

# Contrasting Supersymmetry and Universal Extra Dimensions at the CLIC Multi-TeV $e^+e^-$ Collider

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[hep-ph/0502041](https://arxiv.org/abs/hep-ph/0502041)

*2005 International Linear Collider Workshop  
Stanford University  
March 18-22, 2005*

# Plan

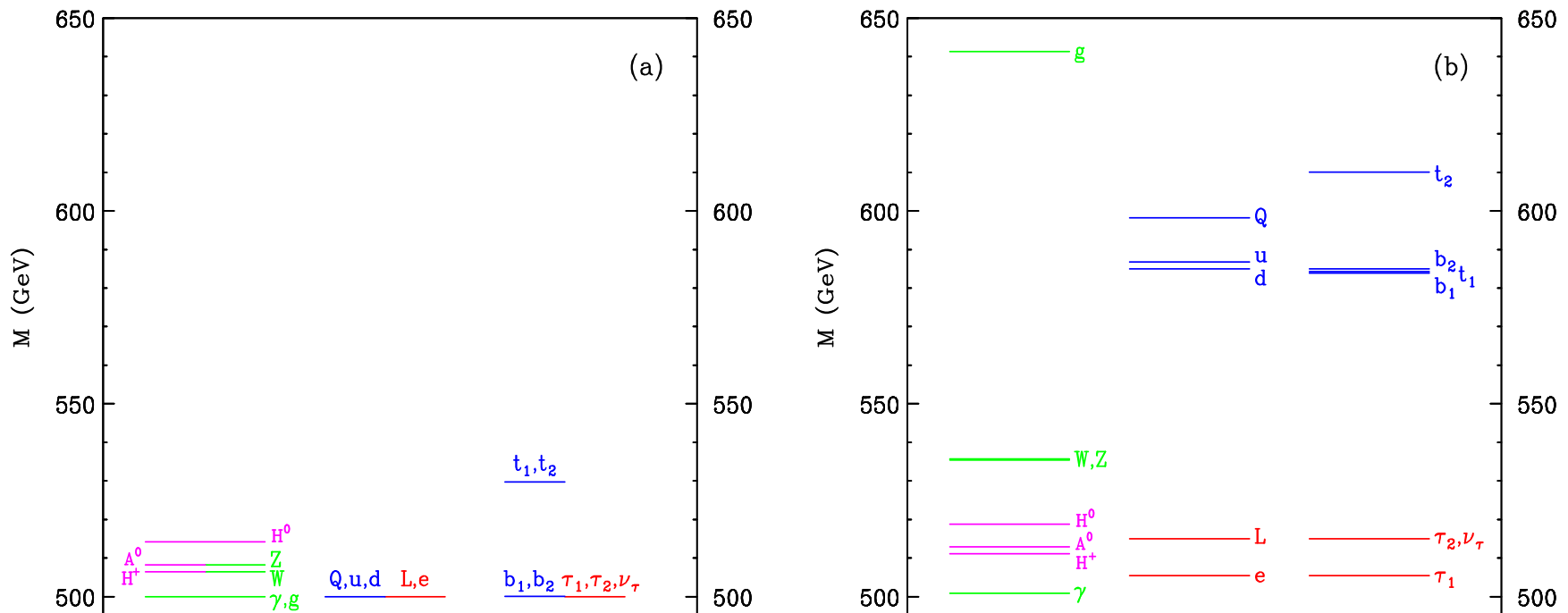
- Minimal Universal Extra Dimensions (MUEDs)
- Collider phenomenology of MUEDs
- Discovery reach for MUEDs at LHC
  - $4l + \cancel{E}_T$  with Level 1 KK
  - $2l$  with Level 2 KK
- Spin determination at LHC
- Phenomenology at  $e^+e^-$  collider :  $\mu^+\mu^- + \cancel{E}_T$ 
  - Angular distribution
  - $\mu$  energy distribution
  - Threshold scan
  - Photon energy distribution
- Summary

# Minimal Universal Extra Dimensions

- UEDs : All SM particles in the bulk!  
Appelquist, Cheng, Dobrescu hep-ph/0012100
- Minimal model :  $d=4+1$ , ED compactified on  $S^1/Z_2$
- Symmetries
  - $Z_2$  : project out unwanted zero modes and introduce chiral fermions in 5D
  - KK number : broken down to KK parity  
 $(-1)^n \Rightarrow$  Lightest KK particle is stable
- KK towers for each SM particle
  - identical spins/couplings as the SM particles
  - unknown masses of order of  $n/R$
- The model is very predictive :  $\{R, \Lambda, m_h\}$
- EW constraints      Appelquist, Cheng, Dobrescu hep-ph/0012100  
Appelquist, Yee hep-ph/0211023
  - no effect at tree level due to KK parity
  - $R^{-1} \geq 250 GeV$
- Cosmological bound      Servant, Tait hep-ph/0206071
  - $\Omega h^2 < 0.129$
  - $R^{-1} \leq \mathcal{O}(1) TeV$

