Universal Extra Dimensions

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Outline

- What kind of new physics is in store?
  - More of the same: new families, new gauge symmetries...
  - New dimensions: supersymmetry or extra dimensions!
- Universal Extra Dimensions (UED)
  - introduction, analogies to supersymmetry (SUSY)
  - collider phenomenology: discovery signatures at LHC
- Discriminating SUSY and UED
  - Discovery of the Kaluza-Klein tower
  - Spin measurements
  - Characteristic dark matter signals?

Supersymmetry

- Supersymmetry is an extra dimension theory with new anticommuting coordinates $\theta_\alpha \Longrightarrow$ superspace $\{x^\mu, \theta_\alpha\}$:

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

- SUSY relates SM particles and their superpartners ($\phi \leftrightarrow \psi$)
  - quarks, leptons $\Leftrightarrow$ squarks, sleptons
  - gauge bosons: g, $W^\pm$, W_3^0, B^0 $\Leftrightarrow$ gauginos: $\tilde{g}$, $\tilde{w}^\pm$, $\tilde{w}^0$, $\tilde{b}^0$
  - Higgs bosons: h^0, H^0, A^0, $H^\pm$ $\Leftrightarrow$ higgsinos: $\tilde{h}^\pm$, $\tilde{h}_u^0$, $\tilde{h}_d^0$
  - graviton: G $\Leftrightarrow$ gravitino: $\tilde{G}$
- The superpartners have
  - spins differing by 1/2
  - identical couplings
  - unknown masses (model-dependent)
- Prove discovery of SUSY $\Longleftrightarrow$ prove the above
- The superpartners are charged under a conserved R-parity
  - SM particles: $R = +1$
  - superpartners: $R = -1 \Longrightarrow$ stable LSP (DM?).
- No tree-level contributions to precision electroweak data

Universal Extra Dimensions

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):

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

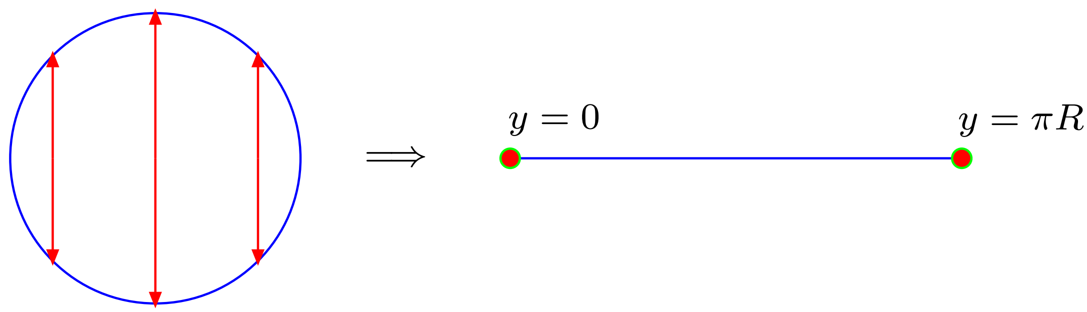
- Each SM field ϕ ($n = 0$) has an infinite tower of Kaluza-Klein (KK) partners ϕ^n and χ^n with
  - identical spins
  - identical couplings
  - unknown masses of order n/R
- Prove discovery of UED $\Longleftrightarrow$ prove the above
- KK number $n \Longleftarrow$ units of p_y.
- Bulk interactions: conserve KK number $\Longleftarrow$ p_y conservation.

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

- Problem: chiral fermions.

KK number versus KK parity

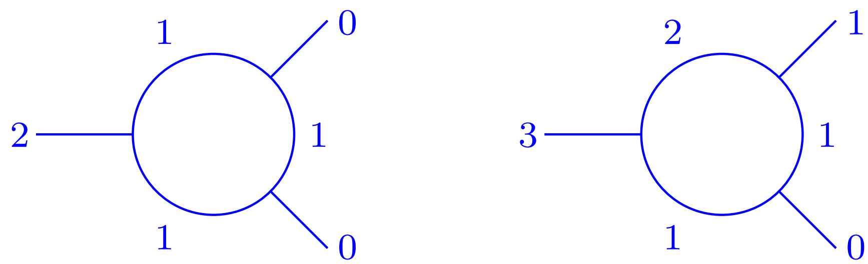
- The ED is not really a circle, but orbifold S_1/Z_2:



- Loop corrections generate boundary terms

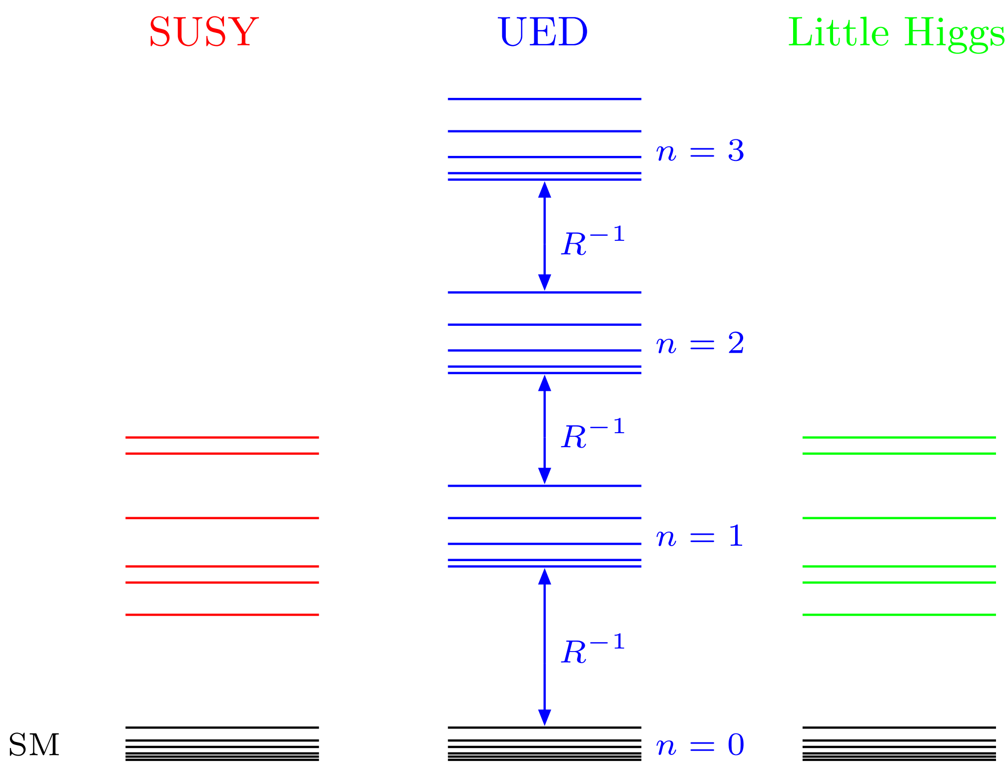
$$S = \int d^4x dy \left[\delta(y) + \delta(y - \pi R)\right] \left\{ F_4(\mu)\overline{\Psi} i \not{D} \Psi + \ldots \right\}$$

which break KK number n down to KK parity $(-1)^n$



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

An annoying proliferation of models



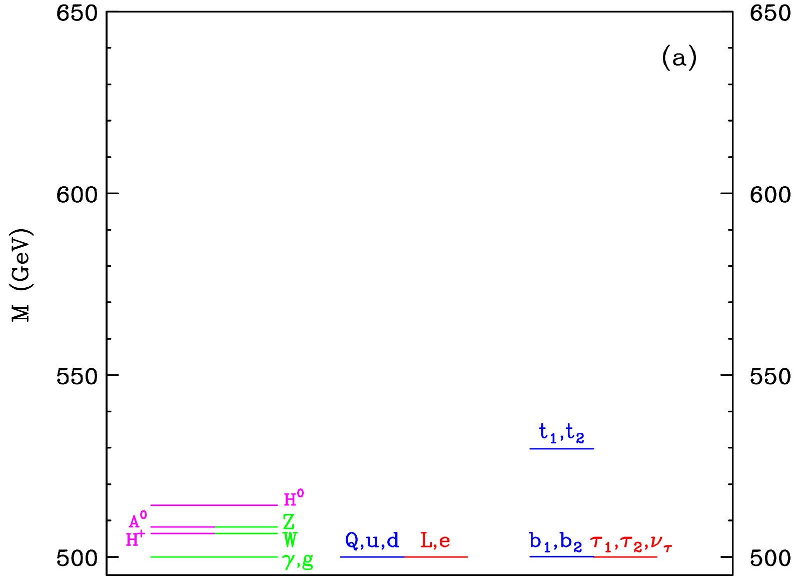
	SUSY	UED	Little Higgs
Symmetry	R-parity	KK-parity	T-parity
DM particle	LSP	LKP	LTP
Spin	1/2	1	0
Mass range	50-200 GeV	600-800 GeV	400-800 GeV

