Scalar Particle Properties with and without R parity at the ILC

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$$\tilde{f}_L, \tilde{f}_R$$

main reference :

INTERNATIONAL LINEAR COLLIDER

REFERENCE DESIGN REPORT

ILC Global Design Effort and World Wide Study

AUGUST, 2007

(and references therein)

my apologies to all (many) whose results I am showing without explicitely quoting their work !

ILC can add a lot of information after discovery of SUSY at LHC → ***precision measurements*** in the light part of the spectrum, expecially ***sleptons and ew gauginos***

- ***masses, decay widths, cross sections, mixing angles ...***
- are they really the SUSY partners ?

  → ***check spin and parity, gauge quantum numbers and couplings***
- ***reconstruct the low-energy SUSY breaking parameters***

$\tilde{f}_L, \tilde{f}_R$ spin-0 partner of chiral fermions f_L, f_R

$$\mathcal{M}^2_{\tilde{f}} = \begin{pmatrix} m^2_{\tilde{f}_L} & a^*_{\tilde{f}} m_f \\ a_{\tilde{f}} m_f & m^2_{\tilde{f}_R} \end{pmatrix}$$

$$m^2_{\tilde{f}_i} = M^2_{\tilde{F}_i} + m^2_Z \cos 2\beta \,(I^3_{f_i} - Q_f \sin^2\theta_W) + m^2_f$$

$$a_{\tilde{f}} = A_{\tilde{f}} - \mu^* (\tan\beta)^{-2I^3_f}$$

$$A_{\tilde{f}} = |A_{\tilde{f}}| e^{i\varphi_{A_{\tilde{f}}}}$$

$$\mu = |\mu| e^{i\varphi_\mu}$$

mixing between L and R states important when :

$$\Delta_{\tilde{f}} = m^2_{\tilde{f}_L} - m^2_{\tilde{f}_R} \leq |a_{\tilde{f}} m_f|$$

(not for selectron and smuons)

$$\tilde{f}_1 = \tilde{f}_L e^{i\varphi_{\tilde{f}}} \cos\theta_{\tilde{f}} + \tilde{f}_R \sin\theta_{\tilde{f}}$$

$$\tilde{f}_2 = -\tilde{f}_L \sin\theta_{\tilde{f}} + \tilde{f}_R e^{-i\varphi_{\tilde{f}}} \cos\theta_{\tilde{f}}$$

$$m^2_{\tilde{f}^{\pm}_{1,2}} = (m^2_{\tilde{f}_L} + m^2_{\tilde{f}_R} \mp [\Delta^2_{\tilde{f}} + 4|a_{\tilde{f}} m_f|^2]^{1/2})/2$$

$$\tan\theta_{\tilde{f}} = (m^2_{\tilde{f}_1} - m^2_{\tilde{f}_L})/|a_{\tilde{f}} m_f|$$

$$\varphi_{\tilde{f}} = arg(A_{\tilde{f}} - \mu^* (\tan\beta)^{-2I^3_f})$$

SUSY in the bulk region (SPS1a)

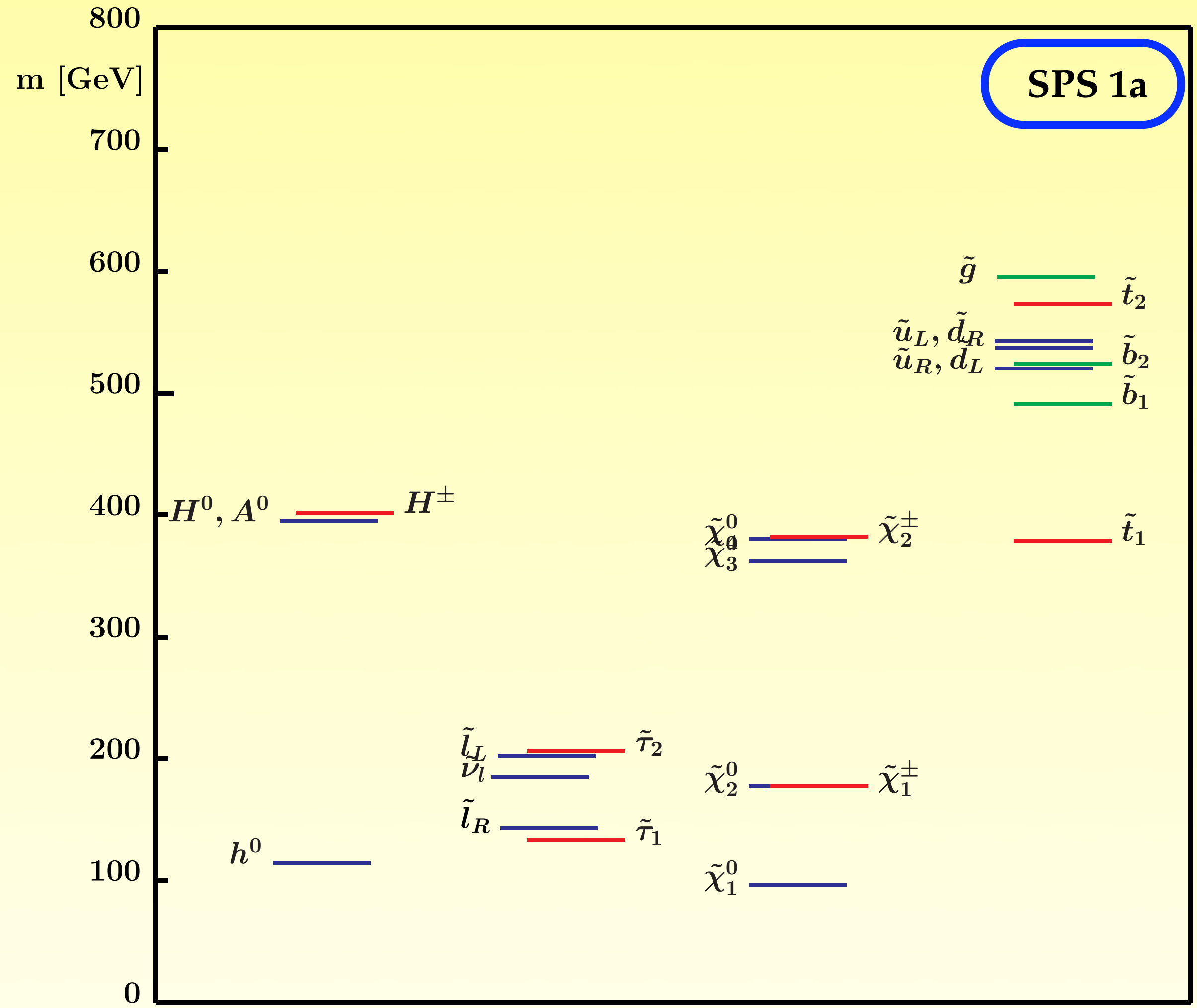
most studies done here !

- A scenario with many SUSY signal at LHC and LC has been studied extensively (SPS1a)
- LHC sees coloured superpartners directly and uncoloured ones in cascades
- ILC sees most uncoloured super-partners

$$m_0 = 100\ \text{GeV}, \qquad m_{1/2} = 250\ \text{GeV},$$
$$\tan\beta = 10, \qquad A = -100\ \text{GeV}, \qquad \mu > 0,$$

