C. A. HEUSCH

La Thuile 2002

SUSY PRECISION MEASUREMENTS AT THE LINEAR COLLIDER

SLEPTON MASS MEASUREMENTS:

SELECTRONS, SMUONS

NEUTRALINO MASSES AND PHASES

FLAVOR VIOLATION

Acknowledgments to

Claus Bloechinger
David Miller
Michael Peskin
Jonathan Feng, H.S. Chen

The greatest challenge for our understanding of Supersymmetry will be our capability to determine a key set of its ~120 parameters:

masses
couplings
phases
mixing parameters ...

Let us start with

SLEPTON MASSES

$\tilde{e}_R, \tilde{e}_L$ $\tilde{\mu}_R, \tilde{\mu}_L$

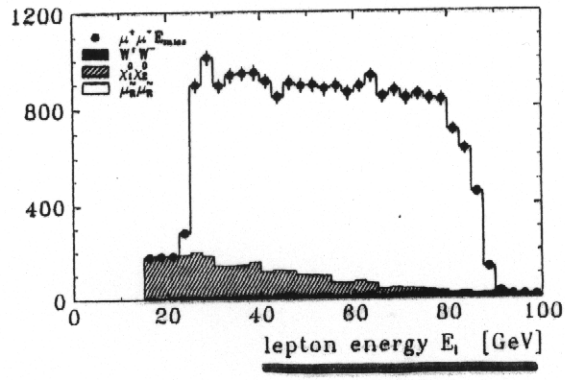
Even if the LHC "finds" them, their precise values will have to be found at the Linear Collider.

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

Scalar sleptons decay isotropically in their rest frame

→ flat lepton spectrum in lab frame

endpoints give slepton, neutralino masses

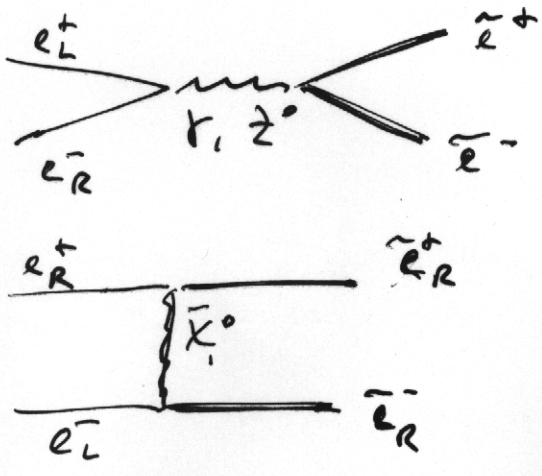


H.U. Martyn

More precise: threshold scan of production cross section

But recall: take selectron case,

expect $m(\tilde{e}_L) > m(\tilde{e}_R)$



$\sigma \sim \beta^3$

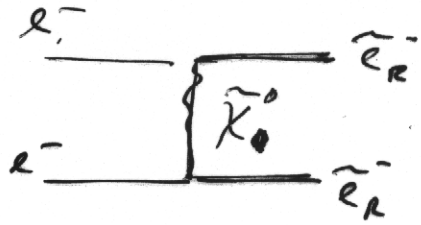
angular momentum barrier

hard-to-remove backgrounds!

Bonus:

If we have highly polarised e^-_R, e^-_L beams,

study threshold of $e^-e^- \to \tilde{e}^-_R \tilde{e}^-_R$

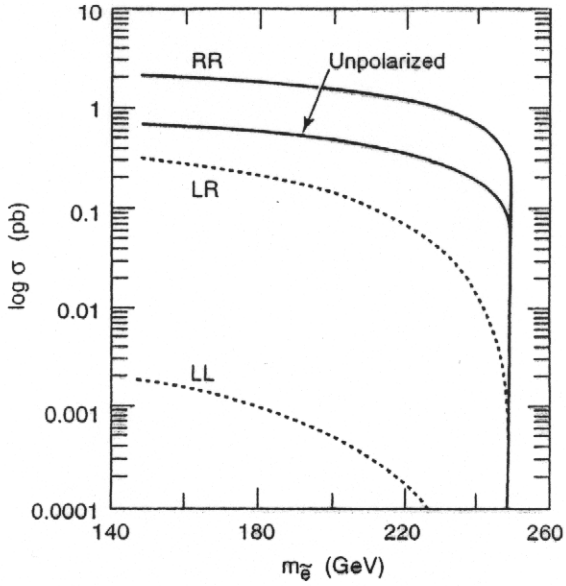


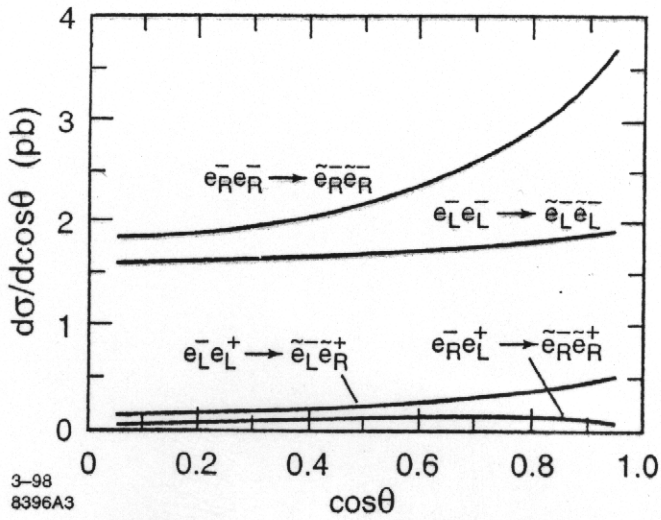
$\sigma \sim \beta$ at threshold

STEEP RISE

e^-_L switches off most backgrounds!

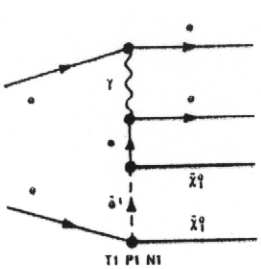
$$
\begin{aligned}
e^-_R e^+_L \to \tilde{e}^-_R \tilde{e}^+_R &: \frac{\pi\alpha^2}{2s}\beta^3 \sin^2\theta \left|\frac{s}{M_1^2} N_{RR}(t) - (1 + \frac{s_w^2}{c_w^2}\frac{s}{s-m_Z^2})\right|^2 \\
e^-_R e^+_L \to \tilde{e}^-_L \tilde{e}^+_L &: \frac{\pi\alpha^2}{2s}\beta^3 \sin^2\theta \left|1 - \frac{\frac{1}{2} - s_w^2}{c_w^2}\frac{s}{s-m_Z^2}\right|^2 \\
e^-_R e^+_R \to \tilde{e}^-_R \tilde{e}^+_L &: \frac{2\pi\alpha^2}{s}\beta\frac{s}{M_1^2}\left|M_{LR}(t)\right|^2 \\
e^-_L e^+_L \to \tilde{e}^-_L \tilde{e}^+_R &: \frac{2\pi\alpha^2}{s}\beta\frac{s}{M_1^2}\left|M_{LR}(t)\right|^2 \\
e^-_L e^+_R \to \tilde{e}^-_R \tilde{e}^+_R &: \frac{\pi\alpha^2}{2s}\beta^3 \sin^2\theta \left|1 - \frac{\frac{1}{2} - s_w^2}{c_w^2}\frac{s}{s-m_Z^2}\right|^2 \\
e^-_L e^+_R \to \tilde{e}^-_L \tilde{e}^+_L &: \frac{\pi\alpha^2}{2s}\beta^3 \sin^2\theta \left|\frac{s}{M_1^2} N_{LL}(t) - (1 + \frac{(\frac{1}{2} - s_w^2)^2}{c_w^2 s_w^2}\frac{s}{s-m_Z^2})\right|^2 \\
e^-_R e^-_R \to \tilde{e}^-_R \tilde{e}^-_R &: \frac{2\pi\alpha^2}{s}\beta\frac{s}{M_1^2}\left|M_{RR}(t) + M_{RR}(u)\right|^2 \\
e^-_L e^-_R \to \tilde{e}^-_L \tilde{e}^-_R &: \frac{\pi\alpha^2}{2s}\beta^3 \sin^2\theta \left|\frac{s}{M_1^2} N_{LR}(t)\right|^2 \\
e^-_L e^-_L \to \tilde{e}^-_L \tilde{e}^-_L &: \frac{2\pi\alpha^2}{s}\beta\frac{s}{M_1^2}\left|M_{LL}(t) + M_{LL}(u)\right|^2 .
\end{aligned}
$$



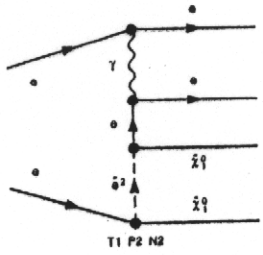


. Differential cross sections for four slepton production processes, computed at a point in the Higgsino region, with $m_2/\mu = -5$ for $\tan\beta = 4$. I have taken $M_1 = 50$, $m(e_R) = 150$, $m(e_L) = 200$, $\sqrt{s} = 500$ GeV.

