SUSY Limits from LEP $\Rightarrow$ input for the searches at the LHC?

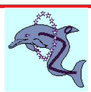
The Outline:

- Why SUSY ?
- The M_{SSM}odel $\Rightarrow$ is SUSY predictive ?
- Searches at LEP $\Rightarrow$ results
- Input for the LHC ?
- Conclusions

All results are preliminary

All limits are 95% confidence level

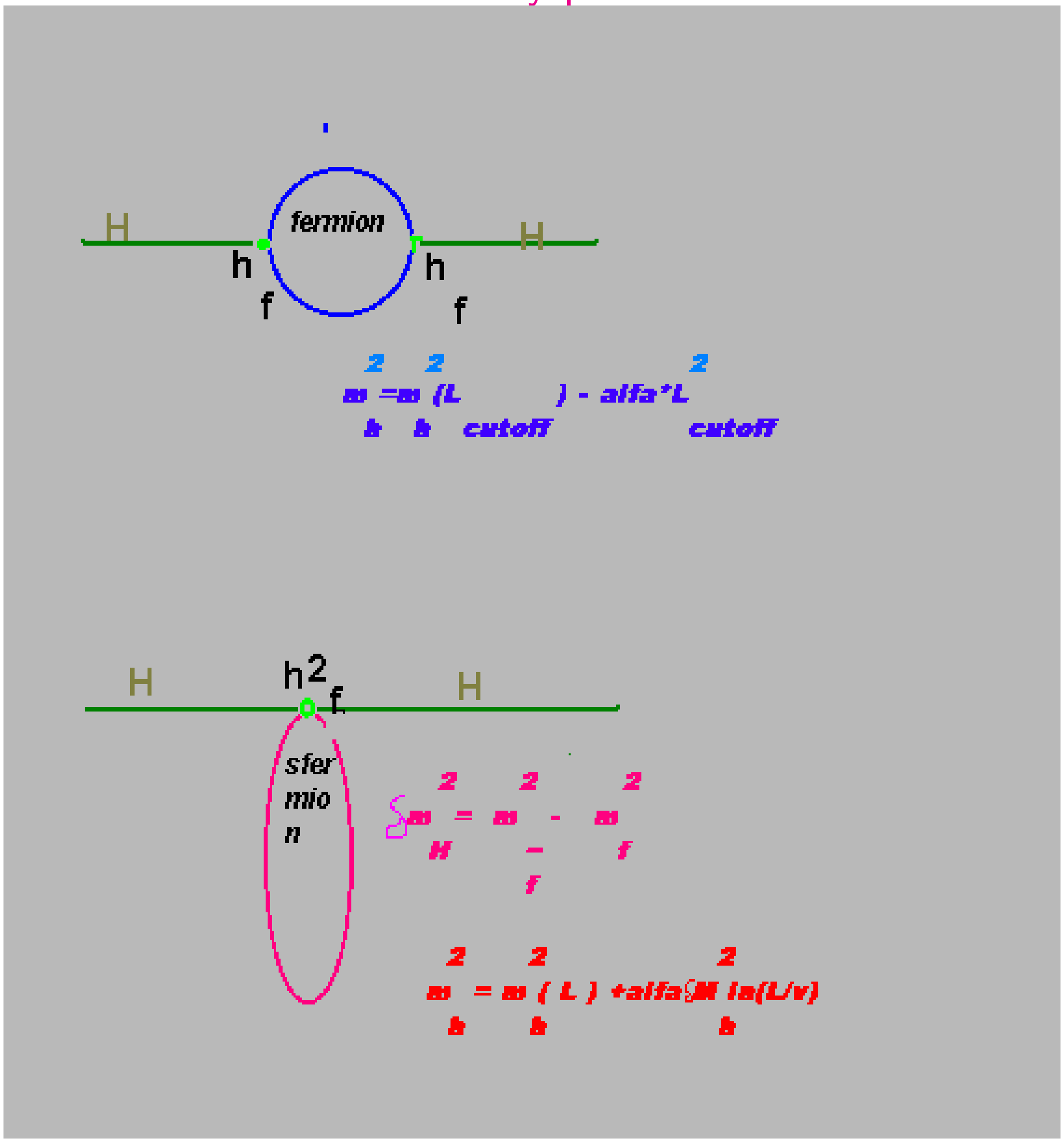
My conclusions are even more preliminary than the results..



Anna Lipniacka
Stockholm

Oslo
17 March, 2001

In a minimal SUSY every SM particle has a partner with spin differing by 1/2 but **the same couplings**. $\Rightarrow$ very useful to cancel large loop corrections to the Higgs mass $\Rightarrow$ Naturalness $\Rightarrow$ hierarchy problem

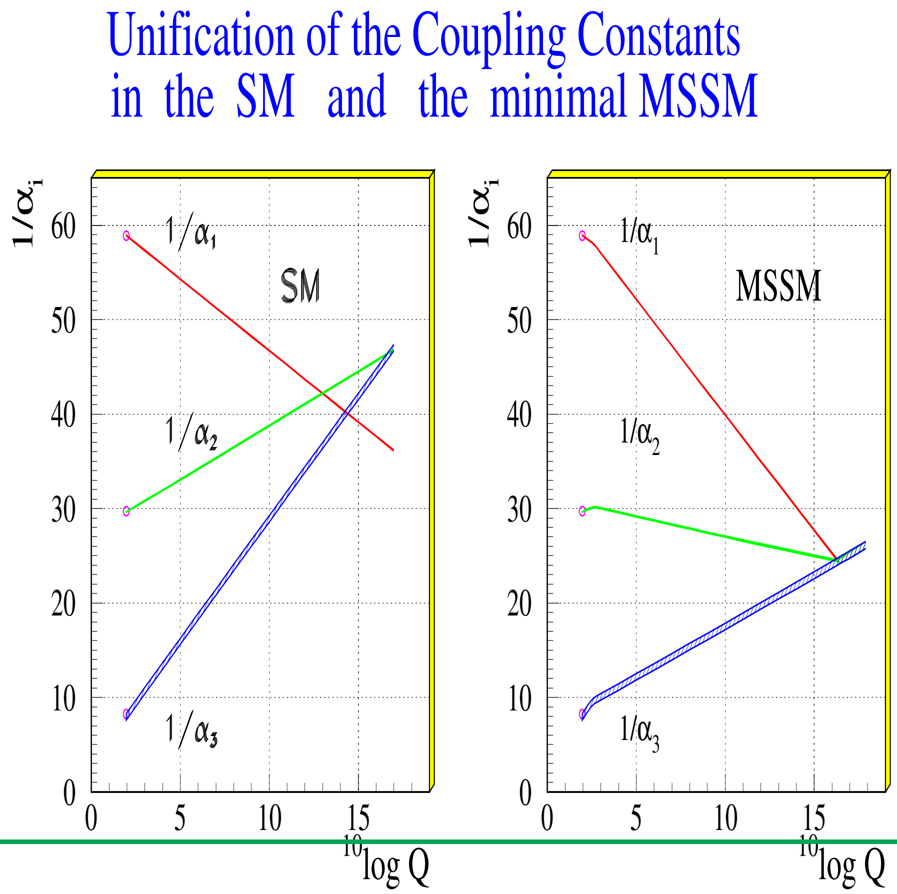


$$m_h^2 = m_h^2 (L_{cutoff}) - alfa * L_{cutoff}^2$$

$$\delta m_H^2 = m_{\tilde{f}}^2 - m_f^2$$

$$m_h^2 = m_h^2 (L) + alfa\,\delta M_h^2 \ln(L/v)$$

Minimal SUSY unifies Electromagnetic(1), Weak(2), Strong(3) coupling constants at scale characteristic for GUT. With $M_{GUT} \sim 10^{16}$ GeV, $M_{SUSY} \sim 1$ TeV.

