Detecting Spins at the LHC

Jennifer Smillie, HEP Theory, Cavendish

18th November, 2005

This talk is based on

JS & Bryan Webber [JHEP 10 (2005) 069]

which extends

Alan Barr [PLB 596 (2004) 205]

Goto, Kawagoe & Nojiri [PRD 70 (2004) 075016]

Related work done by

Datta, Kong & Matchev [hep-ph/0509246]

Macesanu, McMullen & Nandi [PRD **66** (2002) 015009]

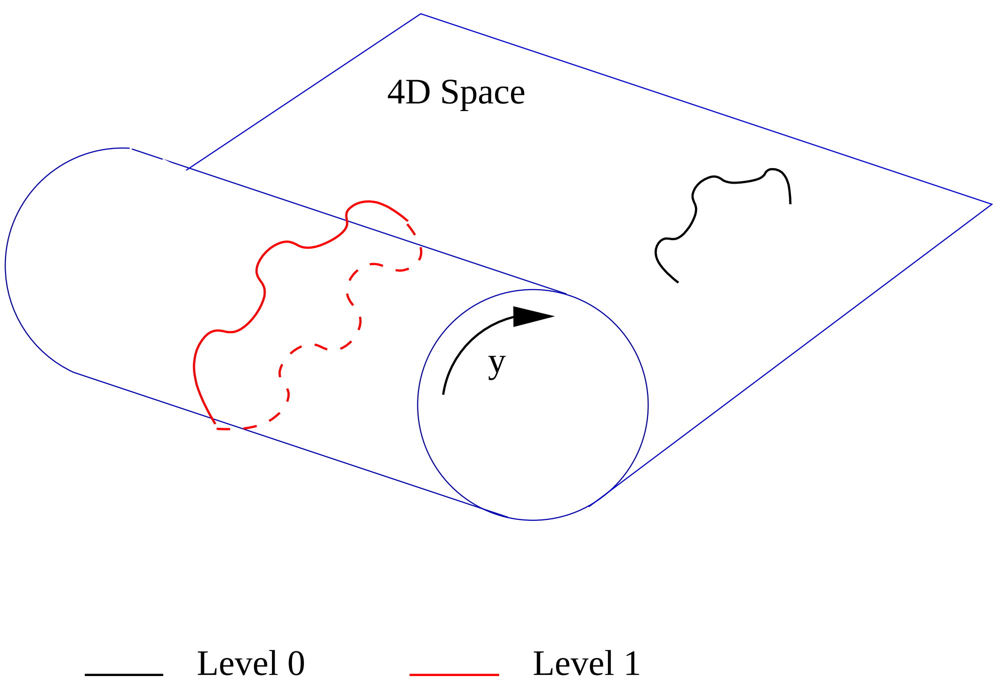
Outline

- Introduction to Universal Extra Dimensions
- Experimental Signatures of UED and the MSSM
- Extracting Spin Information
- Issues with Detection
- Final Result

Universal Extra Dimensions

A Universal Extra Dimensions (UED) model is one with at least one extra spatial dimension in addition to the usual 3, into which *all* gauge fields can propagate.

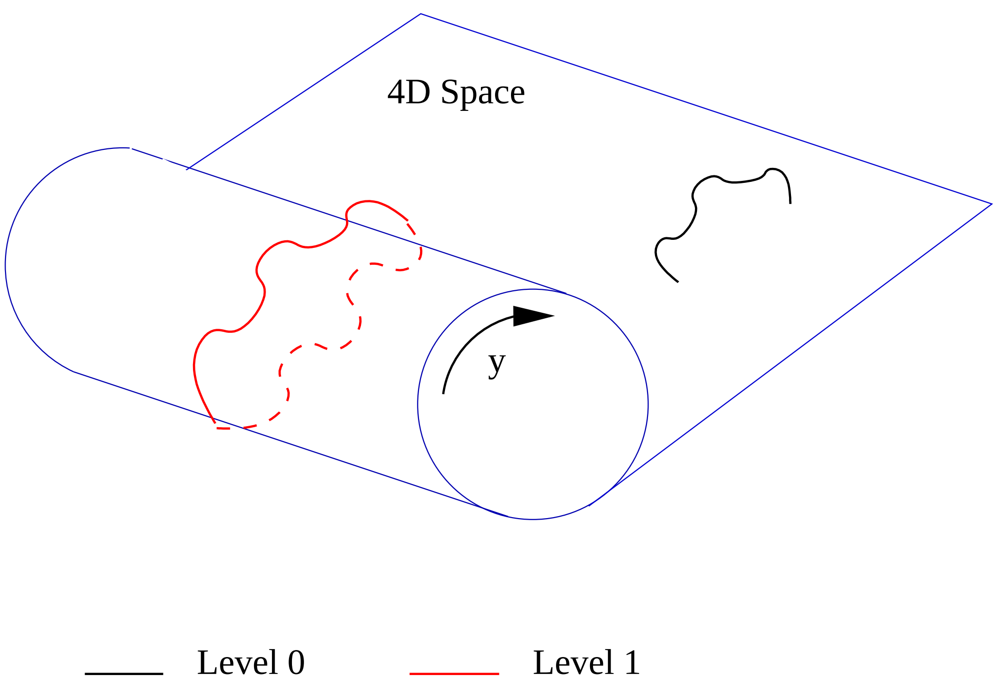
The extra dimensions must be compact (rolled up).



Universal Extra Dimensions

A Universal Extra Dimensions (UED) model is one with at least one extra spatial dimension in addition to the usual 3, into which *all* gauge fields can propagate.

The extra dimensions must be compact (rolled up).



Fields wrap around the extra dimension(s) to give excited Kaluza-Klein modes.

Universal Extra Dimensions

- We will work with one circular extra dimension, y, with radius R.

Universal Extra Dimensions

- We will work with one circular extra dimension, y, with radius R.
- We express 5D fields as a Fourier expansion in y:

$$F(x,y) = F_0(x) + \sum_{n=1}^{\infty} F_n(x) \cos\left(\frac{ny}{R}\right) + F'_n(x) \sin\left(\frac{ny}{R}\right)$$

x labels the usual 4 dimensions.

Universal Extra Dimensions

- We will work with one circular extra dimension, y, with radius R.

- We express 5D fields as a Fourier expansion in y:

$$F(x,y) = F_0(x) + \sum_{n=1}^{\infty} F_n(x) \cos\left(\frac{ny}{R}\right) + F'_n(x) \sin\left(\frac{ny}{R}\right)$$

x labels the usual 4 dimensions.

- Momentum Conservation in the 5^{th} dimension leads to conservation of KK mode number at each vertex.

$$e^{ip.y} = e^{ip.(y+2\pi R)} \Rightarrow p = n$$

for a free particle.

Universal Extra Dimensions

- We must now introduce handedness and remove extra degrees of freedom. We compactify on an orbifold which is equivalent to identifying $y \equiv -y$.

  Keep terms in $\mathcal{L}$ which are even under $y \to -y$.

Universal Extra Dimensions

- We must now introduce handedness and remove extra degrees of freedom. We compactify on an orbifold which is equivalent to identifying $y \equiv -y$.

  Keep terms in $\mathcal{L}$ which are even under $y \to -y$.

- This breaks conservation of KK mode number to conservation of KK parity:

$$(-1)^n$$

  n labels KK mode number.

Universal Extra Dimensions

- We must now introduce handedness and remove extra degrees of freedom. We compactify on an orbifold which is equivalent to identifying $y \equiv -y$.

  Keep terms in $\mathcal{L}$ which are even under $y \to -y$.

- This breaks conservation of KK mode number to conservation of KK parity:

  $$(-1)^n$$

  n labels KK mode number.

- Level 1 excitation still produced in pairs, so lightest Level 1 mode is stable.

UED Particle Content

The model has the following particle towers in addition to the Standard Model particles (the relevant zero modes).

Fermions	$q_n^\bullet \; q_n^\circ$ $l_n^\bullet \; l_n^\circ$ $\nu_n^\bullet \; \nu_n^\circ$

$$q = u, d, c, s, t, b; \quad l = e, \mu, \tau; \quad \nu = \nu_e, \nu_\mu, \nu_\tau$$

Each fermion has 2 corresponding towers (cf. MSSM).

