Spin Analysis of Supersymmetric Particles

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New Theory ⇔ SUSY?

Smuons
General Analysis
Selectrons
Charginos/Neutralinos

Summary

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New Theory

- Particles: mass, spin, parity, internal quantum numbers
- Scenarios: potentially isomorphic patterns

$$\begin{aligned} \text{SUSY} &: \tilde{q}_L \to q\tilde{\chi}_2^0 \to q\ell^+\tilde{\ell}^- \to q\ell^+\ell^-\tilde{\chi}_1^0 \to q\ell^+\ell^- E_{miss} \\ \text{UED} &: q_1 \to qZ_1 \to q\ell^+\ell_1^- \to q\ell^+\ell^-\gamma_1 \to q\ell^+\ell^- E_{miss} \end{aligned}$$

LHC $[q, \ell^+, \ell^-]$ invariant masses affected by intermediate spins

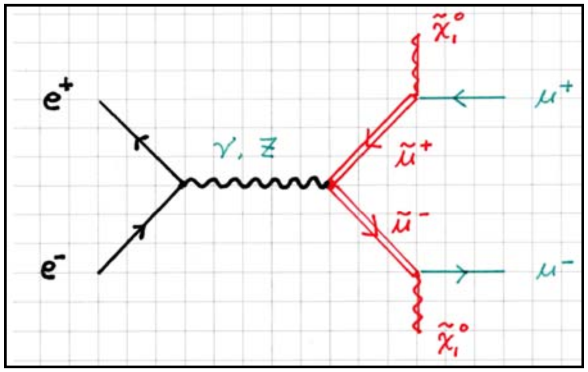
ILC model-independent spin analysis for

$$\begin{aligned} e^+e^- &\to \tilde{\mu}_R^+\tilde{\mu}_R^- \text{ and } \tilde{e}_R^+\tilde{e}_R^- \\ e^+e^- &\to \tilde{\chi}_1^+\tilde{\chi}_1^- \text{ and } \tilde{\chi}_2^0\tilde{\chi}_2^0 \end{aligned}$$

(i) threshold excitation
(ii) production angular distribution
(iii) decay angular distributions

Smuons

$$e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-$$
$$\to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



SUSY

$$\text{threshold} \quad : \sigma\left[\tilde{\mu}_R^+\tilde{\mu}_R^-\right] = \frac{\pi\alpha^2}{6s}\beta^3\left[Q_L^2 + Q_R^2\right] \quad \sim \beta^3$$

$$\text{ang distrib} : \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}\left[\tilde{\mu}_R^+\tilde{\mu}_R^-\right] = \frac{3}{4}\sin^2\theta \quad \sim \sin^2\theta$$

UED

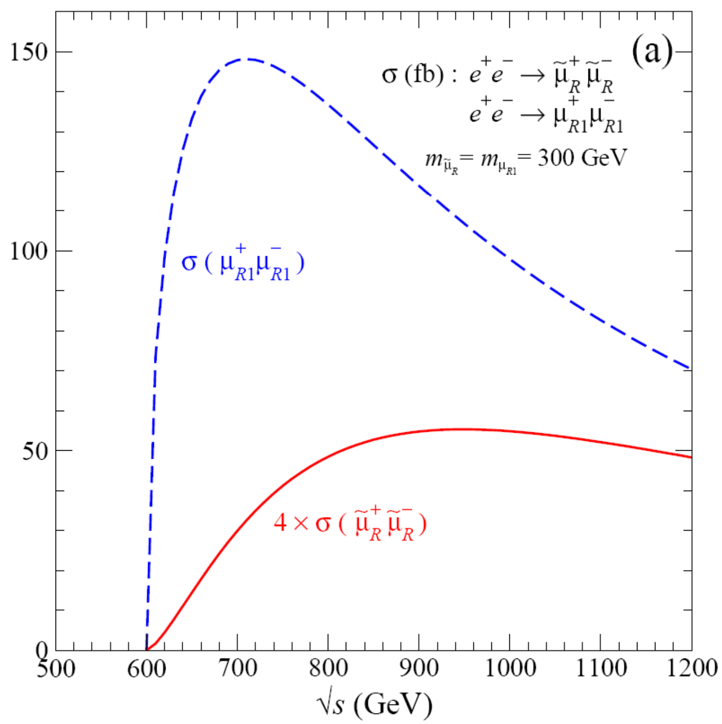
$$\text{threshold} \quad : \sigma[\mu_{R1}^+\mu_{R1}^-] = \frac{2\pi\alpha^2}{3s}\,\beta\,\frac{(3-\beta^2)}{2}\left[Q_L^2 + Q_R^2\right] \quad \sim \beta$$

