

Spin determination at the LHC

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DESY

in collaboration with:

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Phys. Lett. B699 (2011) 158; arXiv:1102.0293

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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
- recall great importance of Stern-Gerlach experiment for quantum mechanics

Outline

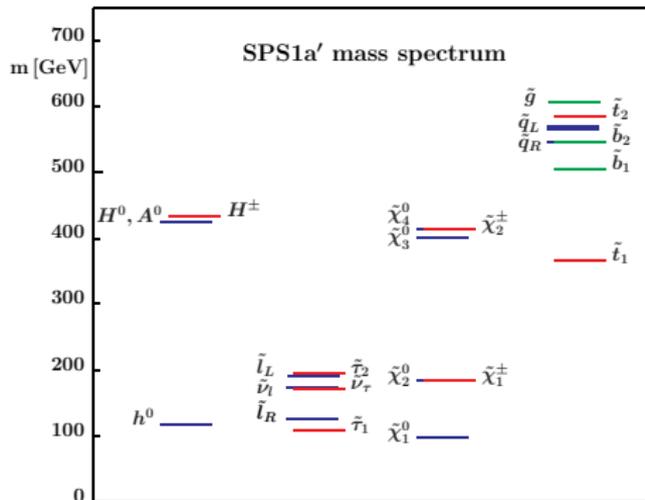
- 1 Introduction
- 2 Slepton case
- 3 Spin determination with squarks and gluinos
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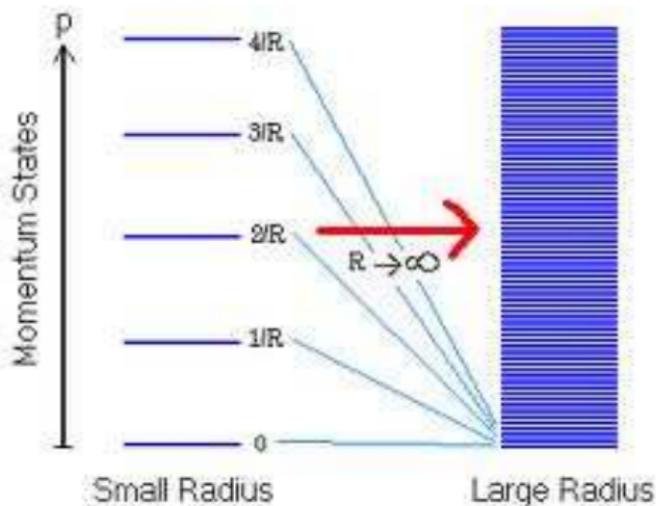
Sample SUSY spectrum

- spins and couplings fixed by construction
- spins of new particles differ by 1/2 from their SM partners
- more freedom with masses as these are fixed by mechanism of SUSY breaking
- typically quite a large mass differences up to a few 100s GeV



Extra dimensions models

- 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 of **the same spin**
- many extensions of SM possible, also predicting different spins (e.g. 5D vs. 6D models)



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*
 - ⇒ ILC case: sleptons and gauginos; Choi ea, hep-ph/0612301
 - ⇒ LHC case: sleptons; Barr, hep-ph/0511115

squark/gluino production – this talk
- threshold behavior of cross-section: $\sim \beta$ vs. $\sim \beta^3$
- **angular distributions** in rest frames of decaying particles
 - ⇒ 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 specific decay chain
- or specific production mechanism
- assume particular coupling structure
- need significant luminosity/statistics

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

Outline

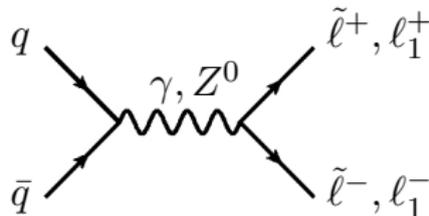
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Slepton spin measurement

Consider the process of sleptons/KK-leptons production.

$$q\bar{q} \rightarrow Z^0/\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^- \quad \text{SUSY}$$

$$q\bar{q} \rightarrow Z^0/\gamma \rightarrow \ell_1^+\ell_1^- \quad \text{UED}$$



