Sleptons: masses, couplings, mixings

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1. Overview
2. Theoretical picture
3. Experimental methods: masses, mixings, couplings

Overview

SUSY analysis program:

1. Establish supersymmetry breaking pattern
   ↳ { Determine slepton masses and mixings
   ↳ { Extrapolate to high scales → talk of W. Porod

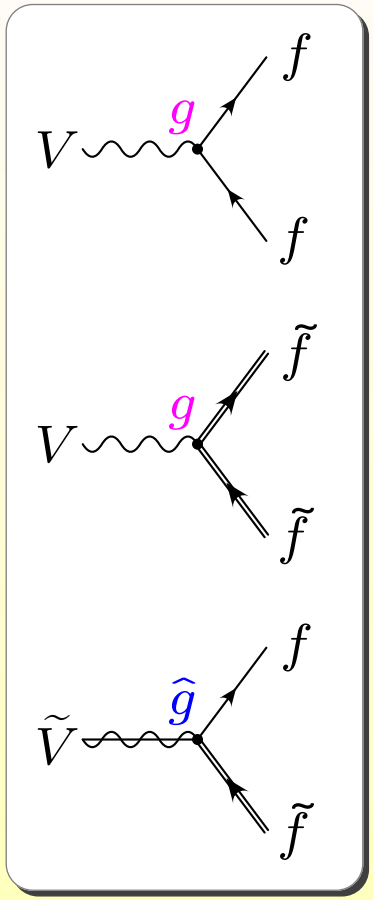
2. Establish fundamental supersymmetry relation

   Gauge coupling g = Yukawa coupling $\hat{g}$

   → required to resolve hierarchy problem

   → compare precise cross-section measurements with theoretical predictions

3. Identify particle spins



Precision measurements: ideal at high-energy e^+e^- collider

Masses and decay characteristics

Use different decay modes to disentangle $\tilde{l}_R, \tilde{l}_L$

$\tilde{l}_R \to l^- \, \tilde{\chi}_1^0$ $\qquad \Gamma_{\tilde{l}_R} = 210$ MeV

$\tilde{l}_L \to l^- \, \tilde{\chi}_2^0$ $\qquad \Gamma_{\tilde{l}_L} = 250$ MeV

$\hookrightarrow \tau^+ \tau^- \, \tilde{\chi}_1^0$

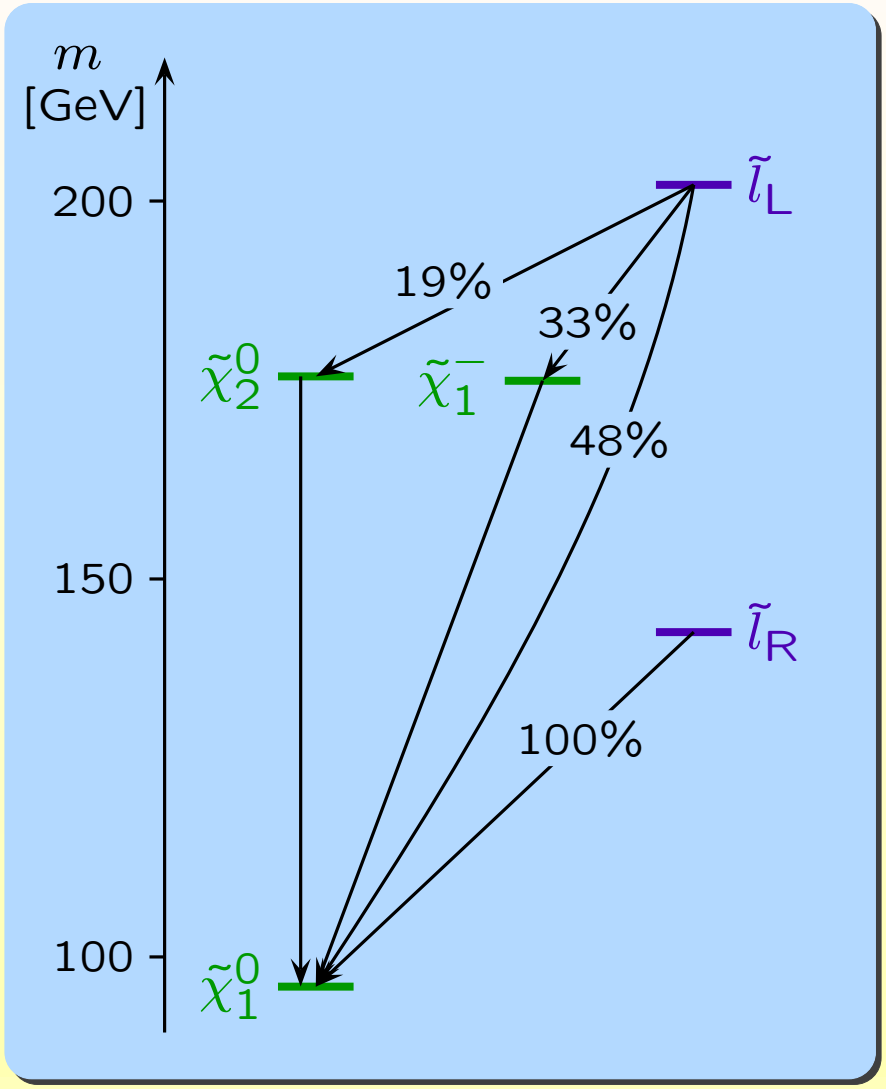
$\to \nu_l \, \tilde{\chi}_1^-$

$\hookrightarrow \tau^- \nu_\tau \, \tilde{\chi}_1^0$

very clean signature:

few leptons $+ \not{E}$

SPS1a scenario



Sneutrinos mainly decay invisibly in SPS1a:

$\tilde{\nu}_e \to \nu_e \tilde{\chi}_1^0$ $\qquad \Gamma_{\tilde{\nu}_e} = 160$ MeV

