Supersymmetry Physics at Linear Colliders
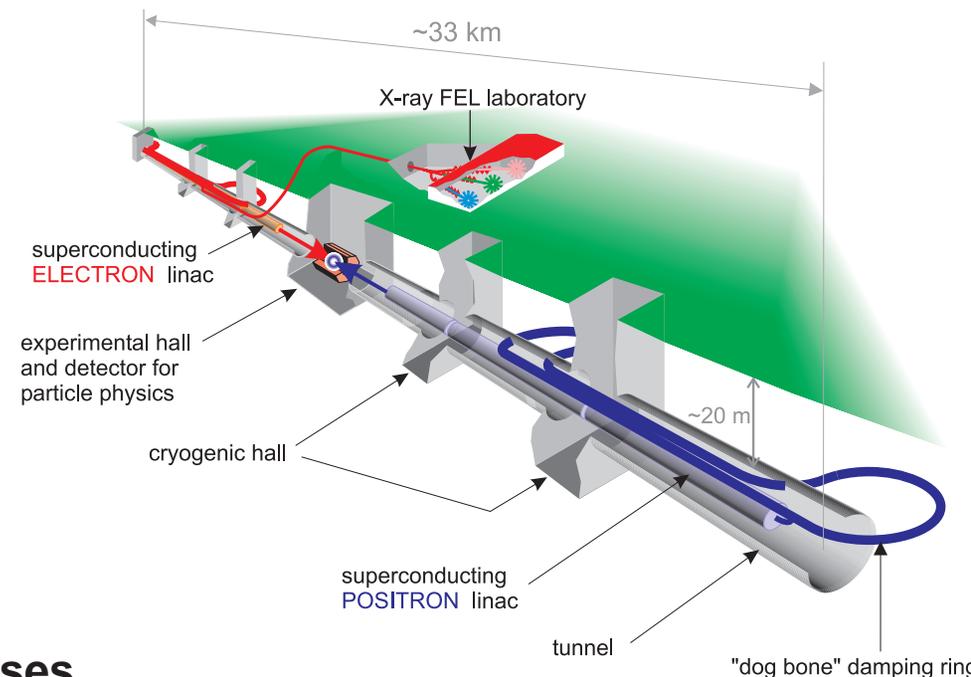
Hans-Ulrich Martyn   *RWTH Aachen*

Science (fiction?) in the year 201x

Supersymmetry will be discovered

★ **Physics programme of LC starts**

▷ **associate particle ⇔ superpartner**

– **spins differ by 1/2**

– **same gauge quantum numbers**

– **identical couplings**

▷ **precise measurements**

– **masses, widths, branching ratios**

– **cross sections, couplings**

– **production and decay properties**

– **mixing parameters, $\mathcal{CP}$ violating phases**

▷ **determine SUSY breaking mechanism**

– **reconstruction of fundamental theory**

– **extrapolation to high scales**

~33 km

X-ray FEL laboratory

superconducting ELECTRON linac

experimental hall and detector for particle physics

cryogenic hall

~20 m

superconducting POSITRON linac

tunnel

"dog bone" damping ring

Exploration of Supersymmetry

▷ **Tools**

    – **LC performance goals**

    – **Polarisation**

    – **Benchmarks**

▷ **Superpartner spectrum**

    – **Sleptons**

    – **Charginos & Neutralinos**

    – **Scalar top**

    – **Run scenarios**

▷ **SUSY scenarios**

    – **mSUGRA** R_p **conserving & violating**

    – **GMSB**

    – **AMSB**

SUSY Physics
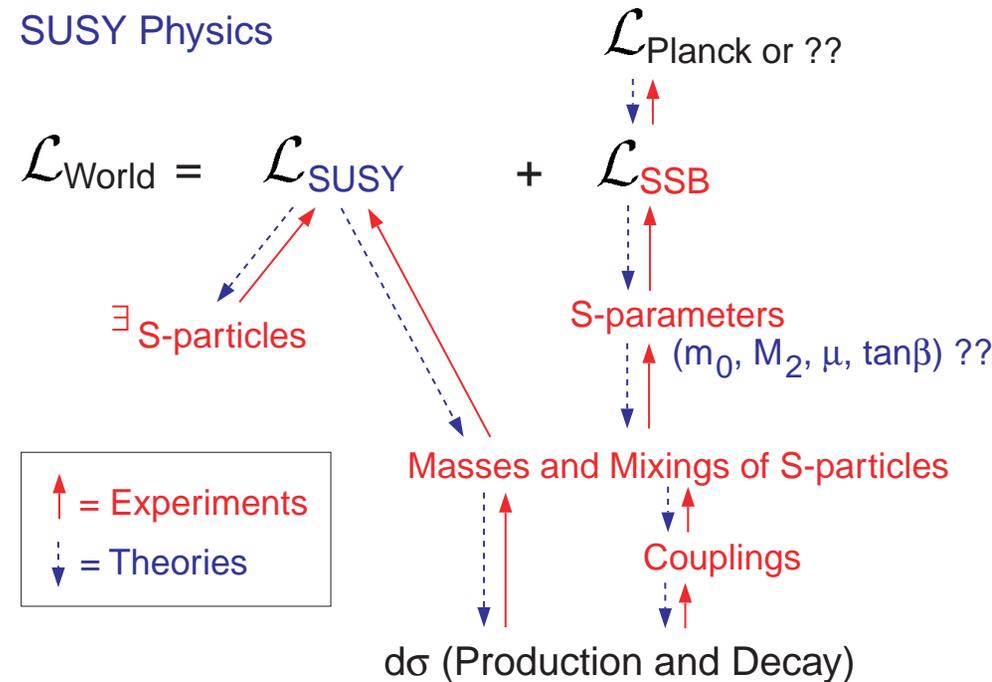
$$\mathcal{L}_{World} = \mathcal{L}_{SUSY} + \mathcal{L}_{SSB}$$

$\mathcal{L}_{Planck\ or\ ??}$

$\exists$ S-particles

S-parameters

$(m_0, M_2, \mu, \tan\beta)$??

↑ = Experiments	
↓ = Theories	

Masses and Mixings of S-particles

Couplings

dσ (Production and Decay)

LC Performance Goals

▷ **Collider requirements**

tunable energy

high luminosity

low beamstrahlung

polarised e^- and e^+ beams

parameter	TESLA		NLC/JLC		CLIC
cms energy [GeV]	500	800	500	1000	3000
accelerating gradient [MV/m]	23.4	35	48	48	150
luminosity L [10^{34}cm^{-2}s^{-1}]	3.4	5.8	2.0	3.4	10
$\mathcal{L}_{int}/10^7$s [fb^{-1}]	340	580	200	340	1000
beamstrahlung spread [%]	3.2	4.3	4.7	10.2	31
$\sigma_{\mu\mu}$ [fb]	1050		275		35
polarisation	$\mathcal{P}_{e^-}$ = 0.80		$\mathcal{P}_{e^+}$ = 0.60		
beam options	e^-e^-		$e^-\gamma$		$\gamma\gamma$

▷ **Detector requirements**

lepton & quark flavour ID

excellent energy resolution

hermeticity $\quad \cos\theta < 0.996$

e, γ **veto** $\quad \theta > 5$ **mrad**

$(e^+e^- \to e^+e^-\ \ell\ell/\pi\pi)$
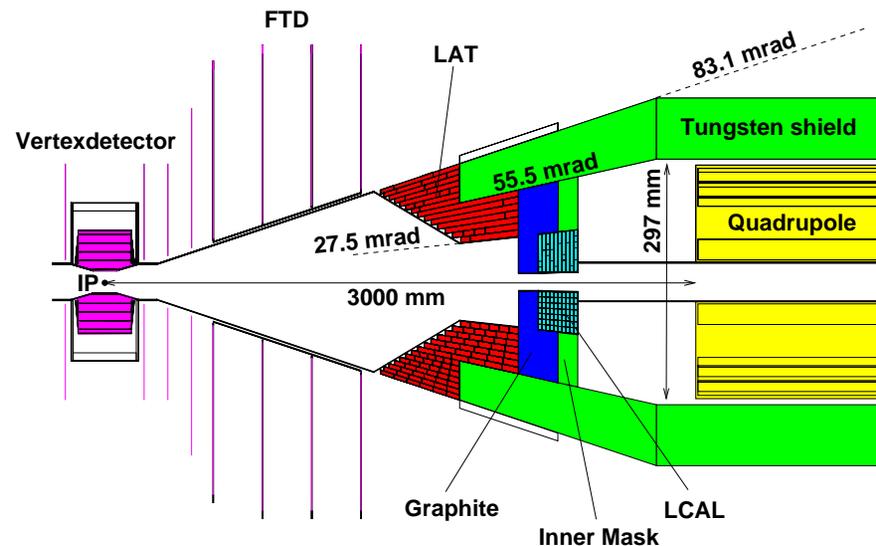
# Polarisation

- e^- **polarisation indispensible** $\qquad \mathcal{P}_{e^-} = 80\%$

  - **associate chiral couplings R, L to superpartners** $\quad e_R^- \to \tilde{f}_R$ **and** $e_L^- \to \tilde{f}_L$
    enhance signal $\qquad\qquad \sigma_R(\tilde{\mu}_R\tilde{\mu}_R) > \sigma_L(\tilde{\mu}_R\tilde{\mu}_R)$
    suppress background $\quad \sigma_R(WW) \ll \sigma_L(WW)$

  - **determine couplings, mixings, ...**

- e^+ **polarisation highly desirable** $\qquad \mathcal{P}_{e^+} = 60\%$

  - **further degree of freedom, gain in analysis power**

  - $e_L^- e_R^+,\; e_R^- e_L^+$ **increased event rate, higher sensitivity to rare** γ/Z **exchange processes**

  - $e_L^- e_L^+,\; e_R^- e_R^+$ **window to new physics of spin 0 particle exchange** $\qquad e^+e^- \to \tilde{e}_L\tilde{e}_R,\; \tilde{\nu}_\mu$
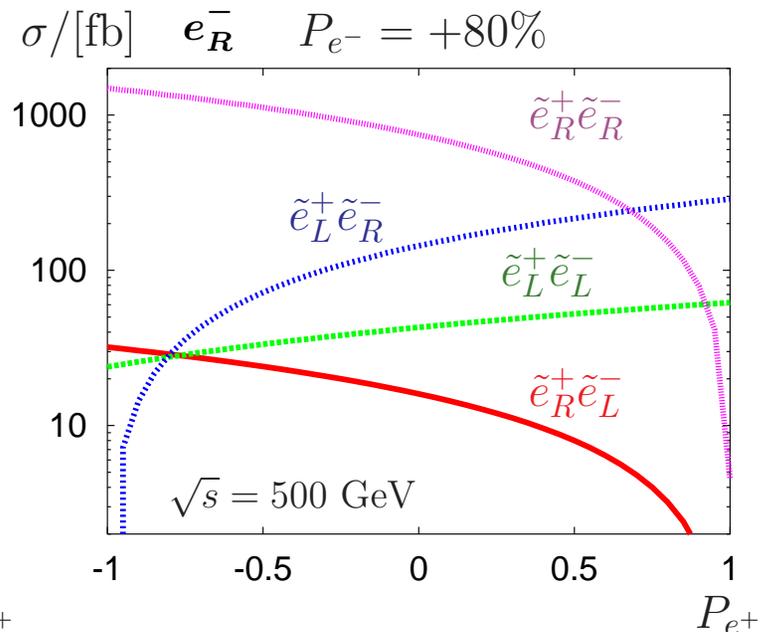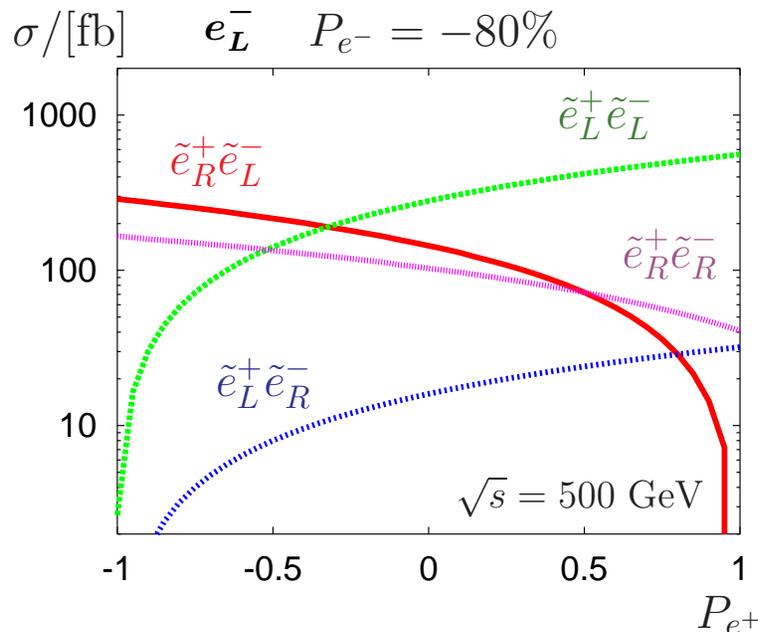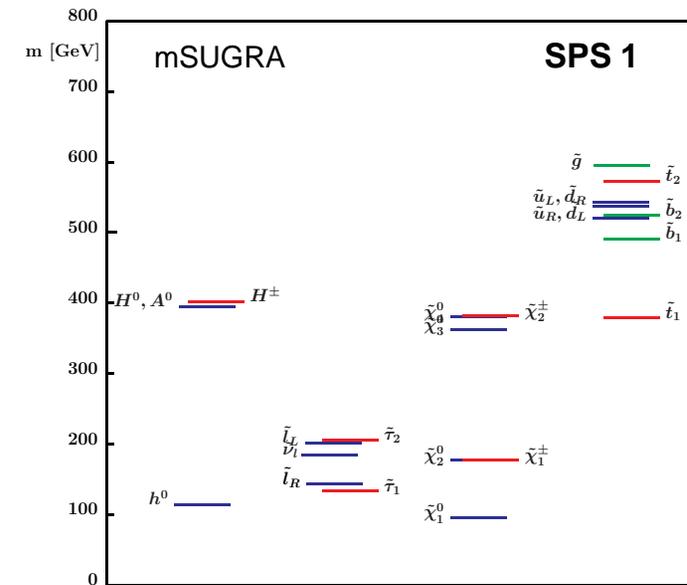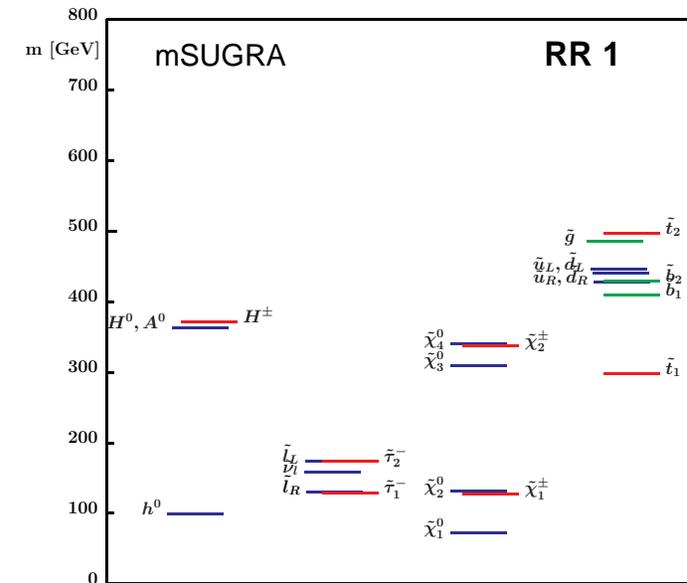
mSUGRA Benchmark Scenarios

