelquist, Cheng, Dobrescu,hep-ph/0012100)
- Current Tevatron limit: $R^{-1} > 280$ GeV in $3\ell + \not{E}_T$ channel at 95% C.L. (CDF)
- Region preferred by WMAP: $R^{-1} \sim 500 - 600$ GeV

  (Kong, Matchev, hep-ph/0509119, Burnell, Kribs, hep-ph/0509118, Servant, Tait, hep-ph/0206071)
- LHC reach: $R^{-1} \sim 1.5$ TeV in $4\ell + \not{E}_T$ channel

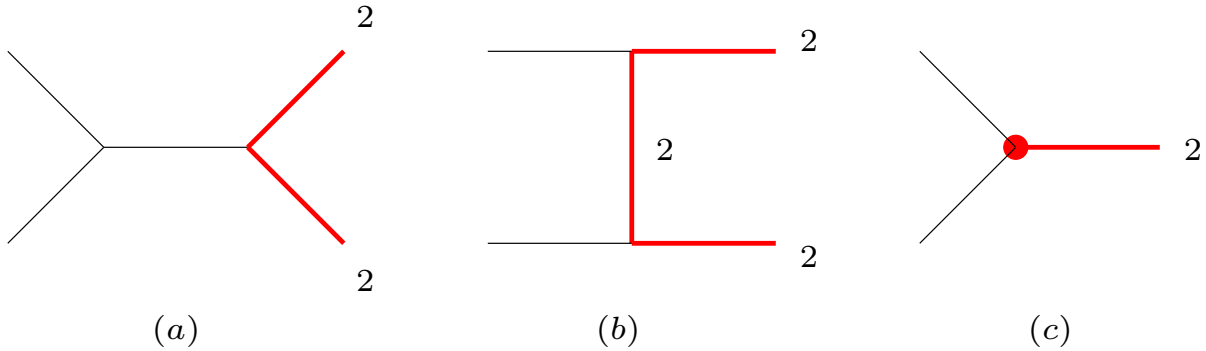
  (Cheng, Matchev, Schmaltz, hep-ph/0204342, hep-ph/0205314)



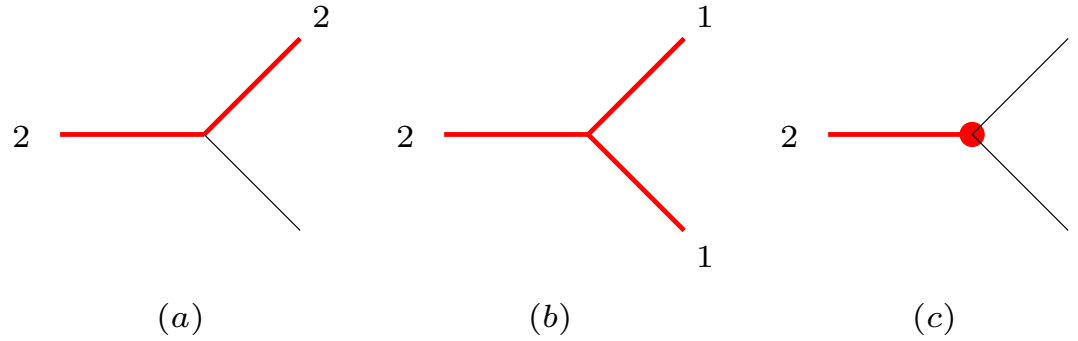


Looking for level 2 KK partners

- $n = 1$ ($M_1 = \frac{1}{R}$) is like MSSM and can be discovered: look for $n = 2$ ($M_2 = \frac{2}{R}$)
- Production:

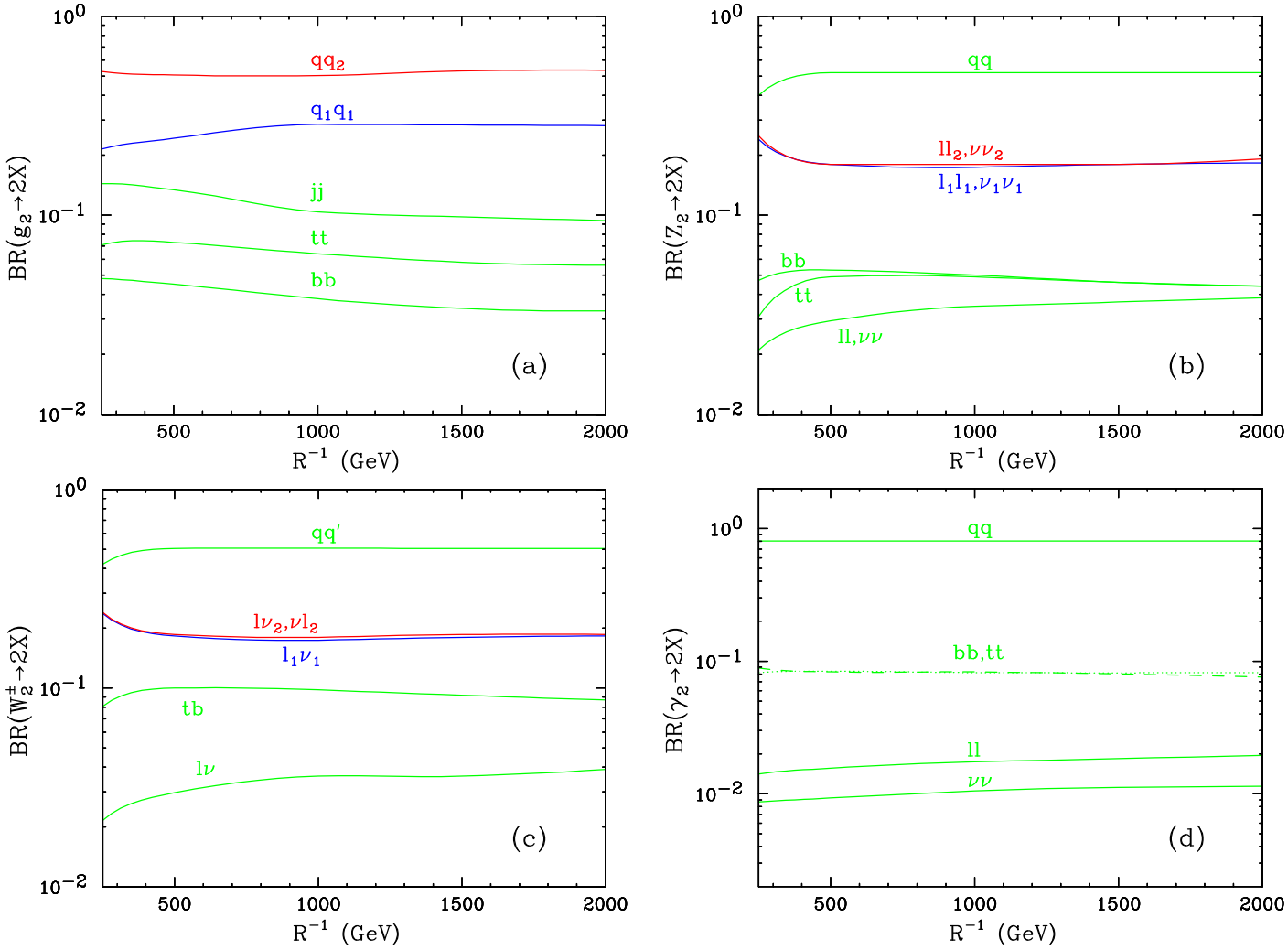


  - a, b: kinematically suppressed / c: suppressed couplings
  - only V_2 have KK number violating couplings to SM
  - Q_2 and L_2 : either forbidden or higher dimensional operator
- Decay:



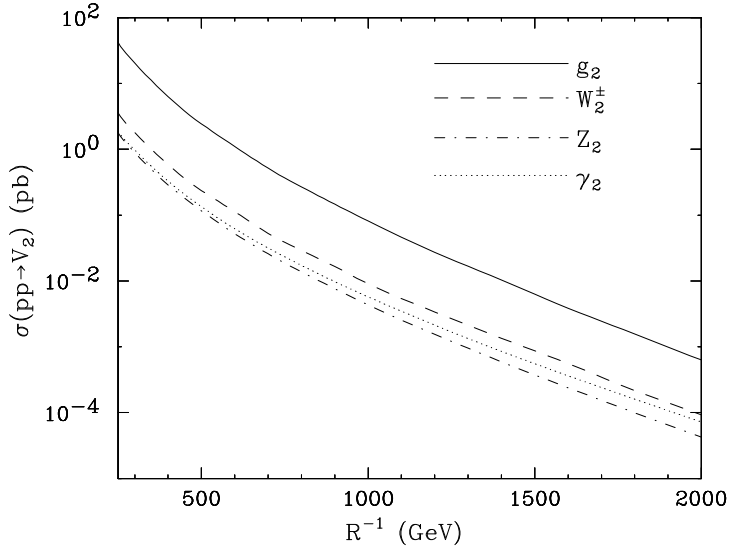
  - a: SM particle is soft / b: direct $n = 1$ production? / c: resonance

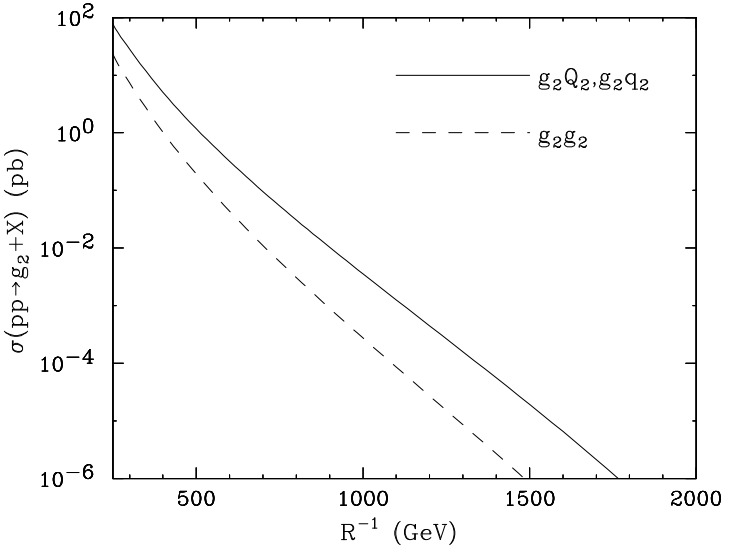
Branching fractions of level 2 Gauge Bosons