$\to \nu_e \tilde{\chi}_2^0$

$\hookrightarrow \tau^+ \tau^- \tilde{\chi}_1^0$

$\to e^\pm \tilde{\chi}_1^\mp$

$\hookrightarrow \tau^\mp \nu_\tau \tilde{\chi}_1^0$

For sneutrino pair production consider the mode

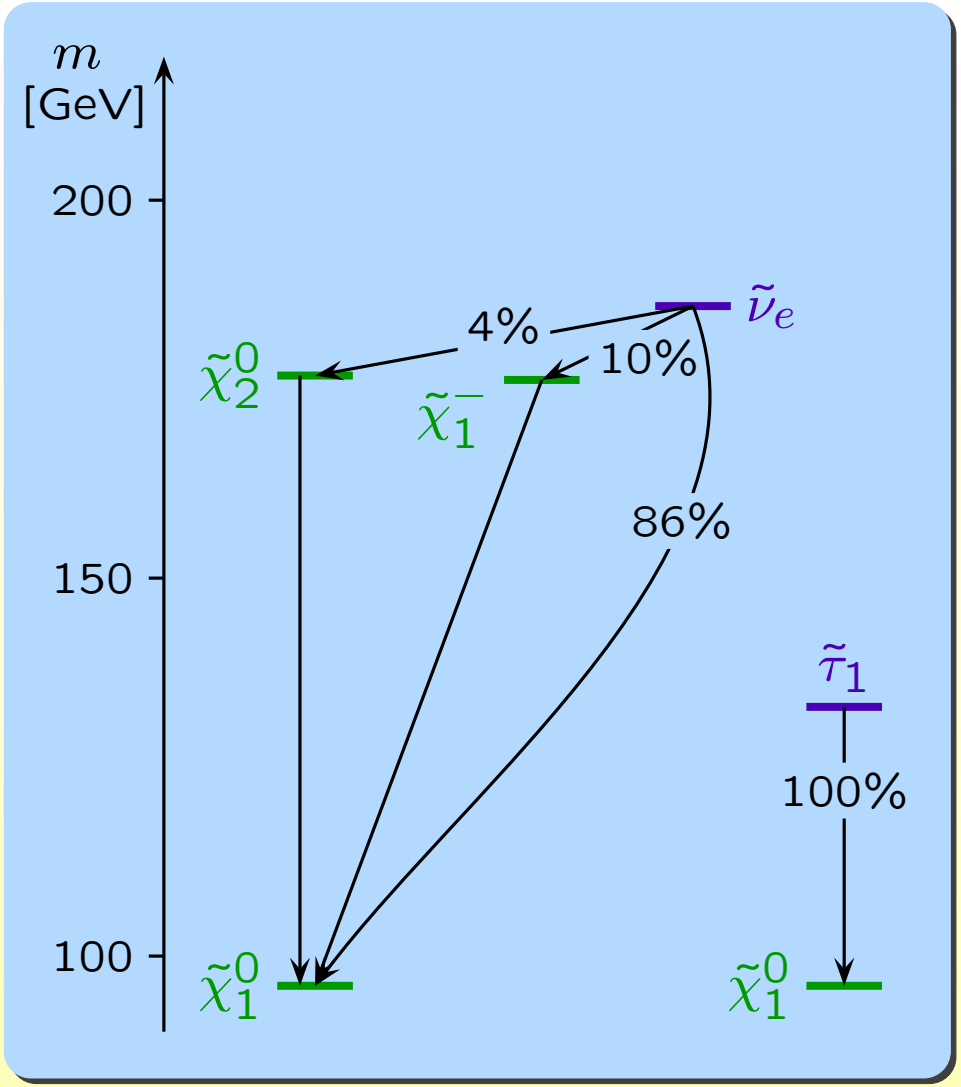
$e^+e^- \to \tilde{\nu}_e \tilde{\nu}_e^* \to \nu_e \tilde{\chi}_1^0 \, e^\pm \tilde{\chi}_1^\mp$

$\hookrightarrow \tau^\mp \nu_\tau \tilde{\chi}_1^0$

Only consider lighter $\tilde{\tau}$ here:

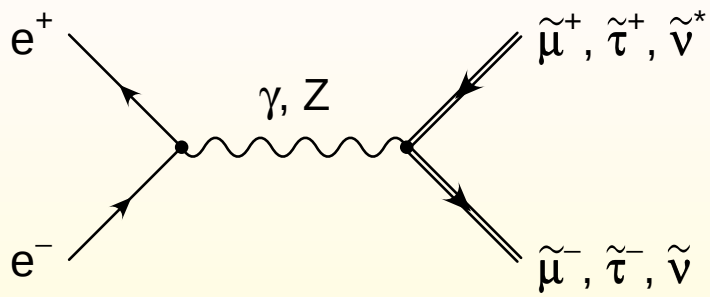
$\tilde{\tau}_1 \to \tau^- \tilde{\chi}_1^0$ $\qquad \Gamma_{\tilde{\tau}_1} = 150$ MeV

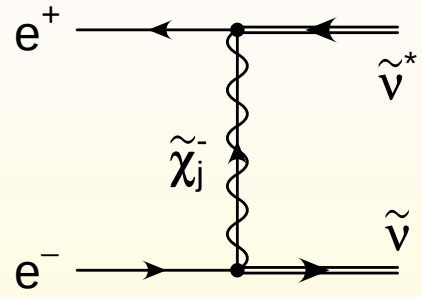
(No experimental studies for $\tilde{\tau}_2$ in SPS1a yet)



SPS1a scenario

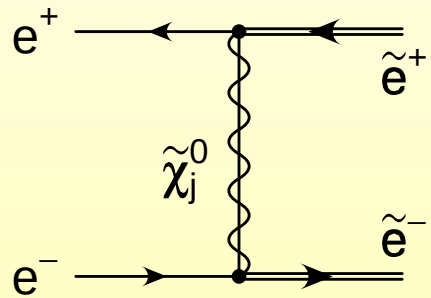
Slepton production

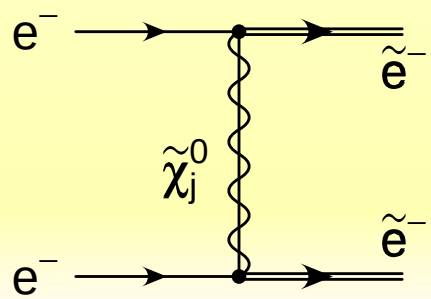




In general P-wave excitation $\propto \beta^3$

Additional t-channel neutralino exchange for selectrons:





$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-$	$[\gamma, Z, \tilde{\chi}^0]$	$\propto \beta^3$ (P-wave)
$e^+e^- \to \tilde{e}_R^+\tilde{e}_L^-$	$[\tilde{\chi}^0]$	$\propto \beta$ (S-wave)
$e^+e^- \to \tilde{e}_L^+\tilde{e}_L^-$	$[\gamma, Z, \tilde{\chi}^0]$	$\propto \beta^3$ (P-wave)
$e^-e^- \to \tilde{e}_R^-\tilde{e}_R^-$	$[\tilde{\chi}^0]$	$\propto \beta$ (S-wave)
$e^-e^- \to \tilde{e}_R^-\tilde{e}_L^-$	$[\tilde{\chi}^0]$	$\propto \beta^3$ (P-wave)
$e^-e^- \to \tilde{e}_L^-\tilde{e}_L^-$	$[\tilde{\chi}^0]$	$\propto \beta$ (S-wave)

Theoretical picture

Threshold analysis

Goal:

Measurements of slepton masses with high accuracy in threshold scans

Requirements for precise theoretical predictions:

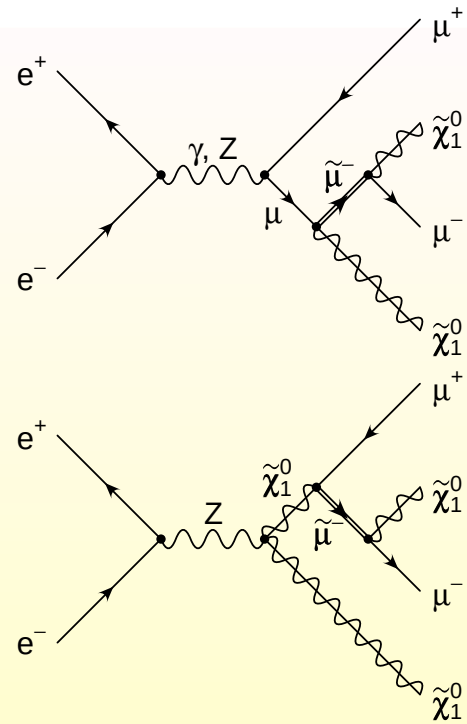
- Non-zero widths, gauge invariance
- Sommerfeld rescattering effects
- ISR / beamstrahlung
- (Backgrounds from SM and SUSY)

Non-zero width, gauge invariance

Gauge invariance can be violated by

- Production of off-shell Smuons

  → **Additional diagrams**
  with same final state

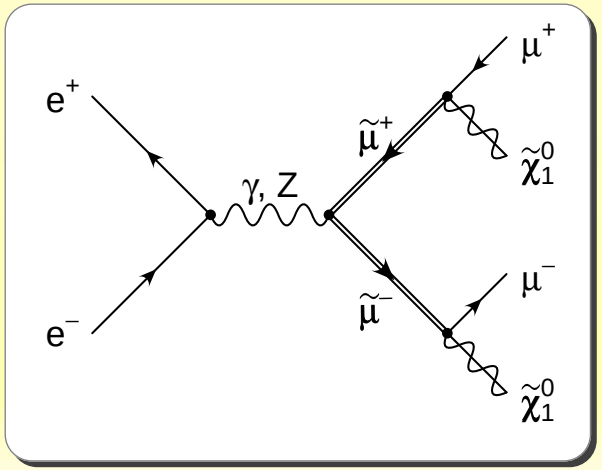


- Inclusion of finite widths
  (sub-class of higher order corrections)

  → **Complex mass:**

$$m_{\tilde{\mu}}^2 \to m_{\tilde{\mu}}^2 - i m_{\tilde{\mu}} \Gamma_{\tilde{\mu}}$$

  preserves all Ward identities

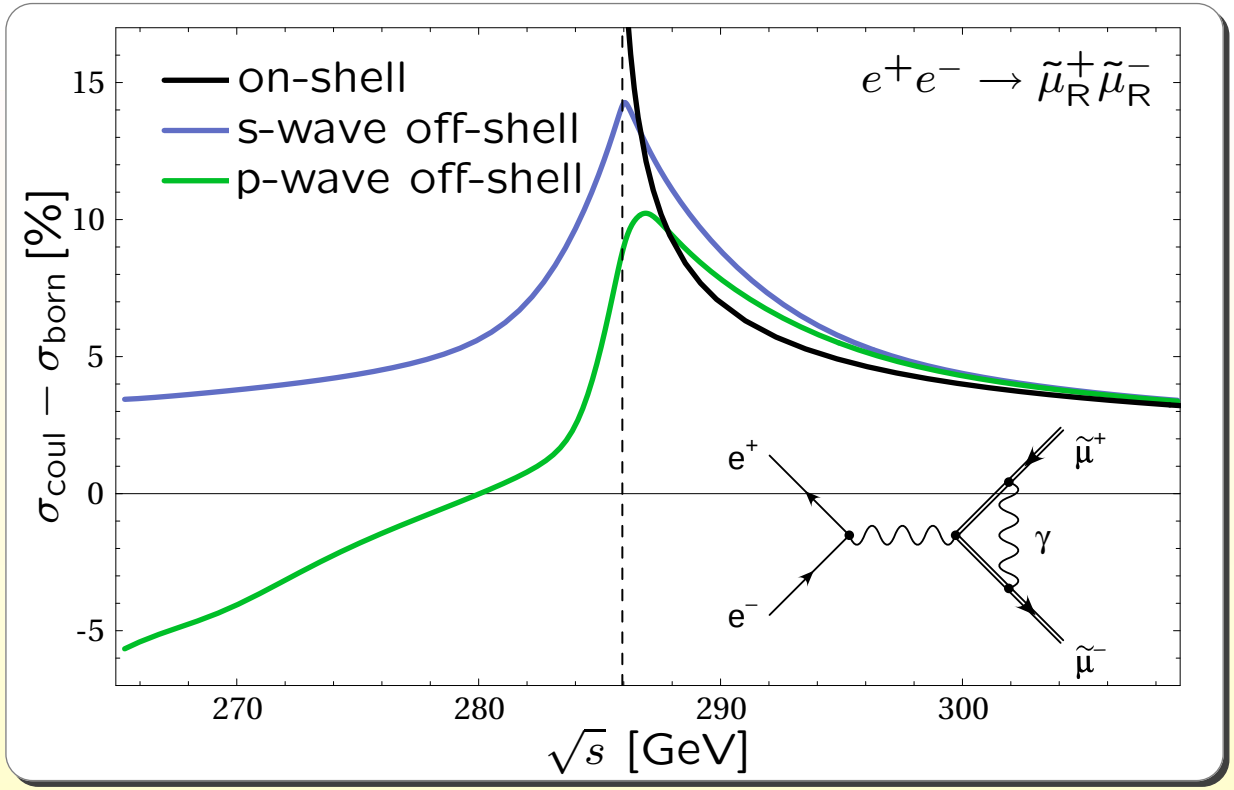


Coulomb correction

Slowly moving $\tilde{l}$'s near threshold

$\longrightarrow$ large corrections from γ exchange for

$$\beta = \sqrt{1 - \frac{4m^2}{s}} \longrightarrow 0$$



Off-shellness of the $\tilde{l}$'s:

Effective screening of Coulomb singularity

$$\sigma_{\rm coul} = \sigma_{\rm born}\,\frac{\alpha\pi}{2\beta}\left[1 - \frac{2}{\pi}\arctan\frac{|\beta_M|^2 - \beta^2}{2\,\beta\,\Im m\,\beta_M}\right]\Re e\,\mathcal{C}_l \qquad \mathcal{C}_l = \left[\frac{\beta^2 + \beta_M{}^2}{2\beta^2}\right]^l$$

$$\beta_M = \frac{1}{s}\sqrt{(s - M_+^2 - M_-^2)^2 - 4M_+^2M_-^2}, \qquad M_\pm^2 = m_\pm^2 - i m_\pm \Gamma_\pm$$

Slepton production in the continuum

Goal:

- Precise determination of supersymmetric couplings
- Mixing in third generation

$\rightarrow$ requires calculation of radiative corrections

$\mathcal{O}(\alpha)$ corrections completed for all relevant processes:

- Sfermion decay $\tilde{f} \to f\,\tilde{\chi}_i^0$, $\tilde{f} \to f'\,\tilde{\chi}_j^\pm$ — Guasch, Hollik, Solà '01
- Slepton production of first/second generation
  $e^+e^- \to \tilde{e}^+\tilde{e}^-$, $\tilde{\mu}^+\tilde{\mu}^-$, $\tilde{\nu}\tilde{\nu}^*$
  $e^-e^- \to \tilde{e}^-\tilde{e}^-$ — Freitas, v.Manteuffel, Zerwas '02,04
- Third generation slepton production
  $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$ — Arhrib, Hollik '03
  Kovařík, Weber, Eberl, Majerotto '04

Renormalization

SPA conventions: → talks of W. Majerotto, T. Fritzsche

- On-shell (pole mass) renormalization for masses
- SUSY Lagrange parameters in $\overline{\text{DR}}$ with $\tilde{\mu} = 1$ TeV
- Mixing angles and matrices in $\overline{\text{DR}}$ with $\tilde{\mu} = 1$ TeV

→ for sleptons:

- Slepton masses fixed on-shell
- Neutralino/chargino system fixed through on-shell masses
- Slepton mixing angle and $\tan\beta$ fixed in $\overline{\text{DR}}$

Neutralino/chargino renormalization

$$X = \begin{pmatrix} M_2 & \sqrt{2}M_W s_\beta \\ \sqrt{2}M_W c_\beta & \mu \end{pmatrix} \qquad Y = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$\rightarrow$ 3 parameters (M_1, M_2, μ) and 6 physical particles ($\tilde{\chi}^{\pm}_{1,2}$, $\tilde{\chi}^0_{1\ldots4}$)

1. On-shell conditions for all particles
2. Determine counterterms for M_1, M_2, μ from conditions for e.g. $\tilde{\chi}^{\pm}_{1,2}$, $\tilde{\chi}^0_1$
3. Calculate other mass counterterms ($\tilde{\chi}^0_{2,3,4}$)
   $\rightarrow$ shift in $m_{\tilde{\chi}^0_{2,3,4}}$ predicted

Two technically different but equivalent prescriptions on market:

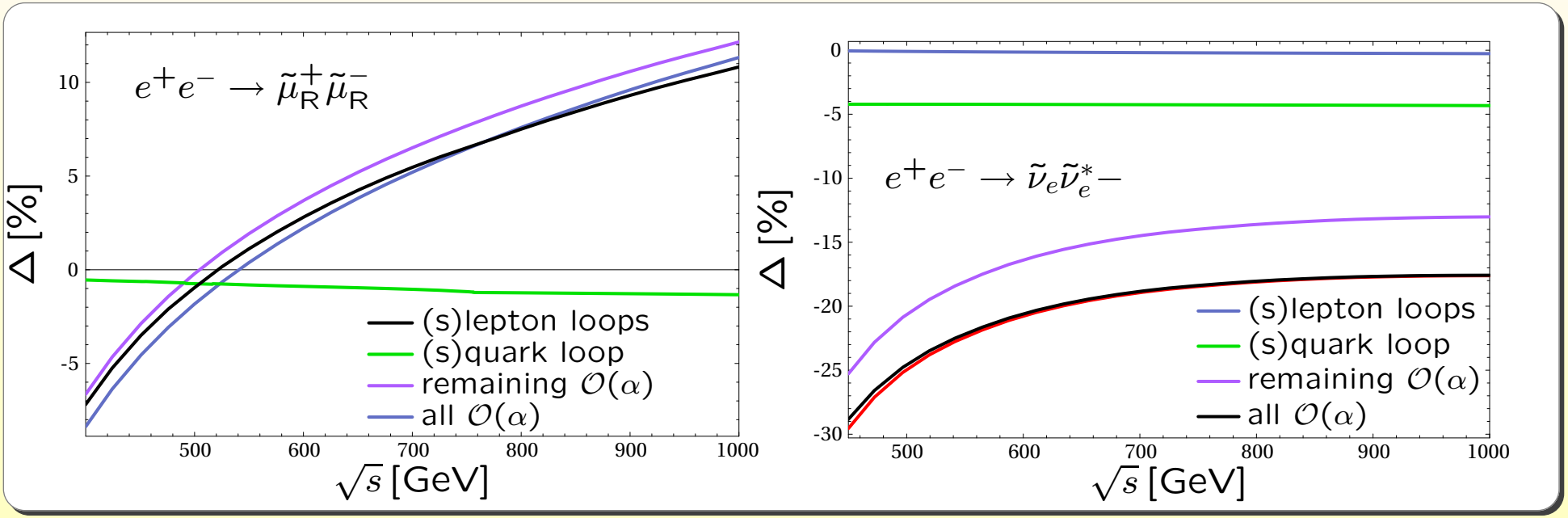
Eberl, Majerotto, Kincel, Yamada '01

Pierce Papadopoulos '94

Fritzsche,Hollik '02

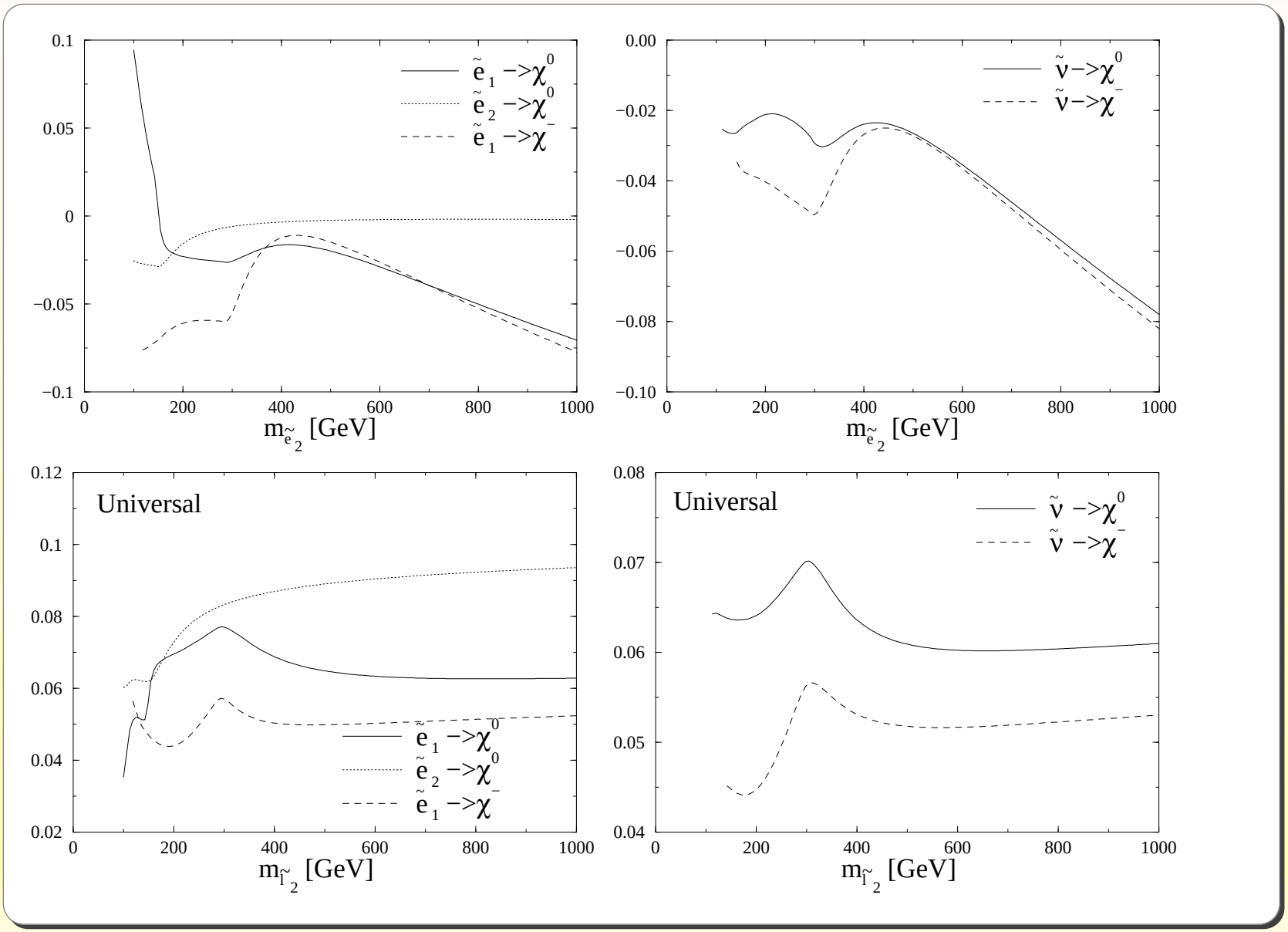
Typical examples

- Slepton production:



$$\Delta = \frac{\sigma_\alpha - \sigma_{\text{Born}}}{\sigma_{\text{Born}}}$$

Slepton decay:



Experimental methods: masses, mixings, couplings

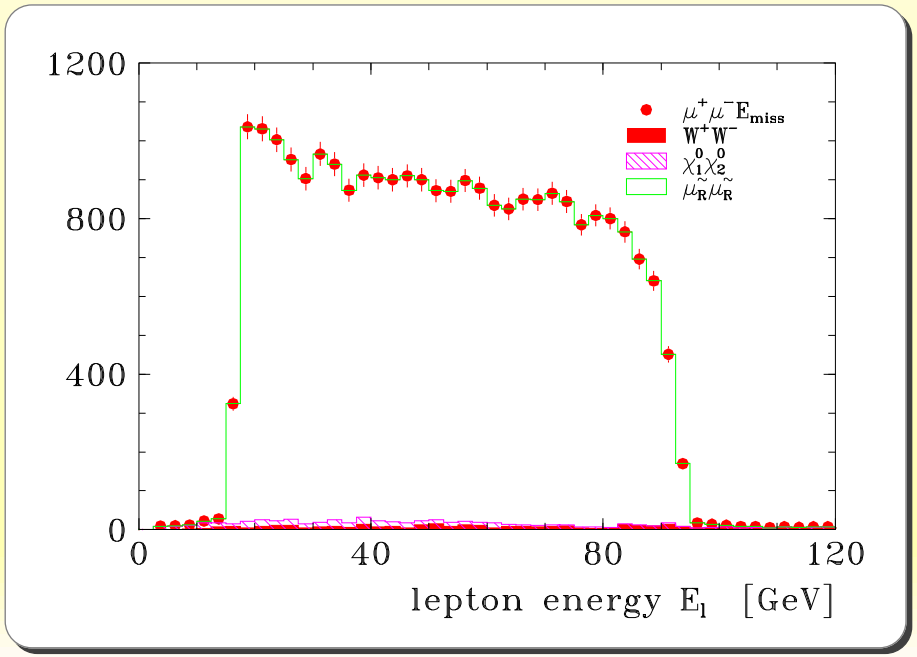
Slepton masses

- From edges in decay energy distributions

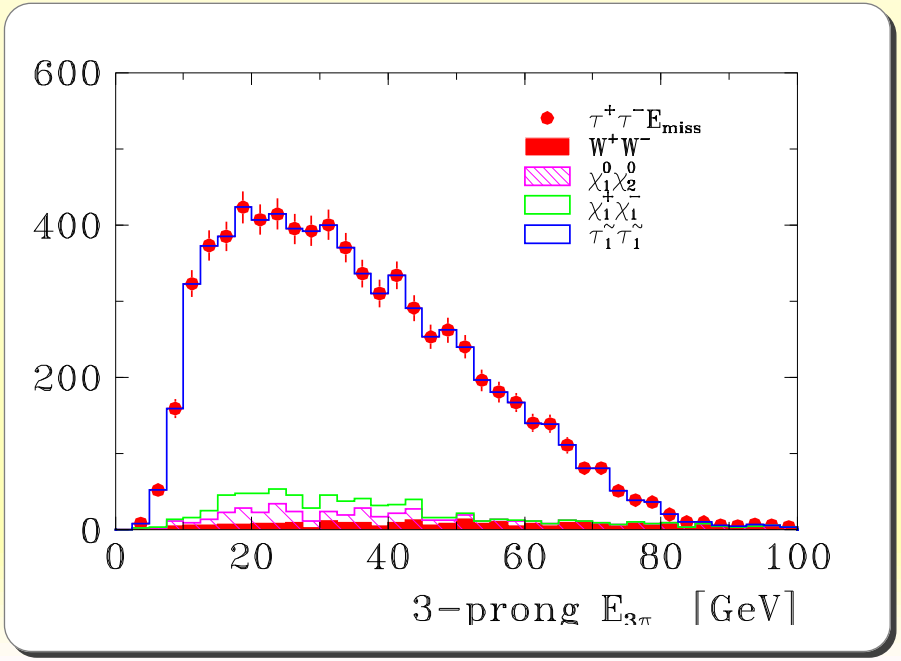
Examples:

Martyn '03

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



$\tilde{\tau}_1 \to \tilde{\chi}_1^0 \tau \to 3\pi + \not{E}$

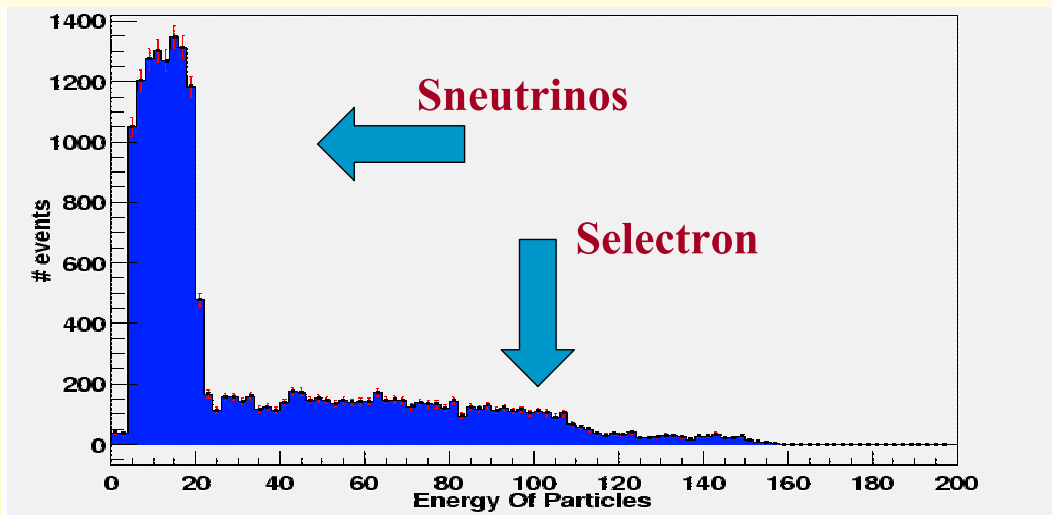


Note: For selectrons can also use subtraction of polarized e^+ and e^- spectra to reduce backgrounds

Sneutrino spectrum: One $\tilde{\nu}$ decaying invisibly

$$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e^* \to \nu_e\tilde{\chi}_1^0\, e^\pm\tilde{\chi}_1^\mp \to \nu_e\tilde{\chi}_1^0\, e^\pm\, \tau^\mp\nu_\tau\, \tilde{\chi}_1^0 \to e^\pm\mu^\mp + \not{E}$$

Nauenberg et al. '02



■ Threshold scans

Freitas, v.Manteuffel, Martyn, Zerwas '00–04

in general P-waves $\propto \beta^3$

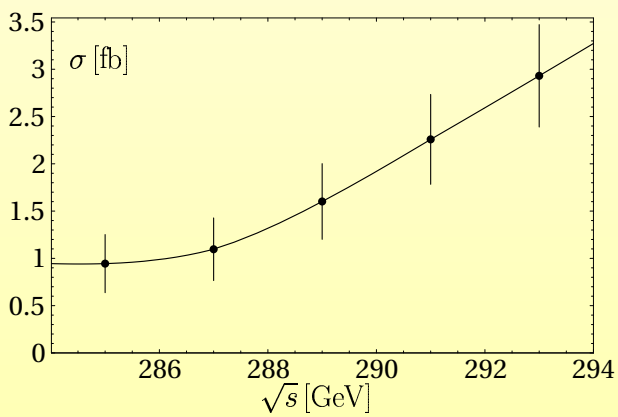
exceptions: (S-waves)
$$\left.\begin{array}{l} e^+_L e^-_L \to \tilde{e}^+_R \tilde{e}^-_L \\ e^-_R e^-_R \to \tilde{e}^-_R \tilde{e}^-_R, \ldots \end{array}\right\} \propto \beta$$

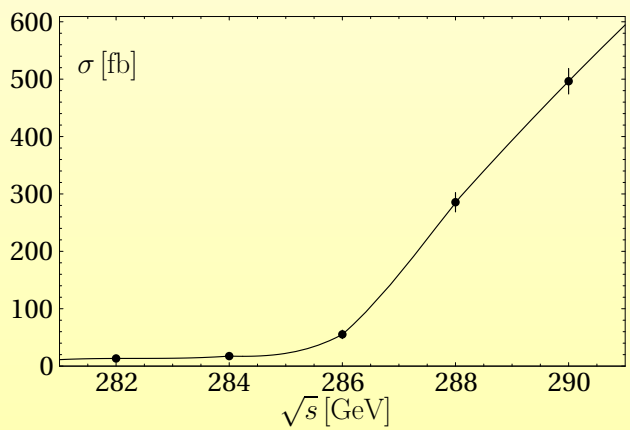
typically
5×10 fb^{-1} in e^+e^-
$5 \times \ \ 1$ fb^{-1} in e^-e^-

