united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR.1317 - 12

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

PHENOMENOLOGY OF SUPERSYMMETRY

Lecture V

H. HABER
Department of Physics
University of California at Santa Cruz
Santa Cruz, CA 95064, USA

Please note: These are preliminary notes intended for internal distribution only.

VIII. CONSTRAINING THE MSSM

The MSSM parameter count

Sutter, Dimopoulos

In the previous lecture, we constructed the MSSM. But to simplify the presentation, flavor degrees of freedom were suppressed.

Now, it is time to review the full set of parameters of the MSSM, given three generations of quarks and leptons. [Generation labels: $i, j, k = 1,2,3$]

Slight change of notation.

$\hat{H}_1 \longrightarrow \hat{H}_D$ 　the subscript indicates which right-handed quark superfield couples to $\hat{H}_1$ and $\hat{H}_2$.

$\hat{H}_2 \longrightarrow \hat{H}_U$

$m_{12}^2 = B\mu$ 　the "B-term"

Remark on the Fayet-Iliopoulos term

Since the MSSM gauge group contains a $U(1)$ factor, I could introduce an associated Fayet-Iliopoulos term (and parameter ξ). I choose to omit this term. Presumably, it does not arise if $SU(3)\times SU(2)\times U(1)$ is the broken subgroup of some non-abelian grand unified group.

There exists a non-renormalization theorem that states that if $\mathrm{Tr}\, T^a = 0$, then by setting $\xi = 0$ at tree level, it remains zero to all orders in perturbation theory. (Conversely, if $\mathrm{Tr}\, T^a \neq 0$, there is only one renormalization at one-loop order. But it is quadratically divergent!)

Parameters of the MSSM

SUSY-conserving sector

$g_1,\ g_2,\ g_3,\ \theta_{QCD}$

$\mu\,\hat{H}_D\hat{H}_U$

$h^{\ell}_{jk}\,\hat{H}_D\hat{L}_j\hat{E}_k$

$h^{D}_{jk}\,\hat{H}_D\hat{Q}_j\hat{D}_k$

$h^{U}_{jk}\,\hat{H}_U\hat{Q}_j\hat{U}_k$

SUSY-breaking sector

$B\mu\,H_DH_U$

$(h^{\ell}A^{\ell})_{jk}\,H_D\tilde{L}_j\tilde{E}_k$

$(h^{D}A^{D})_{jk}\,H_D\tilde{Q}_j\tilde{D}_k$

$(h^{U}A^{U})_{jk}\,H_U\tilde{Q}_j\tilde{U}_k$

$M_D^2\,H_D^{\dagger}H_D + M_U^2\,H_U^{\dagger}H_U$

$(M^2_{\tilde{Q}})_{ij}\,\tilde{Q}_i^{\dagger}\tilde{Q}_j + (M^2_{\tilde{L}})_{ij}\,\tilde{L}_i^{\dagger}\tilde{L}_j$

$(M^2_{\tilde{D}})_{ij}\,\tilde{D}_i^{\dagger}\tilde{D}_j + (M^2_{\tilde{U}})_{ij}\,\tilde{U}_i^{\dagger}\tilde{U}_j + (M^2_{\tilde{E}})_{ij}\,\tilde{E}_i^{\dagger}\tilde{E}_j$

$M_1\,\widetilde{B}\widetilde{B} + M_2\,\widetilde{W}^a\widetilde{W}^2 + M_3\,\widetilde{g}\widetilde{g}$

To see how to count parameters, let us first consider the Standard Model. Its parameters are:

$g_1, g_2, g_3,\ \theta_{QCD}$	$3+1$	θ_{QCD} can be regarded as the imaginary part of the strong coupling constant.
Higgs sector: v^2, λ	2	
$V_{Higgs} = \lambda(\phi^2 - v^2)^2$		
Yukawas: h_u, h_d, h_e	$\underbrace{27}_{\text{real}} + \underbrace{27}_{\text{imaginary}}$	

Here we have used the fact that h is a 3×3 complex matrix with no special properties.

But, most of these degrees of freedom are unphysical.
In the limit of $h_u = h_d = h_e = 0$, the Standard Model possesses an exact $U(3)^5$ global symmetry corresponding to three generations of the five $SU(3)\times SU(2)\times U(1)$ multiplets:

$$(\nu, e^-)_L\ ,\ e^+_L\ ,\ (u,d)_L\ ,\ u_L^c\ ,\ d_L^c$$

Note that by gauge invariance, I must rotate each multiplet by a unique global symmetry rotation.
So, $U(3)^5$ rotations leave the total $\mathcal{L}$ invariant if $h_u = h_d = h_e = 0$.
If h_u, h_d and h_e are non-zero, the $U(3)^5$ rotation does not leave $\mathcal{L}$ invariant. In particular, the Yukawa terms of the Lagrangian would shift. But I can also view the $U(3)^5$ rotation as a field-redefinition, which does not alter the physical predictions of the theory.
Thus, I can use these rotations to remove unphysical degrees of freedom from the parameters.

How many degrees of freedom can be removed?

answer: the number of parameters that define the $U(3)^5$ rotation minus the number of parameters of any subgroup of $U(3)^5$ that does leave $\mathcal{L}$ invariant (since the latter has no effect on the parameters).

$U(3)$ is parameterized by 3 angles and 6 phases

$U(3)^5$ is parameterized by 15 angles and 30 phases

Four global symmetries that live inside $U(3)^5$ leave $\mathcal{L}$ invariant. These are B and the three separate lepton numbers L_e, L_μ, L_τ (remember that ν is massless in the Standard Model). These are $U(1)$-phase rotations.

Thus, we started with

$$32 \text{ real} + 28 \text{ phases}$$

Using $U(1)^5 - B - L_e - L_\mu - L_\tau$, we can remove

$$15 \text{ real} + 26 \text{ phases}$$

What remains are 17 real parameters and 2 phases*
for a total of 19 Standard Model parameters.

* one of which is θ_{QCD}.

In fact, we can explicitly identify them:

$g_1, g_2, g_3, \theta_{QCD}, m_H, m_Z$, 6 quark masses, 3 lepton masses, 3 CKM mixing angles and 1 CKM phase,

for a total of 19 parameters. ✓

The MSSM count

	real + imaginary
$g_1, g_2, g_3, \theta_{QCD}$	$3 + 1$
gaugino masses M_1, M_2, M_3	$3 + 3$
$m_{H_U}^2, m_{H_D}^2$	2
B, μ	$2 + 2$
h_U, h_D, h_E	$27 + 27$
A_U, A_D, A_E	$27 + 27$
$M_{\tilde{Q}}^2, M_{\tilde{U}}^2, M_{\tilde{D}}^2, M_{\tilde{L}}^2, M_{\tilde{E}}^2$	$30 + 15$
	$94 + 75$

equivalently: v_U and v_D OR v and $\tan\beta$

note: a 3×3 hermitian matrix contains 6 real parameters and 3 imaginary parameters.

Removing unphysical degrees of freedom

This time, I apply the $U(3)^5$-rotation to the five $SU(3)\times SU(2)\times U(1)$ supermultiplets:

$$\hat{L}, \hat{E}, \hat{Q}, \hat{U}, \hat{D}$$

In this way, I protect supersymmetric interactions such as $A^* \psi \lambda + h.c.$, since I am rotating simultaneously the partners and superpartners.

Among the $U(3)^5$-rotations, only B and L leave $\mathcal{L}_{MSSM}$ invariant. Note that L_e, L_μ, and L_τ are not separately conserved, assuming that sneutrinos are not mass-degenerate. We can introduce CKM-like rotations in the slepton sector which need not align with the corresponding definitions of L_e, L_μ, L_τ.

Using $U(3)^5 - B - L$, we can remove

15 real + 28 phases.

There are two other global symmetries that we can use to remove degrees of freedom. They correspond, respectively, to global chiral symmetries that protect gaugino and higgsino masses while leaving $\lambda \Psi A^* + h.c$ interactions and $\mu \hat{H}_U \hat{H}_D$ invariant. Consider these $U(1)$ transformations

PQ = Peccei-Quinn

	$U(1)_R$	$U(1)_{PQ}$
$\tilde{Q}, \tilde{U}, \tilde{D}, \tilde{L}, \tilde{E}$	$1/2$	1
H_D, H_U	1	-2
h_u, h_d, h_e	0	0
A_U, A_D, A_E	-2	0
M_1, M_2, M_3	-2	0
μ	0	4
$m_{12}^2 = B\mu$	-2	4
gauge bosons	0	0
gauginos	1	0

Here, I pretended that the parameters also rotate under the $U(1)$ transformation, and chose the corresponding $U(1)$ quantum numbers that make $\mathcal{L}$ invariant. Of course, the parameters do <u>not</u> rotate, so if they have a non-zero entry above, this means that the parameter shifts under the $U(1)$-rotation, and the latter can be used to remove unphysical degrees of freedom.

We therefore use $U(1)_R$ to remove a phase from M_3, and we use $U(1)_{PQ}$ to remove a phase from $m_{12}^2 = B\mu$.

In fact, we have implicitly performed this last step, when we studied the Higgs sector and noticed that we could redefine the phases of the Higgs fields such that m_{12}^2 was real and $v_1, v_2 > 0$.

<u>Note:</u> As a result, the tree-level MSSM Higgs sector is automatically CP-conserving.

The final count

	real	imaginary
original count	94	75
remove with $U(3)^5 - B - L$	−15	−28
remove with $U(1)_R \times U(1)_{PQ}$		−2
	79	45

TOTAL 124

I call this theory MSSM-124.

The Breakdown

18 Standard Model parameters (include v^2 but not λ)
2 Higgs-sector parameters (m_A, $\tan\beta$)
104 SUSY-parameters

124

real parameters		phases	
6	quark masses	1	CKM phase
3	lepton masses	40	super-CKM phases
12	squark masses ($\tilde{q}_L, \tilde{q}_R \times 6$ flavors)	1	θ_{QCD}
9	slepton masses (no $\tilde{\nu}_R$ here)	3	$\arg M_1$, $\arg M_2$, $\arg \mu$
3	CKM angles	45	
36	super-CKM angles		
7	$\lvert M_1\rvert, \lvert M_2\rvert, M_3, B\mu, m^2_{H_U}, m^2_{H_D}, \lvert\mu\rvert$		
3	g_1, g_2, g_3		
79			

Note in particular 36 super-CKM angles and 40 super-CKM phases. These arise since squarks and sleptons need not be diagonal in the basis in which quarks and leptons are diagonal.

Unconstrained Low-Energy SUSY is not Viable

- No conservation of lepton numbers L_e, L_μ and L_τ
- Unsuppressed flavor-changing neutral-currents
- New sources of CP-violation in conflict with experimental constraints

The MSSM is a phenomenologically viable theory only in tiny "exceptional" regions of the full parameter space. That is, there needs to be many *a priori* unexplained small (soft-SUSY-breaking) parameters in the model.

In the bottom-up approach, one attempts to assess the viable parameter regimes and deduce implications for the fundamental theory of SUSY-breaking.

In the top-down approach, one looks for simple theories of SUSY-breaking that yield acceptable low-energy SUSY parameters.

Examples of the bottom-up approach

Place constraints directly on the ("low-energy") MSSM parameters. Two alternatives are:

1. Horizontal universality

Take $M^2_{\tilde{Q}}, M^2_{\tilde{U}}, M^2_{\tilde{D}}, M^2_{\tilde{L}}, M^2_{\tilde{E}}$ and the associated matrix A-parameters to be proportional to $I_{3\times 3}$.

2. Flavor alignment

Take $M^2_{\tilde{Q}}, M^2_{\tilde{U}}, M^2_{\tilde{D}}, M^2_{\tilde{L}}, M^2_{\tilde{E}}$ are the associated matrix A-parameters to be flavor diagonal in a basis where the quark and lepton mass matrices are flavor diagonal

These alternatives are phenomenologically viable, but rather ad-hoc from a theoretical perspective.

The top-down approach

The MSSM parameters evolve with energy scale according to renormalization group equations (RGE's). Impose a particular (simple) structure on the soft-SUSY-breaking terms at a common high energy scale (e.g. M_{PL}).
The initial conditions depend on the theory of supersymmetry breaking. Then, using RG-evolution, one can compute the low-energy SUSY spectrum.

possible bonus: radiative electroweak symmetry breaking

Evolution of SUSY parameters – the SUSY RGE's

notation:

$$a_t = h_t A_t$$
$$a_b = h_b A_b$$
$$a_\tau = h_\tau A_\tau$$
$$b = B\mu$$

$$X_t = 2h_t^2(m_{H_u}^2 + m_{Q_3}^2 + m_{U_3}^2) + 2a_t^2$$
$$X_b = 2h_b^2(m_{H_d}^2 + m_{Q_3}^2 + m_{D_3}^2) + 2a_b^2$$
$$X_\tau = 2h_\tau^2(m_{H_d}^2 + m_{L_3}^2 + m_{E_3}^2) + 2a_\tau^2$$

$$\frac{d}{dt} = \mu \frac{d}{d\mu} \qquad \mu = \text{evolution scale}$$

Keeping just the 3$^{\text{RD}}$ generation Yukawas, and assuming all parameters real, $g_1^2 = \frac{5}{3} g'^2$

$$\frac{dh_t}{dt} = \frac{h_t}{16\pi^2}\left[6h_t^2 + h_b^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right]$$

$$\frac{dh_b}{dt} = \frac{h_b}{16\pi^2}\left[6h_b^2 + h_t^2 + h_\tau^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2\right]$$

$$\frac{dh_\tau}{dt} = \frac{h_\tau}{16\pi^2}\left[4h_\tau^2 + 3h_b^2 - 3g_2^2 - \frac{9}{5}g_1^2\right]$$

$$\frac{d\mu}{dt} = \frac{\mu}{16\pi^2}\left[3h_t^2 + 3h_b^2 + h_\tau^2 - 3g_2^2 - \frac{3}{5}g_1^2\right]$$

μ = supersymmetric Higgs mass parameter.

$$\frac{d}{dt} M_a = \frac{b_a g_a^2 M_a}{8\pi^2}$$

$b_a = \left(\frac{33}{5}, 1, -3\right)$

M_a = gaugino mass $a = 1, 2, 3$

$$\frac{d}{dt} g_a = \frac{b_a g_a^3}{16\pi^2}$$

Thus, $\frac{d}{dt}\left(\frac{M_a}{g_a^2}\right) = 0$ [at one-loop only]

In grand unified models, both g_a and M_a unify at the grand unification scale, M_X. That is,

$$g_a(M_X) = g_U$$
$$M_a(M_X) = M_U$$

Then,

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} \quad \text{at any scale.}$$

e.g.

$$M_3 = \frac{g_3^2}{g_2^2} M_2 \simeq 3.5 M_2$$ gluino mass

$$M_1 = \frac{5}{3}\frac{g'^2}{g_2^2} M_2 \simeq 0.5 M_2$$ bino mass (often the lightest SUSY particle)