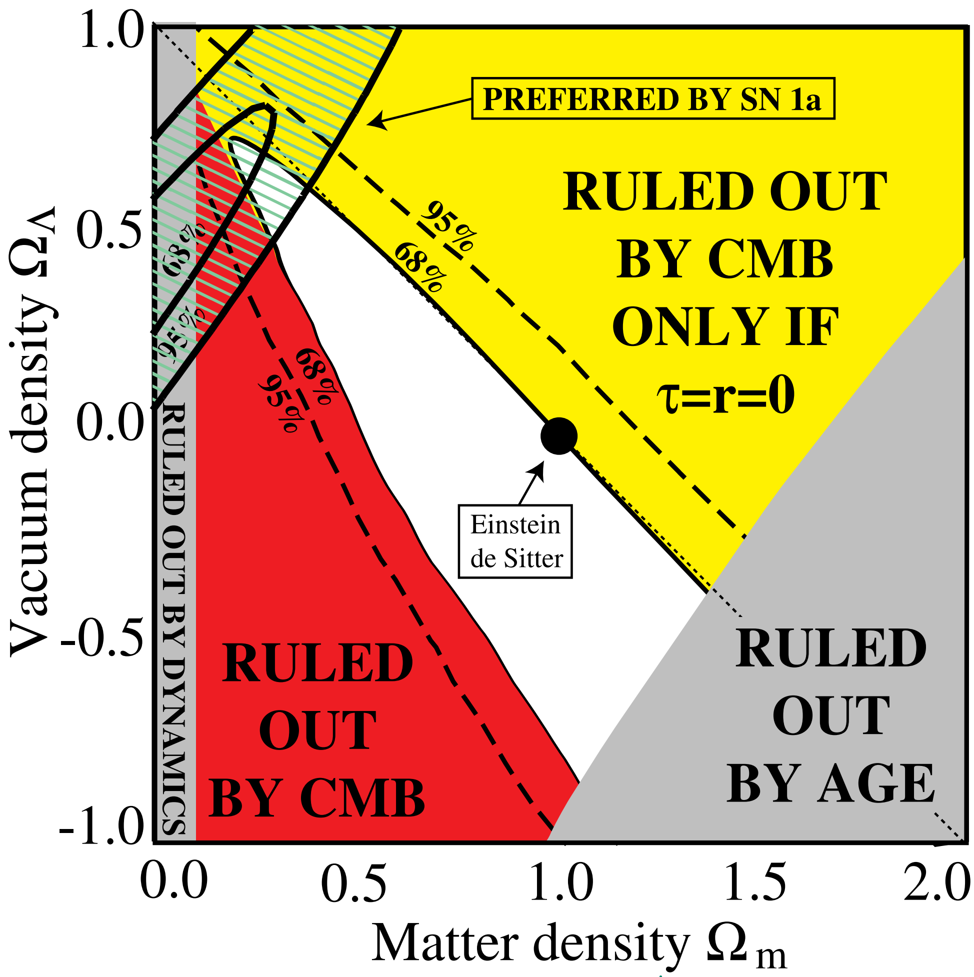


LSP is a useful by-product of SUSY models

To save the proton from decaying, an “ad-hoc” multiplicative symmetry is proposed $\Rightarrow$ R-parity $= \pm 1$ $\Rightarrow$ the LSP (R=-1) cannot decay to SM particles (R=+1) $\Rightarrow$ stable LSP.

In a class of SUSY models with gravity mediated SUSY breaking, the LSP is usually a partner of (mixture of) Z_0, γ or Higgs boson $\Rightarrow$ Weak coupling

Why SUSY - the LSP Dark Matter ?



$\Rightarrow \Omega$ = "normalized density" $= \rho/\rho_{critical}$

$\rho_{critical} \sim$ 5 GeV / m^3 (20 %)

Ω_M=0.375 $\pm$ 0.125 , $\rho_M \sim$ 1.9 GeV / m^3 , $\rho_{baryon} \sim$ 0.17 $\pm$ 0.09 GeV / m^3

$\Rightarrow$We need to account for $\sim$ 1 GeV/m^3 in unknown non-baryonic matter in the Universe (more than 400 GeV in this room !)

Our local halo energy density is 90% non-baryonic and amounts to $\sim$ 300 000 GeV/m^3 $\Rightarrow$ $1.2 * 10^8$ GeV in this room $\Rightarrow$ $2 * 10^{-16}$ gram .

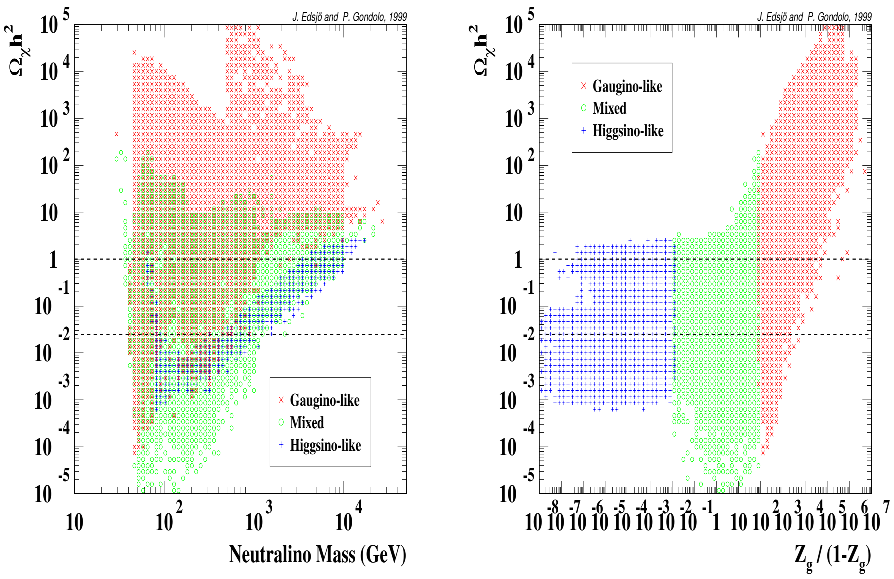
Why SUSY- Can the LSP be the Dark Matter?

