SUSY Search and Study Scenario at Linear e^+e^- Colliders

Experimental Aspects

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Introduction

SUSY Study Scenario

- A Sample Case
  - Sleptons
  - Charginos
  - Squarks
- 3-rd Generation
  - Stau

Summary

Introduction

SUSY Physics

Discovery Phase

$\exists$ Light H^0 - - - -> Probably SUSY

Not necessarily

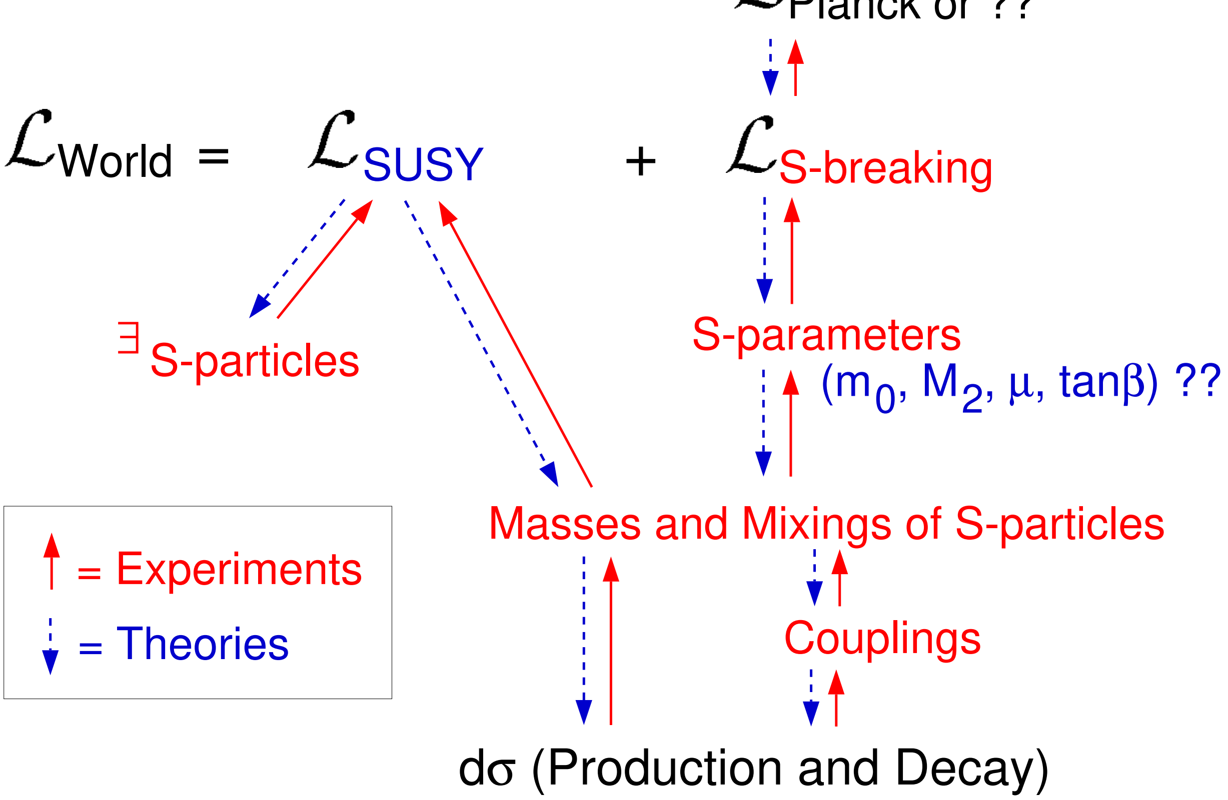
- - - -> Need to find at least one SUSY particle!

Once a SUSY particle is found.....

It is only the beginning!

True excitements come after this!

Precision Study Phase



Quantitative tests of $\mathcal{L}_{\text{SUSY}}$

Studies of $\mathcal{L}_{\text{S-breaking}}$ - - - -> $\mathcal{L}_{\text{Planck}}$?

Mass Relations

Gaugino Masses

GUT Relation

$$M_i = M \cdot \frac{\alpha_i\,(m_Z)}{\alpha_{GUT}} \qquad : i = \begin{cases} 1 \; U(1)_Y \\ 2 \; SU(2)_L \\ 3 \; SU(3)_C \end{cases}$$

$$\dashrightarrow \; \underset{\tilde{B}}{M_1} : \underset{\tilde{W}}{M_2} : \underset{\tilde{g}}{M_3} \cong \underbrace{1 \; : \; 2 \; : \; 7}$$

Sizes of groups
1 < 2 < 3

$$\dashrightarrow \; m_{\tilde{\chi}_1^\pm} \lesssim \frac{1}{3}\, m_{\tilde{g}}$$

Lighter Chargino

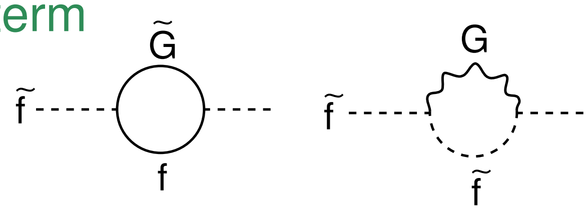
Sfermion Masses

D-term $\lesssim O(1)$

$$m_{\tilde{f}}^2 = m_0^2 + G_{\tilde{f}} \cdot M^2 + D_{\tilde{f}} \cdot m_Z^2$$

Gauge term

Common scalar mass



$$\dashrightarrow \begin{cases} G_{\tilde{q}} > G_{\tilde{l}} & (3 > 2,\, 1) \\ G_{\tilde{f}_L} > G_{\tilde{f}_R} & (2 > 1) \end{cases}$$

$$\boxed{\begin{array}{c} m_{colorless} < m_{colored} \\ m_{\tilde{f}_R} < m_{\tilde{f}_L} \end{array}}$$

First SUSY Particle (FSP)

$$\dashrightarrow \; \text{FSP} = \begin{cases} \tilde{\chi}_1^\pm \\ \tilde{l}_R^\pm \end{cases}$$

Take a sample parameter set

Ref. PRD51(1995)3153

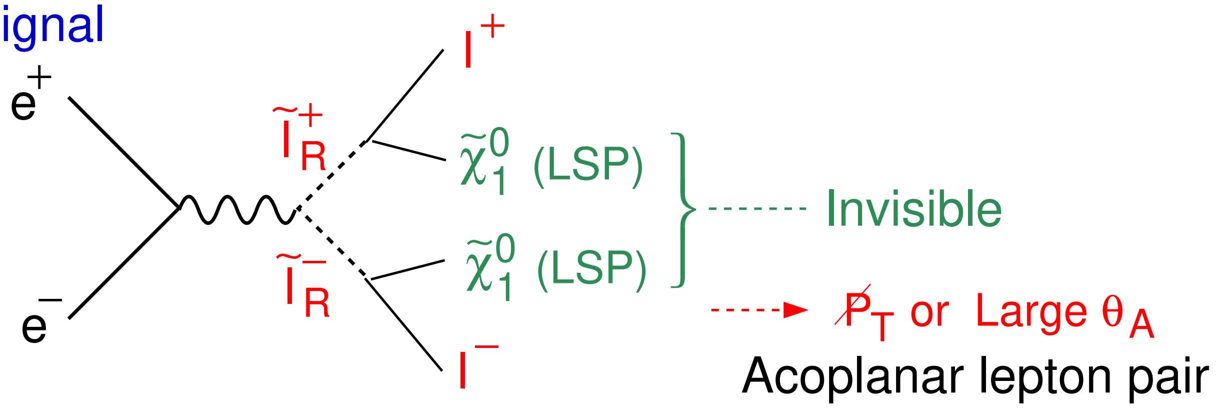
$$(m_0, M_2, \mu, \tan\beta) = \overbrace{(70{,}250{,}400{,}2)}^{\text{GeV}} \longleftrightarrow \text{FSP} = \tilde{l}_R^\pm$$

and see how a typical SUSY study scenario goes.

SUSY Study Scenario; A Sample Case

$\tilde{l}_R^{\pm}$ Study ($l \neq \tau$)

Signal



BG

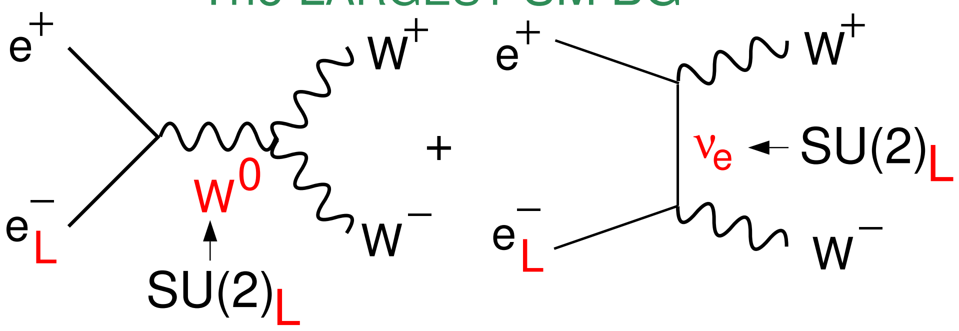
SM processes with ν's which mimic LSP.

Key Point

Polarized e^- beam is VERY POWERFUL!

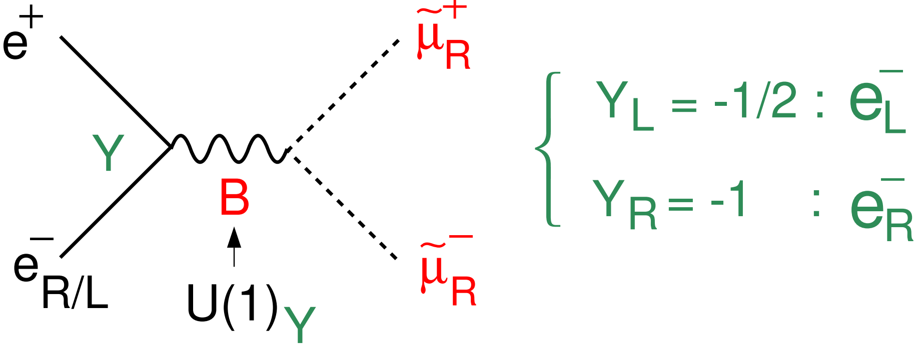
(e.g.) $e^+e^- \to W^+W^-$ ($W \to l\nu$)

The LARGEST SM BG



In the symmetry limit, $\sigma_{WW} \to 0$ for e_R^- !

On the other hand,



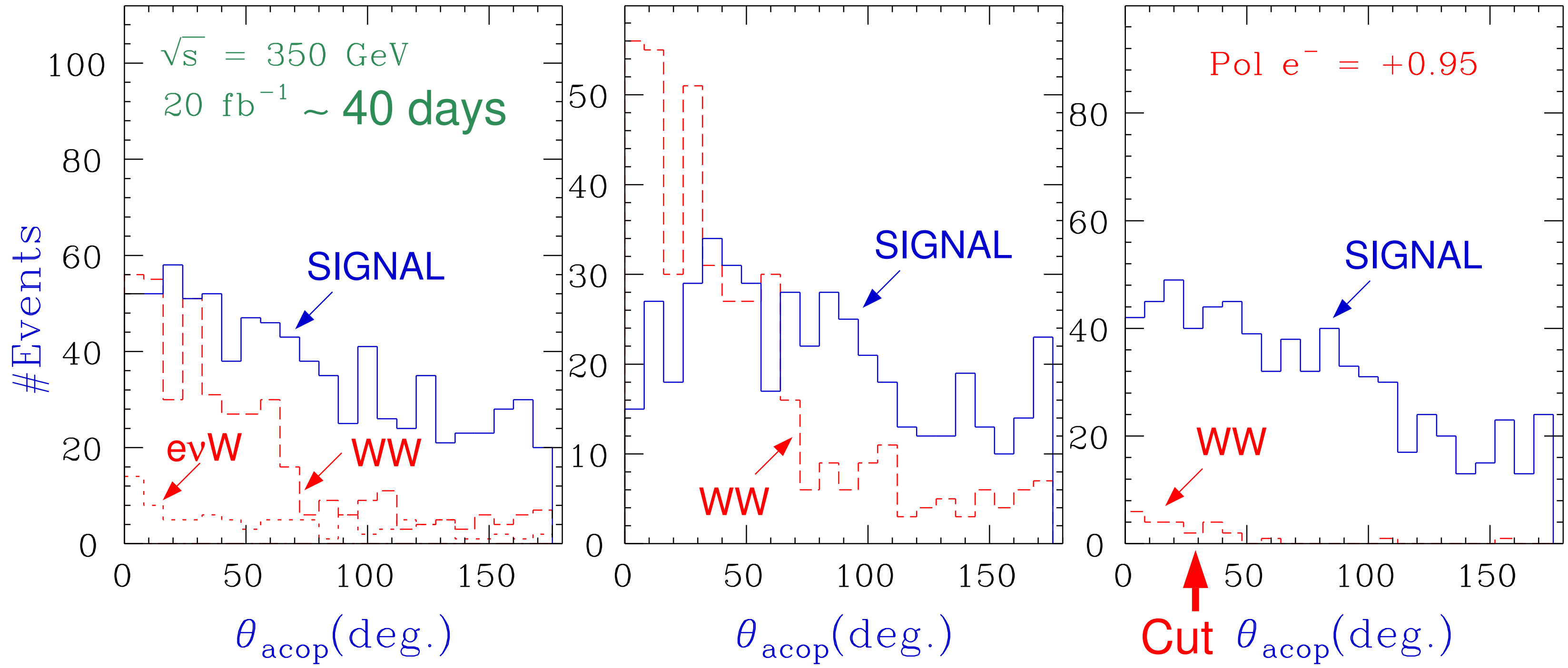
In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