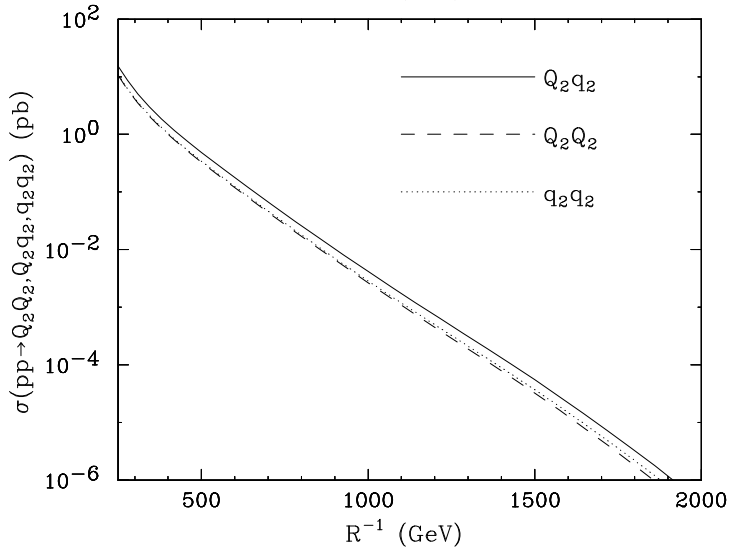


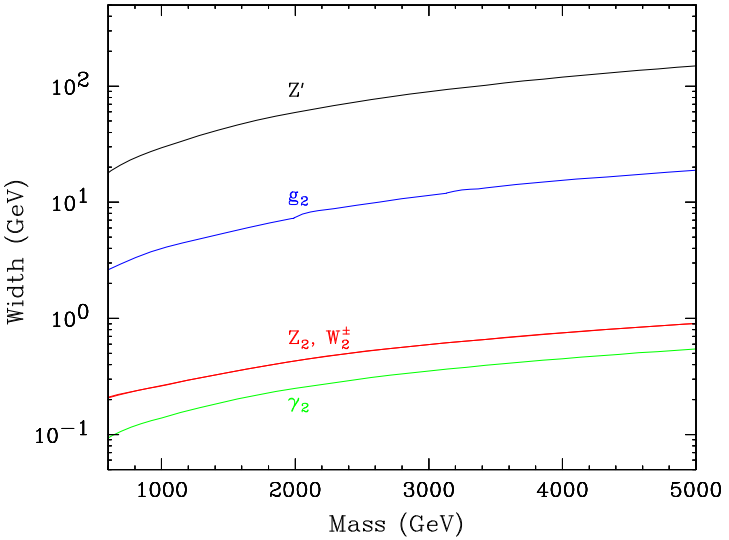
- γ_2: almost Lepto-phobic
- $\gamma_2 + Z_2 + g_2 \longrightarrow$ one single bump in dijet