Yes ! The relic density of Dark Matter particles is determined by their concentration at the "decoupling time" (t) $\Rightarrow$ when the Universe gets too big for them to annihilate effectively $\Rightarrow$ if the annihilation rate Γ was too big, all DM particles would disappear.

$$\Gamma = (\rho_m / M_m)\sigma v \sim t^{-1}$$

with $\sigma \sim 10^{-36}\ cm^2$ we get ρ_m close to ρ_c.

Relic density versus mass and composition



We need a Weakly Interacting Massive Particle $\Rightarrow$ LSP is an ideal candidate.

Particles in Minimal SUSY

One fermionic/bosonic partner to the SM fermions/bosons
with SM coupling

Particle	Spin	S-particle	Spin	Name
$l = e, \mu, \tau, \nu$	1/2	$\tilde{l}_R, \tilde{l}_L$	0	slepton
$q = u, d, s, c, b, t$	1/2	$\tilde{q}_R, \tilde{q}_L$	0	squark
g	1	$\tilde{g}$	1/2	gluino
γ	1	$\tilde{\gamma}$	1/2	photino
$W^{\pm}$	1	$\tilde{W}^{\pm}$	1/2	wino
Z	1	$\tilde{Z}$	1/2	zino
H_1^0, H_2^0	0	$\tilde{H}_1^0, \tilde{H}_2^0$	1/2	higgsino
$H^{\pm}$	0	$\tilde{H}^{\pm}$	1/2	higgsino

$\boxed{\text{particle} \quad R\text{-parity} = 1}$ $\quad \overset{\tilde{J} = J \pm \frac{1}{2}}{\Longleftrightarrow} \quad$ $R = (-1)^{2J+3B+L}$ $\quad \boxed{\text{S-particle} \quad R\text{-parity} = -1}$

Gauge Eigenstates | *Mass Eigenstates*

$\tilde{W}^{\pm}\ ,\ \tilde{H}^{\pm} \quad \longleftrightarrow \quad \tilde{\chi}^{\pm}_{1\,,\,2}$ (Charginos)

$\tilde{B}\ ,\ \tilde{W}^0\ ,\ \tilde{H}_1^0\ ,\ \tilde{H}_2^0 \quad \longleftrightarrow \quad \tilde{\chi}^{0}_{1\,,\,2\,,\,3\,,\,4}$ (Neutralinos)

Fermion Eigenstates | *Mass Eigenstates*

$\tilde{t}_L\ ,\ \tilde{t}_R \quad \longleftrightarrow \quad \tilde{t}_1\ ,\ \tilde{t}_2$ (stop)

$\tilde{b}_L\ ,\ \tilde{b}_R \quad \longleftrightarrow \quad \tilde{b}_1\ ,\ \tilde{b}_2$ (sbottom)

$\tilde{\tau}_L\ ,\ \tilde{\tau}_R \quad \longleftrightarrow \quad \tilde{\tau}_1\ ,\ \tilde{\tau}_2$ (stau)

The M_{SSM}odel $\Rightarrow$ is SUSY predictive ?

Higgs sector: h^0, A, $H^{\pm}$, H^0 is well constrained:

free parameters: $tan\beta = < H_1 > / < H_2 >$, M_A

tree level $\Rightarrow$ $M_{\mathrm{h}^0} = M_Z * |(\tan\beta^2 - 1)/(\tan\beta^2 + 1)|$

$\Rightarrow M_{\mathrm{h}^0} \leq M_Z$

loop corrections (t, $\tilde{t}$, b , $\tilde{b}$)

$M_{\mathrm{h}^0} = M_{tree} + \Delta M(m_t, M_{susy}, M_{\tilde{\mathrm{b}}}, M_{\tilde{\mathrm{t}}})$,

$\Rightarrow M_{\mathrm{h}^0} \lesssim 135$ GeV

$\Rightarrow$ grows with m_t, M_A, mass splitting in $M_{\tilde{\mathrm{t}}}$

For $M_A > 300$ GeV h^0 SM-like !!!

LEP (DELPHI) limit :

$\Rightarrow$ 114.3 GeV $< M_{\mathrm{h}^0}$ for $\tan\beta \lesssim 3$

$\Rightarrow \sigma(hZ) * Br(h \to bb) \lesssim$ 0.07pb

LEP "evidence" (2.9 σ) :

$\Rightarrow$ 114 GeV $< M_{\mathrm{h}^0} <$ 116 GeV,

$\Rightarrow$ 0.03 pb$< \sigma(hZ) * Br(h \to bb) <$ 0.07pb

The M_{SSM}odel $\Rightarrow$ is SUSY predictive ?

Lightest Higgs the most powerful tool to search for/ exclude MSSM

What about other (s)particles ?

Consider:

"Simplest SUSY" $\rightarrow$ MSSM "gravity mediated"

R parity conservation is supposed (stable LSP)
LSP $= \tilde{\chi}_1^0$
sparticle masses free parameters $\rightarrow$ make some of the assumptions:

Unification at the GUT scale $\rightarrow$

1) $m_{1/2}$ GUT	$\leftarrow$	$M_1 = M_{\tilde{B}}$,$M_2 = M_{\tilde{W}}$, $M_3 = M_{\tilde{g}}$
2) m_0 GUT	$\leftarrow$	$m_{\tilde{q}}, m_{\tilde{l}}$
3) m_0 GUT	$\leftarrow$	$m_{\tilde{q}}, m_{\tilde{l}}, M_{\mathrm{h}^0}$
4) A_0 GUT	$\leftarrow$	A_t, A_b, A_τ
5) if 3)	$\leftarrow$	fix HPM for right M_Z

The M_{SSM}odel $\Rightarrow$ is SUSY predictive ?

Typical LEP assumptions 1) +2) CMSSM :

very reasonable is the spirit of GUT coupling unification:

1) $m_{1/2}\ GUT \quad \leftarrow \quad M_1 = M_{\tilde{B}}\ , M_2 = M_{\tilde{W}},\ M_3 = M_{\tilde{g}}$

$\rightarrow$ Leads to a (tree level) relation at the Electroweak Scale:

$M_1 = \frac{5}{3}\, tan^2\theta_W M_2 \simeq 0.5\ M_2 \simeq 0.15\ M_3$

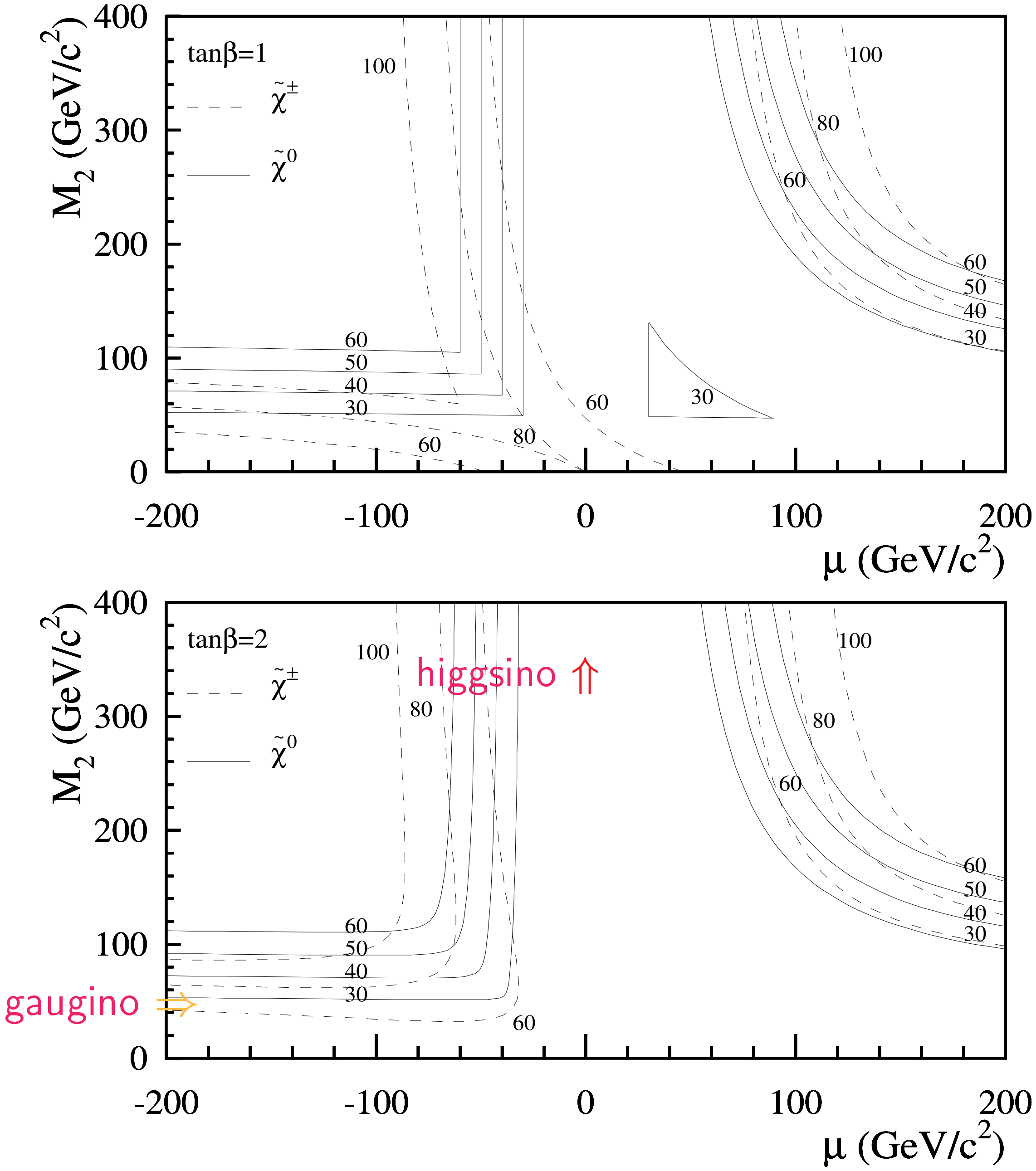
Free parameters: $tan\beta$, M_2, A_t, A_b, A_τ =Yukawa couplings, μ=Higgsino mixing parameter, M_A , masses of all sfermions.

2) $m_0\ GUT \quad \leftarrow \quad m_{\tilde{q}}, m_{\tilde{l}}$

$\Rightarrow$ masses of sfermions are fixed in terms of m_0, M_2, $\tan\beta$

$\Rightarrow$ for the third family mass splitting $A_t - \mu/\tan\beta$ $A_\tau - \mu\tan\beta$ etc..

$M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\chi}_1^\pm}$ $\Rightarrow$ M_2 (M_1), μ, tanβ.



tan$\beta >> 1$ "gaugino region" : $M_{\chi_0} \simeq 0.5\ M_{\chi^\pm} \simeq 0.5\ M_2$

tan$\beta >> 1$ "higgsino region" : $M_{\chi_0} \simeq M_{\chi^\pm} \simeq 0.5\ |\mu|$

$M_{\tilde{g}} \simeq 3.3\ M_2$

Masses and MSSM parameters

Sfermion masses, examples:

$$M_{\tilde{\nu}}^2 = m_0^2 + 0.77M_2^2 + 0.5M_Z^2 cos(2\beta)$$

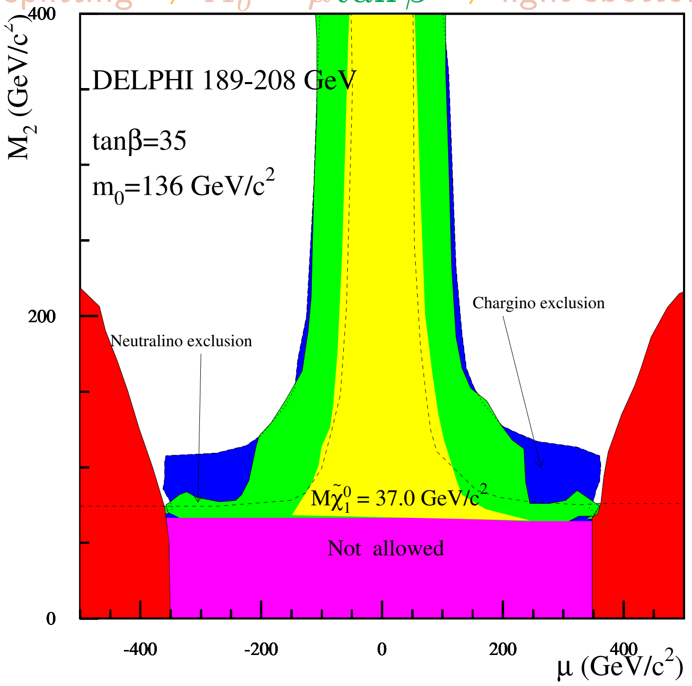
$$M_{\tilde{e}_L}^2 = m_0^2 + 0.77M_2^2 - 0.27M_Z^2 cos(2\beta)$$

$$M_{\tilde{e}_R}^2 = m_0^2 + 0.22M_2^2 - 0.23M_Z^2 cos(2\beta)$$

$M_{\tilde{q}}{}^2 \sim m_0^2 + 10M_2^2 + O(M_Z^2 cos(2\beta)) \pm$ (splitting term)

splitting $\Rightarrow A_t - \mu/\tan\beta \Rightarrow$ light stop for low $\tan\beta$

splitting $\Rightarrow A_b - \mu\tan\beta \Rightarrow$ light sbottom for high $\tan\beta$



The M_{SSM}odel $\Rightarrow$ is SUSY predictive ?

