Lecture

4

The MSSM Higgs Sector

2 CP-even states h, H $\longrightarrow$ mixing angle α
1 CP-odd A 1 charged Higgs $H^{\pm}$

- At tree level:

$$m_h \leq M_Z$$

Input param. $\longrightarrow$ m_A and $\tan\beta \equiv v_2/v_1$

- After quantum effects:

mass spectrum depends on M_t and the stop and sbottom sectors:

$$m_h \leq 130\text{GeV}$$

$\Longrightarrow$ stringent direct test of the MSSM

– Effect of rad. corrections on Higgs couplings to fermions and gauge bosons

- change basic relation $\frac{g_{\phi b\bar{b}}}{g_{\phi\tau\tau}} \neq \frac{M_b}{M_\tau}$
- strong suppression of $BR(\phi \to b\bar{b})$

$\Longrightarrow$ depending on the MSSM param. space $\to$ change drastically the Higgs bosons search strategies.

To define potential of a collider for Higgs searches it is necessary to explore the most challenging configurations

Neutral MSSM Higgs production cross sections at the Tevatron $\sqrt{s} = 2$ TeV

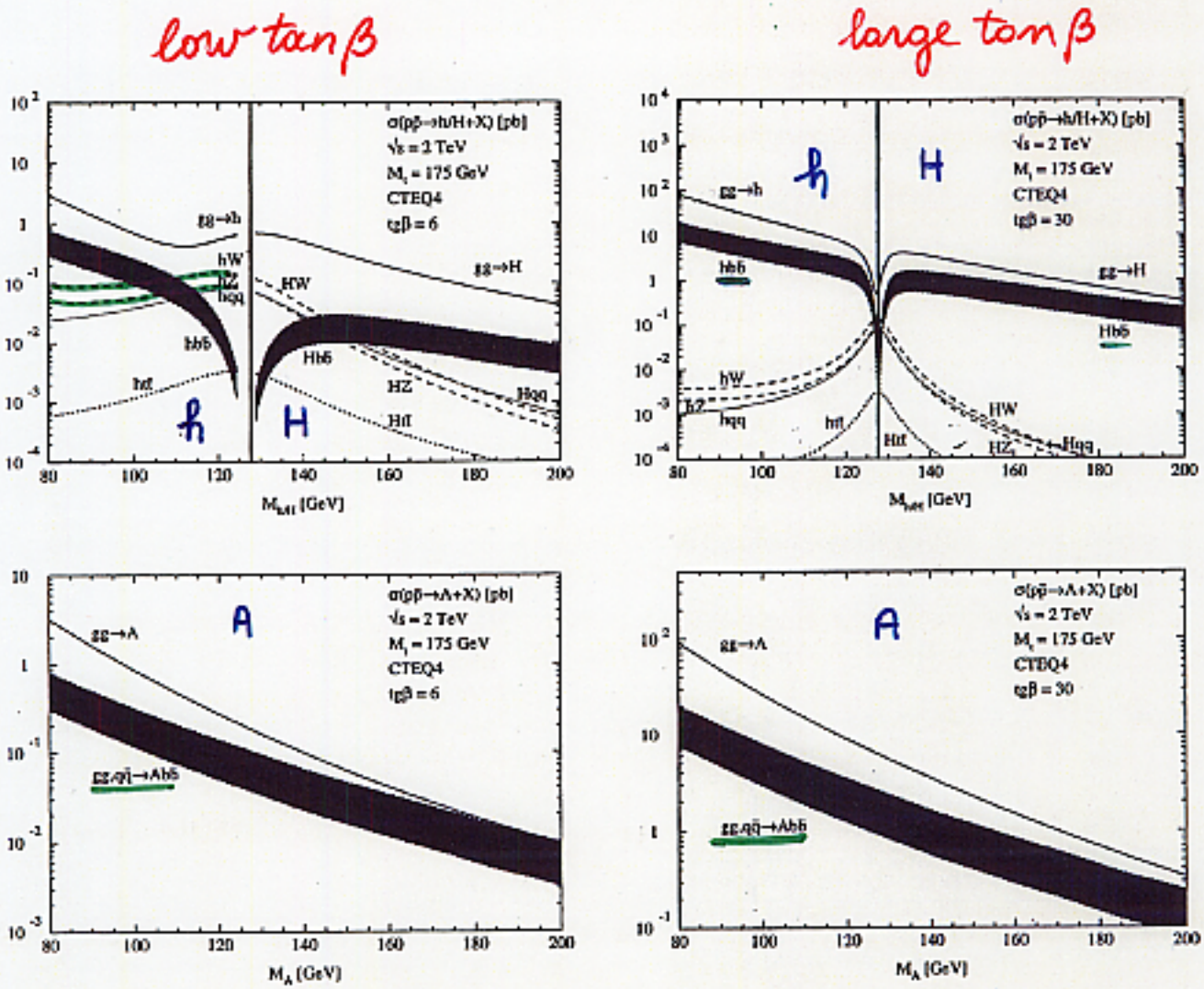
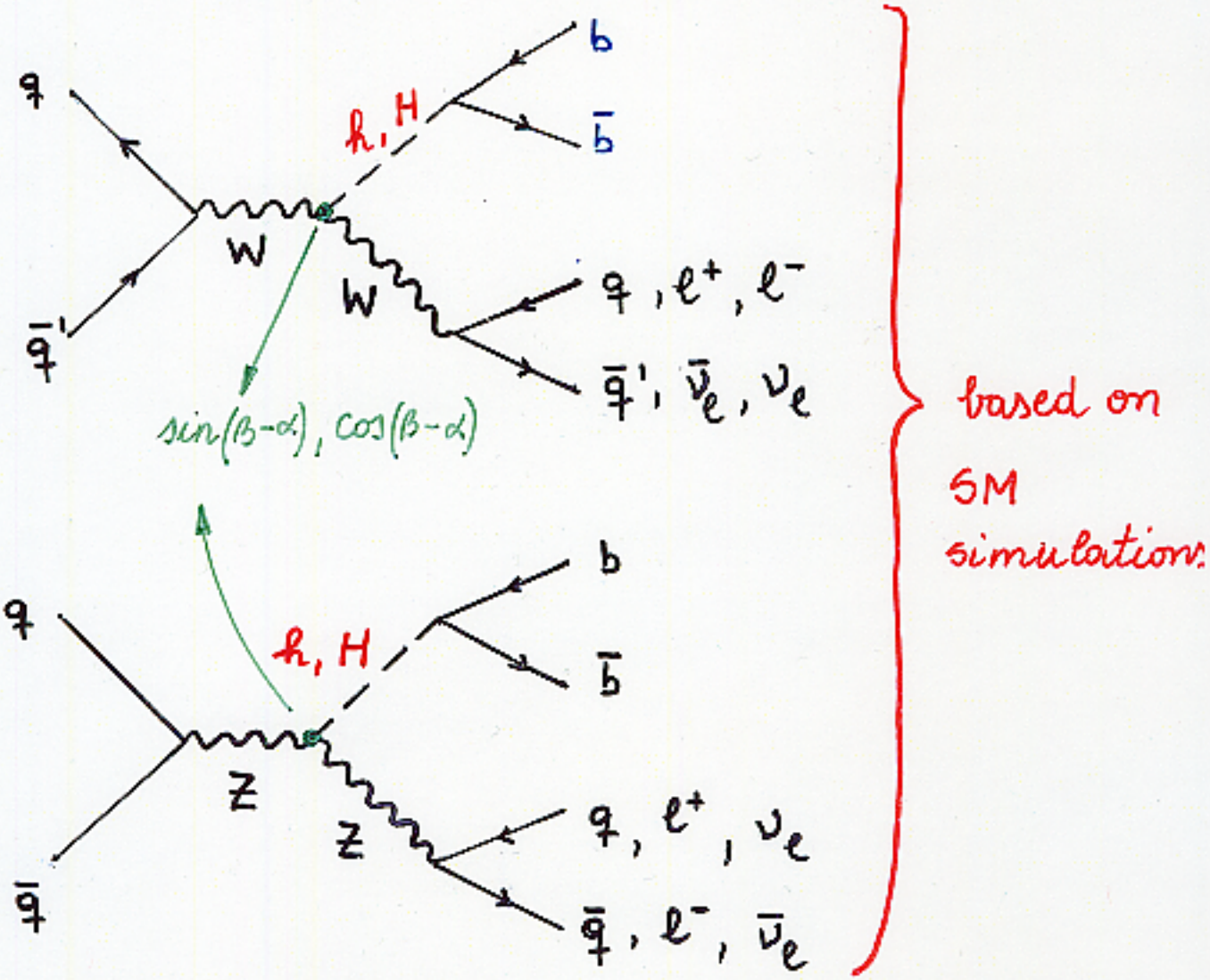
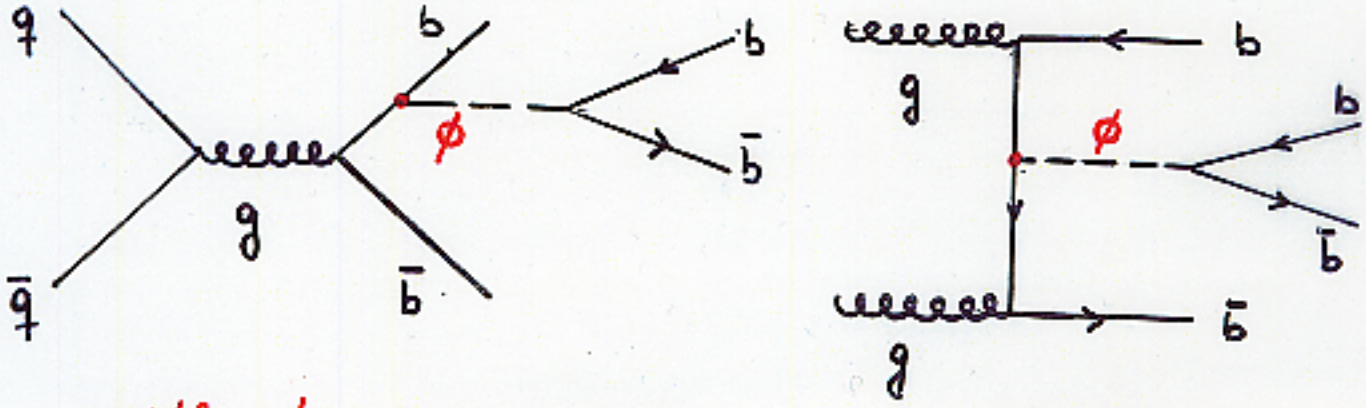


FIGURE 17. Neutral MSSM Higgs production cross sections at the Tevatron [$\sqrt{s} = 2$ TeV] for gluon fusion $gg \to \Phi$, vector-boson fusion $qq \to qqVV \to qqh$, qqH, vector-boson bremsstrahlung $q\bar{q} \to V^* \to hV/HV$ and the associated production $gg, q\bar{q} \to \Phi b\bar{b}/\Phi t\bar{t}$ including all known QCD corrections. (a) h, H production for $\tan\beta = 6$, (b) h, H production for $\tan\beta = 30$, (c) A production for $\tan\beta = 6$, (d) A production for $\tan\beta = 30$.

