MSSM, SUGRA SUSY Searches at LEP

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on behalf of the four LEP experiments

-LEPII Performance

-SUSY MSSM, MSUGRA

-Searches at LEP ⇒ Limits (95% C.L.):

➢ Sfermions:

-scalar leptons

-scalar quarks

➢ Gauginos, higgsinos:

-charginos

-neutralinos

-Limit on the LSP

-Conclusion

LEPII PERFORMANCE

ALEPH DELPHI L3 OPAL

year	$\sqrt{S}$(GeV)	$\int L\,dt$ (pb^{-1})	
1997	183	**55**	
1998	189	**170**	
1999	192	28	**228**
	196	80	
	200	80	
	202	40	
2000	203	10	**214**
	205	75	
	207	120	
	208	9	

luminosity/experiment ≈ 665 pb^{-1}

The Minimal Supersymmetric Standard Model

Supergravity Breaking Model $\longrightarrow$ **MSSM**

The relevant parameters of the **MSSM** with **RP** conservation are:

$\mathbf{M_1, M_2, M_3}$ **:** Gaugino mass terms related to $\mathbf{m_{1/2}}$

$\mathbf{m_i}$ **:** Scalar fermion masses related to $\mathbf{m_0}$

A's : Trilinear couplings

tan β **:** Ratio of the two Higgs doublets VEV's

μ **:** Mixing Higgs mass parameter

M.SUGRA
tan β, $\mathbf{m_0, m_{1/2}}$, **A,sign(**μ**)**

Imposing Grand Unification relations $\longrightarrow$ M_1, M_2, M_3 are related

MSSM $\longrightarrow$ **CMSSM**

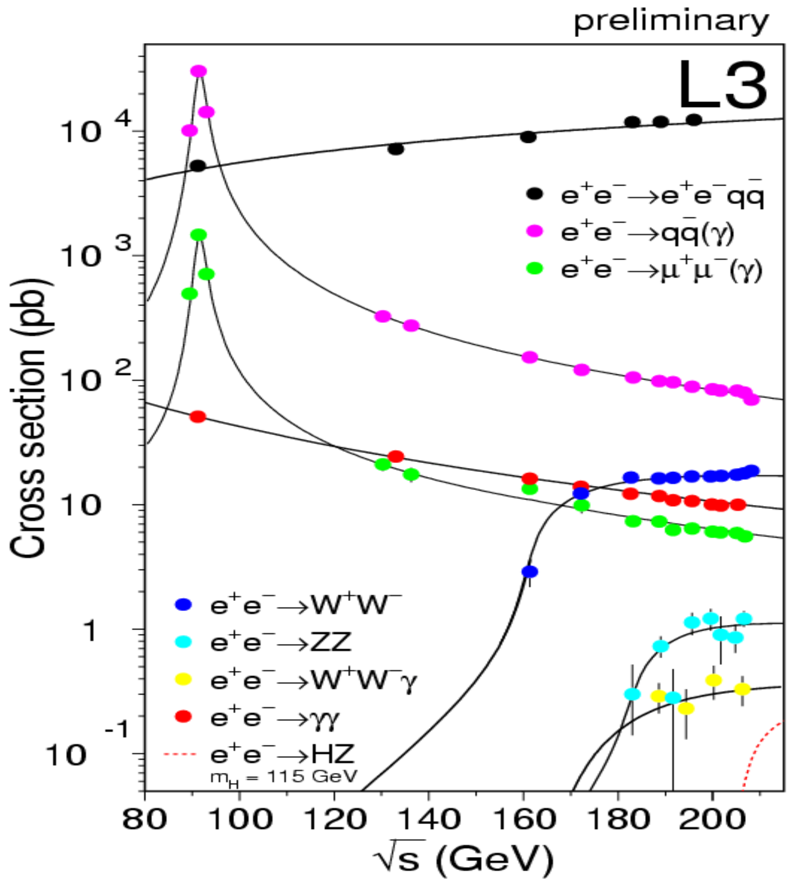
The lightest neutralino $\tilde{\chi}_1^{\circ}$ is the LSP for most of these parameters

General Features

$\Delta M = M(\text{SUSY particle}) - M(\tilde{\chi}_1^\circ)$

At low ΔM two-photon physics background is dominant

At high ΔM two and four-fermion final states are dominant (WW,ZZ,..)



Scalar Leptons, Scalar Quarks

Two kinds of sleptons (squarks) $\tilde{l}_L, \tilde{l}_R$ $(\tilde{q}_L, \tilde{q}_R)$

At LEP ⟶ pair produced (**s channel**) except for
selectrons (+ **t channel**)

Right sfermion is lighter than left sfermion for $\tan\beta > 1$

Left and right sleptons (squark) can mix ⟶ $\tilde{l}_1, \tilde{l}_2$ $(\tilde{q}_1, \tilde{q}_2)$.

mixing proportional to fermionic partner mass ⟶ third generation

$$M_{\tilde{\tau}} = \begin{pmatrix} m^2_{\tilde{\tau},L} & m_\tau(A_\tau - \mu \tan\beta) \\ & m^2_{\tilde{\tau},R} \end{pmatrix}$$

large mixing $\Rightarrow m_{\tilde{\tau},1}$ small

if scalars have a common mass at GUT
$\tilde{t}_1, \tilde{b}_1, \tilde{\tau}_1$ should be the lightest

$$\tilde{\tau}_1 = \tilde{\tau}_L \cos(\theta_\tau) + \tilde{\tau}_R \sin(\theta_\tau)$$

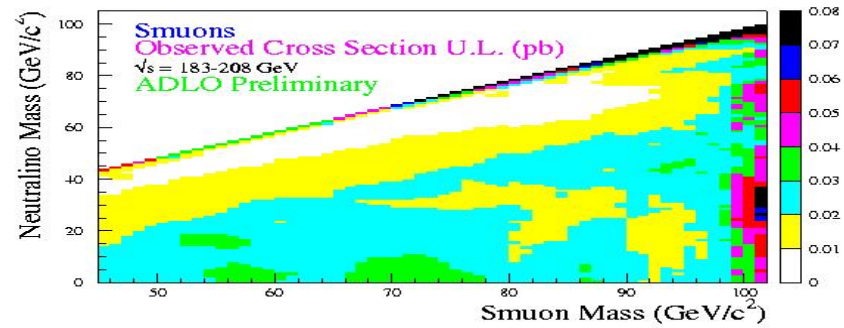
SMUONS

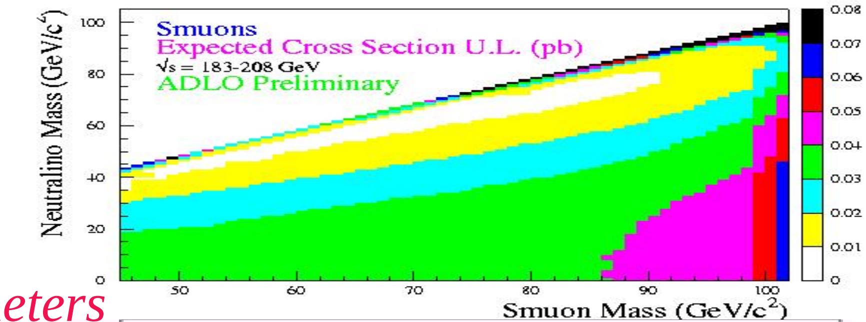
$e^{+}\ e^{-} \longrightarrow \tilde{\mu}_R \tilde{\mu}_R, \tilde{\mu}_L \tilde{\mu}_L$