UED Spectrum - Tree level

- 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.

$$e_1 \longrightarrow \gamma_1 e_0?$$

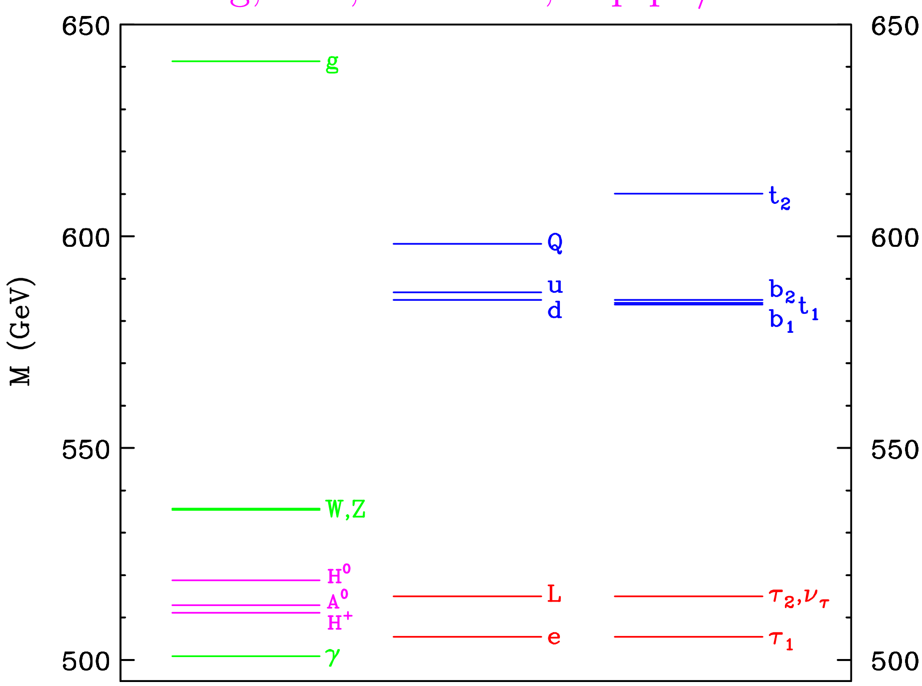
$$m_{e_1} - (m_{\gamma_1} + m_{e_0}) \sim -R^{-1}\left(\frac{m_e}{R^{-1}}\right) \sim -R^{-1}10^{-6}$$

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

UED spectrum at level 1

- Including radiative corrections, the mass spectrum of level 1 KK modes looks something like this: ($R^{-1} = 500$ GeV)

Cheng, KM, Schmaltz, hep-ph/0204342



- Mimics supersymmetry!
- Seems challenging: "degenerate SUSY"?
- $W_1^{\pm}$, Z_1 have pure leptonic branchings!
- $\sin^2\theta_W^1 \approx 0 \Longrightarrow \gamma^1 \approx B^1$, similar to $\tilde{B}$ in SUSY.

The KK Weinberg angles

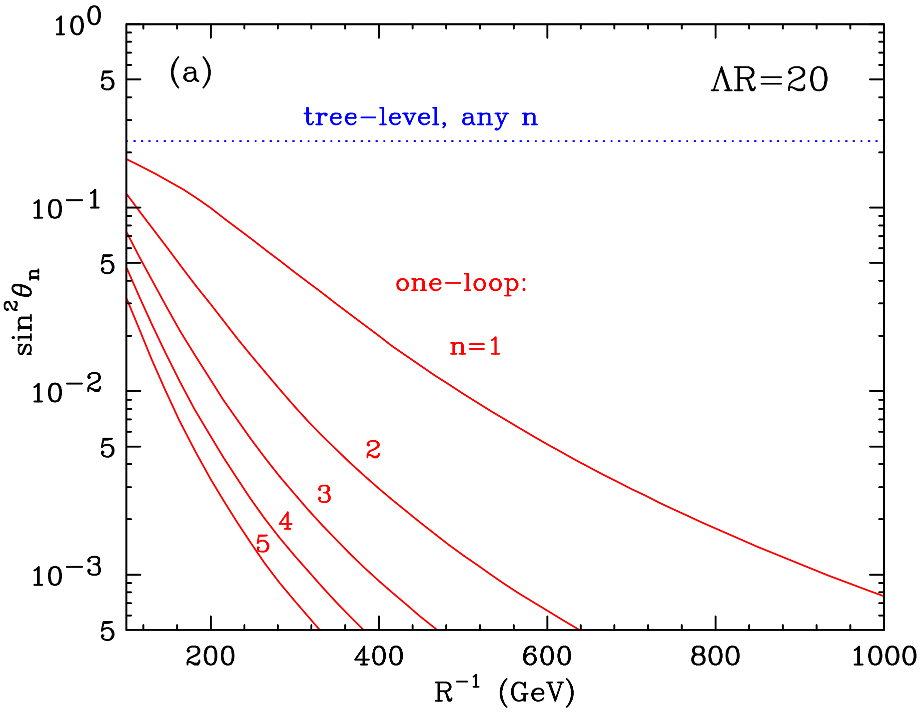
- Mass matrix for the EW neutral gauge bosons at level n

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

- The Weinberg angle θ_n at KK level n

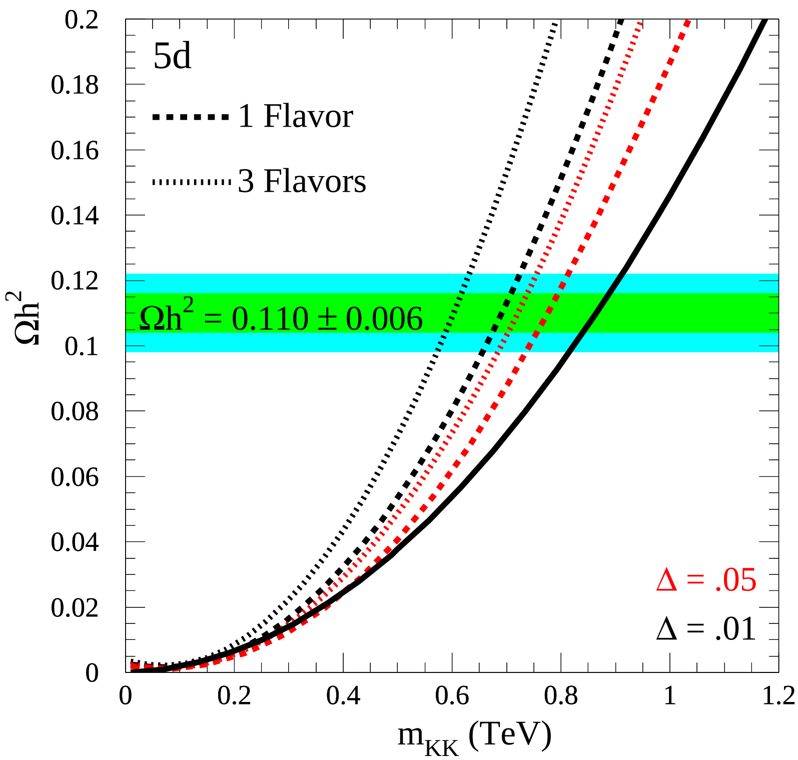
$$\gamma_n = \cos\theta_n B_n^0 + \sin\theta_n W_n^0 \approx B_n^0.$$

