2 - Supersymétrie

2.1 - Histoire et motivations

2.2 - Structure d'une théorie supersymétrique

2.3 - Vers des modèles réalistes

2.4 - Contraintes expérimentales

2.5 - Comment découvrir la supersymétrie

2.1 - Early History and Motivations

Attempts to combine internal/external symmetries

$SU(3) \rightarrow SU(6)\ ,\ \tilde{U}(12), \ldots$ 1960's

No-go theorems Coleman + Mandula

for any bosonic charges 1967

Extension of Poincaré algebra with fermionic charges Gol'fand + Likhtman 1971

Two-dimensional supersymmetry

dual (string) models with fermions 1971

Neveu + Schwarz, Ramond

Nonlinear realization of supersymmetry

for neutrinos Volkov + Akulov 1973

4-dimensional supersymmetric field theories

mesons ⇔ baryons Wess + Zumino 1973, 197

Absences of many divergences

Wess + Zumino, Iliopoulos, Ferrara 1974

Supergravity = local supersymmetry

Freedman + van Nieuwenhuizen + Ferrara 1976

Deser + Zumino

Early Ideas for Using Supersymmetry

- Unify bosons and fermions

- Neutrino as Goldstone fermion

  data × low-energy theorems DeWit + Freedman

- Fewer infinities, may be finite

  $N=1$ susy $N=4$, some $N=2$

- Link Higgs to other particles

  $H \Leftrightarrow$ lepton? $(\Delta L \neq 0)$ $H_0 \Leftrightarrow f_{1/2} \Leftrightarrow W_1$ Fayet

- Last possible symmetry of S-matrix Haag + Łopuszański + Sohnius

  CH: "Anything not forbidden is compulsory"

  nuclear physics, atomic physics, critical phenomena.

- Local supersymmetry involves gravity

  $G(J=2) \rightarrow \tilde{G}\,(J=3/2)$

- Unification of all interactions

  $N>2$: $G \rightarrow \tilde{G} \rightarrow$ gauge $(J=1) \rightarrow \ldots$?

No clue about sparticle masses: could be m

10^{19} GeV

Archives

Ref.TH.1794-CERN

A LAGRANGIAN MODEL INVARIANT UNDER SUPERGAUGE TRANSFORMATIONS

J. Wess
Karlsruhe University

and

B. Zumino
CERN - Geneva

A B S T R A C T

We study, in the one-loop approximation, a Lagrangian model invariant under supergauge transformations. The model involves a scalar, a pseudoscalar and a spinor field. Supergauge invariance gives rise to relations among the masses and the couplings of these fields and implies the existence of a conserved current. The renormalization procedure is discussed and the relations among masses and couplings are shown to be preserved by renormalization.

Ref.TH.1794-CERN
13 December 1973

Why Supersymmetry?

Hierarchy Problem:

why is $m_W \ll m_P$? energy: gravity ~ other forces: $m_P \sim 10^{19}$ GeV

alternatively

why is $G_F \gg G_N$? $\frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_P^2}$

or

why is $V_{Coulomb} \gg V_{Newton}$? $e^2 \gg G_N m^2 \sim m^2/m_P^2$

Set by hand?

what about quantum corrections?

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2 \gg m_H^2$$

cut off $\Lambda \sim m_P$?

made naturally small by supersymmetry:

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)(m_B^2 - m_F^2)$$

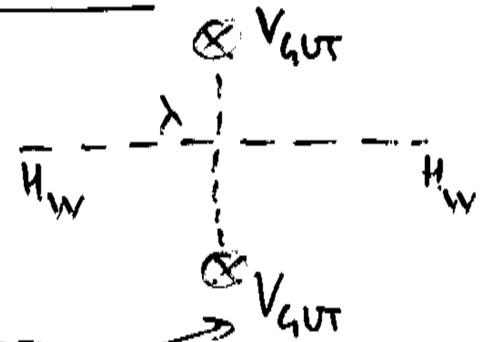
$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2$$

Low-energy supersymmetry

in theories with large, small scales

"Leakage" of large → small scale

e.g. Grand Unified Theory



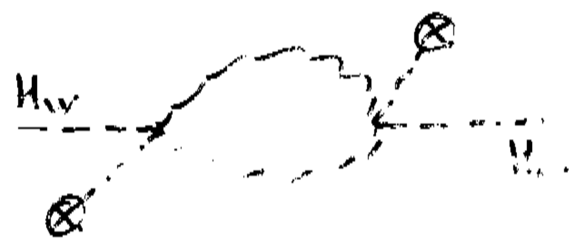
$$\delta m_H^2 \simeq \lambda . V_{GUT}^2$$

large v.e.v.

even if $\lambda = 0$ at tree level (why? hierarchy)

non-zero coupling regenerated by radiative correction

$$\delta m_H^2 \simeq O\left(\frac{\alpha}{\pi}\right)^2 V_{GUT}^2$$



need symmetry to suppress many orders of perturbation theory!

e.g. Quantum Gravity?

$$\delta m_H^2 = O(m_P^2) \quad ?$$

to be sure, need consistent quantization of gravity

only theory available is string

difficult (impossible?) to formulate without supersymmetry

(S)Experimental Hints

2 indications from precision (LEP) data

- Higgs boson probably light

  global fit: $m_H \lesssim 200$ GeV

  consistent with prediction of MSSM:

$$m_H \lesssim 130 \text{ GeV}$$

- Measured gauge couplings favour supersymmetric grand unified theories

  minimal non-supersymmetric GUT:

$$\sin^2\theta_W(m_Z)\Big|_{\overline{MS}} \simeq 0.214 \pm 0.004$$

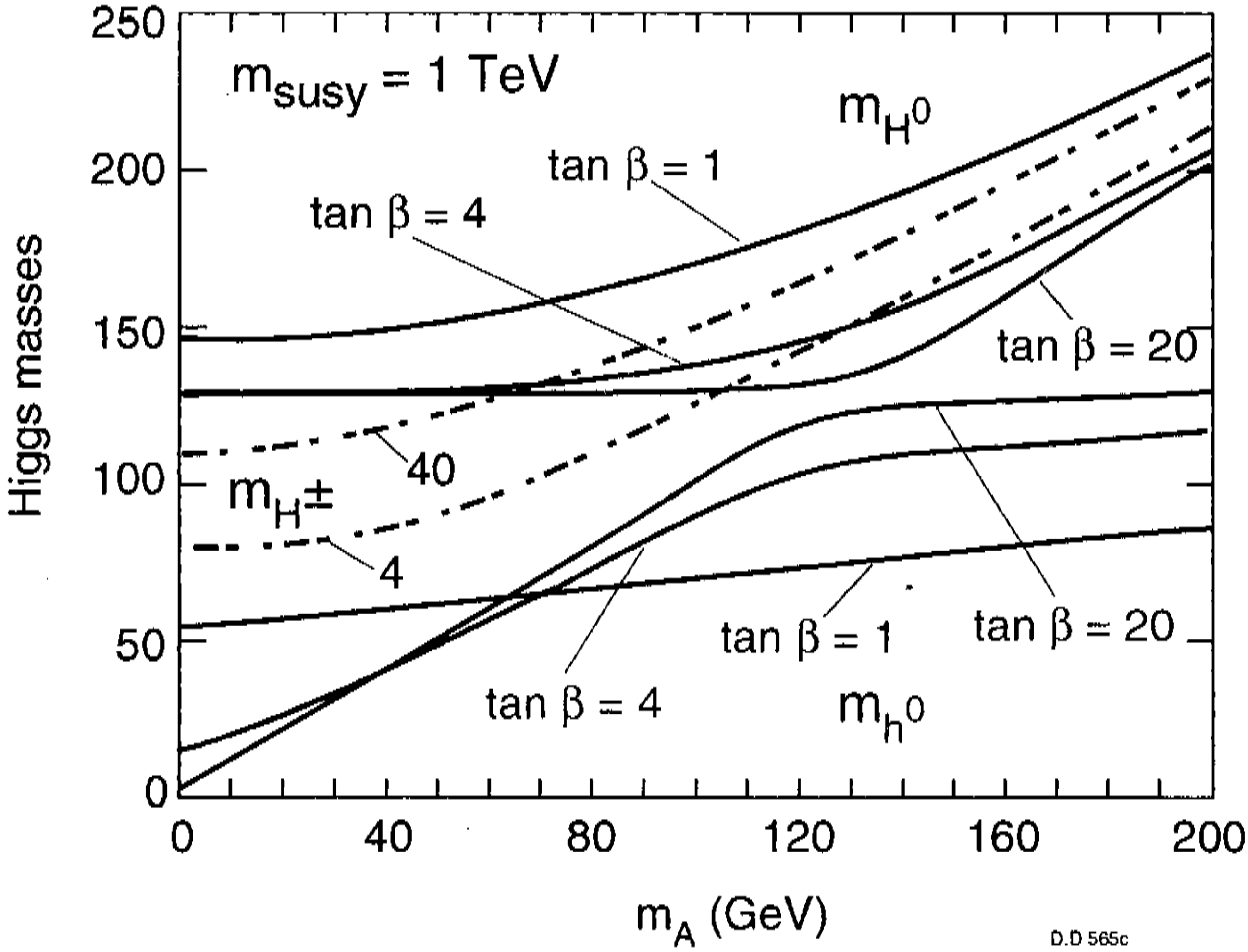
  experimental value:

$$\sin^2\theta_W(m_Z)_{\overline{MS}} \simeq 0.232 \pm$$

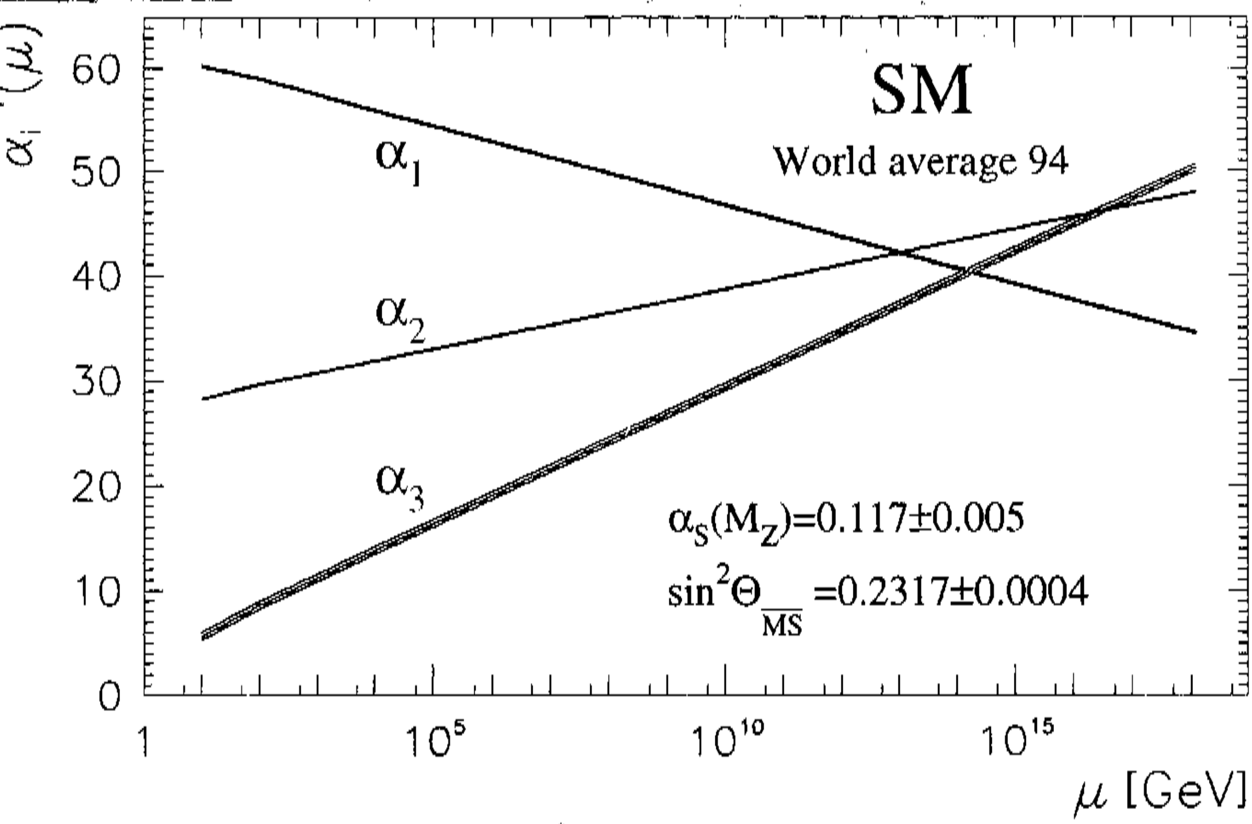
depends on spartiole masses

Higgs Masses in Supersymmetry

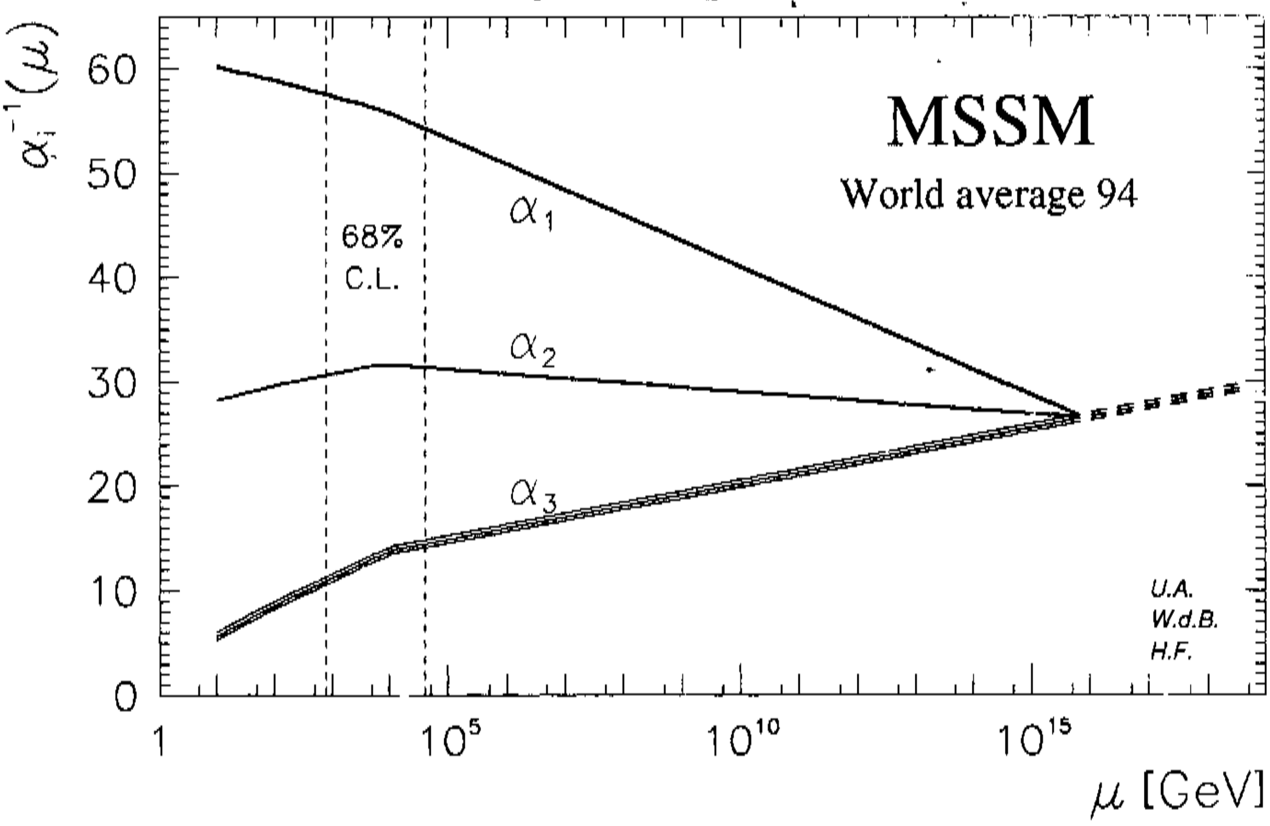
$m_{h,\,H,\,H^{\pm}}$ versus m_A, for various tg β
and M_{top} = 174 GeV



Unification!



with



1990

S.E. + Kelley + Nanopou

Langacker + Luo

Amaldi de Boer Fürstenau

1991

Glasgow HEP Conference 1994 :

$M_S=10^{3.7\pm0.8\pm0.4}$ GeV $\qquad M_U=10^{15.9\pm0.2\pm0.1}$ GeV

return to this later!