# Mass Spectrum : Tree level and radiative corrections

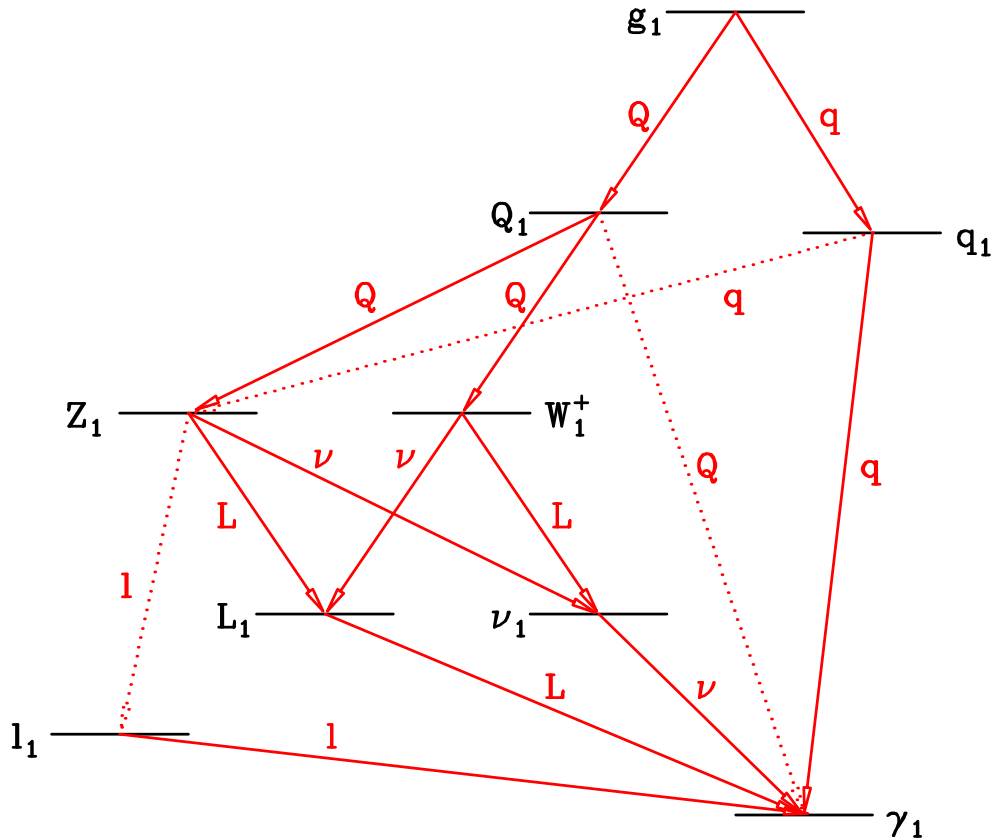
(Cheng, Matchev, Schmaltz, hep-ph/0204342, hep-ph/0205314)



- Tree level mass  $m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m^2}$ ,  $e_1$  is stable ...
- Radiative corrections are important ! (Cheng, Matchev, Schmaltz)
  - All but LKP decay promptly  $\rightarrow$  missing energy signals

# Collider phenomenology of MUEDs

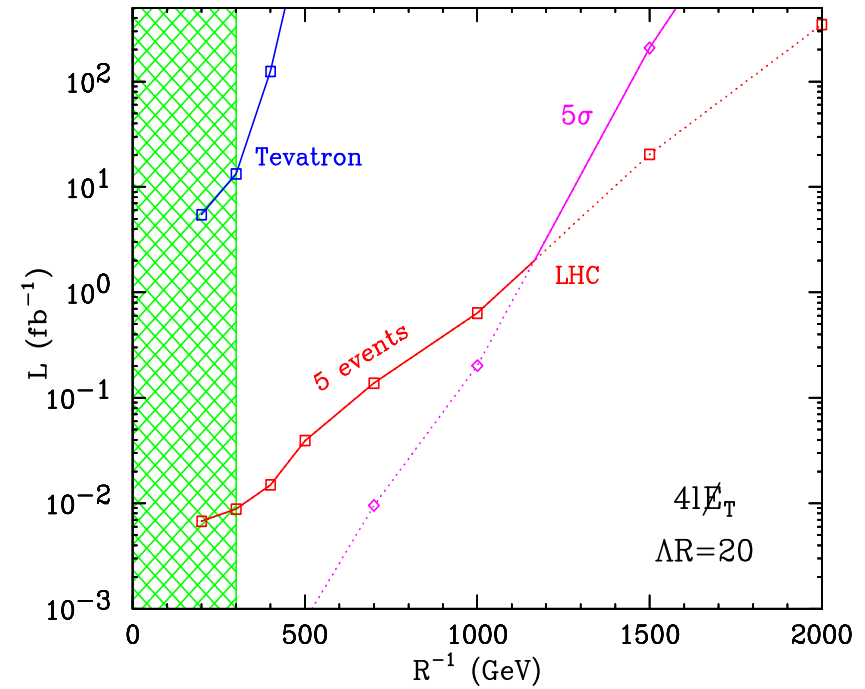
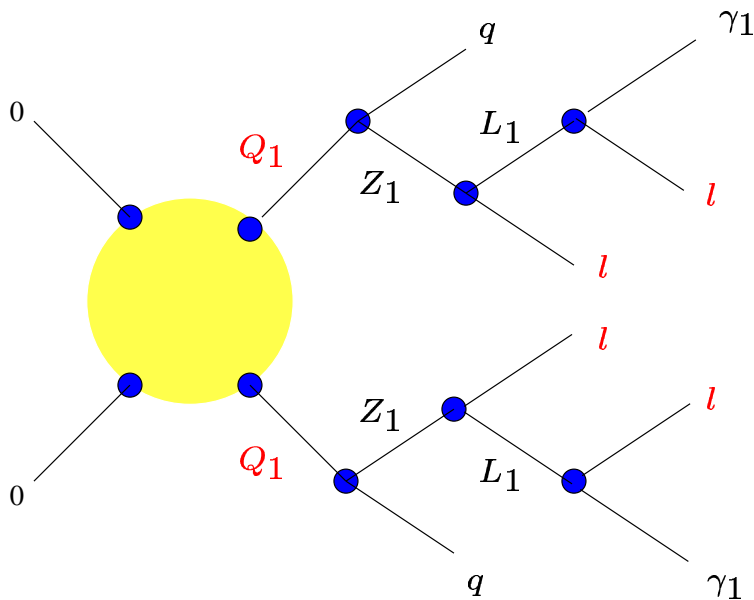
(Cheng, Matchev, Schmaltz, hep-ph/0205314)



