E

EWSB: SUPERSYMMETRY

AGAIN: WE WOULD EXPECT SUSY SIGNALS TO EMERGE FROM

{ EXISTING / APPROVED } COLLIDERS

BY TURN-ON TIME OF THE LINEAR COLLIDER

BUT: SUPERSYMMETRY HAS > 120 PARAMETERS THAT ARE NEEDED TO UNDERSTAND IT AT ENERGIES LIKELY TO BECOME ACCESSIBLE

LHC IS UNLIKELY TO YIELD MUCH IN THE WAY OF PRECISION EXPERIMENTION:

MASSES, COUPLINGS,
PHASES, MIXINGS

⇒ SAME-SIGN COLLIDERS TO THE RESCUE!

WHAT DO WE NEED TO MEASURE?

MASSES THAT ARE ACCESSIBLE

SLEPTONS: $\tilde{e}$ (CARRY CHIRALITY)

$\tilde{\mu}$

$\tilde{\nu}$

GAUGINOS: $\tilde{\chi}^0$ NEUTRALINOS

$\tilde{\chi}^\pm$ CHARGINOS

... VEV's, $\tan\beta$

COUPLINGS

INCLUDING R-PARITY VIOLATION

LEPTON FLAVOR VIOLATION

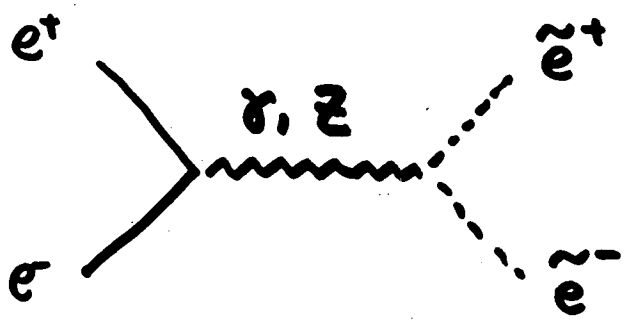
PATTERN OF SUSY BREAKING

PHASES

→ NEUTRALINO MASS MATRIX

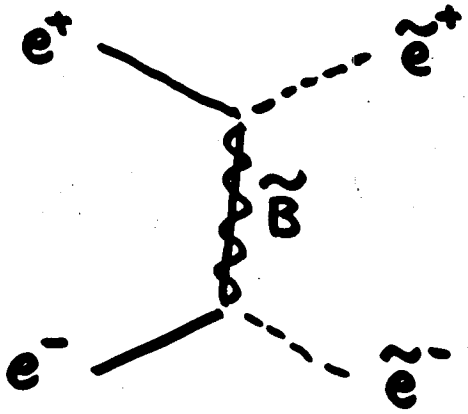
REF's →

DO AS WE DID IN THE PAST: e^+e^- ...



BUT

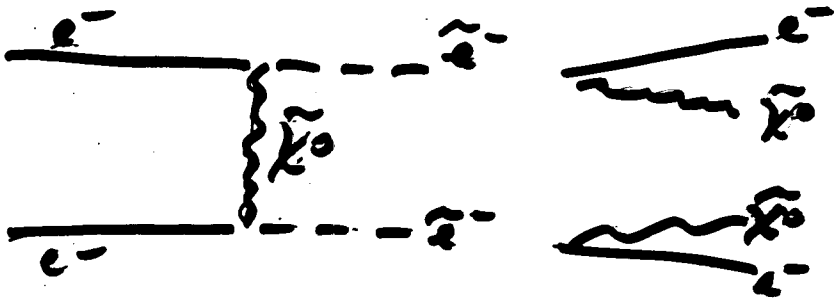
$-$



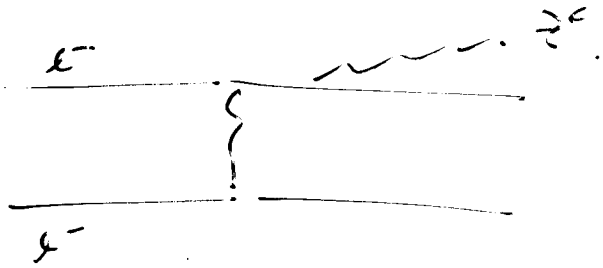
destructive interference

PLENTIFUL BACKGROUNDS

GO TO e^-e^- COLLISIONS:

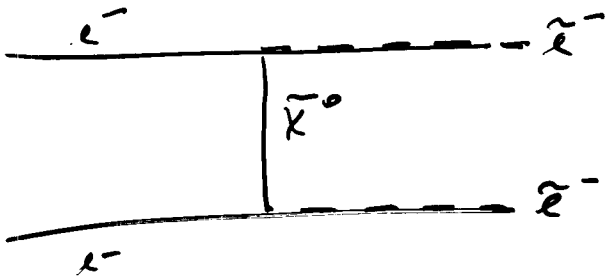


main background



HAS CONSIDERABLE ADVANTAGES

The process



occurs via Majorana neutralino exchange

wino } gaugino
bino }
higgsino

ADVANTAGES:

Cross-sections are rel'ly large (~ 1 R)

strongly polarization-dependent

Final states are

characteristic, detectable

Backgrounds $e^-e^- \to e^-e^-Z^0$ (1)

$\to e^- \nu_e W^-$ (2)
$\hookrightarrow e^- \bar{\nu}_e$

are easily eliminated:

(1) by kinematical cuts on E_e,

(2) by polarization change.

THE IMPORTANCE OF BEING POLARIZED!