Only possible susy algebra

Symmetry generators must commute with Hamiltonian:
$$[Q^i, H] = 0 \qquad i = 1, 2, \ldots, N \text{ [illegible]}$$

Hence so also does anticommutator:
$$[\{Q^i, Q^j\}, H] = 0$$

But there is only one conserved Lorentz vector charge; so
$$\{Q^i, Q^j\} \propto P_\mu$$

Haag + Łopuszanski + Sohnius proved
$$\{Q^i, Q^j\} = 2\delta^{ij} \underset{\gamma^\mu P_\mu}{\underset{\parallel}{\not{P}}} C$$
C = C' [illegible] matrix

$N=1$ susy representations

Supermultiplets:

chiral (matter) $\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix}$ e.g. $\begin{pmatrix} l \\ \tilde{l} \end{pmatrix}$ lepton slepton

gauge $\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix}$ e.g. $\begin{pmatrix} \gamma \\ \tilde{\gamma} \end{pmatrix}$ [illegible]

graviton $\begin{pmatrix} 2 \\ \frac{3}{2} \end{pmatrix}$ graviton gravitino

1.2 - What is susy?

Bosons $\leftrightarrow$ Fermions Q_α

Last possible symmetry?

All previous symmetries have scalar charges Q

$$Q|\text{Spin } J\rangle = |\text{Spin } J\rangle$$

"Impossible" to mix internal/Lorentz symmetries (Coleman + Mandula)

because only possible conserved "tensor" charges are P_μ : 4-momentum. Lorentz scalars

"Proof" : consider $2 \to 2$ scattering $1+2 \to 3+4$

tensor charge? $\Sigma_{\mu\nu}$: $\langle a|\Sigma_{\mu\nu}|a\rangle = \alpha P^a_\mu P^a_\nu + \beta g_{\mu\nu}$

Lorentz invariance

in scattering process:

$$P^1_\mu P^1_\nu + P^2_\mu P^2_\nu = P^3_\mu P^3_\nu + P^4_\mu P^4_\nu$$

so conservation $\Rightarrow$ $P^1_\mu = P^3_\mu$ or P^4_μ

only forward scattering

BUT what about spinor charges Q_α ?

$\langle a|Q_\alpha|a\rangle = 0 \Rightarrow$ CM argument fails

Simplest supersymmetric field theory

left-handed

free fermion and boson: ← complex

$$L_0 = i\bar{\psi}_L \not{\partial} \psi_L + |\partial_\mu \phi|^2$$

drop for simplicity

simplest possible transformation law for boson:

$$\phi \to \phi + \delta\phi \quad : \quad \delta\phi = \bar{\epsilon}\psi \qquad [\psi] = \tfrac{3}{2}$$

$[\phi] = 1 \qquad [\epsilon] = -\tfrac{1}{2}$ must be right-handed

most general transformation for fermion:

$$\psi \to \psi + \delta\psi \quad : \quad \delta\psi = -a\, i(\not{\partial}\phi)\epsilon - F\epsilon^c$$

fix these later   lefty

transformation of full lagrangian:

$$\delta L_0 = \partial_\mu \left(\bar{\psi}\epsilon \partial^\mu \phi + \bar{\epsilon}\gamma^\mu \phi^* \not{\partial}\psi \right]$$

iff $\quad a = 1 \quad , F = 0$

then theory is invariant:

$$\delta A_0 = \delta \int d^4x\, L_0 = 0$$

is it supersymmetry?

$$\phi \xrightarrow{Q} \psi \xrightarrow{Q} \partial\phi \; ; \qquad \psi \xrightarrow{Q} \partial\phi \xrightarrow{Q} \partial\psi$$

"P   "P   YES!

Interacting field theory:

$$L = L_0 - V(\phi^i, \phi^*_j) - \tfrac{1}{2} M_{ij}(\phi, \phi^*) \bar{\chi}^{c,i} \chi^j$$

general potential ... mass, Yukawa

can determine forms of V, M by consistency with sup

eg: suppose M depends non-trivially on ϕ^*:

then $\delta(M \bar{\chi}^c \chi) \ni \frac{\partial M}{\partial \phi^*} \chi^* \bar{\chi}^c \chi$

cannot be compensated by variation of any other term

must vanish $\Rightarrow M = M(\phi)$ alone

also $\delta(M \bar{\chi}^c \chi) \ni \frac{\partial M_{ij}}{\partial \phi^k} E \chi^k \bar{\chi}^{c,i} \chi^j$

vanishes only if $\frac{\partial M_{ij}}{\partial \phi^k}$ symmetric in i, j, k

possible only if $\boxed{M_{ij} = \frac{\partial W}{\partial \phi^i \partial \phi^j}}$

for some function W called the superpotential

also: $\delta(M \bar{\chi}^c \chi) \ni M_{jk} \bar{\chi}^{c,j}\, i \not{\partial} \phi^k E + (\text{herm. conj})$

cancels $\delta(\bar{\chi}_i \not{\partial} \chi^i) \ni -i \bar{\chi}_i \not{\partial} F^i E^c + (\text{herm. conj.})$

if $\frac{\partial F^*_i}{\partial \phi^j} = M_{ij} \Rightarrow \boxed{F^*_i = \frac{\partial W}{\partial \phi^i}}$

Effective Potential

$$\delta V \ni \frac{\partial V}{\partial \phi^i} \bar{\epsilon} \psi^i \quad + \text{(herm. conj.)}$$

cancels $\quad \delta(M \bar{\psi}^c \psi) \ni M_{ij} \bar{\psi}^{c,i} F^j \epsilon^c$

if $\quad \dfrac{\partial V}{\partial \phi^i} = M_{ij} F^j \quad \Rightarrow \quad V = \left| \dfrac{\partial W}{\partial \phi^i} \right|^2 = |F^i|^2$

potential is determined by superpotential

complete interacting supersymmetric model:

$$L = i \bar{\psi}_i \not{\partial} \psi^i + |\partial_\mu \phi^i|^2$$
$$- \left| \frac{\partial W}{\partial \phi^i} \right|^2 - \frac{1}{2} \frac{\partial^2 W}{\partial \phi^i \partial \phi^j} \bar{\psi}^{c,i} \psi^j \quad + \text{(herm. conj.)}$$

is invariant under

$$\delta \phi^i = \bar{\epsilon} \psi^i \,, \quad \delta \psi^i = -i \not{\partial} \phi^i \epsilon - F^i \epsilon^c \,: \; F^i = \left(\frac{\partial W}{\partial \phi^i} \right)^*$$

simplest case: $\quad W = \dfrac{\lambda}{3} \phi^3 + \dfrac{m}{2} \phi^2$

$$L = i \bar{\psi} \not{\partial} \psi + |\partial_\mu \phi|^2 - |m\phi + \lambda \phi^2|^2 - m \bar{\psi}^c \psi - \lambda \phi \bar{\psi}^c \psi$$

equal masses

Yukawa

related to potential

Supersymmetric Gauge Theory

must have vectors A_μ^a

and adjoint fermions χ^a

$\Rightarrow$ unique lagrangian:

$$L = \frac{i}{2}\bar{\chi}^a \not{D}_{ab}\chi^b - \frac{1}{2}F^a_{\mu\nu}F^{\mu\nu a} - \frac{1}{2}(D^a)^2$$

where $D^{ab}_\mu = \delta^{ab}\partial_\mu - g f^{abc}A^c_\mu$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc}A^b_\mu A^c_\nu$$

is automatically supersymmetric

$$\delta A^a_\mu = -\bar{\epsilon}\gamma_\mu\gamma_5\chi^a$$

$$\delta\chi^a = -\frac{i}{2}F^a_{\mu\nu}\gamma^\mu\gamma^\nu\gamma_5\epsilon + D^a\epsilon$$

$$\delta D^a = -i\,\bar{\epsilon}\not{D}^{ab}\chi^b$$

equation of motion $\Rightarrow D^a = 0$

unless matter is included:

add $\Delta L = -\sqrt{2}\,g\,\chi^a\phi^*_i (T^a)^i_j \psi^j + (\text{herm. conj.})$

$$+ g\,(\phi^*_i (T^a)^i_j \phi^j)\,D^a$$

now equation of motion $\Rightarrow D^a = g\,\phi^*_i (T^a)^i_j \phi^j$

full potential: $\boxed{V = \sum_i |F_i|^2 + \sum_a \frac{1}{2}(D^a)^2}$

Why $N > 1$ not useful

Parity Violation

consider simplest extension: $N = 2$

helicity

$$\begin{tikzcd}
& \frac{1}{2} \arrow[dl, "Q_1"'] \arrow[dr, "Q_2"] & \\
0 \arrow[dr, "Q_2"'] & & 0 \arrow[dl, "Q_1"] \\
& -\frac{1}{2} &
\end{tikzcd}$$

Q_1, Q_2

if right-handed fermion: $+\frac{1}{2}$ helicity

is in representation R of gauge group

so also is left-handed fermion: $-\frac{1}{2}$

would $\Rightarrow$ $W^{\pm}$ couple identically to q_L, q_R

$\Rightarrow$ no parity violation

similar argument for

$$\begin{tikzcd}
& +1 \arrow[dl, "Q_1"'] \arrow[dr, "Q_2"] & \\
+\frac{1}{2} \arrow[dr, "Q_2"'] & & +\frac{1}{2} \arrow[dl, "Q_1"] \\
& 0 &
\end{tikzcd}
\qquad
\begin{tikzcd}
& 0 \arrow[dl, "Q_1"'] \arrow[dr, "Q_2"] & \\
-\frac{1}{2} \arrow[dr, "Q_2"'] & & -\frac{1}{2} \arrow[dl, "Q_1"] \\
& -1 &
\end{tikzcd}$$

same (adjoint) representation for

$$+1 \longrightarrow +\frac{1}{2} \quad \cong \quad -\frac{1}{2} \longleftarrow -1$$

2.3 Model-Building

Known fermions $\Leftrightarrow$ "known" bosons?

q, l $\qquad\qquad$ γ, W, Z, H, g

Fayet

× q $\underline{3}$ of colour $\neq$ $\underline{1}, \underline{8}$

× l $L=1$ lepton number $\neq$ $L=0$

in particular $\begin{pmatrix} l \\ H \end{pmatrix}$: $\langle 0|H|0\rangle \neq 0 \Rightarrow \Delta L \neq 0$

$\Rightarrow$ introduce spartners for all particles

	J	sparticle	J
q	$\frac{1}{2}$	$\tilde{q}$ squark	0
l	$\frac{1}{2}$	$\tilde{l}$ slepton	0
γ	1	$\tilde{\gamma}$ photino	$\frac{1}{2}$
Z	1	$\tilde{Z}$ zino	$\frac{1}{2}$
$W^{\pm}$	1	$\tilde{W}^{\pm}$ wino	$\frac{1}{2}$
$H^{\pm,0}$	0	$\tilde{H}^{\pm,0}$ higgsino	$\frac{1}{2}$

candidate for Dark Matter

economy of principle, not of # particles!

Minimal Supersymmetric Extension of the Standard Model

$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{susy\times} \rightsquigarrow \text{later}$$

gauge interactions as in Standard Model

Yukawa interactions ← superpotential

analytic function of left-handed fields: $\psi_R \Rightarrow E^c, \ldots$

$$W = \sum_{L,E^c} \lambda_L \, L E^c H_1 + \sum_{Q,U^c} \lambda_U \, Q U^c H_2$$

e.w. doublets (L, Q); u_R, c_R, t_R (U^c)

$$\Downarrow \qquad\qquad \Downarrow$$

$$m_l = \lambda_L v_1 \qquad\qquad m_u = \lambda_u v_2$$

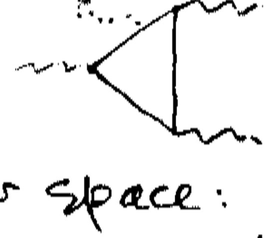
$$+ \sum_{Q,D^c} \lambda_D \, Q D^c H_1 + \mu H_1 H_2$$

$$\Downarrow \qquad\qquad \Downarrow$$

$m_d = \lambda_D v_1$ Higgs mixing

two Higgs doublets needed:

analytic W, cancel anomalies



Yukawa couplings matrices in flavour space:

diagonalization ⇒ Kobayashi-Maskawa angles

Effective potential:

$$V = \sum_i |F_i|^2 + \frac{1}{2} \sum_a (D^a)^2$$

$F_i^* = \partial W / \partial \phi^i$ sum over chiral fields 3 gauge groups $D_a = g_a \phi_i^* (T^a)^i_j \phi^j$

Supersymmetric Higgs Bosons

Five particles predicted:

3 neutrals — h; H, A

2 charged — $H^{\pm}$

lightest resembles Standard Model Higgs

predicted to be relatively light:

$m_h < m_Z$ @ classical (tree) level

$m_h \lesssim 130\,\text{GeV}$ including quantum corrections

kada et al)
:.E, Ridolfi, Zwirner)
laber + Hempfling)

consistent with analysis of electroweak data

more circumstantial evidence for supersymmetry?

