Signals of Universal Extra Dimension at the Linear Collider

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- In Universal Extra Dimension (UED) type models,all standard model particles are placed in the bulk , no need for branes. (Appelquist, Cheng and Dobrescu, PRD 64, 035002, 2001)
- Best candidate to mimic SUSY, and an alternative to SUSY to give cold dark matter

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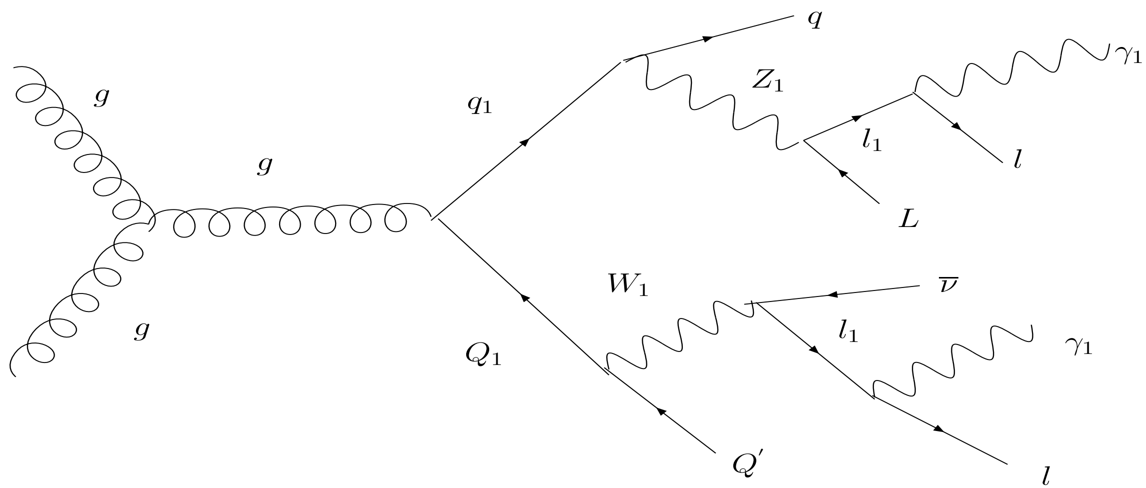
- $n = 1$ particles must be pair produced(Conservation of KK Parity) and decay to γ_1 (LKP:DM Candidate)

Expectation from LHC

- LHC: KK gluon and KK quarks can be produced copiously
- Collider signature of UED: Multijet + multilepton + Missing energy (Cheng Matchev, Schmaltz PRD 2002)



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Difference : UED vs SUSY

- Spins are different

  (Spin measurement is difficult at the LHC)
- n=2,3 .... excited states

  (People have studied Z_2,γ_2 production at the LHC)
- Higgs sector

  (UED: one doublet + KK modes SUSY: two doublets + superpartners)

n = 2 Gauge Bosons

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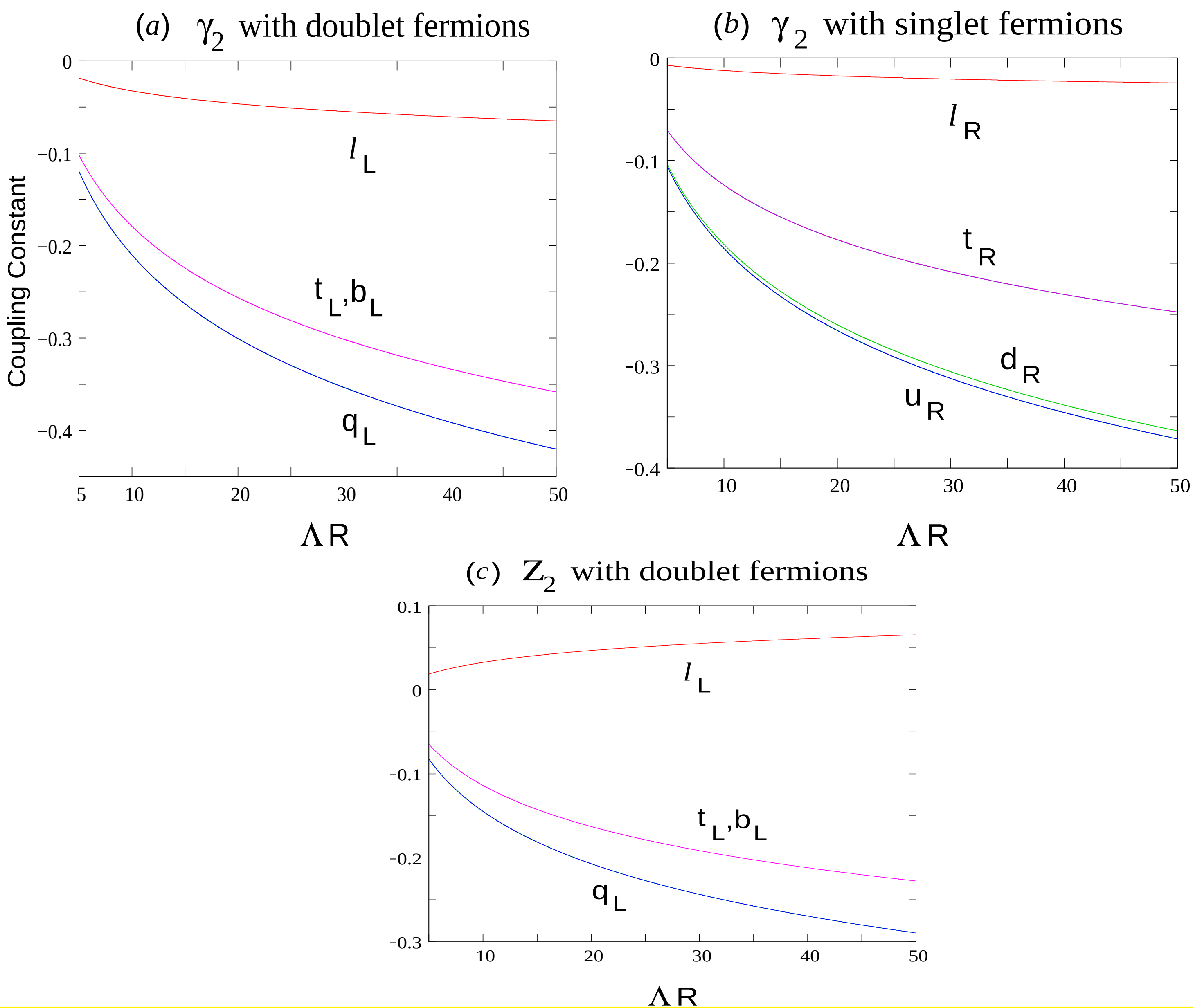
- Need same energy to produce two $n = 1$ states or one $n = 2$ state
- The production goes through the coupling