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

$\mu^-\mu^- \to \tilde{\mu}^-\tilde{\mu}^-$

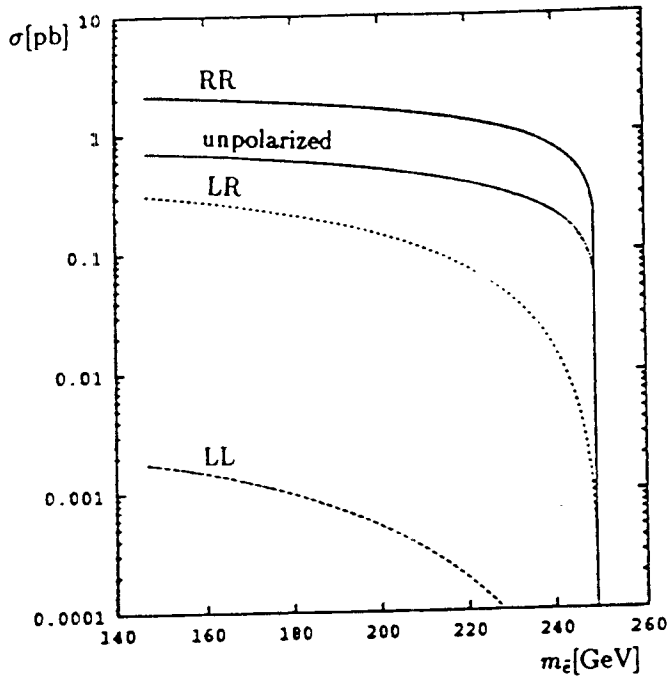


Figure 12: Cross-section of selectron pair production for a given SUSY parameter set, as a function of selectron mass, for different helicity combinations of the incoming e^- beams, at a 500 GeV NLC.

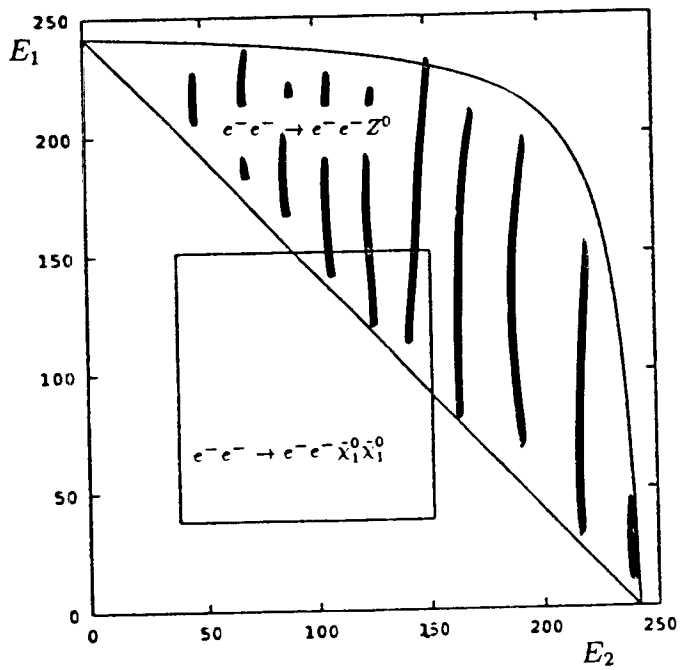


Figure 13: The allowed electron ranges for a pair of 200 GeV selectrons decaying into e^-e^- plus a pair of 100 GeV neutralinos (box) and for the principal background, Z "bremsstrahlung" ($e^-e^- \to e^-e^-Z$). This example illustrates the relative ease with which backgrounds can be removed by cuts on the final-state electrons (from ref. 26).

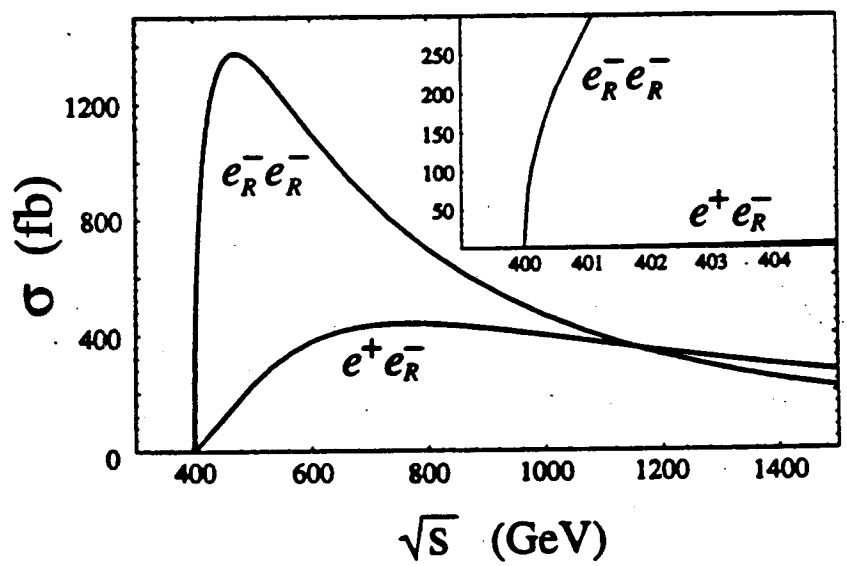
THE PRODUCTION OF PAIRS OF SCALARS AT THRESHOLD HAPPENS IN AN S STATE

($e^+e^- \to$ P STATE, β^3 FACTOR!)

(ANG 'MOM' BARRIER)

PRECISION DETERMINATION

OF SELECTRON / SMUON } MASS



Cross sections $\sigma(e_R^- e_R^- \to \tilde{e}_R^- \tilde{e}_R^-)$ and $\sigma(e^+ e_R^- \to \tilde{e}_R^+ \tilde{e}_R^-)$ for $m_{\tilde{e}_R} = 200$ GeV and $m_{\tilde{B}} = 100$ GeV. The inset is a magnified view for $\sqrt{s}$ near threshold. Effects of initial state radiation, beamstrahlung, and the selectron width are not included.