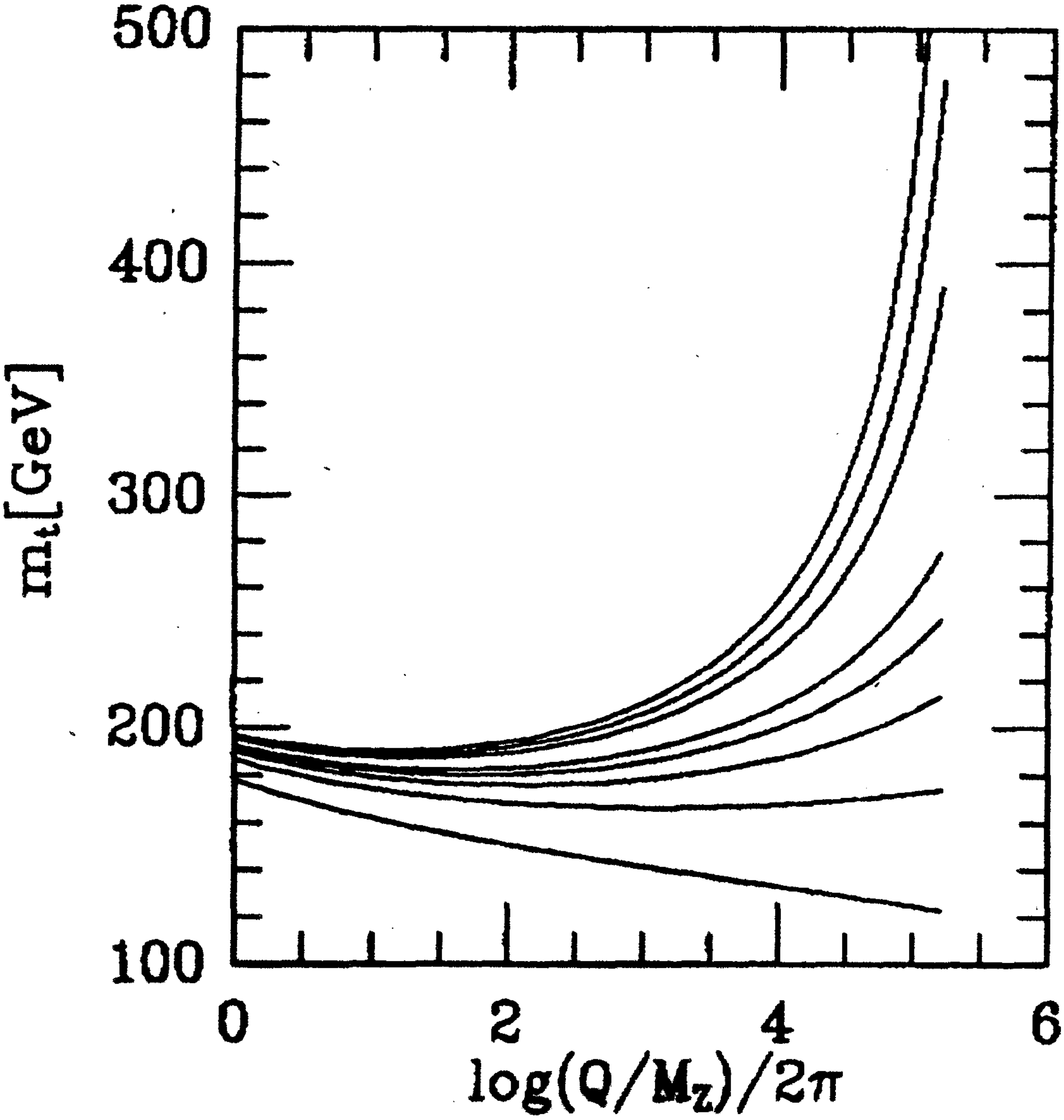


Fig. 1

$$16\pi^2 \frac{da_t}{dt} = a_t\left[18h_t^2 + h_b^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right] + 2a_b h_b h_t + h_t\left[\frac{32}{3}g_3^2 M_3 + 6g_2^2 M_2 + \frac{26}{15}g_1^2 M_1\right]$$

$$16\pi^2 \frac{da_b}{dt} = a_b\left[18h_b^2 + h_t^2 + h_\tau^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2\right] + 2a_t h_b h_t + 2a_\tau h_\tau h_b + h_b\left[\frac{32}{3}g_3^2 M_3 + 6g_2^2 M_2 + \frac{14}{15}g_1^2 M_1\right]$$

$$16\pi^2 \frac{da_\tau}{dt} = a_\tau\left[12h_\tau^2 + 3h_b^2 - 3g_2^2 - \frac{9}{5}g_1^2\right] + 6a_b h_b h_\tau + h_\tau\left[6g_2^2 M_2 + \frac{18}{5}g_1^2 M_1\right]$$

$$16\pi^2 \frac{db}{dt} = b\left[3h_t^2 + 3h_b^2 + h_\tau^2 - 3g_2^2 - \frac{3}{5}g_1^2\right] + \mu\left[6a_t h_t + 6a_b h_b + 2a_\tau h_\tau + 6g_2^2 M_2 + \frac{6}{5}g_1^2 M_1\right]$$

$$16\pi^2 \frac{dm_{Q_3}^2}{dt} = Y_t + Y_b - \frac{32}{3}g_3^2 M_3^2 - 6g_2^2 M_2^2 - \frac{2}{15}g_1^2 M_1^2$$

$$16\pi^2 \frac{dm_{U_3}^2}{dt} = 2Y_t - \frac{32}{3}g_3^2 M_3^2 - \frac{32}{15}g_1^2 M_1^2$$

$$16\pi^2 \frac{dm_{D_3}^2}{dt} = 2Y_b - \frac{32}{3}g_3^2 M_3^2 - \frac{8}{15}g_1^2 M_1^2$$

$$16\pi^2 \frac{dm_{L_3}^2}{dt} = Y_\tau - 6g_2^2 M_2^2 - \frac{6}{5}g_1^2 M_1^2$$

$$16\pi^2 \frac{dm_{E_3}^2}{dt} = 2Y_t - \frac{24}{5}g_1^2 M_1^2$$

For the first two generations, the soft-SUSY-breaking squared-masses obey

$$16\pi^2 \frac{d}{dt} m_\phi^2 = -\sum_a 8 g_a^2 C_a^\phi M_a^2$$

where:

$$C_3^\phi = \begin{cases} 4/3 & \text{for } \phi = \tilde{Q}, \tilde{U}, \tilde{D} \\ 0 & \text{for } \phi = \tilde{L}, \tilde{E}, H_U, H_D \end{cases}$$

$$C_2^\phi = \begin{cases} 3/4 & \text{for } \phi = \tilde{Q}, \tilde{L}, H_U, H_D \\ 0 & \text{for } \phi = \tilde{U}, \tilde{D}, \tilde{E} \end{cases}$$

$$C_1^\phi = \frac{3}{20} Y_\phi^2 \qquad \text{where } Y_\phi \text{ is the hypercharge of } \phi.$$

Finally, the soft-SUSY-breaking squared-masses for H_U and H_D satisfy:

$$16\pi^2 \frac{dm_{H_U}^2}{dt} = 3X_t - 6 g_2^2 M_2^2 - \frac{6}{5} g_1^2 M_1^2$$

$$16\pi^2 \frac{dm_{H_D}^2}{dt} = 3X_b + X_t - 6 g_2^2 M_2^2 - \frac{6}{5} g_1^2 M_1^2$$

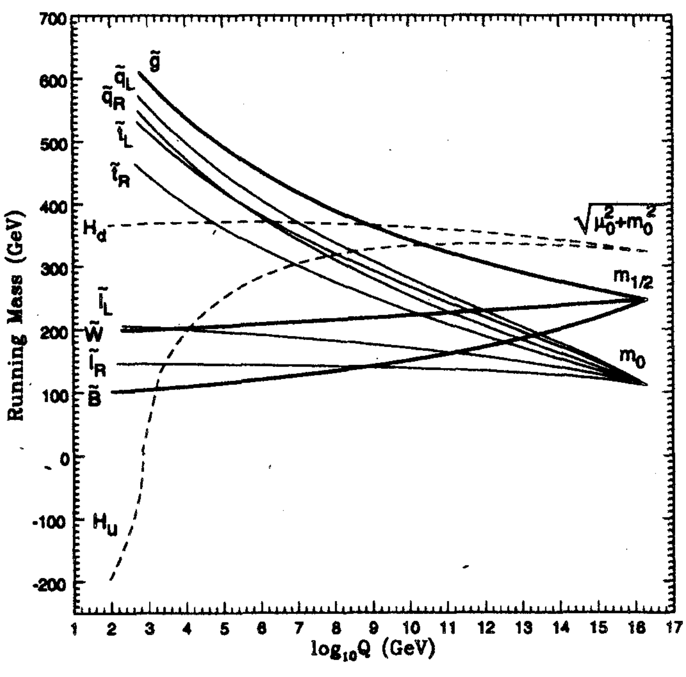
Since $X_t = 2h_t^2 (m_{H_U}^2 + m_{Q_3}^2 + m_{U_3}^2) + 2a_t^2$ and $h_t \simeq 1$, we see that $\frac{dm_{H_U}^2}{dt} > 0$. That is, $m_{H_U}^2$ decreases as one evolves from the high energy scale to the low-energy scale. Thus, $m_{H_U}^2$ will be the first squared-mass to be driven negative, thus triggering electroweak symmetry breaking. This is a feasable mechanism because h_t is of $O(1)$, or equivalently because m_t is so large.

Electroweak Symmetry Breaking and Low-Energy Supersymmetry

The Minimal Supersymmetric Standard Model (MSSM)

- Add a second complex Higgs doublet
- Add corresponding super-partners and allow for all possible supersymmetric interactions (consistent with B and L)
- Add supersymmetry-breaking (subject to experimental limits on super-partner masses)

Electroweak symmetry breaking is radiatively generated.



Constraining SUSY—Top-down

Models of SUSY-Breaking

Gravity-mediated SUSY-breaking

- SUSY-breaking effects mediated by Planck-scale physics
- The minimal model (mSUGRA) assumes a universal scalar mass, m_0, a universal gaugino mass, $m_{1/2}$, and a universal A-parameter, A_0 at the Planck scale. In addition, the parameters μ and B can be traded in for the Higgs vevs, v_d and v_u, with a two-fold ambiguity in $\mathrm{sign}(\mu)$. The W mass fixes $v_d^2 + v_u^2 = (246\ \mathrm{GeV})^2$, while $\tan\beta \equiv v_u/v_d$ remains a free parameter.
- Use RGEs to predict the MSSM spectrum. In particular,

$$M_3 = (g_3^2/g_2^2)M_2\ , \qquad M_1 = (5g_1^2/3g_2^2)M_2 \simeq 0.5M_2$$

- $m_{3/2} \sim 1$ TeV; $\widetilde{g}_{3/2}$ is irrelevant for phenomenology.

Anomaly-mediated SUSY-breaking (AMSB)

Randall and Sundrum
Giudice, Luty, Murayama and Rattazzi

- A model-independent contribution to super-partner masses (and A-terms) arises from the super-conformal anomaly of supergravity.

- If tree-level gaugino masses are absent, then

$$M_i \simeq \frac{b_i g_i^2}{16\pi^2} m_{3/2} \,,$$

where b_i are the coefficients of the MSSM gauge beta-functions: $(b_1, b_2, b_3) = (33/5, 1, -3)$.

Gauge-mediated SUSY-breaking (GMSB)

Dine, Nelson and Shirman

- SUSY-breaking effects mediated by gauge forces generated at intermediate-scales (between m_Z and $M_{\rm PL}$)

- $m_{3/2} \sim 1$ eV–1 keV with phenomenological consequences

Supergravity models

In gravity models, Lagrangians are no longer renormalizable. For example, the kinetic energy of a scalar field is modified:

$$\mathcal{L}_{\text{kinetic}} = \frac{\partial K(\phi_i, \phi_i^*)}{\partial \phi_i \, \partial \phi_j^*} \partial_\mu \phi_i \, \partial^\mu \phi_j^*$$

where K is called the Kähler potential. In supergravity, such terms arise from:

$$\int d^4\theta \, \mathbb{K}(\Phi, \bar{\Phi})$$

where $\mathbb{K}$ is a function of chiral and anti-chiral superfields. In global supersymmetry, $\mathbb{K}(\Phi, \bar{\Phi}) = \bar{\Phi}\Phi$, and we recover the conventional kinetic energy terms. In supergravity, K is expected to be more complicated.

In minimal supergravity (mSUGRA),

$$K = \kappa^2 \phi_i^* \phi_i + \ln(\kappa^6 |W|^2)$$

where $W = W(\phi)$ is the superpotential evaluated by plugging in the scalar field components, and κ^{-1} is the reduced Planck mass:

$$\kappa^{-1} = \frac{M_{PL}}{\sqrt{8\pi}}$$

In global-SUSY, the F-term contribution to the scalar potential was

$$V_{\text{scalar}} = F_i^* F_i = \left| \frac{dW}{d\phi_i} \right|^2$$

In supergravity, this is modified to

$$V_{scalar} = e^{K} \kappa^{-4} \left[\frac{\partial K}{\partial \phi_i} \frac{\partial K^{-1}}{\partial \phi_i \partial \phi_j^*} \frac{\partial K}{\partial \phi_j} - 3 \right]$$

Plugging in $K = \kappa^2 \phi_i^* \phi_i + \ln(\kappa^6 |W|^2)$ and noting, e.g. that $\frac{\partial K^{-1}}{\partial \phi_i \partial \phi_j^*} = \kappa^{-2} \delta_{ij}$ since W is holomorphic in ϕ, we obtain:

$$V_{scalar} = e^{\kappa^2 \phi_i^* \phi_i} \left[\left| \frac{dW}{d\phi_i} + \kappa^2 \phi_i^* W \right|^2 - 3\kappa^2 |W|^2 \right]$$

Note that as $\kappa \to 0$ (where we return to the global SUSY limit), we recover $V_{scalar} = \left| \frac{dW}{d\phi_i} \right|^2$. But now, V_{scalar} is no longer positive definite. In fact, by fine-tuning the vacuum energy to zero, we can achieve a sensible flat space limit even in the presence of SUSY-breaking

Note that $\langle F_\Phi \rangle / M_{PL} \sim O(1\text{ TeV}) \implies \langle F_\Phi \rangle \sim (10^{11}\text{ GeV})^2$.
Thus the "primordial" scale of SUSY-breaking may be significantly higher than the TeV-scale.

The dimensionless parameters f_a, k_{ij}, $\tilde{\mu}_{ij}$, $\tilde{h}_{ijk}$ depend on the underlying theory at the Planck scale. Since this theory is unknown, it is tempting to make some "minimal" assumptions.

If one assumes that the normalization of the kinetic energy terms and gauge interactions are of a "minimal" form, even in the full non-renormalizable supergravity Lagrangian, considerable simplification follows:

(i) $f_a = f$ independent of a

(ii) $k_{ij} = k\,\delta_{ij}$ for all scalars

(iii) $\tilde{\mu}_{ij} = \beta\,\mu_{ij}$

(iv) $\tilde{h}_{ijk} = \alpha\,h_{ijk}$

μ_{ij}, h_{ijk} are the corresponding terms in the superpotential
α, β are universal constants

Then, the soft-SUSY-breaking terms depend on just four parameters:

$$m_{1/2} = \frac{f \langle F_\Phi \rangle}{M_{PL}}, \quad m_0^2 = \frac{k |\langle F_\Phi \rangle|^2}{M_{PL}^2}, \quad A_0 = \frac{\alpha \langle F_\Phi \rangle}{M_{PL}},$$

$$B_0 = \frac{\beta \langle F_\Phi \rangle}{M_{PL}}.$$

mSUGRA Planck-scale boundary conditions

$$M_1 = M_2 = M_3 = m_{1/2}.$$

$$M_{\tilde{Q}}^2 = M_{\tilde{U}}^2 = M_{\tilde{D}}^2 = M_{\tilde{L}}^2 = M_{\tilde{E}}^2 = m_0^2 I_{3\times 3}$$

$$m_{H_U}^2 = m_{H_D}^2 = m_0^2$$

$$A_t = A_b = A_\tau = A_0$$

$$B = B_0$$

The universal nature of the boundary conditions is enough to prevent FCNC's from appearing at a level in conflict with experimental limits.

However, despite the fact that gravity is flavor blind, there is no known theoretical principle that enforces the mSUGRA structure (minimal Kahler potential and gauge kinetic function).

Nevertheless, the reduction of MSSM parameters is significant. In addition to 18 Standard Model parameters (excluding the Higgs mass), one must specify m_0, $m_{1/2}$, A_0, B_0 and μ. Actually, B_0 and μ^2 are traded in for v^2 (which is one of the 18 Standard Model parameters) and $\tan\beta$, with both signs of μ allowed. So, the new free SUSY parameters are just:

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta \text{ and } \mathrm{sgn}(\mu).$$

This model is sometimes called the constrained MSSM or CMSSM.

Actually, there is one more free parameter – the gravitino mass (which is directly related to the scale of SUSY-breaking, $\langle F_\Phi \rangle$ by:

$$m_{3/2} = \frac{\langle F_\Phi \rangle}{\sqrt{3}\, M_{PL}}$$

Such a gravitino has no role to play in collider physics. But, it can cause trouble in the evolution of the early universe, so it must be treated with care.