$$\text{ang distrib} : \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}[\mu_{R1}^+\mu_{R1}^-] = \frac{3}{8}\frac{2}{(3-\beta^2)}\left[1+\cos^2\theta + (1-\beta^2)\sin^2\theta\right]$$

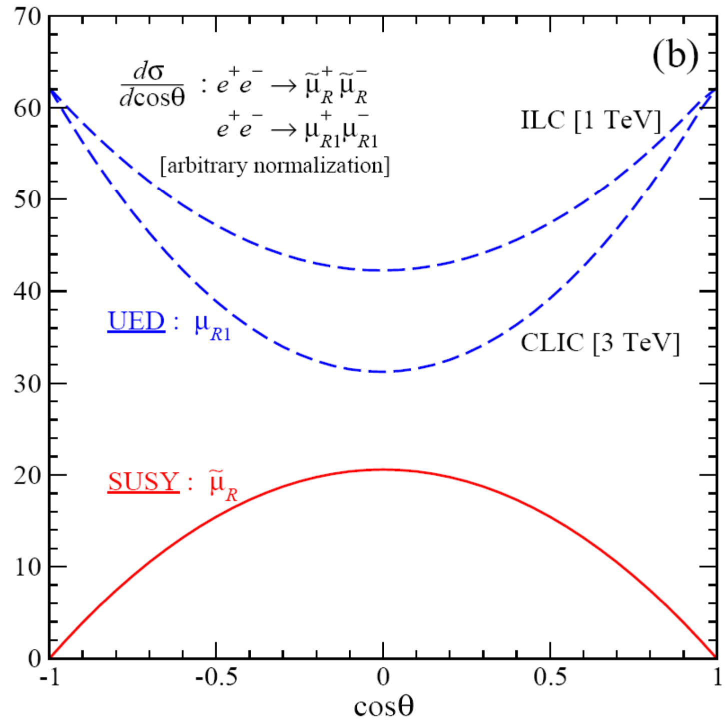
$$\sim 1 \to [1+\cos^2\theta]$$

SUSY ⇔ UED

Threshold excitation



Polar-angle distribution



General Analysis

$$e^+e^- \to F^J_{\lambda_1}\bar{F}^J_{\lambda_2} \;\; via\; \gamma, Z \text{ exchange}$$

$$\sigma = \frac{\pi\alpha^2}{3s}\beta\,(Q_L^2+Q_R^2)\left[\sum_\lambda \left(|\mathcal{T}_{\lambda,\lambda-1}|^2+|\mathcal{T}_{\lambda,\lambda+1}|^2\right)+\sum_\lambda |\mathcal{T}_{\lambda\lambda}|^2\right]$$

$$\frac{d\sigma^s}{d\cos\theta} = \frac{\pi\alpha^2}{4s}\beta\,(Q_L^2+Q_R^2)\left[\frac{1+\cos^2\theta}{2}\sum_\lambda \left(|\mathcal{T}_{\lambda,\lambda-1}|^2+|\mathcal{T}_{\lambda,\lambda+1}|^2\right)+\sin^2\theta\sum_\lambda |\mathcal{T}_{\lambda\lambda}|^2\right]$$