- 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

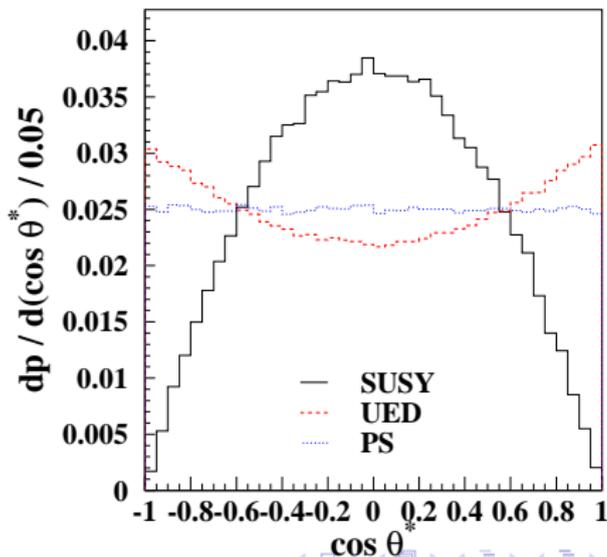
Angular behavior

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

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

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

Barr: JHEP0206 042, hep-ph/0511115

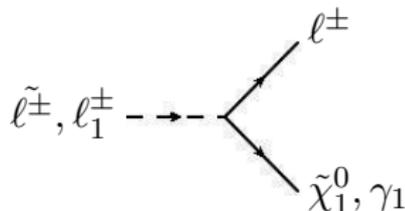


Spin sensitive observable

- 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,

$$\tilde{\ell}^+ \tilde{\ell}^- \rightarrow \tilde{\chi}_1^0 \ell^+ \tilde{\chi}_1^0 \ell^- \quad \text{SUSY}$$

$$\ell_1^+ \ell_1^- \rightarrow \gamma_1 \ell^+ \gamma_1 \ell^- \quad \text{UED}$$



- Use longitudinally boost invariant observable,

$$\cos \theta_{\ell\ell}^* = \tanh(\Delta\eta_{\ell\ell}/2) \quad , \quad \Delta\eta_{\ell\ell} = \eta_{e^+} - \eta_{e^-}$$

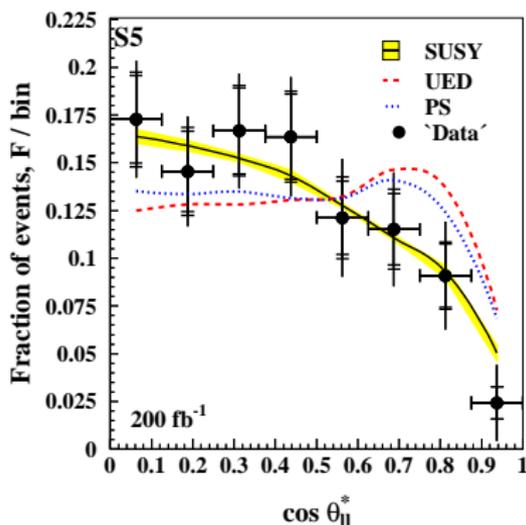
$\Rightarrow \cos \theta_{\ell\ell}^*$ is cosine of the polar angle between leptons and the beam axis in the frame where pseudorapidities of the leptons are equal and opposite

Barr: JHEP0206 042, [hep-ph/0511115](https://arxiv.org/abs/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