$\tilde{\mu} \longrightarrow \mu + \tilde{\chi}_1^{\circ}$

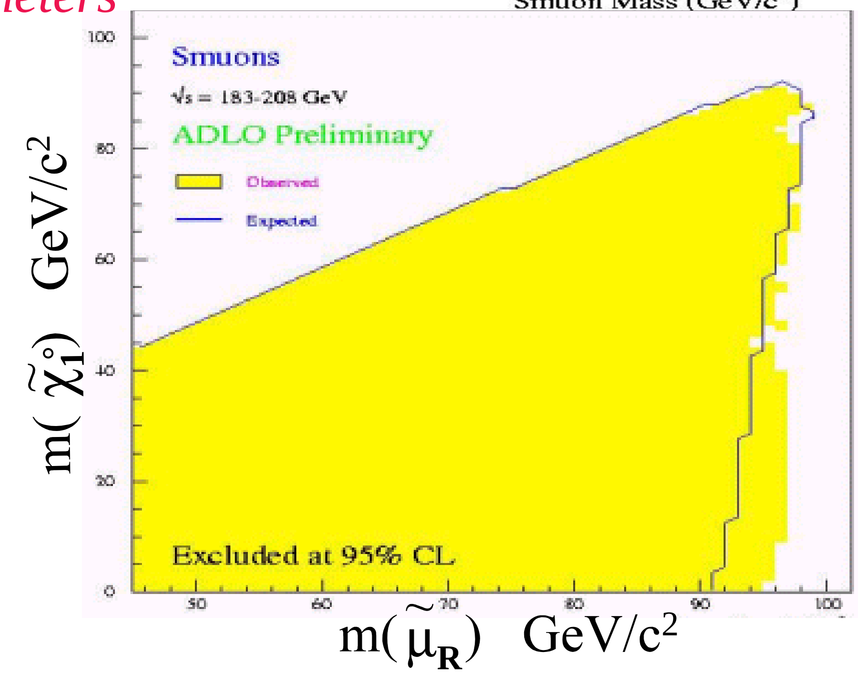
Characteristics: Two acoplanar muons
$+ \not{E}$

Cross section independent of SUSY parameters





Negative searches
➡ limit on the smuon mass.



LEP SUSY W.G
$m(\tilde{\mu}_R) > 96.4$ GeV for $M(\tilde{\chi}_1^{\circ}) = 40$ GeV

STAUS

$e^+ e^- \longrightarrow \tilde{\tau}_1 \tilde{\tau}_1, \tilde{\tau}_2 \tilde{\tau}_2, \tilde{\tau}_1 \tilde{\tau}_2$

$\tilde{\tau} \longrightarrow \tau + \tilde{\chi}_1^\circ$

Characteristics: two low-multiplicity acoplanar jets with missing energy

Cross section depends on the mixing angle:

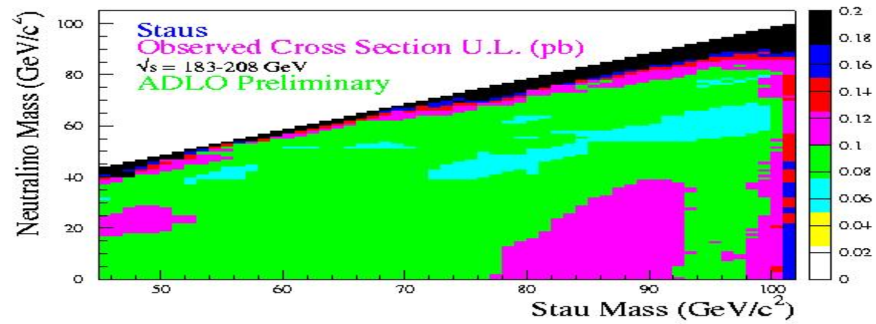
for $\Theta_\tau = 52^\circ$

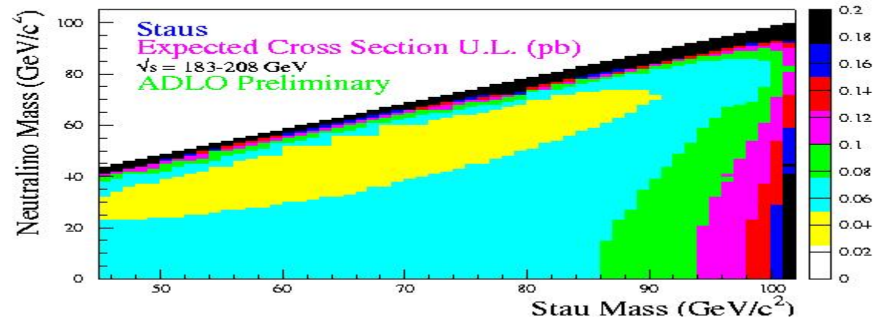
$\tilde{\tau}_1 \tilde{\tau}_1 Z^\circ$ vertex is absent (**decoupling**)