Cheng, KM, Schmaltz, hep-ph/0204342



KK dark matter relic density

- Relic density: G.Servant, T.Tait, hep-ph/0206071



- Unlike supersymmetry: no helicity suppression

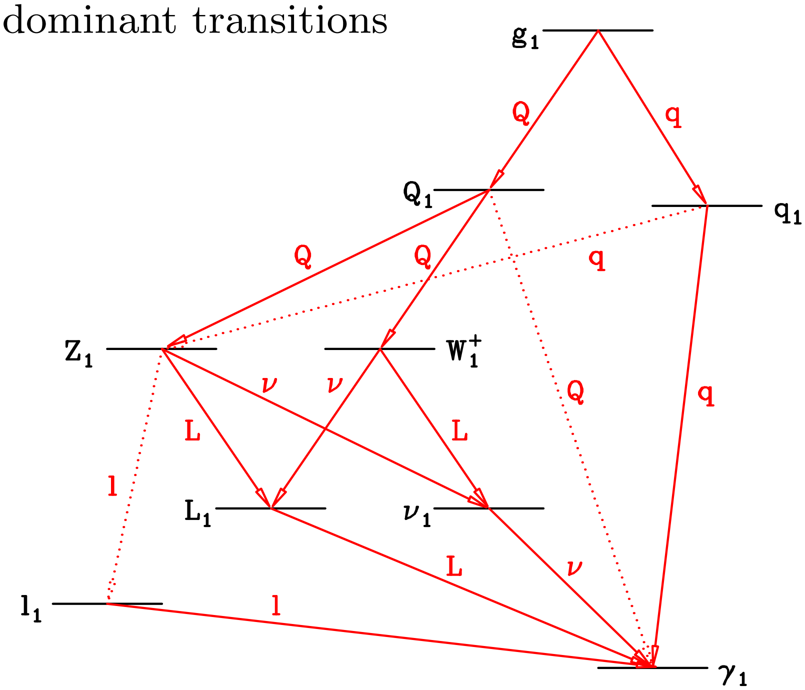
$$\Omega h^2 = \frac{1.04\ 10^9\ \mathrm{GeV}^{-1}}{M_P\sqrt{g_*}} \frac{x_F}{a + 3b/x_F}; \qquad x_F = \frac{M_{KK}}{T_F}$$

$$a = \frac{\alpha_1^2}{M_{KK}^2}\frac{380\pi}{81}; \qquad b = -\frac{\alpha_1^2}{M_{KK}^2}\frac{95\pi}{162}.$$

- Unlike supersymmetry: coannihilation lowers the bound

Collider phenomenology of UED

- Allowed dominant transitions

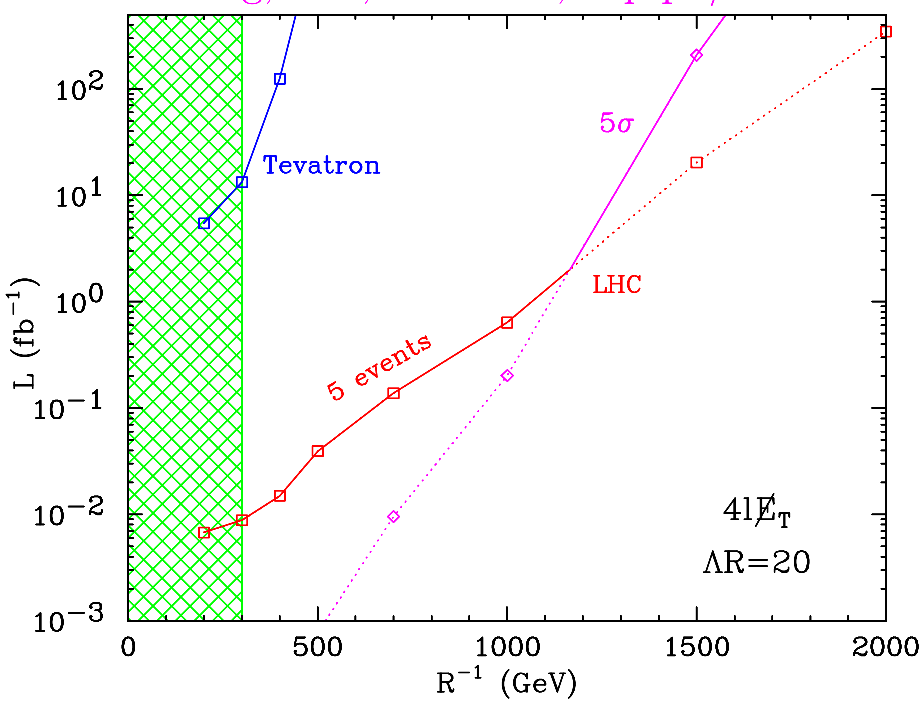


- KK gluon: $B(g_1 \to Q_1 Q_0) \simeq B(g_1 \to q_1 q_0) \simeq 50\%$.
- SU(2)-singlet KK quarks: preferentially $q_1 \to \gamma_1 q_0$
- SU(2)-doublet KK quarks: preferentially to W_1 and Z_1
- KK W- and Z-bosons: only leptonic decays!
- KK leptons: 100% directly to the LKP.
- At hadron colliders we want: strong production, weak decays!
- Cleanest signature at LHC: $4\ell + \not{E}_T$.

UED discovery reach at the Tevatron and LHC

- Discovery reach in the $pp \to Q_1 Q_1 \to 4\ell \not{E}_T$ channel.

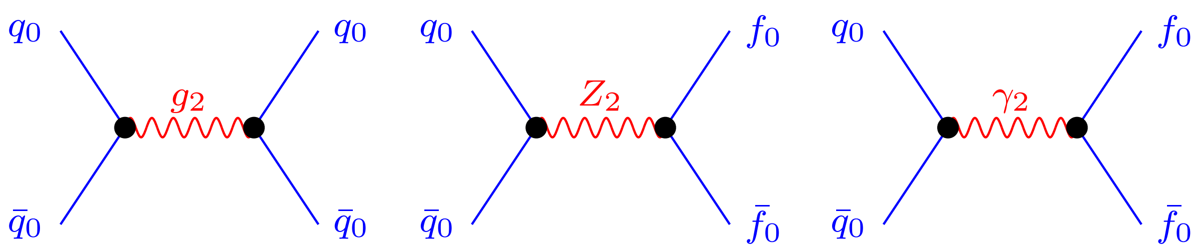
Cheng, KM, Schmaltz, hep-ph/0204342



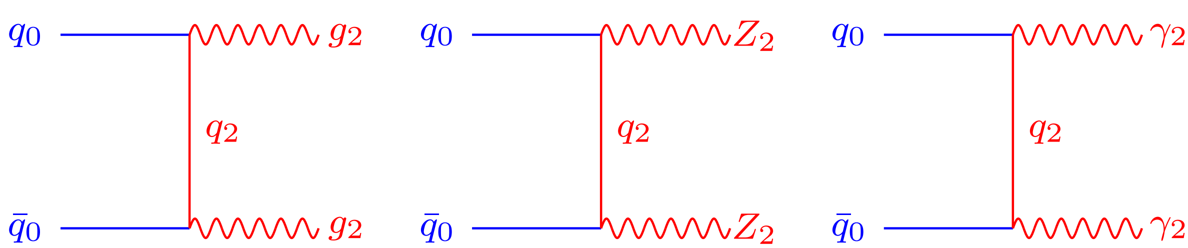
- Other typical signatures include:
  - soft leptons, soft jets, not a lot of $\not{E}_T$
  - a lot of missing mass (unobservable at hadron colliders)
- The "good" dark matter region is covered

Is it SUSY or Universal Extra Dimensions?