Fermions

$$j_\mu = \bar\psi_{\alpha_1\cdots\alpha_n}\gamma_\mu\psi^{\alpha_1\cdots\alpha_n} \qquad [\text{spin } J = n+1/2]$$

$$= j^e_\mu + j^m_\mu : \qquad j^e_\mu = \frac{1}{2m}\bar\psi_{\alpha_1,\ldots,\alpha_n}\, i\,\overleftrightarrow{\partial_\mu}\,\psi^{\alpha_1,\ldots,\alpha_n}$$

Fierz–Pauli

$$j^m_\mu = \frac{1}{2m}\partial^\nu\left(\bar\psi_{\alpha_1,\ldots,\alpha_n}\,\sigma_{\mu\nu}\,\psi^{\alpha_1,\ldots,\alpha_n}\right)$$

$$\mathcal{T}^e_{\lambda\lambda} = \beta^2\mathcal{Q}^J_\lambda$$

$$\mathcal{T}^m_{\lambda\lambda} = -\mathcal{Q}^J_\lambda$$

$$\mathcal{Q}^J_\lambda = \frac{\gamma}{\sqrt{2}}\left[\frac{(J+\lambda)}{2J}\,\mathcal{Q}^{J-1/2}_{\lambda-1/2}(\gamma) - \frac{(J-\lambda)}{2J}\,\mathcal{Q}^{J-1/2}_{\lambda+1/2}(\gamma)\right]$$

$$\mathcal{Q}^N_n(\gamma) = \frac{2^N(N+n)!\,(N-n)!}{(2N)!}\,\Sigma'\,\Pi^N_{i=1}\,\frac{(2\gamma^2\delta_{\lambda_i 0}-1)}{(1+\lambda_i)!\,(1-\lambda_i)!}$$

$$\mathcal{T}^m_{\lambda,\lambda\pm1} = \mathcal{Q}^J_{\lambda\pm} \;\Rightarrow\; g = 1/J$$

$$\Rightarrow\; g = 2 \quad [\text{non-min cplg :: asy unitarity}]$$

Hagen et al
Ferrara et al

J>0: non-zero magnetic contribution in forward-backward directions

General Analysis

$e^+e^- \to F^J_{\lambda_1} \bar{F}^J_{\lambda_2}$ *via* γ, Z exchange

$$\sigma = \frac{\pi\alpha^2}{3s}\beta\,(Q_L^2 + Q_R^2)\left[\sum_\lambda \left(|\mathcal{T}_{\lambda,\lambda-1}|^2 + |\mathcal{T}_{\lambda,\lambda+1}|^2\right) + \sum_\lambda |\mathcal{T}_{\lambda\lambda}|^2\right]$$

$$\frac{d\sigma^s}{d\cos\theta} = \frac{\pi\alpha^2}{4s}\beta\,(Q_L^2 + Q_R^2)\left[\frac{1+\cos^2\theta}{2}\sum_\lambda \left(|\mathcal{T}_{\lambda,\lambda-1}|^2 + |\mathcal{T}_{\lambda,\lambda+1}|^2\right) + \sin^2\theta \sum_\lambda |\mathcal{T}_{\lambda\lambda}|^2\right]$$

Bosons

$$j_\mu = j_\mu^e + j_\mu^m : \qquad j_\mu^e = i\,\varphi^*_{\alpha_1\cdots\alpha_J}\,\overleftrightarrow{\partial_\mu}\,\varphi^{\alpha_1\cdots\alpha_J} \qquad \text{for } J > 0$$

$$j_\mu^m = -i\,\partial^\nu\left(\varphi^{*\alpha_2\ldots\alpha_J}_{[\mu}\,\varphi_{\nu]\alpha_2\ldots\alpha_J}\right)$$

Hagen et al

$$\mathcal{T}^e_{\lambda\lambda} = \beta\mathcal{Q}'^J_\lambda$$

$\mathcal{T}^m_{\lambda,\lambda\pm1} = \beta\mathcal{Q}'^J_{\lambda\pm}$: non-zero contribution : $g = 1/J \;\Rightarrow\; 2$

