Discriminating Spin Through Quantum Interference

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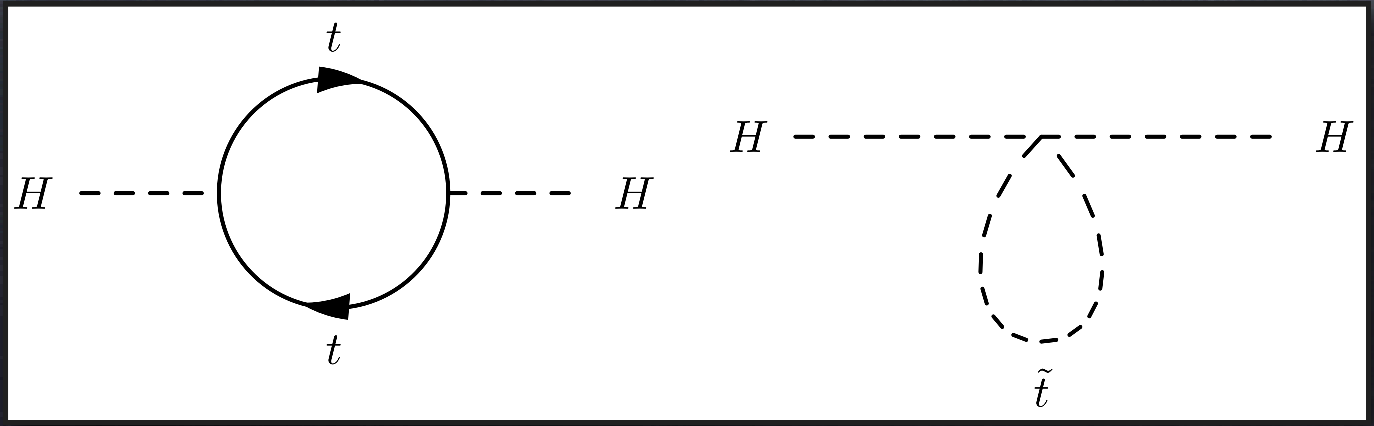
Beyond the SM

- Naturalness and hierarchy problems
  - Suggest some new physics at ~1 TeV

Supersymmetry? Technicolor? Extra Dimensions?

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



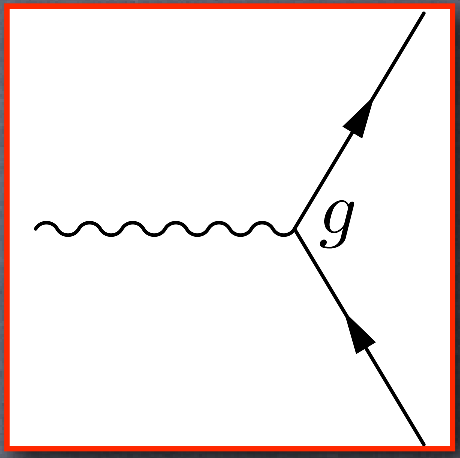
- Universal Extra Dimensions solves the problem by having a TeV-scaled extra dimension. That is, the Planck scale is the EW scale

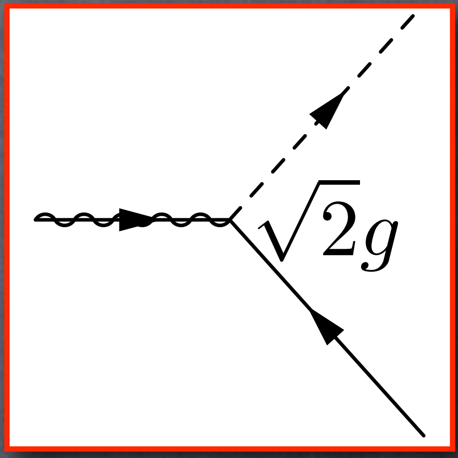
$$M_{Pl}^2 = M^{2+d}(2\pi R)^d$$

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:





$$
\begin{aligned}
W^{\pm}, Z, A &\rightarrow \tilde{W}^{\pm}, \tilde{Z}, \tilde{A}\ (\tilde{\chi}_i^{\pm}, \tilde{\chi}_i^{0}) && \text{(SUSY)} \\
&\rightarrow W_1^{\pm}, Z_1, A_1, W_2^{\pm}, Z_2, A_2, \ldots && \text{(UED)}
\end{aligned}
$$

Spin measurements may be the defining experimental difference

Spin at LHC/ILC

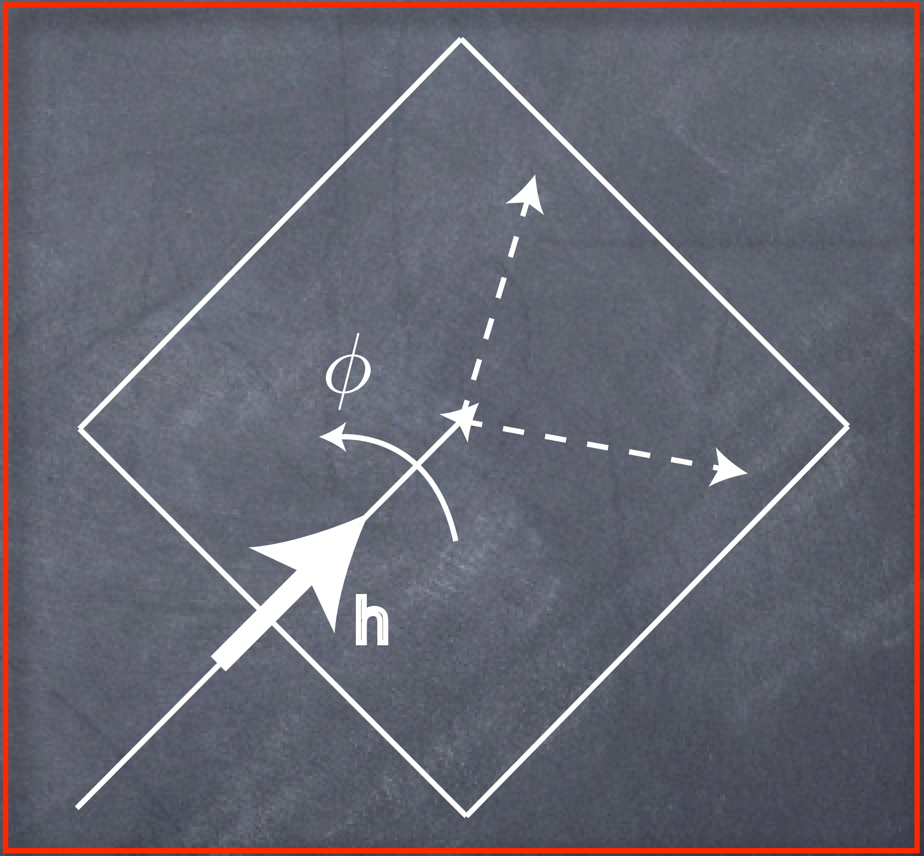
- Most methods attempt to distinguish specific models
  - Comparison of total cross sections: $\sigma_{SUSY} < \sigma_{UED}$
    - Not a measurement of spin
  - Can look for KK>1 towers
    - Could be too heavy for colliders, could be seeing non-minimal SUSY states
- Threshold scans at ILC
  - Both spinors 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