Typical LHC (Tevatron) assumptions 1) to 5) mSUGRA:

Free parameters: $tan\beta$, M_2 or $m_{1/2}$, A_0 , $sign\ of\ |\mu|$, m_0 ,

$\Rightarrow$ μ fixed up to a sign in terms m_0, $m_{1/2}$, $\tan\beta$ and $> M_Z$

$\Rightarrow$ masses of Higgses fixed in terms of m_0, $m_{1/2}$, $\tan\beta$, A_0

$M_{\chi 0} \simeq$ 0.5 $M_{\chi^{\pm}} \simeq$ 0.5 $M_2 \simeq$ 0.4 $m_{1/2}$

$M_{\tilde{g}} \simeq$ 2.8 $m_{1/2} \simeq$ 2.8 $M_{\chi^{\pm}}$

$M^2_{\tilde{e}_R} = m_0^2 + 0.2m^2_{1/2} - 0.23M_Z^2 cos(2\beta)$

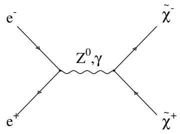
${M_{\tilde{\mathrm{q}}}}^2 \sim m_0^2 + 7m^2_{1/2} + O(M_Z^2 cos(2\beta)) \pm$ (splitting term)

---

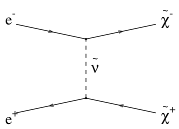
for 1 & 2 family $M_{\tilde{\mathrm{q}}} \gtrsim$ 3 $M_{\chi^{\pm}}$

LEP searches $\Rightarrow$ production

Chargino

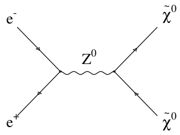


Large σ $\sim$ 1 - 10 pb

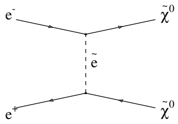


reduces σ
(when $\tilde{\chi}^{\pm}$ is gaugino)

Neutralino

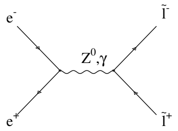


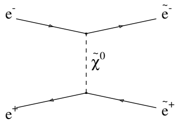
Large σ $\sim$ 1 - 5 pb
(when $\tilde{\chi}^0$ is higgsino)



Enhances σ
(when $\tilde{\chi}^0$ is gaugino)

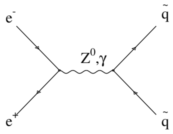
Sleptons





Large σ (when $\tilde{\chi}^0$ is gaugino)

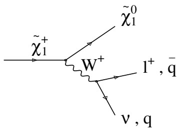
Squarks

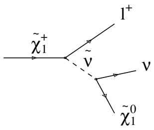


σ $\sim$ depend on θ_{mixing} for $\tilde{b}$,$\tilde{t}$

LEP searches ⇒ decays

Chargino

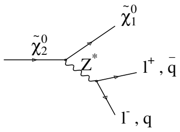


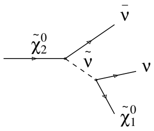


$l\nu = 32$ % , $q\bar q = 68$ %

Enhances leptonic BR

Neutralino

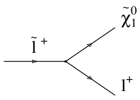




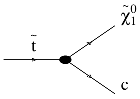
$l^+l^- = 10$ % , $q\bar q = 70$ %
$\nu\bar\nu = 20$ %

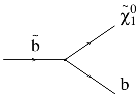
Enhances the invisible decay

Sleptons



Squarks

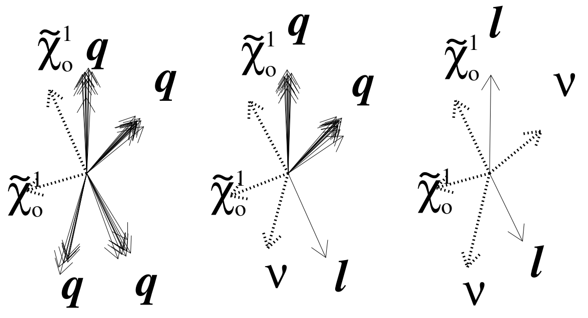




Example topologies: chargino and neutralino

Charginos :

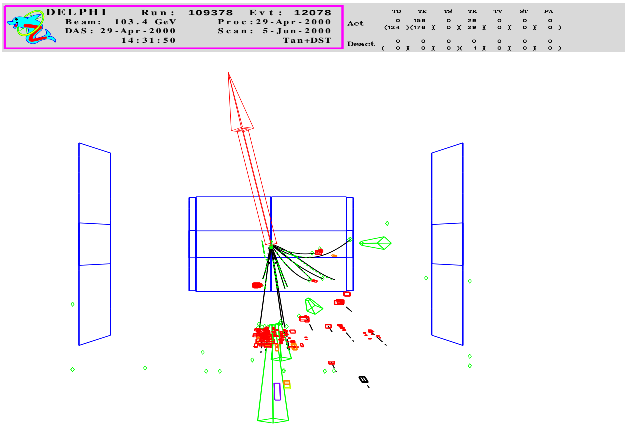
$e^+ \, e^- \rightarrow \tilde{\chi}^+ \, \tilde{\chi}^- \qquad \tilde{\chi}^{\pm} -> W^* \, \chi_1^0$

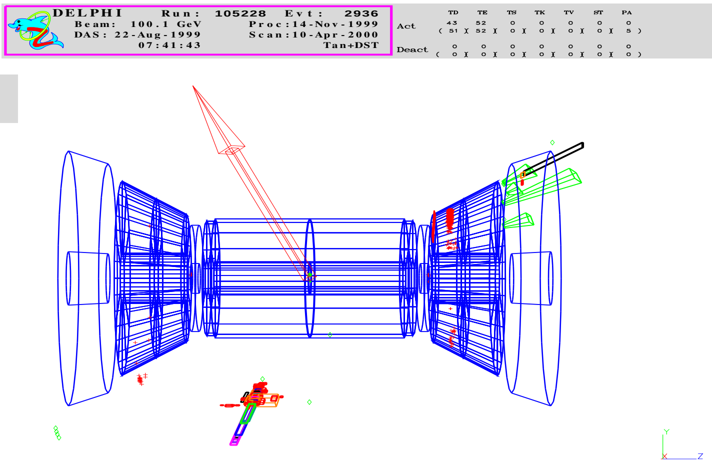


(a) *(b)* *(c)*

Neutralinos (example):

$e^+ \, e^- \rightarrow \tilde{\chi}_1^0 \, \tilde{\chi}_{2,3,4}^0 \qquad e^+ \, e^- \rightarrow \tilde{\chi}_{4,3}^0 \, \tilde{\chi}_2^0$





$\tilde{\chi}_2^0 \rightarrow Z^* \, \tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \rightarrow \gamma \, \tilde{\chi}_1^0$

ALEPH, DELPHI, L3, OPAL:

$\sqrt{s}$ $\sim$ 207 GeV	$\sim$ 470 pb^{-1}
$\sqrt{s}$ $\sim$ 205 GeV	$\sim$ 360 pb^{-1}
$\sqrt{s}$ 188 GeV -204 GeV	1575 pb^{-1}
$\sqrt{s}$ above WW below 188 GeV	300 pb^{-1}
$\sqrt{s}$ above Z_0 below WW	50 pb^{-1}

In year 2000

$\Rightarrow$ $\sim$ 900 $\mathrm{e^+e^-} \to \mathrm{ZZ}$ events

$\Rightarrow$ $\sim$ 12300 $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$ events