$f_n^\bullet \leftrightarrow SU(2)$ doublet (left-handed) field
$f_n^\circ \leftrightarrow SU(2)$ singlet (right-handed) field.

They have no definite chirality themselves.

UED Particle Content

The model has the following particle towers in addition to the Standard Model particles (the relevant zero modes).

Fermions	$q_n^\bullet\ q_n^\circ$ $l_n^\bullet\ l_n^\circ$ $\nu_n^\bullet\ \nu_n^\circ$
Vector Bosons	$\gamma_n^{*\mu}\ Z_n^{*\mu}\ W_n^{\pm*\mu}$ $g_n^{*\mu}$

At Level 1 and higher the $\gamma_n^{*\mu}$ and $Z_n^{*\mu}$ are almost pure excitations of the $U(1)$ B^μ field and $SU(2)$ A_3^μ field - the mixing angle is very small.

UED Particle Content

The model has the following particle towers in addition to the Standard Model particles (the relevant zero modes).

Fermions	$q_n^\bullet\ q_n^\circ$ $l_n^\bullet\ l_n^\circ$ $\nu_n^\bullet\ \nu_n^\circ$
Vector Bosons	$\gamma_n^{*\mu}\ Z_n^{*\mu}\ W_n^{\pm*\mu}$ $g_n^{*\mu}$
Scalars	h_n $H_n^\pm\ A_n^0$

The ‘new’ scalars $H_n^\pm\ A_n^0$ are a linear combination of the Higgs components and the 5^{th} component of the corresponding vector field.

UED Particle Content

The model has the following particle towers in addition to the Standard Model particles (the relevant zero modes).

Fermions	$q_n^\bullet\ q_n^\circ$ $l_n^\bullet\ l_n^\circ$ $\nu_n^\bullet\ \nu_n^\circ$
Vector Bosons	$\gamma_n^{*\mu}\ Z_n^{*\mu}\ W_n^{\pm *\mu}$ $g_n^{*\mu}$
Scalars	h_n $H_n^\pm\ A_n^0$

At tree level the masses are given by $m_n = \sqrt{\frac{n^2}{R^2} + m_{\mathrm{SM}}^2}$.

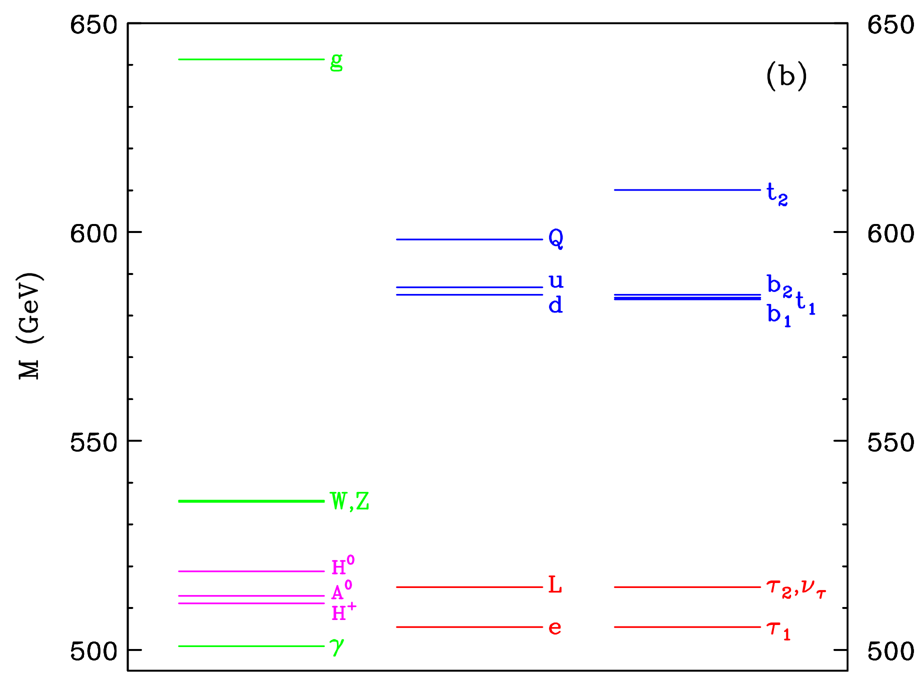
A Typical Mass Spectrum

Here is the mass spectrum calculated by Cheng, Matchev & Schmaltz with

$R^{-1} = 500$ GeV

$\Lambda R = 20$

$m_h = 120$ GeV.



[Phys. Rev. D 66 (2002) 036005]

Note the Lightest Kaluza-Klein particle is the Level 1 photon $\gamma_1^{*\mu}$ — consistent with a dark matter candidate as it is uncharged.

Current Experimental Limits

The strongest limits available on the size of the extra dimension, R, come from measurements of the precision electroweak variables $\hat{S}$, $\hat{T}$, $\hat{U}$, X, Y & W.

Recently, Flacke, Hooper & March-Russell used LEP1 and LEP2 measurements of these variables to give a 99% confidence lower limit of

$$R^{-1} = 700 \text{ GeV}$$
$$R = 0.28 \text{ am}$$

[hep-ph/0509352]

Current Experimental Limits

The strongest limits available on the size of the extra dimension, R, come from measurements of the precision electroweak variables $\hat{S}$, $\hat{T}$, $\hat{U}$, X, Y & W.

Recently, Flacke, Hooper & March-Russell used LEP1 and LEP2 measurements of these variables to give a 99% confidence lower limit of

$$R^{-1} = 700 \text{ GeV}$$
$$R = 0.28 \text{ am}$$

[hep-ph/0509352]

The following calculations were performed before this, using $R^{-1} = 500$ GeV.

UED versus SUSY

Each Standard Model (SM) particle has

- a tower of excited Kaluza-Klein (KK) modes

  $q_L \leftrightarrow q^*_{L_n},\ l \leftrightarrow l^*_n$

- ⋆ one supersymmetric partner

  $q_L \leftrightarrow \tilde{q}_L,\ l \leftrightarrow \tilde{l}$

UED versus SUSY

Each Standard Model (SM) particle has

- a tower of excited Kaluza-Klein (KK) modes

  $q_L \leftrightarrow q^*_{L_n},\ l \leftrightarrow l^*_n$

- ⋆ one supersymmetric partner

  $q_L \leftrightarrow \tilde{q}_L,\ l \leftrightarrow \tilde{l}$

The spin of the corresponding particle

- is the <u>same</u> as the SM
- ⋆ <u>differs</u> by 1/2 to the SM

UED versus SUSY

Each Standard Model (SM) particle has

• a tower of excited Kaluza-Klein (KK) modes	⋆ one supersymmetric partner
$q_L \leftrightarrow q^*_{L_n},\ l \leftrightarrow l^*_n$	$q_L \leftrightarrow \tilde{q}_L,\ l \leftrightarrow \tilde{l}$

The spin of the corresponding particle

• is the <u>same</u> as the SM	⋆ <u>differs</u> by 1/2 to the SM

A typical mass spectrum is

• very degenerate	⋆ less degenerate

UED versus SUSY

Each Standard Model (SM) particle has

UED	SUSY
• a tower of excited Kaluza-Klein (KK) modes $q_L \leftrightarrow q^*_{L_n},\ l \leftrightarrow l^*_n$	⋆ one supersymmetric partner $q_L \leftrightarrow \tilde{q}_L,\ l \leftrightarrow \tilde{l}$

The spin of the corresponding particle

UED	SUSY
• is the <u>same</u> as the SM	⋆ <u>differs</u> by 1/2 to the SM

A typical mass spectrum is

UED	SUSY
• very degenerate	⋆ less degenerate

A good dark matter candidate is the

UED	SUSY
• Lightest KK Particle	⋆ Lightest Super Particle

UED versus SUSY

Level 1 UED modes and R-parity conserving SUSY have common key experimental signatures:

- SM partners are produced in pairs,
- events will have missing energy,

so we must find a way to differentiate between these two models.

