SUSY Working Group Summary

- SUSY $\Longrightarrow$ many free parameters: large uncertainty in spectrum

$\downarrow$

different options based on $\neq$ ~~SUSY~~ SUSY schemes

- SUGRA-type of models

i) minimal SUGRA:

$$m_0, \; M_{1/2}, \; A, \; \tan\beta, \; \mu \left(\begin{array}{c} EWSB \\ \Downarrow \\ \text{sign of } \mu \\ \mu^2 \gg M_{1/2}^2 \end{array} \right)$$

$M_{\tilde{g}} \simeq 2.6 \, M_{1/2}$ $\quad$ $M_{\tilde{W}} \simeq 2 \cdot M_{\tilde{B}} \simeq 0.8 \, M_{1/2}$

$m^2_{\tilde{q}_{1,2}} \simeq m_0^2 + 6 M_{1/2}^2$ $\quad$ $m^2_{\tilde{\ell}_{L(R)}} \simeq m_0^2 + 0.5 \, (0.15) \, M_{1/2}^2$

if $m_0 \gg M_{1/2} \longrightarrow m_{\tilde{q}_{1,2}} \simeq m_{\tilde{\ell}} > M_{\tilde{g}}$

if $m_0 \ll M_{1/2} \longrightarrow M_{\tilde{g}} > m_{\tilde{q}_{1,2}} > m_{\tilde{t}} > m_{\tilde{\ell}} \simeq m_{\tilde{W}}$

ii) non-universality in scalar sector

$$- \; m_{H_1}(M_{GUT}) \neq m_{H_2}(M_{GUT}) \neq m_0$$

$$m_0 \swarrow m_5 \quad \searrow m_{10}$$

* may allow smaller $\mu \, (\ll M_{1/2})$

- <u>Gauge Mediated SUSY models</u>

hierarchy among masses: related to α_i coupl.

$$m_{\tilde{Q}}/m_{\tilde{\ell}_L} \propto \alpha_3/\alpha_2$$

$$M_{\tilde{g}} \simeq m_{\tilde{Q}} \quad ; \quad M_{\tilde{W}} \simeq m_{\tilde{\ell}_L} \quad ; \quad M_{\tilde{B}} \simeq m_{\tilde{\ell}_R}$$

Similar to SUGRA: $M_{\tilde{g}}/M_{\tilde{W}} \propto \alpha_3/\alpha_2$

$$M_{\tilde{W}}/M_{\tilde{B}} \propto \alpha_2/\alpha_1$$

large values of μ => gaugino-like $\tilde{\chi}_1^\pm$ & $\tilde{\chi}_{1,2}^0$

- <u>R-parity violating scenarios</u>

$$R = (-1)^{3B+L+2S} \begin{cases} \text{SM particles: } R = 1 \\ \text{SUSY partners: } R = -1 \end{cases}$$

if $\cancel{R}$ => SUSY particles may be produced in odd number.

$$\underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{lepton \# violation}} + \cancel{\lambda''_{ijk} U_i D_j \bar{D}_k}$$

lepton # violation

⟨bounded by present data⟩

easier way to avoid proton decay

- Flavor Mixing

S. Raby / H-C. Cheng

Generic feature of SUSY models

- if univ. scalar masses & trilinear couplings ⟨diag. mass matrices⟩ at high energies

  $\Rightarrow L_e, L_\mu, L_\tau$ conserved

  MSSM forbids $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conv.
  $\tau \to \mu\gamma$

- if messenger scale for SUSY is above the scale generating fermion mass structure

$\Longrightarrow$ in general New Flavor mixing matrices appear at the gaugino-fermion-sfermion vertices

LEPTON FLAVOR VIOLATION is highly model dependent

$\downarrow$

is a Window to GUT scale Physics

One KEY Point for SUSY Scenarios

$\Longrightarrow$ light Higgs

$m_h \lesssim 130$ GeV (MSSM) fig.

$m_h \lesssim 140$ GeV (in almost all SUSY th.)

hence,

i) we expect to have seen the Higgs

at LEP: if $m_h \lesssim 100$ GeV

Tevatron: if $m_h \lesssim 120$ GeV (?)

⟨in Wh or Zh channels
with $25 fb^{-1}$
improved reach combining
channels $\longrightarrow 10 fb^{-1}$?⟩

LHC: MSSM $\longrightarrow$ discover sooner ($\lesssim 30 fb^{-1}$)
or later depending on discovery mode
NMSSM $\longrightarrow$ "holes" dep. on exact spectra