$$\overline{f_0} f_0 V_2 \longrightarrow (-ig\gamma^\mu T_a P_+) \frac{\sqrt{2}}{2} \left(\frac{\bar{\delta}(m_{V_2}^2)}{m_2^2} - 2\frac{\bar{\delta}(m_{f_2})}{m_2} \right)$$

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

(Cheng Matchev, Schmaltz PRD 2002)

Couplings


(a) γ_2 with doublet fermions
(b) γ_2 with singlet fermions
(c) Z_2 with doublet fermions
Coupling Constant
ΛR
l_L
t_L,b_L
q_L
l_R
t_R
d_R
u_R
0
−0.1
−0.2
−0.3
−0.4
0.1
5
10
20
30
40
50

Z_2/γ_2 Physics

- Z_2 can decay to leptonic KK-conserving channels (kinematics) or KK-violating channels, but it is almost W_3, so couples only to doublets

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- These two peaks may or may not be resolvable.

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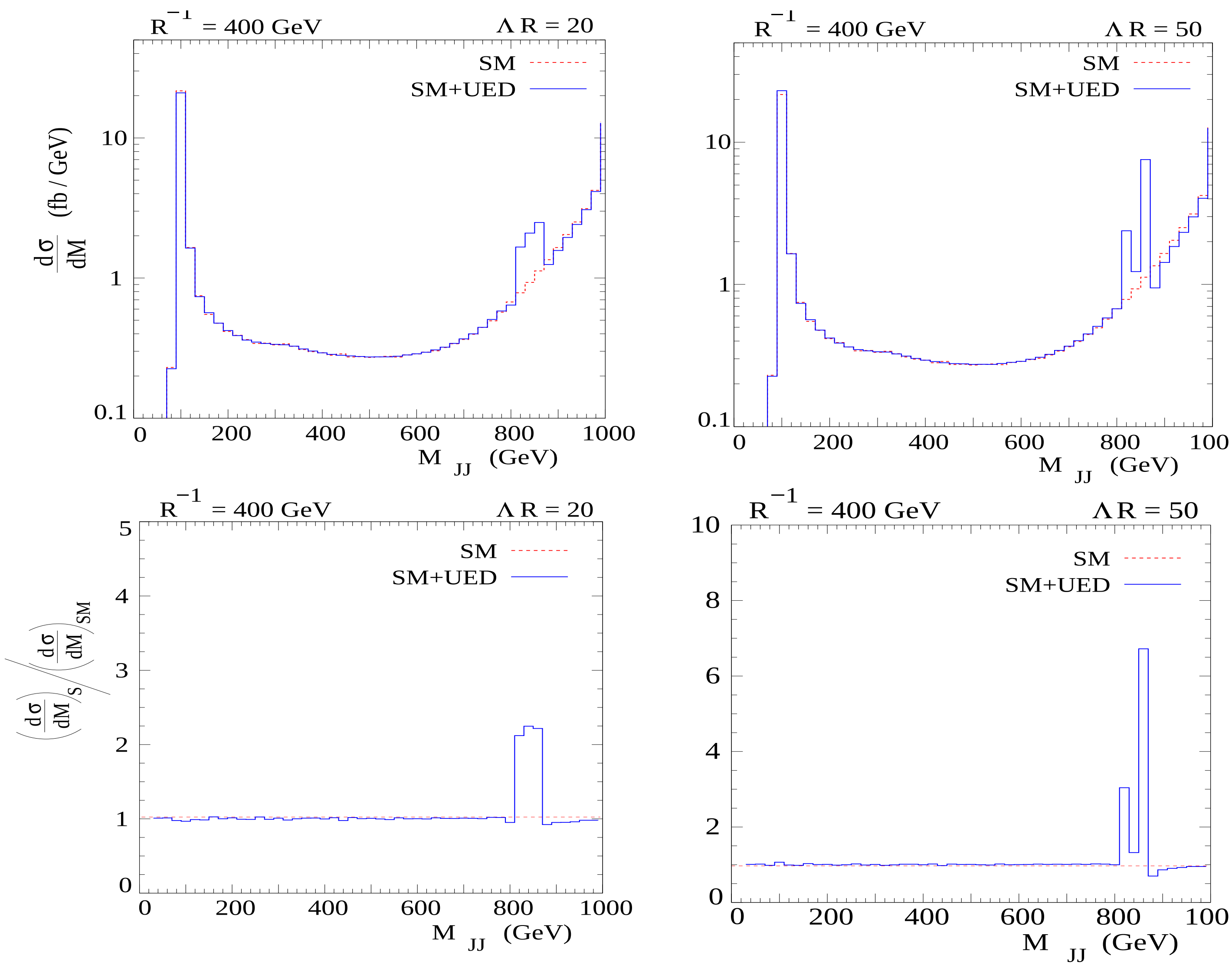
  $\Longrightarrow$ no signal of any significance.
- Radiative return will save us.