Production/Widths of level 2 Gauge Bosons





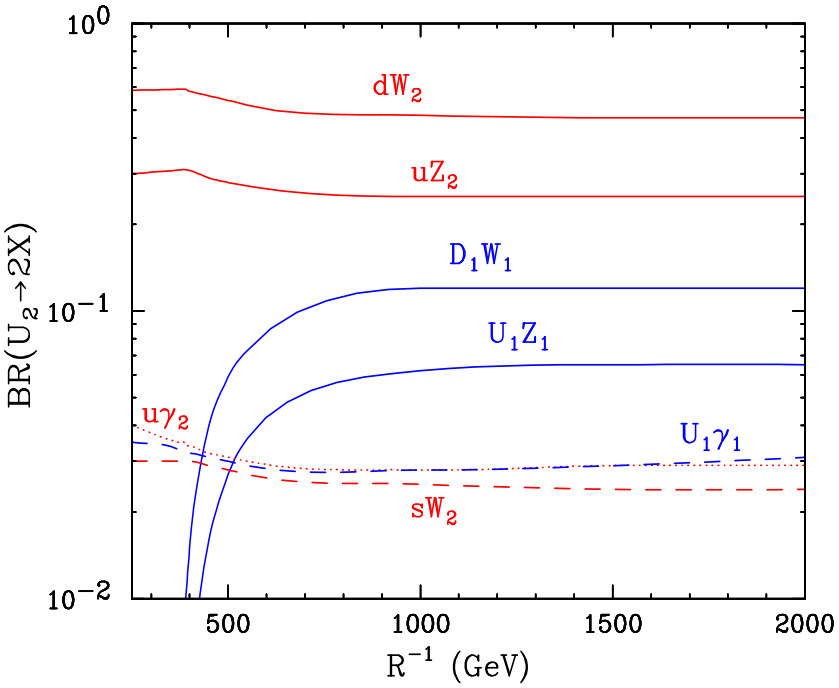


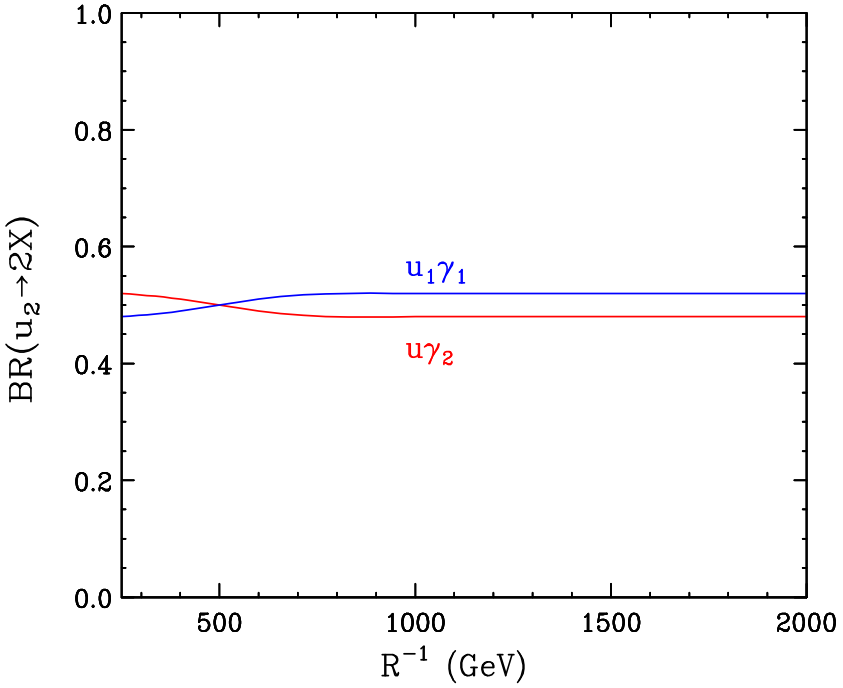


- Indirect production is important

Branching Ratios of level 2 KK quarks

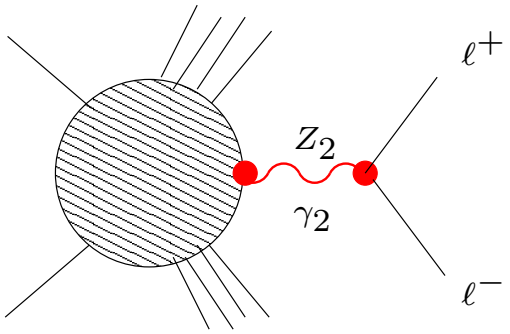
(Datta, Kong, Matchev, hep-ph/0509246)





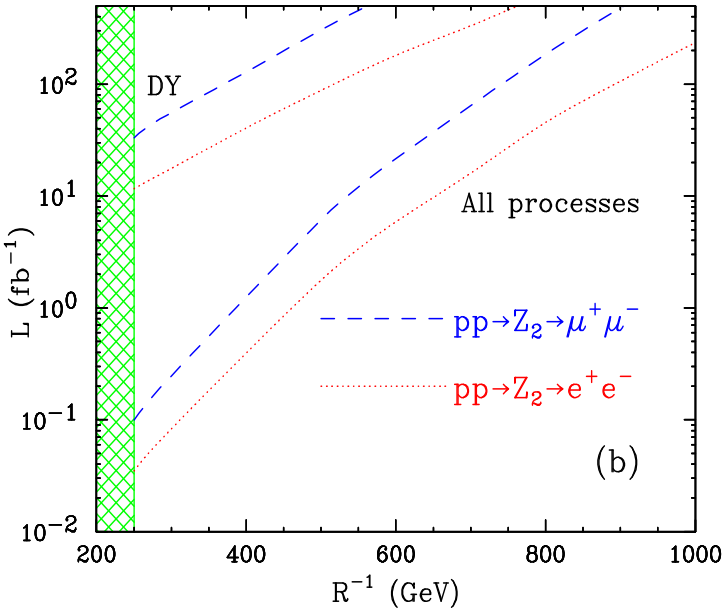
- Large Branching ratios into level 2 gauge bosons
  - $BR(Q_2 \to Z_2 Q_0) \geq 25\%$
  - $BR(Q_2 \to \gamma_2 Q_0) \geq 3\%$
  - $BR(q_2 \to \gamma_2 Q_0) \approx 50\%$
  - $BR(g_2 \to Q_2 Q_0 + q_2 q_0) \approx 50\%$

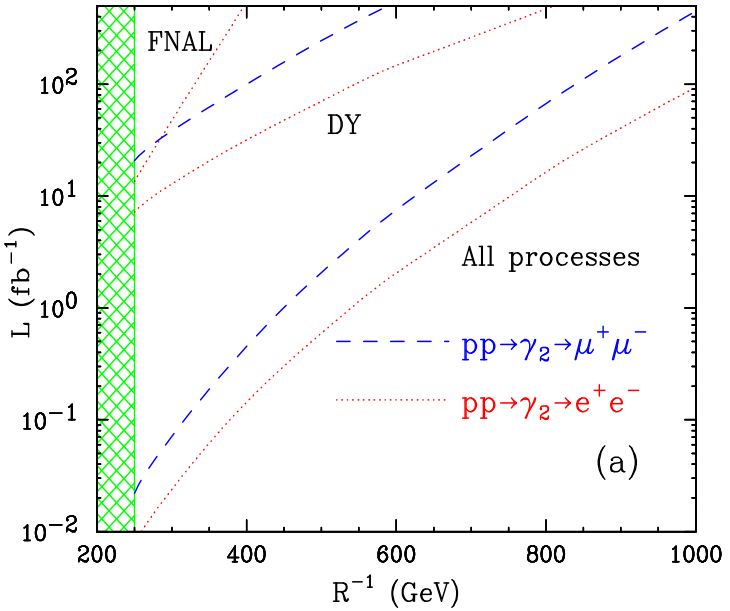
Discovery reach for MUED at LHC in inclusive dilepton channel



- $|p_t| > 20$ GeV, $|\eta| < 2.4$, $|M_{\ell^+\ell^-} - M_{V_2}| < 2\Delta M_{\ell^+\ell^-}$
- $\Delta M_{\ell^+\ell^-} = \sqrt{(\Gamma(V_2 \to \ell^+\ell^-))^2 + (\delta m)^2} \approx \delta m$
  - $\delta m = 0.01 M_{V_2}$ for e^+e^-
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1TeV} \right)$ for $\mu^+\mu^-$
- Background with Pythia