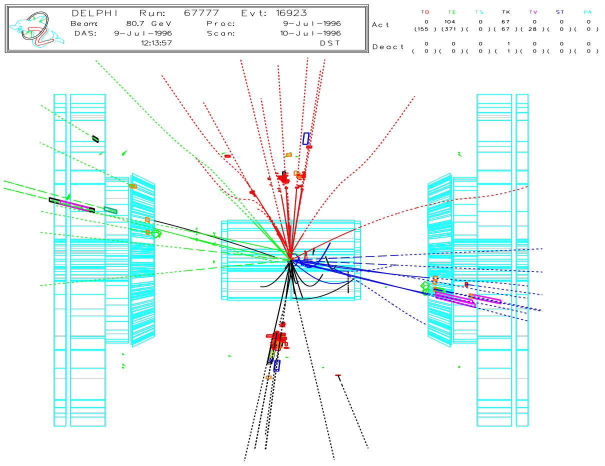
$\Rightarrow$???? $\sim$ 40 $\mathrm{e^+e^-} \to \mathrm{h^0}$Z events with $M_{\mathrm{h}^0} = 115$ GeV????

SUSY models $\Rightarrow$ 0-12000 events expected....

Main backgrounds at 161-208 GeV

Four-fermion events

W^+W^- (charged current)

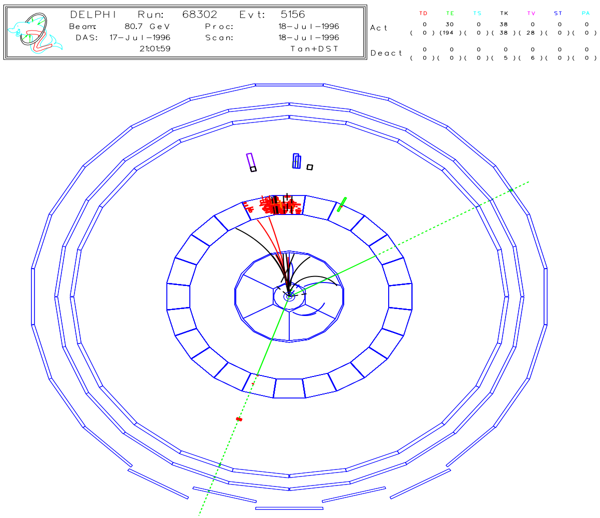


W^+W^-

$\sigma \simeq 16pb$ at $\sqrt{s} = 202$ GeV

$We\nu$

$\sigma \simeq 0.6pb$ at $\sqrt{s} = 202$ GeV



ZZ

$\sigma \simeq 1.1pb$ at $\sqrt{s} = 202$ GeV

$Z(Z/\gamma)^*$ $\sigma \simeq 1.6pb$

if $M_{\gamma*} > 13GeV$

$Z^*(Z/\gamma)^*$ (neutral current)

LEP Results:

⇒ Higgs evidence , besides alas LIMITS!!

⇒ “Nearly unconditional” kinematical limits for sparticles

$M_{\tilde{\chi}_1^\pm} > 103.5$ GeV, $M_{\tilde{\chi}_1^0} > 50$ GeV, $M_{\tilde{\mathrm{e}}_R} > 98$ GeV, $M_{\tilde{\mathrm{t}}} > 90$ GeV

⇒ except of pathological situations , see later.

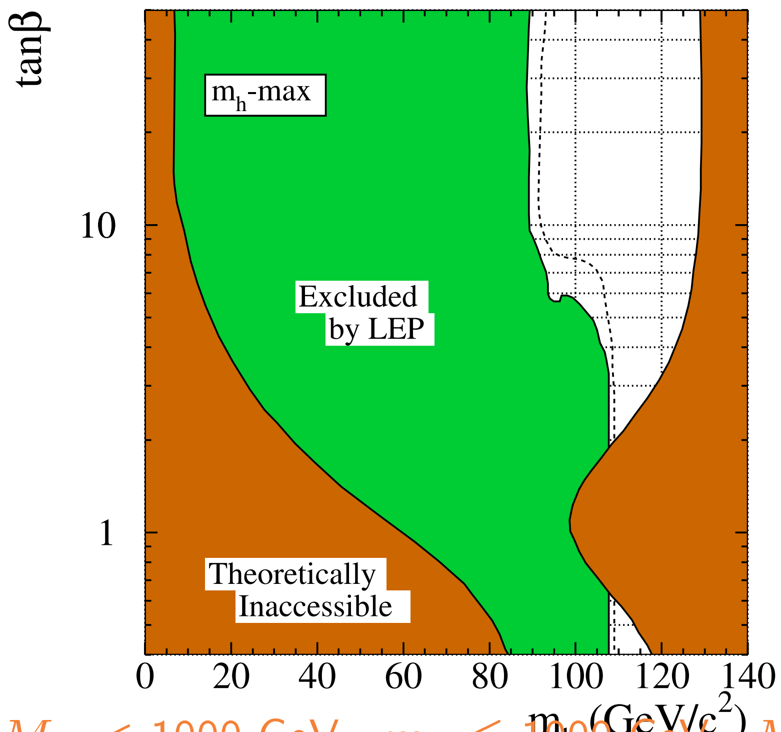
⇒ ⇒ Hadron collider limits are always conditional, apply only in a limited space of the model : from CDF $M_{\tilde{\mathrm{t}}} > 115$ GeV, IF $M_{\tilde{\chi}_1^0} < 50$ GeV

⇒ LIMITS extend BEYOND kinematical limit when iterpretted within a model (hadron colliders style) ⇒ becouse masses of different sparticles are related, examples later.

⇒ Pathological cases are covered “within the model”

⇒ Also within the model we set limits on particles we cannot directly search for like the gluino, and the sneutrino

$0.5 < \tan\beta < 2.2$ excluded in general MSSM, conservative , maximal M_{h^0}.



