

**Implementing Universal Extra Dimensions  
in COMPHEP**

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## Outline

- UED as a SUSY “look-alike”
- Basic facts about UED model
  - KK-number  $n$  versus KK-parity  $(-1)^n$
  - Interactions of KK modes
  - KK mass spectrum - importance of radiative corrections
  - Widths of the KK modes
- UED phenomenology at hadron colliders
- Why did we choose COMPHEP?
- Details of the implementation
- Contrasting UED and supersymmetry (Marco)



## Identifying the new physics

- When we discover supersymmetry, how will we know it is not ...
  - something else? Bad question.
  - extra dimensions (KK gravitons)? Easy.
  - “little Higgs”? Easy.
  - technicolor? Easy.
  - something that looks like SUSY yet is not SUSY (example: UED)?
- UED was **not** invented for the purpose of faking SUSY and has sufficient motivation on its own.
  - EWSB (Arkani-Hamed, Cheng, Dobrescu, Hall...)
  - neutrino masses (Appelquist, Dobrescu, Ponton, Yee; Mohapatra, Perez-Lorenzana)
  - number of generations (Dobrescu, Poppitz)
  - proton stability (Appelquist, Dobrescu, Ponton, Yee)
  - dark matter (Servant, Tait; Cheng, Feng, KM)



## Fermionic extra dimensions (supersymmetry)

- Supersymmetry is an extra dimension theory with new **anticommuting** coordinates  $\theta_\alpha$ :

$$\Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha$$

- If  $\psi^\alpha$  are the SM fermions,  $\phi$  are their superpartners (sfermions) with
  - spins differing by 1/2
  - identical couplings
  - unknown masses
- Discovering new particles with those properties **IS** discovering supersymmetry
- $R$ -parity conservation  $\implies$  stable LSP.
- Neutral LSP (neutralinos)  $\implies$  SUSY WIMPs.



## Bosonic extra dimensions (UED, bosonic supersymmetry)

Appelquist, Cheng, Dobrescu, hep-ph/0012100

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

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

- If  $\phi$  is a SM field,  $\phi^n$  and  $\chi^n$  are KK partners with
  - identical spins
  - identical couplings
  - unknown masses of order  $n/R$
- Discovering new particles with those properties IS discovering extra dimensions
- Conservation of  $KK$ -number  $n$  (valid only at tree level)
- Conservation of  $KK$ -parity  $(-1)^n \implies$  stable LKP.
- Neutral LKP ( $B_\mu^1$ )  $\implies$  Kaluza-Klein WIMP.

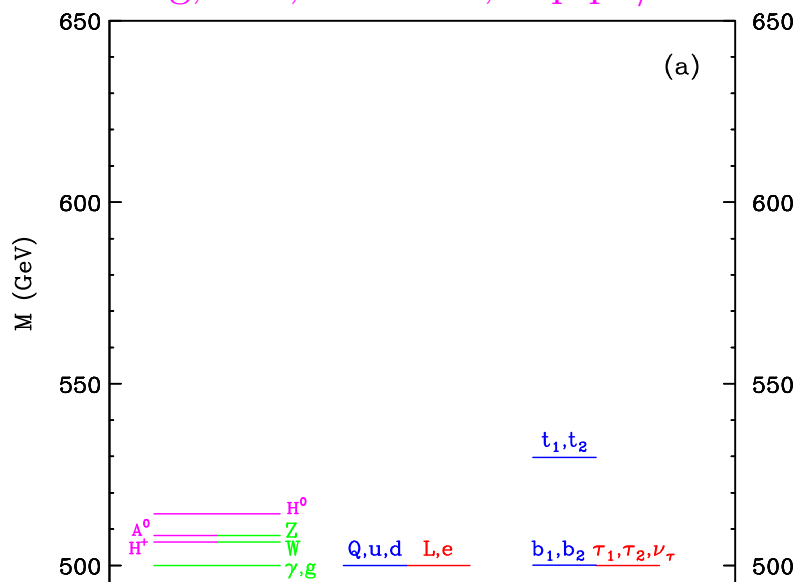


## UED Spectrum

- **Universal** extra dimensions: everybody in the bulk. There is a KK tower of states for every SM particle.
- The KK modes at each KK level  $n$  are extremely degenerate:

$$m_n^2 = \left(\frac{n}{R}\right)^2 + m_0^2$$

Cheng, KM, Schmaltz, hep-ph/0204342



- The radiative corrections are crucial for phenomenology, e.g.

$$e_1 \rightarrow \gamma_1 e_0?$$

$$m_{e_1} - (m_{\gamma_1} + m_{e_0}) \sim -R^{-1} \left(\frac{m_e}{R^{-1}}\right) \sim -R^{-1} 10^{-6}$$

- Lots of stable (charged, colored) heavy particles...