Acoplanarity Distributions

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

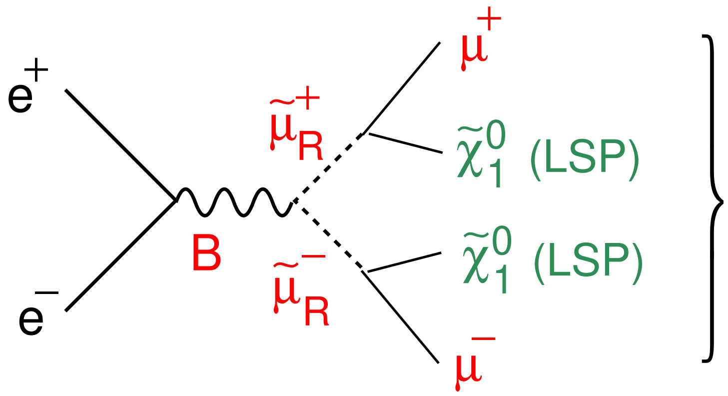
Pol $e^- = 0$ $\qquad$ Pol $e^- = 0$ $\qquad$ Pol $e^- = +0.95$

$\cong e_R^-$



Very Clean Sample for Precision Studies!

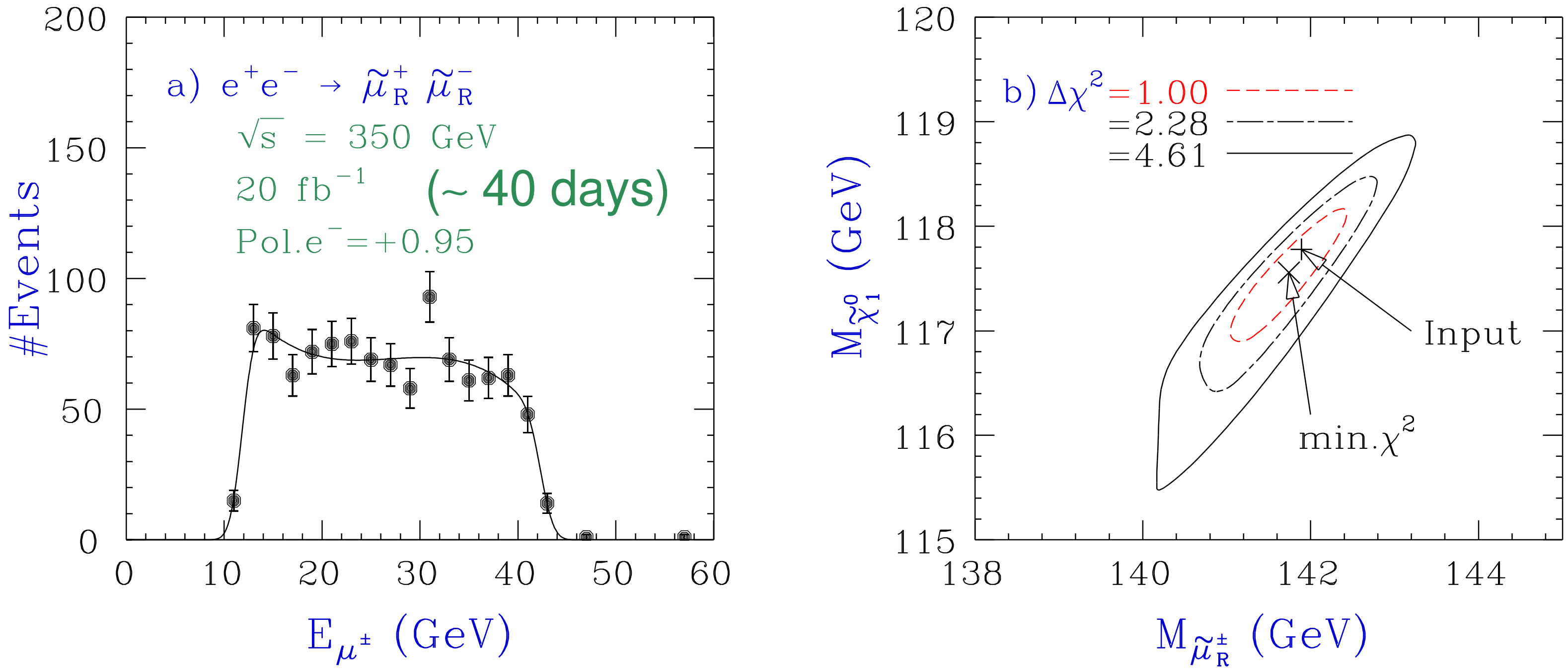
Mass Determination



Measure $E_{\mu^\pm}$

End points

$\rightarrow (m_{\tilde{\mu}_R^\pm}, m_{\tilde{\chi}_1^0})$



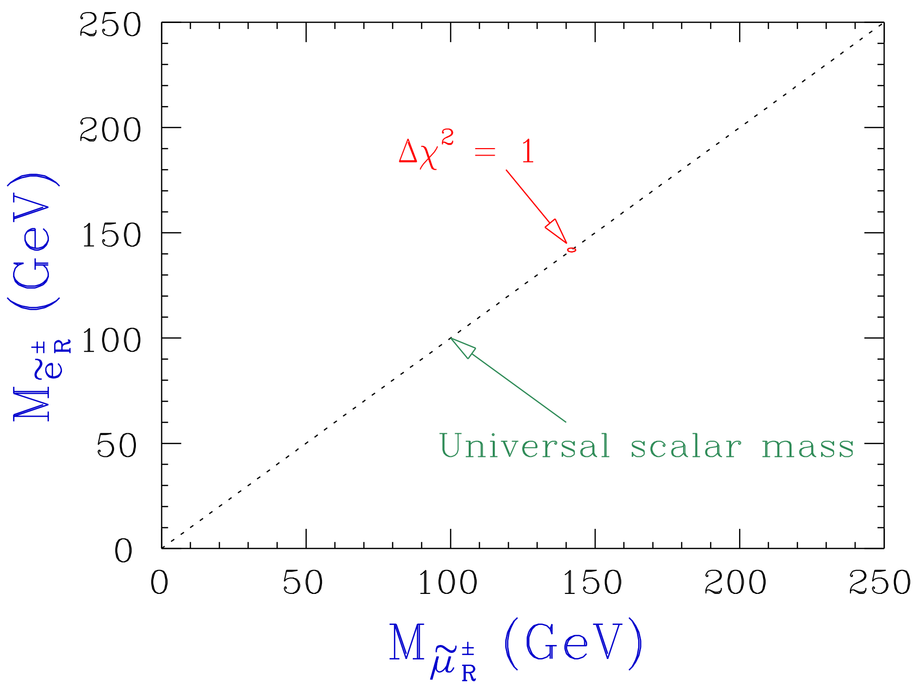
$\rightarrow \Delta m/m \lesssim 1\%$!

Test of Generation Independence

Hidden Sector SUSY Breaking

→ Universal Scalar Mass

→ $m_{\tilde{\mu}_R^\pm} = m_{\tilde{e}_R^\pm}$

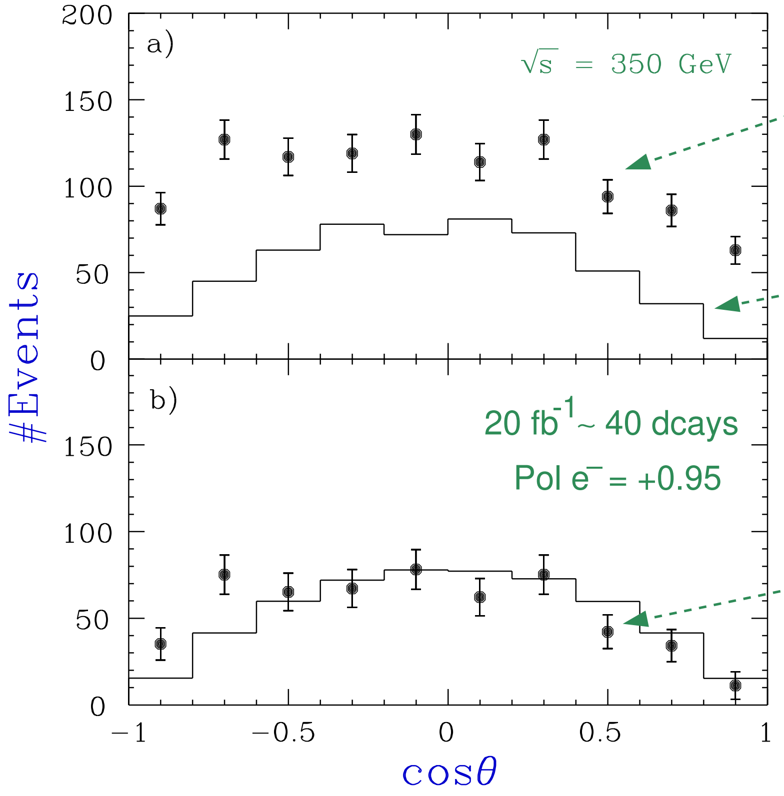


→ Precision test ($\lesssim$ 1%) of universal scalar mass hypothesis is possible!

Differential Cross Section Measurements

$(m_{\tilde{l}^\pm_R}, m_{\tilde{\chi}^0_1})$: known ⇢ Can solve KINEMATICS up to 2-fold ambiguities!

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



Reconstructed 2 solutions

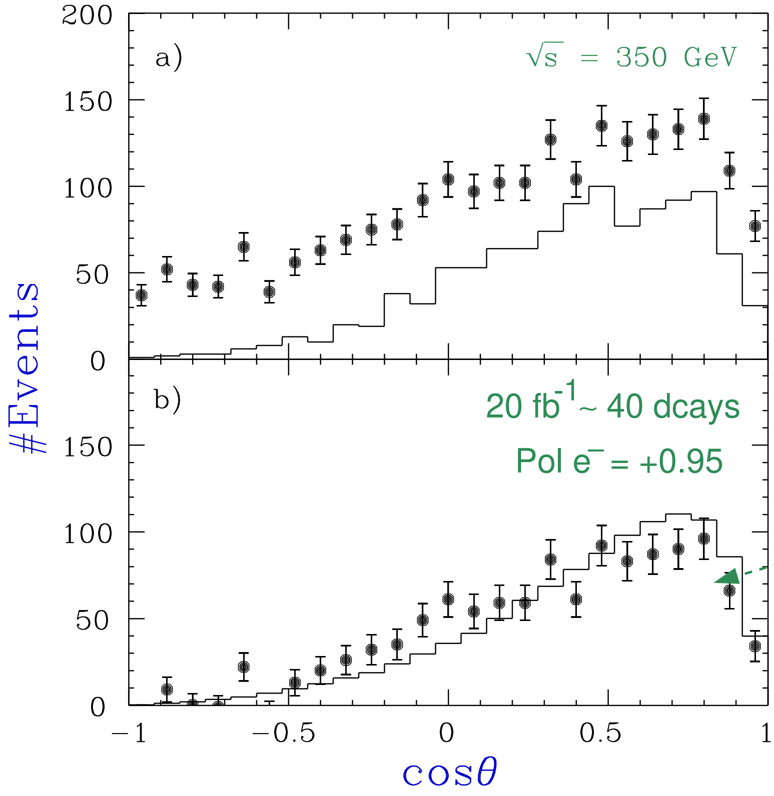
$\theta_{generated}$ for selected sample