$M_A < 1000$ GeV , $m_0 \leq 1000$ GeV , $M_{top} = 175$ GeV

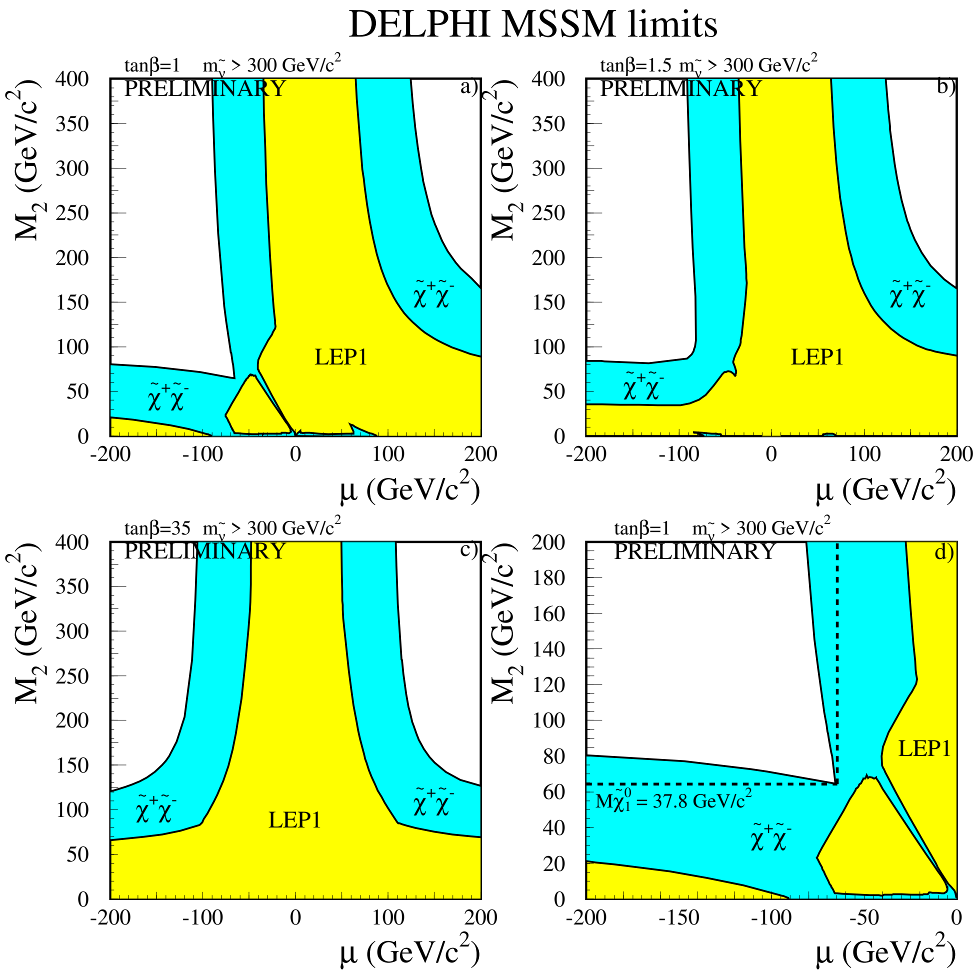
$A_t - \mu/\tan\beta \Rightarrow M_{h^0}$ maximal $\Rightarrow M_{h^0}$ is maximized by putting high M_A and tuning mixing in the stop sector $\Rightarrow A_t$.

$0.5 < \tan\beta < 9.7$ excluded in general MSSM, if no mixing .

sparticles of any mass are excluded if $0.5 < \tan\beta < 2.2$, or $0.5 < \tan\beta < 9.7$ (no mixing)

LEP limits "beyond" kinematics, examples

For -100 GeV $\lesssim$ μ $\lesssim$ 100 GeV M_2 $\lesssim$ 1400 GeV excluded in the CMSSM .



$\Rightarrow$ For this $|\mu|$ range sfermions and gluino are excluded up to 1.5 - 5 TeV !!!

In nearly all $|\mu|$ range gluino and first and second family squarks have to be heavier than 300 GeV $\Rightarrow$ from chargino mass limit!

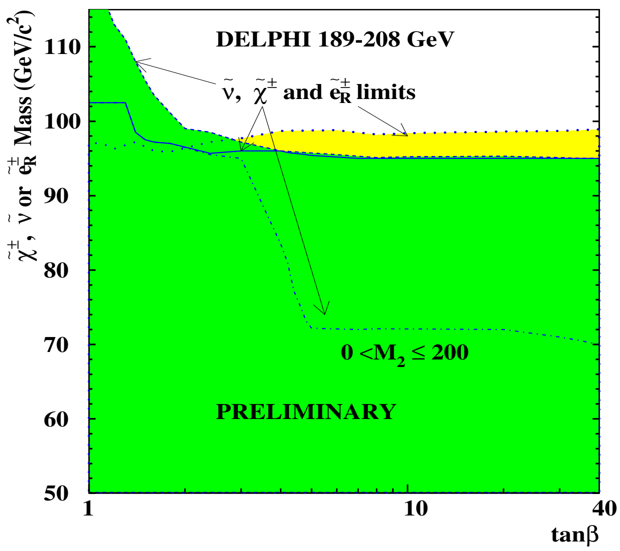
these are just some examples, check your favourite corner !

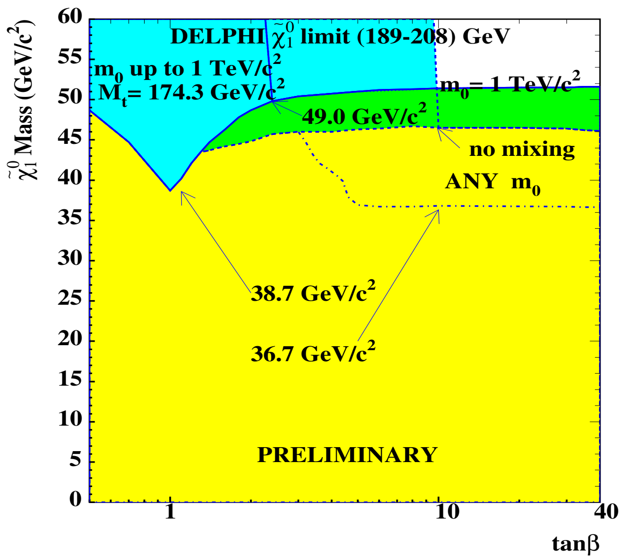
Pathological cases, indirect limits

connected with light sfermions: $\Rightarrow$ partially covered by sfermion searches.

$\tilde{\chi}^{\pm} \rightarrow l\ \tilde{\nu}$	invisible for small $M_{\tilde{\chi}^{\pm}} - M_{\tilde{\nu}}$	$\tilde{\nu}$ corridor
$\tilde{\chi}^{\pm} \rightarrow \tilde{\tau}_1\ \nu$	invisible for small $M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$	$\tilde{\tau}_1$ corridor
$\tilde{\chi}^{\pm} \rightarrow \tilde{l}^*\ \nu$	invisible for small $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$	
$\tilde{\chi}_2^0 \rightarrow \tilde{\nu}\ \nu$	invisible	

Combining searches





indirect limit on the sneutrino mass $\simeq$ 95 GeV

Into the LHC realm ...

Start with mSUGRA , $A_0 = 0$, *Ellis, Falk, Olive, Ganis..*

$\Rightarrow M_{\tilde{\chi}_1^0} > 150\ GeV$, $M_{\tilde{\chi}_1^\pm} > 300\ GeV \Rightarrow M_{\tilde{g}} > 1\ TeV$

$\Rightarrow$ *depends on the choice of* $A_0 = 0$, *and* $M_t = 175\ GeV$.