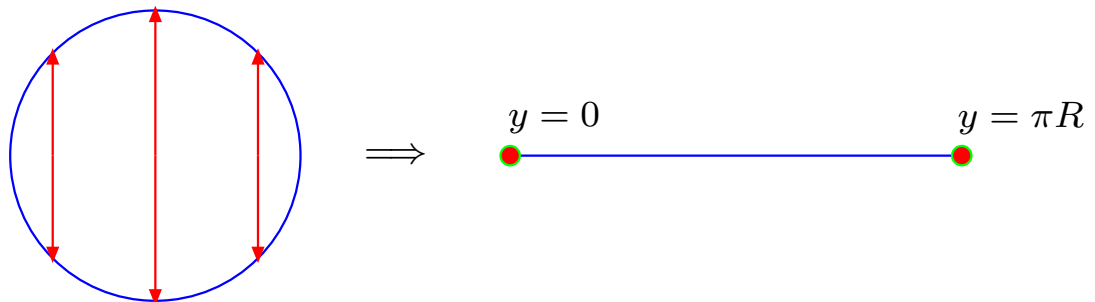


## UED interactions (KK number versus KK parity)

- Bulk interactions:

$$S = \int d^4x dy \mathcal{L}_{SM}$$

- Bulk interactions conserve KK number  $\Leftarrow p_y$  conservation.
- Allowed decays:  $1 \rightarrow 10$ ;  $2 \rightarrow 20, 2 \rightarrow 11$ ;  $3 \rightarrow 30, 3 \rightarrow 21$ .
- Not really a circle, but orbifold  $S_1/Z_2$ :



- Boundary interactions:

$$S = \int d^4x dy \left[ \delta(y) + \delta(y - \pi R) \right] \left\{ F_4(\mu) \bar{\Psi} i \not{D} \Psi + \dots \right\}$$

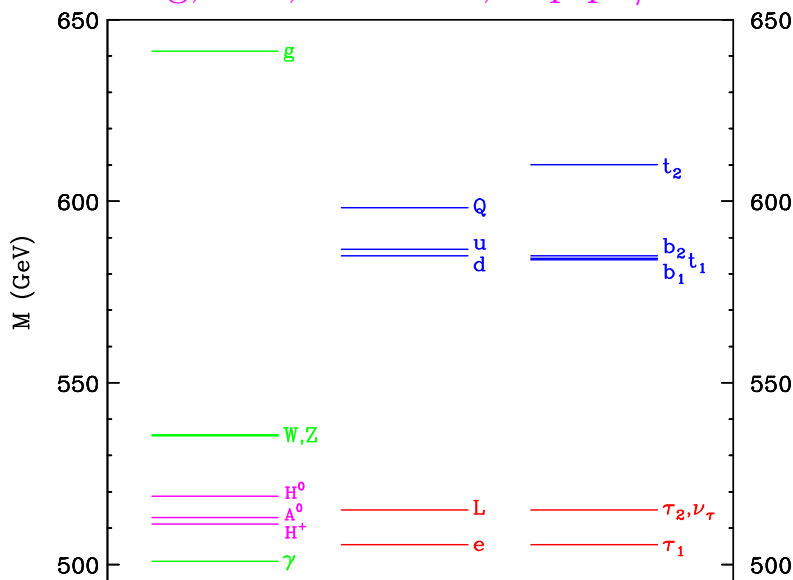
- Boundary terms break KK number  $n$  down to KK parity  $(-1)^n$
- Additional allowed decays:  $2 \rightarrow 00, 3 \rightarrow 10$ .



## Bosonic supersymmetry spectrum

- Including radiative corrections due to both bulk and boundary terms, the KK mass spectrum for  $n = 1$  looks something like this:

Cheng, KM, Schmaltz, hep-ph/0204342



- Mimics (fermionic) supersymmetry!
- Prompt decays of all KK modes except LKP.
- Seems difficult to discover at the LHC, but...
- $W_1^\pm, Z_1$  have pure leptonic branchings!
- $\sin^2 \theta_W^1 \approx 0 \implies \gamma^1 \approx B^1$ , similar to  $\tilde{B}$  in SUSY.