(mSUGRA) *(R parity conserved)*

$\tilde{\ell}$	m [GeV]	decay	$\mathcal{B}$
$\tilde{e}_R$	143.0	$\tilde{\chi}_1^0 e^-$	1.000
$\tilde{e}_L$	202.1	$\tilde{\chi}_1^0 e^-$	0.490
		$\tilde{\chi}_2^0 e^-$	0.187
		$\tilde{\chi}_1^- \nu_e$	0.323
$\tilde{\nu}_e$	186.0	$\tilde{\chi}_1^0 \nu_e$	0.885
		$\tilde{\chi}_2^0 \nu_e$	0.031
		$\tilde{\chi}_1^+ e^-$	0.083
$\tilde{\mu}_R$	143.0	$\tilde{\chi}_1^0 \mu^-$	1.000
$\tilde{\mu}_L$	202.1	$\tilde{\chi}_1^0 \mu^-$	0.490
		$\tilde{\chi}_2^0 \mu^-$	0.187
		$\tilde{\chi}_1^- \nu_\mu$	0.323
$\tilde{\nu}_\mu$	186.0	$\tilde{\chi}_1^0 \nu_\mu$	0.885
		$\tilde{\chi}_2^0 \nu_\mu$	0.031
		$\tilde{\chi}_1^+ \mu^-$	0.083
$\tilde{\tau}_1$	133.2	$\tilde{\chi}_1^0 \tau^-$	1.000
$\tilde{\tau}_2$	206.1	$\tilde{\chi}_1^0 \tau^-$	0.526
		$\tilde{\chi}_2^0 \tau^-$	0.174
		$\tilde{\chi}_1^- \nu_\tau$	0.300
$\tilde{\nu}_\tau$	185.1	$\tilde{\chi}_1^0 \nu_\tau$	0.906
		$\tilde{\chi}_1^+ \tau^-$	0.067



$$M_{\tilde{g}} = 595.2, \quad \mu = 352.4, \quad M_A = 393.6, \quad \tan\beta = 10, \quad M_1 = 99.1, \quad M_2 = 192.7$$

$$M_{\tilde{q}1_L} = M_{\tilde{q}2_L} = 539.9, \quad M_{\tilde{d}_R} = 519.5, \quad M_{\tilde{u}_R} = 521.7, \quad M_{\tilde{e}_L} = 196.6, \quad M_{\tilde{e}_R} = 136.2$$

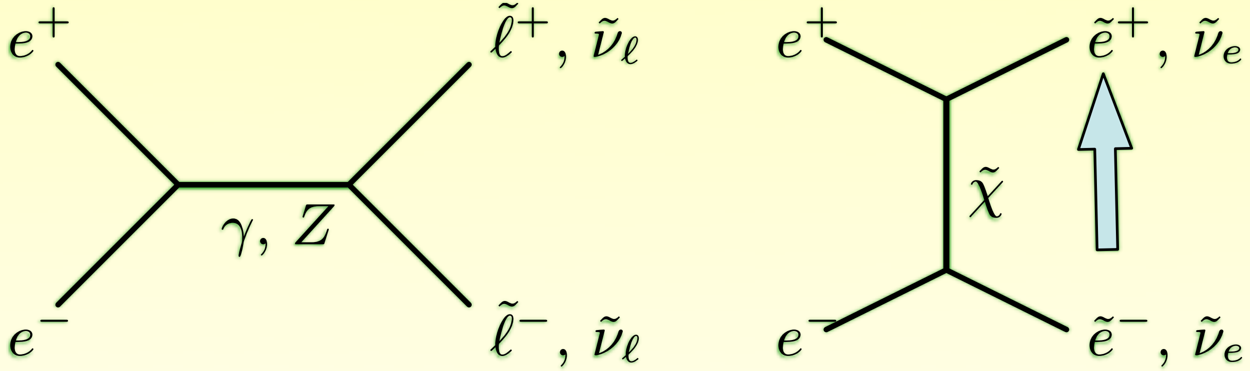
$$M_{\tilde{q}3_L} = 495.9, \quad M_{\tilde{b}_R} = 516.9, \quad M_{\tilde{t}_R} = 424.8, \quad M_{\tilde{\tau}_L} = 195.8, \quad M_{\tilde{\tau}_R} = 133.6,$$

$$A_t = -510.0, \quad A_b = -772.7, \quad A_\tau = -254.2$$

sleptons produced mostly in pairs

$$e^+e^- \;\rightarrow\; \tilde{\ell}_i^+\tilde{\ell}_j^-,\; \tilde{\nu}_\ell\bar{\tilde{\nu}}_\ell \qquad \ell = e,\, \mu,\, \tau$$

$$[i,j = L, R \text{ or } 1,2]$$



$$\tilde{\ell}^- \;\rightarrow\; \ell^-\,\tilde{\chi}^0,\; \nu_\ell\,\tilde{\chi}^-$$

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

$\tilde{f}_L, \tilde{f}_R$ ***mass measurements***

$\rightarrow$ *two main strategies :*

- charged slepton production in continuum
- threshold scan

$\rightarrow$ **note!** ***beam polarization*** *enhances different chiral states !*

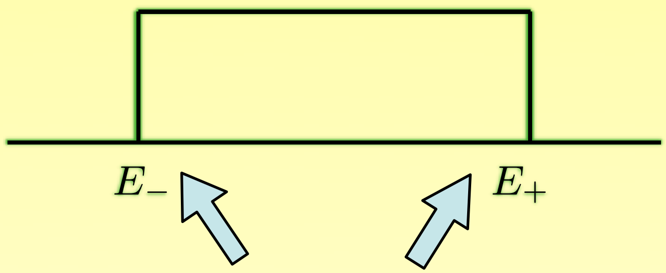
here we assume : $\mathcal{P}_{e^-} = \pm 0.8 \qquad \mathcal{P}_{e^+} = \pm 0.6$

$$\tilde{\ell}^- \rightarrow \ell^- \tilde{\chi}_i^0$$

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

isotropic decays

decay lepton energy spectrum



$$E_{+/-} = \frac{\sqrt{s}}{4}\left(1 - \frac{m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}^2}\right)(1 \pm \beta)$$

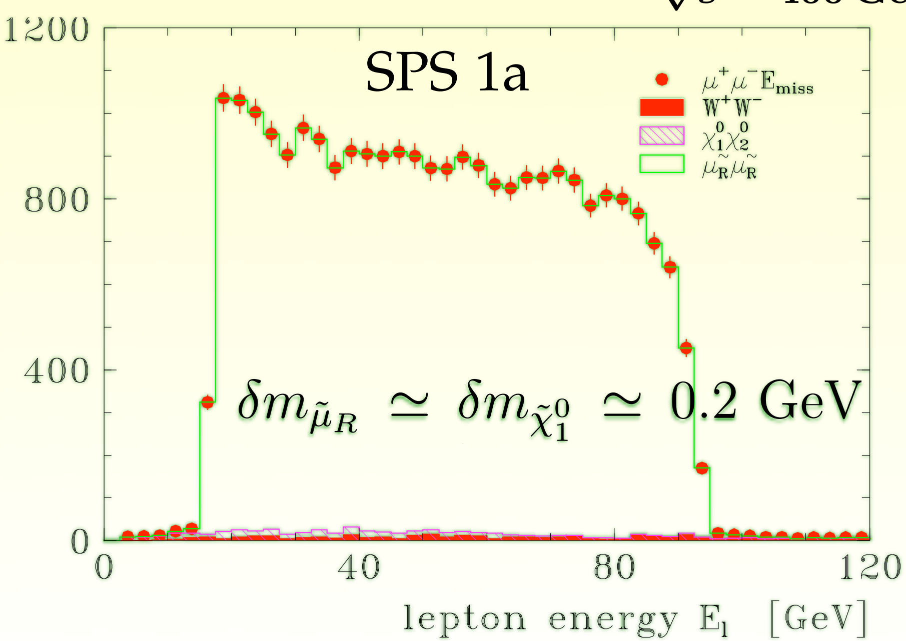
$$m_{\tilde{l}} = \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+}\,,$$

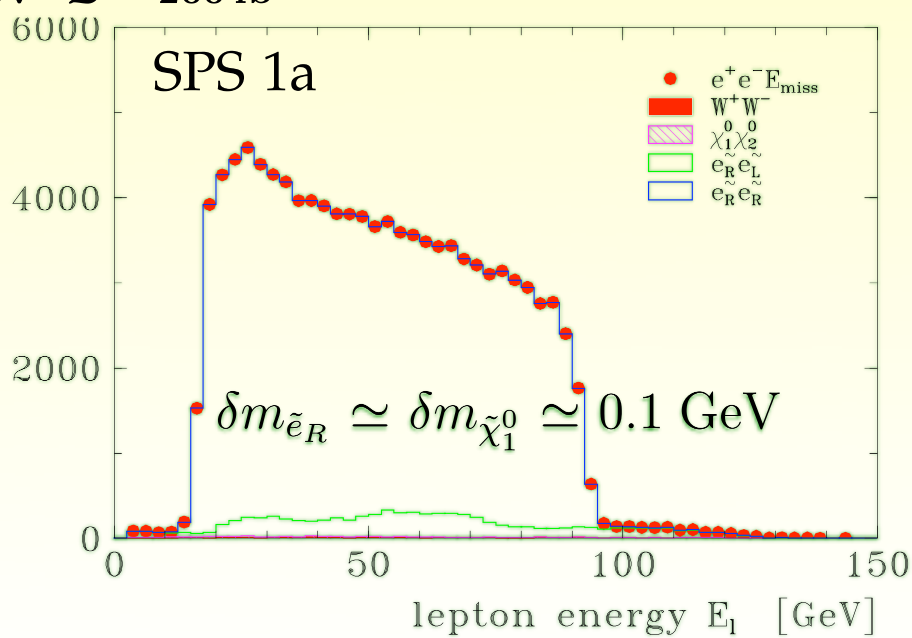
$$m_{\tilde{\chi}} = m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}$$

accurate determination of masses of primary sleptons and secondary gauginos from 'endpoints'