- 1st Level looks like SUSY
- KK gluon :  $BR(g_1 \rightarrow Q_1 Q_0) \approx BR(g_1 \rightarrow q_1 q_0) \sim 0.5$
- SU(2) singlet KK quarks :  $q_1 \rightarrow \gamma_1 q_0$
- SU(2) doublet KK quarks :  $Q_1 \rightarrow W_1 Q'_0$  or  $Z_1 Q_0$
- KK W and Z bosons : only leptonic decays
- KK leptons : 100 % directly to LKP
- Weinberg angles for KK small :  $Z_1 \sim W_1^3$  and  $\gamma_1 \sim B_1$
- At hadron collider we want : strong production and weak decays

# UED discovery reach at the Tevatron and LHC

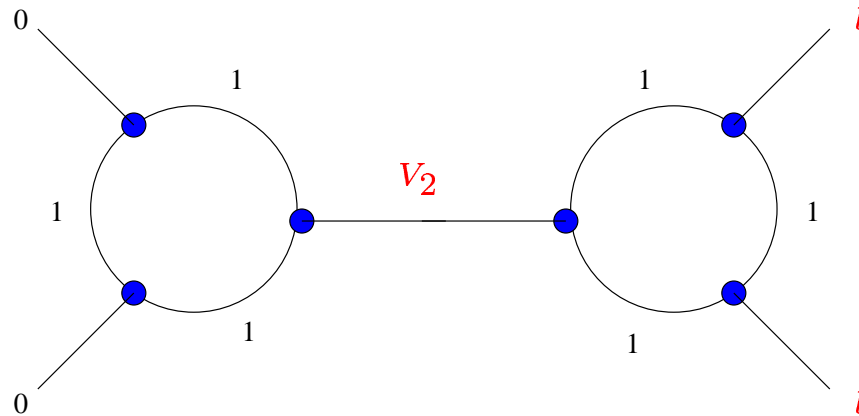
(Cheng, Matchev, Schmaltz, hep-ph/0205314)



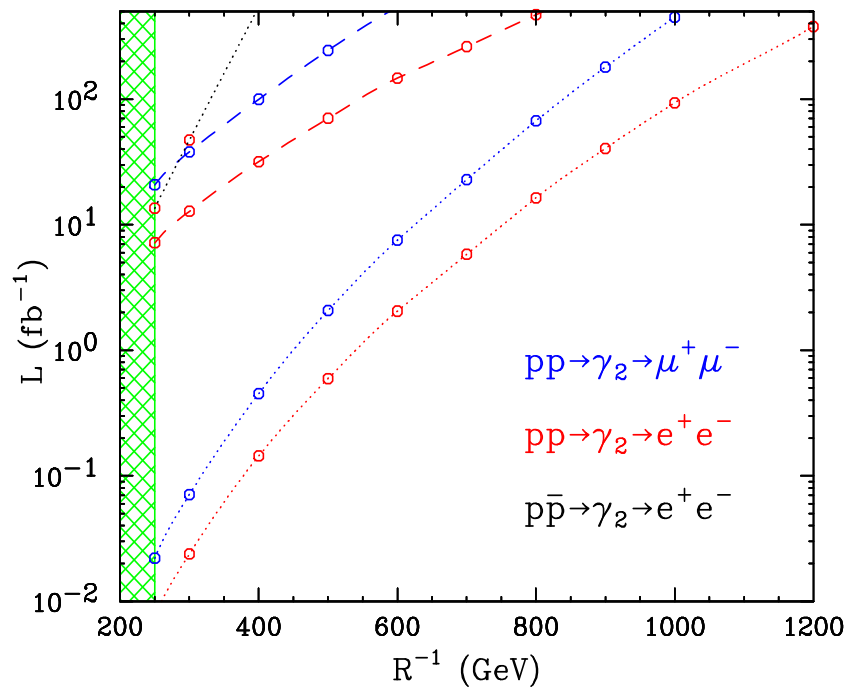
- Discovery reach in the  $Q_1 Q_1 \rightarrow Z_1 Z_1 \rightarrow 4l + \cancel{E}_T$  channel