ii) s-channel Higgs production at $\sqrt{s} \simeq m_h$

$\longrightarrow$ first goal of the FMC

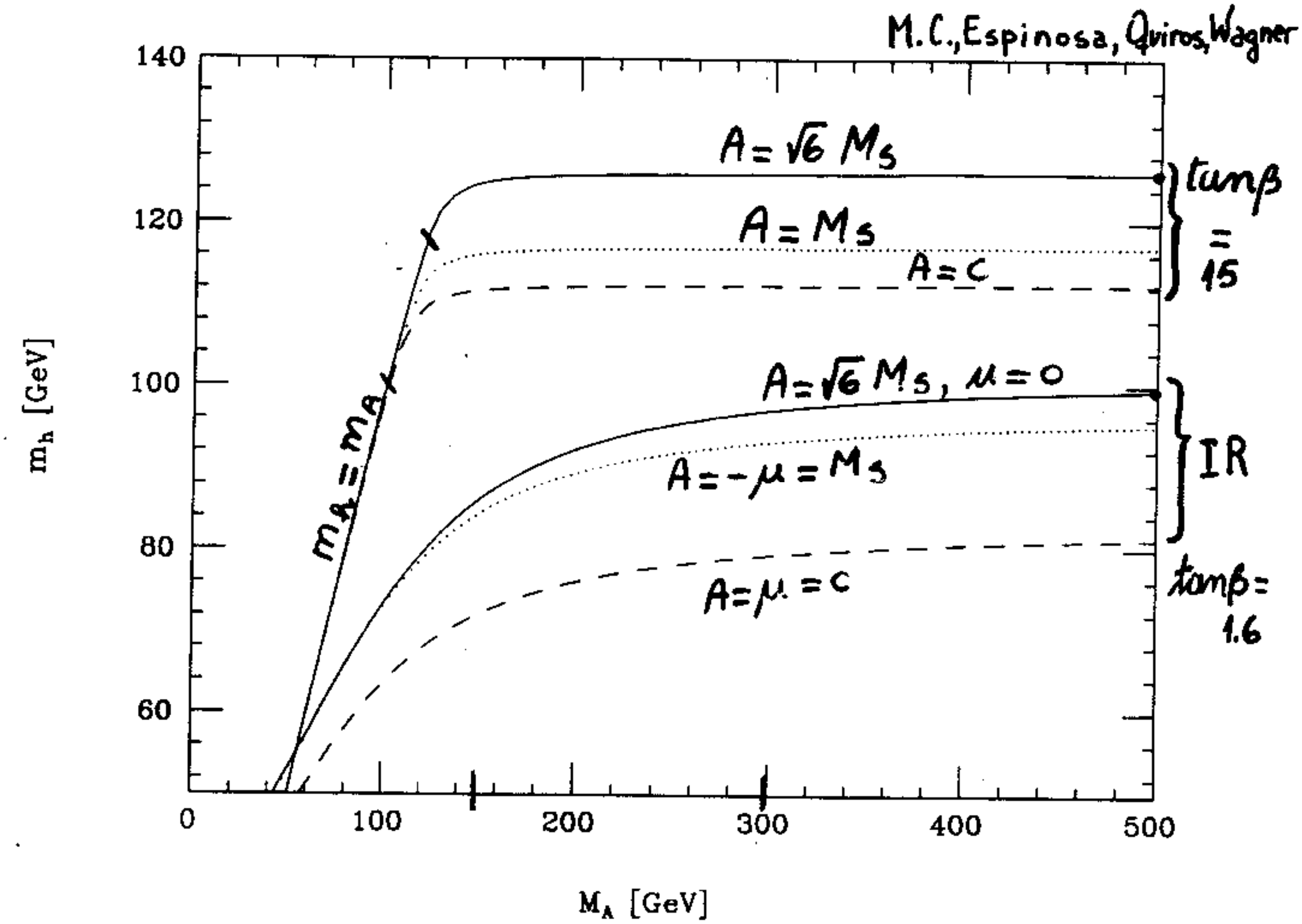
⟨to vs time issue⟩

see plenary talks
J. Gunion & V. Barger
+ T. Han WG summary

Lightest Higgs Mass Vs. CP-odd Higgs Mass

– Variation with A and μ param.

M.C., Espinosa, Quiros, Wagner



- large $\tan\beta$: mixing effect very weakly dep. on μ (unless $\tan\beta \simeq m_t/m_b$)
- low $\tan\beta$ (IR): important A & μ dep.

above: $M_t = 175$ GeV

$M_S = 1$ TeV

- Charginos: Berger

$\mu^+\mu^- \longrightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$ 2 - point threshold measurement

- present LEP limit $m_{\tilde{\chi}_1^\pm} > 88$ GeV (close to 100 GeV after LEP).
- Tevatron reach $m^{MAX}_{\tilde{\chi}_1^\pm} \simeq 200$ GeV if $\mathcal{L} \simeq 10\, fb^{-1}$
  <good coverage for lightest chargino but no lower limit possible>
- LHC $\rightarrow$ mainly mass difference $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

from LEP alone $\Rightarrow$ measurement will be for $\sqrt{s} \geq 200$ GeV

for $\sqrt{s} = 200$ GeV $\qquad m_{\chi_1^+} = 100$ GeV

1 year $\Rightarrow$ 1-2 fb^{-1} $\Longrightarrow$ $\Delta m_{\tilde{\chi}_1^+} \simeq 300$ MeV

for $\sqrt{s} = 400$ GeV $\qquad m_{\chi_1^+} = 200$ GeV

$\mathcal{L} \rightarrow 7\, fb^{-1}$/year $\qquad \Delta m_{\tilde{\chi}_1^+} = 300\,(700)$ MeV

if $m_{\tilde{\nu}_\mu} = 500\,(300)$ GeV

- "comparing" with similar studies at NLC

$\mathcal{L}$ Vs Energy resolution $\simeq$ compensates

- chargino mass can be also measured by finding the endpoint in the spectrum of the chargino decay products

end point method $\rightarrow$ less precision but useful to determine $\simeq m_{\tilde{\chi}_1^\pm}$

Polarization:

- useful tool to measure the gaugino and Higgsino components of the chargino

- only gaugino comp. couples to t-channel sneutrino exchange

if $\tilde{\chi}_1^+$ mainly gaugino $\equiv$ mainly wino and couples to μ_L only

$\Rightarrow$ right-handed μ can be use to

- turn off $\tilde{\nu}_\mu$ contribution

⟨also to reduce WW background (other ways ...) better⟩

- Sleptons

at LEP → high $\mathcal{L}$ needed to approach kin. lim.
for $\sqrt{s} \simeq 192$ GeV & $\mathcal{L} = 500\,pb^{-1}$

$$m_{\tilde{e}} \lesssim \frac{\sqrt{s}}{2} - 5\text{ GeV}\ ,\quad m_{\tilde{\mu}} \lesssim \sqrt{s}/2 - 20\text{GeV} \quad m_{\tilde{\tau}}\ (?)$$

at LHC → some masses if $\lesssim 300$ GeV
(hard to study unless $\chi_2^0 \to \tilde{\ell}\ell$)