Effective Low-Energy Theory

with softly-broken supersymmetry

$$\underbrace{m_0 \ , \ m_{1/2} \ , \ A}\quad (B)$$

parameters renormalized analogously to g_a

gaugino masses

same renormalization as α_i @ 1 loop:

$$M_a = \frac{\alpha_a}{\alpha_{GUT}} \cdot m_{1/2}$$

$+ \cdots$

assume universal (?) input @ M_{GUT}

scalar masses

$$\frac{dm_{0_i}^2}{dt} = \frac{1}{16\pi^2}\left[\lambda^2 (m_0^2 + A_\lambda^2) - g_a^2 M_a^2 \right]$$

group-theoretical coefficients

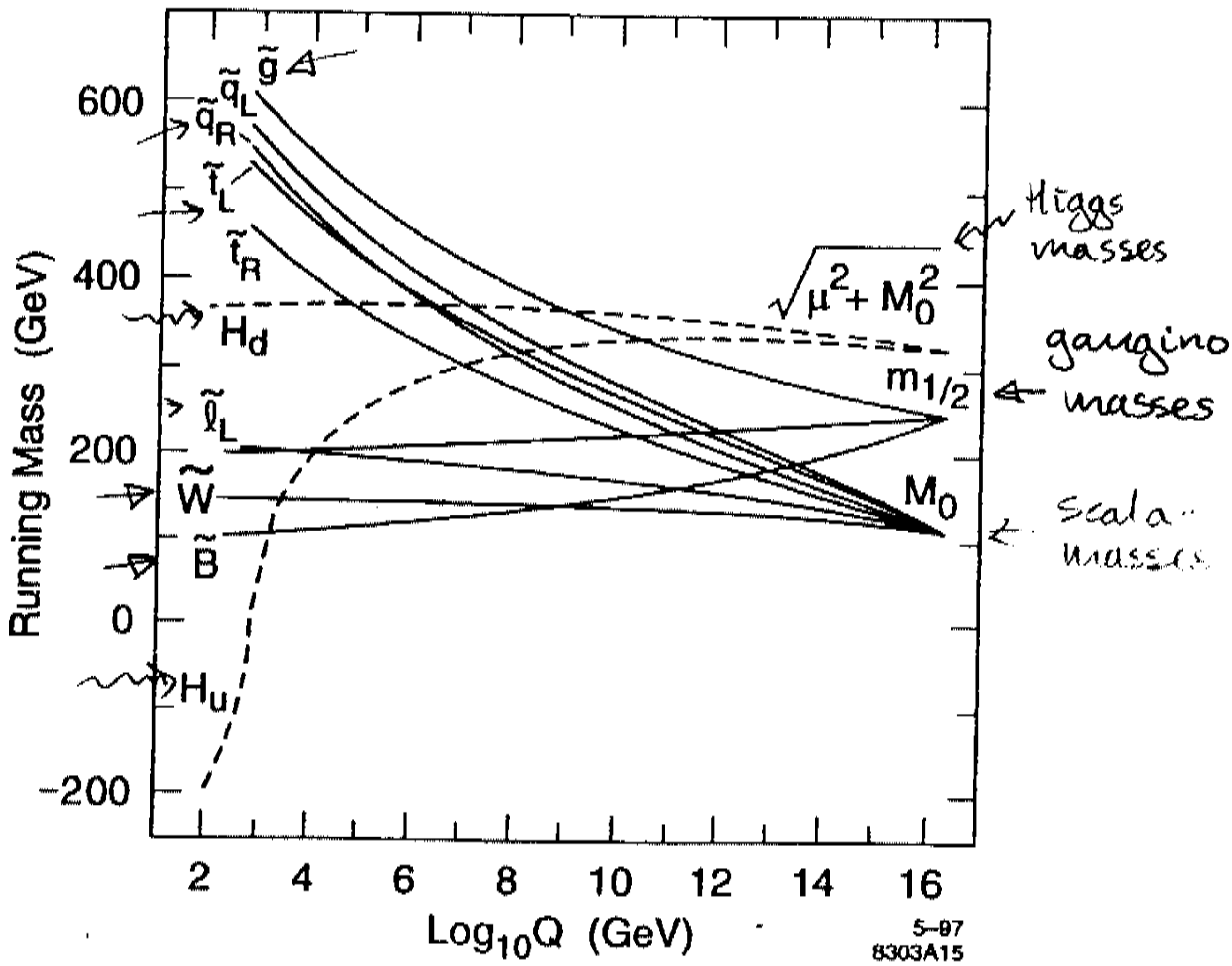
negligible for first two generations:

$$m_{0_i}^2 = m_0^2 + C_i \, m_{1/2}^2$$

calculable

important for third generation, Higgs

Renormalization of Soft Susy X Parameters



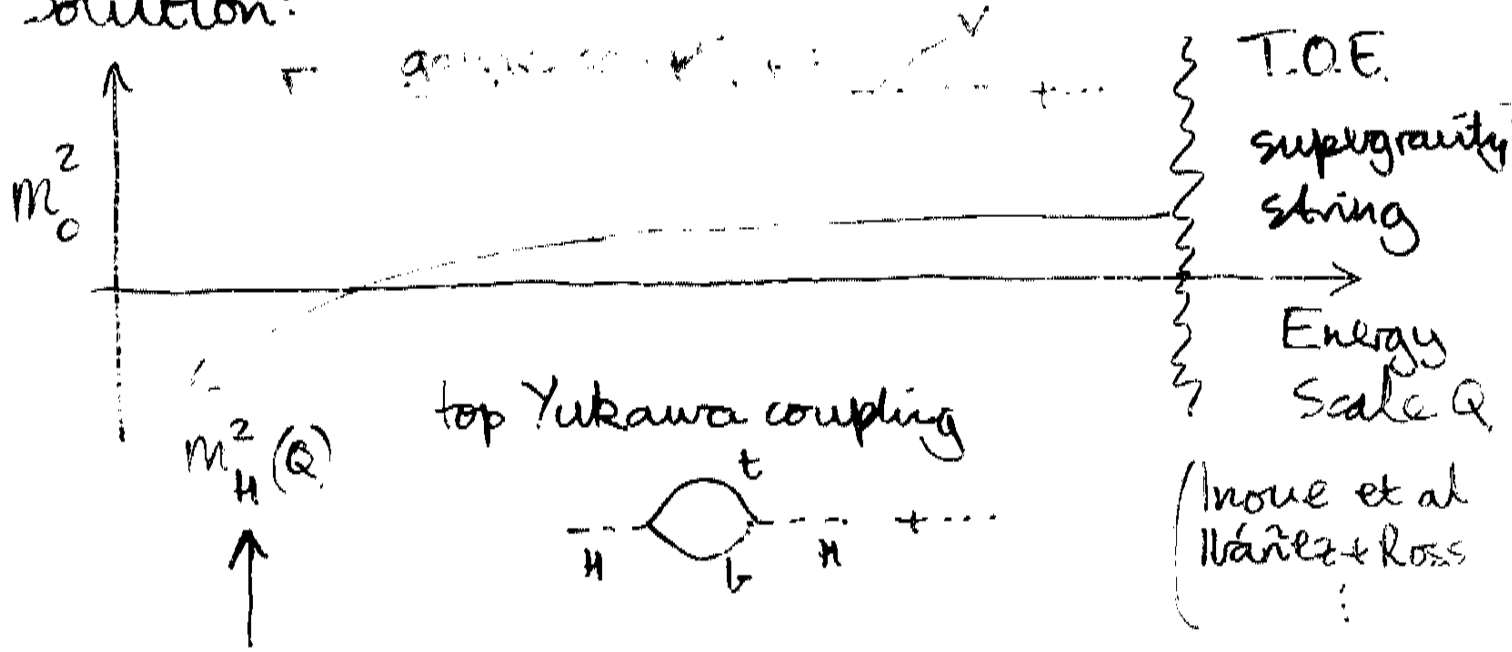
Electroweak Symmetry Breaking

driven by renormalization of susy X parameters?

Problem: super-Higgs mechanism $\Rightarrow$ $m_0^2 > 0$

EW Higgs mechanism $\Leftarrow$ $m_H^2 < 0$

Solution:



(Inoue et al
Ibáñez + Ross
⋮

EW symmetry breaking possible when

$$m_H^2(Q) < 0$$

requires "large" top quark Yukawa coupling (mass)

$$\frac{m_W}{m_P} = \exp\left(-\frac{O(1)}{\alpha_t}\right) \; : \; \alpha_t = \frac{\lambda_t^2}{4\pi}$$

$$m_t = \lambda_t \langle H \rangle$$

typical dynamical calculations:

$$m_t \simeq (60 \text{ to } 200) \text{ GeV}$$

Sparticle Masses and Mixing

sfermions

supersymmetric partners of f_L, f_R

$$M^2_{\tilde f} = \begin{pmatrix} m^2_{\tilde f_{LL}} & m^2_{\tilde f_{LR}} \\ m^2_{\tilde f_{LR}} & m^2_{\tilde f_{RR}} \end{pmatrix}$$

where $m^2_{\tilde f_{LL,RR}} = \tilde m^2_{\tilde f_{L,R}} + m^2_{\tilde f_{L,R}}(\text{D-term}) + m^2_f$

soft susy

and $m^2_{\tilde f_{LR}} = m_f \left(A_f + \mu \begin{matrix} \tan\beta \\ \cot\beta \end{matrix} \right)$

$$m^2(\text{D-term}) = M_Z^2 \cos 2\beta \left(I_3 - \sin^2\theta_W Q \right)$$

mixing important for $\tilde t$ $(\tilde b, \tilde \tau)$

charginos

$$-\tfrac{1}{2}(\tilde W^-, \tilde H_1^-)\, M_c \begin{pmatrix} \tilde W^+ \\ \tilde H_2^+ \end{pmatrix}$$

where $M_c = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$

diagonalize $\chi_1^\pm, \chi_2^\pm$

Neutralino Mass Matrix

$$\begin{pmatrix} M_2 & 0 & -\frac{g_2 v_2}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} \\ 0 & M_1 & \frac{g' v_2}{\sqrt{2}} & -\frac{g' v_1}{\sqrt{2}} \\ -\frac{g_2 v_2}{\sqrt{2}} & \frac{g' v_2}{\sqrt{2}} & 0 & \mu \\ \frac{g_2 v_1}{\sqrt{2}} & -\frac{g' v_1}{\sqrt{2}} & \mu & 0 \end{pmatrix}$$

conventional assumption:

$$M_2 = M_1 \qquad \text{CMSSM}$$

renormalization to lower scales:

$$M_2 : M_1 = \alpha_2 : \alpha_1$$

ratio of Higgs v.e.v.'s

$$\tan\beta = v_2/v_1$$

other parameters relevant to abundance, scattering calculations: Higgs sector

$$(m_h, \tan\beta) \quad \text{or} \quad (m_A, \tan\beta)$$

↑ must take m_t into account

scalar masses: $m_{\tilde{q}_i}^2 = m_0^2 + C_i\, m_{1/2}^2$

CMSSN

my favourite candidate for Cold Dark Matter

Lightest Supersymmetric Particle ?

- Expected to be stable in most models

  ⇒ present in Universe as cosmological relic

- Because of multiplicatively-conserved quantum number:

$$R \text{ parity} = \begin{cases} +1 & \text{for all particles} \\ -1 & \text{for all sparticles} \end{cases}$$ (Fayet

- Conservation related to those of baryon, lepton numbers:

$$R = (-1)^{3B+L+2S} \leftarrow \text{spin}$$

- Violation possible via spontaneous/explicit L X

$$\langle 0 | \tilde{\nu} | 0 \rangle \neq 0 \ ? \qquad HL \text{ coupling}$$

$$\uparrow \qquad\qquad \uparrow$$

constraints from laboratory, cosmology

3 important consequences of R conservation:

1) Sparticles always produced in pairs

   e.g. $pp \to \tilde{q}\tilde{g}X$, $e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$

2) Heavier sparticles decay into lighter ones

   e.g. $\tilde{q} \to q\tilde{g}$, $\tilde{\mu} \to \mu\tilde{\gamma}$

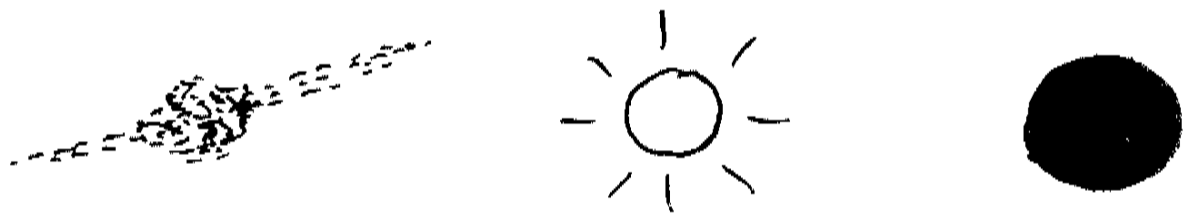
3) Lightest sparticle stable

   no legal decay mode!