# Discovery reach for level 2 at LHC

- SUSY or UED ? Look for  $n=2$  resonances



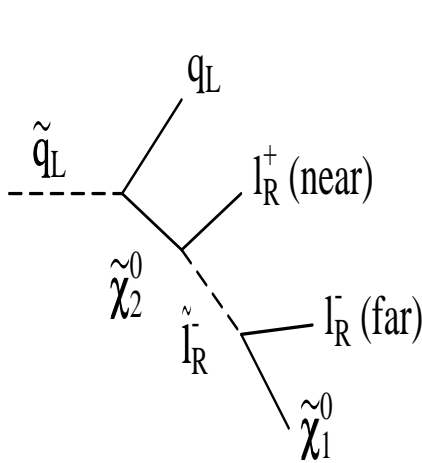
(Datta, Kong, Matchev, Preliminary)



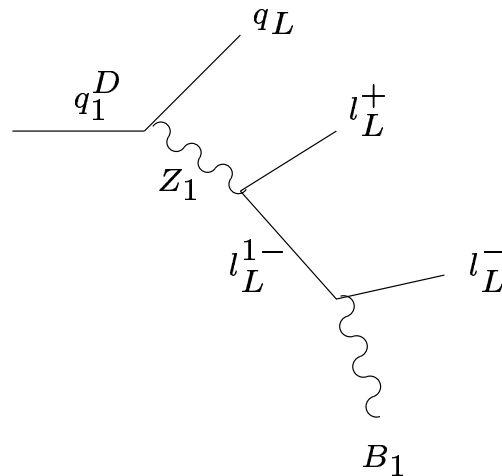
- $|p_t| > 20 \text{ GeV}, |\eta| < 2.4$
- $|M_{l+l-} - M_{V_2}| < 2\Gamma_{l+l-}$
- $\Gamma_{\mu^+\mu^-} \approx \text{Mass resolution} (\Gamma_{V_2} \ll 1\text{GeV})$
- $Z'$  ?

# How to distinguish the models at LHC

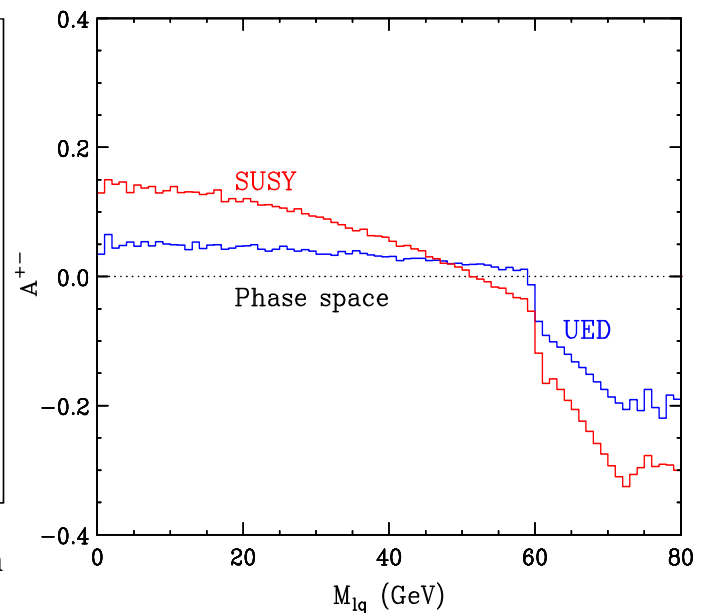
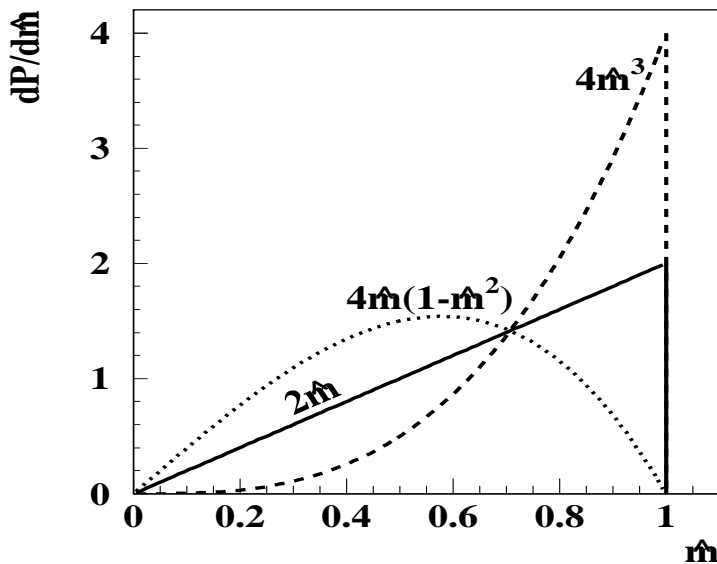
- Level 1 KK looks like SUSY
- Level 2 KK bosons look like  $Z'$  in SUSY  
→ Need to measure the spins !
- Charge asymmetry (Barr, Phys.Lett.B596:205-212,2004)



