Supersymmetry & Superpartners

Summary P3 at LCWS 2000

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RWTH Aachen

- Polarisation
- Sleptons
- Charginos & Neutralinos
- Determining SUSY Parameters
- SUSY at CLIC

SUSY Scenarios

particle		J	SUSY partner		J	mixed states
leptons	$\ell,\ \nu_\ell$	$\frac{1}{2}$	sleptons	$\tilde{\ell},\ \tilde{\nu}_\ell$	0	$\tilde{\tau}_1,\ \tilde{\tau}_2$
quarks	q	$\frac{1}{2}$	squarks	$\tilde{q}$	0	$\tilde{t}_1,\ \tilde{t}_2$
gluon	g	1	gluino	$\tilde{g}$	$\frac{1}{2}$	
bosons	γ, Z, W	1	gauginos	$\tilde{\gamma}, \tilde{Z}, \tilde{W}$	$\frac{1}{2}$	$\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$
Higgs	$h, A, H, H^\pm$	0	higgsinos	$\tilde{h}, \tilde{A}, \tilde{H}, \tilde{H}^\pm$	$\frac{1}{2}$	$\chi_1^\pm, \chi_2^\pm$

▷ **MSSM** **105 + 19 (SM) parameters**

▷ **mSUGRA** **5 parameters** **LSP = χ_1^0** **⇒ large $\not{E}$**

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\ \mu$

$M_i = (\alpha_i/\alpha_{GUT})\, m_{1/2} \qquad M_1 \simeq 0.5\, M_2$

▷ **Gauge Mediated Symmetry Breaking** **LSP = $\tilde{G}$**

$M_{\text{mess}},\ N_{\text{mess}},\ \Lambda,\ \tan\beta,\ \text{sign}\ \mu$

$$m_{3/2} \equiv m_{\tilde{G}} \simeq \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^2 2.37\ \text{eV}$$

NLSP unstable

$$c\tau \simeq \frac{1}{100\, \mathcal{B}} \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4 \left(\frac{m_{NLSP}}{100\ \text{GeV}}\right)^{-5} \text{cm}$$

$$\chi_1^0 \rightarrow \gamma\, \tilde{G},\ f\, \bar{f}\, \tilde{G}$$
$$\tilde{\ell}^\pm \rightarrow \ell^\pm\, \tilde{G}$$

⇒ **displaced & time delayed γ, secondary vertex(?)**
long lived heavy leptons

▷ Anomaly Mediated Symmetry Breaking

contribution to soft mass parameters from the 'super–Weyl (superconformal) anomaly'

AMSB gives the dominant contributions to the scalar and gaugino masses if SUSY breaking is not directly communicated from a hidden sector

LSP = χ_1^0 wino-like

m_0, $m_{3/2}$, $\tan\beta$, sign μ

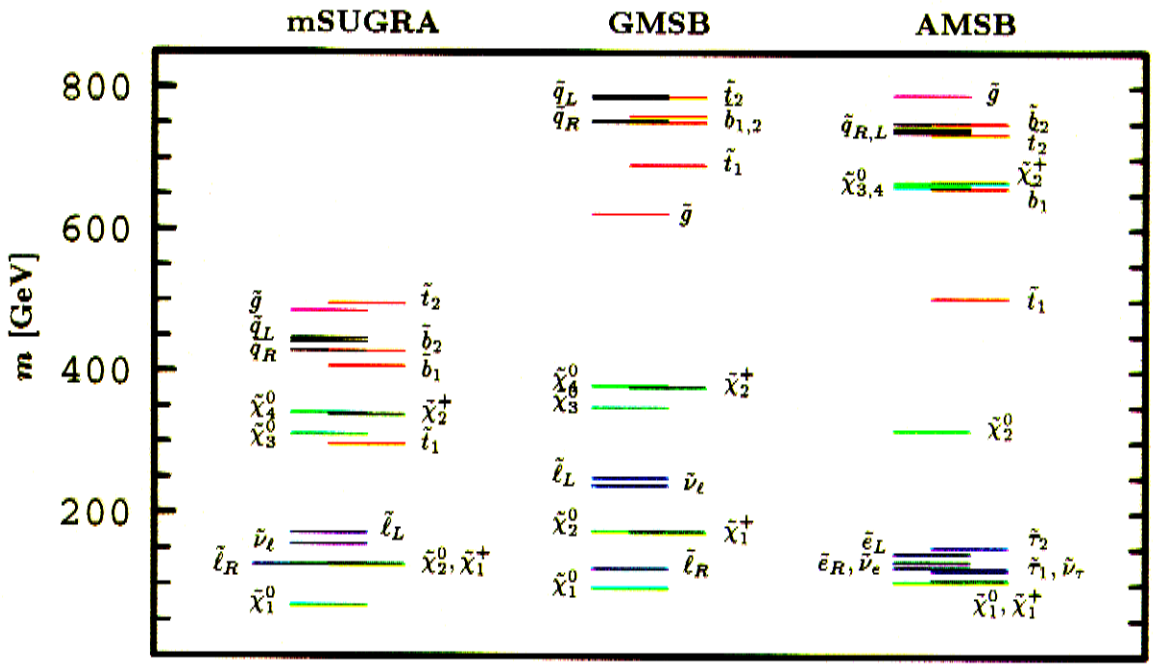
$M_i = (\beta_i/g_i)\, m_{3/2}$ $\qquad$ $M_1 \sim 3.2\, M_2$

⇒ characteristic properties

near mass deneracy of $\chi_1^\pm$ and χ_1^0

near mass deneracy of $\tilde{\ell}_R$ and $\tilde{\ell}_L$

SUSY Particle Spectra



$\tan\beta = 3$, sign(μ) +

mSUGRA	$m_0 = 100$ GeV, $m_{1/2} = 200$ GeV
GMSB	$\Lambda = 70$ TeV, $M_{\rm mess} = 100$ TeV, $N_{\rm mess} = 1$
AMSB	$m_0 = 200$ GeV, $m_{3/2} = 35$ TeV

POLARISATION

POLARISATION

Motivation

Why do we need the Linear Collider?

- Discovery of new physics
- High precision measurements of SM
- Determination of new physics

Why do we need Beam Polarisation?

- Beam polarisation $\leftrightarrow$ chiral couplings
- Enhancing/suppressing of special channels
  $\rightarrow$ Better statistics
  $\rightarrow$ Extraction of couplings
  $\rightarrow$ Background suppression

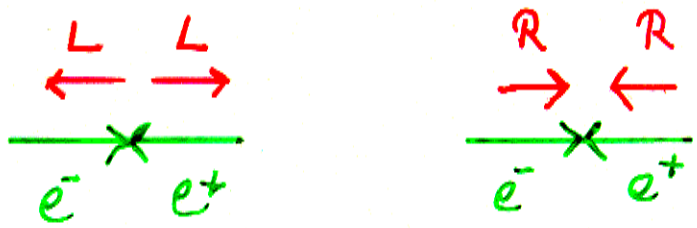
Electron Polarisation is well under control
$\rightarrow$ Experience and know-how from SLC!
$\rightarrow$ $P_{e^-} = (77.34 \pm 0.61)\%$ Ch. Baltay, Obernai Oct '99

So why do we need Positron Polarisation?

Longitudinal Polarisation

SM-Processes demand:

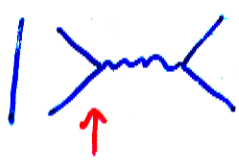
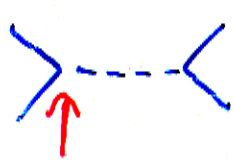
In "New Physics" possible:



$\Rightarrow$ e^+-Polarisation important for

- Indication of "NP"
- Increase of effective Polarisation
- Further background suppression

In principle:

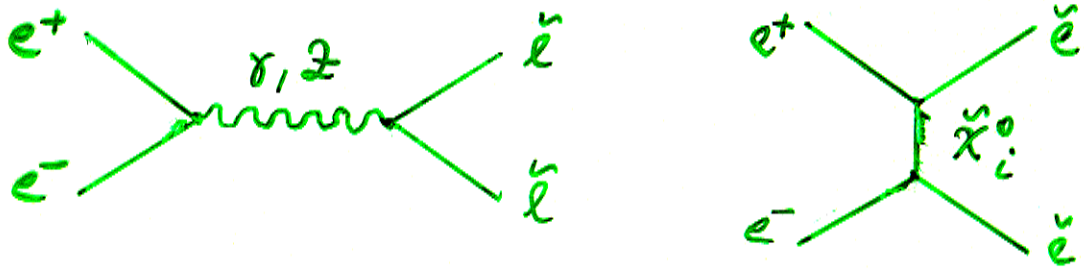
$|T|^2 \sim |$  $+$  $+ \; \ldots \; |^2$

$f_1(P_{e^-}, P_{e^+})$ $\quad$ $f_2(P_{e^-}, P_{e^+})$ $\quad$ ....

$\Rightarrow$ $\boxed{\text{Polarisation} \mathrel{\hat{=}} \text{"Weighting Factors"}}$

SUSY – Effects of $P(e^+)$

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



→ Better separation of $\tilde{\ell}_L \leftrightarrow \tilde{\ell}_R$

$e^-_L e^+_R \to \tilde{\ell}_L\tilde{\ell}_L$, $e^-_R e^+_L \to \tilde{\ell}_R\tilde{\ell}_R$ and $e^+_{(R)(L)} e^-_{(R)(L)} \to \tilde{e}_R\tilde{e}_L$

$$P(e^-) = -80\%: \begin{cases} \sigma(\tilde{e}_L\tilde{e}_L) = 900\,fb \\ \sigma(\tilde{e}_L\tilde{e}_R) = 200\,fb \\ \sigma(\tilde{e}_R\tilde{e}_R) = 50\,fb \end{cases} \xrightarrow{P(e^+)=60\%} \begin{cases} 1100\,fb \\ 100\,fb \\ 30\,fb \end{cases}$$

- $e^+e^- \to \tilde{t}_1\tilde{t}_1$: $m_{\tilde{t}}$, $\theta_{\tilde{t}}$

$\mathcal{L} = 500\,fb^{-1}$: $\Delta m_{\tilde{t}_1} = 1.1\,GeV$, $\Delta\cos\theta_{\tilde{t}} = 0.01$

⇒ improved by $\sim 20\%$ with $|P(e^-)| = 80\%$ and $|P(e^+)| = 60\%$

- $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$

with $|P(e^+)| = 60\%$ ⇒ $P_{eff} = 80\% \xrightarrow{P(e^+)} 95\%$

⇒ error decreased in : M_2, μ, $\tan\beta$, $m_{\tilde{\nu}}$

- $e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0$ in (MSSM, NMSSM, E6)

⇒ Enlarging Reach and Separation between Models

- Rare Processes with "wrong" helicities: $e^+e^- \to \tilde{\nu}$, $e^+e^- \to \tilde{\chi}\tilde{e}\nu_e$

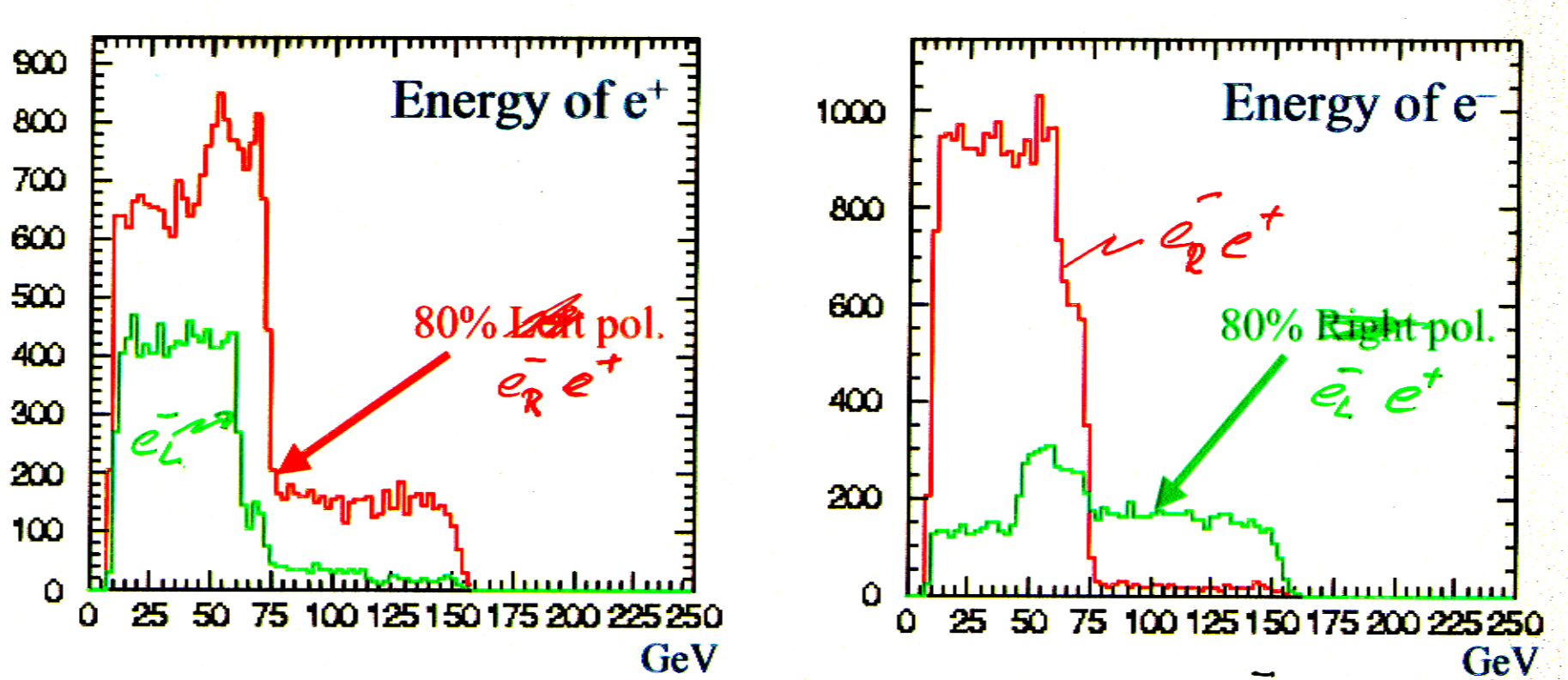
⇒ $P(e^+)$ is absolutely needed for NP!

$e^-_{L,R}\, e^+ \to \tilde{e}^+ \tilde{e}^-$

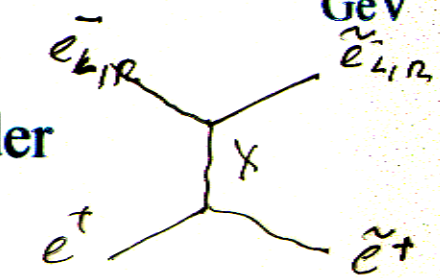
$\tilde{e}_R$: 157 GeV, $\tilde{e}_L$: 238 GeV

χ^0_1 : 128 GeV

SUSY vs. SM

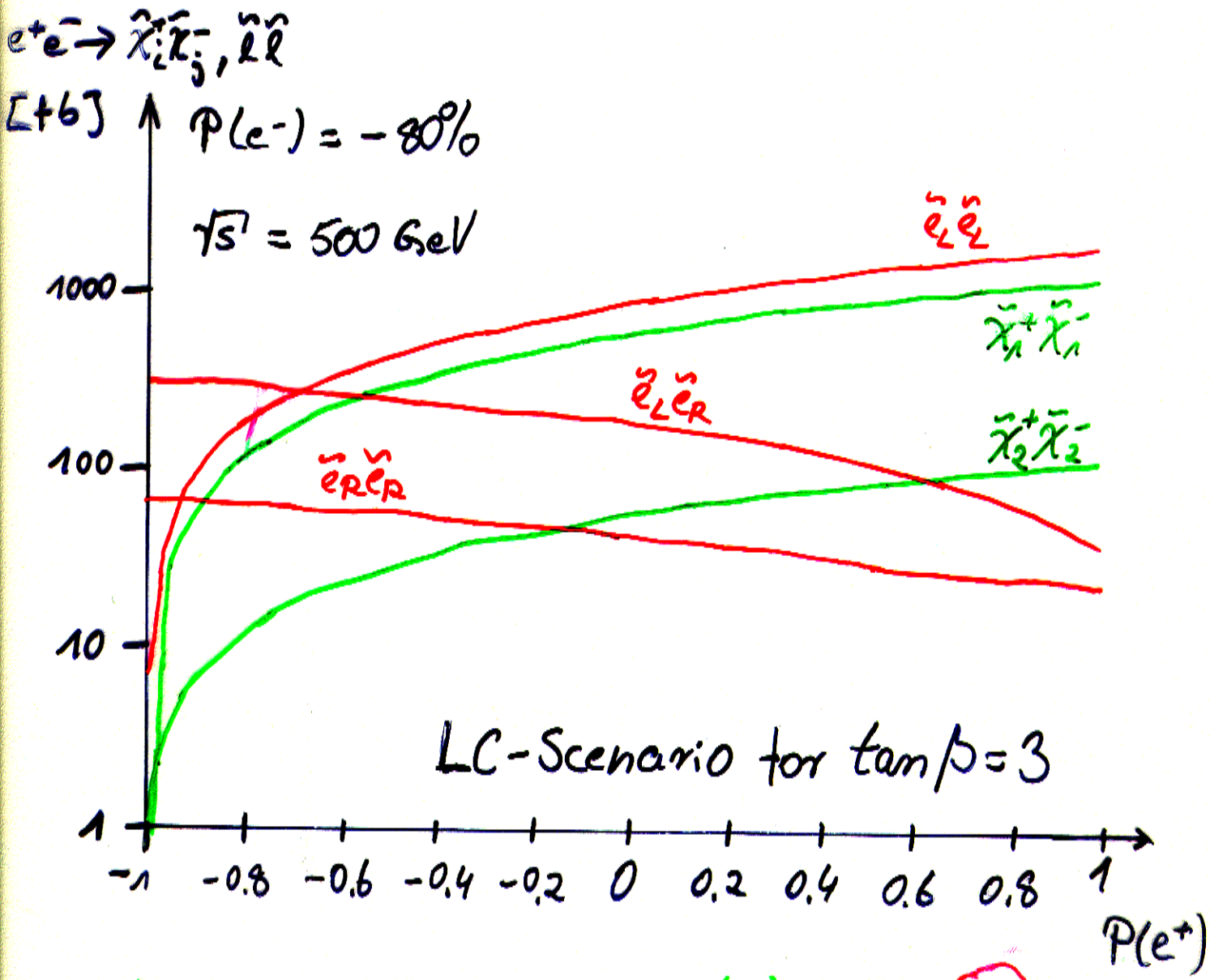


No SM signal has this type of behavior under L/R polarization change



SUSY – MSSM

LC-Reference Scenario for $\tan\beta = 3$



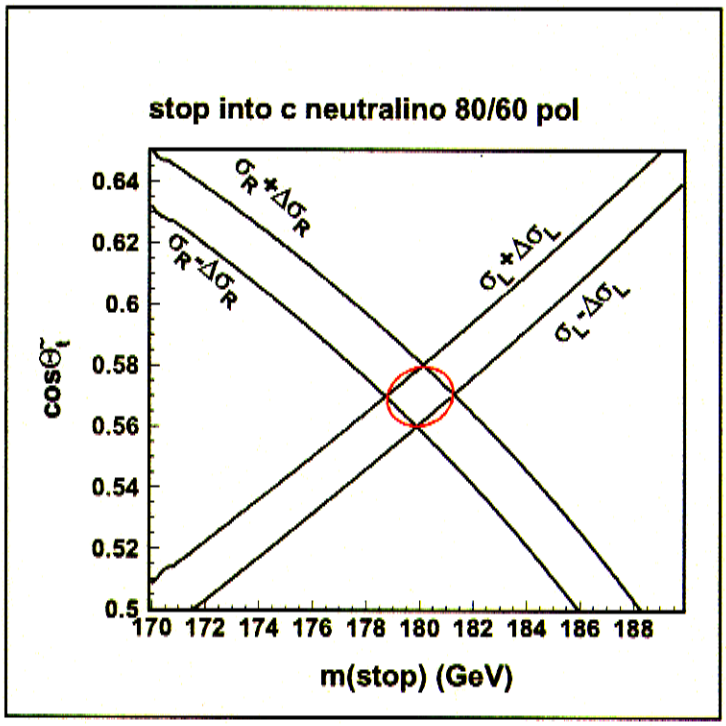
with $P(e^-) = -80\%$, $P(e^+) = 0$: $\sigma^{(-0)}(\tilde{\chi}_1^+\tilde{\chi}_1^-) = 1.8\,\sigma^{(00)}(\tilde{\chi}_1^+\tilde{\chi}_1^-)$

– " – , $P(e^+) = 60\%$: $\sigma^{(-+)}(\tilde{\chi}_1^+\tilde{\chi}_1^-) = 2.9\,\sigma^{(00)}(\tilde{\chi}_1^+\tilde{\chi}_1^-)$!