Bump hunting at the ILC

Bhattacherjee,Rai,Raychaudhuri,Kundu PRD (2008)



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No

Other models

Possible source of a single bump in the dijet invariant mass spectrum :

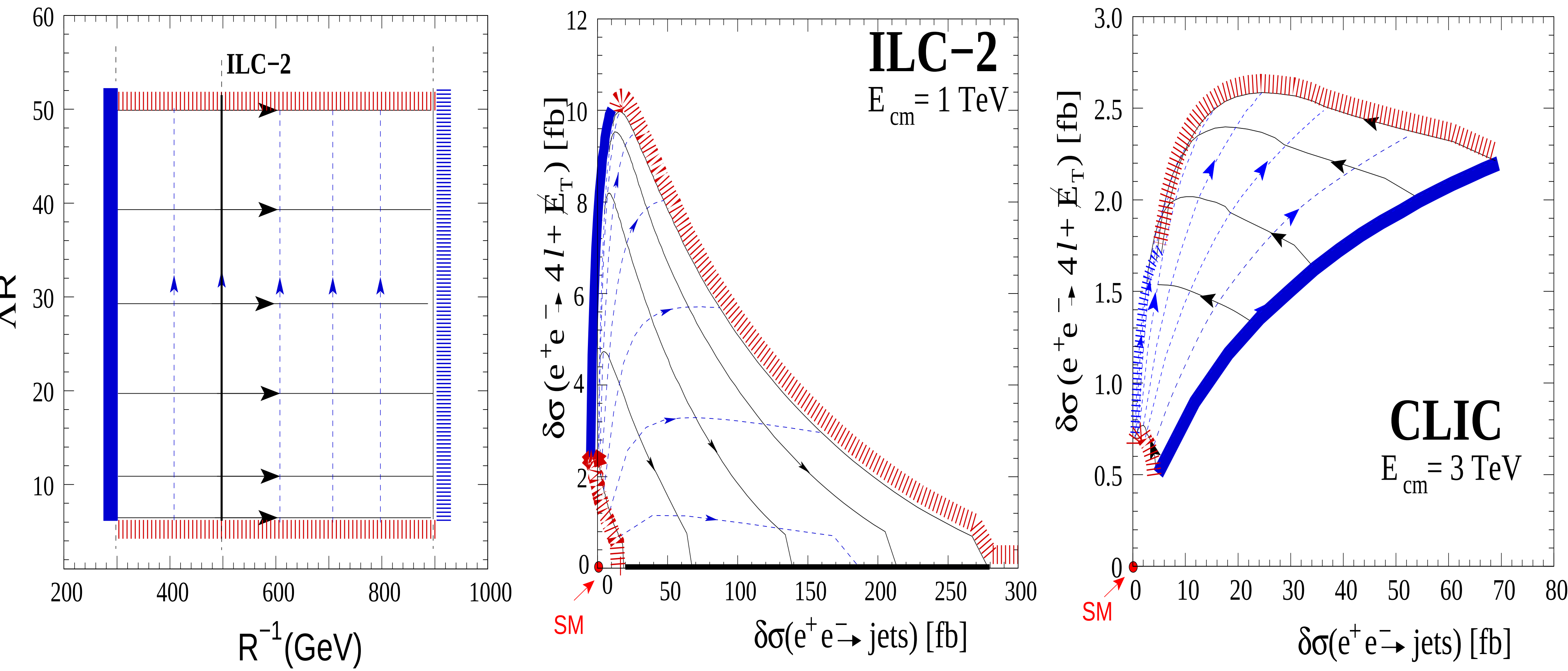
- A resonant Z' boson, predicted in models with extra $U(1)$ symmetries.
- A heavy sneutrino $\widetilde{\nu}_\mu$ or $\widetilde{\nu}_\tau$ in a SUSY model with R-parity-violating couplings.
- A massive graviton G_1, predicted in the Randall-Sundrum model.

We should correlate other signals of UED like $4\ell + \not{E}_T$ with dijet excess

Possible source of $4\ell + \not{E}_T$ signal, standing alone.

- A pair of heavy Z' bosons, with an ordinary Z boson radiated from any of the fermion legs
- a pair of heavy $W'^{\pm}$ bosons, with an ordinary Z boson radiated from any of the fermion legs
- A pair of heavy neutralinos $\widetilde{\chi}_i^0 \widetilde{\chi}_j^0$ $(i, j > 1)$, each of which decays as $\widetilde{\chi}_i^0 \to \ell \widetilde{\ell} \to \ell(\ell \widetilde{\chi}_1^0)$ (irreducible)

Correlation plot



ILC Summary

- LHC may provide hints of UED but ILC will settle the issue.
- There is no ‘smoking gun’ signal of UED.
- One can look for peaks in the invariant mass distribution and four lepton excess to identify an underlying UED.
- ILC environment is cleaner than LHC
- Correlation plot can be used to pin down parameters R^{-1} and ΛR; may also hint at nonminimal UED.
- By measuring angular distributions, threshold scan, one can reconfirm UED (Battaglia et al. JHEP 2005).
- ILC is needed to identify UED!

Scalar sector of UED

The n-th level Higgs field is parametrized as

$$H_n = \begin{pmatrix} \chi_n^+ \\ \frac{h_n - i\chi_n^0}{\sqrt{2}} \end{pmatrix}$$

where χ_n^+ , h_n and χ_n^0 are excitations of charged scalar ,CP even neutral and CP odd neutral scalars.

There are three more scalars ,which are 5th components of excitations of gauge bosons Z_n^5 ,$W_n^{5\pm}$.

Scalar sector of UED(cont.)

The Goldstone combinations are given by

$$G_n^0 = \frac{1}{m_{Z_n}} \left[m_Z \chi_n^0 - \frac{n}{R} Z_n^5 \right],$$

$$G_n^\pm = \frac{1}{m_{W_n}} \left[m_W \chi_n^\pm - \frac{n}{R} W_n^{5\pm} \right].$$

The orthogonal combinations are the physical fields given by $H_n^\pm$, A_n^0

if 1/R $\gg M_{(W,Z)}$,the $n \neq 0$ Goldstones are the 5th component of gauge bosons.