(Barr, Phys.Lett.B596:205-212,2004)



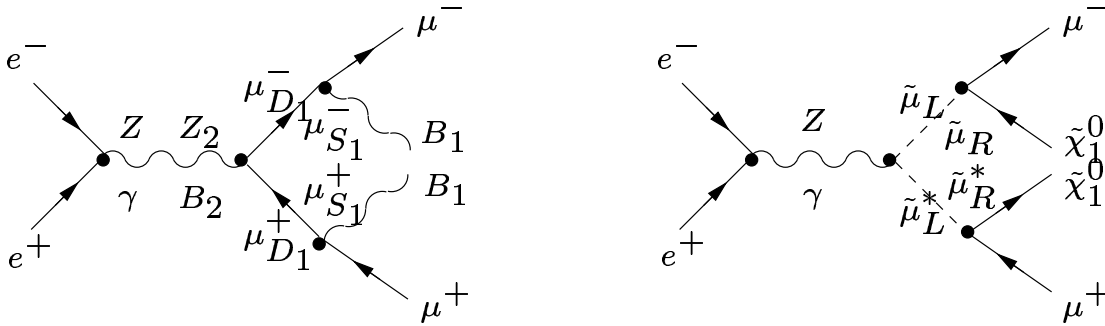
(Datta, Kong, Matchev, Preliminary)



- Same sign of asymmetry :  $A^{+-} = \frac{s^+ - s^-}{s^+ + s^-}$ ,  $s^\pm = \frac{d\sigma}{d(m_{l\pm q})}$
- Chirality of sleptons



# SUSY vs UED at LC in $\mu^+\mu^- + \cancel{E}_T$ channel



- Angular distribution

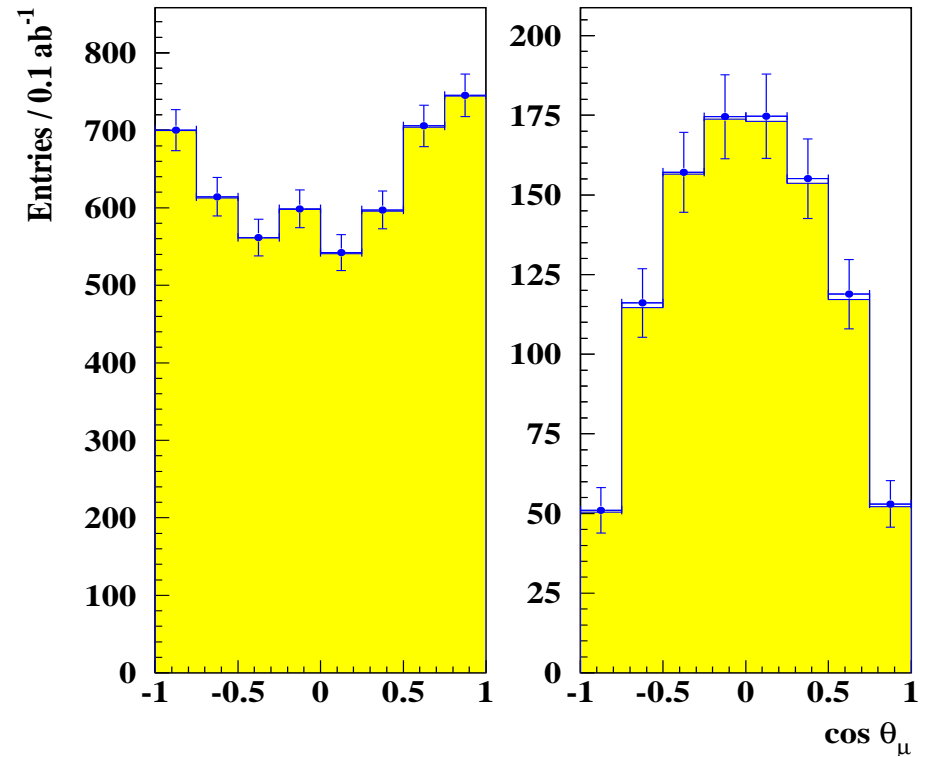
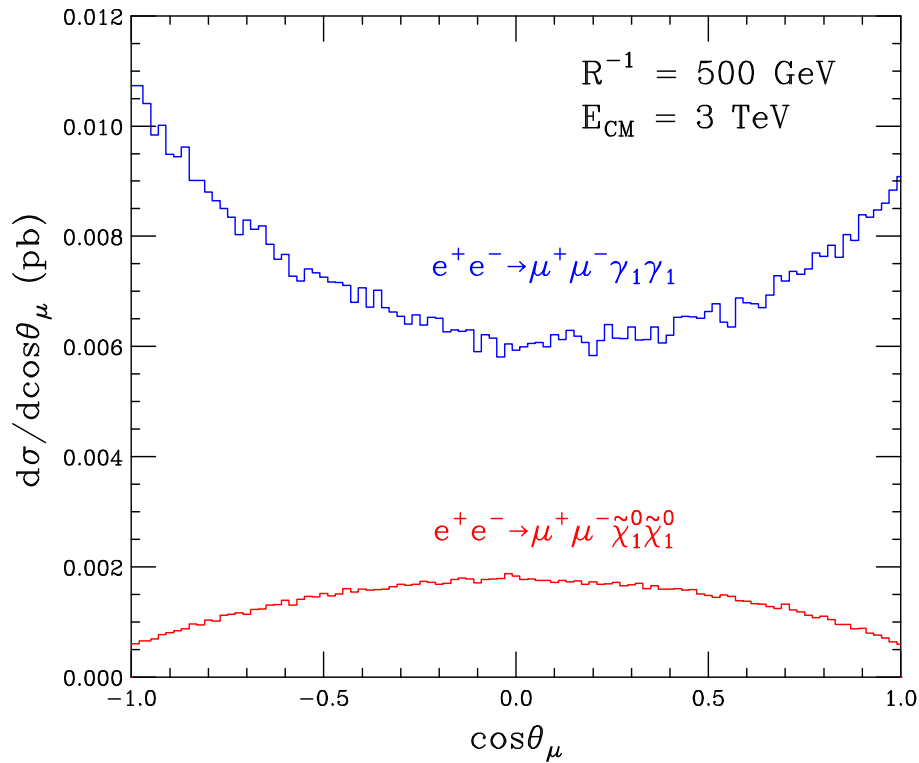
$$\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \frac{E_{\mu_1}^2 - M_{\mu_1}^2}{E_{\mu_1}^2 + M_{\mu_1}^2} \cos^2\theta \quad \left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$$