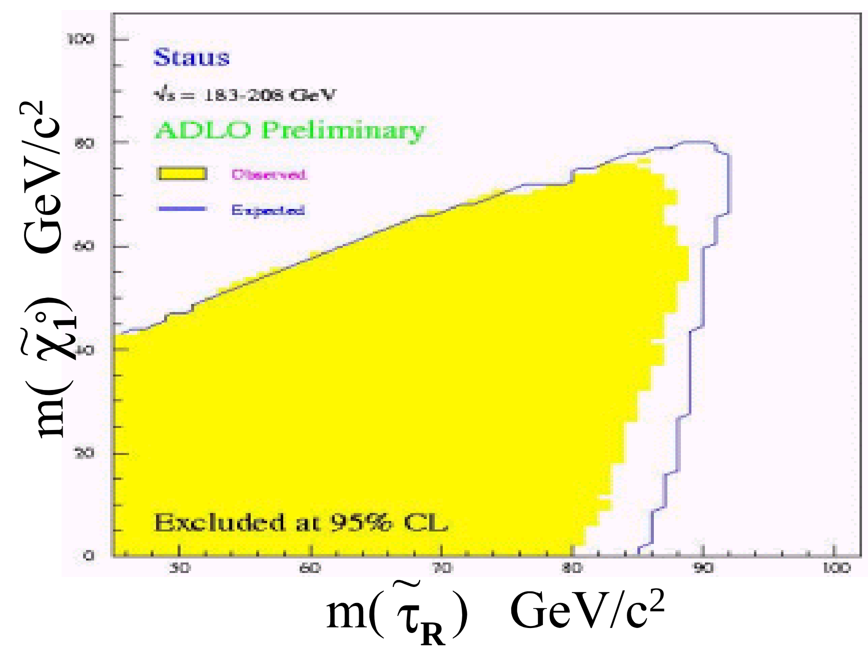
→ minimal cross-section

LEP SUSY W.G

$m(\tilde{\tau}_1) > 87.1$ GeV for $M(\tilde{\chi}_1^\circ) = 40$ GeV



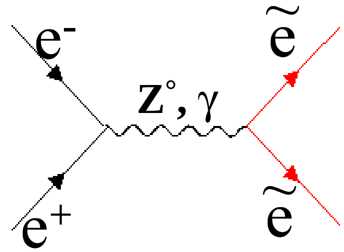


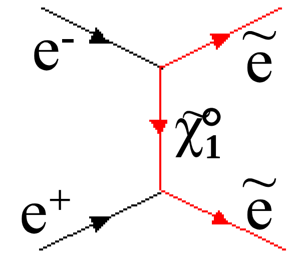


SELECTRONS

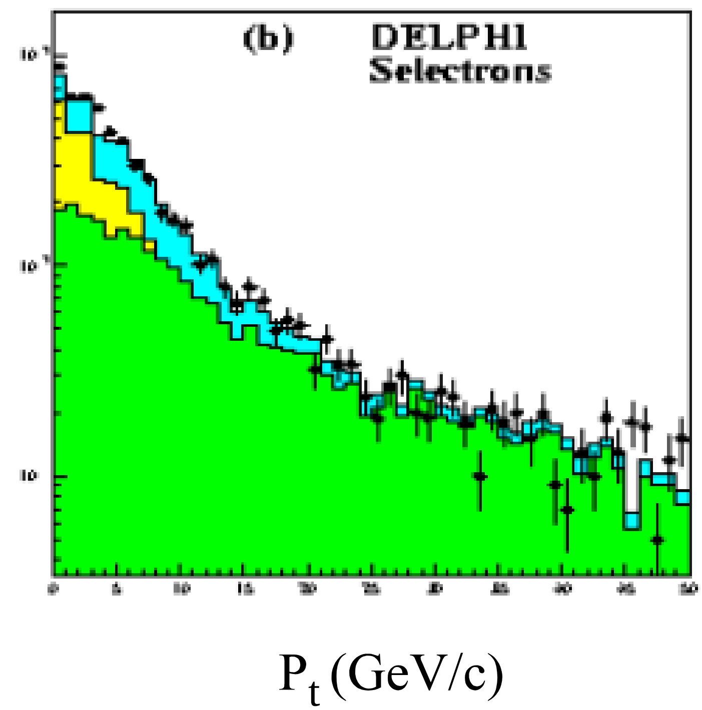
a) $e^+, e^- \longrightarrow \tilde{e}_R \tilde{e}_R \; \tilde{e}_L \tilde{e}_L$

$\tilde{e} \longrightarrow e + \tilde{\chi}_1^\circ$





Characteristics: Two acoplanar electrons $+ \; \not{E}$



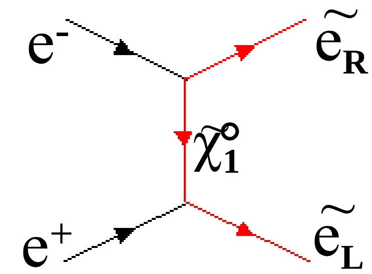
t-channel contribution depends on μ and **tan** β

Simulations at μ = **-200**, **tan** β **=2**
(lowest cross section)

SELECTRONS

b) $e^+ \; e^- \longrightarrow \tilde{e}_R \; \tilde{e}_L$

$\tilde{e} \longrightarrow e + \tilde{\chi}_1^\circ$

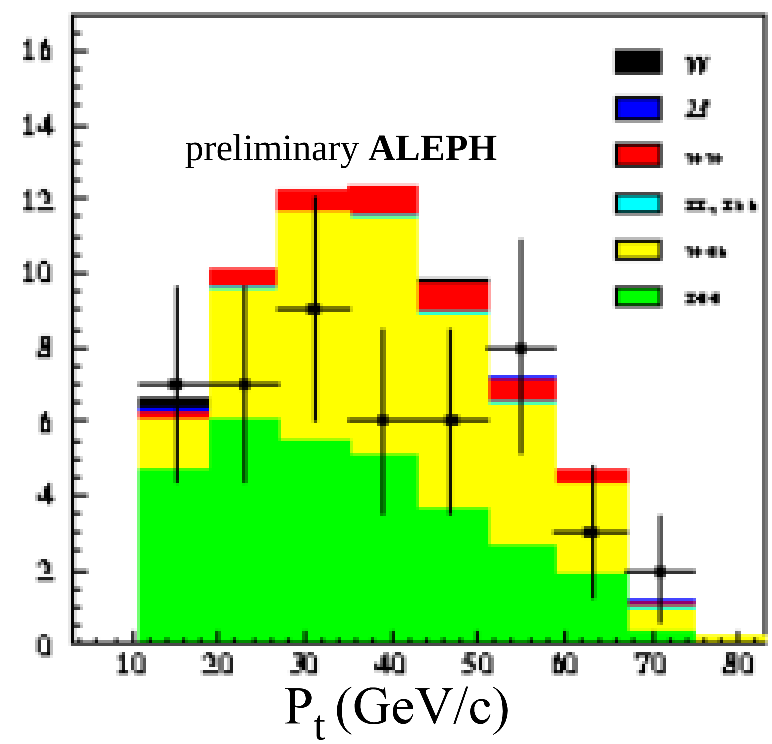


Important if:

1) $\tilde{e}_L \tilde{e}_L$ inaccessible

2) Very low Δ**M =M(** $\tilde{e}_R$**)-M(**$\tilde{\chi}_1^\circ$**)**

- two soft electrons
- no trigger



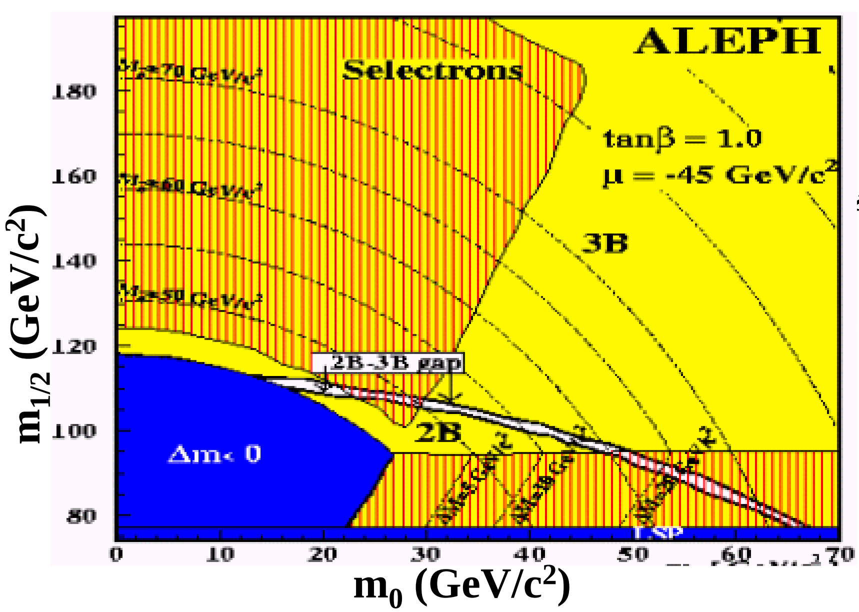
Characteristics: Single identified electron with possible low activity.

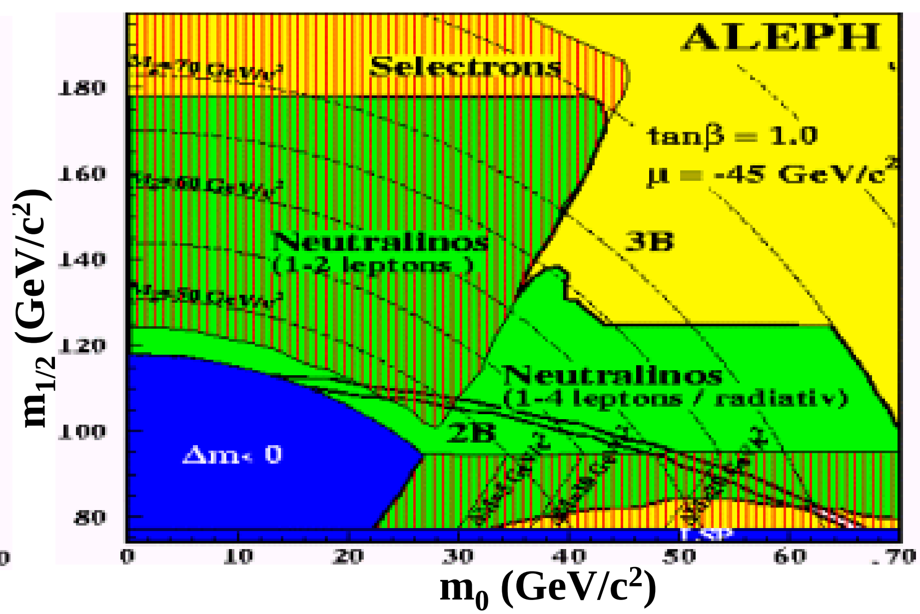
SELECTRONS

At high ΔM (>5) pair production search
At low ΔM (<5) single electron search

$M(\tilde{e}_R) > M(\tilde{\chi}_1^+)$ ➡ Cascade: $\tilde{e}_R \longrightarrow \tilde{\chi}_1^+ + \nu \longrightarrow \tilde{\nu} + \nu + e \longrightarrow \tilde{\chi}_1^\circ + e + \nu + \nu$
inefficient when $M(\tilde{\chi}_1^+) \approx M(\tilde{\nu})$ (corridor region obtained at low values of **tan β**, $|\mu|$ and m_0)