Nature of Lightest Supersymmetric Particle

cannot have { electromagnetic charge / strong interactions

If it did, it would dissipate energy, condense into



be detectable as anomalous heavy isotopes

BUT upper limits $\ll$ expected abundance

$$\frac{n_{heavy}}{n_{normal}} \lesssim 10^{-15} \rightarrow 10^{-30}$$

$\Rightarrow$ relic does not bind to ordinary nuclei

$\Rightarrow$ no strong or electromagnetic interactions

Supersymmetric candidates

Spin:	0	½	1	3/2
	sneutrino	neutralino	—	gravitino
	excluded by LEP, dark matter searches	$\tilde{\gamma}/\tilde{H}/\tilde{Z}$ ← ↓		$\tilde{\chi}_1$ generally heavier tha

4 - Experimental constraints

no sparticles seen: $m_{\chi^\pm} \gtrsim 104\,\text{GeV}$

spartner of $W^\pm/H^\pm$ →

$m_{\tilde{e}} \gtrsim 100\,\text{GeV}$

also squarks, gluinos, ...

no Higgs seen: $m_H > 114.4\,\text{GeV}$

sensitive to sparticle masses:

$$\delta m_H^2 \propto \frac{m_t^4}{m_W^2} \ln\left(\tilde{m}^2/m_t^2\right)$$

$b \to s\gamma$ decay:

agreement with Standard Model leaves

sparticle loop contributions

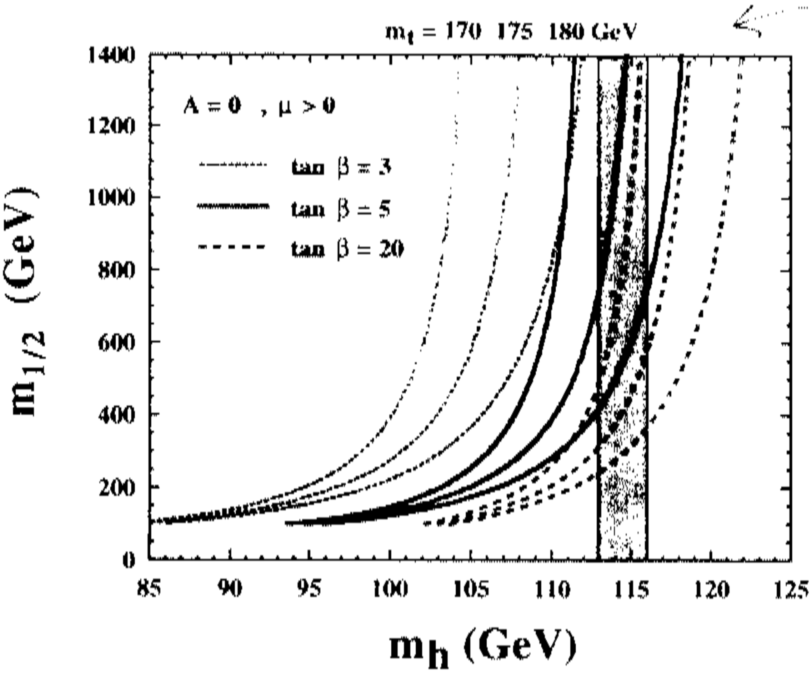
$(g-2)_\mu$:

consistent with MSSM:

is discrepancy significant?

cosmological relic density

very dependent on m_t



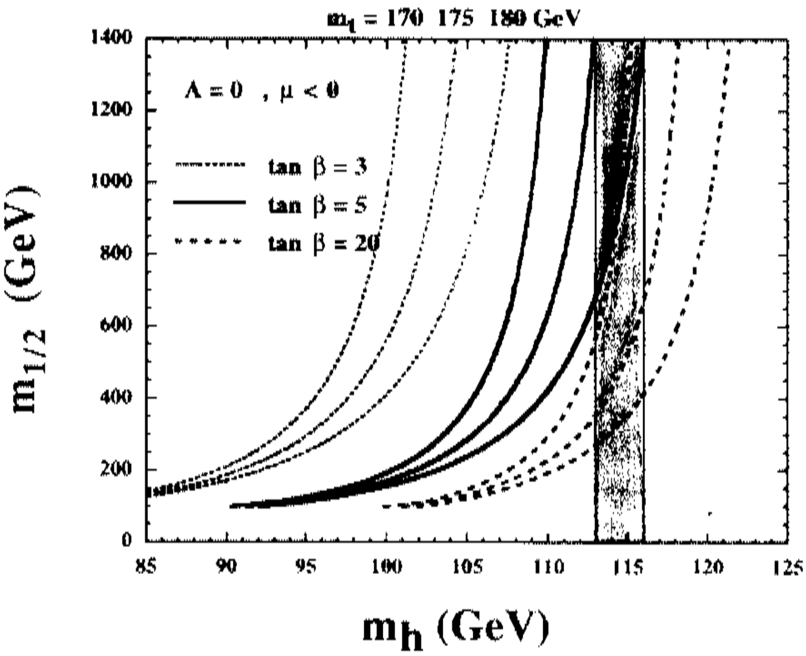


Figure 2: *The sensitivity of m_h to $m_{1/2}$ in the CMSSM for (a) $\mu > 0$ and (b) $\mu < 0$. The no-scale value $A = 0$ is assumed for definiteness. The dotted (green), solid (red) and dashed (blue) lines are for* $\tan\beta = 3, 5$ *and* 20, *each for* $m_t = 170, 175$ *and* 180 *GeV (from left to right). The lines are relatively unchanged as one varies* $\tan\beta \gtrsim 10$, *where they are also insensitive to the sign of μ. The shaded vertical strip corresponds to* 113 GeV $\le m_h \le$ 116 GeV.

<u>Sensitivity to $m_{1/2}$</u>

(EGNO

Supersymmetric Parameter Space after WMAP

assuming universal
scalar masses m_0 } @ M_{GUT}
fermion masses $m_{1/2}$ }

before/**after** WMAP

✓ cold dark matter

✓ $g_\mu - 2$

× $\leftarrow m_\chi < m_{\tilde{\tau}_1}$

× $b \to s\gamma$

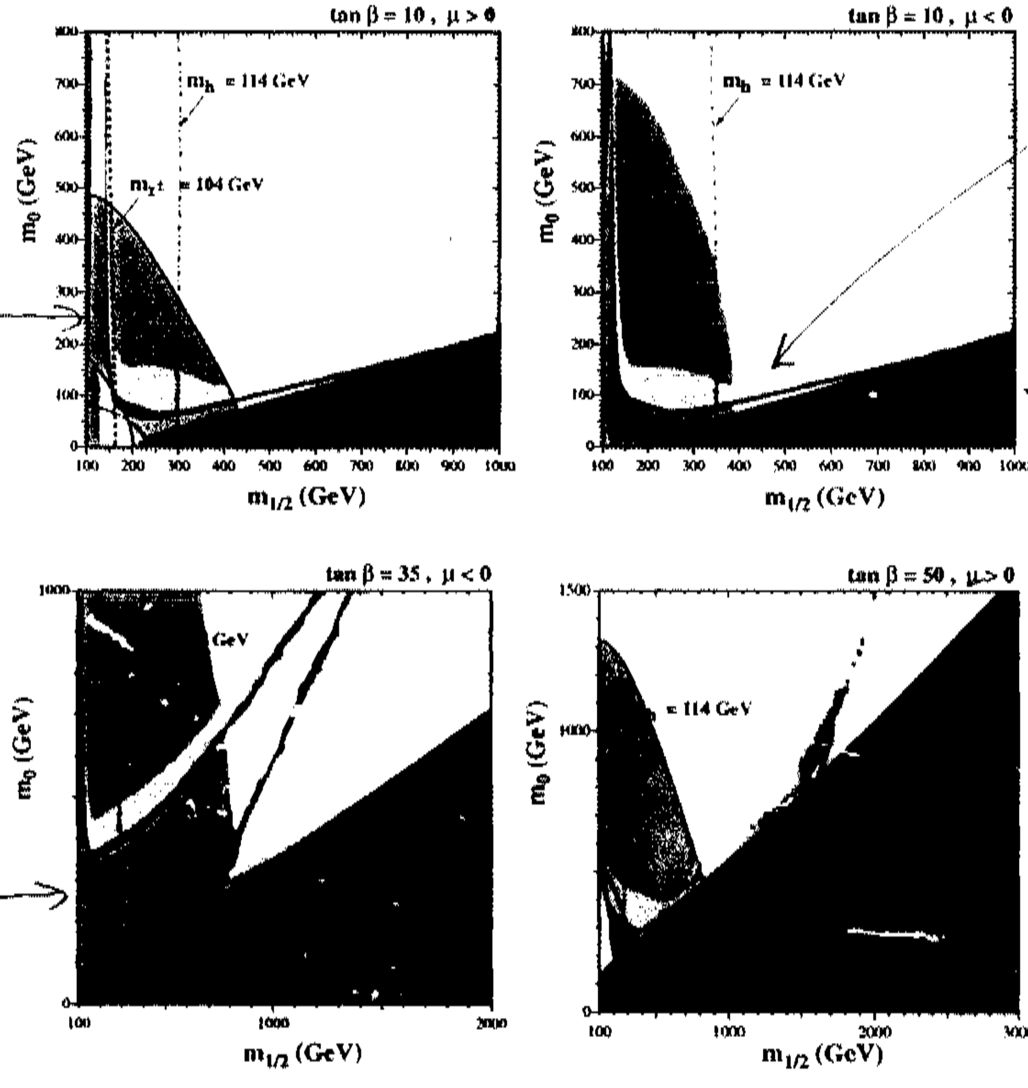
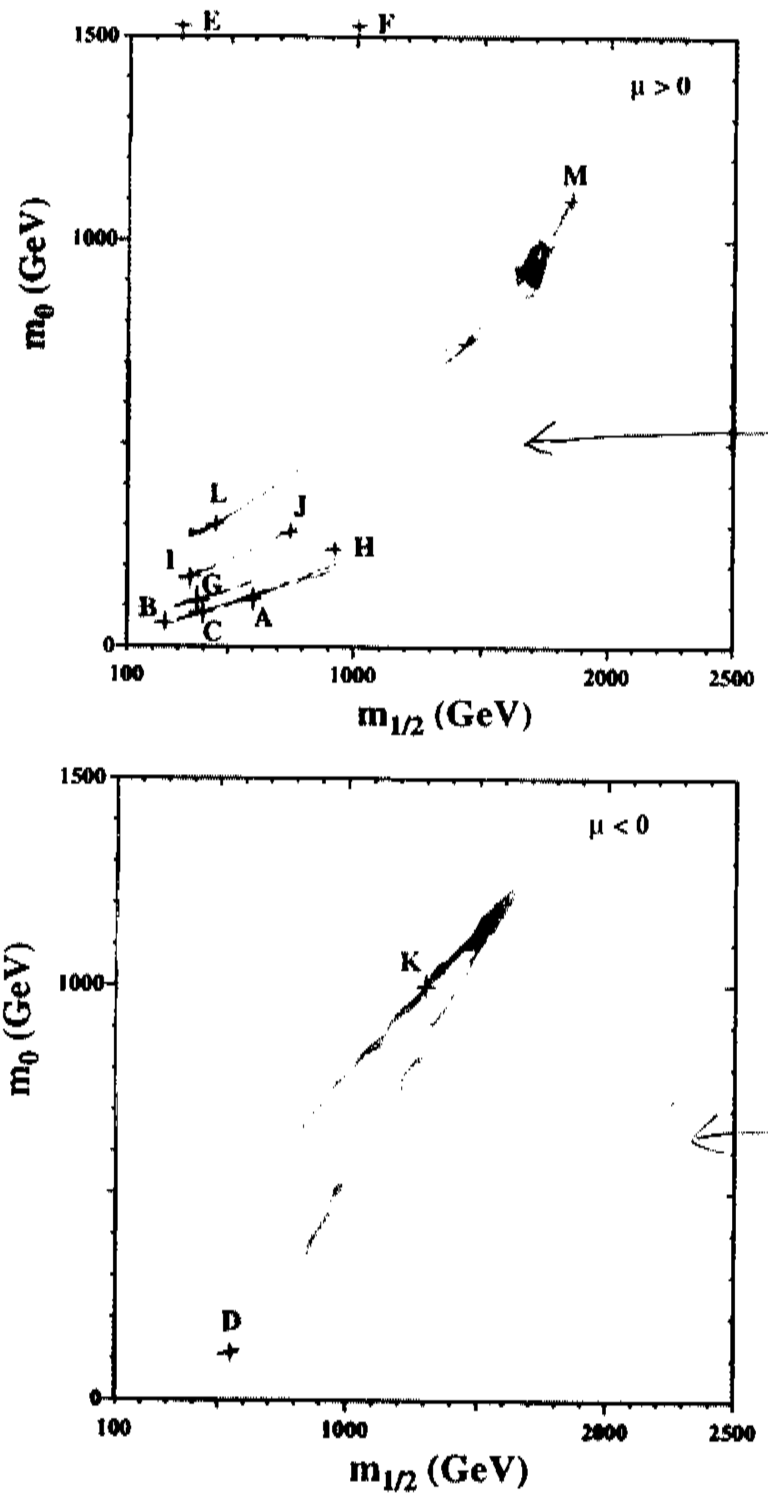


Figure 1: *The $(m_{1/2}, m_0)$ planes for (a) $\tan\beta = 10, \mu > 0$, (b) $\tan\beta = 10, \mu < 0$, (c) $\tan\beta = 35, \mu < 0$, and (d) $\tan\beta = 50, \mu > 0$. In each panel, the region allowed by the older cosmological constraint $0.1 \le \Omega_\chi h^2 \le 0.3$ has medium shading, and the region allowed by the newer cosmological constraint $0.094 \le \Omega_\chi h^2 \le 0.129$ has very dark shading. The disallowed region where $m_{\tilde{\tau}_1} < m_\chi$ has dark (red) shading. The regions excluded by $b \to s\gamma$ have medium (green) shading, and those in panels (a,d) that are favoured by $g_\mu - 2$ at the 2-σ level have medium (pink) shading. A dot-dashed line in panel (a) delineates the LEP constraint on the $\tilde{e}$ mass and the contours $m_{\chi^\pm} = 104$ GeV ($m_h = 114$ GeV) are shown as near-vertical black dashed (red dot-dashed) lines in panel (a) (each panel).*

(J.E. + Olive + Santoso + Spanos:
hep-ph/0303043

Locations of updated benchmarks on WMAP lines

focus points



strips allowed by cosmology for $\tan\beta = 5, 10, 20, 35, 50$

$\tan\beta = 10, 35$

Figure 1: *The strips display the regions of the $(m_{1/2}, m_0)$ plane that are compatible with $0.094 < \Omega_\chi h^2 < 0.129$ in the 'bulk', coannihilation 'tail', and rapid-annihilation 'funnel' regions, as well as the laboratory constraints, for (a) $\mu > 0$ and $\tan\beta = 5, 10, 20, 35$ and 50, and (b) for $\mu < 0$ and $\tan\beta = 10$ and 35. The parts of the $\mu > 0$ strips compatible with $g_\mu - 2$ at the 2-σ level have darker shading. The updated post-WMAP benchmark scenarios are marked in red. Points (E,F) in the focus-point region are at larger values of m_0.*

BDEGOF

Looking for Supersymmetry

Proposed Supersymmetric Benchmarks

MSSM ≡ mSUGRA:

(Battaglia + De Roeck + J.E. + Gianotti + (Matchev) + Olive + Pape + (Wilson)
hep-ph/0106204, hep-ph/0306219

- post-LEP

  sparticle, Higgs ← Theoretical uncertainties

- $b \to s\gamma$

- cosmological relic density

  $0.1 \leq \Omega_\chi h^2 \leq 0.3$ ← hard upper limit

  0.094 0.129 (WMAP

- $g_\mu - 2$

  favour $\Delta(g_\mu - 2) \leq 2\sigma$: not required *

Choose points that illustrate possibilities

not 'fair' sampling of parameter sp.