- Superpartners or Kaluza-Klein partners?
- UED: look for resonances of the higher $(n > 1)$ KK modes
- Single production proceeds through boundary terms



- Loop suppression at both production and decay
- Pair-production is kinematically suppressed, but non-negligible.

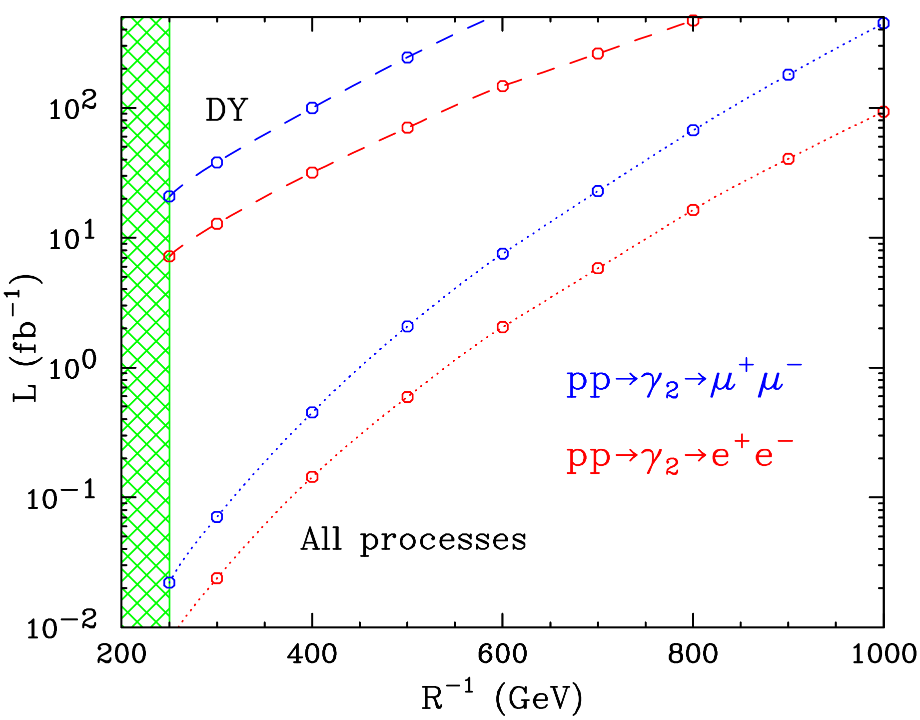


- Investigate the inclusive dilepton signature a la Z'.

LHC reach for level 2 gauge bosons

- The 5σ reach for $pp \to \gamma_2 \to \ell^+\ell^-$ at the LHC

Datta,Kong,KM (preliminary)



- As in SUSY, the dominant production is indirect, through

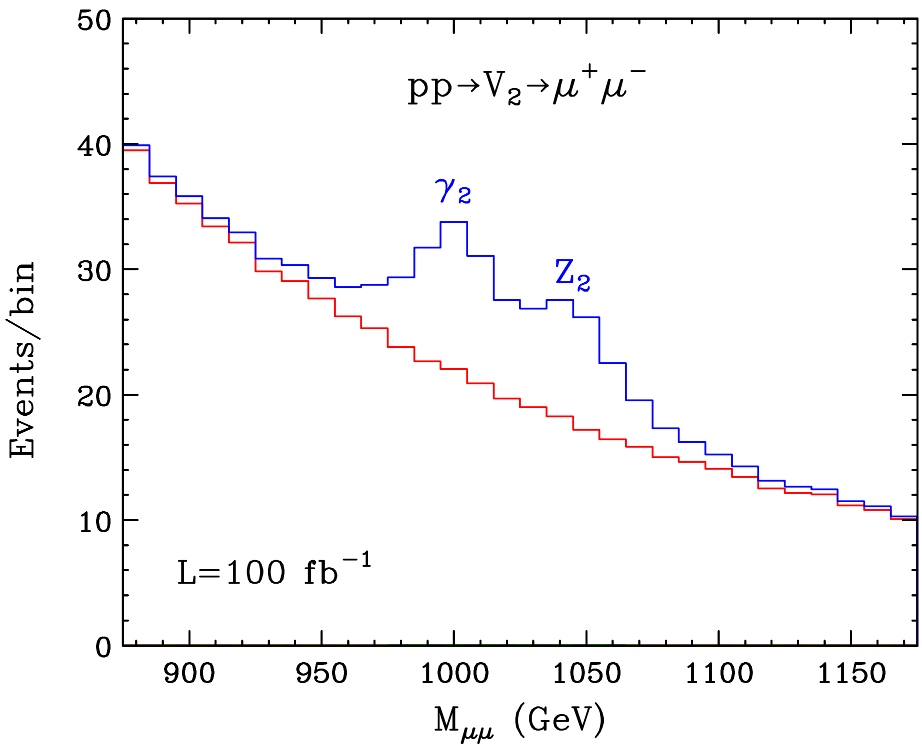
$$pp \to \{g_2, Q_2, q_2\} \to \gamma_2 + X$$

- The reach for Z_2 is very similar.

Discriminating close resonances: dimuon channel

- γ_2 and Z_2 are very close in mass: can they be discriminated?
- Very small widths $\Longrightarrow$ detector resolution?
- The dimuon mass resolution is inferior:

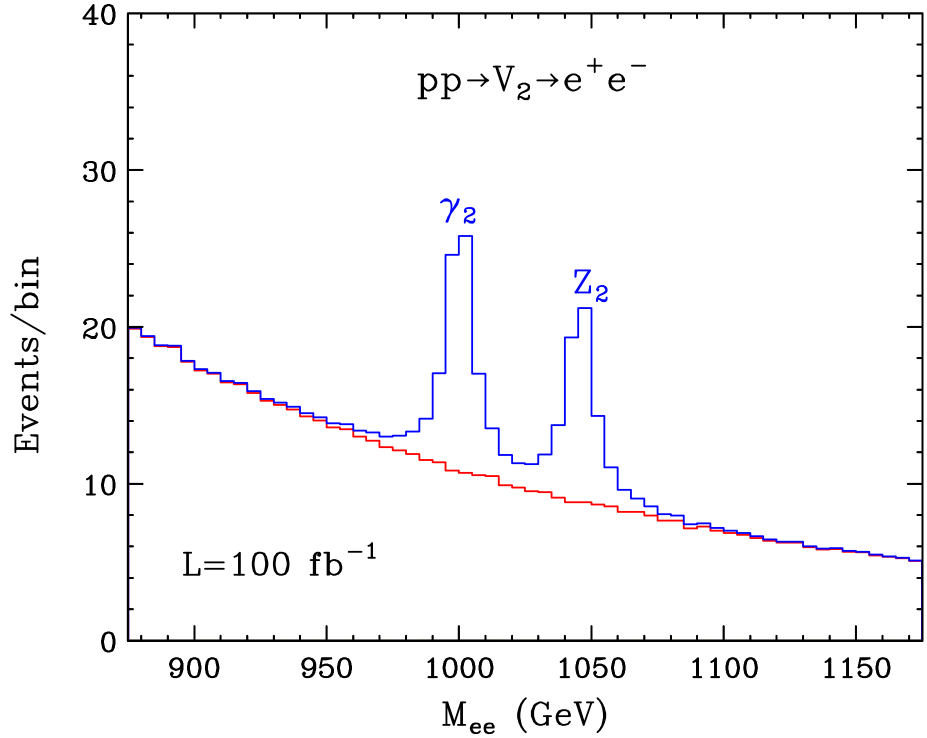
Datta,Kong,KM (preliminary)



Discriminating close resonances: dielectron channel

- γ_2 and Z_2 are more easily distinguished in e^+e^-

Datta,Kong,KM (preliminary)



- Still, is it UED or SUSY + Z's? Measure the spins!