$$\mathcal{M} \propto e^{iJ_z\phi}$$

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



Spin and Quantum Interference

- If particle produced in multiple helicities, then

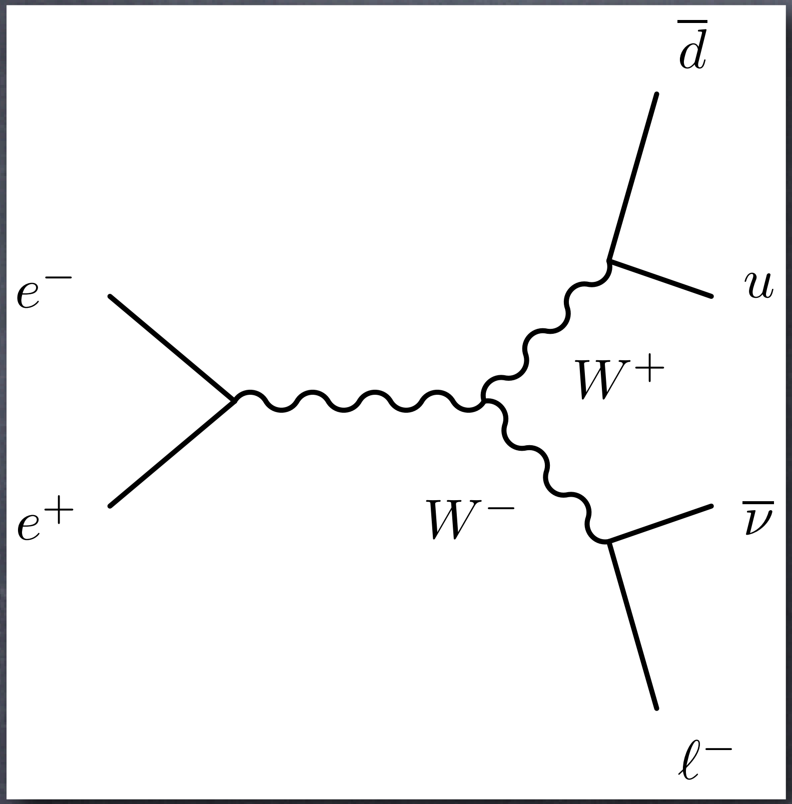
$$\sigma \propto \left| \sum \mathcal{M}_{prod.} \mathcal{M}_{decay} \right|^2$$

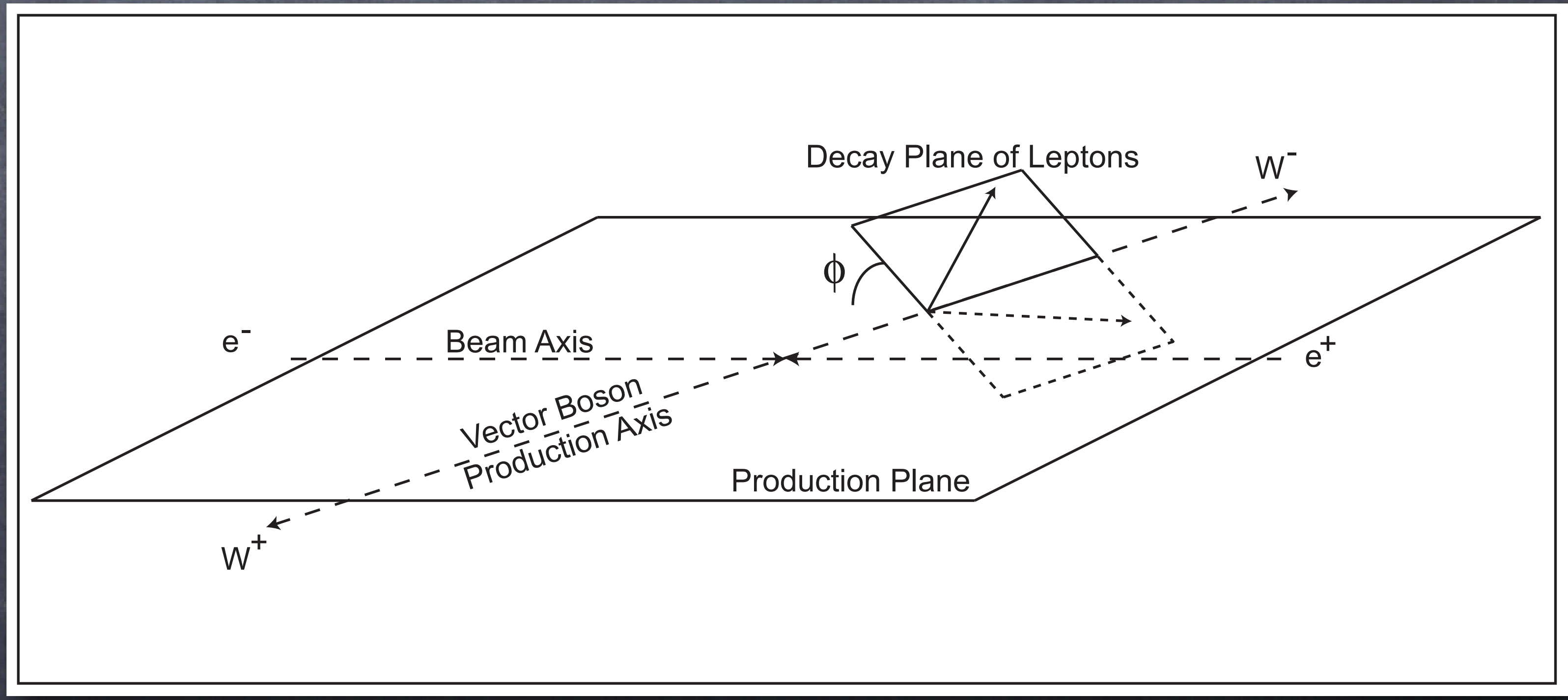
$$\mathcal{M}_{decay} = e^{ih\phi} \mathcal{M}_{decay}(h, \phi = 0)$$

- Different helicity states interfere as they decay
- The ϕ dependence of cross section allows us to determine what helicities interfered.

$$\sigma = A_0 + A_1 \cos(\phi) + \cdots + A_n \cos(n\phi), \;\; n = 2 \times \mathrm{spin}$$