Neutral MSSM Higgs Channel Studies at the Upgraded Tevatron





with $\phi = h, A$ or H, A → large $\tan^2\beta$ enhancem. in σ_{prod}

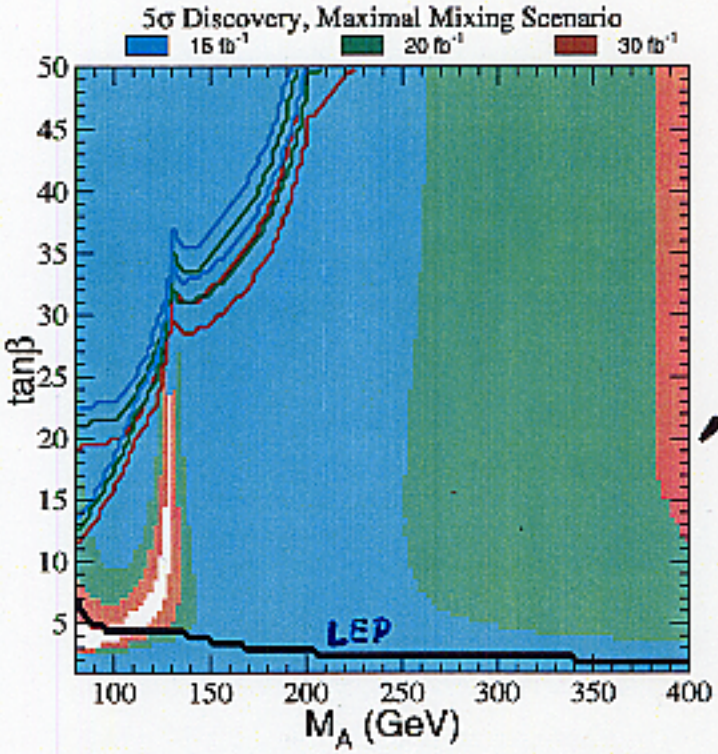
MSSM Higgs sector Feasibility Studies

Tevatron Higgs WG '00

maximal mixing scenario

⇓

$m_h^{max} \simeq 130$ GeV



5σ discovery

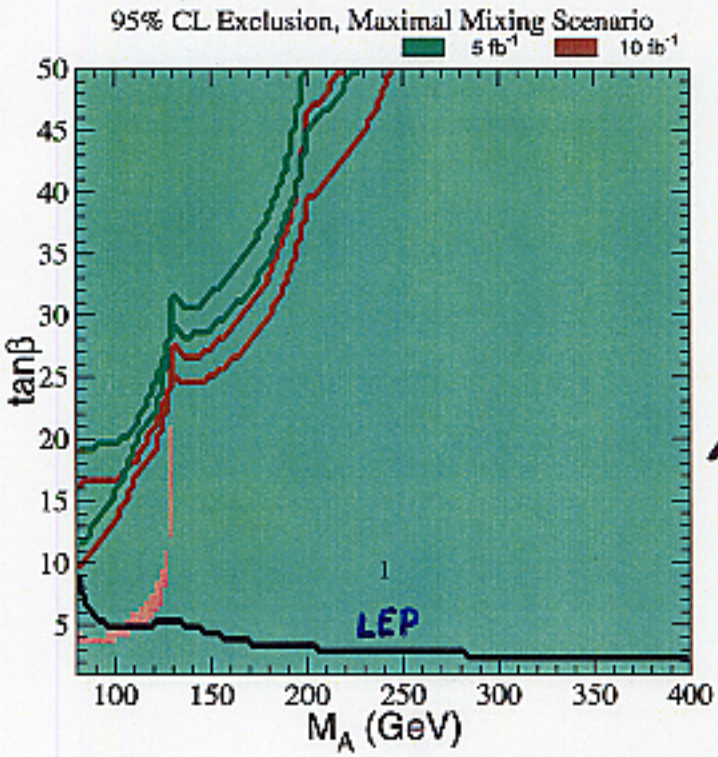
$p\bar{p} \to Vh/H \to Vb\bar{b}$ (shaded areas)

$p\bar{p} \to \phi b\bar{b} \to b\bar{b}b\bar{b}$ (solid lines)

<ϕ = A/h or A/H tanβ-enhanced $b\bar{b}$ coupling>

most part of param. space explored with $\simeq 5\,fb^{-1}$ (95% CL. excl.)

but good coverage for discovery ⇒ ~ 20 fb^{-1} required



95% C.L. Exclusion

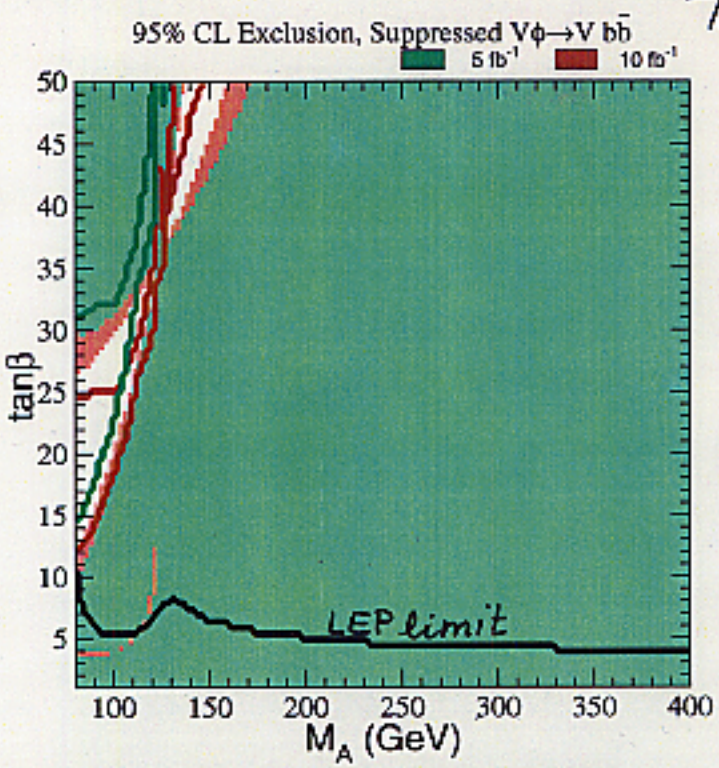
155M Higgs sector Feasibility studies

Tevatron Higgs WG '00
Carena, Conway, Habe
Hobbs et. al

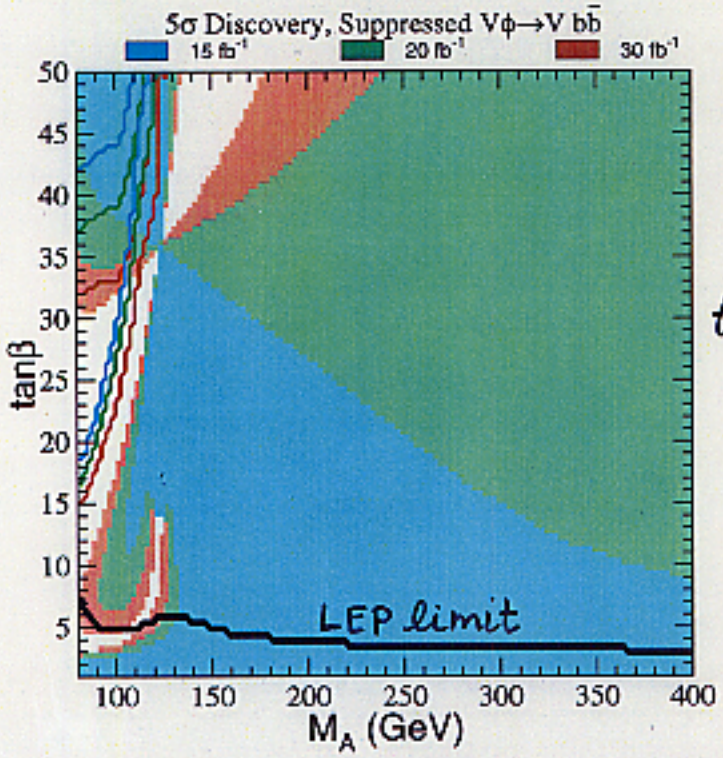
ost challenging
enario for
he Tevatron

↓

$h^{max} \sim 120$ GeV
but
mportant
egions of
uppressed
$b\bar{b}$ coupling
$= h/H$
strong coupling
W, Z



$p\bar{p} \to Vh/H \to Vb\bar{b}$
(shaded areas)

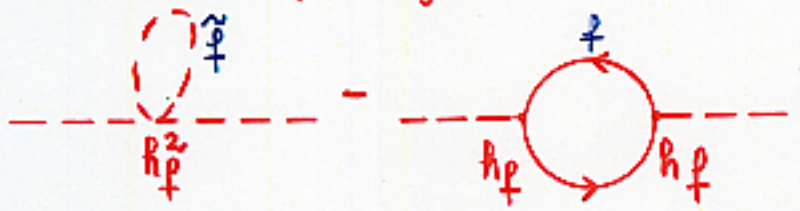


$p\bar{p} \to \phi b\bar{b} \to b\bar{b}b\bar{b}$
(solid lines)
$\phi = A/h$ or AH
$\tan\beta$ enhanced coupl. to $b\bar{b}$

ood exclusion if no signal with $5-10\ fb^{-1}$
ood coverage for discovery $\longrightarrow > 15\ fb^{-1}$

Soft SUSY Breaking

- SUSY must be broken in nature
- cancellation of quad. div. has to do with relation between couplings



$\longrightarrow \delta m_H^2 \simeq h_f^2 \left(m_{\tilde{f}}^2 - m_f^2\right)$

$\Rightarrow$ Soft SUSY breaking terms $\equiv$ all gauge inv. masses allowed in the theory

$$\mathcal{L}_{\not{SUSY}} = -\sum_{\text{scalars}} \underbrace{m_i^2}_{m_{\tilde{\ell}_{soft}}^2} A_i^2 - \sum_{\text{gauginos}} M_i \left(\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i\right)$$

$$+ \left(B\, P^{(2)}[A] + \sum_k A_k P^{(3)}_{(k)}[A] + h.c.\right)$$

tra Higgs mass term

$B\mu\, \epsilon_{ij} H_1^i H_2^j$

Trilinear Terms

$\left(A_b h_b \tilde{Q}^j \tilde{D} H_1^i + A_t h_t \tilde{Q}^j \tilde{U} H_2^i + A_\tau h_\tau \tilde{L}^j \tilde{E} H_1^i\right)\epsilon_{ij}$