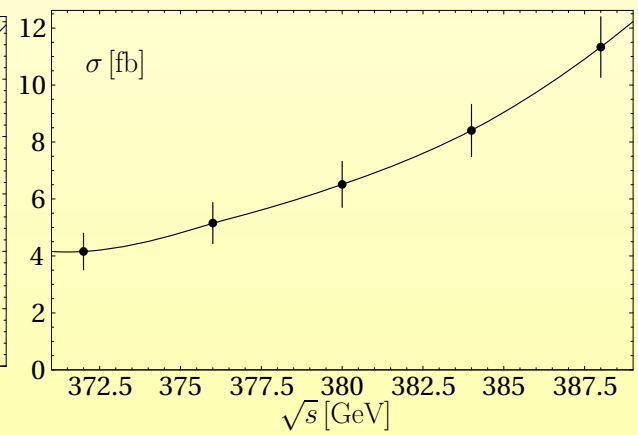
$$e^+e^- \to \tilde{\mu}^+_R \tilde{\mu}^-_R \to \mu^+ \mu^- + \not{E}$$
$\propto \beta^3$

$$e^-e^- \to \tilde{e}^-_R \tilde{e}^-_R \to e^- e^- + \not{E}$$
$\propto \beta$

$$e^+e^- \to \tilde{\nu}^*_e \tilde{\nu}_e \to e^+ \tilde{\chi}^0_1 \, \nu_e \tilde{\chi}^-_1 \to e^+ \tau^- + \not{E}$$
$\propto \beta^3$







incl. beamstrahlung, ISR, etc.

Results for SPS1a:

	m [GeV]	Δm [GeV] spectra	thr. scans	combine	Γ [GeV]
$\tilde{\chi}_1^0$	96.1	0.10	–	$0.065^{(a)}$	–
$\tilde{e}_R$	143.0	0.08	0.05	0.05	0.21 ± 0.05
$\tilde{e}_L$	202.1	0.8	0.2	0.2	0.25 ± 0.02
$\tilde{\nu}_e$	186.0	1.2	1.1	1.1	$0.16^{+0.7}_{-0.5}$
$\tilde{\mu}_R$	143.0	0.2	0.2	$0.085^{(b)}$	0.2 ± 0.2
$\tilde{\mu}_L$	202.1	–	$0.5^{(c)}$		?
$\tilde{\tau}_1$	133.2	0.3	?		?
$\tilde{\tau}_2$	133.2	?	$1.1^{(d)}$		?

$^{(a)}$ from $\tilde{e}_R$ spectrum using selectron mass determined at threshold
$^{(b)}$ from $\tilde{\mu}_R$ spectrum using $\tilde{\chi}_1^0$ mass as input
$^{(c,d)}$ estimate for threshold scan [P. Grannis]

3rd generation

Determination of $\tilde{\tau}$ masses as before

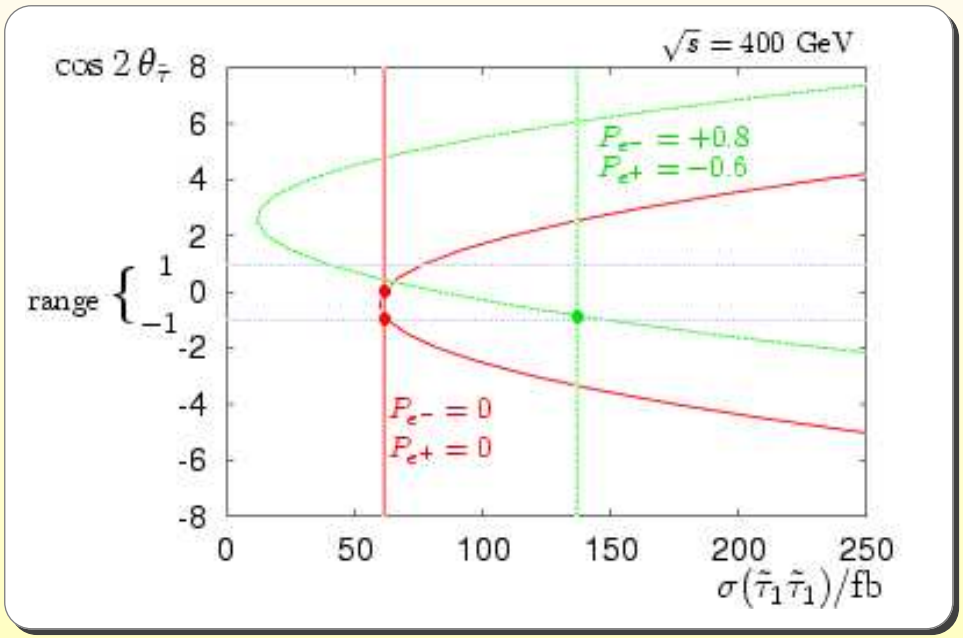
$m_{\tilde{\tau}_2}$ at SPS1a not yet clear

Mixing angle $\theta_{\tilde{\tau}}$ from $\sigma(\tilde{\tau}_1\tilde{\tau}_1)$ with polarized $e^{\pm}$ beams

$\rightarrow$ $\tilde{\tau}_1$, $\tilde{\tau}_2$ couple differently to Z

$\Rightarrow$ $\cos 2\theta_{\tilde{\tau}} = -0.84 \pm 0.04$

Martyn '03



Ultimate goal:

Extract A_τ using

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

from χ sector

intern: τ polarization

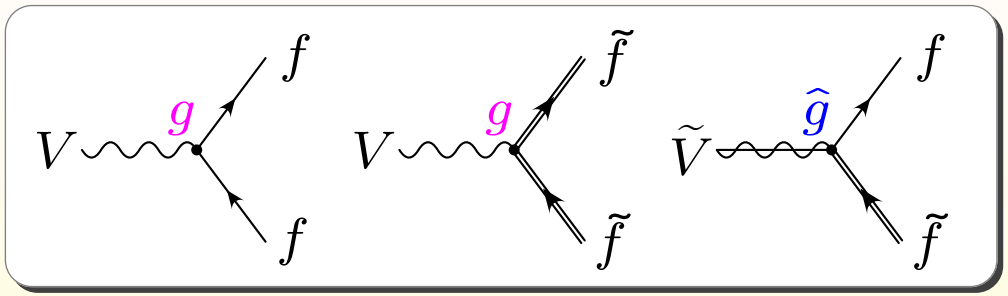
extern: χ or Higgs sector

Boos et al. '03

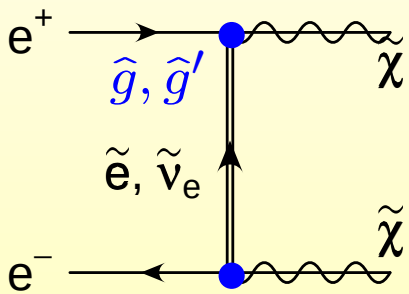
$\rightarrow$ difficult due to large cancellations