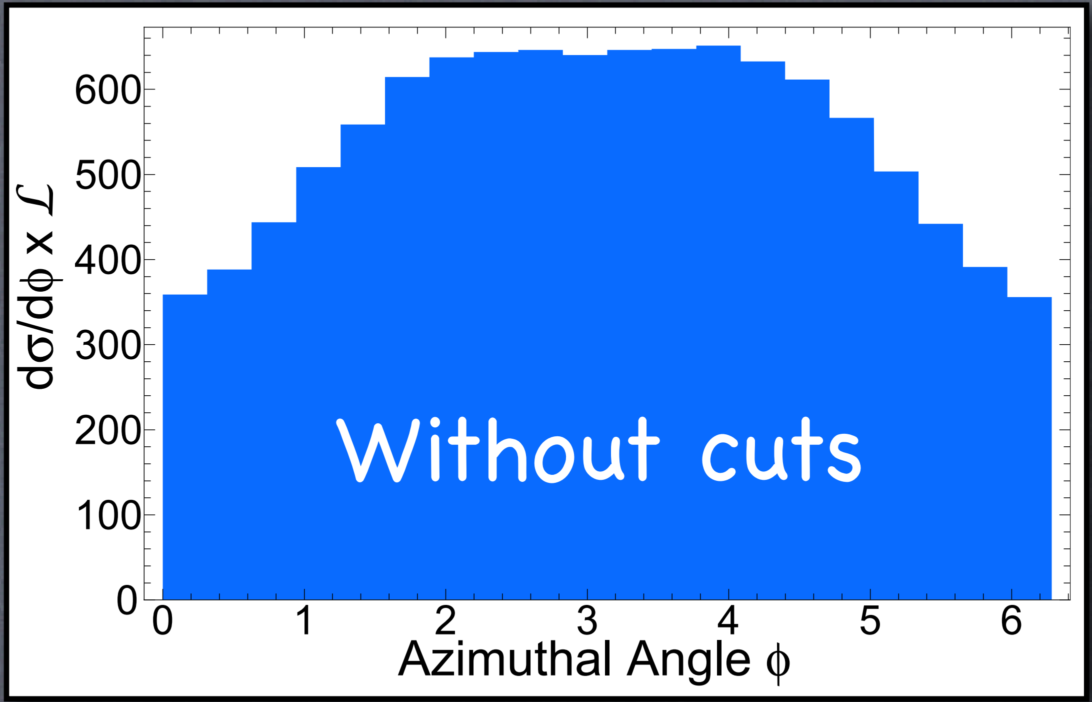
Coherent Sums and Kinematics

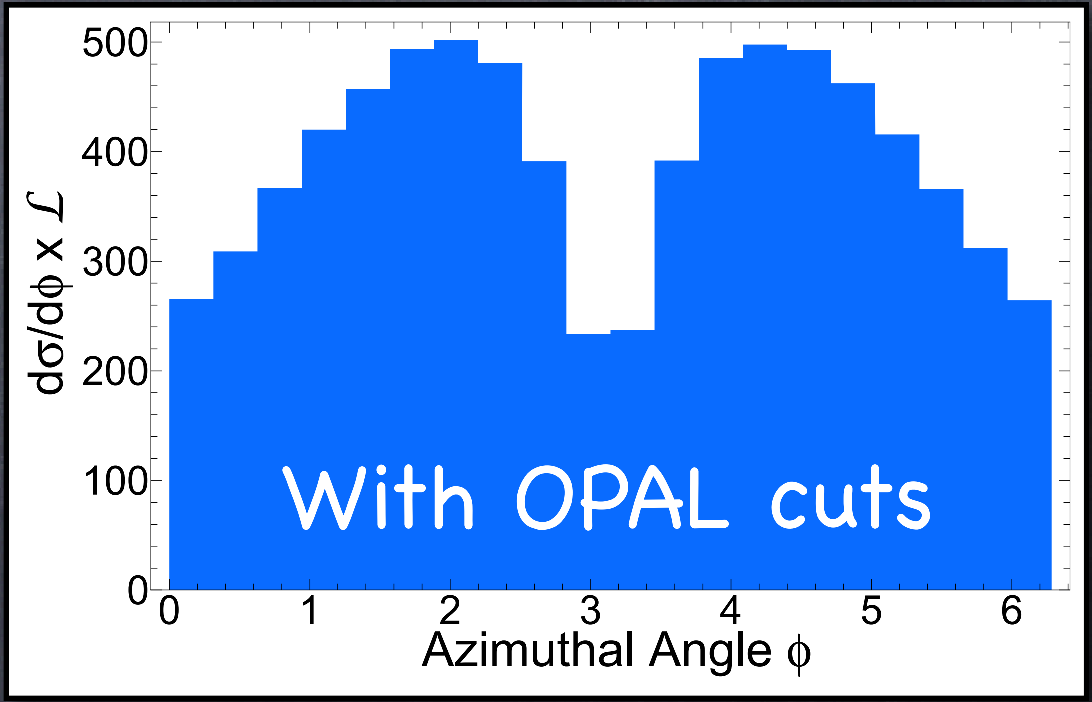




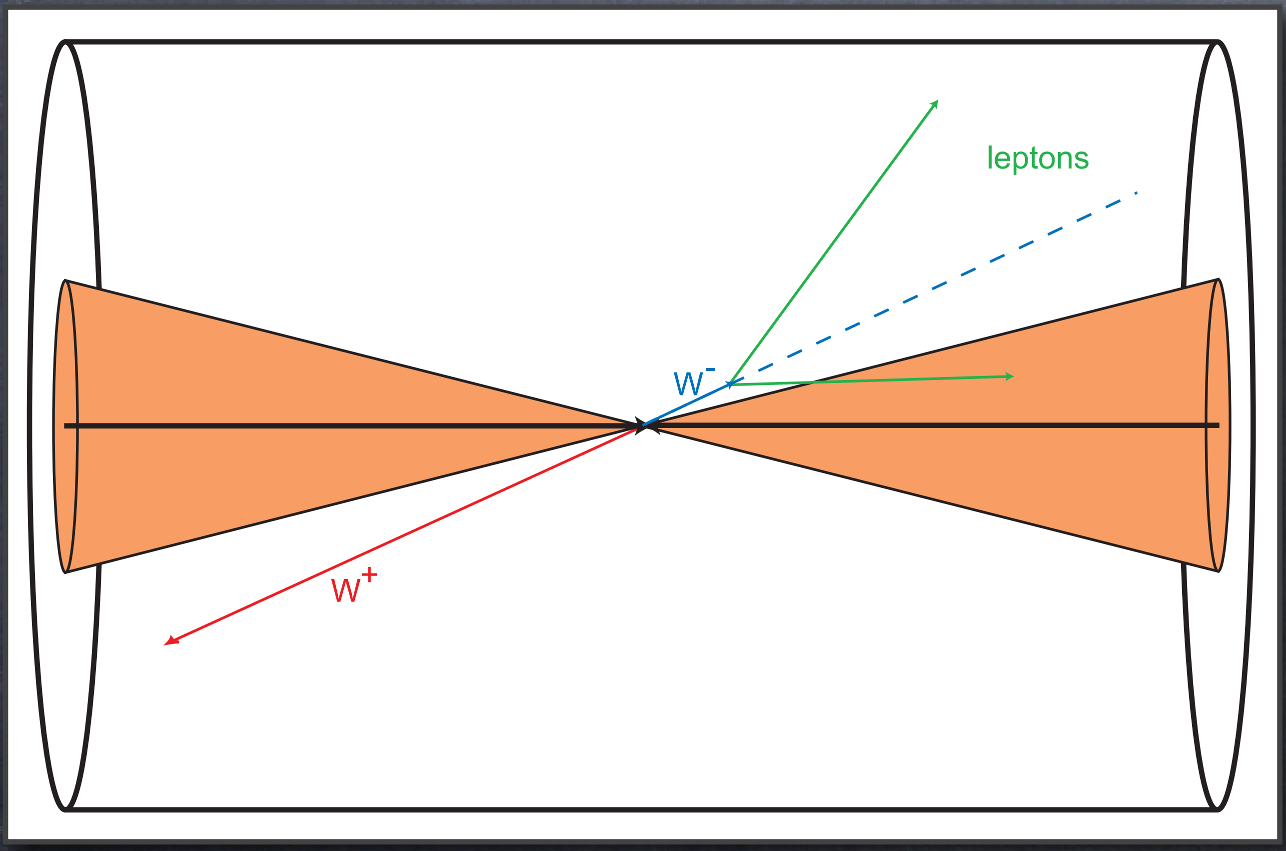
LEP II W Pair Production

- 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





LEP II W Pair Production

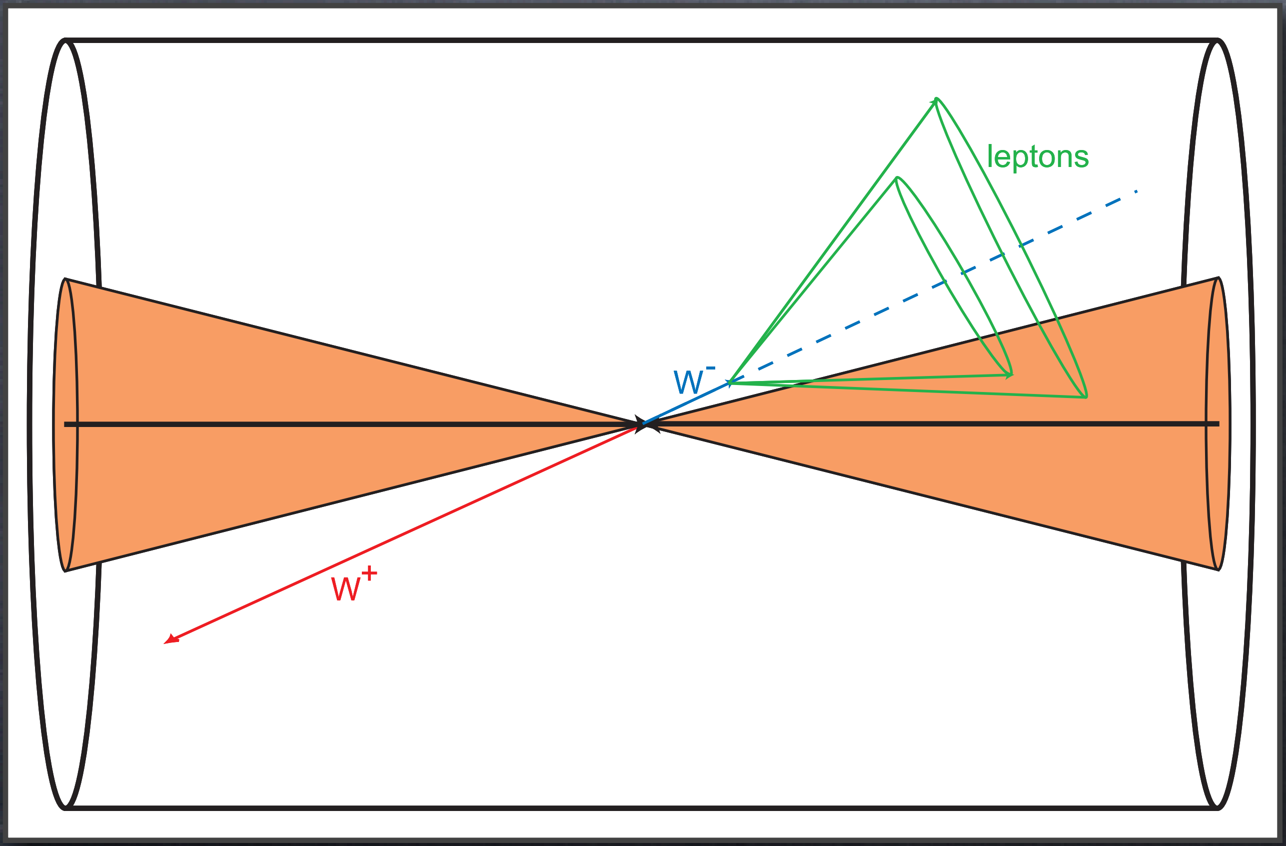


