Spin determination at the LHC

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arXiv:1102.0293 [hep-ph]

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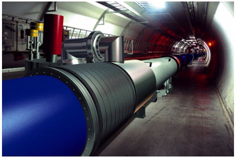
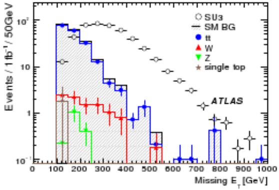
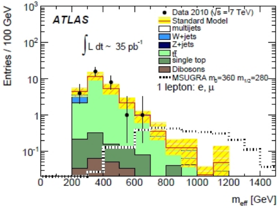
bctp Bethe Center for Theoretical Physics

The search for TeV physics is underway.

- LHC has switched on and is running well.
- We are all eagerly awaiting (praying for) any signs of new physics.
- Unfortunately so far we have only seen ....
- Without large datasets can we make difficult measurements? ($m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 1$ TeV)







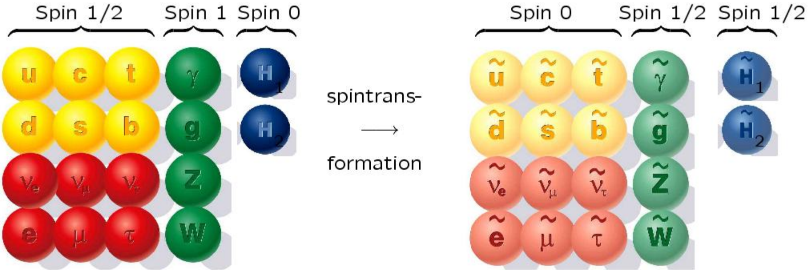
Supersymmetry (SUSY)

Supersymmetry relates fermions and bosons.

- $Q|boson >= |fermion >$
- $Q|fermion >= |boson >$

All SM particles get a 'Superpartner'.

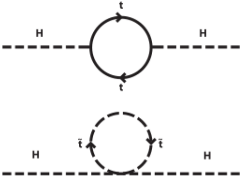
- Same quantum numbers.
- Differ in spin by 1/2.

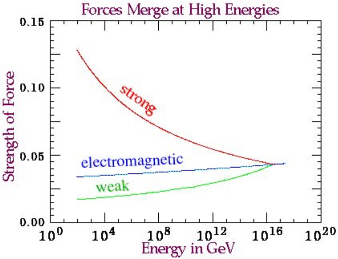


Motivations

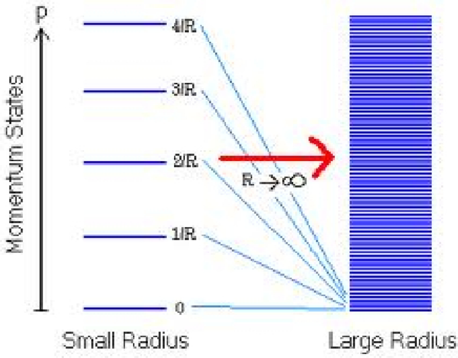
SUSY is one of the best motivated extensions of the SM.

- Offers a solution to the hierarchy problem.
- Provides a 'natural' dark matter candidate.
    - If R-parity is assumed.
- Unique extension of the Poincaré group.
- Unification of coupling constants.





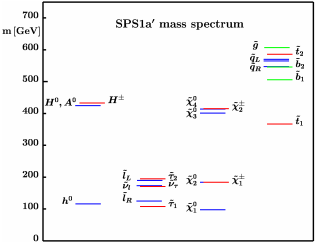
- Extend the spacetime by one or more (compactified) extra dimensions (ED).
- Allow some or all of SM to propagate in ED.
- SM will be accompanied by a 'tower' of heavy Kaluza-Klein states (same spin).
- Many extensions of SM possible, (e.g. 5D vs. 6D models, different compactifications....)