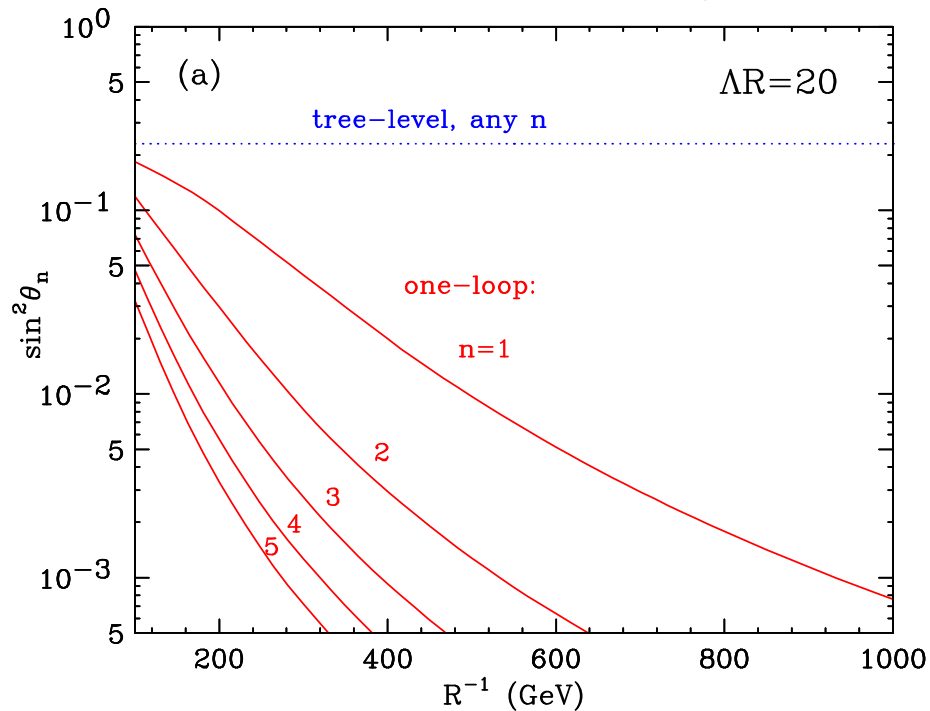
## The KK Weinberg Angle

- Mass matrix for the neutral gauge bosons

$$\begin{pmatrix} \frac{n^2}{R^2} + \frac{1}{4}g_1^2v^2 + \hat{\delta}m_{B_n}^2 & \frac{1}{4}g_1g_2v^2 \\ \frac{1}{4}g_1g_2v^2 & \frac{n^2}{R^2} + \frac{1}{4}g_2^2v^2 + \hat{\delta}m_{W_n}^2 \end{pmatrix}$$

- The Weinberg angle  $\theta_n$  at KK level  $n$ 
  - At tree level: the same for all  $n$
  - At one loop: decreasing with  $n$ , much smaller than  $\theta_0$ .

Cheng, KM, Schmaltz, hep-ph/0204342

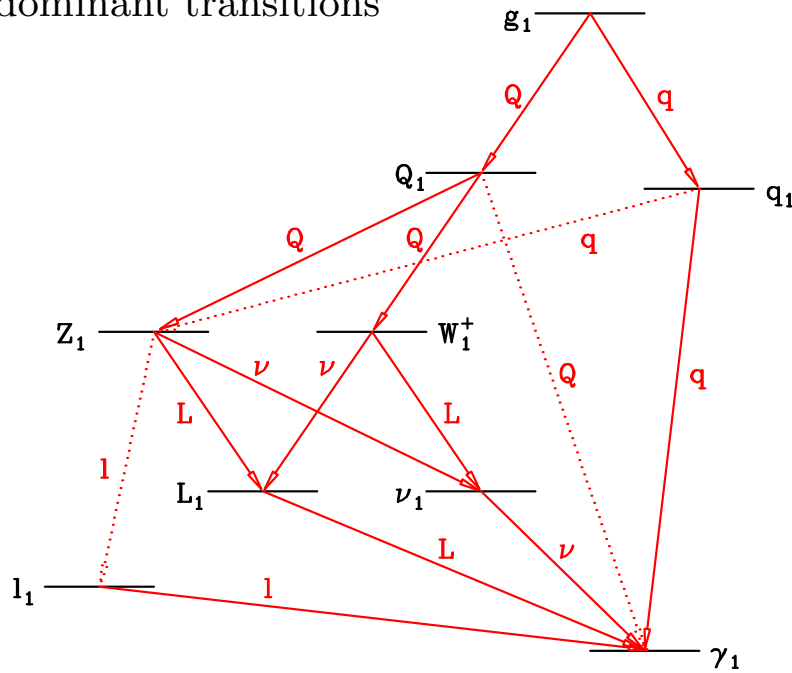


- KK gauge bosons implemented in the approximation  $\theta_n = 0$ .