$$\sim 1 + \cos^2\theta$$

- $\mu^-$  energy distribution
- Threshold scan
- Photon energy distribution

# The Angular Distribution (LC)

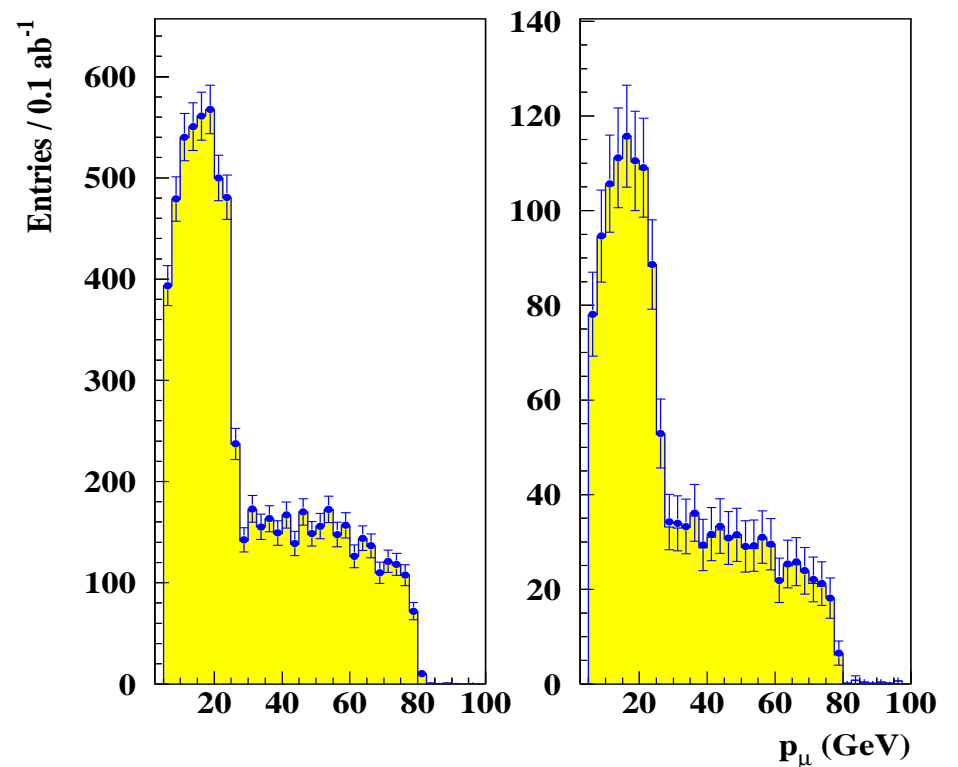
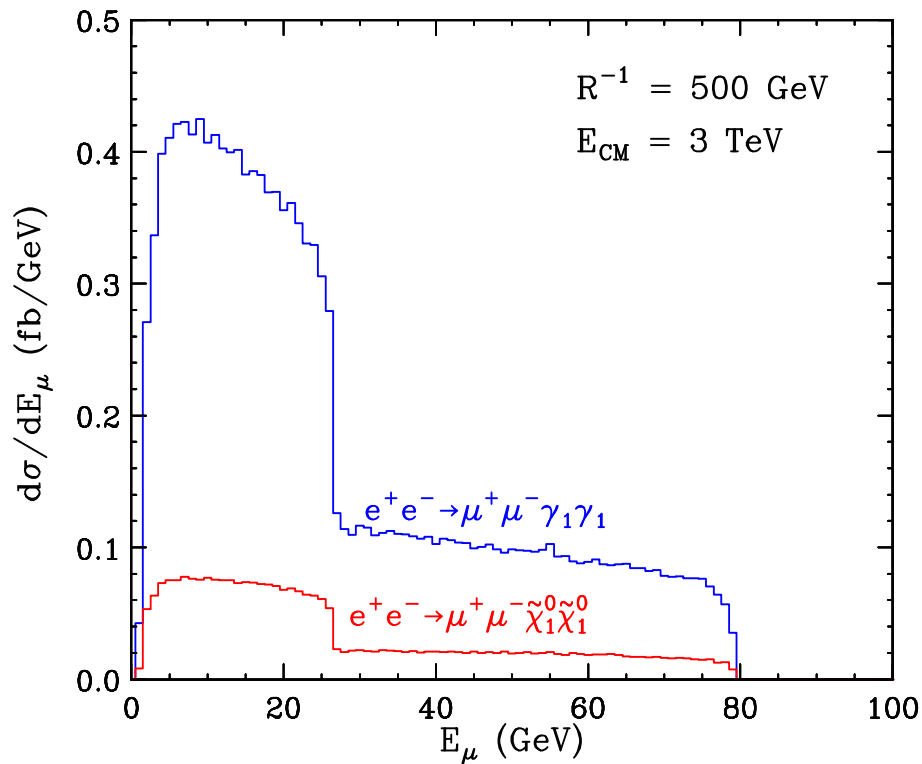
(Battaglia, Datta, De Roeck, Kong, Matchev, hep-ph/0502041 )