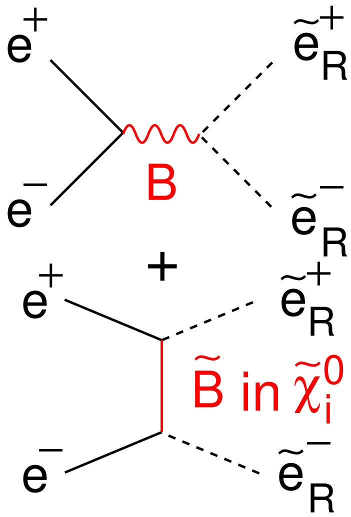
Wrong Solution = Flat BG

BG subtracted $\sin^2\theta$

$\therefore J = 0$

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





Forward Peak

$\therefore\ ^{\exists}$t-channel

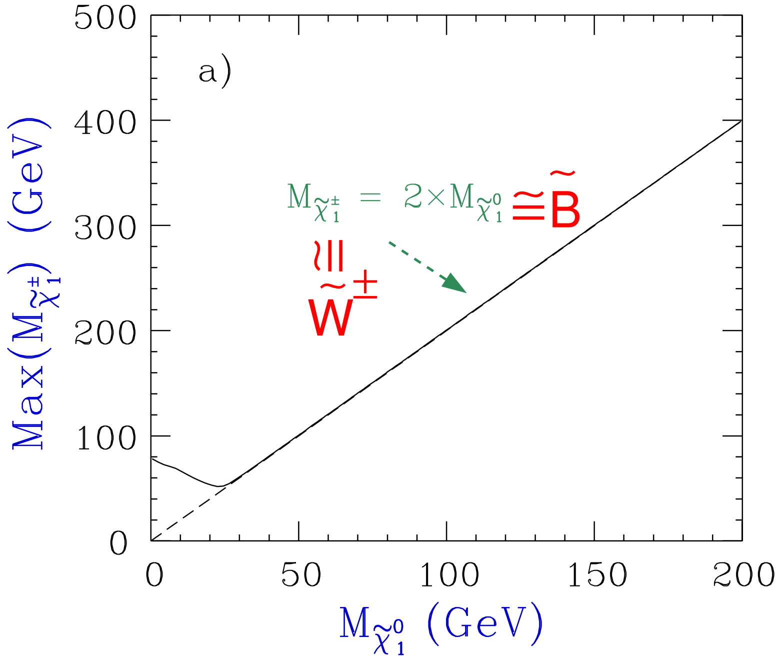
$\tilde{\chi}^0_1 \cong \tilde{B}$

$\tilde{\chi}_1^\pm$ Study

m_{LSP} ($\tilde{l}_R^\pm$ Studies) $\longrightarrow$ Upper limits on $m_{\tilde{\chi}_1^\pm}$

$\parallel$

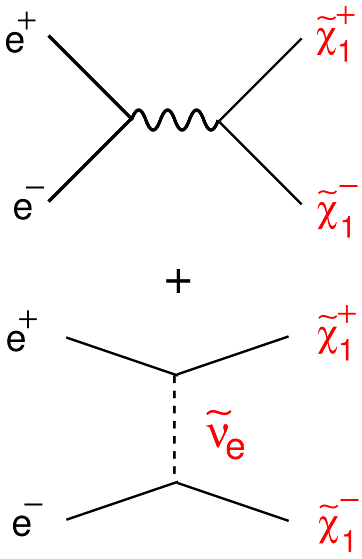
$\tilde{\chi}_1^0$

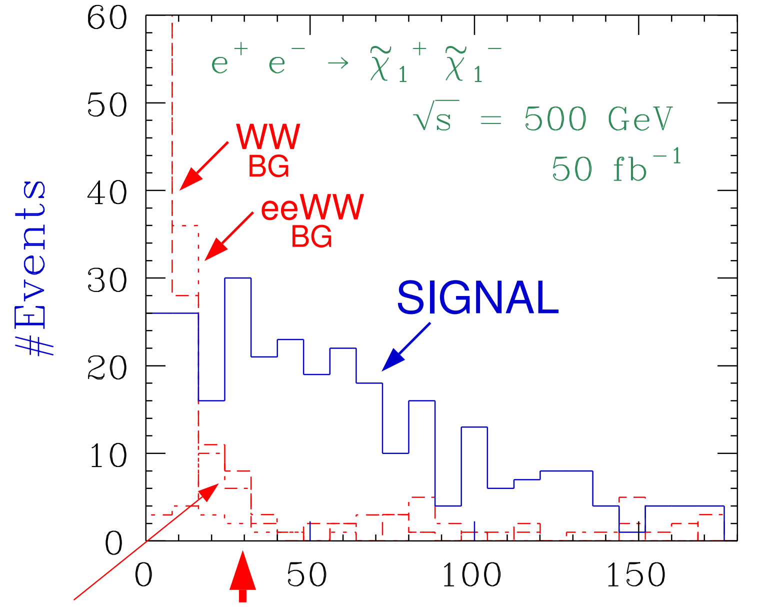


$\dashrightarrow$ Set $\sqrt{s}$ just above 4× m_{LSP}, look for $\tilde{\chi}_1^\pm$

$\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$ $\dashrightarrow$ Signal = Acoplanar W^+W^-

$\hookrightarrow q\bar{q}'$ $\hookrightarrow q\bar{q}'$ 4 Jets



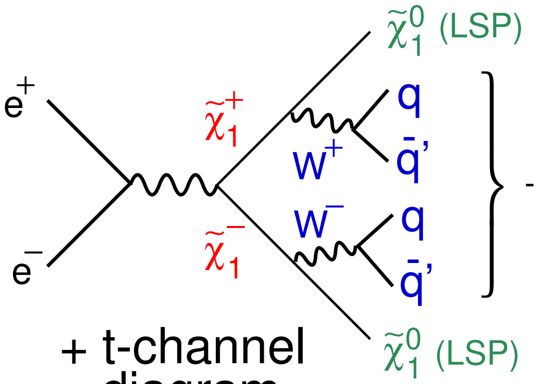


ννWW, eνWZ, WWZ BG $\hookrightarrow \nu\bar{\nu}$

Cut θ_{acop}(deg.)

$\dashrightarrow$ Fairly Clean Sample for Precision Studies !

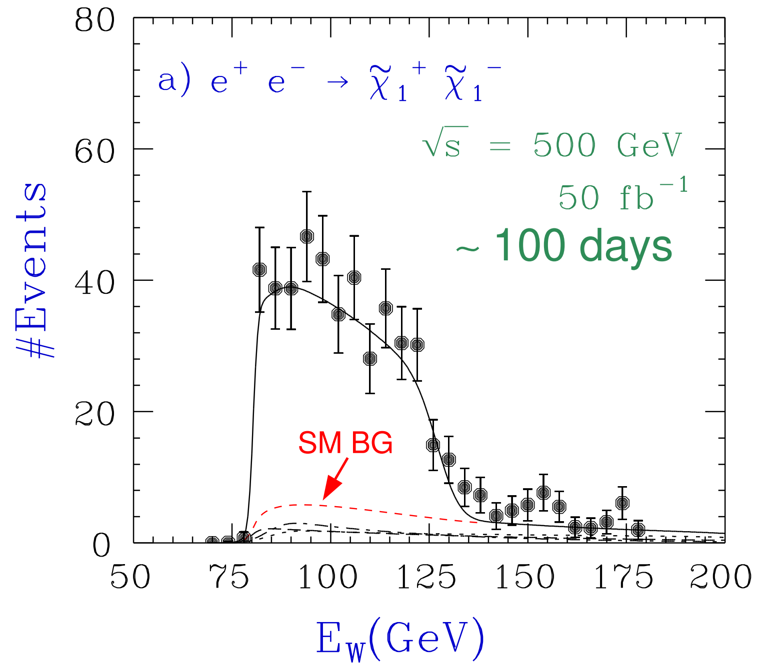
Mass Determination

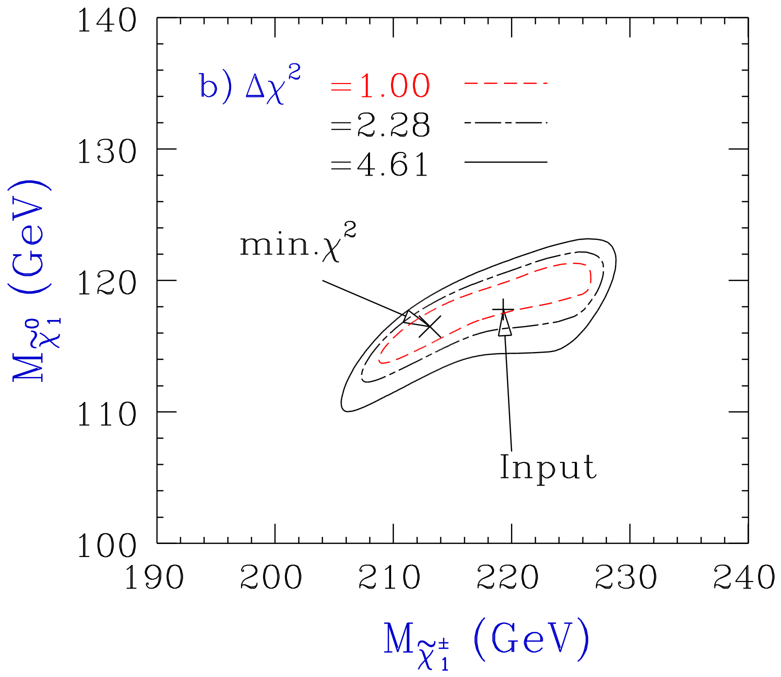


+ t-channel diagram

Measure $E_{W^\pm}$

End points $\rightarrow$ $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$



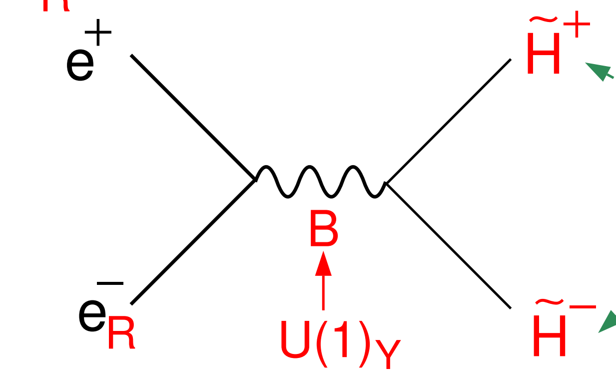


$\rightarrow$ $\Delta m_{\tilde{\chi}_1^\pm} \cong 8$ GeV $\rightarrow$ 5 GeV

$m_{\tilde{\chi}_1^0}$ from $\tilde{l}_R^\pm$ studies

$\sigma_{\tilde{\chi}_1^+\tilde{\chi}_1^-}$ Measurement

e_R^- Beam



Only $\tilde{H}^\pm$ components in $\tilde{\chi}_1^\pm$ contribute !

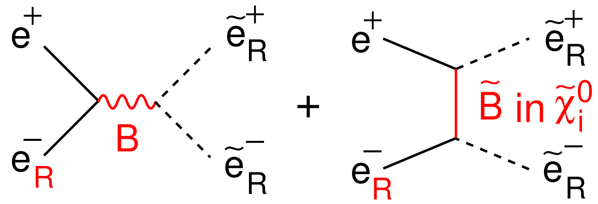
cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}_1^\pm = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}_1^\pm \rangle$$

$\dashrightarrow$ We can determine the composition of $\tilde{\chi}_1^\pm$!

Global Fit



We know

$m_{\tilde{\chi}_1^0}$ (= LSP) $\quad m_{\tilde{\chi}_1^\pm} \quad \sigma(e^+e_R^- \to \tilde{e}_R^+\tilde{e}_R^-) \quad \sigma(e^+e_R^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$

Mass Matrices $\quad \langle \tilde{B} | \tilde{\chi}_1^0 \rangle \quad \langle \tilde{H}^\pm | \tilde{\chi}_1^\pm \rangle$

$$(M_1, M_2, \mu, \tan\beta)$$

Forget the GUT relation and test if the GUT relation between M_1 and M_2 actually holds !