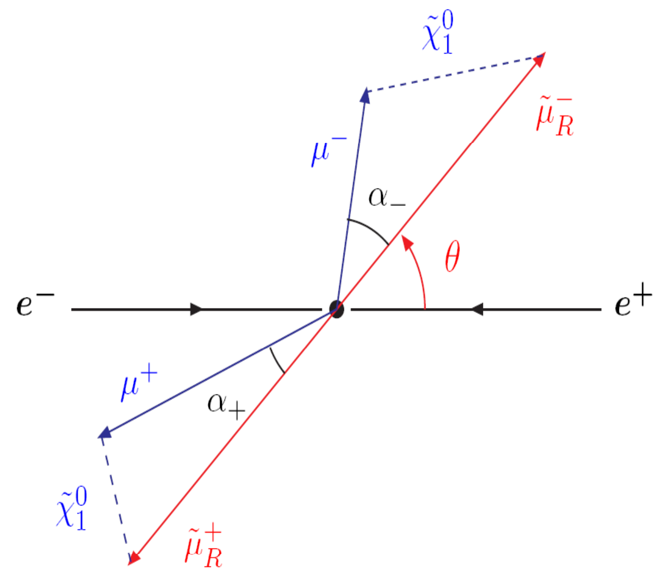
Ferrara et al

Any J > 0: non−zero magnetic contribution in FB directions
different from scalar J = 0 particles

Experimental Analysis

Event axis reconstruction

$$\tilde{\mu}_R^+\tilde{\mu}_R^- \to [\mu^+\tilde{\chi}_1^0] + [\mu^-\tilde{\chi}_1^0]$$



$$m^2_{\mu_R^\pm} - m^2_{\tilde{\chi}_1^0} = \sqrt{s}E_{\mu^\pm}(1 - \beta_{\tilde{\mu}_R^\pm}\cos\alpha_\pm)$$