At muon collider: end point method   Paige

- select 2 acollinear leptons from

$$\ell^+\ell^- \longrightarrow \tilde{\ell}^+\tilde{\ell}^-$$
$$\tilde{\ell}^- \longrightarrow \tilde{\chi}_1^0\,\ell^-$$
$$\tilde{\ell}^+ \longrightarrow \tilde{\chi}_1^0\,\ell^+$$

(Fig)

- use lepton energy distribution, find END POINTS and use that to extract: $m_{\tilde{\ell}}$ & $m_{\tilde{\chi}_1^0}$

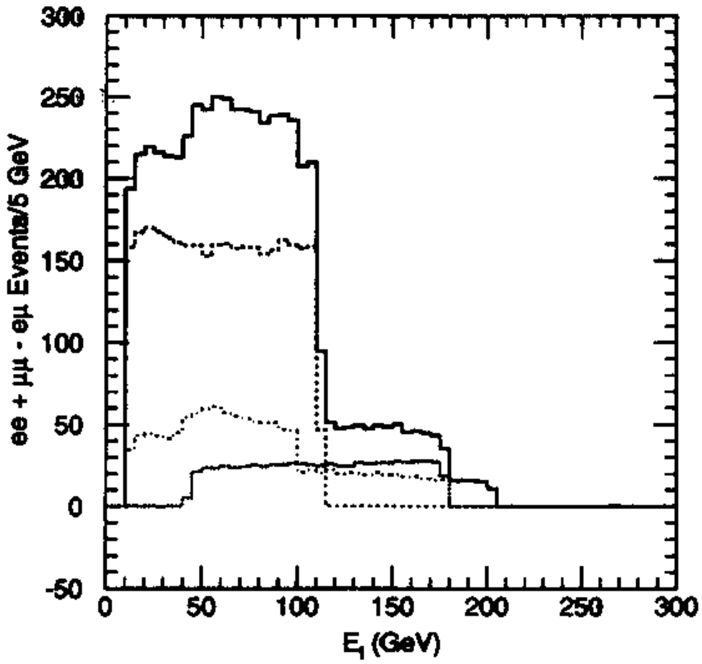
- Polarization is useful but not crucial to reject background

- Signal may be complex & require high $\mathcal{L}$
⟨Any FLC can complement well LHC⟩

Example: $m_{\tilde{e}_R} \simeq 150$ GeV $\Rightarrow \Delta m_{\tilde{e}_R} \simeq 1$ GeV
$\mathcal{L} = 10\,fb^{-1}$

- Ability to measure low-E end points is crucial!

Signal composition: RR = dash, LL = dot, and RL = dash-dot:

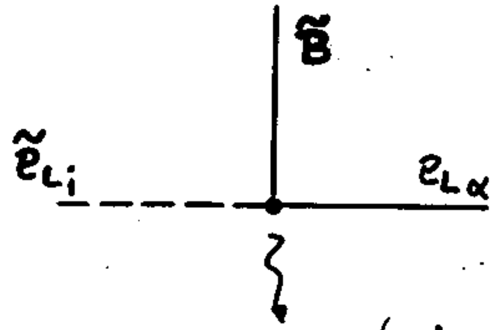


Easy to observe signal. Want to make precision measurements to complement LHC ones.

Easiest edge to measure is RR one at 111 GeV. Use it to measure to $\sim 1\,\mathrm{GeV}$

$$\frac{1}{4}\left[1-\frac{M^2\left(\tilde{\chi}_1^0\right)}{M^2\left(\tilde{\ell}_R\right)}\right]\left[\sqrt{s}+\sqrt{s-4M^2\left(\tilde{\ell}_R\right)}\right]$$

- New Flavor Mixings



$W_{i\alpha} = \left(U^{+}_{E_L} V_{E_L}\right)_{i\alpha}$

$(\tilde{e}_L \; \tilde{\mu}_L \; \tilde{\tau}_L)^* \, m^2_{E_L} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \end{pmatrix}$

$(\bar{e}_R \; \bar{\mu}_R \; \bar{\tau}_R) \, M_E \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}$

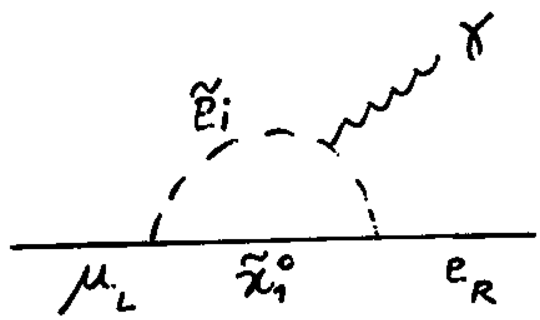
$e_L \to V_{E_L} e_L \qquad \tilde{e}_L \to U_{E_L} \tilde{e}_L$