## Level 1 Spectroscopy

- Allowed dominant transitions



- KK gluon:  $B(g_1 \rightarrow Q_1 Q_0) \simeq B(g_1 \rightarrow q_1 q_0) \simeq 0.5$ .
- Singlet KK quarks: preferentially  $q \rightarrow \gamma_1 q_0$
- Doublet KK quarks:

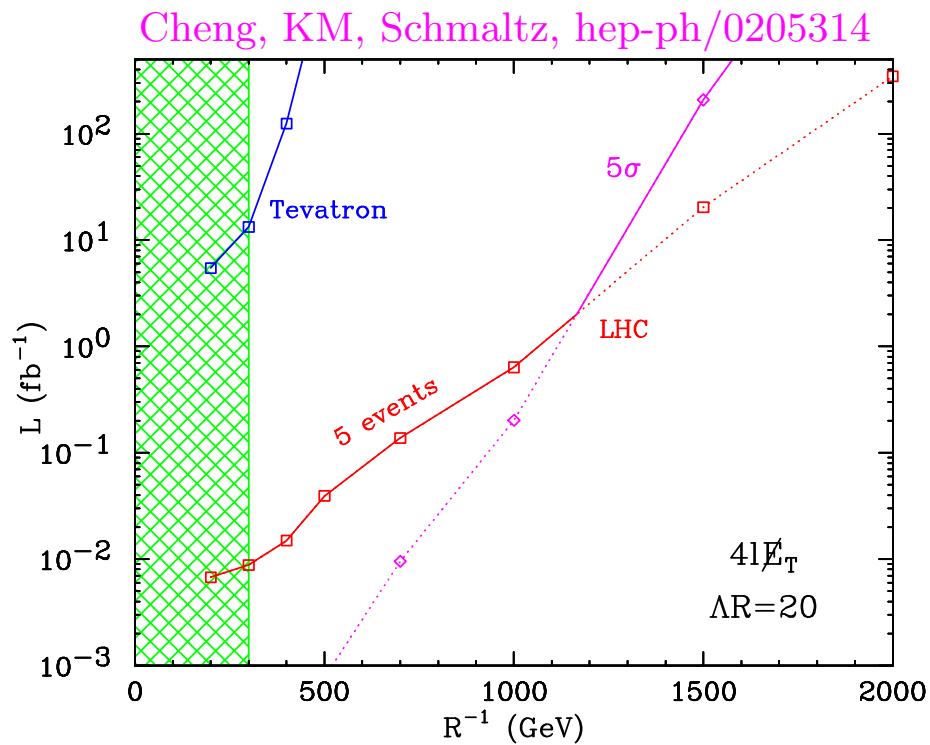
$$B(Q_1 \rightarrow W_1^\pm Q'_0) \sim 65\% \quad B(Q_1 \rightarrow Z_1 Q_0) \sim 33\%$$

- KK  $W$ - and  $Z$ -bosons: only leptonic decays!
- KK leptons: 100% directly to the LKP.
- At hadron colliders we want: **strong** production, **weak** decays!



## UED discovery reach at Tevatron/LHC

- Discovery reach in the  $Q_1 Q_1 \rightarrow 4\ell \cancel{E}_T$  channel.