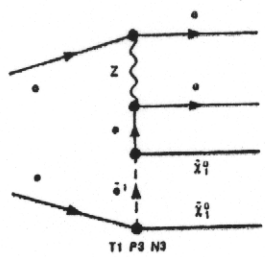
$e\ e \rightarrow e\ e\ \tilde{\chi}_1^0\ \tilde{\chi}_1^0$



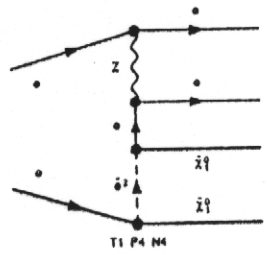
T1 P1 N1



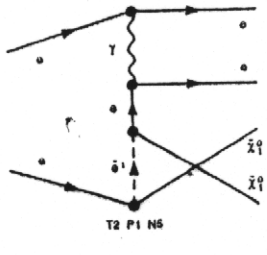
T1 P2 N2



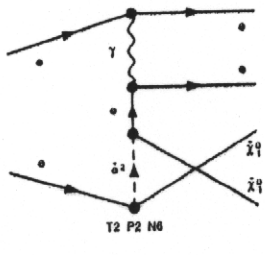
T1 P3 N3



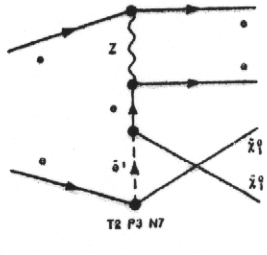
T1 P4 N4



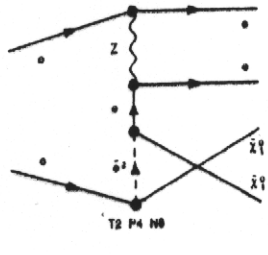
T2 P1 N5



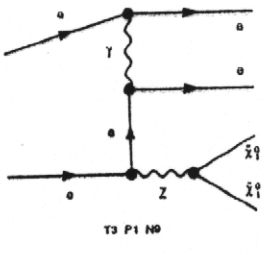
T2 P2 N6



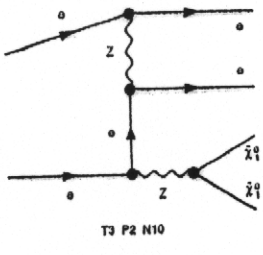
T2 P3 N7



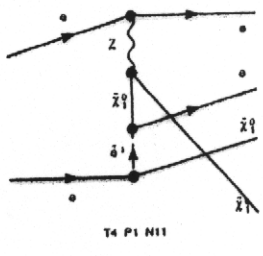
T2 P4 N8



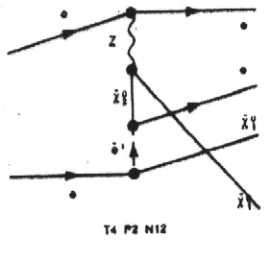
T3 P1 N9



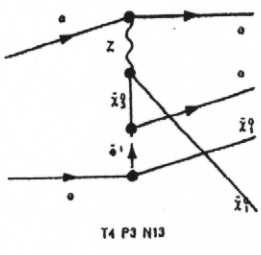
T3 P2 N10



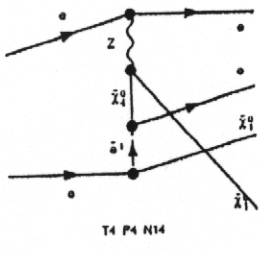
T4 P1 N11



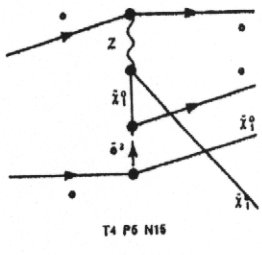
T4 P2 N12



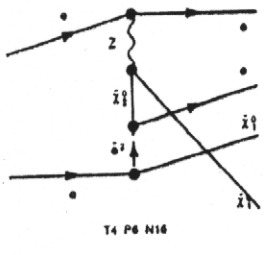
T4 P3 N13



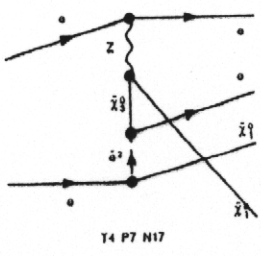
T4 P4 N14



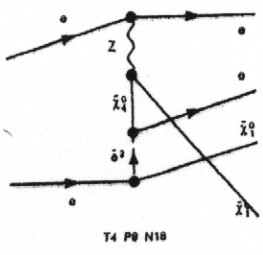
T4 P5 N15



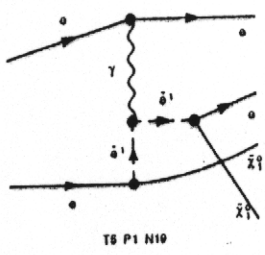
T4 P6 N16



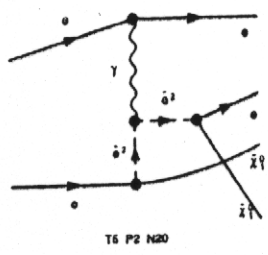
T4 P7 N17



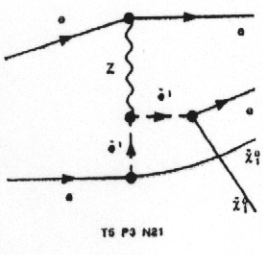
T4 P8 N18



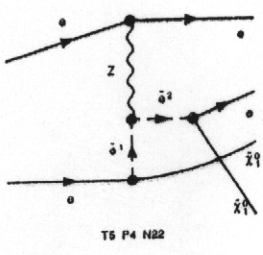
T5 P1 N19



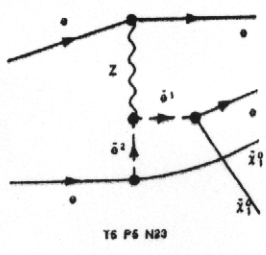
T5 P2 N20



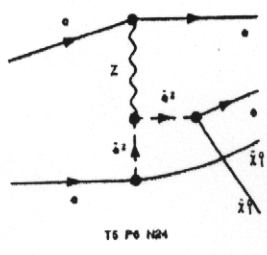
T5 P3 N21



T5 P4 N22



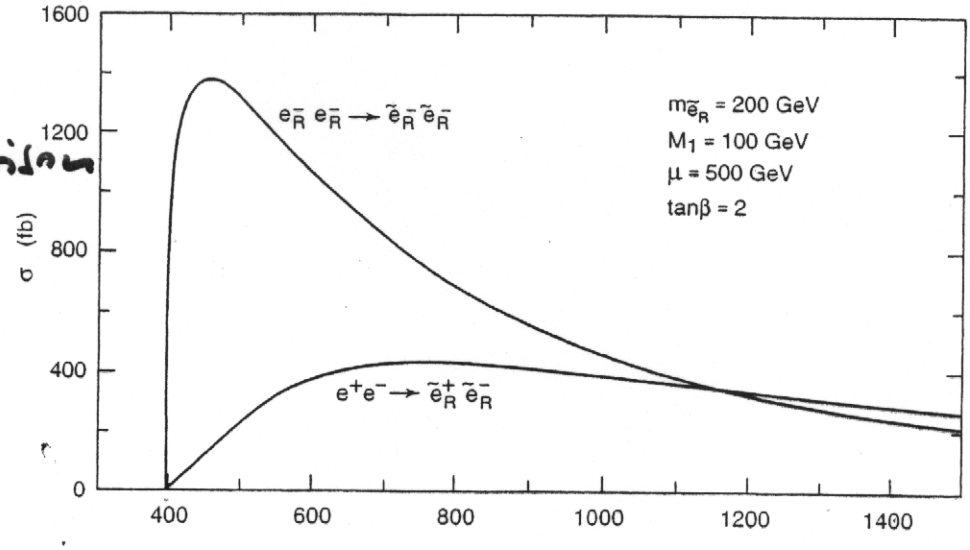
T5 P5 N23



T5 P6 N24

before $\tilde{e}^-$ width, beamstrahlung, rad 'cor's