5 in 'bulk' of cosmological region

4 spread along coannihilation 'tail'

2 in 'focus-point' region

2 in rapid-annihilation 'funnels'

$\tan\beta = 5, 10, 20, 35, 50$

two points with $\mu < 0$ *

Spartides Observable at Different Colliders

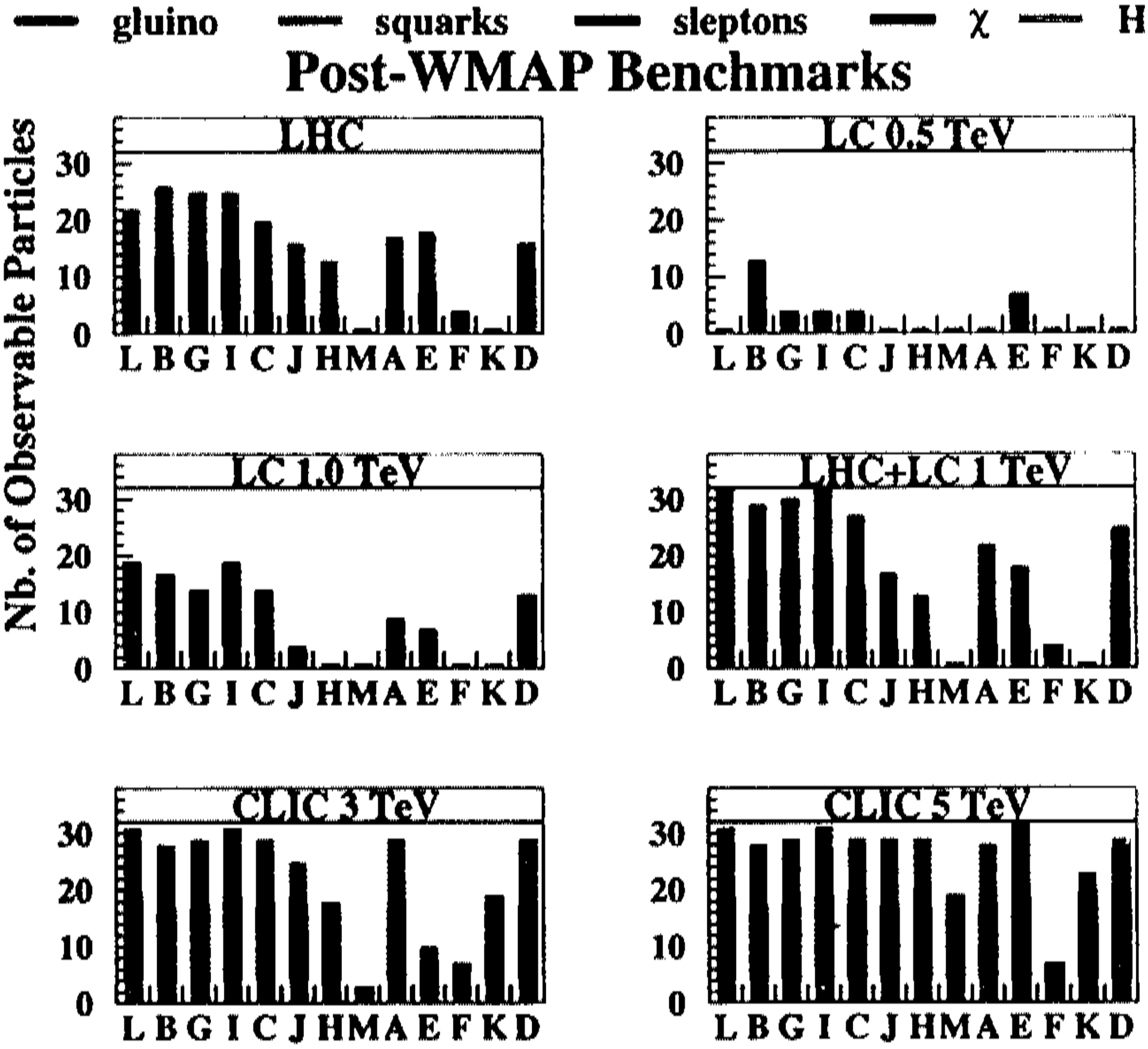


Figure 3: *Summary of the numbers of MSSM particles that may be detectable at various accelerators in the updated benchmark scenarios. As in [3], we see that the capabilities of the LHC and of linear e^+e^- colliders are largely complementary. We re-emphasize that mass and coupling measurements at e^+e^- colliders are usually much cleaner and more precise than at hadron-hadron colliders such as the LHC, where, for example, it is not known how to distinguish the light squark flavours.*

(BNEGOP
hep-ph/0306

1.5 - Prospects for Supersymmetry Discovery

Tevatron most of parameter space $\subset$ LEP
disfavoured by Higgs 'limit'
little chance?

LHC 'guaranteed' discovery
can 'cover' cosmological region
rich opportunities in cascades
some sensitivity to sleptons, $\chi^{\pm}$, ...

Supersymmetry @ LHC

GEANT figure

mSUGRA : $m_0 = 1000$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

$\tilde{g} \to \tilde{t}_1\, \bar{t}$

$\to W^- + \bar{b}$ (jet4, E_T = 113 GeV)

$\to s$ (jet5, E_T = 79 GeV) $+ \bar{c}$

$\to \tilde{\chi}_2^{\pm} + b$ (jet3, E_T = 536 GeV)

$\to \tilde{\chi}_1^{\pm} + Z \to$

$\to + W^+ \to \tau^+$

$\to e^+$

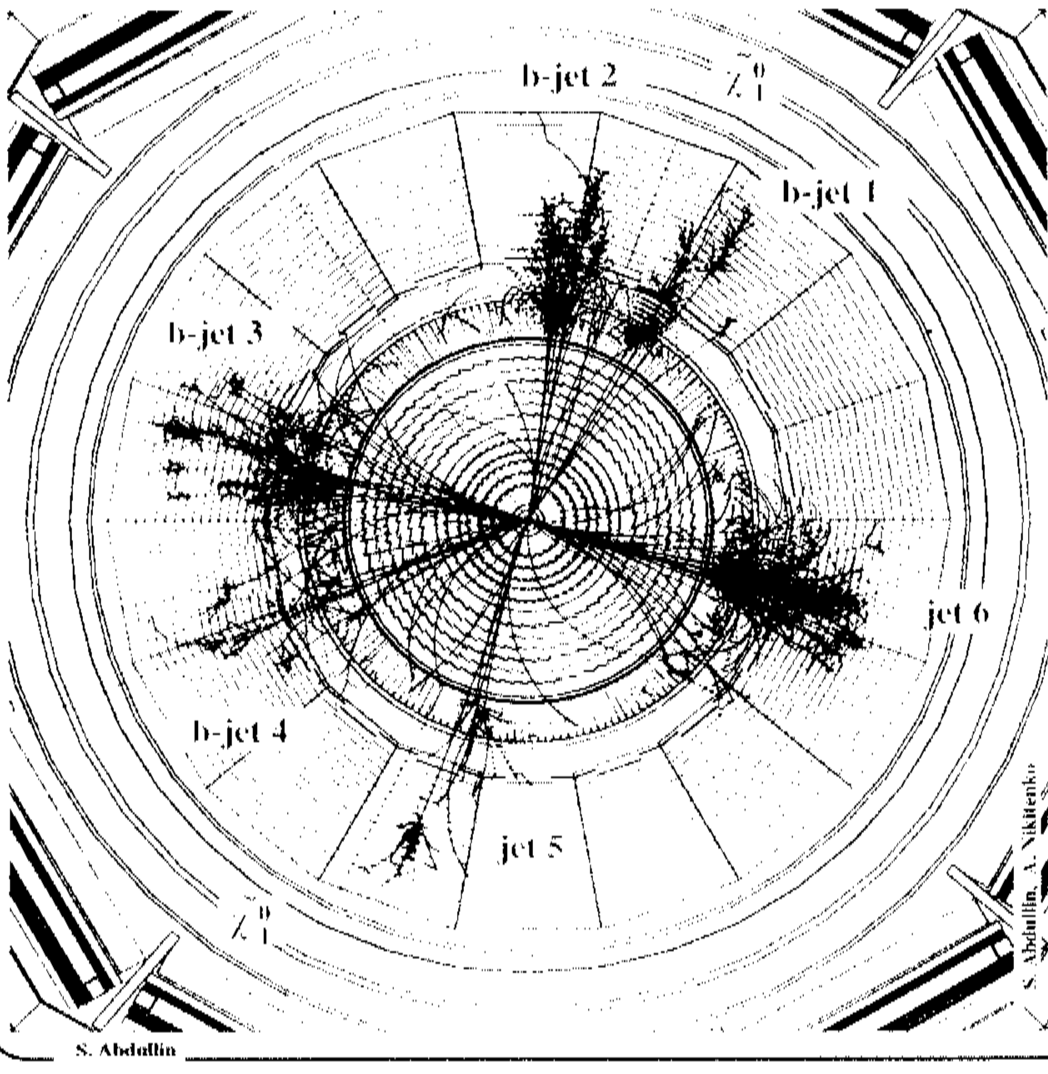
$\tilde{u}_L \to \tilde{\chi}_2^0 + u$ (jet6, E_T = 1196 GeV)

$\to + h$

$\to b$ (jet1, E_T = 206 GeV)

$\to \bar{b}$ (jet2, E_T = 320 GeV)