SUSY versus UED at a LC

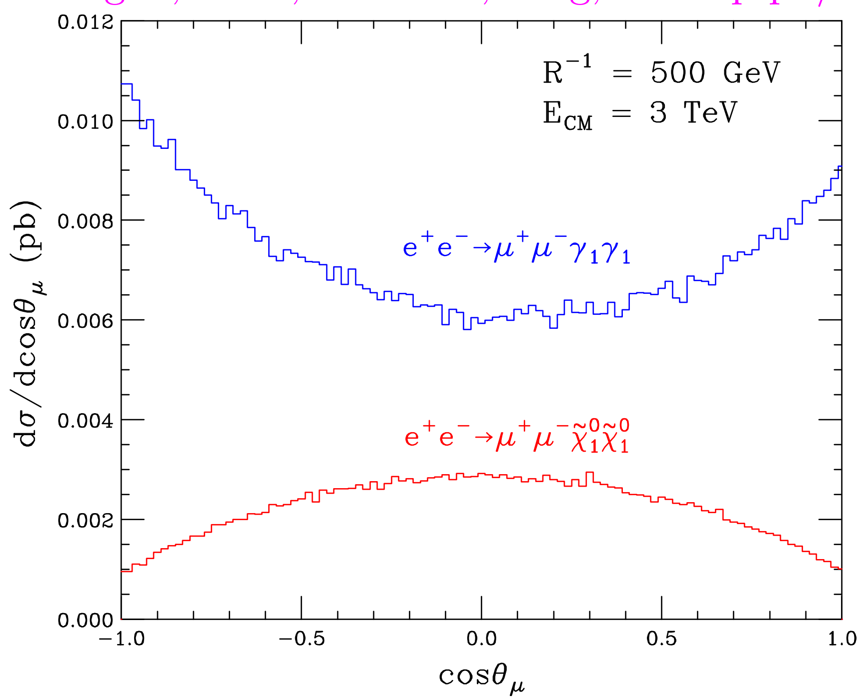
- The spin information is encoded in the angular distributions!

SUSY: $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$

UED: $e^+e^- \to \mu_1^+\mu_1^- \to \mu^+\mu^-\gamma_1\gamma_1$

$$\frac{d\sigma}{d\cos\theta} \sim 1 - \cos^2\theta \qquad \frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta$$

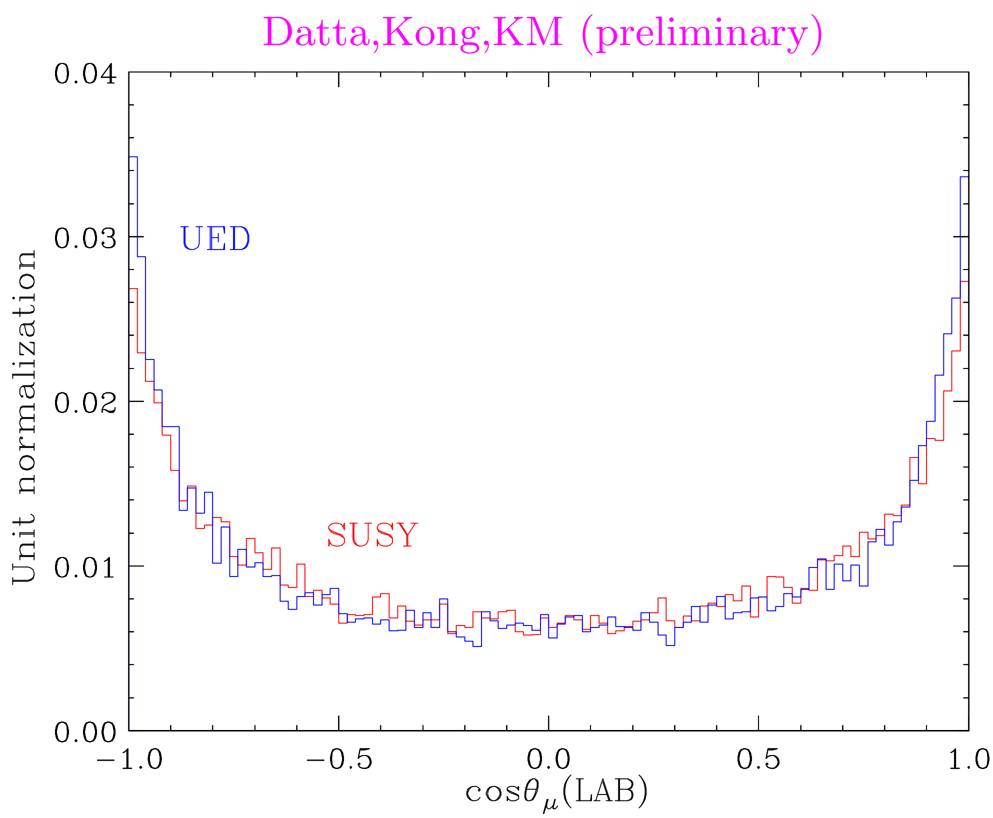
Battaglia,Datta,De Roeck,Kong,KM hep-ph/0502041



- Significant difference in the total cross-section as well!
- The masses can be extracted from the E_μ distribution.
- Threshold scan would confirm the spins.

Spin determination at the LHC?

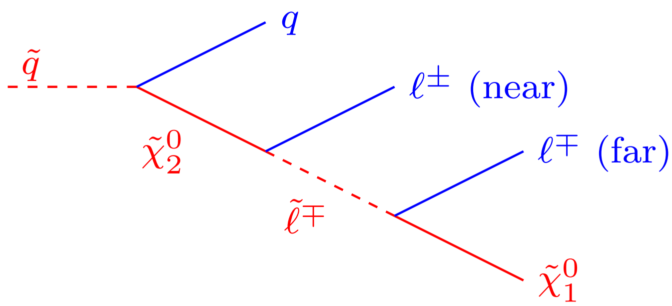
- If we simply do the same trick, it doesn't work:



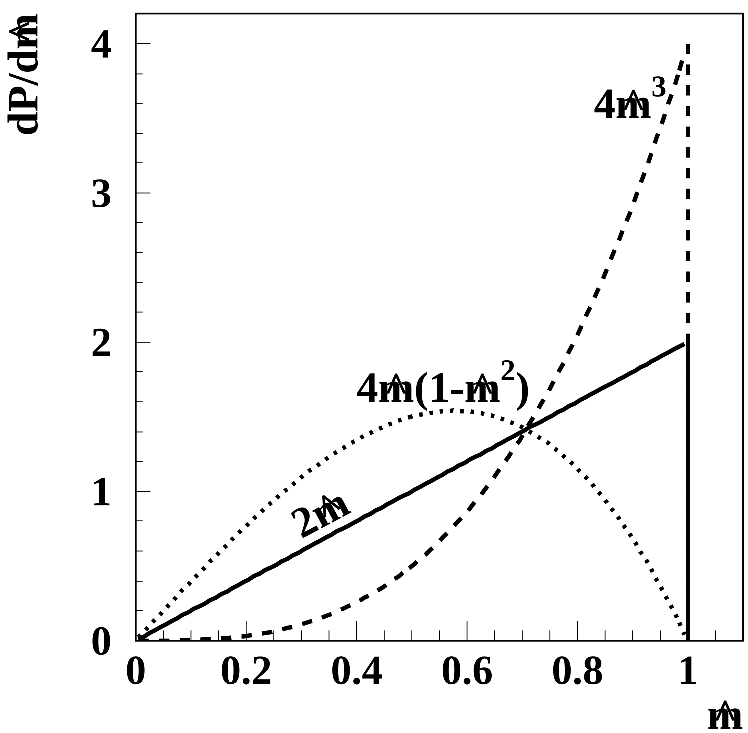
- We need to somehow account for the LAB-to-CM boost.
- Can only do it on a statistical basis, very difficult