$\tilde{\chi}_1^\circ\ \tilde{\chi}_3^\circ$ production with $\tilde{\chi}_3^\circ$ decaying through sleptons covers the corridor region



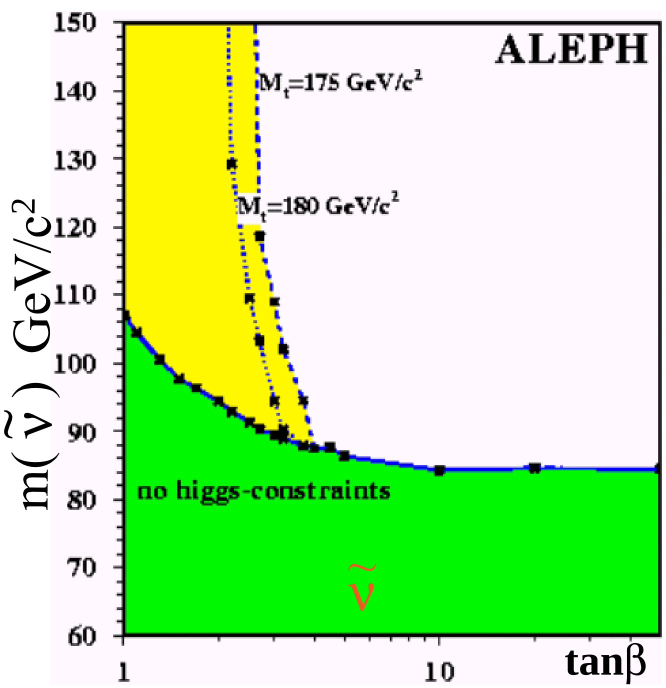


SELECTRONS , SNEUTRINOS

Negative results of selectrons, neutralinos and charginos →
constraints on $\tilde{e}_L$ and $\tilde{\nu}$ masses assuming common gauginos ($m_{1/2}$) and scalars (m_0) masses

$m(\tilde{\nu}) = m_0^2 + 0.77\, M_2^2 + 0.5\, m_Z^2 \cos(2\beta)$
$m(\tilde{e}_L) = m_0^2 + 0.77\, M_2^2 - 0.27\, m_Z^2 \cos(2\beta)$
$m(\tilde{e}_R) = m_0^2 + 0.22\, M_2^2 - 0.2\,3\, m_Z^2 \cos(2\beta)$

Negative CP-Higgs search → exclusion areas in $\tan\beta$, m_0 and $m_{1/2}$ →
constraints on selectrons and sneutrinos (A_t is chosen to maximise M_{h°)

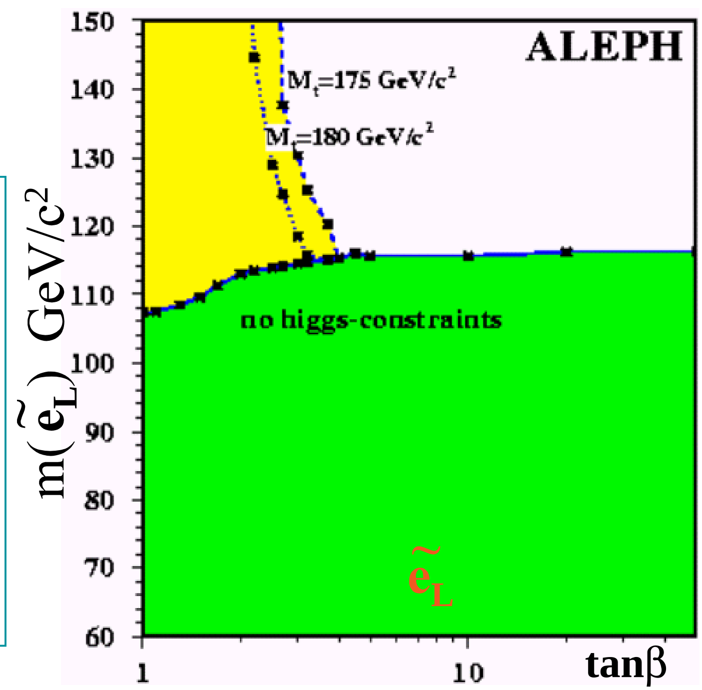


ALEPH

$M(\tilde{e}_R) > 73$ GeV

$M(\tilde{e}_L) > 107$GeV

$M(\tilde{\nu}) > 83$ GeV



SQUARKS

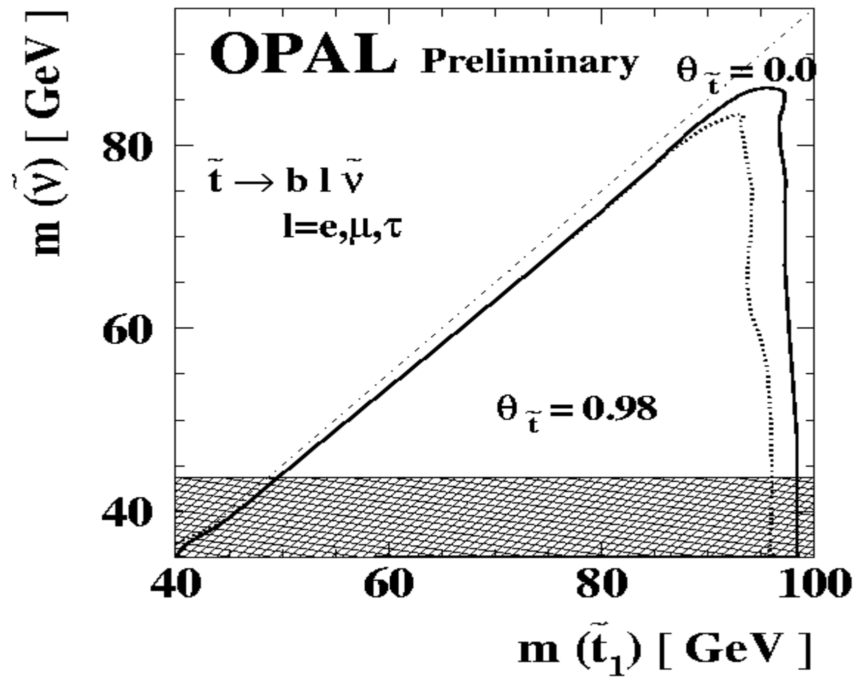
STOP $e^+ e^- \longrightarrow \tilde{t}_1 \tilde{t}_1$