CP-violation

One can define the gluino mass to be real. So, the only possible phases lie in A_0 and μ. These phases are often neglected. They could lead to electric dipole moments for the neutron or electron above the present limits, and this provides constraints on the parameters.

Deviations from universality

One can tweak the mSUGRA model by relaxing various assumptions. For example, perhaps $m_{H_U}^2$ and $m_{H_D}^2$ are not degenerate with the squark/slepton squared-masses or each other at M_{PL}.

Therefore, be careful to place too much stock in strong CMSSM pronouncements.

Gauge-mediated SUSY-breaking (GMSB)

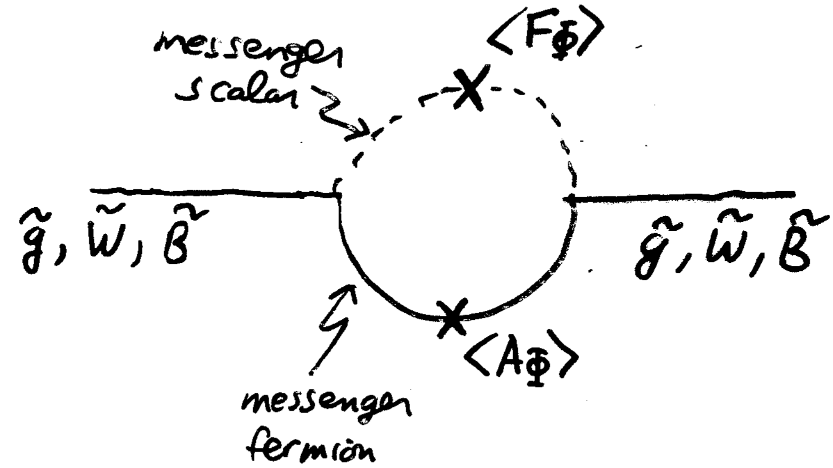
GMSB posits that SUSY-breaking is transmitted to the MSSM via gauge forces. Since gauge forces are flavor universal, one automatically achieves the squark and slepton universality necessary to avoid large FCNC's.

The basic idea: introduce new chiral supermultiplets, called messengers, which couple to the ultimate source of SUSY-breaking, and which also couple indirectly to the MSSM particles via $SU(3)\times SU(2)\times U(1)$ gauge and gaugino interactions.

Squarks and gaugino acquire masses via radiative corrections, which avoids the problem of generating a positive $\mathrm{Str}\,M^2$. The radiative corrections involve loops containing the messengers [which carry $SU(3)\times SU(2)\times U(1)$ quantum numbers and thus couple to the gauginos]. The coupling of the messengers to the SUSY-breaking source causes splittings in the messenger masses.

These mass-splittings encode the SUSY-breaking which is then transmitted to the gauginos via loops.

Here, I quote a number of simple results which are discussed in more detail in S. Martin, "Supersymmetric Primer"

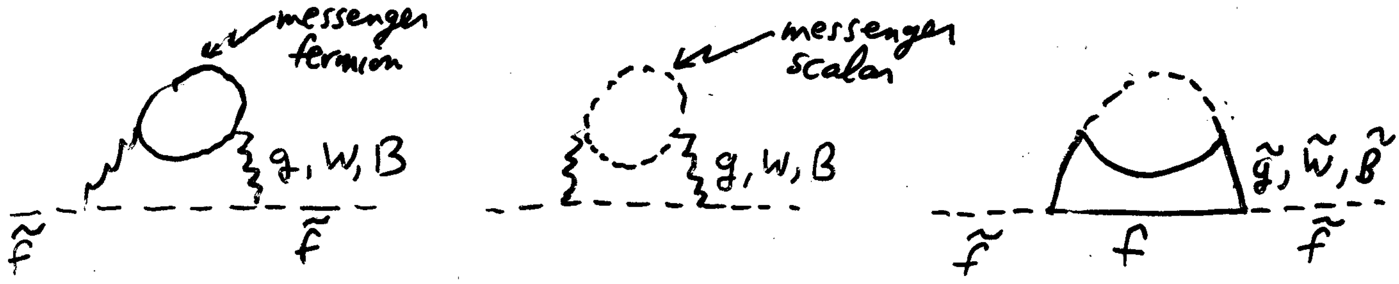


Φ = chiral superfield responsible for SUSY-breaking (an $SU(3)\times SU(2)\times U(1)$ singlet, hence a member of the "hidden" sector)

Result:

$$M_a = \frac{g_a^2}{16\pi^2}\Lambda \qquad \Lambda = \frac{\langle F_\Phi \rangle}{\langle A_\Phi \rangle}$$

The squarks and sleptons acquire mass at 2-loops, since they do not couple directly to the messengers. Typical graphs include:



Result:

$$m_\phi^2 = 2\Lambda^2 \sum_a \left(\frac{g_a^2}{16\pi^2}\right)^2 C_a^\phi$$

$C_a^\phi \delta_{ij} = (T^a T^a)_{ij}$, which was written down earlier for the various cases.

The soft-SUSY-breaking Higgs squared-mass is likewise generated.

Remarks:

1. Note that the loop-generated gaugino and squark/slepton masses are of the same order.

2. If $M_a, m_\phi \lesssim O(1\ \text{TeV})$, then we need $\Lambda \lesssim O(100\ \text{TeV})$.

3. The value of $\sqrt{F_\Phi}$ required for a successful model is highly model dependent. A survey of models in the literature finds a range of values:

$$100\ \text{TeV} \lesssim \sqrt{F_\Phi} \lesssim 3000\ \text{TeV}$$

This is relevant for the gravitino mass. We still expect the super-Higgs mechanism to take place (otherwise, the model will contain a zero mass Goldstino). Then,

$$m_{3/2} = \frac{F_\Phi}{\sqrt{3} M_{PL}} \simeq 2.5 \left(\frac{\sqrt{F_\Phi}}{100\ \text{TeV}} \right)^2 \text{eV}$$

The upper bound $F_\Phi \lesssim 3000$ GeV comes from cosmological constraints; otherwise $\tilde{g}_{3/2}$ would overclose the universe.

On the other hand, $\tilde{g}_{3/2}$ could play a significant role as "warm" dark matter.

GMSB parameter count

The gaugino masses and scalar squared-masses are all determined in terms of one parameter Λ, so the model in minimal form is slightly more restrictive than mSUGRA. In addition, the A-parameters are predicted to be small.

The μ and B parameters are very model dependent (lying somewhat outside of the GMSB ansatz).

Initial conditions for RGE running are fixed at the messenger scale (~ average mass of messenger particles). In principle this can lie anywhere between Λ and M_{PL}. (Once it approaches M_{PL}, supergravity effects are no longer negligible.)

Hence, the relevant parameters beyond the usual 18 Standard Model parameters are: $\sqrt{F_\Phi}$, Λ, $\tan\beta$ and $\arg(\mu)$ [after trading in B and $|\mu|^2$ for v^2 and $\tan\beta$]. There is also weak dependence on the messenger scale, which enters as the initial energy scale for RGE running.

Warning:

Minimal GMSB is not a fully realized model. The sector of SUSY-breaking dynamics can be quite complex. No complete model of GMSB yet exists that is both simple and compelling.

IX PHENOMENOLOGY OF LOW-ENERGY SUPERSYMMETRY

Ultimately, experiments will be the final arbiter as to whether low-energy supersymmetry exists in nature.

So far, results from experiments have not been kind. No supersymmetric particle production has been observed.

However, perhaps this is not too surprising since we have just begun the exploration of the TeV-scale.

A few tantalizing hints may be present in the data - some anomalies (a few sigma at most), which could be "explained" as the effects of virtual supersymmetric particle exchange.

This year the $(g-2)_\mu$ anomaly has attracted the most attention, so I'll briefly discuss why a supersymmetric explanation can be viable.

Science Times

The New York Times

TUESDAY, JANUARY 5, 1993

315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus ~~included the~~ Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

In trying to ferret out ever deeper layers of nature's secrets, scientists are being forced to accept a markedly slower pace of discovery in many fields of research, and the consequent rising cost of experiments has prompted public and polit~~ical criticism.~~

To some, the elaborate trappings and null result of the latest Fermilab experiment seem to typify both the lofty goals and the staggering difficulties of "Big Science," a term coined in 1961 by Dr. Alvin M. Weinberg of Oak Ridge National Laboratory. Some regard such failures as proof that high-energy physics, one of the biggest avenues of big science, is fast approaching a dead end.

Others ~~call the latest experiment a useful, though~~ inconclusive, step toward gauging the ultimate basis of material existence. The difficulty of science is increasing

Defenders see the experiment as useful though not decisive in gauging the nature of matter.

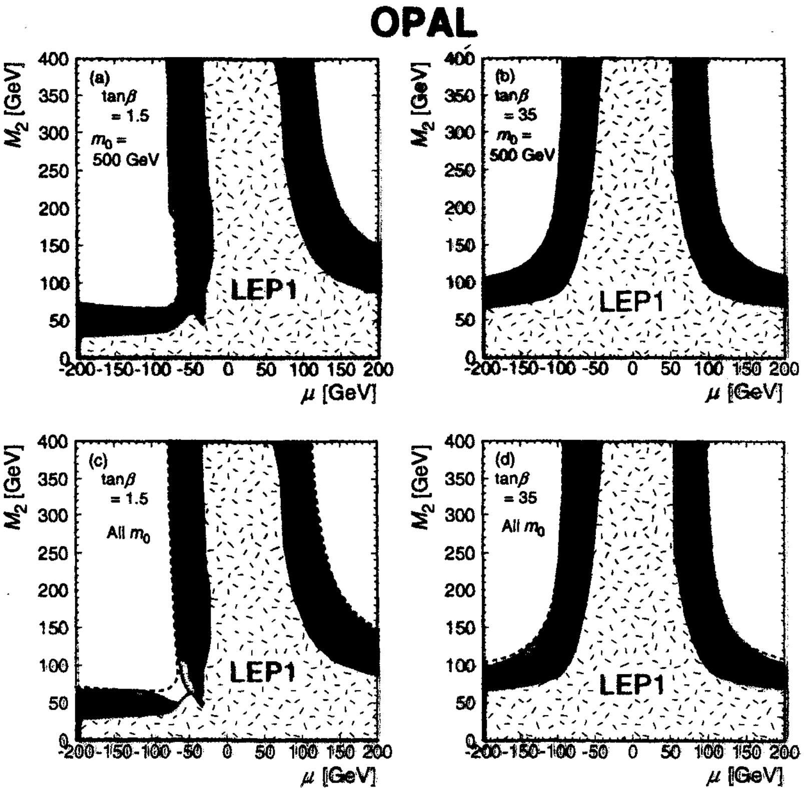


FIGURE 22. Exclusion regions at 95% C.L. in the (M_2,μ) plane with $m_0 \geq 500$ GeV for (a) $\tan\beta = 1.5$ and for (b) $\tan\beta = 35$. Exclusion regions valid for all m_0 for (c) $\tan\beta = 1.5$ and for (d) $\tan\beta = 35$. The speckled areas show the LEP1 excluded regions and the dark shaded areas show the additional exclusion region using the data from $\sqrt{s} = 181$–184 GeV. The kinematical boundaries for $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production are shown by the dashed curves. The light shaded region in (a) extending beyond the kinematical boundary of the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production is obtained due to the interpretation of the results from the direct neutralino searches. The light shaded regions elsewhere show the additional exclusion regions due to direct neutralino searches and other OPAL search results (see [6]).

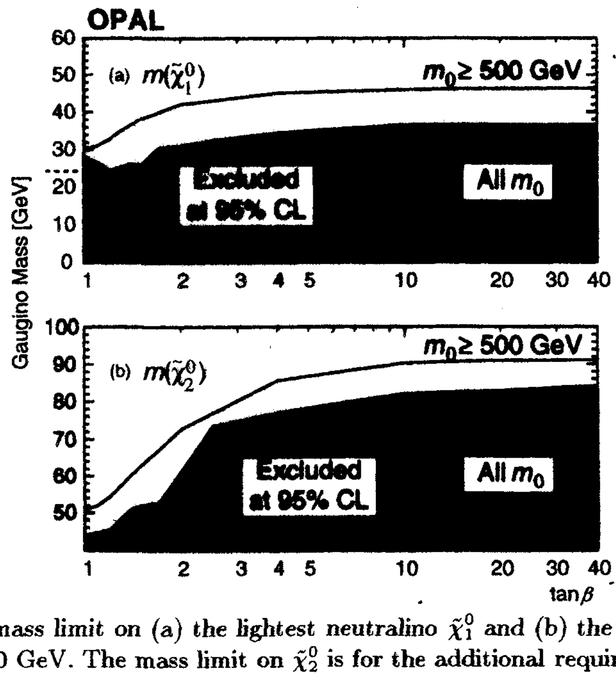


FIGURE 23. The 95% C.L. mass limit on (a) the lightest neutralino $\tilde{\chi}_1^0$ and (b) the second-lightest neutralino $\tilde{\chi}_2^0$ as a function of $\tan\beta$ for $m_0 \geq 500$ GeV. The mass limit on $\tilde{\chi}_2^0$ is for the additional requirement of $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 10$ GeV. The exclusion region for $m_0 \geq 500$ GeV is shown by the light shaded area and the excluded region valid for all m_0 values by the dark shaded area.

Implications of $(g-2)_\mu$

$$a_\mu \equiv \frac{1}{2}(g-2)_\mu$$

BNL measurement

$$a_\mu^{exp} = 11\,659\,203\,(15) \times 10^{-10}$$

SM prediction

Czarnecki and Marciano
Davier and Höcker

QED	$11\,658\,470.56\,(0.29) \times 10^{-10}$
weak	$15.1\,(0.4)$
hadronic	$673.9\,(6.7)$

$$a_\mu^{SM} = 11\,659\,159.6\,(6.7) \times 10^{-10}$$

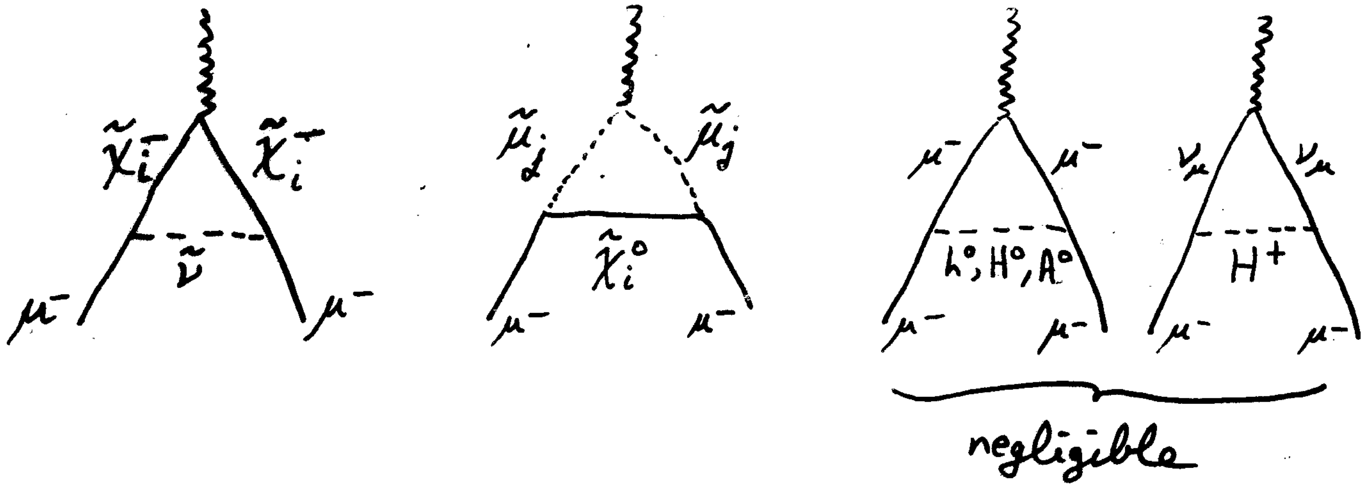
main question: is the hadronic correction reliable? Is its error estimate believable?

