Early spin determination at the LHC?

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in collaboration with:

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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
4. Summary
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spins and couplings fixed by construction
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)
we focus here on Universal Extra Dimensions (5D)

classical 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!
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: \textit{P-wave vs S-wave}
  - ILC case: sleptons and gauginos; Choi et al., 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
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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.

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,

\[
\tilde{\nu}^+ \tilde{\nu}^- \to \tilde{\chi}_1^0 \ell^+ \tilde{\chi}_1^0 \ell^- \\
\ell^+_1 \ell^-_1 \to \gamma_1 \ell^+ \gamma_1 \ell^- \\
\tilde{\chi}_1^0, \gamma_1
\]

- Use longitudinally boost invariant observable,

\[
\cos \theta^*_\ell \ell = \tanh \left( \frac{\Delta \eta_{\ell \ell}}{2} \right), \quad \Delta \eta_{\ell \ell} = \eta_{\ell^+} - \eta_{\ell^-}
\]

\[
\Rightarrow \cos \theta^*_\ell \ell \text{ is cosine of the polar angle between leptons and the beam axis in the frame where } \eta_{\ell^+} = -\eta_{\ell^-} \text{ of the leptons are equal and opposite}
\]

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

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

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

Spin determination with squarks and gluinos

**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
  
  \[ pp \rightarrow \tilde{q}_i \tilde{q}_j^{(*)} \]

  \[ pp \rightarrow \tilde{g} \tilde{g} \]

  \[ pp \rightarrow \tilde{g} \tilde{q}_i \]

angular distributions in the center of mass frame

UED production significantly more in forward direction

Spin determination with squarks and gluinos

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.

\[
pp \to \tilde{q}_R \tilde{q}_R \to q q \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad \text{SUSY}
\]

\[
pp \to q_{R1} q_{R1} \to q q \gamma_1 \gamma_1 \quad \text{UED}
\]

Rapidity difference as the spin sensitive observable

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

\[
\Delta \eta_{qq} = \eta_{q_1} - \eta_{q_2}
\]
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 $|\eta_{\ell}| < 2.5$.
- $\Delta \phi(j_1, E_T^{\text{miss}}) > 0.2$, $\Delta \phi(j_2, E_T^{\text{miss}}) > 0.2$
- $E_T^{\text{miss}} > 0.3M_{\text{eff}}$, $M_{\text{eff}} > 800$ GeV

Event simulation:

- BSM signal: Herwig++
- SM background: Sherpa ($W + \text{jets}$, $Z + \text{jets}$, $tt\bar{t}$)
- detector effects: Delphes
hints of spin structure can be seen already with integrated luminosity of $\mathcal{O}(1 \text{ fb}^{-1})$ at $\sqrt{s} = 14$ TeV

this assumes SUSY mass spectrum

cuts and SM background included, hardest jets taken to construct spin observable $\cos \theta_{jj}^*$

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Define an asymmetry

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

For SU6 scenario:

- \( A_{\text{SUSY}}^{hl} = -0.226 \)
- \( A_{\text{UED}}^{hl} = 0.016 \)

Those values only weakly depend on the overall mass scale.
Spin determination with squarks and gluinos

So far we see...

CMS preliminary

\[ \alpha_T \int L dt = 1.1 \text{ fb}^{-1} \quad \sqrt{s} = 7 \text{ TeV} \]

95% C.L. Limits:
- Observed Limit (NLO), CL_s
- Observed Limit (NLO), PL
- Median Expected Limit \pm 1 \sigma, PL
- Observed Limit (NLO), FC, 35pb^{-1}

\[ \tan \beta = 10, \ A_0 = 0, \mu > 0 \]

\[ \mu = 5, \ A_0 = 10, \ A_\beta \tan \beta, \ q^+, g^- \]

CDF \( \tilde{g}, \tilde{q}, \tan \beta = 5, \mu < 0 \)

D0 \( \tilde{g}, \tilde{q}, \tan \beta = 3, \mu < 0 \)

LEP2 \( \tilde{\chi}_1^\pm \)

LEP2 \( \tilde{t} \)

LEP2 \( \tilde{\chi}_1 \)

K. Rolbiecki (DESY)

SUSY11, 30.09.2011 20 / 24
So far we see...
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

$\Rightarrow \sigma(14$ TeV$) = 0.4$ pb

$\Rightarrow$ modify the cuts: $p_{T}^{j_1} > 400$ GeV and $p_{T}^{j_2} > 200$ 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**

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

$A_{\text{UED}}^{\text{hl}} = -0.02$
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!
small mass differences $m_{\tilde{q}, \tilde{g}} \sim 600 \text{ GeV}, m_{\text{LSP}} \sim 500 \text{ GeV}$

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

$A_{\text{SUSY}}^{10 \text{ fb}^{-1}} = -0.15$

$A_{\text{UED}}^{10 \text{ fb}^{-1}} = -0.05$
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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.
$A_{\text{SUSY}}^h = -0.32$

$A_{\text{UED}}^h = -0.02$
Cuts for the UED masses

- require at least 4 jets
- event selection based on radiation jets: $p_T^{j_1} > 150 \text{ GeV}$ and $p_T^{j_2} > 100 \text{ GeV}$
- 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 $50 < p_T < 100 \text{ GeV}$
  $\Rightarrow$ 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
  \[ \eta = - \log \tan \frac{\theta}{2} \]
Methods discussed in literature

- The total cross section Datta et al., hep-ph/0510204
- Observation of higher KK modes Datta et al., PhysRev.D72,096006
- 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 et al., JHEP,0810,081; Ehrenfeld et al., JHEP,0907,056; Alves et al., PhysRev.D74,095010
- Kinematic reconstruction of missing momentum Cho et al., PhysRev.D79; Cheng et al. JHEP,1011,122; Moortgat-Pick et al. 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 et al., arXiv:1102.0293