Studying spin through quantum interference

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Focus week on LHC@IPMU, Dec 18, 2007

work with
Matt Buckley, Willie Klemm, Vikram Rentala
arXiv:0711.0364 and many more to follow
Motivation
New physics looks alike

missing $E_T$, multiple jets, b-jets, (like-sign) leptons

SUSY
New physics looks alike

missing $E_T$, multiple jets, b-jets, (like-sign) leptons

UED

SUSY
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UED  SUSY  technicolor
New physics looks alike

missing $E_T$, multiple jets, b-jets, (like-sign) leptons

UED
spin 1

SUSY
spin 1/2

technicolor
spin 0
Thought of not yet.
precision new physics measurements

- spectroscopy
- kinematic fits, partial wave analysis, Dalitz analysis, etc
- precision mass, BR measurements
- key: spin-parity
precision new physics

spectroscopy

kinematic fits, partial wave analysis, Dalitz analysis, etc

precision mass, measurements

key: spin-parity

**Squarks**

\[ j = 0? \]

PDG 2012

The following data are averaged over all light flavors, presumably \( u, d, s, c \) with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

### SQUARK MASS

<table>
<thead>
<tr>
<th>VALUE (GeV)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 538 \pm 10 )</td>
<td>OUR FIT 1</td>
<td>CMS</td>
<td>mSUGRA assumptions</td>
</tr>
<tr>
<td>532 \pm 11</td>
<td>ABDIENDI 11D</td>
<td>CMS</td>
<td>Missing ET with mSUGRA assumptions</td>
</tr>
<tr>
<td>541 \pm 14</td>
<td>ADLER 11O</td>
<td>ATLAS</td>
<td>Missing ET with mSUGRA assumptions</td>
</tr>
<tr>
<td>652 \pm 105</td>
<td>ABDIENDI 11K</td>
<td>CMS</td>
<td>extended mSUGRA assumptions with 5 more parameters</td>
</tr>
</tbody>
</table>

1 ABDIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set \( A_0 = 0 \) and \( \tan \beta = 3 \). See Fig. 5 of the paper for other choices of \( A_0 \) and \( \tan \beta \). The result is correlated with the gluino mass \( M_3 \). See listing for gluino.

2 ADLER 11O uses the same set of assumptions as ABDIENDI 11D, but with \( \tan \beta = 5 \).

3 ABDIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for \( H_u, H_d, S^+ \) and 10 scalars at the GUT scale.

### SQUARK DECAY MODES

<table>
<thead>
<tr>
<th>MODE</th>
<th>BR(%)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tbody>
<tr>
<td>( j \pm \text{miss} )</td>
<td>32 \pm 5</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td>lepton universality</td>
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<tr>
<td>( j \perp \pm \text{miss} )</td>
<td>73 \pm 10</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td></td>
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<tr>
<td>( j \pm \text{miss} )</td>
<td>22 \pm 8</td>
<td>ABE 10U</td>
<td>ATLAS</td>
<td></td>
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<tr>
<td>( j \mu \pm \text{miss} )</td>
<td>25 \pm 7</td>
<td>ABE 10U</td>
<td>ATLAS</td>
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<tr>
<td>( q \chi )</td>
<td>seen</td>
<td>ABE 10U</td>
<td>ATLAS</td>
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</table>
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Spin 0?

\[ e^+e^- \rightarrow \mu^+\mu^- \]
\[ \sqrt{s} = 350 \text{ GeV} \]
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relies on the absence of t,u-channel!

Spin 0?
How can we obtain information on spins without any model assumptions?

Back to basics: quantum mechanics

angular momentum generates rotation $U(\theta) = e^{i\vec{J} \cdot \vec{\theta} / \hbar}$

there is no orbital angular momentum along the momentum, and spin can be isolated
General Principle
Decay of particle with spin \( h \) along the momentum axis

Rotations about z-axis of decay plane given by

\[
M \propto e^{i J_z \phi}
\]

\[
J_z = \frac{(\vec{s} + \vec{x} \times \vec{p}) \cdot \vec{p}}{|\vec{p}|} = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} = h
\]

Rotational invariance: a single helicity state has flat distribution in \( \phi \)
Quantum Interference among helicities

If particles produced in multiple helicities:

\[ \sigma \propto \left| \sum M_{\text{prod}} M_{\text{decay}} \right|^2 \]

\[ M_{\text{decay}} = e^{ih\phi} M_{\text{decay}}(h, \phi = 0) \]
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Can measure only helicity differences (akin to neutrino oscillation)
Spin and Quantum Interference

Vector Boson Decay:

\[ M_+ \propto e^{i\phi_1} \]
\[ M_0 \propto 1 \]
\[ M_- \propto e^{-i\phi_1} \]

Spinor Decay:

\[ M^{\uparrow} \propto e^{i\phi_1/2} \]
\[ M^{\downarrow} \propto e^{-i\phi_1/2} \]

