Discriminating Spin Through Quantum Interference

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Outline

- Motivation
- Spin measurements and quantum interference
- Scalar vs. Spinor measurements
- Spinor vs. Vector measurements
- Spin at the LHC?
- Conclusions

Beyond the SM

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

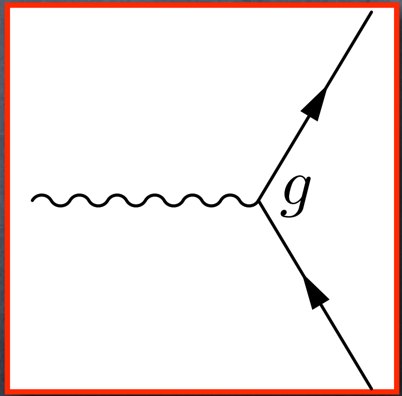
Supersymmetry? Technicolor? Extra Dimensions?

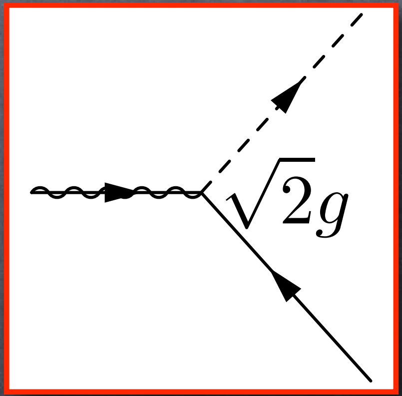
- Solutions often propose partners to Standard Model particles

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

SUSY vs. UED

- Both specta contain ‘copies’ of SM
  - UED has tower of KK modes
- New particles have similar interaction strengths:





- Spin measurements may be the defining experimental difference.

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)

Minimal UED

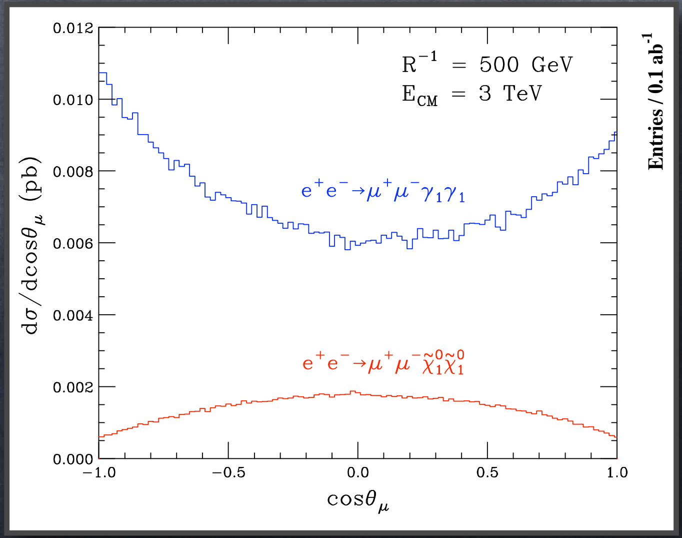
- Minimal UED model needs 3 parameters specified:
    - Radius of extra dimension R
        - $R^{-1} > 300 \text{ GeV}$ required by electroweak precision measurements
    - Scale Λ
    - Higgs mass

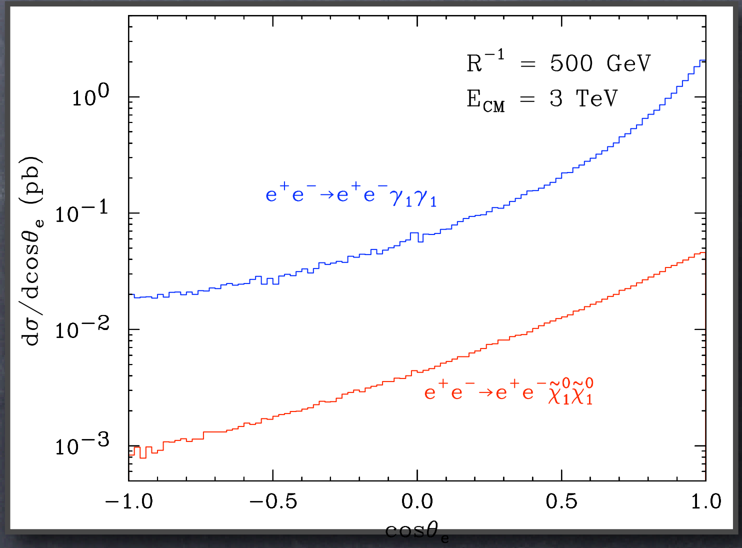
Spin at LHC/ILC

- Can compare total cross sections: $\sigma_{SUSY} < \sigma_{UED}$
    - Need to have a model in mind
    - Not a measurement of spin
- Can look for KK>1 towers
    - Could be too heavy for colliders, could be seeing non-minimal SUSY states
    - Again, not a spin measurement
- Threshold scans at ILC
    - Both spinors and vector bosons have $\sigma \propto \beta$

Spin at LHC/ILC

- At ILC, reconstruct production angle:
  - Scalar production $\propto \sin^2\theta$
  - Spinor production (away from thres.) $\propto 1+\cos^2\theta$
  - T-channel creates forward peak: model dependence

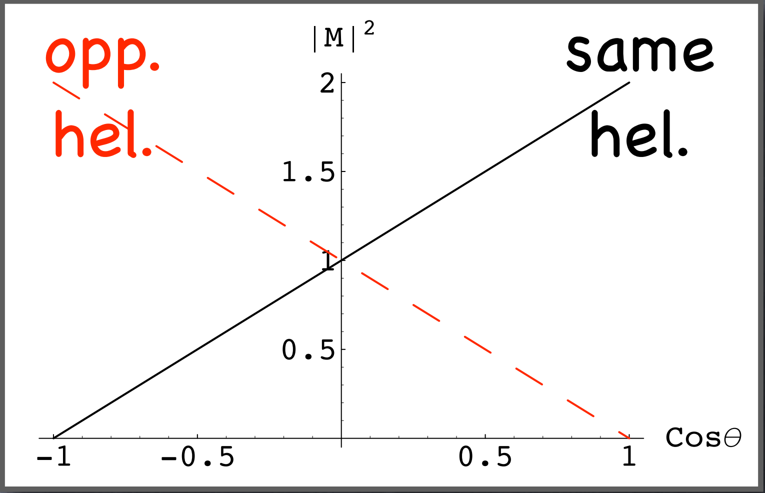


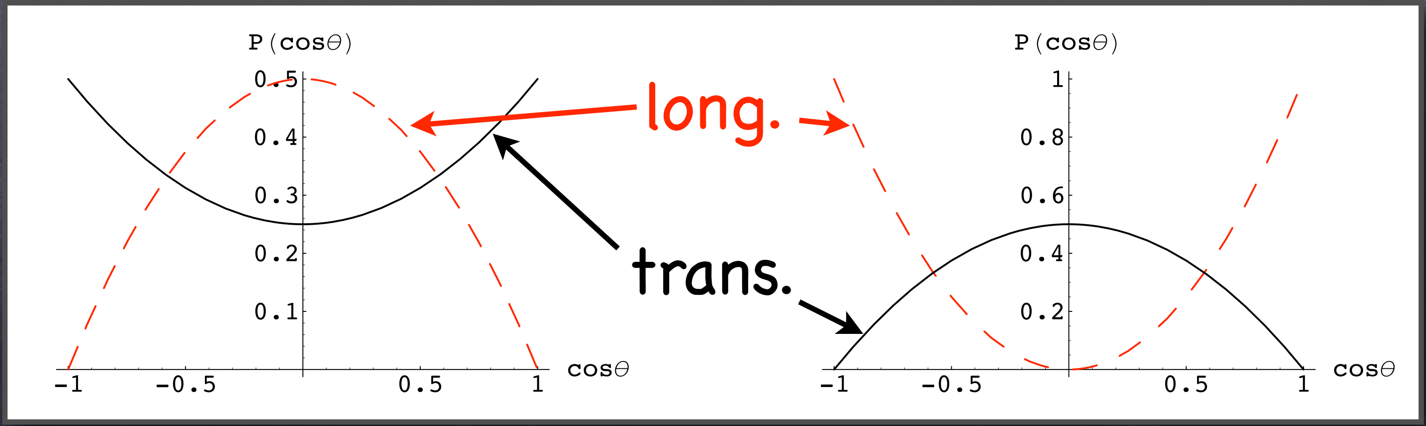


hep-ph/0502041

Spin at LHC/ILC

- Decay of polarized spinor to spinor/scalar
  - Model dependent assumptions of chiral couplings.
- Decay of vector boson





to spinors

to bosons

hep-ph/0605296

Spin at LHC/ILC

near

- Charge asymmetry: $\tilde{q}_L \to \tilde{\chi}_2^0 q_L \to \tilde{\ell}_R^{\pm} \ell^{\mp} q_L \to \ell^{\pm} \ell^{\mp} q_L \tilde{\chi}_1^0$

far

$$\hat{m} \equiv m_{\ell q}^{near} / (m_{\ell q}^{near})_{max} = \sin\theta^*/2$$

