Spin determination at the LHC

Krzysztof Rolbiecki
DESY

in collaboration with:
O. Kittel, G. Moortgat-Pick, and J. Tattersall
Phys. Lett. B699 (2011) 158; arXiv:1102.0293 and work in progress

Implications of LHC results for TeV-scale physics
12–17 July 2012, CERN

Motivation

- spin and mass are the fundamental properties of particles
- different models of new physics predict different spins for newly discovered particles (and also different mass patterns)
- though many features could hint at the particular model, measurement of spins will be crucial for establishing a new theory

Outline

Outline

UED vs SUSY

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

In the following we will assume that the lightest neutralino in SUSY and the lightest KK-particle (KK-photon) are stable. This provides a dark matter candidate and gives the characteristic signature at the LHC – missing transverse energy.

How can we get a handle on spins?

- angular distribution in the center of mass of initially produced particles: P-wave vs S-wave
  - $\Rightarrow$ ILC case: sleptons and gauginos; Choi ea, hep-ph/0612301
  - $\Rightarrow$ LHC case: sleptons; Barr, hep-ph/0511115

  squark/gluino and gaugino production – this talk
- threshold behavior of cross-section: $\sim \beta$ vs. $\sim \beta^3$
- angular distributions in rest frames of decaying particles
  - $\Rightarrow$ requires reconstruction of invisible particles
- invariant masses of decay products
- quantum interference effects of different helicity states

How can we get a handle on spins?

Most of the methods discussed in the literature

- require a specific decay chain
- or a specific production mechanism
- assume a particular coupling structure
- need significant luminosity/statistics

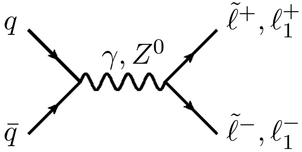
In this talk I will discuss a method that could overcome these limitations

Outline

Slepton spin measurement

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

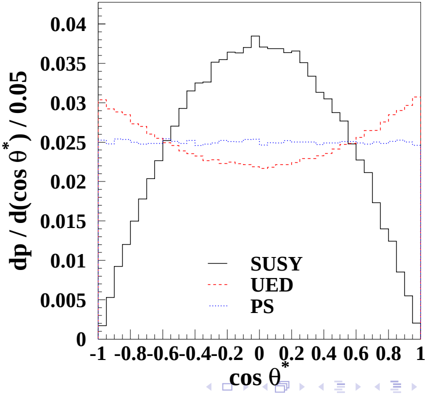
Angular behavior

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

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

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

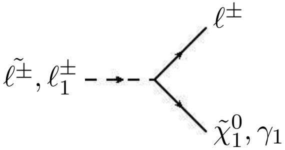
Barr: JHEP0206 042, hep-ph/0511115



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,

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



- Use longitudinally boost invariant observable,

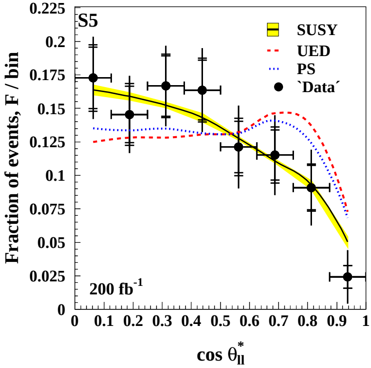
$$\cos\theta^*_{\ell\ell} = \tanh\left(\Delta\eta_{\ell\ell}/2\right)\ , \qquad \Delta\eta_{\ell\ell} = \eta_{\ell^+} - \eta_{\ell^-}$$

⇒ $\cos\theta^*_{\ell\ell}$ is cosine of the polar angle between leptons and the beam axis in the frame where pseudorapidities of the leptons are equal and opposite   Barr: JHEP0206 042, hep-ph/0511115

Simulation results

- slepton production cross section is rather low at the LHC (electroweak process)
- large luminosity required to obtain significant result
- however, determination is unambiguous