- $\left(\frac{d\sigma}{d\cos\theta}\right)_{UED} \sim 1 + \cos^2\theta$
- $\left(\frac{d\sigma}{d\cos\theta}\right)_{SUSY} \sim 1 - \cos^2\theta$

# The $\mu$ Energy Distribution (LC)

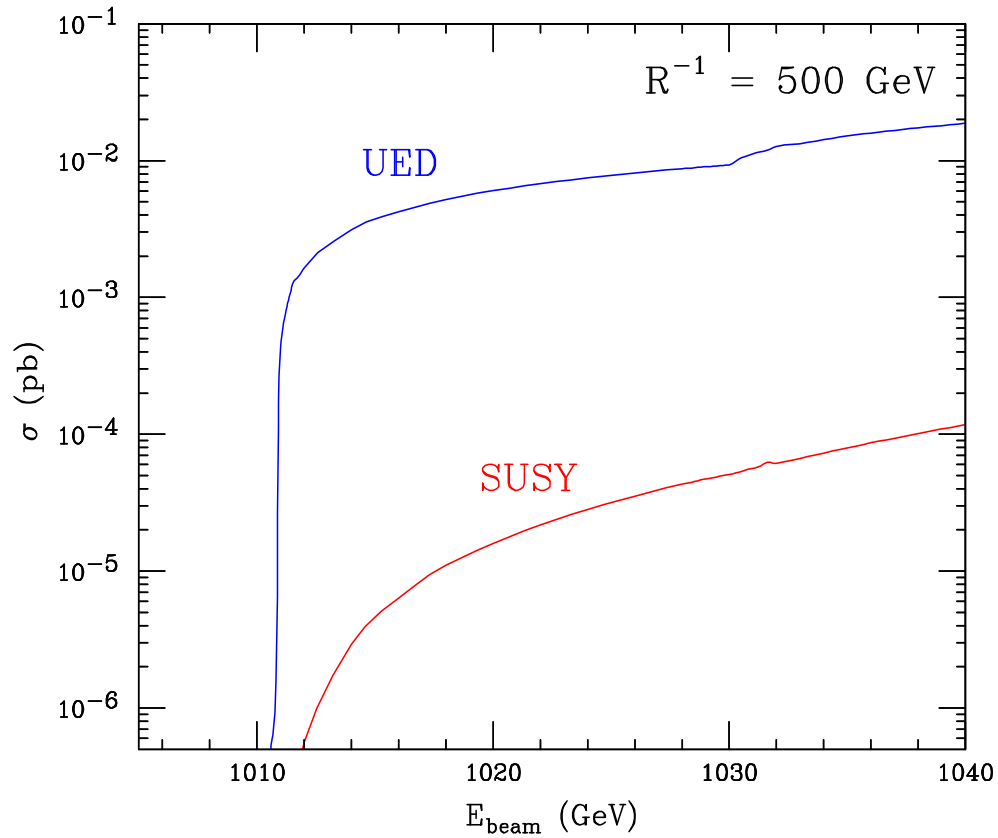
(Battaglia, Datta, De Roeck, Kong, Matchev, hep-ph/0502041 )



- $E_{\text{max/min}} = \frac{1}{2}M_{\mu^*} \left( 1 - \frac{M_N^2}{M_{\mu^*}^2} \right) \gamma(1 \pm \beta)$ 
  - $M_{\mu^*}$  : mass of smuon or KK muon
  - $M_N$  : LSP or LKP mass
  - $\gamma = \frac{1}{\sqrt{1-\beta^2}}$  with  $\beta = \sqrt{1 - M_{\mu^*}^2/E_{\text{beam}}^2}$  ( $\mu^*$  boost)