New Results

A Sopczak

$\tilde{t}_1 \to c\,\chi_1^0$



$P_{e^-} = 80\%$

$P_{e^+} = 60\%$

improvement by 20% wrt $P_{e^+} = 0$

$\Delta m_{\tilde{t}_1} = 0.8$ **GeV and** $\cos\theta_{LR} = 0.008$

$\tilde{t}_1 = t_2 \cos\Theta_{\tilde{t}} + t_3 \cos\Theta_{\tilde{t}}$

$m_{\tilde{t}_1} = 180$ GeV

$m_{\chi_1^0} = 100$ GeV

$\sqrt{s} = 500$ GeV

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

$e^+e^- \to \tilde{\chi}^0_1 \tilde{\chi}^0_2$: MSSM $\longleftrightarrow$ NMSSM

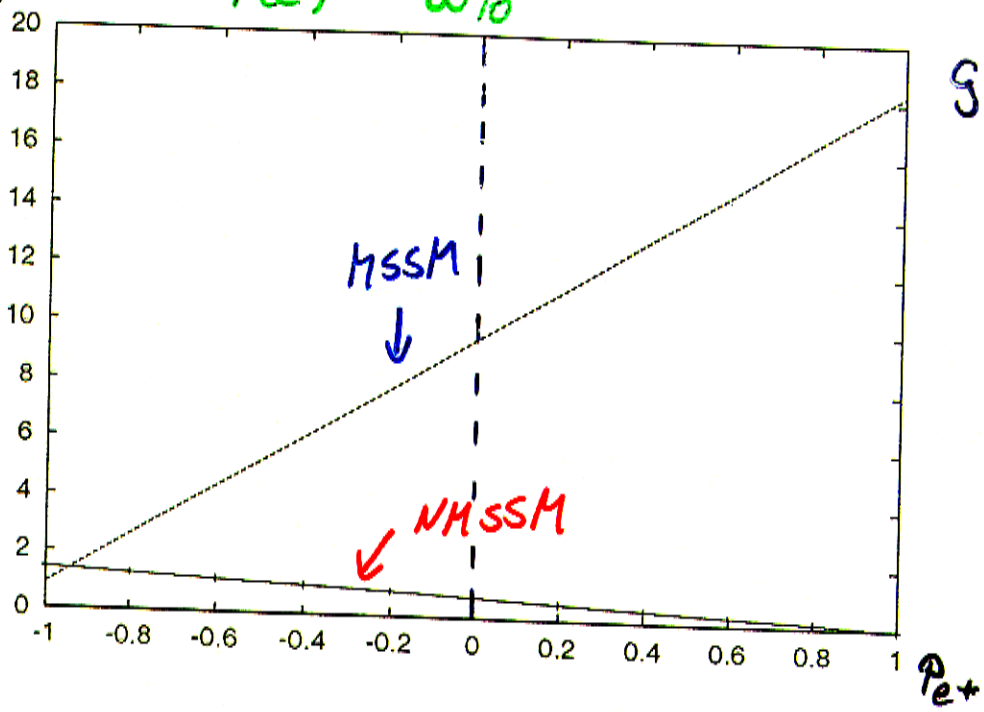
$\Rightarrow$ Different polarisation dependence !

$\sigma(\tilde{\chi}^0_1 \tilde{\chi}^0_2)$ [fb]

$P(e^-) = -80\%$

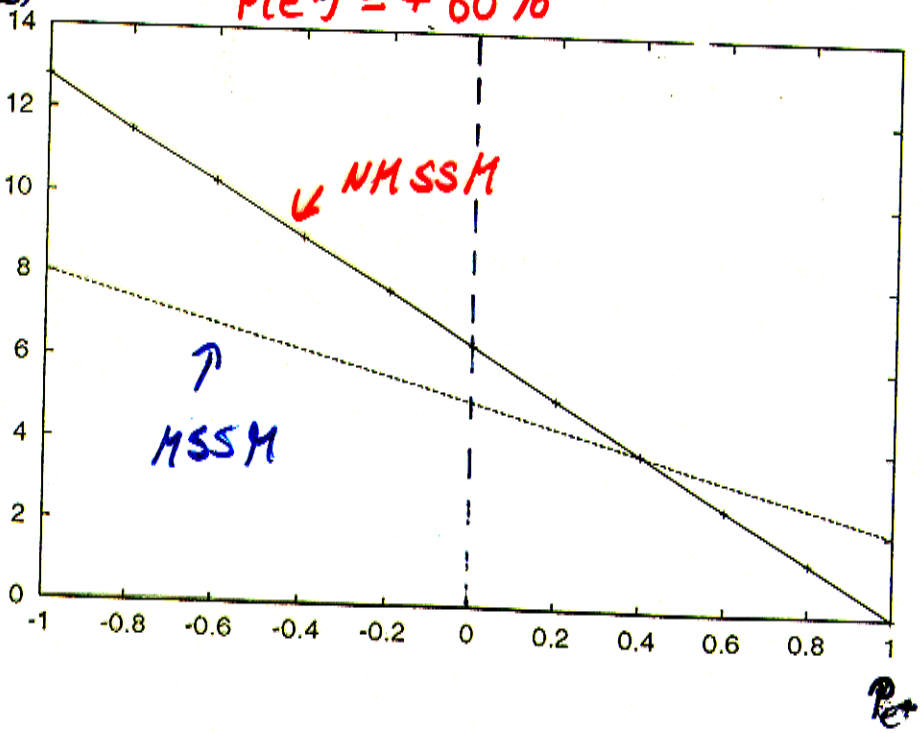
$\sqrt{s} = 500$ GeV

GMP, F. Franke



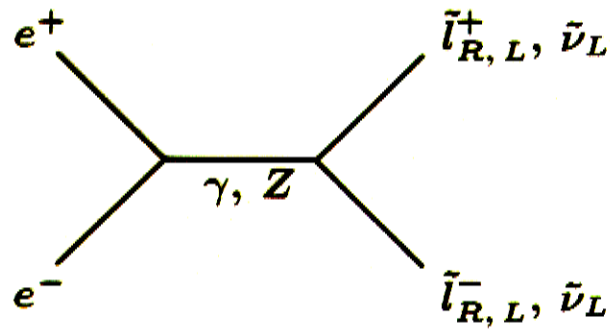
$\sigma(\tilde{\chi}^0_1 \tilde{\chi}^0_2)$ [fb]

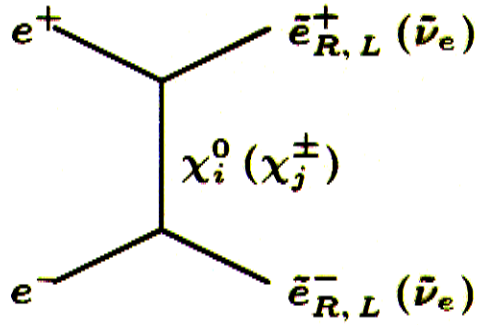
$P(e^-) = +80\%$



SLEPTONS

Scalar Leptons





Scalar lepton production

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

$$e^+ e^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R,\ \tilde{\mu}_L \tilde{\mu}_L$$

$$e^+ e^- \rightarrow \tilde{\tau}_R \tilde{\tau}_R,\ \tilde{\tau}_L \tilde{\tau}_L$$

$$e^+ e^- \rightarrow \tilde{\nu}_L \tilde{\nu}_L$$

s channel exchange

$$\frac{d\sigma(e^+ e^- \rightarrow \tilde{l}^+ \tilde{l}^-)}{d\Omega} = \frac{\alpha^2}{8\,s} \beta^3 \sin^2\theta\, |\mathcal{M}_\gamma + \mathcal{M}_Z|^2$$

Scalar lepton decays (via SM particles)

$$\tilde{l}^\pm_{L,R} \rightarrow l^\pm \chi^0_{1,2,3,4} \qquad \chi^0_1 = \text{LSP}$$

$$\tilde{l}^\pm_L \rightarrow \nu\, \chi^\pm_{1,2}$$

$$\tilde{\nu}_L \rightarrow l^\mp \chi^\pm_{1,2}$$

$$E_{l\,min}^{max} = \frac{m_{\tilde{l}}}{2}\left(1 - \frac{m_\chi^2}{m_{\tilde{l}}^2}\right)\gamma\,(1 \pm \beta) \quad \text{flat spectrum}$$

Scalar lepton signature

acoplanar lepton pair $l^+ l^-$ + missing energy

Third generation slepton mass measurements as probe for mSUGRA + RHN models

$\tilde{\nu}_R$

based on hep-ph/0010068

Superk $\nu_\mu \leftrightarrow \nu_\tau$ $\rightarrow$ ν_R should exist $\rightarrow$ $\tilde{\nu}_R$ search in SUSY

measure mixing $\tilde{\tau}_1 = \tilde{\tau}_L \cos\theta_{\tilde{\tau}} + \tilde{\tau}_R \sin\theta_{\tilde{\tau}}$

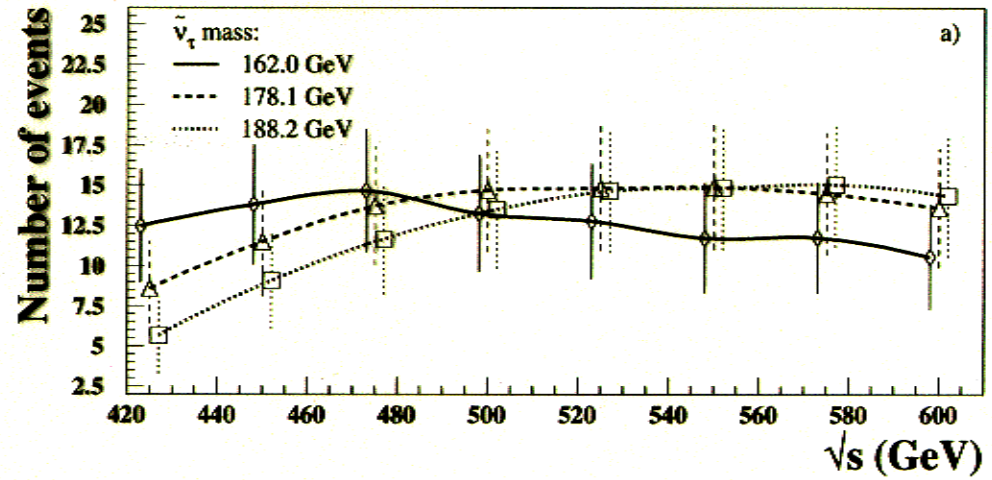
$\tilde{\tau}_2 = -\tilde{\tau}_L \sin\theta_{\tilde{\tau}} + \tilde{\tau}_R \cos\theta_{\tilde{\tau}}$

J. K. Mizukoshi*

H. Baer, C. Balázs, X. Tata

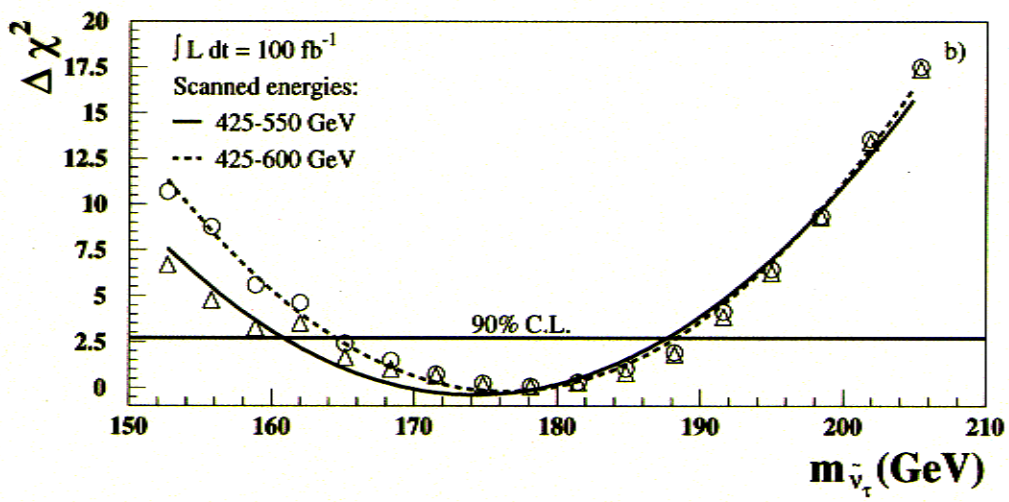
LCWS, October 2000

$$e^+e^- \to \tilde{\nu}_\tau \tilde{\nu}_\tau \to \tau\tau ljj + \not{E}_T$$



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

$m_{\tilde{\nu}_\tau} = 178 \pm 18$ GeV



Note: threshold scan

Hsu, Blair

$\Delta m_{\tilde{\nu}_\tau} < 1$ GeV

(a) The total number of events for $\tau\tau ljj + \not{E}_T$ topology from the signal only for three different sneutrino masses versus the center-of-mass energy. (b) The values of $\Delta\chi^2$ versus $m_{\tilde{\nu}_\tau}$ from the energy scan, where test case has taken to be the "data".

J K Mizukoshi

Stau polarization

In the MSSM

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

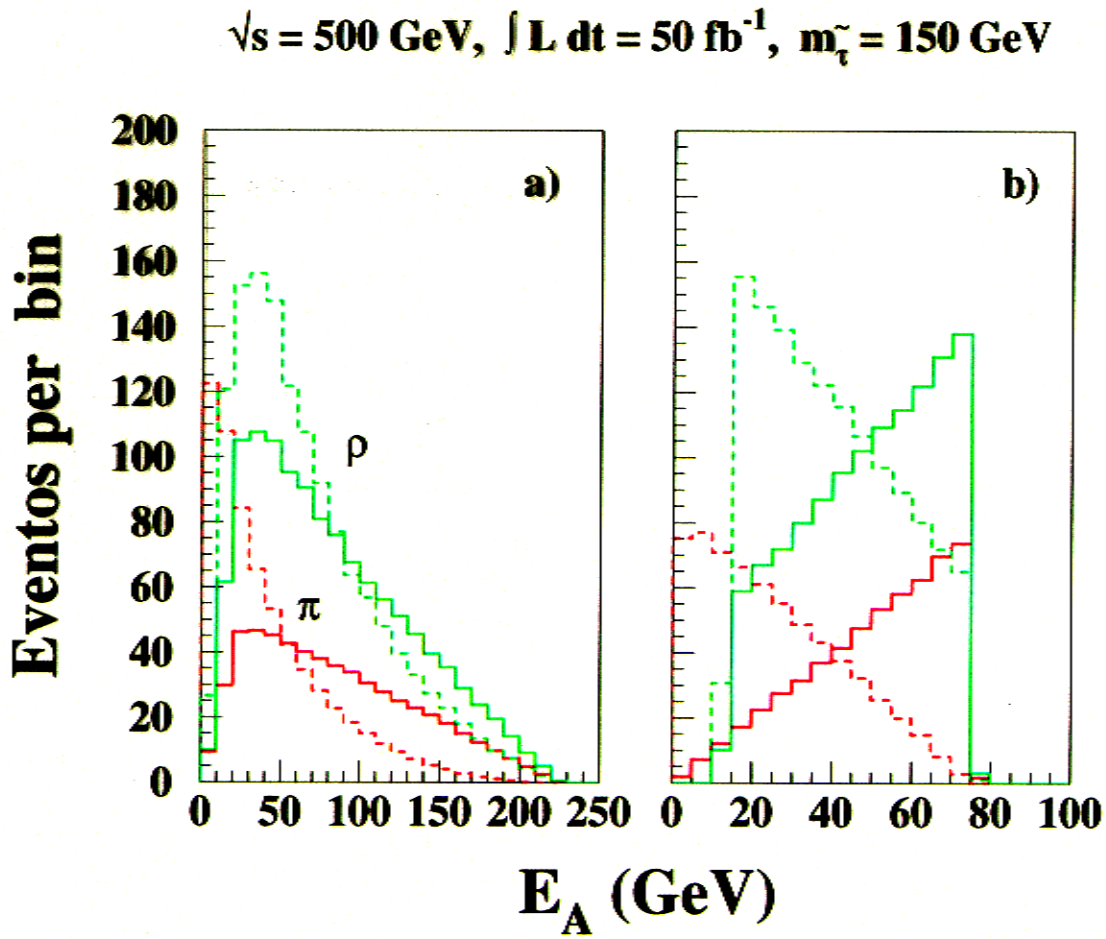
Mixing angle $\theta_{\tilde{\tau}}$ determination:

- cross section is very sensitive to polarized electron beam
- τ polarization analysis:

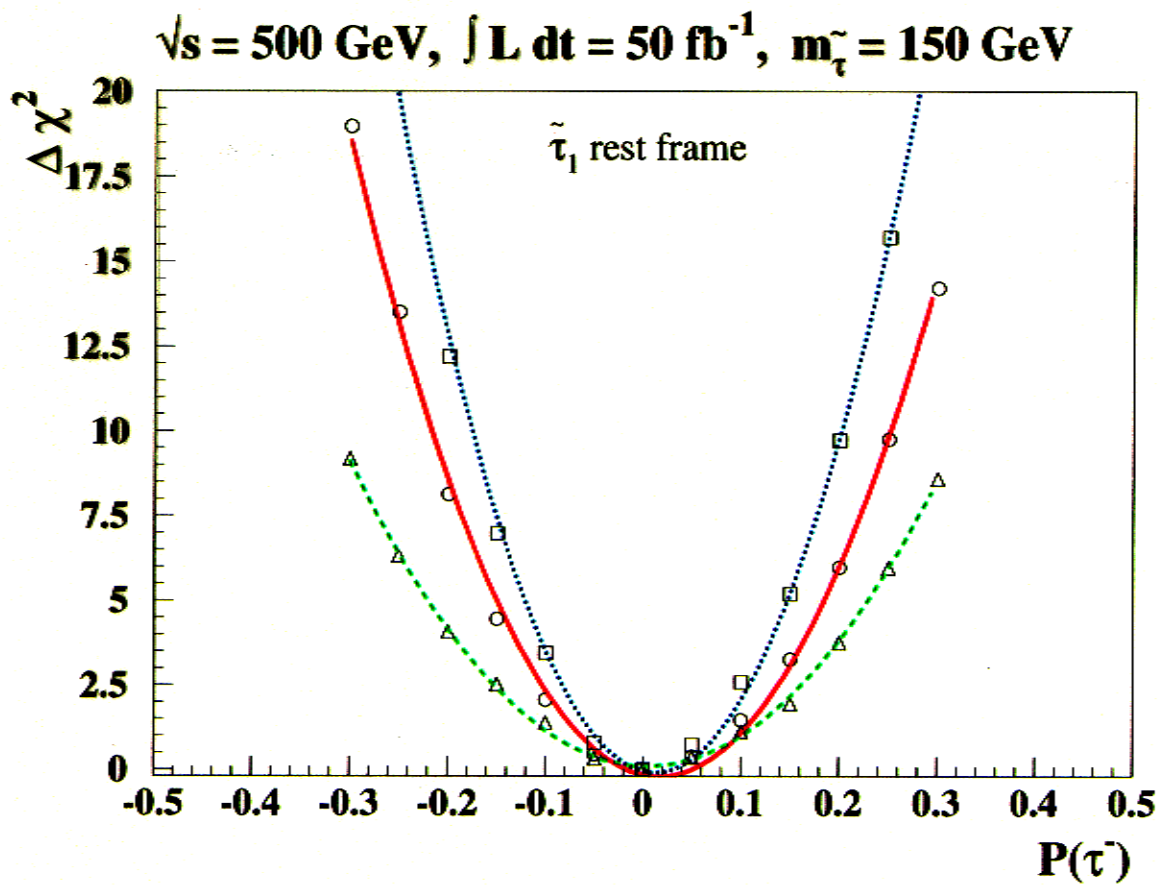
  $\tilde{\tau}_1^{\pm} \to \tau^{\pm}\tilde{G}$

  $\tau\tilde{\tau}\tilde{G}$: chirality conserving interaction

$$\boxed{P(\tau) = \sin^2\theta_{\tilde{\tau}} - \cos^2\theta_{\tilde{\tau}}}$$



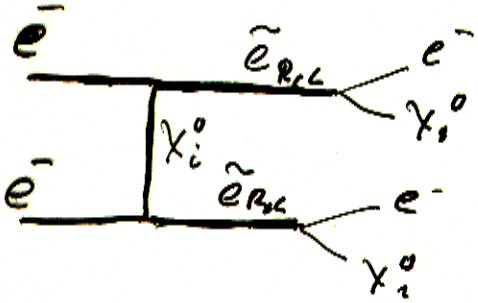
Energy distribution for the $\pi^{\pm}$ and $\rho^{\pm}$ decaying from right- (solid line) and left-handed (dashed line) $\tilde{\tau}$. In a) lab. frame, b) $\tilde{\tau}$ rest frame.



$\Delta\chi^2$ compared to the reference point $P(\tau) = 0$ for $\pi^\pm$ (solid line) $\rho^\pm$ (dashed line) and combined (dotted line) energy distribution fit.

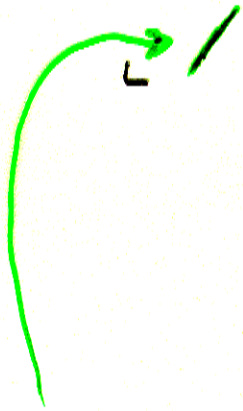
$e\,e \to e_R\, e_R$

C HEUSCH



$\sigma(e^-e^-) \sim \beta$

$\sigma(e^+e^-) \sim \beta^3$



TESLA

$\mathcal{L}_{e^-e^-} \sim \frac{1}{8}\,\mathcal{L}_{e^+e^-}$

$\sim 50\ fb^{-1}$ at $\sqrt{s} = 400\,GeV$

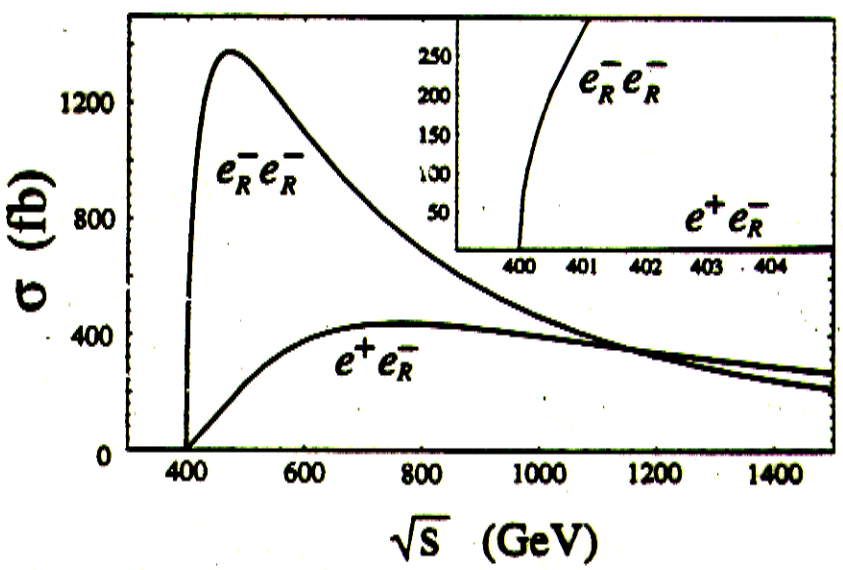
THE PRODUCTION OF PAIRS OF SCALARS AT THRESHOLD HAPPENS IN AN S STATE

($e^+e^- \to$ P STATE, β^3 FACTOR!)

(ANG 'MOM' BARRIER)

PRECISION DETERMINATION

OF SELECTRON / SMUON } MASS



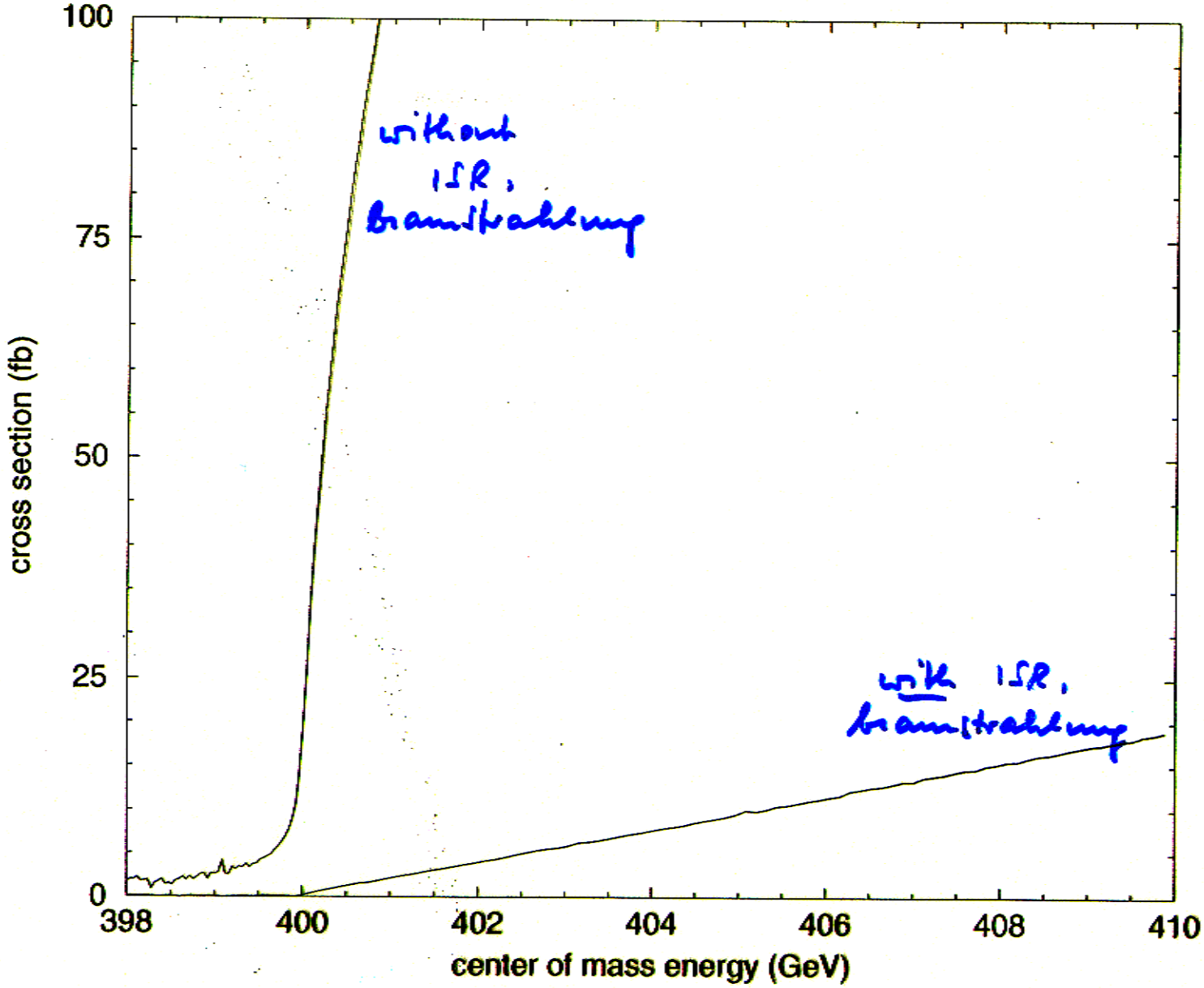
Cross sections $\sigma(e_R^- e_R^- \to \tilde{e}_R^- \tilde{e}_R^-)$ and $\sigma(e^+ e_R^- \to \tilde{e}_R^+ \tilde{e}_R^-)$ for $m_{\tilde{e}_R} = 200$ GeV and $m_{\tilde{\mu}} = 100$ GeV. The inset is a magnified view for $\sqrt{s}$ near threshold. Effects of initial state radiation, beamstrahlung,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

MODULO ΔE_{BEAM}

rad' corrections

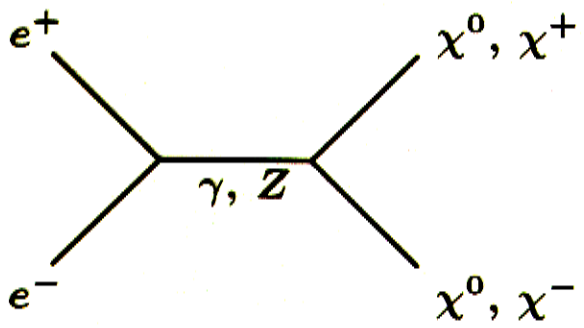
$\Gamma_{\tilde{e}}, \tilde{\mu}$

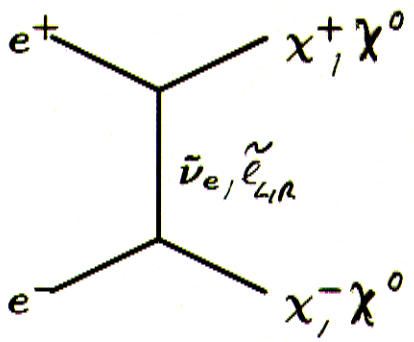
} see below


100
75
50
25
0
cross section (fb)
398
400
402
404
406
408
410
center of mass energy (GeV)
without ISR, bremstrahlung
with ISR, bremstrahlung

CHARGINOS / NEUTRALINOS

Charginos and Neutralinos





Chargino and neutralino production

$$e^+ e^- \rightarrow \chi_i^+ \chi_j^- \qquad [i, j = 1, 2]$$

$$e^+ e^- \rightarrow \chi_i^0 \chi_j^0 \qquad [i, j = 1, \ldots, 4]$$

***s* channel exchange**

$$\frac{d\sigma(e^+ e^- \rightarrow \chi\chi)}{d\Omega} = \frac{\alpha^2}{4s} \beta \left\{ (1 + \beta^2 \cos^2\theta)\, Q_1 + (1 - \beta^2)\, Q_2 + 2\beta \cos\theta\, Q_3 \right\}$$

Chargino and neutralino decays (via SM particles)

$$\chi_k \rightarrow Z/W\, \chi_1$$

$$\chi_1^\pm \rightarrow W\, \chi_1^0 \qquad \chi_1^0 = \text{LSP}$$

$$\chi^\pm \rightarrow l^\pm \tilde{\nu} \qquad \text{if } m_{\tilde{\nu}} < m_{\chi^\pm}$$

Chargino coupling to gaugino and higgsino

$$\chi_1^\pm = \alpha \tilde{W}^\pm + \beta \tilde{H}^\pm$$

Polarised beams:

	s channel		*t* channel
e_L^-	$\tilde{H}^\pm$	$\tilde{W}^\pm$	$\tilde{W}^\pm$
e_R^-	$\tilde{H}^\pm$	—	—

T KAMON

Introduction: A Large $\tan\beta$ Scenario

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

$$[M(\tilde{\ell}) > M(\tilde{\chi}_1^\pm) > M(\tilde{\tau}_1^\pm) > M(\tilde{\chi}_1^0)]$$

- **Can we study $\tilde{\chi}_1^\pm$ and $\tilde{\tau}_1^\pm$, and $\tilde{\chi}_1^0$, if the Nature choose MC Pt.#3 ($M_0 = 200, M_1 = 87.8, M_2 = 180, \mu = -400, \tan\beta = 50$) ?**

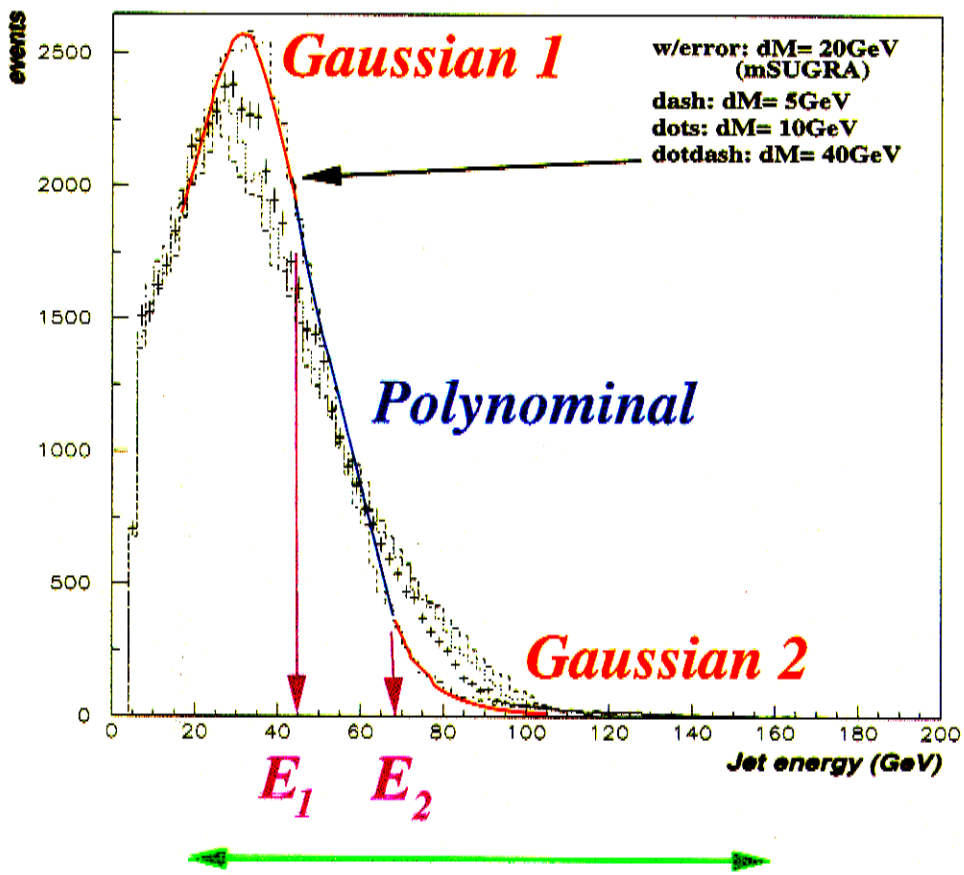
MC Point	$M(\tilde{\chi}_1^\pm)$	$M(\tilde{\tau}_1)$	$M(\tilde{\chi}_1^0)$	ΔM ($\equiv M(\tilde{\chi}_1^+) - M(\tilde{\tau})$)
1.	157.5	152.7	86.8	5
2.	162.5	152.7	86.8	10
3. (SUGRA)	172.5	152.7	86.8	20
4.	192.5	152.7	86.8	40