UED versus SUSY

Level 1 UED modes and R-parity conserving SUSY have common key experimental signatures:

- SM partners are produced in pairs,
- events will have missing energy,

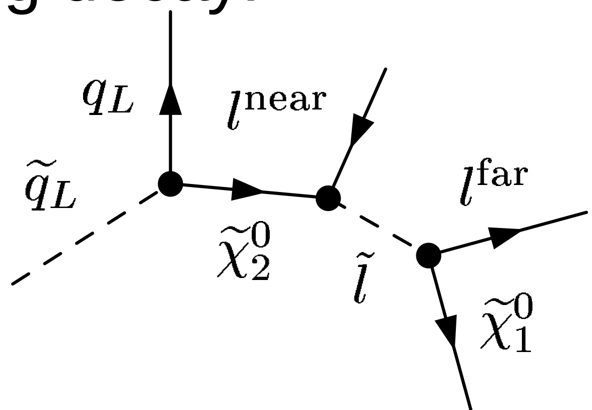
so we must find a way to differentiate between these two models.

SPIN

We will try to extract information about the spin of the particles produced at the Large Hadron Collider (LHC).

Spin

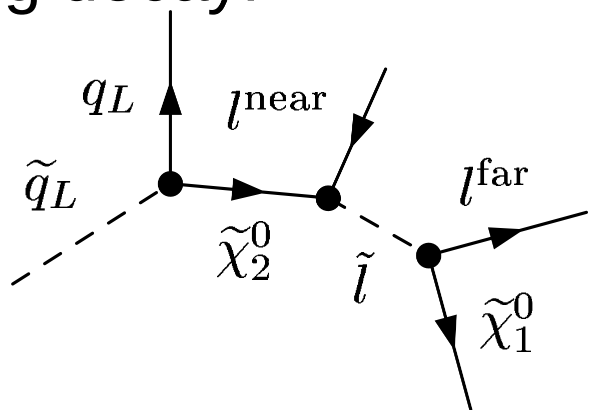
Alan Barr showed that there was an observable difference in the invariant mass distributions of SUSY and phase space in the following decay:



[Phys. Lett. B 596 (2004) 205]

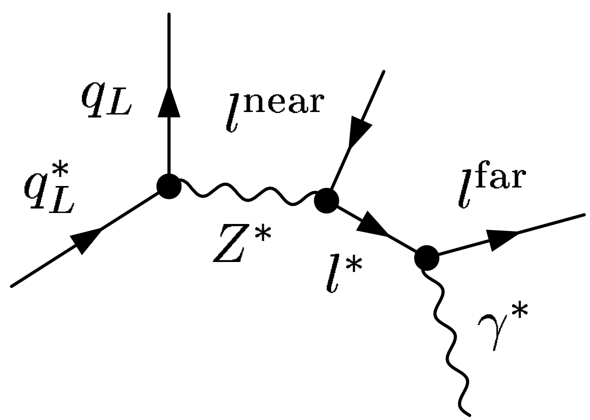
Spin

Alan Barr showed that there was an observable difference in the invariant mass distributions of SUSY and phase space in the following decay:



[Phys. Lett. B 596 (2004) 205]

We will compare these with the same distributions for the UED decay:



Masses

In this analysis, we assume that the masses in the decay chain have already been determined.

Masses

In this analysis, we assume that the masses in the decay chain have already been determined.

We will study two mass spectra - one typical of a UED scenario:

UED masses

γ^*	Z^*	q_L^*	l_R^*	l_L^*
501	536	598	505	515

and one typical of an MSSM scenario:

SPS1_a masses

$\widetilde{\chi}_1^0$	$\widetilde{\chi}_2^0$	$\widetilde{u}_L$	$\widetilde{e}_R$	$\widetilde{e}_L$
96	177	537	143	202

All masses in GeV.

$q\ l^{\text{near}}$

We define the $q\ l^{\text{near}}$ invariant mass as

$$\widehat{m}_{ql}^{\text{near}} \propto (p_q + p_l^{\text{near}})^2 = 2p_q.p_l^{\text{near}}$$

as we treat SM particles as massless. It is normalised so the maximum is 1.

The invariant mass distribution is $\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}\widehat{m}}$.

$q\ l^{\text{near}}$

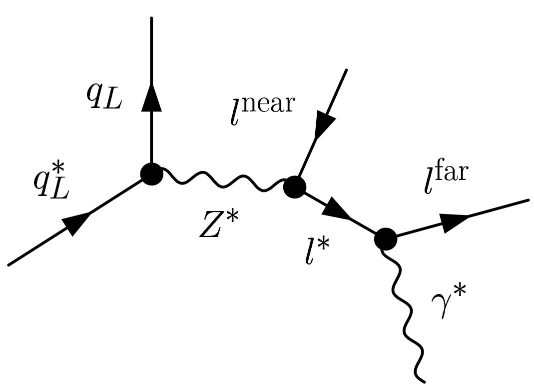
We define the $q\ l^{\text{near}}$ invariant mass as

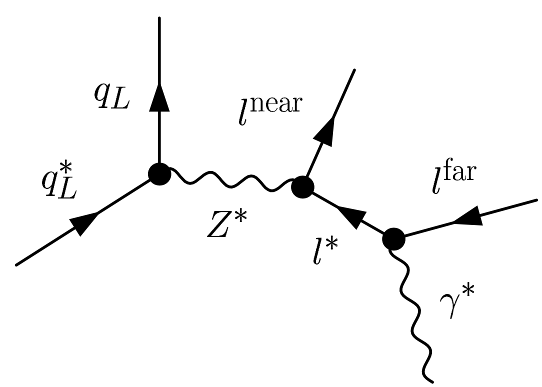
$$\widehat{m}_{ql}^{\text{near}} \propto (p_q + p_l^{\text{near}})^2 = 2p_q.p_l^{\text{near}}$$

as we treat SM particles as massless. It is normalised so the maximum is 1.

The invariant mass distribution is $\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}\widehat{m}}$.

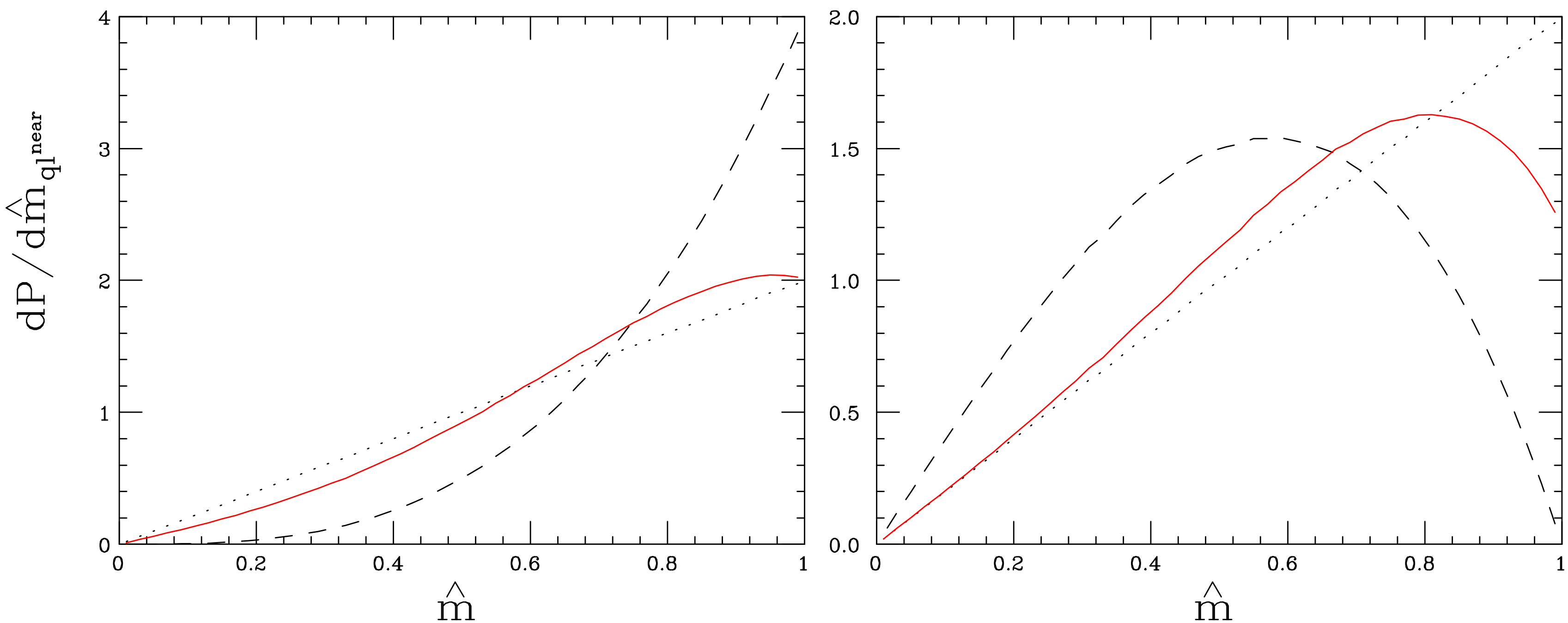
We must consider $l^{\text{near}} = l^+$ and $l^{\text{near}} = l^-$ separately.