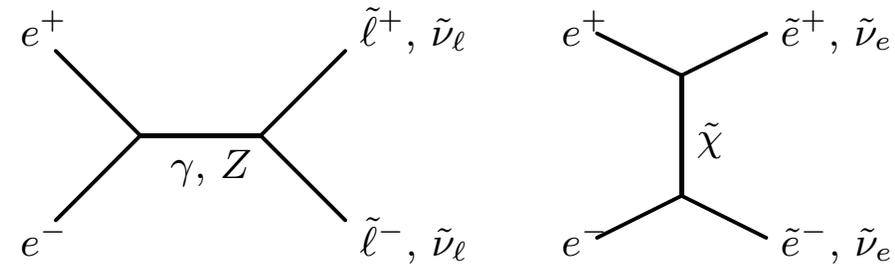**TESLA TDR   RR 1 & 2**

Snowmass consensus   SPS 1 – 9

|		mSUGRA	m_0	$m_{1/2}$	A_0	$\tan\beta$	μ
★	RR 1	typical point	100	200	0	3	+
★	RR 2	typical point	160	200	600	30	+
★	SPS 1	typical point	100	250	−100	10	+
	SPS 2	focus point	1450	300	0	10	+
	SPS 3	coannihilation	90	400	0	10	+
	SPS 4	large $\tan\beta$	400	300	0	50	+
	SPS 5	light stop	150	300	−1000	5	+
	SPS 6	non-unified M_i	150	300	0	10	+
		GMSB	Λ	M_{mess}	N_m	$\tan\beta$	μ
	SPS 7	NLSP = $\tilde{\tau}_1$	40,000	80,000	3	15	+
(★)	SPS 8	NLSP = $\tilde{\chi}_1^0$	100,000	200,000	1	15	+
		AMSB	m_0	$m_{3/2}$		$\tan\beta$	μ
(★)	SPS 9	small $\Delta m_{\tilde{\chi}_1}$	400	60,000		10	+

masses and scales in GeV

Scalar Leptons

$$e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$$
$$\rightarrow \tilde{\nu}_\ell\tilde{\nu}_\ell$$

$$\tilde{\ell}^- \rightarrow \ell^-\tilde{\chi}^0, \, \nu_\ell\tilde{\chi}^-$$
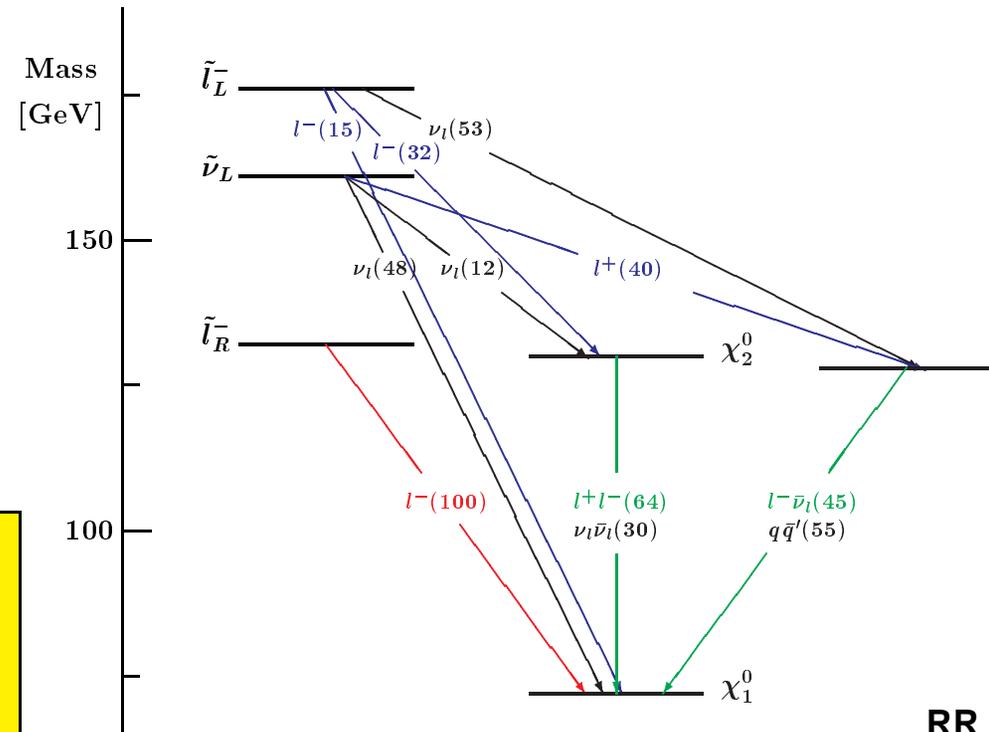$$\tilde{\nu}_\ell \rightarrow \nu_\ell\tilde{\chi}^0, \, \ell^-\tilde{\chi}^+$$

decay lepton energy spectrum
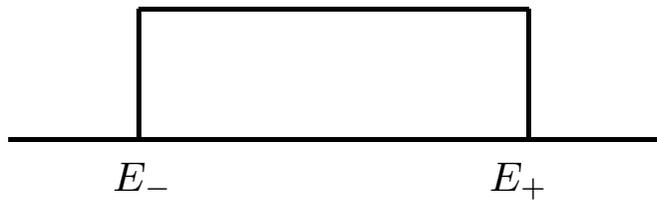
$$E_{+/-} = \frac{m_{\tilde{\ell}}}{2}\left(1 - \frac{m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}^2}\right)\gamma\,(1 \pm \beta)$$
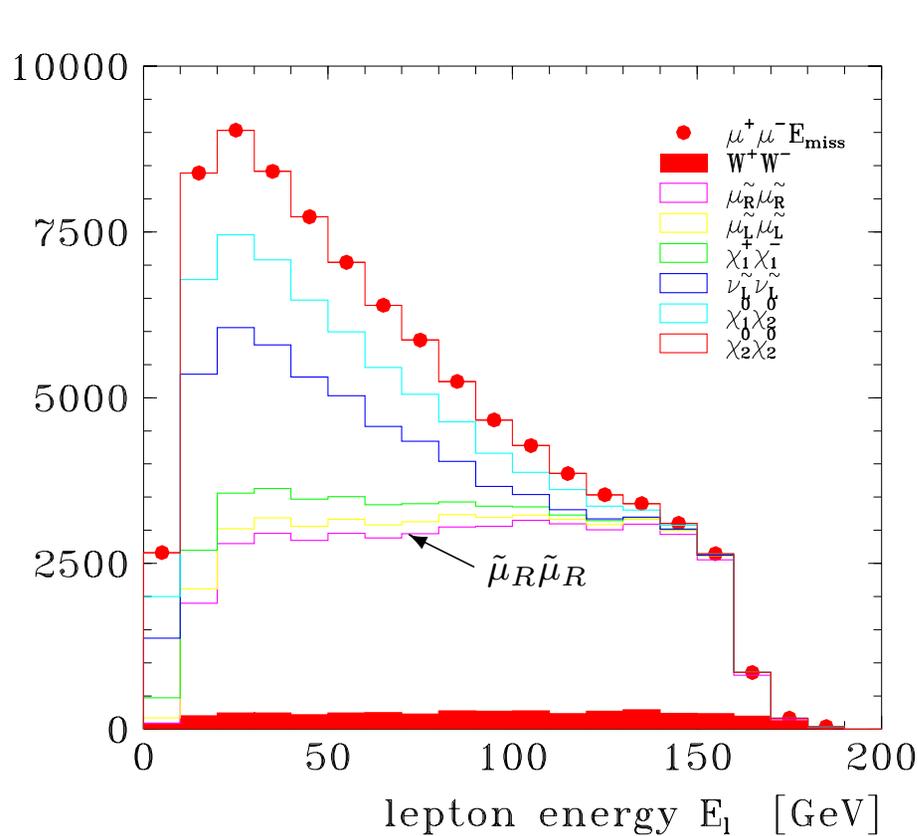
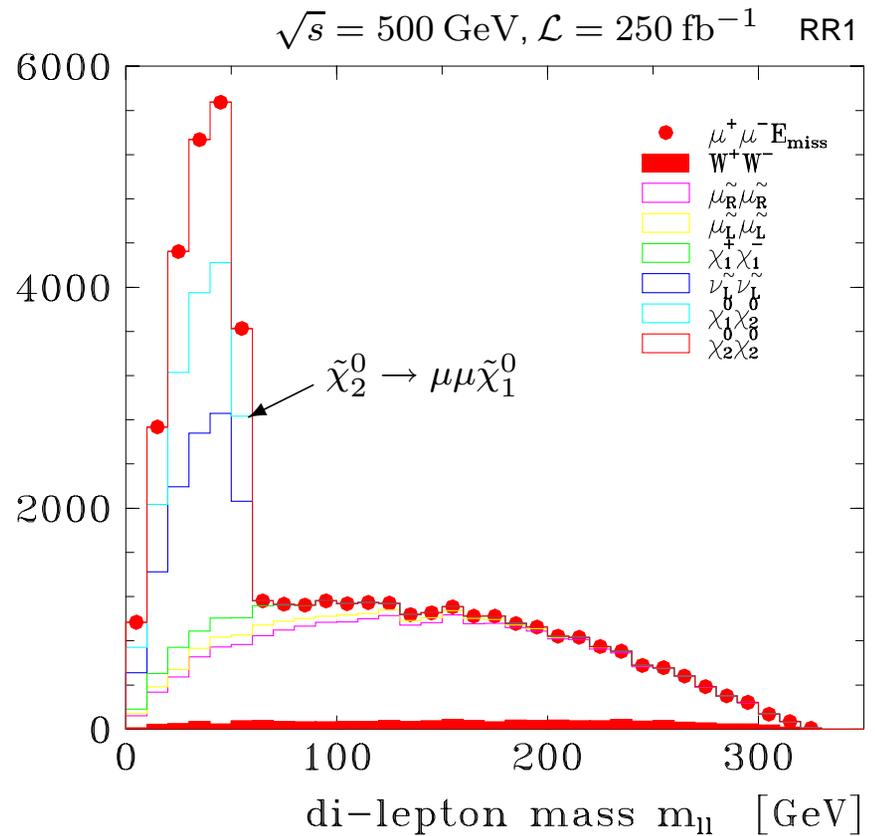| parameter	method
mass, width	$E_\ell, m_{min}(\tilde{\ell}), \sigma_{thr}$
spin	$d\sigma/d\cos\theta_{\tilde{\ell}}, \sigma_{thr} \propto \beta^3$
mixing, couplings	σ_{pol}

RR 1

Di-muon SUSY signatures

Search scalar muons $\qquad e^+e^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \chi_1^0 \, \mu^- \chi_1^0$

Signature $\qquad$ acoplanar $\mu^+\mu^-$ pair and large missing energy

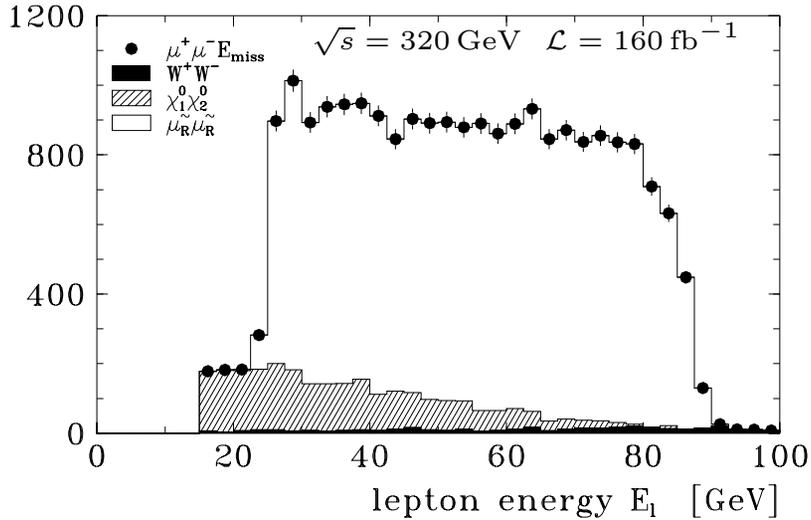$m_{\tilde{\mu}_R} = 132 \pm 5.5 \, \text{GeV} \quad m_{\tilde{\chi}_1^0} = 72 \pm 3 \, \text{GeV}$

$\Delta m_{\tilde{\chi}_2^0 - \tilde{\chi}_1^0} = 58.4 \pm 0.25 \, \text{GeV}$
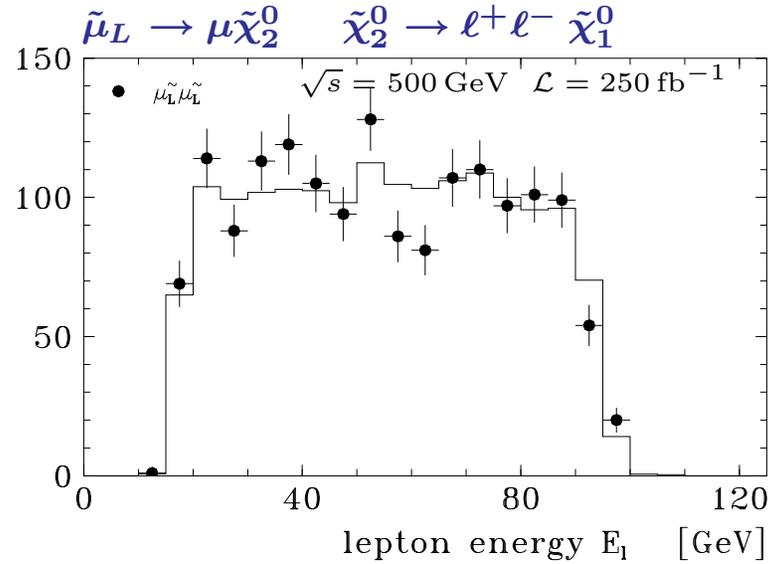
▷ **negligible SM background** $\qquad$ **SUSY is its own background**

▷ **important:** $\qquad$ **proper choice of energy AND polarisation**

Scalar Muon Properties

$$e_R^- e_L^+ \to \tilde{\mu}_R^- \tilde{\mu}_R^+ \to \mu^- \tilde{\chi}_1^0 \, \mu^+ \tilde{\chi}_1^0$$

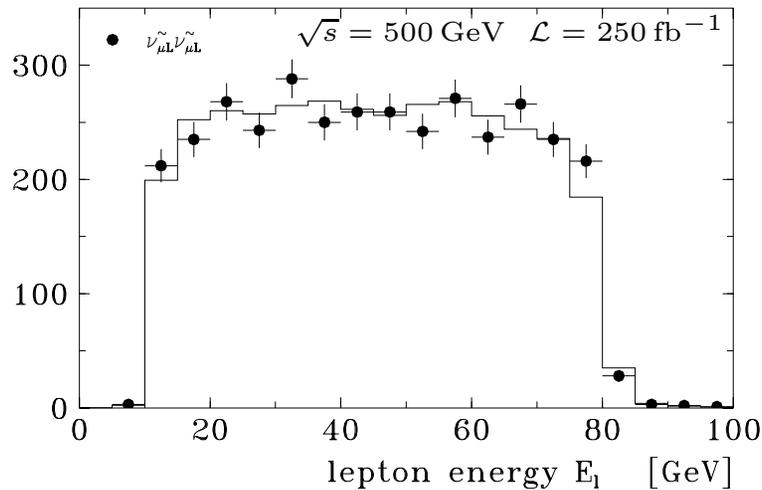$$e_L^- e_R^+ \to \tilde{\mu}_L^- \tilde{\mu}_L^+ \to \mu^- \mu^+ \, 4\,\ell^\pm$$

$$\tilde{\mu}_L \to \mu\tilde{\chi}_2^0 \qquad \tilde{\chi}_2^0 \to \ell^+\ell^- \, \tilde{\chi}_1^0$$

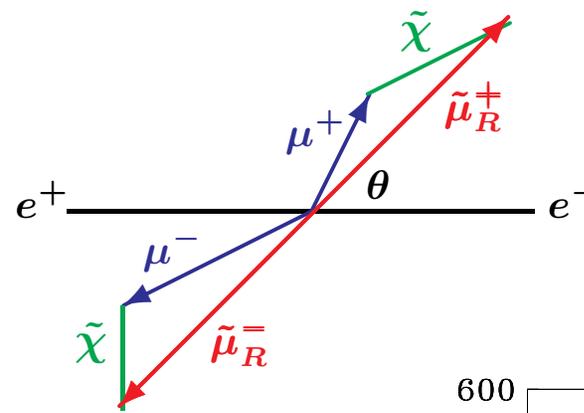$$e_L^- e_R^+ \to \tilde{\nu}_\mu \tilde{\nu}_\mu \to \mu^- \mu^+ \ell^\pm jj \,\&\, \mu^- \mu^+ \, 4\,j$$

$$\tilde{\nu}_\mu \to \mu^- \tilde{\chi}_1^+ \qquad \tilde{\chi}_1^\pm \to \ell^\pm \nu_\ell \, \tilde{\chi}_1^0,\ q\bar{q}' \, \tilde{\chi}_1^0$$

$\tilde{\ell}$	m [GeV]	$\tilde{\chi}$	m [GeV]
$\tilde{\mu}_R$	132.0 ± 0.3	$\tilde{\chi}_1^0$	71.9 ± 0.2
$\tilde{\mu}_L$	176.0 ± 0.3	$\tilde{\chi}_2^0$	130.5 ± 0.2
$\tilde{\nu}_\mu$	160.6 ± 0.2	$\tilde{\chi}_1^\pm$	126.8 ± 0.2

Much higher statistics in $\tilde{e}$, $\tilde{\nu}_e$ sector!
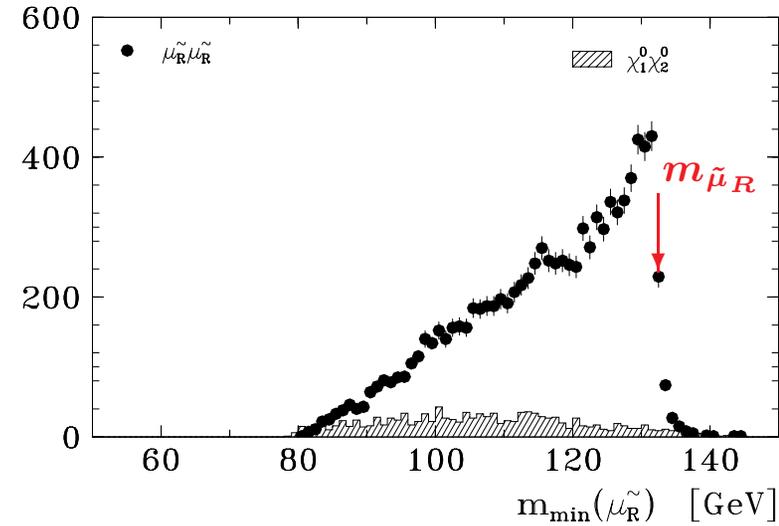
Typical gain of factor 2 in resolution

minimum mass $m_{min}(\tilde{\mu}_R)$

$m_{\tilde{\chi}}$ **known**   **construct minimum kinematically allowed mass** $m_{min}(\tilde{\mu}_R)$
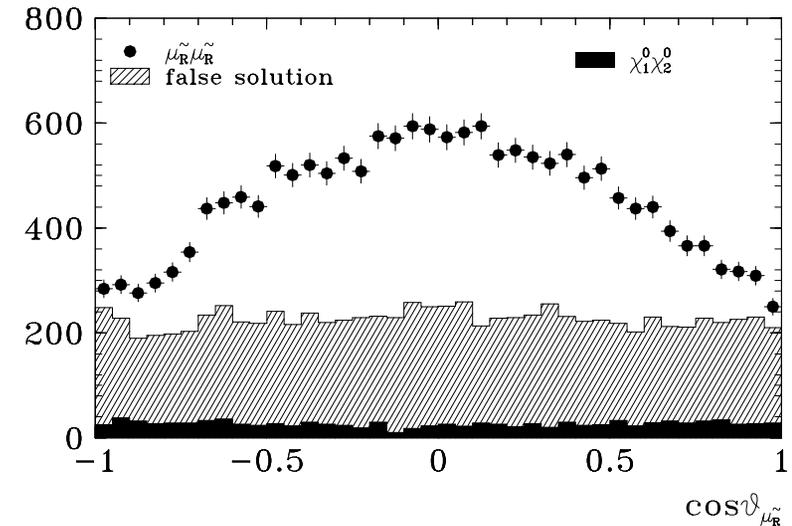**flat background**