- **Three $\tau\tau + \not{E}_T$ final states in e^+e^- collisions:**

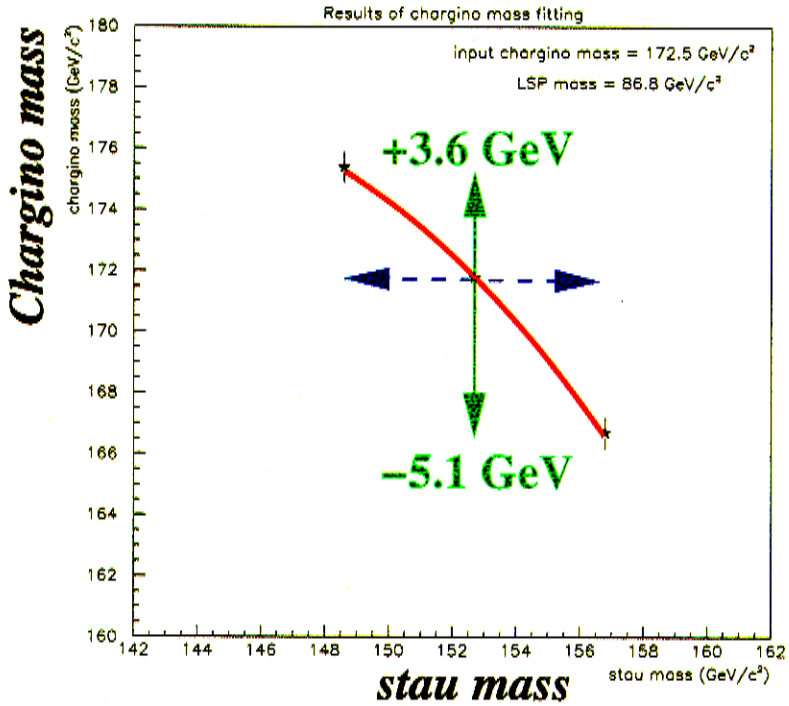
$$\to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\tau}^+\nu\ \tilde{\tau}^-\nu \to (\tau^+\nu\tilde{\chi}_1^0)(\tau^-\nu\tilde{\chi}_1^0)$$
$$\to \tilde{\tau}^+\tilde{\tau}^- \to (\tau^+\tilde{\chi}_1^0)(\tau^-\tilde{\chi}_1^0)$$
$$\to W^+W^- \to (\tau^+\nu)(\tau^-\nu)$$

Determination of Chargino Mass: L Design

- **Setp 1:** $N_{gen} = 100{,}000 \longrightarrow N_{acc} \approx 37,000$
- **Step 2: Fit the $E(j)$ distribution:**



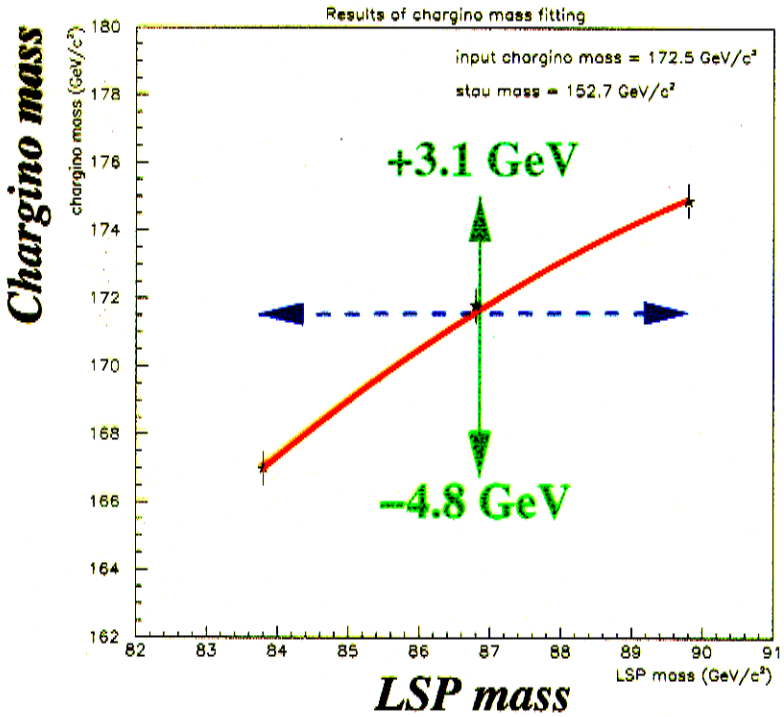
- **Step 3: Fit the parameters including E_1 and E_2 as a function of $M(\tilde{\chi}_1^{\pm}) \longrightarrow$ *templates***



$m_{\chi_1^+} = 172.5 \pm 5$ GeV

$m_{\tilde{\tau}_1} = 152.5 \pm 4.1$ GeV

$m_{\chi_1^0} = 86.8 \pm 3$ GeV



∃ KALINOWSKI

2. -Ino sector

* $\boxed{\text{charginos}}$ (in $\tilde{W}^-, \tilde{H}^-$ basis)

$$M_c = \begin{pmatrix} M_2 & \sqrt{2}\, m_W \cos\beta \\ \sqrt{2}\, m_W \sin\beta & |\mu|\, e^{i\phi_\mu} \end{pmatrix}$$

↑ $\not{CP}$ phase

to diagonalise: $(\tilde{W}, \tilde{H} \Rightarrow \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$

$$U_{L,R} = \begin{pmatrix} \cos\phi_{L,R} & e^{-i\beta_{L,R}} \sin\phi_{L,R} \\ -e^{-i\beta_{L,R}} \sin\phi_{L,R} & \cos\phi_{L,R} \end{pmatrix} \cdot \begin{pmatrix} e^{i\gamma_1} & \\ & e^{i\gamma_2} \end{pmatrix}$$

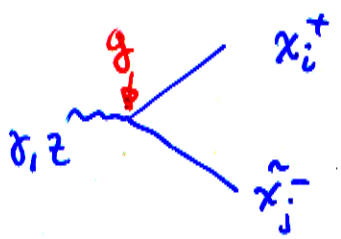
$$\Rightarrow \boxed{m_{\tilde{\chi}_1^\pm},\ m_{\tilde{\chi}_2^\pm},\ \phi_L,\ \phi_R}$$

$$m^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2}\left(M_2^2 + |\mu|^2 + 2m_W^2 \mp \Delta\right)$$

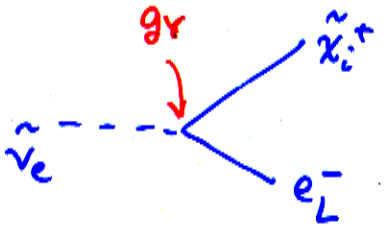
$$\Delta^2 = (M_2^2 + |\mu|^2 + 2m_W^2)^2 + 4m_W^2 (M_2^2 + |\mu|^2) + 8m_W^2 M_2 \mu \sin 2\beta \cos\phi_\mu$$

$$\cos 2\phi_{L,R} = -\left(M_2^2 - |\mu|^2 \mp 2m_W^2 \cos 2\beta\right) / \Delta$$

Couplings



$i=j$ real, $i \neq j$ complex



complex

S.Y. Choi et al., '00

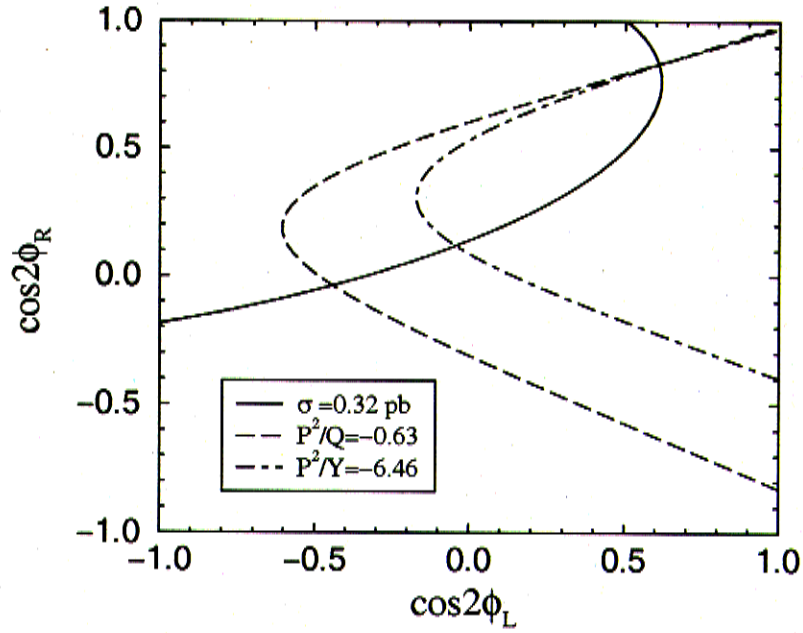


Figure 5: *Contours for the "measured values" of the total cross section (solid line), $\mathcal{P}^2/\mathcal{Q}$ (dashed line), and $\mathcal{P}^2/\mathcal{Y}$ (dot-dashed line) in the $[\cos 2\phi_L, \cos 2\phi_R]$ plane for the set* ***RR1*** $[\tan\beta = 3,\ m_0 = 100$ GeV, $M_{1/2} = 200$ GeV$]$ *at the e^+e^- c.m. energy of 400 GeV.*

7cm

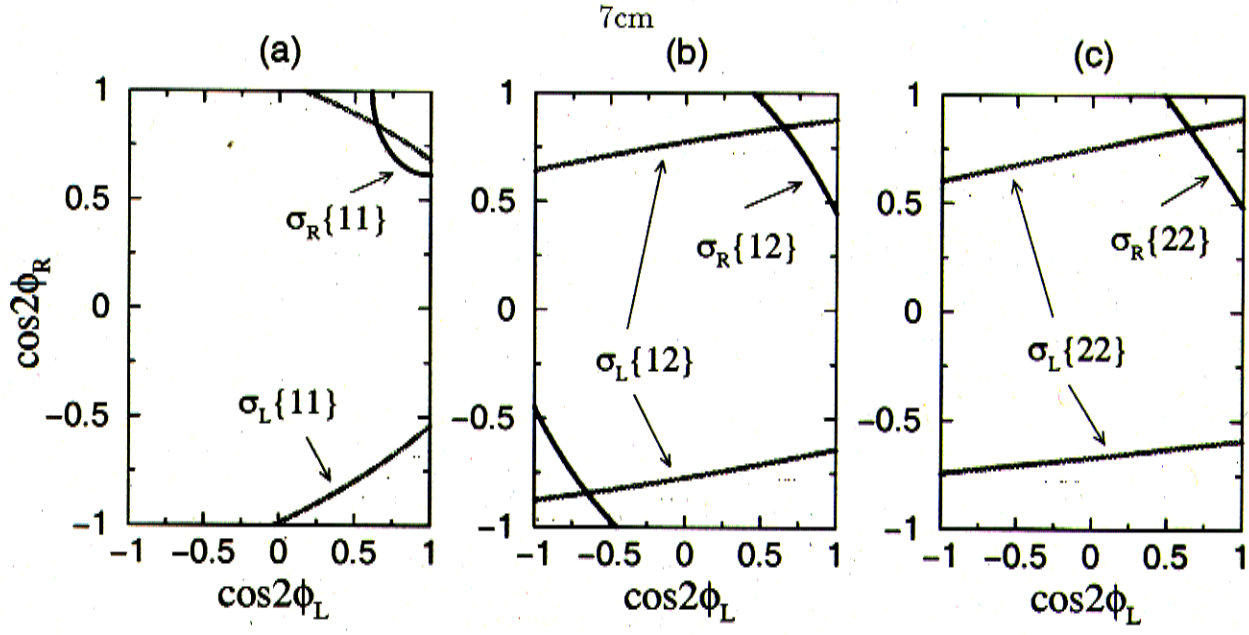


Figure 6: *Contours of the cross sections (a) $\{\sigma_R\{11\}, \sigma_L\{11\}\}$, (b) $\{\sigma_R\{12\}, \sigma_L\{12\}\}$, and (c) $\{\sigma_R\{22\}, \sigma_L\{22\}\}$ in the $[\cos 2\phi_L, \cos 2\phi_R]$ plane for the set* ***RR1*** $[\tan\beta = 3,\ m_0 = 100$ GeV, $M_{1/2} = 200$ GeV$]$ *at the c.m. energy of 800 GeV.*

Reconstructing fundamental parameters

from $m_{\tilde{\chi}_1^+}$, $m_{\tilde{\chi}_2^+}$, $\cos 2\phi_L$, $\cos 2\phi_R$ $\Rightarrow$

$$\tan^2\beta = \frac{4m_W^2 + (m^2_{\tilde{\chi}_2^+} - m^2_{\tilde{\chi}_1^+})(\cos 2\phi_R - \cos 2\phi_L)}{4m_W^2 - (m^2_{\tilde{\chi}_2^+} - m^2_{\tilde{\chi}_1^+})(\cos 2\phi_R - \cos 2\phi_L)}$$

$$\begin{pmatrix} M_2 \\ \mu \end{pmatrix}^2 = m^2_{\tilde{\chi}_2^+} + m^2_{\tilde{\chi}_1^+} - 2m_W^2 \mp \frac{1}{2}(m^2_{\tilde{\chi}_2^+} - m^2_{\tilde{\chi}_1^+})(\cos 2\phi_R - \cos 2\phi_L)$$

$$\cos\phi_\mu = \frac{(m^2_{\tilde{\chi}_2^+} - m^2_{\tilde{\chi}_1^+})^2 - (M_2^2 - \mu^2)^2 - 4m_W^2(M_2^2 + \mu^2) - 4m_W^4\cos^2 2\beta}{8m_W^2 M\mu \sin 2\beta}$$

unique analytical solution for

M_2, μ, $\tan\beta$, $\cos\phi_\mu$

note:

without $m_{\tilde{\chi}_2^\pm}$ (below $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$ threshold)

$\Rightarrow$ at most 2-fold ambiguity

(in the real case).

two reference points (CP conserving)

	RR1	RR2
$\tan\beta$	3	30
m_0	100	160
$M_{1/2}$	200	200
$\tilde{\chi}_1^\pm$	128	132
$\tilde{\chi}_2^\pm$	346	295
$\tilde{\chi}_1^0$	70	72
$\tilde{\nu}$	166	206

take 1σ error for σ_L, σ_R @ $1000\ fb^{-1}$

$$\Delta(\cos 2\phi_L) = 0.02$$
$$\Delta(\cos 2\phi_R) = 0.005$$

assume $\Delta m_{\tilde{\chi}} \simeq 200$ MeV

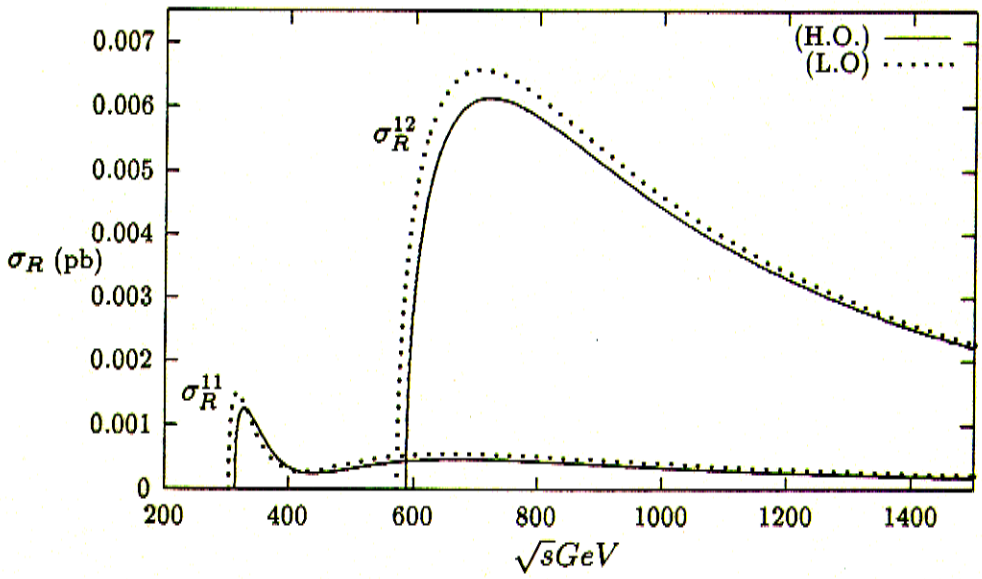
M_2	152 ± 1.8	150 ± 1.2
μ	316 ± 0.9	263 ± 0.7
$\tan\beta$	3 ± 0.7	30^{+30}_{-20}
g_Y/g	1 ± 0.001	1 ± 0.001
M_1	$+78_{-67} \pm 0.7$	$75_{-74} \pm 0.4$

$\Rightarrow$

← from other processes?

need $\sigma(\tilde{\chi}_1^0 \tilde{\chi}_2^0)$ to fix unique solution

$\sigma_R^{ij}(e_R^- e_L^+ \to \tilde{\chi}_j^+ \tilde{\chi}_i^-)$ vs $\sqrt{s}$



input parameters:

$M = 165$ GeV

$\mu = 400$ GeV

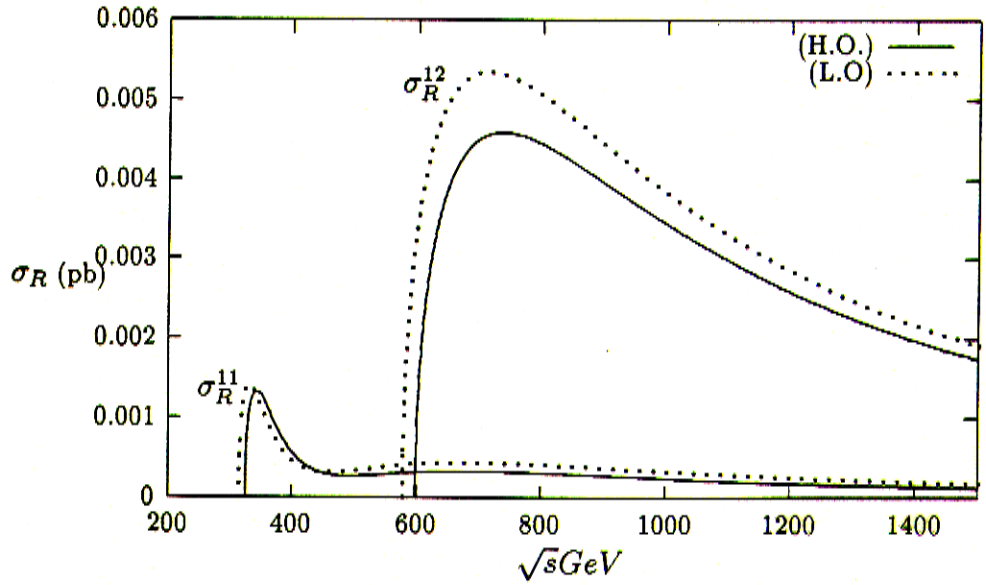
$t_\beta = 5$

$M_Q = A = m_{\tilde{t}_R} = 500$ GeV

Typical corrections for σ_R^{11} are 5-15%

and for σ_R^{12} are 3-10%

$\sigma_R^{ij}(e_R^- e_L^+ \to \tilde{\chi}_j^+ \tilde{\chi}_i)$ vs $\sqrt{s}$



input parameters:

$M = 165$ GeV

$\mu = 400$ GeV

$t_\beta = 50$

$M_Q = A = m_{\tilde{\nu}_e} = 500$ GeV

Typical corrections for σ_R^{11} are 10-20 %

and for σ_R^{12} are 10-15 %

	L.O.	H.O.
(Bookeeping 1)	$m_{\chi_1} = 157$	$m_{\chi_1} = 163$
	$m_{\chi_2} = 419$	$m_{\chi_2} = 435$