Barr: JHEP0206 042, hep-ph/0511115

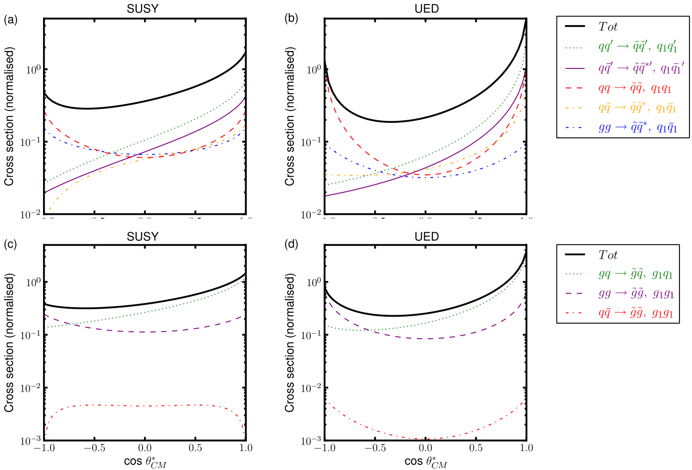


$$m_{\tilde{e}_R} = 191 \text{ GeV}$$
$$m_{\tilde{\chi}_1^0} = 120 \text{ GeV}$$
$$\sigma(\tilde{e}\tilde{e}^*) = 48 \text{ fb}$$

Outline

Colored Production

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



Moortgat-Pick, KR, Tattersall, arXiv:1102.0293

Squark spin measurement

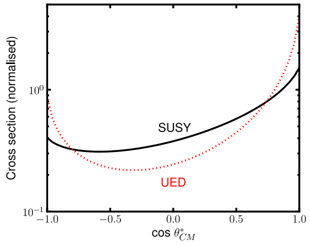
- enhanced cross section
  - $\Rightarrow$ earliest discovery channel for many models
- applicable for many decay chains/models
  - $\Rightarrow$ independent of the coupling structure
- consider production process like

$$pp \longrightarrow \tilde{q}_i\, \tilde{q}_j^{(\prime)} \qquad pp \longrightarrow \tilde{q}_i\, \tilde{q}_j^{*(\prime)}$$

$$pp \longrightarrow \tilde{g}\, \tilde{g} \qquad pp \longrightarrow \tilde{g}\, \tilde{q}_i$$

angular distributions in the center of mass frame
UED production significantly more in forward direction

Moortgat-Pick, KR, Tattersall, arXiv:1102.0293



Spin sensitive observable at the parton level

- production angles of squarks/KK-quarks are not directly accessible due to particles escaping detection in the final state
- include decays, e.g.

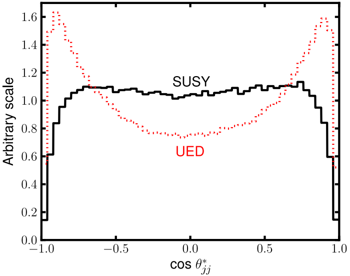
$$pp \longrightarrow \tilde{q}_R\, \tilde{q}_R \longrightarrow q\, q\, \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \qquad \text{SUSY}$$

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

rapidity difference as the spin sensitive observable

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

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



Selection cuts and simulation

Scenario chosen: SU6, $m_{\tilde{q},\tilde{g}} \sim 850$ GeV

Cuts used (see arXiv:0901.0512):

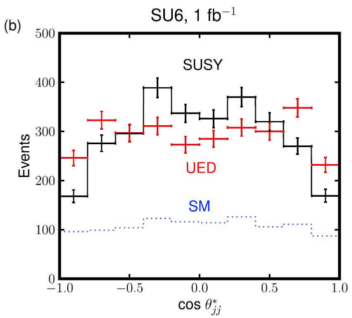
- At least two jets with $p_T^{j_1} > 150$ GeV and $p_T^{j_2} > 100$ GeV for the hardest and second-hardest jet, respectively.
- No electrons and muons with $p_T > 15$ GeV and $|\eta_\ell| < 2.5$
- $\Delta\phi(j_1, E_T^{\text{miss}}) > 0.2$, $\Delta\phi(j_2, E_T^{\text{miss}}) > 0.2$
- $E_T^{\text{miss}} > 0.3 M_{\text{eff}}$, $M_{\text{eff}} > 800$ GeV

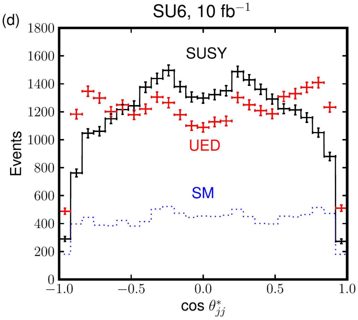
Event simulation:

- BSM signal: `Herwig++`
- SM background: `Sherpa` ($W + \text{jets}, Z + \text{jets}, t\bar{t}$)
- detector effects: `Delphes`

Simulation results

- this assumes SUSY mass spectrum
- cuts and SM background included, hardest jets taken to construct spin observable $\cos\theta^*_{jj}$





High luminosity limit

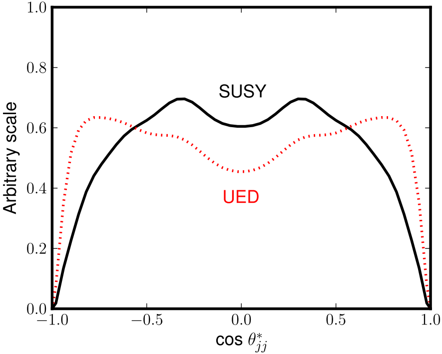
Define an asymmetry

$$\mathcal{A} = \frac{N(|\cos\theta^*_{jj}| > 0.5) - N(|\cos\theta^*_{jj}| < 0.5)}{N_{\text{tot}}}$$

For SU6 scenario:

$$\mathcal{A}^{\text{hl}}_{\text{SUSY}} = -0.226$$
$$\mathcal{A}^{\text{hl}}_{\text{UED}} = 0.016$$

Those values only weakly depend on the overall mass scale



Heavy mass scenario

The method also works with significantly heavier particles

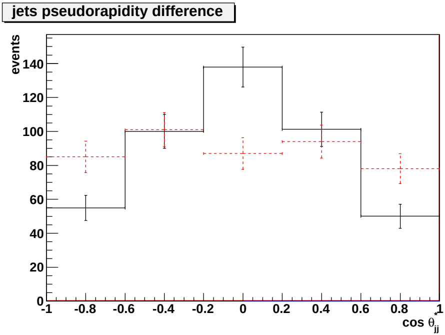
- $\Rightarrow$ $m_{\tilde{q},\tilde{g}} \sim 1.3$ TeV; SUG5 scenario from Cassel ea, arXiv:1101.4664
- $\Rightarrow$ $\sigma(14\ \mathrm{TeV}) = 0.4$ pb
- $\Rightarrow$ modify the cuts: $p_T^{j_1} > 400$ GeV and $p_T^{j_2} > 200$ GeV

Observed asymmetry

$$\mathcal{A}_{\mathrm{SUSY}}^{10\ \mathrm{fb}^{-1}} = -0.28 \pm 0.05$$
$$\mathcal{A}_{\mathrm{UED}}^{10\ \mathrm{fb}^{-1}} = -0.01 \pm 0.05$$

High lumi expectation

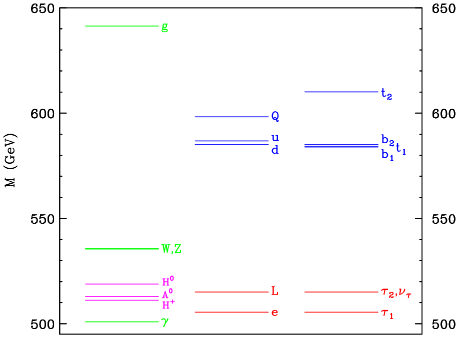
$$\mathcal{A}_{\mathrm{SUSY}}^{\mathrm{hl}} = -0.32$$
$$\mathcal{A}_{\mathrm{UED}}^{\mathrm{hl}} = -0.02$$



Outline

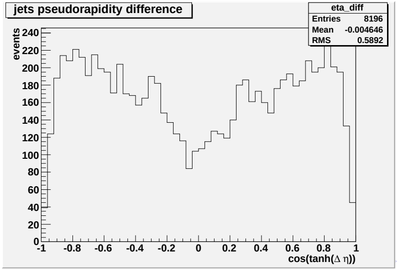
Sample UED spectrum

- simplest UED models predict compressed mass spectrum
- recently small mass differences studied also in SUSY models
- this type of spectrum will be in any case challenging!