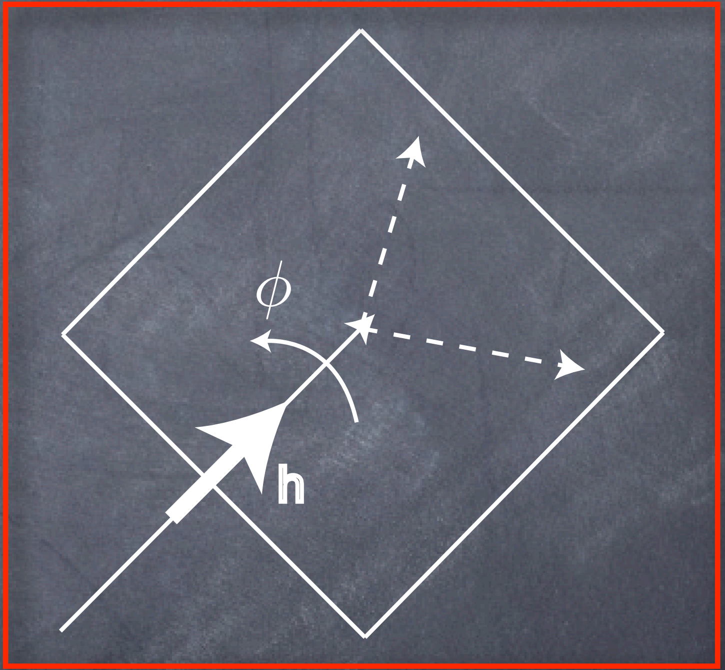
  - Spinor $\tilde{\chi}_2^0$ has $\sigma \propto \hat{m}^3$ compared to $\sigma \propto \hat{m}$ for phase space.
  - Signal polluted by $\bar{\tilde{q}}_L$ decays, and cannot distinguish near/far leptons
  - Signal survives in charge asymmetry of $\dfrac{d\sigma}{dm_{\ell^{\pm} q}}$
- Model dependent assumption of $\tilde{\chi}_2^0$ chiral couplings.

Spin and Quantum Interference

- Decay of particle with helicity h:
  - Rotations about z-axis of decay plane imply

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

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



Spin and Quantum Interference

- If particle produced in multiple helicities with approximately equal probabilities, then

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

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

- If we can measure the ϕ dependence of cross section, we can determine what helicities contributed to the interference.

Spin and Quantum Interference

- Vector Boson Decay:

$$\boxed{\begin{aligned} \mathcal{M}_+ &\propto e^{i\phi_1} \\ \mathcal{M}_0 &\propto 1 \\ \mathcal{M}_- &\propto e^{-i\phi_1} \end{aligned}}$$

$$\left|\sum \mathcal{M}\right|^2 = \underline{A + B\cos\phi_1 + C\cos 2\phi_1}$$

- Spinor Decay:

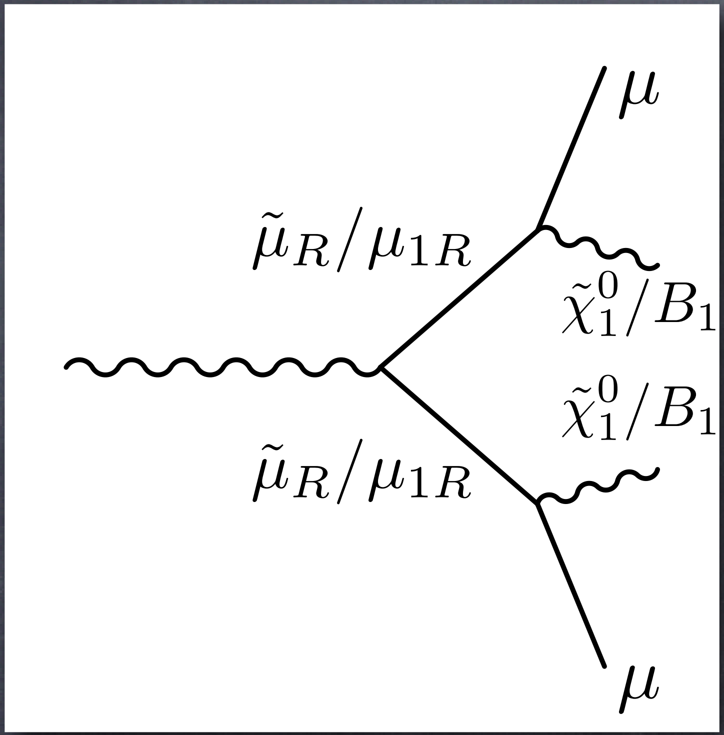
$$\boxed{\begin{aligned} \mathcal{M}_\uparrow &\propto e^{i\phi_1/2} \\ \mathcal{M}_\downarrow &\propto e^{-i\phi_1/2} \end{aligned}}$$

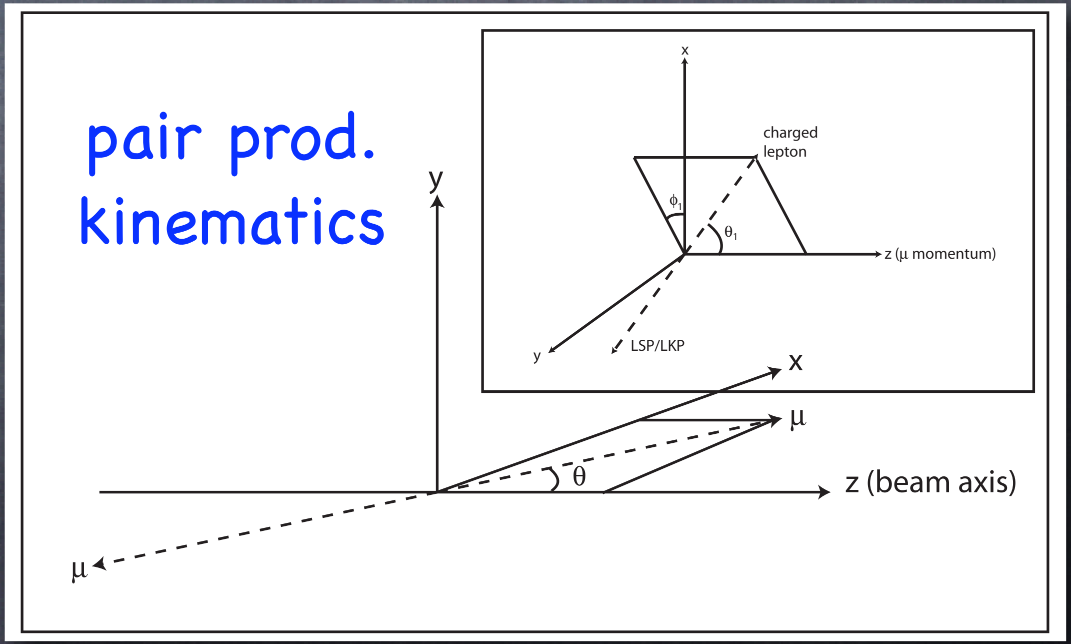
$$\left|\sum \mathcal{M}\right|^2 = \underline{A + B\cos\phi_1}$$

- Scalar Decay:

$$\underline{\left|\sum \mathcal{M}\right|^2 = A}$$

Coherent Sums and Kinematics




pair prod. kinematics

Scalar vs. Spinor at ILC

$$e^- e^+ \to \tilde{\mu}_R^+ \tilde{\mu}_R^- \to \mu^+ \mu^- \tilde{\chi}_0^1 \tilde{\chi}_0^1$$
$$e^- e^+ \to \mu_{1R}^+ \mu_{1R}^- \to \mu^+ \mu^- B_1 B_1$$

- Scalar decay:

$$\sigma \propto |\mathcal{M}|^2 = A$$

- Spinor decay:

$$\begin{aligned} \sigma &\propto |\mathcal{M}_\uparrow + \mathcal{M}_\downarrow|^2 \\ &= A + B\cos\phi_i \end{aligned}$$