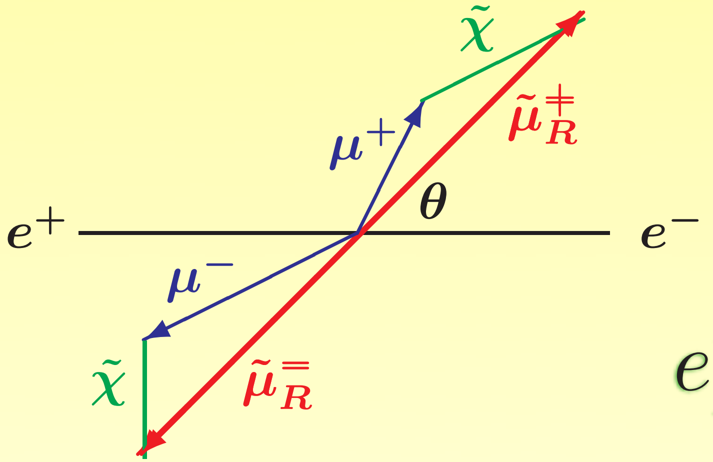
$$e_L^+ e_R^- \rightarrow \tilde{\mu}_R^+ \tilde{\mu}_R^- \rightarrow \mu^+ \tilde{\chi}_1^0\, \mu^- \tilde{\chi}_1^0 \qquad e_L^+ e_R^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^- \rightarrow e^+ \tilde{\chi}_1^0\, e^- \tilde{\chi}_1^0$$

$\sqrt{s} = 400$ GeV $\mathcal{L} = 200$ fb^{-1}

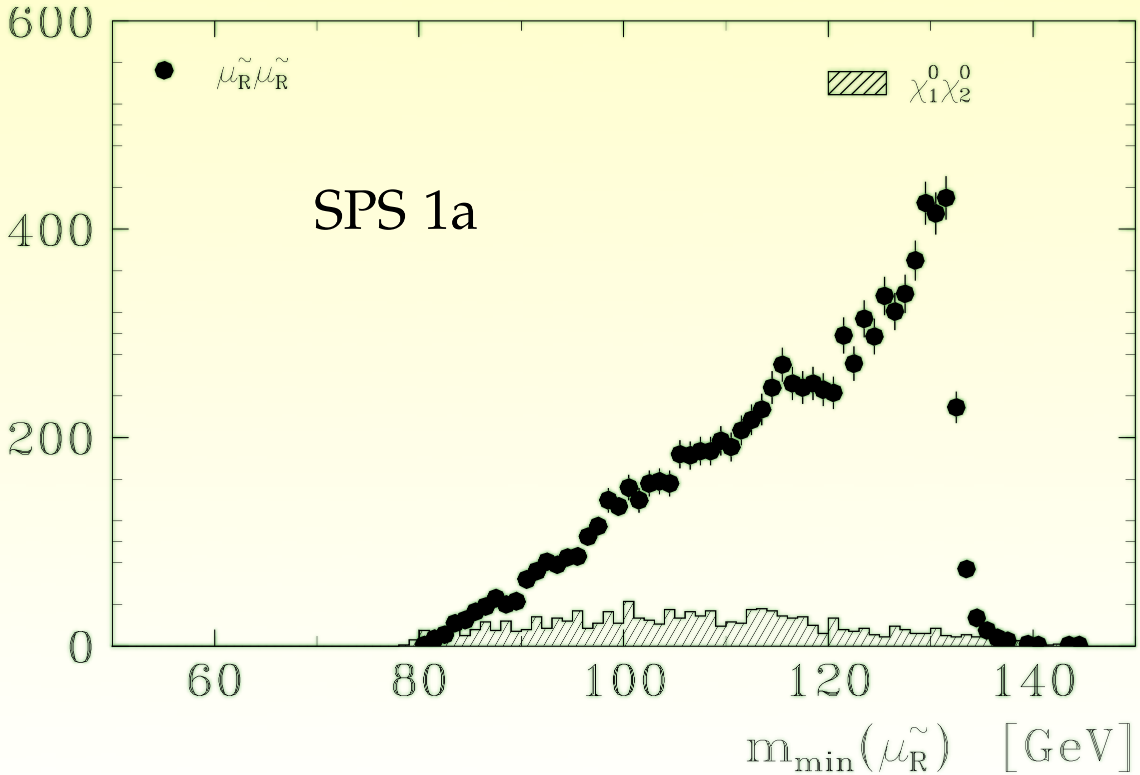




if $\tilde{\chi}$ mass is known, exploit momentum correlations :



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



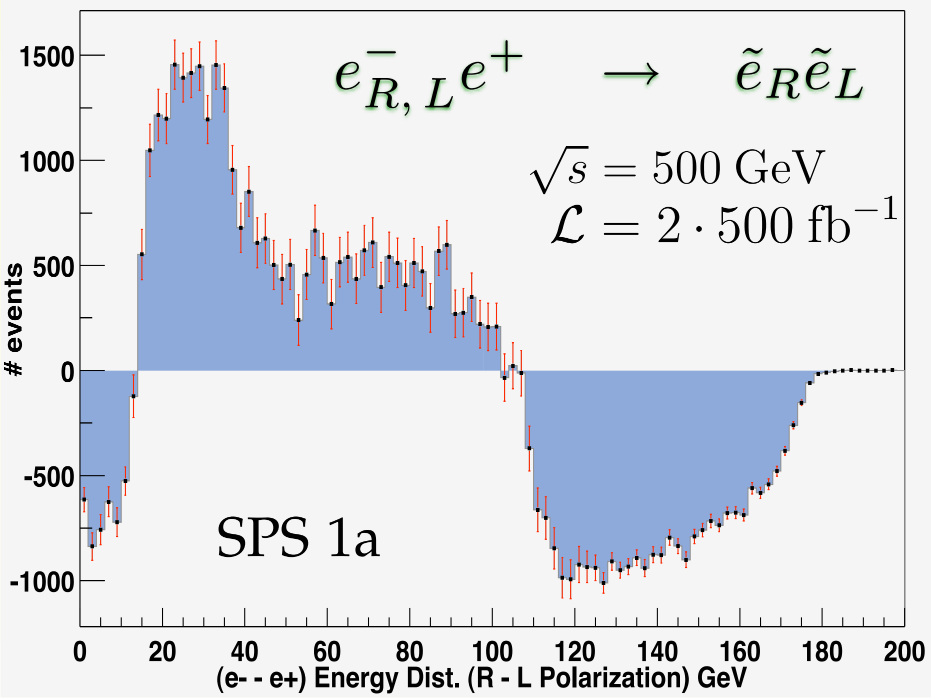
edge in minimum mass improves mass resolution by factor 2

exp problems for selectrons :

a) overlap of $\tilde{e}^-_R\tilde{e}^+_L, \tilde{e}^-_R\tilde{e}^+_R, \tilde{e}^-_L\tilde{e}^+_L$ flat energy distributions
b) large SM bckgr

double subtraction of the spectra (for opposite P_e):

$$(E_{e^-} - E_{e^+})_{e^-_R} - (E_{e^-} - E_{e^+})_{e^-_L}$$



disentangle $e^-_{R,L}e^+ \to \tilde{e}_R\tilde{e}_L$ from all charge symmetric bckgr

(clean) endpoint from $\tilde{e}_R$ and $\tilde{e}_L$ decays easily measurable

$$\delta m_{\tilde{e}_R,\tilde{e}_L} \sim 0.8 \text{ GeV}$$

Large mixing expected in the tau sector

⇨ $\tilde{\tau}_1$ is the lightest sleptons !