$$m_{\tilde{e}_R} = 191 \text{ GeV}$$

$$m_{\tilde{\chi}_1^0} = 120 \text{ GeV}$$

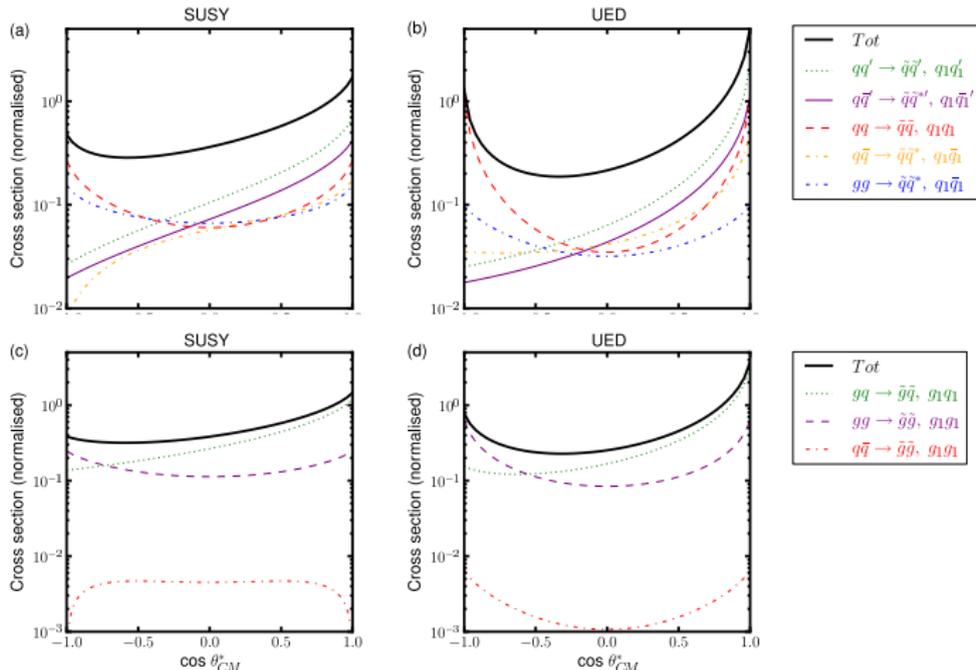
$$\sigma(\tilde{e}\tilde{e}^*) = 48 \text{ fb}$$

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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
 - ⇒ earliest discovery channel for many models
- applicable for many decay chains/models
 - ⇒ independent of the coupling structure
- consider production process like

$$pp \rightarrow \tilde{q}_i \tilde{q}_j^{(\prime)}$$

$$pp \rightarrow \tilde{g} \tilde{g}$$

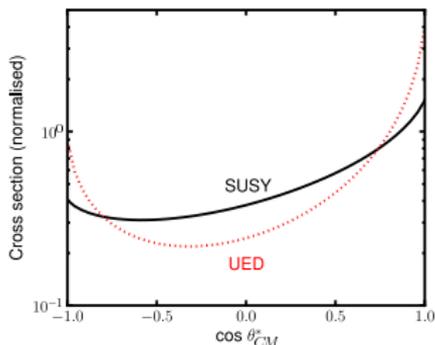
$$pp \rightarrow \tilde{q}_i \tilde{q}_j^{*\prime}$$

$$pp \rightarrow \tilde{g} \tilde{q}_i$$

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.

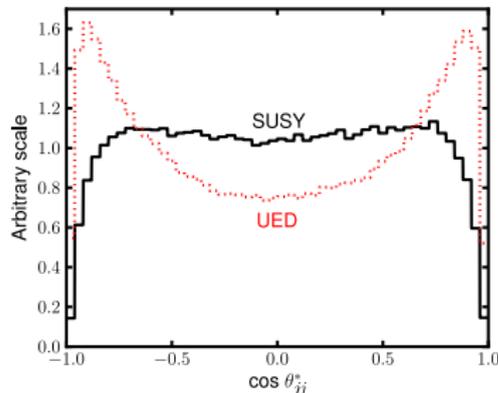
$$pp \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow qq \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad \text{SUSY}$$

$$pp \rightarrow q_{R1} q_{R1} \rightarrow qq \gamma_1 \gamma_1 \quad \text{UED}$$

rapidity difference as the spin sensitive observable

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

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



Selection cuts and simulation

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

Cuts used (see [arXiv:0901.0512](https://arxiv.org/abs/0901.0512)):