Finite set of soft $\not{SUSY}$ parameters

$m_i \qquad M_i \qquad B \qquad A_k$

$\Rightarrow$ wide range of possible high E values $\Rightarrow$ dependeng on $\not{SUSY}$ mechanism

Renormalization group Evolution

$\hookrightarrow$ determine low energy values

Mechanism of SUSY → not well understood yet and models of SUSY are not so simple:

In general, spontaneous/dynamical breakdown of SUSY in some new (hidden) sector at high energies, where some components of the new sector adquires v.e.v.: $< F > \longrightarrow$ dim. m^2

- Interaction between those components and the MSSM superfields $\Longrightarrow$ give rise to soft SUSY breaking terms: $\tilde{m} \propto < F > / M$

M: scale of transmission of SUSY breaking (messenger scale)

Phenomenological approach:

- define Boundary conditions at scale M_{Pl} or below at which SUSY breaking is transmitted from hidden sector to observable sector

- use Renormalization Group evolution of soft SUSY breaking parameters from SUSY breaking scale down to low energies → define the SUSY particle spectrum

- two main scenarios of SUSY
  - gravity mediated
  - gauge mediated

Sugra Scenarios

moduli fields T, S (hidden sector) adquire v.e.v.'s $< F_{T,S} > \neq 0$ and interact with MSSM fields through $1/M_{pl}$ interactions $\int d^4\theta\, T\bar{T}\Phi^\dagger\Phi/M_{pl}^2 \propto m^2_{\tilde{f}_{soft}}$

$m_{\tilde{f}_{soft}} \propto < F_S > /M_{pl} + < F_T > /M_{pl} \propto m_0$ → gravitino mass.

$M_i \propto < F_S > /M_{pl} \propto M_{1/2}$

$A_0 \propto < F_{T,S} > /M_{pl} \qquad B\mu_0 \propto < F_T^2 > /M_{pl}^2$

This are the boundary conditions at M_{pl}, then RG evolution till M_{SUSY} (scale of SUSY particles)

To have $m_{\tilde{f}_{soft}} \propto < F_{T,S} > /M_{pl} \simeq 1$ TeV
$\Longrightarrow \sqrt{F_{T,S}} \simeq 10^{11}$ GeV.

Problems of the SUGRA scenarios:

- sensitivity to UV physics
- lack of predictivity
- sensitivity to flavour violation → hard to suppress contrib. from SUSY to B, K, μ physics

Specific Minimal–Sugra features:

Including electroweak symmetry breaking condition,

$\Longrightarrow$ the whole SUSY particle spectrum defined by:

$m_0 \longrightarrow$ universal scalar mass

$M_{1/2} \longrightarrow$ universal gaugino mass

$A_0 \longrightarrow$ universal cubic coupling scaling factor

$\tan\beta = \frac{v_2}{v_1} \longrightarrow$ ratio of Higgs v.e.v.'s

sign of $\mu \longrightarrow$ SUSY Higgs mass parameter

radiative ELW symm. breaking

$\Longrightarrow$ in general $|\mu| \gg M_{1/2}$

- light neutralino/chargino states $\longrightarrow$ gaugino like
- heavy states $\longrightarrow$ higgsino-like

$$2m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_2^0} \simeq \frac{1}{3}M_{\tilde{g}} \simeq \mathcal{O}(M_{1/2})$$

$$m_{\tilde{\chi}_3^0} \simeq m_{\tilde{\chi}_4^0} \simeq m_{\tilde{\chi}_2^\pm} \simeq |\mu| \gg m_{\tilde{\chi}_1^\pm}$$

Furthermore:

- *if* $m_0 \gg M_{1/2} \longrightarrow m_{\tilde{q}_{1,2}} \simeq m_{\tilde{l}} > M_{\tilde{g}}$
- *if* $m_0 \ll M_{1/2} \longrightarrow M_{\tilde{g}} > m_{\tilde{q}_{1,2}} > m_{\tilde{b}} > m_{\tilde{t}} > m_{\tilde{l}_L} \simeq M_{\tilde{W}}$

$$M_{\tilde{W}} > m_{\tilde{l}_R} \simeq M_{\tilde{B}}$$

Extensions of MSUGRA:

- CP Violation

• complex phases for all soft SUSY breaking parameters, but at least two cannot be rotated away choosing those as ϕ_μ and ϕ_A

$\Longrightarrow$ six param. determine the sparticle spectrum:

$$m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \phi_\mu,\ \phi_A$$

• Interesting constraints on SUSY param. space from EDM's of electron and u,d quarks

$$\left(\frac{d_f}{e}\right)^{1l.} \sim 10^{-25}\,\mathrm{cm}\frac{(\mathrm{Im}\mu, \mathrm{Im}A_f)}{max.(m_{\tilde{f}}, m_\lambda)}\left(\frac{1\mathrm{TeV}}{max.(m_{\tilde{f}}, m_\lambda)}\right)^2\left(\frac{m_f}{10\mathrm{MeV}}\right)$$

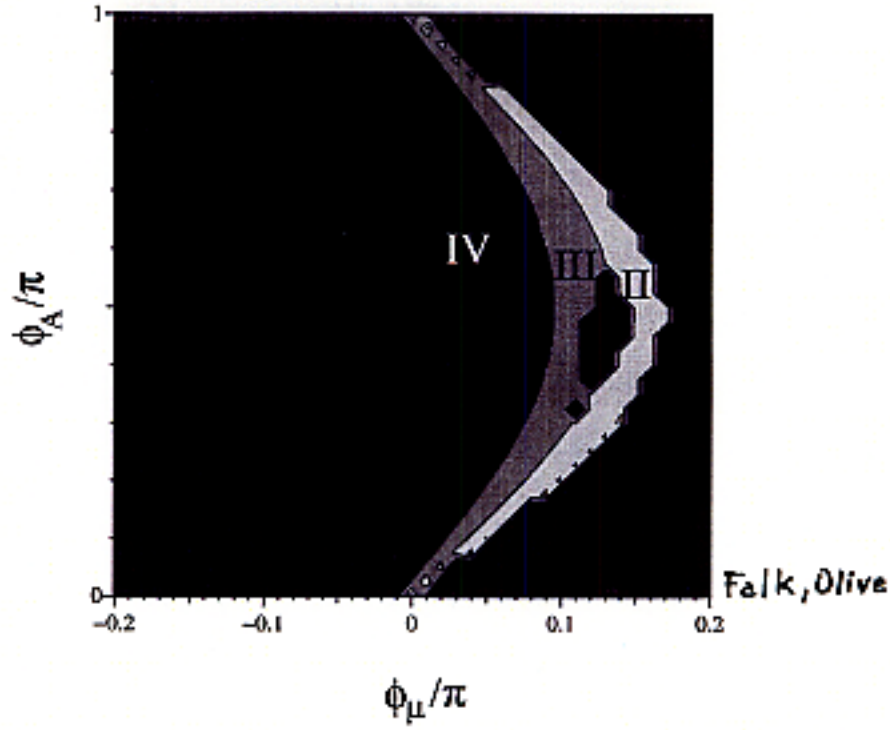
To resolve the one-loop CP crisis:

• $\mathrm{Im}\mu/|\mu|, \mathrm{Im}A_f/A_f \leq 10^{-2}$, with $(m_{\tilde{f}}, m_\lambda) \sim 200\,\mathrm{GeV}$

• CP phases ~ 1, <u>but</u> $m_{\tilde{f}} > 1$ TeV for $\tilde{f} = \tilde{e}, \tilde{u}, \tilde{d}, \tilde{\nu}_L$

• Cancellations between different EDM terms

$$\Downarrow$$



Required values of $M_{1/2}$ to satisfy electron and neutron EDM's for $\tan\beta$ =2, m_0 = 100 GeV, A_0 = 1 TeV. Zones labelled II, III and IV correspond to: 200 GeV $\leq M_{1/2}^{min} \leq$300 GeV, 300 GeV $\leq M_{1/2}^{min} \leq$450 GeV and $M_{1/2}^{min} \geq$450 GeV

- Two-loop contributions to EDM's $\Longrightarrow$ constraints on CPV parameters of 3rd. gen. squarks, specially for large $\tan\beta \longrightarrow$ important for Higgs physics

- CPV makes more difficult to reconstruct param. of SUSY particles from experimental data

– Non-Universality of Soft Terms

Universality of soft terms comes from assumption that Kähler potential does not have generational dependent couplings with hidden sector

Relaxing this $\longrightarrow$ non-univ. scalar masses
$\Longrightarrow$ FCNC constraints
However, Higgs sector univ. or 3rd. generation sector univ. is not strongly contrained

Non-universality produces identifiable signatures at low energy

– R-Parity Violation ~~(see E. Perez's talk)~~

Analysis of MSUGRA signatures depend strongly on R-parity invariance or violation

If R-parity conserved $\Longrightarrow$ LSP stable
$\Longrightarrow$ lots of $\not{E}_T \rightarrow$ distinctive SUSY signature

The Flavour Problem & SUSY Breaking

strong constraints on flavor structure of SUSY terms

$\longrightarrow$ from constraints on FCNC processes

in $\mathcal{L}_{\text{soft SUSY}}$ $\longrightarrow$ only indep. mass terms for each scala

$\sum_i m_i^2 |A_i|^2$, but one could write mass terms which mix scalars: $\sum_{ij} m_{ij}^2 \phi_i \phi_j^*$

In the basis where quarks are diagonal (if diag. of fermion sector is done in a SUSY way)

$\Rightarrow$ substantial off-diag. $\tilde{q}$ terms not possible

$\Delta\mathcal{L} = \Delta M^2 \tilde{s}^+ \tilde{d} \Longrightarrow$

would induce excesive contrib. to $K_L - K_S$ mass diff.