$\Rightarrow$ **improved resolution** $\delta m_{\tilde{\mu}_R}$ **by factor 2**

Spin $J = 0$ **of** $\tilde{\mu}_R$

$m_{\tilde{\mu}_R}$ **and** $m_{\tilde{\chi}}$ **known**   **construct** $\tilde{\mu}_R$ **direction with twofold ambiguity**
flat background

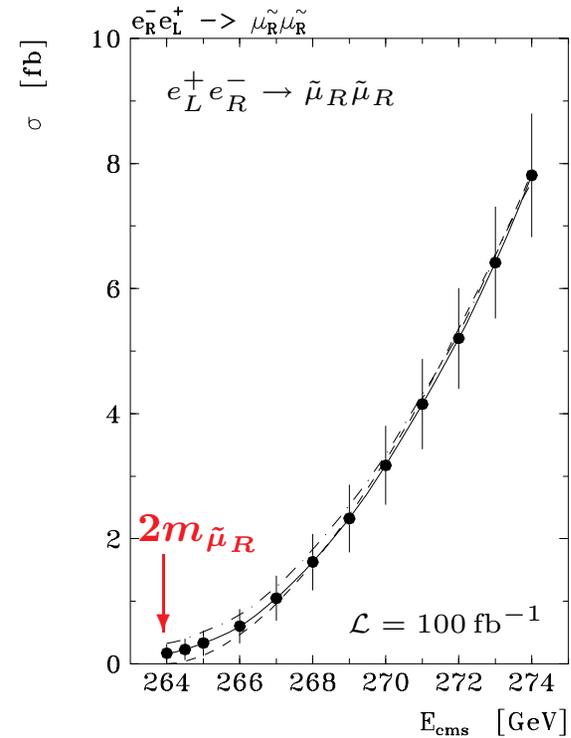$\Rightarrow \mathrm{d}\sigma/\mathrm{d}\cos\theta_{\tilde{\mu}_R} \propto \sin^2\theta_{\tilde{\mu}_R}$

$m_{\tilde{\mu}_R}$ **from threshold scan** $\sigma_{\tilde{\mu}\tilde{\mu}} \propto \beta^3$

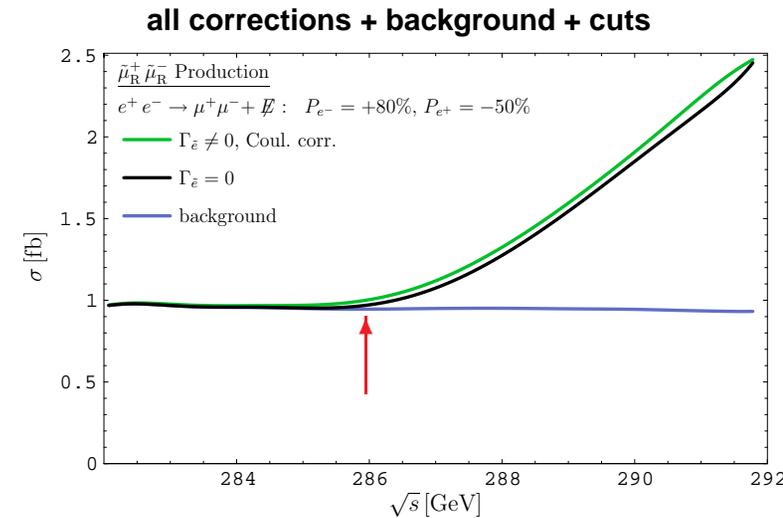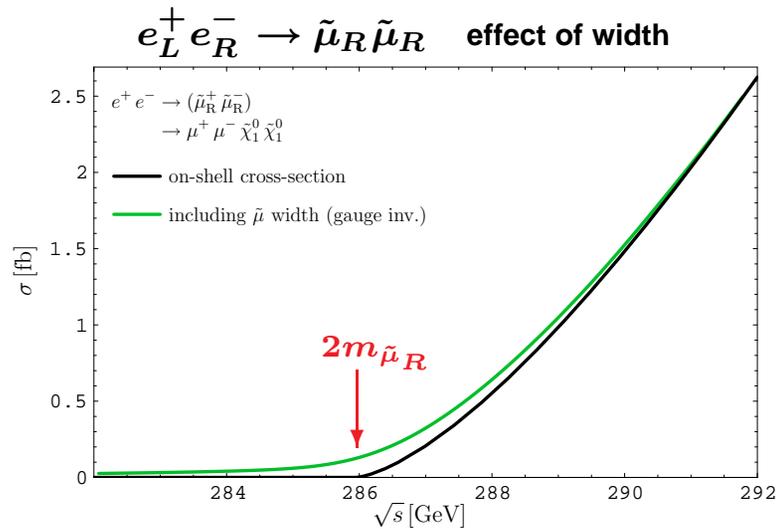**width effects non-negligible**

consistency test spin $J = 0$

$m_{\tilde{\mu}_R} \, [\text{GeV}]$	$\Gamma_{\tilde{\mu}_R} \, [\text{GeV}]$
132.0 ± 0.08	fixed
$132.0 \, {}^{+0.17}_{-0.13}$	$0.31 \, {}^{+0.56}_{-0.23}$

$$\beta = \sqrt{1 - m_{\tilde{\mu}}^2}$$

Important:

gauge invariant treatment of signal & background cross section calculation

$e_L^+ e_R^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R$ **effect of width**

all corrections + background + cuts

Selectron Properties
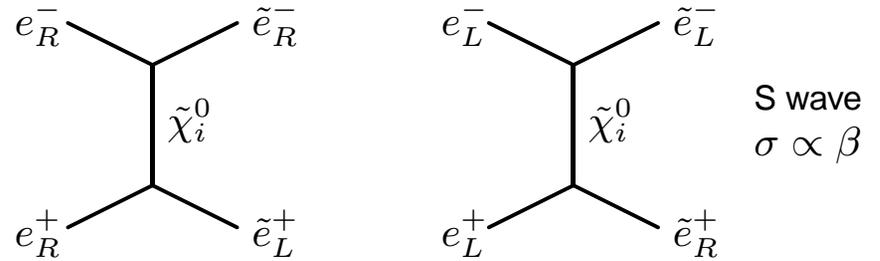
Association $e_R \to \tilde{e}_R$ and $e_L \to \tilde{e}_L$
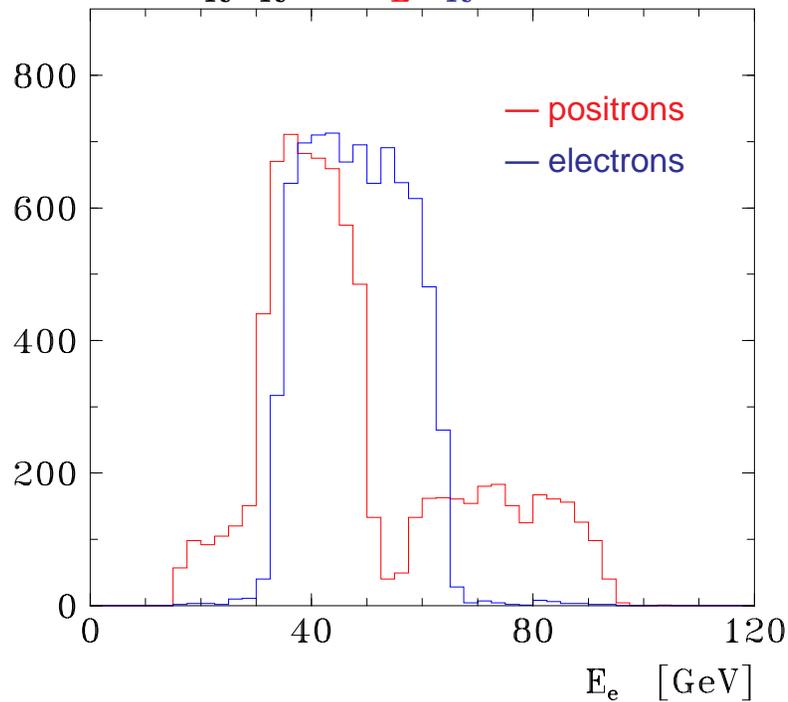
$$e^+ e^- \to \tilde{e}_R \tilde{e}_L$$

t channel $\tilde{\chi}$ exchange
'chirality' flow at $e\tilde{e}\tilde{\chi}$ vertex

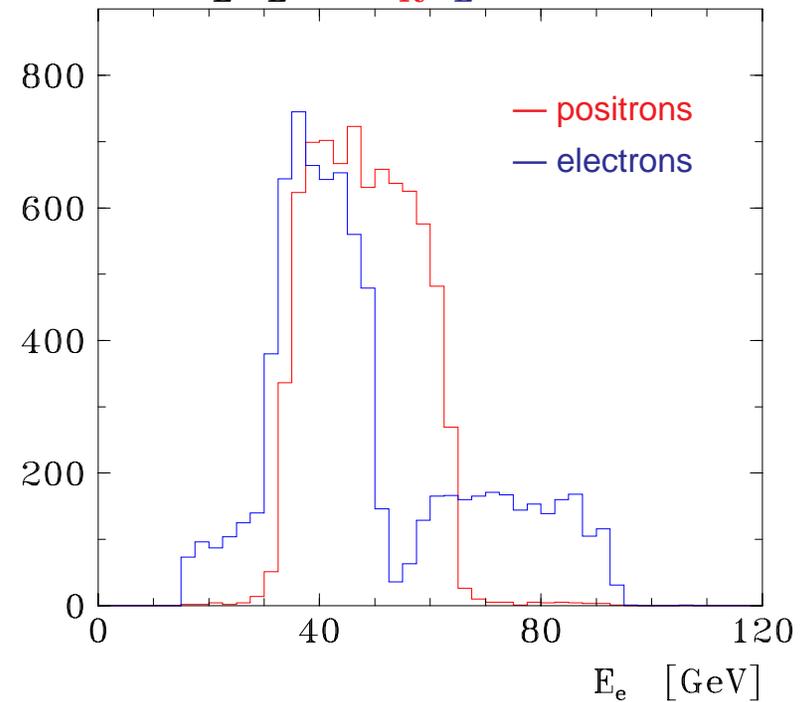$\Rightarrow$ **tag $\tilde{e}_R$, $\tilde{e}_L$ via charge of decay electron**

S wave
$\sigma \propto \beta$

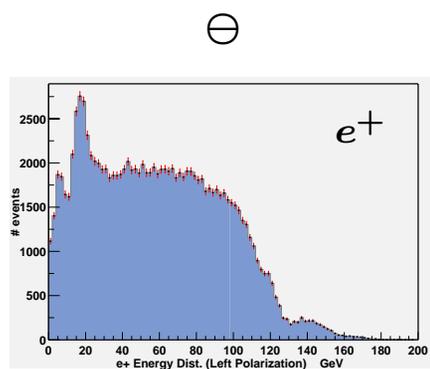charge symmetric $\tilde{e}_R^+ \tilde{e}_R^-$, $\tilde{e}_L^+ \tilde{e}_L^-$ and background reactions

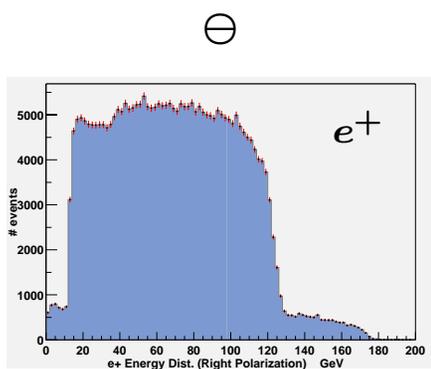$$e^+e^- \rightarrow \tilde{e}_R\tilde{e}_L \rightarrow e^+e^- + E_{miss}$$

$$e^+e^- \rightarrow \tilde{e}_R\tilde{e}_R,\ \tilde{e}_R\tilde{e}_L,\ \tilde{e}_L\tilde{e}_L \qquad \text{simultaneous production at } \sqrt{s} = 500 \text{ GeV}$$

eliminate background: subtraction of e^-/e^+ spectra with different polarisations $\mathcal{P}_{e^-}$

$$
\begin{aligned}
\tilde{e}_R(143) &\rightarrow & e\,\tilde{\chi}_1^0(96) & \quad \textbf{flat spectrum} \\
\tilde{e}_L(202) &\rightarrow & e\,\tilde{\chi}_1^0(96) & \quad \textbf{flat spectrum} \\
&\rightarrow & \nu\,\tilde{\chi}_1^-(176) & \quad \textbf{soft spectrum}
\end{aligned}
$$

$$\mathcal{P}_{e^-} = +0.8 \qquad\qquad \mathcal{P}_{e^-} = -0.8$$
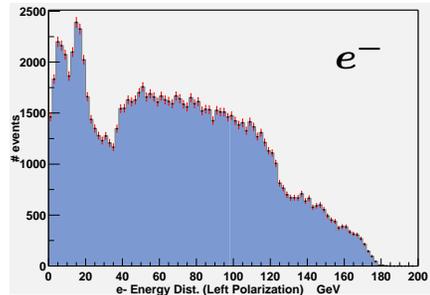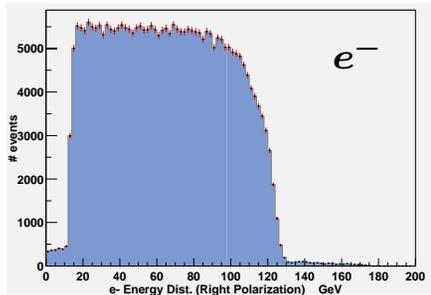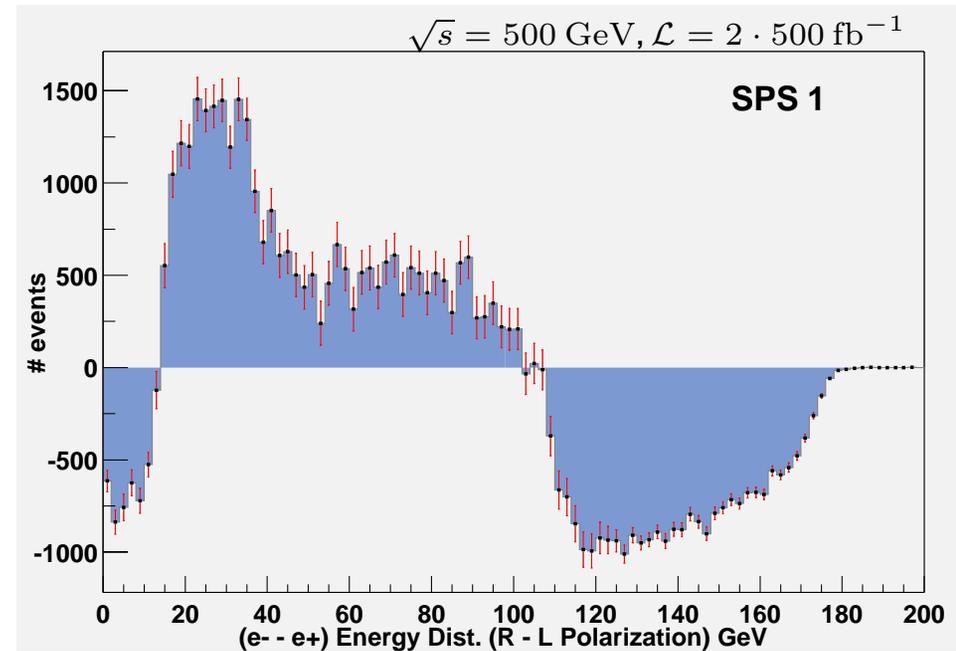
$$\delta m_{\tilde{e}} \sim \mathcal{O}(0.2 - 0.5 \text{ GeV})$$

e^-e^- **Collisions**

$$e^-e^- \to \tilde{e}^-\tilde{e}^- \text{ vs } e^+e^- \to \tilde{e}^+\tilde{e}^-$$

$$e^-e^- \to \tilde{e}_R^-\tilde{e}_R^-,\ \tilde{e}_L^-\tilde{e}_L^-$$

large cross section

low background

steep rise $\quad \sigma_{\tilde{e}^-\tilde{e}^-} \propto \beta$

consistency test spin $J = 0$
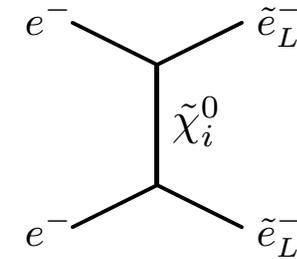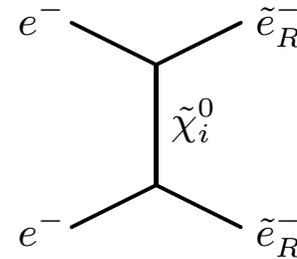
but $\quad L_{e^-e^-} \simeq 0.15 \cdot L_{e^+e^-}$
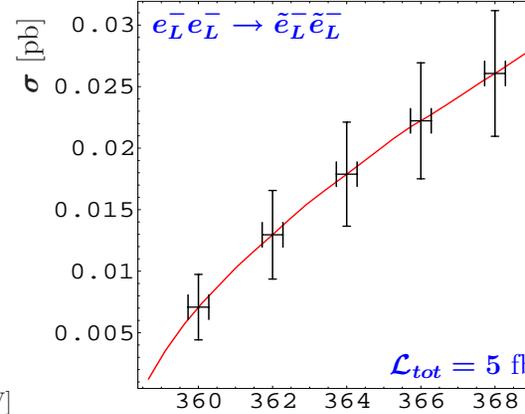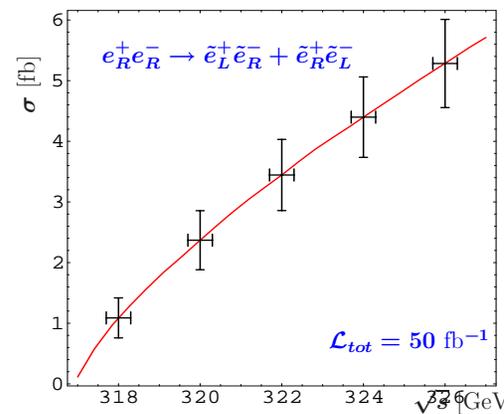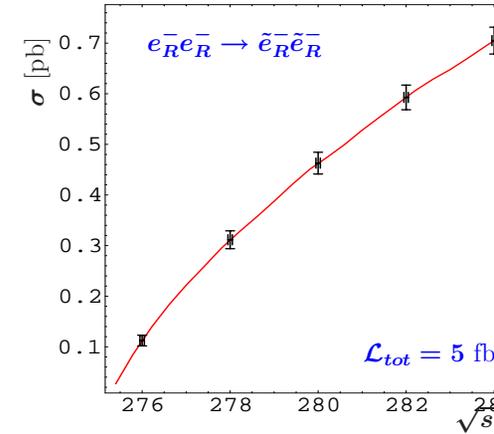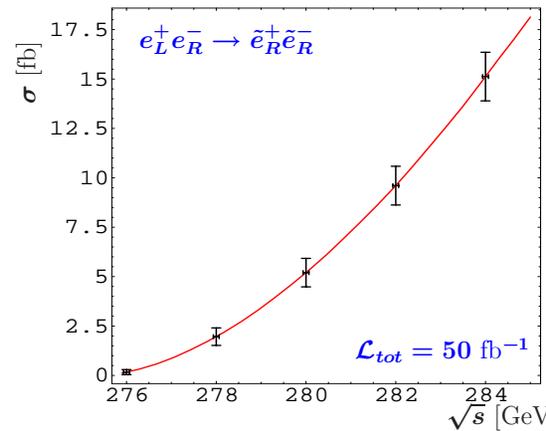
	$\mathcal{L} = 50\,\text{fb}^{-1}$	$\mathcal{L} = 5\,\text{fb}^{-1}$
	$m_{\tilde{e}}^{(e^+e^-)}$ [GeV]	$m_{\tilde{e}}^{(e^-e^-)}$ [GeV]
$\tilde{e}_R$	137.7 ± 0.07	137.7 ± 0.05
$\tilde{e}_L$	179.3 ± 0.30	179.3 ± 0.28