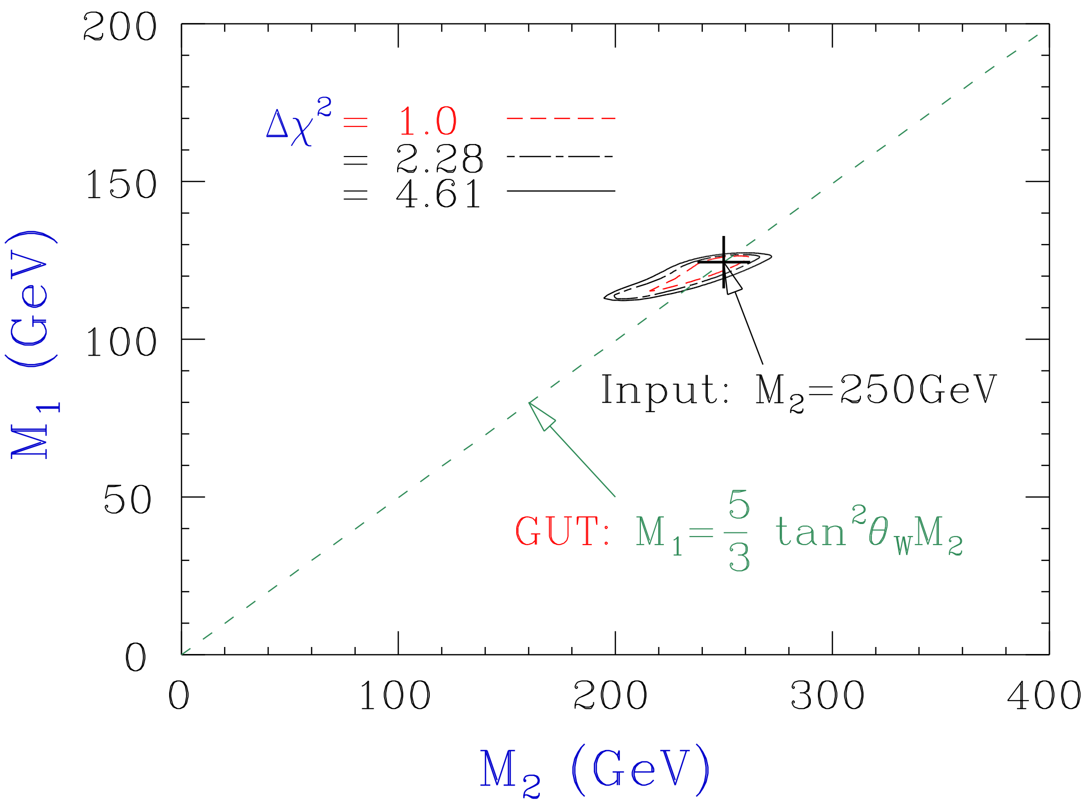
Test of GUT Relation

Common Gaugino Mass
at the GUT scale

GUT

$$\frac{M_i}{\alpha_i(m_Z)} = \frac{M}{\alpha_{GUT}}$$

$$i = \begin{cases} 1 & U(1)_Y \\ 2 & SU(2)_L \\ 3 & SU(3)_C \end{cases}$$



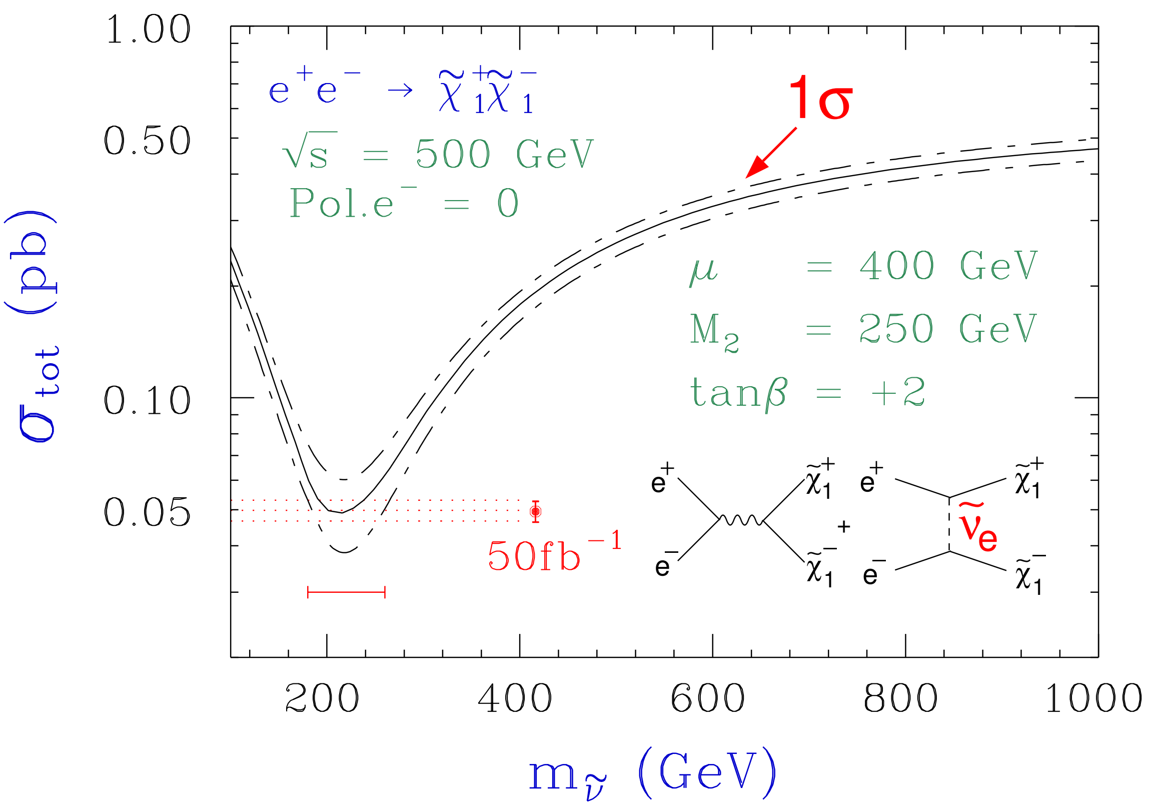
If things turn out this way, we will be forced to believe GUT !

Upper Limit on $m_{\tilde{l}_L^{\pm}}$

Since we know $m_{\tilde{\chi}_1^{\pm}}$ and

$$\tilde{\chi}_1^{\pm} = \bigcirc \cdot \tilde{W}^{\pm} + \bullet \cdot \tilde{H}^{\pm}$$

only UNKNOWN in $\sigma_{\tilde{\chi}_1^+ \tilde{\chi}_1^-}$ is $m_{\tilde{\nu}_e}$!



Measure $\sigma_{\tilde{\chi}_1^+ \tilde{\chi}_1^-}$ (Pol $e^- = 0$) to get $m_{\tilde{\nu}_e}$

$$m_{\tilde{e}_L^{\pm}}{}^2 \leq m_{\tilde{\nu}_e}{}^2 + 0.77\, m_Z{}^2$$

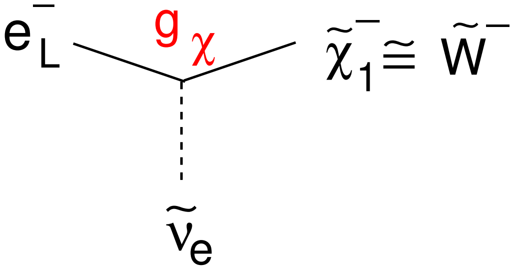
We now have an upper limit on $m_{\tilde{e}_L^{\pm}}$,
look for $\tilde{e}_L^+$ in $e^+e_R^- \to \tilde{e}_L^+\tilde{e}_R^-$!

Quantitative Test of SUSY

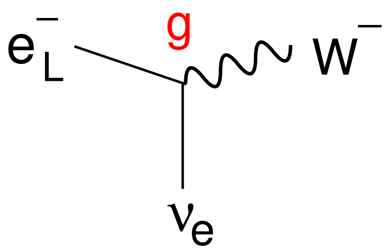
Ref. Feng-Peskin-Murayama-Tata

Consider the case in which $\tilde{\chi}_1^{\pm} \cong \tilde{W}^{\pm}$

Question



$\overset{?}{=}$



Observables to Use :

$$d\sigma \cong d\sigma(m_{\tilde{\chi}_1^{\pm}}, m_{\tilde{\nu}_e}, g_\chi)$$

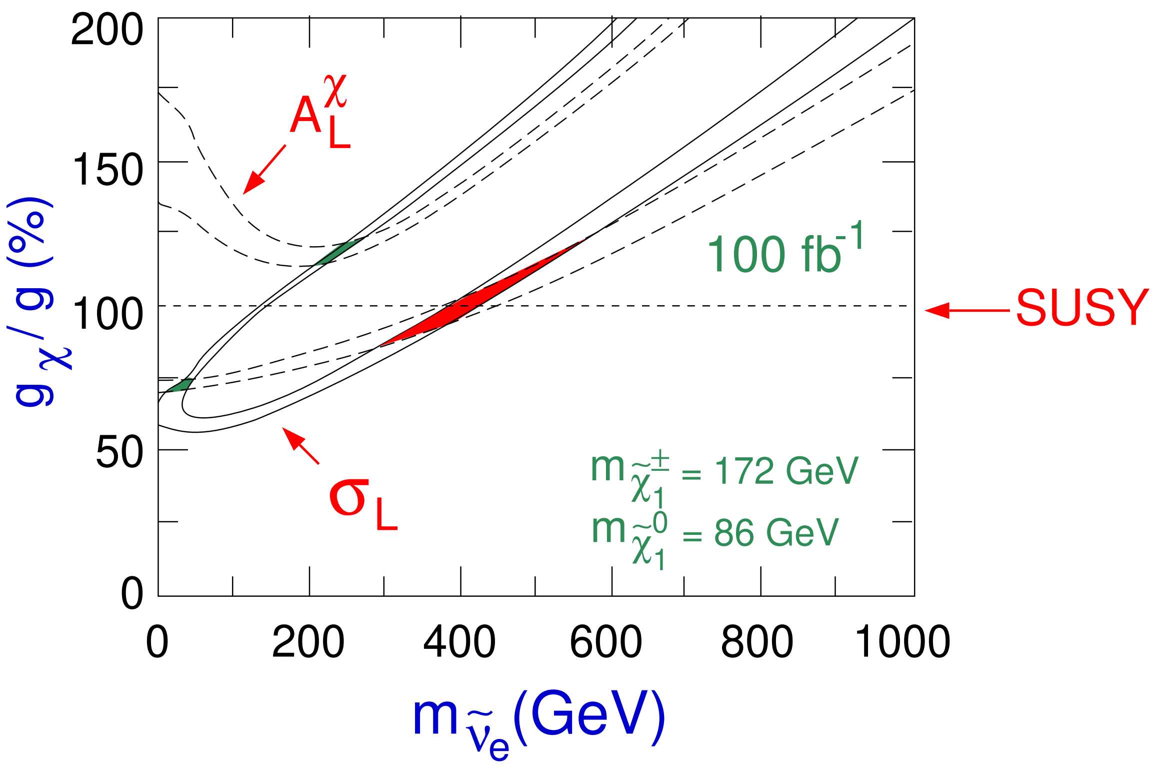
known

$$\begin{cases} \sigma_L = \sigma(e^+ e_L^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-) \\ A_L^\chi = \dfrac{\sigma_L(0<\cos\theta<0.707) - \sigma_L(-1<\cos\theta<0)}{\sigma_L(-1<\cos\theta<0.707)} \end{cases}$$

$$A_L^\chi \updownarrow A_L^{had=W}$$

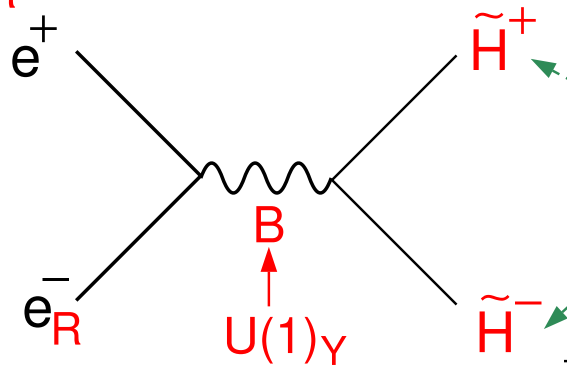
Test of SUSY

$(m_{\tilde{l}}, m_{\tilde{q}}, M_2, \mu, \tan\beta) = (400,700,170,-500,4)$



If there is substantial mixing

e_R^- Beam



$$\tilde{\chi}_1^\pm = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

Only $\tilde{H}^\pm$ components in $\tilde{\chi}_1^\pm$ contribute !