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

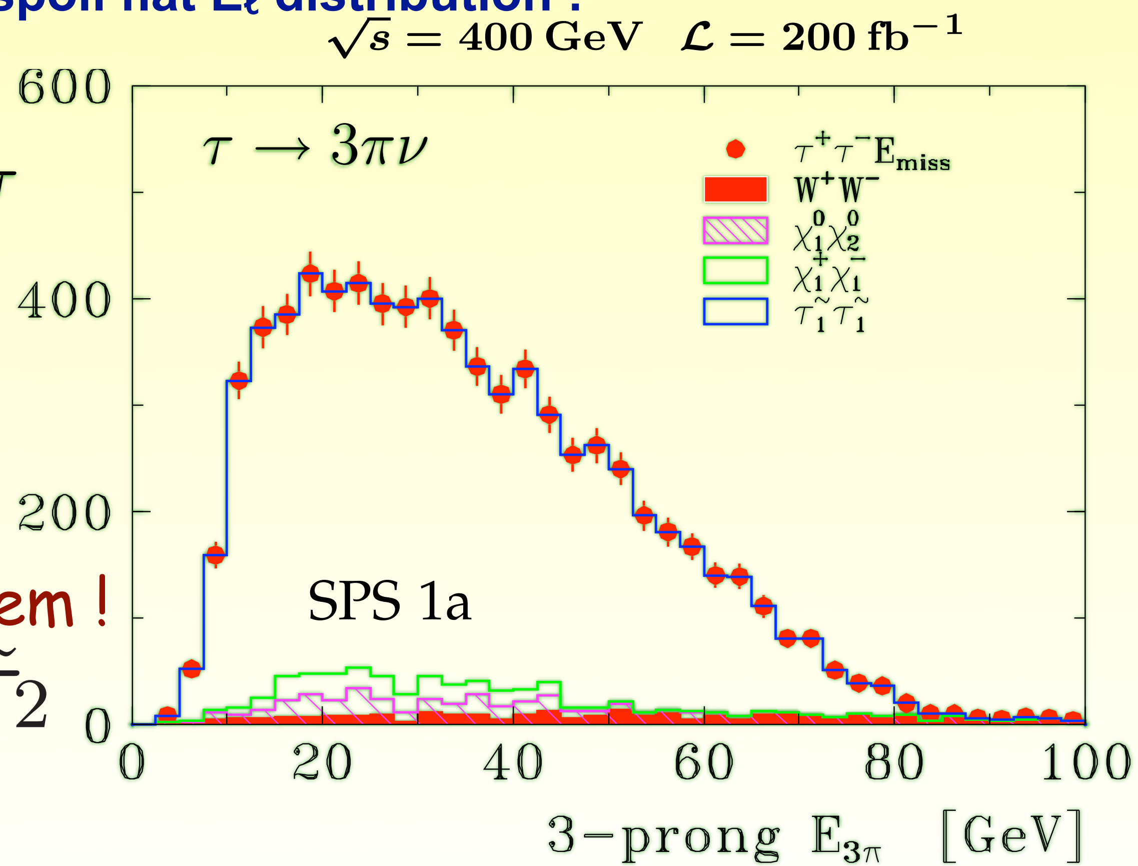
neutrinos in $\tau \to \mu\nu\nu$ spoil flat Eℓ distribution :

⇨ $\tau \to \rho\nu_\tau, \; 3\pi\nu_\tau$

$$\delta m_{\tilde{\tau}_1} = 0.3 \text{ GeV}$$

(if $m_{\tilde{\chi}_1^0}$ known)

$m_{\tilde{\tau}_2}$ still an open problem !
difficult to disentangle $\tilde{\tau}_2$ decay products from $\tilde{\tau}_1$



$\tilde{\nu}_\ell$ more involved ! (mostly invisible)

SPS 1a

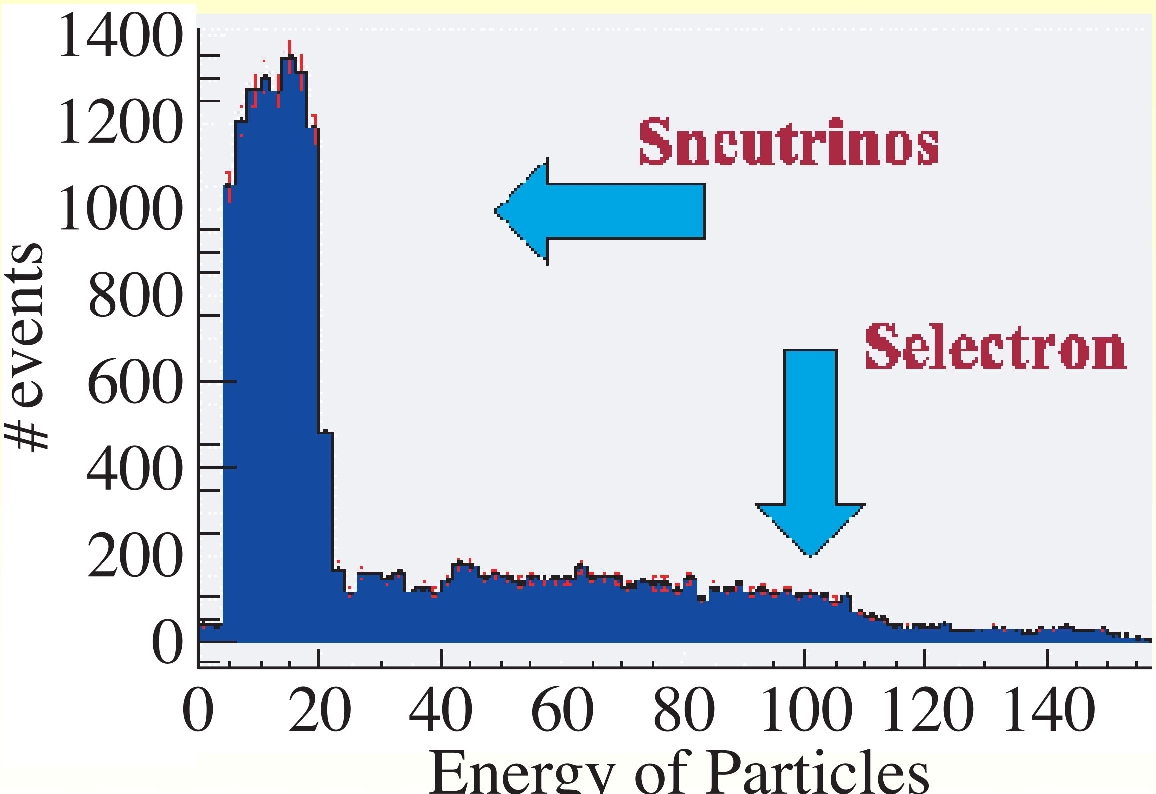
use : $\tilde{\nu}_\ell \;\rightarrow\; \ell^- \tilde{\chi}_i^+$ (~10%)

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu \rightarrow \tau\nu\,\tilde{\chi}_1^0$$

t-channel via chargino exchange can contribute (otherwise small σ's) :

$$e^+e^-_L \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow \nu_e\tilde{\chi}^0\, e^\pm\tilde{\chi}_1^\mp \rightarrow e^\pm\tau^\mp \not{E}$$

$$\tau \rightarrow \mu\nu\nu$$



$\tilde{\nu}_\mu$ and $\tilde{\nu}_\tau$

challenging !!!

from primary $e^\pm$ spectrum :

$$\delta m_{\tilde{\nu}_e} = 1.2 \text{ GeV}$$

$\tilde{f}_L, \tilde{f}_R$ mass measurements

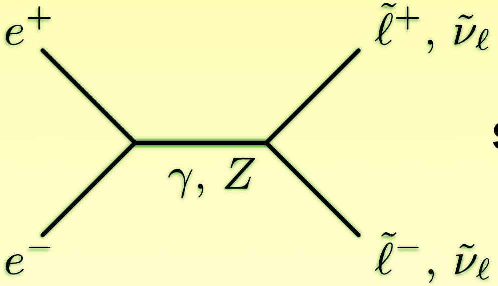
→ *two main strategies :*

- charged slepton production in continuum
- threshold scan

→ note ! ***beam polarization*** *enhances different chiral states !*

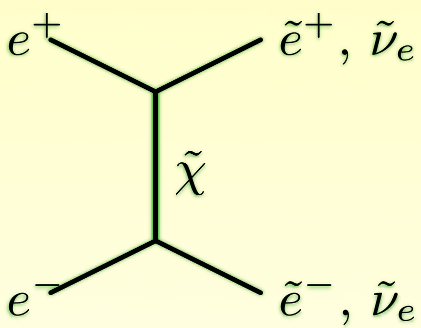
here we assume : $\mathcal{P}_{e^-} = \pm 0.8 \quad \mathcal{P}_{e^+} = \pm 0.6$