(similar for $B-\bar{B}$, $D-\bar{D}$, $\mu \to e\gamma$)

- Alternative way to see it: diag. indep. fermions & sfermion
  $\longrightarrow$ then have direct contrib. to neutral current $\Rightarrow$

In the SM $\longrightarrow$ GIM Mechanism

$$\psi_u^{L,R} = \begin{pmatrix} u \\ c \\ t \end{pmatrix}_{L,R} \qquad \psi_d^{L,R} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{L,R}$$

$$W_\mu^+ \bar{\psi}_u^L \gamma^\mu \psi_d^L + \dots$$

$$A_\mu^\gamma \left(\bar{\psi}_u^L \gamma^\mu \psi_u^L + \bar{\psi}_u^R \gamma^\mu \psi_u^R + \dots \right)$$

Mass term: $(\bar{\psi}_u^L)_i \, M_{ij}^u \, (\psi_u^R)_j + h.c.$

and $M^u_{Diag} = U_L^+ M^u U_R$ $\qquad \bar{\psi}_u^L = \bar{\psi}^L_{u,Diag} U^+$

$M^d_{Diag} = D_L^+ M^d D_R$

going from the interaction to the mass eigenstate basis, in the neutral sector $\Rightarrow U_L^+ U_L = I = D_L^+ D_L$

but in the charged sector $K = U_L^+ D_L$

K close to identity:

- no tree level FCNC
- loop correct. suppressed by mixing angles

<similar arguments in lepton sector
$\mu \not\to e\gamma$ in SM if $m_\nu = 0$, if not>

Flavor Problem and SUSY Breaking

SM: $M^u_{Diag} = U_L^+ M^u U_R$ $\qquad$ $M^d_{Diag} = D_L^+ M_d D_R$

neutral currents conserve flavour

$$A_\mu (\bar{q}_u^L \gamma^\mu q_u^L) \equiv A_\mu (\bar{q}_{u,D}^L \gamma^\mu q_{u,D}^L)$$

in SUSY

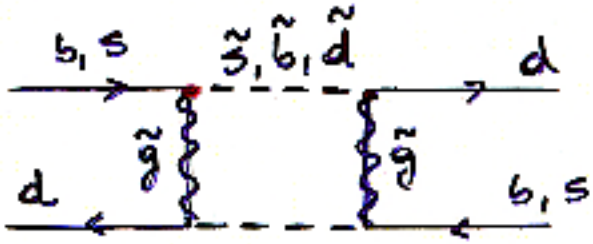
$$\bar{q}_u^L \phi_u^L \cdot \tilde{\lambda} \longrightarrow \bar{q}_{u,D_{diag}}^L \overbrace{U_L^+ \underline{\tilde{U}_L}}^{K} \tilde{\lambda} \phi_{u,D_{diag}}^L$$

$s\,\tilde{g}\,\tilde{s}$

where $\tilde{U}_L$ comes from the diagonalization

$$\phi_u^{*L} [\underbrace{m_u^2}_{\text{soft SUSY}} + \underbrace{M^u M^{u+}}_{\text{SUSY}}] \phi_u^L = \phi_{u,D}^{*L} m_{u,D}^2 \phi_{u,D}^L$$

if $\tilde{U}_L \neq U_L$



$\Rightarrow$ contrib. to $K_L - K_S$ mass diff or to $D-\bar{D}$, $B-\bar{B}$ mixing which are not possible

If $m_u^2 \sim m_0^2 I \Rightarrow \tilde{U}_L = U_L$ $\Longrightarrow$ universality sol.

(diag. in any basis)

also $\rightarrow$ by virtue of flavor symm $\Rightarrow$ alignment of $\tilde{q}$ & q

Gauge-Mediated SUSY breaking Scenarios

- Superpartner masses proportional to $\Lambda = F_S/M$
  $\sqrt{F_S}$: intrinsic SUSY breaking scale
  M: mass scale of the messenger sector

- Minimal set of parameters:

$$\Lambda,\ M,\ \mathrm{N},\ \tan\beta,\ sign(\mu),\ C_G$$

N: number of messenger generations, C_G: constant relating SUSY breaking scale felt by the messengers and F (F_S)

- Hierarchy of SUSY particle masses $\longrightarrow$ related to gauge couplings

$m_{\tilde{q}}/m_{\tilde{l}_L} \propto \alpha_3/\alpha_2$

$m_{\tilde{g}} \propto m_{\tilde{q}}$ $\qquad m_{\tilde{W}} \propto m_{\tilde{l}_L}$ $\qquad m_{\tilde{B}} \propto m_{\tilde{l}_R}$

Similar to SUGRA:

$m_{\tilde{g}}/m_{\tilde{W}} \propto \alpha_3/\alpha_2$ and $m_{\tilde{W}}/m_{\tilde{B}} \propto \alpha_2/\alpha_1$

- Special feature $\longrightarrow$ light (gravitino) Goldstino

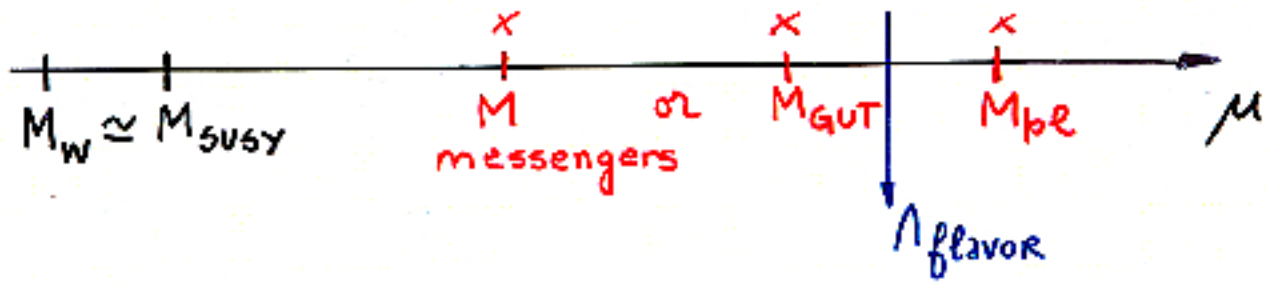
$m_{\tilde{G}} \sim F/M_{Pl} \sim 10^{-14}\ M\ [GeV]$

The Goldstino couples to each SM particle and the corresponding SM superpartner with strength 1/F

• In thinking about soft SUSY param. there are two important issues:

a) Flavor violation restrictions

b) Renormalization group evolution



given the value of soft SUSY param. at the scale of SUSY ($\Lambda = M, M_{GUT}, M_{Pl}$)

$\Longrightarrow$ they evolve down to low energies where they define the SUSY particle spectrum

$$m^2_{\tilde{f}_{SUSY}}(\mu) \simeq -2\, c_i^{\tilde{f}}/b_i \left(\alpha_i^2(\mu) - \alpha_i^2(\Lambda)\right) \frac{M_i^2(\Lambda)}{\alpha_i^2(\Lambda)} + m^2_{\tilde{f}_{SUSY}}(\Lambda) + \text{Yuk. terms}$$

$$M_i(\mu) \simeq \alpha_i(\mu) \frac{M_i(\Lambda)}{\alpha_i(\Lambda)}$$

Gluino Mass

$\longrightarrow$ from soft SUSY term

$$\mathcal{L}_{\tilde{g}} = -M_3 \lambda^a \lambda^a \qquad a = 1-8,\ SU(3) \text{ generators}$$

Squark Masses – 1st & 2nd generation –

- governed by soft SUSY mass param. $m_{U_{1,2}}, m_{D_{1,2}}, m_{Q_{1,}}$
- from $V[A] \longrightarrow |\partial P[A]/\partial \tilde{q}^i|^2,\ |\partial P[A]/\partial \tilde{D}|^2,\ |\partial P[A]/\partial \tilde{u}|^2$

$\langle$ recall $P[A] \rightarrow \epsilon_{ij}[h_d H_1^i \tilde{Q}^j \tilde{D} + h_u H_2^i \tilde{Q}^j \tilde{u}]\rangle$

– gives mass equal to SM quark partner

$\frac{1}{2} D^a D^a$ term $\longrightarrow \begin{cases} D_{\tilde{q}_L} = M_Z^2 \cos 2\beta\,(T_{3q} - Q_q \sin^2\theta_W) \\ D_{\tilde{q}_R} = M_Z^2 \cos 2\beta\, Q_q \sin^2\theta_W \end{cases}$

$$M^2_{\tilde{u}} = \begin{bmatrix} m^2_{Q_{1,2}} + m^2_{up} + D_{\tilde{u}_L} & \simeq 0 \\ \simeq 0 & m^2_{U_{1,2}} + m^2_{up} + D_{\tilde{u}_R} \end{bmatrix}$$

$$M^2_{\tilde{D}} = \begin{bmatrix} m^2_{Q_{1,2}} + m^2_{down} + D_{\tilde{d}_L} & \simeq 0 \\ \simeq 0 & m^2_{D_{1,2}} + m^2_{down} + D_{\tilde{d}_R} \end{bmatrix}$$

$\tilde{u}_{L,R},\ \tilde{c}_{L,R}$

$\tilde{d}_{L,R},\ \tilde{s}_{L,R}$

$\Downarrow$

are $\simeq$ mass eigenstates

$\langle$ small $h_{u,d}$ for 1,2 gen. $\rangle$

Scalar Leptons

two sleptons for each SM lepton

$\tilde{e}_L, \tilde{e}_R \rightarrow$ complex, 2 degrees of freedom each assoc. with left & right-handed 2 comp. spinors $e_R, e_L \rightarrow \psi_e^{Dirac} = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$

SUSY limit $\Rightarrow m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_e$ but $\cancel{\text{SUSY}}$

$$\Rightarrow \begin{pmatrix} \tilde{e}_L^* & \tilde{e}_R^* \end{pmatrix} \begin{pmatrix} m_L^2 + m_e^2 + D_{\tilde{e}_L} & m_e(A_e - \mu \tan\beta) \\ m_e(A_e - \mu\tan\beta) & m_E^2 + m_e^2 + D_{\tilde{e}_R} \end{pmatrix} \begin{pmatrix} \tilde{e}_L \\ \tilde{e}_R \end{pmatrix}$$

$D_{\tilde{e}_{L(R)}} \rightarrow \frac{1}{2} D^a D^a$ terms

$m_e \rightarrow$ from $V[A] \rightarrow |\partial P[A]/\partial \tilde{L}|^2, |\partial P[A]/\partial \tilde{R}|^2$ $\quad \varepsilon_{ij} h_e H_1^i \tilde{L}^j \tilde{R}$

$m_L^2, m_E^2, A_e m_e \rightarrow$ soft $\cancel{\text{SUSY}}$ terms

<u>Mass eigenvalues</u> (neglecting $D^a D^a$ gauge contrib.)

$$m^2_{\tilde{e}_{1,2}} = m_e^2 + \frac{m_L^2 + m_E^2}{2} \pm \frac{1}{2}\sqrt{(m_L^2 - m_E^2)^2 + 4 m_e^2 (A_e - \mu\tan\beta)^2}$$

with
$$\tilde{e}_1 = \tilde{e}_L \cos\theta_{\tilde{e}} + \tilde{e}_R \sin\theta_{\tilde{e}}$$
$$\tilde{e}_2 = -\tilde{e}_L \sin\theta_{\tilde{e}} + \tilde{e}_R \cos\theta_{\tilde{e}}$$

$$\tan 2\theta_{\tilde{e}} = \frac{2 m_e (A_e - \mu\tan\beta)}{m_L^2 - m_E^2}$$

- in general: $\tilde{e}_{L,R}, \tilde{\mu}_{L,R} \simeq$ mass eigenvalues

  $\langle h_e, h_\mu \rightarrow$ small $\rangle$

<u>$\tilde{\tau}$ case instead</u> $\rightarrow$ mixing non-trivial

Scalar Top / Scalar Bottom Sector

up/down mass eigenstates $\longrightarrow$ relevant mixing effects

- $\tilde{t}_R, \tilde{t}_L \longrightarrow$ large mixing due to large Yukawa coupl.