$E_T^{miss} = 380$ GeV



$m_{\tilde{g}} = 1266$ GeV

$m_{\tilde{u}_L} = 1450$ GeV

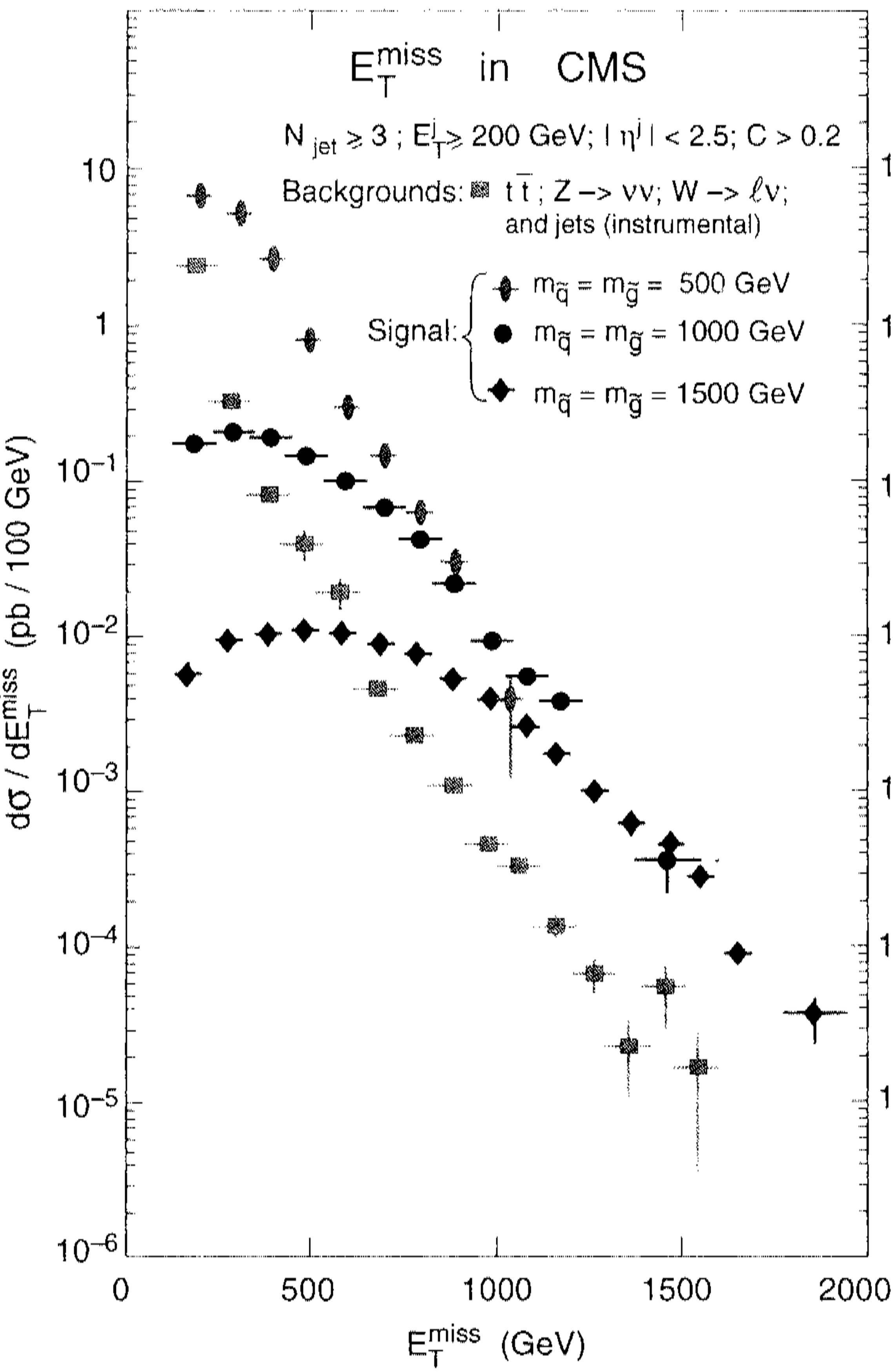
$m_{\tilde{t}_1} = 1026$ GeV

$m_{\tilde{\chi}_2^0} = 410$ GeV

$m_{\tilde{\chi}_1^0} = 214$ GeV

$m_h = 119$ GeV

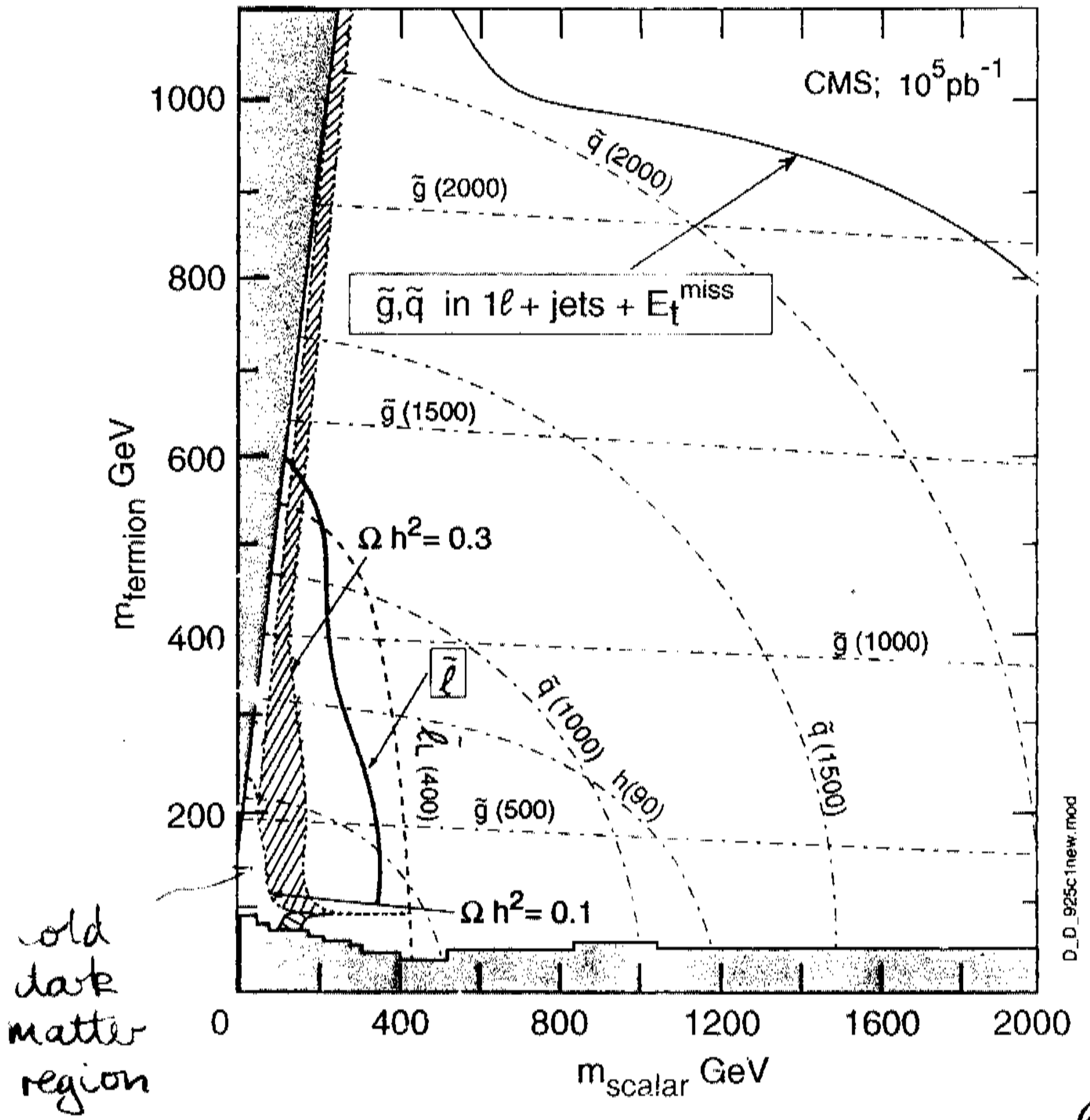
Missing-Energy Signature of Supersymmetry @ LHC



Expected reach in various channels

m SUGRA; tgβ = 2 (~ same up to tgβ ~ 5), $A_0 = 0$, $\mu < 0$

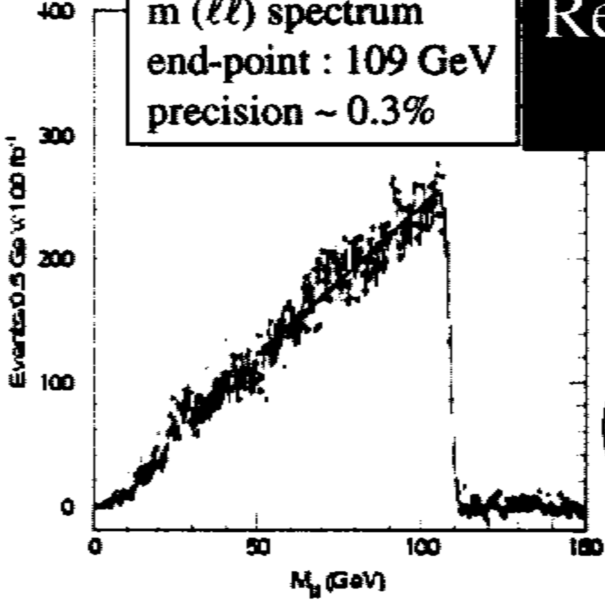
5 σ contours ($N_\sigma = N_{sig}/\sqrt{N_{sig}+N_{bkgd}}$) for $10^5 pb^{-1}$



(CMS

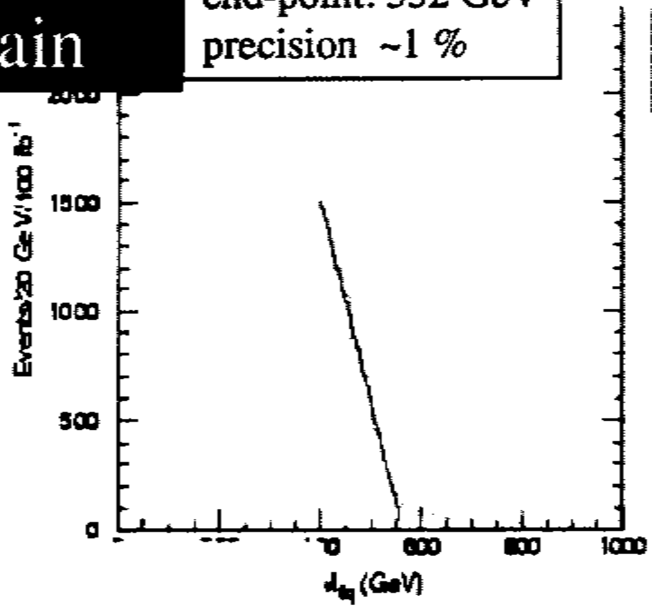
Reconstruction of `Typical' Sparticle Decay Chain

m ($\ell\ell$) spectrum
end-point : 109 GeV
precision ~ 0.3%

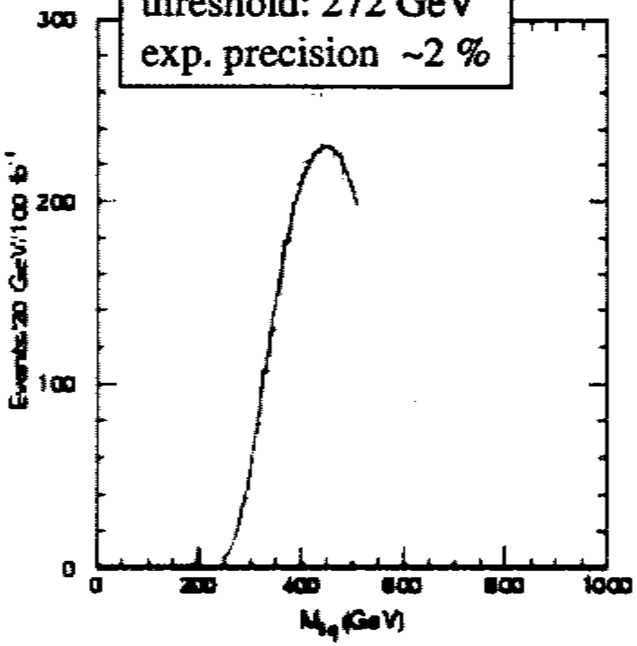


$$\tilde{q}_L \to q\,\chi^0_2 \hookrightarrow \tilde{\ell}_R\,\ell \hookrightarrow \ell\,\chi^0_1$$

m ($\ell\ell$j)^{min} spectrum
end-point: 552 GeV
precision ~1 %

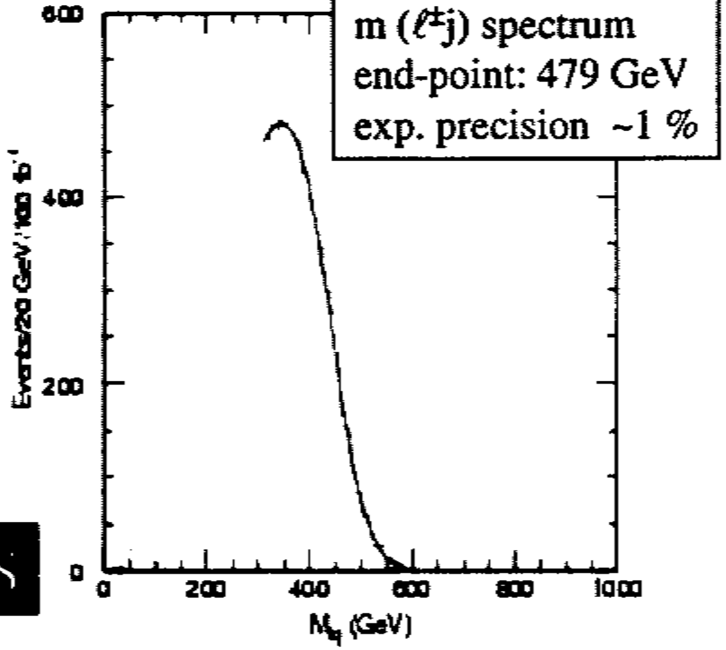


m ($\ell\ell$j)^{max} spectrum
threshold: 272 GeV
exp. precision ~2 %



$M_{squark} = 690$
$M_{\chi'} = 232$
$M_{slepton} = 157$
$M_{\chi} = 121$
(GeV)

m ($\ell^{\pm}$j) spectrum
end-point: 479 GeV
exp. precision ~1 %



ATLAS

Spartide Observability @ LHC

along WMAP lines

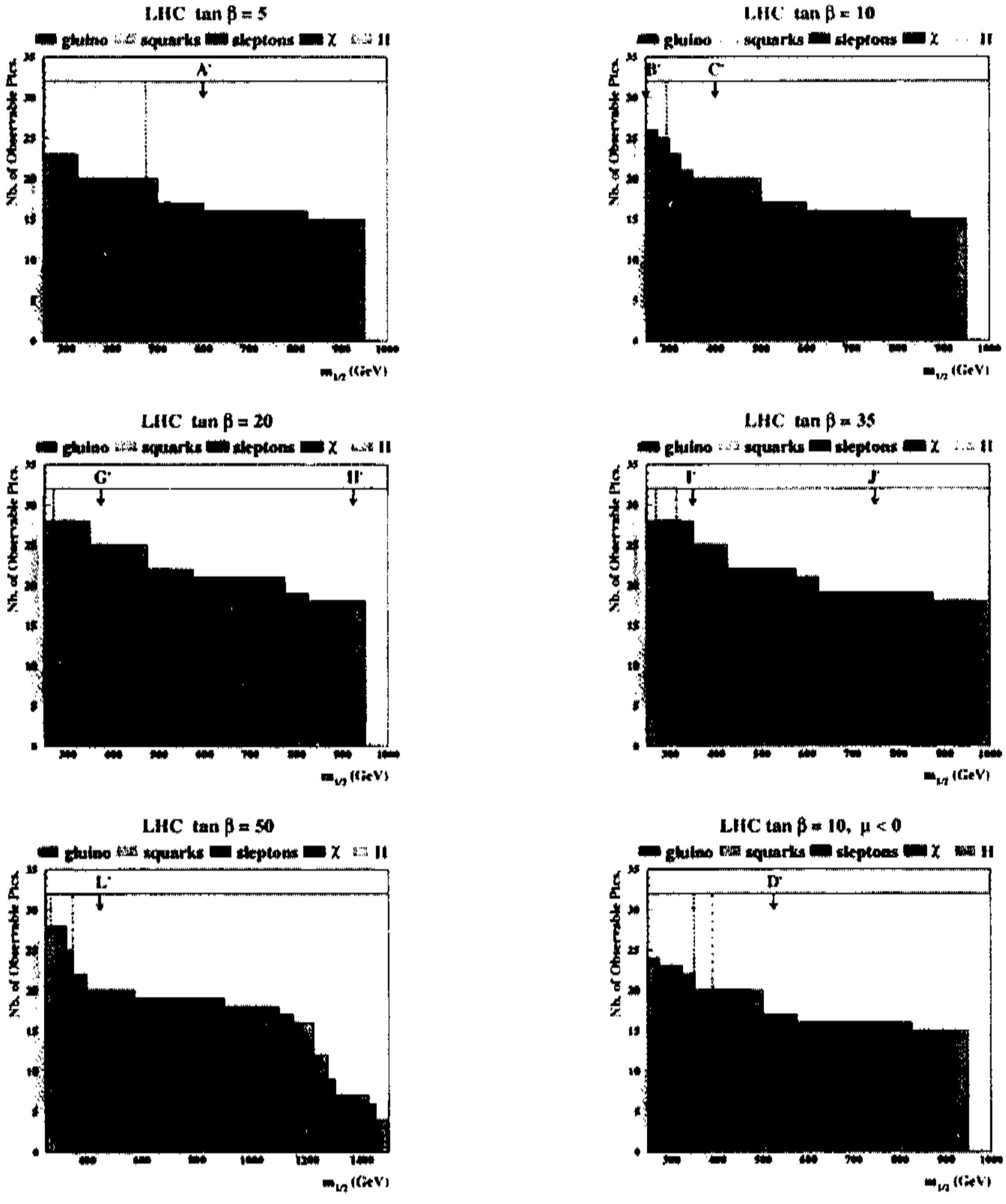
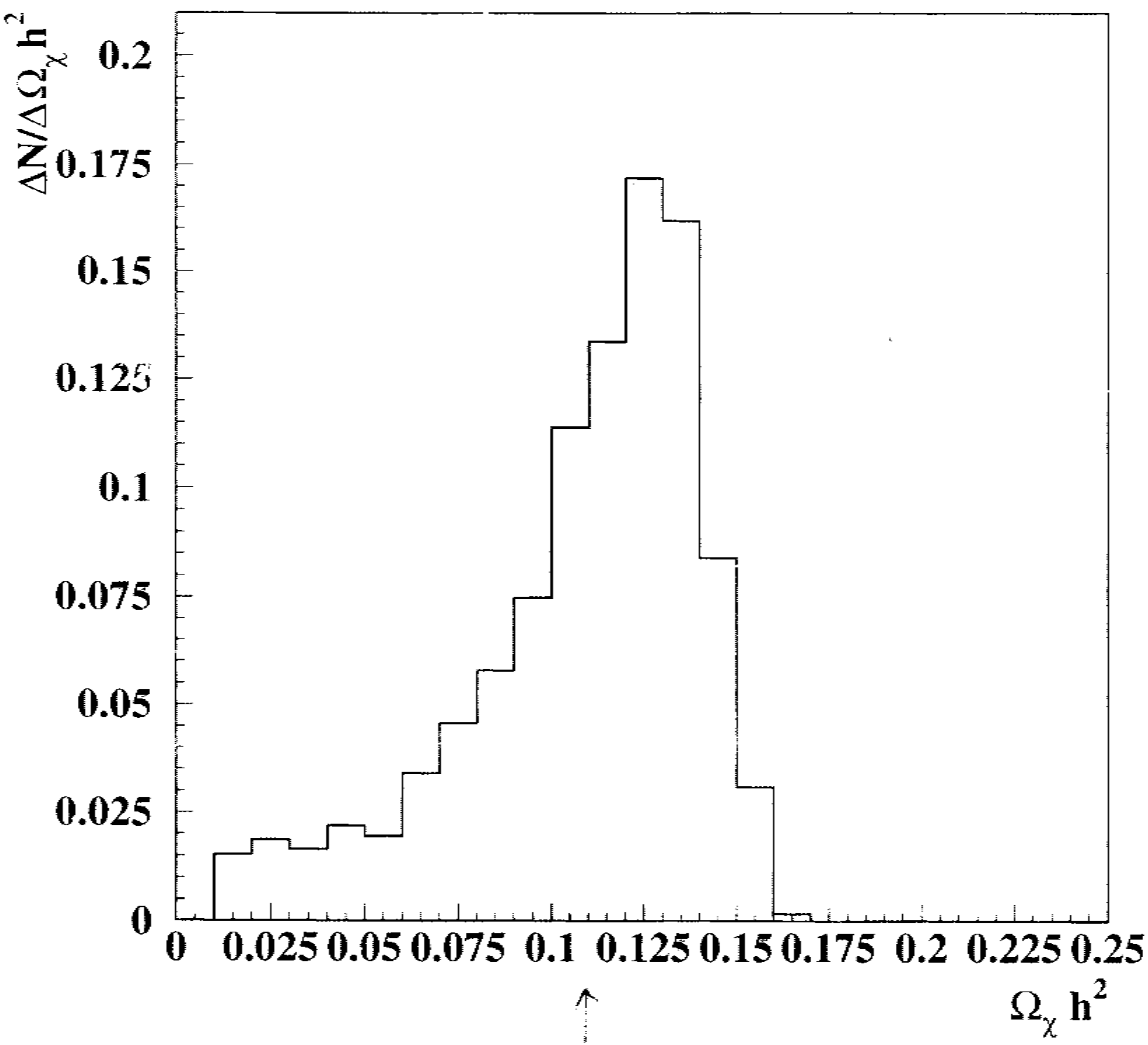