MODULO ΔE_{BEAM}

rad 'corrections

$\Gamma_{\tilde{e}}, \tilde{\mu}$

ACCESS TO TAN β

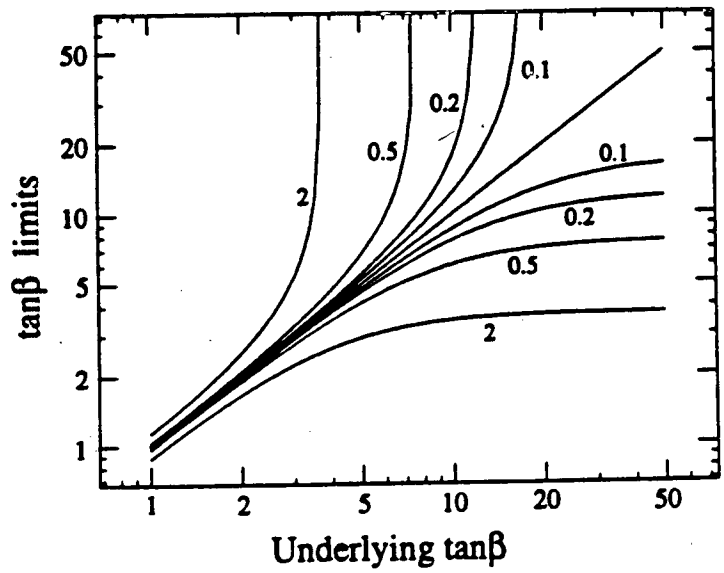


Fig. 3. Contours giving the upper and lower limits on $\tan\beta$ for a given underlying $\tan\beta$ and experimental uncertainty in mass difference $\Delta m \equiv m_{\tilde{\ell}_L} - m_{\tilde{\nu}_e}$ as indicated (in GeV), for fixed $m_{\tilde{\nu}_e} = 200$ GeV.

BINO MASS DETERMINATION:

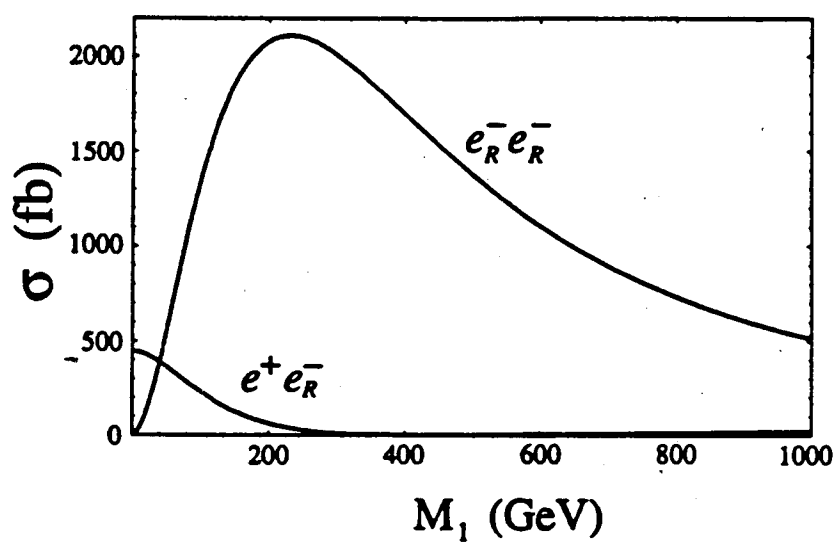


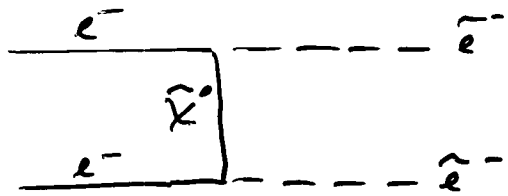
Fig. 5. Cross sections for $\sigma(e_R^- e_R^- \to \tilde{e}_R^- \tilde{e}_R^-)$ and $\sigma(e^+ e_R^- \to \tilde{e}_R^+ \tilde{e}_R^-)$ as functions of the Bino mass M_1 for $m_{\tilde{e}_R} = 200$ GeV and $\sqrt{s} = 500$ GeV. The t-channel mass insertion for the $e^- e^-$ case leads to large cross sections, even for $M_1 \sim \mathcal{O}(1\ \text{TeV})$.