rough comparison



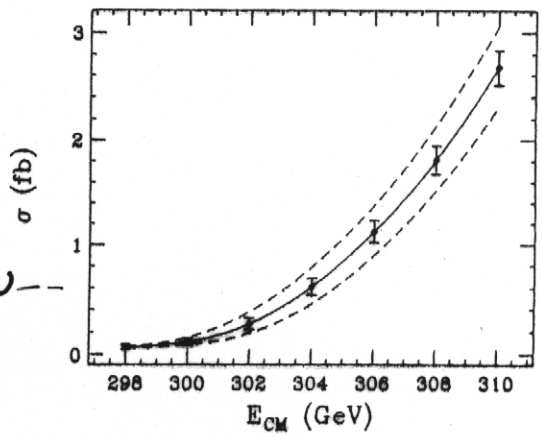
Feng & Peskin compared

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

$P_{e^-} = 0.8$

$\Delta m_{\tilde{e}_R} = \pm 100$ MeV

$1\ fb^{-1}$ per point

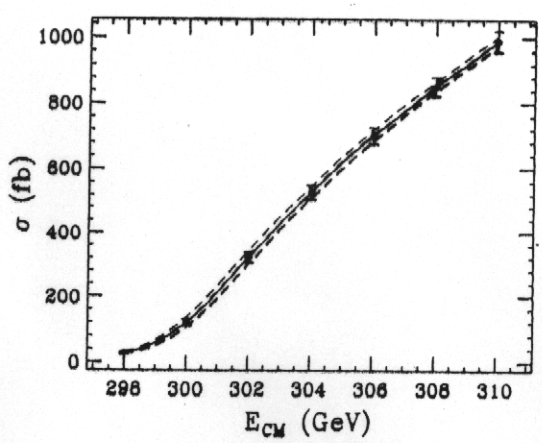


$e^+e^- \to \tilde{e}^+_R \tilde{e}^-_R$

$P_{e^+} = 0,\ P_{e^-} = 0.8$

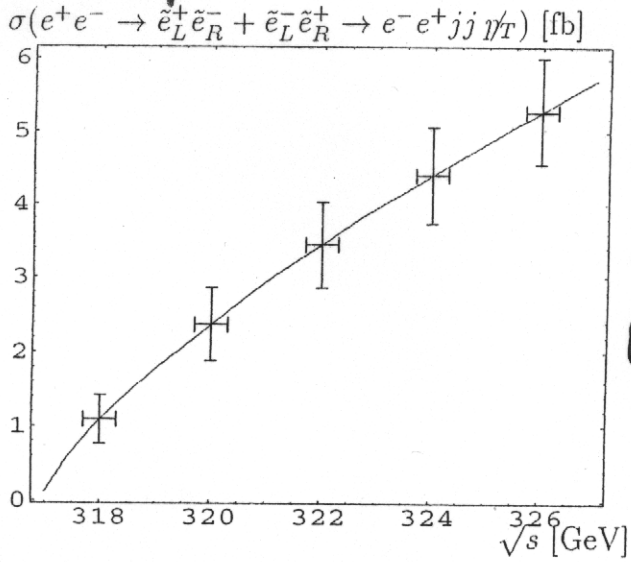
$\Delta m_{\tilde{e}_R} = \pm 400$ MeV

$100\ fb^{-1}$ per point



threshold scan for e^+e^-

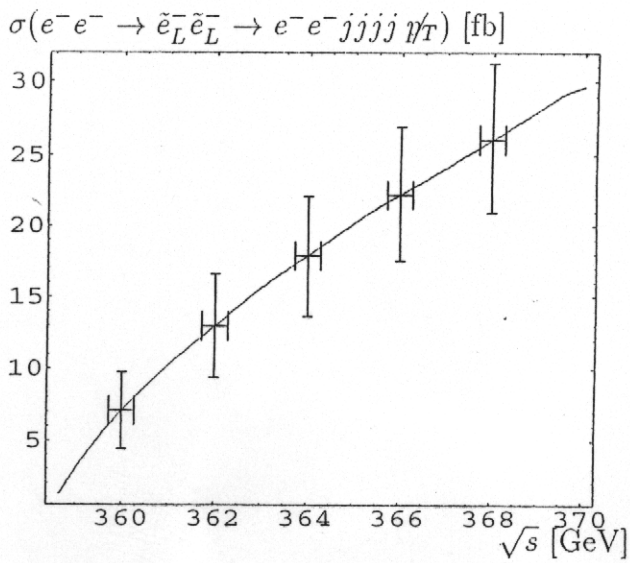
note the small slope



low e^+ pol'n, $m(\tilde{e}_L \neq \tilde{e}_R)$ make for poor threshold quality

Threshold behaviour of the processes $e^+e^- \to \tilde{e}_L^+\tilde{e}_R^- + \tilde{e}_L^-\tilde{e}_R^+ \to e^-e^+jj\ \not{p}_T$ for $P_{e^-} = 0.8$ and $P_{e^+} = 0.6$, $M_2 = 152$ GeV, $\mu = 316$ GeV and $\tan\beta = 3$. ISR corrections and beamstrahlung are included. The error bars show the statistical error for $\mathcal{L} = 10$ fb^{-1}.

... and for e^-e^-



clean signal, well-defined mass resolution!

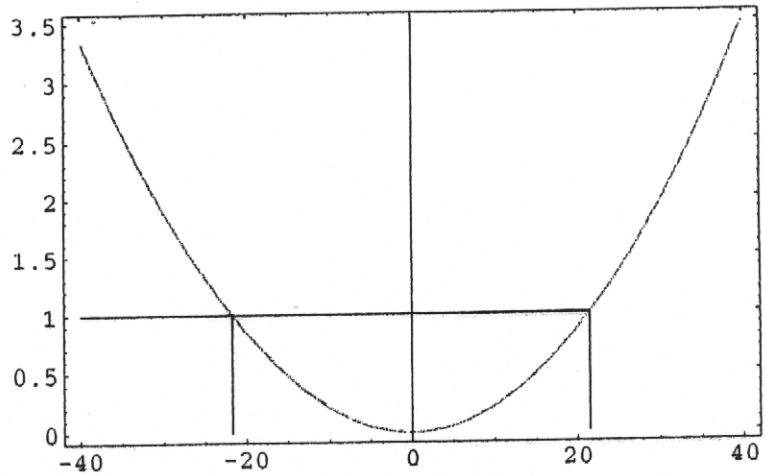
Threshold behaviour of the process in $e^-e^- \to \tilde{e}_L^-\tilde{e}_L^- \to e^-e^-jjjj\not{p}_T$ for $P_{e_1} = -0.8$ and $P_{e_2} = -0.8$. ISR corrections and beamstrahlung are included. The error bars show the statistical error for $\mathcal{L} = 1$ fb^{-1}.