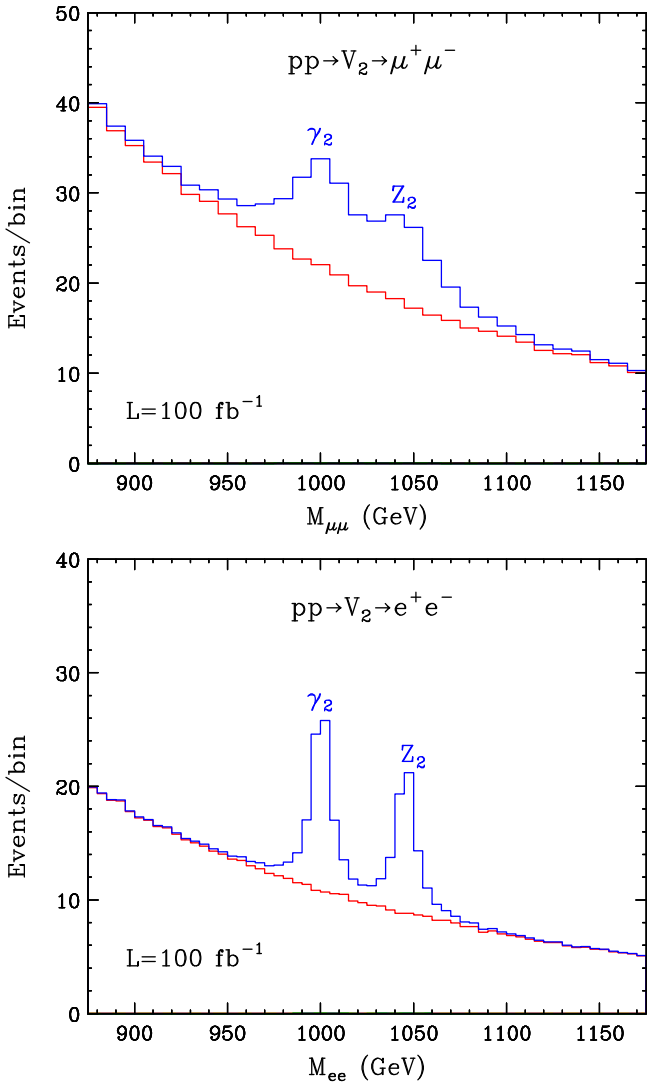
(Datta, Kong, Matchev, hep-ph/0509246)





Two resonances

(Datta, Kong, Matchev, hep-ph/0509246)



- Level 2 resonances can be seen at the LHC:
  - up to $R^{-1} \sim 1$ TeV for 100 fb^{-1}, $M_{ab}^2 = (p_a + p_b)^2$
  - covers dark matter region of MUED
- Mass resolution:
  - $\delta m = 0.01 M_{V_2}$ for e^+e^-
  - $\delta m = 0.0215 M_{V_2} + 0.0128 \left(\frac{M_{V_2}^2}{1TeV} \right)$ for $\mu^+\mu^-$
- Narrow peaks are smeared due to the mass resolution
- Two resonances can be better resolved in e^+e^- channel
- Is this a proof of UED ?
  - Not quite : resonances could still be interpreted as Z's
  - Smoking guns :
    - Their close degeneracy
    - $M_{V_2} \approx 2M_{V_1}$ and one single bump in dijet
    - Mass measurement of $W_2^{\pm}$ KK mode
- However in nonminimal UED models,

  degenerate spectrum is not required

  $\longrightarrow$ just like SUSY with a bunch of Z's

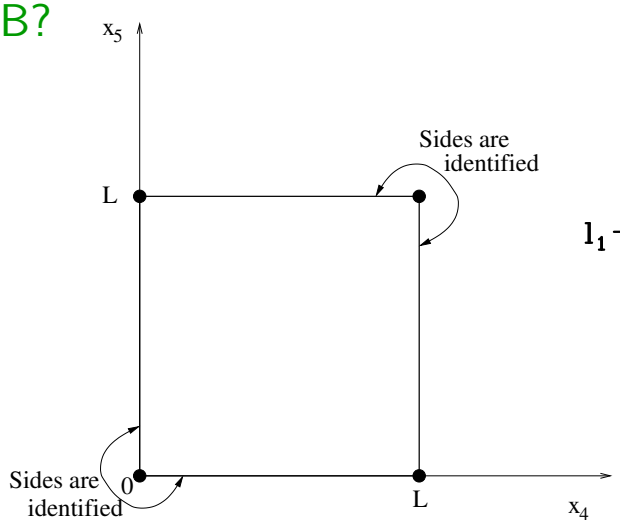
  $\longrightarrow$ need spins to discriminate