SUSY MASS MEASUREMENT IN $e^-e^- \to e^-e^-$

JONATHAN FENG, e^-e^- 97

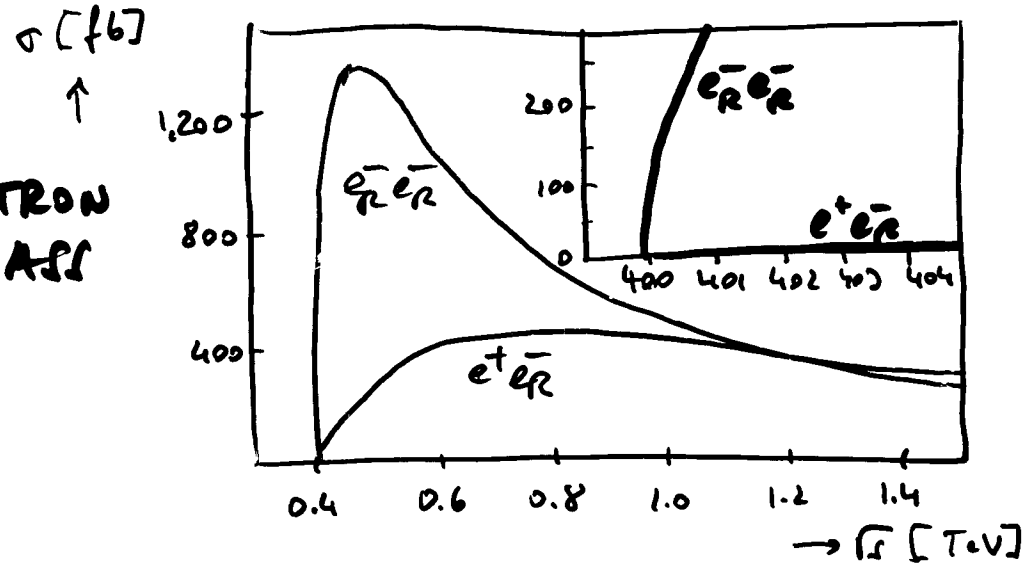
the fermion number-violating process

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



leads to <u>the</u> most precise determinations of $m(\tilde{e}^-)$

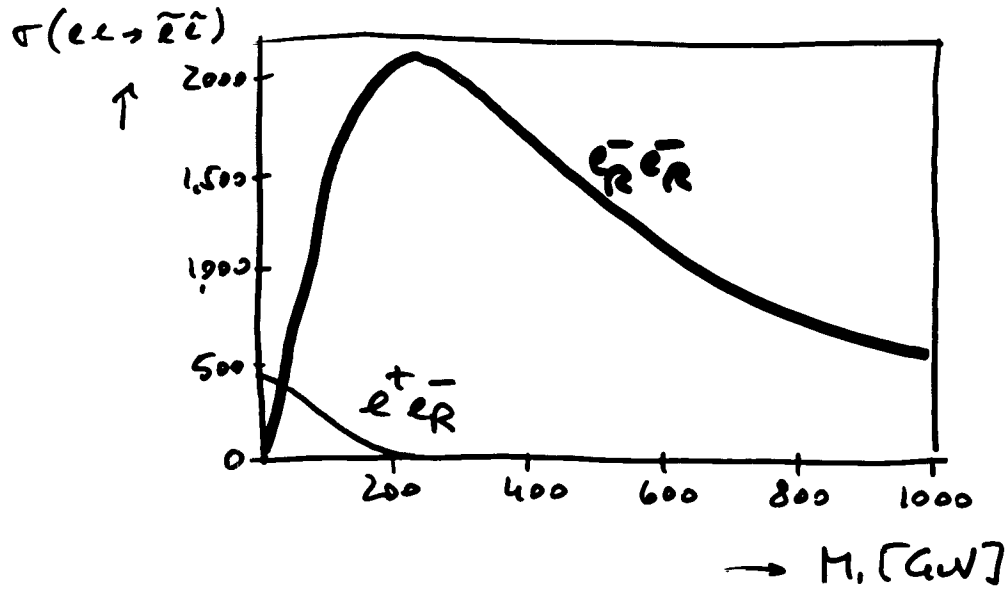
SELECTRON MASS



for
$m_{\tilde{e}_R^-} = 200$ GeV
$m_{\tilde{B}} = 100$ GeV

(assume sharp masses, no beamstrahlung)

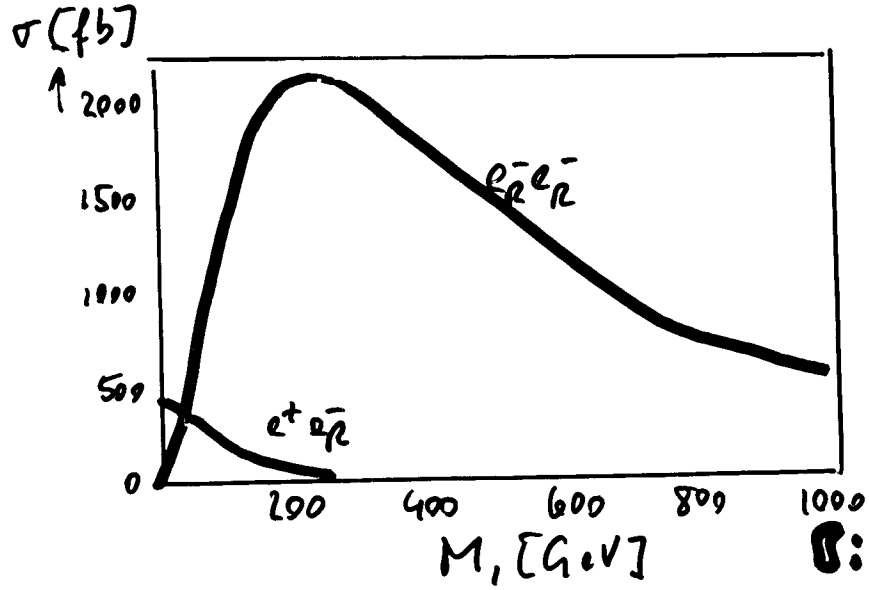
and BINO MASS M_1



M_1 mass measurement:

recall: $\sigma(e_R^- e_R^- \to \tilde{e}_R^- \tilde{e}_R^-) \sim \left|\frac{M_{RR}}{t - M_1^2}\right|^2$