Reconstruct $\phi_{1/2}$ distributions and measure $A,\ B$ parameters

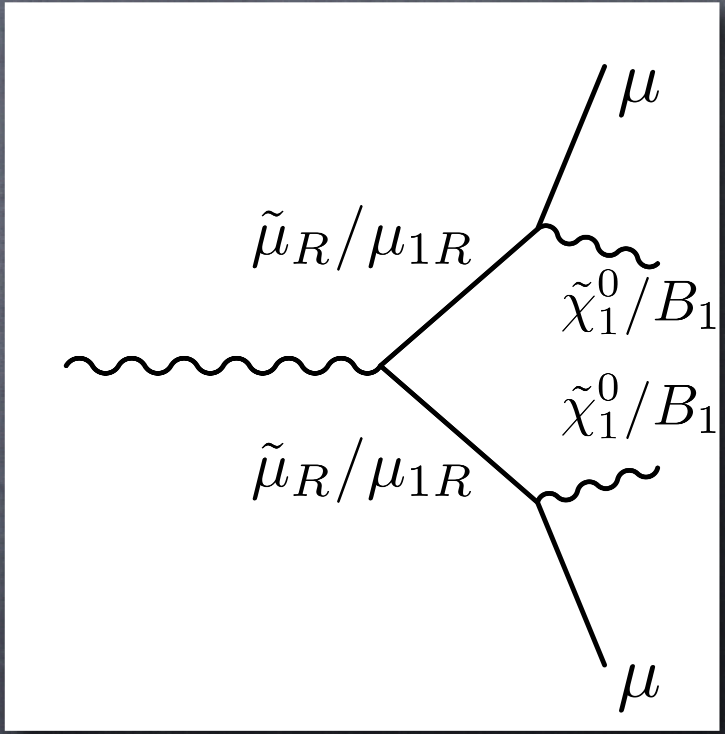
Reconstruction of $\phi_{1/2}$

- Assume masses of μ/B partners known.

4+4 unknown LSP/LKP momenta
-4 measured $\not{p}$
-4 mass relations

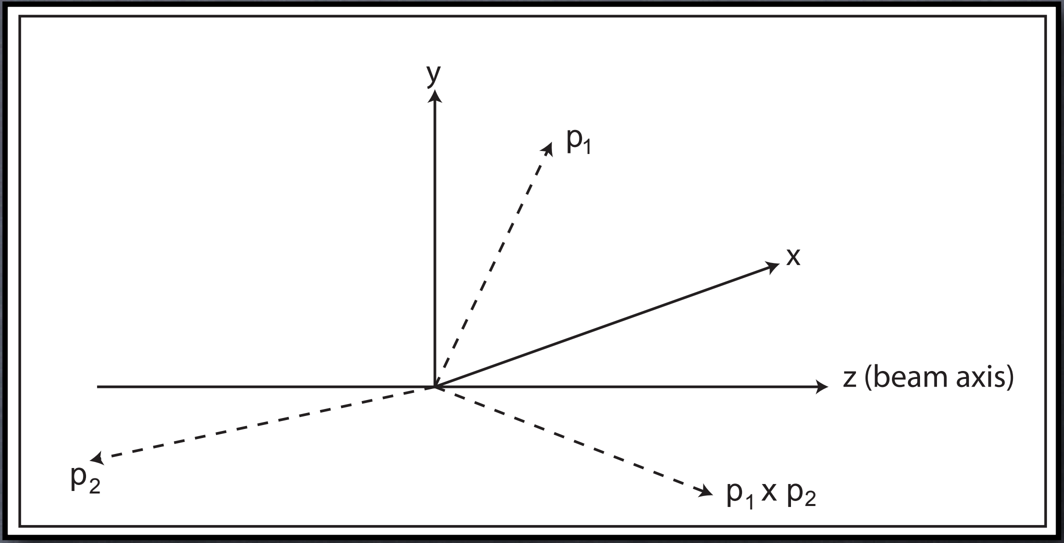
  - system specified up to a 2-fold ambiguity

- Use both solutions: true and false $\vec{p}_{\tilde{\mu}_R}$ to derive true and false values for ϕ_i



Reconstruction Algorithm

$$
\begin{aligned}
c_1 &= \frac{1}{2}(m_{\tilde{B}}^2 - m_{\tilde{\mu}_R}^2 + 2E_b p_1^0) \\
c_2 &= -\frac{1}{2}(m_{\tilde{B}}^2 - m_{\tilde{\mu}_R}^2 + 2E_b p_2^0) \\
t_1 &= \frac{(\vec{p}_2 \cdot \vec{p}_2)c_1 - (\vec{p}_2 \cdot \vec{p}_1)c_2}{(\vec{p}_2 \cdot \vec{p}_2)(\vec{p}_1 \cdot \vec{p}_1) - (\vec{p}_2 \cdot \vec{p}_1)^2} \\
t_2 &= \frac{(\vec{p}_1 \cdot \vec{p}_1)c_2 - (\vec{p}_2 \cdot \vec{p}_1)c_1}{(\vec{p}_2 \cdot \vec{p}_2)(\vec{p}_1 \cdot \vec{p}_1) - (\vec{p}_2 \cdot \vec{p}_1)^2} \\
y &= \sqrt{\frac{E_b^2 - m_{\tilde{\mu}_R}^2 - (t_1^2(\vec{p}_1 \cdot \vec{p}_1) + t_2^2(\vec{p}_2 \cdot \vec{p}_2) + 2t_1 t_2(\vec{p}_2 \cdot \vec{p}_1)}{|\vec{p}_1 \times \vec{p}_2|^2}}
\end{aligned}
$$



$$
\boxed{\vec{p}_{\tilde{\mu}_R} = t_1\vec{p}_1 + t_2\vec{p}_2 \pm y(\vec{p}_1 \times \vec{p}_2)}
$$

Mass Measurements at ILC/LHC

- Reconstruction assumes no mass/momentum measurement errors.
- 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

Backgrounds

- Depending on spectrum and beam energy:

$$W^-W^+ \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu \quad \tilde{\chi}^-\tilde{\chi}^+ \to \mu^+\mu^-\tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu$$

$$\tilde{\mu}_L^-\tilde{\mu}_L^+ \to \mu^+\mu^-\tilde{\chi}^0\tilde{\chi}^0 \quad ZZ \to (\mu^+\mu^-)(\nu\bar{\nu})$$

$$\ldots$$

- BUT: requiring successful reconstruction i.e. that $y \in \mathbb{R}$, and assuming that the decaying particle is a $\tilde{\mu}_R$ cuts $\sim 99\%$ of background.

Scalar vs. Spinor at ILC

- Assume $\sqrt{s} \leq 1\ \mathrm{TeV},\ L = 500\ \mathrm{fb}^{-1}$
- 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

Event Generation

- Differential cross sections calculated using HELAS with narrow-width approx.
  - Cross-checked with MadGraph/CalcHEP where applicable
  - MUED spectrum calculated using Matchev et. al. CalcHEP model
- Monte Carlo implemented with BASES