Jegerlehner – more conservative

Yndurain – initially skeptical, but recent computation now is consistent with above, with somewhat larger errors.

$$\boxed{a_\mu^{exp} - a_\mu^{SM} = 43(16) \times 10^{-10}} \qquad 2.6\,\sigma$$

MSSM contributions to $(g-2)_\mu$



The chargino diagram:

$$\mathcal{L}_{int} = \sum_i \left[\frac{g m_\mu}{\sqrt{2} m_W \cos\beta} \overline{\mu^-}\left(\frac{1-\gamma_5}{2}\right) U_{i2}^* \tilde{\chi}_i^- \tilde{\nu} \right.$$
$$\left. - g\, \overline{\mu^-}\left(\frac{1+\gamma_5}{2}\right) V_{i1} \tilde{\chi}_i^- \tilde{\nu} + h.c. \right]$$

chargino mass matrix

$$X = \begin{pmatrix} M_2 & m_W\sqrt{2}\sin\beta \\ m_W\sqrt{2}\cos\beta & \mu \end{pmatrix}, \qquad U^* X V^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1} & 0 \\ 0 & m_{\tilde{\chi}_2} \end{pmatrix}$$

Leading term for $a_\mu(\tilde{\chi}^- \tilde{\nu})$

$$a_\mu = \frac{-g^2 m_\mu^2}{8\sqrt{2}\pi^2 m_W \cos\beta} \sum_i m_{\tilde{\chi}_i} \mathrm{Re}(V_{i1} U_{i2}) \int_0^1 \frac{x^2\, dx}{x m_{\tilde{\chi}_i}^2 + (1-x) m_{\tilde{\nu}}^2}$$

A simple approximation: $m_{\tilde{\nu}} = 0$

Assume CP-conservation so $V_{i1}U_{i2}$ is real.

$$(U^* X V^\dagger)_{ij} = m_{\tilde{\chi}_i}^2 \delta_{ij} \implies X_{12}^{-1} = \frac{V_{i1} U_{i2}}{m_{\tilde{\chi}_i}}$$

$$X_{12}^{-1} = \frac{-m_W \sqrt{2} \sin\beta}{M_2 \mu - m_W^2 \sin 2\beta}$$

Thus,

$$a_\mu(\tilde{\chi}^- \tilde{\nu}) \simeq \frac{g^2 m_\mu^2 \tan\beta}{16\pi^2 [M_2 \mu - m_W^2 \sin 2\beta]}$$

Take $M_2 \mu \gg m_W^2 \sin 2\beta$. Then

$$a_\mu(\tilde{\chi}^- \tilde{\nu}) \simeq \frac{g^2 m_\mu^2 \tan\beta}{16\pi^2 M_2 \mu}$$

That is, roughly:

$$\boxed{\frac{a_\mu^{SUSY}}{a_\mu^{weak}} \sim \frac{m_W^2}{M_{SUSY}^2} \tan\beta \;\; \mathrm{sgn}(\mu M_2)}$$

Note: $b \to s\gamma$ prefers $\mathrm{sgn}(\mu M_3) > 0$.

Our attention now focuses on future colliders.

The only way to prove that an anomaly is due to virtual supersymmetric particle exchange is to directly find the supersymmetric particles in colliders.

But, keep in mind that low-energy SUSY has been introduced to provide an understanding of electroweak symmetry breaking. Thus, a detailed study of Higgs physics will be essential to achieve a full understanding of TeV-scale physics.

Ultimately, if this enterprise is successful, it may provide a window to the Planck scale and bring us closer to the ultimate fundamental theory of nature.

We now take a brief look at:

(i) Higgs searches at future colliders, in the context of the MSSM

(ii) Supersymmetric particle search with emphasis on:

- the importance of the lightest and next-to-lightest supersymmetric particle for SUSY signals
- classification of SUSY signatures at future collider

Higgs Searches at Future Colliders

At e^+e^- Colliders (LEP2 and NLC)

- $e^+e^- \to Zh^0$, ZH^0

- $e^+e^- \to A^0h^0$, A^0H^0

At the upgraded Tevatron

- $q\bar{q} \to Vh^0$, VH^0

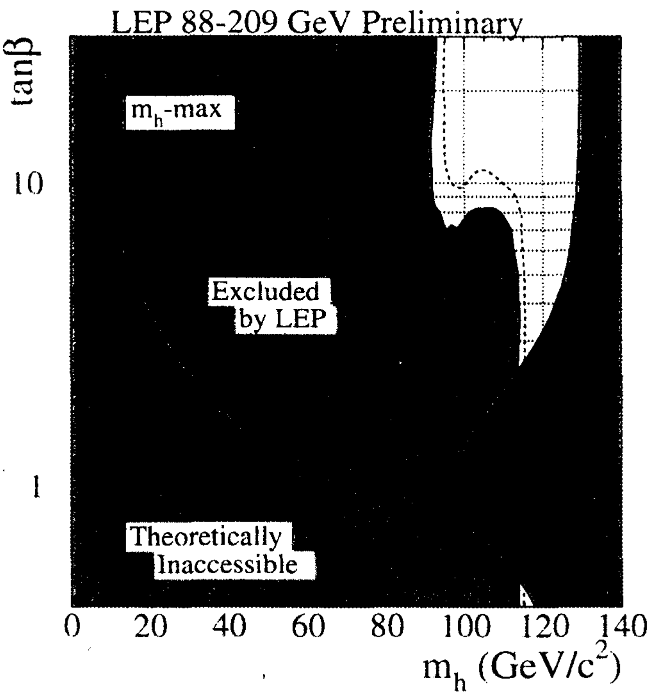
where $V = W$ or Z decays leptonically and h^0, $H^0 \to b\bar{b}$

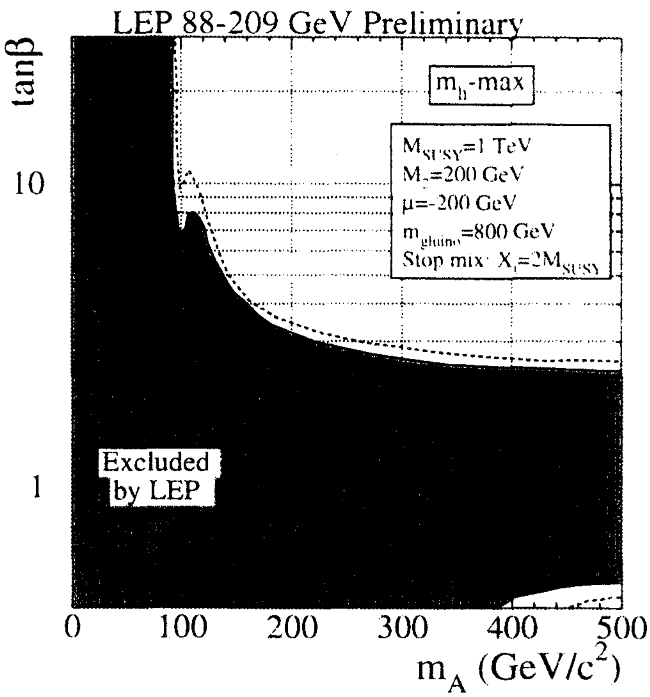
- $gg \to b\bar{b}h^0$, $b\bar{b}H^0$, $b\bar{b}A^0$

At the LHC

- $gg \to h^0$, H^0, A^0

- search strategies depend on region of m_A–$\tan\beta$ plane

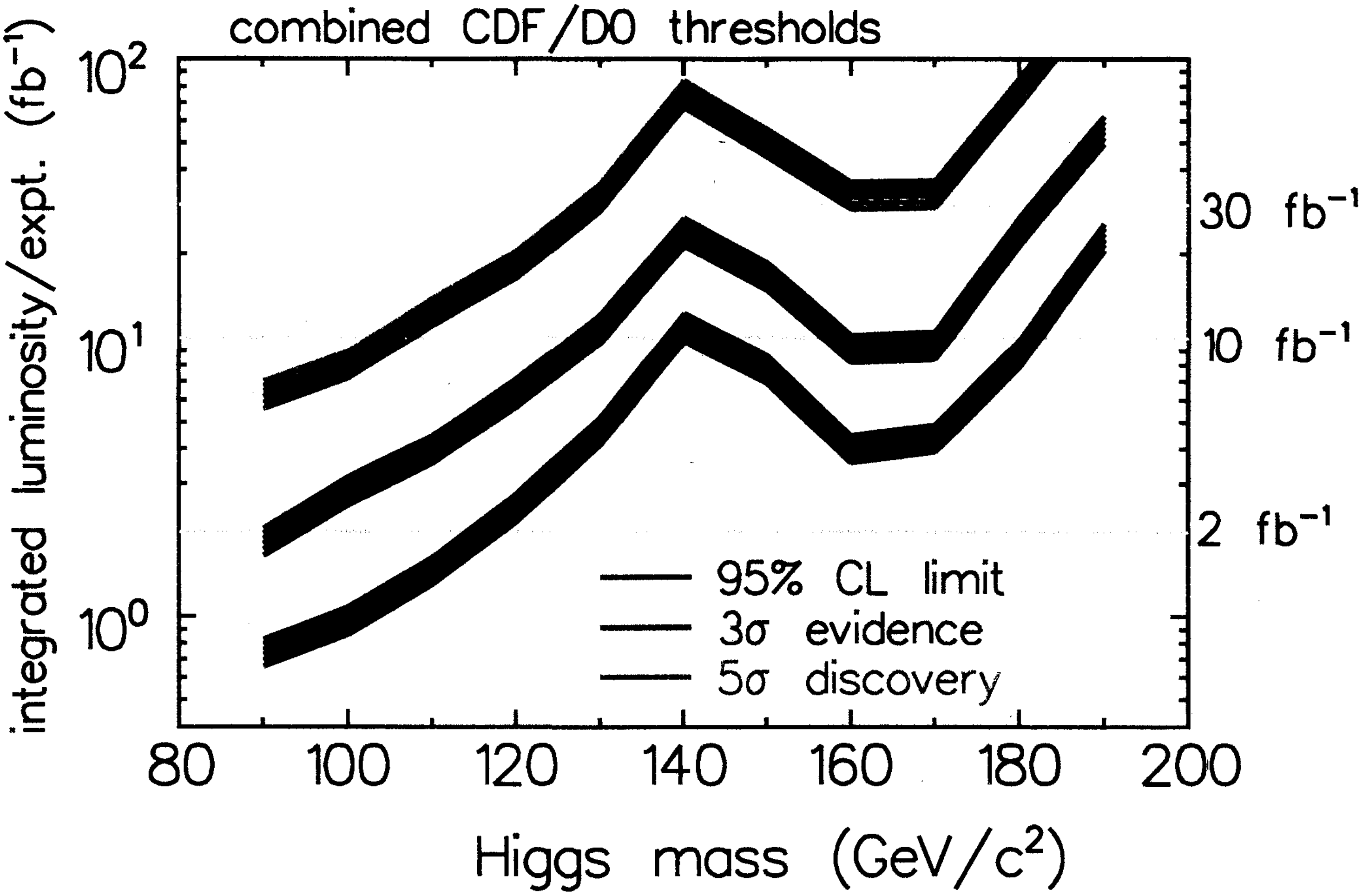




Present status of the LEP Higgs Search [95% CL limits]

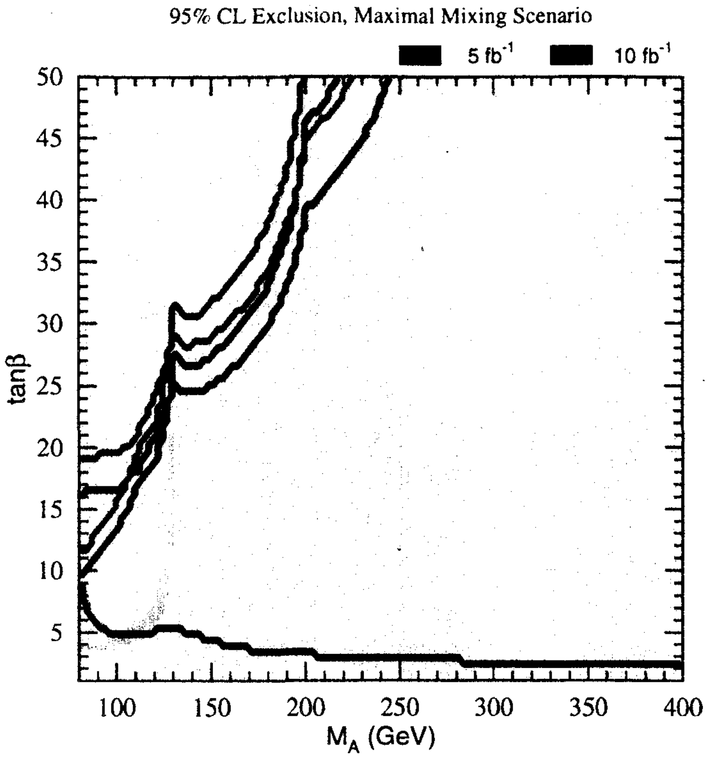
- Standard Model Higgs boson: $m_H > 113.5$ GeV
- Charged Higgs boson: $m_{H^\pm} > 78.5$ GeV
- MSSM Higgs: $m_h > 91.0$ GeV; $m_A > 91.9$ GeV

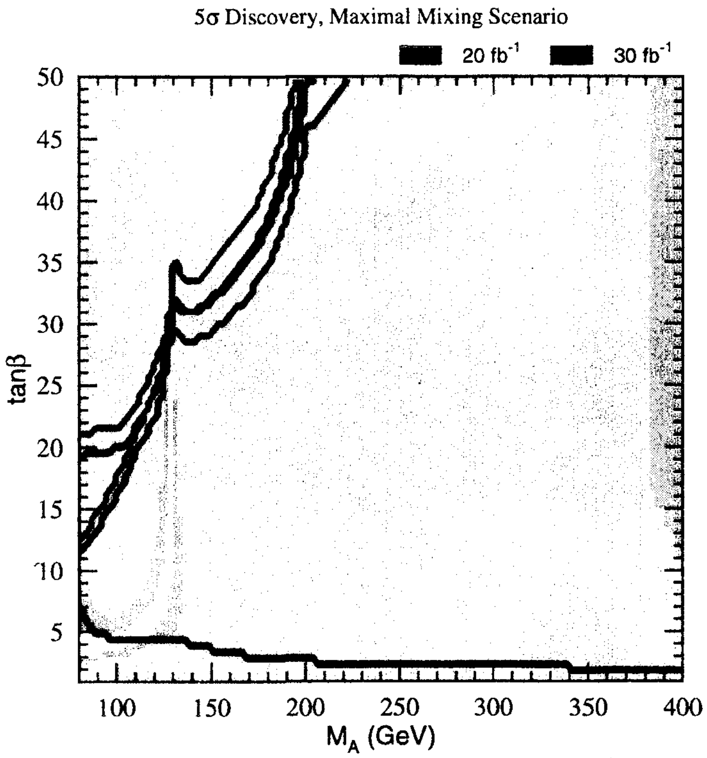
At large $\tan\beta$, supersymmetric radiative corrections can also have a significant impact on the Higgs branching ratios. Example: the dominant decay mode $h \to b\bar{b}$ is suppressed in some regions of MSSM Higgs parameter space.