Radiative correction on scalars

The tree level masses of the excited scalars are given by

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

The radiative correction is given by

$$\delta m_H^2 = m_n^2 \left[\frac{3}{2}g^2 + \frac{3}{4}g'^2 - \lambda\right] \frac{1}{16\pi^2} \ln \frac{\Lambda^2}{\mu^2} + \overline{m_h^2}$$

where $\overline{m_h^2}$ is the boundary mass term for the excited scalars, (not a priori calculable)

A few points to be noted :

- Radiative correction to the excited scalar masses is universal.
- $H^{\pm}$ will be the lowest-lying one.
- The hierarchy $m_{h_n} > m_{A_n^0} > m_{H_n^{\pm}}$ is fixed.
- For larger SM Higgs mass $H_1^{\pm}$ and A_1^0 masses go down if we keep $\overline{m_h^2}$ fixed. h_1 will become more massive.
- The excited scalar sector becomes more massive as $\overline{m_h^2}$ goes up, this affects the decay kinematics.

Charged scalar decay

Region 1: $M_{H_1^\pm} > M_{l_1^\pm}$

- $H_1^\pm \to l_D(e_1, m_1, l_1) \; + \; SM\ Neutrino \; + \; (e, m, l) \; + N_1$

  (gauge coupling dominates over Yukawa, universal branching)

Region 2: $M_{l_1^\pm} > M_{H_1^\pm} > M_{l_2^\pm}$

- $H_1^\pm \to Singlet \quad lepton(l_1) \quad + SM\ Neutrino + \quad h.c$

  (Yukawa coupling, only to tau lepton)

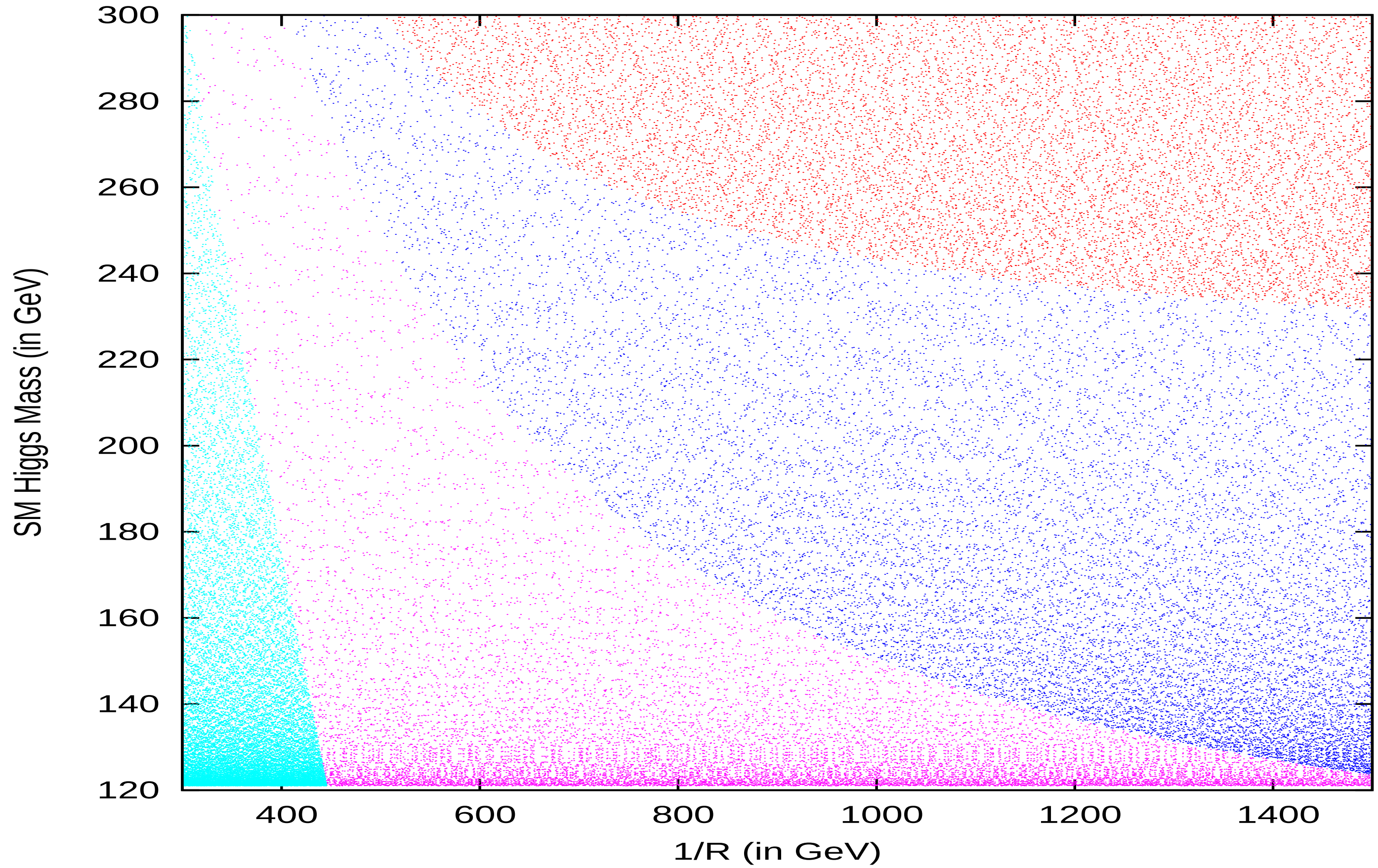
Region 3: $M_{l_2^\pm} > M_{H_1^\pm} > M_{\gamma_1}$

- $H_1^\pm \to \gamma_1 + f\overline{f}$ (Through virtual $W_1^\pm$)