* **neutralinos** $\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0$

$$M_N = \begin{pmatrix} |M_1| e^{i\phi_1} & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -|\mu| e^{i\phi_\mu} \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -|\mu| e^{i\phi_\mu} & 0 \end{pmatrix}$$

$s_W = \sin\theta_W$

$s_\beta = \sin\beta$

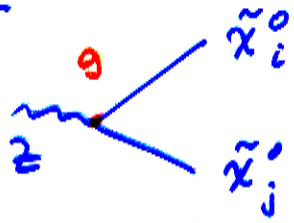
to <u>diagonalize</u> $N^* M_c N^T$

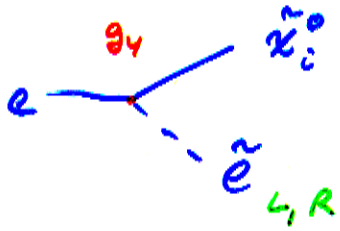
N is a 4×4 mixing matrix

6 mixing angles + 10 phases

$\Rightarrow \quad m_{\tilde{\chi}_i^0}, \quad i = 1, 2, 3, 4$

<u>couplings</u>





<u>Note</u>: non-trivial consistency conditions among physical masses and mixing angles

(Kraus, Moultaka 'PRD61)

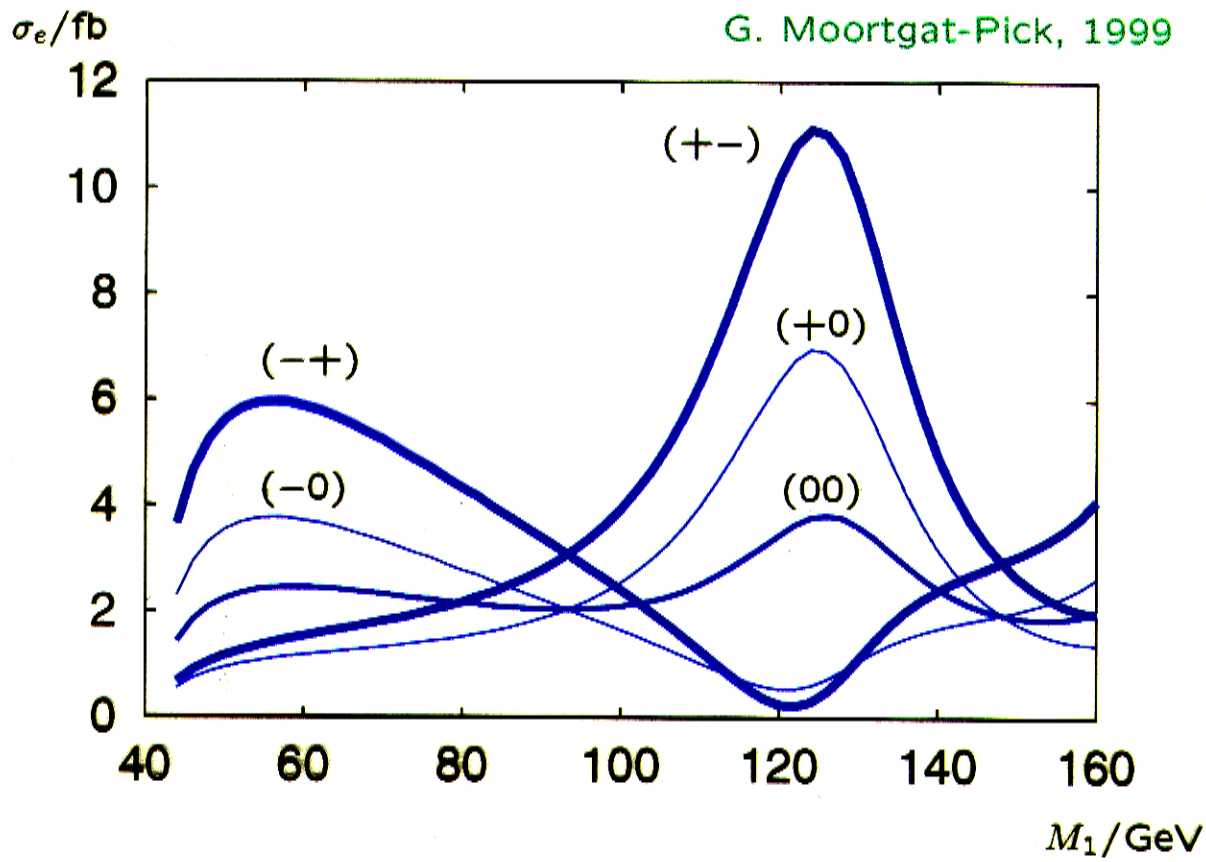
Use χ^0 system to determine additional parameters M_1, $m_{\tilde{e}}$

→ F

C Blöchinger

Total Cross Section σ_e

$$\sigma_e = \sigma\left(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0\right) \times BR\left(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+e^-\right)$$



$\sqrt{s_{ee}} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 30$ GeV

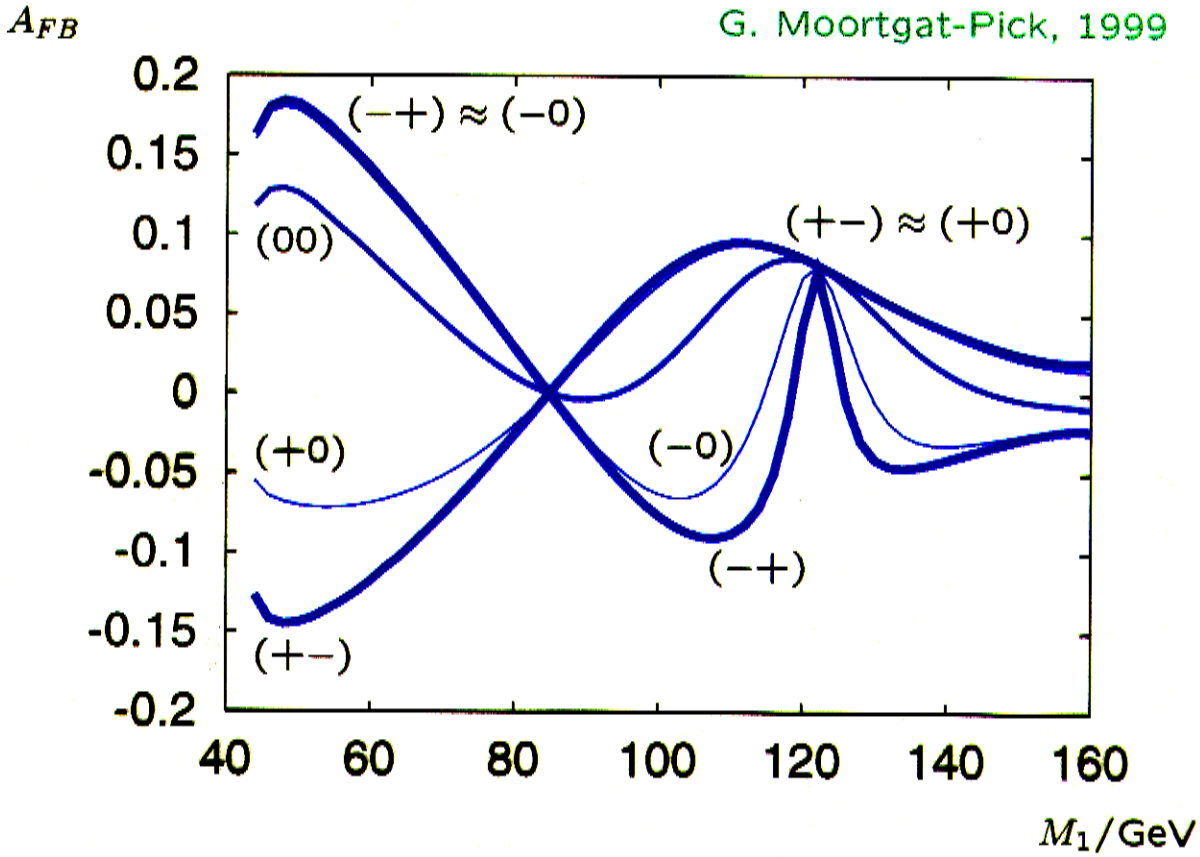
$m_{\tilde{e}_R} = 161$ GeV

$m_{\tilde{e}_L} = 176$ GeV

$P_- = 0, \pm 0.85,\ P_+ = 0, \pm 0.6 \to \left(\mathrm{sgn}(P_-), \mathrm{sgn}(P_+)\right)$

Asymmetry A_{FB} of the decay electron

$$A_{FB} = \frac{\sigma_e(\cos\Theta_e > 0) - \sigma_e(\cos\Theta_e < 0)}{\sigma_e(\cos\Theta_e > 0) + \sigma_e(\cos\Theta_e < 0)}$$



$\sqrt{s_{ee}} = m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0} + 30$ GeV

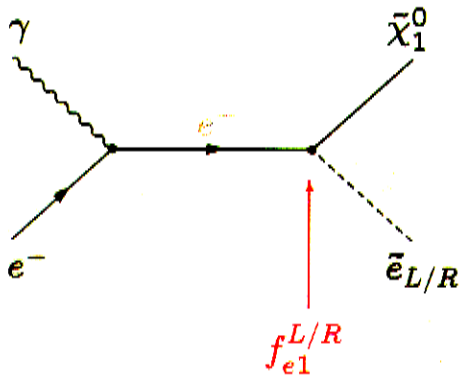
$m_{\tilde{e}_R} = 161$ GeV

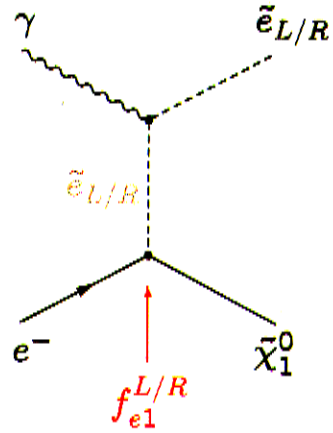
$m_{\tilde{e}_L} = 176$ GeV

$P_- = 0, \pm 0.85,\ P_+ = 0, \pm 0.6 \rightarrow \left(\mathrm{sgn}(P_-), \mathrm{sgn}(P_+)\right)$

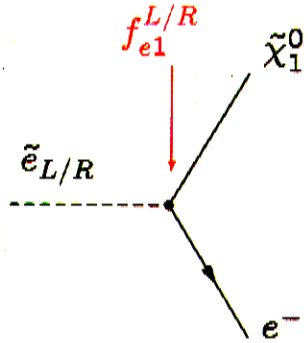
Feynman Graphs for LSP/Selectron Production and Leptonic Decay

Production :





Decay :



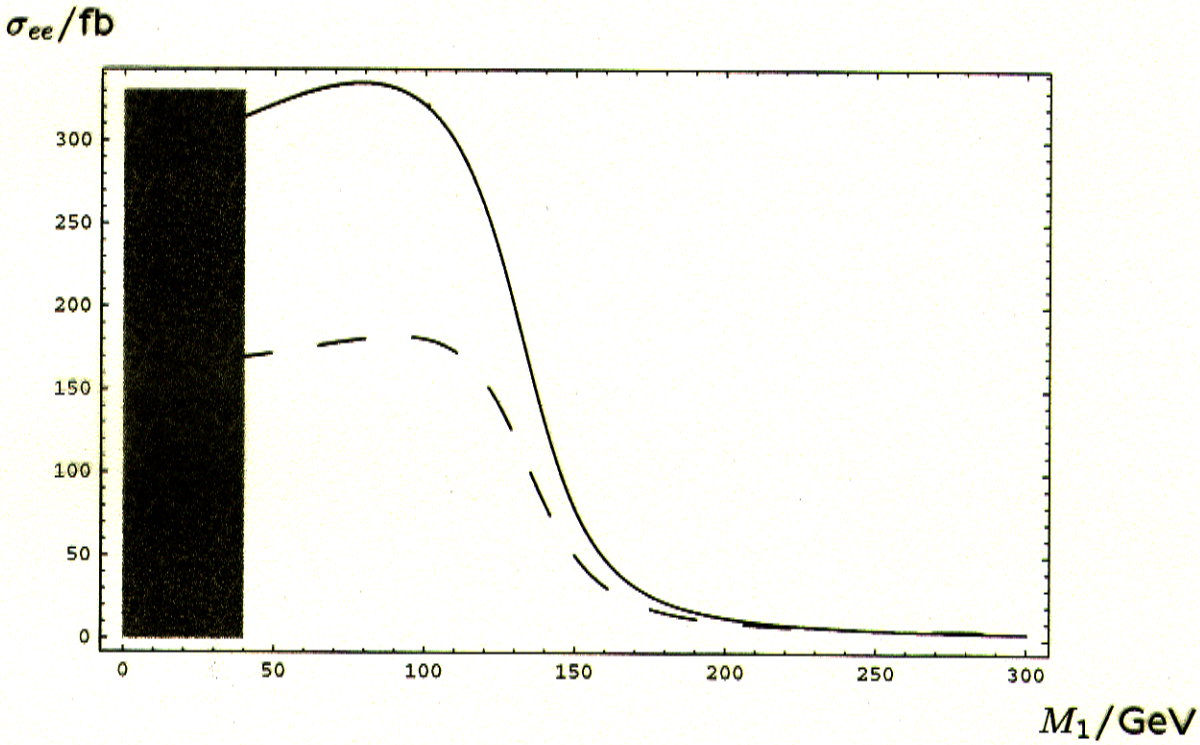
M_1 in Production and Decay:

- mass $m_{\tilde{\chi}_1^0}$
- couplings f_{e1}^L, f_{e1}^R

Total Cross Section
$\sigma_{ee}(\lambda_L = \pm 1)$

Convoluted cross section in the lab. frame:

$$\sigma_{ee}(s_{ee}, P_e, \lambda_k, \lambda_L) = \int dy P(y)\, \sigma_{e\gamma}(s_{e\gamma}) \times BR(\tilde{e}_{L/R} \to \tilde{\chi}_1^0 e^-)$$



$\sqrt{s_{ee}} = 500$ GeV

$P_e = 0.8$

$\lambda_k = +0.8$

$\lambda_L = +1$ ———

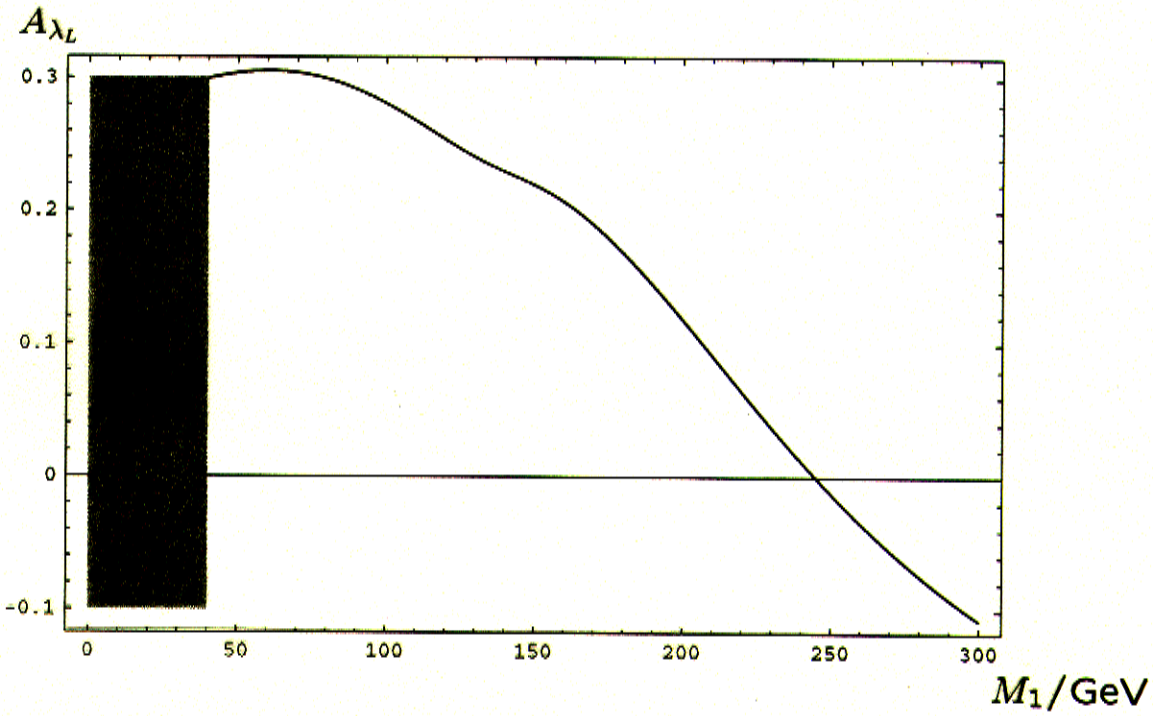
$\lambda_L = -1$ - - - -

$m_{\tilde{e}_L} = 179.3$ GeV

$m_{\tilde{e}_R} = 137.7$ GeV

Polarization Asymmetry A_{λ_L}

$$A_{\lambda_L} = \frac{\sigma_{ee}\left(s_{ee}, P_e, \lambda_k, \lambda_L\right) - \sigma_{ee}\left(s_{ee}, P_e, \lambda_k, -\lambda_L\right)}{\sigma_{ee}\left(s_{ee}, P_e, \lambda_k, \lambda_L\right) + \sigma_{ee}\left(s_{ee}, P_e, \lambda_k, -\lambda_L\right)}$$