S wave
$\sigma \propto \beta$

e-Sneutrino Production

$$e_R^+ e_L^- \rightarrow \tilde{\nu}_e \tilde{\nu}_e \rightarrow e^+ e^- \, \ell^\pm jj \,\&\, e^+ e^- \, 4\,j$$

$$\tilde{\nu}_e \rightarrow e^- \tilde{\chi}_1^+ \qquad \tilde{\chi}_1^\pm \rightarrow \ell^\pm \nu_\ell \, \tilde{\chi}_1^0, \, q\bar{q}' \, \tilde{\chi}_1^0$$

di-jet mass $\qquad m_{jj} \leq \Delta m_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0}$

$m_{\tilde{\nu}_e}$	160.6 ± 0.1 GeV
$m_{\tilde{\chi}_1^\pm}$	126.8 ± 0.1 GeV
$\Delta m_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0}$	55.8 ± 0.05 GeV
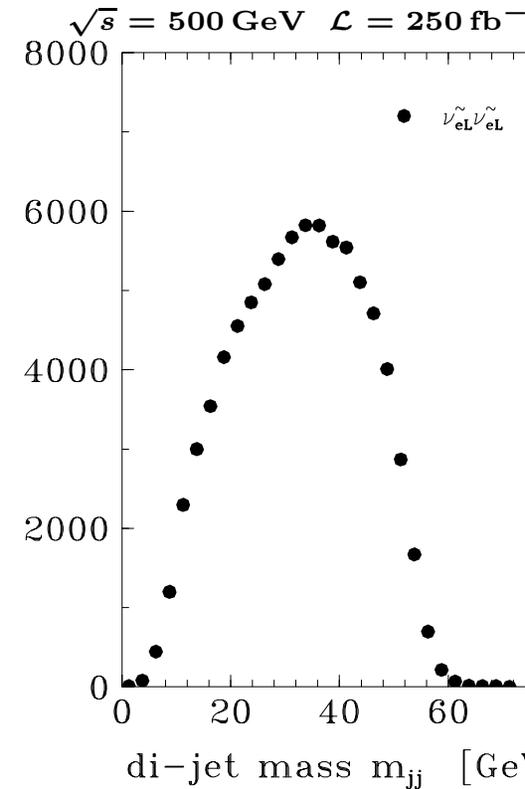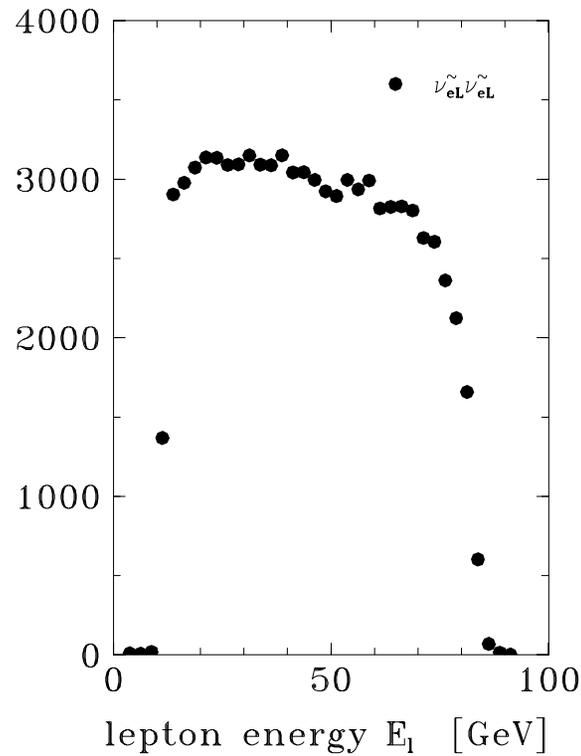
Scalar Tau Properties

$L - R$ **mixing in third generation** $\quad \sim \tan\beta$

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{\tau}} & \sin\theta_{\tilde{\tau}} \\ -\sin\theta_{\tilde{\tau}} & \cos\theta_{\tilde{\tau}} \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}$$

production $\quad e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$

$\qquad\qquad \sigma_L,\, \sigma_R \to m_{\tilde{\tau}_1},\, \theta_{\tilde{\tau}}$

decay $\qquad \tilde{\tau}_1^- \to \tau^-\tilde{\chi}_1^0$

τ **polarisation** $\quad \mathcal{P}_\tau \to \theta_{\tilde{\tau}},\, \tilde{\chi}^0$ **mixing,** $g_{\tilde{V}\tilde{\tau}\tau}$
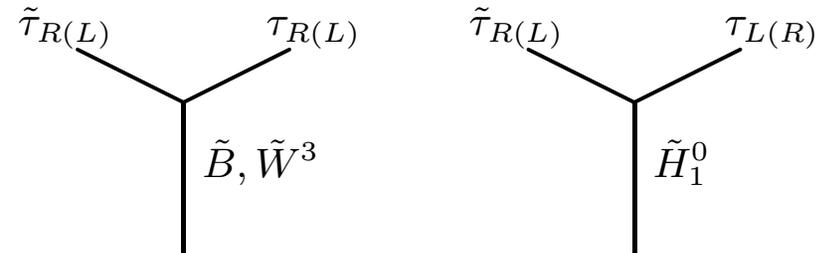
$m_{\tilde{\tau}_1}$ **mass from** τ **decays**

$\tau^- \to \ell^-\nu_\ell\nu_\tau,\, \rho^-\nu_\tau,\, \pi\nu_\tau,\, \dots$
$\qquad\qquad \hookrightarrow \pi^-\pi^0$

$m_{\tilde{\tau}_1} = 150 \pm 1.2\,\text{GeV}$

$m_{\tilde{\chi}_1^0}$ **known**

using $m_{\tilde{\tau}}$ **and** $\sigma \quad \Rightarrow \delta\sin\theta_{\tilde{\tau}} \sim 6.5\%$

analyser $\quad \tau^- \to \rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$

energy sharing between π^-/π^0

$$Z_\pi = E_{\pi^-}/E_\rho$$

$\quad \Rightarrow$ **sensitive to** $\mathcal{P}_\tau$

$\sqrt{s} = 500 \text{ GeV} \quad \mathcal{L} = 200 \text{ fb}^{-1}$

a) τ_R

$\tilde{\tau}^- \dashrightarrow \begin{array}{c} \tau_R^- \\ \tilde{\chi}_1^0 \cong \tilde{B} \end{array}$

Fit
$P_\tau = +1.00 \pm 0.07$

SM BG

$Z_{\pi^\pm} = E_{\pi^\pm}/E_\rho$

b) τ_L

$\tilde{\tau}^- \dashrightarrow \begin{array}{c} \tau_L^- \\ \tilde{\chi}_1^0 \cong \tilde{H}_1^0 \end{array}$

Fit
$P_\tau = -0.99 \pm 0.08$

SM BG

$Z_{\pi^\pm} = E_{\pi^\pm}/E_\rho$

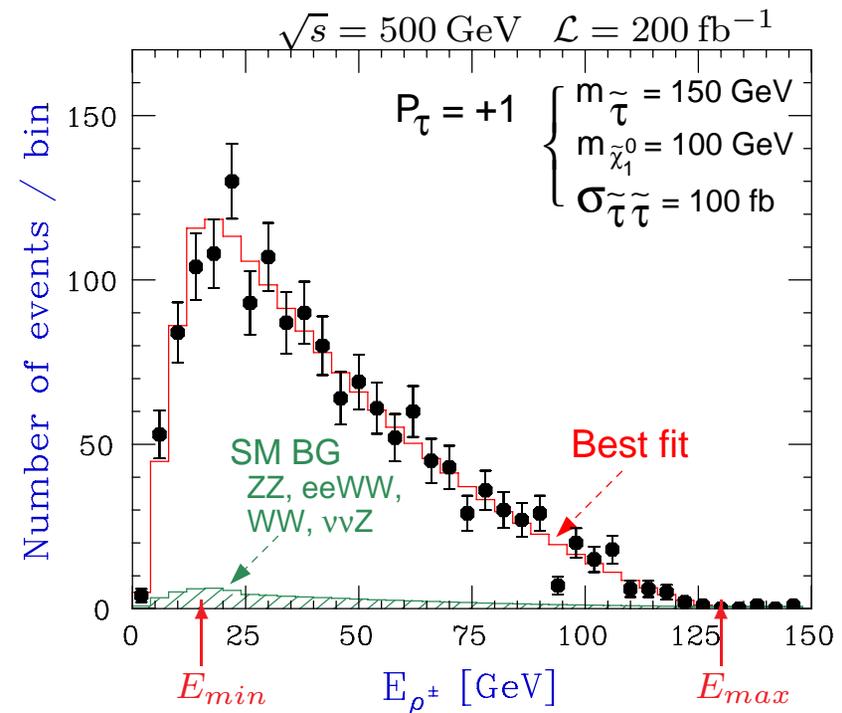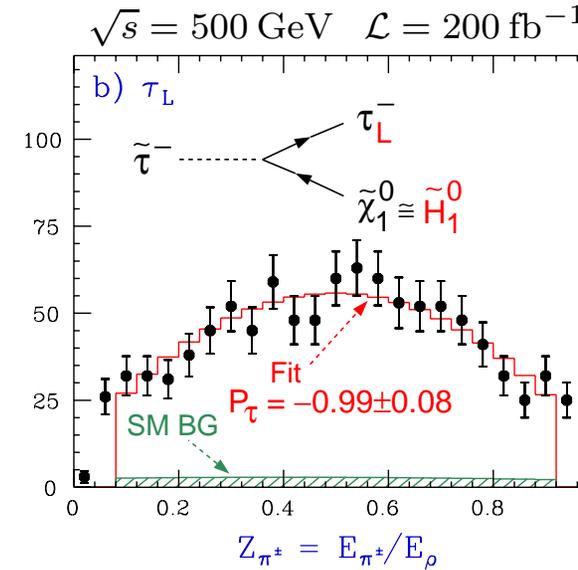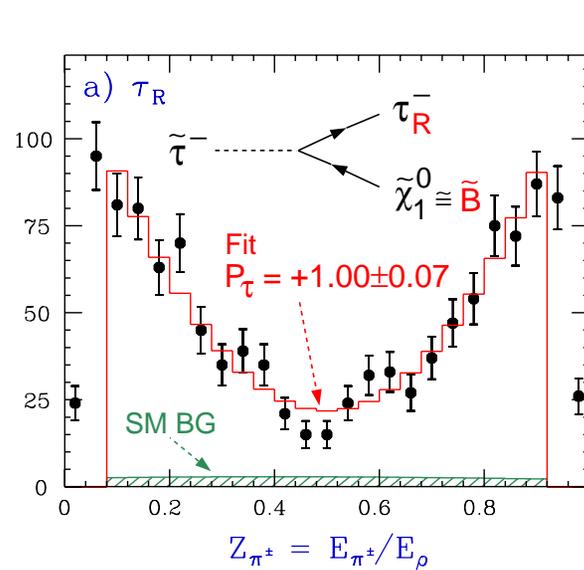## $\mathcal{P}_\tau - \tan\beta$ correlation

simplified case study
no mixing $\quad \tilde{\tau}_1 = \tilde{\tau}_R$
combined slepton sector

$$e^+ e^- \to \tilde{\tau}_1^+ \tilde{\tau}_1^-$$
$$e^+ e^- \to \tilde{e}_R^+ \tilde{e}_R^-$$

$\boxed{\tan\beta = 15 \pm 1.6 \quad M_1 = 150 \text{ GeV}}$

$\sqrt{s} = 500 \text{ GeV} \quad \mathcal{L} = 100 \text{ fb}^{-1}$

$m_{\tilde{\chi}_1^0} = 100\text{GeV}, \ m_{\tilde{e}_R} = 200\text{GeV}, \ m_{\tilde{\tau}_R} = 150\text{GeV}$
$\sqrt{s} = 500\text{GeV} \ \int L dt = 100\text{fb}^{-1}$

$\mu = 154.2\text{GeV}$

-0.4

0

$\mu = 135.2\text{GeV}$

$\mu = 118.5$
GeV

$\mu = 156.2$
GeV

0.4

$P_\tau = 0.8$

$\mu = 173.7\text{GeV}$

$\tan\beta$

$M_1 [\text{GeV}]$
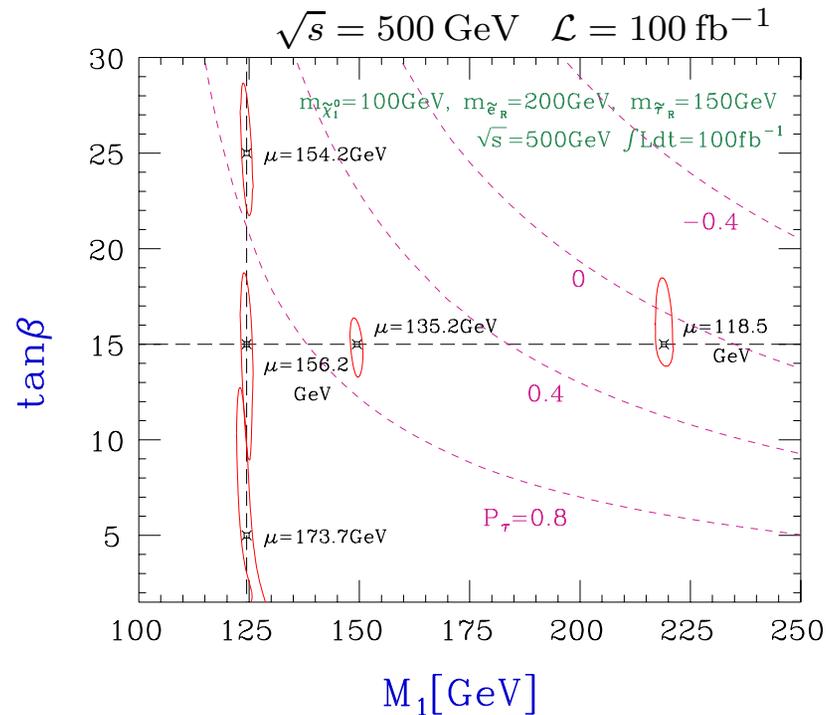
$m_{\tilde{\tau}_1} = 150 \text{ GeV}$

$m_{\tilde{\chi}_1^0} = 100 \text{ GeV}$

$m_{\tilde{e}_R} = 200 \text{ GeV}$

$$\tilde{\chi}_1^0 = \text{pure Bino}$$

$\mathcal{P}_\tau$ vs $\tilde{\tau}$ mixing

general MSSM

$$\sin 2\,\theta_{\tilde\tau} = \frac{(A_\tau - \mu\,\tan\beta)\,2\,m_\tau}{m_{\tilde\tau_1}^2 - m_{\tilde\tau_2}^2}$$

τ Polarization in $\tilde\tau_{1,2}$ decays

Polarization

$P_{\tilde\tau_1}$

$x_W = 1$

$\omega_h = 0$

$P_{\tilde\tau_2}$

$\xi = \tan 2\Theta$
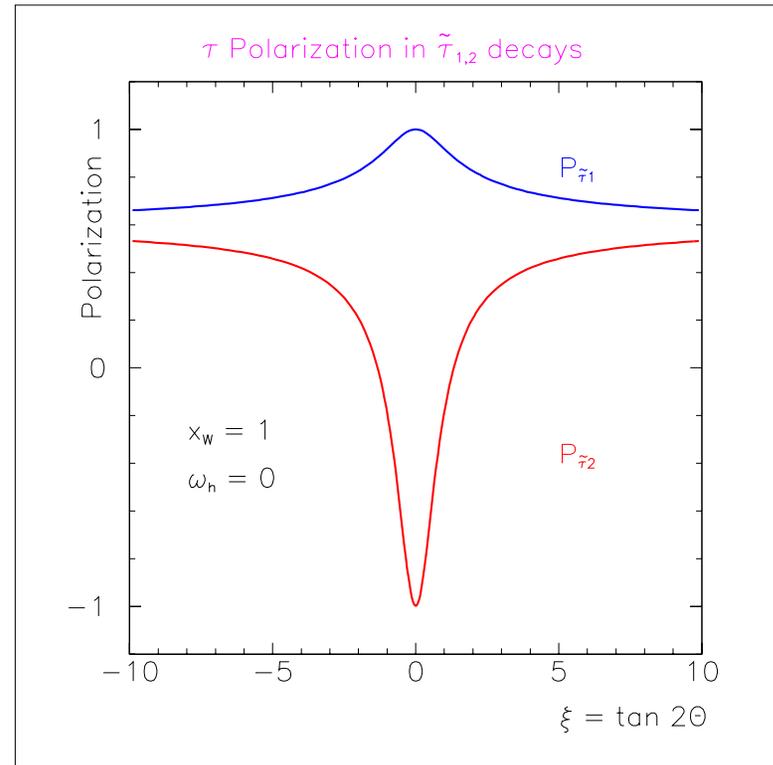
Testing SUSY Relations in Slepton Sector