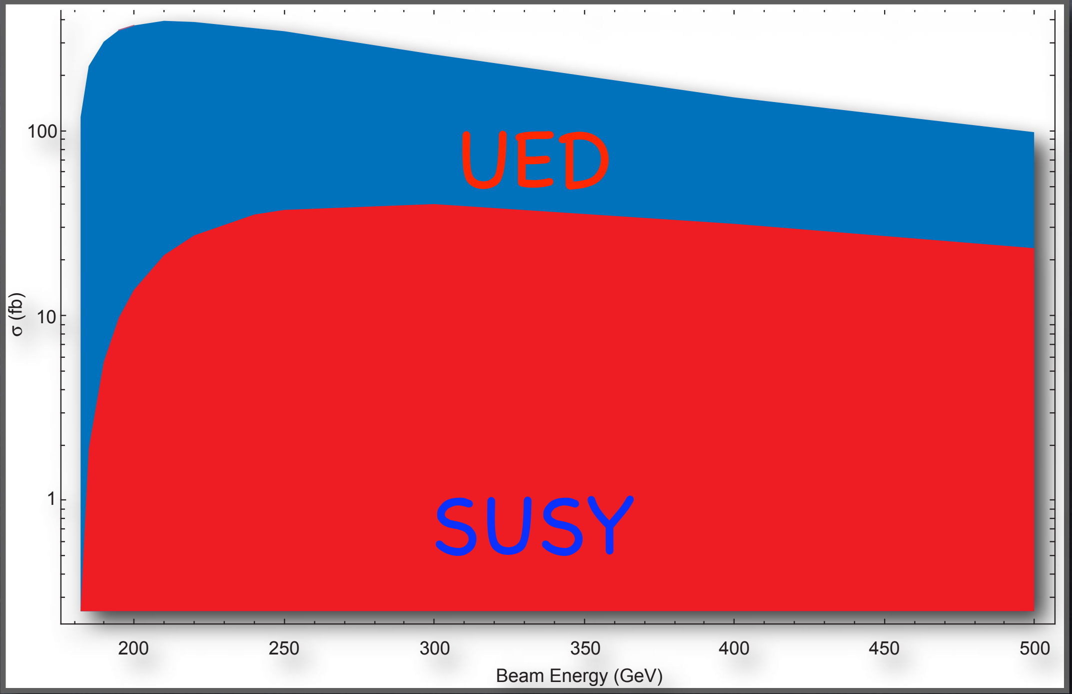
- HELAS: FORTRAN 77 subroutines to calculate helicity amplitudes.
- BASES: adaptive Monte-Carlo FORTRAN 77 subroutines
- MadGraph: publicly available Monte Carlo using HELAS to calculate parton-level amplitudes
  - Does not have UED implimented
- CalcHEP: publicly available Monte Carlo. Implements UED, but slow for 2->4 processes

SPS 3 Analysis

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

- Assuming 500 fb^{-1} of luminosity, have several thousand to several 100k's of events.
- Cut on successful reconstruction of $\tilde{\mu}_R$ and make pseudo-rapidity cuts on leptons and missing energy:

$$\eta \leq 2.5$$

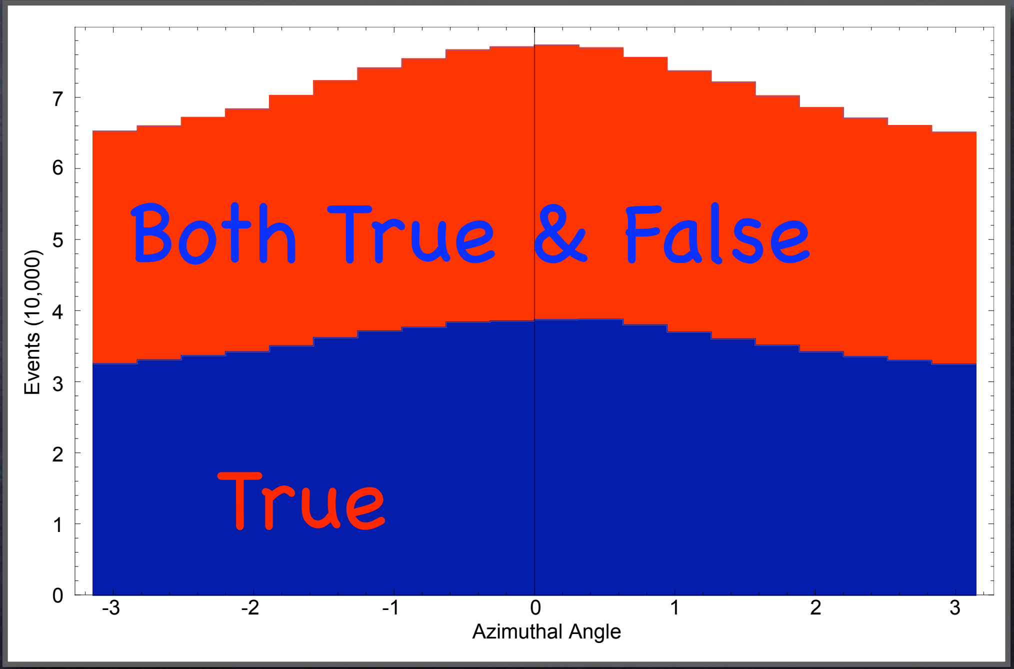


Azimuthal Distributions

- Sum ϕ_1 and ϕ_2 distributions.

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

UED distribution



SUSY distribution

Azimuthal Distributions

- Rapidity cuts and false solutions cause high frequency oscillations in the distribution.
  - Fit to $\boxed{A + B\cos\phi + C\cos 2\phi}$
- Overall scaling depends on total σ, parameter of interest is B/A
  - Presence of $C/A \neq 0$ may cause confusion between spinor and vector boson

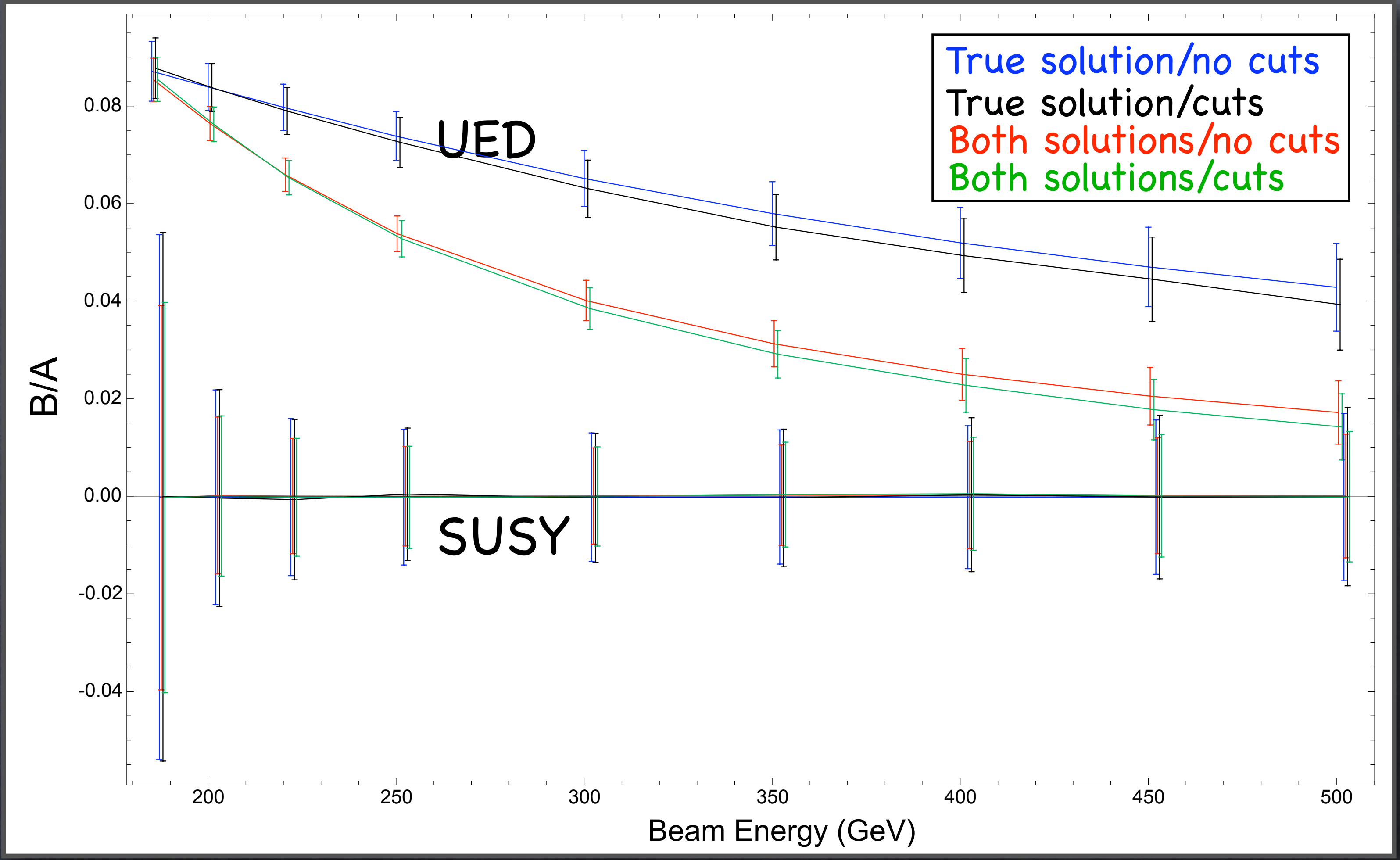
Error Calculations

- Assume $\sqrt{N}$ errors for histogram bins
- Fit A, B, C using method of least squares
  - 95% confidence interval for each variable after marginalizing over the other 2

$$\chi^2 = \sum_{n=1}^{20} \frac{(t_n - \int_{bin} A + B\cos\phi + C\cos 2\phi)^2}{s_n^2}$$