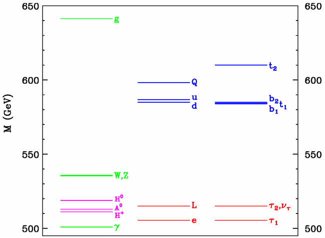


Introduction

Many models of new physics can look surprisingly similar.

Supersymmetry	Universal extra dimensions





- Both models double the number of particles.
- Couplings are similar as models 'copy' the SM content.
- Masses are similar as we hope to find new physics at the LHC.
- Assume lightest partner is stable and neutral $\rightarrow$ dark matter.

What is the unambiguous difference between SUSY and UED?

SM		spin	SUSY		spin	UED		spin
electron	e	$\frac{1}{2}$	selectron	$\tilde{e}_{L,R}$	0	KK-electron	$e_{1L,R}$	$\frac{1}{2}$
quark	q	$\frac{1}{2}$	squark	$\tilde{q}_{L,R}$	0	KK-quark	$q_{1L,R}$	$\frac{1}{2}$
W boson	$W^{\pm}$	1	chargino	$\tilde{\chi}_i^{\pm}$	$\frac{1}{2}$	KK-W	$W_1^{\pm}$	1
Z boson	Z^0	1	neutralino	$\tilde{\chi}_i^0$	$\frac{1}{2}$	KK-Z	Z_1	1
photon	γ	1	neutralino	$\tilde{\chi}_i^0$	$\frac{1}{2}$	KK-photon	γ_1	1
gluon	g	1	gluino	$\tilde{g}$	$\frac{1}{2}$	KK-gluon	g_1	1

- Spin of SUSY partners $\rightarrow$ differ from SM by 1/2.
- Spin of UED (KK) partners $\rightarrow$ same as SM.

- The total cross-section.

  (Datta, Kane and Toharia: hep-ph/0510204)

- Observation of higher KK modes.
  - For extra dimensional models.

  (Datta, Kong and Matchev: Phys. Rev. D72 (2005), hep-ph/0509246)

- Invariant mass distributions between particles in decay chains.

  (Barr: Phys. Lett. B596 (2004) 205-212, hep-ph/0405052)

- Angular distributions of produced particles.

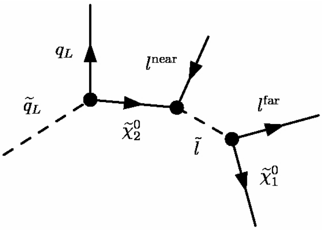
  (Barr: JHEP 02 (2006) 042, hep-ph/0511115)

- Many other papers on the subject......

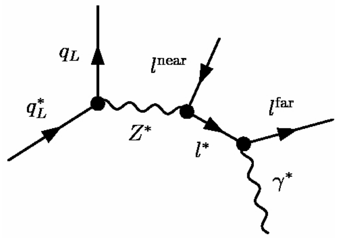
Invariant Mass Distributions

The similar particle spectrums of SUSY and UED can give similar final states.

Supersymmetry



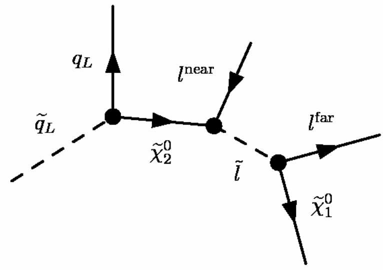
Universal extra dimensions

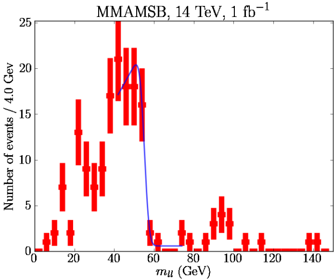


- The invariant distributions allow a measurement of mass spectrum of the model.
- The shape of the invariant distribution (ll, ql_{near}, ql_{far}) depends on the spins of the particles in the decay chain.