$\sim \frac{1}{M_1^2}$ large M_1



for $\sqrt{s} = 0.5$ TeV

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

Bino mass

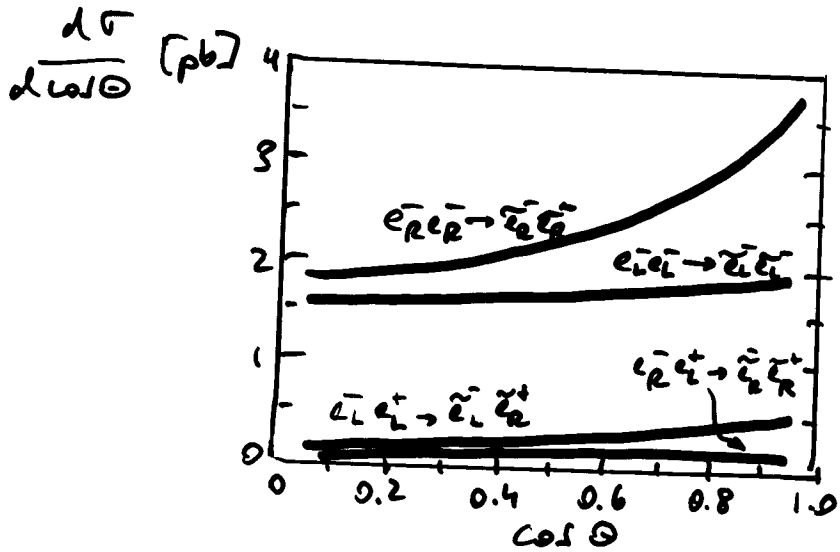
→ take $M_1 = 700$ GeV, find $\underline{1\sigma}$ stat' error from a $100\ fb^{-1}$ high-luminosity measurement $\Delta M_1 \gtrsim 2$ GeV !

once M_1 is measured, M_2 can be measured via

$$\sigma(e_L^- e_L^- \to \tilde{e}_L^- \tilde{e}_L^-)$$

NOTE: SUCH LARGE GAUGINO MASSES (possible in Higgsino region) ARE **VERY** HARD TO MEASURE ELSEWHERE. in gravity mediated models)

to find cross-sections



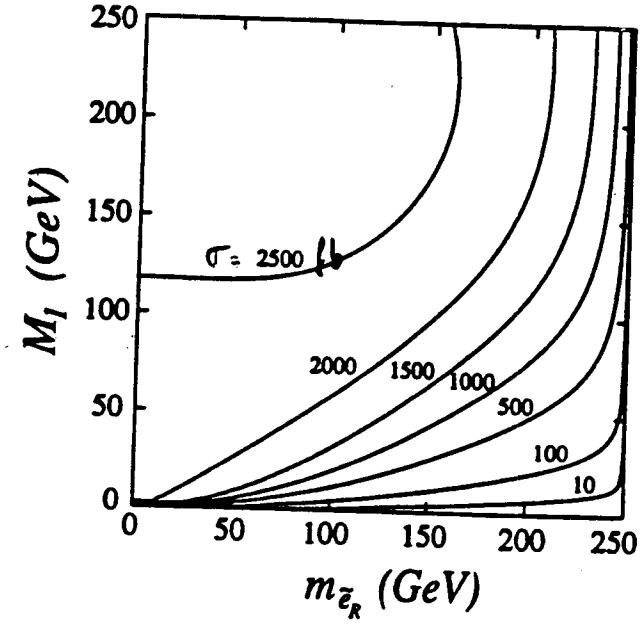
- production processes of $\tilde{e}^-_R \tilde{e}^-_R$ are useful to determine whether we are in the $\left\{\begin{matrix}\text{gaugino}\\ \text{higgsino}\end{matrix}\right\}$ region of neutralino space

- production processes of $\tilde{e}^-_L \tilde{e}^-_L$ are most sensitive to the mass ratio m_1/m_2

- for both, the cross-section has the phase space factor β, not β^3 like $e^+_L e^-_R, \ldots$
  → great improvement in $m(\tilde{e}^-)$ determination

- It turns out that $e^-_L e^-_L \to \tilde{e}^-_L \tilde{e}^-_L$ is particularly sensitive to CP violating phases in the SUSY process → relative phases between $\left\{\begin{matrix}\text{wino}\\ \text{bino}\end{matrix}\right\}$ masses.

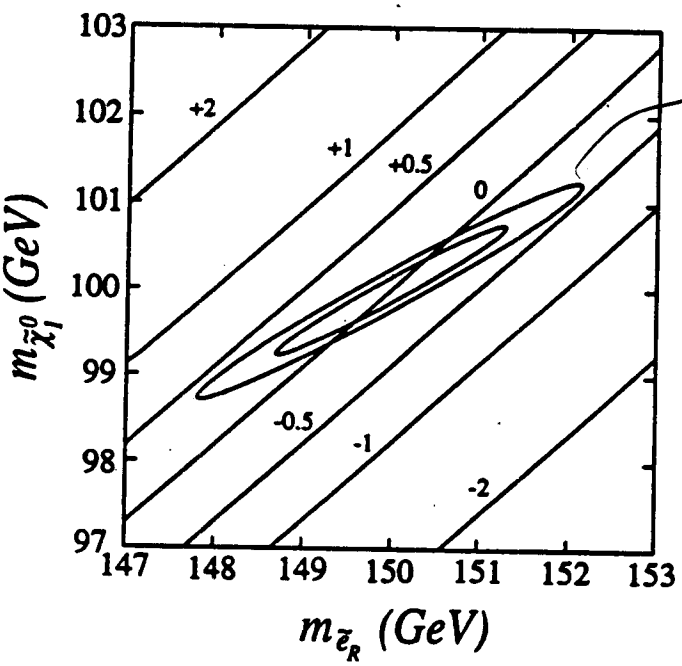
mass determination: $\tilde{e}_R$, M_1



$\sqrt{s} = 500$ GeV

Contours of constant $\sigma_R = \sigma(e^-_R e^-_R \to \tilde{e}^-_R \tilde{e}^-_R)$ in fb in the $(m_{\tilde{e}_R}, M_1)$ plane for $\sqrt{s} = 500$

mass determination: $\tilde{e}_R$, $\tilde{\chi}^0_1$



uncertainty ellipses $\Delta E = 0.3, 0.5$ GeV assuming $m_{\tilde{e}_R} = 150$ GeV, $m_{\tilde{\chi}^0_1} = 100$ GeV, and point measurement of final-state e