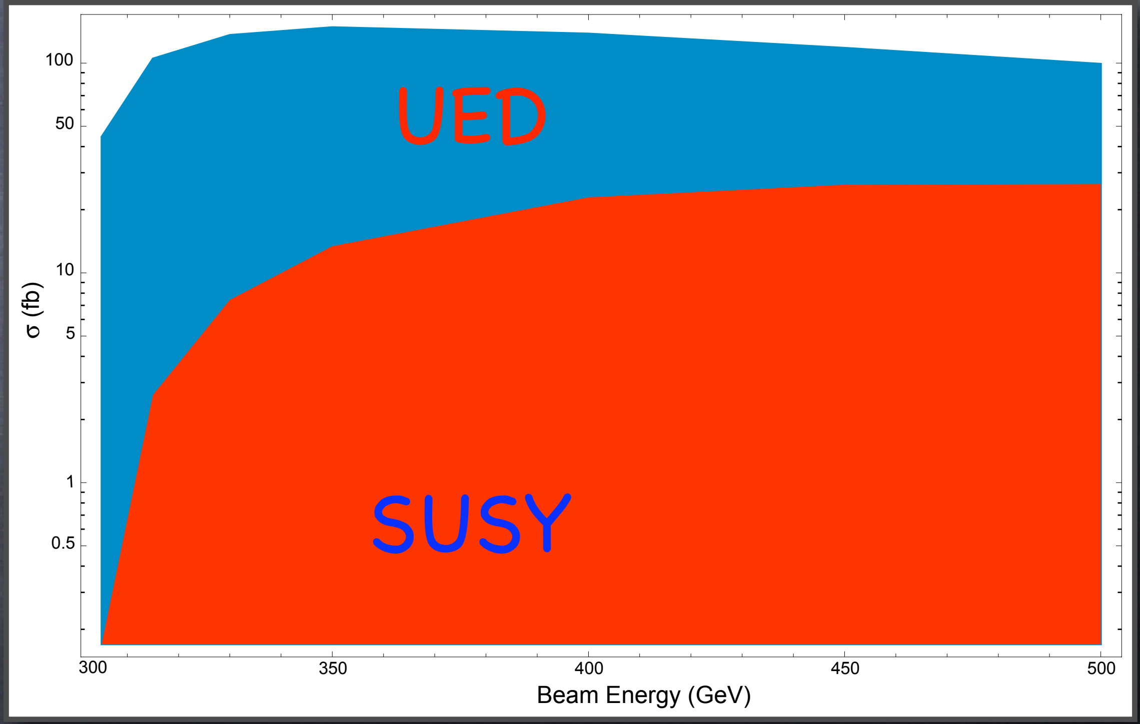
Azimuthal Distributions

SPS3 spectrum



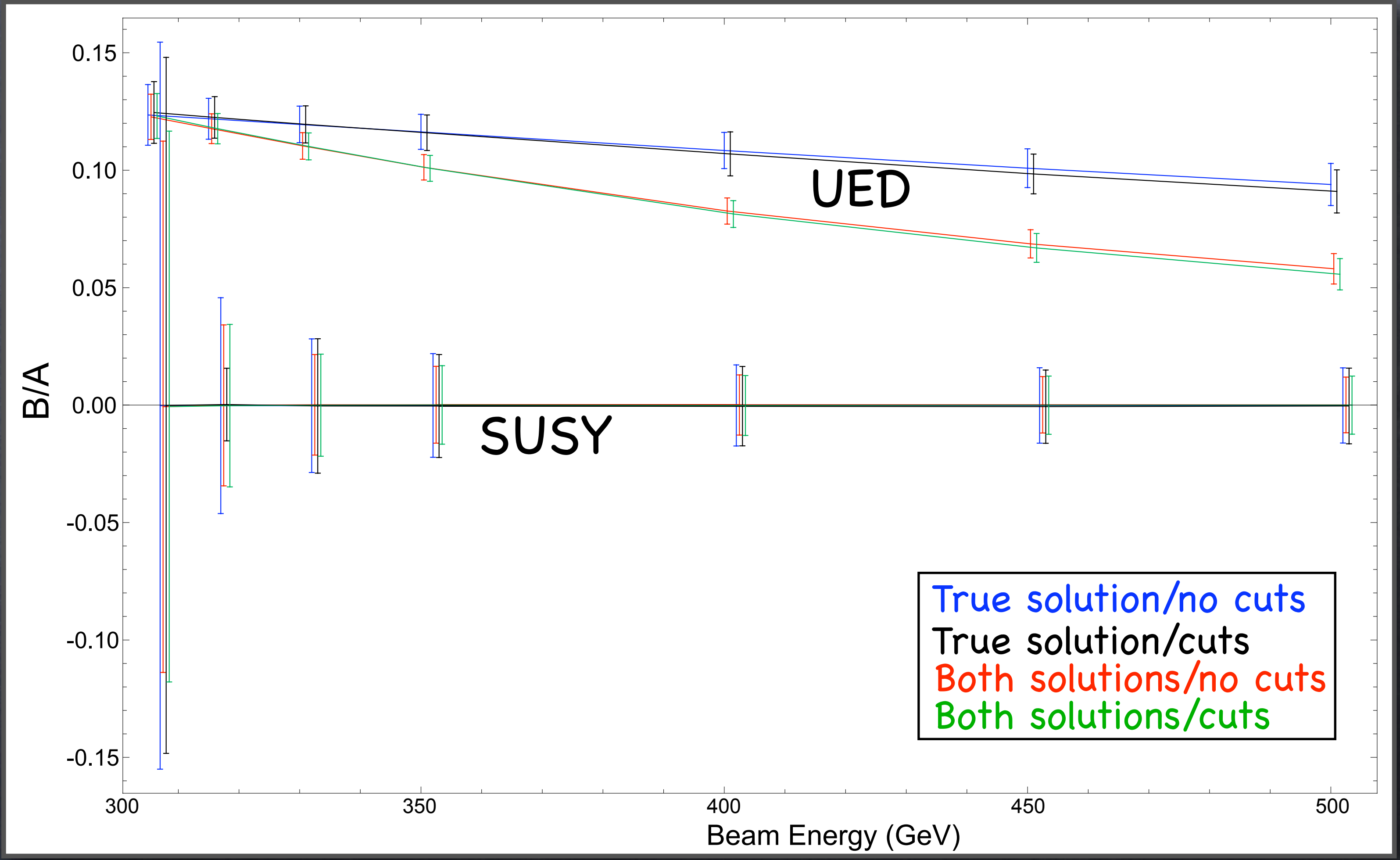
MUED Spectrum

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



Azimuthal Distributions

MUED spectrum



Spinor vs. Vector Boson at ILC

- Spinor azimuthal distribution

$$\boxed{\left|\sum \mathcal{M}\right|^2 = A + B\cos\phi_i}$$

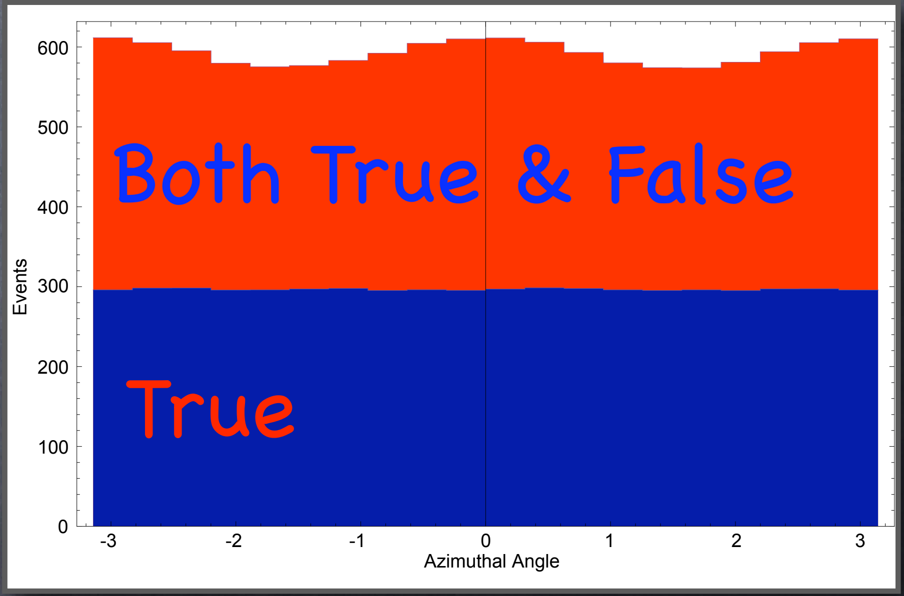
- Vector boson distribution

$$\boxed{\left|\sum \mathcal{M}\right|^2 = A + B\cos\phi_i + C\cos 2\phi_i}$$

  - For C to be large, need equal production of all 3 polarizations.