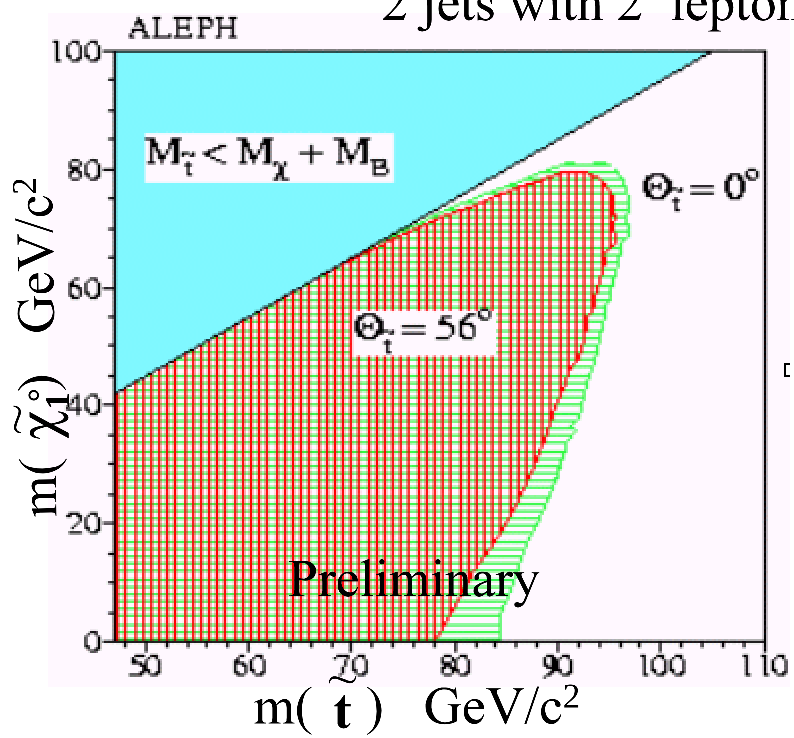
$\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^\circ$ for $\Delta M > 1.5$ GeV

$\tilde{t}_1 \rightarrow u + \tilde{\chi}_1^\circ$ for $\Delta M < 1.5$ GeV

$\tilde{t}_1 \rightarrow b + l + \tilde{\nu}$ $M(\tilde{t}_1) > M(\tilde{\nu}) + M(b)$

2 jets with 2 leptons





corridor problem: $(\tilde{\chi}_1^\circ, \tilde{\chi}_1^+, \tilde{t}_1)$ are almost degenerate in mass.

$\tilde{t}_1 \longrightarrow b f \bar{f}' \tilde{\chi}_1^\circ$ **NEW** (ALEPH): Four-Body decay (virtual chargino, virtual slepton).

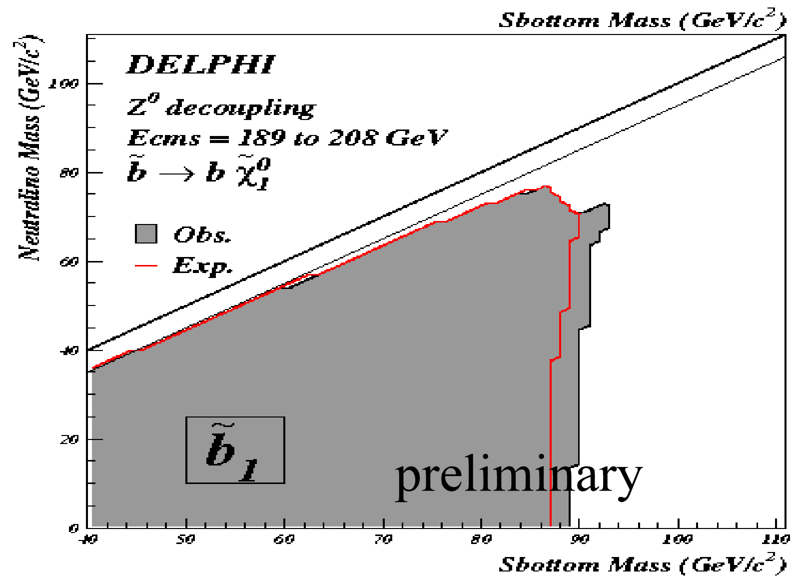
decoupling from the Z° ➡ $\Theta(\tilde{t}_1) = 56^\circ$

SQUARKS

SBOTTOM $e^+ e^- \longrightarrow \tilde{b}_1 \tilde{b}_1$

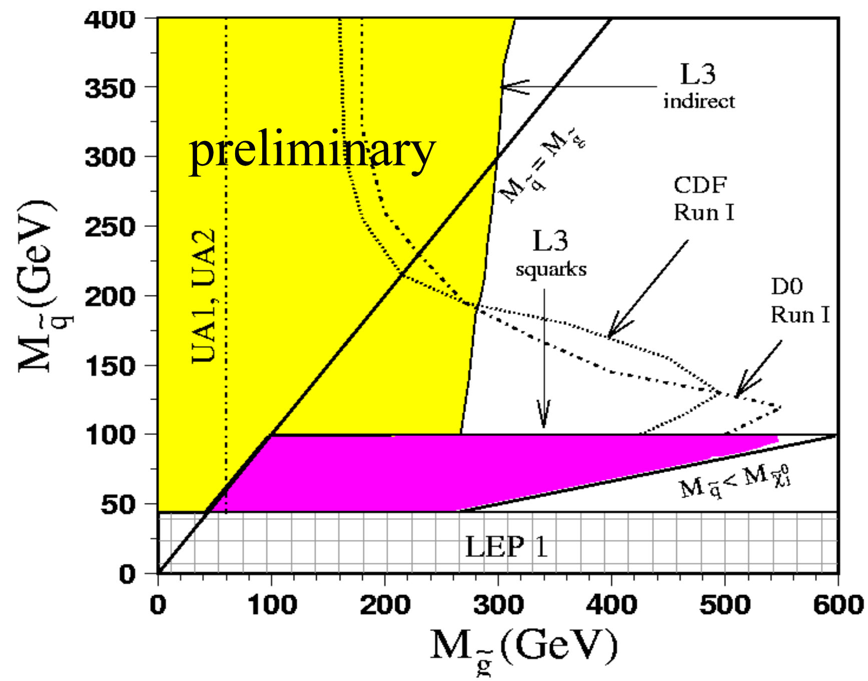
$\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^\circ$ for $\Delta M > 5$ GeV,

acoplanar jets with b-tagging



decoupling from the Z° ➡

$\Theta(\tilde{b}_1) = 68°$



Other Squarks

- Degenerate squark masses
- Unification relation (M2 and M3)
- Absence of acoplanar jets

➡ Lower limit

on squark masses.

CHARGINOS

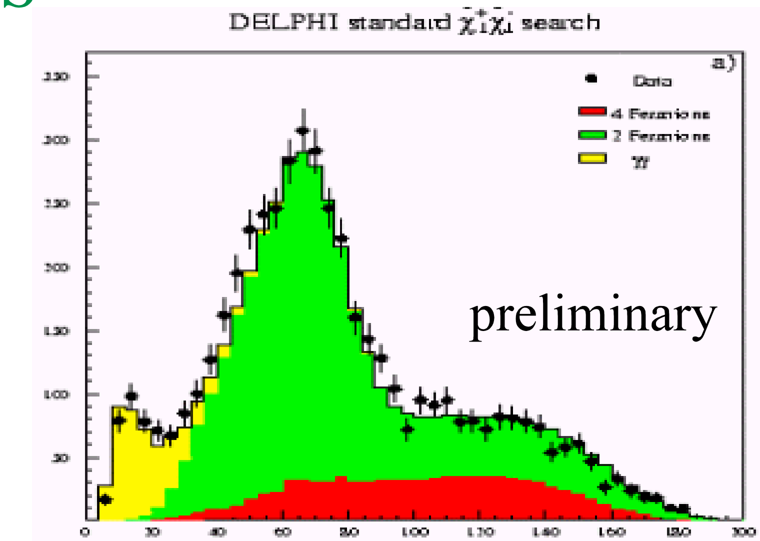
Charginos are mass eigen states of charged higgsinos and gauginos: $\tilde{\chi}_1^+$, $\tilde{\chi}_2^+$

