MSSM SUSY Searches at LEP

Hanna Nowak

DESY Zeuthen

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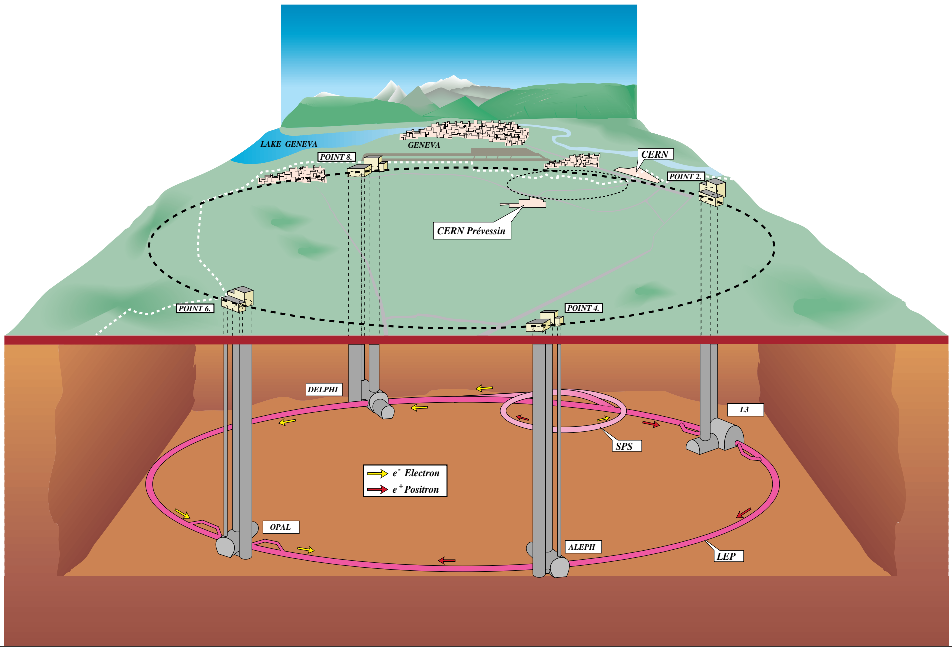
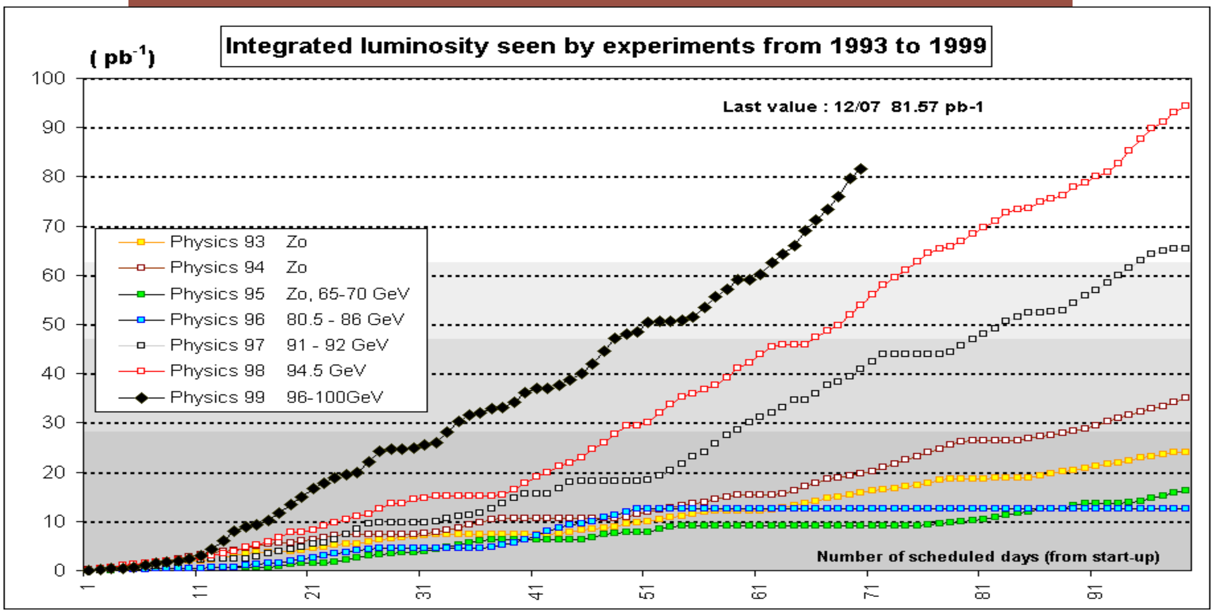
Outline

- **Data : LEP and its Experimental Data**
- **Theory : SUSY and MSSM**
- **Searches at LEP : Topologies and Strategies**
- **Scalar Leptons**
- **Scalar Quarks**
- **Charginos and Neutralinos**
- **Summary and Outlook**

LEP and Data





	$\sqrt{s}$/GeV	Year	Luminosity/pb^{-1}
LEP 1	$\approx$ 91	1989-1995	175
LEP 1.5	130 - 140	1995	5
LEP 2	161 and 172	1996	20
	183	1997	55
	189	1998	175
	192 and 196	1999	$\approx$90

SUSY and MSSM

1. Why SUSY ?

Experiment: SM is o.k. to a level of 0.1%

Theory: Hierarchy Problem - large ($(10^{18} GeV)^2$)) contribution to the Higgs Boson mass to be cancelled in each order of perturbation theory

SUSY is one solution :

- **scalar and fermion interaction - same couplings**
- **natural cancellation of the divergent quadratic contributions to the Higgs boson mass**
- **the three gauge coupling constants join at the unification scale**
- **the stable LSP is a good candidate for cold dark matter**
- **there is a full new zoo of particles to search for**

but: many, many new parameters ...

SUSY and MSSM

Lagrangian SUSY

$$L_W = -\sum_i \left|\frac{\partial W}{\partial z_i}\right|^2 - \frac{1}{2}\sum_{ij}\left[\bar{\psi}_{iL}\,\frac{\partial^2 W}{\partial z_i \partial z_j}\,\psi_{jL} + h.c.\right]$$

the Superpotential contains:

- **all Higgs, Squarks, Slepton Fields**
- **all couplings**

2. MSSM

What do we need at minimum

- **two Higgs doublets $\Longrightarrow$ four neutralinos**
- **an LSP with no electromagnetic or strong interaction**
- **at least 6 parameters:**
  - m_0 **: Common sfermion mass at the GUT scale**
  - $M_{1/2}$ **: Common gaugino mass at the GUT scale**
  - μ **: Higgsino mass parameter**
  - $\tan\beta$ **: vacuum expectation value of the neutral members of the scalar components of the two Higgs doublets**
  - A_0 **: universal trilinear coupling**
  - m_A **: Mass of the CP-odd Higgs A**

SUSY and MSSM

What do we get – the new sparticles

Particle	Sparticle
Bosons	**Fermion**
g	$\tilde{g}$
γ	$\tilde{\gamma}$
$W^{\pm}$	$\tilde{W}^{\pm}$
Z	$\tilde{Z}$
$H_{1,2}$	$\tilde{H}_{1,2}$
G	$\tilde{G}$
Fermions	**Bosons**
l	$\tilde{l}_R, \tilde{l}_L$
q	$\tilde{q}_R, \tilde{q}_L$

How is the scenario?