2 solutions: true ~ $\sin^2\Theta$ while false ~ a little flattened

Experimental Simulation

threshold excitation

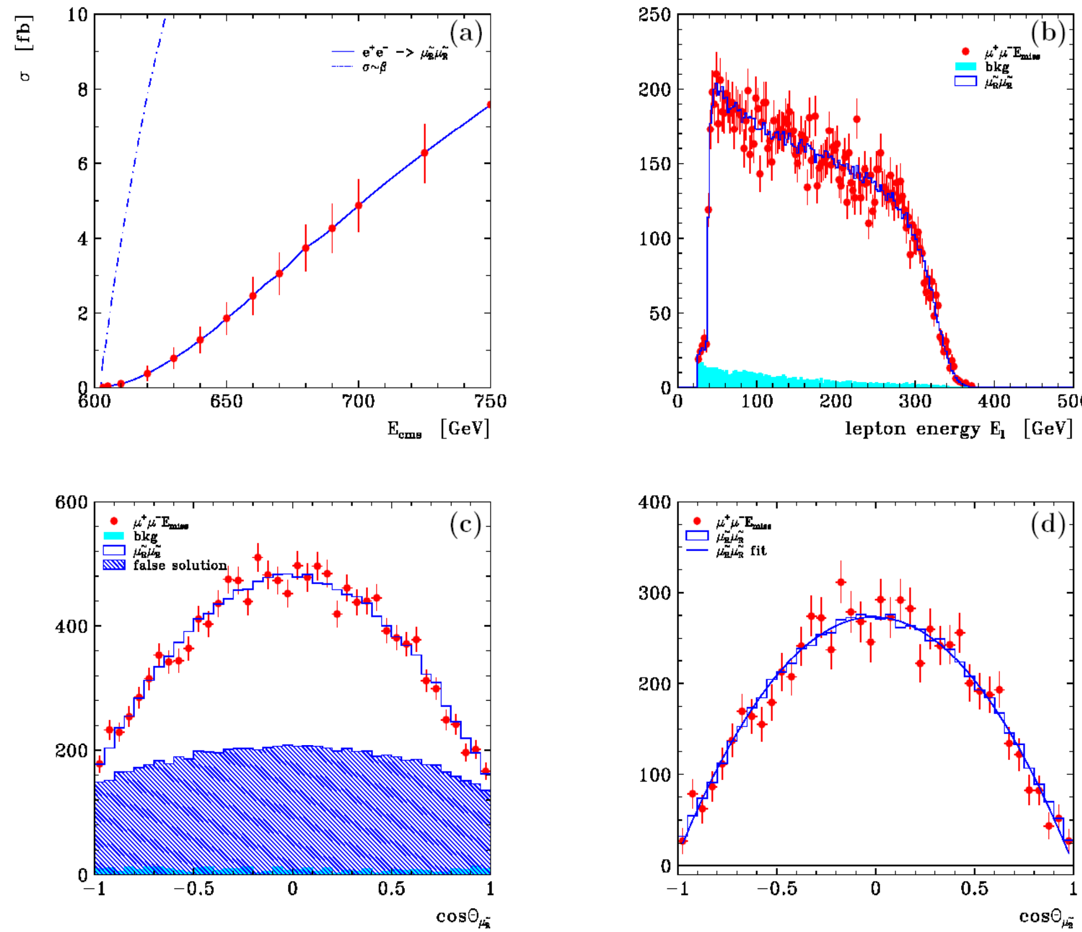
decay distribution

polar angle distribution

$$\frac{d\sigma^{\exp}}{d\cos\theta} \sim 1 + a\cos\theta + b\cos^2\theta$$

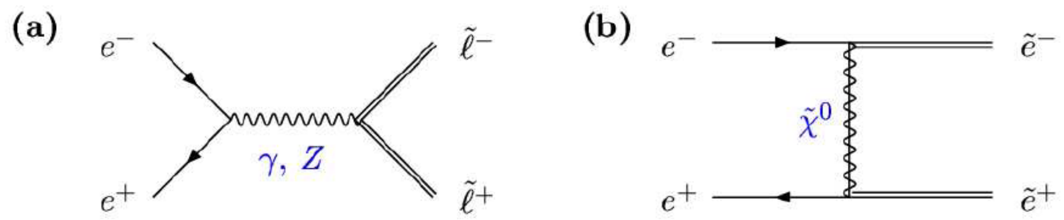
$$a = -0.020 \pm 0.016$$

$$b = -0.979 \pm 0.022$$



Selectrons

$$e^+e^- \longrightarrow \tilde{e}_R^+\tilde{e}_R^-$$
$$\longrightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



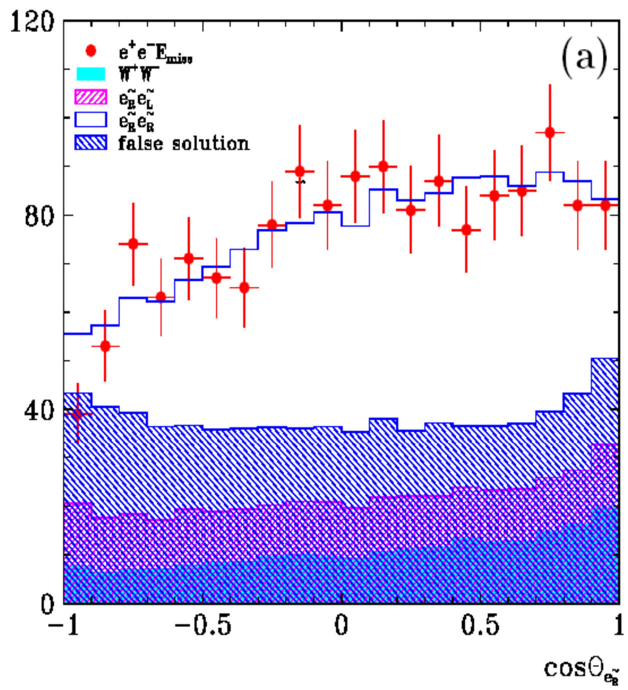
$$\text{threshold} \quad : \sigma\left[\tilde{e}_R^+\tilde{e}_R^-\right] \qquad \sim \beta^3$$