Production at threshold



s-channel in P-waves $\longrightarrow$ **slow rise** $\sigma_{\tilde{\ell}^+\tilde{\ell}^-} \sim \beta^3$

$$\beta = \sqrt{1 - 4\, m_{\tilde{\ell}}^2/s}$$



$$e^+e^- \longrightarrow \tilde{e}_R^{\pm} e_L^{\mp}$$

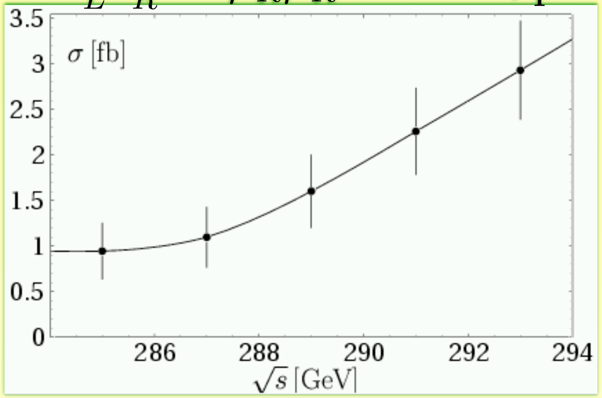
in S-waves $\longrightarrow$ **steep rise** $\sigma \propto \beta$

same for : $e_R^- e_R^- \longrightarrow \tilde{e}_R \tilde{e}_R$

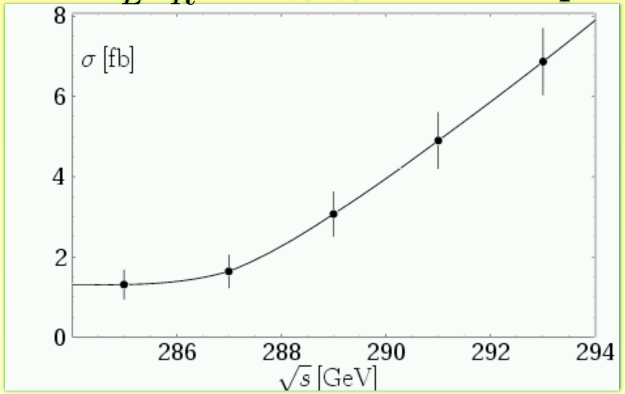
and (R → L)

shape of x-sections carries information on masses and quantum numbers !

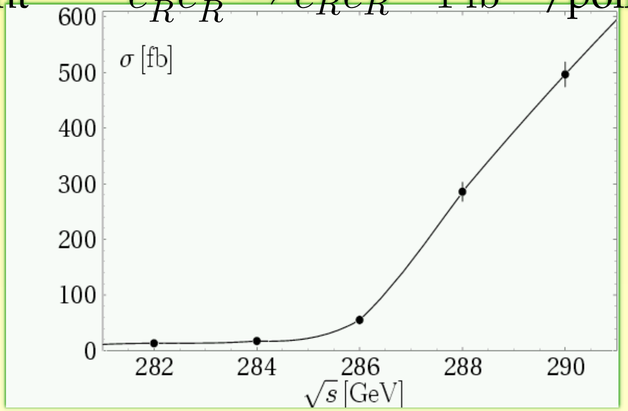
$e_L^+ e_R^- \to \tilde{\mu}_R \tilde{\mu}_R$ 10 fb^{-1}/point



$e_L^+ e_R^- \to \tilde{e}_R \tilde{e}_R$ 10 fb^{-1}/point



$e_R^- e_R^- \to \tilde{e}_R \tilde{e}_R$ 1 fb^{-1}/point



Polarized beams + $\mathcal{L} = 50\ \text{fb}^{-1}$, two parameter fit gives

⇨ $\delta m_{\tilde{e}_R} = 0.20$ GeV $\quad \delta\Gamma_{\tilde{e}_R} = 0.25$ GeV (highly correlated)

- factor-2 worse for $\tilde{\mu}_R \tilde{\mu}_R$
- $e_R^- e_R^- \to \tilde{e}_R \tilde{e}_R \qquad \mathcal{L} = 5\ \text{fb}^{-1}$

  $\delta m_{\tilde{e}_R} = 0.050$ GeV $\quad \delta\Gamma_{\tilde{e}_R} = 0.045$ GeV

⇨ combined with E_ℓ spectrum in continuum $\tilde{e}_R^+ \tilde{e}_R^-$ gives $\delta m_{\tilde{\chi}_1^0} = 0.05$ GeV

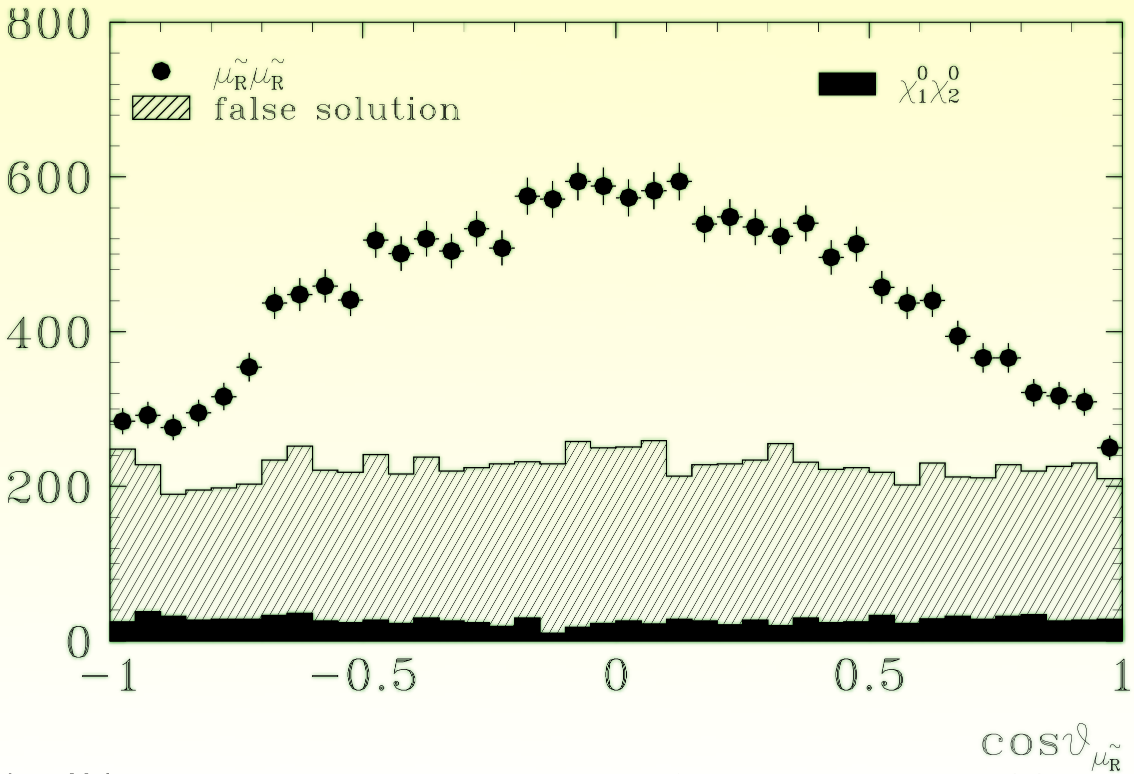
⇨ $\delta m_{\tilde{\mu}_R} < 0.05$ GeV

Spin determination

$\sin^2\theta$ *law in slepton angular distribution*
unique signal of spin-0 character !

(for selectron: close to threshold)

(P-wave excitation : a necessary but not sufficient condition !)