$$\dashrightarrow d\sigma_R(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, \phi_+, \phi_-)$$

Question

$$M_{\tilde{\chi}_1^\pm} = \begin{pmatrix} M_2 & \sqrt{2}\, m_W^\chi \sin\beta^\chi \\ \sqrt{2}\, m_W^\chi \cos\beta^\chi & \mu \end{pmatrix} \dashrightarrow m_W^\chi \overset{?}{=} m_W$$

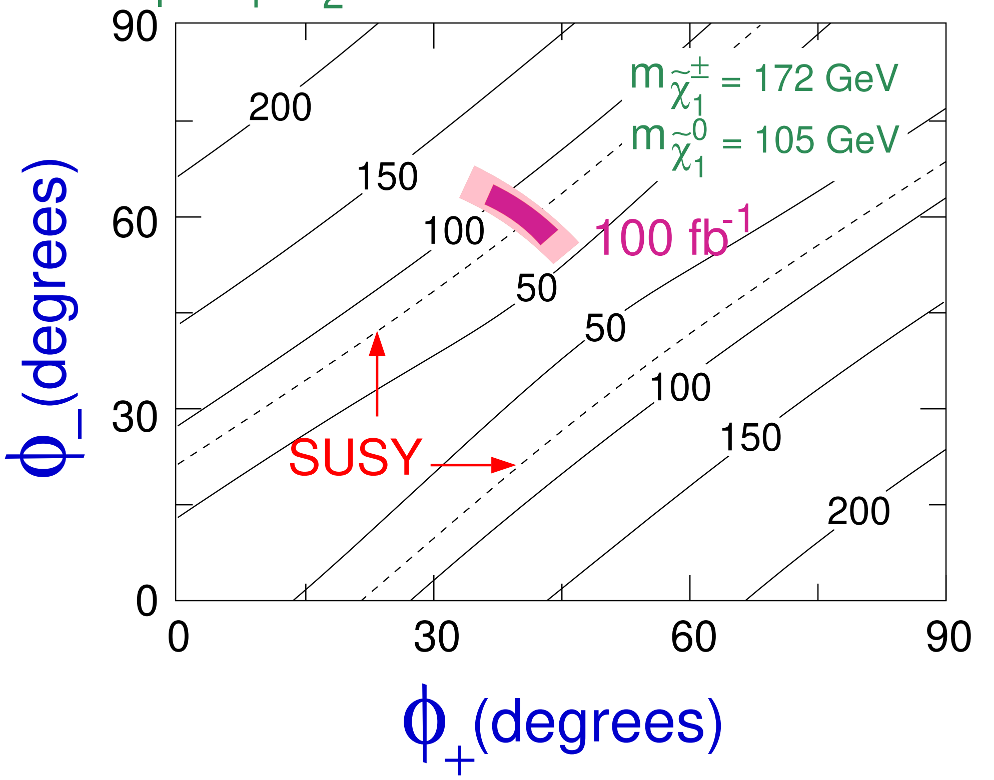
If SUSY, YES !

Observables to Use:

$$\sigma_R \text{ and } A_R^\chi \longleftrightarrow A_R^{had=W}$$

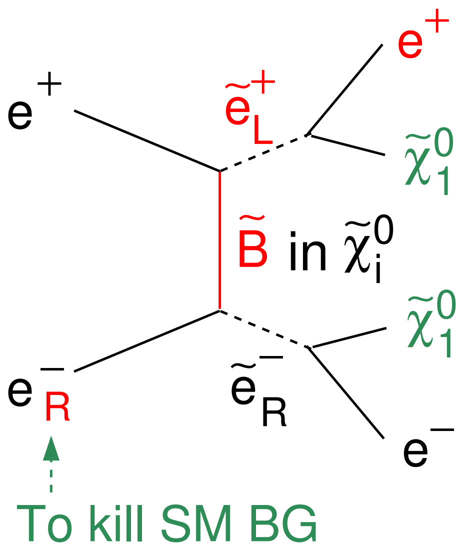
Test of SUSY

$(m_{\tilde{l}}, m_{\tilde{q}}, M_2, \mu, \tan\beta) = (400,700,210,-195,4)$



Situation is much better than the gaugino-rich case !

$\tilde{e}_L^{\pm}$ Study

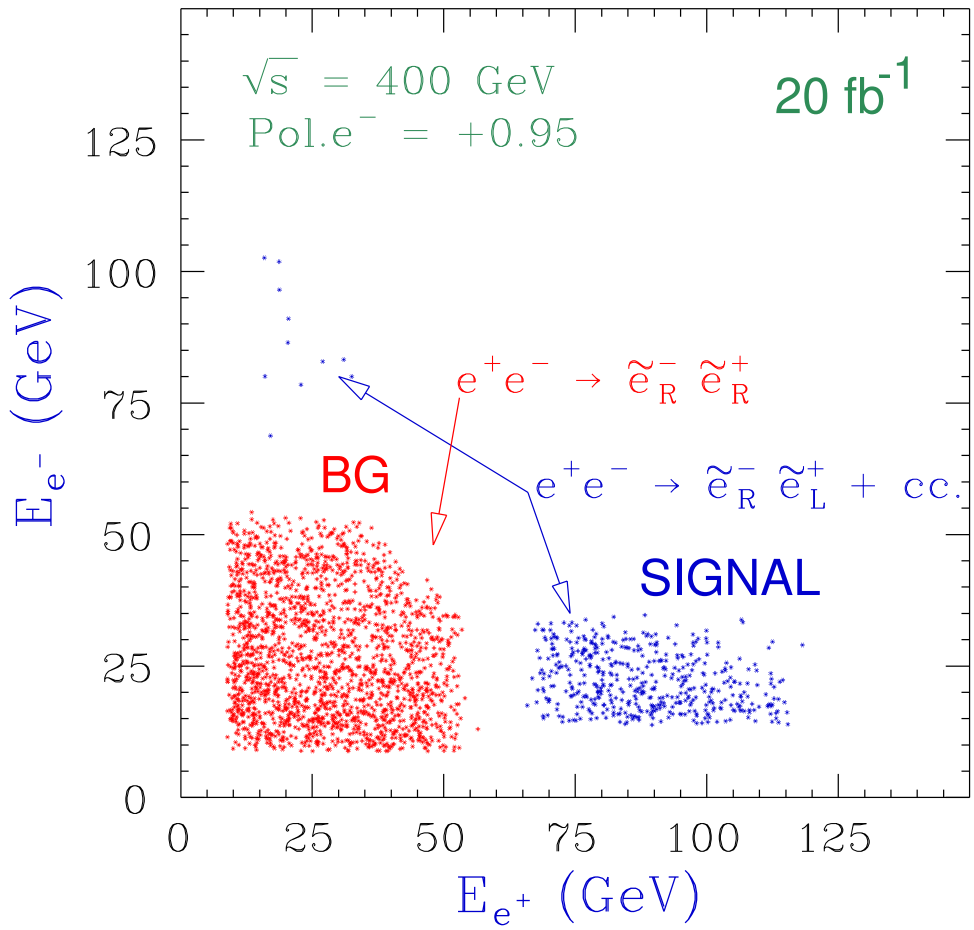


Signal

Acoplanar e^+e^-

BG

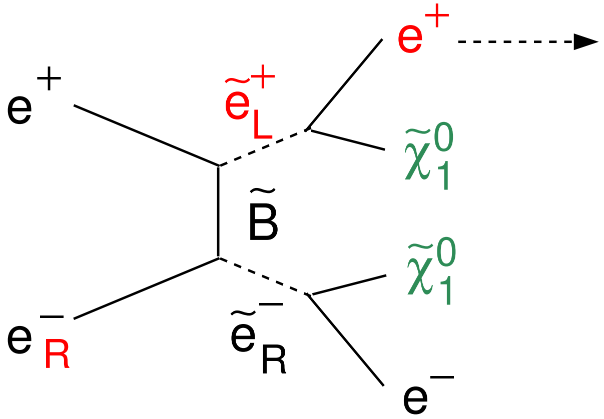
$e^+e^- \rightarrow \tilde{e}_R^+ \tilde{e}_R^-$



$\dashrightarrow$ e^+ carries information on $\tilde{e}_L^+$!

$\dashrightarrow$ Very Clean Sample for Precision Studies !