Bloc̈hinger and Mayer, in preparation

- calculated the total cross section of

$$e^-e^- \to \tilde{e}^-_{L/R}\tilde{e}^-_{L/R} \to e^-e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$$

- Include ISR and beamstrahlung (use **Pandora**)
- Perform χ^2 fit and find:

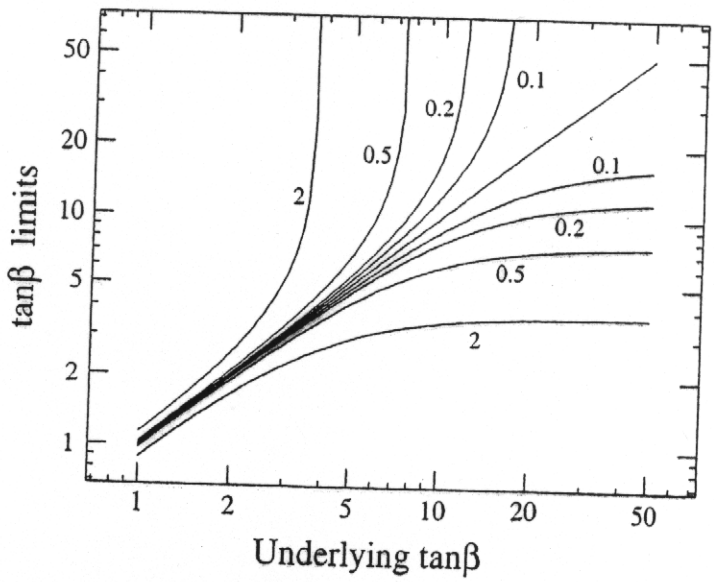


$\Delta m_{\tilde{e}_R} \approx 22 MeV$ with 1 fb^{-1} .

- For the left selectron an error of 400-500 MeV is feasable (preliminary)

Why do we want such precise information on selectron etc. masses?

ACCESS TO $\tan\beta$



Contours giving the upper and lower limits on $\tan\beta$ for a given underlying $\tan\beta$ and experimental uncertainty in mass difference $\Delta m \equiv m_{\tilde{e}_L} - m_{\tilde{\nu}_e}$ as indicated (in GeV), for fixed $m_{\tilde{\nu}_e} = 200$ GeV.

Recall that, at tree level

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

we measure these — we know this

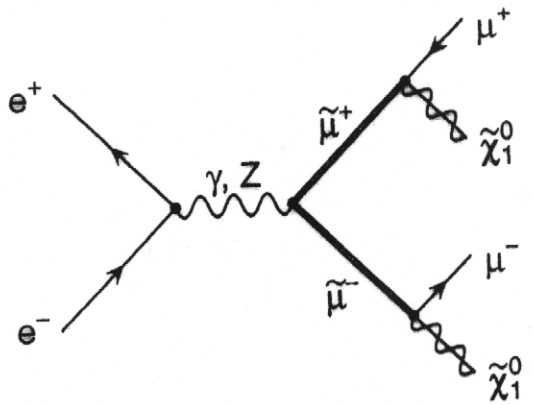
2nd Generation:

3. [redacted] collisions

- s-channel γ, Z exchange
- P-wave $\Rightarrow$ Cross-section $\sim \beta^3$ at threshold
- Restrict to $\tilde{\mu}_R^+ \tilde{\mu}_R^-$ for simplicity
- Dominant decay $\tilde{\mu}_R^- \to \mu^- \tilde{\chi}_1^0$

Choose this final state for easy muon detection

[redacted]

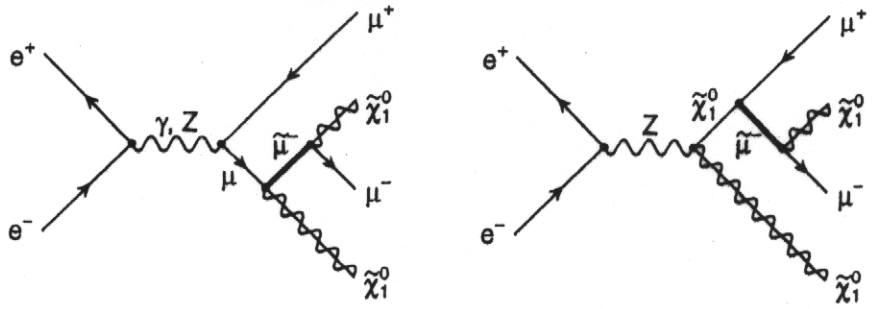


Double resonant graph is gauge dependent.

One can get any answer one likes!

Note:

⇒ **Must include singly resonant graphs in signal to give gauge invariant result**



- Include finite width by introducing the complex mass

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

- Cannot use double pole approximation at threshold
- Many more singly and non-resonant graphs which are now considered as backgrounds
- Signal and background amplitudes calculated using **Feynarts**
- Adaptive weight optimised Monte Carlo integration over phase space
- ISR included using structure function method
- Beamstrahlung included using **CIRCE**

ATTENTION: Unlike in the Selectron case, We now have large BACKGROUNDS

Backgrounds: $e^+e^- \to \mu^+\mu^- + \not{E}$

[redacted] backgrounds easy to remove:

[Blair, Martyn]

- 1. $e^+e^- \to W^+W^-$, $W \to \mu\nu$
- 2. $e^+e^- \to (\gamma/Z)(\gamma/Z)$, $\gamma/Z \to \mu^+\mu^-$, $\gamma/Z \to \nu\bar{\nu}$

Remove 1: W decay leptons lie approx. in an azimuthal plane.

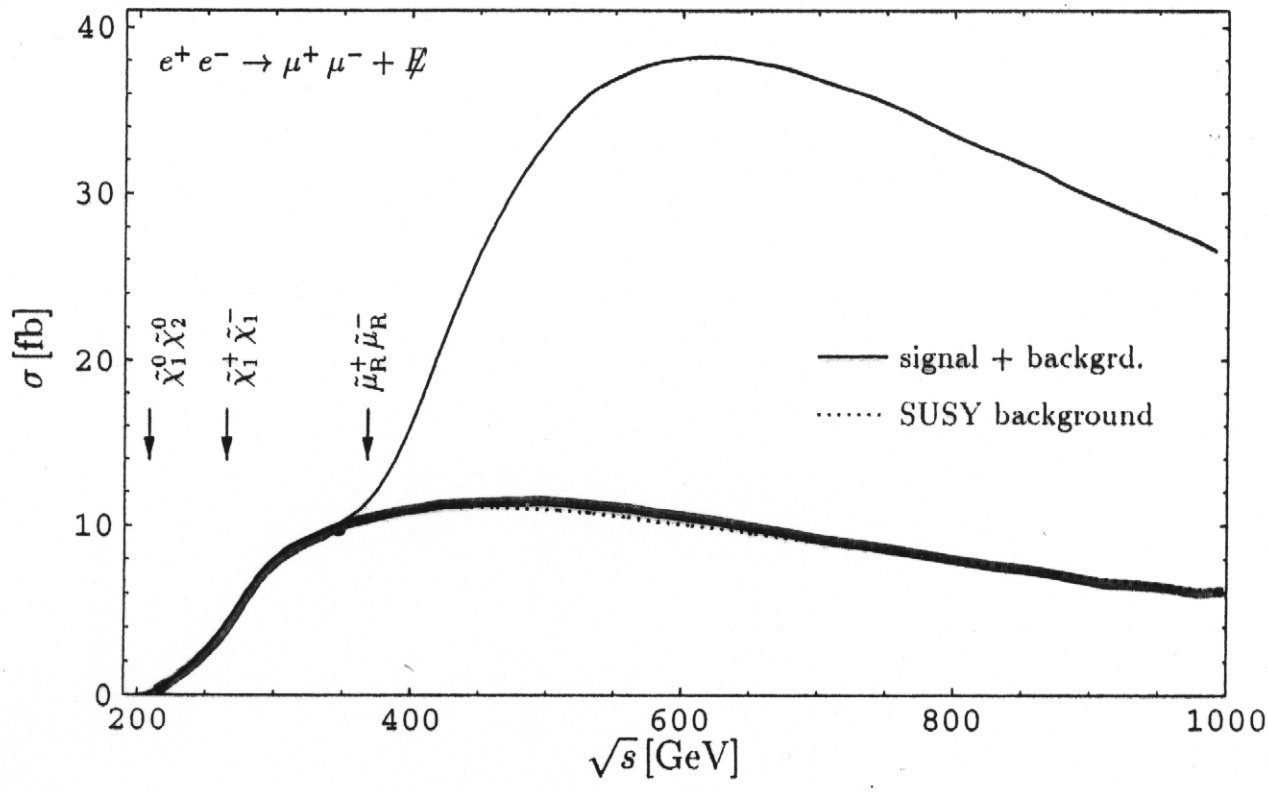
Remove 2: cut lepton pairs which are:

- collinear
- have invariant mass near the Z mass.