Distribution of jets

- masses $m_{\tilde{q},\tilde{g}} \sim 600$ GeV, $m_{\text{LSP}} \sim 500$ GeV
- mass difference $\Delta m = 100$ GeV
- ISR dominates the sample of jets
- jets from decay chains typically soft
- regardless of spin the distribution of leading jets looks the same



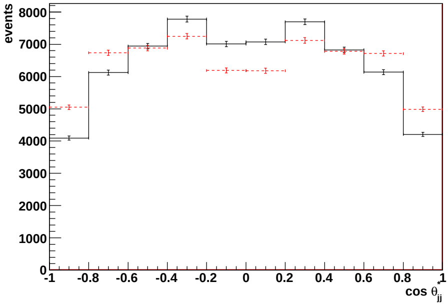
Subleading jets

- small mass differences $m_{\tilde{q},\tilde{g}} \sim 600$ GeV, $m_{\mathrm{LSP}} \sim 500$ GeV
- jets from decay chains typically soft
  - $\Rightarrow$ background from fragmentation, ISR, etc.
- select softer jets for the analysis: here 3rd and 4th in p_T

Observed asymmetry

$$\mathcal{A}^{10\ \mathrm{fb}^{-1}}_{\mathrm{SUSY}} = -0.15$$

$$\mathcal{A}^{10\ \mathrm{fb}^{-1}}_{\mathrm{UED}} = -0.05$$

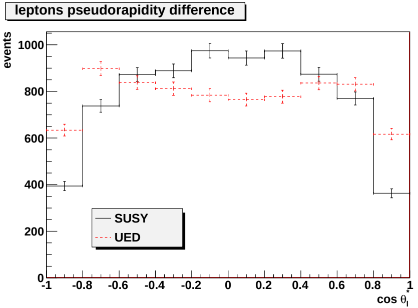


Using final state leptons

- consider a process: $pp \to \tilde{q}\tilde{q} \to \tilde{\chi}_2^0 q\ \tilde{\chi}_1^\pm q \to \tilde{\chi}_1^0 \ell\ell q\ \ell' \nu \tilde{\chi}_1^0 q$
- usual leptonic searches are sensitive to this signal for small mass differences – see a talk by Kazuki Sakurai
- calculate rapidity distance between lepton pair $\ell\ell$ and a single lepton ℓ'

$$\cos\theta_\ell^* = \tanh\left(\frac{\eta_{\ell\ell} - \eta_{\ell'}}{2}\right)$$

where $\eta_{\ell\ell}$ is rapidity of $\ell\ell$ system

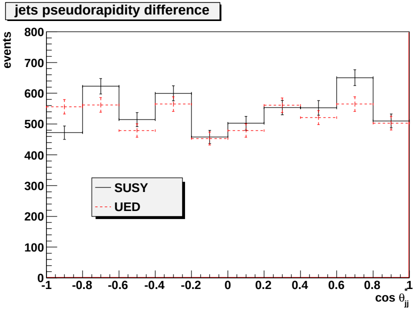


... or jets

- take jets instead of leptons in the same process
  $pp \to \tilde{q}\tilde{q} \to \tilde{\chi}_2^0 q\ \tilde{\chi}_1^\pm q \to \tilde{\chi}_1^0 \ell\ell q\ \ell' \nu \tilde{\chi}_1^0 q$
- calculate rapidity distance between leading jets
- significant contamination from ISR – both spin cases give the same angular distribution

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

$$\Delta\eta_{qq} = \eta_{q1} - \eta_{q2}$$



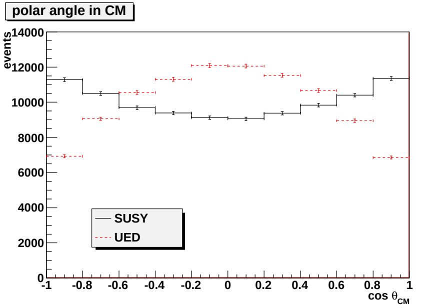
Outline

Gaugino pair production

- exclusion limits for gauginos still weak
- can give tri-lepton signature with low SM background

$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell\ell \; \tilde{\chi}_1^0 \ell' \nu$$

- different angular distributions of gauginos/KK-bosons in hard process CM frame
  - S-wave excitation for spin-$1/2$ SUSY fermions
  - P-wave dominates for spin-1 UED bosons