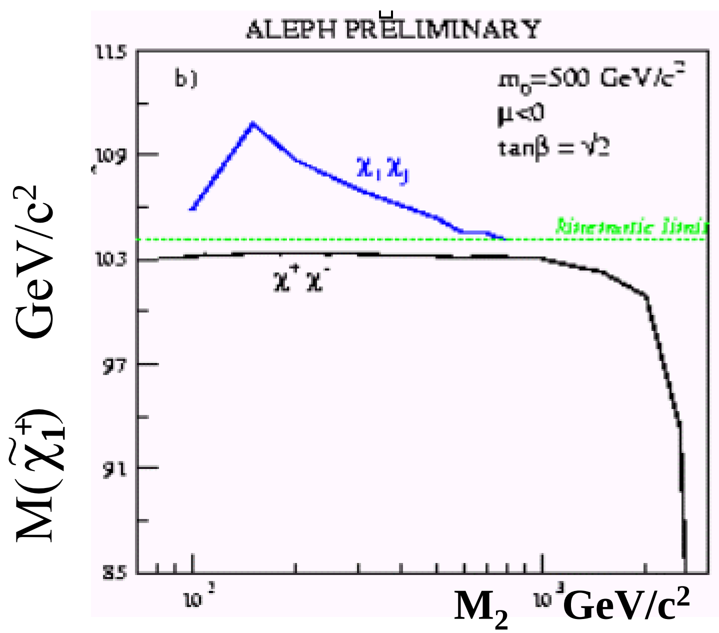
$e^+ e^- \longrightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$

$\Delta M = M(\tilde{\chi}_1^+) - M(\tilde{\chi}_1^\circ)$

Standard search: $\Delta M > 3\text{-}4$ GeV

Different topologies: l l , j j l , jets



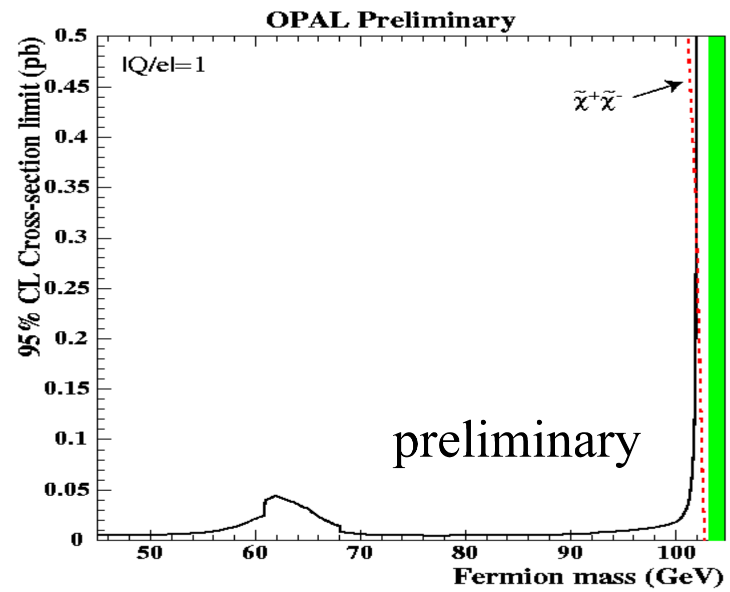


No excess in data ➡ exclusion up to the kinematical limit and beyond using neutralino searches.

LEP SUSY W.G
$M(\tilde{\chi}_1^+) >$ **103.5** GeV
For $M(\tilde{\nu}) >$ 300 GeV
preliminary

CHARGINOS

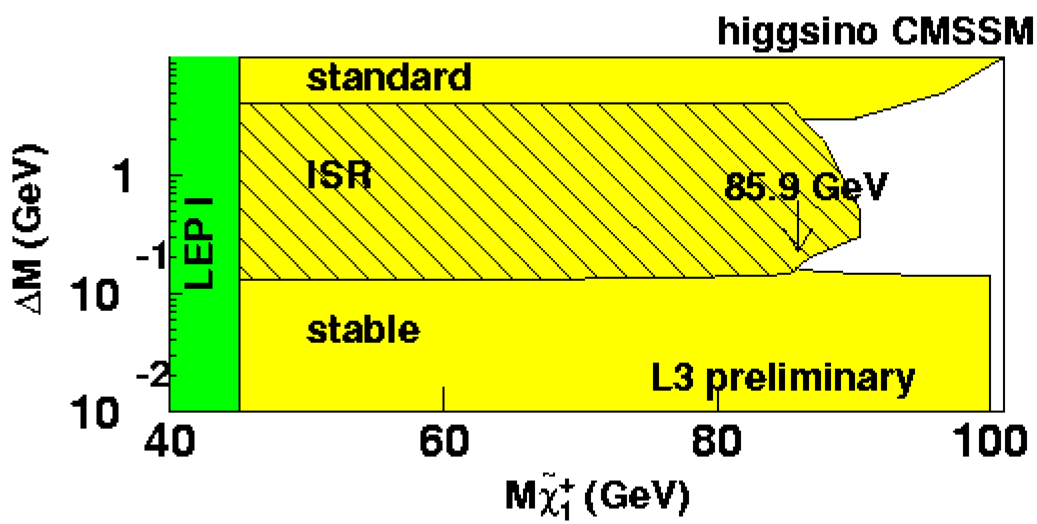
For $\Delta M < 3$-4 GeV



A) Quasi stable chargino: $\Delta M < m(\pi)$
two heavy ionisation muon-like particles

B) Kinks and secondary vertices :

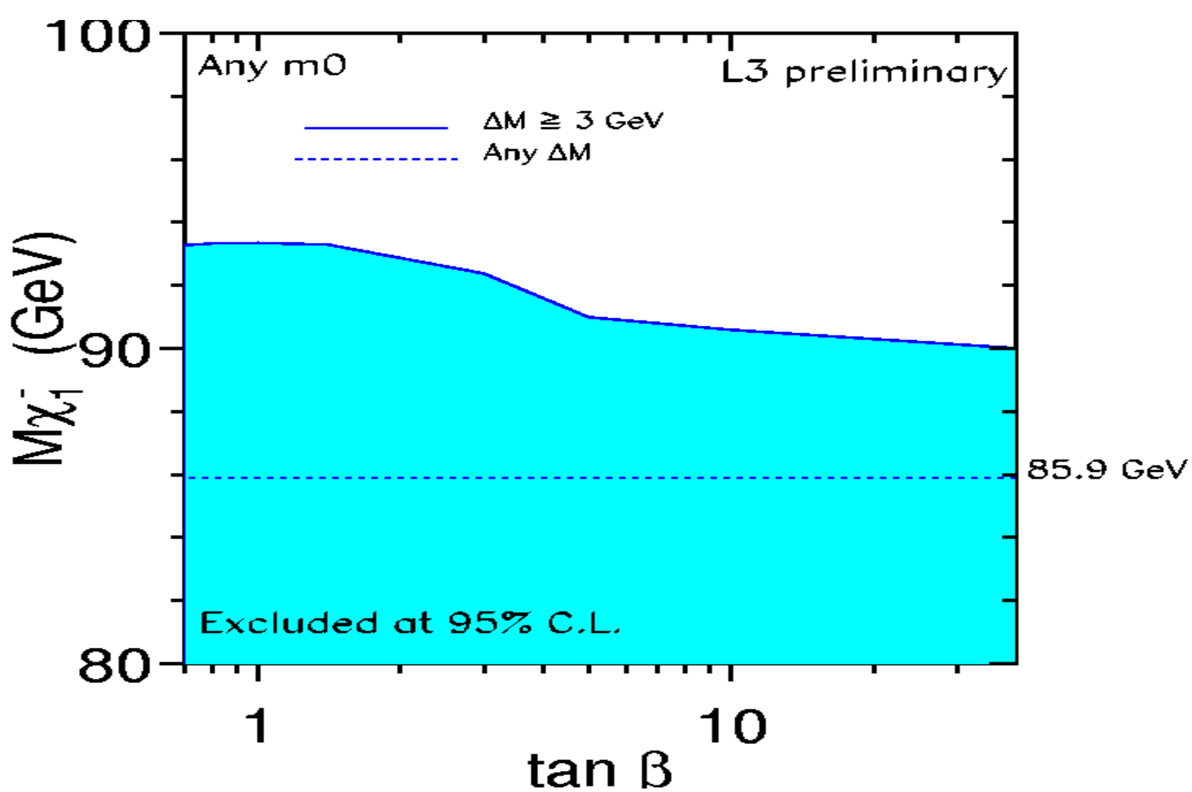
C) Short lifetime: prompt decay but decay products are invisible
➡ troublesome scenario
use ISR γ to trig the event
➡ low efficiency