Effect of Cuts

- Distributions develop $\cos 2\phi$ dependence due to cuts on rapidity.
- False solutions also have $\cos 2\phi$ dependence.
- In $\mu^+_{1R}\mu^-_{1R} \to \mu^+\mu^- B_1 B_1$ this may cause confusion between spinor/vector.

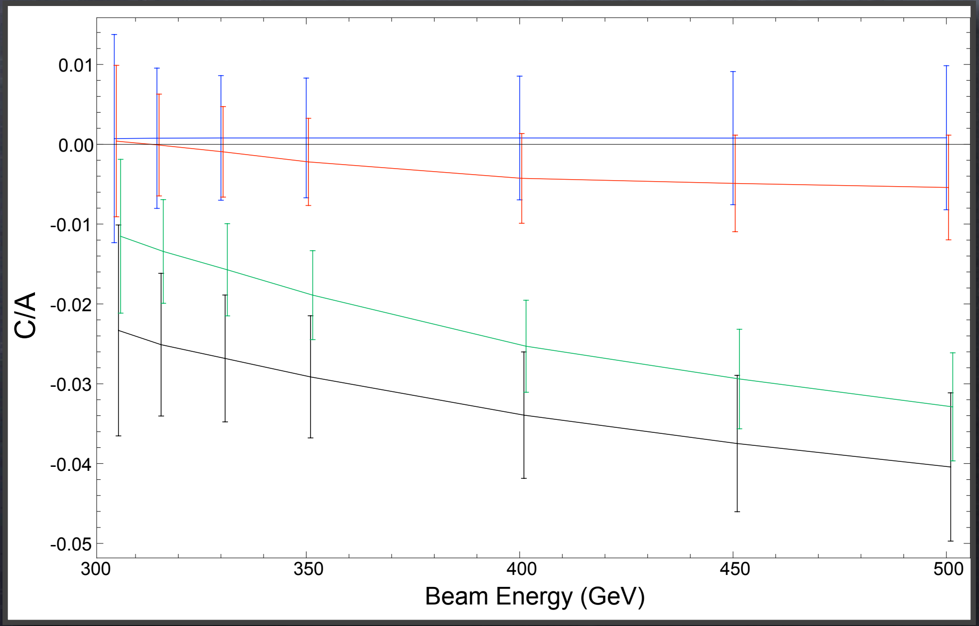


Effects of Cuts on

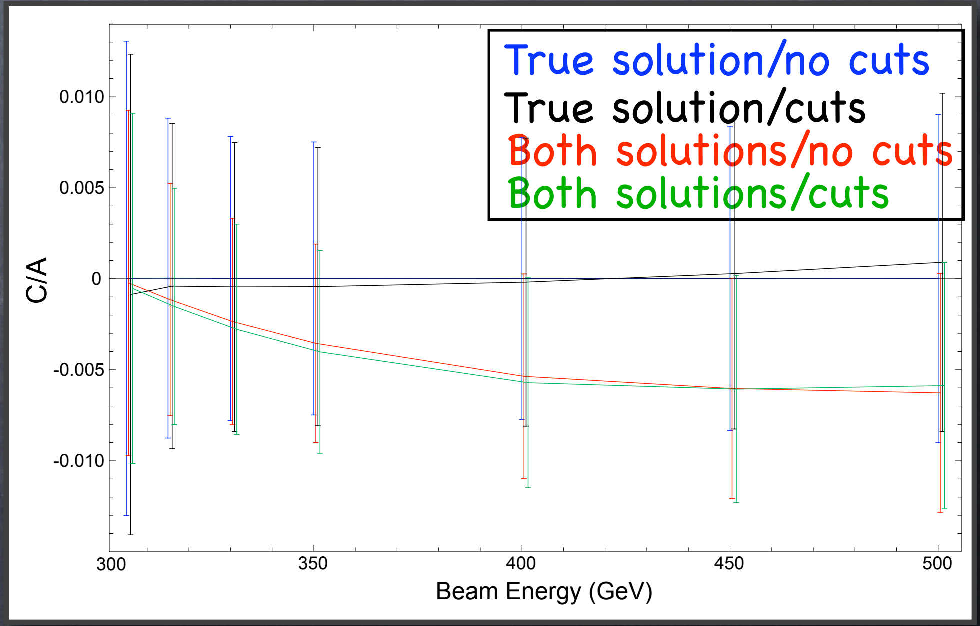
$$e^- e^+ \to \mu^+_{1R} \mu^-_{1R} \to \mu^+ \mu^- B_1 B_1$$

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

MUED uncorrected



MUED corrected



Charged W's at ILC

$$e_L^- e_L^+ \to \tilde{\chi}_1^- \tilde{\chi}_1^+ \to \ell^\pm \ell^\mp \tilde{\nu} \bar{\tilde{\nu}}$$

$$e_L^- e_L^+ \to W_1^- W_1^+ \to \ell^\pm \ell^\mp \nu_1 \bar{\nu}_1$$

SPS3 spectrum

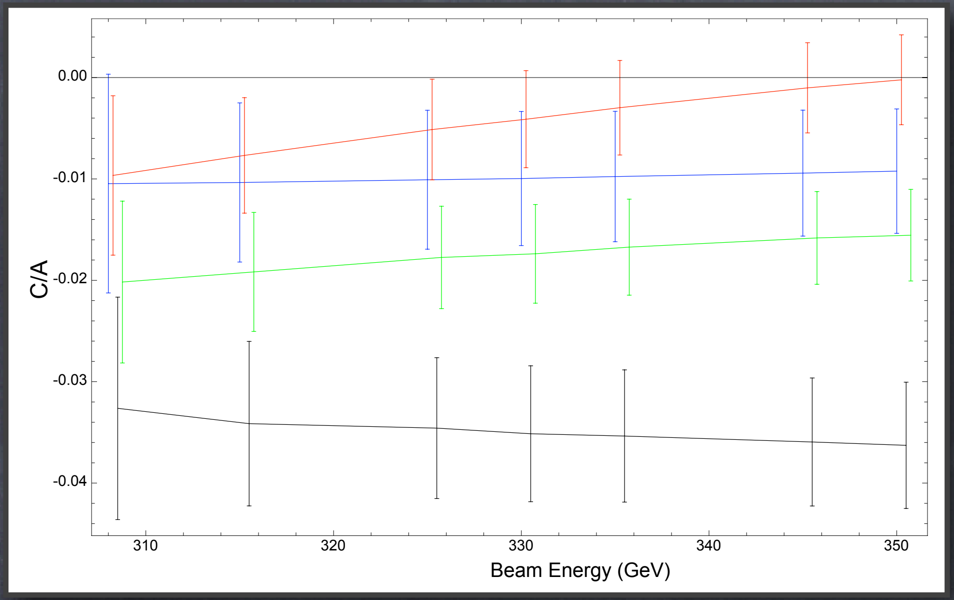
$W_1^\pm / \tilde{\chi}_1^\pm$	306 GeV
$\nu_1 / \tilde{\nu}$	276 GeV