Problem is that E_T, η cuts are not azimuthally symmetric about W-boson axis

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



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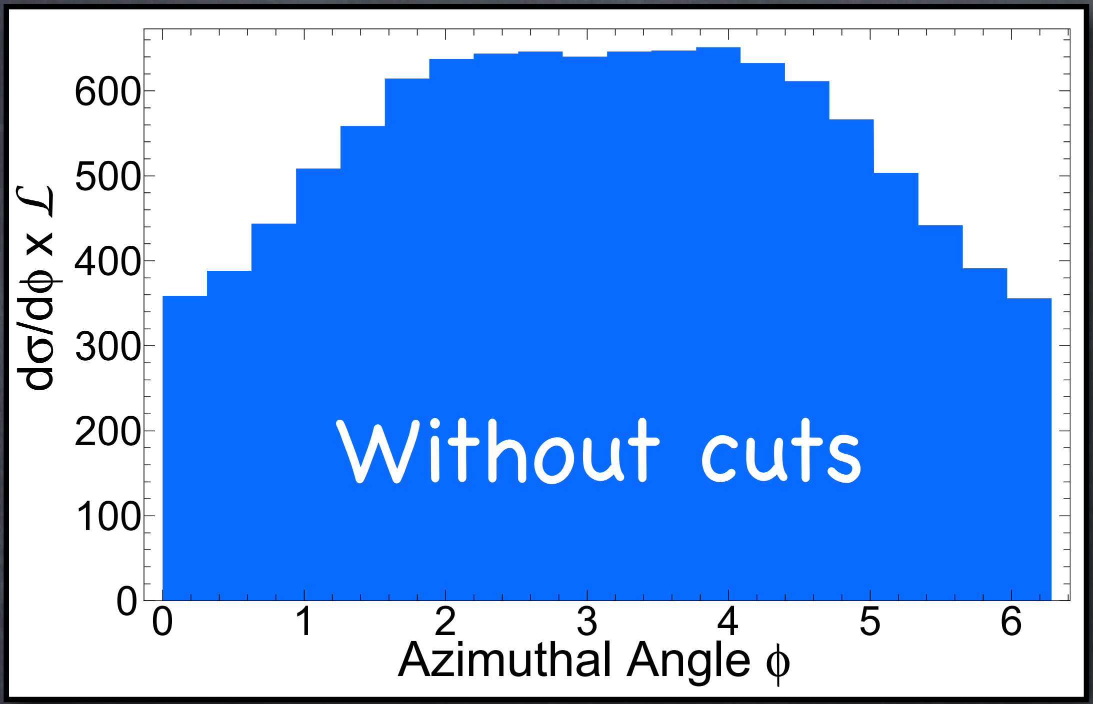
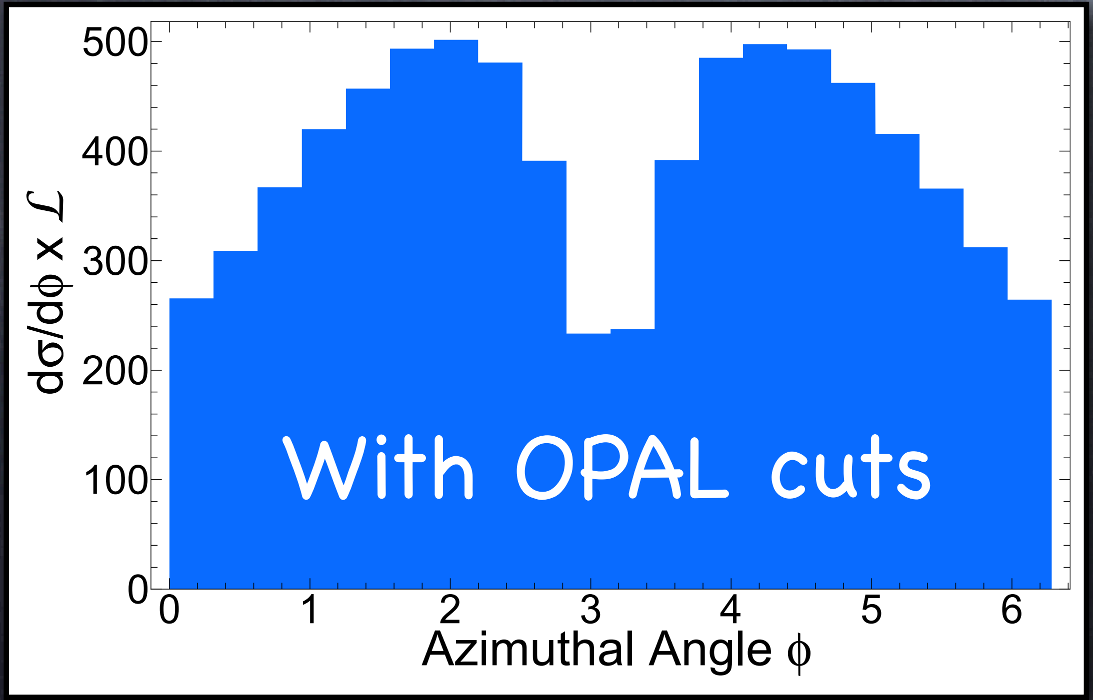
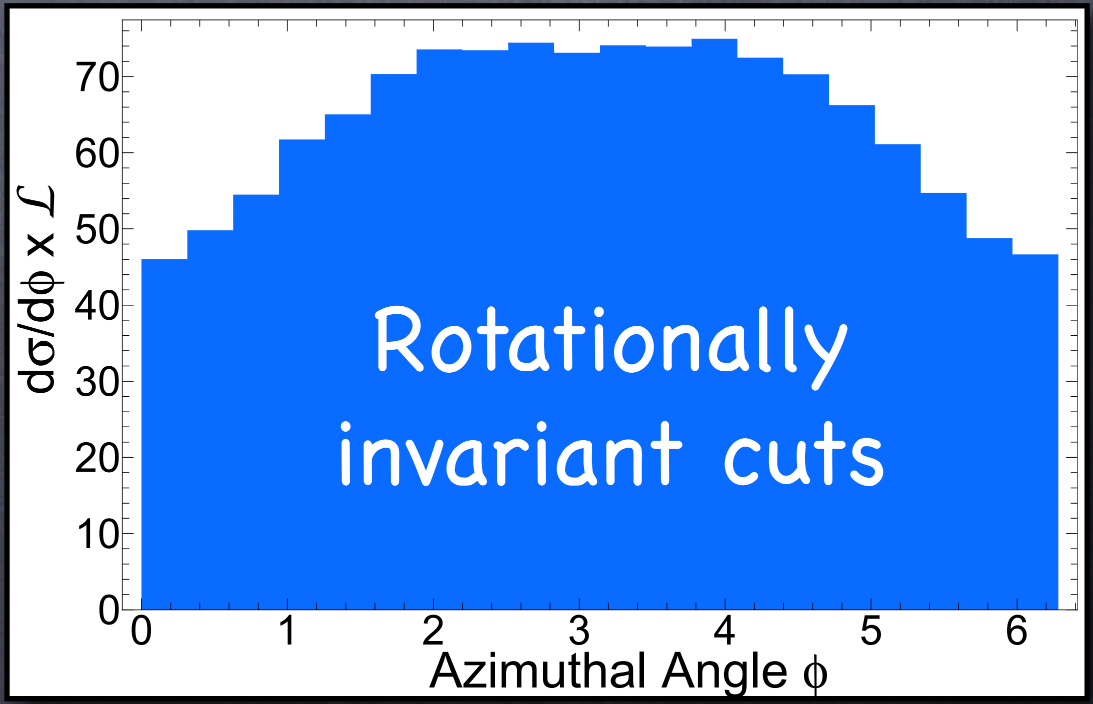