- each helicity state of a fermion has a SUSY partner
- third generation can mix and has at least one low mass eigenstate
- gauginos and higgsinos mix to form eigenstates ($\chi^{\pm}$, χ^{0}, h, A)
- R parity —- quantum number different for particles and sparticles

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

  R parity conservation assumed
- sparticles are produced in pairs
- sparticles decay into sparticles (if R is conserved)
- the LSP is stable - its signature is missing energy

Topologies and Strategies

Common features of all signal topologies:

- **missing momentum** p_{miss}
- **missing mass** M_{miss}

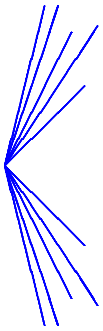
furthermore there is no preferred direction of p_{miss}

- **acoplanar leptons and/or**
- **acoplanar jets in the final state**

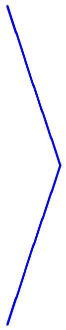
a given signal topology depends on :

- **the nature of the signal**
- **the mass difference between a sparticle and LSP called** $\triangle M$
- **the nature of the decay , e.g. direct decays, cascade decays, higher order processes**

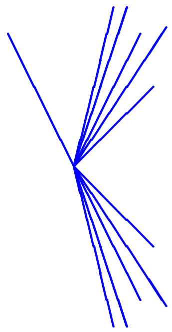
Topologies and Strategies



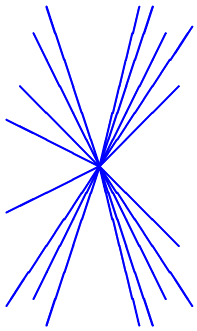
topology : 2 acoplanar jets $+E_{miss}$
signature for : neutralino,squark



topology : 2 acoplanar leptons $+E_{miss}$
signature for : neutralino,chargino,slepton

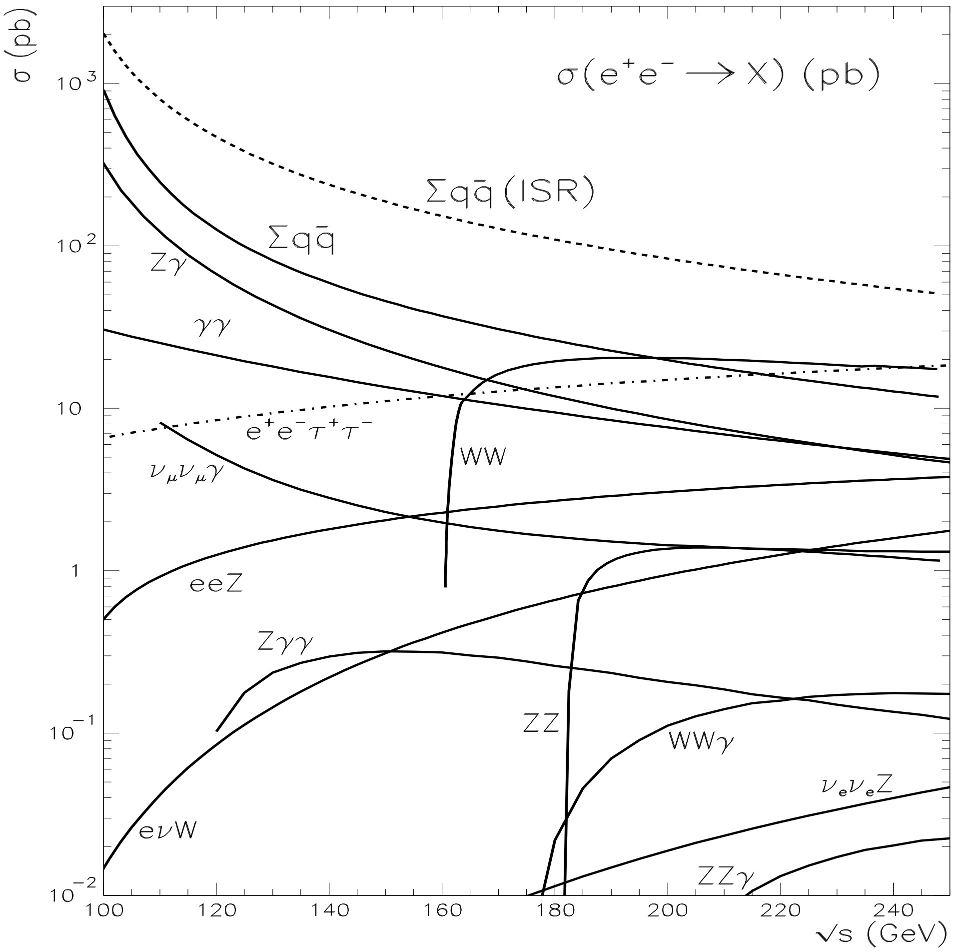


topology : 2 jets $+$ **lepton** $+E_{miss}$
signature for : chargino,squark



topology : 4 jets $+E_{miss}$
signature for : chargino

SM Backgrounds



- two photon collision background cross section 17 nb
- cross section for 90 GeV $\tilde{\chi}_1^\pm$ in the order of 1 pb
- cross section for 90 GeV $\tilde{t}_1$ in the order of 100 fb
- cross section for 90 GeV $\tilde{\tau}$ in the order of 10 fb

Sleptons -

- **mass eigenstates from diagonalisation of L-R matrix**
- **off-diagonal terms negligible for the light ones**

$$\tilde{e}_L,\ \tilde{e}_R,\ \tilde{\mu}_L,\ \tilde{\mu}_R$$

- **off-diagonal term large (for large $\tan\beta$) for third generation)**
- **mixing and possible vanishing coupling to Z for**

$$\tilde{\tau}_1,\ \tilde{\tau}_2$$

Production process

- **for $\tilde{e}_{L,R}$ and $\tilde{\mu}_{L,R}$ s-channel γ/Z exchanges depend only on slepton mass**
- **for $\tilde{e}_{L,R}$ also t-channel $\tilde{\chi}^0_1$ exchange σ depends on M_2, μ , $\tan\beta$**

Slepton searches:

- main decay into lepton + $\tilde{\chi}_1^0$ – pair of acoplanar leptons
- cascade decays into lepton + $\tilde{\chi}_2^0$ or $\nu\tilde{\chi}_1^\pm$
- also search for stable smuon(staus)

main backgrounds: 2 photon collision processes

all 4 experiments have searched for sleptons:

No evidence for any slepton was found $\rightarrow$ limits at 95% C.L.

LEP compilation of the LEP working group

Conditions on the compilation :