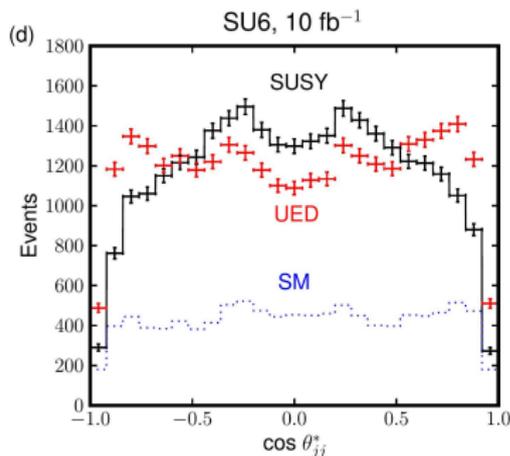
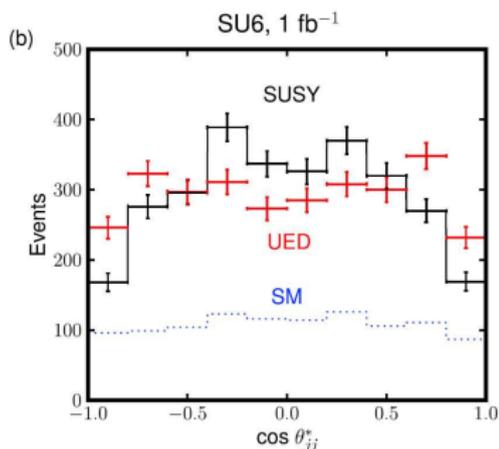
- At least two jets with $p_T^{j_1} > 150$ GeV and $p_T^{j_2} > 100$ GeV for the hardest and second-hardest jet, respectively.
- No electrons and muons with $p_T > 15$ GeV and $|\eta_\ell| < 2.5$
- $\Delta\phi(j_1, E_T^{\text{miss}}) > 0.2$, $\Delta\phi(j_2, E_T^{\text{miss}}) > 0.2$
- $E_T^{\text{miss}}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

Event simulation:

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

Simulation results

- hints of spin structure can be seen already with integrated luminosity of $\mathcal{O}(1 \text{ fb}^{-1})$ at $\sqrt{s} = 14 \text{ TeV}$
- 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

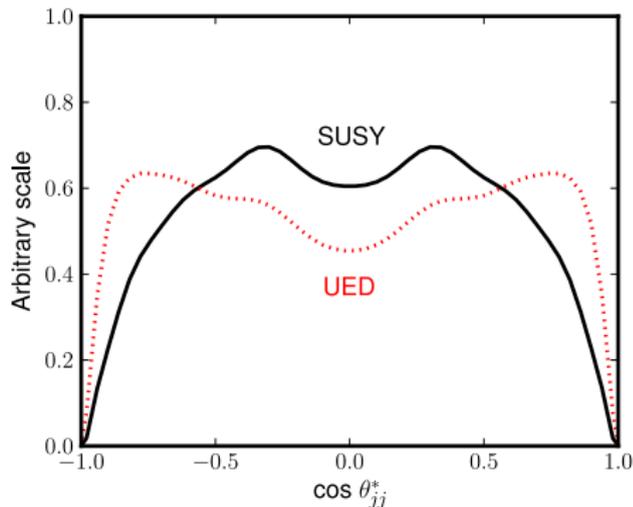
$$\mathcal{A} = \frac{N(|\cos \theta_{jj}^*| > 0.5) - N(|\cos \theta_{jj}^*| < 0.5)}{N_{\text{tot}}}$$

For SU6 scenario:

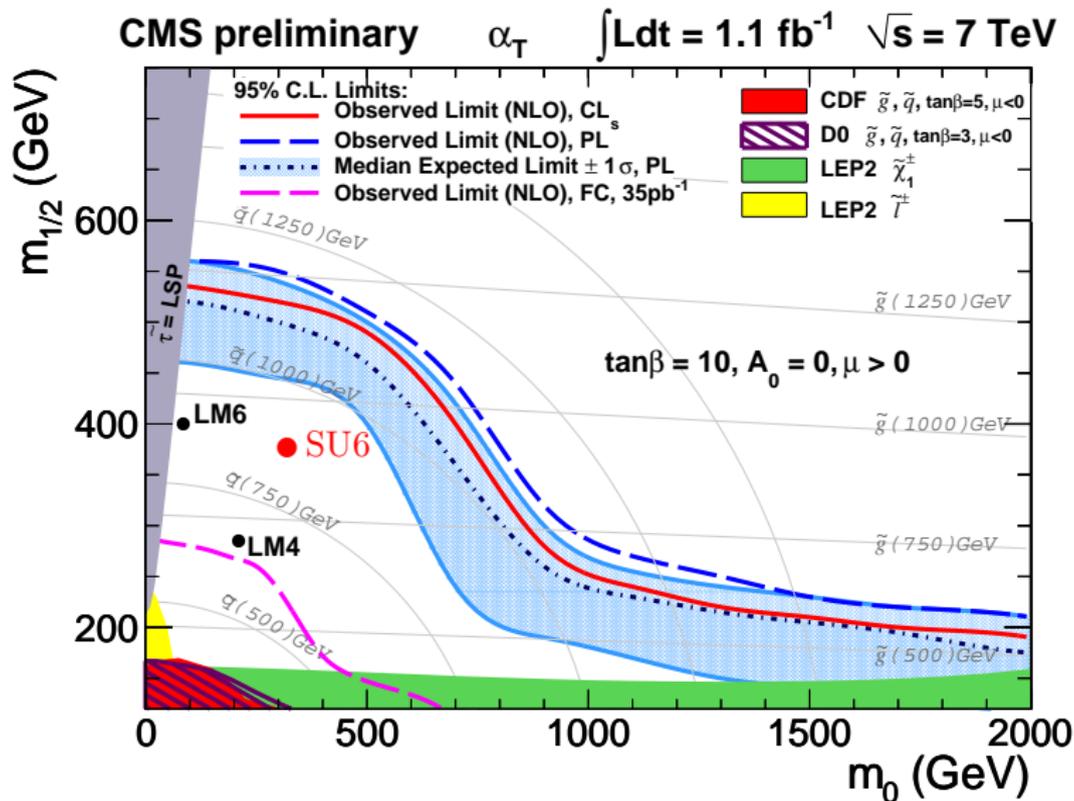
$$\mathcal{A}_{\text{SUSY}}^{\text{hl}} = -0.226$$

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

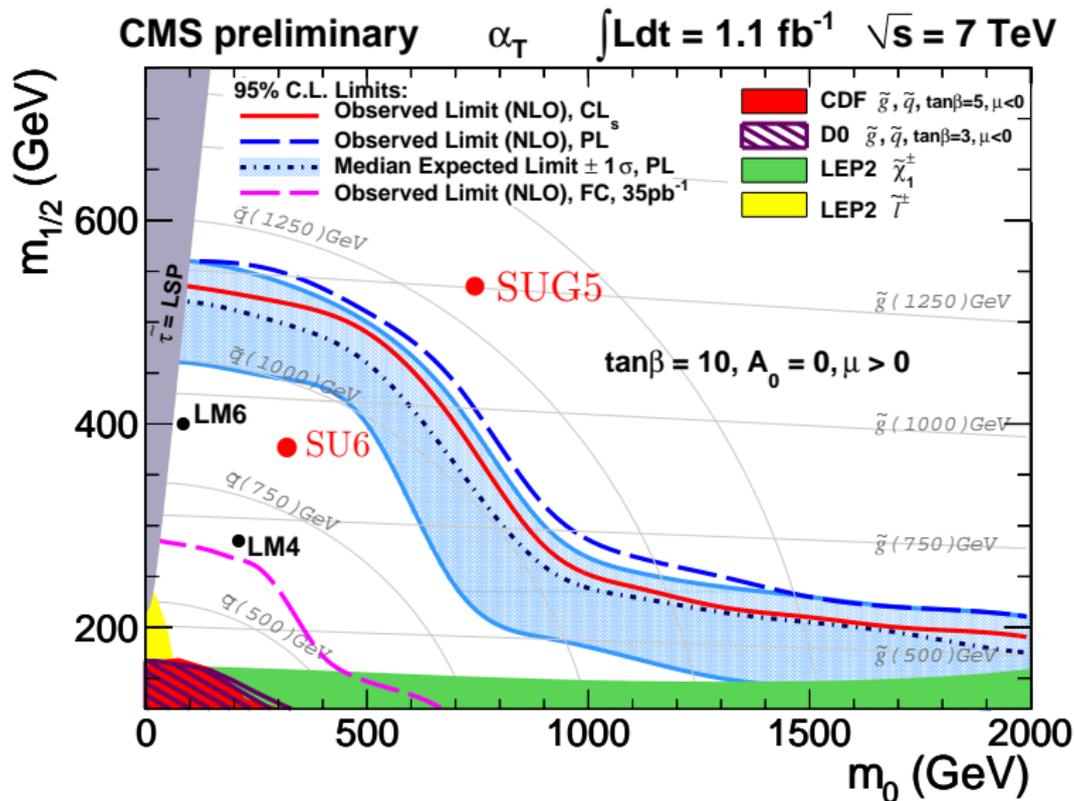
Those values only weakly
depend on the overall
mass scale