$q\ l^{\mathrm{near}}$

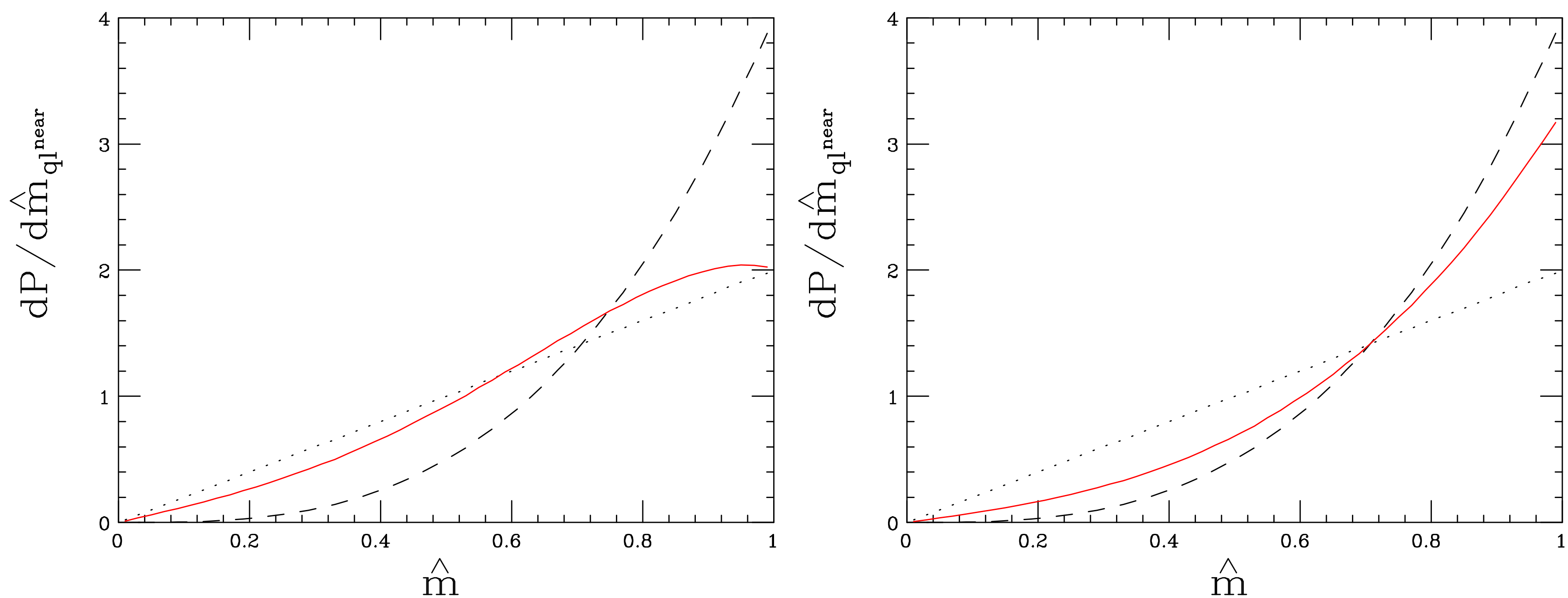
For the SPS1_a SUSY mass spectrum we find the following invariant mass distributions for $l^{\mathrm{near}} = l^{+}$ and $l^{\mathrm{near}} = l^{-}$ respectively.



solid = UED spins dashed = SUSY spins

$q\ l^{\mathrm{near}}$

However, the UED curves are mass-dependent. Here are the distributions for $l^{\mathrm{near}} = l^+$ for a SUSY mass spectrum again, and a UED mass spectrum.



solid = UED spins dashed = SUSY spins

$q\ l^{\text{near}}$

The analytical forms for the $q\ l^{\text{near}}$ invariant mass distributions are ($l^{\text{near}} = l^{+}$)

$$\frac{\mathrm{d}P_1^{\text{SUSY}}}{\mathrm{d}\hat{m}} = 4\hat{m}^3$$

$$\frac{\mathrm{d}P_1^{\text{UED}}}{\mathrm{d}\hat{m}} = \frac{6\hat{m}}{(1+2x)(2+y)}\left[y + 4(1-y+xy)\hat{m}^2 - 4(1-x)(1-y)\hat{m}^4\right]$$

with $x = \frac{m_{Z^*}^2}{m_{q^*}^2}$ and $y = \frac{m_{l^*}^2}{m_{Z^*}^2}$.

$q\ l^{\text{near}}$

The analytical forms for the $q\ l^{\text{near}}$ invariant mass distributions are ($l^{\text{near}} = l^{+}$)

$$\begin{aligned}
\frac{\mathrm{d}P_1^{\text{SUSY}}}{\mathrm{d}\hat{m}} &= 4\hat{m}^3 \\
\frac{\mathrm{d}P_1^{\text{UED}}}{\mathrm{d}\hat{m}} &= \frac{6\hat{m}}{(1+2x)(2+y)}\Big[y + 4(1-y+xy)\hat{m}^2 \\
&\qquad\qquad -4(1-x)(1-y)\hat{m}^4\Big]
\end{aligned}$$

with $x = \frac{m_{Z*}^2}{m_{q*}^2}$ and $y = \frac{m_{l*}^2}{m_{Z*}^2}$.

In the limit $x \to 1, \quad y \to 0$, these become identical.

$q\ l^{\text{near}}$

The analytical forms for the $q\ l^{\text{near}}$ invariant mass distributions are ($l^{\text{near}} = l^{+}$)

$$
\begin{aligned}
\frac{\mathrm{d}P_1^{\text{SUSY}}}{\mathrm{d}\hat{m}} &= 4\hat{m}^3 \\
\frac{\mathrm{d}P_1^{\text{UED}}}{\mathrm{d}\hat{m}} &= \frac{6\hat{m}}{(1+2x)(2+y)}\Big[y + 4(1-y+xy)\hat{m}^2 \\
&\qquad -4(1-x)(1-y)\hat{m}^4\Big]
\end{aligned}
$$