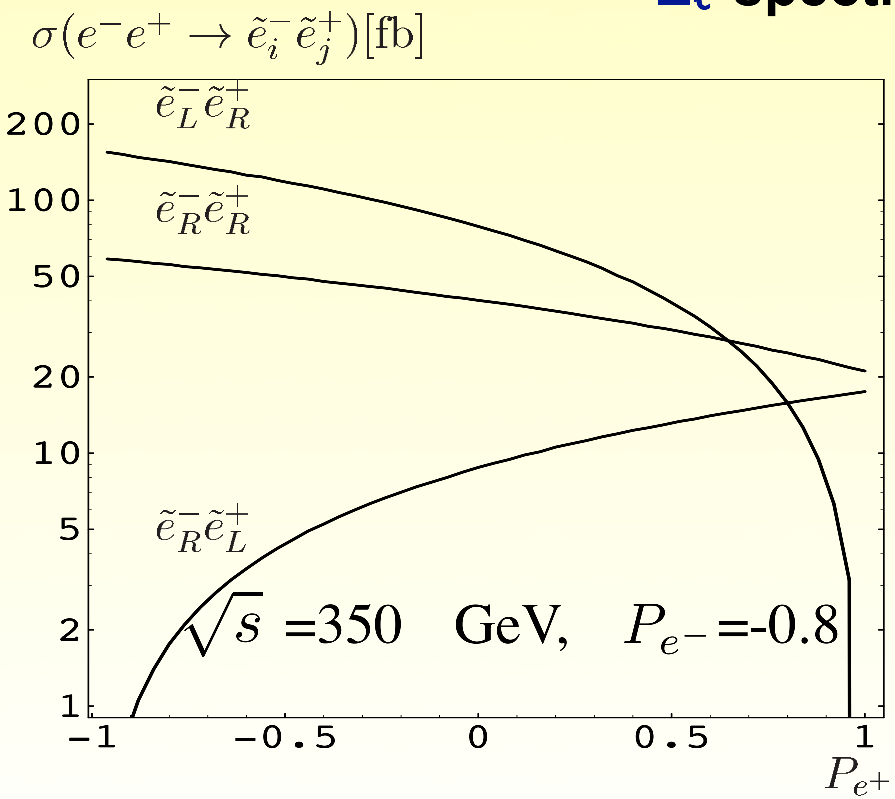


two-fold ambiguity

chiral quantum numbers

t-channel production $e^-_R e^+_R \to \tilde{e}^-_R \tilde{e}^+_L \qquad e^-_L e^+_L \to \tilde{e}^-_L \tilde{e}^+_R$

for polarized beams lepton charge associated to L,R quantum numbers $\longrightarrow$ **E_ℓ spectrum distinguishes** $\tilde{e}$ **chirality**



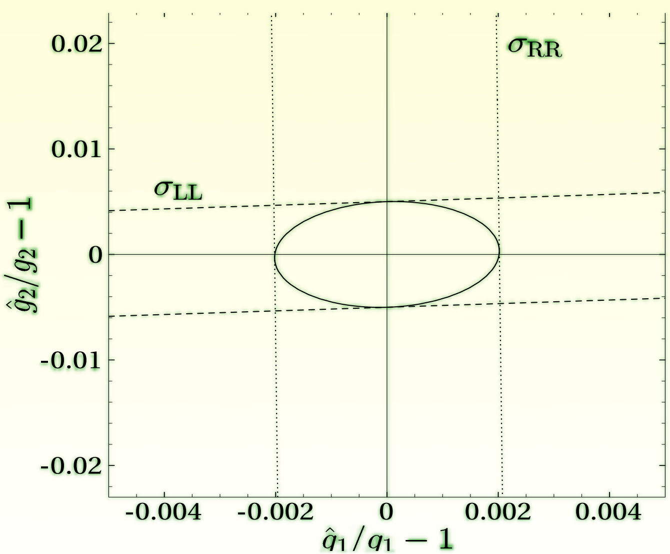
both beams must be polarized to separate s-channel

check SUSY coupling structure

SUSY requires SM **gauge** couplings $g(Vff) = \bar{g}(V\tilde{f}\tilde{f})$ also equal to **Yukawa** couplings $\hat{g}(\tilde{V}f\tilde{f})$

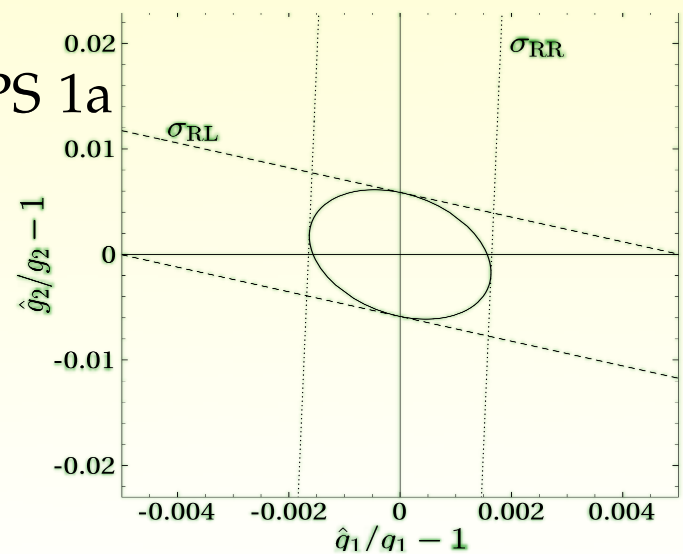
couplings extracted from cross section measurements

$e^-e^- \quad \mathcal{L} = 50 \text{ fb}^{-1}$



SPS 1a

$e^+e^- \quad \mathcal{L} = 500 \text{ fb}^{-1}$



precision on Yukawa couplings :

U(1) :
$\delta\hat{g}_1/\hat{g}_1 \approx 0.2\%$

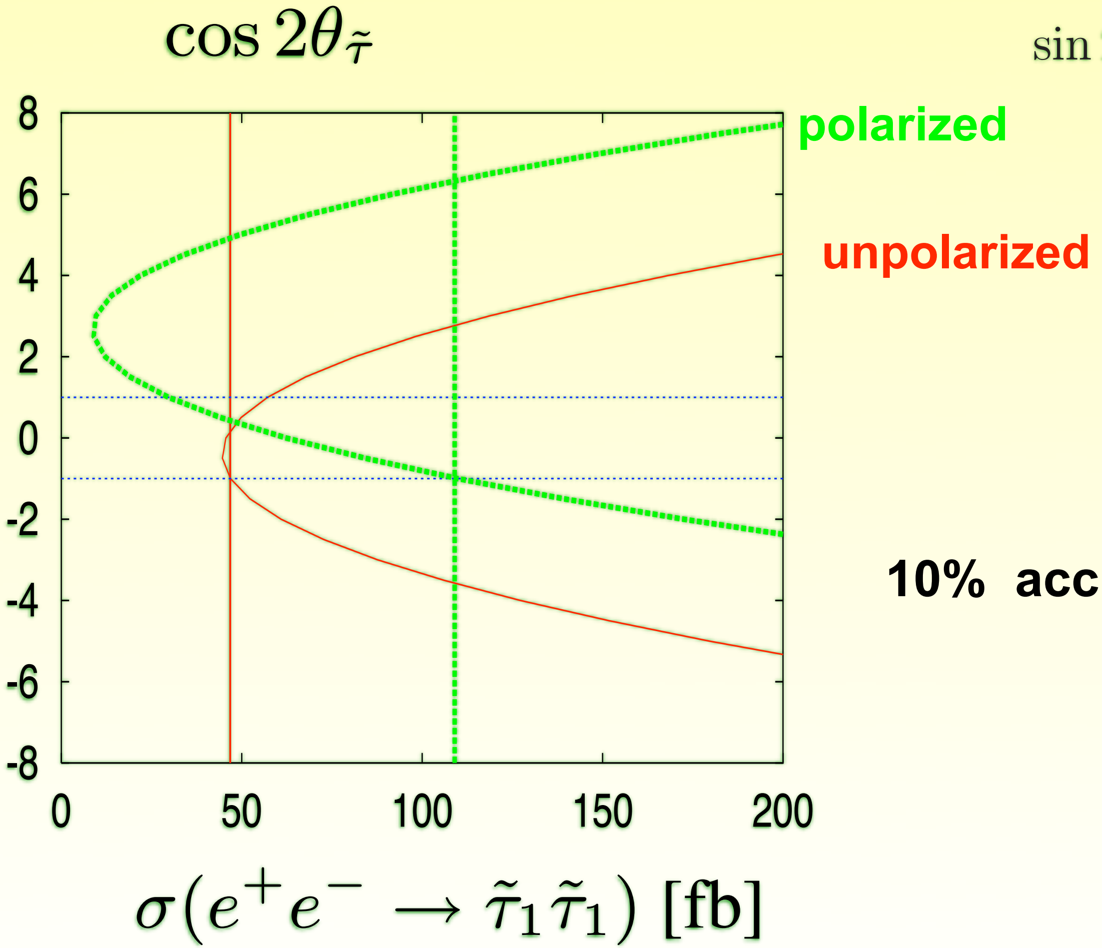
SU(2) :
$\delta\hat{g}_2/\hat{g}_2 \approx 0.8\%$

mixing angles measurement

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

non negligible for taus !