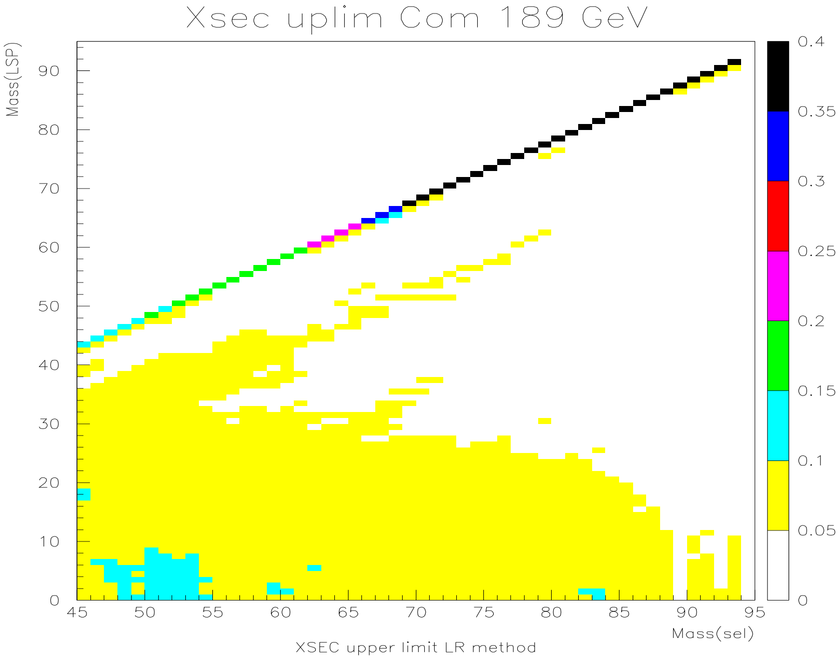
- Unification of gaugino masses

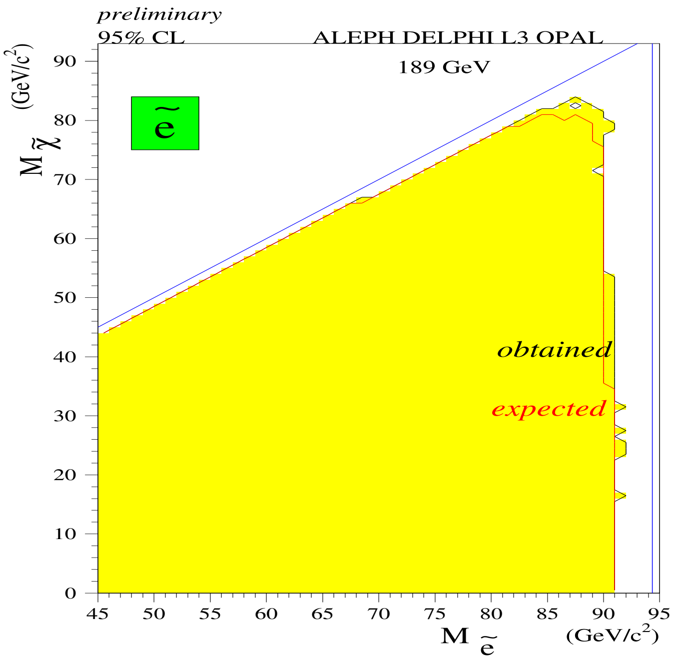
$$M_1 = 5/3 \cdot \tan^2(\Theta_W) \cdot M_2$$

- $\tilde{l}_R$ ($\tilde{l}_L$ out of LEP range)
- branching ratio for the main decay calculated as f(M_2)
- parameters fixed μ to -200 GeV/c^2 , $\tan\beta$ to 1.5
- all exclusion limits are given for $\Delta M > 15$ GeV

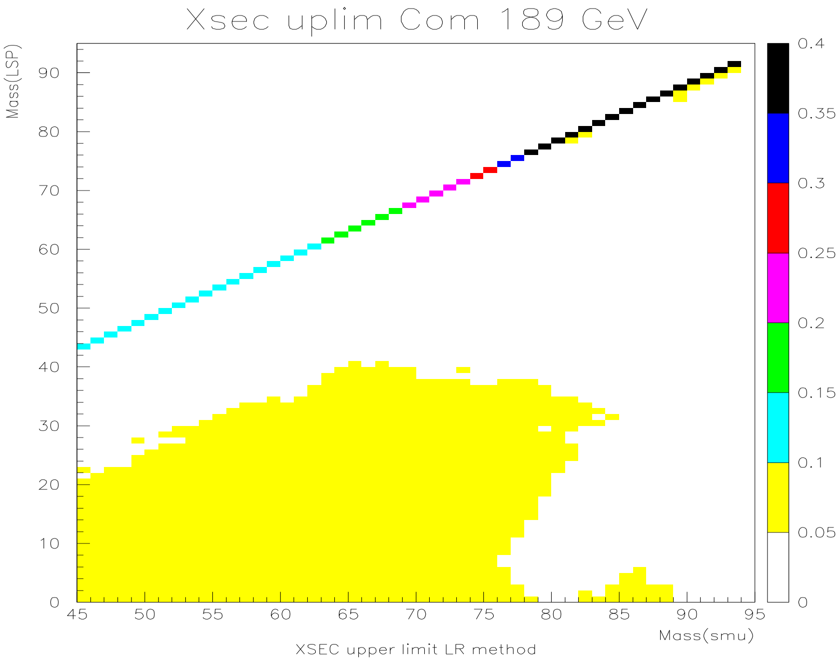
Some plots:

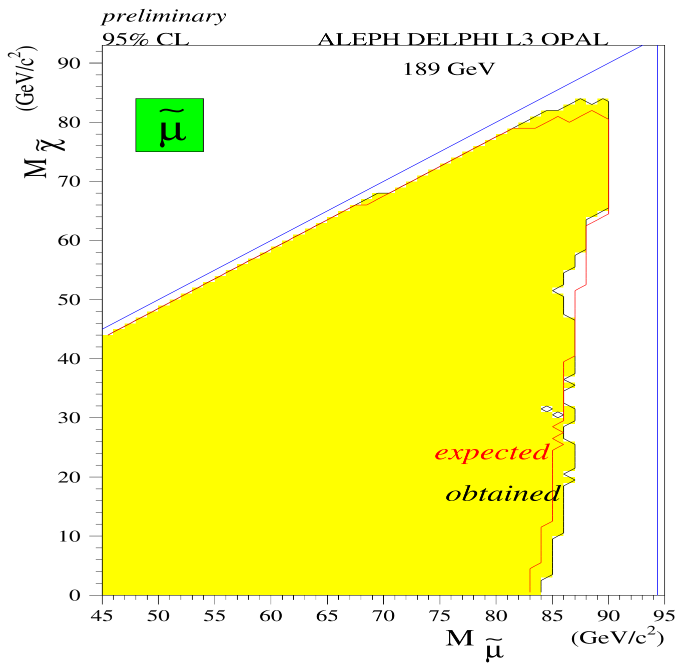
— obtained cross section and mass limits for $\tilde{e}_R$,$\tilde{\mu}_R$,$\tilde{\tau}_R$





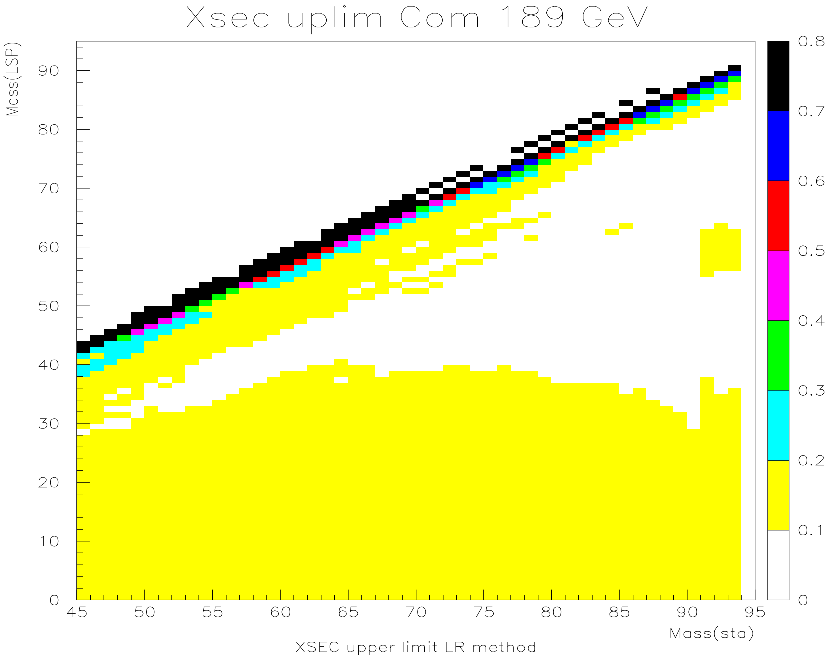
Mass limit for selectron 89 GeV (obtained)
90 GeV (expected)