in general $V_{E_L} \neq U_{E_L}$

At muon collider

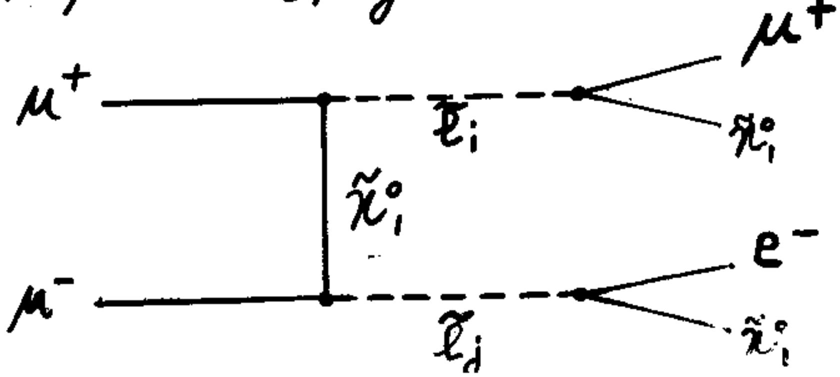
- at the Front End phase

probe by $\mu \to e\gamma$



- Direct production : flavor-changing signal

$\mu^+\mu^- \to l_i^+ l_j^- \tilde{\chi}^0_i \tilde{\chi}^0_i$

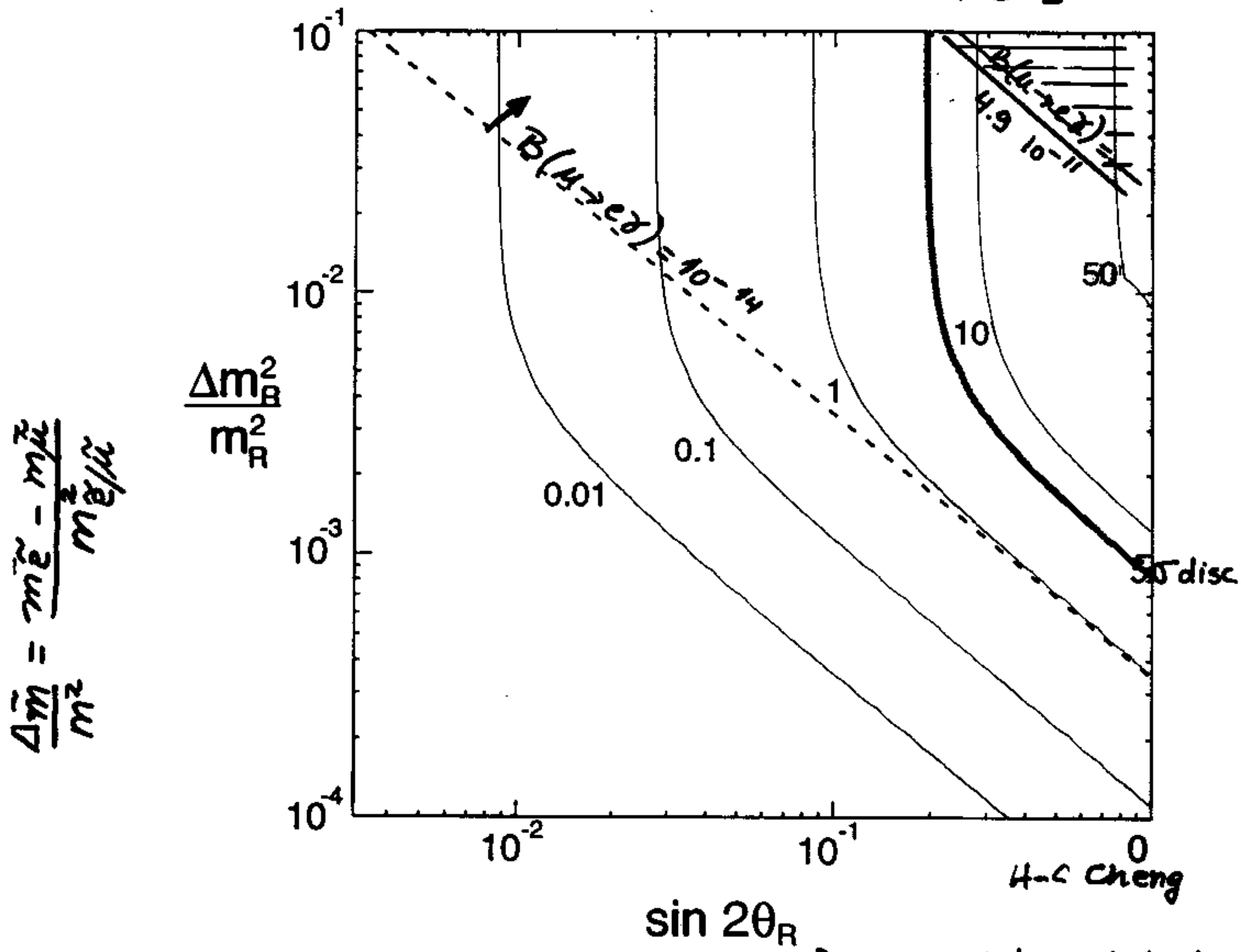


One example:

$M_1 = 130$ GeV $\quad M_2 = 260$ GeV $\quad \mu = -400$ GeV

$m_{\tilde{e}_R} = 200$ GeV $\quad m_{\tilde{e}_L} = 350$ GeV $\quad \tan\beta = 2$

$\sigma(\mu^+\mu^- \to \mu^\pm e^\mp \tilde{\chi}^0\tilde{\chi}^0)$ [fb]



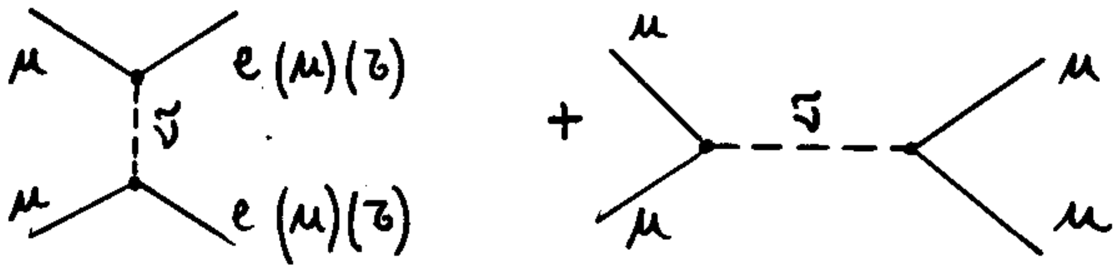
$(\tilde{\mu}\ \tilde{e})\begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\mu \\ e\end{pmatrix}\tilde{B}$

- Muon Collider & NLC complementary
  ($\underline{2i \text{ mix}}$ Vs $1i$ mix)
  stronger (?)