A_1/A_0	-0.211 ± 0.050
A_2/A_0	-0.081 ± 0.049
A_3/A_0	0.000 ± 0.057
A_4/A_0	0.000 ± 0.057





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.

$$\rightarrow \not{E}_T, \not{p}_T$$

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:

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

  - Requiring ψ_R, A_5 odd and ψ_L even under the Z_2 provides chiral fermions in the KK=0 level.
  - Flavor universal boundary terms set to zero at scale Λ
  - Lightest KK=1 state stable: LKP (usually B_1)

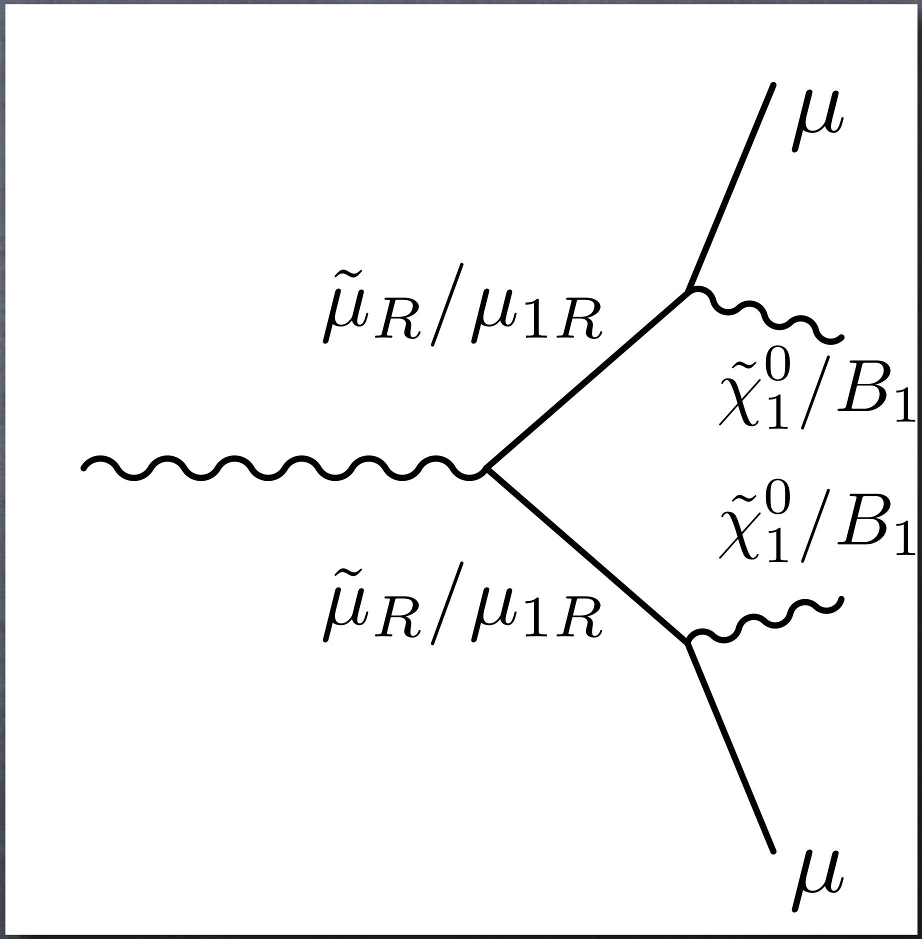
Reconstruction of $\phi_{1/2}$

- Assume masses of μ/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 ϕ_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 $\Delta p_T / p_T = 5 \times 10^{-5} (p_T/\mathrm{GeV})$

	$\Delta m_{cont.}$ (GeV)	Δm_{thres} (GeV)
$\tilde{e}_R$	0.2	0.05
$\tilde{e}_L$	0.2	0.18
$\tilde{\nu}_e$	0.1	0.07
$\tilde{\chi}_1^0$	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