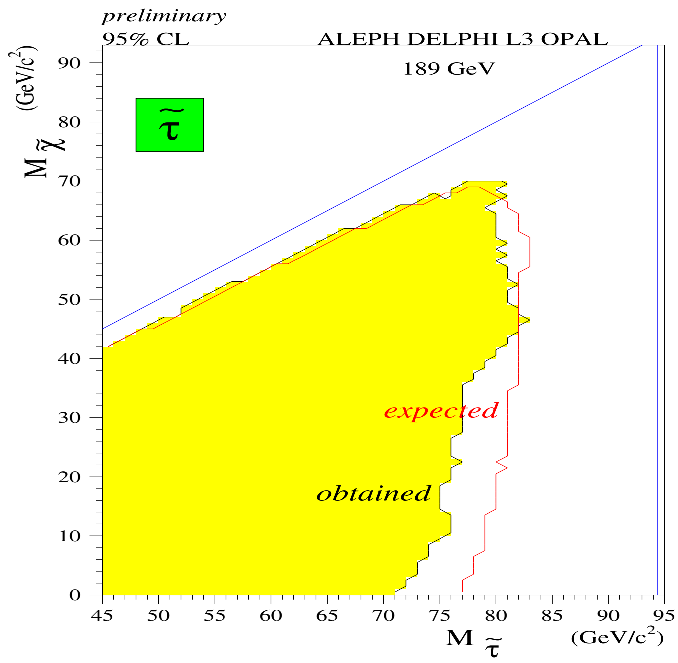




Mass limit for smuon 84 GeV (obtained)
83 GeV (expected)

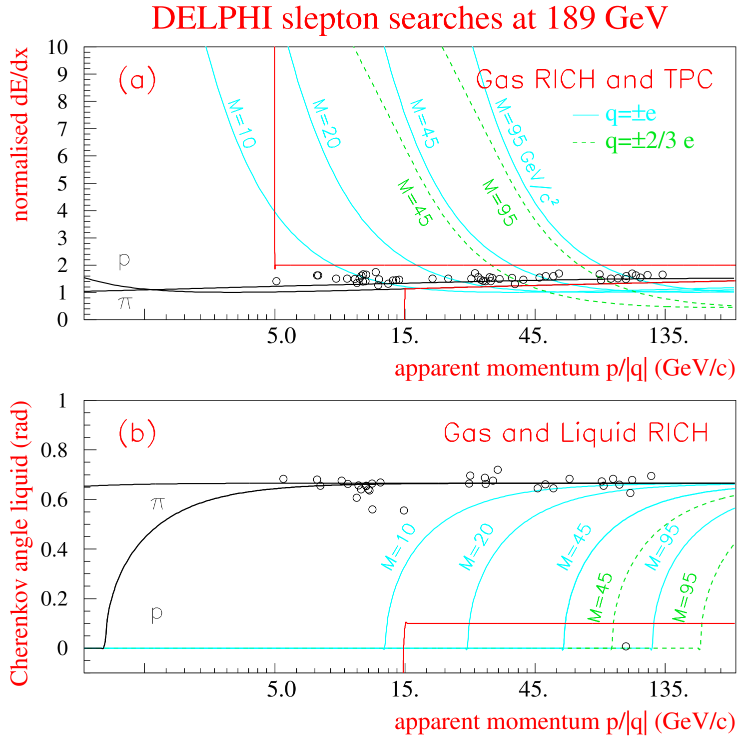
Staus

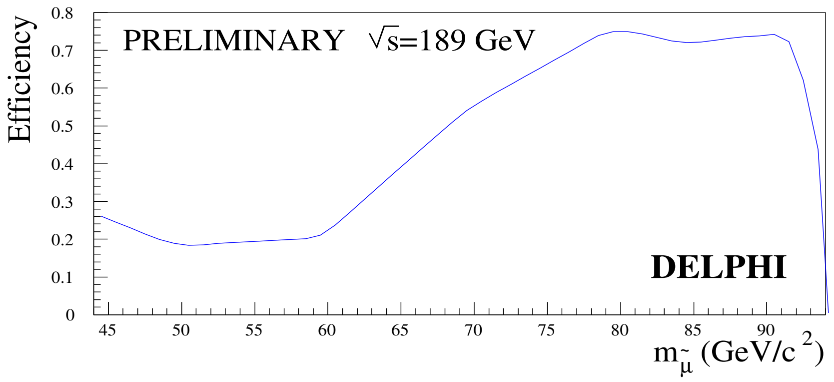


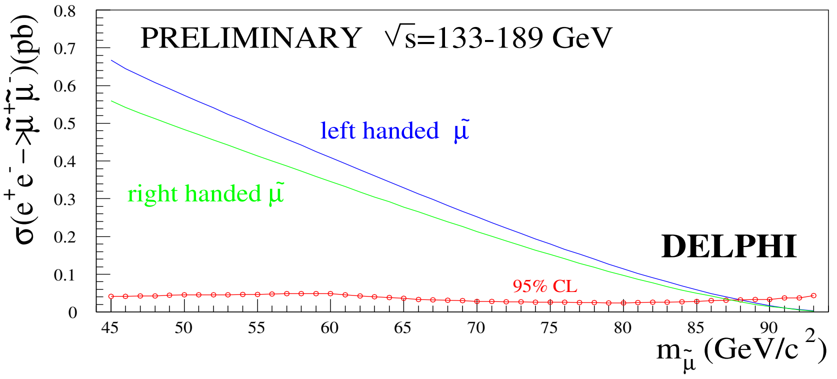


Mass limit for stau 71 GeV (obtained)
77 GeV (expected)

Stable Sleptons







Mass limit for left(right) handed stable $\tilde{\mu}$ and $\tilde{\tau}$:
excluded between 2 and 87.9(87.0) GeV DELPHI
and 88(90) GeV OPAL

Squarks

Squarks -

- SUSY partners of the helicity states of each quark
- mixing proportional to the quark mass

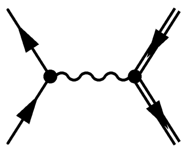
$$\tilde{q}_L, \ \tilde{q}_R, \ \bar{\tilde{q}}_L, \ \bar{\tilde{q}}_R$$

- large mixing, large mass splitting for the third generation

$$\tilde{t}_1 = \tilde{t}_L \cos\theta_{LR} + \tilde{t}_R \sin\theta_{LR}$$

- $\tilde{t}_1$, $\tilde{b}_1$ ($\tan\beta > 10$) in LEP discovery range
- other $\tilde{q}$'s out of LEP range or special assumption of equal masses (ALEPH,L3)

Production process



production via s-channel Z, γ exchange
free parameters : mass and $\cos\theta_{LR}$
if vanishing coupling to Z cross section has its minimum
decays: three-body decay preferred if kinematically allowed

- two-body decays : $\tilde{t}_1 \to c\tilde{\chi}_1^0$, $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$
- three-body decays $\tilde{t}_1 \to bl\tilde{\nu}_l$, for high $\tan\beta$ $l = \tau$ preferred

Squarks

Searching for squarks:

- 2 jets + E_{miss} with and without b-tagging
- 2 jets + 2 (1) leptons + E_{miss} with b-tagging

main backgrounds - depending from ΔM

- low ΔM (5...10 GeV) : 2 photon collision processes
- medium ΔM (20 ...40 GeV): 2f processes
- high ΔM (50 ... 70 GeV): 4f processes (WW, ZZ)

all 4 experiments have searched for $\tilde{t}_1$ and $\tilde{b}_1$:

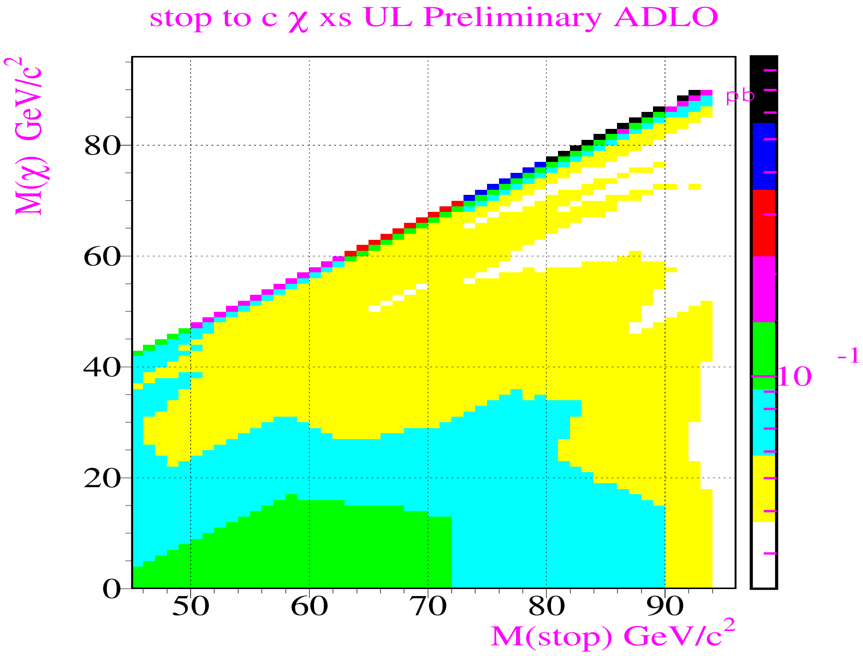
No evidence for any squark was found
$\rightarrow$ limits at 95% C.L.

LEP compilation of the LEP working group

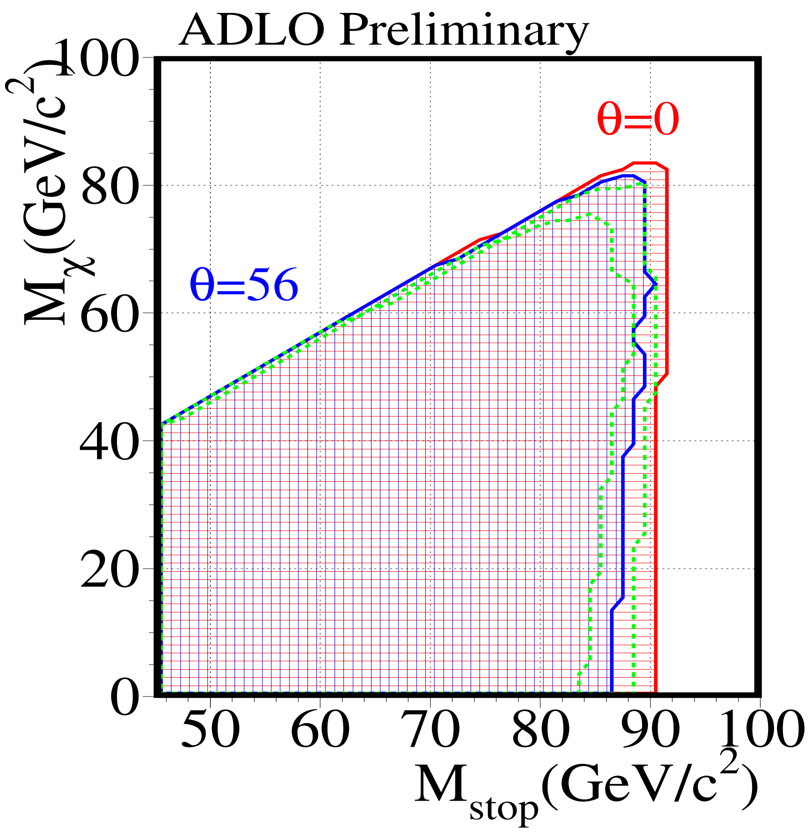
Systematics is taken into account with
100% correlation between the experiments

Background subtraction :
L3 and OPAL all background subtracted
DELPHI 4f background subtracted
ALEPH no background subtracted

Some plots:
— obtained cross section limits and mass limits for $\tilde{t}_1$, $\tilde{b}_1$, $\tilde{t}_1$ three-body decay

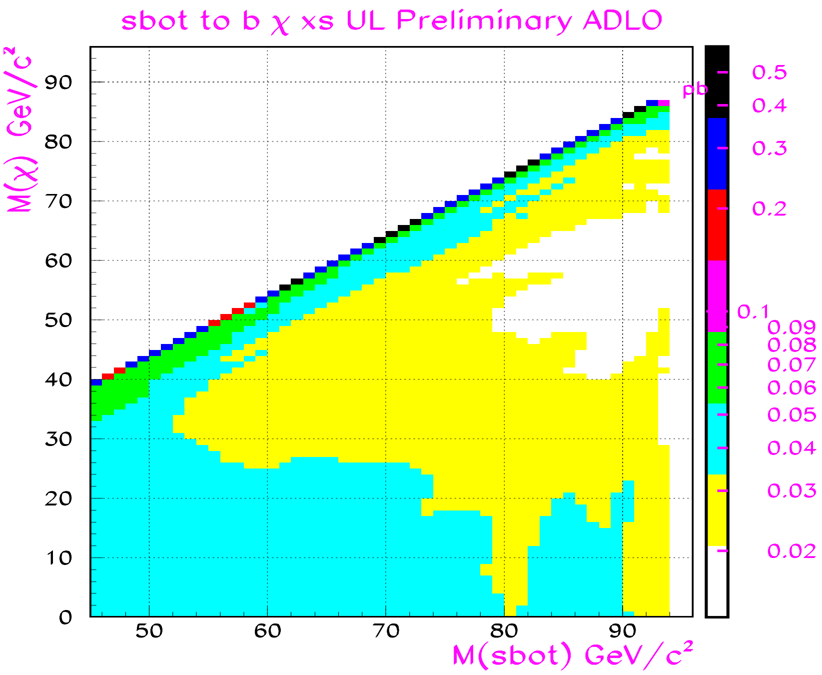


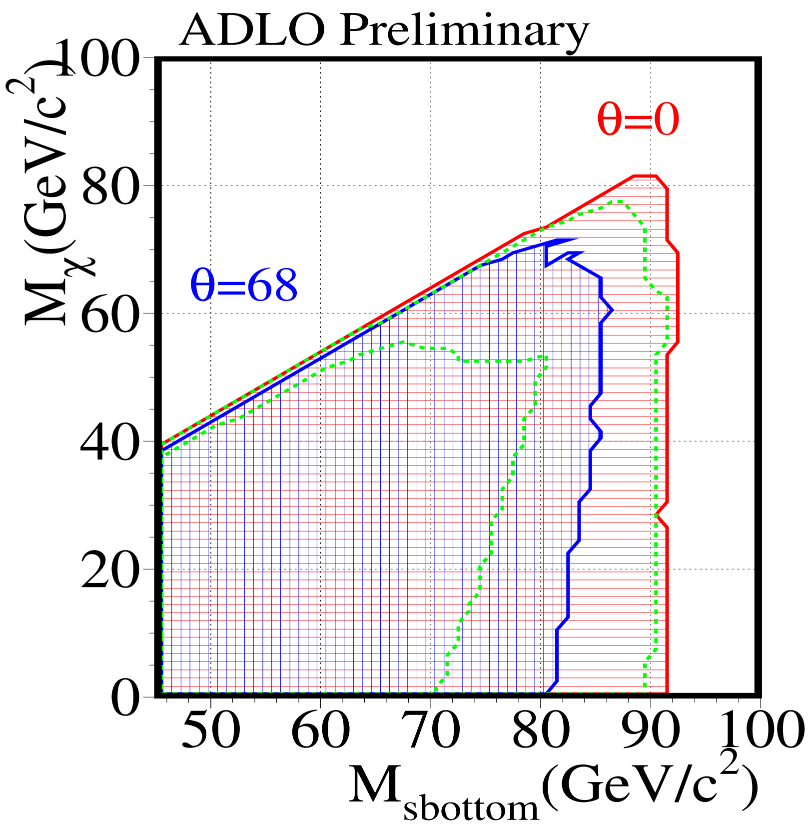
stop to c χ xs UL Preliminary ADLO
M(χ) GeV/c²
M(stop) GeV/c²
pb
10 -1
0
20
40
60
80
50
60
70
80
90