$\sqrt{s_{ee}} = 500$ GeV

$\lambda_L = +1$

$\lambda_k = +0.8$

$P_e = 0.8$

$m_{\tilde{e}_L} = 179.3$ GeV

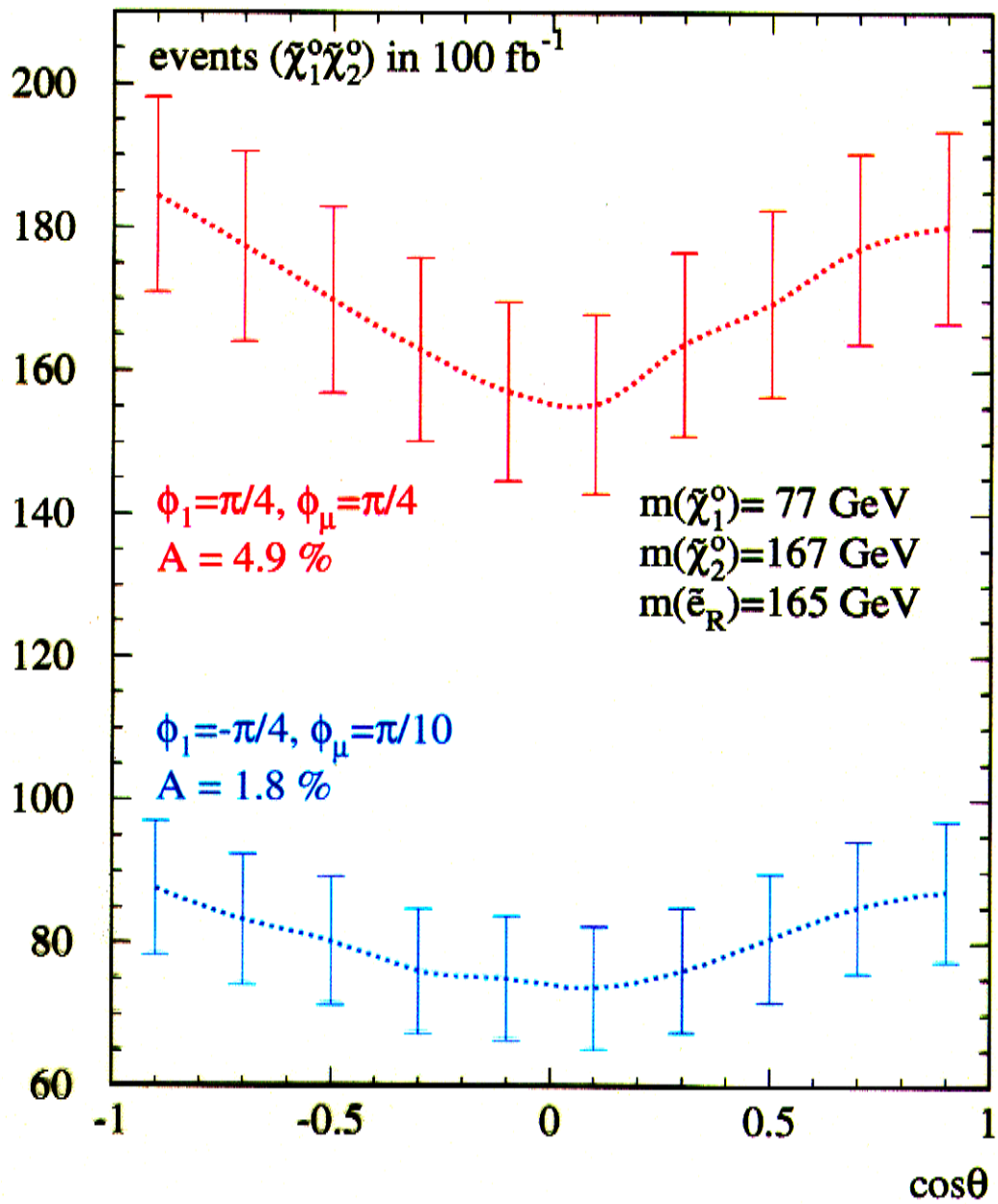
$m_{\tilde{e}_R} = 137.7$ GeV

$e^+e^- \to \chi_1^0 \chi_2^0$

$\hookrightarrow e^+e^- \chi_1^0$

T PLEHN

CP sensitive quantity $\vec{p}_{e^-} \cdot (\vec{k}_{e^-} \times \vec{k}_{e^+}) \propto \cos\theta$



from edm of e, n, Hg CP $\phi \lesssim 10^{-3}$

Potential of the LHC and LC to Study Degenerate Wino Pairs

John F. Gunion and Stephen Mrenna

UC Davis Institute for High Energy Physics

✘ $M_2 \ll M_1, |\mu|$ is "natural" when:

- gaugino masses are dominated by loop corrections
  - ▷ O–II superstring models

    A. Brignole, L.E. Ibanez, and C. Munoz

  - ▷ SUSY–breaking from the conformal anomaly (AMSB)

    G.F. Giudice, M.A. Luty, H. Murayama and R. Rattazzi; L. Randall and R. Sundrum

- SUSY is broken by an F–term that is not an SU(5) singlet

  Snowmass96 Summer Study

✘ LSP and NLSP are Winos with nearly degenerate masses

- Radiative corrections favor $M_{\widetilde{C}_1} - M_{\widetilde{N}_1} > m_\pi$

  S. Mizuta, D. Ng, M. Yamaguchi; A. Papadopoulous, D. Pierce; D. Pierce, J. Bagger, K. Matchev, R.–J. Zhang

See related studies of AMSB-like phenomenology

Gunion, Drees; Gunion, Drees, Chen; Gherghetta, Guidice, Wells; Feng *et al.*; Gunion, SM;

Paige,Wells; Baer, Mizukoshi, Tata

Talk available at:

`http://moose.ucdavis.edu/mrenna/talks/LCsusy.ps`

Lepton Collider Overview

✔ Concentrate on difficult case when scalars are heavy

- $\Delta m_{\tilde{\chi}_1} < m_\pi$

  $\widetilde{C}_1^\pm$ yields a highly–ionizing or disappearing track

  $\widetilde{C}_1^+\widetilde{C}_1^-$ production will be easily seen

- $\Delta m_{\tilde{\chi}_1} > 2 - 3\,\mathrm{GeV}$

  mSUGRA limit at LEP2

✘ $m_\pi < \Delta m_{\tilde{\chi}_1} < 2 - 3\,\mathrm{GeV}$

$\widetilde{C}_1^\pm \to \widetilde{N}_1\pi^\pm$ decay yields a soft π track

STUB ($\Delta m_{\tilde{\chi}_1} < 180\,\mathrm{MeV}$) or HIP ($\Delta m_{\tilde{\chi}_1} < 1\,\mathrm{GeV}$)

▷ $\gamma\gamma \to \pi\pi$ background makes direct $\widetilde{C}_1^+\widetilde{C}_1^-$ unmanageable

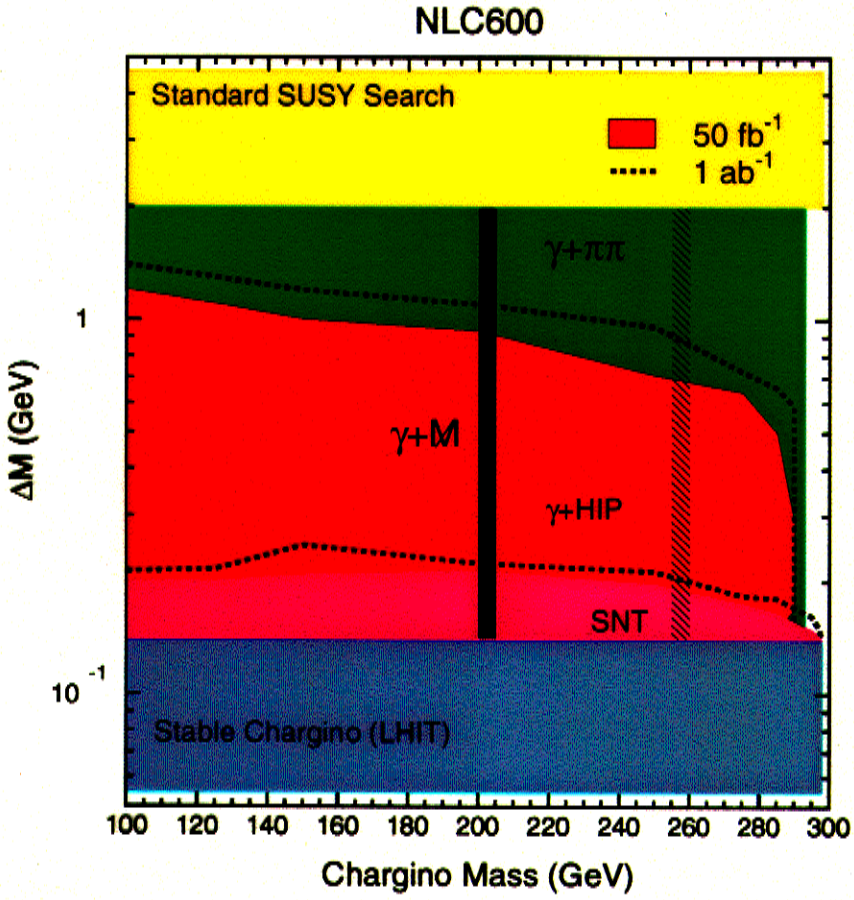
▷ $e^+e^- \to \gamma\widetilde{C}_1^+\widetilde{C}_1^-$ (with $\nu\bar{\nu}\gamma$ background)

$\gamma + \not{E} + \pi\pi$ signature

$p_T^\gamma > 10\,\mathrm{GeV}, 10^\circ \leq \theta_\gamma \leq 170^\circ$

Disclaimer: We assume background to $\gamma + \pi$(s) signal is small. No decent Monte Carlo programs, but measured background after cuts at LEP2 is negligible, even without requiring a high impact parameter for at least one of the π's.

NLC600 reach for 50 fb^{-1}/1 ab^{-1}



- 10 event min for "background free"
- otherwise $S/\sqrt{B} > 5$, $S/B > 0.02$
- For $200\ \mathrm{MeV} < \Delta m_{\tilde{\chi}_1} < 2\ \mathrm{GeV}$, γ tag is necessary for tagging and reducing background

SNT $\Rightarrow$ terminating chargino track

HIP $\Rightarrow$ soft π with significant impact parameter

$\pi\pi \Rightarrow$ two, soft, acollinear pions

Reconstructing Supersymmetric Theories at High Energy Scales

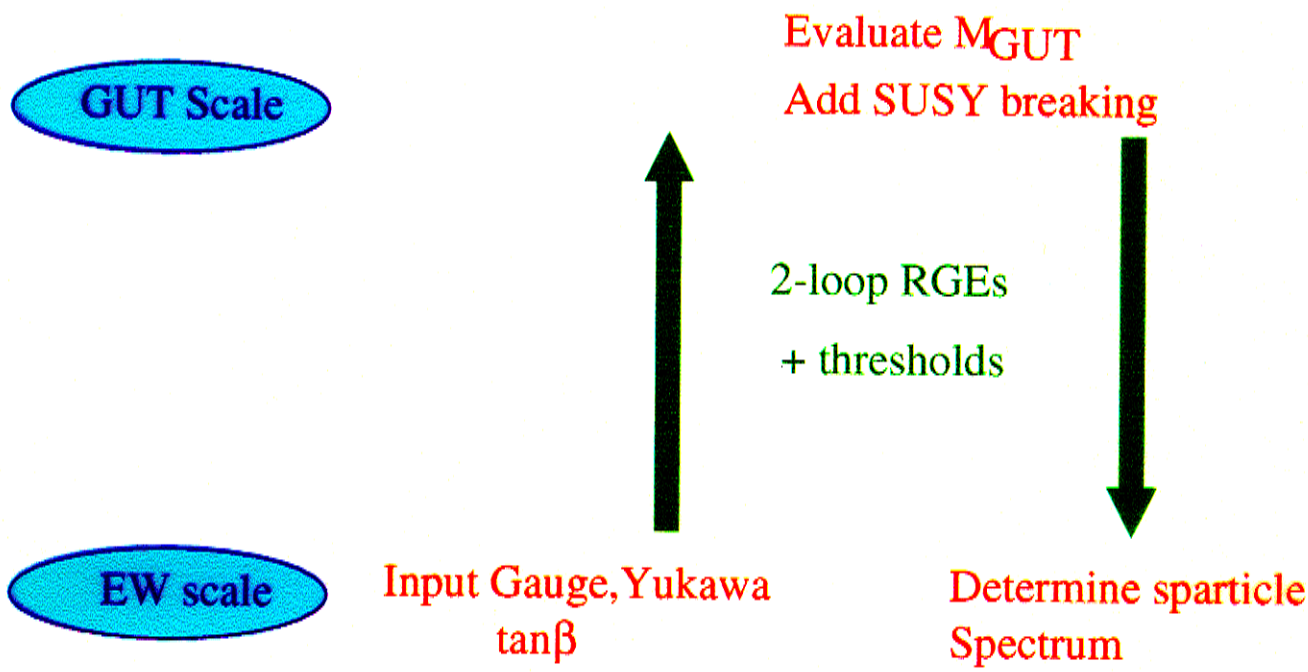
Grahame A. Blair
Royal Holloway, Univ. of London
email: g.blair@rhul.ac.uk

Overview:

- *Statement of the problem*
- *Top-down approach*
- *Bottom-up approach*
- *Experimental Errors*
- *Numerical Procedure*
- *Results*
- *Summary*

G.A. Blair, W. Porod, P.M.Zerwas, hep-ph/0007107

Setting up the Model:



- First determine M_{GUT} (for mSUGRA - M_m for GMSB) by evolving RGE's upwards.
- At M_{GUT}, input the values of M_0,$M_{\frac{1}{2}}$,A, tanβ, sign(μ).
- Evolve downwards to determine electroweak sparticle spectrum.
- Assume radiative electroweak symmetry breaking:

$$|\mu|^2 = \frac{m_{H2}^2 \sin^2\beta - m_{H1}^2 \cos^2\beta}{\cos 2\beta} - \frac{1}{2} m_Z^2 + \text{rad.corr.}$$

RGE's: S.Martin and M.Vaughn, Phys. Rev. D50, 2282 (1994); Y.Yamada, Phys.Rev.D50, 3537 (1994); I.Jack and D.R.T.Jones, Phys Lett B333,372 (1994).

Thresholds: J.Bagger, K Matchev, D.Pierce and R.Zhang, Nucl.Phys.B491,3 (1997).

Top-down extraction of parameters:

Assuming a top-down approach, where M_0,$M_{\frac{1}{2}}$,A, tanβ are allowed to vary at the GUT Scale assuming mSUGRA led to:

parameter	true value	error
m_0	100 GeV	0.09 GeV
$m_{1/2}$	200 GeV	0.10 GeV
A_0	0 GeV	6.3 GeV
$\tan\beta$	3	0.02
sgn(μ)	+	not fit

Allowing M_1 and M_2 to vary independently leads to:

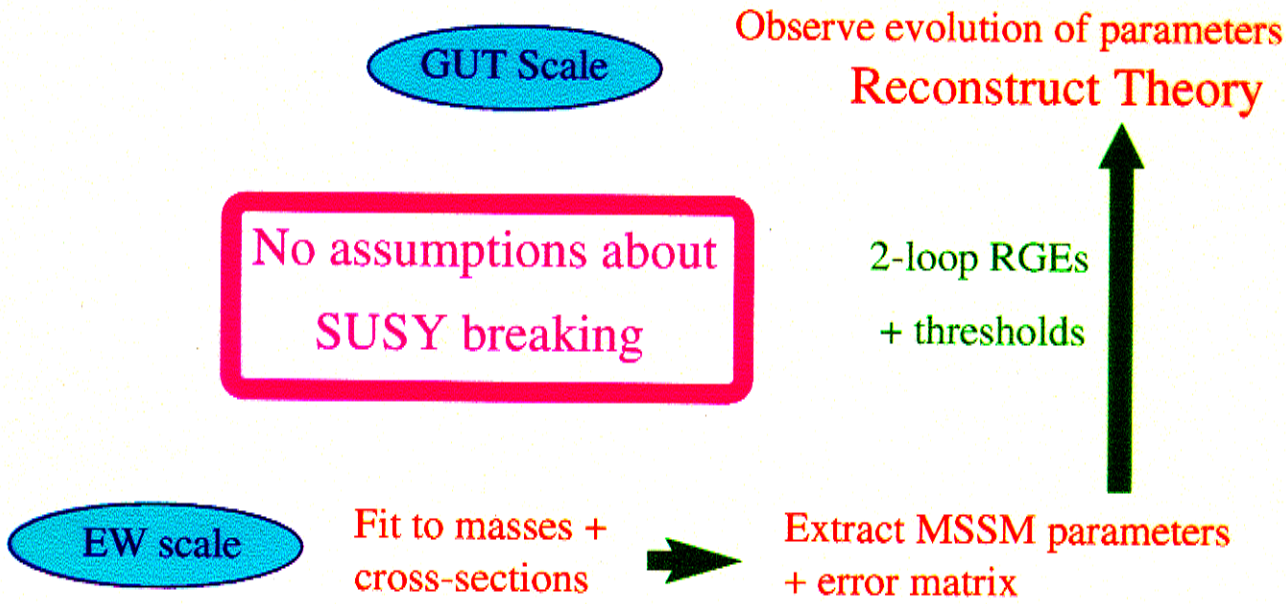
parameter	true value	error
m_0	100 GeV	0.09 GeV
M_1	200 GeV	0.20 GeV
M_2	200 GeV	0.20 GeV
A_0	0 GeV	10.3 GeV
$\tan\beta$	3	0.04
sgn(μ)	+	not fit

Conclusion: the top-down approach, combined with LC errors, gives excellent mSUGRA parameter determination.

BUT: the model assumption could hide the true structure ...

So: Adopt a bottom-up approach:

Bottom-up approach:



- Fit to the mass spectrum + cross-sections at EW scale.
- Use conservative estimates for errors (see below).
- Extract MSSM parameters + error matrix at EW scale

EW scale parameters: $M_{E_k}, M_{L_k}, M_{D_k}, M_{Q_k}, M_{U_k}, A_\tau, A_b, A_t,$ $M_{H_1}, M_{H_2}, M_i, \tan\beta$, k=1,3, $i = 1, 2, 3$

Finally

- Input measured particle spectrum into RGE's.
- Evolve RGE's upwards.
- Importantly: reconstruct theory, without bias.