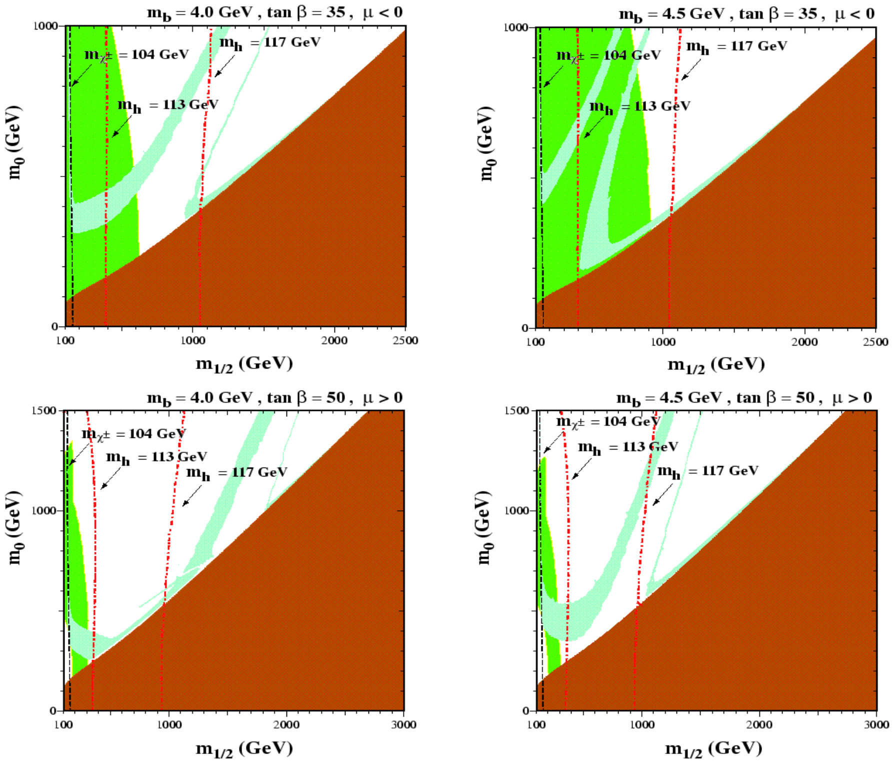
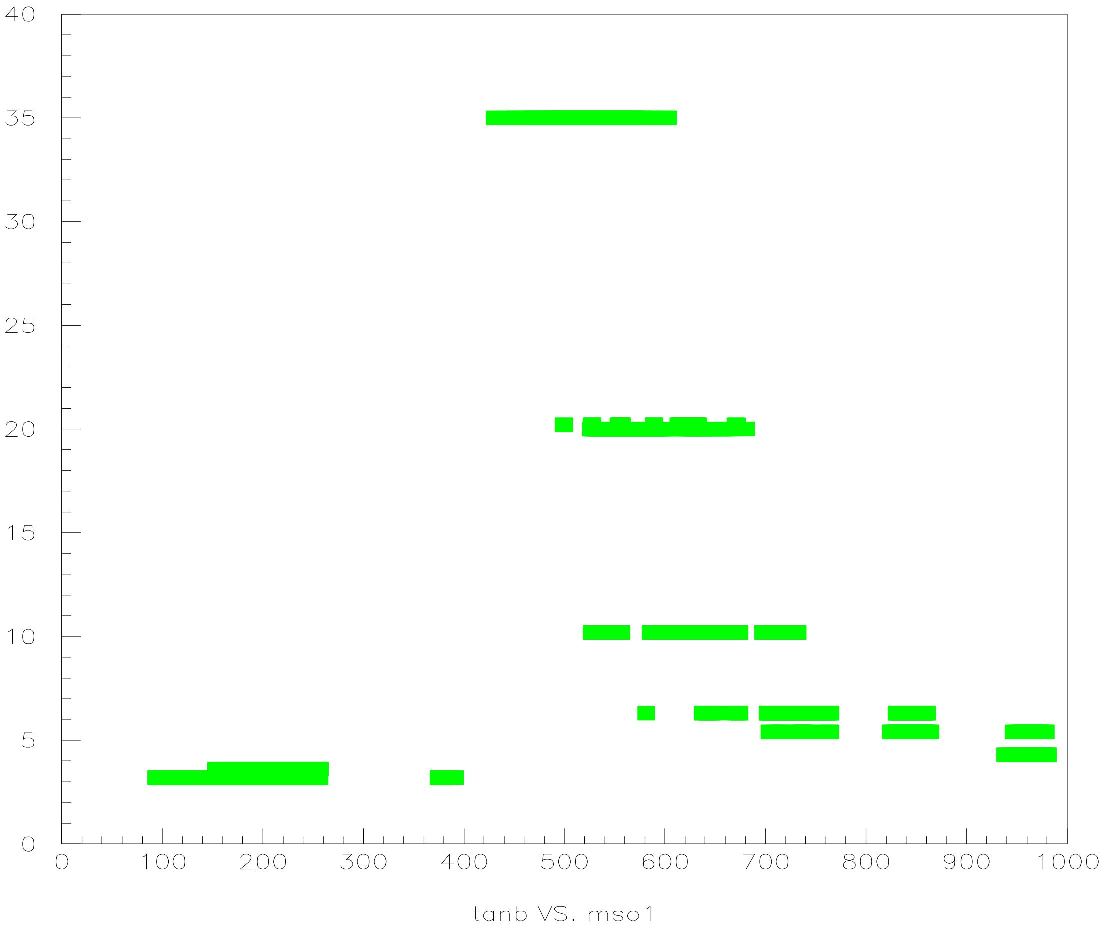


Figure 3: *Comparison between the* $(m_{1/2}, m_0)$ *planes for* $m_b(m_b)^{\overline{MS}}_{SM} = 4.0$ *and* 4.5 *GeV. Panels (a, b) are for for* $\mu < 0, \tan\beta = 35$ *and panels (c, d) for* $\mu > 0, \tan\beta = 50$. *In all cases, we use* $m_t = 175$ *GeV and* $A_0 = 0$. *We see that the channel of low relic density due to rapid annihilation via the* A, H *poles appears at smaller values of* $m_{1/2}/m_0$ *when* $m_b(m_b)^{\overline{MS}}_{SM}$ *is larger.*

CMSSM

$\Rightarrow$ $M_{\tilde{\chi}_1^0} > 50$ GeV, $M_{\tilde{\chi}_1^\pm} > 103$ GeV $\Rightarrow$ $M_{\tilde{g}} > 300$ GeV, same for first, second family squarks.

Stop ??



- Direct LEP limits: “nearly unconditional” kinematical reach
- Indirect LEP limits: beyond kinematics (MSSM): $\tan\beta \gtrsim$ 2.4 (9.7 no mixing)
- Indirect LEP limits: beyond kinematics (CMSSM) example: $M_{\tilde{q}} \gtrsim 300$ GeV, $M_{\tilde{\nu}} \gtrsim 95$ GeV
- Indirect LEP limits into the LHC realm (mSUGRA): $M_{\tilde{g}} \gtrsim$ 1 TeV , $M_{\tilde{\chi}_1^0} >$ 150 GeV, $M_{\tilde{\chi}_1^\pm} >$ 300 GeV
- if true the TeVatron can see the Higgs, but not the sparticles
- everything preliminary, more conclusions to come...