Figure 6: *Estimates of the numbers of MSSM particles that may be detectable at the LHC as functions of $m_{1/2}$ along the WMAP lines for $\mu > 0$ and $\tan\beta = 5, 10, 20, 35$ and 50, and for $\mu < 0$ and $\tan\beta = 10$. The locations of updated benchmark points along these WMAP lines are indicated, as are the nominal lower bounds on $m_{1/2}$ imposed by m_h (dashed lines) and $b \to s\gamma$ (dot-dashed lines).*

(RDEGOP:
hep-ph/0306

how well we might be able to calculate dark matter density using data from LHC



WMAP range

(BDEGOP

Spartide Observability @ 0.5-TeV LC

along WMAP lines

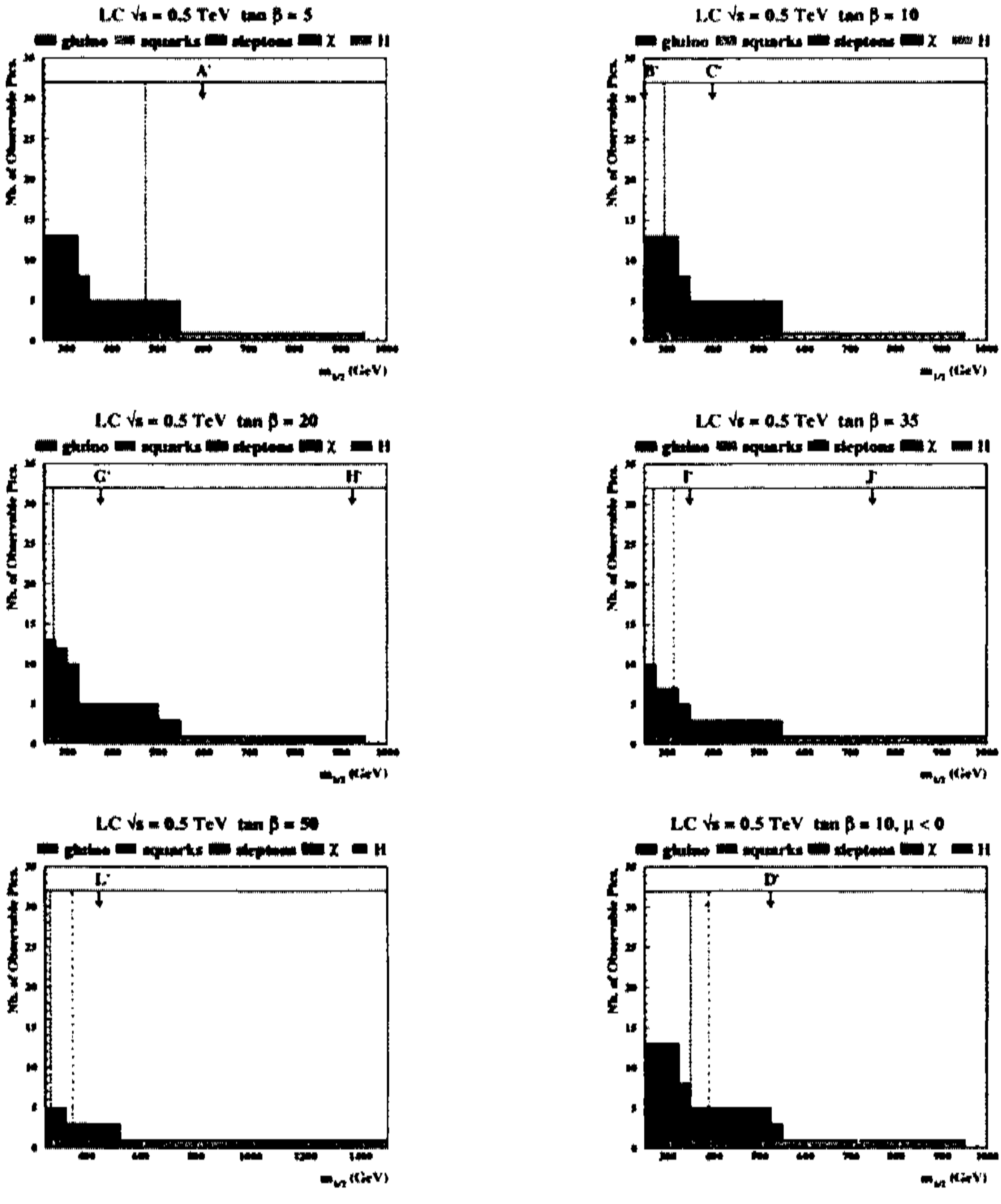


Figure 7: *Estimates of the numbers of MSSM particles that may be detectable at a 0.5-TeV linear e^+e^- collider as functions of $m_{1/2}$ along the WMAP lines for $\mu > 0$ and $\tan\beta = 5, 10, 20, 35$ and 50, and for $\mu < 0$ and $\tan\beta = 10$. The locations of updated benchmark points along these WMAP lines are indicated, as are the nominal lower bounds on $m_{1/2}$ imposed by m_h (dashed lines) and $b \to s\gamma$ (dot-dashed lines).*

(BDEGOP

Spasticle Observability @ 1-TeV LC

along WMAP lines

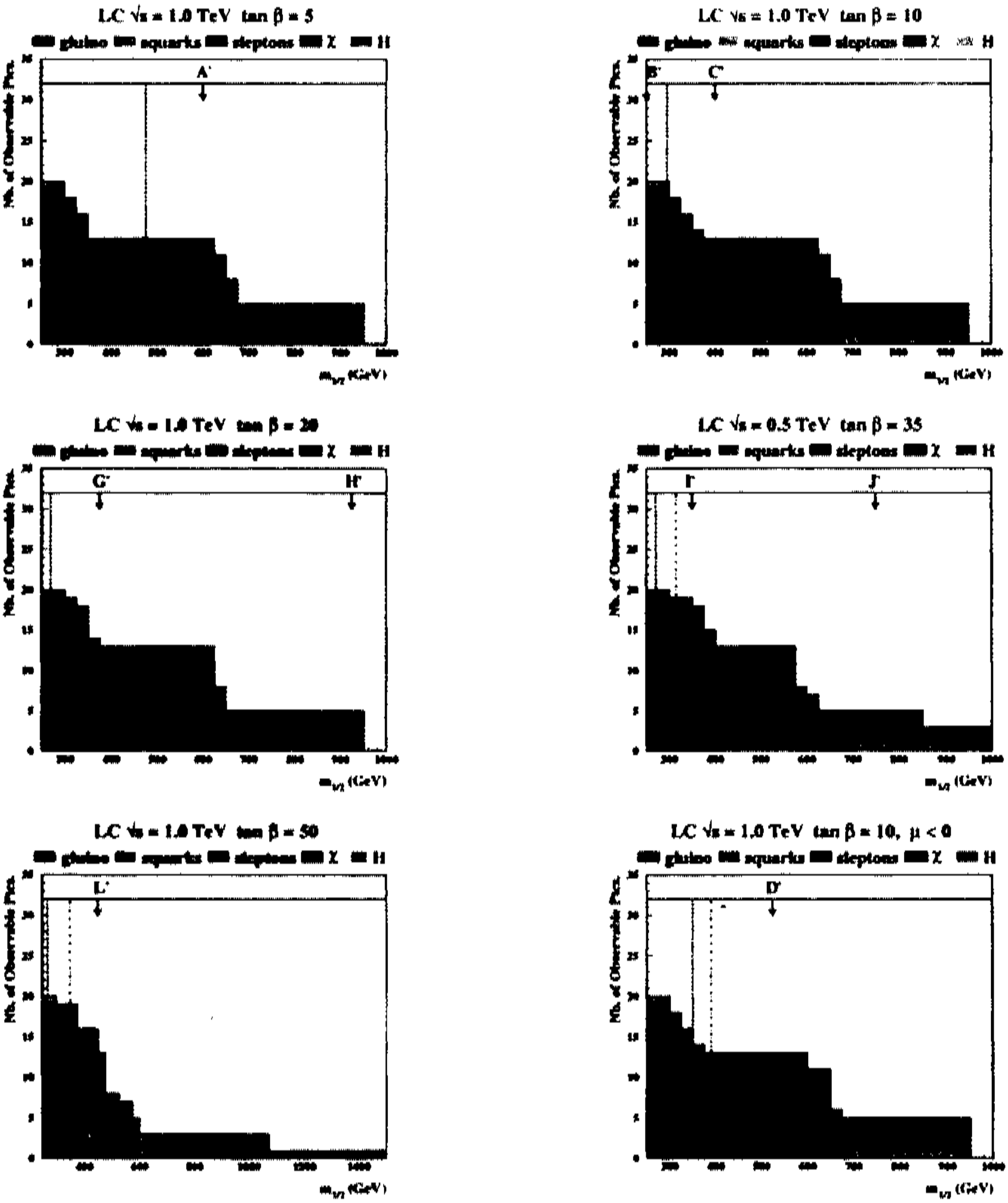


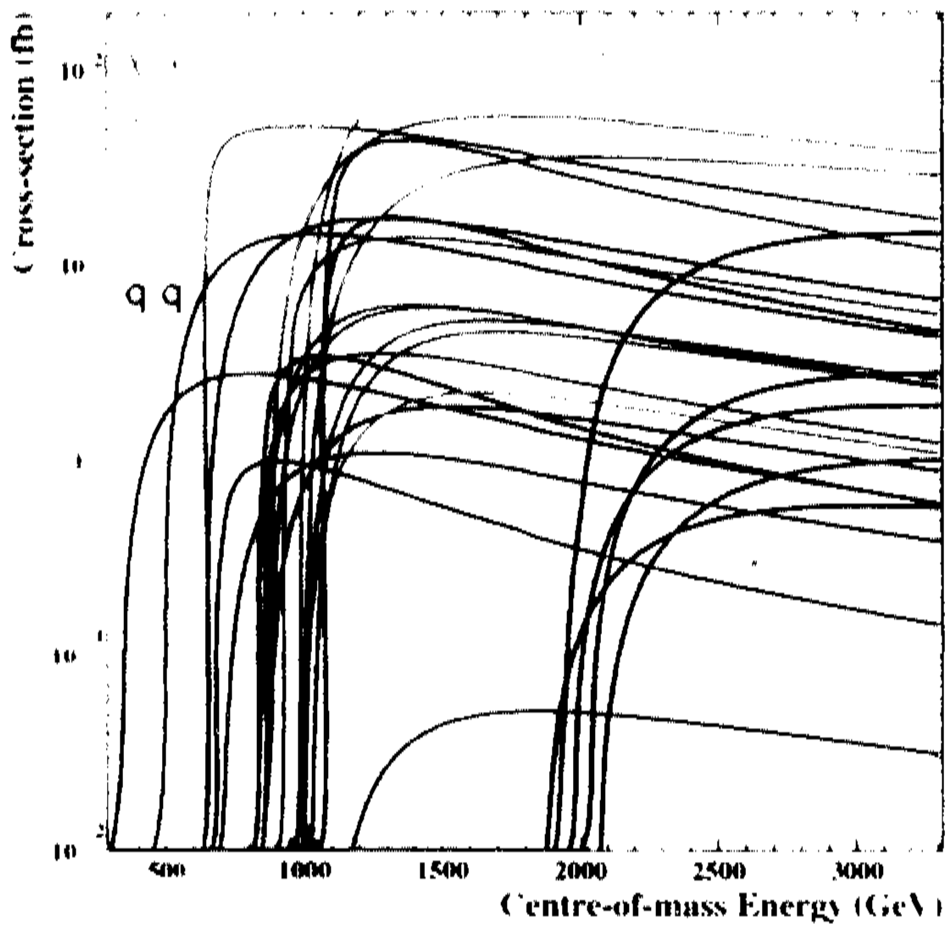
Figure 8: *Estimates of the numbers of MSSM particles that may be detectable at a 1-TeV linear e^+e^- collider as functions of $m_{1/2}$ along the WMAP lines for $\mu > 0$ and $\tan\beta =$ 5, 10, 20, 35 and 50, and for $\mu < 0$ and $\tan\beta = 10$. The locations of updated benchmark points along these WMAP lines are indicated, as are the nominal lower bounds on $m_{1/2}$ imposed by m_h (dashed lines) and $b \to s\gamma$ (dot-dashed lines).*