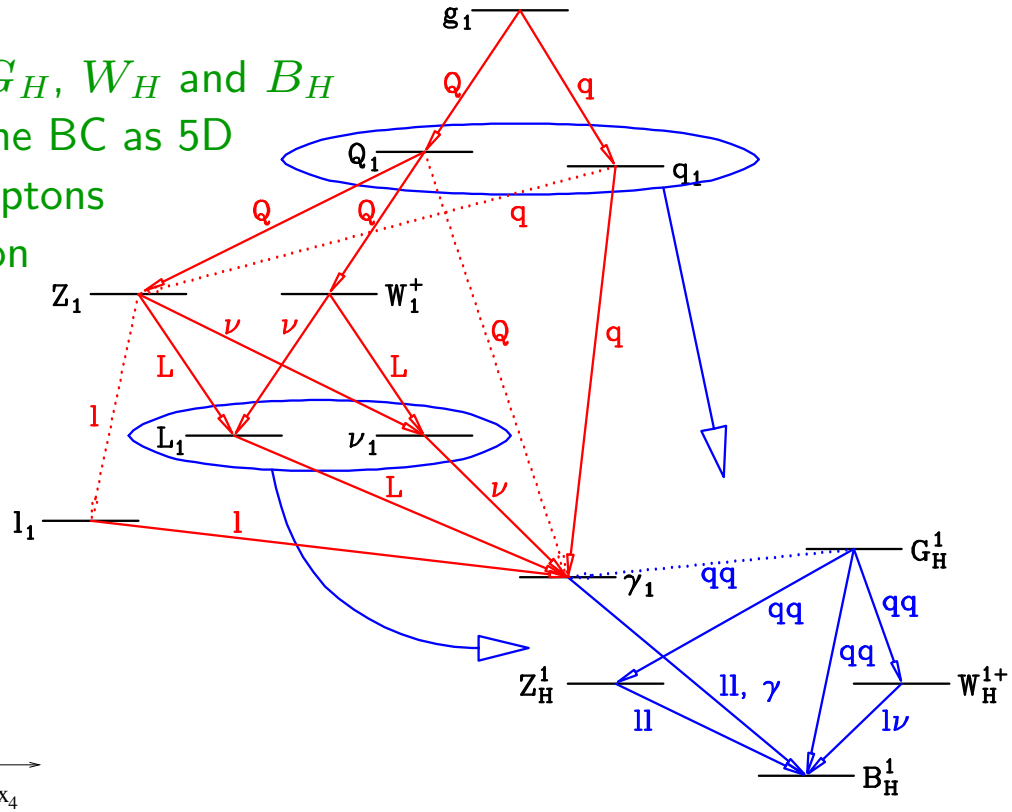
Two Universal Extra Dimensions on Chiral Square

- Motivation:
  - Possible to avoid proton decay (Appelquist, Dobrescu, Ponton hep-ph/0107056)
  - To cancel anomalies $\longrightarrow$ 3 generations (Dobrescu, Poppitz hep-ph/0102010)
- Chiral Square $\longrightarrow$ (n,m) KK-mode (Dobrescu, Ponton, hep-th/0401032)

  (Burdman, Dobrescu, Ponton, hep-ph/0506334) (Ponton, Wang, hep-ph/0512304)
- Explore different phenomenology: (1,0) mode with $M_{(1,0)} \sim \frac{1}{R}$

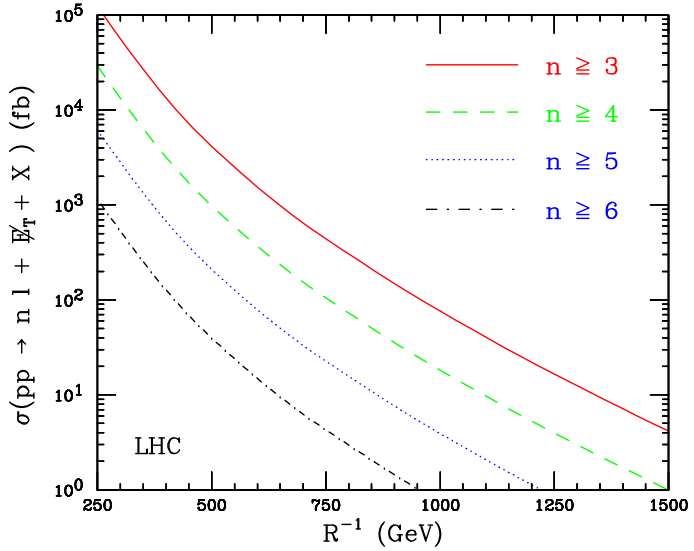
  (Dobrescu, Kong, Mahbubani, hep-ph/0703231)
  - Spinless Adjoints: uneaten NGB, G_H, W_H and B_H
  - B_H: the lightest assuming the same BC as 5D
  - Tree-level 3-body decays $\longrightarrow$ two leptons
  - One-loop 2-body decay $\longrightarrow$ a photon
  - GMSB?