$\Rightarrow$ light mass eigenstate $\tilde{t}_1$ may be the lightest visible spartic

$$M^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_{\tilde{t}_L} & m_t(A_t - \mu/\tan\beta) \\ m_t(A_t - \mu/\tan\beta) & m_U^2 + m_t^2 + D_{\tilde{t}_R} \end{pmatrix} \equiv \begin{pmatrix} m^2_{\tilde{t}_L} & m^2_{\tilde{t}_{LR}} \\ m^2_{\tilde{t}_{LR}} & m^2_{\tilde{t}_R} \end{pmatrix}$$

with
$$D_{\tilde{t}_L} = M_Z^2 \cos 2\beta \,(T_{3_t} - Q_t \sin^2\theta_W)$$
$$D_{\tilde{t}_R} = M_Z^2 \cos 2\beta \; Q_t \sin^2\theta_W$$

$T_{3_t}, Q_t \rightarrow$ isospin / electric charge of top

Hence
$$\tilde{t}_1 = \cos\theta_{\tilde{t}}\, \tilde{t}_L + \sin\theta_{\tilde{t}}\, \tilde{t}_R$$
$$\tilde{t}_2 = -\sin\theta_{\tilde{t}}\, \tilde{t}_L + \cos\theta_{\tilde{t}}\, \tilde{t}_R$$

$$\tan 2\theta_{\tilde{t}} = \frac{2\, m^2_{\tilde{t}_{LR}}}{m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R}}$$

and
$$m^2_{\tilde{t}_{1,2}} = \frac{m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}}{2} \pm \sqrt{\left(\frac{m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R}}{2}\right)^2 + \left|m^2_{\tilde{t}_{LR}}\right|^2}$$

$m_Q, m_U, A_t \longrightarrow$ soft SUSY param. (also m_D, A_b)

- $\tilde{b}_R, \tilde{b}_L$ $\langle$in the large $\tan\beta$ region ($\gtrsim 20$)$\rangle$

$\longrightarrow$ large mixing in sbottom sector possible

$$M^2_{\tilde{b}} = \begin{pmatrix} m_Q^2 + m_{\tilde{b}} + D_{\tilde{b}_L} & m_b(\cancel{A_b} - \mu \tan\beta) \\ m_b(A_b - \mu\tan\beta) & m_D^2 + m_b^2 + D_{\tilde{b}_R} \end{pmatrix}$$

$$m_b = h_b \frac{v_1}{\sqrt{\cos\beta}}$$

Analogously, mass eigenstates $\tilde{b}_1, \tilde{b}_2$ and $m^2_{\tilde{b}_{1,2}}$

Mixing of Charged Gauginos and Higgsinos

- bilinear terms from: $A_k^* \lambda_{kj} \psi_j + h.c$
- superpotential induced: $\mu \, \varepsilon_{ij} H_1^i H_2^j \rightarrow \mu \, \psi_{H_1}^2 \psi_{H_2}^1$
- Soft SUSY: M_i

$\partial P / \partial H_1 H_2$ $\quad \psi_{H_1} \cdot \psi_{H_2}$

Recall $\lambda^\pm = \frac{\lambda^1 \pm i \lambda^2}{\sqrt{2}}$

$$\mathcal{L}_{charginos} = -g \left(v_1 \lambda^+ \psi_{H_1}^2 + v_2 \lambda^- \psi_{H_2}^1 \right) - M_2 \lambda^+ \lambda^- - \mu \, \psi_{H_1}^2 \psi_{H_2}^1 + h.c.$$

defining $\psi_j^+ \rightarrow (\lambda^+, \psi_{H_2}^1)$; $\psi_j^- \rightarrow (\lambda^-, \psi_{H_1}^2)$ $\Longrightarrow$

$$\underline{\underline{\mathcal{L}_{charginos}}} = -\left(\lambda^- \; \psi_{H_1}^2 \right) \underbrace{\begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}}_{\equiv M_{\tilde{\chi}^\pm}} \begin{pmatrix} \lambda^+ \\ \psi_{H_2}^1 \end{pmatrix} + h.c$$

chargino mass matrix diagonalize by two matrices U, V

$$\Longrightarrow M_{\tilde{\chi}^\pm}^{Diag} = V^* M_{\tilde{\chi}^\pm} U$$

mass eigenstates $\longrightarrow \tilde{\chi}_i^+ = U_{ij} \psi_j^+$; $\tilde{\chi}_i^- = V_{ij} \psi_j^-$

$$m^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2} \Big\{ M_2^2 + \mu^2 + 2 M_W^2 \pm \Big[(M_2^2 - \mu^2)^2 + 4 M_W^4 \cos^2 2\beta + 4 M_W^2 (M_2^2 + \mu^2 + 2 M_2 \mu \sin 2\beta) \Big]^{1/2} \Big\}$$

If either μ or M_2 large $\Rightarrow$ pure gaugino, higgsino states

$|\mu| \gg M_Z$ & $M_2 \sim M_Z$ $\Longrightarrow$ $m_{\tilde{\chi}_1^\pm} \sim M_2$ $\quad m_{\tilde{\chi}_2^\pm} \sim |\mu|$

$|\mu| \sim M_Z$ & $M_2 \gg M_Z$ $\Longrightarrow$ $m_{\tilde{\chi}_1^\pm} \sim |\mu|$ $\quad m_{\tilde{\chi}_2^\pm} \sim M_2$

Mixing of Neutral Gauginos and Higgsinos

similar to charged case but $\rightarrow$ four neutral states mixing

$$\mathcal{L}_{neutralinos} = -g/\sqrt{2}\, \lambda^3 \cdot (v_1 \psi^1_{H_1} - v_2 \psi^2_{H_2}) + g'/\sqrt{2}\, \lambda' \cdot (v_1 \psi^1_{H_1} - v_2 \psi^2_{H_2})$$
$$- \frac{M_2}{2} \lambda^3 \cdot \lambda_3 - \frac{M_1}{2} \lambda' \cdot \lambda' + \mu\, \psi^1_{H_1} \cdot \psi^2_{H_2} + h.c.$$

defining $\psi^0_j \rightarrow (\lambda', \lambda^3, \psi^1_{H_1}, \psi^2_{H_2})$

$$\Longrightarrow \mathcal{L}_{neutralinos} \longrightarrow -\tfrac{1}{2} (\psi^0)^T M_{\tilde{\chi}^0} \psi^0 + h.c.$$

$\longrightarrow$ mass matrix:

$$M_{\tilde{\chi}^0} = \begin{bmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{bmatrix}$$

diagonalize by a matrix Z $\longrightarrow$ $M^{Diag}_{\tilde{\chi}^0} = Z^* M_{\tilde{\chi}^0} Z^{-1}$

mass eigenstates $\tilde{\chi}^0_i = Z_{ij}\, \psi^0_j$

For large values of μ or M_2 $\langle M_1 \simeq M_2/2 \rangle$

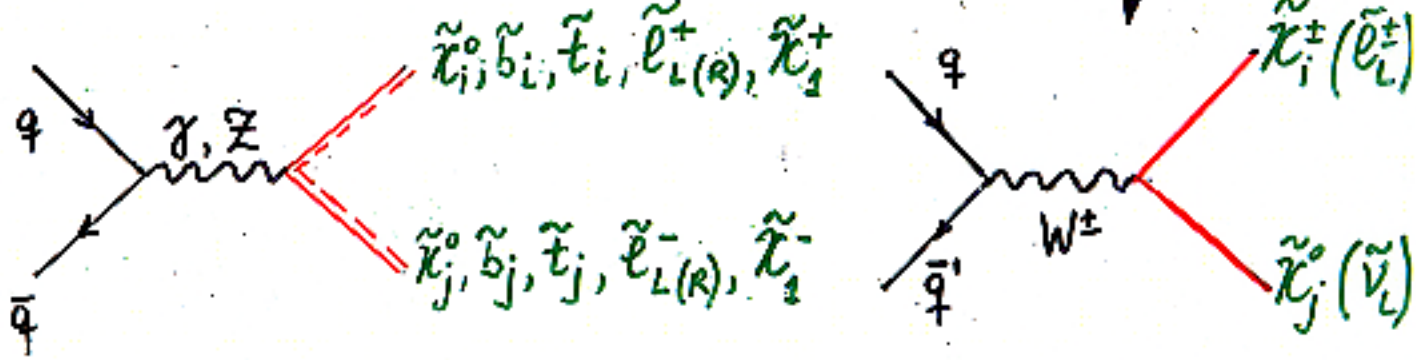
two χ^0s are $\simeq$ pure gauginos and two $\simeq$ pure higgsinos

$|\mu| \gg M_Z$, $M_2 \sim M_Z$ $\Longrightarrow$ $m_{\tilde{\chi}^0_1} \simeq M_1$; $m_{\tilde{\chi}^0_2} \simeq M_2$; $m_{\tilde{\chi}^0_3} \simeq m_{\tilde{\chi}^0_4} \simeq |\mu|$

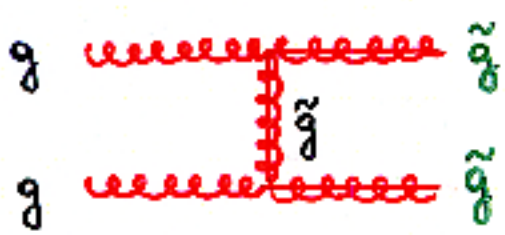
$|\mu| \sim M_Z$, $M_2 \gg M_Z$ $\Longrightarrow$ $m_{\tilde{\chi}^0_1} \simeq m_{\tilde{\chi}^0_2} \simeq |\mu|$; $m_{\tilde{\chi}^0_3} \simeq M_1$; $m_{\tilde{\chi}^0_4} \simeq M_2$

Typical SUSY Production Processes at the Tevatron

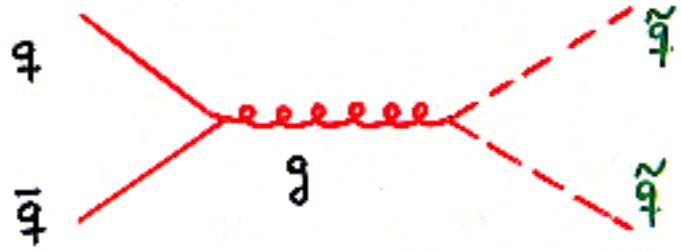
- apart from channels analogous to LEP ($e^+e^- \leftrightarrow q\bar{q}$) with s-channel Z/γ mediation and also



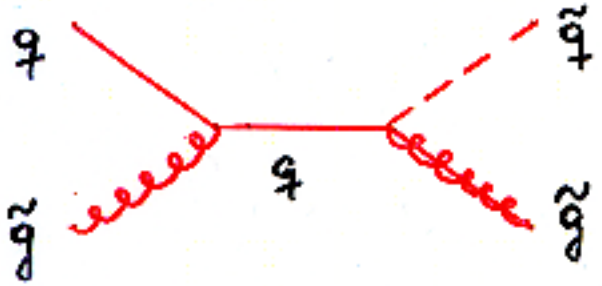
- Strong interaction processes from gluon fusion / $q\bar{q}$ scattering / gluon-quark scatt.