Region 4: $M_{H_1^\pm} > M_{W_1^\pm}$

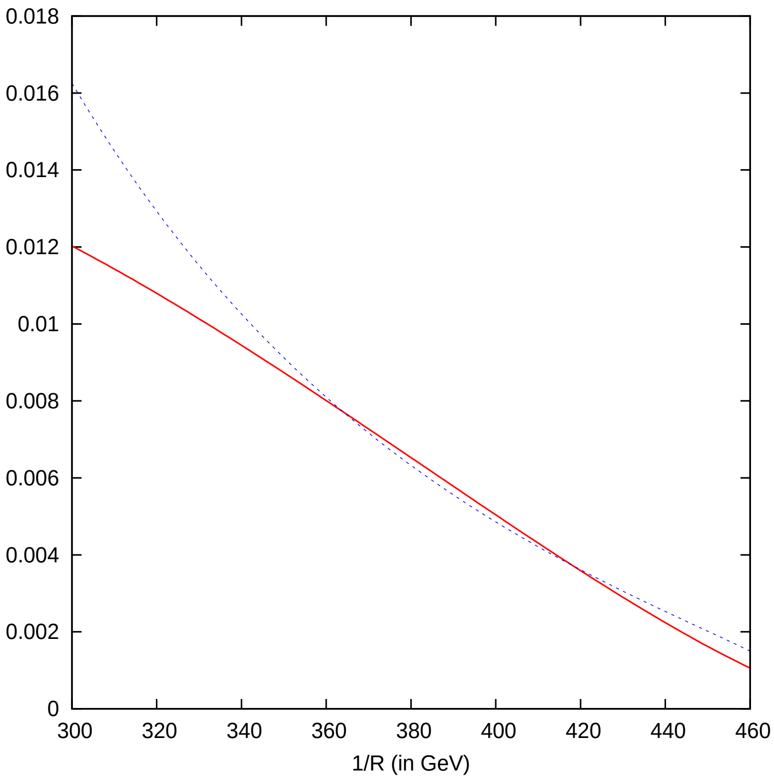
- $H_1^\pm \to W_1^\pm + f\overline{f}$ (Through virtual $W^\pm$)

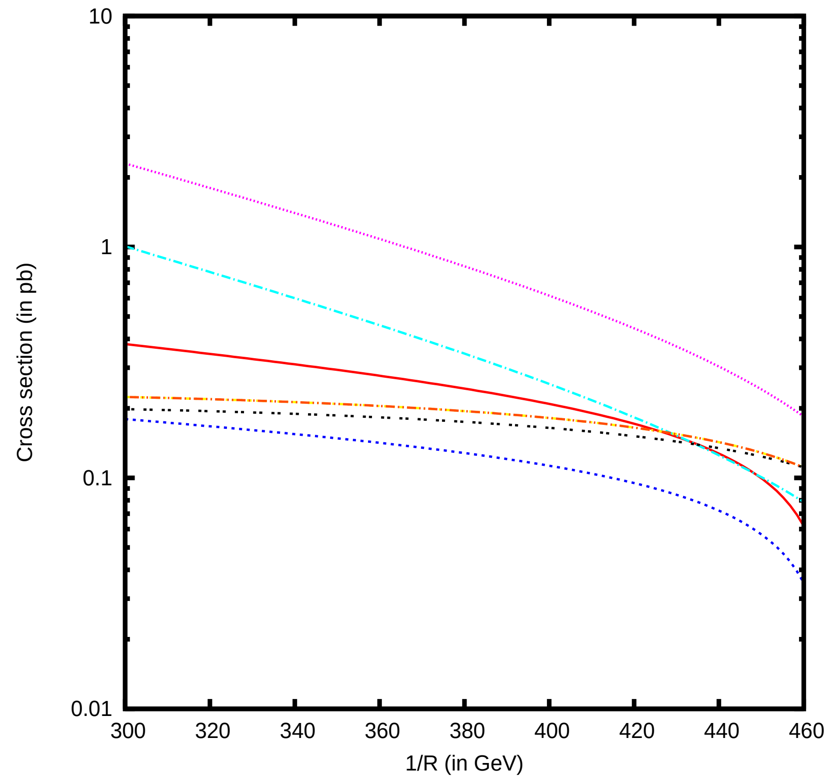
Parameter space



Red: $H^{\pm}$ is LKP, Blue : $M_{l_2{}^{\pm}} > M_{H_1{}^{\pm}} > M_{\gamma_1}$, Magenta: $M_{l_1{}^{\pm}} > M_{H_1{}^{\pm}} > M_{l_2{}^{\pm}}$, Cyan: $M_{H_1{}^{\pm}} > M_{l_1{}^{\pm}}$

Cross section





Illustrating the signal cross section and UED backgrounds for R^{-1} =350 GeV

Left: blue $\longrightarrow$ $W_1^{\pm}\ H_1^{\pm}$ + h.c , red $\longrightarrow$ $H_1^{+}\ H_1^{-}$

Right: From top to bottom $\longrightarrow e_1^{+} e_1^{-}$,$e_2^{+} e_2^{-}$, W_1^{+}, W_1^{-}, $m_1 \bar{m}_1$, $m_2 \bar{m}_2$, $Z_1 Z_1$

(Thomas G. Rizzo,PRD 2001).