MSSM chargino nature
higgsino: $\mathbf{M_2} \gg |\mu|$
gaugino: $\mathbf{M_2} \ll |\mu|$ (unification relation between M_2, M_1 relaxed)

CHARGINOS

Combining high and low ΔM negative searches within the CMSSM



L3

$M(\tilde{\chi}_1^+) > 85.9$ GeV

NEUTRALINOS

Neutrqlinos are mass eigen states of neutral higgsinos and gauginos:

$\tilde{\chi}_1^\circ, \tilde{\chi}_2^\circ, \tilde{\chi}_3^\circ, \tilde{\chi}_4^\circ$

$e^+ e^- \longrightarrow \tilde{\chi}_1^\circ \tilde{\chi}_1^\circ$ invisible

Different topologies corresponding to different channels:

Acoplanar jets, acoplanar leptons ($\tilde{\chi}_1^\circ, \tilde{\chi}_2^\circ$): with $\tilde{\chi}_2^\circ$ decaying to $\tilde{\chi}_1^\circ$+dileptons or diquarks or a gamma

Multi-jets, multi-leptons ($\tilde{\chi}_i^\circ, \tilde{\chi}_j^\circ$) i,j>1: with $\tilde{\chi}_i^\circ, \tilde{\chi}_j^\circ$ decaying through cascades

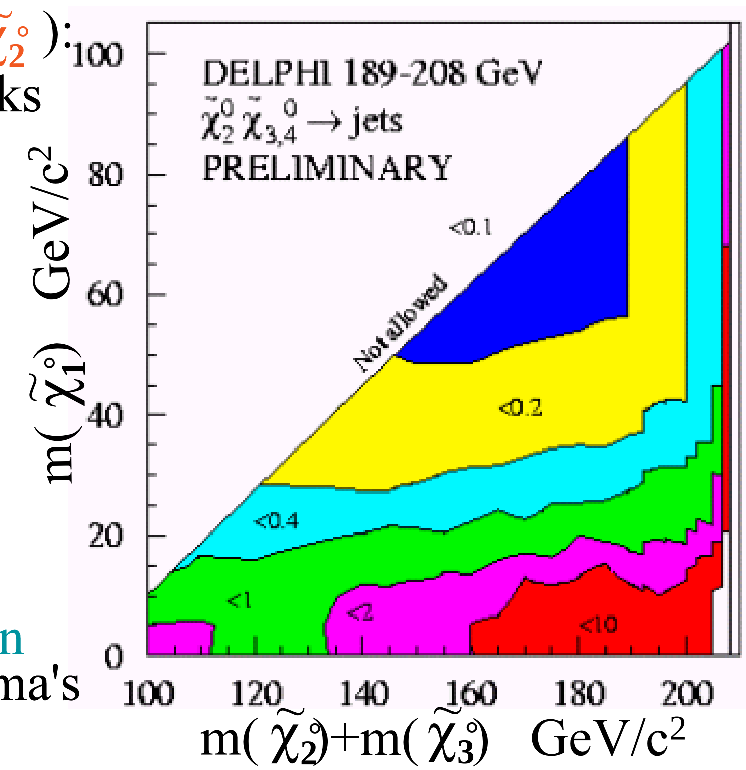
Tau cascade ($\tilde{\chi}_1^\circ, \tilde{\chi}_2^\circ$)

Tau cascades ($\tilde{\chi}_2^\circ, \tilde{\chi}_2^\circ$)

with $\tilde{\chi}_2^\circ$ decaying to $\tilde{\tau}_1 \tau$

$\tilde{\chi}_2^\circ \tilde{\chi}^\circ_{3,4}$ production

multi-jets without gamma's

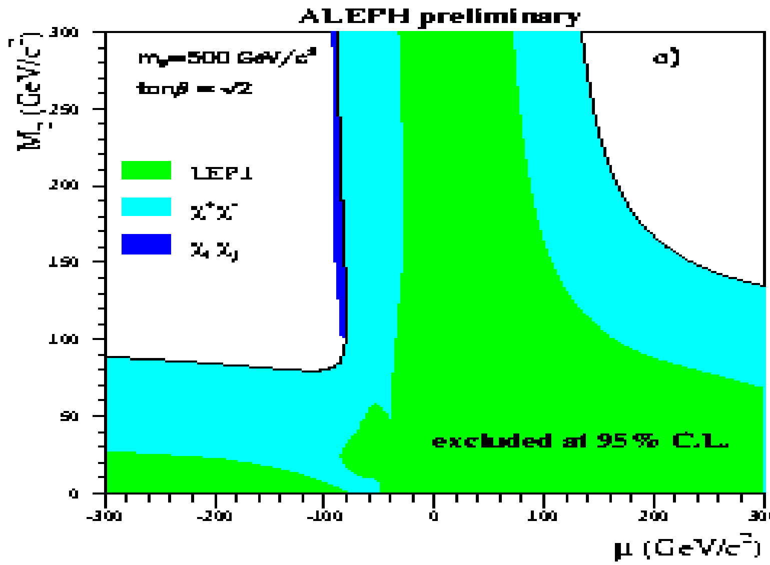


Limits on the LSP

How to obtain the lower limit on the LSP mass?

LSP mass depends on M_2, μ and $\tan\beta$.
The **negative** searches results → exclusion in **SUSY** parameters space (M_2, μ, $\tan\beta$, m_0, A …..)

1) build (M_2, μ) exclusion planes for many values of $\tan\beta$, m_0 and A



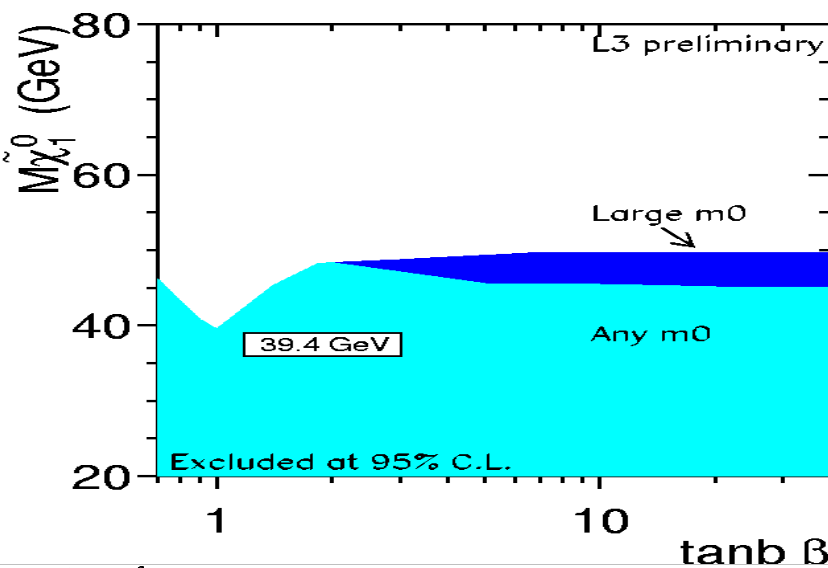
2) take **LSP** mass corresponding to the lowest limit.