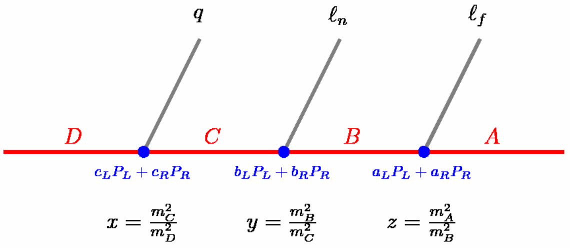
- Most of the effort at parameter determination at the LHC has focused on using mass edges.
  (Gjelsten, Miller, Osland; hep-ph/0410303)
- We take invariants between particles in the decay chain.
- For example $m_{\ell\ell}^{\max}$,

$$m_{\ell\ell}^{\max} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\ell}}^2}.$$





Try to be as model independent as possible by including all spin configurations.

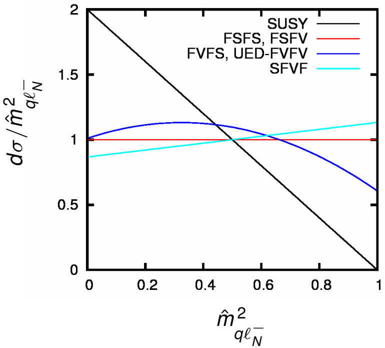


Spins	D	C	B	A	Example
SFSF	Scalar	Fermion	Scalar	Fermion	$\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$
FSFS	Fermion	Scalar	Fermion	Scalar	$q_1 \to Z_H \to \ell_1 \to \gamma_H$
FSFV	Fermion	Scalar	Fermion	Vector	$q_1 \to Z_H \to \ell_1 \to \gamma_1$
FVFS	Fermion	Vector	Fermion	Scalar	$q_1 \to Z_1 \to \ell_1 \to \gamma_H$
FVFV	Fermion	Vector	Fermion	Vector	$q_1 \to Z_1 \to \ell_1 \to \gamma_1$
SFVF	Scalar	Fermion	Vector	Fermion	—

(Athanasiou, Lester, Smillie, Webber: JHEP 08 (2006) 055, hep-ph/0605286)

(Burns, Kong, Matchev, Park: JHEP 10 (2008) 081, arXiv:0808.2472)

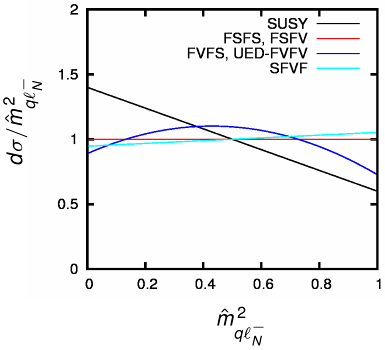
Take invariant mass of q and near ℓ^- as an example.



- Clear differences between spin structures (scalar, fermion or vector) can be seen.
- Assume that model contains SUSY mSUGRA couplings and masses (SPS1a').

Conjugate decay dilution

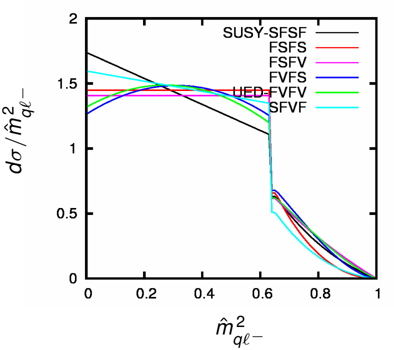
Unfortunately, life at the LHC is slightly more complicated.



- Distribution from $\tilde{q}^*$ has an opposite shape to that of $\tilde{q}$.
- Luckily LHC is a *pp* collider otherwise most distributions would cancel.
- Distributions are diluted.

Lepton ambiguity

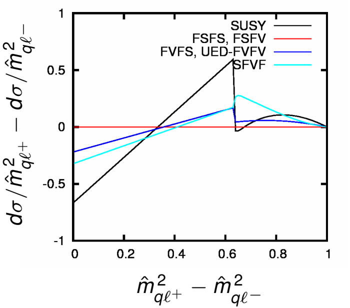
The same problem occurs with the final state leptons.