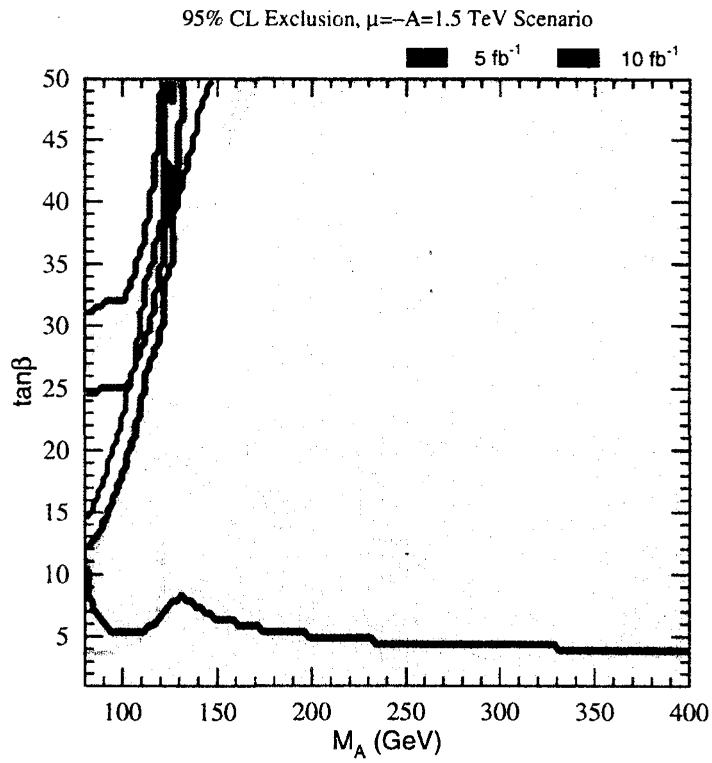
The integrated luminosity required per experiment, to either exclude a SM Higgs at 95% CL or discover it at the 3σ or 5σ level, as a function of the Higgs mass. These results are based on the combined statistical power of both experiments. The curves shown are obtained by combining the $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$ and $\ell^+\ell^- b\bar{b}$ channels using the neural network selection in the low-mass Higgs region (below 130 GeV) and the in the high-mass Higgs region (above 130 GeV). The lower edge of the bands is the calculated threshold; the bands extend upward from these nominal thresholds by 30% as an indication of the uncertainties in b-tagging efficiency, background rate, mass resolution, and other effects.

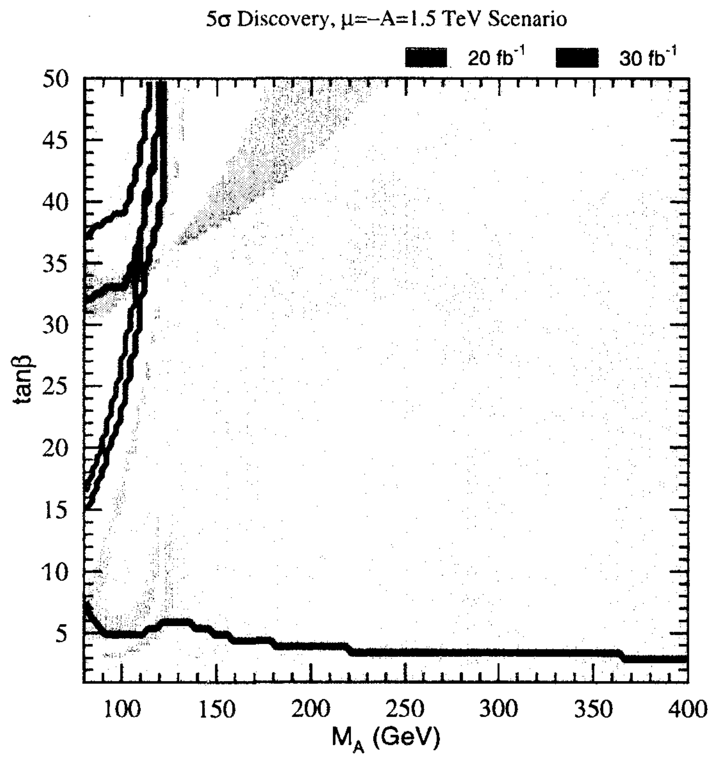
from the Tevatron Higgs Working Group Report
M. Carena, J. Conway, H.E. Haber and J.D. Hobbs et al.





M. Carena
H.E. Haber
S. Mrenna
C.E.M. Wagner


95% CL Exclusion, μ=−A=1.5 TeV Scenario
5 fb-1
10 fb-1
tanβ
M_A (GeV)


5σ Discovery, μ=−A=1.5 TeV Scenario
20 fb-1
30 fb-1
tanβ
M_A (GeV)

Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

- 5σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1TeV

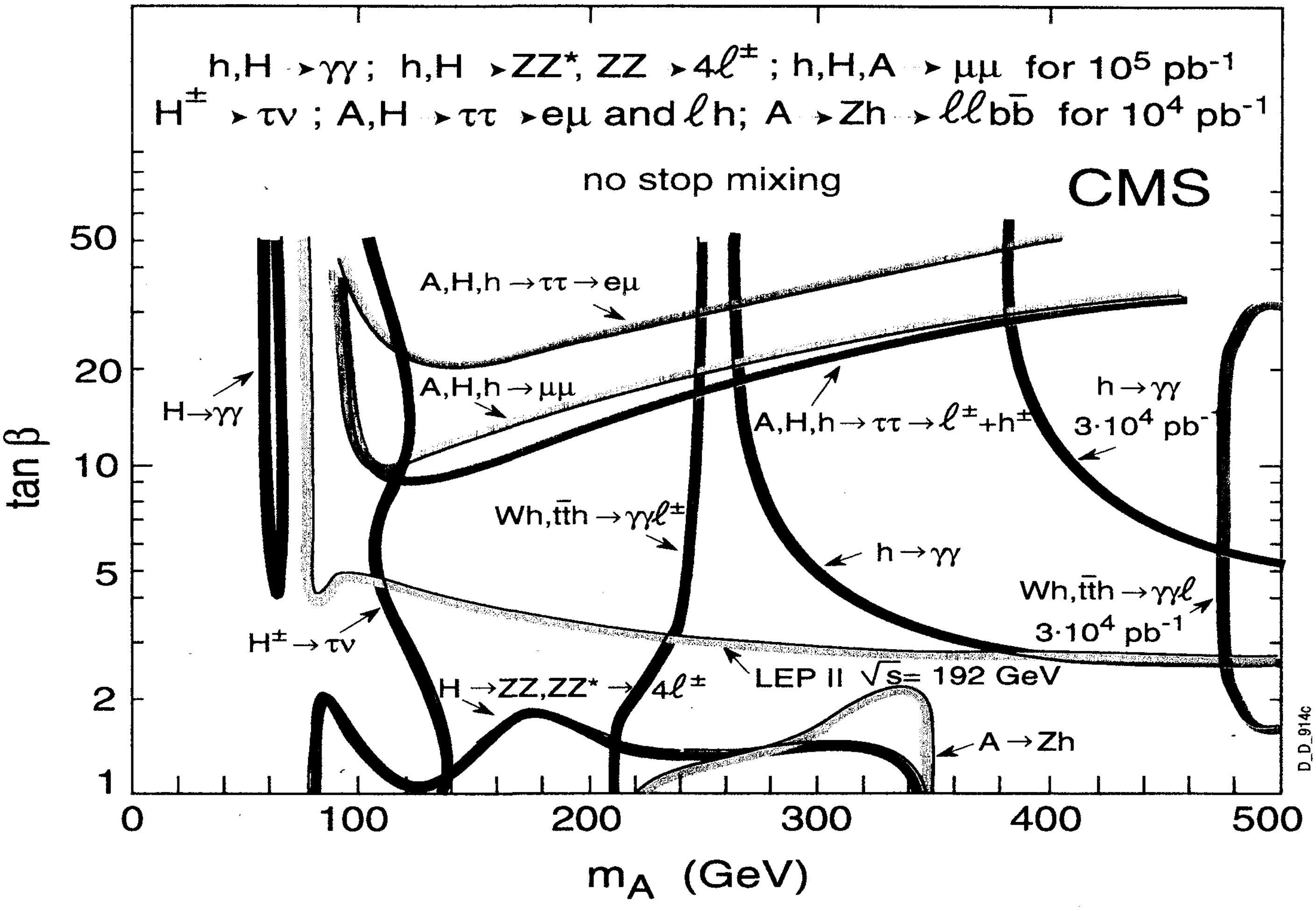


Figure 7: Regions of the parameter space ($M_A - \tan\beta$) covered by the 5σ discovery contours of various MSSM Higgs signals from the CMS experiment [13].

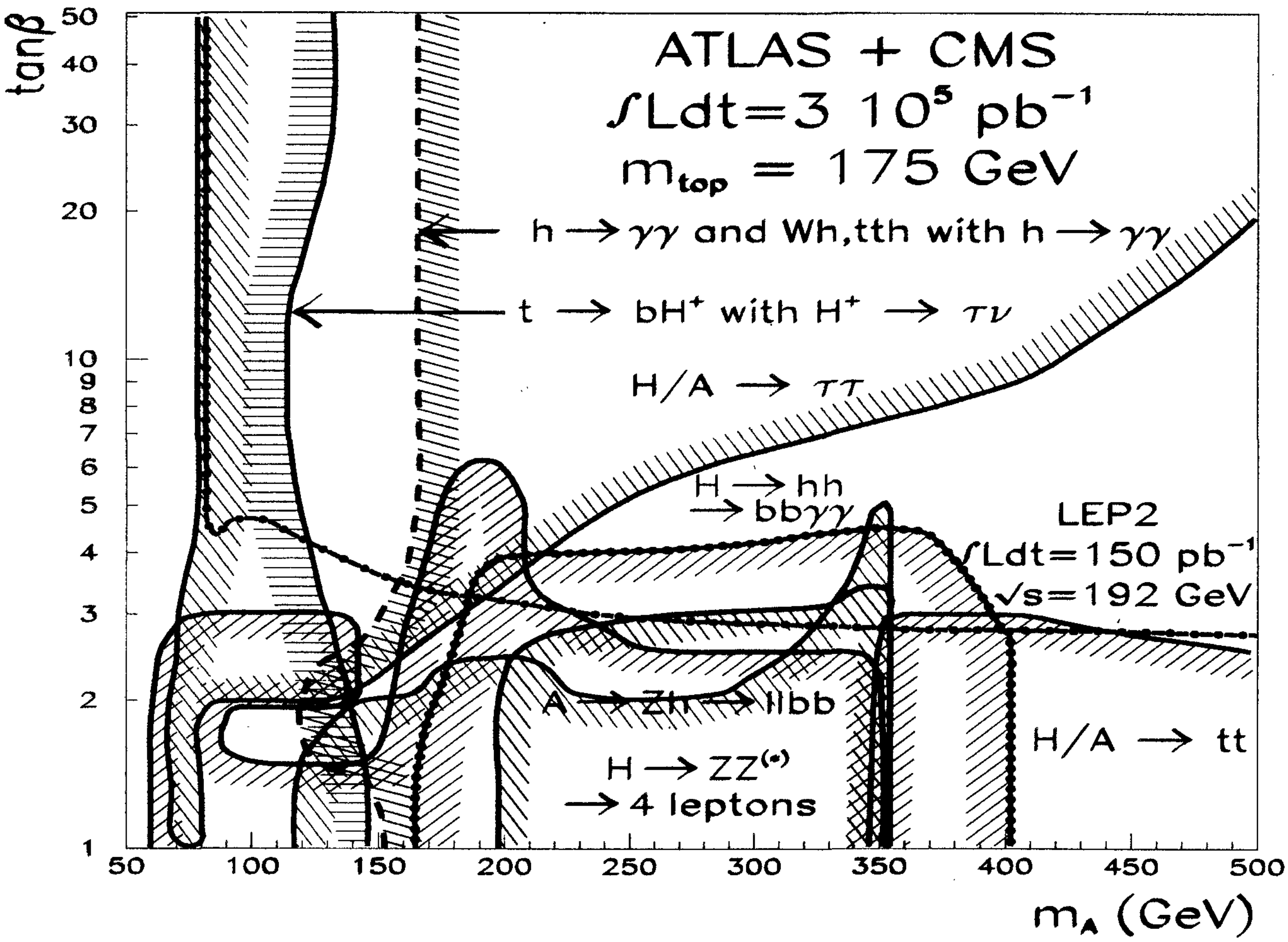
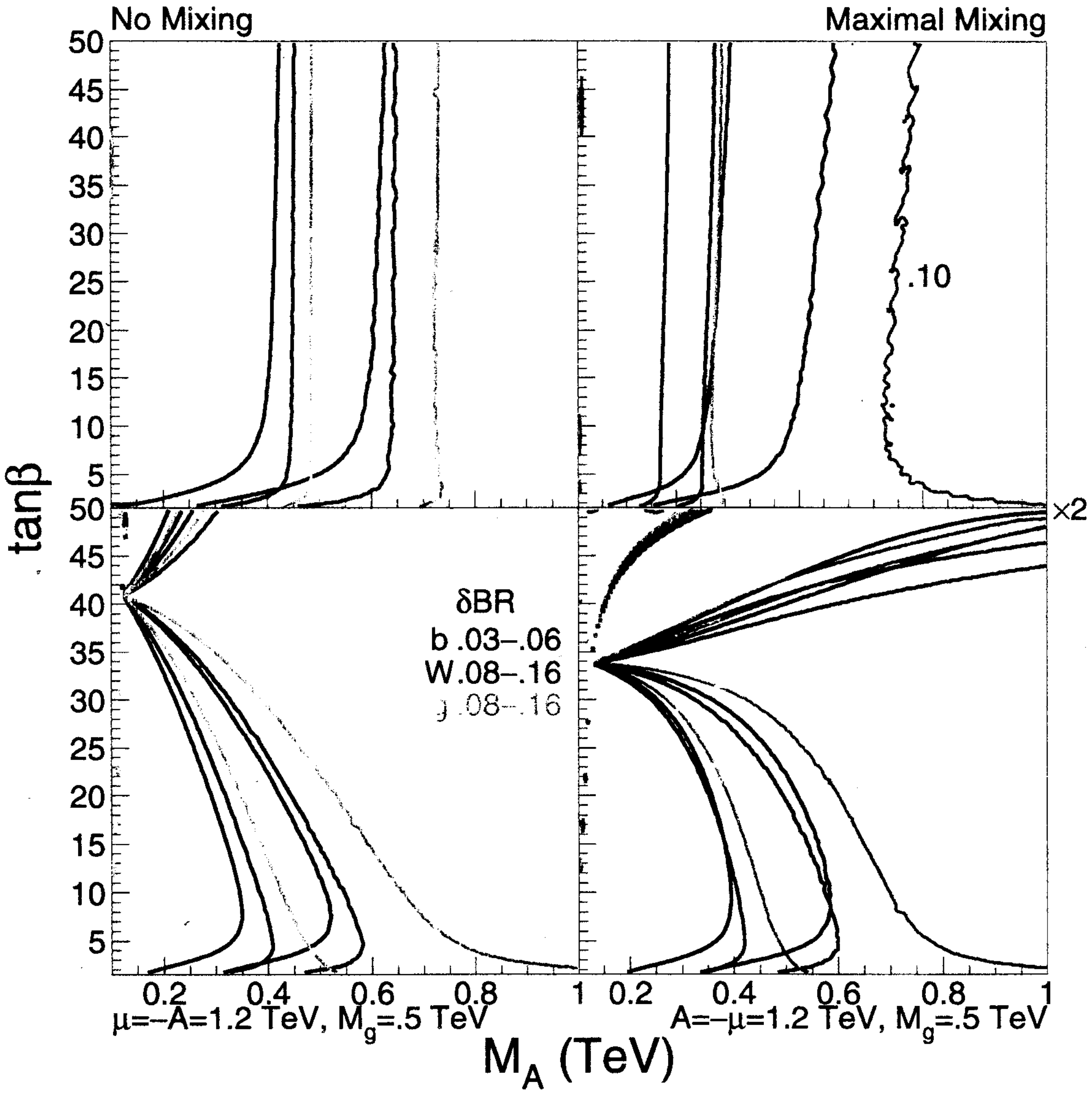


Figure 8: Regions of the parameter space ($M_A - \tan\beta$) covered by the 5σ discovery contours of various MSSM Higgs signals from the combined ATLAS + CMS experiments after 3 years of high luminosity run of LHC [17].

Implications for the MSSM Higgs sector [Carena, Haber, Logan, and Mrenna]

Contours of $\delta\mathrm{BR} \equiv [\mathrm{BR}_{\mathrm{MSSM}} - \mathrm{BR}_{\mathrm{SM}}]/\mathrm{BR}_{\mathrm{SM}}$ in the m_A—$\tan\beta$ plane for different MSSM parameter scenarios.



