Discriminating Spin Through Quantum Interference

Matthew Buckley
U.C. Berkeley/IPMU
with H. Murayama, William Klemm, and Vikram Rentala
0711.0364

Sendai 4/3/08
Beyond the SM

- Naturalness and hierarchy problems
- Suggest some new physics at $\sim 1$ TeV

Supersymmetry? Technicolor? Extra Dimensions?

Supersymmetry solves naturalness problem by introducing new-particles with opposite spin statistics to cut off loop corrections.

Universal Extra Dimensions solves the problem by having a TeV-scaled extra dimension. That is, the Planck scale is the EW scale

$$M_{Pl}^2 = M^{2+d} (2\pi R)^d$$
SUSY vs. UED

- Both spectra contain 'copies' of SM
  - SUSY has superpartners
  - UED has tower of Kaluza-Klein modes

New particles have similar interaction strengths:

\[ W^\pm, Z, A \rightarrow \tilde{W}^\pm, \tilde{Z}, \tilde{A} (\tilde{\chi}_i^\pm, \tilde{\chi}_i^0) \]
\[ \rightarrow W_1^\pm, Z_1, A_1, W_2^\pm, Z_2, A_2, \ldots \]

(SUSY) (UED)

Spin measurements may be the defining experimental difference
Spin at LHC/ILC

Most methods attempt to distinguish specific models

Comparison of total cross sections: $\sigma_{\text{SUSY}} < \sigma_{\text{UED}}$

Not a measurement of spin

Can look for KK$>1$ towers

Could be too heavy for colliders, could be seeing non-minimal SUSY states

Threshold scans at ILC

Both spinors and vector bosons have $\sigma \propto \beta$

Production or decay angular dependance

Assumptions about t-channel, chiral couplings
Spin and Quantum Interference

Decay of particle with helicity $h$:

Rotation about z-axis of decay plane implies

$$\mathcal{M} \propto e^{i J_z \phi}$$

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

$$= \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} = h$$
Spin and Quantum Interference

If particle produced in multiple helicities, then

$$\sigma \propto \left| \sum M_{\text{prod}}.M_{\text{decay}} \right|^2$$

$$M_{\text{decay}} = e^{ih\phi} M_{\text{decay}}(h, \phi = 0)$$

Different helicity states interfere as they decay.

The $\phi$ dependence of cross section allows us to determine what helicities interfered.

$$\sigma = A_0 + A_1 \cos(\phi) + \cdots + A_n \cos(n\phi), \; n = 2 \times \text{spin}.$$
Coherent Sums and Kinematics

\[ e^- + W^+ - e^+ + e^- + \ell^- + \bar{d} + u \]

Production Plane

Decay Plane of Leptons

Beam Axis

Vector Boson

Production Axis

Production Plane
LEP II $W$ Pair Production

- Semi-leptonic decays, fully reconstructable
- Simulated OPAL data from 1997–2000:
  - $\mathcal{L} = 682 \text{ pb}^{-1}$
  - Before cuts have 3400 events available
  - 2450 events after cuts
Problem is that $E_T$, $\eta$ cuts are not azimuthally symmetric about W-boson axis.

Rotationally invariant cuts: require that leptons pass acceptance cuts for all rotations about the W-boson axis.

This cut is $\sim 15\%$ efficient.
Problem is that $E_T, \eta$ cuts are not azimuthally symmetric about W-boson axis.

Rotationally invariant cuts: require that leptons pass acceptance cuts for all rotations about the W-boson axis.

This cut is $\sim 15\%$ efficient.
LEP II $W$ Pair Production

Without cuts

Rotational invariant cuts

| $A_1/A_0$     | $-0.211 \pm 0.050$ |
|---------------|---------------------|
| $A_2/A_0$     | $-0.081 \pm 0.049$  |
| $A_3/A_0$     | $0.000 \pm 0.057$   |
| $A_4/A_0$     | $0.000 \pm 0.057$   |

Azimuthal Angle $\phi$
Scalar vs. Spinor at ILC

\[ e^- e^+ \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \mu^- \tilde{\chi}_0^1 \tilde{\chi}_0^1 \]
\[ e^- e^+ \rightarrow \mu_{1R}^+ \mu_{1R}^- \rightarrow \mu^+ \mu^- B_1 B_1 \]

Many SM extensions have new particles charged under additional symmetry (R-parity for SUSY, T-parity for Little Higgs, \( Z_2 \) parity in extra-dim).