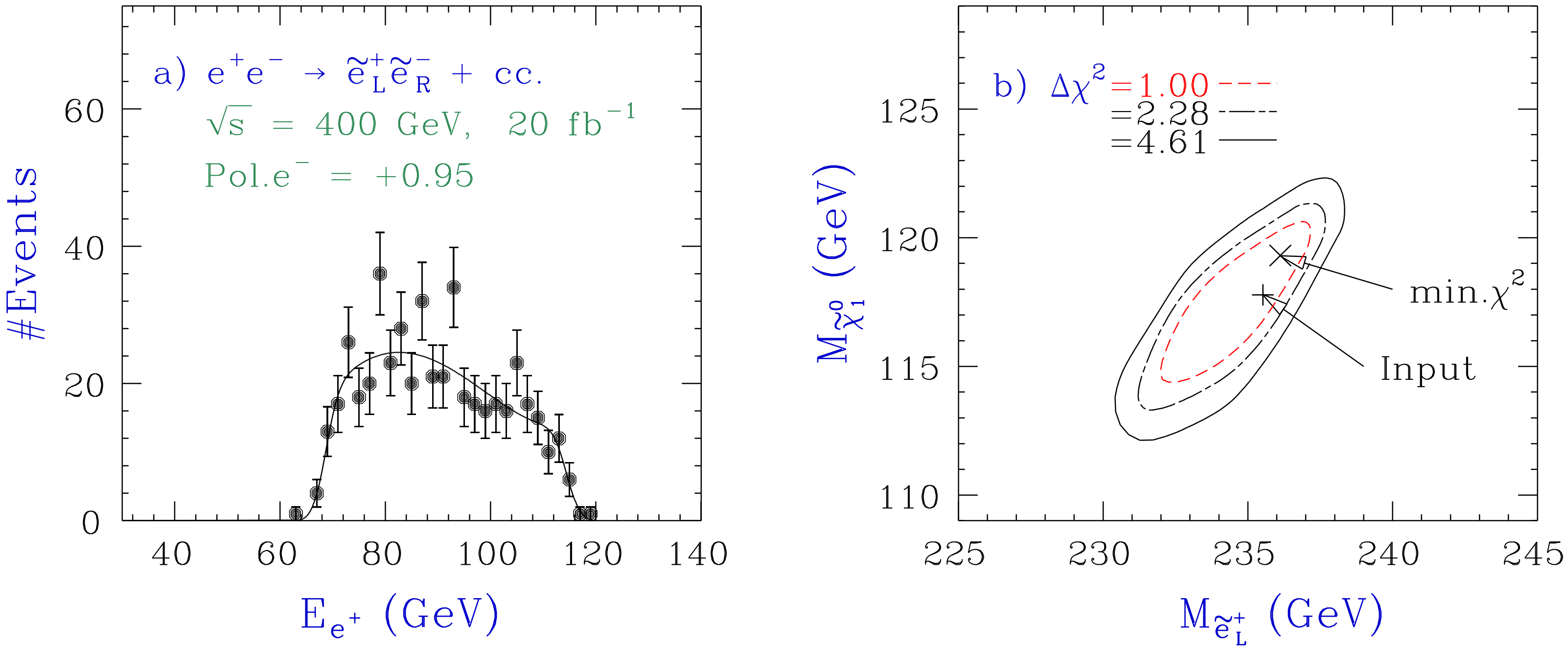
Mass Determination



Measure E_{e^+}

End points

$(m_{\tilde{e}_L^\pm}, m_{\tilde{\chi}_1^0})$



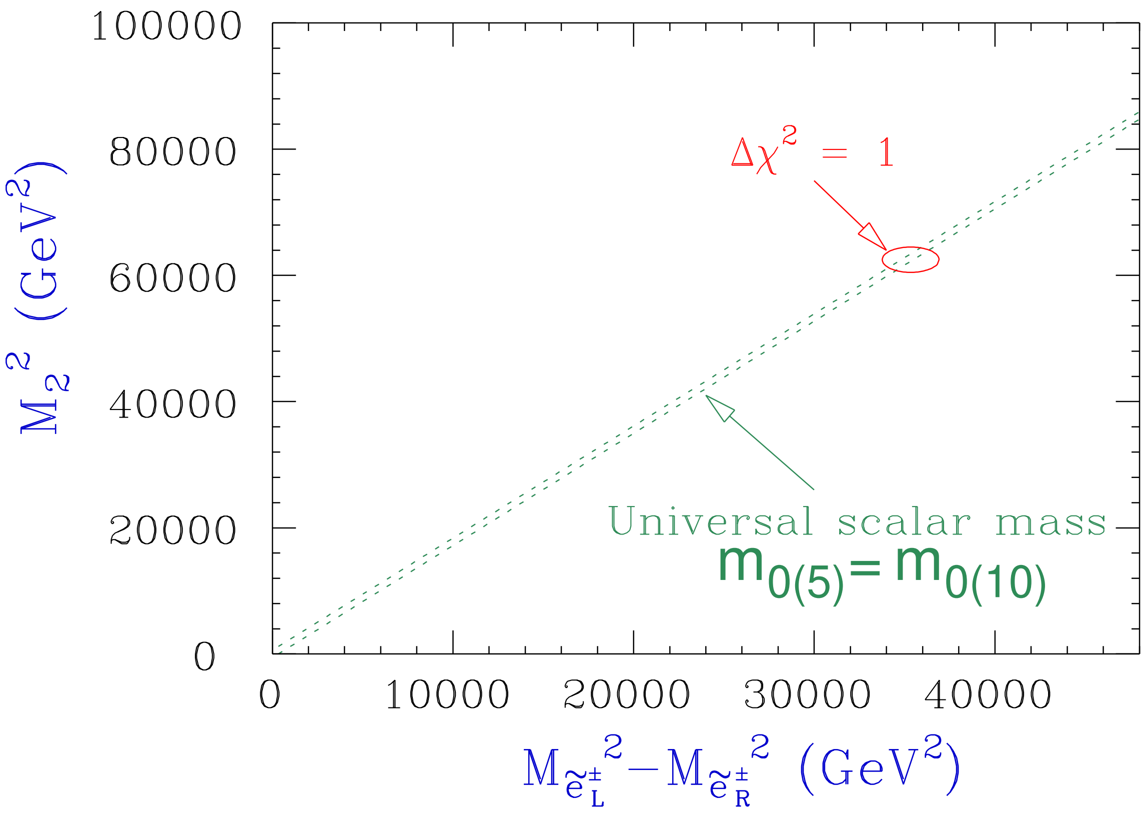
$\Delta m/m \lesssim 1\%$!

Test of Universal Scalar Mass

Sfermion Mass Formula

$$\underset{\mathbf{5}}{m^2_{\tilde{e}_L}} - \underset{\mathbf{10}}{m^2_{\tilde{e}_R}} = m^2_{0(5)} - m^2_{0(10)} + 0.53\, M_2^2 - \underbrace{0.44\, D}_{\text{Small}} \qquad D \simeq m_Z^2 \cos 2\beta < 0$$

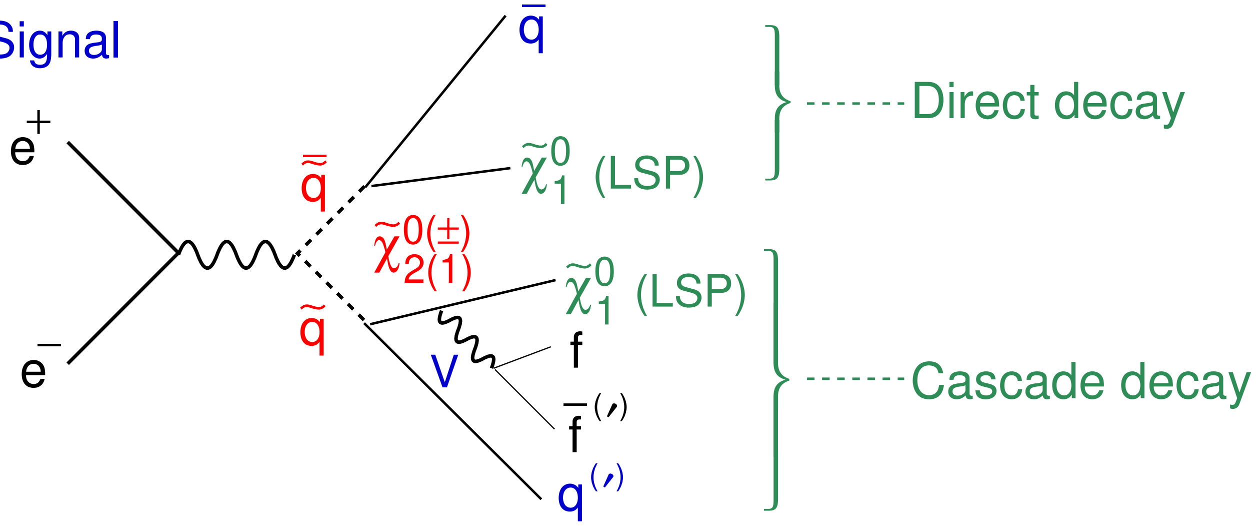
Test of Representation Independence



Once the GUT relation is confirmed and the universal scalar mass hypothesis is verified in the slepton sector, we can set, with confidence, the next target energy for $\tilde{q}$ pair production !

$\tilde{q}_G$ Study (G=1,2)

Signal



→ Acoplanar 2 jets (+ leptons / V=W/Z)

BG

WW, eνW, ννZ, $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_i^0\tilde{\chi}_j^0$ → Negligible for

- $m_{q\bar{q}} > 100$ GeV
- $\not{P}_T > 35$ GeV
- $\theta_A > 30°$

$m_{q\bar{q}} = m_{W^{(*)}/Z^{(*)}} < 100$ GeV !

→ We can use both e^-_L and e^-_R beams !

Chirality Selection

Much better than the slepton case !

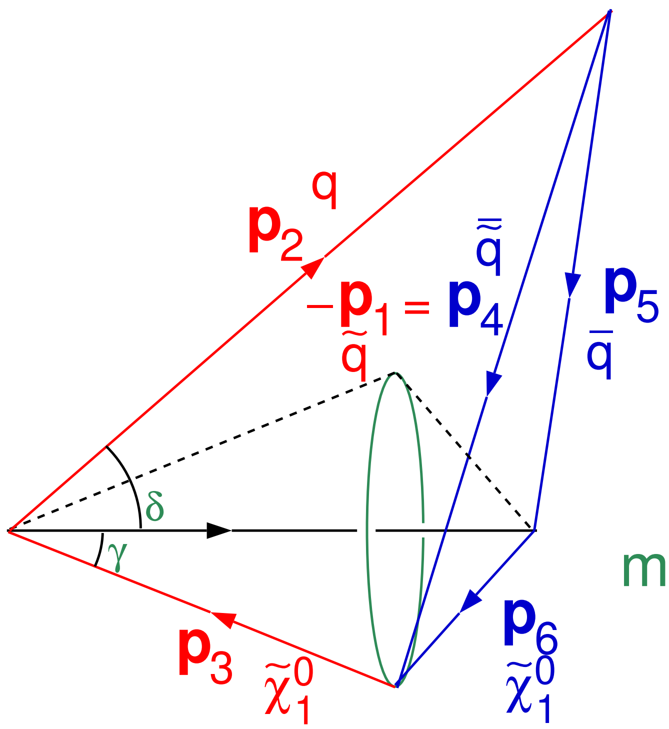
$$\sigma_R(\tilde{q}_R\bar{\tilde{q}}_R) : \sigma_R(\tilde{q}_L\bar{\tilde{q}}_L) \cong \sigma_L(\tilde{q}_L\bar{\tilde{q}}_L) : \sigma_L(\tilde{q}_R\bar{\tilde{q}}_R) \cong 10 : 1$$

if $m_{\tilde{q}_R} \cong m_{\tilde{q}_L}$

Mass Determination

We can use the endpoint method as with $\tilde{l}^{\pm}$ and $\tilde{\chi}_1^{\pm}$

Better quantity proposed by Feng-Finnell



$m_{\tilde{\chi}_1^0}$: known

Minimal Kinematically Allowed Squark Mass

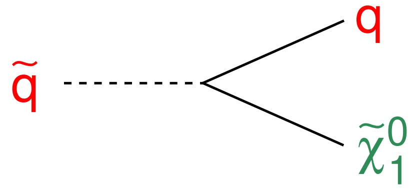
$$(m_{\tilde{q}}^{min})^2 = E_{BM}^2 - |\mathbf{p}_1|_{max}^2$$

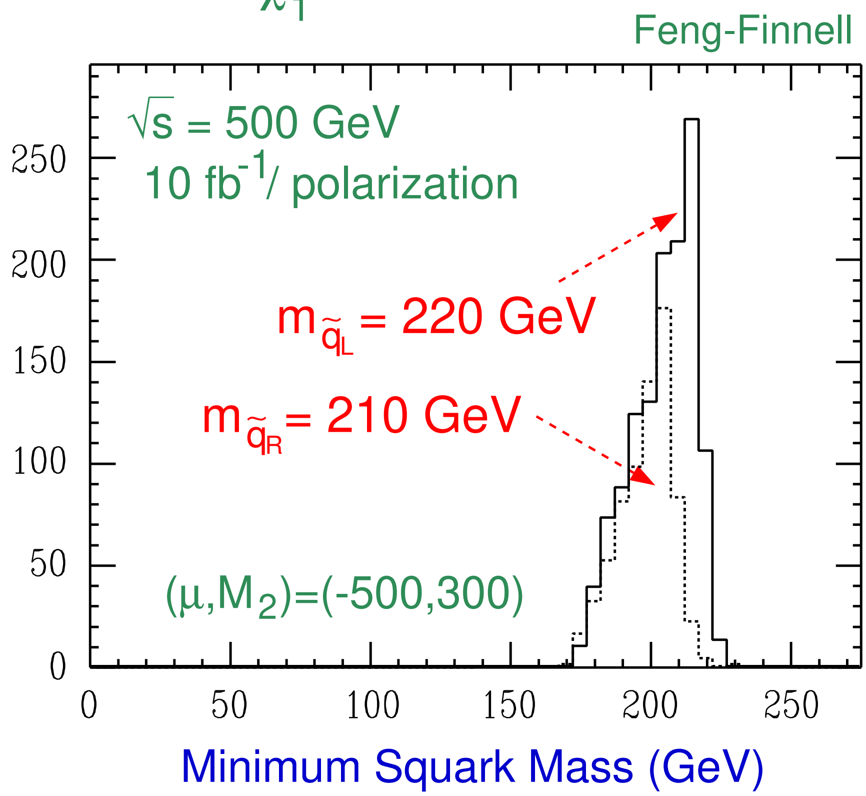
$$= E_{BM}^2 - |\mathbf{p}_2|^2 - |\mathbf{p}_3|^2 + 2\,|\mathbf{p}_2|\cdot|\mathbf{p}_3|\cos(\delta+\gamma)$$

Use the information contained in

the relative configuration of q and $\bar{q}$!