R-parity violation @ muon collider

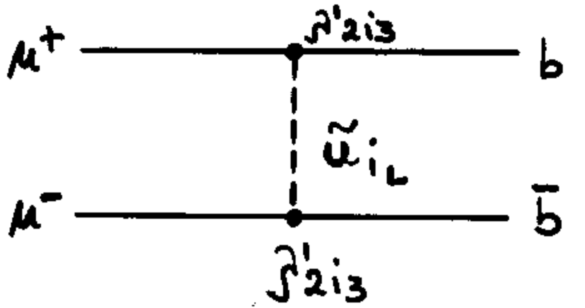
Raychaudhuri ....
Choudhury

- $\lambda_{ijk}\ L_i L_j \bar{E}_k$



s-channel
$\tilde{\nu}$ resonnance

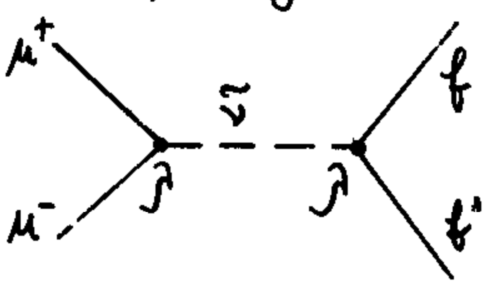
- $\lambda'_{2i3}\ L_2 Q_i D_3$

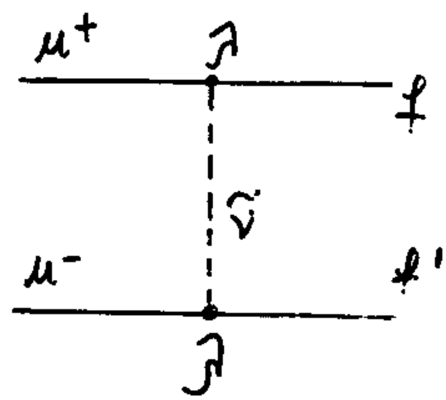


(b-tagging)

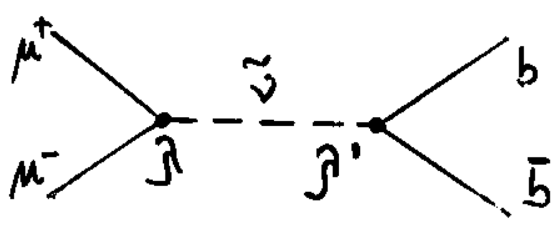
- Product of couplings

$\lambda\lambda \longrightarrow$



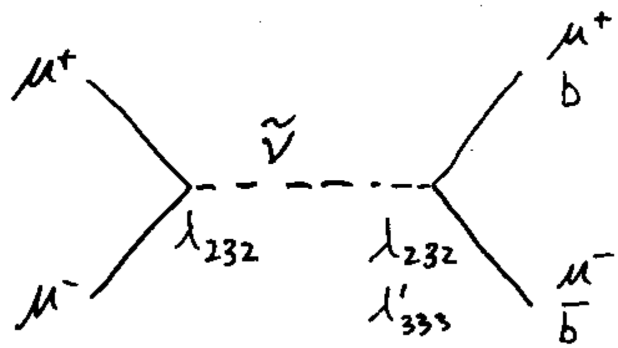


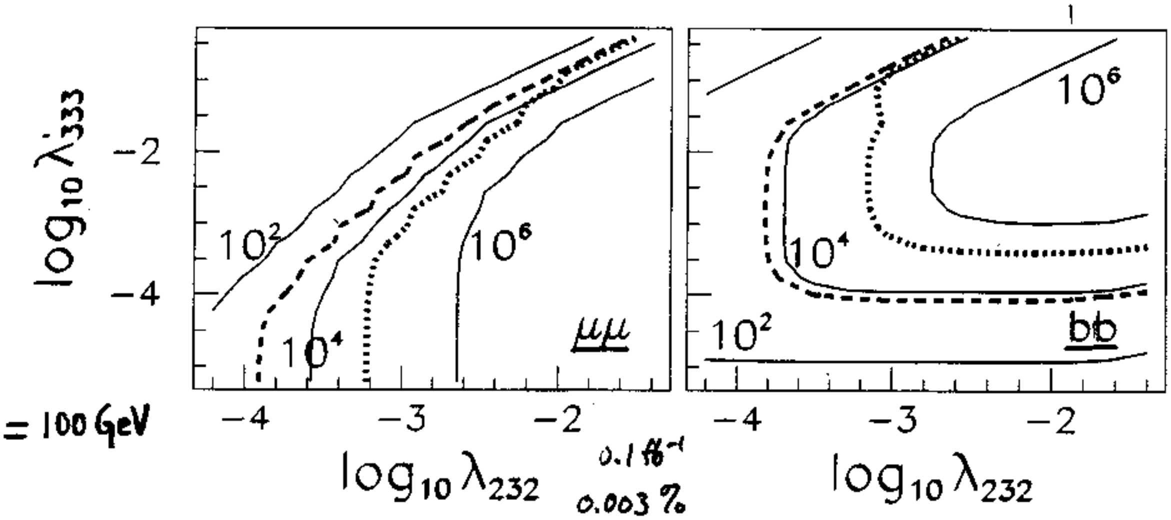
$\lambda\lambda' \longrightarrow$



R-parity Violation ⇒ $\tilde{\nu}$ Resonance

J. Feng talk
J. Gunion
T. Han





$m_{\tilde{\nu}} = 100$ GeV

$0.1\ fb^{-1}$
0.003 %

σ in fb : can be O(nb)

Discover resonance for $\lambda, \lambda' \gtrsim 10^{-3}, 10^{-4}$

Measure R-parity couplings to ~10%.