So far we see...



So far we see...



Heavy mass scenario

The method also works with significantly heavier particles

⇒ $m_{\tilde{q}, \tilde{g}} \sim 1.3$ TeV; SUG5 scenario from [Cassel et al, arXiv:1101.4664](#)

⇒ $\sigma(14 \text{ TeV}) = 0.4$ pb

⇒ modify the cuts: $p_T^{j1} > 400$ GeV and $p_T^{j2} > 200$ GeV

Observed asymmetry

$$A_{\text{SUSY}}^{10 \text{ fb}^{-1}} = -0.28 \pm 0.05$$

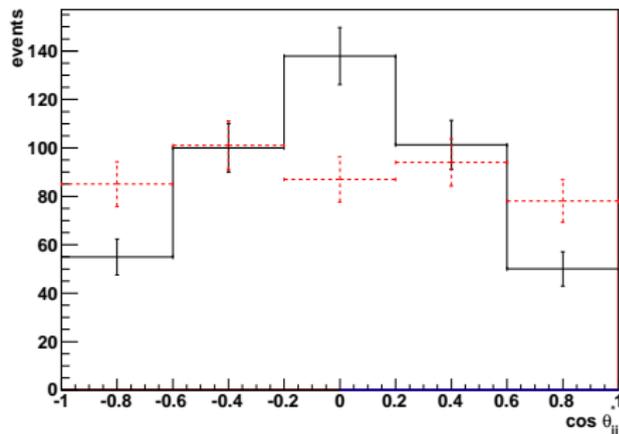
$$A_{\text{UED}}^{10 \text{ fb}^{-1}} = -0.01 \pm 0.05$$

High lumi expectation

$$A_{\text{SUSY}}^{\text{hl}} = -0.32$$

$$A_{\text{UED}}^{\text{hl}} = -0.02$$

jets pseudorapidity difference



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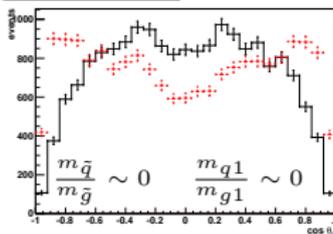
Summary

- **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.
 - ⇒ Works in many models (GMSB/AMSB/...).
 - ⇒ Different decays chains are possible.