Direct Decays

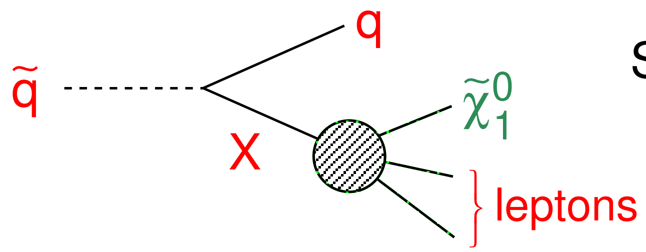




$\Delta m_{\tilde{q}} \cong$ 1 GeV at 95% CL

if $m_{\tilde{\chi}_1^0}$: known

Cascade Decays



Select

2 q-jets + leptons

$m_X \cong m_{\tilde{\chi}_1^\pm} \cong m_{\tilde{\chi}_2^0}$ ------→ Replace $\tilde{\chi}_1^0$ by X = $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$

$m_{\tilde{q}}^{min}$ ------→ $\Delta m_{\tilde{q}} \cong$ 2.4 GeV at 95% CL

(μ, M_2)=(-500,200)

if $m_{\tilde{\chi}_1^\pm} \cong m_{\tilde{\chi}_2^0}$: known

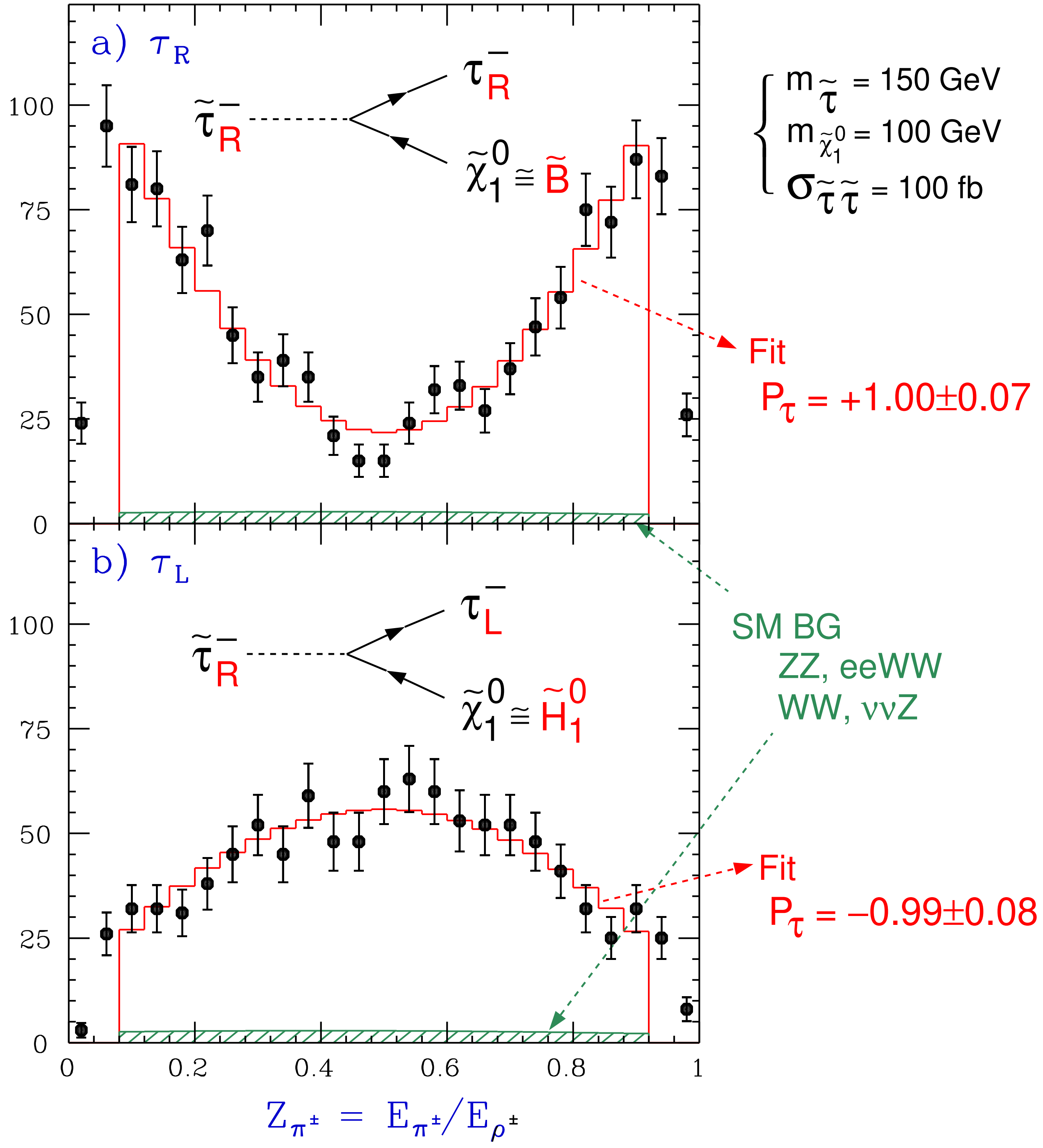
SUSY Study Scenario; 3rd Generation

$\tilde{\tau}^{\pm}$ Study

Ref. Nojiri-Tsukamoto-KF

Measurement of P_τ

$\sqrt{s}$ = 500 GeV Pol e^- = +0.95 100 fb^{-1}

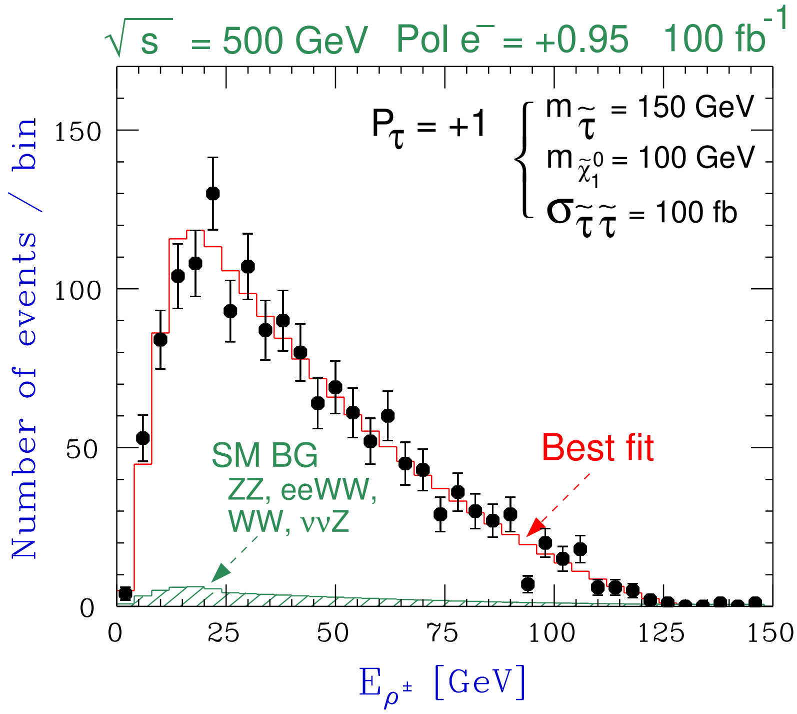


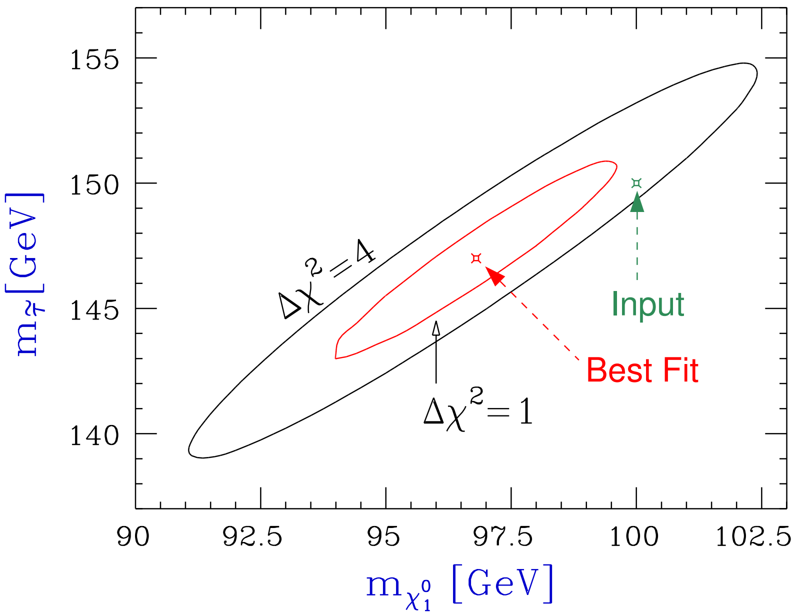
$\Delta P_\tau \cong 0.1$ possible with 100 fb^{-1}

Mass Determination

Can't measure E_τ because of a missing ν, however, we can still measure

$E_{\rho^\pm}$ distribution $\dashrightarrow$ $(m_{\tilde{\tau}^\pm}, m_{\tilde{\chi}_1^0})$





If we combine $m_{\tilde{\chi}_1^0}$ from $\tilde{e}_R^\pm$ and $\tilde{\mu}_R^\pm$ studies

$\Delta m_{\tilde{\tau}} / m_{\tilde{\tau}} \lesssim 1\%$ possible with 100 fb^{-1}

Determination of Mixing Angle

Staus can mix:

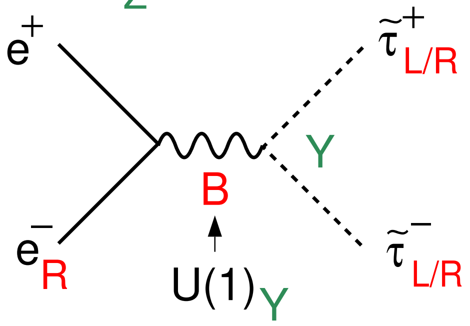
$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_\tau & \sin\theta_\tau \\ -\sin\theta_\tau & \cos\theta_\tau \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}$$

through the off-diagonal element of the stau mass marix:

$$-m_\tau(A_\tau + \mu\tan\beta)$$

$\dashrightarrow$ $m_{\tilde{\tau}_1}$ and $\sigma_{\tilde{\tau}_1^+\tilde{\tau}_1^-}$: functions of θ_τ

If $\sqrt{s} \gg m_Z$,

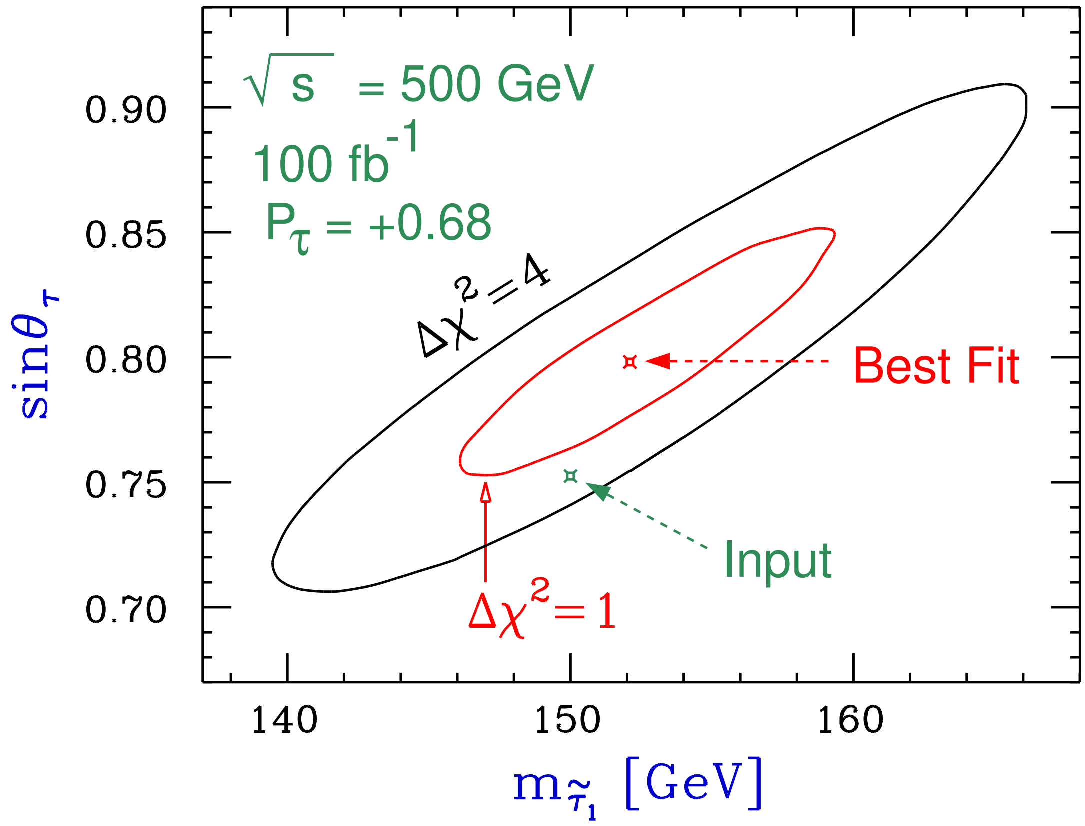


$$\begin{cases} Y_L = -1/2 \\ Y_R = -1 \end{cases}$$

$\sigma_R = 4\,\sigma_L$

$$\sigma_{\tilde{\tau}_1^+\tilde{\tau}_1^-} = (\cos^2\theta_\tau + 2\sin^2\theta_\tau)^2\sigma_L$$

Expected Precision



Slepton Sector Global Fit

Strategy

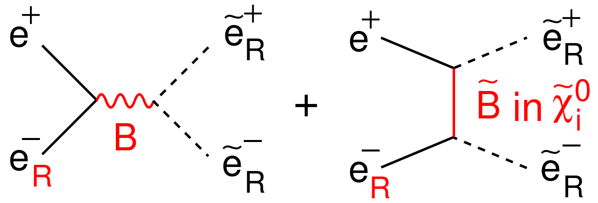
$(M_1, \mu, \tan\beta)$

$m_{\tilde{\chi}_1^0}$: precisely measured !