- $\not R$ t-channel only Raychaudhuri

for $\sqrt{s} = 500$ GeV & $10\ fb^{-1}$

can cover λ or $\lambda' > 0.02$

- $\not R$ s-channel resonance

$\lambda \lesssim 10^{-2} - 10^{-3}$

some effects within 1 year

$\Delta\lambda \simeq 10\%$

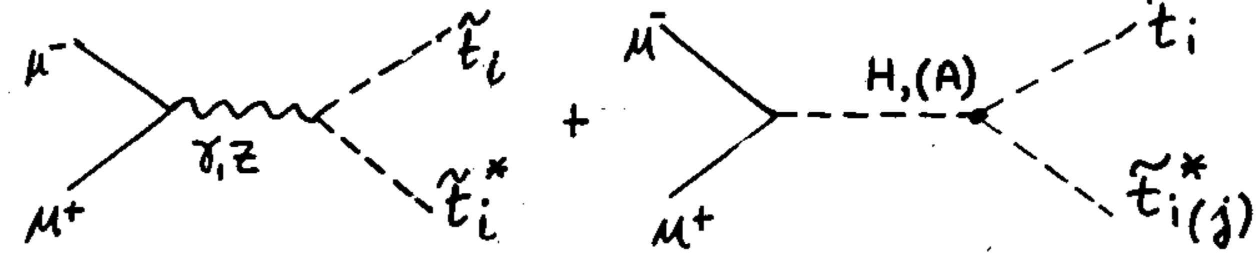
- Complementarity of couplings which can be measured at NLC and muon Collider

<LHC cannot measure any absolute value of λ>

Stop production @ muon collider

W. Porod

$\mu^+\mu^- \longrightarrow \tilde{t}_i \tilde{t}_j^*$ (also $\tilde{b}_i \tilde{b}_j^*$)



need to know m_H, m_A already

can be important tool to probe neutral Higgs - stop - stop coupling and it is sensitive to A_t/μ at the Higgs resonance

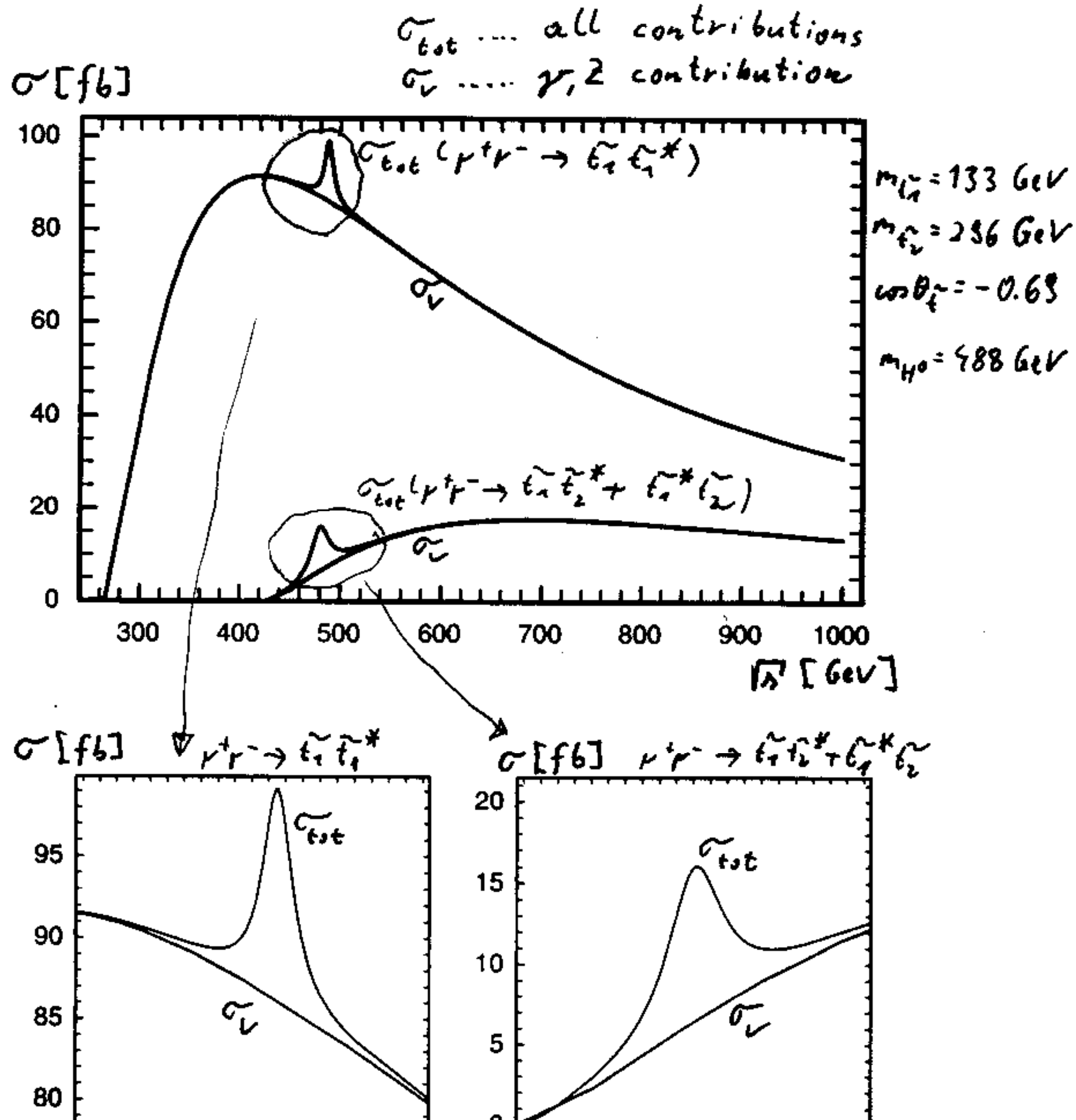
For case considered → fig.