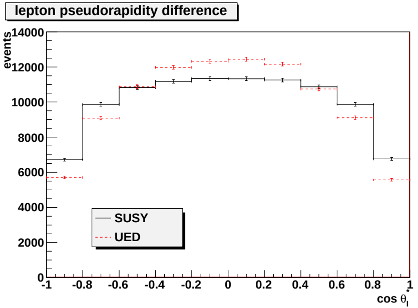
Rapidity again

- calculate rapidity difference of lepton pair vs single lepton

$$\cos\theta^*_\ell = \tanh\left(\frac{\eta_{\ell\ell} - \eta_{\ell'}}{2}\right)$$

  where $\eta_{\ell\ell}$ is rapidity of $\ell\ell$ system
- unfortunately that does not offer a great discriminating power

- conclusion doesn't depend on the details of decays – 3-body vs 2-body decays



Why the trick fails...

- the crucial assumption was a high boost of produced particles
- SUSY gauginos are produced very close to threshold hence a low boost
- leptons from SUSY decays don't reproduce the gaugino direction

$\Rightarrow$ the method is not supposed to work, and it doesn't

- on the other hand UED bosons are produced far from threshold and give significant boost to the final state leptons

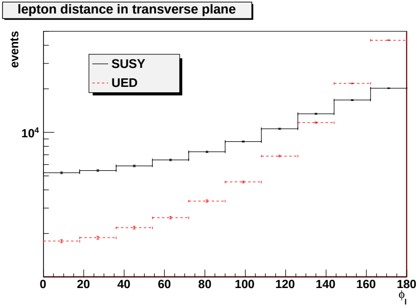
$\Rightarrow$ look at the lepton distribution in transverse plane

Transverse distribution

- transverse distribution gives a hint of a boost given to the final state leptons from initially produced particles
- large separation signals a large boost, like in UED case
- this can discriminate between P- and S-wave excitations and together with rapidity distribution point to the right model