- Major backgrounds

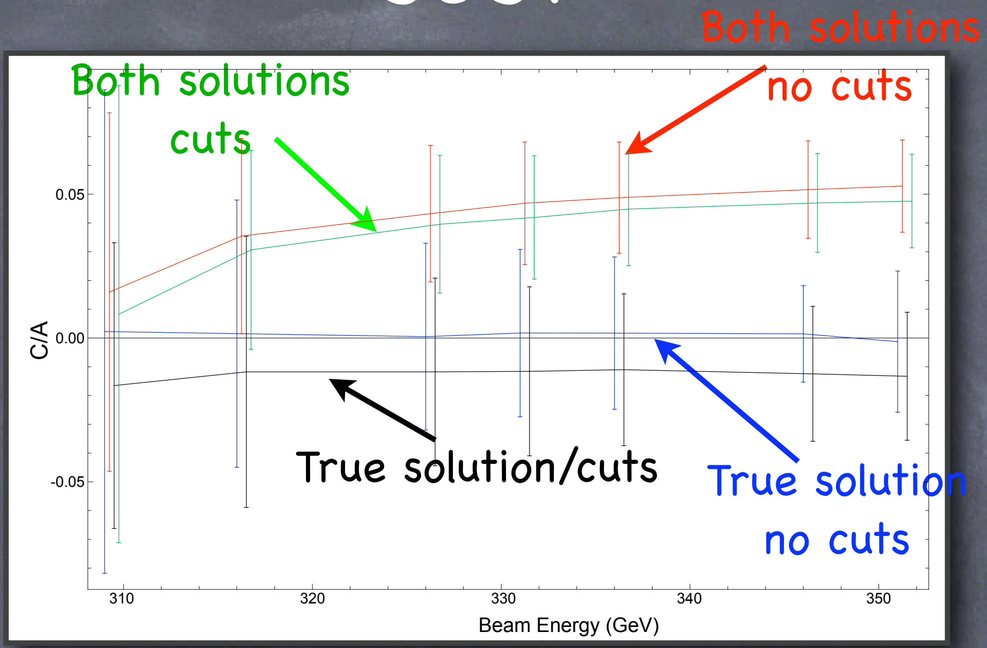
  $W^- W^+ \to \ell^\pm \ell^\mp \nu \bar{\nu}$ $\quad$ $\tilde{\ell}^- \tilde{\ell}^+ \to \ell^\pm \ell^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0$

  - Again can be greatly reduced by requiring successful reconstruction of $\tilde{\chi}_1^\pm$

MUED



SUSY

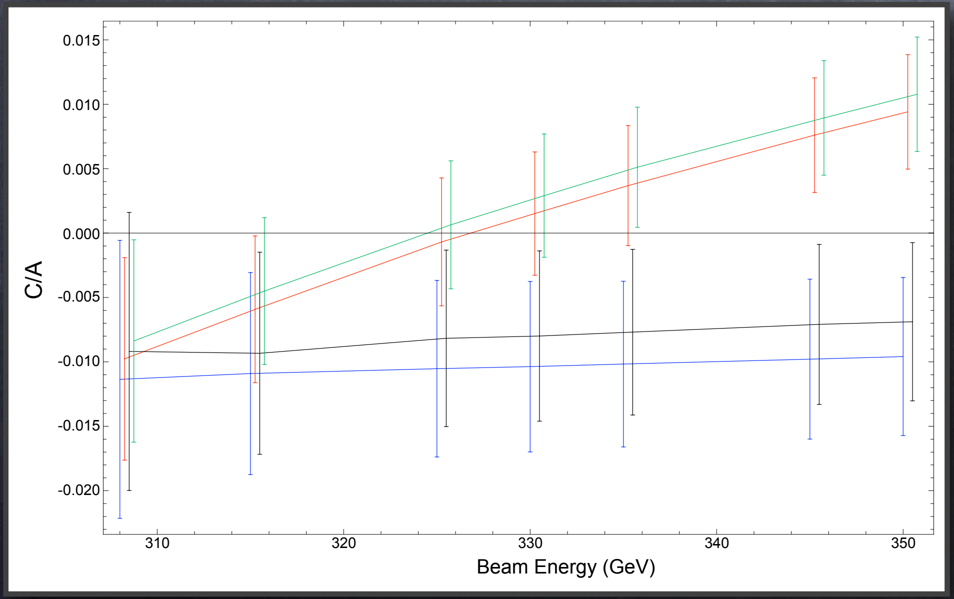

Both solutions no cuts

Both solutions cuts

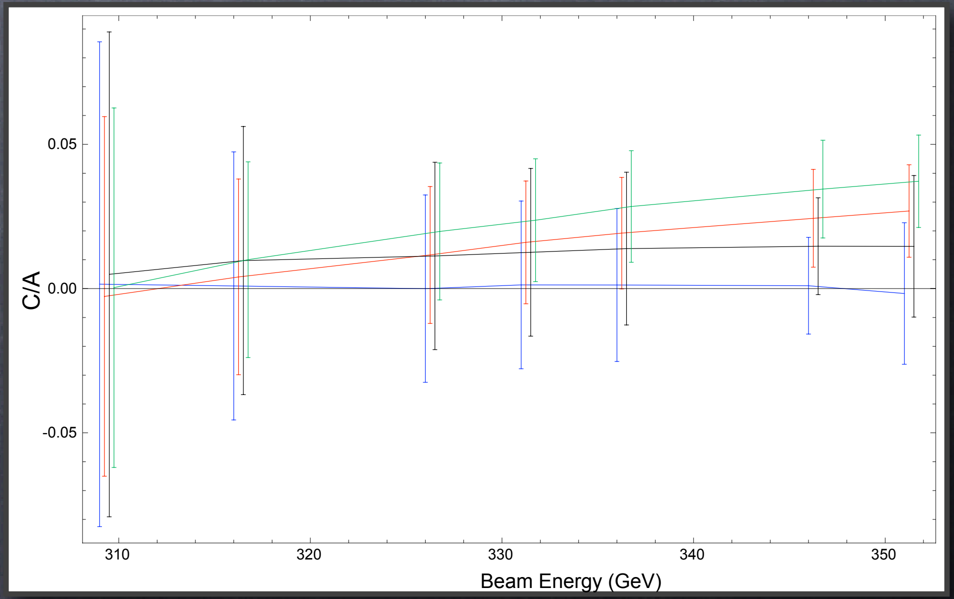
True solution/cuts

True solution no cuts

MUED Adjusted



SUSY Adjusted



Charged W's at ILC

- Statistics limited:

$$\sigma_{UED} \times BR = 87.7 \text{ fb}$$
$$\sigma_{SUSY} \times BR = 2.9 \text{ fb}$$
$$(\sqrt{s} = 650 \text{ GeV})$$

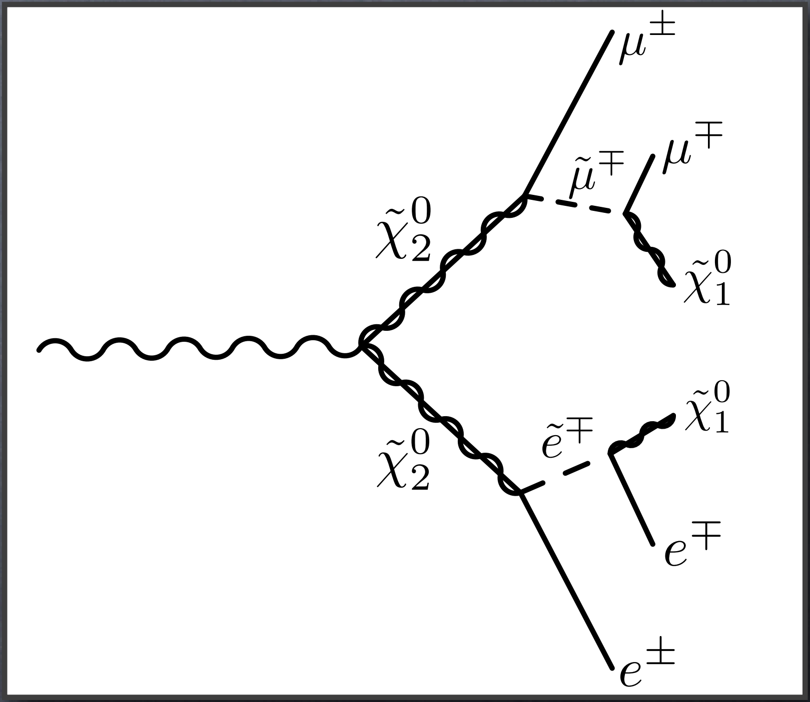
  - Requires $\sim 1 \text{ ab}^{-1}$ to distinguish UED vector bosons true solution from spinors.
- Poor understanding of false distribution
- Flat distribution in θ_i, ϕ_i does not capture effect of cuts on non-trivial distributions.

Full Reconstruction of Events

- If masses of $\tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\ell}^{\pm}$ known then

4+4 unknown LSP/LKP momenta
-4 measured $\not{p}$
-6 mass relations

- Near/far ambiguity potential problem, but with precision mass & momentum knowledge, this can be overcome.