- **Achievable precisions for sleptons**

generation	$\delta m/m$	couplings	
$\tilde{e}_R,\ \tilde{e}_L,\ \tilde{\nu}_e$	$0.05 - 0.1\ \%$	$\delta\hat{g}'_{\tilde{B}e\tilde{e}} \sim 0.25\ \%$	$\delta\hat{g}_{\tilde{W}e\tilde{e}} \sim 1\ \%$
$\tilde{\mu}_R,\ \tilde{\mu}_L,\ \tilde{\nu}_\mu$	$0.1 - 0.5\ \%$	$\delta\bar{g}'_{B\tilde{\mu}\tilde{\mu}} \sim 1\%$	
$\tilde{\tau}_1,\ \tilde{\tau}_2,\ \tilde{\nu}_\tau$	$0.5 - 2\ \%$	$\delta\hat{g}'_{\tilde{B}\tau\tilde{\tau}} \sim 2\ \%$	

▷ **Check universality, flavour dependence of slepton masses at per mil level**

▷ **Superpartners $\tilde{\nu}_R$ of right-handed neutrinos?**

$$2\,(m^2_{\tilde{\nu}_R} - m^2_{\tilde{\nu}_\tau}) \;\approx\; m^2_{\tilde{e}_R} - m^2_{\tilde{\tau}_1} \qquad \text{(up to higher orders)}$$

To become observable, present data require 2.5% mass resolutions

▷ **Determination of $\tan\beta$**

- 1st **generation** $\qquad \tan\beta = 3.0 \pm 0.1 \rightarrow 10 \pm 5$

$$m^2_{\tilde{\ell}_L} - m^2_{\tilde{\nu}_\ell} \;=\; -M^2_W \cos 2\beta$$

- $\tilde{\tau}$ **sector** $\qquad \tan\beta = 30 \pm 0.3$

$$\mu\,\tan\beta \;=\; A_\tau - \frac{(m^2_{\tilde{\tau}_1} - m^2_{\tilde{\tau}_2})\,\sin 2\,\theta_{\tilde{\tau}}}{2\,m_\tau}$$

Charginos & Neutralinos

$$e^+e^- \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^- \quad [i,j = 1,2]$$
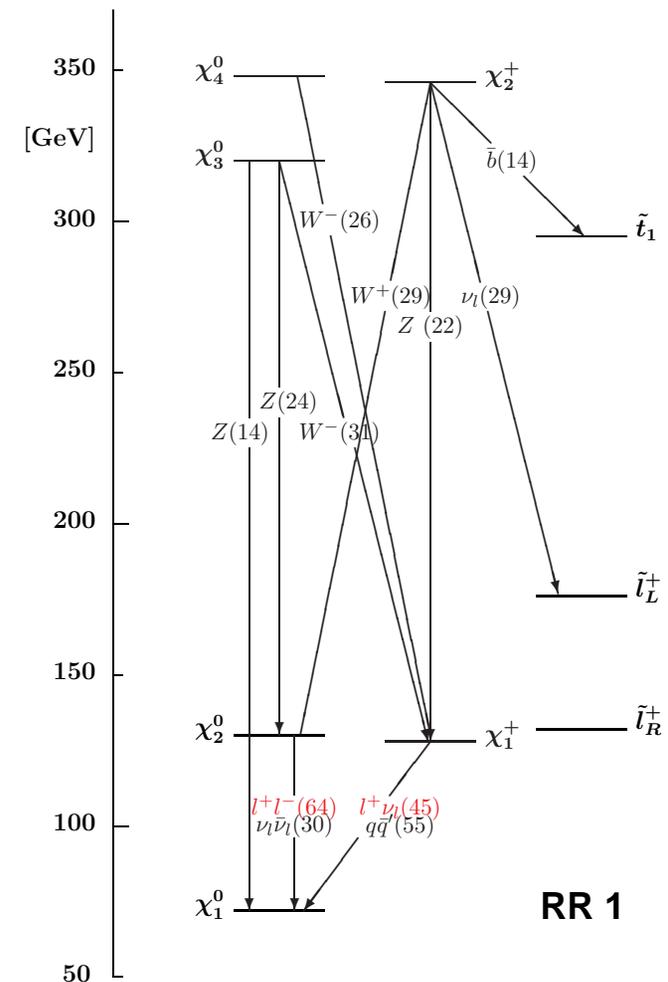$$\rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0 \quad [i,j = 1,4]$$

$$\tilde{\chi}_i \rightarrow Z/W\, \tilde{\chi}_j,\, h\, \tilde{\chi}_j$$
$$\tilde{\chi}_1^+ \rightarrow \ell^+ \tilde{\nu}_\ell\, \tilde{\chi}_1^0,\, q\bar{q}'\, \tilde{\chi}_1^0$$
$$\rightarrow \tilde{\ell}^+ \nu_\ell \rightarrow \ell^+ \nu_\ell\, \tilde{\chi}_1^0$$
$$\tilde{\chi}_2^0 \rightarrow \ell\ell\, \tilde{\chi}_1^0,\, q\bar{q}\, \tilde{\chi}_1^0$$
$$\rightarrow \tilde{\ell}\ell \rightarrow \ell\ell\, \tilde{\chi}_1^0$$
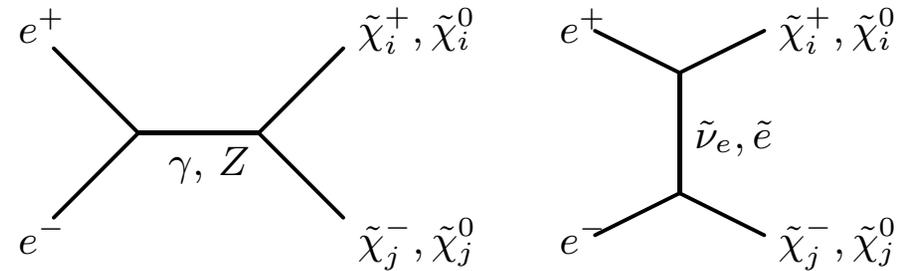
parameter	method
mass, width	$E_{\ell\ell},\, E_{jj},\, \sigma_{thr}$
mass differences	$m_{\ell\ell},\, m_{jj}$
spin	$d\sigma/d\cos\theta_{\tilde{\chi}},\, \sigma_{thr} \propto \beta$
mixing, couplings	σ_{pol}, spin correlations

Chargino Properties

$$e_R^+ e_L^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \ell^\pm \, 2\, jets$$

$\tilde{\chi}_1^\pm \to \ell^\pm \nu_\ell \, \tilde{\chi}_1^0$ $\tilde{\chi}_1^\pm \to q\bar{q}' \, \tilde{\chi}_1^0$

$m_{\tilde{\chi}^\pm}$ **from threshold scan** $\sigma_{\tilde{\chi}\tilde{\chi}} \propto \beta$

consistency test spin $J = 1/2$

di-jet energy $E_{jj} \to m_{\tilde{\chi}_1^\pm}, \, m_{\tilde{\chi}_1^0}$

di-jet mass $m_{jj} \leq \Delta m_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0}$

$m_{\tilde{\chi}_1^\pm}$ 127.7 ± 0.2 GeV
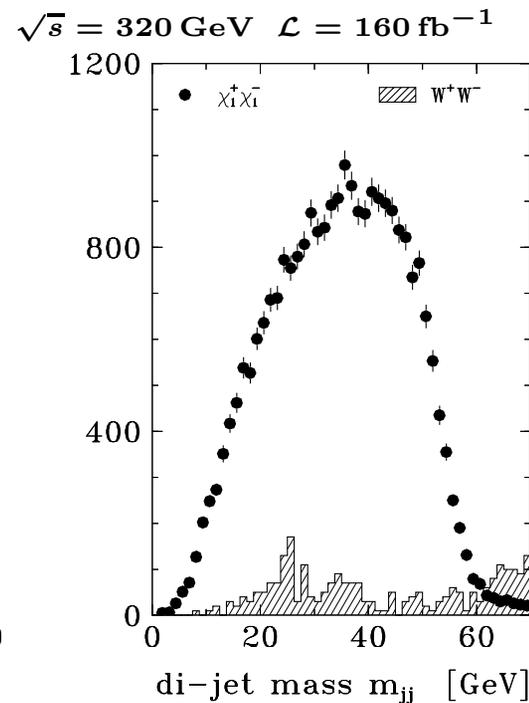$\Delta m_{\tilde{\chi}_1^\pm - \tilde{\chi}_1^0}$ 55.8 ± 0.15 GeV

$m_{\tilde{\chi}_1^\pm}$ 127.7 ± 0.04 GeV
$m_{\tilde{\chi}_2^\pm}$ 345.8 ± 0.25 GeV

$\sqrt{s} = 320$ GeV $\mathcal{L} = 160$ fb^{-1}

$e_R^+ e_L^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

$2m_{\tilde{\chi}_1^\pm}$

$\mathcal{L} = 100$ fb^{-1}
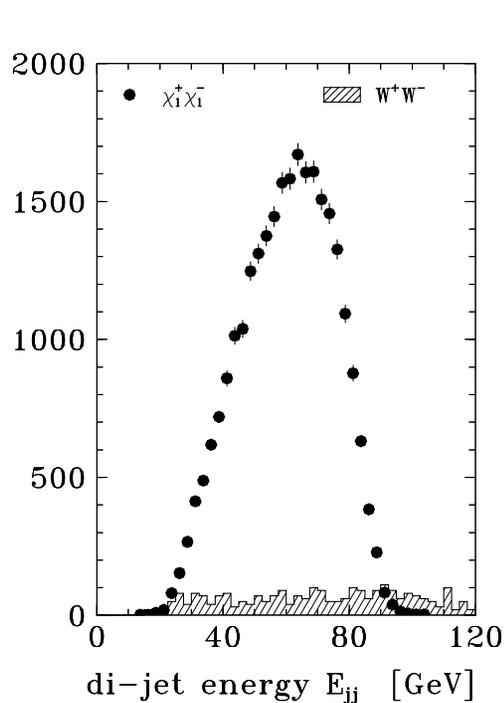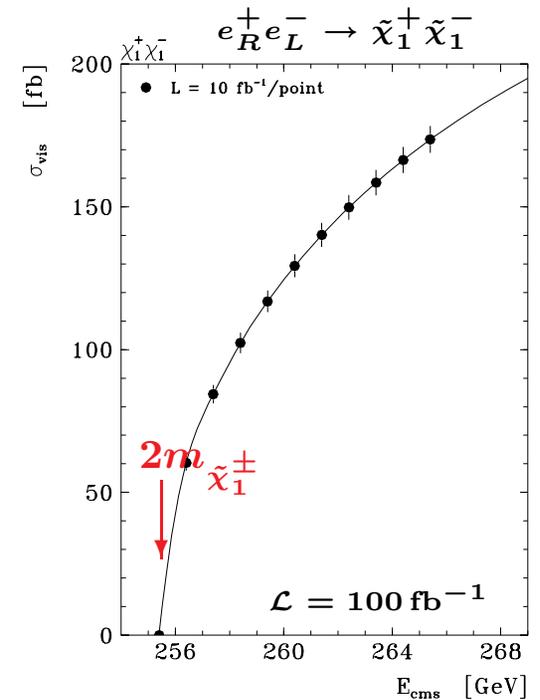
$m_{\tilde{\nu}_e}$ **dependence of** $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$

$\tilde{\nu}_e$ **exchange in** t **channel**

$$\tilde{\chi}_1^\pm \rightarrow e^\pm \nu_e \, \tilde{\chi}_1^0$$

▷ **polaristion dependent cross section**

▷ **spin correlations**

$\Rightarrow$ **asymmetry in** e^+ **decay distribution**   **resolves ambiguity**
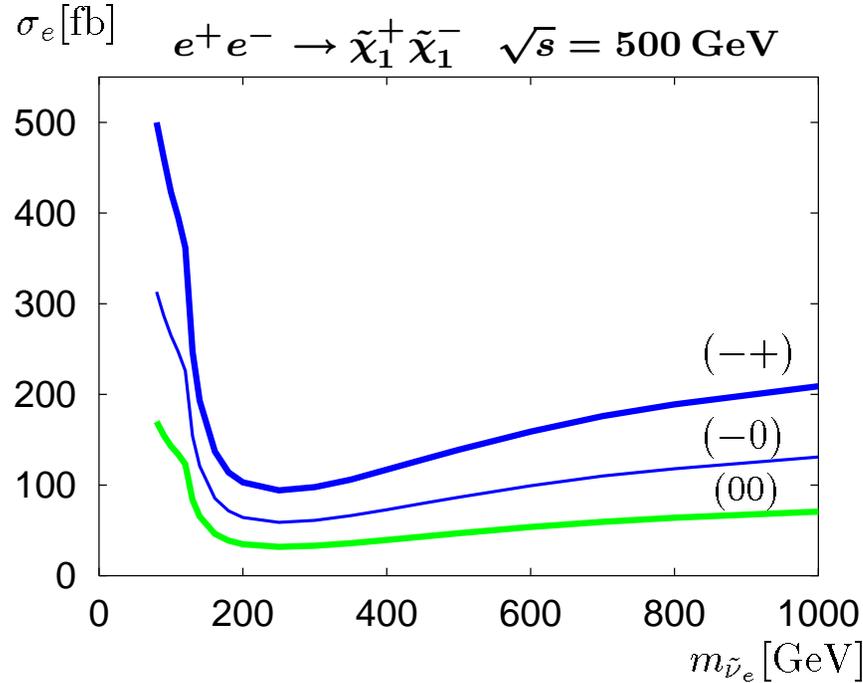
$$\boxed{\delta m_{\tilde{\nu}_e} \sim 10\,\mathrm{GeV} \text{ up to } 1\,\mathrm{TeV}}$$
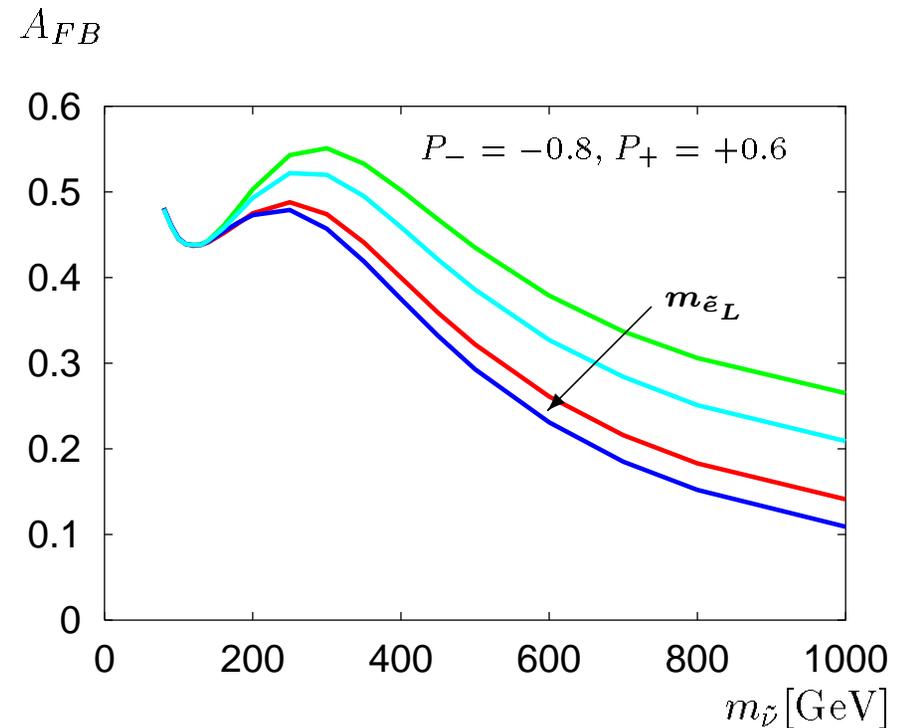
Neutralino Properties

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow 4\,\ell^{\pm}\,\tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\,\tilde{\chi}_1^0 \quad (\ell = \mu,\, e)$$

di-lepton energy $\quad E_{\ell\ell} \rightarrow m_{\tilde{\chi}_2^0},\, m_{\tilde{\chi}_1^0}$

di-lepton mass $\quad m_{\ell\ell} \leq \Delta m_{\tilde{\chi}_2^0 - \tilde{\chi}_1^0}$

$m_{\tilde{\chi}^0}$ **from threshold scan** $\qquad \sigma_{\tilde{\chi}\tilde{\chi}} \propto \beta$

consistency test spin $J = 1/2$

$m_{\tilde{\chi}_2^0}$	130.3 ± 0.3 GeV
$\Delta m_{\tilde{\chi}_2^0 - \tilde{\chi}_1^0}$	58.6 ± 0.15 GeV

$m_{\tilde{\chi}_2^0}$	130.3 ± 0.07 GeV
$m_{\tilde{\chi}_3^0}$	319.8 ± 0.30 GeV
$m_{\tilde{\chi}_4^0}$	348.2 ± 0.52 GeV