$$\Delta\phi = \phi_{\ell\ell} - \phi_{\ell'} \mod \pi$$

where $\phi_{\ell\ell}$ is an azimuthal angle of the $\ell\ell$ system



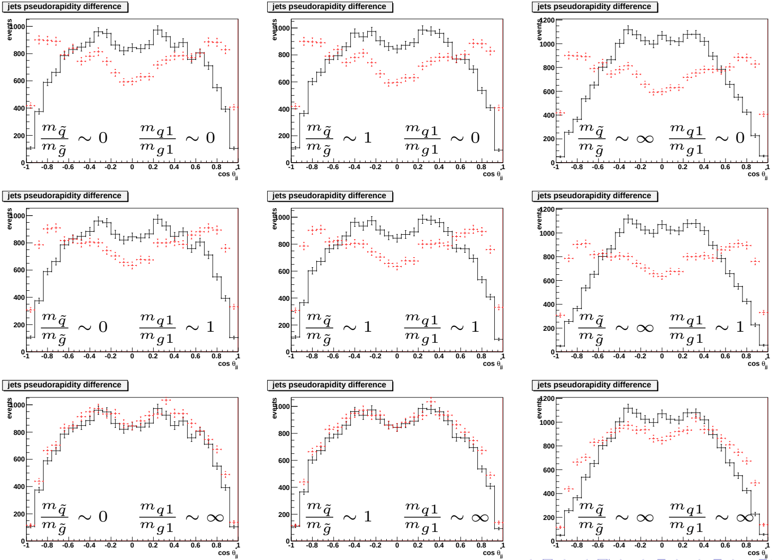
Outline

Summary

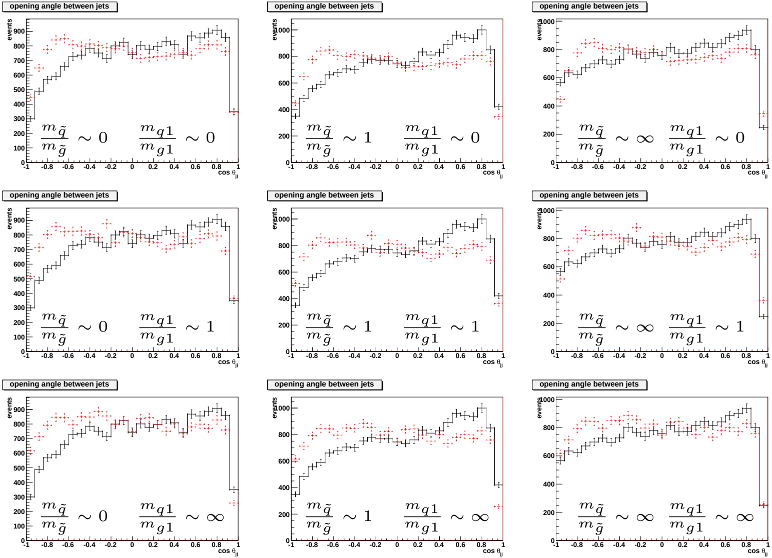
- New models of physics can share many similar properties.
- We must determine the spin of any new states to determine the model.
- Aim to be as model independent as possible.
- Production distributions are a spin sensitive observable.
  - $\Rightarrow$ Hints of the spin structure maybe seen with early data.
  - $\Rightarrow$ Works in many models (GMSB/AMSB/...).
  - $\Rightarrow$ Different decays chains are possible.

BACKUP

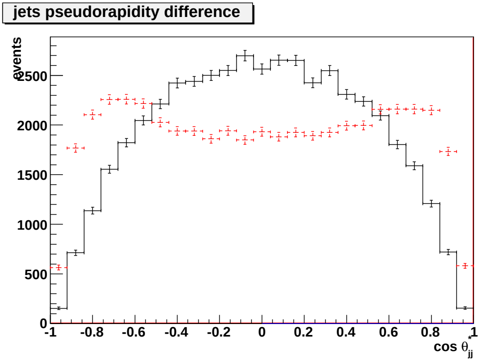
Comparison of different mass hierarchies



Opening angle



SUG5 high luminosity



$$\mathcal{A}^{\rm hl}_{\rm SUSY} = -0.32$$
$$\mathcal{A}^{\rm hl}_{\rm UED} = -0.02$$

Cuts for the UED masses

- require at least 4 jets
- event selection based on radiation jets: $p_T^{j_1} > 150$ GeV and $p_T^{j_2} > 100$ GeV
- distributions of radiation jets will have different behavior wrt cuts compared to jets from decay chains
  - $\Rightarrow$ a way to distinguish different mass hierarchies?
- two additional jets with $50 < p_T < 100$ GeV
  - $\Rightarrow$ used in the spin analysis
- the rest of the cuts as for SU6 scenario

Rapidity and pseudorapidity

- Rapidity

$$y = \frac{1}{2}\log\left(\frac{E+p_L}{E-p_L}\right) = \log\left(\frac{E+p_L}{\sqrt{m^2+p_T^2}}\right)$$

- Rapidity is additive under Lorentz boosts along the beam direction
- The difference in rapidity of two particles is invariant under boosts along the beam axis
- For massless particles we have

$$y = \frac{1}{2}\log\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\log\tan\frac{\theta}{2}$$

- Define pseudorapidity as

$$\eta = -\log\tan\frac{\theta}{2}$$

Back to talk

Methods discussed in literature

- The total cross section Datta ea, hep-ph/0510204
- Observation of higher KK modes Datta ea, PhysRev,D72,096006
- Kinematic distributions of quarks from quark partners decays Nojiri, Shu, arXiv:1101.2701; Hallenbeck ea, PhysRev,D79,075024
- Particle production in vector boson fusion Buckley, Ramsey-Musolf arXiv:1008.5151
- Invariant masses of lepton-jet and lepton-photon pairs in squark/KK-quark and gluino/KK-gluon decay chains Barr, PhysLett,B596,205; Smillie, Webber, JHEP,0510,069; Wang, Yavin, JHEP,0704,032; Burns ea, JHEP,0810,081; Ehrenfeld ea, JHEP,0907,056; Alves ea, PhysRev,D74,095010
- Kinematic reconstruction of missing momentum Cho ea PhysRev,D79; Cheng ea JHEP,1011,122; Moortgat-Pick ea in preparation
- Angular distributions of leptons from sleptons decays and jets from squarks decays Barr, JHEP,0602,042; Horton arXiv:1006.0148; Alves, Eboli, PhysRev,D74,115013; Moortgat-Pick ea, arXiv:1102.0293