Assumptions Used in Fits:

- $\mathcal{L}$= 100 fb^{-1} for each scanned point
- $\mathcal{L}$= 500 fb^{-1} for each polarized cross-section measurement.
- Polarization: e$^-$:80%, e$^+$:60%.
- No colour- (or charge-) breaking minima are allowed as solutions in fit.
- Representative LHC errors† assumed for more massive sparticles

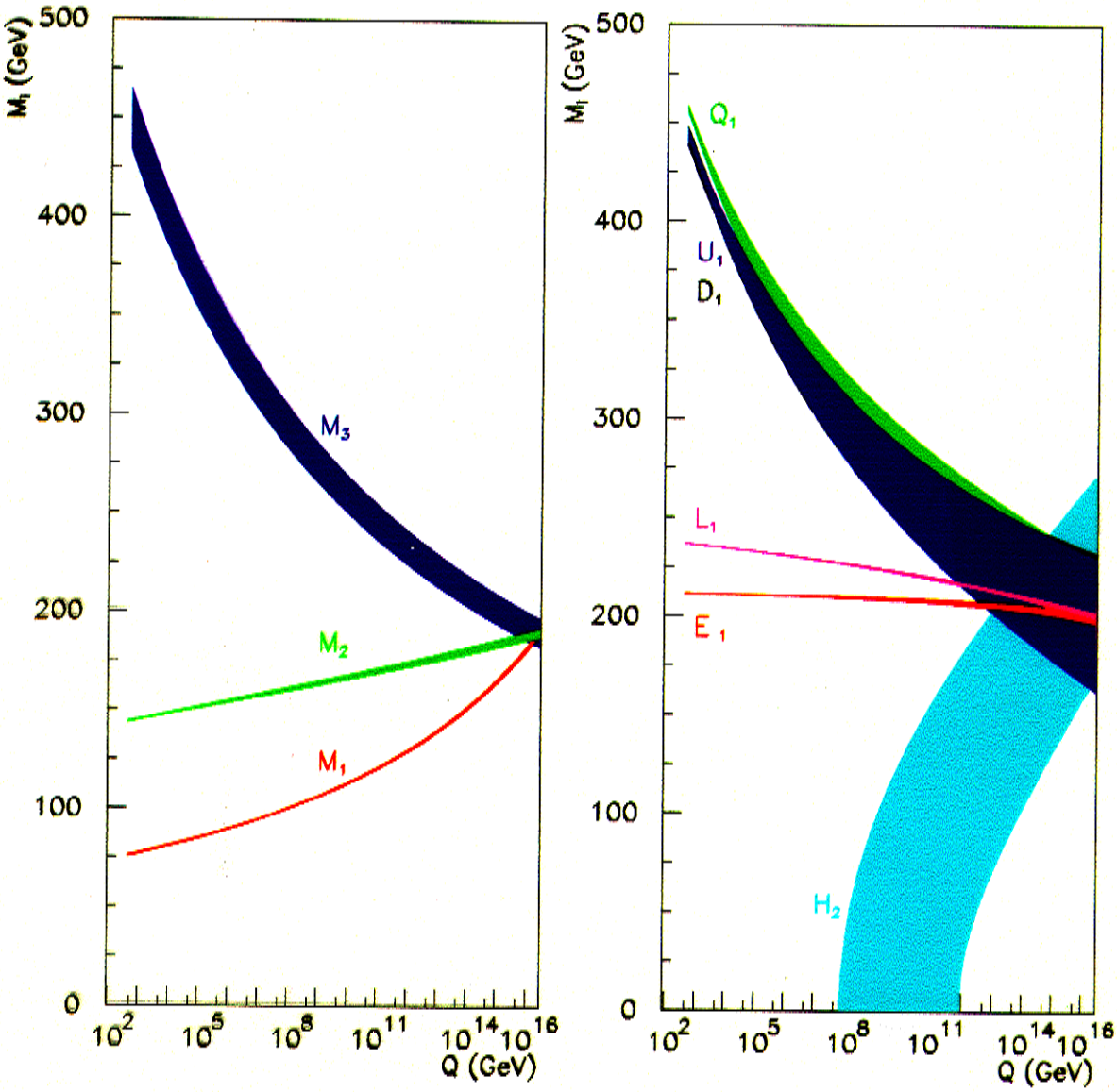
mSUGRA model

Particle	M(GeV) Mass	Δ M(GeV) LHC	Δ M(GeV) LHC+LC
h^0	109	0.2	0.05
A^0	191	3	1.5
χ_1^+	133	3	0.11
χ_1^0	72.6	3	0.15
$\tilde{\nu}_e$	233	3	0.1
$\tilde{e}_1$	217	3	0.15
$\tilde{\nu}_\tau$	214	3	0.8
$\tilde{\tau}_1$	154	3	0.7
$\tilde{u}_1$	466	10	1
$\tilde{t}_1$	377	10	1
$\tilde{g}$	470	10	10

† ATLAS TDR, CERN/LHCC/99-15.

mSUGRA

$\tan\beta = 30$, M_0=200 GeV, $M_{\frac{1}{2}}$=190 GeV, A_0=550 GeV, sign(μ)=-1

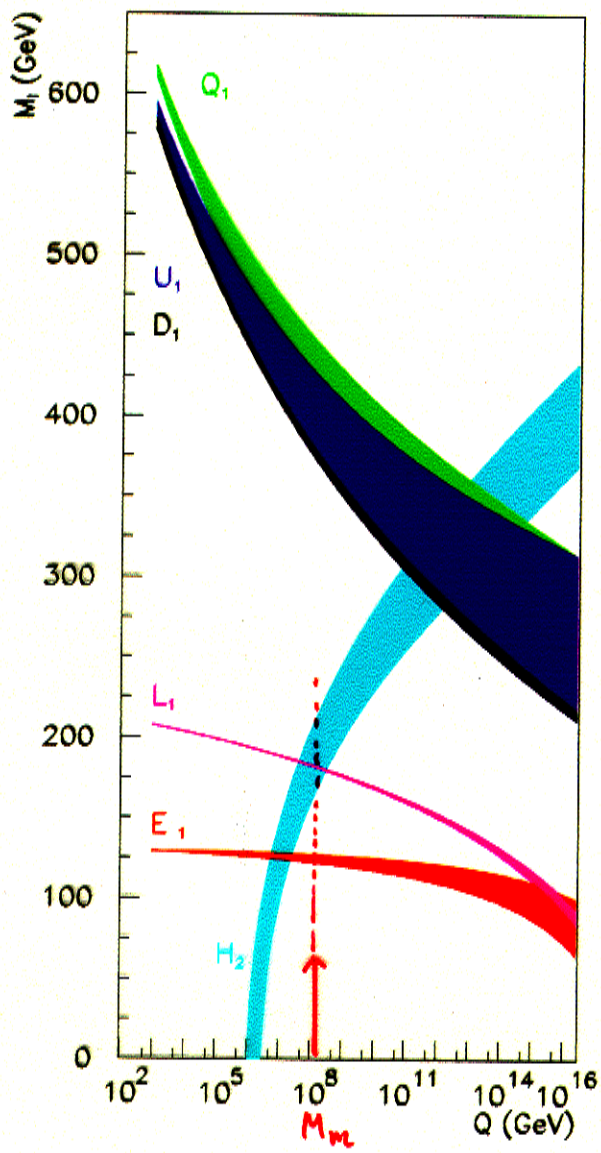


The widths of the bands indicate the 95% CL.

- Slepton sector is under very good control
- M_3 accuracy limited by the gluino mass precision.
- Unification of parameters is reconstructed.

GMSB

$\tan\beta = 30$, $M_m = 2 \times 10^5$ TeV, Λ =28 TeV, N_5 =3, $A_0 = 0$, sign(μ)=-1.

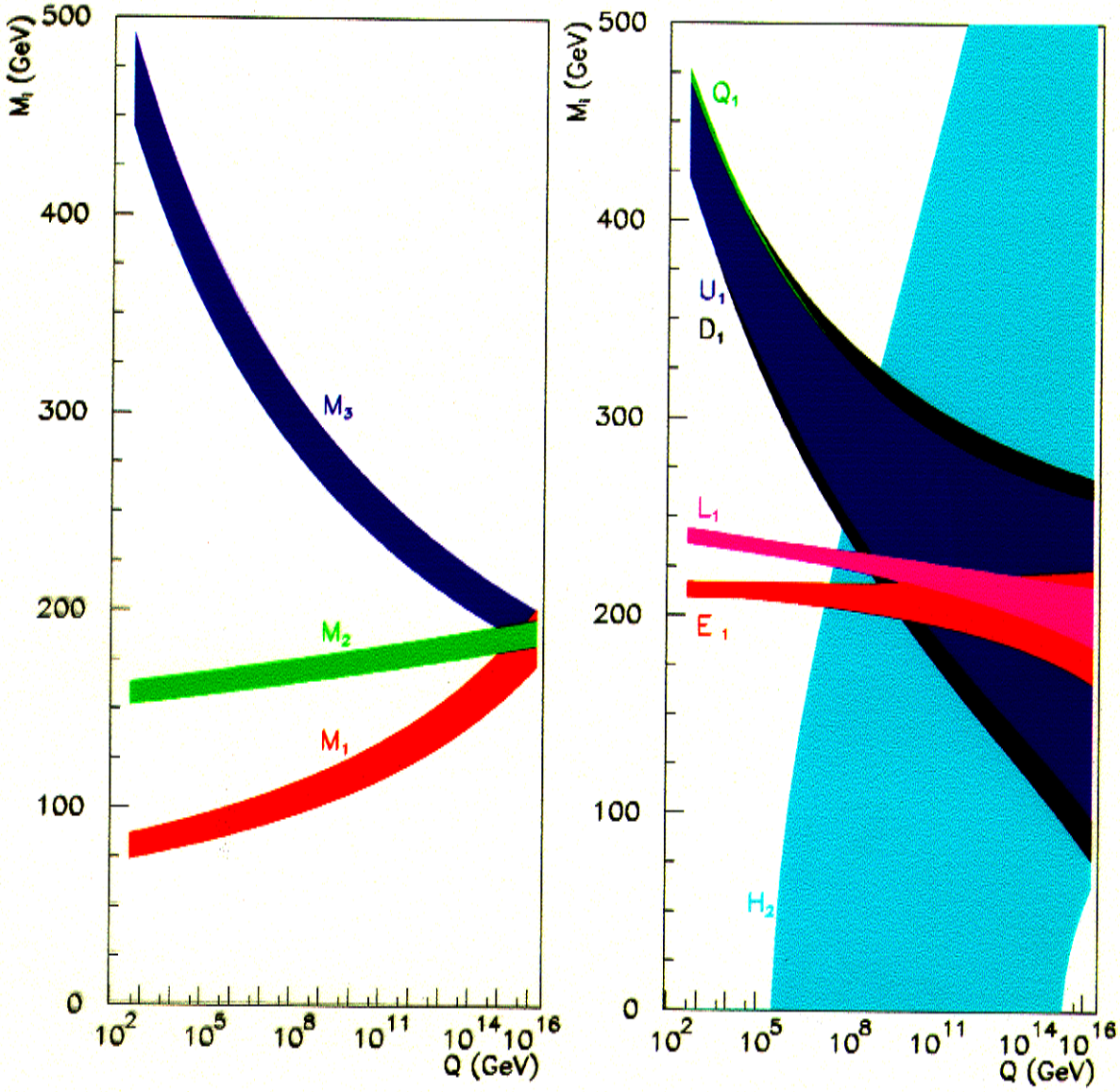


The widths of the bands indicate the 95% CL.

- No confusion with mSUGRA.
- Reconstruction of Unification of $M^2_{L_1}$ and $M^2_{H_2}$ at M_m.

SUGRA with LHC only errors

$\tan\beta = 30$, M_0=200 GeV, $M_{\frac{1}{2}}$=190 GeV, A_0=550 GeV, sign(μ)=-1

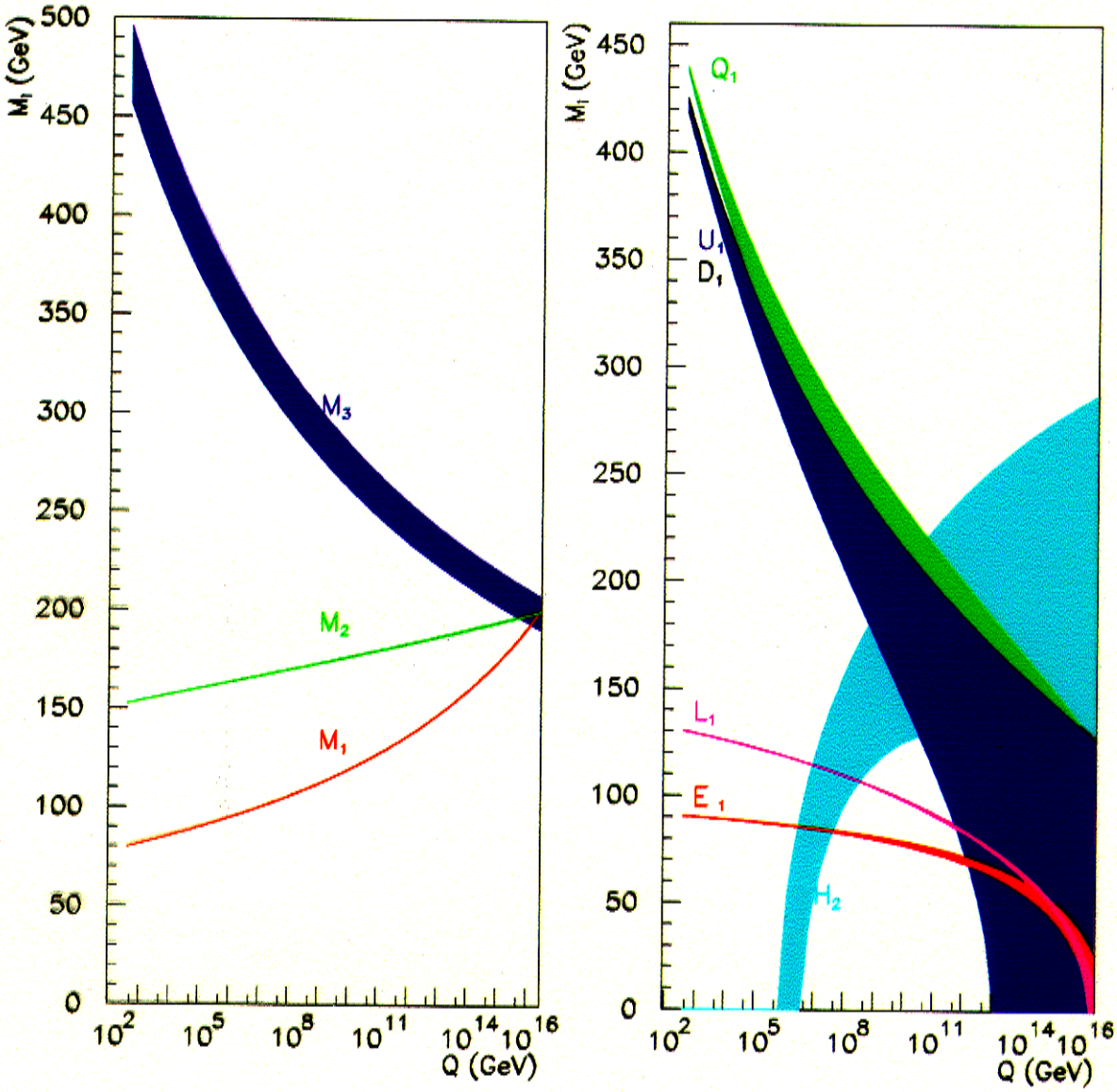


The widths of the bands indicate the 95% CL.

- Assumption of unification is less secure.
- Top-down approach may lead to incomplete picture.

A Gaugino-Mediated Model

$\tan\beta = 2.5$, M_0=5 GeV, $M_{\frac{1}{2}}$=200 GeV, A_0=0 GeV,
$M_{H_1} = 300$GeV, $M_{H_2} = 200$GeV, sign(μ)=-1†



- Higher efficiency (80%) used for cross-section measurements.
- Experimental errors increased for sneutrinos (invisible decays).

† Z.Chacko, M.A.Luty, A.E.Nelson,E.Ponton hep-ph/9911323

J Feng

CONCLUSIONS

- Cosmology provides no useful bounds on sparticle masses

- In simple scenarios, focusing and low energy constraints $\Rightarrow$ we should consider $m_0 \gtrsim 1$ TeV

- Ongoing dark matter searches are promising, highly complementary to other supersymmetry searches

- In mSUGRA,
SUSY at 500 GeV LC $\Rightarrow$ SUSY *before* LHC

- Beyond mSUGRA? Quite robust — work in progress

Conclusion

G Anderson

- Any claims about the expected values of sparticle masses based on unprincipled fine-tuning criteria should be treated with extreme skepticism. In most cases they should be disregarded.

- Contrary to claims in the literature, I find no evidence that third generation squarks in the multi-TeV region are compatible with the absence of fine-tuning.

- Supersymmetry (in whatever form) if relevant to the weak scale should provide a multitude of sparticles kinematically accessible at a 1 TeV NLC.

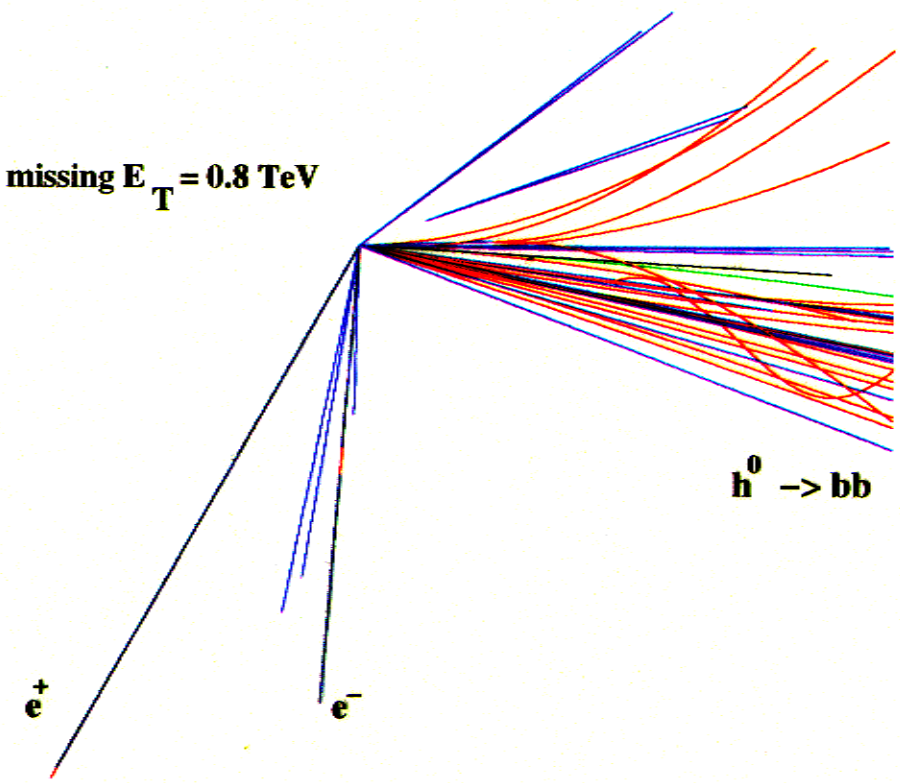
- Naturalness arguments do not guarantee that the entire spectrum of superpartners would be kinematically accessible at 1 TeV NLC.

Completing the Sparticle Spectrum at a multi-TeV collider?