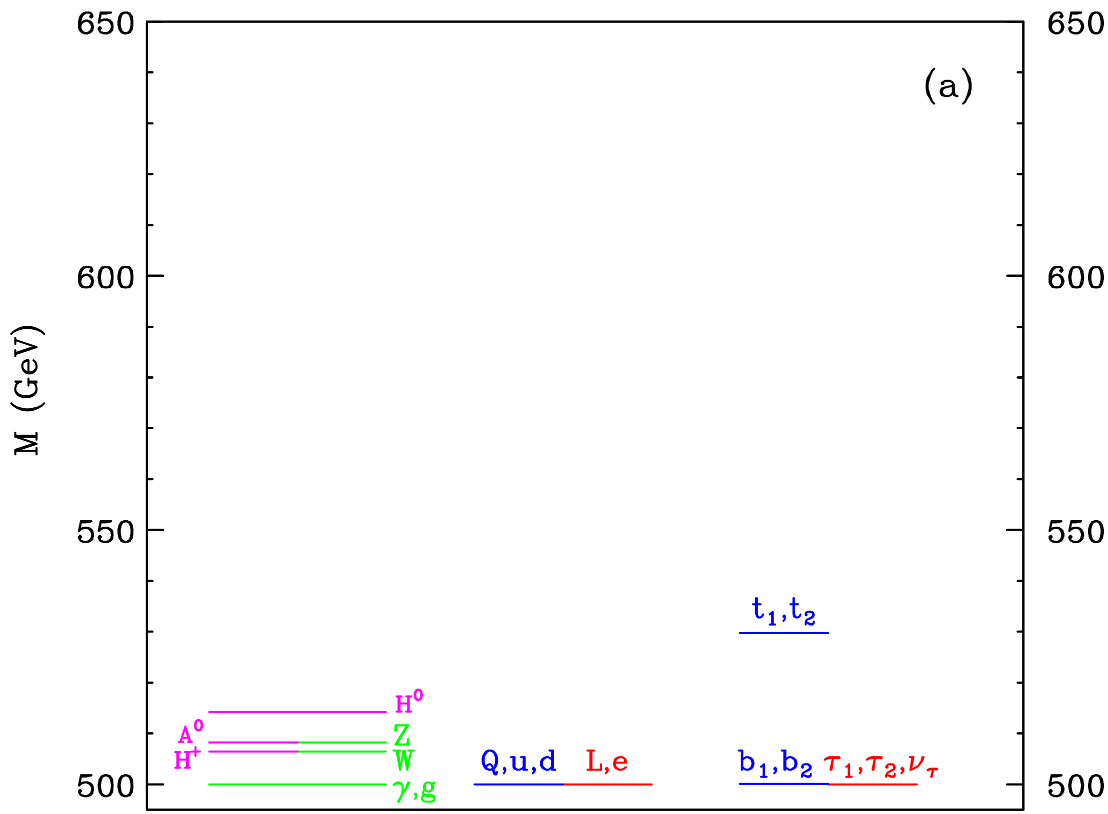
Summary

- Minimal UED model contains three scalars: $H_n^{\pm}$, h_n^0, A_n^0
- Masses depend on Λ, R^{-1}, m_h and $\overline{m_h^2}$
- These Higgses can decay only leptonically
- Spectrum dictates that the leptons must be soft
- This poses a serious challenge in their detection
- The detector limitation may remove the majority of the signal
- One can study the the scalar sector with polarized beam

  We also stress that this talk is more of a qualitative nature, and a detailed quantitative study should be taken up.

Thank You

UED Spectrum



Radiative correction is not included. $R^{-1} = 500$ GeV. Taken from Cheng, Matchev, Schmaltz, PRD 66, 036005, 2002