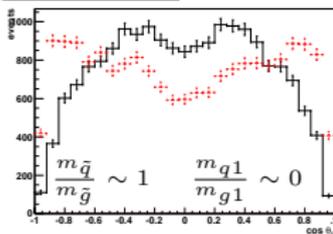
BACKUP

Comparison of different mass hierarchies

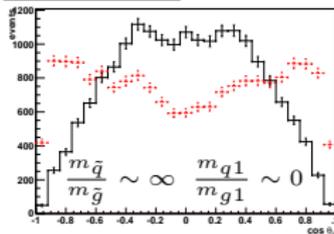
jets pseudorapidity difference



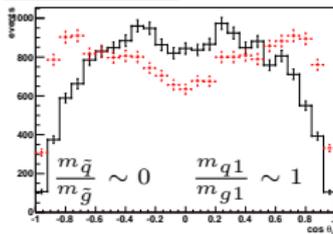
jets pseudorapidity difference



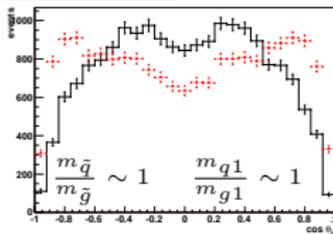
jets pseudorapidity difference



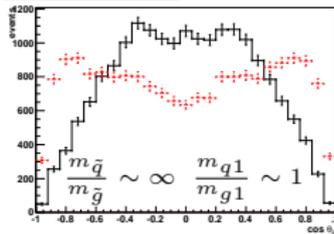
jets pseudorapidity difference



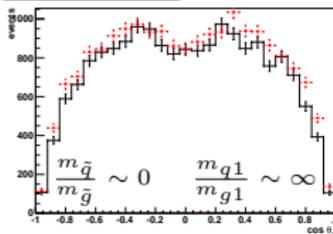
jets pseudorapidity difference



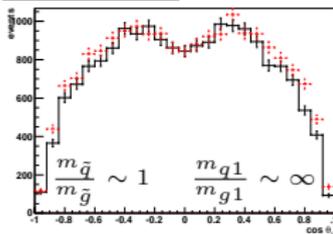
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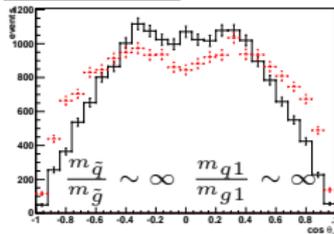
jets pseudorapidity difference



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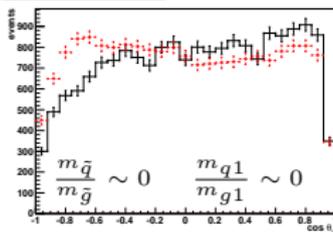