- We cannot distinguish the near and far leptons.
- Distributions become more messy when we take the combination.
- Is there a better observable?

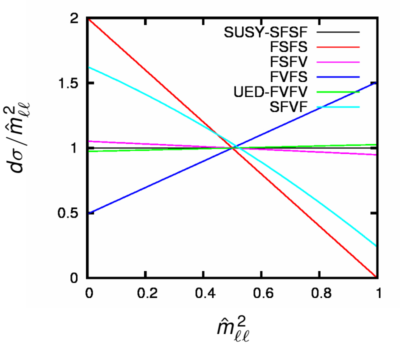
Use the difference between the $q\ell^+$ and $q\ell^-$ distributions.

(Barr: Phys. Lett. B596 (2004) 205-212, hep-ph/0405052)



- Spin structures again seem separable.
- With 150 fb^{-1} a measurement can be made.
- $m_{\tilde{q}} \sim 630$ GeV, $m_{\tilde{g}} \sim 720$ GeV, BR$(\chi^0_2 \to \tilde{\ell}^{\pm}\ell^{\mp}) \sim 25\%$
- New LHC bounds, study begins to look difficult, $(\sim 1\text{ab}^{-1})$
- We also haven't discussed the couplings.....

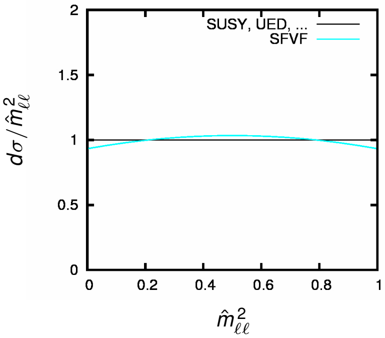
$m_{\ell\ell}$ offers the cleanest experimental observable.



- Under the assumption that the model contains mSUGRA couplings.
- 100% polarised intermediate particle.

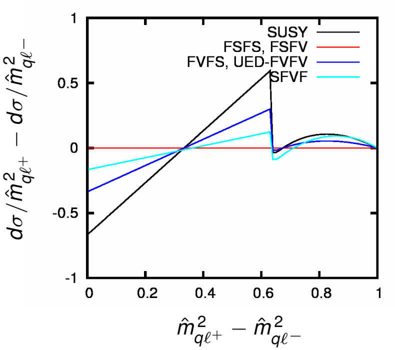
Invariant Masses

If we instead allow the couplings to vary in each spin model,



- Any spin structure can provide a good fit to the distribution.
- Only the relative size of right and left couplings important.
- Branching ratios can remain the same.

The fit can be performed for all distributions.

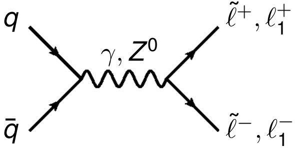


- SUSY is now less distinguishable.
- UED model can have the same shape.
- Background rejection will be important.
- Most optimistic SUSY scenario chosen (CMSSM).

Production Distributions

Consider the process of sleptons/KK-leptons production.

$$q\bar{q} \to Z^0/\gamma \to \tilde{\ell}^+\tilde{\ell}^- \qquad \text{SUSY}$$
$$q\bar{q} \to Z^0/\gamma \to \ell_1^+\ell_1^- \qquad \text{UED}$$



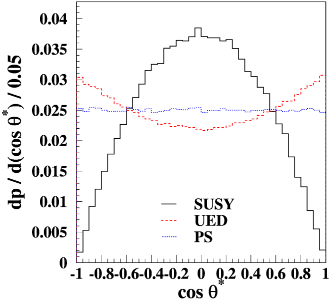
- In SUSY, scalar sleptons are exclusively produced in *P*-wave.
- In UED, fermionic KK-leptons are produced in *S*-wave.
- This results in a different angular behavior in the center of mass frame.