Graham W. Wilson
University of Manchester
LCWS2000, 26 October

CLIC 3 TeV

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



$m_{\tilde{e}} = 1050$ GeV

$m_{h^0} = 115$ GeV

$\tilde{e}_L \to e\,\tilde{\chi}^0_2$

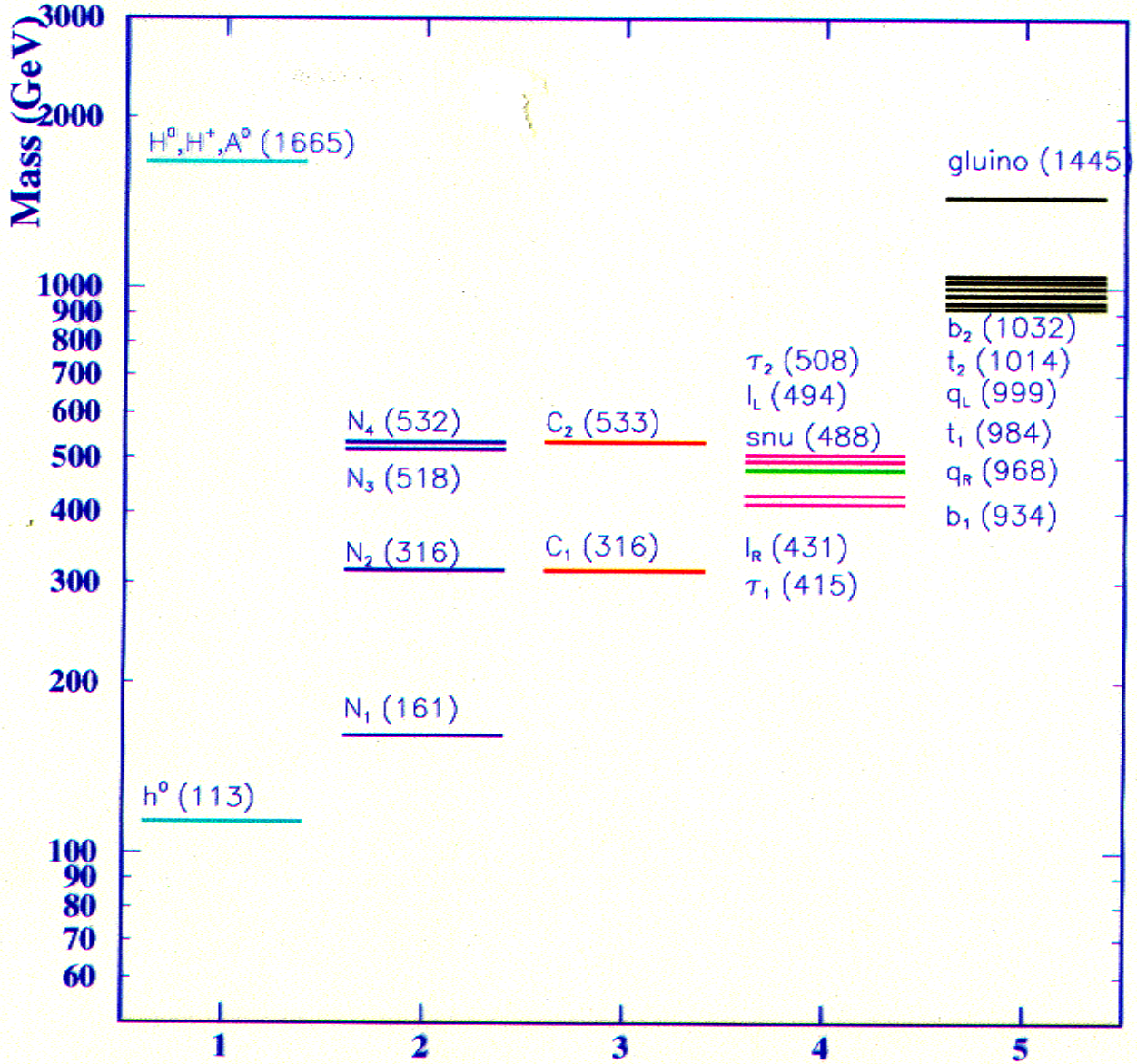
$\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h$

$h \to b\bar{b}$

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

Sparticle Mass Spectrum

MODEL 1



Mass spectrum is clumped

$m_0 = 400$ GeV

$m_{1/2} = 400$ GeV

$\tan\beta = 35$

$A = -400$ GeV

$\mathrm{sgn}(\mu) < 0$

Using $N_i = \tilde{\chi}^0_i$, $C_j = \tilde{\chi}^\pm_j$ notation.

CHANNELS

MODEL 1

SIGNAL

$$\tilde{\nu}_e \, \tilde{\nu}_e \; (488) \longrightarrow e^+ \tilde{\chi}_1^- \; e^- \tilde{\chi}_1^+ \; (316)$$

BACKGROUND

$$\tilde{e}_L \, \tilde{e}_L \; (494) \longrightarrow e^+ \tilde{\chi}_2^0 \; e^- \tilde{\chi}_2^0 \; (316)$$

$$\tilde{e}_R \, \tilde{e}_R \; (431) \longrightarrow e^+ \tilde{\chi}_1^0 \; e^- \tilde{\chi}_1^0 \; (161)$$

$$\tilde{e}_L^+ \, \tilde{e}_R^- \longrightarrow e^+ \tilde{\chi}_2^0 \; e^- \tilde{\chi}_1^0$$

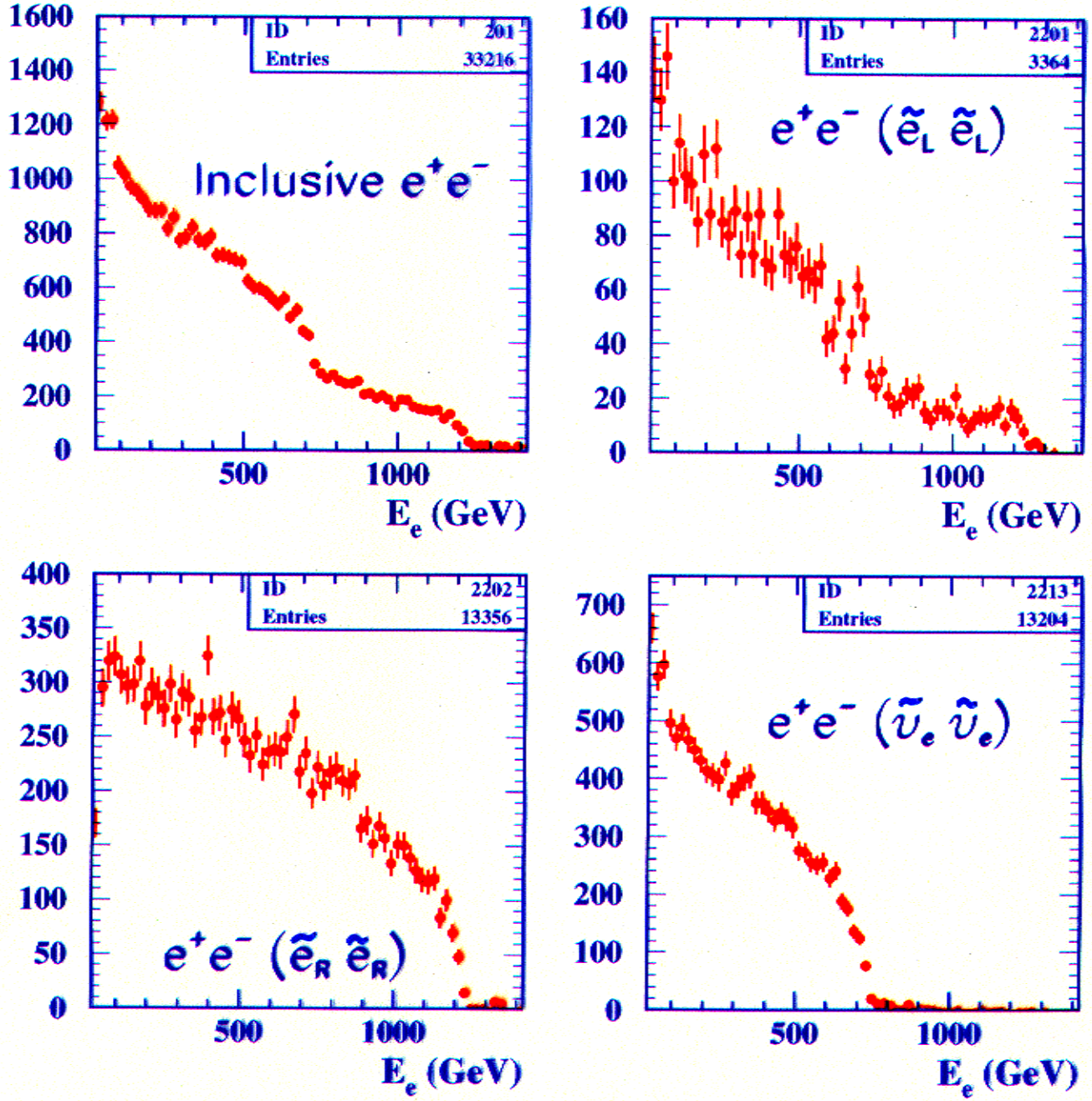
$$\tilde{\chi}_2^+ \, \tilde{\chi}_2^- \; (533) \longrightarrow e\nu \tilde{\chi}_2^0 \; e\nu \tilde{\chi}_2^0$$

$$ee \tilde{\chi}_1^+ \; \nu\bar{\nu} \tilde{\chi}_1^- \; \text{etc}$$

etc.

MODEL 1.

CLIC beamstrahlung (10^{35})

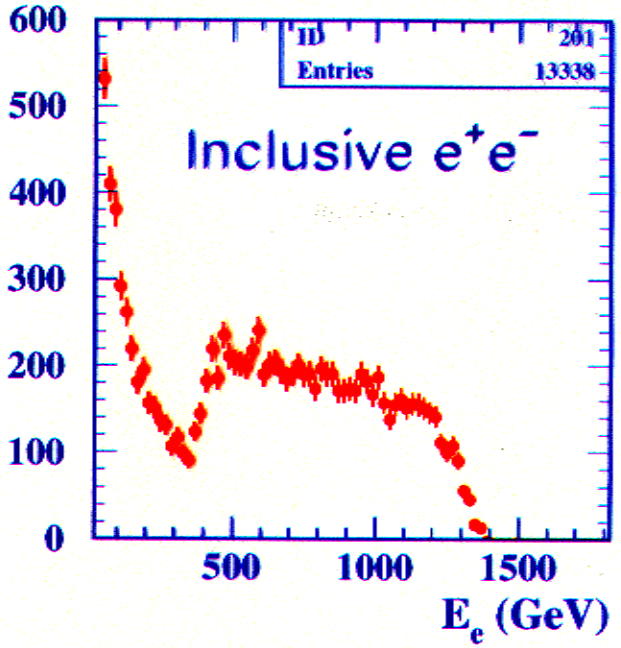


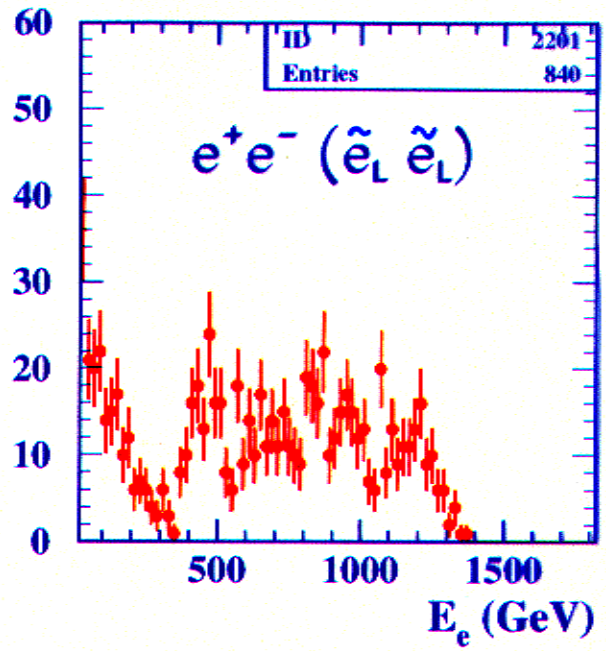
CLIC beamstrahlung (10^{35})

$\sqrt{s} = 3.5$ TeV

$\int \mathcal{L}\,dt = 650\,fb^{-1}$

(high m_0 model)



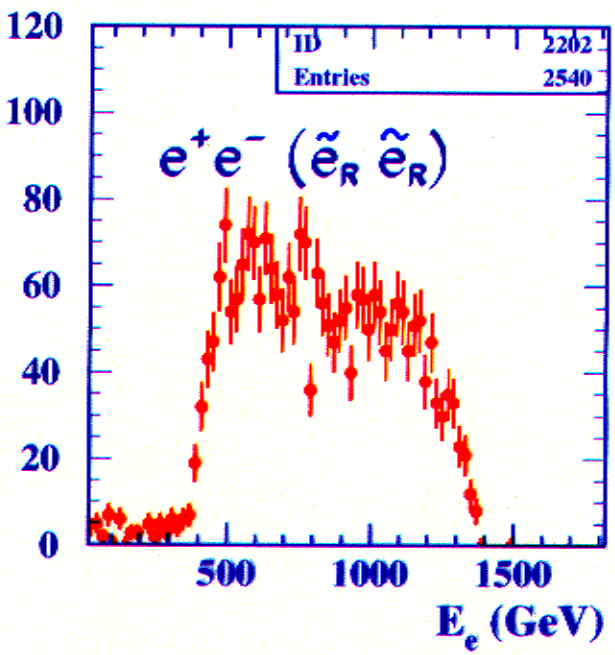


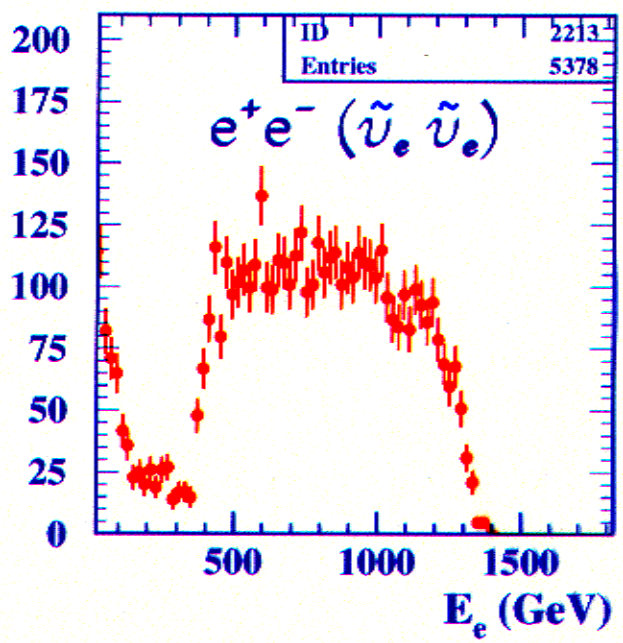
$m_{\tilde{e}} \simeq 1450$ GeV

closer to threshold

$\Rightarrow$ edges are sharper

BUT spectra are $\approx$ degenerate



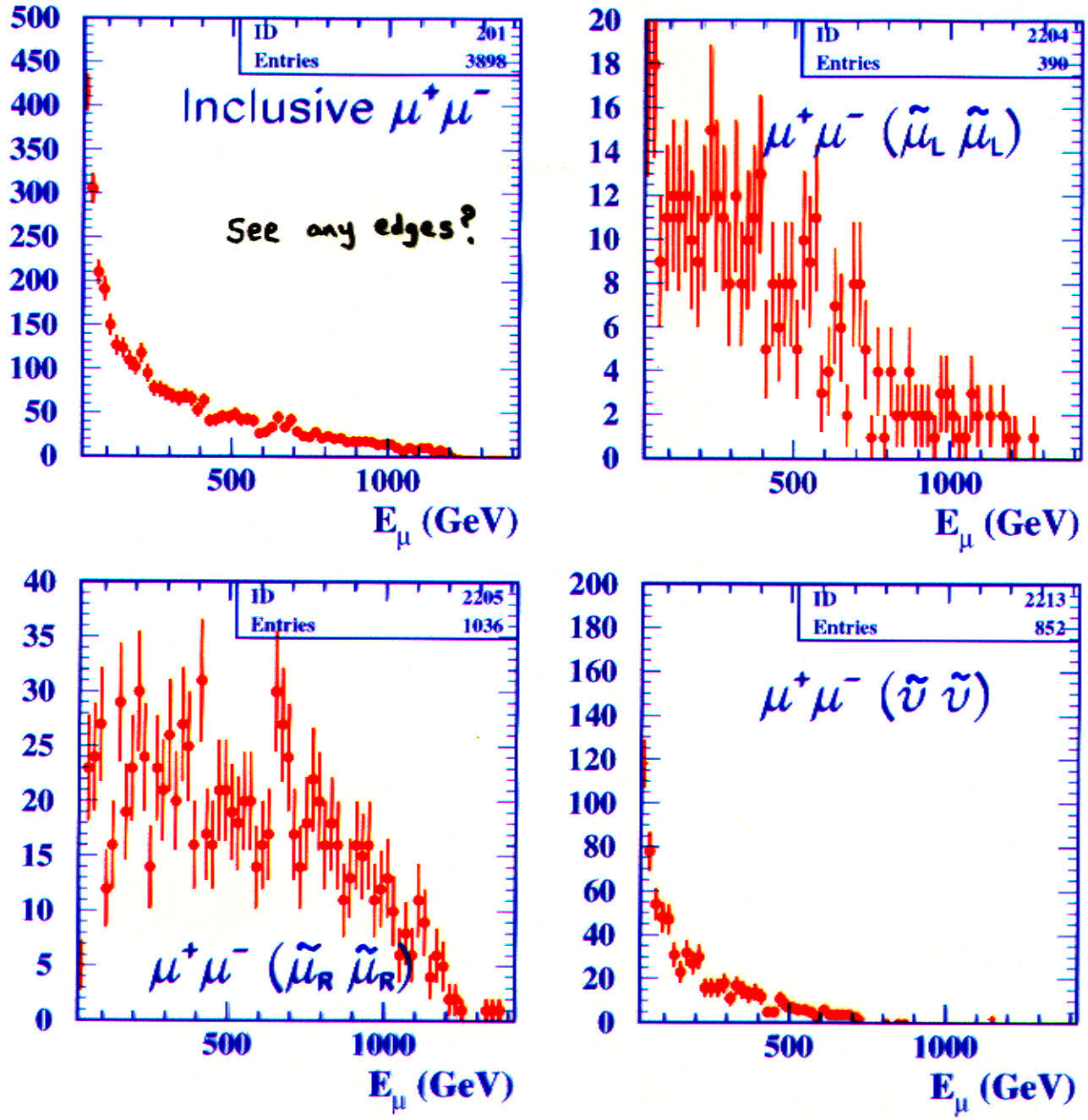


Model 1.

CLIC beamstrahlung (10^{35})

Select $e^+e^- \to \mu^+\mu^- X \not{E}_T$

140 fb^{-1}



Smuons and muon sneutrinos are much tougher.

Cross-sections not t-channel enhanced and p resolution worse ..

Staus and tau sneutrinos will be even tougher !

Threshold scans may save the day.