Where is it obtained?

The weakest limits are obtained for:

$M(\tilde{\chi}_1^+) \approx M(\tilde{\nu})$ (m_0 effect)

$M(\tilde{\chi}_1^\circ) \approx M(\tilde{\tau}_1)$ (A effect)



Limits on the LSP

What else?

Higgs searches are sensetive to:

$\tan\beta$ directly

A_t, $m_{1/2}$ and m_0 through ($\tilde{t}_1$).

Negative Higgs searches

➡ exclusion

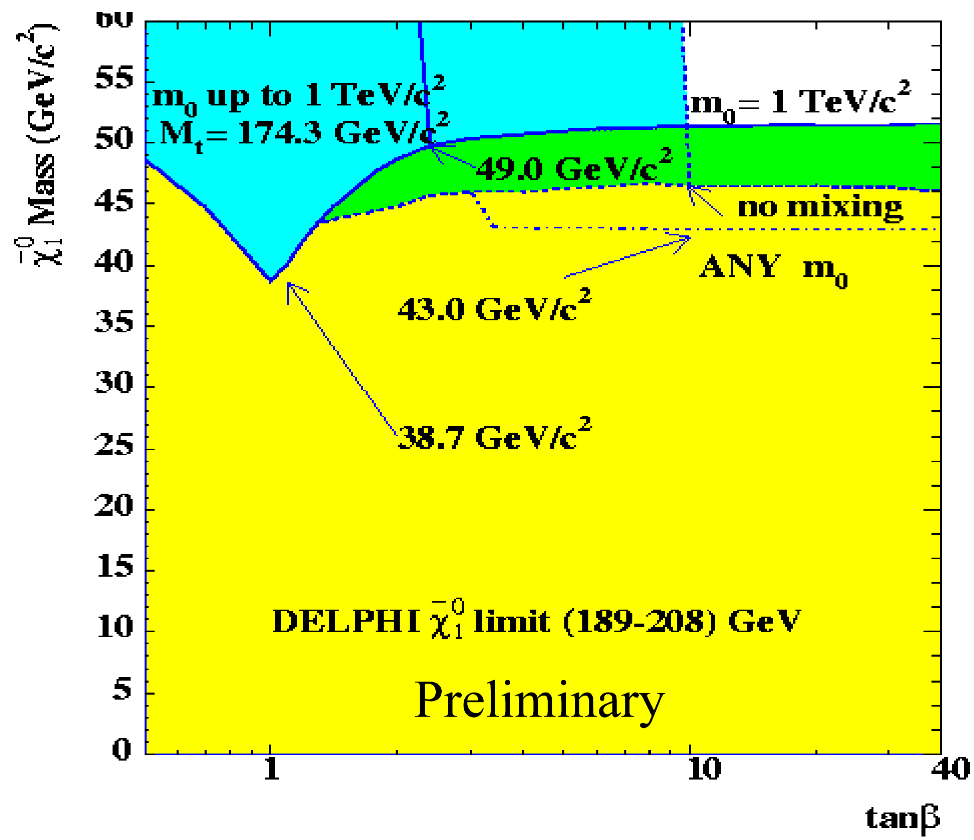
Maximal M_{h° scenario:

$A_t - \mu/\tan\beta = \sqrt{6}$

➡ constrain $\tan\beta$

➡ improve LSP mass limit:

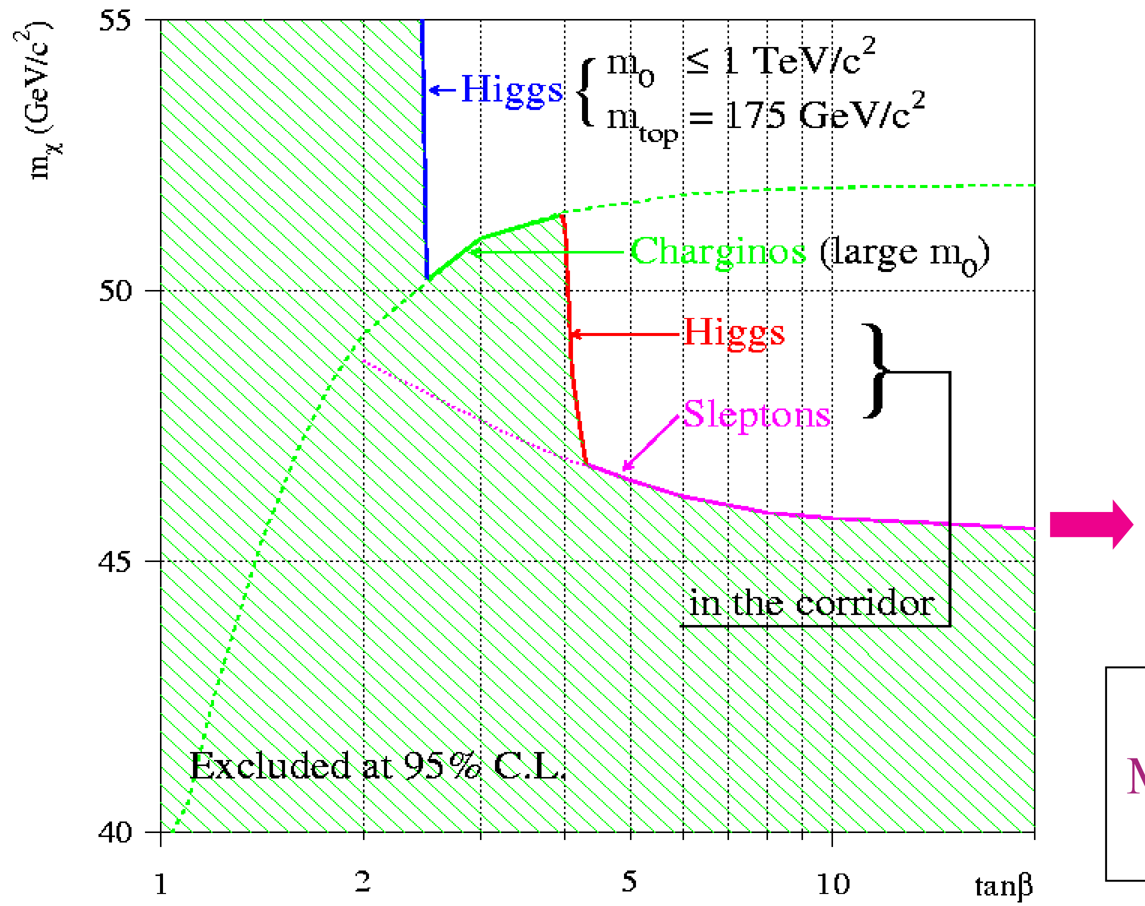
(Delphi: 43 GeV)



Warning: limit sensitive to the top quark

Limits on the LSP

LEP SUSY W.G preliminary combined limit on **LSP** mass



46 GeV
CMSSM

52.2 GeV
M.SUGRA
$A_0=0$

Conclusion

- The four **LEP** experiments are still working on the **SUSY** analyses to provide as soon as possible solid limits on the different SUSY particles in the most general **MSSM** scenarios.
- New analyses were born after the end of LEP trying to exploit all the rich data collected by LEPII.
- LEPII was a powerful tool to hunt SUSY.

It is interesting to see the achievement of LEPII within the CMSSM frame:

	LEPI	LEPII (preliminary))
Neutralino	≥ 23 GeV (tan β>3	≥ 39.6 GeV (≥ 46 if Higgs)
Chargino	≥ 45 GeV	≥ 85.9 GeV
Sneutrino	≥ 41.8 GeV	≥ 83 GeV
Selectron	≥ 45 GeV	≥ 73 GeV(≥ 75 if Higgs)