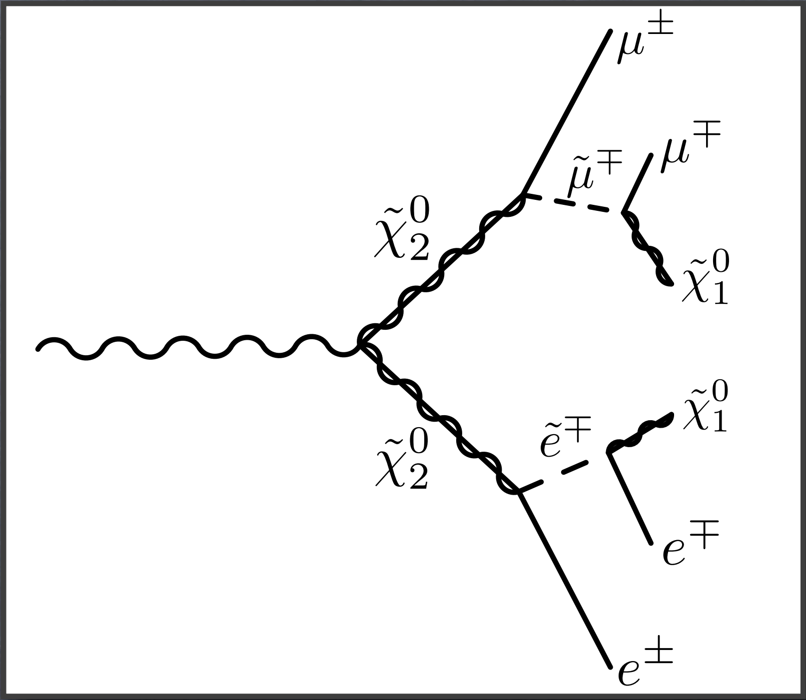


$$\begin{aligned}\tilde{\chi}_2^0\tilde{\chi}_2^0 &\rightarrow (\mu^\pm\tilde{\mu}^\mp)(e^\pm\tilde{e}^\mp) \rightarrow (\mu^\pm\mu^\mp\tilde{\chi}_1^0)(e^\pm e^\mp\tilde{\chi}_1^0) \\ W_1^3W_1^3 &\rightarrow (\mu^\pm\mu_1^\mp)(e^\pm e_1^\mp) \rightarrow (\mu^\pm\mu^\mp B_1)(e^\pm e^\mp B_1)\end{aligned}$$

- Can reconstruct using either $\mu^\pm\mu^\mp$/$e^\pm e^\mp$ combined momentum or just near $\mu^\pm$/$e^\pm$
- Now have near/far ambiguity. Demanding agreement between the two methods eliminates false solutions.
- Statistics limited, cross section at ILC only:

$$\sigma_{UED} \times BR \sim 1 \text{ fb}$$

$$\sigma_{SUSY} \times BR \sim 0.1 \text{ fb}$$



Top Spin at the Tevatron

$$t \to bW^+$$

- Can completely reconstruct top momentum in semi-leptonic decays
- With known bottom and W spin, top spin can be either $1/2$ or $3/2$
  - Fit azimuthal distribution to

$$\sum_{n=0}^{3} A_i \cos(n\phi)$$

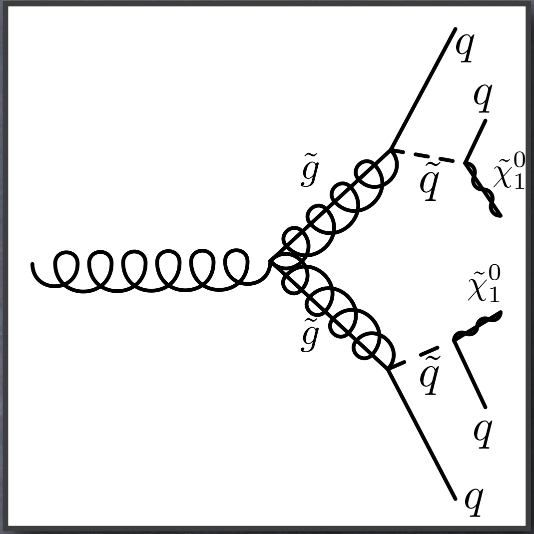
  - Spin $1/2$ implies $A_2 = A_3 = 0$

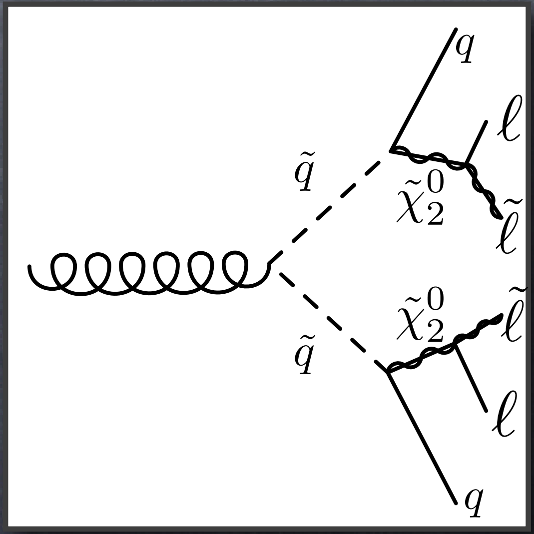
Spin at LHC

- 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 $\not{p}_T$
-6 mass relations

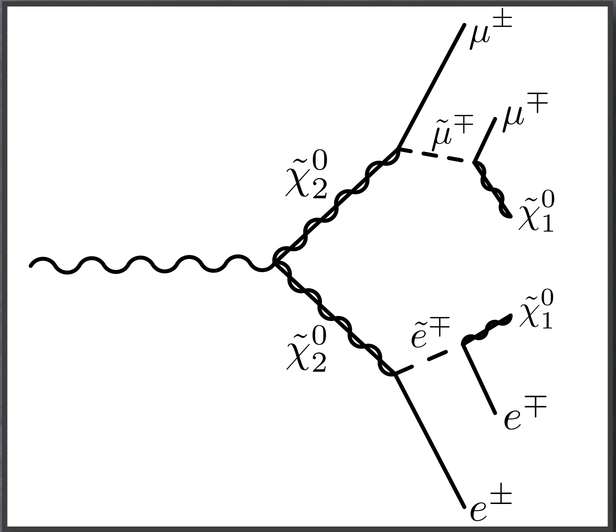
- Much higher statistics available; $\sigma \sim 1\ \mathrm{pb}$

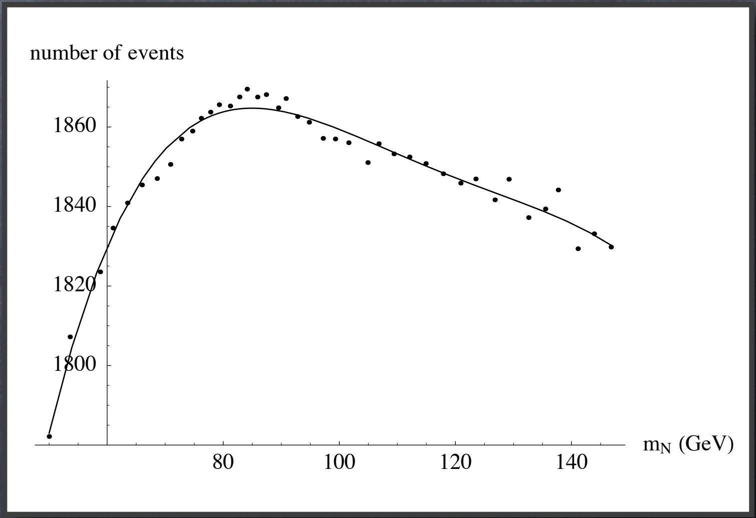




Mass measurements at LHC

- Cheng, Gunion et. al. 0707.0030
- Fit unknown masses (i.e. $m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{\chi}}$), require real solutions to the reconstruction
  - Solutions describe 3D volume in parameter space
  - With detector effects included, real masses correspond to values where the # of real solutions to data changes rapidly





$$2900 \text{ events} \longrightarrow$$

$$m_{\tilde{\chi}_2} = 252.2 \pm 4.3, m_{\tilde{\mu}} = 130.4 \pm 4.3, m_{\tilde{\chi}_1} = 86.2 \pm 4.3 \text{ GeV}$$

Conclusions

- Quantum interference between helicity/ polarization states can serve as a fully model independent probe of spin in an event
  - A linear collider is capable of distinguishing scalars from higher spins
  - Distinguishing vector and spinor may be possible with higher luminosity and a better understanding of cuts and false solutions.

Conclusions

- Method utilizes reconstruction of event up to two-fold ambiguity; longer decay chains may remove this ambiguity and allow for better discrimination of spin.
  - Investigated chains all suffer from poor statistics
- At LHC, similar events would allow for 2-fold reconstruction, and with large # of events, allow for direct spin measurements