Anticipated BR measurements at the LC

$\sqrt{s} = 500$ GeV

$\int \mathcal{L}\, dt = 500\ fb^{-1}$

	Battaglia/Desch (rescaled)	Brau et. al.
$b\bar{b}$	3.6%	2.9%
WW^*	7.7%	9.3%
$\tau^+\tau^-$	7.5%	7.9%
$c\bar{c}$	12.8%	39%
gg	8.3%	18%
$\gamma\gamma$	29%	

Anticipated fractional uncertainties of Higgs couplings [Battaglia/Desch rescaled]

	$\delta g/g$	$\delta\Gamma/\Gamma$
WW	1.8%	3.6%
ZZ	1.8%	3.6%
tt	3.3%	6.6%
bb	3.2%	6.3%
cc	4.7%	9.3%
$\tau^+\tau^-$	4.8%	9.6%

The LSP and NLSP

LSP = lightest supersymmetric particle
NLSP = second (or "next to") lightest SUSY particle

In R-parity-conserving models,

- any interaction vertex contains an even number of SUSY particles (R-odd)
- heavy SUSY particles decay quickly into lighter states; at the end of the decay chain, the only remaining SUSY particle is the LSP
- the LSP is absolutely stable. It's interactions in matter are weak (it behaves like a neutrino)

[the LSP is an excellent candidate for cold dark matter]

- In mSUGRA, the LSP is typically the lightest neutralino $\tilde{\chi}_1^0 \sim \tilde{B}$, whose wave function is dominated by its U(1)-gaugino (or "bino") component.

- In more general SUGRA models, the LSP might be $\tilde{\chi}_1^0$ (with arbitrary gaugino/higgsino components), $\tilde{\nu}$, and even the $\tilde{g}$ (in some unconventional models)

osmology strongly argues against a charged (stable) LSP.

- In AMSB models, $\tilde{\chi}_1^0 \simeq \tilde{W}_3^0$ is the LSP and $\tilde{\chi}_1^\pm \simeq \tilde{W}^\pm$ is the NLSP with $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \lesssim 1$ GeV.

This presents some severe challenges for experimental observation.

- In GMSB models, $\tilde{g}_{3/2}$ is the LSP with mass in the eV – keV range. In this case, the NLSP plays a key role in the phenomenology.

typical choices for the NLSP: $\tilde{\chi}_1^0$, $\tilde{\tau}_R^\pm$

The NLSP decays to its SM-partner + $\tilde{g}_{3/2}$. Its lifetime is very sensitive to model parameters, so the SUSY phenomenology is quite varied depending on whether the decay takes place:

- "instantaneously"
- with a visible track between production and decay
- outside the detector

- More complicated GMSB scenarios: co-NLSP's
  example: $m_{\chi_1^0} \sim m_{\tilde{\tau}_R}$ so that neither $\tilde{\tau}_R \to \tau^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^0 \to \tilde{\tau}_R^\pm \tau^\mp$ are kinematically allowed decays

inally, in R-parity-violating models, the LSP decays into SM particles. In this case, the LSP can be either neutral or charged. Phenomenology depends on the same three above alternatives.

Classes of SUSY signals at colliders

(1) Missing (transverse) energy signatures

In R-parity-conserving models, the LSP behaves like a neutrino. So, look in colliders for events with large missing energy and argue (statistically) that such events cannot be due to:

- neutrinos (e.g. large transverse momentum Z's which decay 20% of the time into $\nu\bar{\nu}$)
- cracks in the detector
- mis-measurements in the calorimeter

(2) Lepton (e, μ and τ) signatures

Complex decay chains of heavy SUSY particles can yield multiple leptons. Two distinctive classes of events are:

(a) tri-lepton signals

example: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \longrightarrow (\ell^\pm \nu \tilde{\chi}_1^0)(\ell^+\ell^- \tilde{\chi}_1^0)$

with little hadronic activity apart from initial state radiation of jets off of the annihilating quarks at hadron colliders

(b) like-sign dilepton signals

example: $\tilde{g}\tilde{g}$ production at hadron colliders, with

$$\tilde{g} \to q\bar{q}\tilde{\chi}_1^{\pm} \longrightarrow q\bar{q}'\ell^{\pm}\nu\tilde{\chi}_1^0$$

each gluon can decay with equal probability to either ℓ^+ or ℓ^- (ultimately as a result of the Majorana nature of the $\tilde{g}$).

③ Multiple b-quark signatures

In some models, $\tilde{g} \to \tilde{b}\bar{b}, \bar{\tilde{b}}b$ may be the dominant decay.

More generally, one expects $\tilde{g} \to q\bar{q}\tilde{\chi}$, with multiple -quarks in at least 20% of all gluino decays.

$\Longrightarrow$ events with b-jets in association with E_T^{miss}.

④ Signatures involving photons + E_T^{miss}

example: in GMSB models with $\tilde{\chi}_1^0$ the NLSP and $\tilde{\chi}_1^0 \to \gamma\tilde{g}_{3/2}$ a dominant decay mode.

⑤ Kinks and long-lived heavy particles

examples: (1) long-lived NLSP in GMSB models
(2) long-lived LSP in RPV models

In GMSB models with a characteristic SUSY-breaking scale of $\sqrt{F}$ (in the "hidden" or SUSY-breaking sector),

$$(c\tau)_{\tilde{\chi}_1^0 \to \gamma \tilde{g}_{3/2}} \simeq 130 \left(\frac{100 \text{ GeV}}{m_{\tilde{\chi}_1^0}} \right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \mu m$$

Warnings and challenges

- difficult regions of SUSY-parameter space

  example: AMSB with $m_{\chi_1^+} \simeq m_{\tilde{\chi}_1^0}$.

  so $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$

  where the π's are very soft. So, $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ may be difficult to observe [background: $e^+e^- \to e^+e^- \pi^+\pi^-$ via $\gamma\gamma$-process, with forward $e^\pm$ not detected]

- unconventional SUSY models
  - suppressed or absent E_T^{miss} signatures

SUSY at future colliders — prospects

Three-step strategy:

① Discover SUSY-particle production

- assess discovery reach of future colliders
- detect SUSY signatures in future experiments and prove that the signal (above SM backgrounds) is statistically significant.

② Make a convincing case for the SUSY interpretation.

example: if LEP were to discover $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$, how would you know that you had not discovered a fourth generation lepton?

To accomplish step 2, you would need to detect multiple SUSY signals and identify some fraction of the SUSY particle spectrum.

Eventually, you would look for consistency checks. (perhaps virtual SUSY contributions to various processes would play some role) Finally, the "gold-plated" measurement would check a SUSY relation, e.g. measure the $\tilde{e}^+ e^- \tilde{\chi}_1^0$ or $q \tilde{q} \tilde{g}$ interaction strengths which are related by SUSY to gauge couplings.

③ Precision measurements of the MSSM-124 parameters (and additional parameters that can arise in non-minimal extensions)

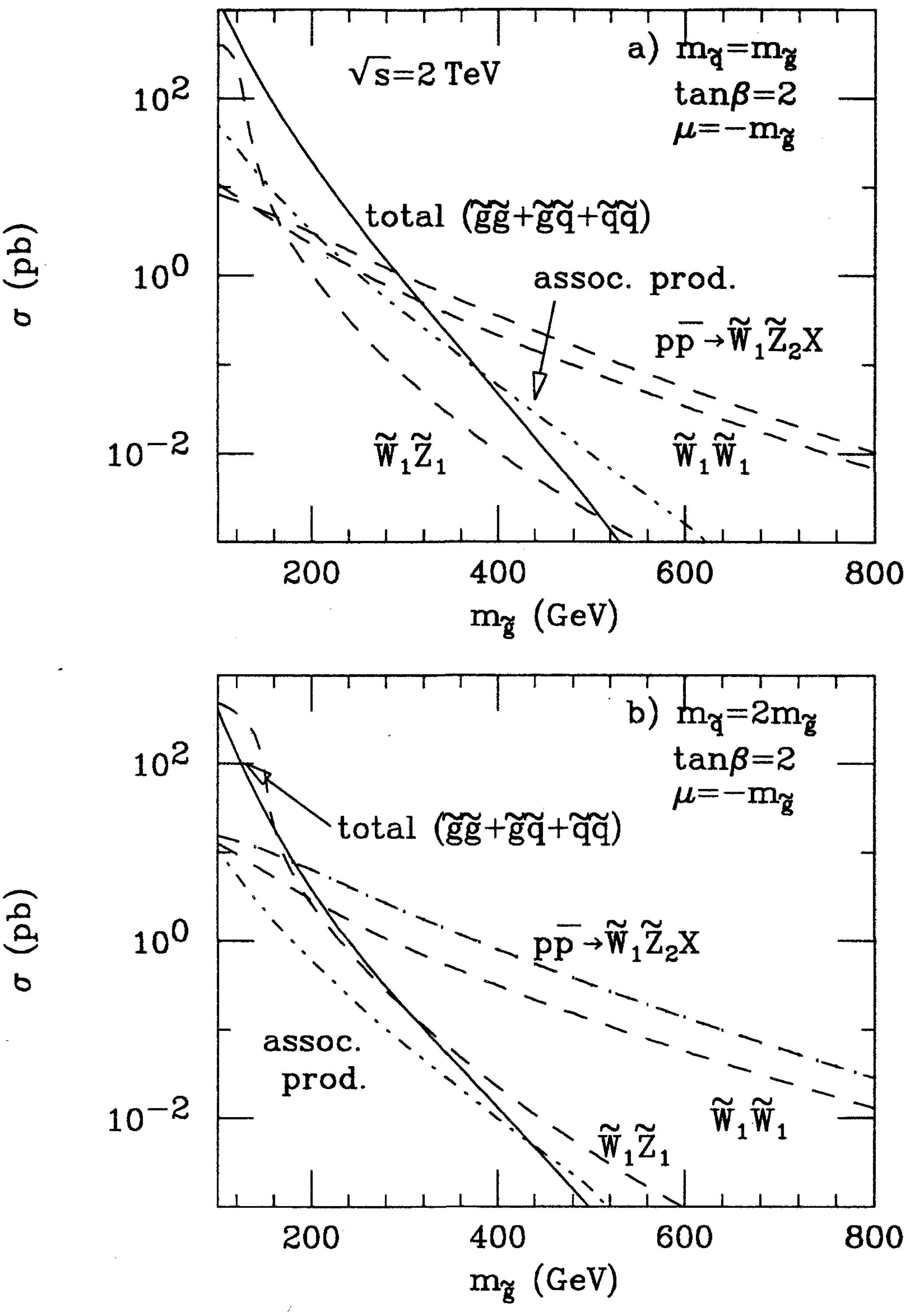
with a final goals of

- uncovering the structure underlying supersymmetry-breaking in the low-energy (TeV-scale) theory

- extrapolating to high energies to make connections with more fundamental theories of nature

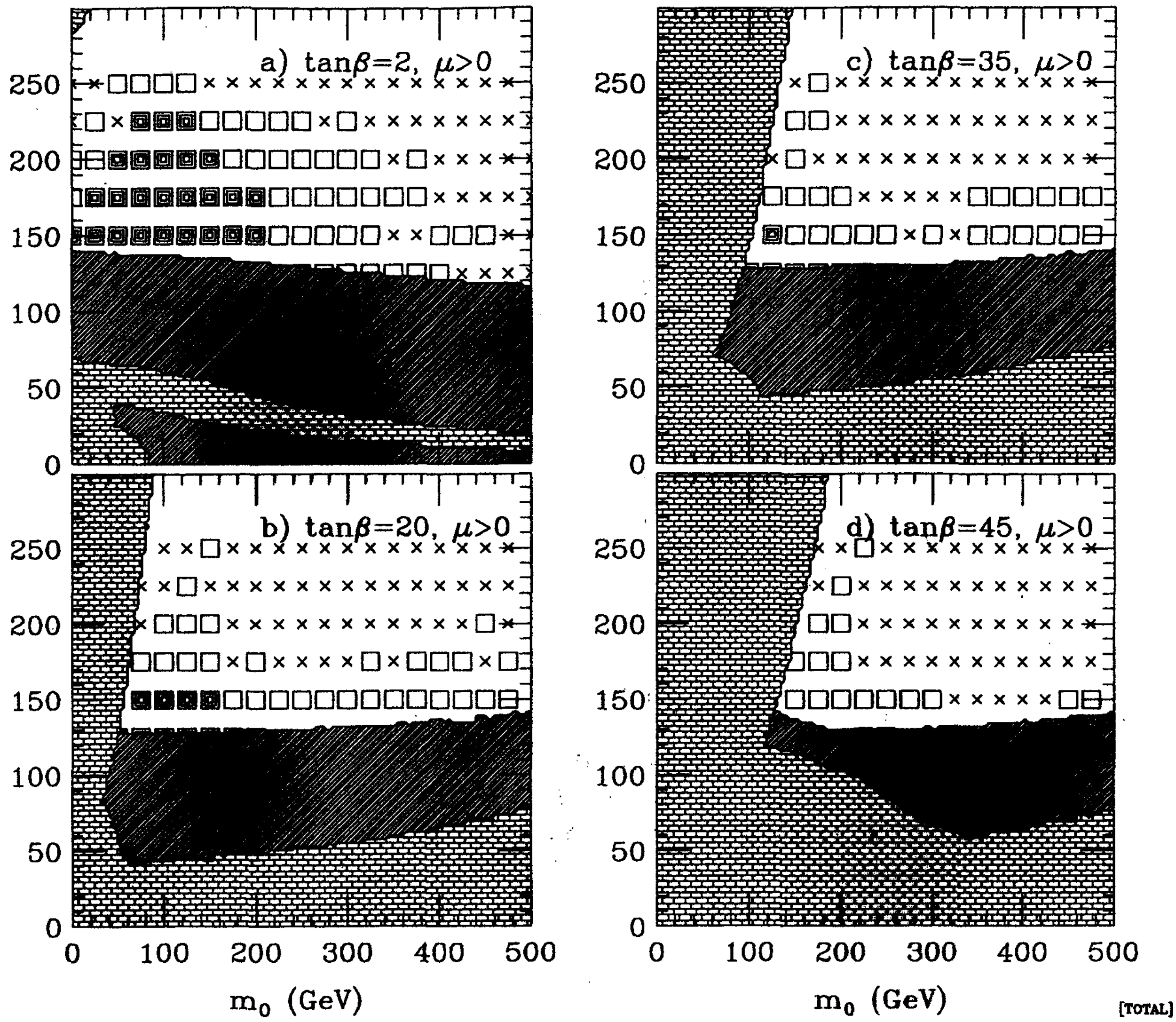
FUTURE COLLIDER PROSPECTS

	starting	discover SUSY?	Is it really SUSY?	Precision measurements
Tevatron Run 2 $\sqrt{s} = 2$ TeV	spring 2001	**	*	?
LHC $\sqrt{s} = 14$ TeV	2006	*****	***	***
Future lepton collider $\sqrt{s} = 500$ GeV $\to$?	??	***	****	****



'igure 3: Total cross sections for various sparticle production processes by $p\bar p$ collisions at $\sqrt{s} = 2$ TeV.