$\sqrt{s} = 320\,\mathrm{GeV} \quad \mathcal{L} = 160\,\mathrm{fb}^{-1}$

$e_R^+ e_L^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$

$2m_{\tilde{\chi}_2^0}$

$\mathcal{L} = 100\,\mathrm{fb}^{-1}$

di-lepton mass m_{ll} [GeV]

di-lepton energy E_{ll} [GeV]
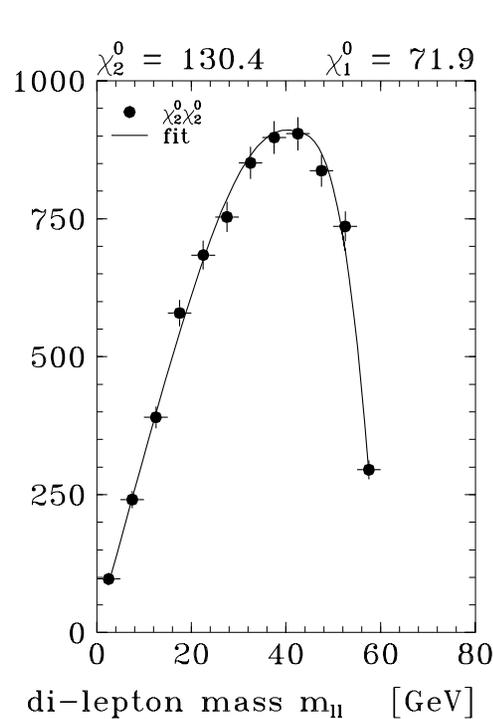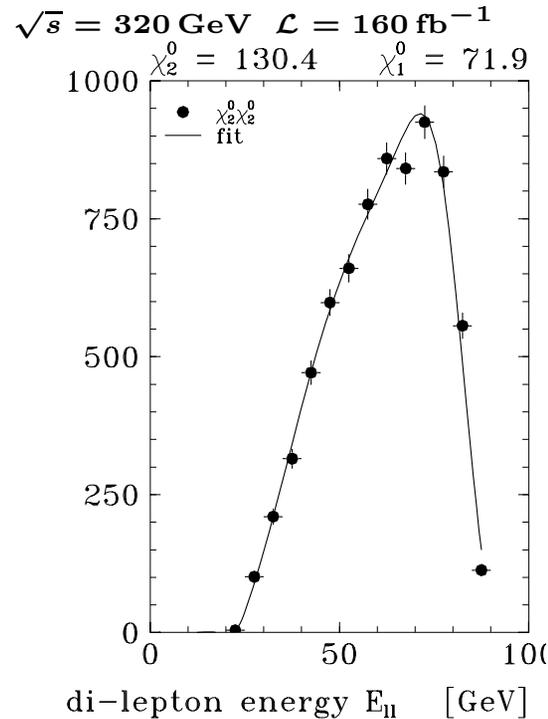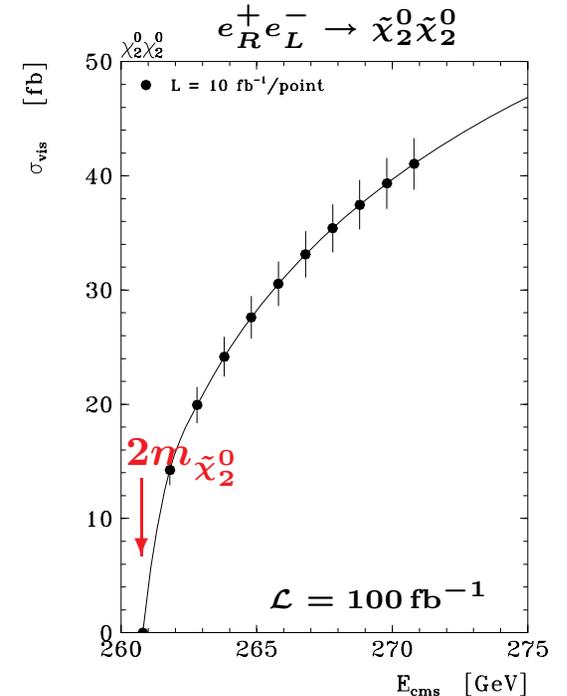
$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

Production and decay depend on gaugino parameter M_1

▷ **sensitivity to polarised cross sections**

▷ **spin correlations** ⇒ **asymmetry in e^+ decay distribution of $\tilde{\chi}_2^0 \to e^+e^- \tilde{\chi}_1^0$**

▷ **Polarisation resolves ambiguity!**
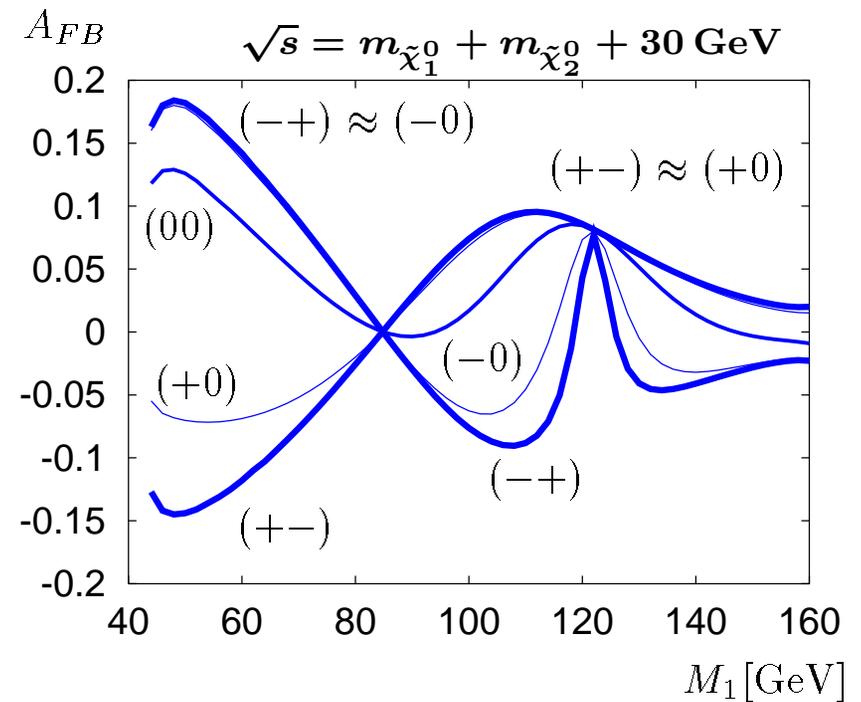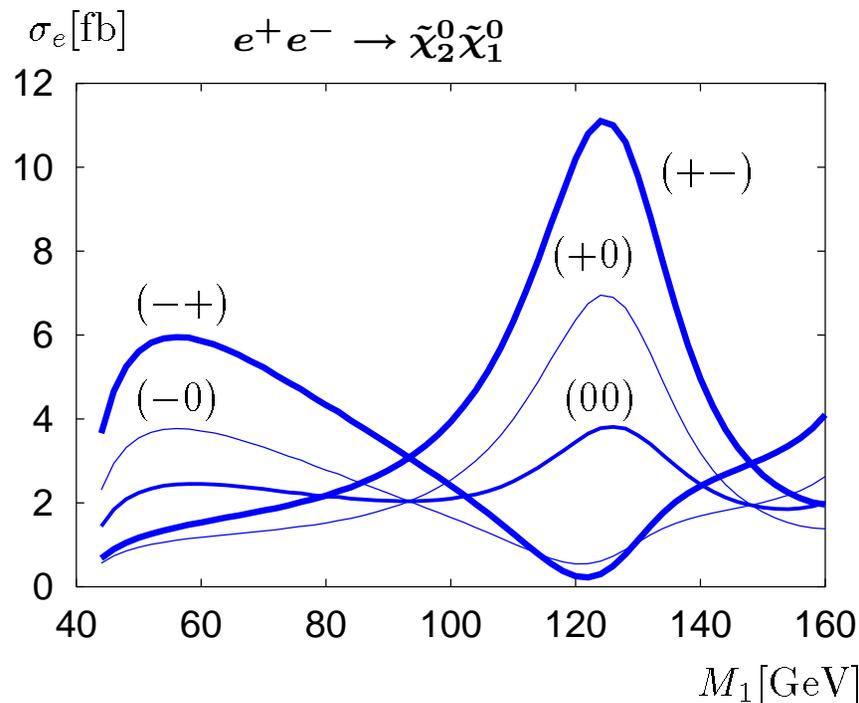
▷ $\mathcal{CP}$ **sensitive observable** $\qquad \cos\psi = \vec{p}_{beam} \cdot (\vec{p}_{e^+} \times \vec{p}_{e^-})$

expected $\mathcal{CP}$ asymmetry $\qquad \mathcal{O}(0.1 - 1.5\,\%)$ **challenge to experiment!**

Chargino & Neutralino Systems

- **Achievable precisions for charginos & neutralinos**

	δm	couplings	parameters
$\tilde{\chi}_{1,2}^{\pm}$	$0.1 - 0.5\ \%$	$\delta g_{\tilde{W}}/g \sim 0.01$	$M_2, \mu, \tan\beta$
$\tilde{\chi}_{1,2,3,4}^{0}$	$0.1 - 0.5\ \%$	$\delta g_{\tilde{B}}/g' \sim 0.05$	$M_1, M_2, \mu, \tan\beta$

polarised cross sections $\qquad \delta\sigma \sim \mathcal{O}(\%)$

$\triangleright$ **Reconstructing parameters**

overconstrained system of measurements

	scenario RR1	scenario RR2
M_2	152 ± 1.8 GeV	150 ± 1.2 GeV
μ	316 ± 0.9 GeV	263 ± 0.7 GeV
$\tan\beta$	3 ± 0.7	$30\,^{+30}_{-20}$
M_1	78.7 ± 0.7 GeV	78.0 ± 0.4 GeV

general case $\mu,\ M_1$ **complex** $\quad \Rightarrow \mathcal{CP}$ **phases**

Scalar Top Quark

Scalar top $\tilde{t}$ may be lightest squark

$$\tilde{t}_1 = \tilde{t}_L \cos\theta_{\tilde{t}} + \tilde{t}_R \sin\theta_{\tilde{t}}$$
$$e^+ e^- \to \tilde{t}_1 \tilde{t}_1$$

large $\tilde{t}_R - \tilde{t}_L$ mixing expected due to heavy top mass
light $m_{\tilde{t}_1} < 250\,\mathrm{GeV}$ may not be detected at LHC

minimum mass $m_{min}(\tilde{t}_1)$

$$\tilde{t}_1 \to q\,\tilde{\chi}_1^0$$

$$\sigma_L,\ \sigma_R \to m_{\tilde{t}_1},\ \theta_{\tilde{t}}$$

$$e_L^- e_R^+ \to \tilde{t}_1 \tilde{t}_1 \quad e_R^- e_L^+ \to \tilde{t}_1 \tilde{t}_1 \qquad \tilde{t}_1 \to b\,\tilde{\chi}_1^{\pm}$$
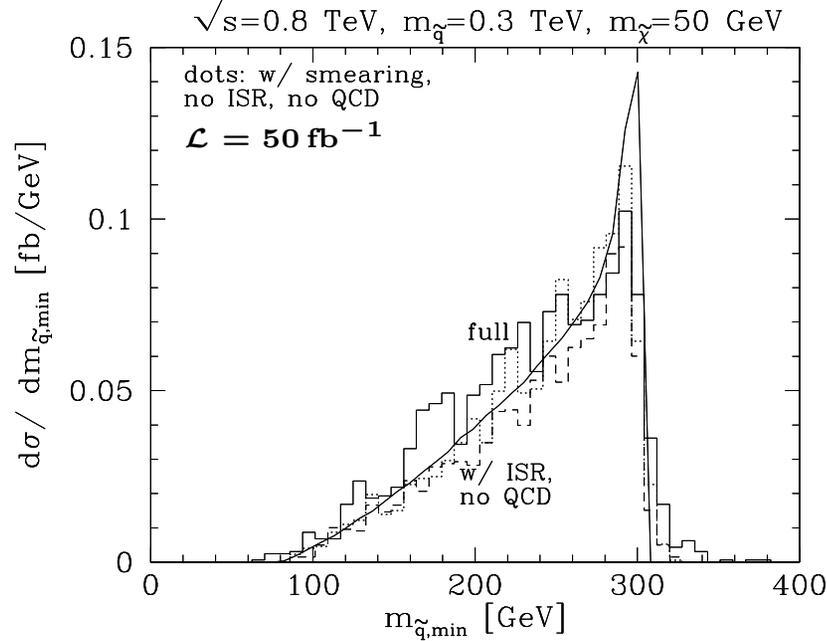
exploit momentum correlations, $m_{\tilde{\chi}}$ known

$$m_{\tilde{t}_1} = 300 \pm 2\,\mathrm{GeV}$$
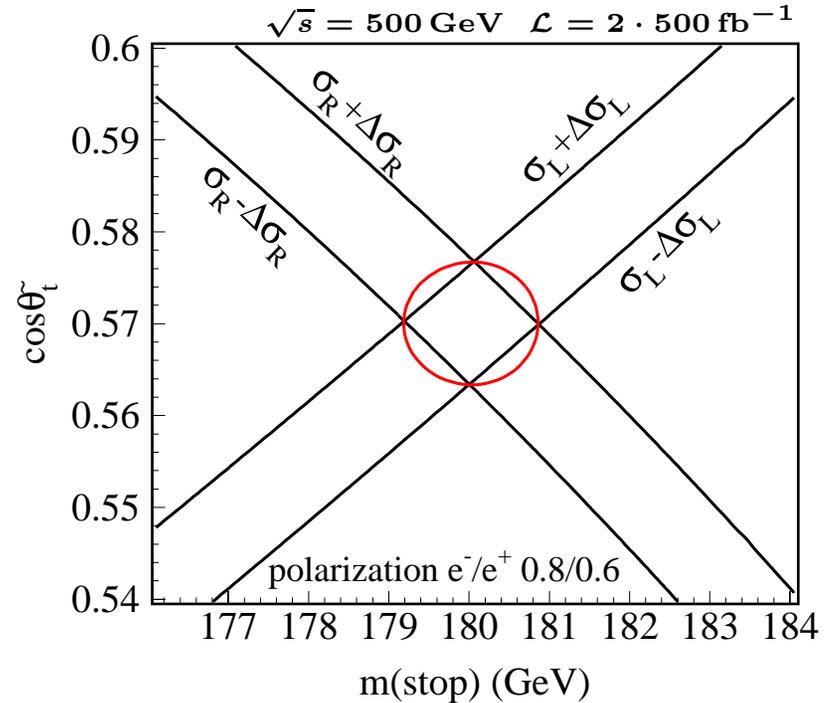
$$m_{\tilde{t}_1} = 180 \pm 0.8\,\mathrm{GeV}$$
$$\cos\theta_{\tilde{t}} = 0.57 \pm 0.008$$

LC Run Scenario

Exploration of mSUGRA benchmark SPS 1

Distribution of $\mathcal{L} = 1000 \, \text{fb}^{-1}$ (equivalent @ 500 GeV) achievable in reasonable time

	$\sqrt{s}$	$\mathcal{P}_{e^-}$	$\mathcal{L}\,[\text{fb}^{-1}]$	Comments
e^+e^-	500	L/R	335	sit at top energy
e^+e^-	270	L/R	100	scan $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\tau}_1\tilde{\tau}_1$
e^+e^-	285	R	50	scan $\tilde{\mu}_R\tilde{\mu}_R$, $\tilde{e}_R\tilde{e}_R$
e^+e^-	350	L/R	40	scan $t\bar{t}$, $\tilde{e}_R\tilde{e}_L$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$
e^+e^-	410	L/R	100	scan $\tilde{\tau}_2\tilde{\tau}_2$
e^+e^-	580	L/R	90	continuum $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$
e^-e^-	285	RR	10	scan $\tilde{e}_R\tilde{e}_R$

Accuracy on mSUGRA parameters

$m_0 = 100 \pm 0.08 \, \text{GeV}$ $m_{1/2} = 250 \pm 0.20 \, \text{GeV}$
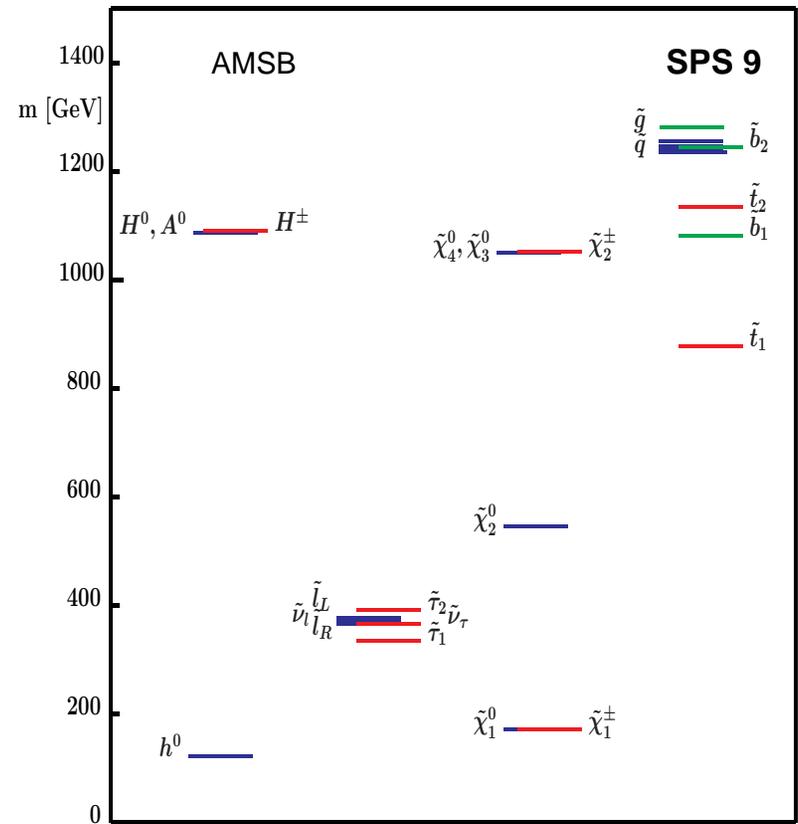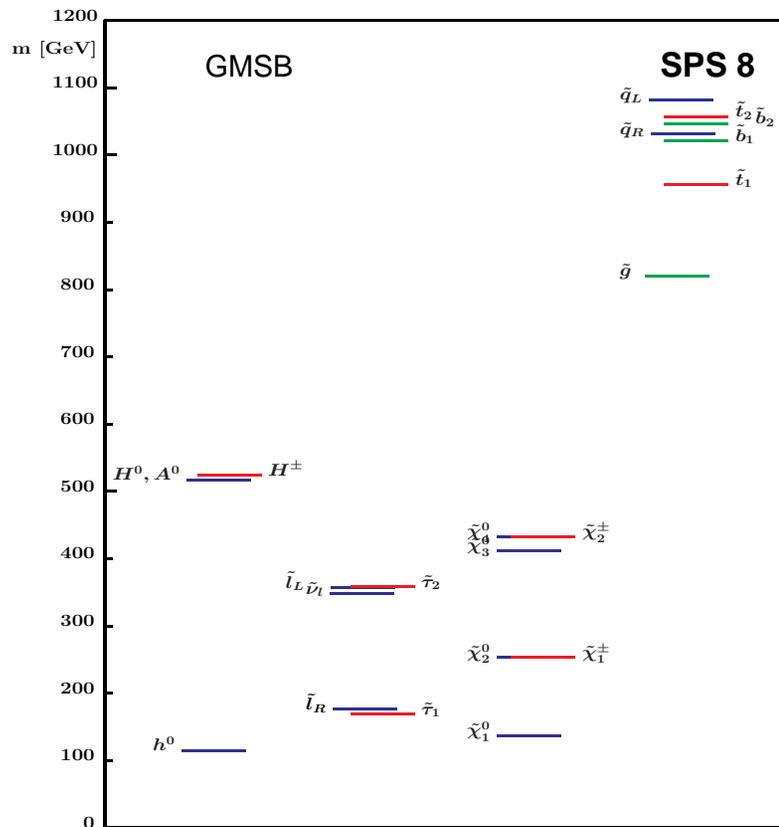
$A_0 = 0 \pm 13 \, \text{GeV}$ $\tan\beta = 10 \pm 0.5$