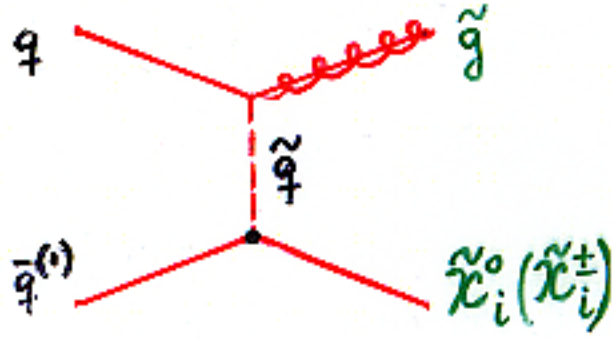


(also $\tilde{q}$'s)



(also $\tilde{g}$'s)





(associated prod.)

SUSY Signatures at the Tevatron

(SUGRA-type)

Production	Key Decay Modes	Signature
$\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, $q\bar{q}'\tilde{\chi}_1^\pm$, $g\tilde{\chi}_1^0$ $\Big\}$ $m_{\tilde{q}} > m_{\tilde{g}}$	$\not{E}_T$ + multijets + (lepton/s)
	$\tilde{q} \to q\tilde{\chi}_i^0$, $\tilde{q} \to q'\tilde{\chi}_i^\pm$ $\Big\}$ $m_{\tilde{g}} > m_{\tilde{q}}$	
$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell\nu$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$	Trilepton + $\not{E}_T$
	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$	Dilepton + $\not{E}_T$ + jets
$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+\nu$	Dilepton + $\not{E}_T$
$\tilde{\chi}_i^0 \tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + X$, $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + X'$	$\not{E}_T$ + (jets) + (lepton)
$\tilde{t}_1 \tilde{t}_1$	$\tilde{t}_1 \to \tilde{\chi}_1^0 c$	$\not{E}_T$ + 2 acollin. jets
	$\tilde{t}_1 \to \tilde{\chi}_1^\pm b$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell^\pm\nu$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$	Single lept. + $\not{E}_T$ + b's
	$\tilde{t}_1 \to \tilde{\chi}_1^\pm b$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell^\pm\nu$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell^\pm\nu$	Dilepton + $\not{E}_T$ + b's
$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}_i^0$, $\tilde{\ell}_L^\pm \to \nu_\ell \tilde{\chi}_L^\pm$	Dilepton + $\not{E}_T$
	$\tilde{\nu} \to \nu \tilde{\chi}_1^0$	Single lept. + $\not{E}_T$ + (jets) ($\not{E}_T$)

Necessary: good parton identification to handle high $\mathcal{L}$

- good lepton (e, μ), $\not{E}_T$ (ν, LSP), b jets, light quarks/gluon jet identification

Three relevant ranges of NLSP decay lengths:

- prompt decays $\Longrightarrow$ particles appear as originating from interaction point

$\Downarrow$

Signature of SUSY pair: 2 hard photons + $\not{E}_T$ from $\tilde{G}$

- macroscopic decay length but within the detector (smoking gun of low energy SUSY)

$\Downarrow$

$\star$ displaced photons (accurate photon pointing);
$\star$ ID of high momentum partons from secondary vertices;
$\star$ high ionizing track (HIT) with a kink to a minimum ionizing track (MIT) or a tau jet

- decay length well outside the detector:

$\Downarrow$

$\star$ if neutralino-like NLSP $\rightarrow$ $\not{E}_T$ like SUGRA
$\star$ if slepton NLSP $\rightarrow$ HIT without much $\not{E}_T$,
time of flight in the search for slow moving leptons.

Stop and Sbottom Searches

In many models (MSUGRA, extended Gauge– and Anomaly–Mediated) $\longrightarrow$ $\tilde{t}$'s and $\tilde{b}$'s quite light

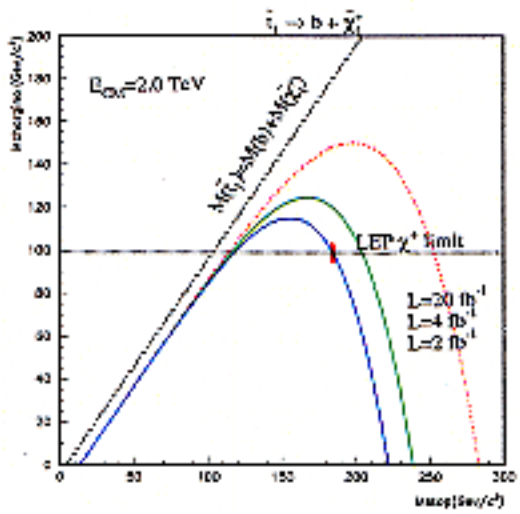
- If $m_{\tilde{t}_1} > m_{\tilde{\chi}_1^\pm} + m_b$ or $> M_W + m_{\tilde{\chi}_1^0} + m_b$
  or $> m_l + m_{\tilde{\nu}} + m_b$ or $> m_{\tilde{l}} + m_\nu + m_b$

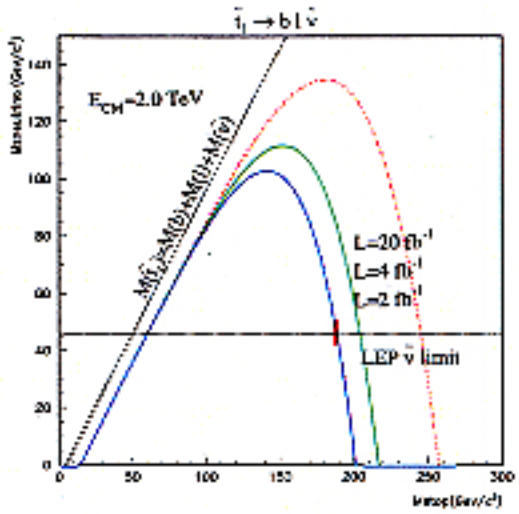
$\Longrightarrow \tilde{t}_1 \to b\tilde{\chi}_1^{\pm(*)} \to b\tilde{\chi}_1^0 f\bar{f}'$ with $f\bar{f}' = l\bar{\nu}$ or $q\bar{q}'$

Signals: 2b jets + 2 W's + $\not\!\!E_T$, 2b jets + 2l's + $\not\!\!E_T$

$\Downarrow$

Selection: b-jet + jet + l + $\not\!\!E_T$, 2l's + jet + $\not\!\!E_T$



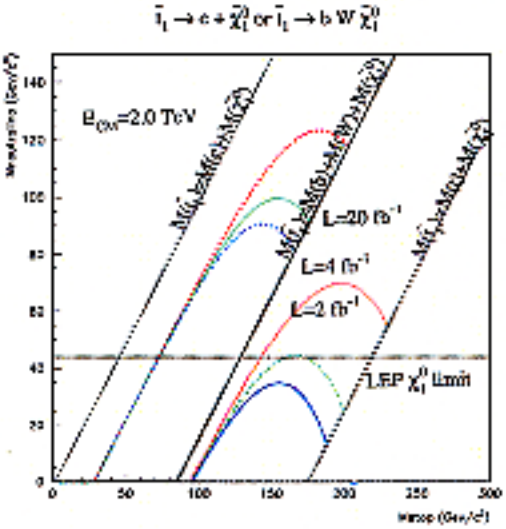


- If the above modes not kinematically allowed

$\tilde{t}_1 \to c\tilde{\chi}_1^0$

(via $b\tilde{\chi}_1^{\pm}$ loop)

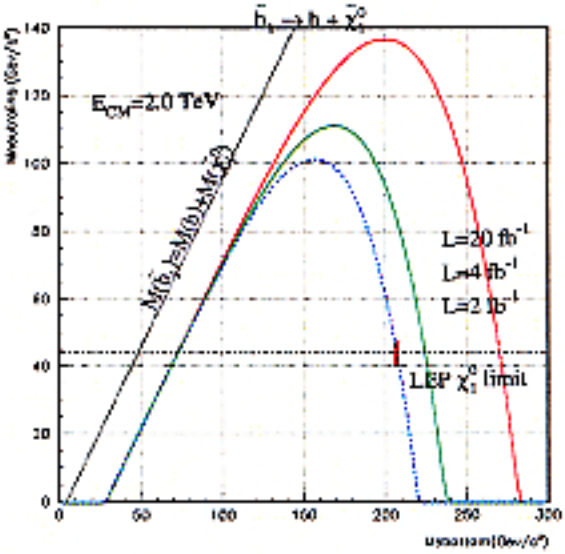
Signal/Selection:
2c jets + $\not{E}_T$



- Sbottoms:

$\Longrightarrow \tilde{b}_1 \to b\tilde{\chi}_1^0$

100 % BR
if $m_{\tilde{\chi}_2^0} > m_{\tilde{b}} - m_b$



if $\tilde{b} \to b\tilde{\chi}_2^0$ allowed, limit degraded in 30-40 GeV

In summary:

Robust studies from Theoretical/experimental collab. at the Higgs/SUSY Workshop to define Tevatron reach for stops and sbottoms

With $\int \mathcal{L}dt = 2\ (20)\ \mathrm{fb}^{-1}$

$m_{\tilde{t}_1} \leq 185/190\ (260/250)$ GeV	in $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}/\tilde{t}_1 \to bl\tilde{\nu}$
$m_{\tilde{t}_1} \leq 160\ (200)$ GeV	in $\tilde{t}_1 \to c\tilde{\chi}_1^0$
$m_{\tilde{b}_1} \leq 210\ (270)$ GeV	in $\tilde{b}_1 \to b\tilde{\chi}_1^0$

Interesting: light right-handed stops $m_{\tilde{t}_R} \sim 150$ GeV + MSSM Higgs $m_h \sim$ 100-115 GeV

→ 118 GeV if $m_Q \sim 2$ TeV

$\Longrightarrow$ compatible with ELW Baryogenesis Mechanism with proper generation of Baryon asymmetry for CPV phases compatible with EDM constraints

Tevatron Run2 reach for Higgs and stops
$\Longrightarrow$ probe Baryogenesis at the Electroweak scale !