Baer, Chen, Kao and Tata



Combined SUSY reach of the upgraded Tevatron in mSUGRA

grey squares $2\ fb^{-1}$

hollow squares $25\ fb^{-1}$

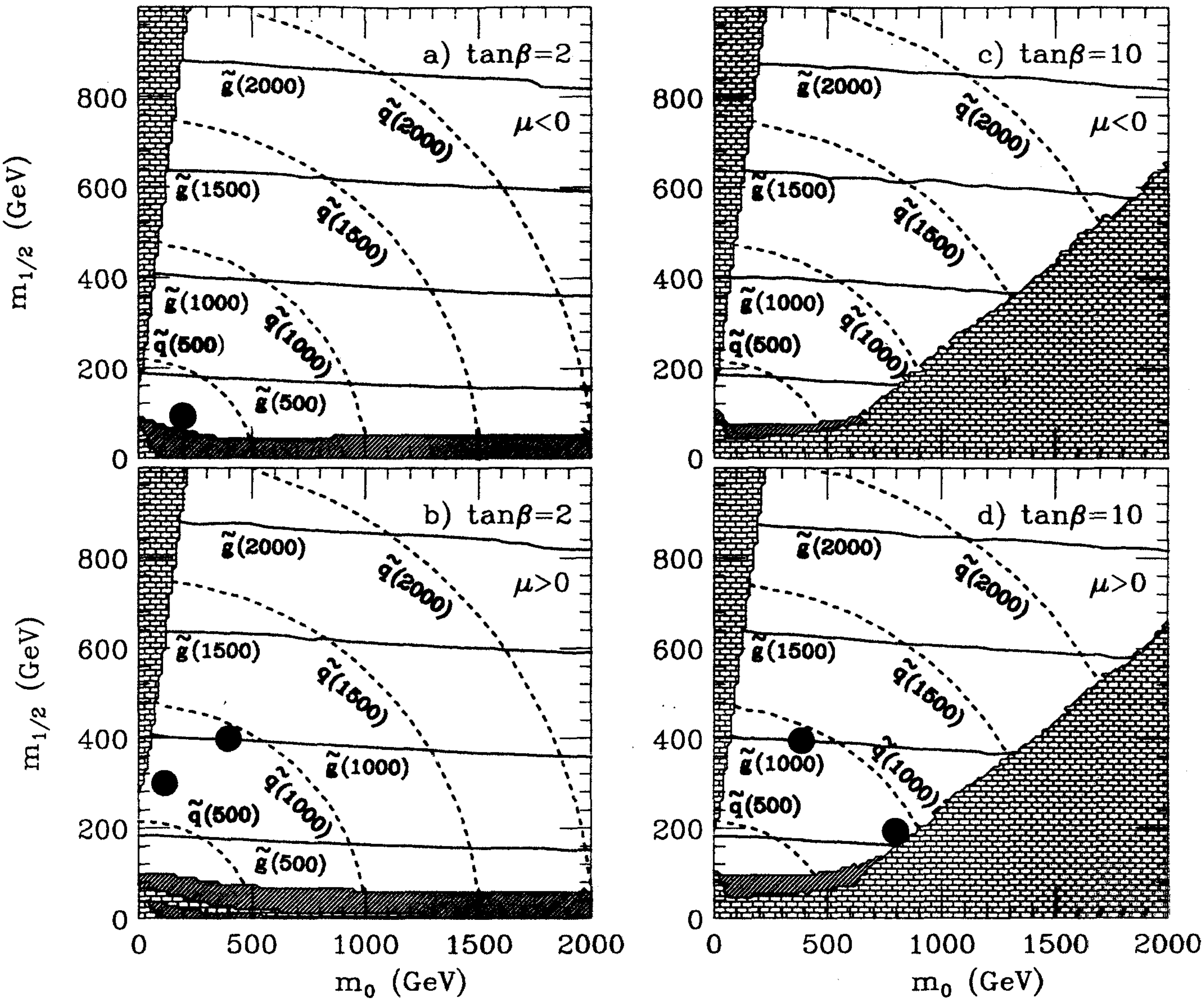
bricked region excluded by theoretical constraints

hatched region excluded by experimental constraints

based on E_T^{miss}, E_T^{miss} + tagged b, tri-lepton and tri-lepton with tagged τ channels.

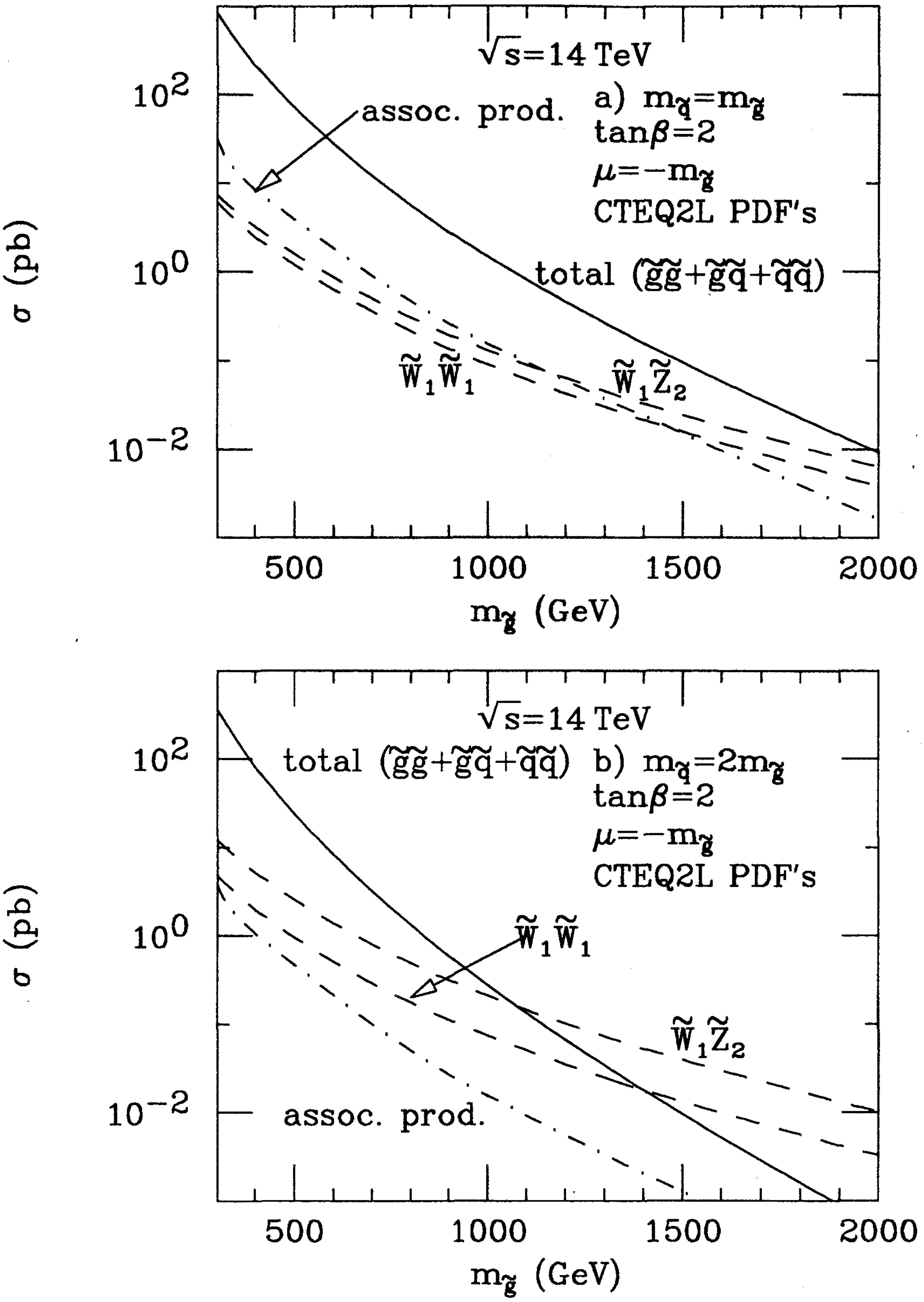
Baer, Chen, Drees, Paige and Tata

contributed to the Tevatron SUGRA Working Group Report.

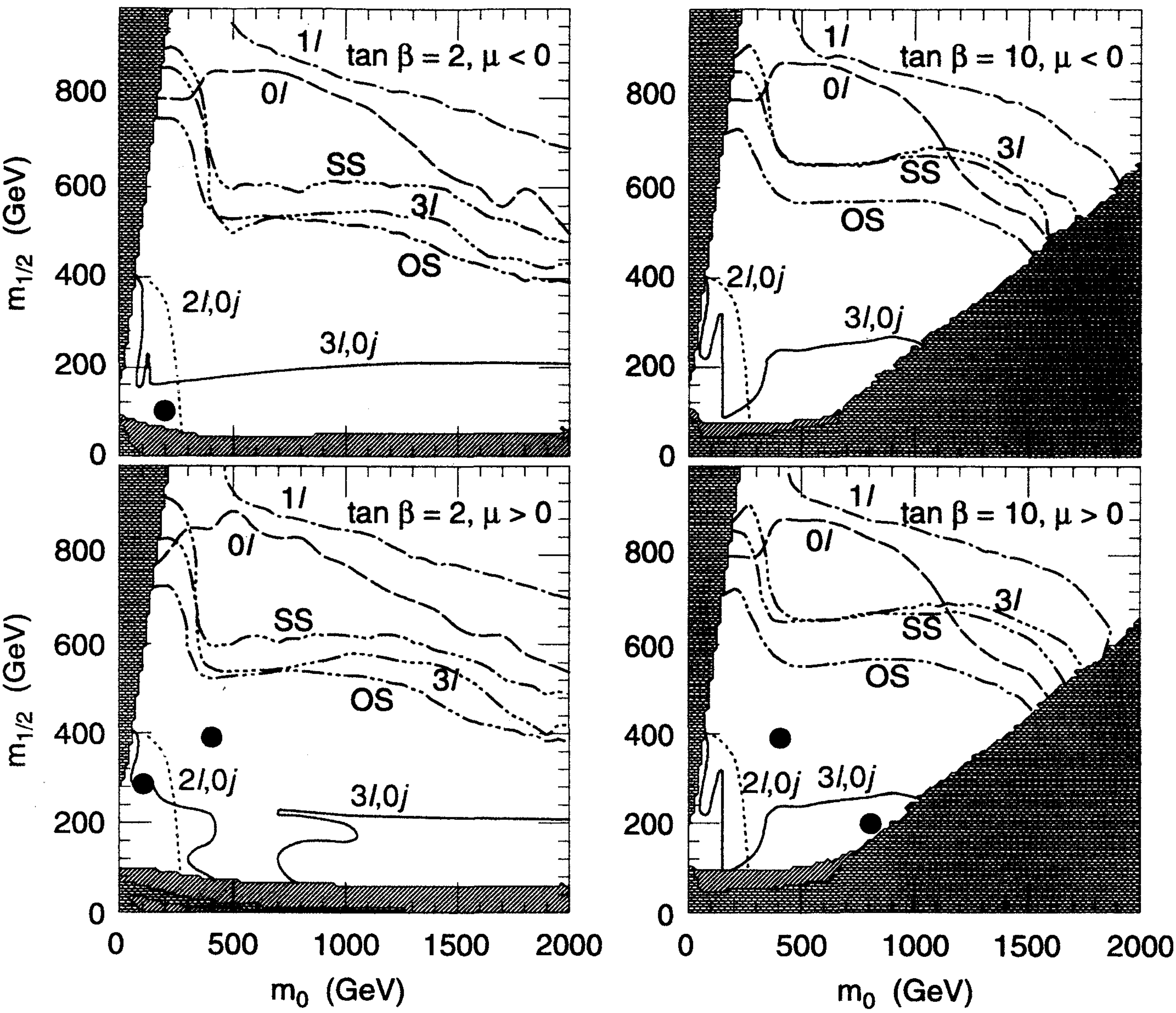


Baer, Chen, Paige and Tata

- five mSUGRA points selected by the LHCC for detailed study by ATLAS and CMS



igure 4: Total cross sections for various sparticle production processes by pp collisions at $\sqrt{s} = 14$ TeV.

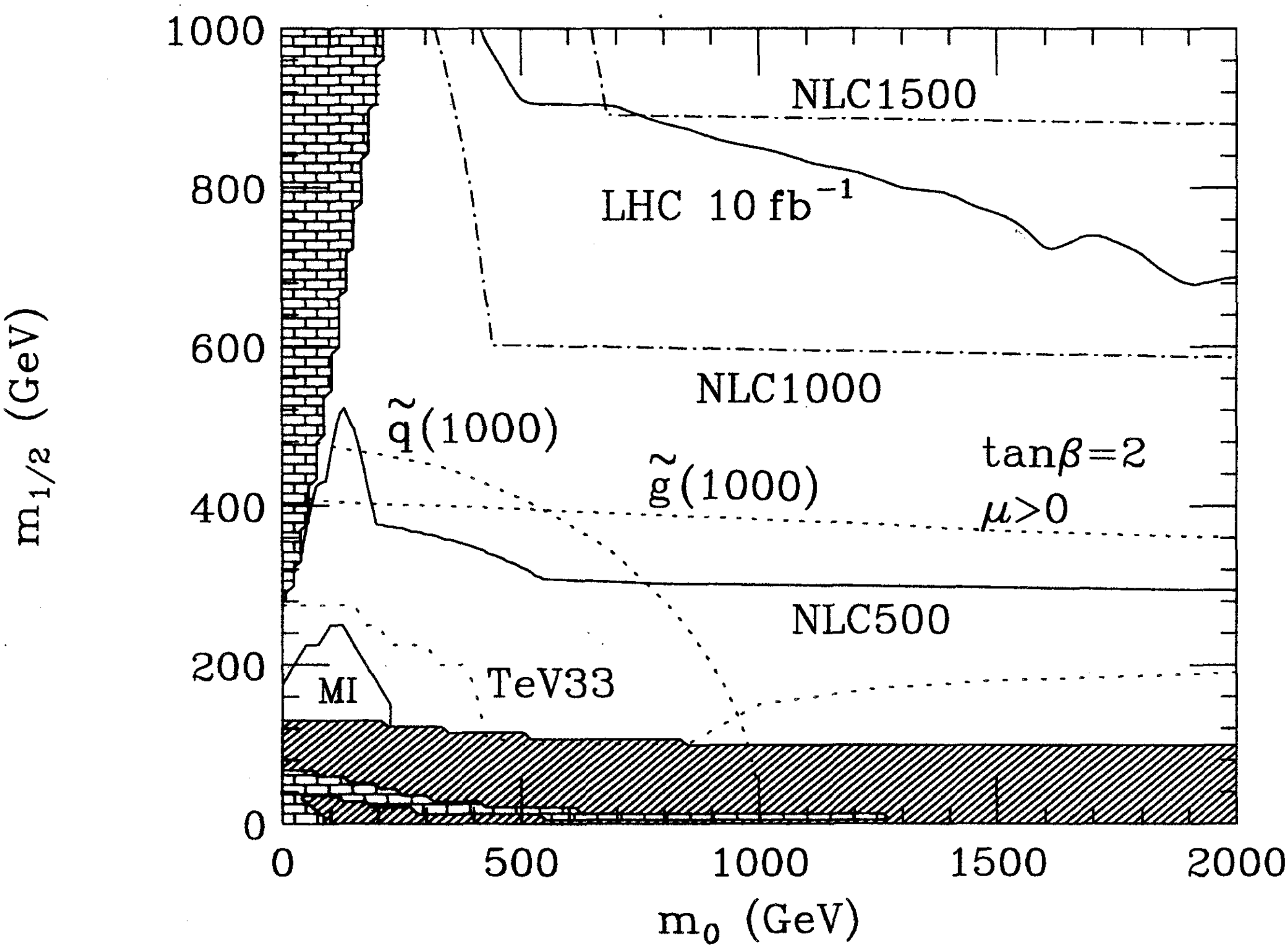


from the ATLAS Technical Design Report, Vol 2 (May 1999).