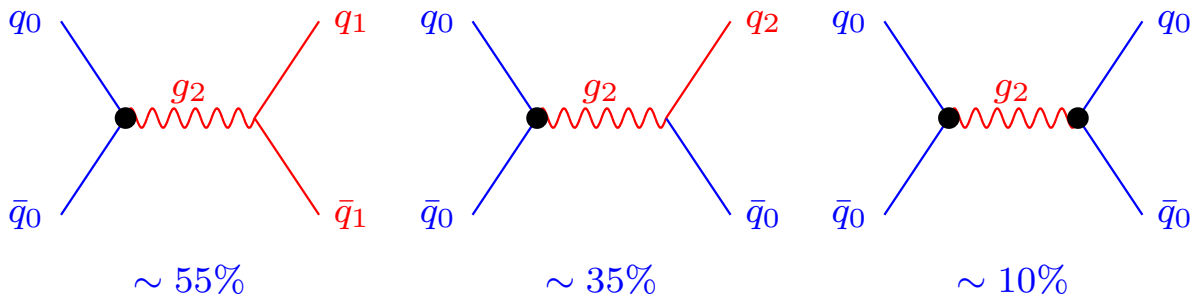


- Typical signatures include:
  - soft leptons, soft jets, not a lot of  $\cancel{E}_T$
  - a lot of missing mass (LHC can't measure it)



## Bosonic or fermionic supersymmetry?

- Can you tell SUSY from UED?
- Yes. Tenth Conference on String Phenomenology in 2011.  
[J.Ellis hep-ph/0208109](#)
- Look for the higher KK levels: e.g.  $g_2$  resonance.
- Single production of KK level 2 is suppressed (involves KK-number violating couplings).



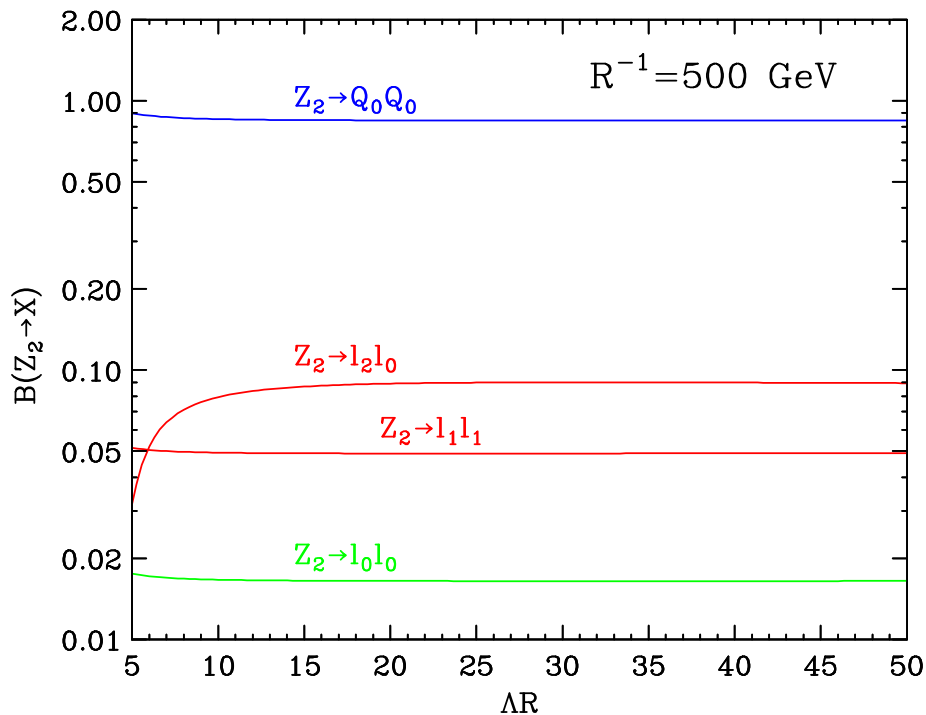
- $g_2$  appears a high mass dijet resonance. Coloron?  $Z'$ ?
- Pair production? Typically the rate is too small.



## Looking for KK level 2: $Z_2$ resonance

- $Z_2$  appears promising:  $Z_2 \rightarrow Q_1 Q_1$  and  $Z_2 \rightarrow Q_2 Q_0$  are closed. Lots of hard leptons? No!  $Z_2 \rightarrow Q_0 Q_0$  wins over  $Z_2 \rightarrow l_0 l_0$ .
- $Z_2$  branching fractions:

Datta, Kong, KM preliminary



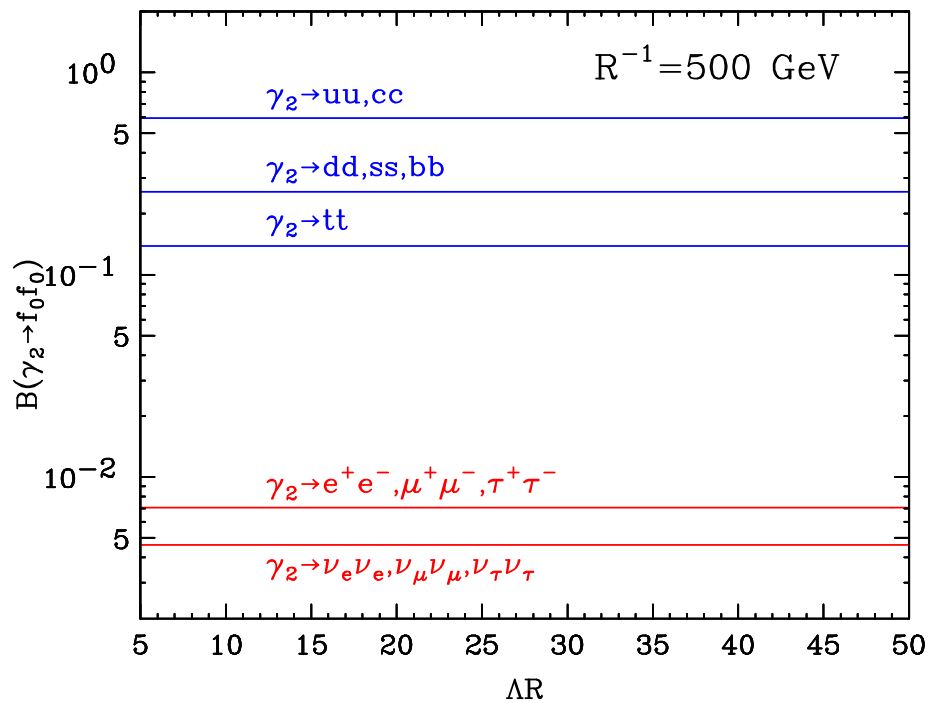
- $Z_2$  also a high mass dijet resonance. Coloron?  $Z'$ ?  $g_2$ ?



## Looking for KK level 2: $\gamma_2$ resonance

- $\gamma_2$  appears most promising. All  $\gamma_2 \rightarrow f_2 f_0$  and  $\gamma_2 \rightarrow f_1 f_1$  decays are closed. Every  $\gamma_2$  decay dumps a lot of energy.
- $\gamma_2$  branching fractions:

Datta, Kong, KM (preliminary)



- $\gamma_2$  **also** a high mass dijet resonance. Coloron?  $Z'$ ?  $g_2$ ?  $Z_2$ ?
- In all cases the natural width is negligible compared to the detector dijet mass resolution.



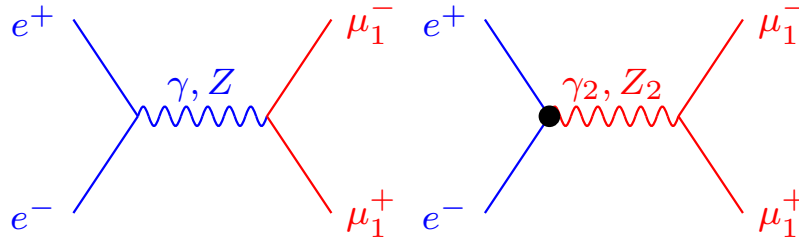
## UED implementation in COMPHEP

- Why COMPHEP?
  - Spin correlations accounted for.
  - Automated: ideal for new models which are straightforward generalizations of the Standard Model (UED, little Higgs).
  - Once the Feynman rules are defined, any final state signature can be studied.
  - It already has SUSY.
  - It is interfaced to PYTHIA.
  - The experimentalists know how to deal with it.
- What we have done so far:
  - Level 1 is fully implemented with correct 1-loop masses. Approximation:  $Z_1 \approx W_1^3$ ,  $\gamma_1 \approx B_1$ . Widths: reasonable guess, but can be recalculated with COMPHEP.
  - Level 2 partially implemented ( $Z_2 \approx W_2^3$ ,  $\gamma_2 \approx B_2$ ,  $\ell_2$ ) with the correct widths.