Barr: JHEP 02 (2006) 042, hep-ph/0511115.

$$\left(\frac{d\sigma}{d\cos\theta^*}\right)_{\mathrm{UED}} \propto 1 + \left(\frac{E_{\ell_1}^2 - M_{\ell_1}^2}{E_{\ell_1}^2 + M_{\ell_1}^2}\right)\cos^2\theta^*$$

$$\left(\frac{d\sigma}{d\cos\theta^*}\right)_{\mathrm{SUSY}} \propto 1 - \cos^2\theta^*$$

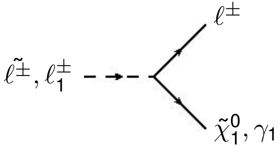
$$\left(\frac{d\sigma}{d\cos\theta^*}\right)_{\mathrm{PS}} \propto \text{constant}$$



Spin sensitive observable

- Production angles of sleptons/KK-leptons are not directly accessible due to particles escaping detection in the final state.
- However, decay products carry some information about the production angle,

$$\tilde{\ell}^+\tilde{\ell}^- \rightarrow \tilde{\chi}_1^0\ell^+ \; \tilde{\chi}_1^0\ell^- \qquad \text{SUSY}$$
$$\ell_1^+\ell_1^- \rightarrow \gamma_1\ell^+ \; \gamma_1\ell^- \qquad \text{UED}$$



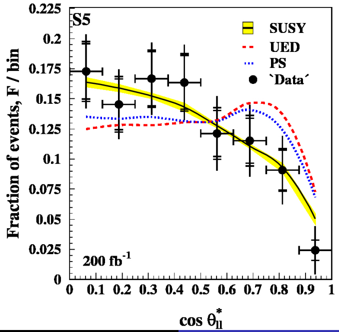
- Use longitudinally boost invariant observable,

$$\cos\theta^*_{\ell\ell} = \tanh\left(\Delta\eta_{\ell\ell}/2\right) \; , \qquad \Delta\eta_{\ell\ell} = \eta_{\ell^+} - \eta_{\ell^-}$$

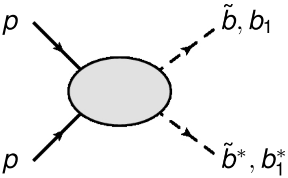
$\Rightarrow$ $\cos\theta^*_{\ell\ell}$ is cosine of the polar angle between leptons and the beam axis in the frame where pseudo-rapidities of the leptons are equal and opposite.

- Slepton production cross section is rather low at the LHC (electroweak process).
- Large luminosity required to obtain significant result.
  - $\mathcal{O}$ 200 fb^{-1} for $m_{\tilde{\ell}_R} \sim 150$ GeV.
- However, determination is unambiguous.

Barr: JHEP 02 (2006) 042, hep-ph/0511115.



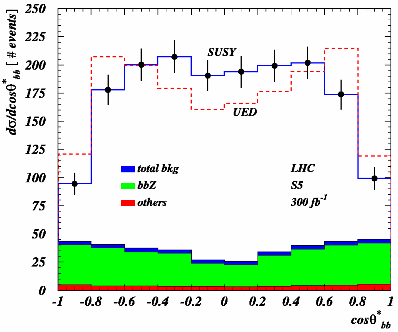
- Problem is low cross sections.
- We would like a method that can be used with early data.
- LHC is a hadron collider.
  - The cross section for QCD particle production is much larger.
  - Initial idea to measure bottom partner production.



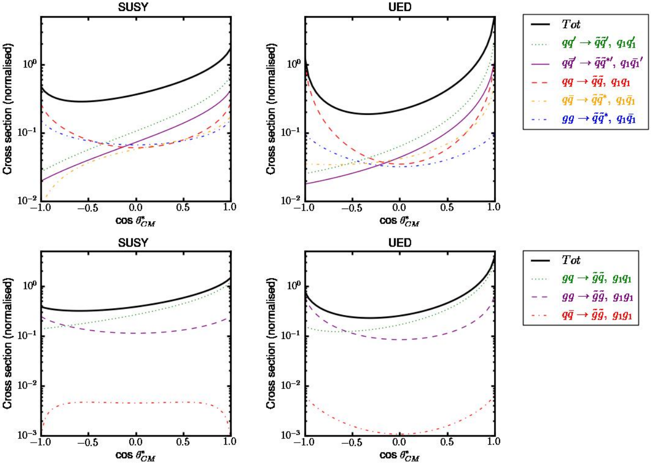
- More complicated as we have more channels.