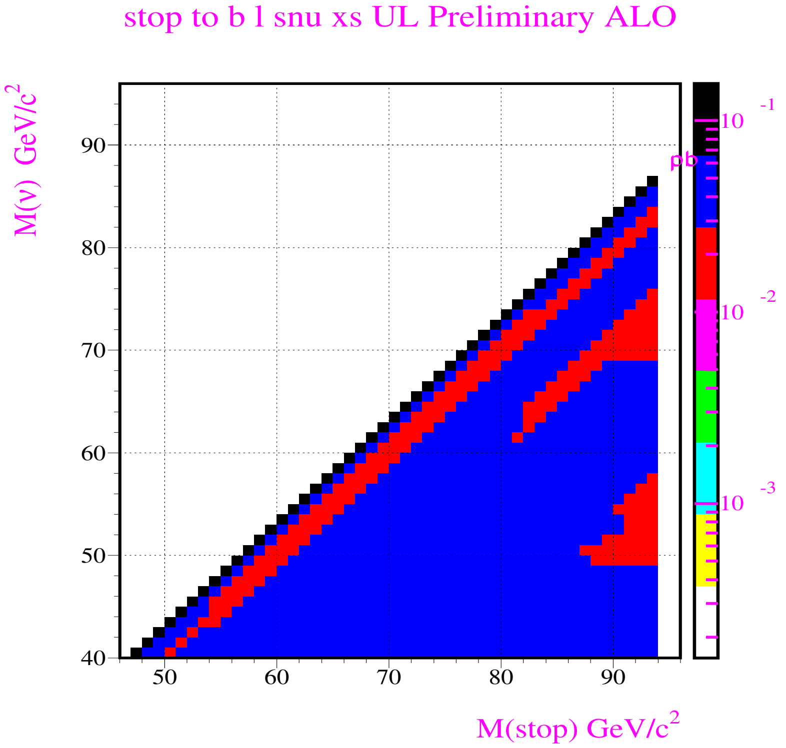


ADLO Preliminary
θ=0
θ=56
M_χ(GeV/c²)
M_stop(GeV/c²)
0
20
40
60
80
100
50
60
70
80
90
100

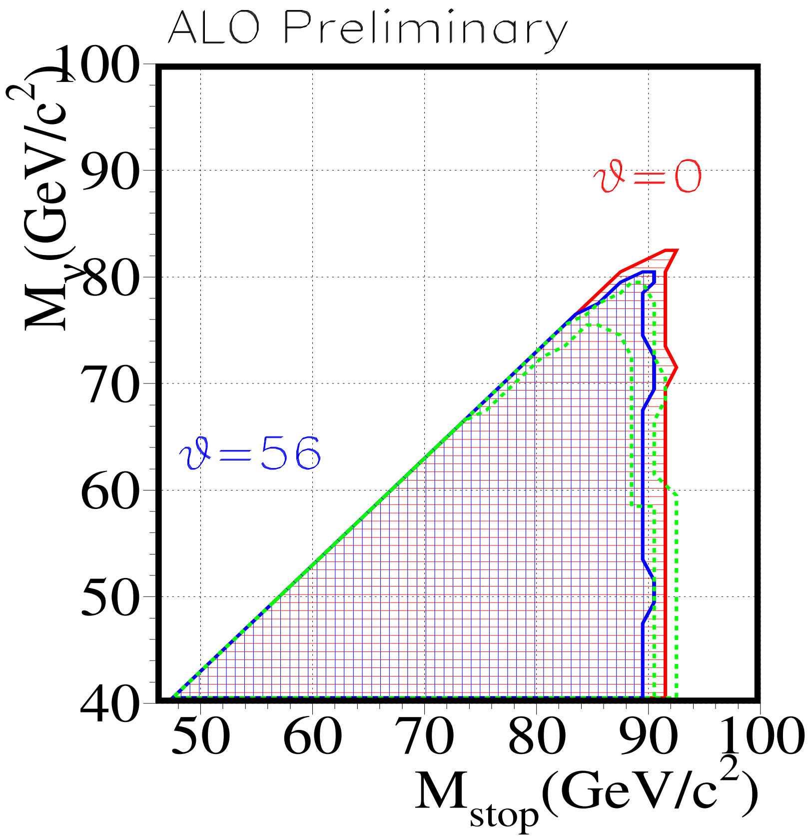
Sbottom $\rightarrow$ b $\tilde{\chi}_1^{\pm}$





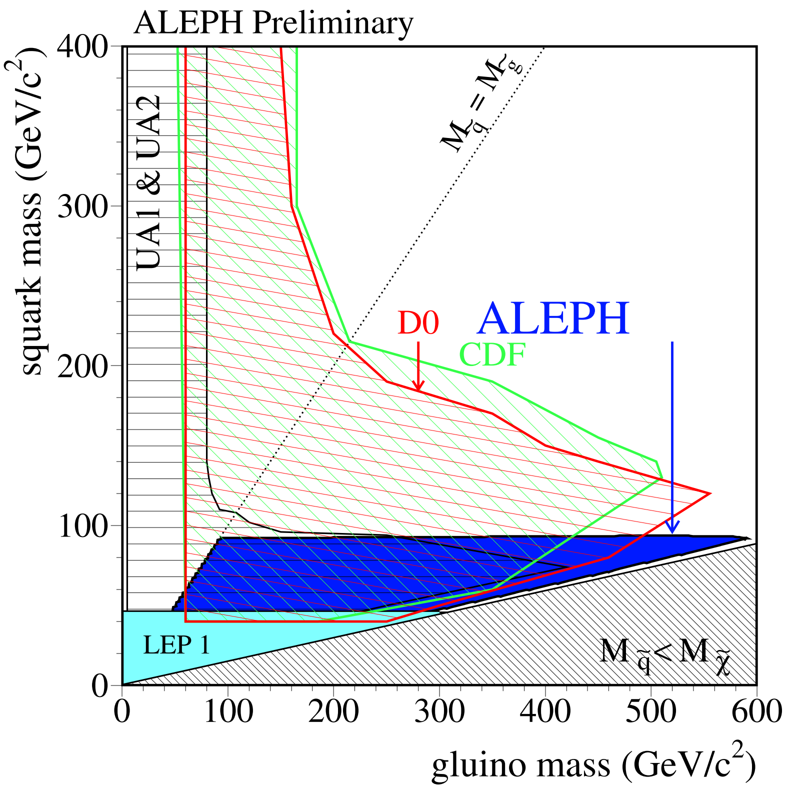


stop to b l snu xs UL Preliminary ALO
M(ν) GeV/c²
M(stop) GeV/c²
pb



ALO Preliminary
ϑ=0
ϑ=56
M_ν(GeV/c²)
M_stop(GeV/c²)

ALEPH : Exclusion region for degenerated squarks: $\tan\beta$**= 4 and** μ **= -400 GeV/**c^2