Cuts and detector acceptance → signal efficiency of 50%

Main SUSY backgrounds:

- $e^+e^- \to \tilde{\chi}_k^0\tilde{\chi}_1^0,\ \tilde{\chi}_k^0 \to \mu^+\mu^-\tilde{\chi}_1^0$
- $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0,\ \tilde{\chi}_2^0 \to \mu^+\mu^-\tilde{\chi}_1^0,\ \tilde{\chi}_2^0 \to \nu\bar{\nu}\tilde{\chi}_1^0$
- $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^\pm \to \tilde{\mu}^\pm\nu_{\tilde{\mu}}\tilde{\chi}_1^0$
- $e^+e^- \to ZZ,\ Z \to \mu^+\mu^-,\ Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0$
- $e^+e^- \to Zh_0/H_0,\ Z \to \mu^+\mu^-,\ h_0/H_0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$



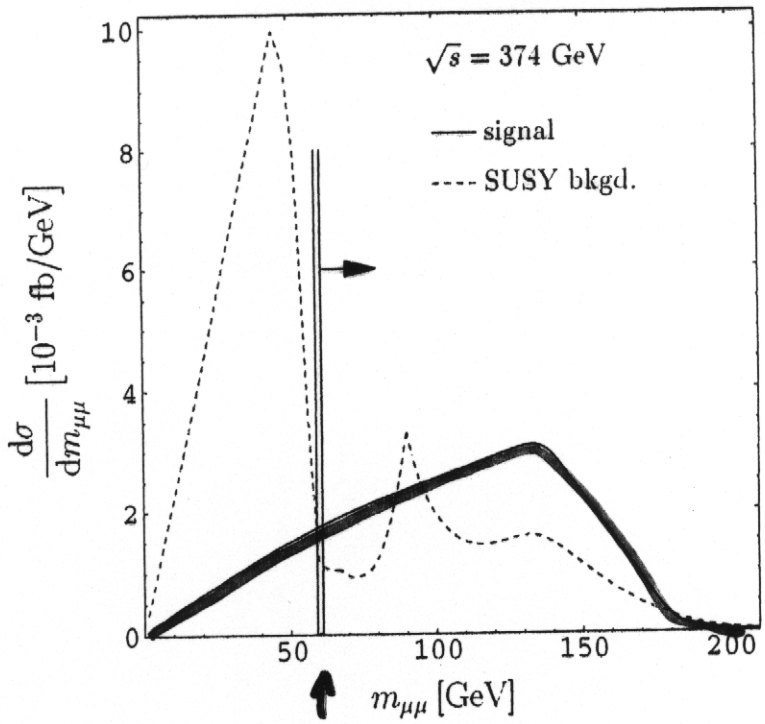
Removal of SUSY backgrounds

1. Cascade decays ⇒ extra missing energy

↓

[redacted]

Then make cut on muon pair invariant mass:



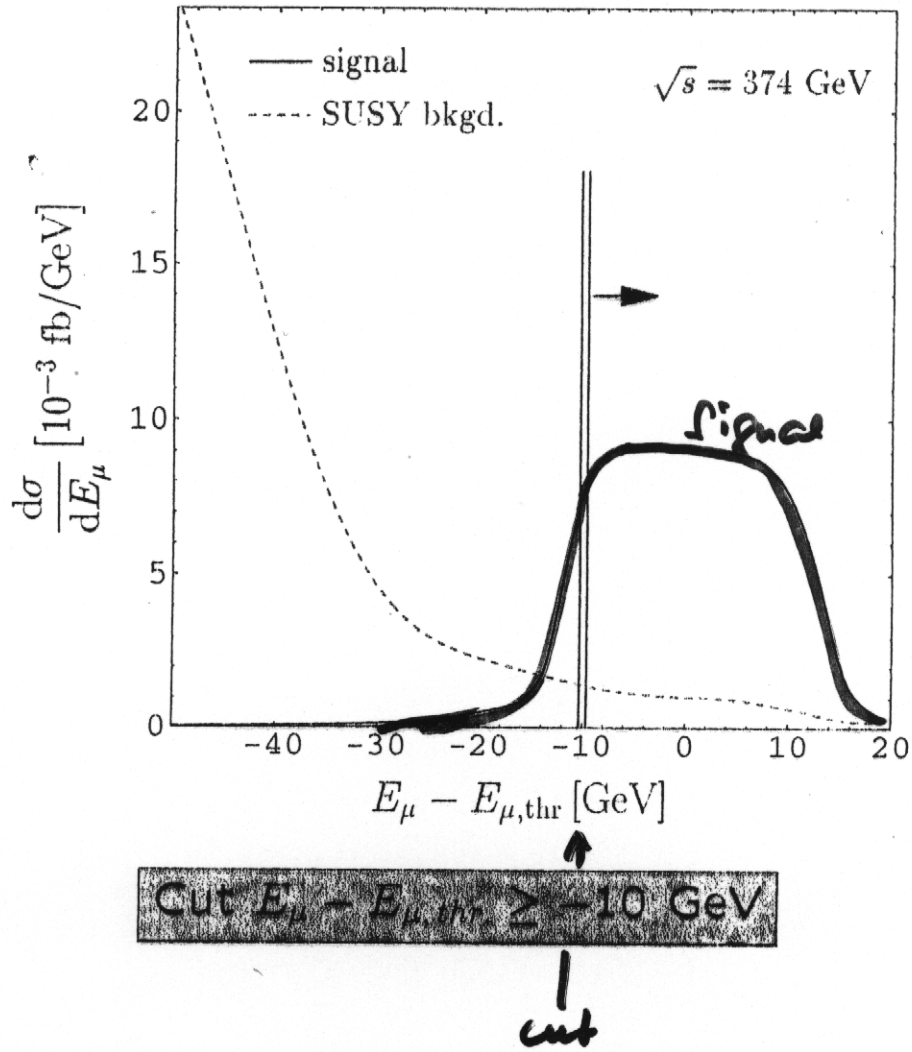
↑

$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

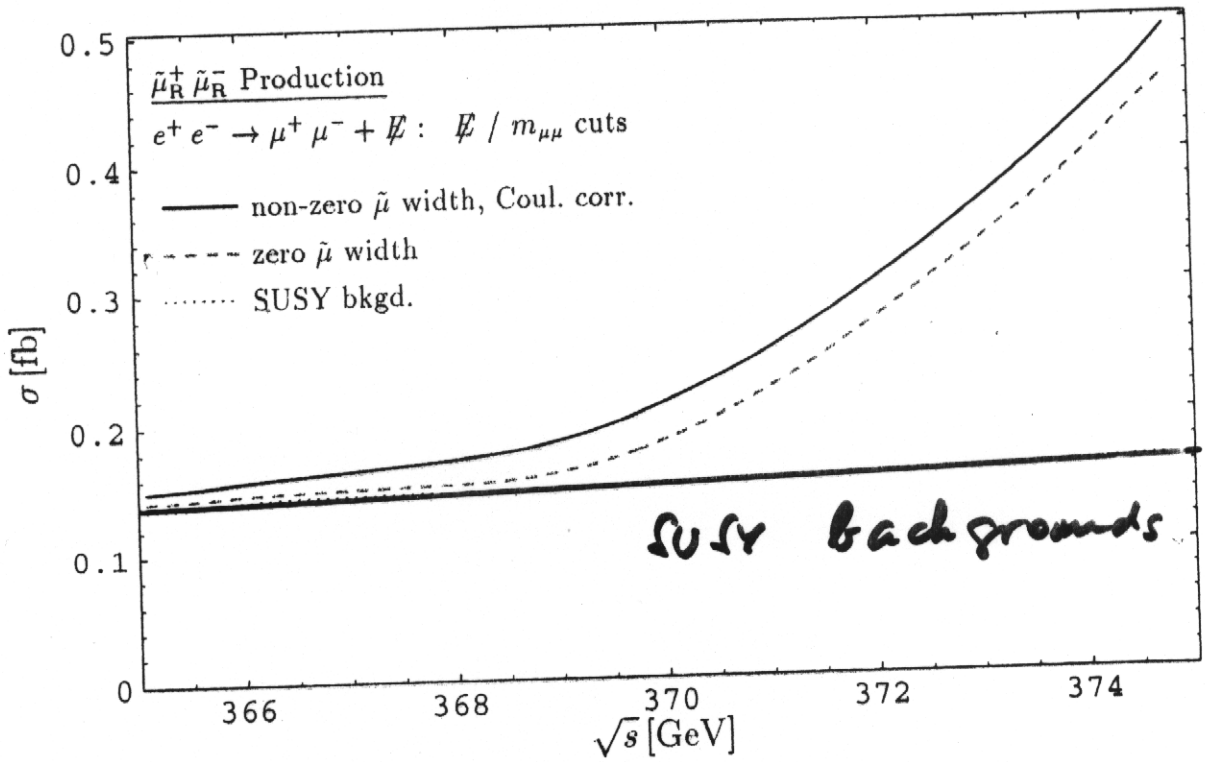
OR -

Alternatively:

2. Signal: Muon energies near threshold energy
   Background: Much lower E_μ



Results



Remaining backgrounds smooth over threshold region

↓

Remove in a model independent way by extrapolating from below

Conclusions on $\tilde{e}$'s, $\tilde{\mu}$'s

Selectrons

- e^-e^- option much better than e^+e^- for measuring selectron mass
- Negligible backgrounds
- Very accurate mass measurement with little luminosity

Smuons

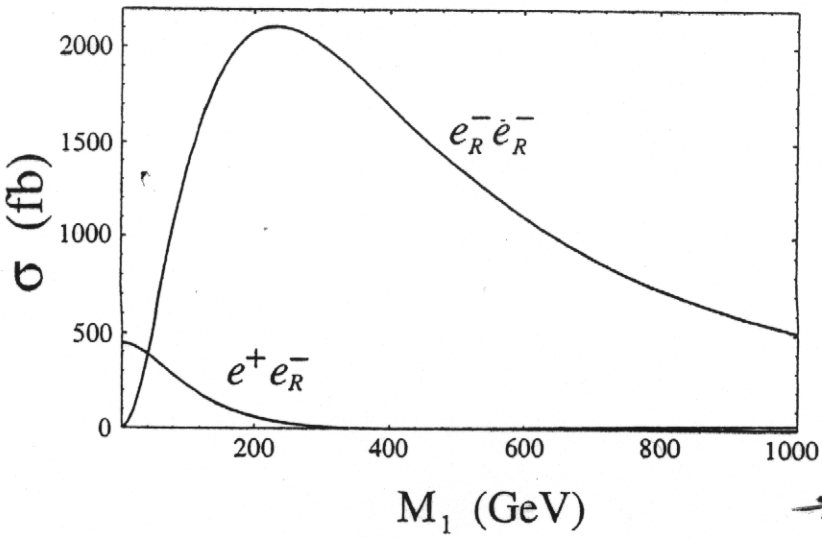
- More theoretically challenging
- Must beware of gauge dependence
- Cuts can be devised to remove backgrounds
- Accurate mass measurement looks promising

Must include radiative corrections for per mille accuracy

↑

Work on this underway

GAUGINO, NEUTRALINO MASSES



→ Bino mass

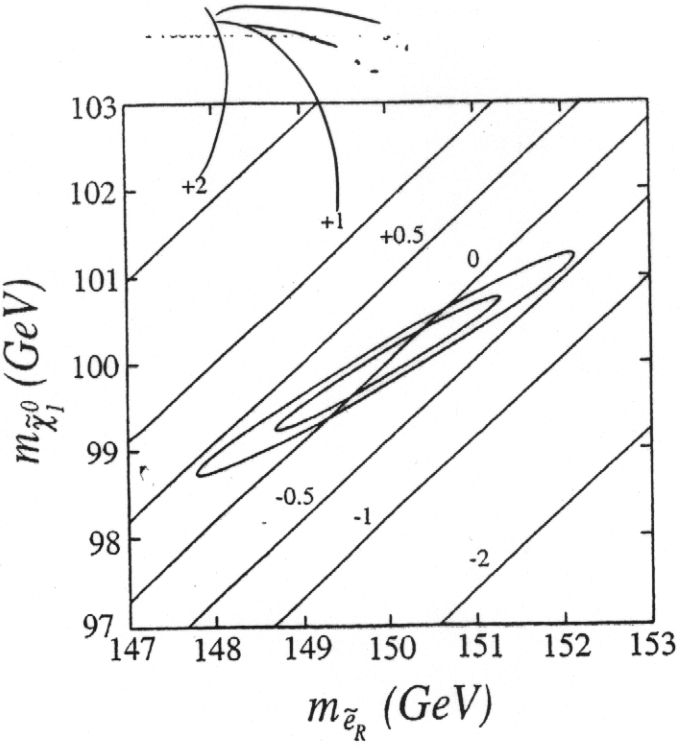
Cross sections for $\sigma(e_R^- e_R^- \to \tilde{e}_R^- \tilde{e}_R^-)$ and $\sigma(e^+ e_R^- \to \tilde{e}_R^+ \tilde{e}_R^-)$ as functions of the Bino mass M_1 for $m_{\tilde{e}_R} = 200$ GeV and $\sqrt{s} = 500$ GeV. The t-channel mass insertion for the e^-e^- case leads to large cross sections, even for $M_1 \sim \mathcal{O}(1\text{ TeV})$.

for $\sqrt{s} = 500$ GeV

$\sigma(\tilde{e}_R^- \tilde{e}_R^-)$ – which we measure precisely –

determines the bino mass precisely once we know $m(\tilde{e}_R)$.

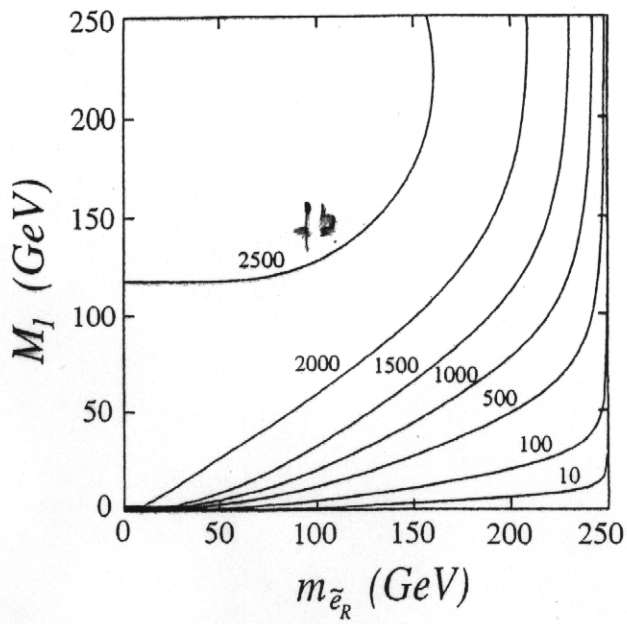
difference in % of σ_R from the central value parameters