The allowed regions, "uncertainty ellipses," of the $(m_{\tilde{e}_R}, m_{\tilde{\chi}^0_1})$ plane, determined by measurements of the end points of final state electron energy distributions with uncertainties $\Delta E =$ 0.3 GeV and 0.5 GeV. The underlying central values are $(m_{\tilde{e}_R}, m_{\tilde{\chi}^0_1}) = (150$ GeV, 100 GeV), and $\sqrt{s} = 500$ GeV. We also superimpose contours (in percent) of the fractional variation of σ_R with respect to its value at the underlying parameters.

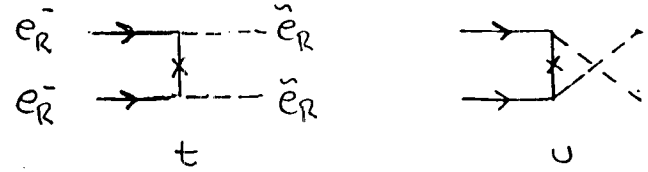
ACCESS TO PHASES

Scott Thomas
e^-e^- 97

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

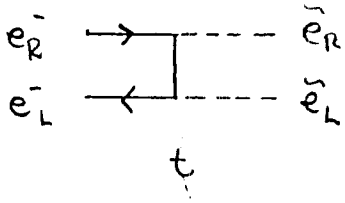
χ_i^0 exchange : (Only b,w Components.)

RR



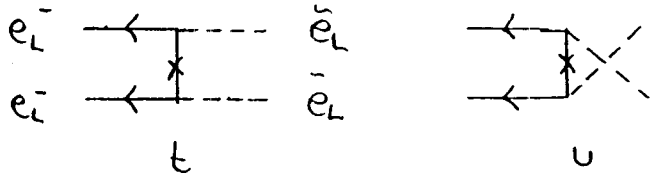
$\Delta\chi = -2$

RL



$\Delta\chi = 0$

LL



$\Delta\chi = 2$

$$V_{Ri} = \frac{1}{\cos\theta_w} V_{1i}$$

$$V_{Li} = \frac{1}{2\cos\theta_w} V_{1i} + \frac{1}{2\sin\theta_w} V_{2i}$$

$$\mathcal{N}_{ab} = \sum_i V_{ai}^* \frac{1}{|m_i|^2 - t} V_{bi}$$

$$\mathcal{M}_{ab} = \sum_i V_{ai} \frac{m_i}{|m_i|^2 - t} V_{bi}$$

Note that $\mathrm{Im}\mathcal{N}_{aa} = 0$.

Cross sections

$$\frac{d\sigma}{dt}(e_R^- e_R^- \to \tilde{e}_R^- \tilde{e}_R^-) = \frac{3}{2} R \; |\mathcal{M}_{RR}(t) + \mathcal{M}_{RR}(u)|^2$$

$$\frac{d\sigma}{dt}(e_L^- e_L^- \to \tilde{e}_L^- \tilde{e}_L^-) = \frac{3}{2} R \; |\mathcal{M}_{LL}(t) + \mathcal{M}_{LL}(u)|^2$$

$$\frac{d\sigma}{dt}(e_L^- e_R^- \to \tilde{e}_L^- \tilde{e}_R^-) = 3R \left(\frac{(t - m_{\tilde{e}_L}^2)(m_{\tilde{e}_R}^2 - t)}{s} - t \right) \; |\mathcal{N}_{LR}(t)|^2$$

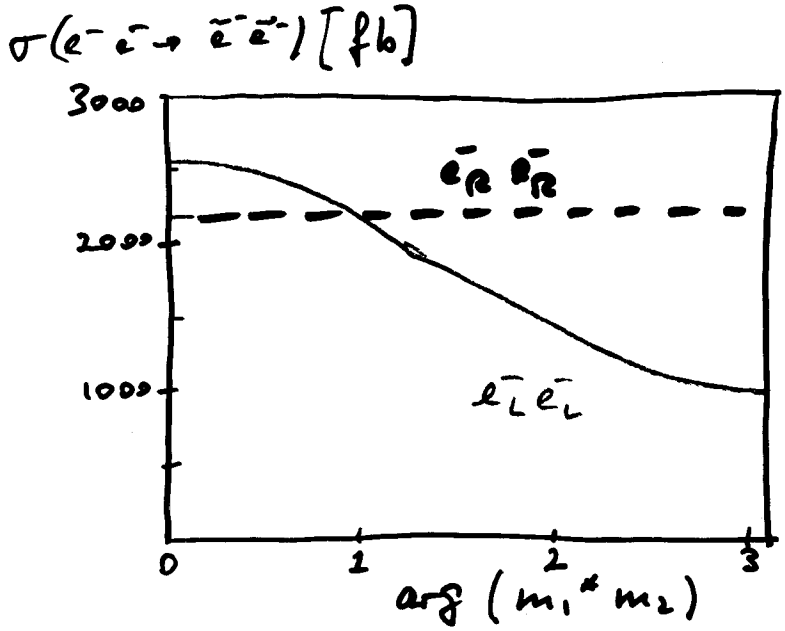
S. Thomas

CP violating phases:

phase-dependent interference takes place between different neutralino mass eigenstates in the same channel,

not suppressed well above threshold

TOTAL CROSS SECTION in pure $\left\{ \begin{matrix} \text{higgsino} \\ \text{gaugino} \end{matrix} \right\}$ limit:



$\sqrt{s} = 0.5$ TeV

$|m_1| = 100$ GeV

$|m_2| = 200$ GeV

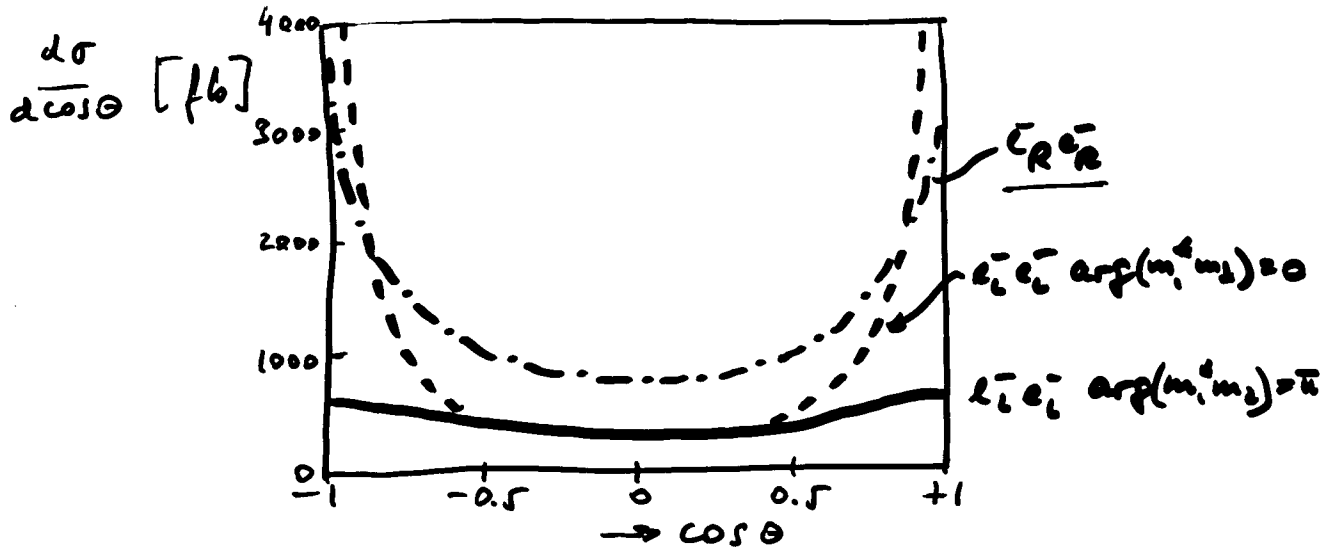
$m_{\tilde{e}_R} = 130$ GeV

$m_{\tilde{e}_L} = 180$ GeV

For comparison, note that

$R(\sqrt{s} = 0.5\ \text{TeV}) = 400$ fb

SENSITIVITY OF SELECTRON PAIR PRODUCTION TO PHASES IN THE MASS MATRIX



$\sqrt{s} = 0.5$ TeV ; masses as above

→ Higgsino or gaugino limit but features remain similar away from limits.

→ LEFT-HANDED SELECTRON PAIR PRODUCTION IS THE MOST SENSITIVE PROBE OF RELATIVE BINO AND WINO MASSES.

This provides the best chance to measure a CP-odd phase at the L.C.

⇝ complementary to low-energy electric dipole measurements !

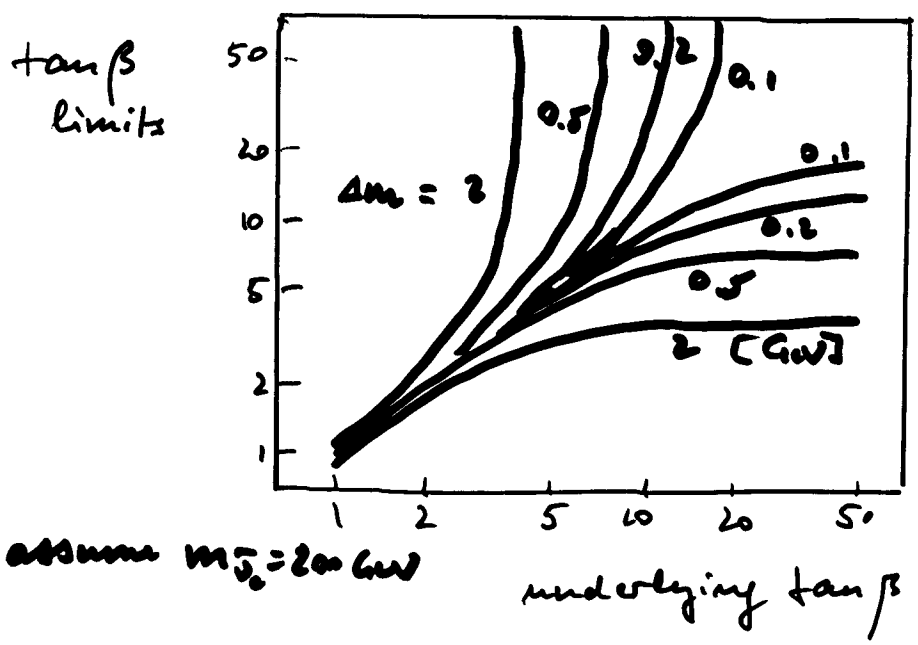
Access to $\tan\beta$:

the high precision of mass measurement is very useful, e.g., to use the tree-level def'

$$m_{\tilde{e}_L}^2 - m_{\tilde{\nu}_e}^2 = -M_W^2 \cos 2\beta$$

→ measure $m_{\tilde{e}_L}$ at threshold,

$m_{\tilde{\nu}_e}$ from chargino decay



... AND A WINDOW ON LEPTON FLAVOR VIOLATION

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

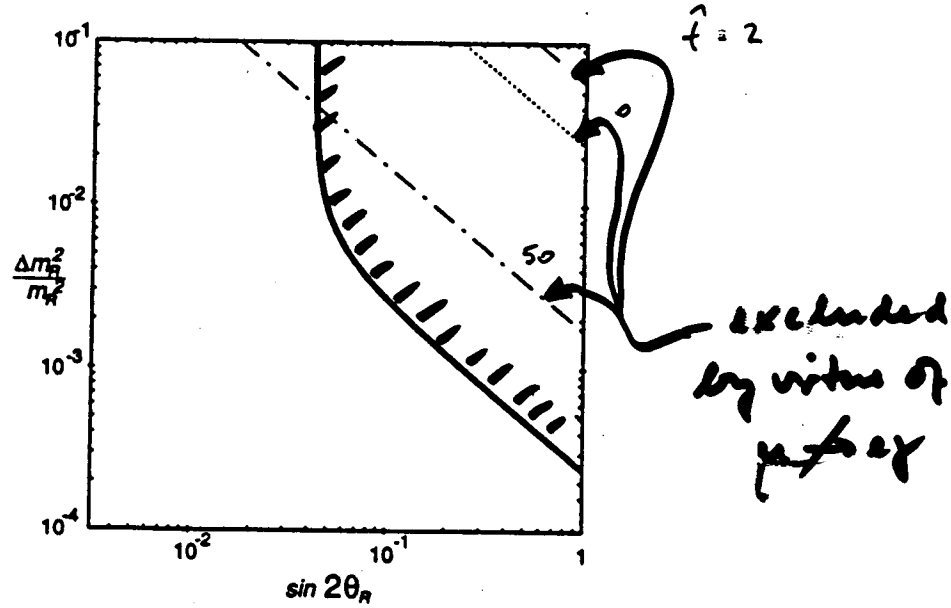


Fig. 4. The discovery reach (solid) for lepton flavor violation through the signal $e_R^- e_R^- \to e^- \mu^- \chi\chi$ for 200 GeV slepton masses, $m_\chi = 100$ GeV, $\sqrt{s} = 500$ GeV, and an integrated luminosity $L = 20$ fb^{-1}. Regions of the plane to the upper-right are excluded by the current 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.

$$\Delta m_R^2 \equiv m_{\tilde{e}_R}^2 - m_{\tilde{\mu}_R}^2$$

$$m_R^2 = \frac{1}{2}(\cdots + \cdots)$$

LR mixing parameter $\hat{t} \equiv \frac{1}{m_R}(-A + \mu \tan\beta)$

CONCLUSIONS

- THE ESSENTIAL SIMPLICITY OF THE PROCESS

$$e^- e^- \to \tilde{e}^- \tilde{e}^- \quad \text{or} \quad \mu^\pm \mu^\pm \to \tilde{\mu}^\pm \tilde{\mu}^\pm$$

MAKES IT A WONDERFUL PROBE FOR A NUMBER OF VERY SOPHISTICATED ASPECTS OF SUSY AND ITS EFFECTIVE LAGRANGEAN

- THE FACT THAT WE HAVE EASY AND RAPID ACCESS TO THE

DEFINITION AND REVERSAL
OF <u>BOTH</u> INCOMING BEAM POLARIZATIONS

GIVES US ADDITIONAL VITAL HELP IN DETERMINING

MASSES
PHASES
COUPLINGS
MIXINGS

THAT DESCRIBE THE M.S.S.M. AND ITS MANY POSSIBLE EXTENSIONS

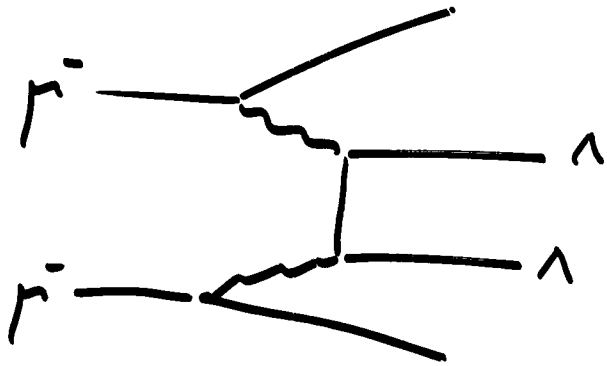
- THE $\begin{pmatrix} e^- e^- \\ \text{LIKE-SIGN} \end{pmatrix}$ VERSION OF THE $\begin{pmatrix} \text{LINEAR} \\ \text{MUON} \end{pmatrix}$ COLLIDER CLEARLY IS THE INCONTROVERTIBLE FAVORITE AS OUR MOST PROMISING TOOL TO PIN DOWN THE PRINCIPAL PARAMETERS (LOWER ENERGY) SUSY.

FOR VERY-HIGH-ENERGY μ COLLIDER:

GAUGE-MEDIATED SUSY

MESSENGER PAIR PRODUCTION

BY ZZ FUSION



long-lived, heavy ($\gtrsim$ 10 TeV?)

might provide a clue to the simplest way of breaking SUSY.