$\mu^+\mu^- \rightarrow \tilde{t}_1 \tilde{t}_1^*$ ⟶ 20% increase of σ at resonance

$\mu^+\mu^- \rightarrow \tilde{t}_1 \tilde{t}_2^*$ ⟶ > 100%

preliminary studies seem to show that at least 5–10 fb^{-1} necessary ⇒ $H, A \gtrsim 400$ GeV preliminary

$\tilde{t}$ Production



$m_Q = 160$ GeV, $m_U = 145$ GeV, $m_D = 175$ GeV, $A_t = A_b = 350$ GeV

$\mu = 300$ GeV, $M_2 = 140$ GeV, $\tan\beta = 2$, $m_{A_0} = 480$ GeV

$m_t = 175$ GeV, $m_b = 5$ GeV

Printed by Mathematica for Students

Many Channel Search in Scenarios with multi-cascade decays:

SUSY Signatures/Model Discrimination at Muon Colliders

J. Kelly, UW Madison

First Muon Collider Workshop, 1997, FNAL

low energy ($\sqrt{s} = 500$ GeV) but specially interesting for large energy ($\sqrt{s} \simeq 3.6$ TeV)

- We calculate event numbers for pair production of all sleptons, squarks, charginos, neutralinos and Higgs bosons in the MSSM using ISAJET 7.29. Models are mSUGRA type (using ISASUGRA).

- For each pair we decay in all possible ways obtaining event numbers associated with signatures in final states described by numbers of: t, b, other jets, e^+, e^-, μ^+, μ^-, τ^+, τ^-, h^0, Z^0, W^+, W^- (reconstructible modes only).

- Unique signatures (with respect to other SUSY modes) can be considered a discovery tool within a given mSUGRA model; however...

- ...No SM backgrounds included in code yet. We should be wary of simple signals such as $\ell^+\ell^- + \mathrm{E_{miss}}$.

- In considering the mass scales in a particular scenario, we are now working on including what may be known from lower energy experiments.

- In simple two-body decays such as $\tilde{e}_R^- \to e^- + \tilde{\chi}_1^0$ the energy endpoints of the electron will provide mass bounds on $\tilde{e}_R$.

- We outline a procedure for placing bounds on 23 MSSM parameters based on the sensitivity of the signature rates (summed over produced pairs) to parameter space location. Very preliminary studies look extremely promising... multi channel fit to constrain param. of MSSM

- ...However, one must make sure tha Monte Carlo fluctuations aren't responsible for apparent sensitivity to any of the 23 parameters.

- All of this can be accomplished without looking at final state kinematics ... just counting beans!