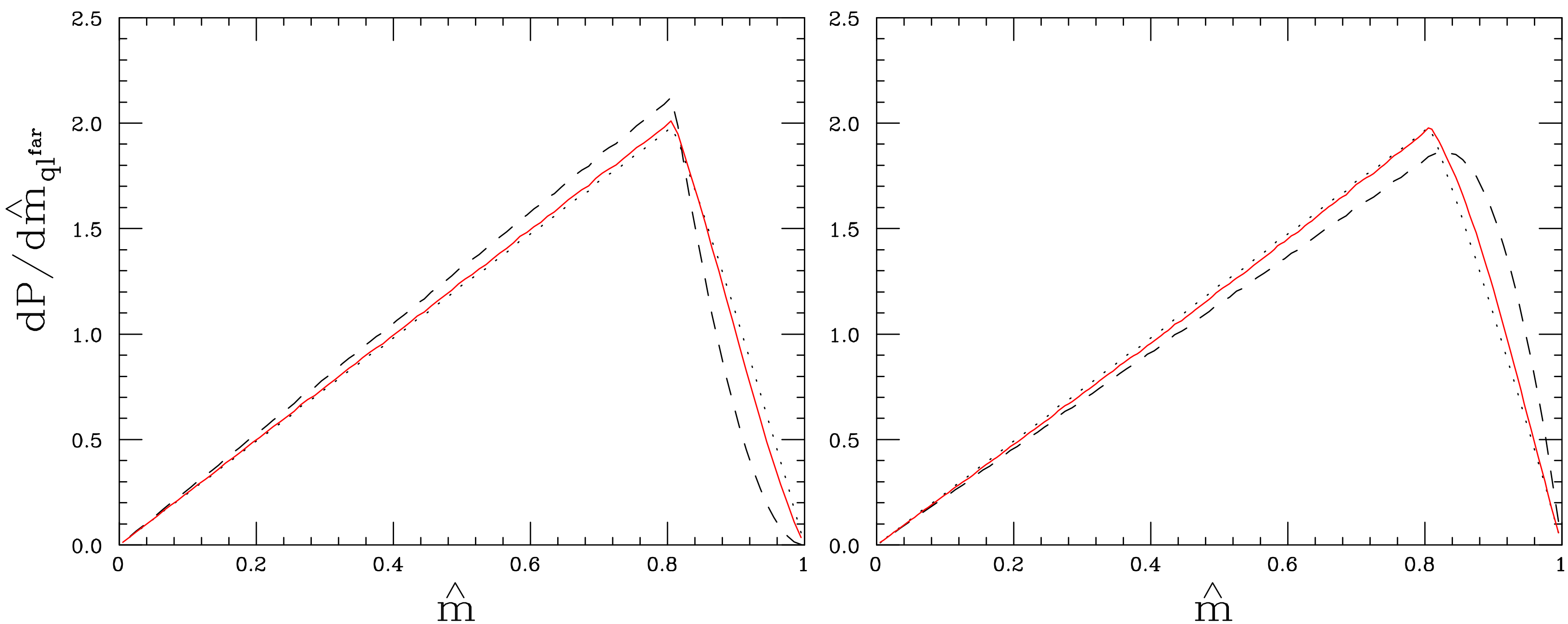
with $x = \frac{m_{Z^*}^2}{m_{q^*}^2}$ and $y = \frac{m_{l^*}^2}{m_{Z^*}^2}$.

In the previous plots,

	x	y
SPS1_a	0.11	0.65
UED	0.80	0.92

$q\ l^{\text{far}}$

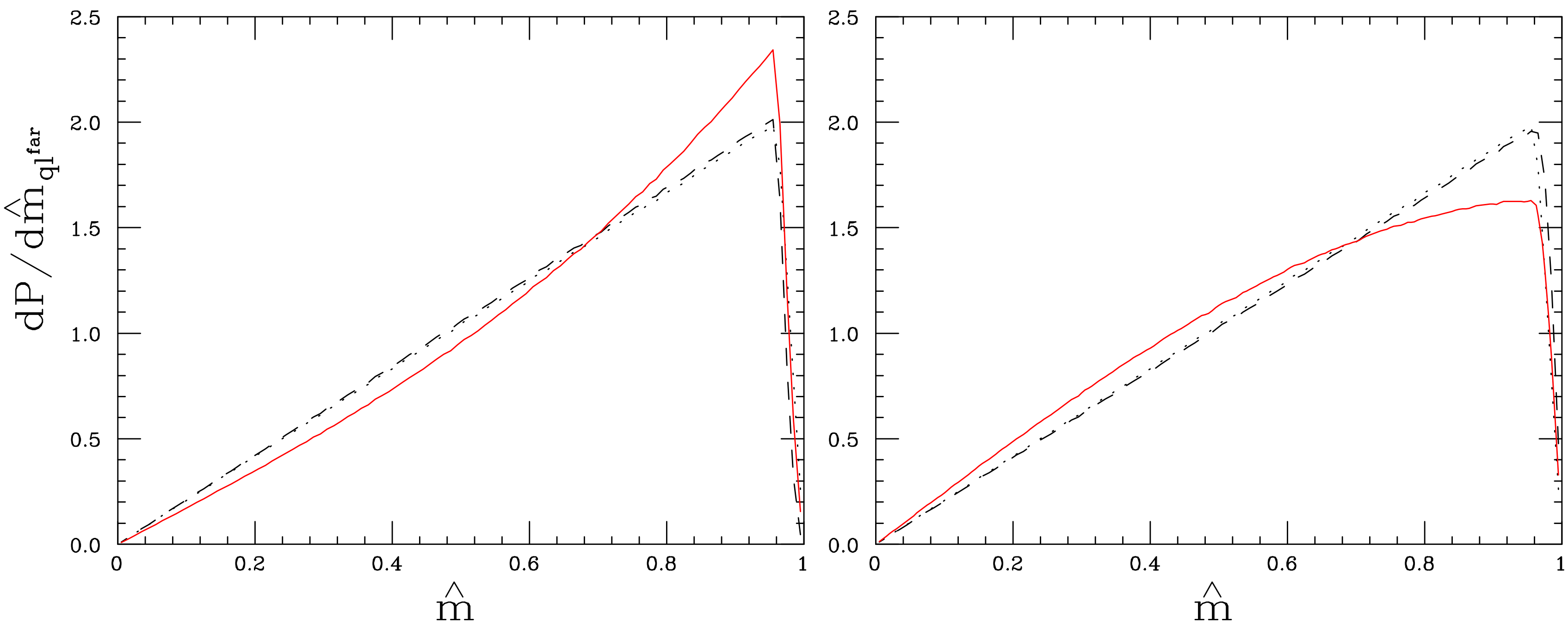
We can repeat the same thing for invariant mass of the quark and the far lepton. For the SPS1_a SUSY mass spectrum we get