Masses from Continuum & Scan

	m [GeV]	δm_{c}	δm_{s}	δm_{SPS1}
$\tilde{e}_R$	143	0.19	0.02	0.02
$\tilde{e}_L$	202	0.27	0.30	0.20
$\tilde{\mu}_R$	143	0.08	0.13	0.07
$\tilde{\mu}_L$	202	0.70	0.76	0.51
$\tilde{\tau}_1$	135	1 - 2	0.64	0.64
$\tilde{\tau}_2$	206	–	0.86	0.86
$\tilde{\nu}_e$	186	0.23	–	0.23
$\tilde{\nu}_\mu$	186	7.0	–	7.0
$\tilde{\nu}_\tau$	185	–	–	–
$\tilde{\chi}_1^0$	96	0.07	–	0.07
$\tilde{\chi}_2^0$	175	1 - 2	0.12	0.12
$\tilde{\chi}_3^0$	343	8.5	–	8.5
$\tilde{\chi}_4^0$	364	–	–	–
$\tilde{\chi}_1^{\pm}$	175	0.19	0.18	0.13
$\tilde{\chi}_2^{\pm}$	364	4.1	–	4.1

Other SUSY Scenarios

- R_p **violating supersymmetry**

- **GMSB scenario**

- **AMSB scenario**

R-Parity Violation

R_p **violation** $\qquad R_p = (-1)^{3B+L+2S} \qquad\qquad R_p = +1$ **SM particles** $\qquad R_p = -1$ **superpartners**

$$W_{R_p} = \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k}_{\delta L \neq 0} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{D}_k}_{\delta L \neq 0} + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\delta B \neq 0} + \underbrace{\epsilon_i \, L_i H_2}_{\delta L \neq 0}$$

▷ **single sparticle production** $\qquad e^+ e^- \to \tilde{\nu} \to \mu^- \tilde{\chi}_1^+$

▷ **unstable LSP** $\qquad \chi_1^0 \to \ell\ell\ell, \; \ell qq, \; qqq,$ **multi-leptons, multi-jets (no E_{miss})**
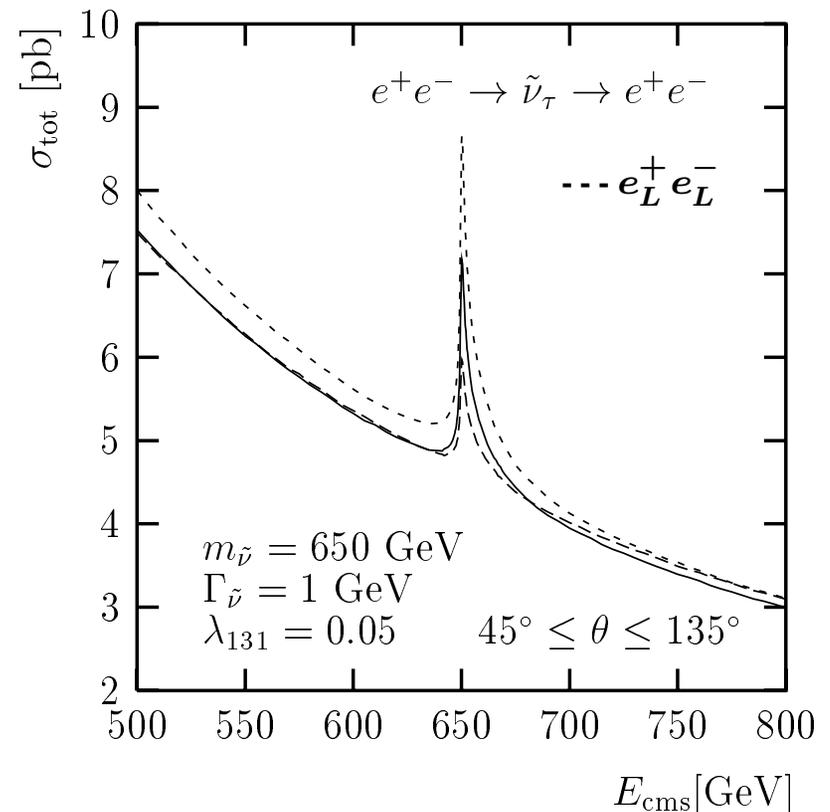
$$\boxed{e^+ e^- \to \tilde{\nu}_\tau \to e^+ e^-}$$

narrow resonance production
enhanced by 'unusual' polarisation $e_L^+ e_L^-$

contact interactions $\qquad m_{\tilde{\nu}} \gg \sqrt{s}$
sensitivity

$$\boxed{\lambda_{1j1} = 0.1 \quad m_{\tilde{\nu}} \simeq 1.8 \, \text{TeV}}$$

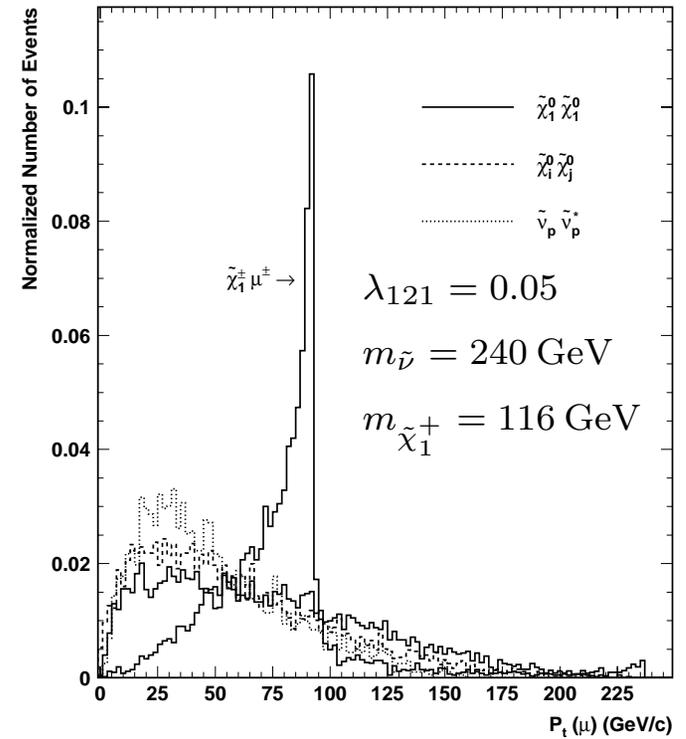$$e^+ e^- \rightarrow \mu^\mp \tilde{\chi}_1^\pm \rightarrow \mu^\mp \, 3\,\ell$$

$$\tilde{\chi}_1^+ \rightarrow \ell^+ \nu_\ell \, \tilde{\chi}_1^0 \qquad \tilde{\chi}_1^0 \rightarrow ee\nu_\mu, \, \mu e \nu_e$$

s channel polarisation enhancement

$$e_L^+ e_L^- \rightarrow \tilde{\chi}_1^- \mu^+ \text{ or } e_R^+ e_R^- \rightarrow \tilde{\chi}_1^+ \mu^-$$

sensitivity

$$\lambda_{121} = 10^{-4} \quad m_{\tilde{\nu}} \simeq 150 - 600 \text{ GeV}$$

Plot: Normalized Number of Events vs $P_t(\mu)$ (GeV/c), with legend $\tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_i^0 \tilde{\chi}_j^0$, $\tilde{\nu}_p \tilde{\nu}_p^*$. $\tilde{\chi}_1^\pm \mu^\pm \rightarrow$, $\lambda_{121} = 0.05$, $m_{\tilde{\nu}} = 240$ GeV, $m_{\tilde{\chi}_1^+} = 116$ GeV

Multi-leptons & multi-jets in $\tilde{\chi}$ decays

$$e^+ e^- \rightarrow \tilde{\chi}_i^0 \, \tilde{\chi}_j^0, \, \tilde{\chi}_i^+ \tilde{\chi}_j^-$$

$$m_{\tilde{\chi}_2^0} = 112 \text{ GeV}, \quad m_{\tilde{\chi}_1^0} = 54 \text{ GeV}$$

$$m_{\tilde{\chi}_1^+} = 112 \text{ GeV}, \quad m_{\tilde{e}} = 150 \text{ GeV}$$

distinct signatures

$\lambda > 0$	**2–8 leptons**	
$\lambda' > 0$	**2–6 leptons**	**4–8 jets**
$\lambda'' > 0$	**0–4 leptons**	**6–10 jets**

$\lambda > 0 \qquad \sqrt{s} = 500$ GeV

Signature	$\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\chi}_2^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^+\tilde{\chi}_1^-$	Signal (fb)	Bkgd. (fb)
$1\ell + \not{E}_T$	1.1	0.4	0.2	1.5	3.2	8272.5
$2\ell + \not{E}_T$	14.9	5.2	1.8	15.3	37.2	2347.4
$3\ell + \not{E}_T$	91.7	25.3	7.2	71.6	195.8	1.5
$4\ell + \not{E}_T$	212.8	49.6	13.6	152.8	428.8	0.4
$5\ell + \not{E}_T$	0.0	37.8	19.3	113.5	170.6	—
$6\ell + \not{E}_T$	0.0	39.6	21.6	26.9	88.0	—
$7\ell + \not{E}_T$	0.0	0.0	11.9	0.0	11.9	—
$8\ell + \not{E}_T$	0.0	0.0	8.0	0.0	8.0	—

AMSB Scenario

Anomaly Mediated Supersymmetry Breaking $\qquad m_0,\ m_{3/2},\ \tan\beta,\ \text{sign}\,\mu$

SUSY breaking may not be directly communicated from hidden to visible sector. Dynamic generation of gaugino (one loop) and scalar (twoo loops) masses via 'super–Weyl (superconformal) anomaly'

gaugino parameters $\qquad M_i = (\beta_i/g_i)\, m_{3/2} \qquad M_1 \simeq 3\, M_2 \qquad$ **mSUGRA** $\quad M_1 \simeq 0.5\, M_2$

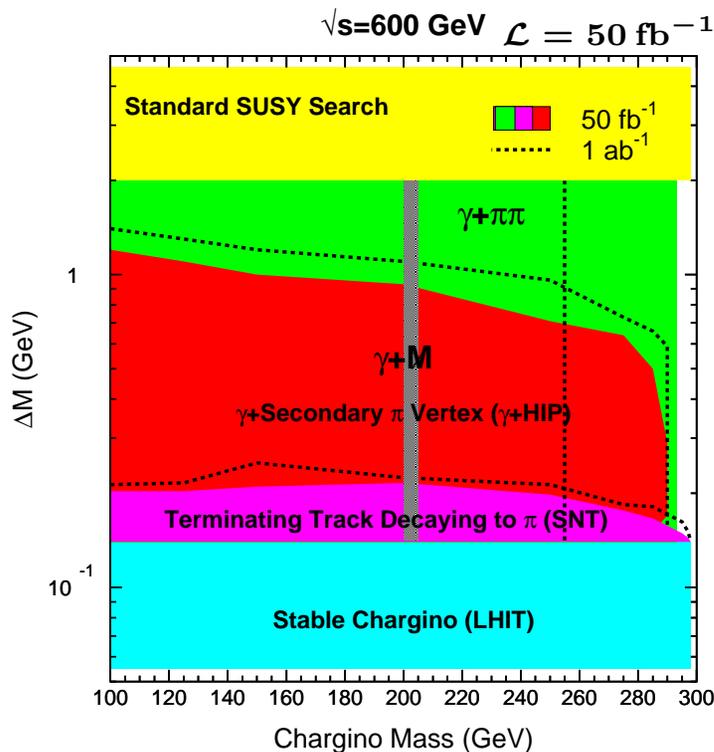**LSP = wino-like $\tilde{\chi}_1^0$ $\qquad$ almost degenerate with $\tilde{\chi}_1^\pm$**

small $\Delta m_{\tilde{\chi}_1} = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ $\qquad$ controls lifetime and decay modes of $\tilde{\chi}_1^\pm$

$\boxed{e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-\, (\gamma)}$ **search strategy** $\qquad\qquad \boxed{\Delta m_{\tilde{\chi}_1}\ \text{determination}}$

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

E_π in $m_{\tilde{\chi}\tilde{\chi}}$ rest frame
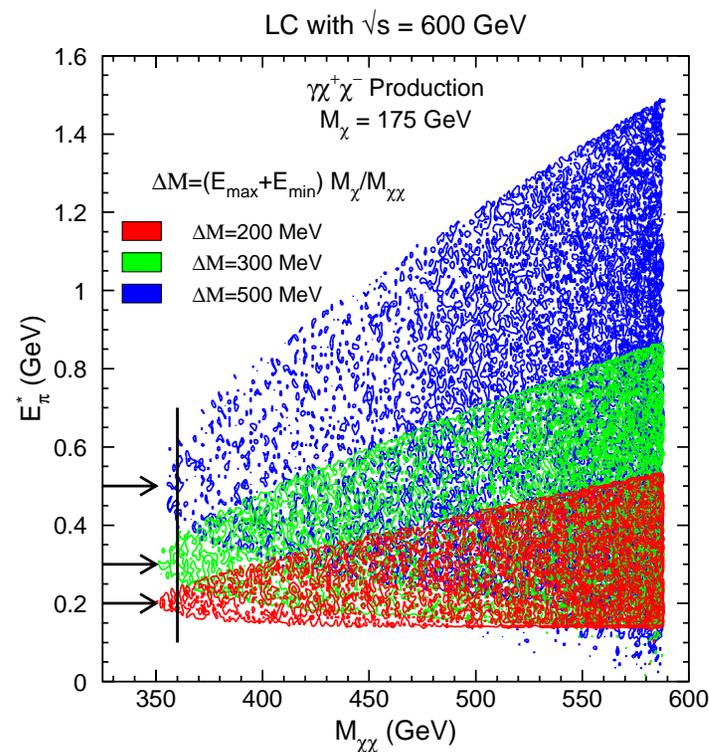
GMSB Scenario

Gauge Mediated Supersymmetry Breaking $M_{\mathrm{mess}},\ N_{\mathrm{mess}},\ \Lambda,\ \tan\beta,\ \mathrm{sign}\,\mu$

Gauge interactions at scale $\sqrt{F} \sim \mathcal{O}(100\,\mathrm{TeV})$ **serve as messengers**
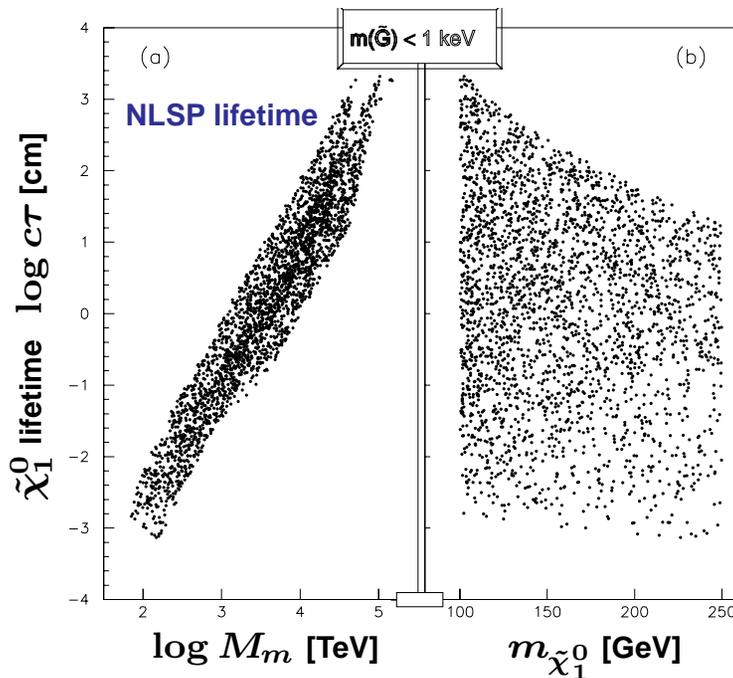
LSP = gravitino $\tilde{G}$ $m_{\tilde{G}} \simeq (\sqrt{F}/100\,\mathrm{TeV})^2\ \mathrm{eV}$

NLSP unstable $c\,\tau \propto (\sqrt{F})^4/(m_{\mathrm{NLSP}})^5$

$\tilde{\chi}_1^0 \to \gamma\,\tilde{G},\ f\bar{f}\tilde{G}$ $\Rightarrow$ **displaced & time delayed** γ**, secondary vertex(?)**