(RDEGOP

SUSY

Particle pair thresholds

$m_{1/2} = 400$ GeV, $m_0 = 400$ GeV, $\tan\beta = 35$,
$A = -400$ GeV, $sign(\mu) < 0$ (mSUGRA)



Many new particles with nearly degenerate masses

Combined Observability @ LHC + 1-TeV LC

along WMAP lines

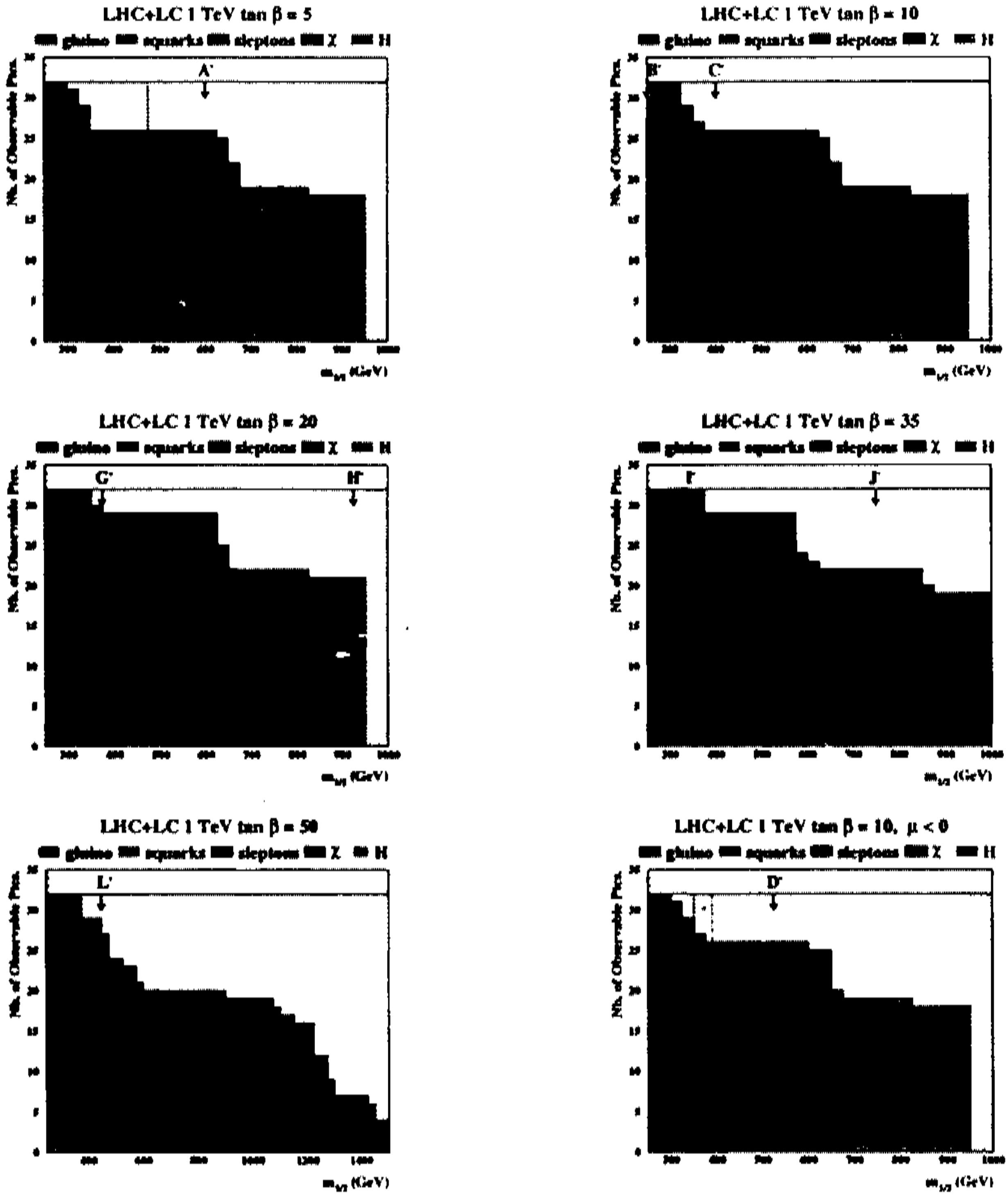


Figure 9: *Estimates of the combined numbers of MSSM particles that may be detectable at a combination of the LHC and a 1-TeV linear e^+e^- collider as functions of $m_{1/2}$ along the WMAP lines for $\mu > 0$ and $\tan\beta = 5, 10, 20, 35$ and 50, and for $\mu < 0$ and $\tan\beta = 10$. The locations of updated benchmark points along these WMAP lines are indicated, as are the nominal lower bounds on $m_{1/2}$ imposed by m_h (dashed lines) and $b \to s\gamma$ (dot-dashed lines).*

(BDEGOP

Neutralino LSP

full sample
accessible to LHC
dark matter (directly detectable)

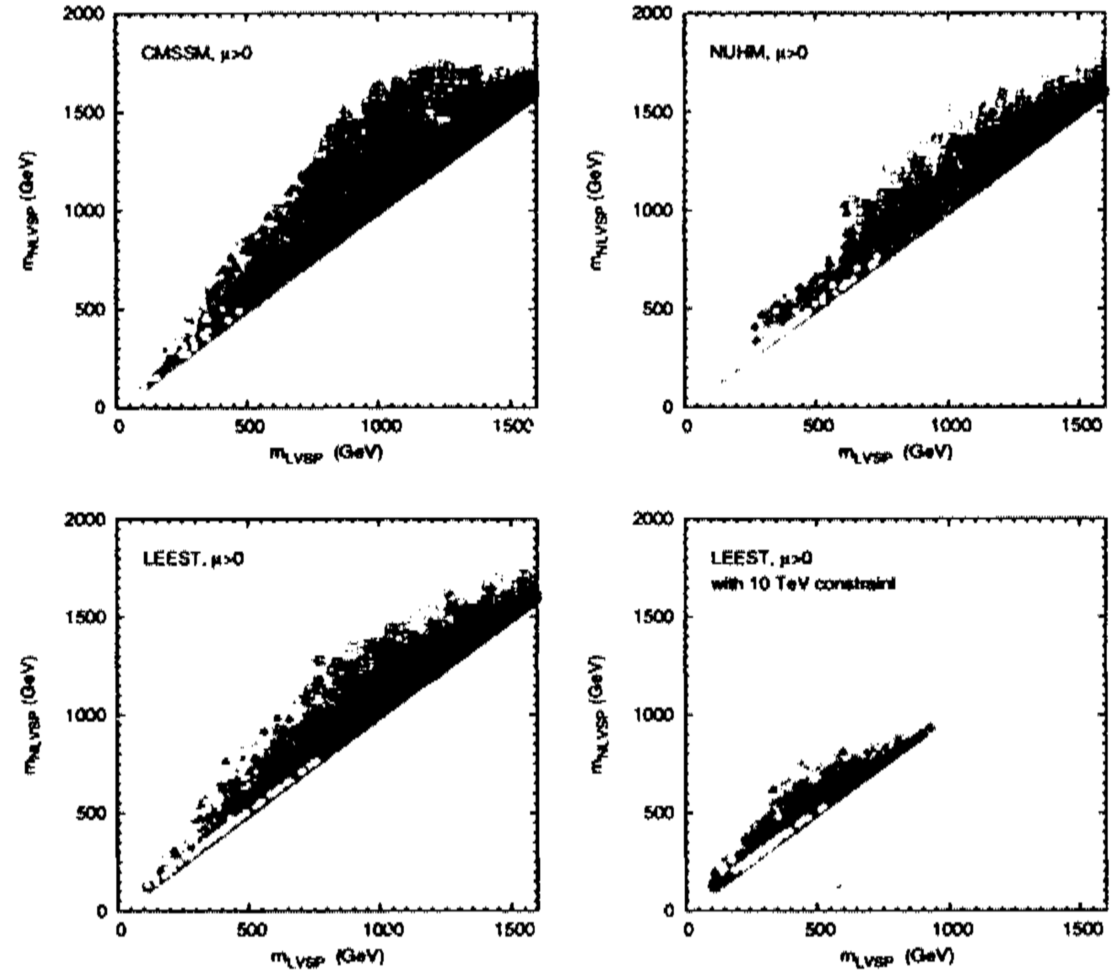


Figure 1: *Scatter plots of the masses of the lightest visible supersymmetric particle (LVSP) and the next-to-lightest visible supersymmetric particle (NLVSP) in (a) the CMSSM, (b) the NUHM, (c) the LEEST and (d) the LEEST10, all for $\mu > 0$. The darker (blue) triangles satisfy all the laboratory, astrophysical and cosmological constraints. For comparison, the dark (red) squares and medium-shaded (green) crosses respect the laboratory constraints, but not those imposed by astrophysics and cosmology. In addition, the (green) crosses represent models which are expected to be visible at the LHC. The very light (yellow) points are those for which direct detection of supersymmetric dark matter might be possible according to the criterion discussed in the text.*

Gravitino LSP

full sample

accessible to LHC

dark matter (directly detectable)

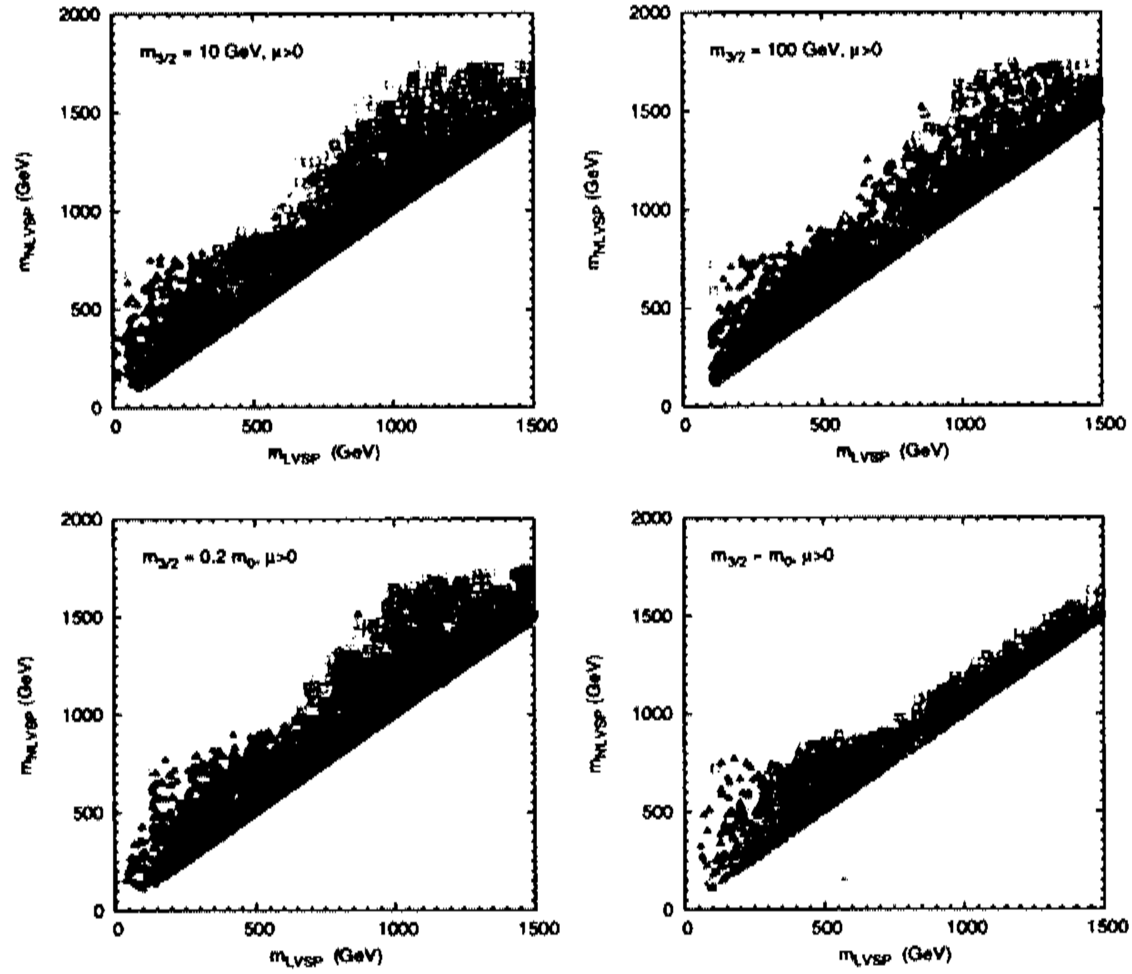


Figure 3: *Scatter plots of the masses of the lightest visible supersymmetric particle (LVSP) and the next-to-lightest visible supersymmetric particle (NLVSP) in the GDM with (a) $m_{3/2} = 10$ GeV, (b) $m_{3/2} = 100$ GeV, (c) $m_{3/2} = 0.2 m_0$ and (d) $m_{3/2} = m_0$, all for $\mu > 0$. The darker (blue) triangles satisfy all the laboratory, astrophysical and cosmological constraints. For comparison, the dark (red) squares and medium-shaded (green) crosses respect the laboratory constraints, but not those imposed by astrophysics and cosmology. In addition, the (green) crosses represent models which are expected to be visible at the LHC.*