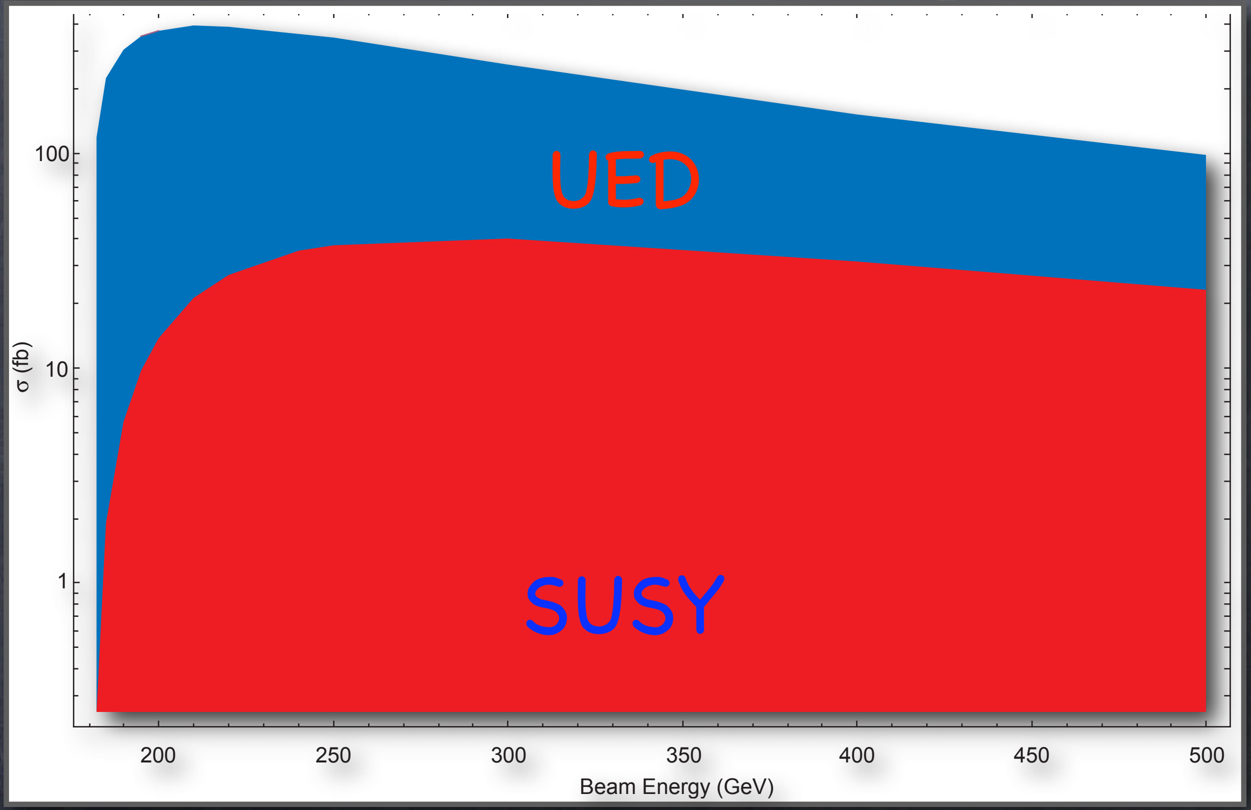
m_0	90 GeV
$m_{1/2}$	400 GeV
A_0	0
$\tan\beta$	10
μ	> 0