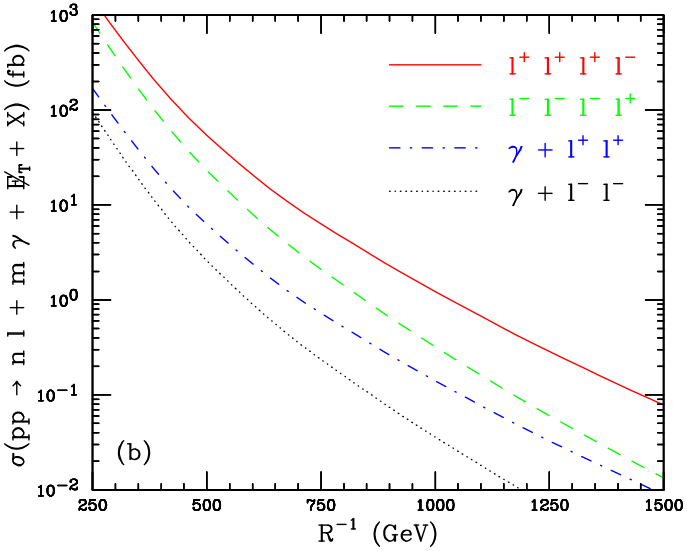


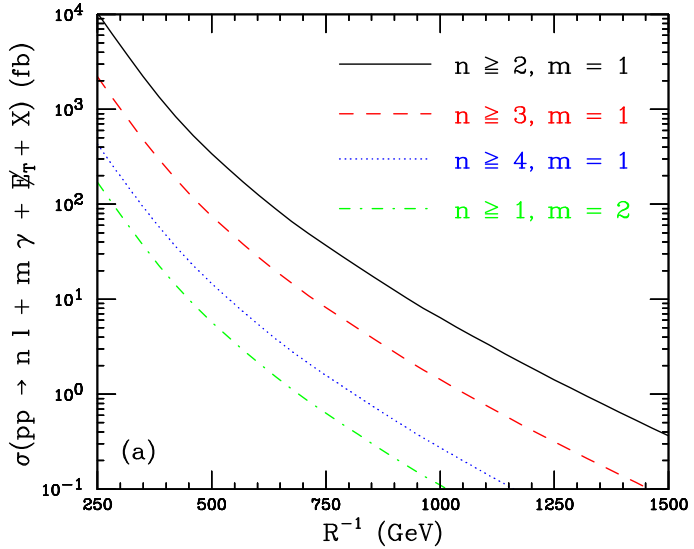


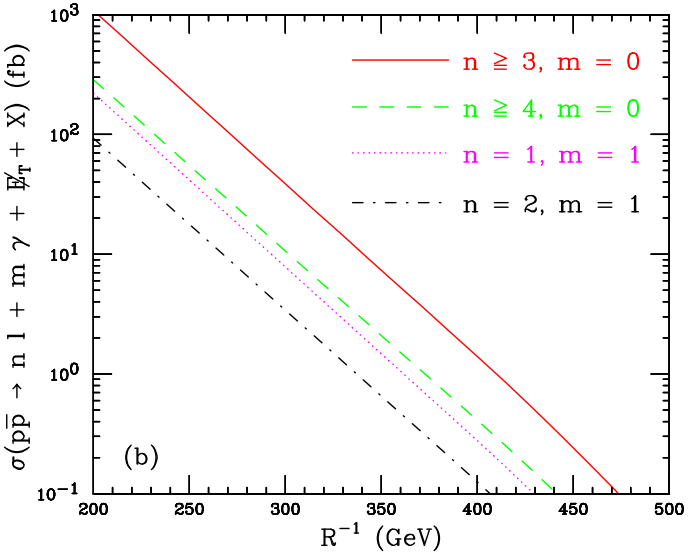
Leptons/Photons in Two Universal Extra Dimensions

(Dobrescu, Kong, Mahbubani, hep-ph/0703231)





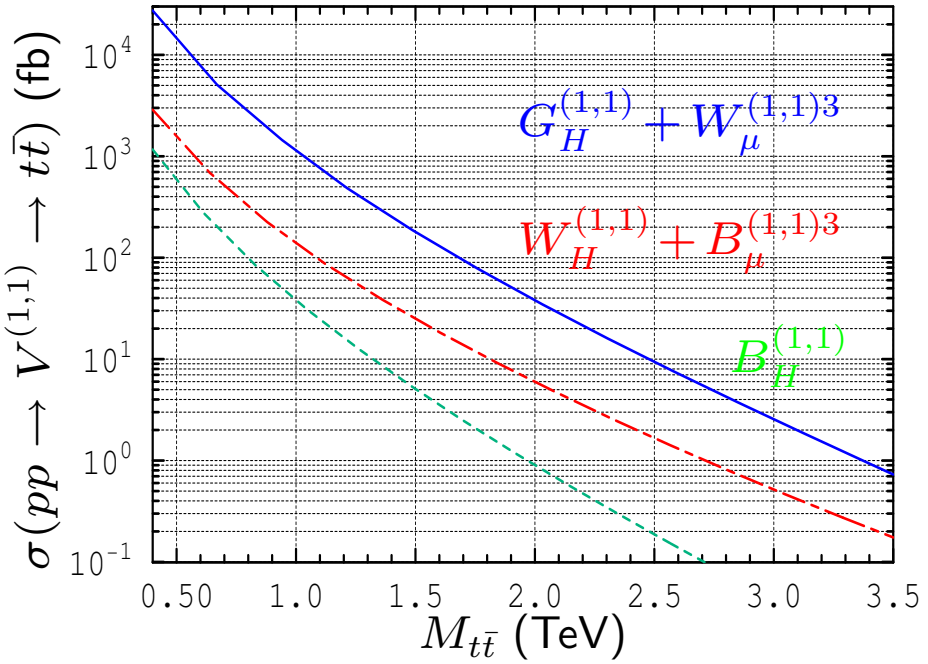




Resonances in Two Universal Extra Dimensions

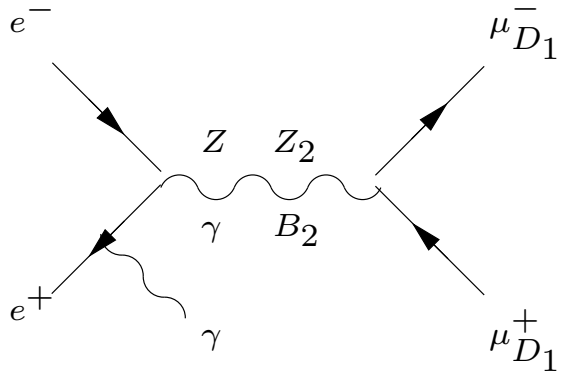
(Burdman, Dobrescu, Ponton, hep-ph/0601186)