Spin measurements at LHC: Barr method

- Look at the invariant mass $\hat{m}$ of $\ell^{near} q$ in squark decays



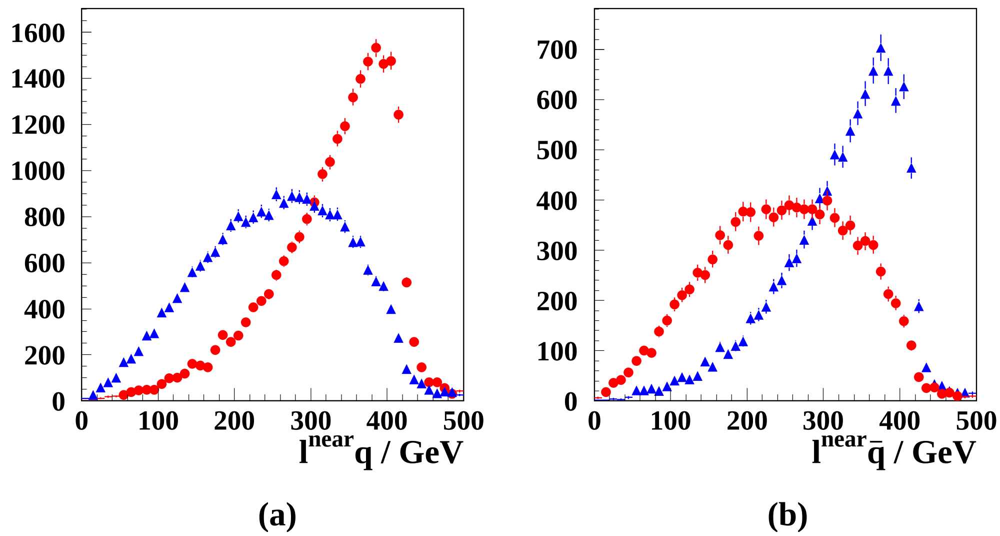
A. Barr, hep-ph/0405052



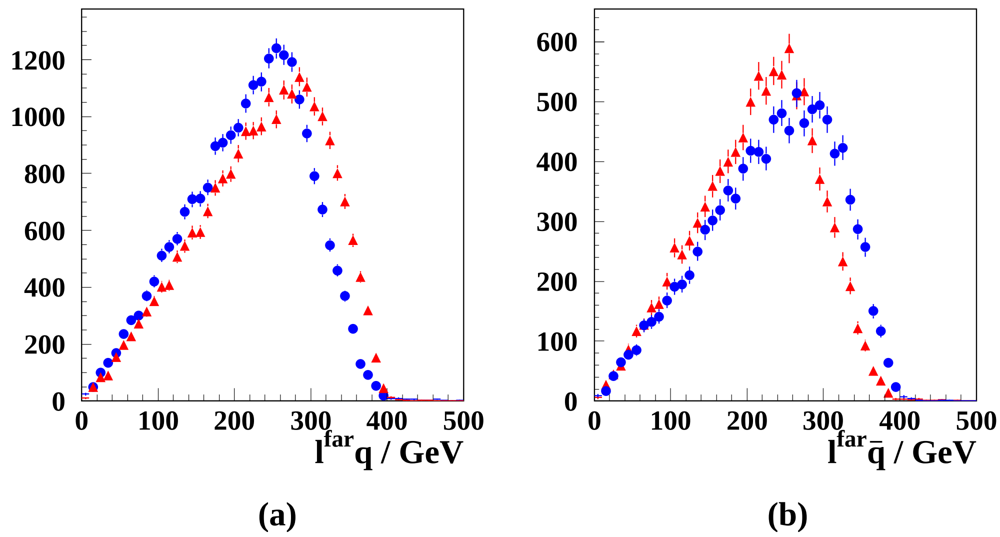
Spin measurements at LHC: Barr method

- Use that LHC is pp collider: makes more $\tilde{q}$ than $\tilde{q}^*$

A. Barr, hep-ph/0405052



- Pollution from the far lepton

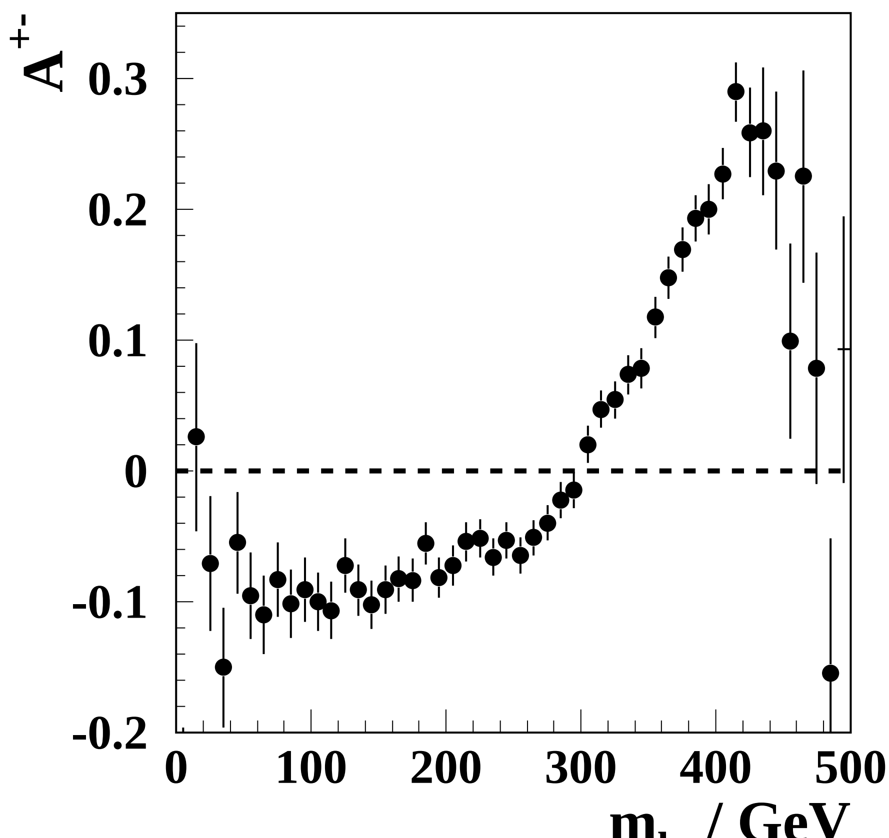


Spin measurements at LHC: Barr method

- Charge asymmetry in the differential cross-section

$$A^{+-} = \frac{\sigma(\ell^+) - \sigma(\ell^-)}{\sigma(\ell^+) + \sigma(\ell^-)}$$