solid = UED spins dashed = SUSY spins

$q\ l^{\text{far}}$

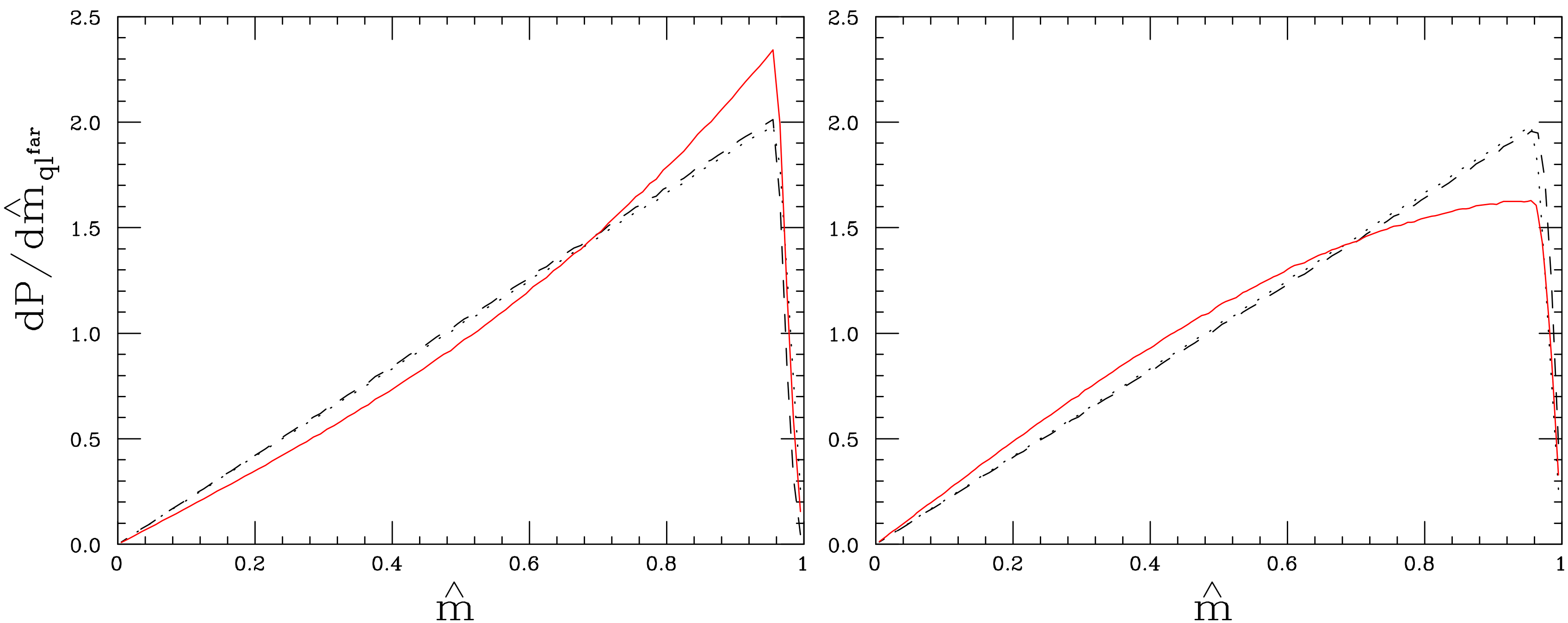
And for the UED mass spectrum we get



solid = UED spins dashed = SUSY spins

$q\ l^{\text{far}}$

And for the UED mass spectrum we get

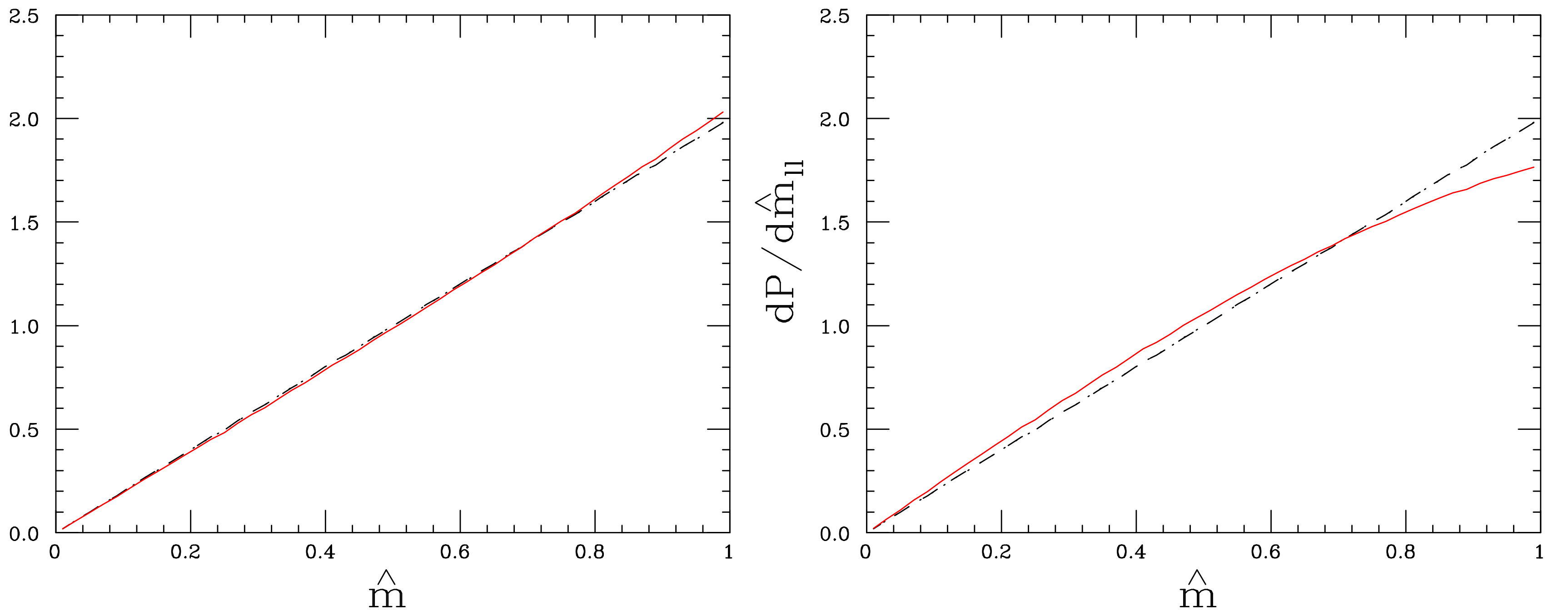


solid = UED spins　　　dashed = SUSY spins

These have a small effect, but not as small as...

$l^{\rm near}\ l^{\rm far}$

... $l^{\rm near}\ l^{\rm far}$ distributions, shown here for the SPS1_a and UED mass spectra



solid = UED spins   dashed = SUSY spins

But...

it is not possible to measure these distributions directly for the following reasons:

- A detector is unable to distinguish l^{near} and l^{far}:

  ql^{near} and ql^{far} distributions mix.

But...

it is not possible to measure these distributions directly for the following reasons:

- A detector is unable to distinguish l^{near} and l^{far}:

  $ql^{\rm near}$ and $ql^{\rm far}$ distributions mix.

- Not only two chains - $l^{\text{near}} = l^+$ or l^- from before but:
  - Decays of excited (q^*,$\tilde{q}$) and ($\bar{q}^*$,$\tilde{\bar{q}}$) have same two distributions
  - Left and Right-Handed leptons give opposite distributions.

But...

it is not possible to measure these distributions directly for the following reasons:

- A detector is unable to distinguish l^{near} and l^{far}:

  ql^{near} and ql^{far} distributions mix.

- Not only two chains - $l^{\text{near}} = l^+$ or l^- from before but:

$$
\begin{aligned}
\text{Process 1}: \{q, l^{\text{near}}, l^{\text{far}}\} &= \{q_L, l_L^-, l_L^+\}, \{\bar{q}_L, l_L^+, l_L^-\}, \\
&\quad \{q_L, l_R^+, l_R^-\}, \{\bar{q}_L, l_R^-, l_R^+\}; \\
\text{Process 2}: \{q, l^{\text{near}}, l^{\text{far}}\} &= \{q_L, l_L^+, l_L^-\}, \{\bar{q}_L, l_L^-, l_L^+\}, \\
&\quad \{q_L, l_R^-, l_R^+\}, \{\bar{q}_L, l_R^+, l_R^-\};
\end{aligned}
$$

in Barr's notation

$jl^{\pm}$

In reality, we can only hope to measure jet and lepton combinations.

These are given by:

$$\frac{\mathrm{d}P}{\mathrm{d}m_{jl^+}} = f_q \left(\frac{\mathrm{d}P_2}{\mathrm{d}m_{ql}^{\mathrm{near}}} + \frac{\mathrm{d}P_1}{\mathrm{d}m_{ql}^{\mathrm{far}}} \right) + f_{\bar{q}} \left(\frac{\mathrm{d}P_1}{\mathrm{d}m_{ql}^{\mathrm{near}}} + \frac{\mathrm{d}P_2}{\mathrm{d}m_{ql}^{\mathrm{far}}} \right)$$

for jl^+, and

$$\frac{\mathrm{d}P}{\mathrm{d}m_{jl^-}} = f_q \left(\frac{\mathrm{d}P_1}{\mathrm{d}m_{ql}^{\mathrm{near}}} + \frac{\mathrm{d}P_2}{\mathrm{d}m_{ql}^{\mathrm{far}}} \right) + f_{\bar{q}} \left(\frac{\mathrm{d}P_2}{\mathrm{d}m_{ql}^{\mathrm{near}}} + \frac{\mathrm{d}P_1}{\mathrm{d}m_{ql}^{\mathrm{far}}} \right)$$

for jl^-.

Production

As our analysis is reliant on a bias towards q production over $\bar{q}$ production, it is important to study this.

We calculated production matrix elements for all UED $2 \to 2$ strong processes. We found errors in Macesanu, McMullen & Nandi [Phys./ Rev./ D 66 (2002) 015009] in the process.

Production

As our analysis is reliant on a bias towards q production over $\bar{q}$ production, it is important to study this.

We calculated production matrix elements for all UED $2 \to 2$ strong processes. We found errors in Macesanu, McMullen & Nandi [Phys./ Rev./ D 66 (2002) 015009] in the process.