In general:

\[ \sigma = A_0 + A_1 \cos(\phi) + \cdots + A_n \cos(n\phi), \quad n = 2 \times \text{spin} \]
Simple example

\[ e^-_Le^+_R \rightarrow \tilde{\nu}^-\tilde{\nu}^+ \rightarrow (\mu^-\tilde{\nu}^*_\mu)(e^+\tilde{\nu}_e) \]

\[ M(--) \propto (1 + \cos \theta) \cos \frac{\hat{\theta}_1}{2} e^{-i\phi_1/2} \cos \frac{\hat{\theta}_1}{2} e^{-i\phi_2/2} \]

\[ M(+-) \propto (1 - \cos \theta) \sin \frac{\hat{\theta}_1}{2} e^{+i\phi_1/2} \sin \frac{\hat{\theta}_1}{2} e^{+i\phi_2/2} \]

\[ M(--) \propto -\sin \theta \frac{M}{E} \cos \frac{\hat{\theta}_1}{2} e^{-i\phi_1/2} \sin \frac{\hat{\theta}_1}{2} e^{+i\phi_2/2} \]

\[ M(++ \propto -\sin \theta \frac{M}{E} \sin \frac{\hat{\theta}_1}{2} e^{+i\phi_1/2} \cos \frac{\hat{\theta}_1}{2} e^{-i\phi_2/2} \]

(HM: LCWS 2000 @ Fermilab)
Real-life Examples
$e^+e^- \rightarrow W^+ W^-$

study semileptonic

$W^- \rightarrow l^- \nu$

$W^+ \rightarrow j \ j$

$s = 200 \text{ GeV}$

$A_1/A_0 = -26\%$

$A_2/A_0 = -8.6\%$
$e^+e^- \rightarrow W^+ W^-$

study semileptonic
  $W^- \rightarrow l^- \nu$
  $W^+ \rightarrow j j$

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Tevatron

- $p \, p_{\bar{p}} \rightarrow Z + \text{gluon}$
- Study $Z \rightarrow l^+ l^-$
- $A_1/A_0 = 6.0\%$
- $A_2/A_0 = 12\%$
- Used $p_T(g) > 7$ GeV
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Other distributions

* cos θ distribution of the production shows t- and u-channel process, no spin information

* cos θ distribution of the decay does not show a big spin effect because the process is primarily near threshold
Lessons

We can extract interesting spin information from the existing data.
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- Effect particularly strong near threshold.
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Effect particularly strong near threshold (good news for future hadron collider!)

Seeing $\cos(n\phi)$ dependence implies $\text{spin} \geq n/2$

Works well if fully reconstructible.
Challenges
Many new physics scenarios have *more than one invisible particle* in their events.
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Once masses measured, reconstructible up to a two-fold ambiguity.
Azimuthal Distributions

- Sum $\phi_1$ and $\phi_2$ distributions. $\sqrt{s} = 370$ GeV
- 183 GeV decaying into muon and 161 GeV

**UED distribution**

**SUSY distribution**

![Graphs showing UED and SUSY distributions with True and Both True & False categories.](image-url)
Fake solution

- We do not fully understand yet how exactly the fake solutions contribute to the apparent $\cos(n\phi)$ dependence.
- Obviously it can be studied within a model.
- But we wish to subtract the fake contribution with as little model-dependent assumptions as possible.
Spin at LHC

- Lose two constraints: center of momentum frame and \( \sqrt{\hat{s}} \)
- Still can reconstruct up to two-fold ambiguity

4+4 unknown LSP/LKP momenta
- 2 measured \( p_T \)
- 6 mass relations

- Much higher statistics available;
  \[ \sigma \sim 1 \text{ pb} \]
- Not studied yet!
Spin at LHC

In $e^+e^-$ or $p\ p\bar{p}$ collisions:

- Sign ambiguity with identical beams

\[ \phi \rightarrow \phi + \pi \]

- Makes odd $\cos n\phi$ non-physical
Spin at LHC

Can still determine $\cos \phi$ contribution from correlations of $\phi_1, \phi_2$

$$\langle \cos \phi_1 \cos \phi_2 \rangle \propto \frac{A_1^2}{A_0^2}$$

Look at sign asymmetry between $\phi_1, \phi_2$
\[ p p \rightarrow t \bar{t} \]

dominated by \( gg \rightarrow t \bar{t} \) at LHC

\[ \langle \cos \phi_1 \cos \phi_2 \rangle = 0.8\% \]

small but statistically possible at LHC (>1M/year)

systematics in reconstruction, background, “cross talk” between two tops via gluon exchange, etc

\( W \) spin effect has only \( \cos \phi \) in top rest frame because \( t \rightarrow bW^+ \) decay has only \( h=0,-1 \) for \( W^+ \)
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- Should be demonstrable in the existing LEP-II and Tevatron data
- Particularly useful near threshold when other spin correlations are not very prominent
- Full reconstruction really helps
- Partial reconstruction may be used, but more studies needed