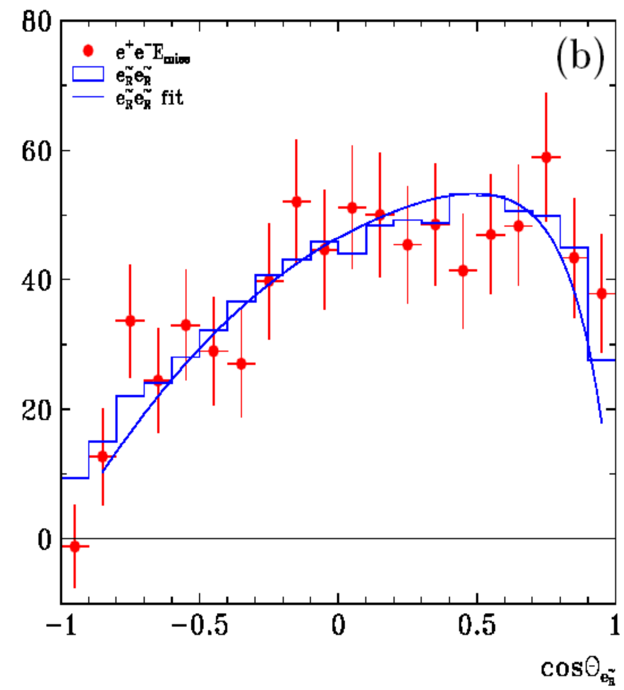
$$\text{ang distrib} : \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}\left[\tilde{e}_R^+\tilde{e}_R^-\right] \sim \sin^2\theta\,\mathcal{G}(\cos^2\theta) \rightarrow \sin^2\theta$$

t-channel: contribution rising steeply above threshold
⇔ modifying $\sin^2\Theta$ law
⇔ switched off partly with polarized beams

e_L^- not cpld to $\tilde{e}_R^-$	$\mathcal{P}[e^-] = -80\%$
e_R^+ not cpld to $\tilde{e}_R^+$	$\mathcal{P}[e^+] = +60\%$

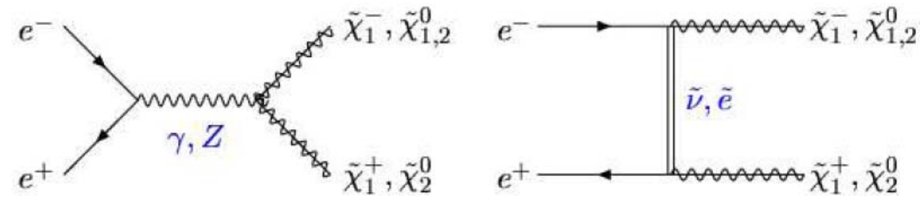
Experimental Simulation





Charginos and Neutralinos

$$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$$
$$\to \tilde{\chi}_2^0\tilde{\chi}_2^0$$



Charginos

$$\sigma = \frac{\pi\alpha^2 f_s}{2s}\beta\left\{\langle Q_1\rangle + \beta^2\langle\cos^2\theta\, Q_1\rangle + 4\mu^2\langle Q_2\rangle + 2\beta\langle\cos\theta\, Q_3\rangle\right\} \quad \text{threshold} : \sim \beta\ /\!\!\!\mathcal{S}$$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\beta\left\{[1+\beta^2\cos^2\theta]Q_1 + 4\mu^2 Q_2 + 2\beta\cos\theta Q_3\right\} \quad \text{threshold} : \sim 1$$

Neutralinos

threshold excitation [Majorana $/\!\!\!\mathcal{P}$] : $\sim\ \beta^3$

angular distribution : $\sim\ [1+\cos^2\theta] \to \cos^2 / \sin^2\theta$ mix

Comparison

		thr excitation	thr ang distrib
SUSY	$\tilde{\chi}^+\tilde{\chi}^-$	β	flat
UED	$W_1^+W_1^-$	β	flat
GENERAL	*Dirac pair*	β	flat
SUSY	$\tilde{\chi}^0\tilde{\chi}^0$ $[Majorana]$	β^3	$1+\kappa\cos^2\theta$
UED	Z_1Z_1 $[Dirac]$	β	flat
GENERAL	*Majorana pair*	β^3	$1+\kappa\cos^2\theta$

Threshold/angular distributions are unique
neither for charginos nor for neutralinos!!