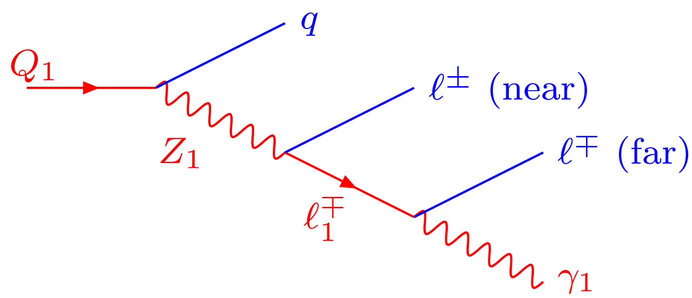
A. Barr, hep-ph/0405052



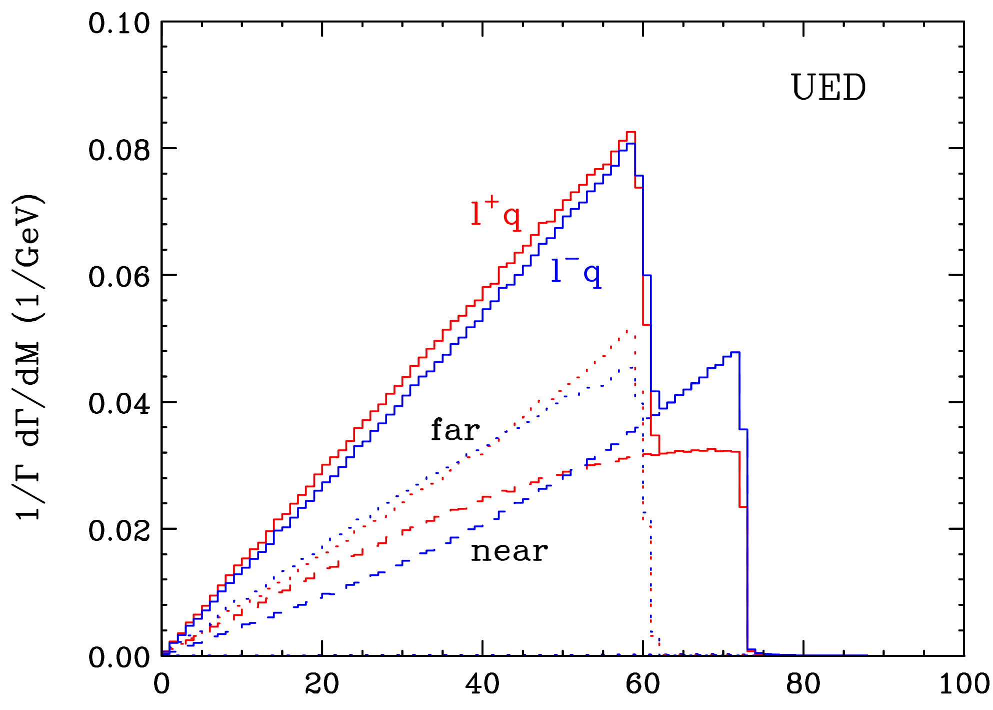
- Shows that SUSY is different from pure phase space decays

Spin measurements at LHC: SUSY vs UED

- Attempt to discriminate SUSY and UED ($R^{-1} = 500$ GeV)

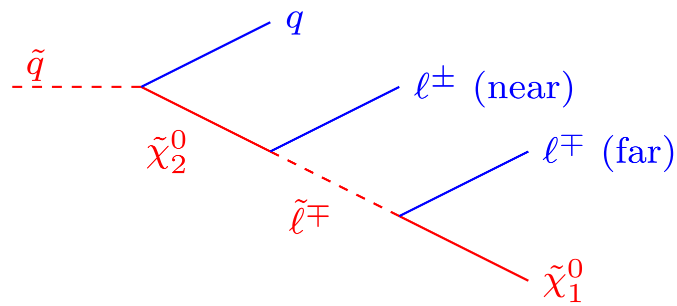


Kong,KM (preliminary)



Spin measurements at LHC: SUSY vs UED

- Choose a SUSY point with a matching mass spectrum



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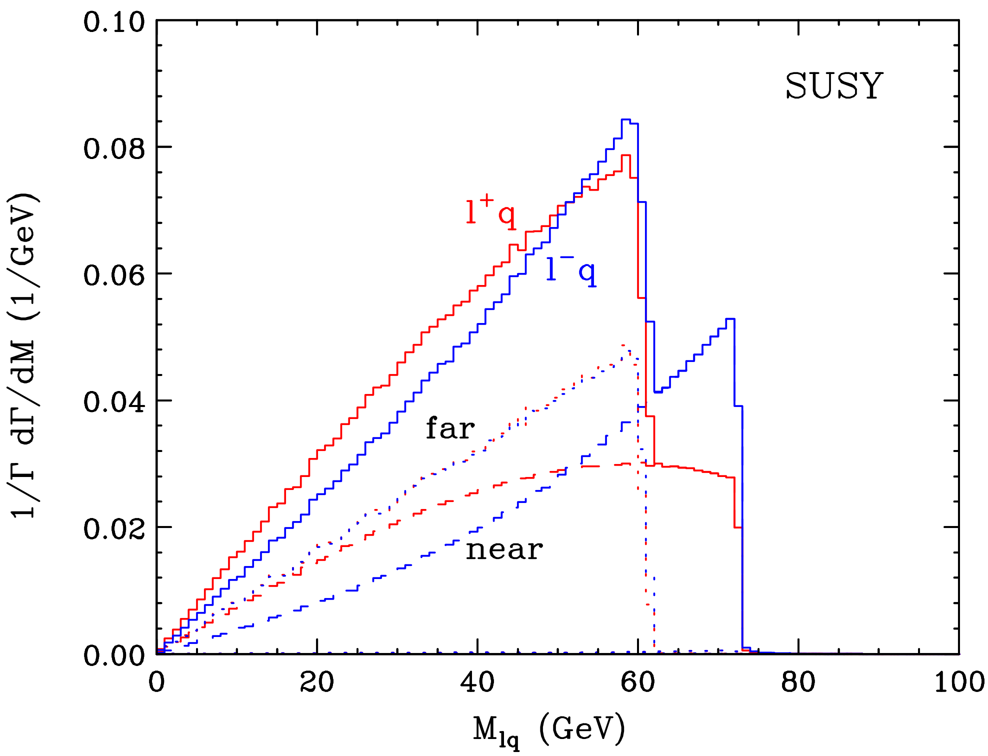
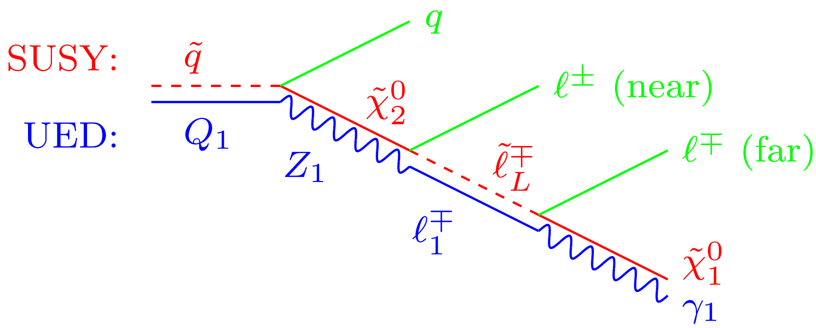
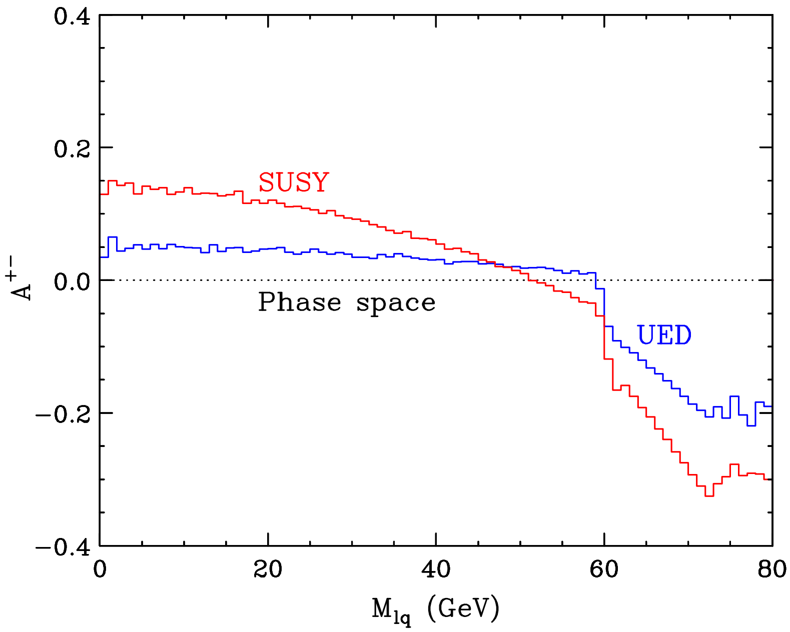