$\tilde{\ell}^{\pm} \to \ell^{\pm}\,\tilde{G}$ $\Rightarrow$ **long lived heavy leptons**

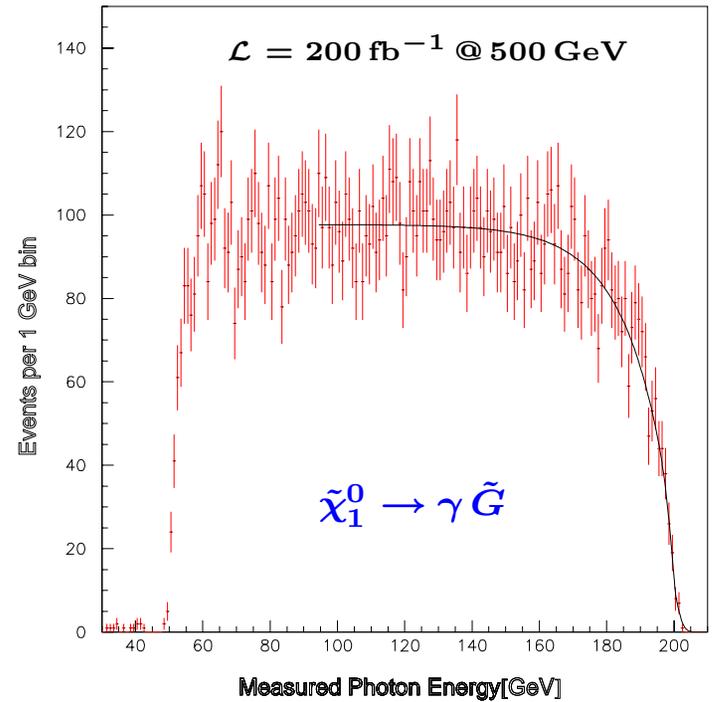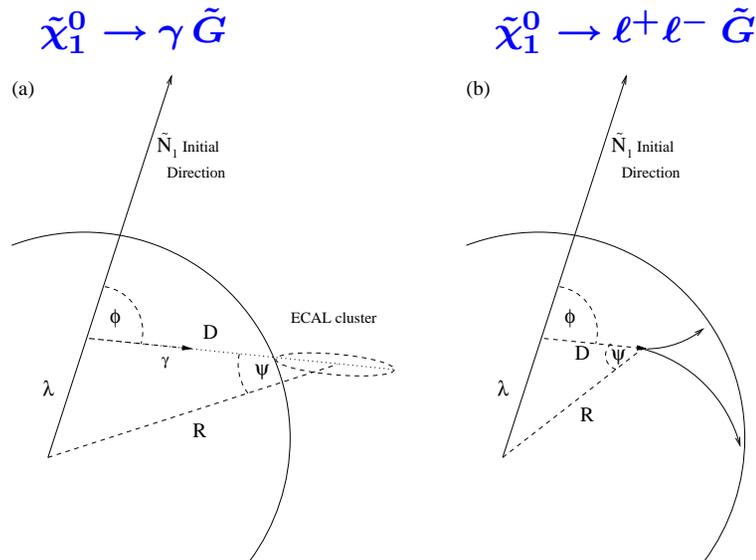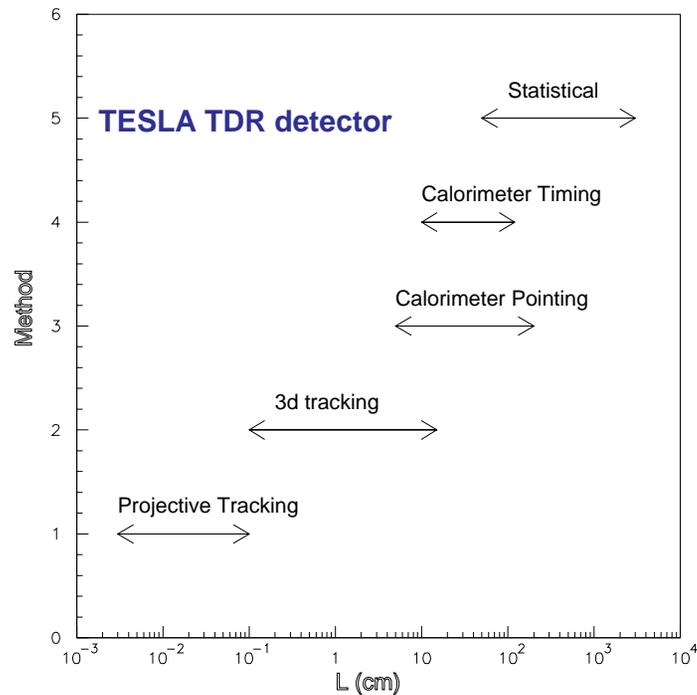$\tilde{\chi}_1^0 = \mathsf{NLSP}$ $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0$

$$\tilde{\chi}_1^0 \to \gamma \tilde{G} \qquad \tilde{\chi}_1^0 \to \ell^+\ell^- \tilde{G}$$

(a) (b)

$\tilde{N}_1$ Initial Direction

$\tilde{N}_1$ Initial Direction

ϕ

ϕ

D

ECAL cluster

D ψ

γ

ψ

λ

λ

R

R

Summary of Techniques

TESLA TDR detector

Statistical

Calorimeter Timing

Calorimeter Pointing

3d tracking

Projective Tracking

Method

L (cm)

$\mathcal{L} = 200\,\mathrm{fb}^{-1}$ @ 500 GeV

$\tilde{\chi}_1^0 \to \gamma \tilde{G}$

Events per 1 GeV bin

Measured Photon Energy[GeV]
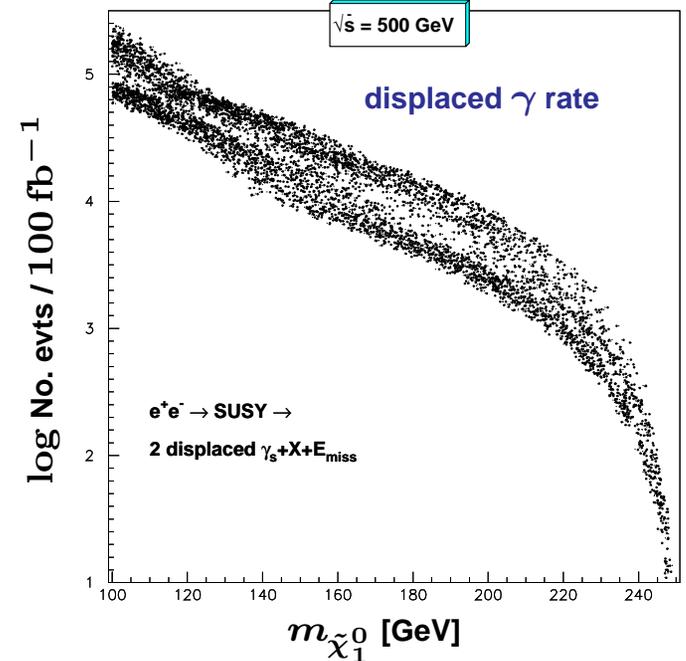
$$m_{\tilde{\chi}_1^0} = 197.7 \pm 0.3\ \mathrm{GeV}$$

sensitivity on scale $\sqrt{F}$ from lifetime measurements

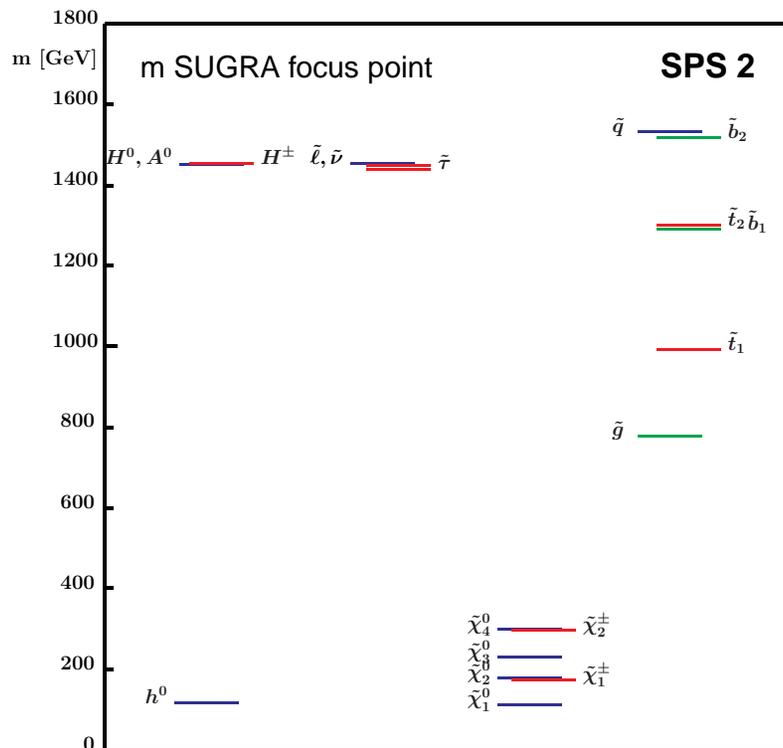$$\delta\,c\tau_{\tilde{\chi}}/c\tau_{\tilde{\chi}} < 10\% \qquad 30\,\mu m < c\tau < 40\,m$$

$$\delta\,\sqrt{F}/\sqrt{F} < 5\% \qquad 1 \lesssim \sqrt{F} \lesssim 10^4\ \mathrm{TeV}$$
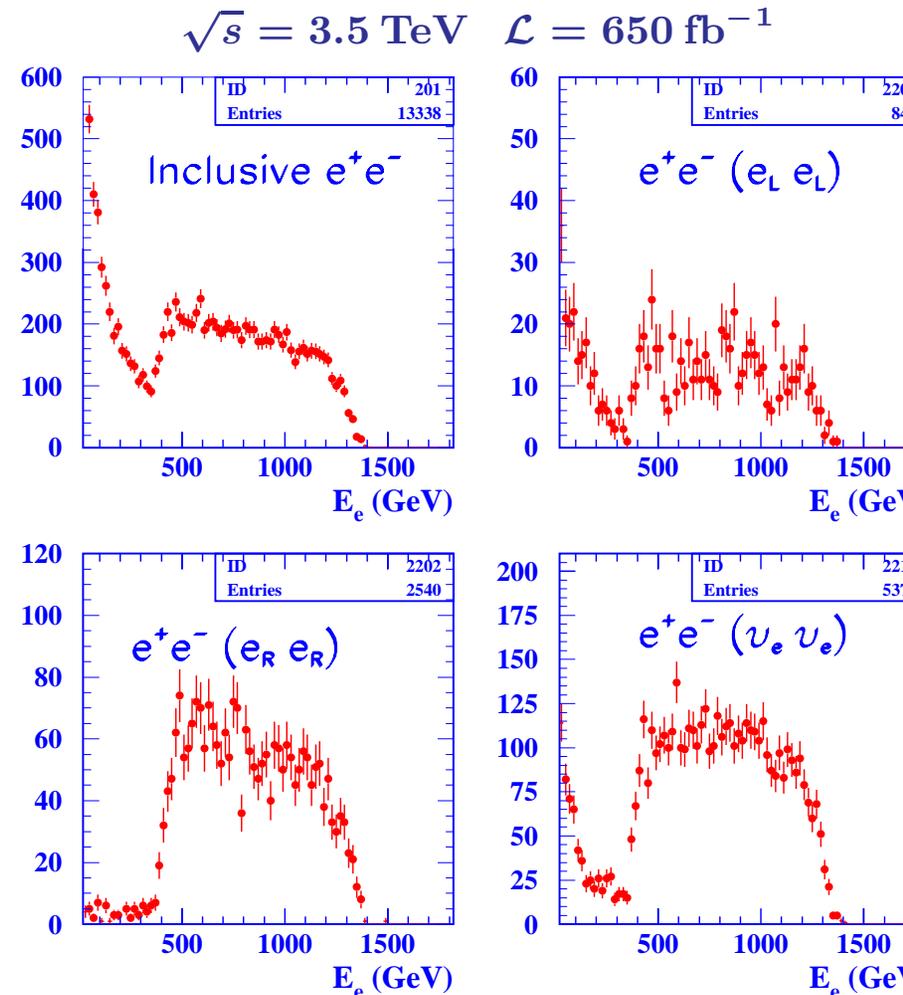
Experimentation at CLIC

Completing sparticle spectrum, accessing very heavy squarks or sleptons may require a multi-TeV LC

CLIC simulation of SPS 2

observe end points in E_e spectrum

difficult to disentangle

masses $\tilde{e}_R, \tilde{e}_L, \tilde{\nu}_e$ overlap within widths

$$e^+ e^- \to \tilde{e}_R \tilde{e}_R,\ \tilde{e}_L \tilde{e}_L,\ \tilde{\nu}_e \tilde{\nu}_e \to e^+ e^- X$$

Conclusions

▷ **Experiments at a future e^+e^- Linear Collider are essential to establish the basic concepts of supersymmetry**

▷ **The clean environment will enable precise measurements of the accessible superpartner spectrum**

$m, \Gamma, \mathcal{B}, \sigma_{pol}, \tilde{g}, J^{PC}$, **mixing parameters**

quantum numbers, $\mathcal{CP}$ phases

▷ **Only high precision measurements will allow a model independent analysis of the detailed structure of the underlying supersymmetry theory, determine its parameters and its symmetry breaking mechanism**

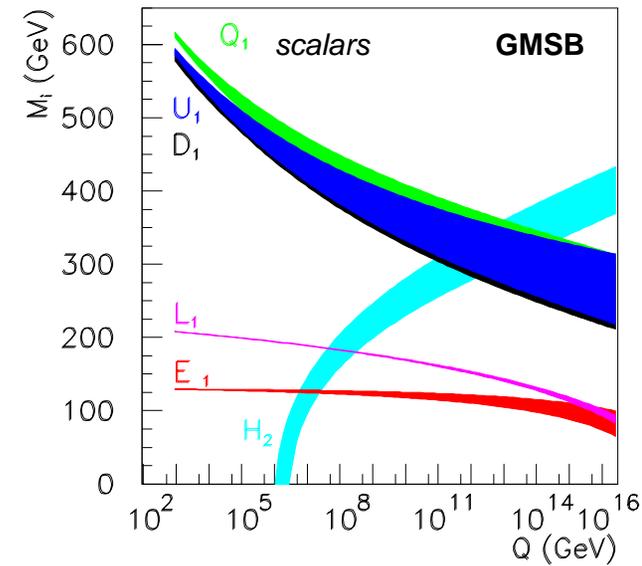▷ **Reliable extrapolations to high energies may indicate the way to unification and towards energy scales close to the Planck scale**
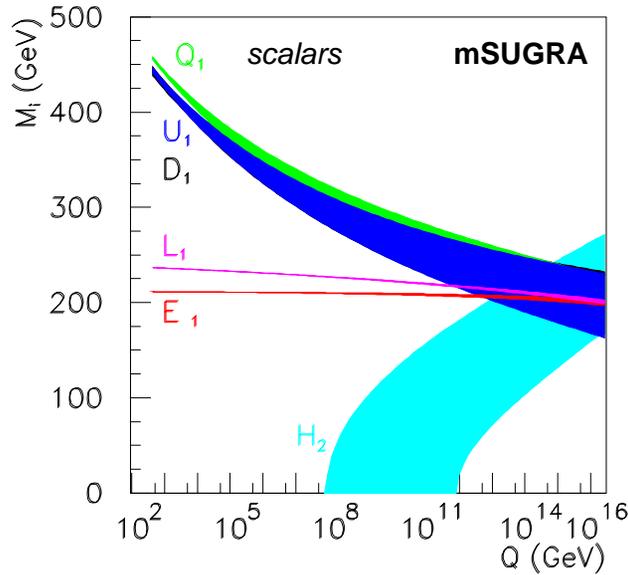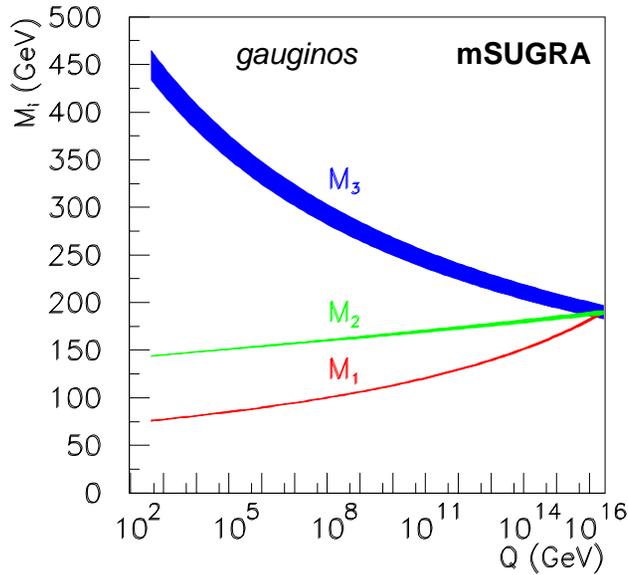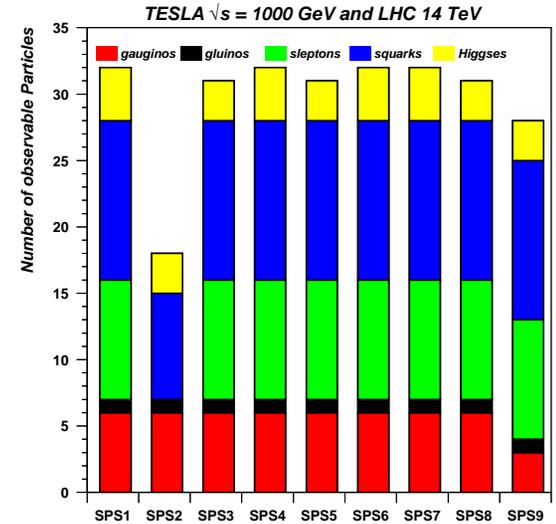
Perspectives for the year 201x + 5

Complementarity of LC and LHC

Access to Snowmass benchmarks

SUSY parameters at high scales

Discover fundamental SUSY theory

Support the worldwide project of a e^+e^- Linear Collider!