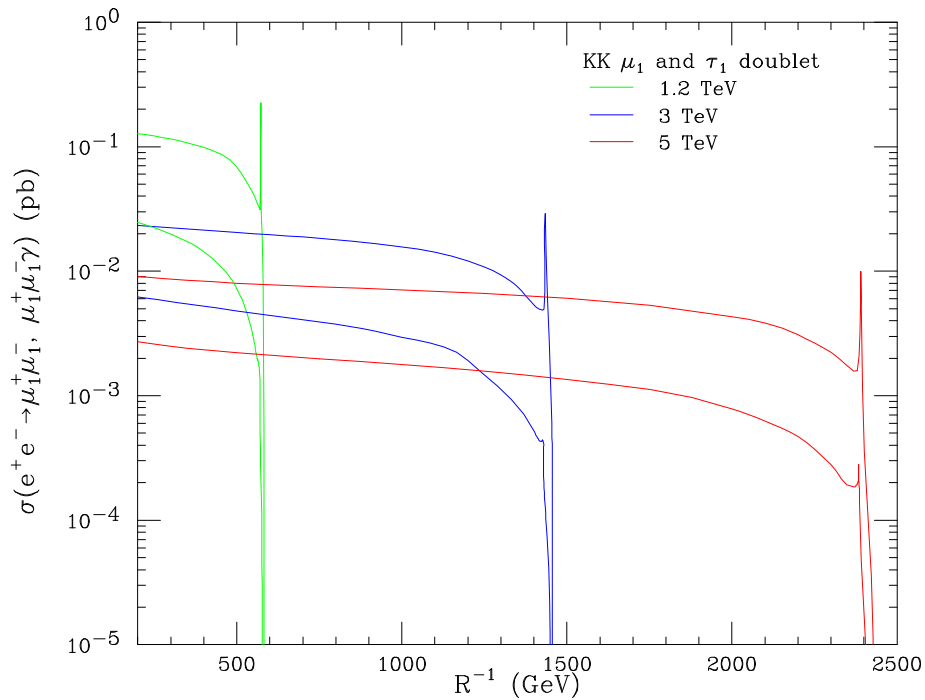


## UED phenomenology: Lepton colliders

- The importance of the level 2 widths.

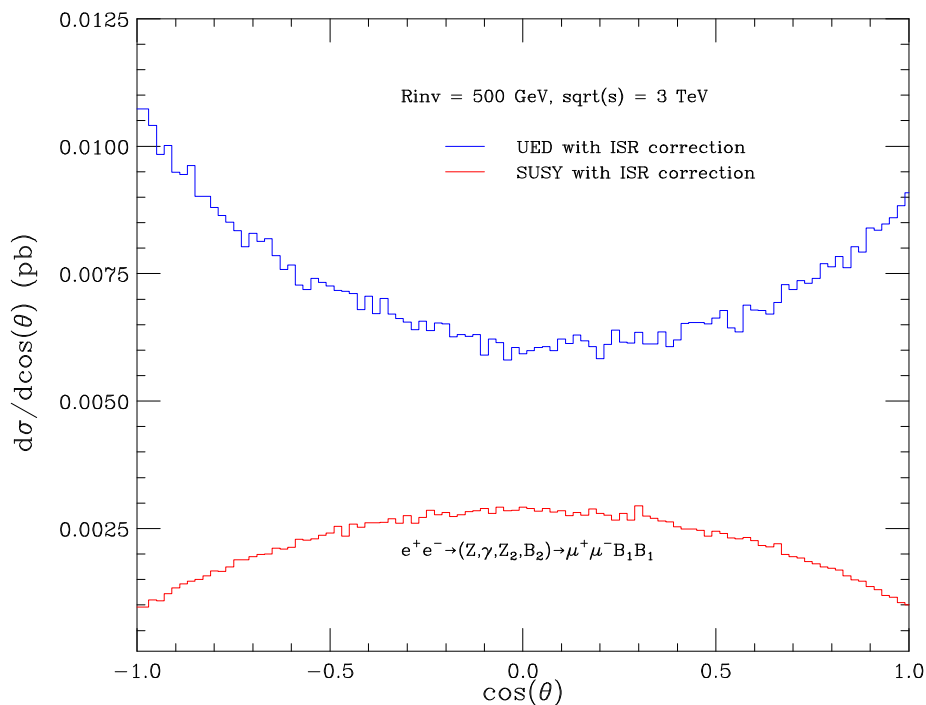


- Comparative study of SUSY and UED at LCs under way.



## UED versus supersymmetry

- The spin information is encoded in the angular distributions!
- Compare SUSY and UED for  $e^+e^- \rightarrow \mu_1^+ \mu_1^-$ :



- Significant difference in the total cross-section as well!
- The masses can be extracted from the  $E_\mu$  distribution.
- Threshold scan would confirm the spins.
- For details, stick around for Marco's talk.