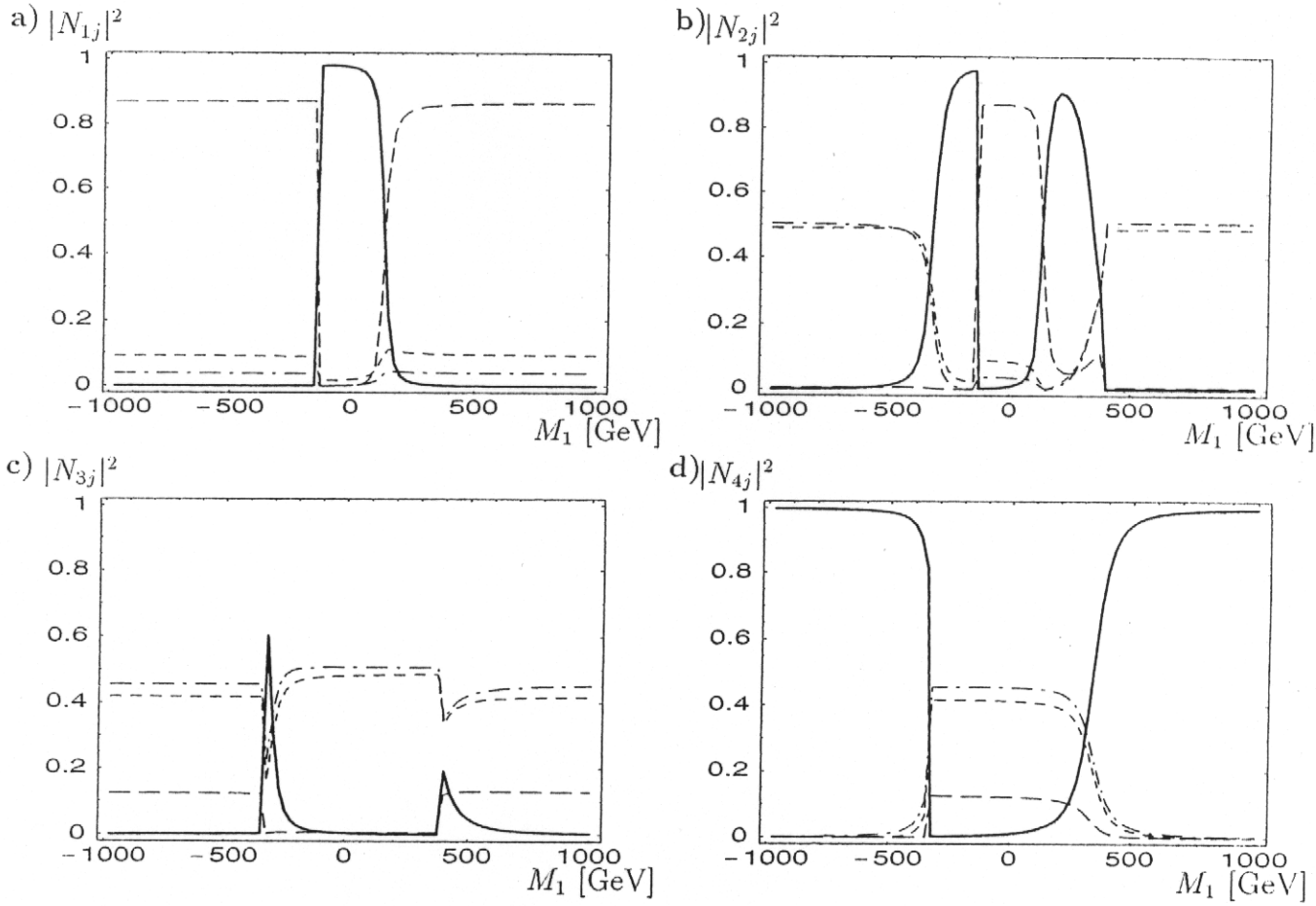


Uncertainty ellipses determined by final-state electron energy endpoints at $\sqrt{s} = 0.5$ TeV

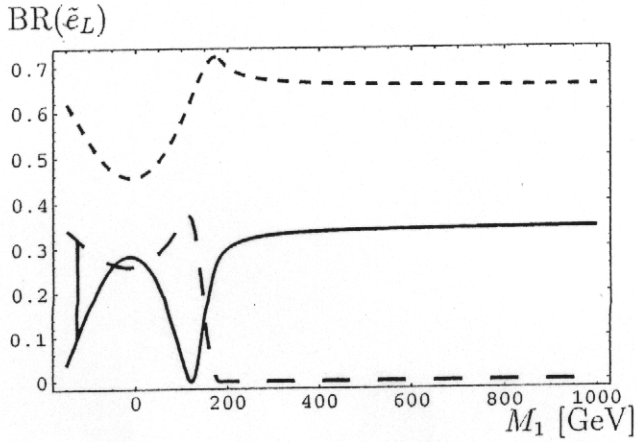
assuming $m_{\tilde{e}_R} = 150$ GeV
$m_{\tilde{\chi}_1^0} = 100$ GeV

Measure $\sigma(e_R^- e_R^+)$, find M_1 (or $m_{\tilde{e}_R}$) if not previously known

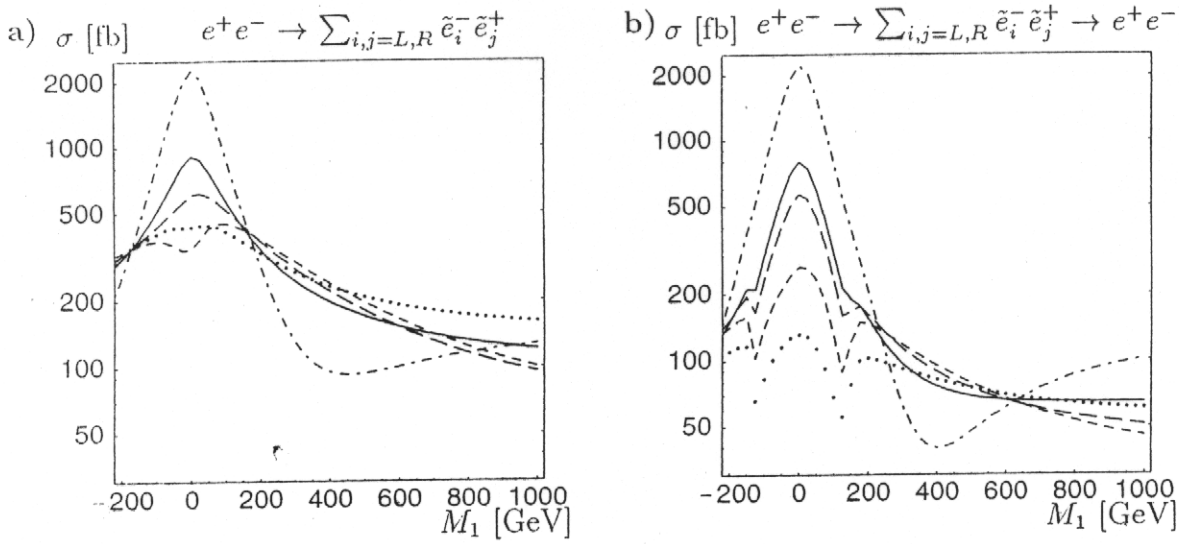




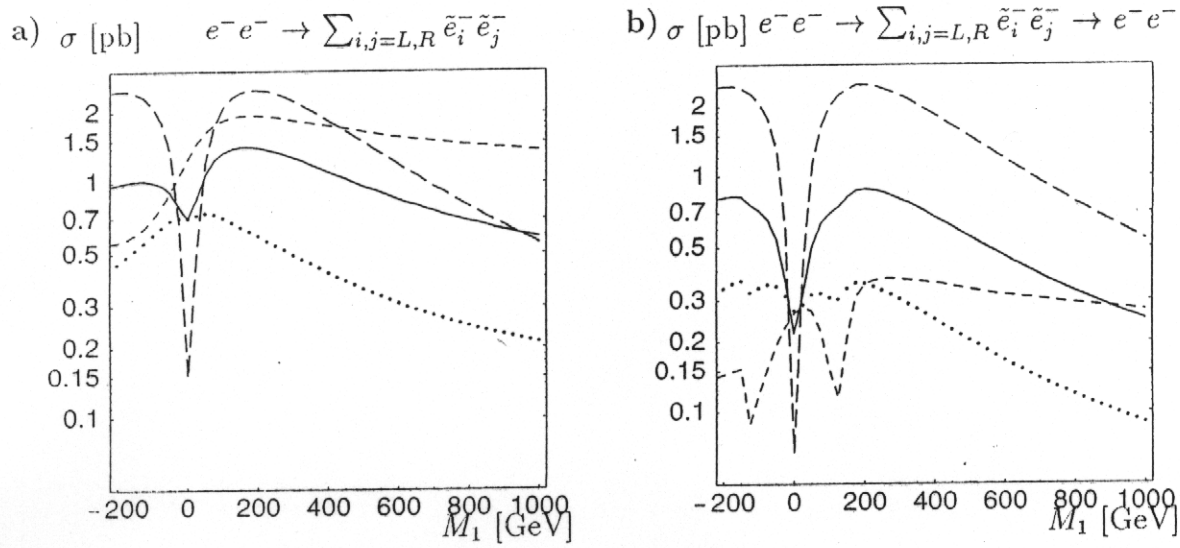
a) $|N_{1j}|^2$, b) $|N_{2j}|^2$, c) $|N_{3j}|^2$, and d) $|N_{4j}|^2$ as a function of M_1 for $M_2 = 152$ GeV, $\mu = 316$ GeV and $\tan\beta = 3$. The graphs correspond to the following components: full line $\tilde{B}$, long dashed line $\tilde{W}_3$, dashed line $\tilde{H}_d^0$ and long short dashed line $\tilde{H}_u^0$.