We added these into HERWIG to calculate (in pb):

Masses	Model	$\sigma_{\rm all}$	σ_{q^*}	$\sigma_{\bar{q}^*}$	f_q
UED	UED	252	163	83	0.66
UED	SUSY	28	18	9	0.65
SPS 1a	UED	487	239	103	0.70
SPS 1a	SUSY	55	26	11	0.70

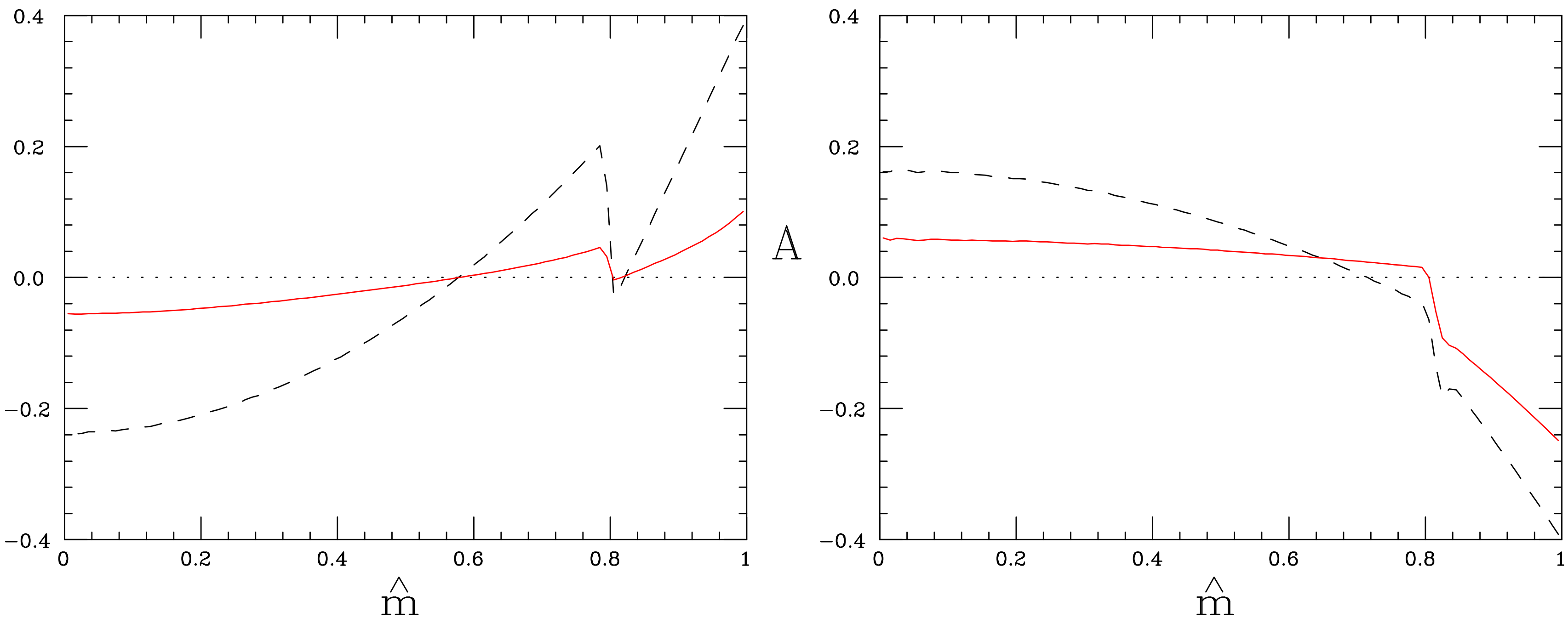
SUSY processes from existing routines in HERWIG.

Theoretical Result

Using these values and not distinguishing $l^{\rm near}$ and $l^{\rm far}$, we get the following distributions for

$$A = \frac{\mathrm{d}P/\mathrm{d}m_{jl^+} - \mathrm{d}P/\mathrm{d}m_{jl^-}}{\mathrm{d}P/\mathrm{d}m_{jl^+} + \mathrm{d}P/\mathrm{d}m_{jl^-}}$$

for the SPS1_a and UED mass spectra.



solid = UED spins dashed = SUSY spins

Detector Simulation

We conducted a detector simulation using first the parton showering, hadronization and underlying event in HERWIG and then the calorimeter simulation and cone jet finder program `GetJet` with cone size $\Delta R = 0.7$. We applied the following cuts:

1. Missing $E_T > 50$ GeV.
2. At least 4 jets with $E_T > 50$ GeV.
3. Sum of missing E_T and 4 highest jet E_Ts > 400 GeV
4. $m_{jl^\pm} \leq (m_{ql})_{\max}$.

Detector Simulation

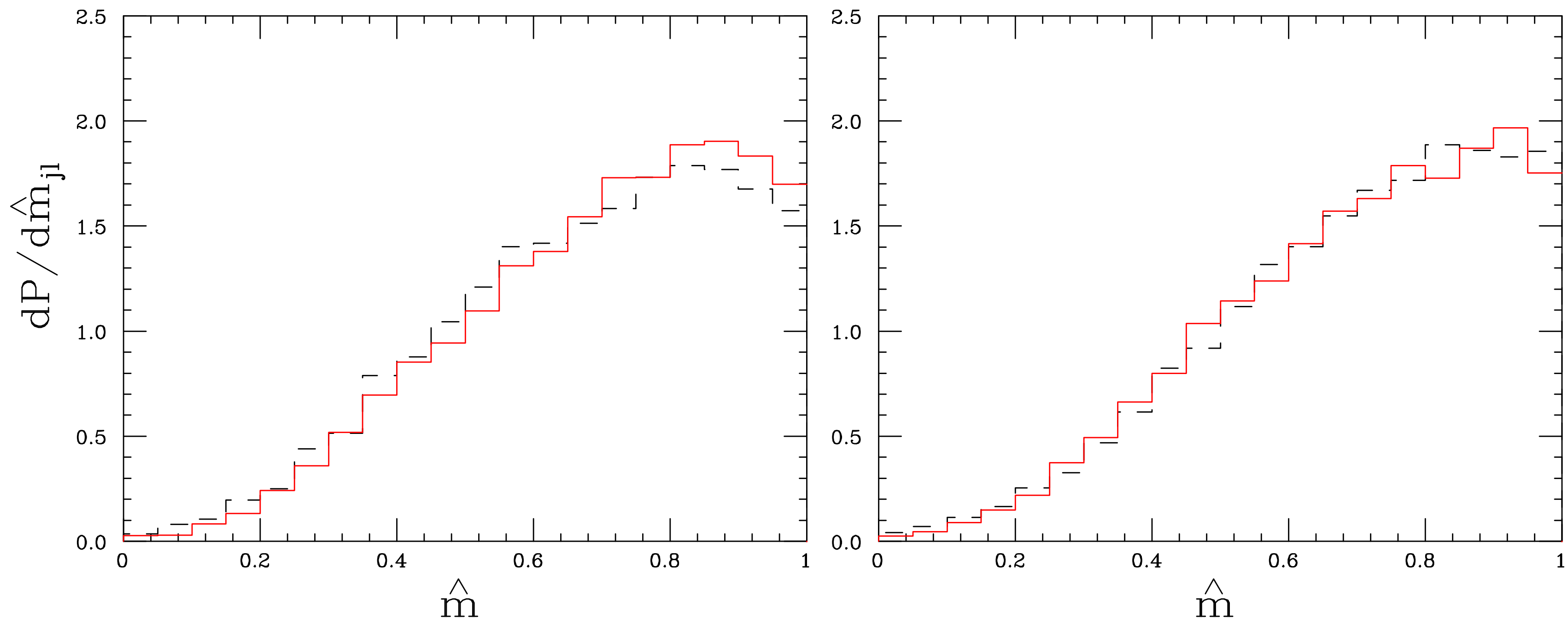
We conducted a detector simulation using first the parton showering, hadronization and underlying event in HERWIG and then the calorimeter simulation and cone jet finder program `GetJet` with cone size $\Delta R = 0.7$. We applied the following cuts:

1. Missing $E_T > 50$ GeV.
2. At least 4 jets with $E_T > 50$ GeV.
3. Sum of missing E_T and 4 highest jet E_Ts > 400 GeV
4. $m_{jl^\pm} \leq (m_{ql})_{\max}$.