# Threshold scans (LC)

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



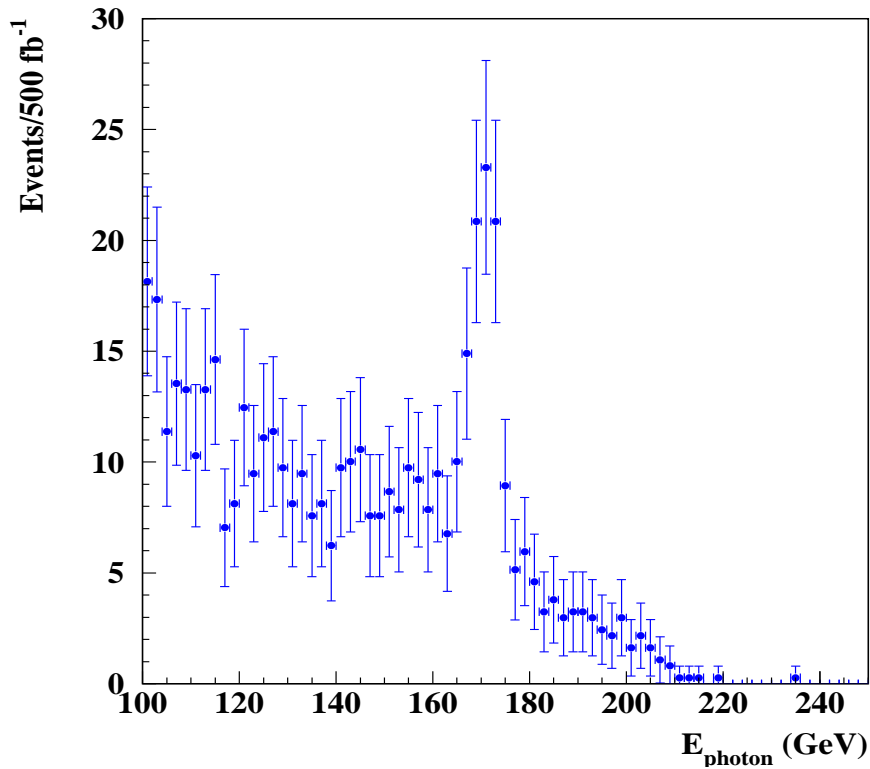
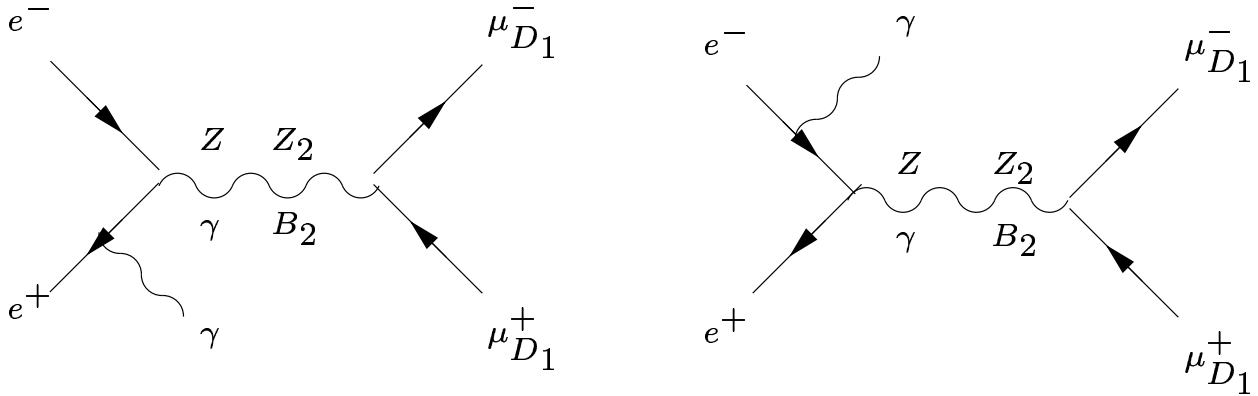
- Mass determination
- Cross section at threshold

– in UED  $\propto \beta$

– in MSSM  $\propto \beta^3$   $\left( \beta = \sqrt{1 - \frac{M^2}{E_{\text{beam}}^2}} \right)$

# The Photon Energy Distribution (LC)

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



- Smuon production is mediated by  $\gamma$  and  $Z$
- On-shell  $Z_2 \rightarrow \mu_1 \bar{\mu}_1$  is allowed by phase space
- Radiative return due to  $Z_2$  pole at  $E_\gamma = \frac{s - M_{Z_2}^2}{2\sqrt{s}}$

# Summary

- LHC can probe most parameter space in MUED
  - $4l + \cancel{E}_T$  with Level 1 KK
  - $2l$  with Level 2 KK
- MUED can fake SUSY
  - Level 1 KK just looks like SUSY
  - Level 2 KK looks like supersymmetric  $Z'$
- How do we distinguish at LHC ?
  - Charge asymmetry ?
  - Experimentally challenging (?)
  - Both MUED and SUSY have similar asymmetry
  - Difficult to get spin information at hadron collider
    - Linear collider
- $\mu^+ \mu^- + \cancel{E}_T$  channel
  - Angular distribution
  - Threshold scan
  - $\mu^-$  energy distribution → mass determination
  - Photon energy distribution →  $Z_2$