Branching ratios of $\tilde{e}_L$ as a function of M_1 for $m_{\tilde{e}_L} = 179.3$ GeV, $M_2 = 152$ GeV , $\mu = 316$ GeV and $\tan\beta = 3$. The graphs correspond to: full line $BR(\tilde{e}_L \to \tilde{\chi}_1^0 e^{\pm})$, long dashed line $BR(\tilde{e}_L \to \tilde{\chi}_2^0 e^{\pm})$ and dashed line $BR(\tilde{e}_L \to \tilde{\chi}_1^{\pm} \nu_e)$.



Cross sections for the processes $\sigma(e^+e^- \to \sum_{i,j=L,R} \tilde{e}_i^- \tilde{e}_j^+)$ (a) and $\sigma(e^+e^- \to \sum_{i,j=L,R} \tilde{e}_i^- \tilde{e}_j^+ \to e^+e^- \not{p}_T)$ (b) as a function of M_1 for various polarizations. The effects of ISR- and beamstrahlung corrections are included. The graphs correspond to the following set of polarizations: full line $P_{e^-} = 0$, $P_{e^+} = 0$, dashed line $P_{e^-} = -0.8$, $P_{e^+} = -0.6$, dashed-dotted line $P_{e^-} = 0.8$, $P_{e^+} = -0.6$, dotted line $P_{e^-} = -0.8$, $P_{e^+} = 0.6$, and long dashed line $P_{e^-} = 0.8$, $P_{e^+} = 0.6$.



Cross sections for the processes $\sigma(e^-e^- \to \sum_{i,j=L,R} \tilde{e}_i^- \tilde{e}_j^-)$ (a) and $\sigma(e^-e^- \to \sum_{i,j=L,R} \tilde{e}_i^- \tilde{e}_j^- \to e^-e^- \not{p}_T)$ (b) as a function of M_1 for various polarizations. The effects of ISR- and beamstrahlung corrections are included. The graphs correspond to the following set of polarizations: full line $P_{e_1} = 0$, $P_{e_2} = 0$, dashed line $P_{e_1} = -0.8$, $P_{e_2} = -0.8$, dotted line $P_{e_1} = -0.8$, $P_{e_2} = 0.8$, and long dashed line $P_{e_1} = 0.8$, $P_{e_2} = 0.8$.

NEUTRALINO CP-VIOLATING PHASES ?

1st-order effect possible in $e_L^- e_L^- \to \tilde{e}_L^- \tilde{e}_L^-$

$e^+ e^-$: $\tilde{e}_L^\pm \tilde{e}_R^\pm$ requires 2nd order in mixing

$e^- e^-$: $e_R^- e_R^-$ $\langle BB \rangle$ only : no interference

$e_L^- e_L^-$ $\langle BB \rangle$, $\langle WW \rangle$:

$m_1 m_2^*$ interference

Work by Scott Thomas

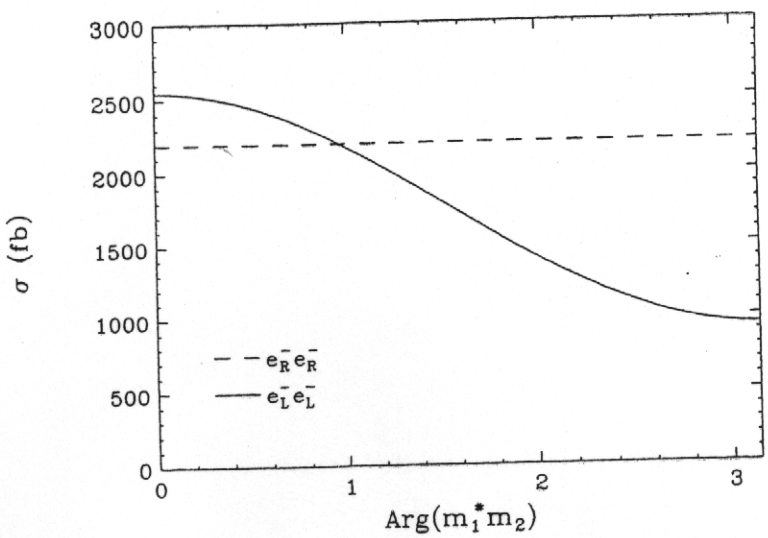
$$\mathcal{L} = -\frac{1}{2}\lambda M \lambda \; + \; h.c.$$

$$M = \begin{pmatrix} m_1 & 0 & -(g'/\sqrt{2})H_d^{0*} & (g'/\sqrt{2})H_u^{0*} \\ 0 & m_2 & (g/\sqrt{2})H_d^{0*} & -(g/\sqrt{2})H_u^{0*} \\ -(g'/\sqrt{2})H_d^{0*} & (g/\sqrt{2})H_d^{0*} & 0 & -\mu \\ (g'/\sqrt{2})H_u^{0*} & -(g/\sqrt{2})H_u^{0*} & -\mu & 0 \end{pmatrix}$$

In $e_L^- e_L^- \to \tilde{e}_L^- \tilde{e}_L^-$, the interference term is important:

$$|M_{LL}(t)|^2 = \frac{1}{16 \sin^4\theta_W}\left(\frac{|m_1|^2 \tan^4\theta_W}{(|m_1|^2 - t)^2} + \frac{2|m_1||m_2|\tan^2\theta_W \cos(\arg(m_1^* m_2))}{(|m_1|^2 - t)(|m_2|^2 - t)} + \frac{|m_2|^2}{(|m_2|^2 - t)^2}\right),$$

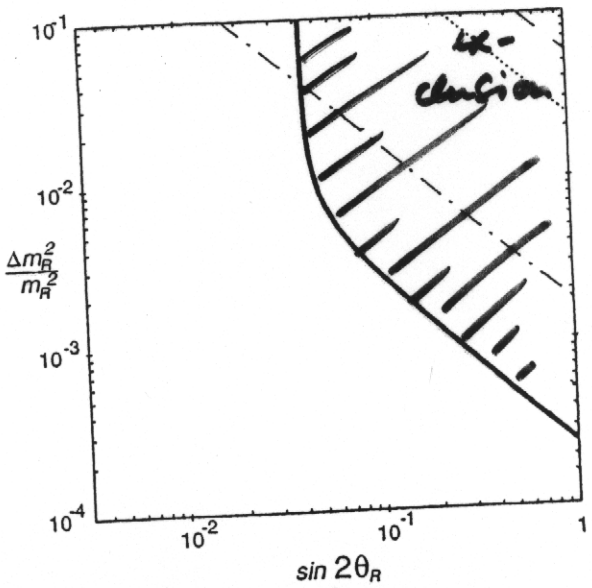
leading to a highly observable effect:



SLEPTON FLAVOR MIXING

Flavor violation is permitted in SUSY
| as at neutral gaugino vertices

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



Reach in view of

$B(\mu \to e\gamma)$

assumed parameters:

The discovery reach (solid) for lepton flavor violation through the signal $e_R^- e_R^- \to e^-\mu^-\chi\chi$ for 200 GeV slepton masses, $m_\chi = 100$ GeV, $\sqrt{s} = 500$ GeV, and an integrated luminosity $L = 20$ fb^{-1}. Regions of the plane to the upper-right are excluded by the current bound $B(\mu \to e\gamma) < 4.9 \times 10^{-11}$ for $\hat{t} = 0$ (dotted), 2 (dashed), and 50 (dot-dashed), where we have assumed $m_{\tilde{l}_L} = 350$ GeV.

In principle, there is room for 7 new CKM matrices
— one for each {fermion / sfermion} species

$f = u_L, u_R, d_L, d_R, e_L, e_R, \nu$