SS = same-sign dileptons
OS = opposite-sign dileptons
l = lepton
j = hadronic jet

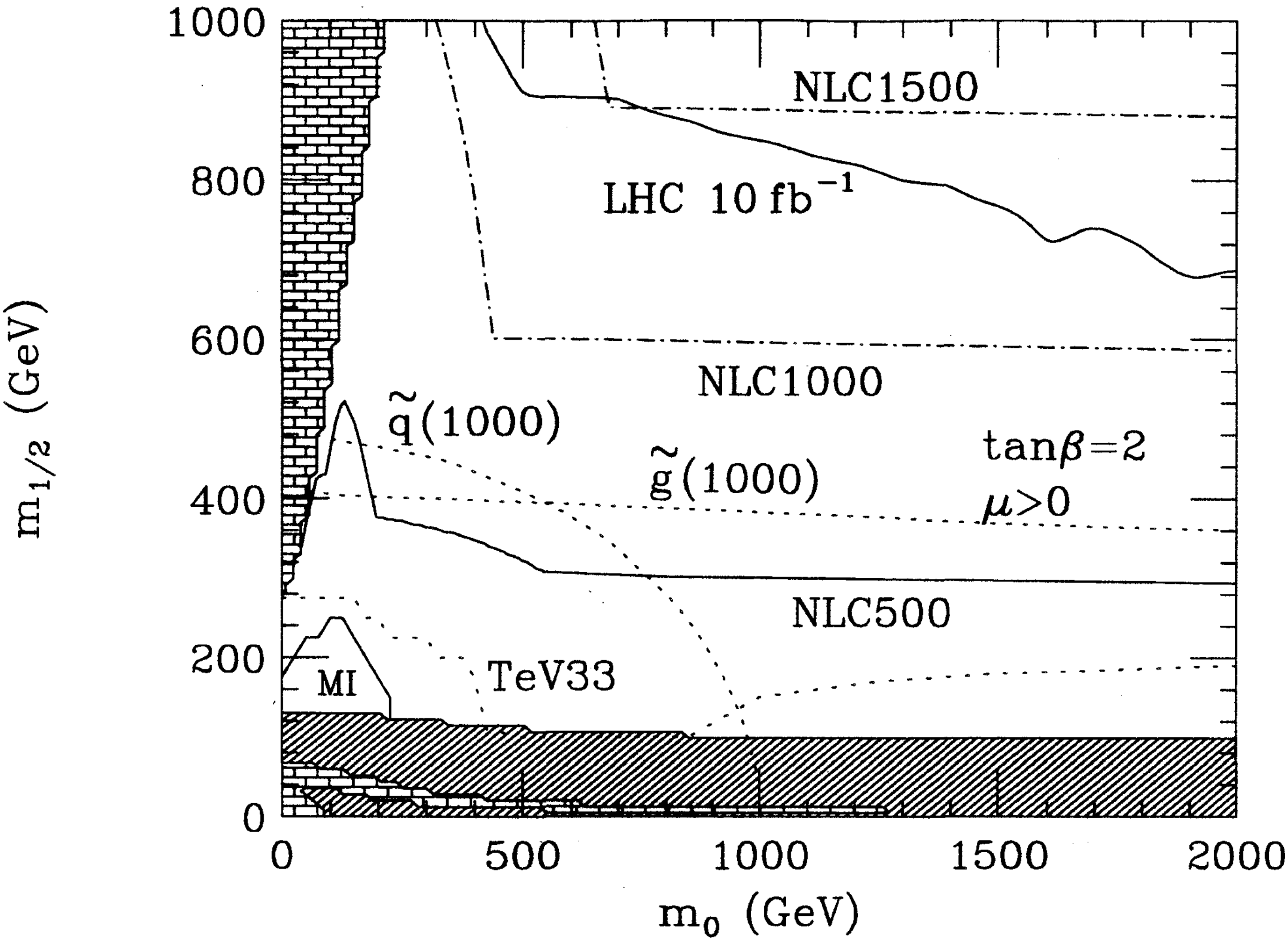
Signal	Tevatron 0.1 fb^{-1} 1.8 TeV	Tevatron 1 fb^{-1} 2 TeV	Tevatron 10 fb^{-1} 2 TeV	LHC 10 fb^{-1} 14 TeV
$\not{E}_T(\tilde{q} \gg \tilde{g})$	$\tilde{g}(210)/\tilde{g}(185)$	$\tilde{g}(270)/\tilde{g}(200)$	$\tilde{g}(340)/\tilde{g}(200)$	$\tilde{g}(1300)$
$l^{\pm}l^{\pm}(\tilde{q} \gg \tilde{g})$	$\tilde{g}(160)$	$\tilde{g}(210)$	$\tilde{g}(270)$	
$all \to 3l\ (\tilde{q} \gg \tilde{g})$	$\tilde{g}(180)$	$\tilde{g}(260)$	$\tilde{g}(430)$	
$\not{E}_T(\tilde{q} \sim \tilde{g})$	$\tilde{g}(300)/\tilde{g}(245)$	$\tilde{g}(350)/\tilde{g}(265)$	$\tilde{g}(400)/\tilde{g}(265)$	$\tilde{g}(2000)$
$l^{\pm}l^{\pm}(\tilde{q} \sim \tilde{g})$	$\tilde{g}(180-230)$	$\tilde{g}(320-325)$	$\tilde{g}(385-405)$	$\tilde{g}(1000)$
$all \to 3l\ (\tilde{q} \sim \tilde{g})$	$\tilde{g}(240-290)$	$\tilde{g}(425-440)$	$\gtrsim \tilde{g}(1000)$	
$\tilde{t}_1 \to c\widetilde{\chi}_1^0$	$\tilde{t}_1$(80–100)	$\tilde{t}_1(120)$		
$\tilde{t}_1 \to b\widetilde{\chi}_1^{\pm}$	$\tilde{t}_1$(80–100)	$\tilde{t}_1(120)$		
$\Theta(\tilde{t}_1\tilde{t}_1^*) \to \gamma\gamma$	—	—	—	$\tilde{t}_1(250)$
$\tilde{\ell}\tilde{\ell}^*$	$\tilde{\ell}(50)$	$\tilde{\ell}(50)$	$\tilde{\ell}(100)$	$\tilde{\ell}$(250–300)

Estimates of the discovery reach of various options of future hadron colliders. The signals have mainly been computed for negative values of μ. [from H. Baer, H. Murayama and X. Tata, in *Electroweak Symmetry Breaking and New Physics at the TeV Scale*]



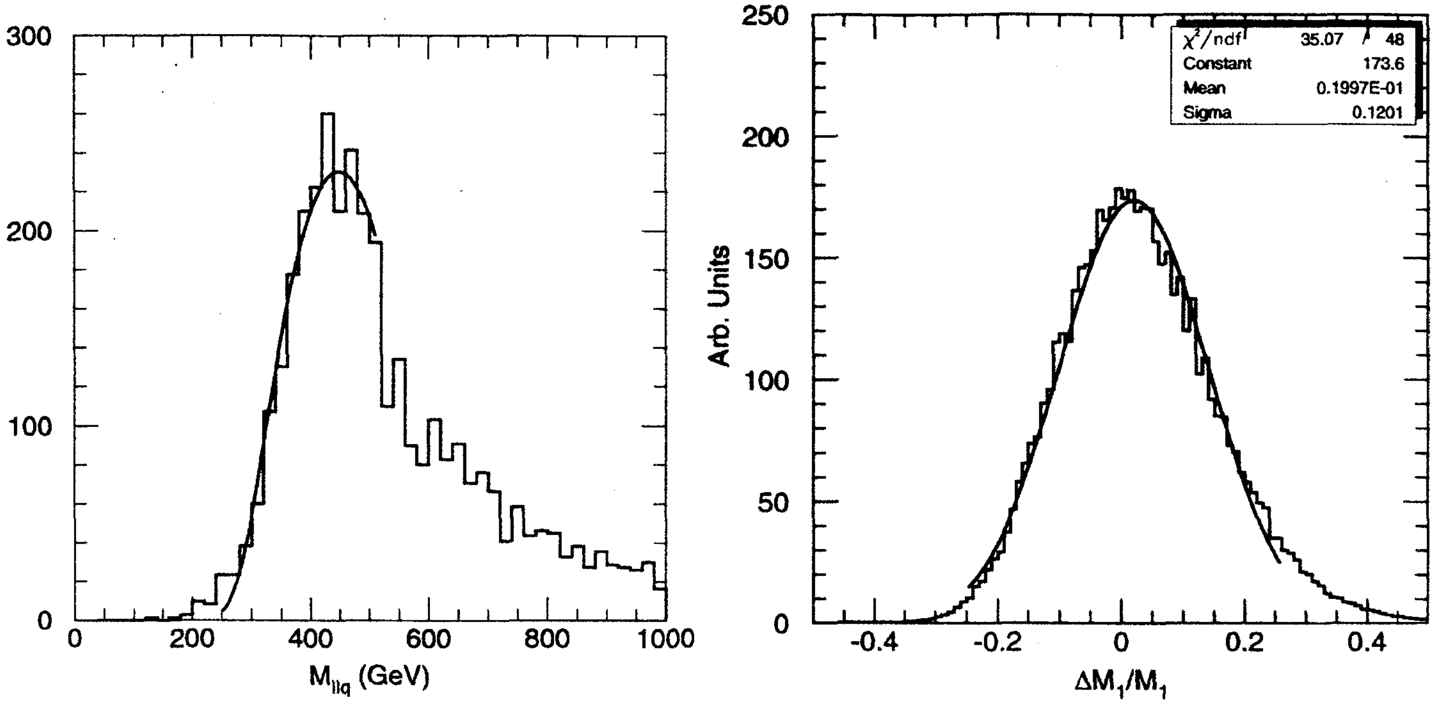
'SY reach for various facilities as given by the mSUGRA ı and $\mu > 0$.

ɜrmediate portion of the contour. The dashed-dotted ɔoundaries of the region where $\widetilde{W}_1$ and/or $\tilde{e}_R$ are kinen at NLC1000 or 1500. Although new backgrounds fron l four-particle production processes have not been ev that this region closely approximates the reach of t



Y reach for various facilities as given by the mSUGRA
nd $\mu > 0$.

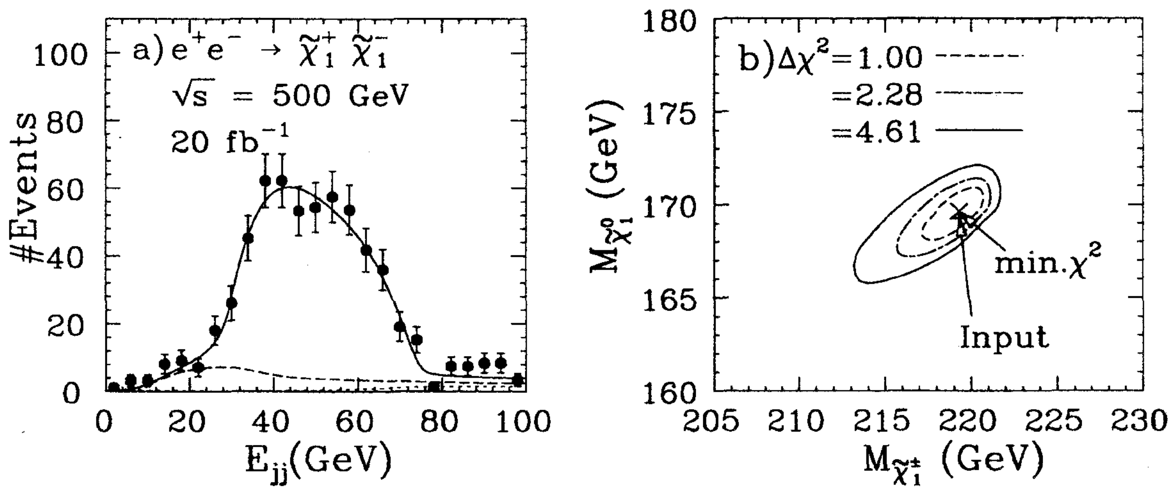
mediate portion of the contour. The dashed-dotted
undaries of the region where $\widetilde{W}_1$ and/or $\tilde{e}_R$ are kinen
NLC1000 or 1500. Although new backgrounds fron
our-particle production processes have not been ev
hat this region closely approximates the reach of t



from the ATLAS TDR

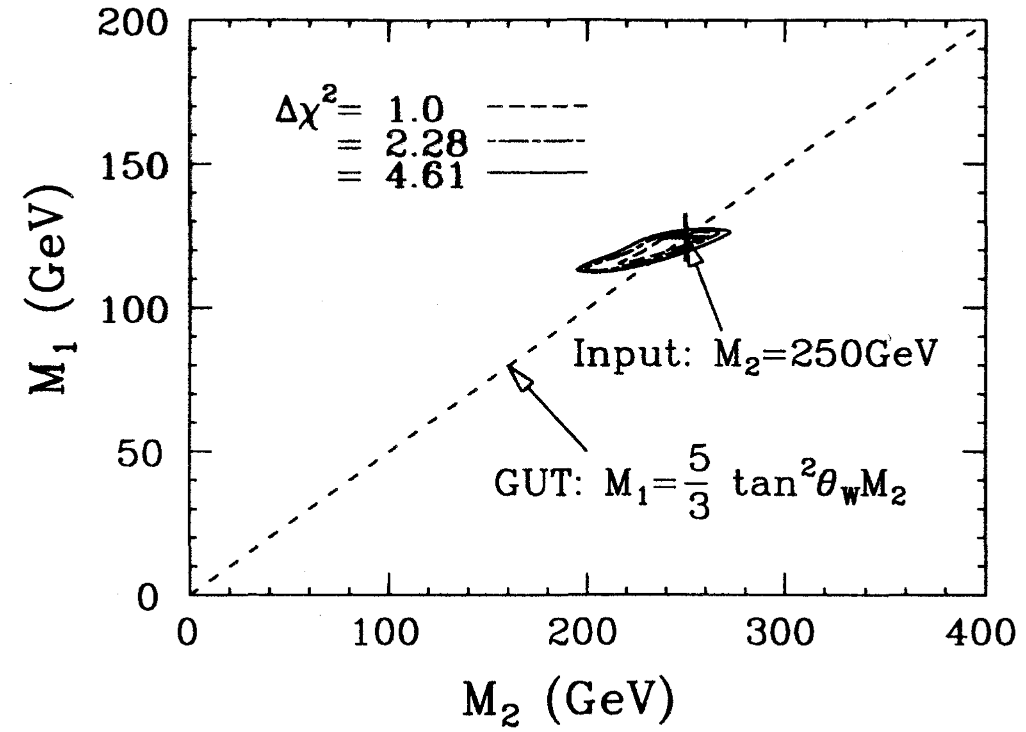
$\tilde{q}_L \to \tilde{\chi}^0_2 q \to \tilde{\ell}^\pm_R \ell^\mp q \to \tilde{\chi}^0_1 \ell^+ \ell^- q$

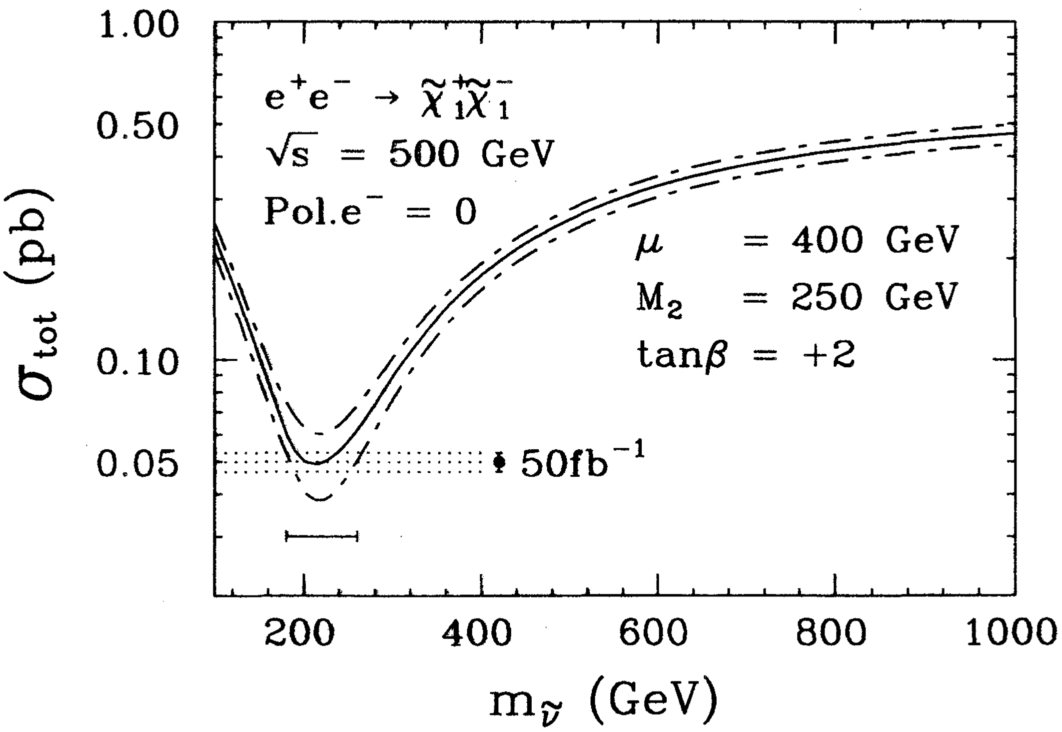
precision measure of $\tilde{\chi}^0_1$ mass. (±12%)



NLC simulation

Tsukamoto, Fujii, Murayama, Yamaguchi and Okada (1995)





Tsukamoto, Fujii, Murayama, Yamaguchi and Okada
NLC simulation