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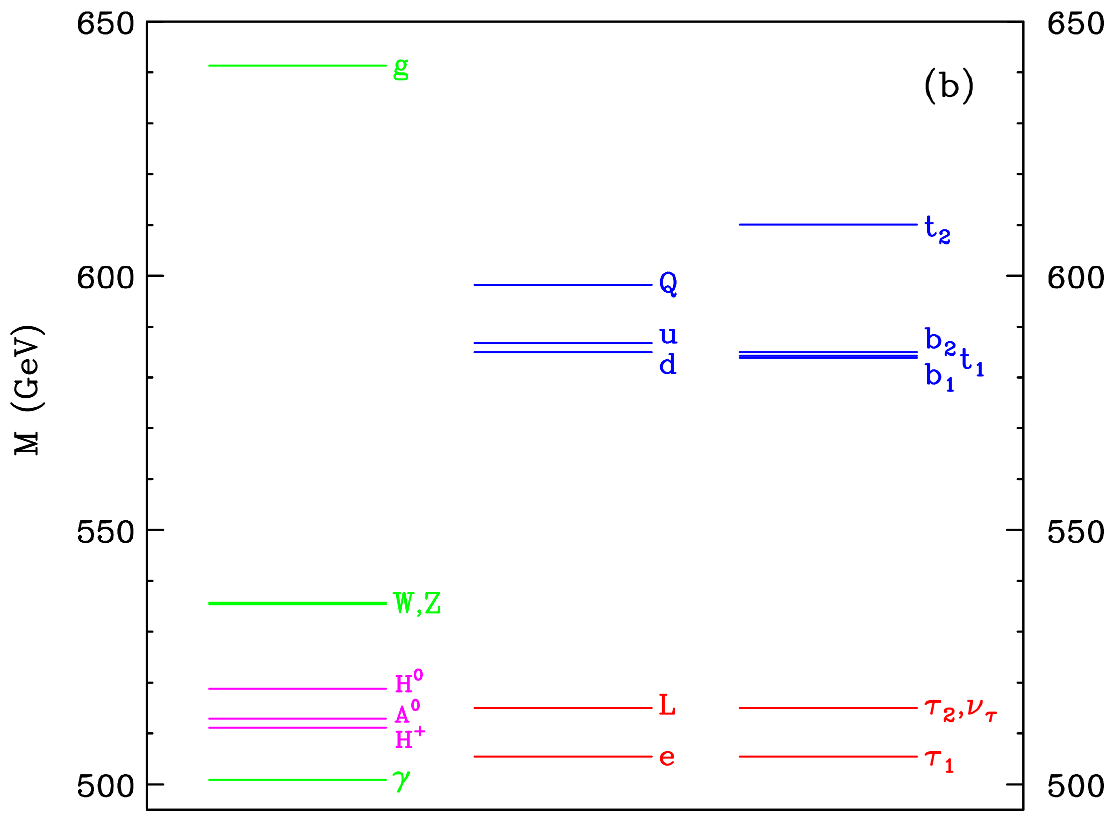
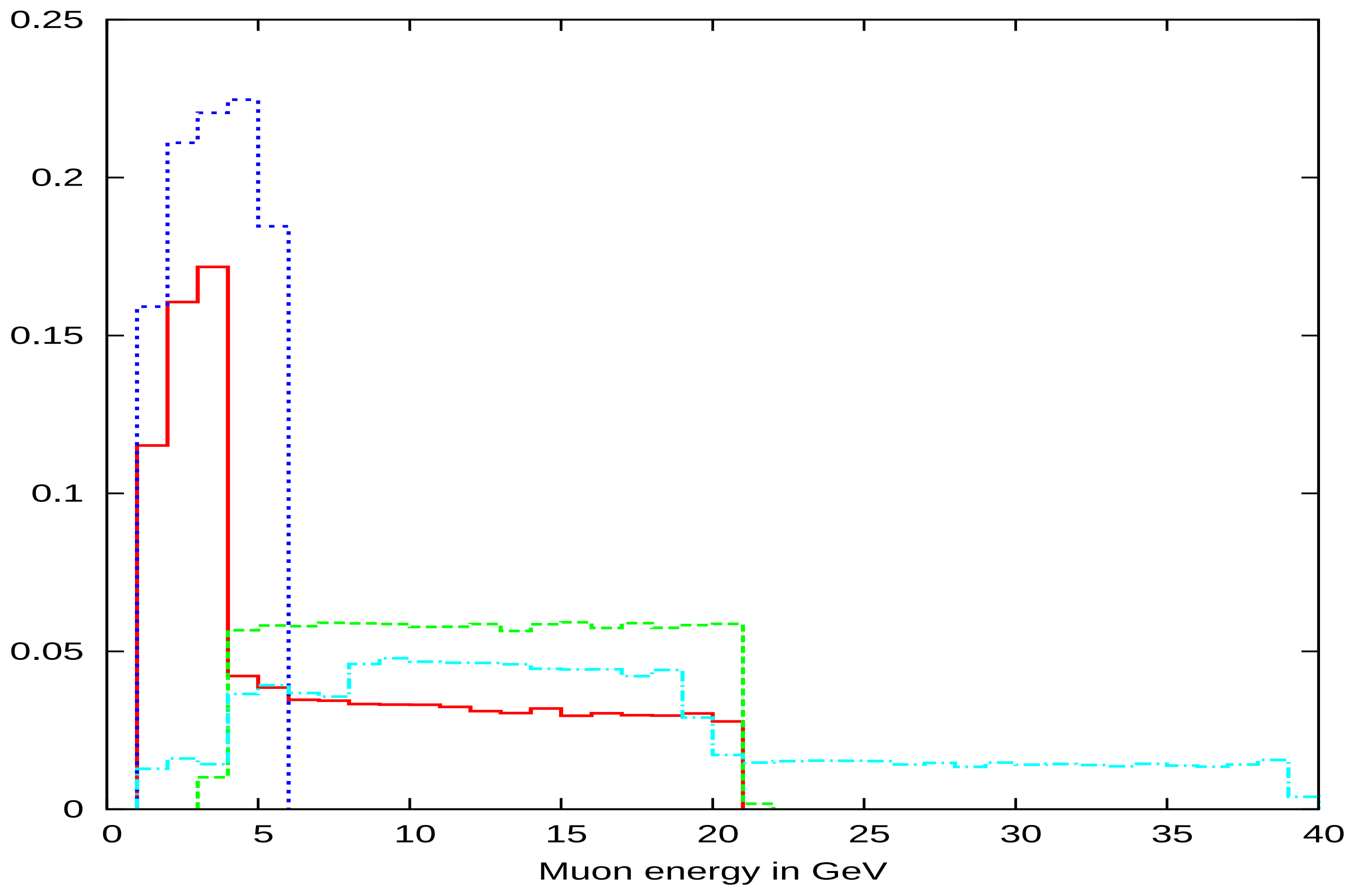


Radiative correction is included. $R^{-1} = 500$ GeV,$\Lambda R = 20$.