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



10% accuracy expected on $|\cos\theta_{\tilde{\tau}}|$

dominant decay mode $\tilde{\tau}_1 \rightarrow \tilde{\chi}_1^0 \tau$ useful to measure a large $\tan\beta$ **(difficult in other sectors !)**

for large higgsino component in the neutralino

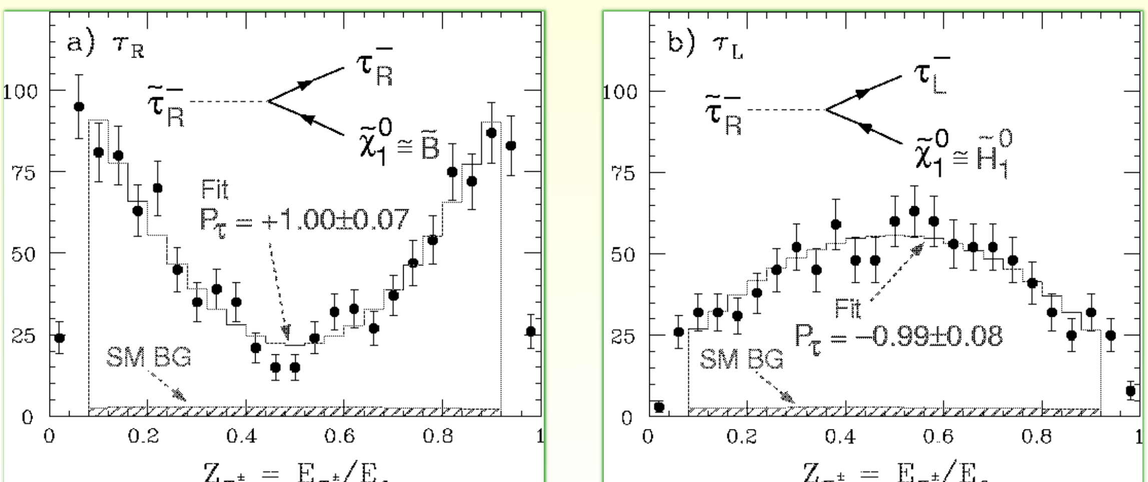
τ polarisation from $\tilde{\tau}$ decays

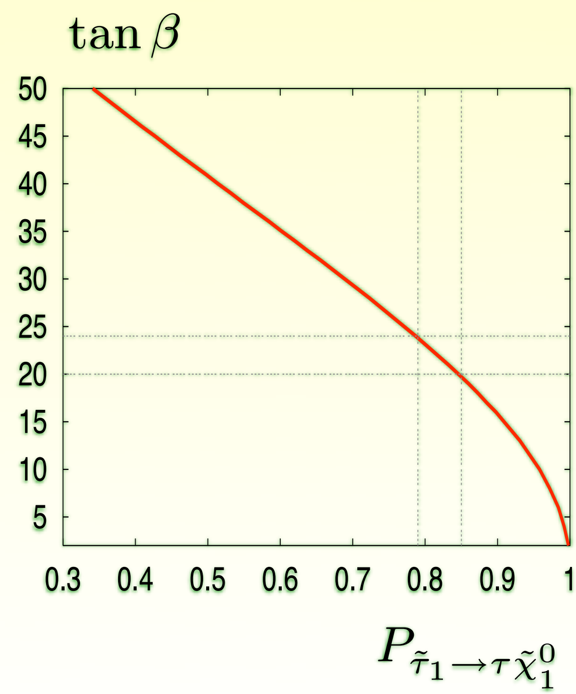
is a sensitive function of stau mixing, neutralino mixing and $\tan\beta$

spectra of $\tau^{\pm} \rightarrow \rho^{\pm}\nu$ and $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$

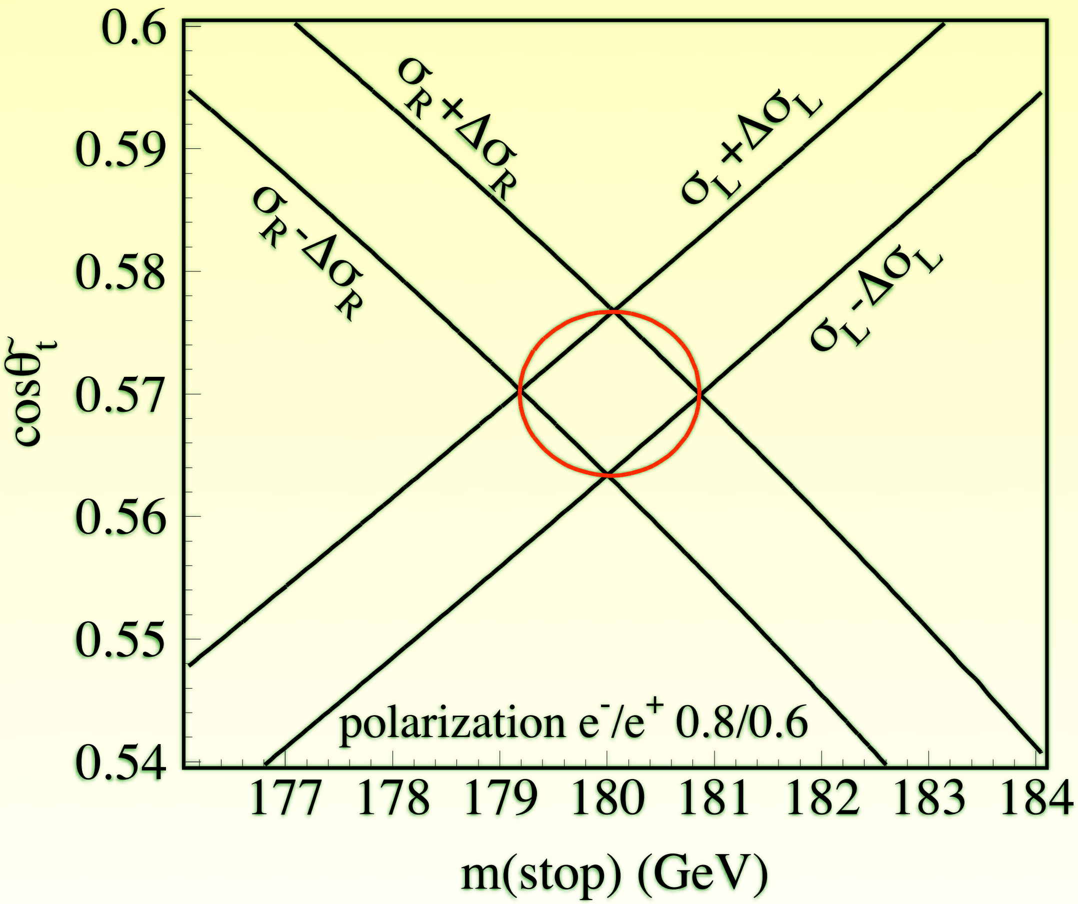
$$\tilde{\tau}_{R(L)} \rightarrow \tau_{R(L)}\, \tilde{B} \qquad \tilde{\tau}_{R(L)} \rightarrow \tau_{L(R)}\, \tilde{H}_1^0$$

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





squarks in general out of reach !



$$\sigma(e^-_R e^+_L \to \tilde{t}_1 \tilde{t}_1)$$

$$\sigma(e^-_L e^+_R \to \tilde{t}_1 \tilde{t}_1)$$

$$\mathcal{L} = 2 \cdot 500 \text{ fb}^{-1}$$

$$\sqrt{s} = 500 \text{ GeV}$$

in case the lightest stop is really light, excellent control on masses and mixings

R-parity violation

- in general $R_p = (-1)^{3B+L+2S}$ assumed conserved
  ⟹ missing energy signature
- no strong theoretical justification
- superpotential admits R-parity violating terms

$$W_{\not R_p} = \underbrace{\epsilon_i L_i H_u}_{\delta L \neq 0} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k}_{\delta L \neq 0} + \underbrace{\lambda'_{ijk} L_i Q_j \bar{D}_k}_{\delta L \neq 0} + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\delta B \neq 0}$$

- phenomenology changes drastically (LSP decays !):
  Emiss ⟶ *multi-lepton, multi-jet* final states (observable!)
- can provide framework for describing mass and mixing in the *SM* ν *sector* (mixing between neutrinos and neutralinos generates ν masses)