MUED

R^{-1}	300 GeV
Λ	$20R^{-1}$
m_H	120 GeV

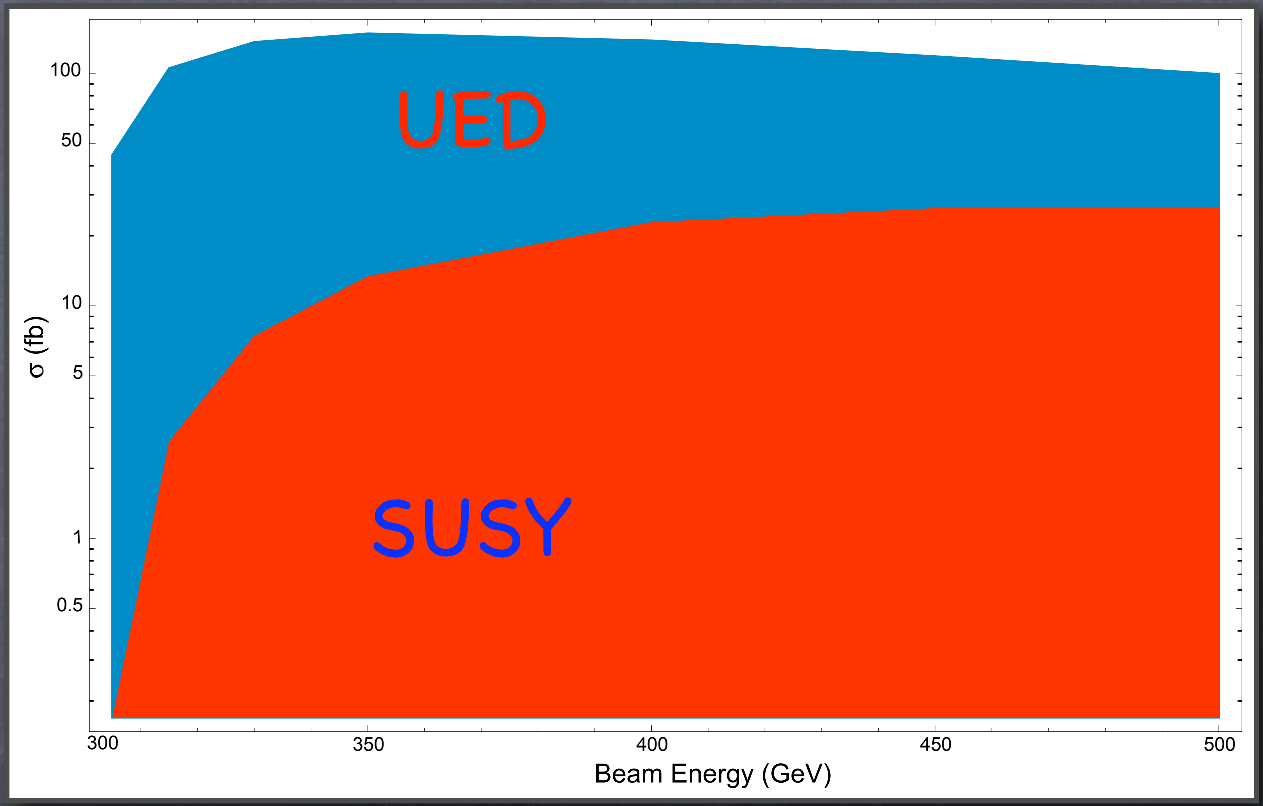
Scalar vs. Spinor at ILC

SPS3



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

MUED



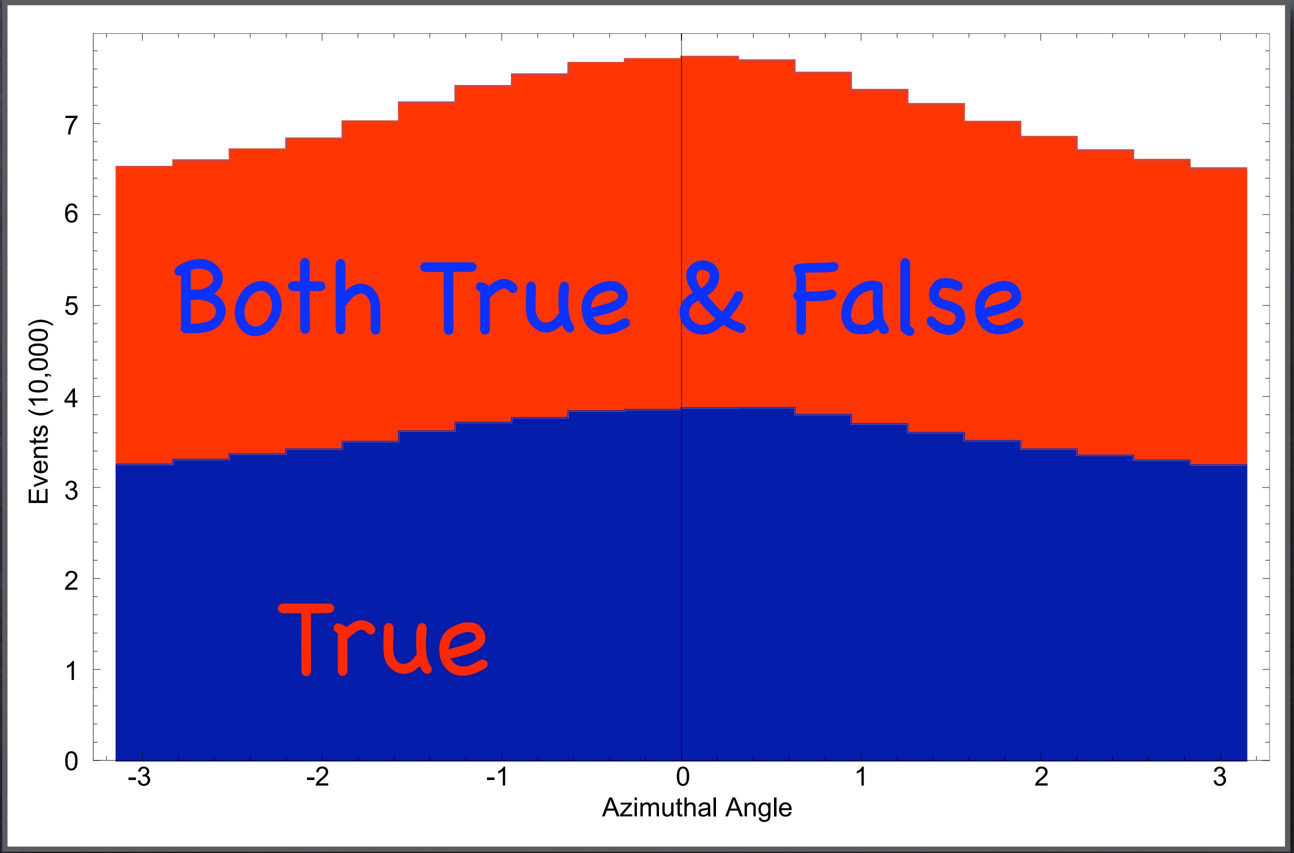
$\tilde{\chi}_1^0/B_1$	301.5 GeV
$\tilde{\mu}_R/\mu_{1R}$	303.3 GeV
$\tilde{\mu}_L/\mu_{1L}$	309.0 GeV

Azimuthal Distributions

- Sum ϕ_1 and ϕ_2 distributions.