We actually selected the jet nearest to the true direction of the quark at parton level...
But, with the masses determined, these ambiguities in the chain reconstruction should be resolved by invt mass fits.

Detector Simulation

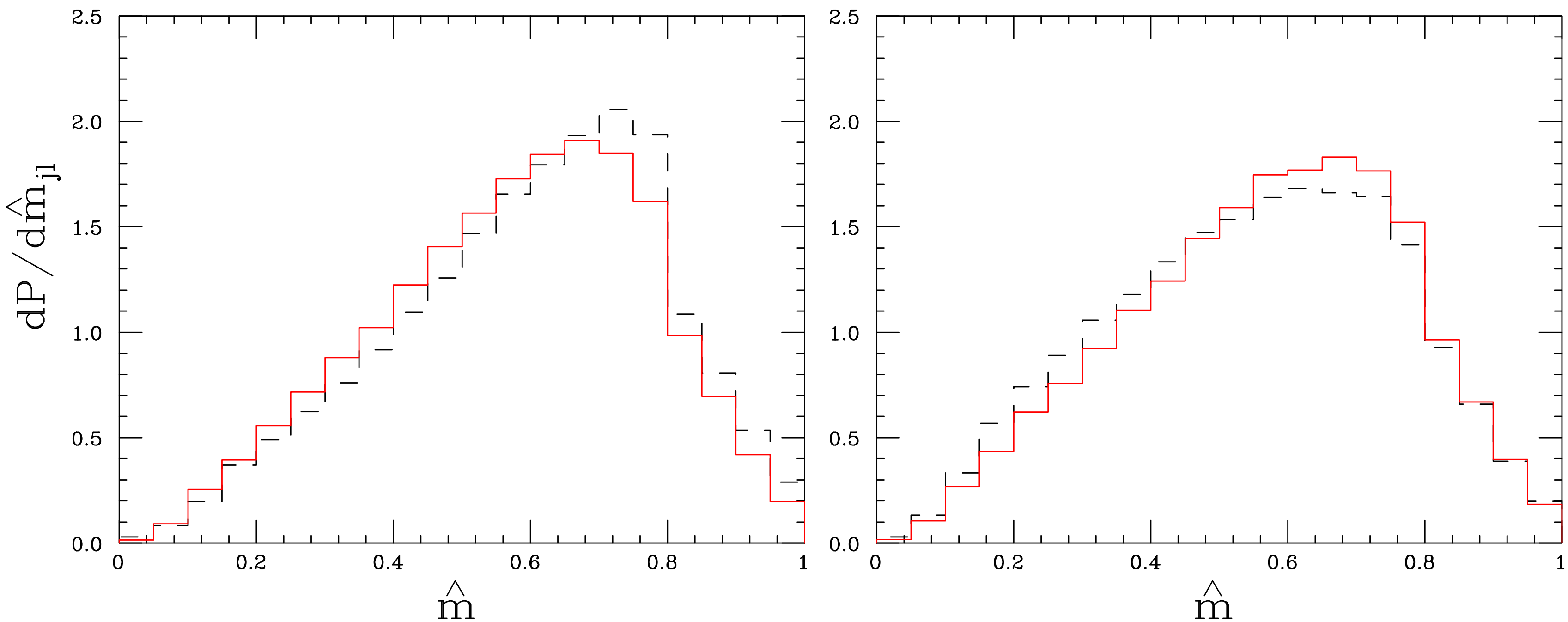
For the UED mass spectrum we get the following distributions for jet + l^+ and jet + l^-



solid = UED spins dashed = SUSY spins

Detector Simulation

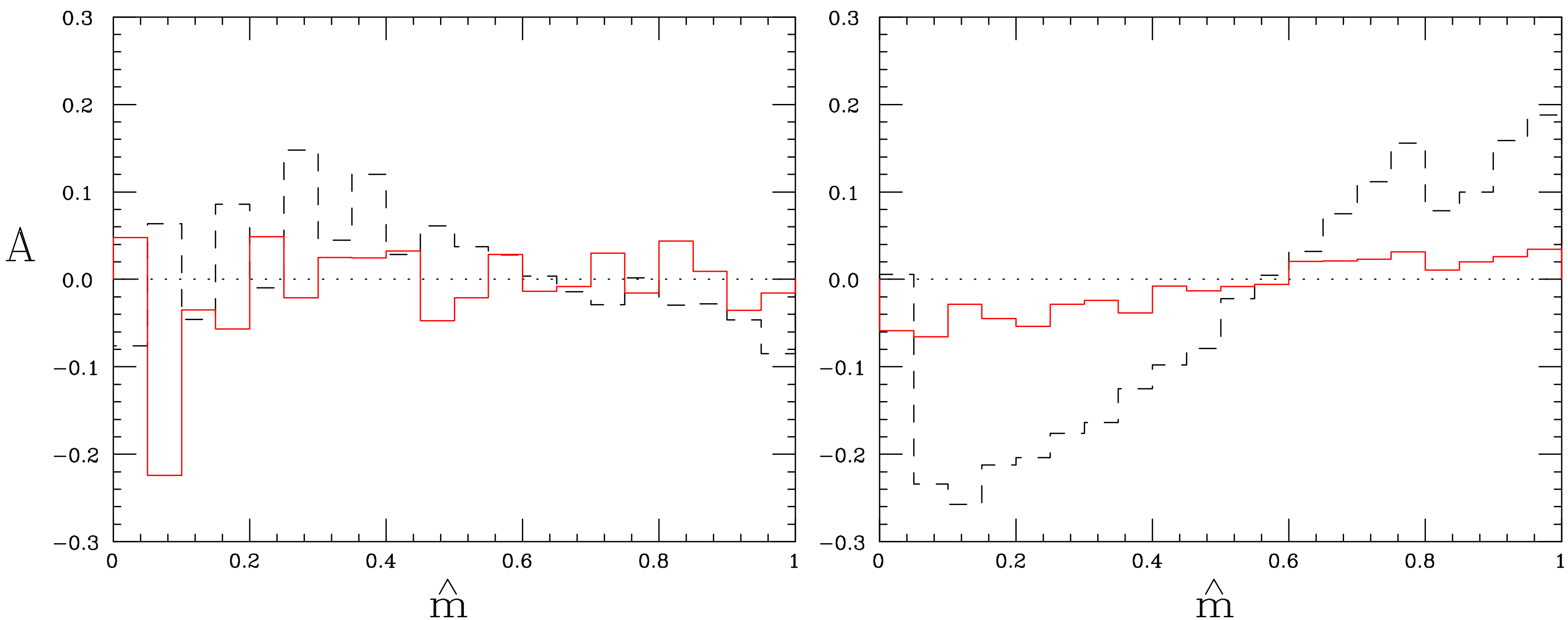
For the SPS1_a mass spectrum we get the following distributions for jet + l^+ and jet + l^-



solid = UED spins dashed = SUSY spins

Detector Simulation

These give the following detector-level charge asymmetries, for UED and SPS1_a mass spectra:



solid = UED spins   dashed = SUSY spins

Conclusions

- We have studied spin correlations in the decays of a q^* in a UED model and $\tilde{q}$ in the MSSM.
  In particular,
  - calculated analytical expressions for the two-particle invariant mass distributions valid for any particle masses
  - presented graphical results for two mass scenarios: one UED-like, one SUSY-like.

Conclusions

- We have studied spin correlations in the decays of a q^* in a UED model and $\tilde{q}$ in the MSSM.
- The near-degeneracy of a UED-like mass spectrum of new particles makes is difficult to distinguish different spin scenarios
- Such degeneracy is less likely in a SUSY-like spectrum,and the prospect of distinguishing spin scenarios is much greater.
- We also rederived production cross sections for KK-partons in a UED model, and found them about 8 times larger than the corresponding sparton production.