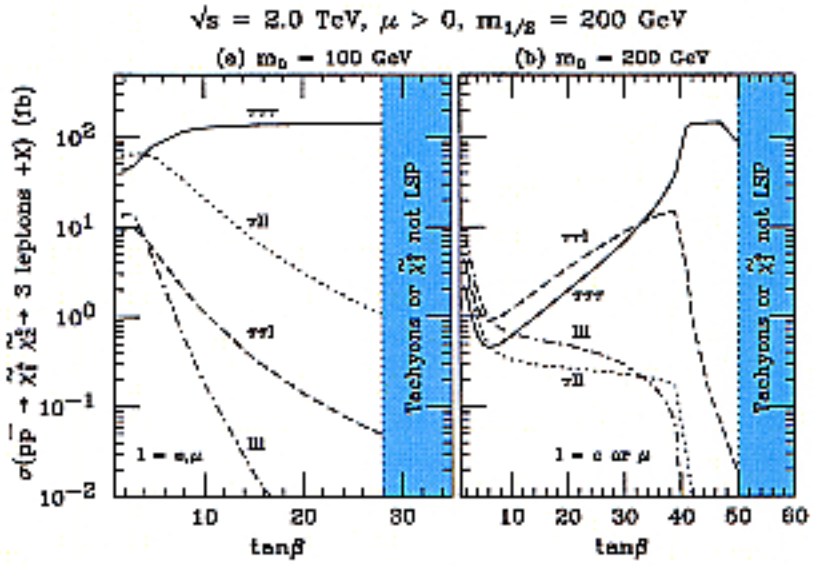
SUGRA Trilepton Mode and SUSY Signatures with Taus at the Tevatron

- Golden channel at the Tevatron

$p\bar{p} \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3l + \not{E}_T \qquad l = e, \mu$

- worst case scenario:

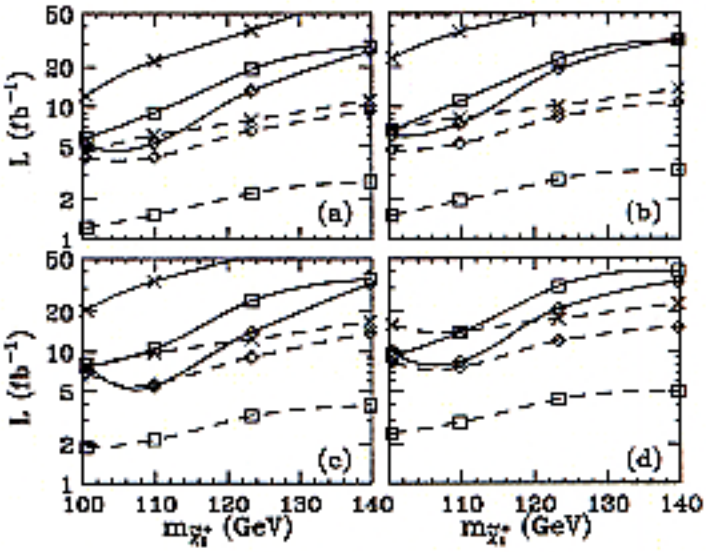
in many models (SUGRA, Gauge mediated):
staus are light ($m_{\tilde{\tau}} < m_{\tilde{\chi}_1^{\pm}}$ or $m_{\tilde{\chi}_2^0}$)
$\Longrightarrow$ golden mode becomes ineffective.
Instead, a lot of τ's



The leptonic tau decays are soft $\Longrightarrow$ harder to identify and cuts need to be re-optimized
Background processes (W^*Z^*, $W^*\gamma^*$) previously unaccounted for are big –need to be cut optimized–
With soft but realistic p_T accep. cuts
$\Longrightarrow$ tau modes contribute importantly

• Light $\tilde{\tau}$ and direct detection of τ's via their hadronic decays

total integrated luminosity needed for a 3 σ (solid) and a 5 σ (dashed) for trileptons (x) and dileptons (□), like-sign dileptons (◇) plus a tau jet



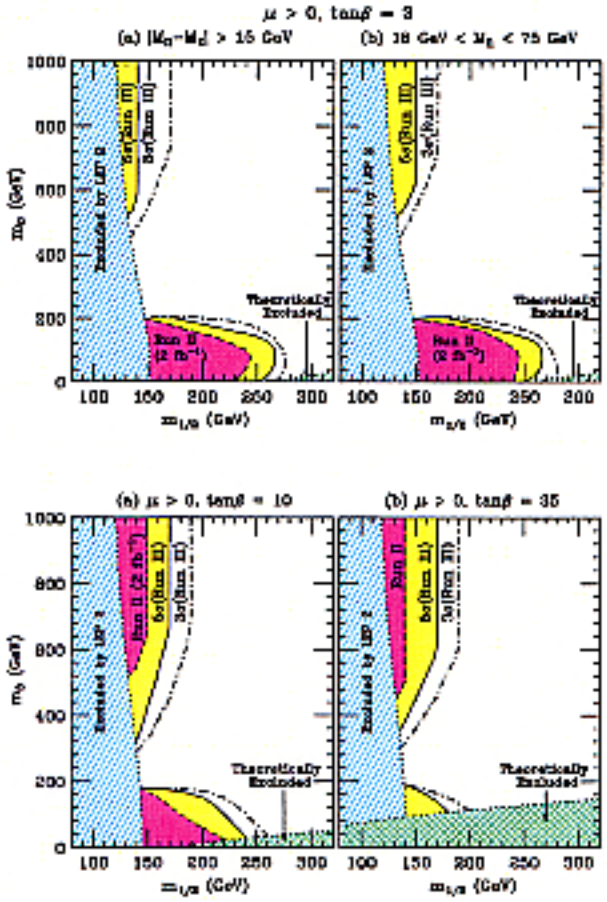
➖ Comparison of trilepton mode with dileptons plus tau jet and like-sign dileptons plus a tau jet

⟶ shows good sensitivity in tau jet channels

(better study of tau trigger eff. needed)

RUN 2 Potential in the mode:
$p\bar{p} \to$ SUSYparticles $\to 3l + X$

(SUSY/Higgs SUGRA report)



- low $\tan\beta \to M_{1/2}$ as high as 250 GeV
- large $\tan\beta \to M_{1/2}$ as high as 140–180 GeV

this includes leptonic tau channels

$m_{\tilde{\chi}_1^\pm} \sim 110$ to 200 GeV $\qquad M_{\tilde{g}} \sim 400$ to 600 GeV

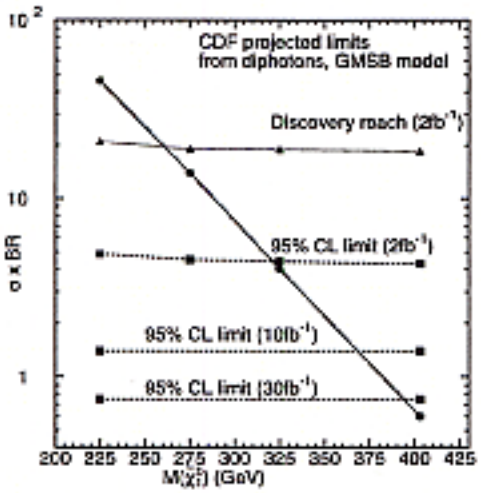
Gauge-mediated diphoton Tevatron reach

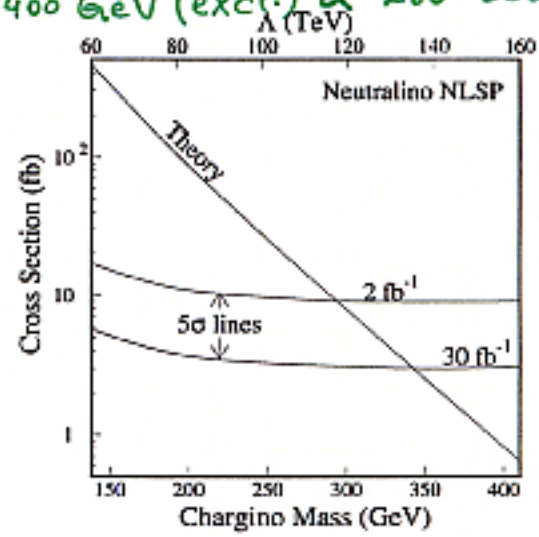
SUSY/Higgs Gauge Mediation Report

- Bino-like NLSP: $\tilde{\chi}_1^0 \to \gamma \tilde{G}$ Signal: $\gamma\gamma X \not{E}_T$ $X = \ell$'s, jets

- Prompt decay

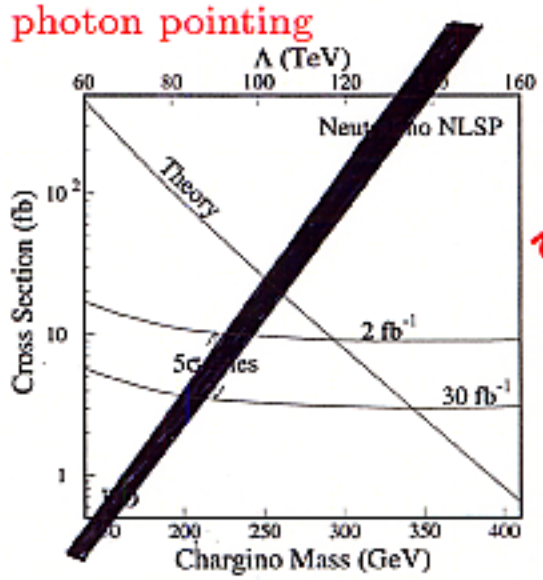
$m_{\tilde{\chi}^\pm} \sim 300-400$ GeV (excl.) & 280-350 (5σ disc)





- Non-prompt decays and photon pointing

it is possible to identify a displaced photon from a secondary vertex and possibly det. decay length using TOF



DØ

$\gamma' jj \not{E}_T$

⇓

$m_{\tilde{\chi}^\pm} \sim 200$ 300 GeV

if $\tau_c \sim$ 500-50 cm

5σ disc. if 2-30 fb⁻¹

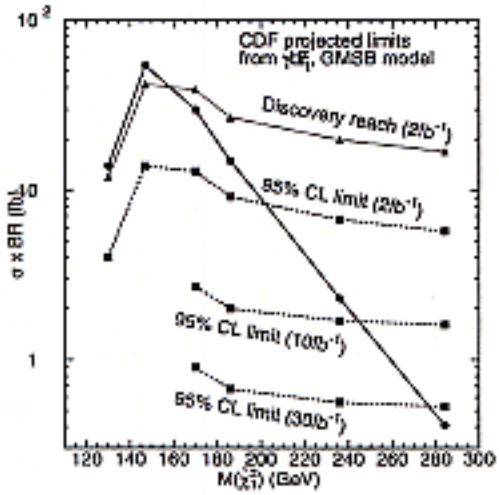
Meas. of decay length → meas. of SUSY breaking scale