$$\sqrt{s} = 370 \text{ GeV}$$

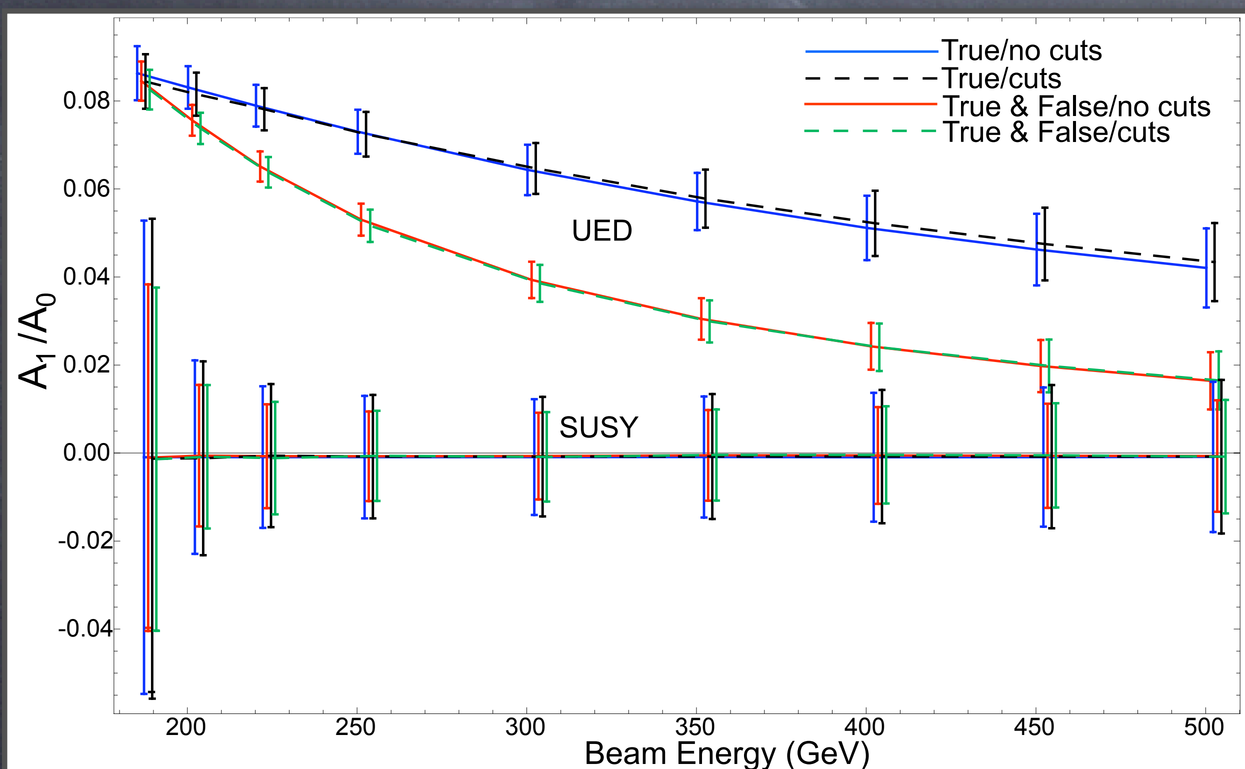
UED distribution



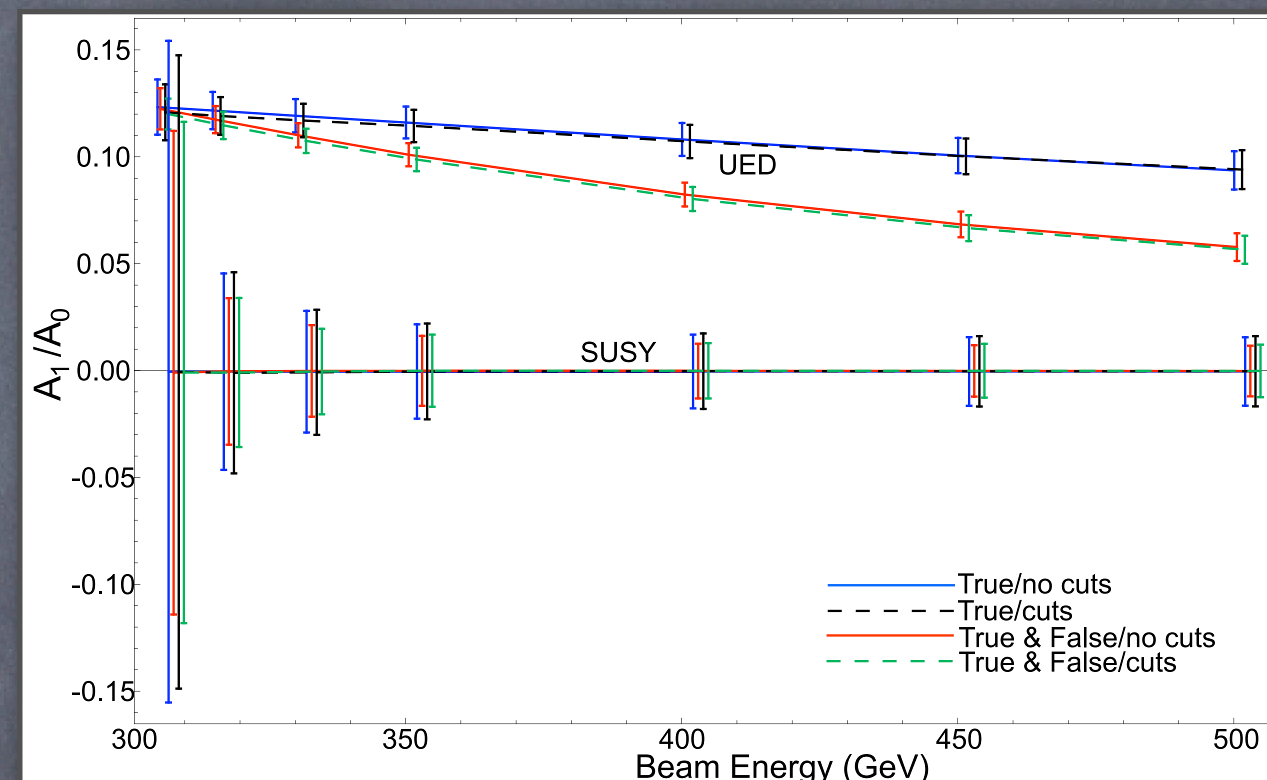
SUSY distribution

Azimuthal Distributions

SPS3



MUED



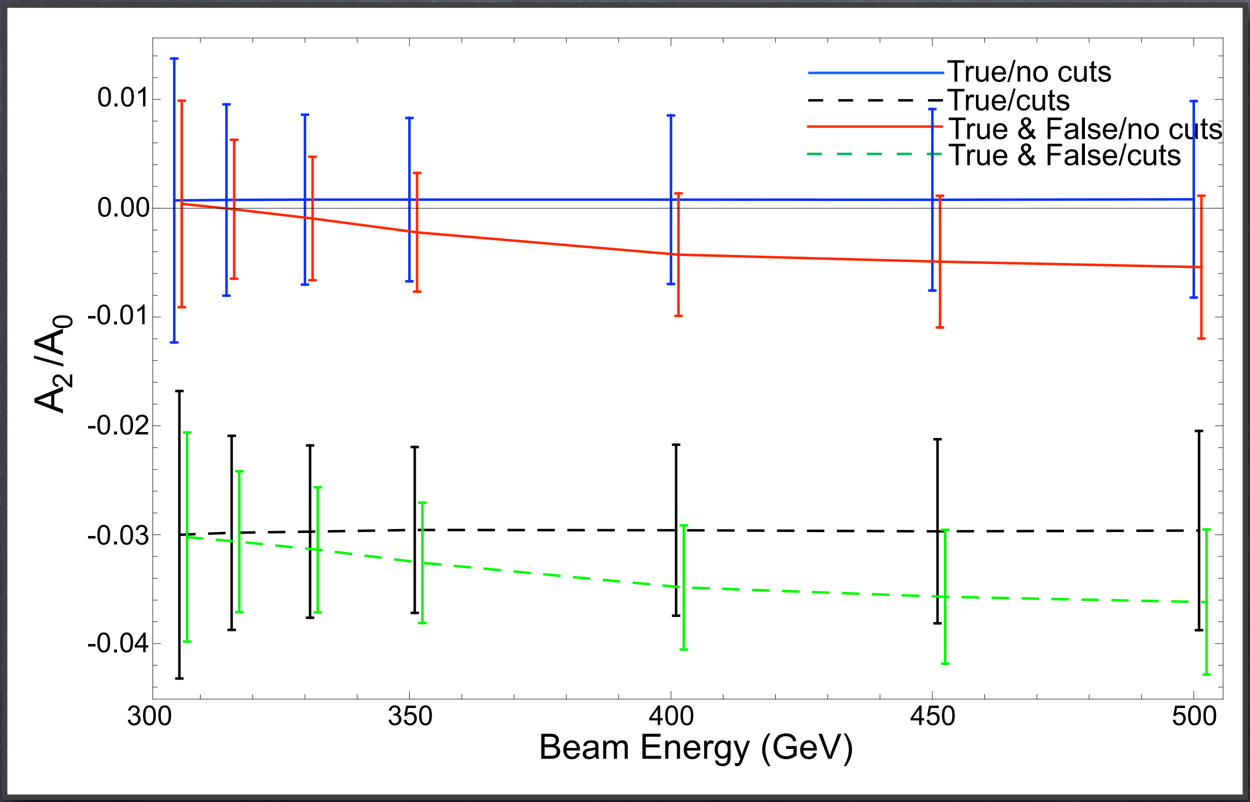
Fit to

$$\sigma = A_0 + A_1 \cos\phi + A_2 \cos 2\phi$$

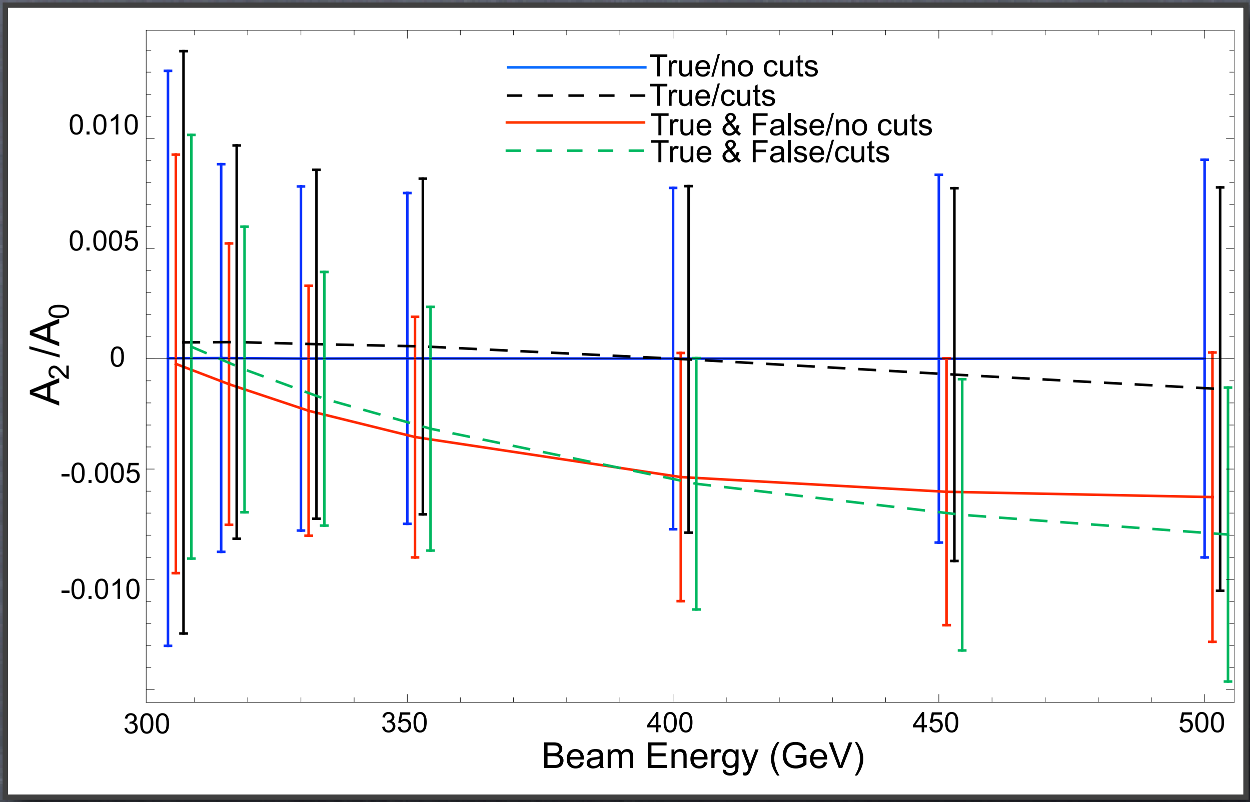
Effects of Cuts on

$$e^- e^+ \to \mu^+_{1R} \mu^-_{1R} \to \mu^+ \mu^- B_1 B_1$$

MUED uncorrected



MUED corrected



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

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.