Alves, Eboli: Phys Rev. D75 (2007) 115013 arXiv:0704.0254.

- More stringent cuts are required to remove background.
- Bottom tagging efficiency is a limiting factor.
- Large luminosity still required to obtain significant result.
  - $\mathcal{O}$ 300 fb^{-1}.
  - $m_{\tilde{b}} \sim$ 630 GeV.



Similar analysis in case of squark/KK-quarks and gluino/KK-gluon production.



Moortgat-Pick, Rolbiecki, JT: Phys.Lett. B699, arXiv:1102.0293

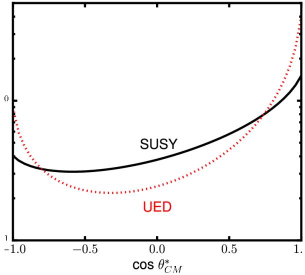
Squark spin measurement

UED production significantly more in forward direction.

- Enhanced cross section (QCD).
  - Earliest discovery channel for many models (2-jet + MET).
- Applicable for many decay chains/models.
- Consider production process,

$$pp \to \tilde{q}_i\,\tilde{q}_j^{(\prime)}, \qquad pp \to \tilde{q}_i\,\tilde{q}_j^{*(\prime)},$$
$$pp \to \tilde{g}\,\tilde{g}\;, \qquad pp \to \tilde{g}\,\tilde{q}_i\;.$$

Angular distributions in the center of mass frame.



Production angles of squarks/KK-quarks are not directly accessible due to particles escaping detection in the final state.

- Include decays, e.g.

$$pp \rightarrow \tilde{q}_R\, \tilde{q}_R \rightarrow q\, q\, \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \qquad \text{SUSY}$$

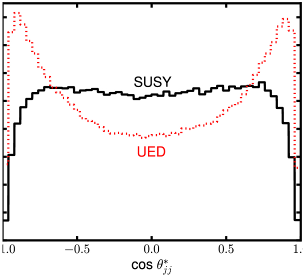
$$pp \rightarrow q_{R1}\, q_{R1} \rightarrow q\, q\, \gamma_1\, \gamma_1 \qquad \text{UED}$$

- Production boost is imprinted onto decay products.
- Assume mass spectrum is identical in both models

Rapidity difference as the spin sensitive observable,

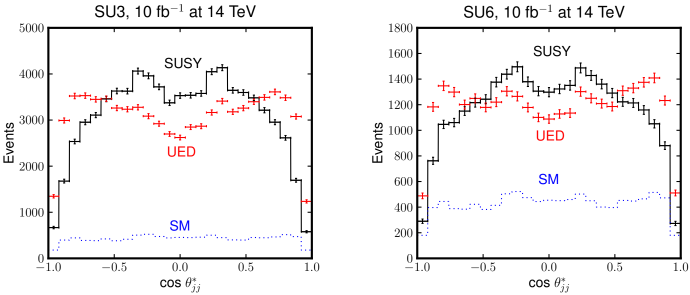
$$\cos\theta^*_{qq} = \tanh\left(\frac{\Delta\eta_{qq}}{2}\right),$$

$$\Delta\eta_{qq} = \eta_{q_1} - \eta_{q_2}.$$



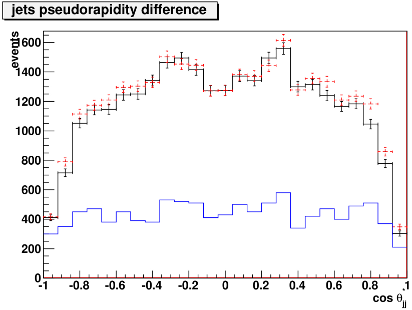
Simulation results

- If particle masses $\lesssim$ 900 GeV hints of spin structure can be seen already with integrated luminosity of 1 fb^{-1} (14 TeV).
- This assumes a SUSY mass spectrum.
- Cuts and SM background included, hardest jets taken to construct spin observable cos θ^*_{jj}.
- Works even for $a_L = a_R$.