Lightest charged particle a good DM candidate but weakly interacting, stable, and invisible in detectors.

\[ \rightarrow E_T, \phi_T \]

Need to reconstruct \( \phi_{1/2} \) distributions to measure \( A_0, A_1 \) parameters
Minimal UED

One extra dimension of radius $R$, compactified to $S^1/Z_2$

Quantized 5th dimension momentum provides tree level mass for KK modes:

$$m^2_n = \frac{n^2}{R^2} + m_0^2$$

Requiring $\psi_R, A_5$ odd and $\psi_L$ even under the $Z_2$ provides chiral fermions in the KK=0 level.

Flavor universal boundary terms set to zero at scale $\Lambda$

Lightest KK=1 state stable: LKP (usually $B_1$)
Reconstruction of $\phi_{1/2}$

- Assume masses of $\mu/B$ partners known.
  - 4+4 unknown momenta
    - 4 measured $\not{p}$
    - 4 mass relations
  - System specified up to a 2-fold ambiguity
- Use both solutions: true/false $\vec{p}_{\tilde{\mu}_R}$ to derive true and false values for $\phi_i$
Mass Measurements at ILC

- Reconstruction assumes no mass/momentum measurement errors.
- Known mass allows effective background cut via successful reconstruction.
- Tracking resolution at ILC expected to have error \( \frac{\Delta p_T}{p_T} = 5 \times 10^{-5} \) (\( p_T \) in GeV)

| \( \tilde{e}_R \) | \( \Delta m_{cont.} \) (GeV) | \( \Delta m_{thres} \) (GeV) |
|-----------------|----------------------|----------------------|
| \( \tilde{e}_L \) | 0.2                  | 0.05                 |
| \( \tilde{\nu}_e \) | 0.2                  | 0.18                 |
| \( \tilde{\chi}^0 \) | 0.1                  | 0.07                 |
| \( \tilde{\chi}_1 \) | 0.1                  | 0.05                 |
Scalar vs. Spinor at ILC

- Assume $\sqrt{s} \leq 1$ TeV, $L = 500$ fb$^{-1}$
- Cut on lepton and missing energy $\eta \leq 2.5$
- Take two possible spectra: a typical SUSY and a typical MUED spectrum.
- Since mass of SM partners assumed known, we 'fake' a MUED model with SUSY spectrum, and vice versa.

| SUSY SPS3 | MUED |
|-----------|------|
| $m_0$ | 90 GeV |
| $m_{1/2}$ | 400 GeV |
| $A_0$ | 0 |
| $\tan \beta$ | 10 |
| $\mu$ | $> 0$ |
| | $R^{-1}$ | 300 GeV |
| | $\Lambda$ | $20R^{-1}$ |
| | $m_H$ | 120 GeV |
Scalar vs. Spinor at ILC

SPS3

MUED

\( \tilde{\chi}_1^0 / B_1 \) 161 GeV
\( \tilde{\mu}_R / \mu_{1R} \) 181 GeV
\( \tilde{\mu}_L / \mu_{1L} \) 289 GeV

\( \tilde{\chi}_1^0 / B_1 \) 301.5 GeV
\( \tilde{\mu}_R / \mu_{1R} \) 303.3 GeV
\( \tilde{\mu}_L / \mu_{1L} \) 309.0 GeV
Azimuthal Distributions

Sum $\phi_1$ and $\phi_2$ distributions.

$\sqrt{s} = 370$ GeV

UED distribution

SUSY distribution
Azimuthal Distributions

SPS3

MUED

Fit to

$$\sigma = A_0 + A_1 \cos \phi + A_2 \cos 2\phi$$
Effects of Cuts on

\[ e^-e^+ \rightarrow \mu^+_1\mu^-_1 \rightarrow \mu^+\mu^- B_1 B_1 \]

Subtract off effect of cuts on flat distribution
to correct for detector effects

- MUED uncorrected
- MUED corrected
Conclusions

- Quantum interference between helicity/polarization states can serve as a fully model independent probe of spin in an event.

We can use this method right now with data already on tape.

A linear collider should be capable of distinguishing scalars from higher spins.
Conclusions

Need better understanding of how to correct for cuts and false solutions

Necessary to distinguish higher spin states

Longer decay chains may remove 2-fold ambiguity.

At LHC, long decay chains would allow for 2-fold reconstruction; large # of events should allow for direct spin measurements.