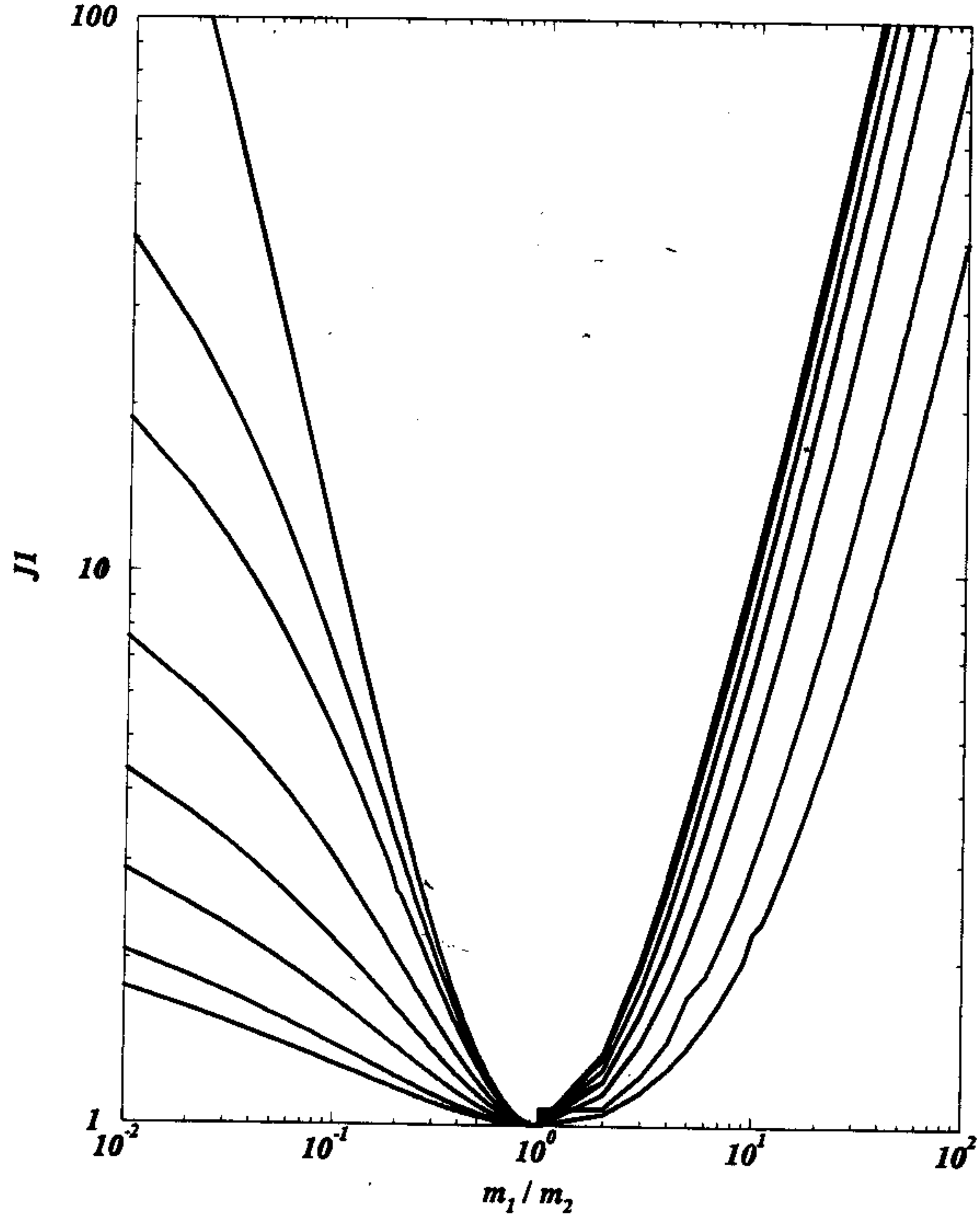
Higgs resonance

beyond minimal framework : operators at scale M_{SUSY}

Possibility of generating radiative fermion couplings (no Yukawa couplings at tree level)

$\Rightarrow$ very different (enhance) couplings of Higgs to fermions ...

$$J_1 = \frac{\overset{\text{ACTUAL YUKAWA COUPLING}}{h_{tb}} \text{ COUPLING}}{\underset{\text{NAIVE YUKAWA COUPLING}}{m_b/\langle H \rangle}} \quad \left(\frac{M_H}{m_{\tilde{t}}} \to 0\right)$$



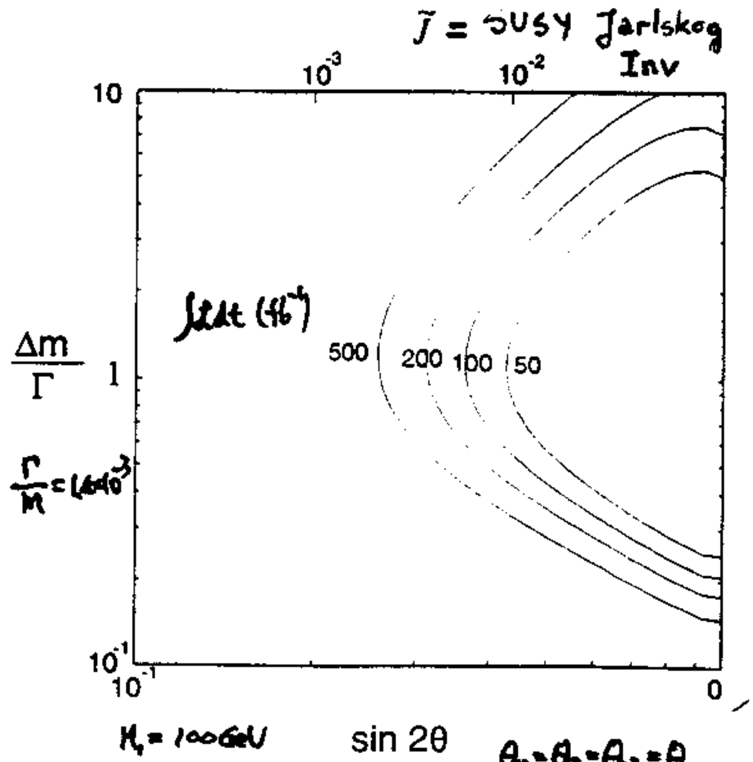
$$\text{CP violation} \Rightarrow N(e^-\mu^+) \neq N(\mu^-e^+)$$

Measuring $W_{i\alpha}$ provide important information about physics at high energies, e.g. GUT, flavor theories ......

W may contain CP phases

CP viol. signal:

asymm. between $N(e^+\mu^-)$ & $N(e^-\mu^+)$



$M_1 = 100$ GeV

$M_2 = 200$ GeV

$\mu = -400$ GeV

$\tan\beta = 2$

$m_{\tilde{l}_R} = 150$ GeV

$\theta_{12} = \theta_{13} = \theta_{23} = \theta$

$\sin\delta = 1$

After LEP, Tevatron & LHC

for SUSY measurements we need

the FUTURE Lepton Colliders

NLC, JLC, DESY LC and/or MC

$\Longrightarrow$ better chances for

- heavy Higgs $A, H, H^{\pm} \longrightarrow$ specially if SUSY decays open.
- sleptons
- in general for precision measurements of masses, couplings, spin, widths chargino mixing, flavor mixing

<u>NLC-type</u>: large electron long. polarization (+ high $\mathcal{L}$o) useful to enhance certain signals & kill backgrounds + probe $\tilde{H}$-$\tilde{W}$ mixing in $\tilde{\chi}_i$

<u>MC</u> $\longrightarrow$ highest energy reach ($\simeq$ 3TeV) with gradual upgrade involving MANY competitive precision measurements studies

- superior beam energy resol. (trade with $\mathcal{L}$o ...)
- s channel Higgs factory, $\tilde{\nu}$ factory ($\not{R}$)

+NLC: complem. in probing new flavor mix. & $\not{R}$ couplings