Slepton couplings

Electroweak gauge & Yukawa couplings can be probed in



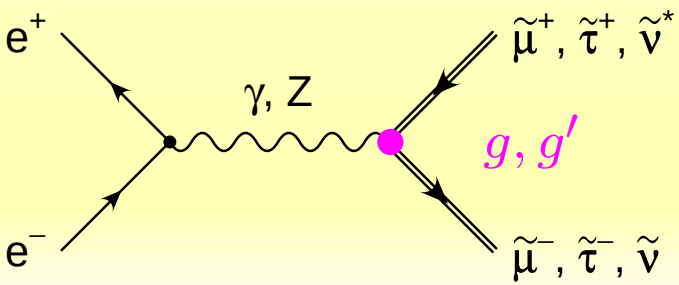
- Neutralino production

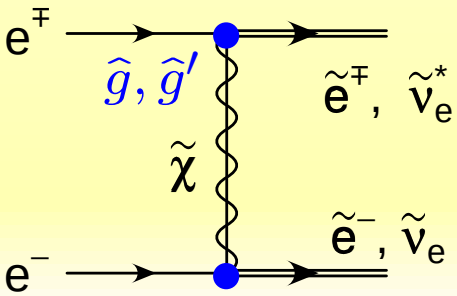


Choi, Kalinowski, Moortgat-Pick, Zerwas '01

- Slepton production

Freitas, v.Manteuffel '02





g' U(1) coupl.

g SU(2) coupl.

Determination of Yukawa couplings

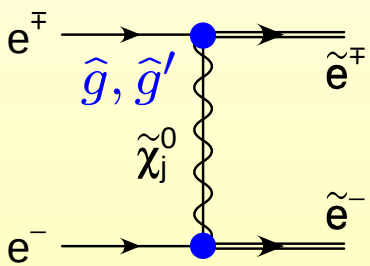
From selectron cross-sections

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

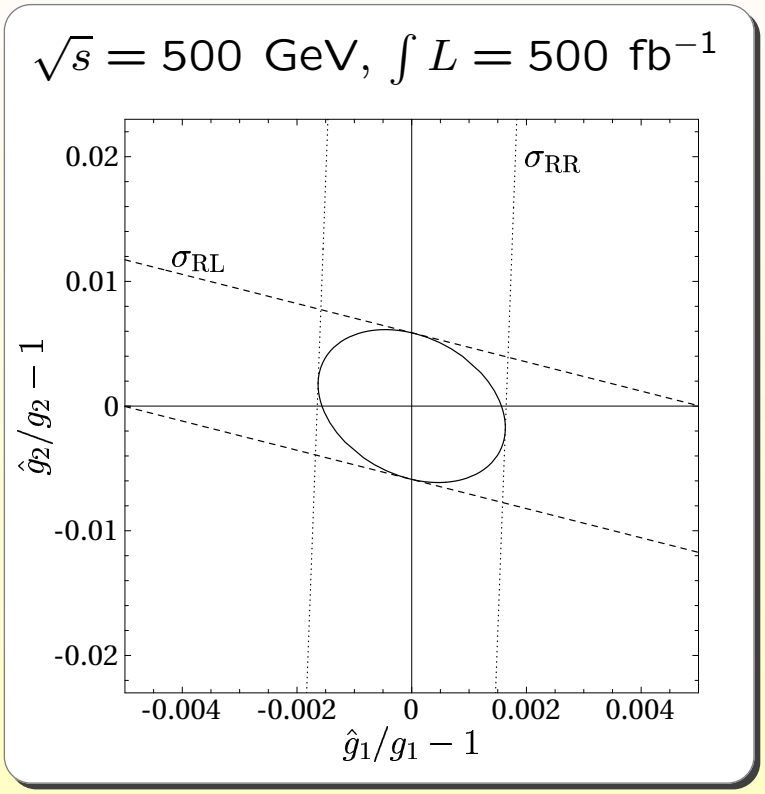
$e^+e^- \to \tilde{e}_R^+\tilde{e}_L^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_2^0$

$\hookrightarrow \tau^+\tau^-\,\tilde{\chi}_1^0$

Use polarized beams to disentangle U(1) and SU(2) couplings



$$\frac{\delta\hat{g}'}{\hat{g}'} \approx 0.2\% \qquad \frac{\delta\hat{g}}{\hat{g}} \approx 0.7\%$$

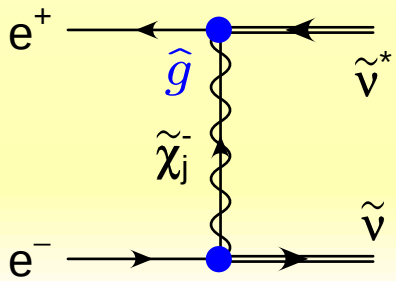


From sneutrino cross-section **only** SU(2) coupling $\hat{g}$

$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e^* \to \nu_e\tilde{\chi}_1^0\, e^\pm\tilde{\chi}_1^\mp$

$\hookrightarrow \tau^\mp\nu_\tau\,\tilde{\chi}_1^0$

$$\frac{\delta\hat{g}}{\hat{g}} \approx 5\%$$



Conclusions

Hunting for SUSY.....

- Slepton sector is **best understood** sector of MSSM – theoretically and experimentally
- Experimental analyses at per-cent to per-mille level
- Theoretical calculations under control at per-cent level $\rightarrow$ more work might be needed
- Testing fundamental concepts of SUSY:
  relation between gauge and Yukawa couplings: $g = \hat{g}$
- Precise determination of masses and mixings:
  $\rightarrow$ base of reconstructing high scale theory of SUSY breaking