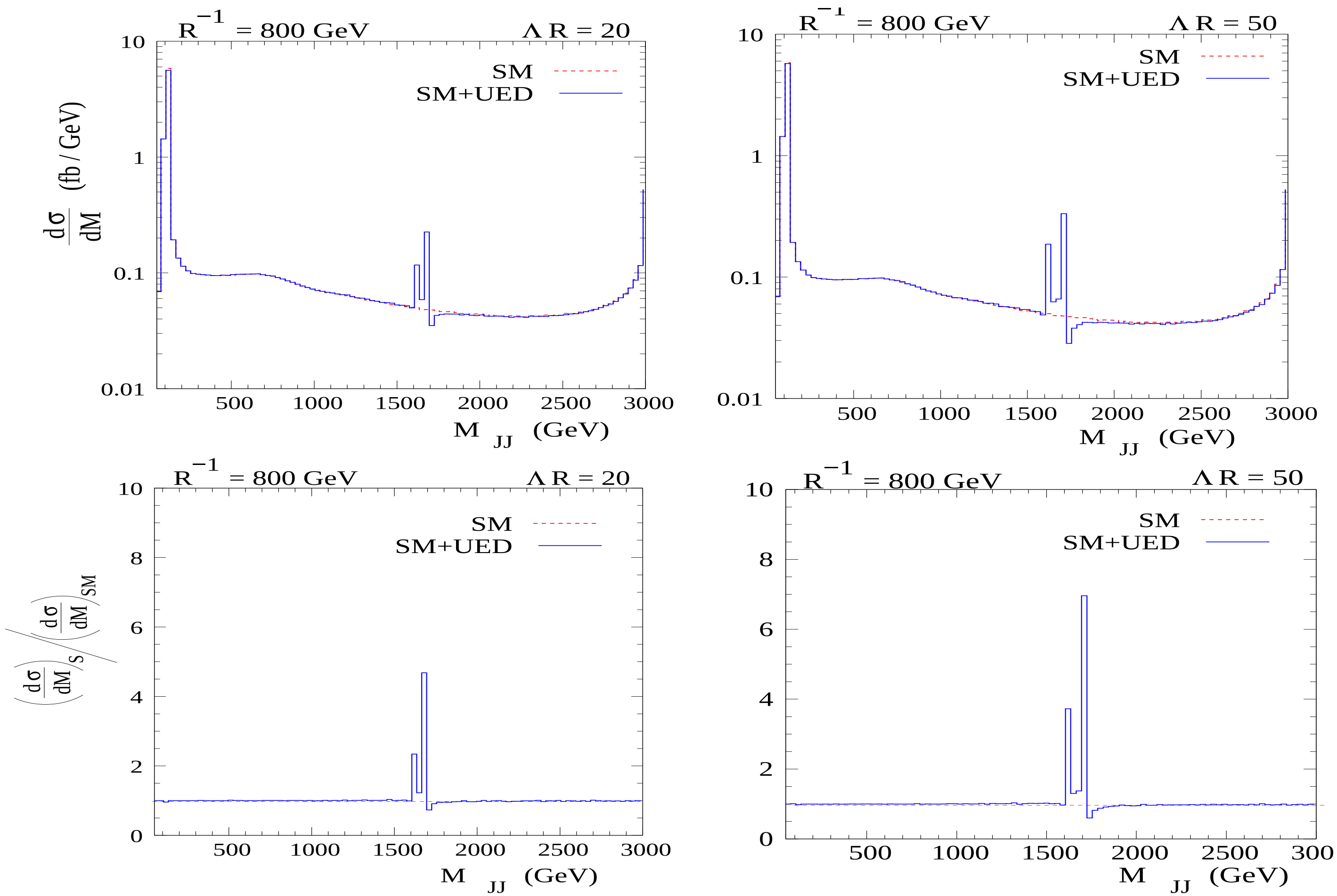
Taken from Cheng, Matchev, Schmaltz, PRD 66, 036005, 2002

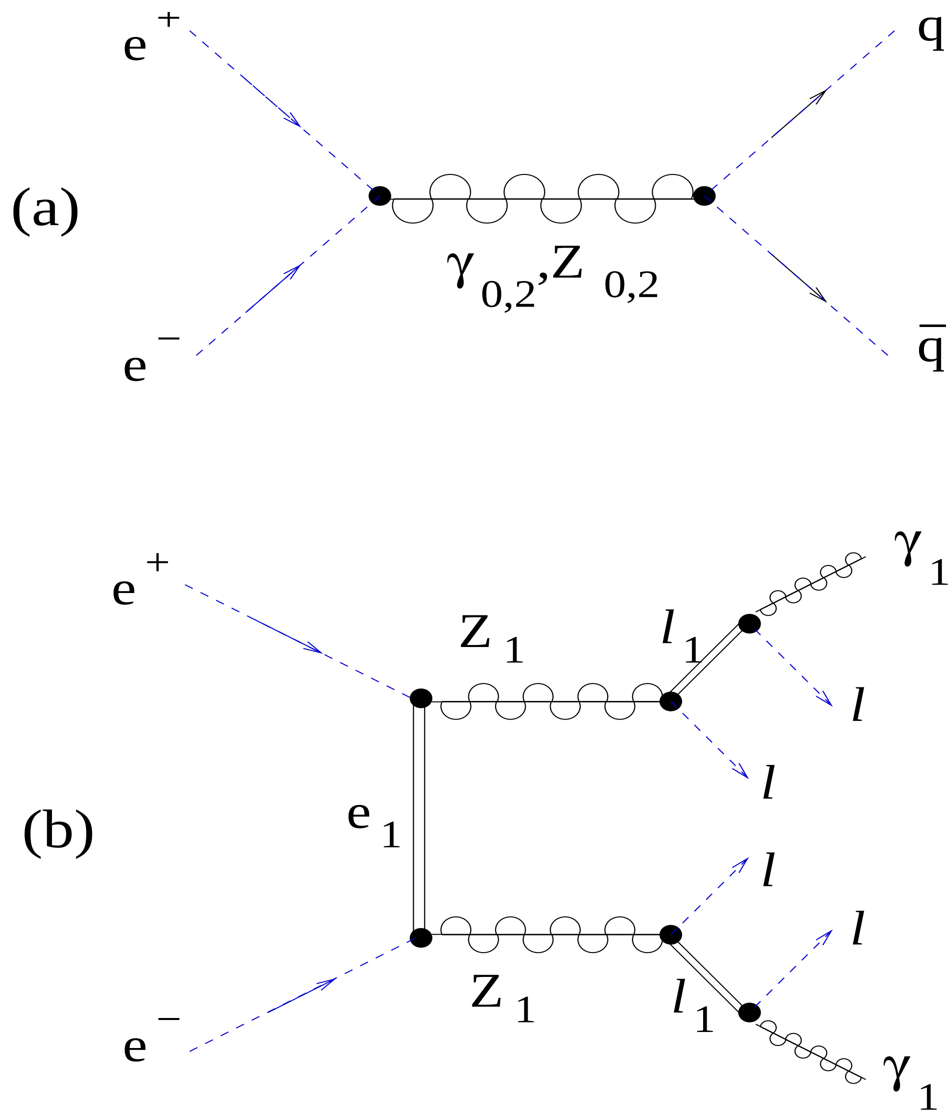
Energy spectrum



Normalized muon energy distribution coming from diffrent UED particles R^{-1}=350 GeV (Red line: muon from $H_1^{\pm}$, Blue line: muon from m_2,Green line: muon from m_1, Cyan line: muon from $W_1^{\pm}$)

Bump hunting at the CLIC




(a)
e+
e−
q
q̄
γ 0,2,Z 0,2
(b)
e+
e−
Z 1
Z 1
e 1
l 1
l 1
l
l
l
l
γ 1
γ 1