⇨ Final state analysis for polarized spin-1/2 charginos

$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$ ⇨

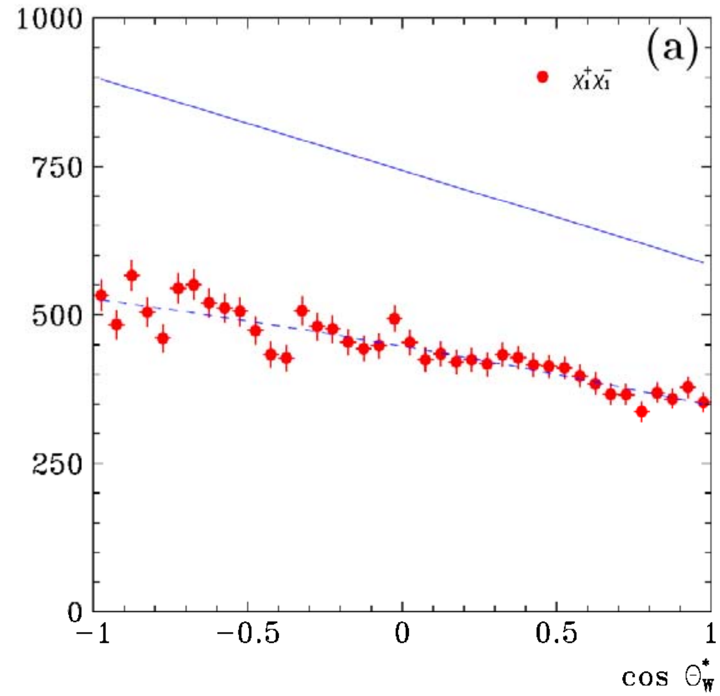
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_W^*} = \frac{1}{2}(1+\kappa_W\cos\theta_W^*)$$

$$E_W = \gamma(E_W^* + \beta p_W^*\cos\theta_W^*)$$

Experimental Simulation

$$\frac{d\sigma}{d\cos\theta_W^*} = 1 + \sum_{n=1}^{2J} a_n \cos n\theta_W^*$$

$$\underline{\text{exp}}: \quad a_1 = -0.203 \pm 0.020$$
$$a_2 = -0.001 \pm 0.020$$



Neutralinos

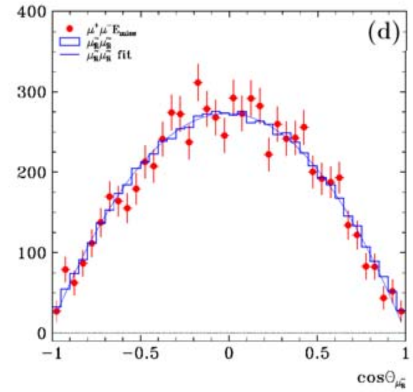
$\tilde{\chi}_2^0 \to Z\tilde{\chi}^0$ Majorana ⇔ flat angular distribution
⇔ Z-polarization analysis

$\tilde{\chi}_2^0 \to \tilde{\ell}_R^+ \ell^-$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\ell-}^*} = \frac{1}{2}(1 + \mathcal{P}_{\tilde{\chi}_2^0} \cos\theta_{\ell-}^*)$$

Summary

[Sleptons]
Angular distribution ~ $\sin^2 \theta$
in pair production in e^+e^- collisions:
unique signal for spin =0



[Charginos]
Threshold excitation ~ β
Flat angular distribution near threshold
Decay angular distribution: no cos n θ for n > 1

[Neutralinos]
Threshold excitation ~ β^3
Angular distribution ~ mixed cos/sin
Decays: Z-polarization analysis or lepton angles

ILC ⇔ powerful spin determination of SUSY particles