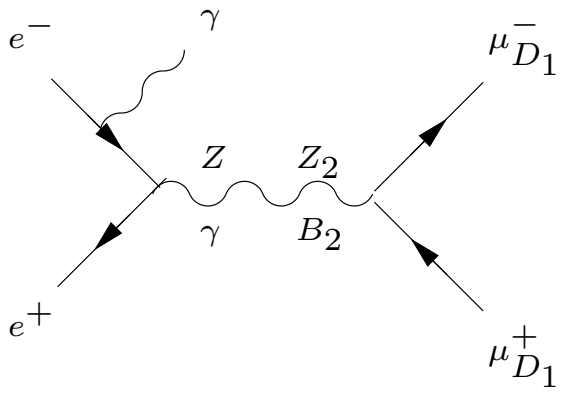
- (1,1) mode: $M_{(1,1)} \sim \frac{\sqrt{2}}{R}$
  - (1,1) mode is lighter than (2,0) mode
  - Three (neutral) gauge bosons: $G_\mu^{(1,1)}$, $W_\mu^{(1,1)}$, $B_\mu^{(1,1)}$
    - Loop-induced couplings $\longrightarrow$ lepto-phobic
    - $Br(W_\mu^{(1,1)},\ B_\mu^{(1,1)} \longrightarrow \ell^+\ell^-\ ) \sim 1\%$
  - Three (neutral) spinless adjoints: $G_H^{(1,1)}$, $W_H^{(1,1)}$, $B_H^{(1,1)}$
    - Derivative coupling, $\bar{q}\gamma^\mu q \partial_\mu X_H^{(1,1)} \longrightarrow Br(X_H^{(1,1)} \longrightarrow t\bar{t}\ ) = 1$
- 5 resonances in $t\bar{t}$: ($Br(G_\mu^{(1,1)} \longrightarrow t\bar{t}\ )$ is small)
  - But only 3 may be resolved:
    - $G_H^{(1,1)} + W_\mu^{(1,1)3} \sim 1.1\frac{\sqrt{2}}{R}$
    - $B_\mu^{(1,1)} + W_H^{(1,1)3} \sim 0.97\frac{\sqrt{2}}{R}$
    - $B_H^{(1,1)} \sim 0.86\frac{\sqrt{2}}{R}$
  - Top reconstruction?
  - Jet-energy resolution?
  - B-tagging?
  - A single bump with $\frac{\Gamma}{M} \sim 0.1$?

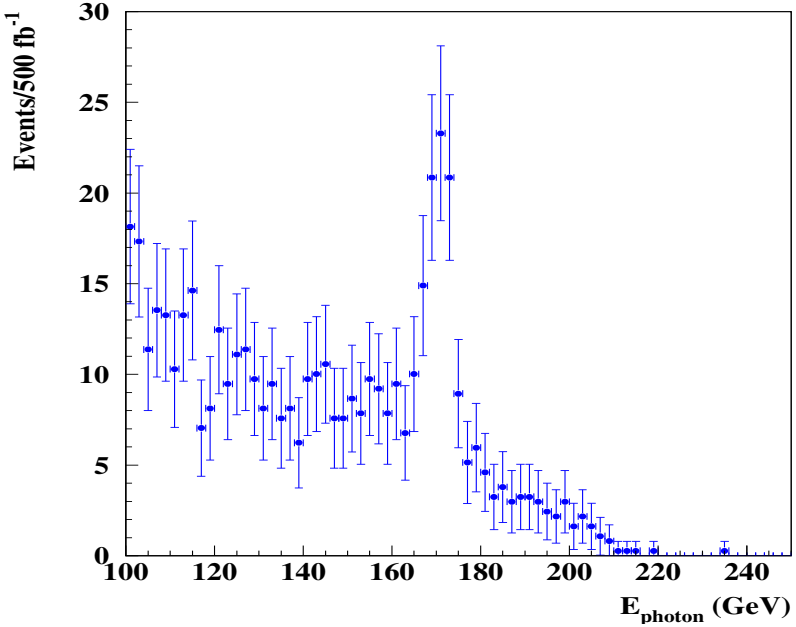


The Photon Energy Distribution (LC)

(Battaglia, Datta, De Roeck, Kong, Matchev,hep-ph/0502041)







- $\mu^+\mu^- + \not{E}_T$
- On-shell $Z_2 \longrightarrow \mu_1\bar{\mu}_1$ is allowed by phase space
- Radiative return due to Z_2 pole at

$$E_\gamma = \frac{s - M^2_{Z_2}}{2\sqrt{s}}$$

Summary

- Resonances:
  - Easy to look for
  - Identity is not clear
- 5D Resonances:
  - Two bumps (γ_2 and Z_2) in dilepton mass, one bump (W_2) in transverse mass
  - Their degeneracy in mass indicates UED
  - Widths are very small $\longrightarrow$ resolving power depends on detector resolution
  - Dijet at LHC/LC?
- 6D Resonances: lepto-phobic, weakly coupled resonances
  - 5 neutral bumps in $t\bar{t}$ channel
  - Resolving power depends on top reconstruction/jet-energy resolution
  - Need realistic study at LHC/LC and Tevatron

	5D level 1	5D level 2 (resonances)	6D (1,0)	6D (1,1) (resonances)
LHC/Tevatron	$4\ell + \not{E}_T, \cdots$	$\ell^+\ell^-$	$n\ell + m\gamma + \not{E}_T$	$t\bar{t}$
LC	$\ell^+\ell^- + \not{E}_T, \cdots$	$\ell^+\ell^-$, ISR	?	?