Fitting to mass spectrum

- Argument assumes that we (approximately) know the new particle masses and spectrum.
- As $m_{q(KK)} \rightarrow \infty$, KK-gluon distributions can begin to mimic SUSY-quark.
- An independent measurement of quark and gluon partner masses is not always so easy.

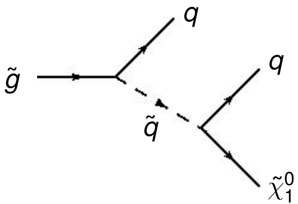


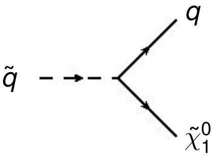
SUSY: Black
UED: Red
SM: Blue

Disentangling to mass spectrum

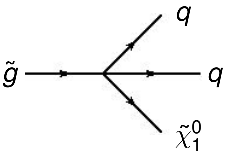
- Gluon partners have to decay to quarks.
- If quarks are heavier, this means three body decays (off-shell quark partner).

$m_{\tilde{g}} \gtrsim m_{\tilde{q}}$ ('Normal')





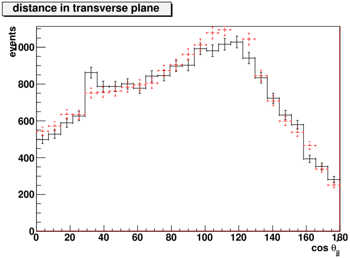
$m_{\tilde{q}} \gg m_{\tilde{g}}$ (UED faking SUSY)

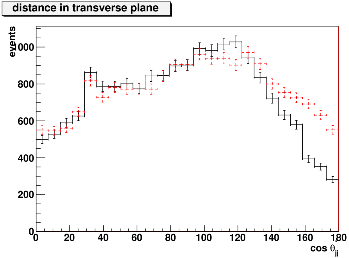


- We can expect alternative distributions to show differences.

Azimuthal distribution of jets

- Azimuthal angle can indicate extra jet activity.
- If two jets are in opposite directions in the azimuthal plane, a difference in pseudorapidity is required to produce missing energy.
- Extra jets allow events to pass missing energy cut more easily.



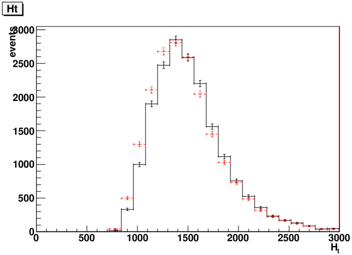


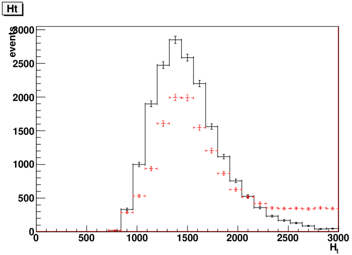
SUSY: Black
UED: Red

H_T distribution

- H_T distribution shows a nice distinction between the 2-body decays of SUSY and 3-body decays of UED.
- Due to extra jet activity in this UED model leading to a tail in H_T.
- Jets are more 'visible' than missing energy.

$$H_T = \sum p_T^i + E_T^{miss}.$$





SUSY: Black
UED: Red

- Other observables as well: jet energies, jet multiplicity .....

Summary

- New models of physics can share many similar properties.
- We must determine the spin of any new states to determine the model.
- Aim to be as model independent as possible.
- Production distributions are a spin sensitive observable.
  - Hints of the spin structure maybe seen with early data.
- Distributions in cascade decays can shed light on the particle spins.
  - Will require a substantial amount of data.
- A linear collider will provide the final word!