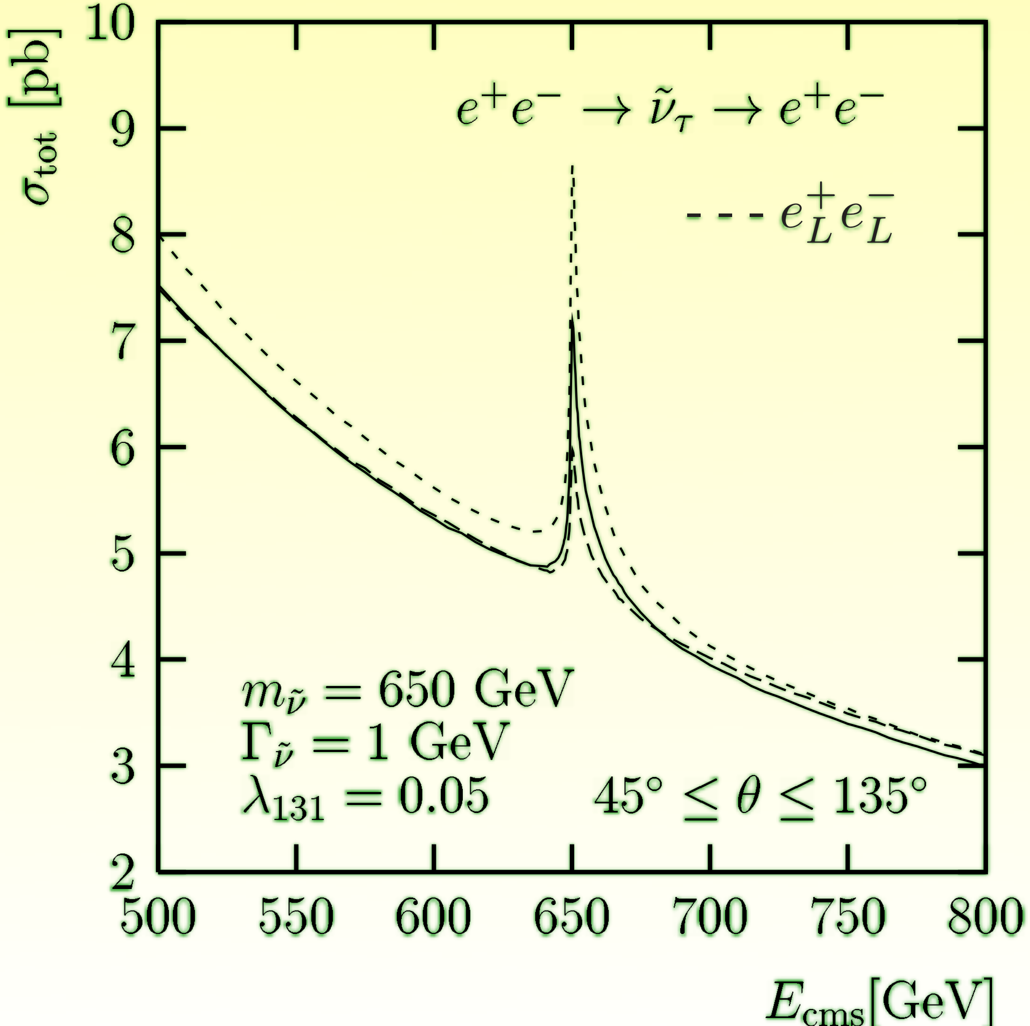
single sparticle production

$$e^+e^- \rightarrow \tilde{\nu} \rightarrow \ell\bar{\ell},\ \ell^\pm\tilde{\chi}_j^\mp$$

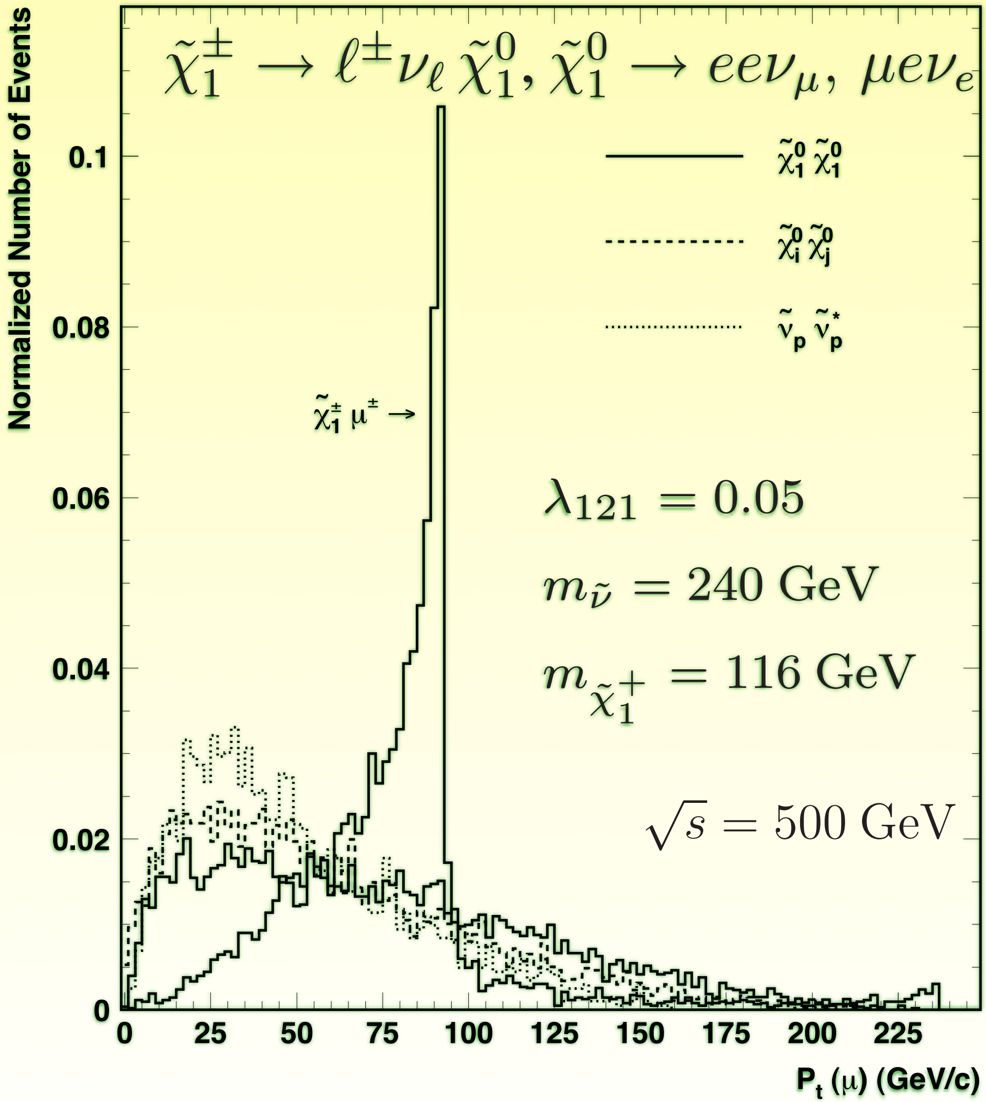
(for not too small $\not{R}_p$)

(enhanced by
beam polarization)

interference with Bhabha scattering



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



peak in recoil muon momentum can give accurate measurement of chargino mass

sensitivity to $\lambda_{121} = 10^{-4}$

for masses $m_{\tilde{\nu}} \simeq 150-600$ GeV

Significant $\not{R}_p$ coupling can also be present in the third generation fermion sector (eg. stop ...). ILC good probe !

Summary from mass precision in SPSa1

	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm, W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0 \tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	3 – 5	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^0 \tilde{\chi}_3^0, \tilde{\chi}_3^0 \tilde{\chi}_4^0$, 750 GeV, $> 1000\ \text{fb}^{-1}$
$\tilde{\chi}_4^0$	377.8	3 – 5	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \tilde{\chi}_4^0, \tilde{\chi}_3^0 \tilde{\chi}_4^0$, 750 GeV, $> 1000\ \text{fb}^{-1}$
$\tilde{e}_R$	143.0	0.05	$e^- e^-$ threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	$e^- e^-$ threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [36]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1} [36]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\min}()$, 1TeV, 1000 fb^{-1}

Conclusions

ILC has a great potential for **probing** both the **main characteristics** and the **fine-structure** of the scalar SUSY partners of SM fermions.