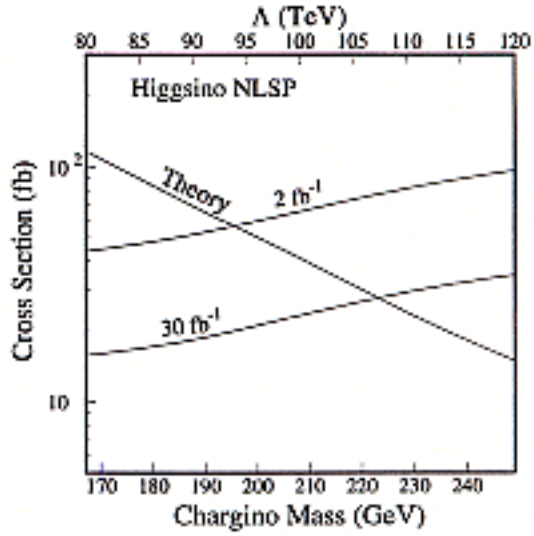
▬ Higgsino-like NLSP:

$\tilde{\chi}_1^0 \to (h, Z, \gamma)\tilde{G}$ Signal: $(hh, h\gamma, hZ, Z\gamma, ZZ, \gamma\gamma)X\not{E}_T$

Diboson Signatures (Z → ll/jj; h → bb)$\not{E}_T$ X = l's jets

- Prompt decays: γ b $\not{E}_T$X channel





$\longrightarrow m_{\tilde{\chi}_1^\pm}$ up to **200**, 250, 280 GeV if 2, 10, 30 fb^{-1} 95% C.L.

bb $\not{E}_T$X channel → less sensitivity; Z leptonic decay → useful

- Non-promt decays (few 100 TeV $\leq \sqrt{F} \leq$ few 1000 TeV)

$\Longrightarrow$ displaced photons or secondary vertices from bb, jj, ll

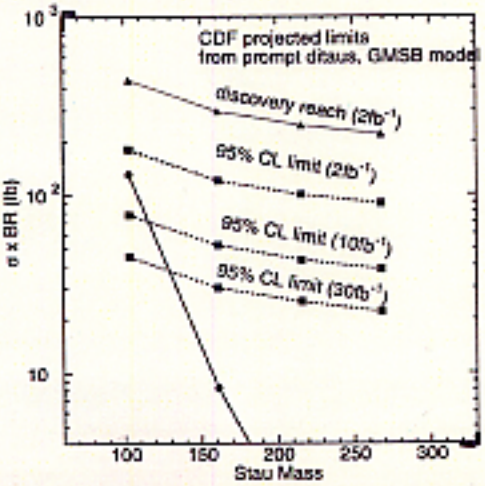
Search for displaced Z bosons using large E_T displaced jet with finite impact parameter or diplaced leptons should be explored.

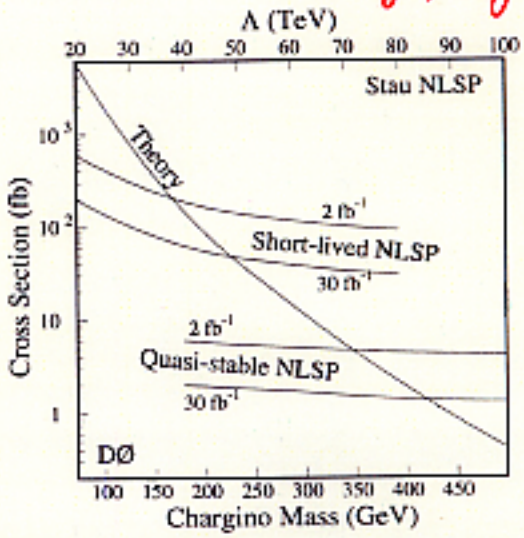
- If $\sqrt{F} \geq$ few 1000 TeV $\Longrightarrow$ outside detector decay looks like traditional $\tilde{\chi}_1^0$ LSP

– Stau NLSP: $\tilde{\tau}_1 \to \tau \tilde{G}$

• prompt decays: Signal: 2 high p_T τ's + high $\not{E}_T$

< leptonic or hadronic decays, high p_T l's/je





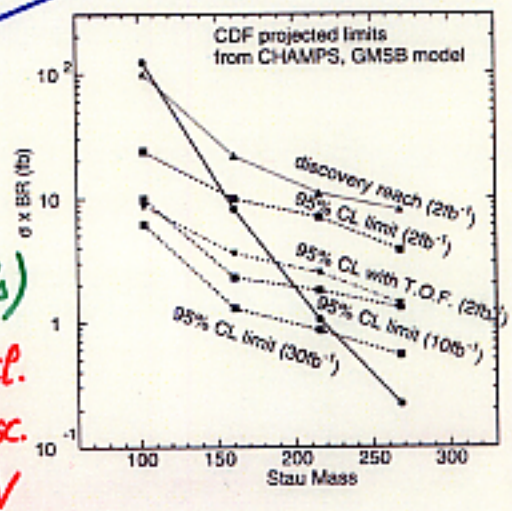
DF: $m_{\tilde{\tau}} \to 100-130$ GeV (95% C.L) if $\mathcal{L} \sim 2-30\ fb^{-1}$

improv. if direct trigger on τ's

DØ: $m_{\tilde{\tau}} \to 80-120$ GeV 5σ disc. if $2-30\ fb^{-1}$

$m_{\tilde{\tau}} \sim 175-220$ GeV ($2-30\ fb^{-1}$) disc.

• Quasi stable $\tilde{\tau}$'s



Signal: HIT's or excess of fake muons (MIT's)

DF: $2\ fb^{-1} \Rightarrow m_{\tilde{\tau}} \sim 150$ GeV excl. ~ 110 GeV disc.

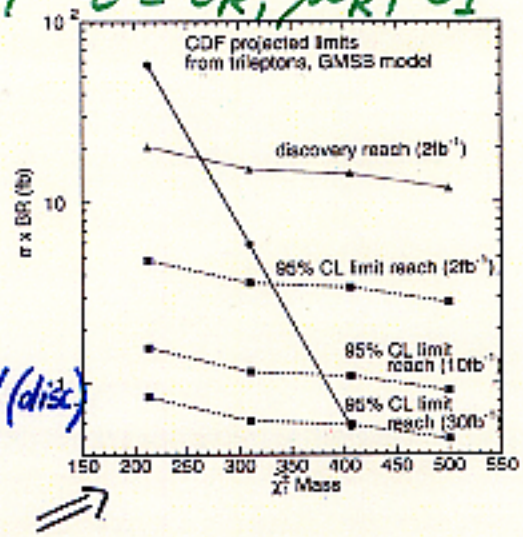
5% C.L. ad. $m_{\tilde{\tau}} \to 200-225$ GeV if $10-30\ fb^{-1}$ (one detector)

– Slepton CO-NLSP:

similar to $\tilde{\tau}$ NLSP but lepton Democracy

if sleptons lighter than other MSSM partners

$\Rightarrow \tilde{\ell} \to \ell \tilde{G}$ with $\tilde{\ell} = \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1$



- **prompt decays**

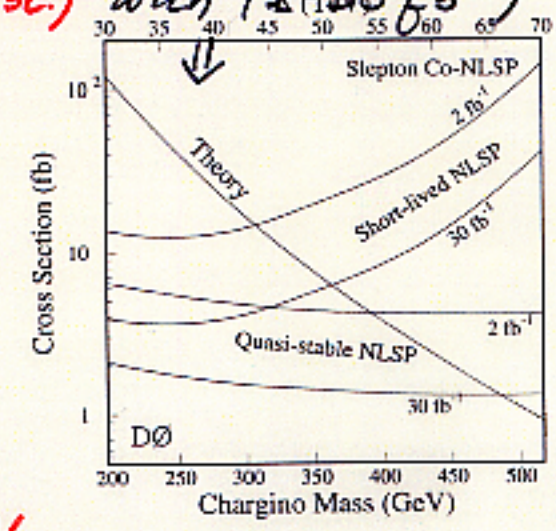
rich in high p_T ℓ's & τ's + $\not{E}_T$

CDF:

$m_{\tilde{\ell}} \to$ 140 GeV (excl.), 120 GeV (disc.) with 2 fb^{-1}

$m_{\tilde{\ell}} \to$ 160-180 GeV (excl.) with 10-30 fb^{-1}

DØ: $m_{\tilde{\ell}} \sim$ 145-160 GeV (disc.) with (2-30 fb^{-1})



- **quasi stable $\tilde{\ell}$'s**

Signal: HIT's
excess of muons
anomalous ToF

DØ: $m_{\tilde{\ell}} \to$ 175-200 GeV disc. with 2-30 fb^{-1} (one detector)

R- parity Violating Scenarios

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

- if R-parity conserved $\Longrightarrow$ large $E\!\!\!/_T$ signature
- if R-parity violating processes allowed
  - ~~Lepton~~ or ~~Baryon~~ processes
  - single sparticle production.
  - LSP $\longrightarrow$ no longer stable $\longrightarrow$ decay to SM particles within the detector
    - may be charged/colored

- strong limits on $\not{R}$ couplings from various processes, but, still open possibilities

$\not{L}$ $\longrightarrow$ enhanced multilepton signatures
$\langle$CDF $\longrightarrow$ like sign electrons + jets$\rangle$

$\not{B}$ $\longrightarrow$ multijets signals $\longrightarrow$ 6 jets from $\tilde{\chi}$ pair prod.

- New resonant and non resonant production mechanism & decay processes

Challenge: identify $\not{R}$ signature as such

Overview

Tevatron Run 2 $\Longrightarrow$ very rich and broad physics potential

- Starting from the first few hundred pb^{-1}:

- B Physics: CP Violation
  $\Longrightarrow \sin(2\beta_{\psi K}) \rightarrow$ tests new physics

- With increasing integrated Luminosity (≥ 2 fb^{-1}):

- precise meas. of M_t & M_W
  $\Longrightarrow$ indirect meas. of m_H

- *Furthermore*, search for new physics via top physics.

- SUSY particle Searches:

$m_{\tilde{t}} \sim 160 - 200$ GeV, $m_{\tilde{b}} \sim 200 - 270$ GeV,
$m_{\tilde{\chi}^{\pm}} \sim 100 - 200$ GeV, $m_{\tilde{g}} \sim 400 - 600$ GeV

test many different scenarios

- Search for Exotic Physics and Extra Dimensions

- Maximal demand on total integrated luminosity and detectors performance:

- Higgs Physics:

SM $\Longrightarrow$ test Higgs mass region preferred by precision data
Probe MSSM through its Higgs sector

High integrated Luminosity $\Longrightarrow$ ≥ 15 fb^{-1}
top priority for Higgs search at the Tevatron.