Spin measurements at LHC: SUSY vs UED



Kong,KM (preliminary)

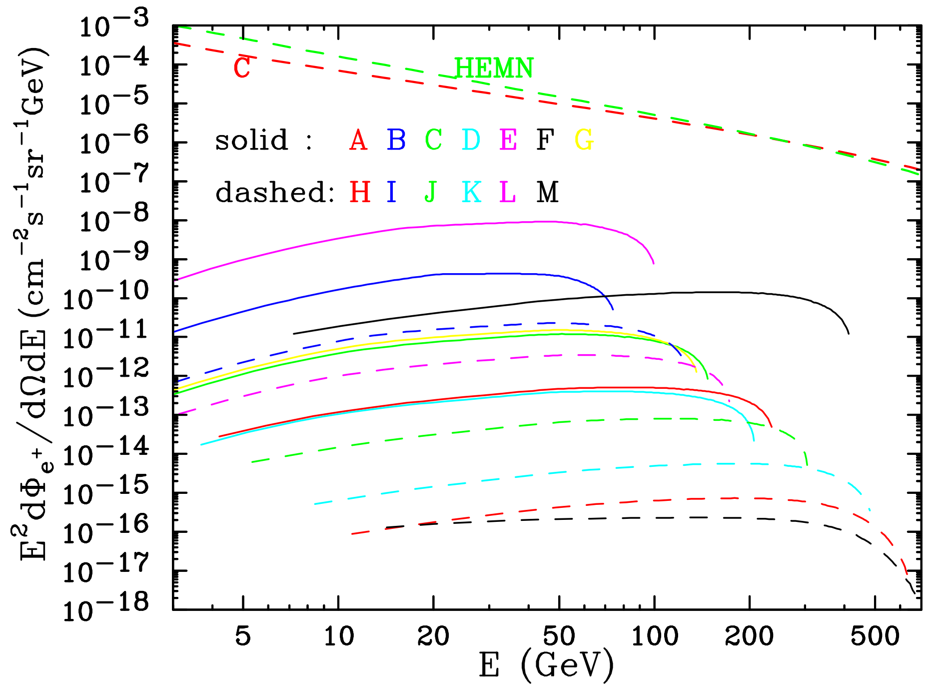


- Does it work?
  - SUSY vs UED harder than SUSY vs phase space.
  - statistical significance? backgrounds?
  - jet and lepton combinatorics?

SUSY Dark Matter: Positron signal

- Cosmic ray positrons are an indirect signature of dark matter
- Direct annihilation $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to e^+e^-$ helicity suppressed
- Hard e^+'s only come from $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ$.

Ellis,Feng,Ferstl,KM,Olive hep-ph/0110225



- Background shape and normalization are uncertain.
- The signal is typically a small fraction of the background, and the shape is not very characteristic.

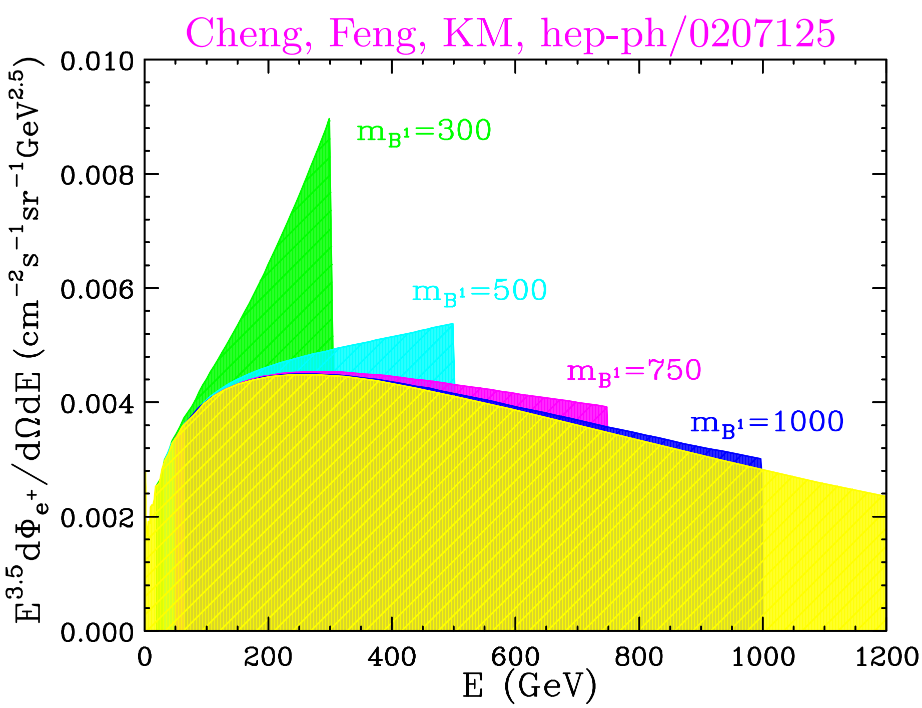
KK DM Indirect Detection: Positrons

- Annihilation into fermion pairs is not helicity suppressed.

$$B(B^1B^1 \to e^+e^-) = 20\%$$

- There is a bump! The positrons are monoenergetic at birth.

Some smearing from propagation through the galaxy.

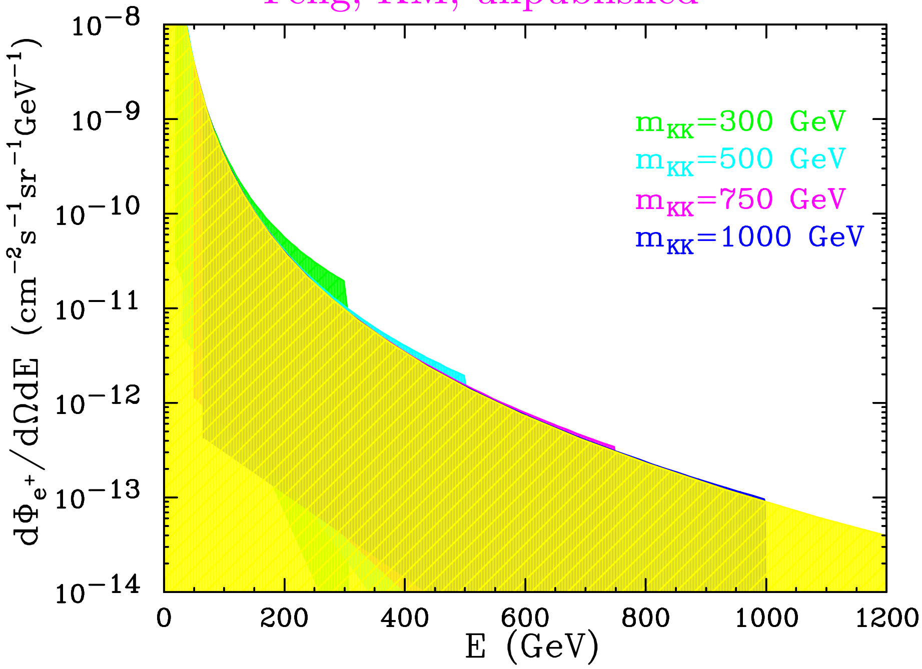


- AMS-II will be able to measure high-p_T positrons!

Positron fluxes in UED: signal versus background

- The positron flux without the E^2 scaling:

Feng, KM, unpublished



A brief summary

- UED is a nice testing ground for SUSY (strawman SUSY?).
- Discriminating the two is a challenge for the LHC
  - Can we see the first few floors of the KK tower?
  - Can we measure the spins? Very difficult, but perhaps not impossible. More work needed.
- New ideas for the LHC analyses:
  - the importance of model-independence
  - the need to ask the right questions
  - the need for new tricks