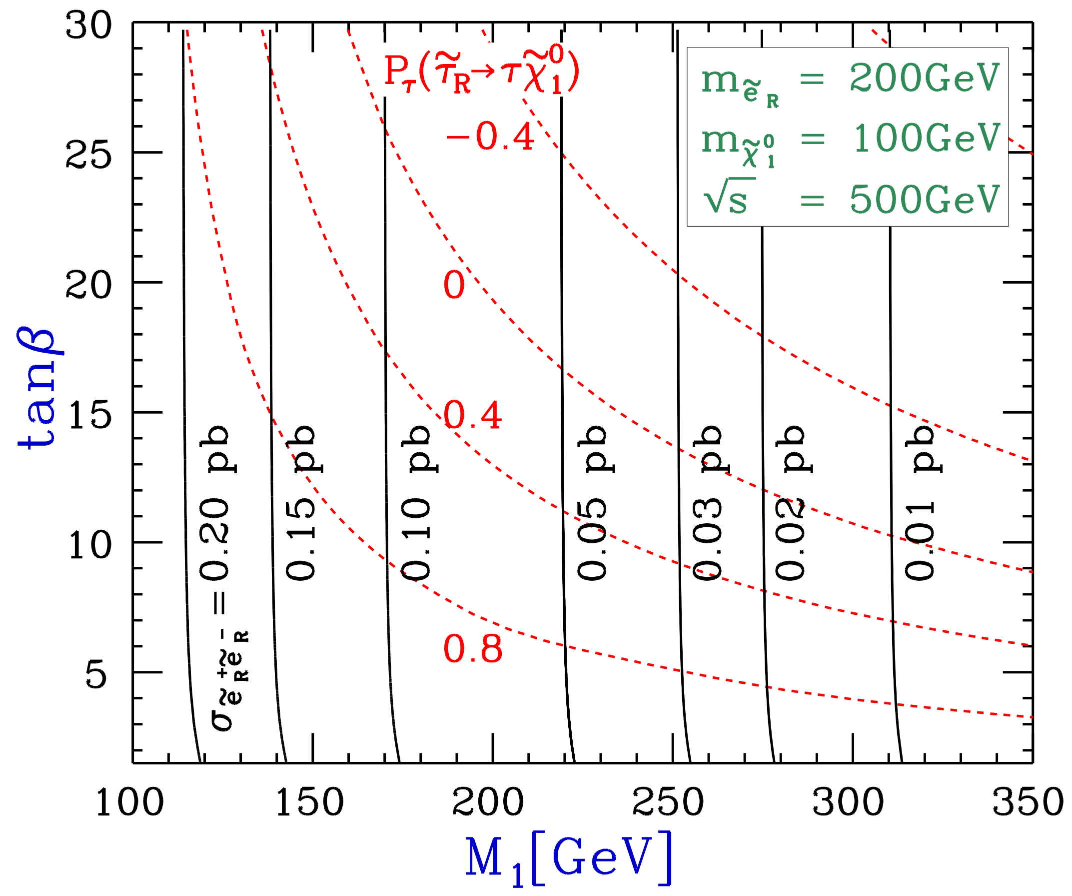
$=$ LSP

$(M_1, \tan\beta)$: to be fixed by two more observables !

$\sigma(e^+ e^-_R \to \tilde{e}^+_R \tilde{e}^-_R) \dashrightarrow \langle \tilde{B} | \tilde{\chi}^0_1 \rangle$

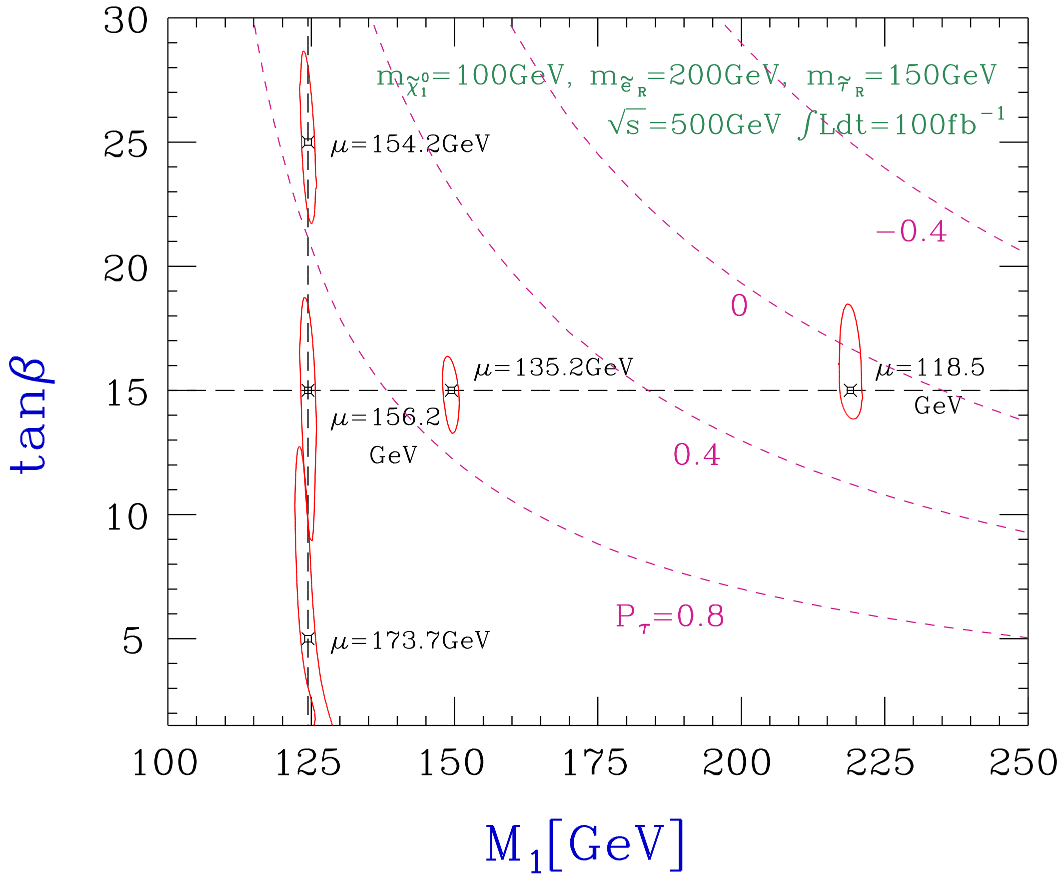


$P_\tau(\tau_R \to \tau \tilde{\chi}^0_1) \dashrightarrow \langle \tilde{H}^0_1 | \tilde{\chi}^0_1 \rangle$



Results from Lepton Sector Global Fit

Sample typical points in the parameter space and see how well we can determine tanβ



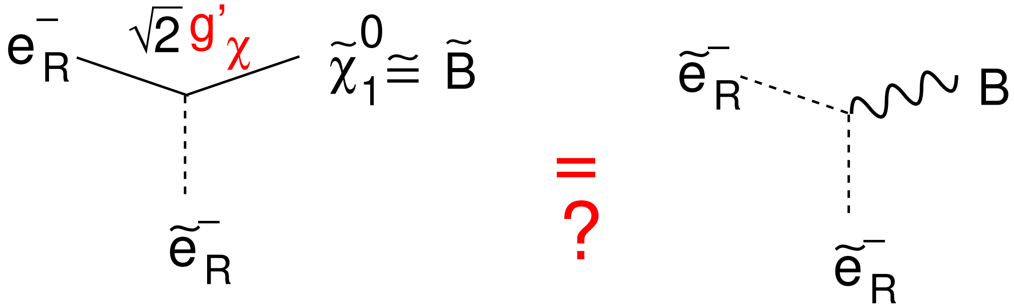
- Quickly lose sensitivity to tanβ as the LSP becomes Bino-rich!
- On the other hand, fairly good measurement is possible if it becomes higgsino-like!

Quantitative Test of SUSY

If $\tilde{\chi}_1^0 \cong \tilde{B}$, tanβ-insensitive.

⇢ Turn this into an advantage and test SUSY !

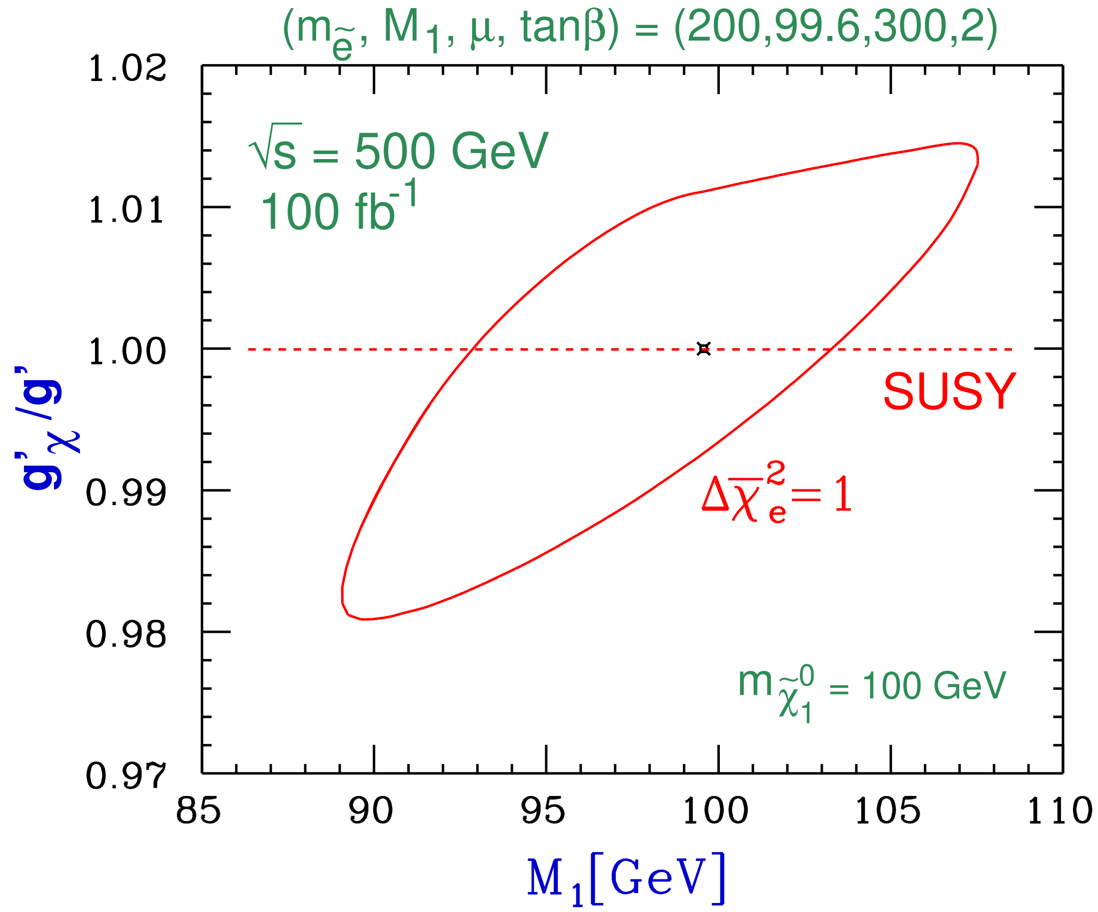
Question



Observables to Use :

$$\begin{cases} d\sigma \cong d\sigma(m_{\tilde{e}_R^\pm}, m_{\tilde{\chi}_1^0}, g'_\chi) \\ E_e \text{ distribution (Endpoints)} \end{cases}$$

Test of SUSY



Summary

Pol e^- Beam

Powerful tool to

i) suppress SM BG and enhance SIGNAL !

ii) sort out sparticle mixings !

Precision Measurements

$$\dashrightarrow \begin{cases} \Delta m/m \lesssim O(1\%) \,! \\ d\sigma/d\Omega \end{cases}$$

$\therefore$ We can learn a lot from the FSP alone !

$\dashrightarrow$ Systematic and Consistent Searches and Studies

FSP $\dashrightarrow$ NSP $\dashrightarrow$ ...... $\dashrightarrow$ N^nSP

S-parameters

$$\dashrightarrow \mathcal{L}_{\text{S-breaking}} \dashrightarrow \mathcal{L}_{\text{Planck?}} \quad !$$

First realistic step toward GUT/Planck scale physics !