jets pseudorapidity difference

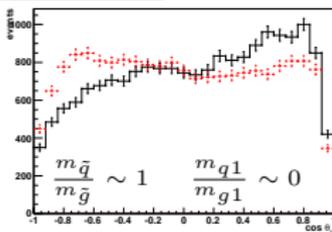


Opening angle

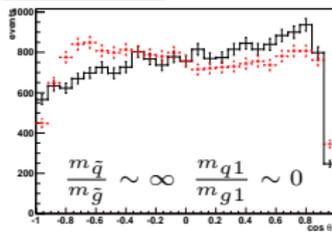
opening angle between jets



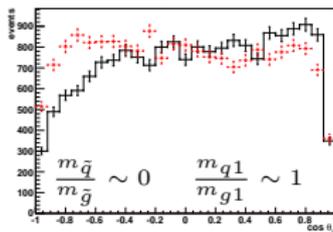
opening angle between jets



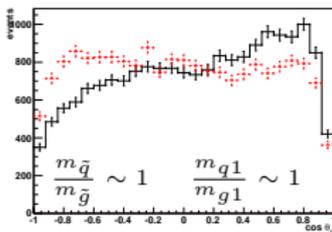
opening angle between jets



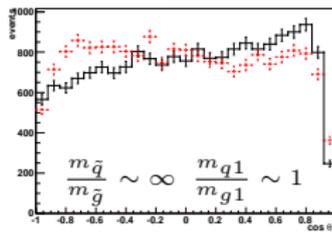
opening angle between jets



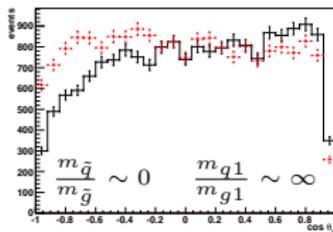
opening angle between jets



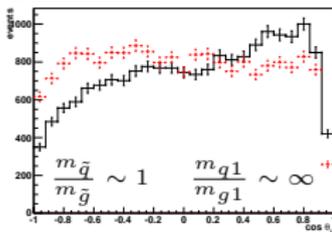
opening angle between jets



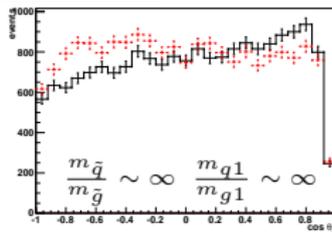
opening angle between jets



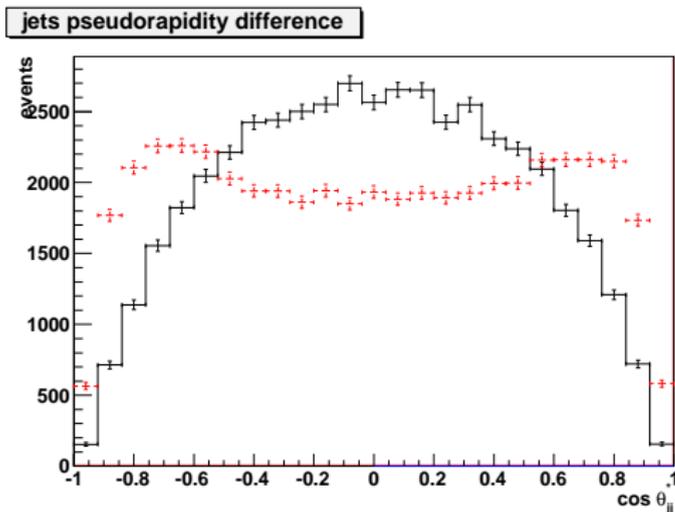
opening angle between jets



opening angle between jets



SUG5 high luminosity

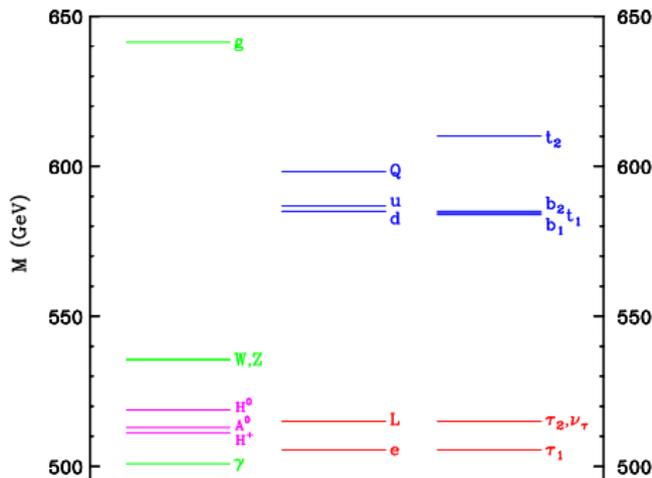


$$A_{\text{SUSY}}^{\text{hl}} = -0.32$$

$$A_{\text{UED}}^{\text{hl}} = -0.02$$

Sample UED spectrum

- we focus here on Universal Extra Dimensions (5D)
- particle content very similar to SUSY
- but **spins different by 1/2**, i.e. the same as in SM
- simplest models predict **compressed** mass spectrum, but extensions/complications are possible
- **this type of spectrum will be in any case challenging!**



Cuts for the UED masses

- require at least 4 jets
- event selection based on radiation jets: $p_T^{j1} > 150 \text{ GeV}$ and $p_T^{j2} > 100 \text{ GeV}$
- distributions of radiation jets will have different behavior wrt cuts compared to jets from decay chains
 - ⇒ a way to distinguish different mass hierarchies?
- two additional jets with $50 < p_T < 100 \text{ GeV}$
 - ⇒ used in the spin analysis
- the rest of the cuts as for SU6 scenario

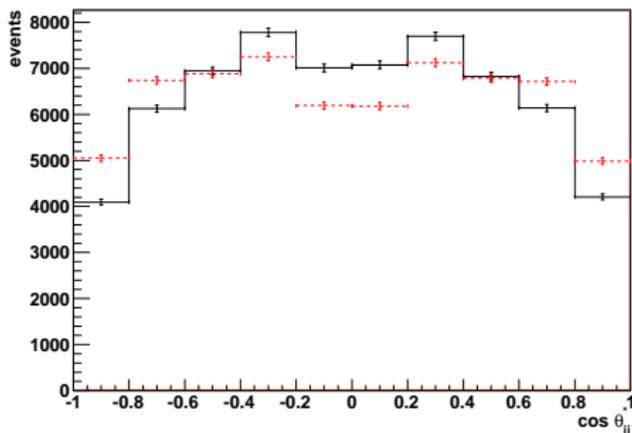
UED mass hierarchy

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

Observed asymmetry

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

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



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

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

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](#)