Scalar quark mass limits from LEP combined

Decay	ΔM	σ_{max}	σ_{min}
$\tilde{t}_1 \to c\tilde{\chi}_1^0$	**10**	**92(90)**	**90(87)**
	20	**92(90)**	**90(88)**
	$>$ **20**	**90(89)**	**87(84)**
$\tilde{t}_1 \to bl\tilde{\nu}_l$	**10**	**93(90)**	**91(87)**
	20	**92(92)**	**91(90)**
	$>$ **20**	**92(93)**	**90(91)**
$\tilde{b}_1 \to b\tilde{\chi}_1^0$	**10**	**91(88)**	**80(68)**
	20	**92(90)**	**86(75)**
	$>$ **20**	**91(90)**	**81(71)**

Charginos and Neutralinos

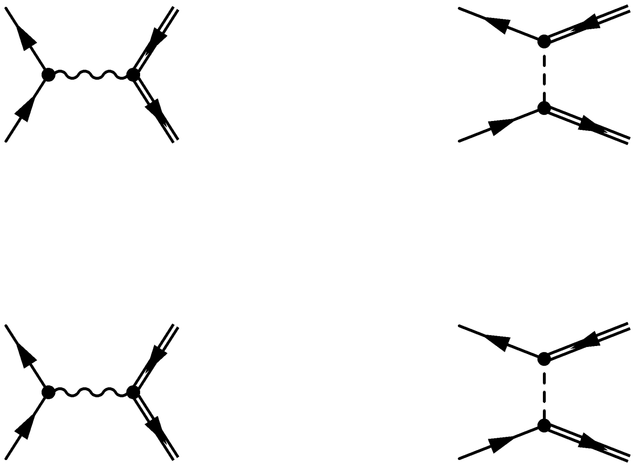
Charginos and Neutralinos

- **In MSSM due to gaugino-higgsino mixing two eigenstates for chargino**
- **and 4 eigenstates for neutralino**
- **lightest neutralino is stable and invisible**

$$\tilde{\chi}_1^{\pm},\ \tilde{\chi}_2^{\pm},\ \tilde{\chi}_1^{0},\ \tilde{\chi}_2^{0},\ \tilde{\chi}_3^{0},\ \tilde{\chi}_4^{0}$$

- **cross section depends on** $M_2, \mu, m_0, \tan\beta$

Production process



CHARGINOS: production via s-channel Z, γ exchange and t-channel $\tilde{\nu}_l$ exchange but for gaugino region ($M_2 << |\mu|$, and low m_0) destructive interference
NEUTRALINOS: production via s-channel Z exchange and t-channel $\tilde{e}$ exchange in gaugino region constructive interference

Charginos and Neutralinos

Decays

- direct decays : $\tilde{\chi}_1^{\pm} \to W^* \tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm} \to \tilde{l}\nu$,
  $\tilde{\chi}_i^0 \to Z^* \tilde{\chi}_1^0, \tilde{\chi}_i^0 \to \tilde{l}l$ with $\tilde{\chi}_1^0$ in final state
- cascade decays $\tilde{\chi}_i^0 \to \tilde{\chi}_1^{\pm} f \bar{f}'$, $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_i^0 f \bar{f}'$
- higher order processes

all these decays are covered by the LEP experiments

Searching for charginos and neutralinos:

ΔM/GeV	experimental signature	SM background
< 0.140	high ionization	2 photon collisions
0.140 - 0.300	kinks	2 phot.coll, 1-prong had. dec.
0.300 - 3.	ISR photons	2 photon collisions
3. - 10.	missing energy	2 photon collisions
10. - 30.	E_{miss}, acoplanar events	2 fermion
30. - 80.	low missing energy	WW events

Charginos and Neutralinos

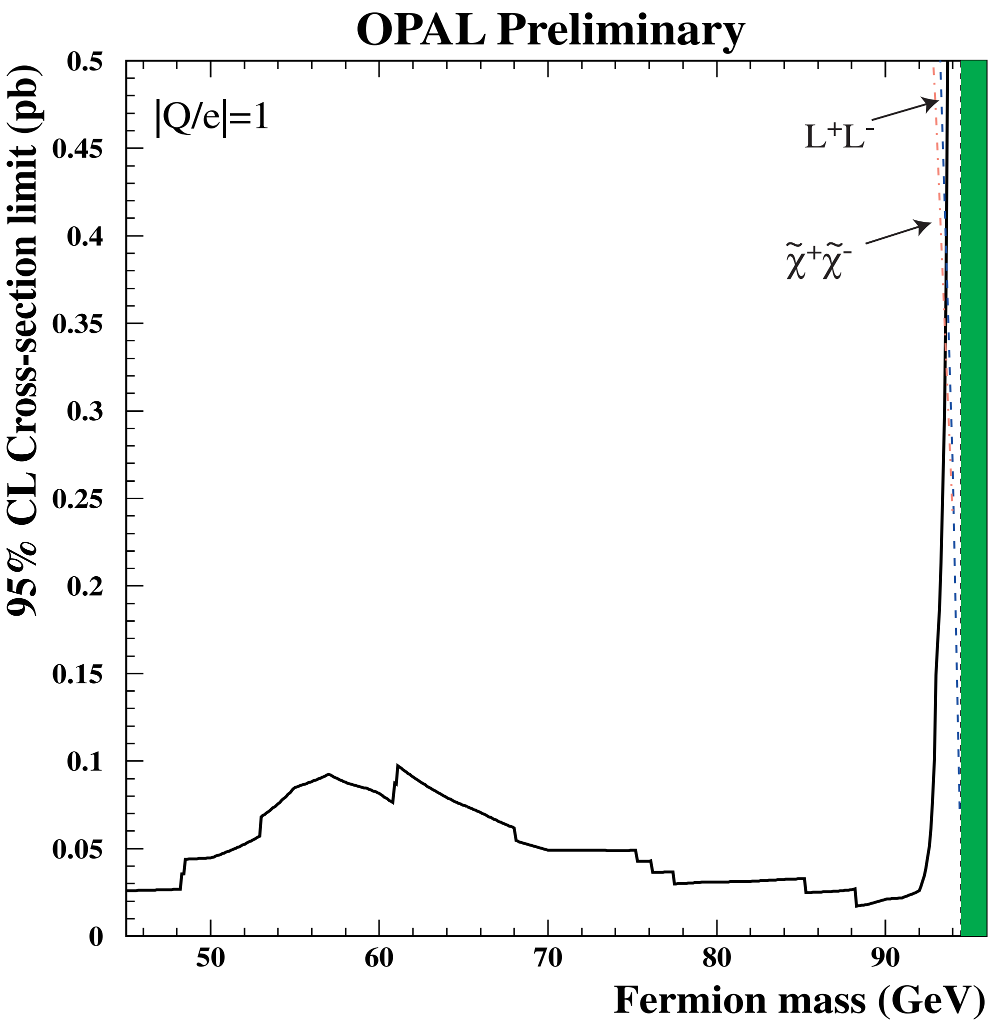
all 4 experiments have searched for $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_i^0$:

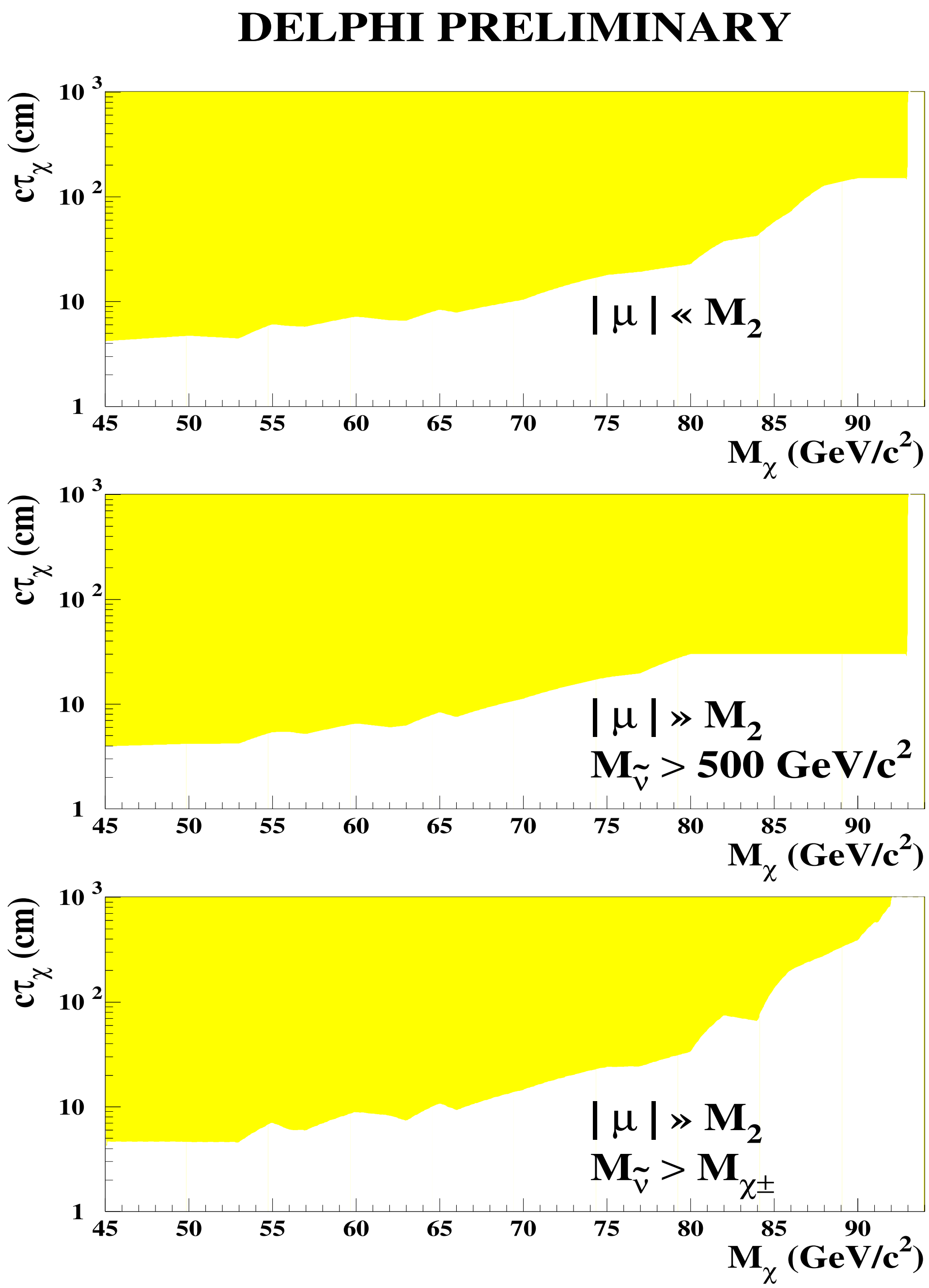
No evidence for any chargino or neutralino was found $\rightarrow$ limits at 95 % C.L.

no LEP compilation of the LEP working group for 189 GeV
but kinematical limit except for very special MSSM regions reached already by each experiment
presentation of experimental results of the 4 experiments
MSSM interpretations next talk (Laurent Serin)

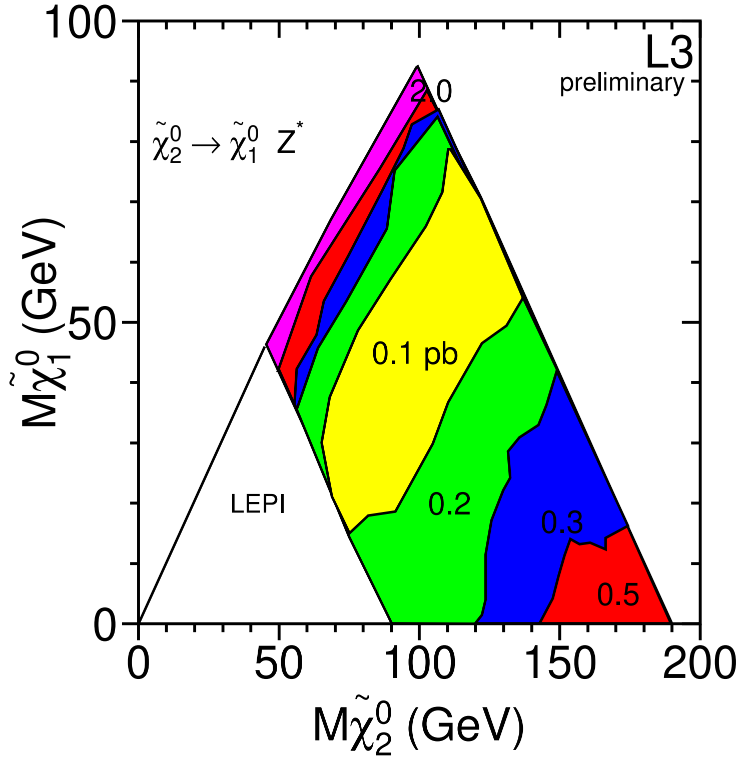
Some plots:
— obtained cross section limits and mass limits for $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$

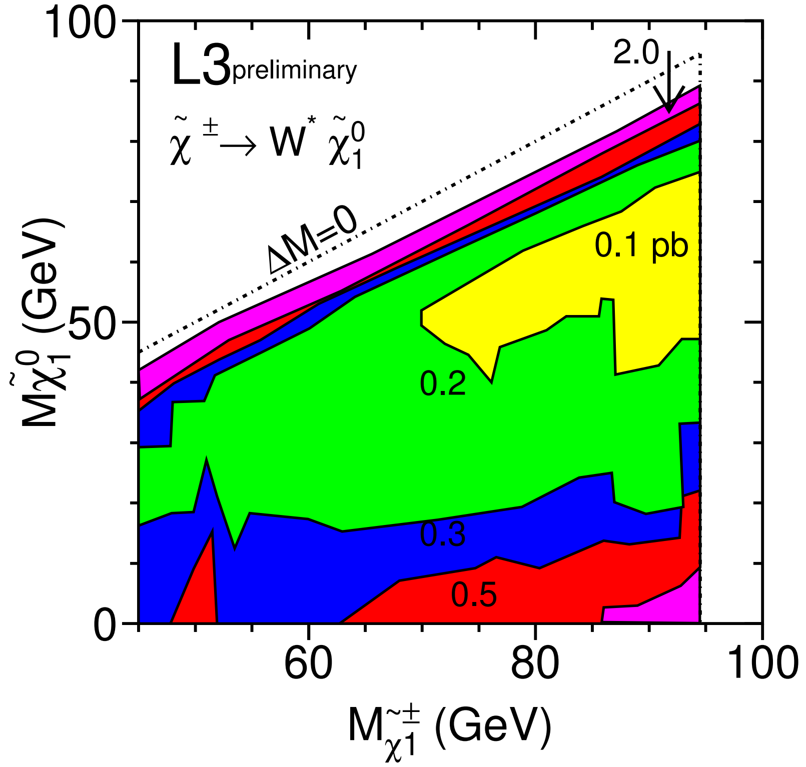
Stable Charginos




DELPHI PRELIMINARY
$c\tau_\chi$ (cm)
$|\mu| \ll M_2$
M_χ (GeV/c^2)
$|\mu| \gg M_2$
$M_{\tilde{\nu}} > 500$ GeV/c^2
$|\mu| \gg M_2$
$M_{\tilde{\nu}} > M_{\chi\pm}$

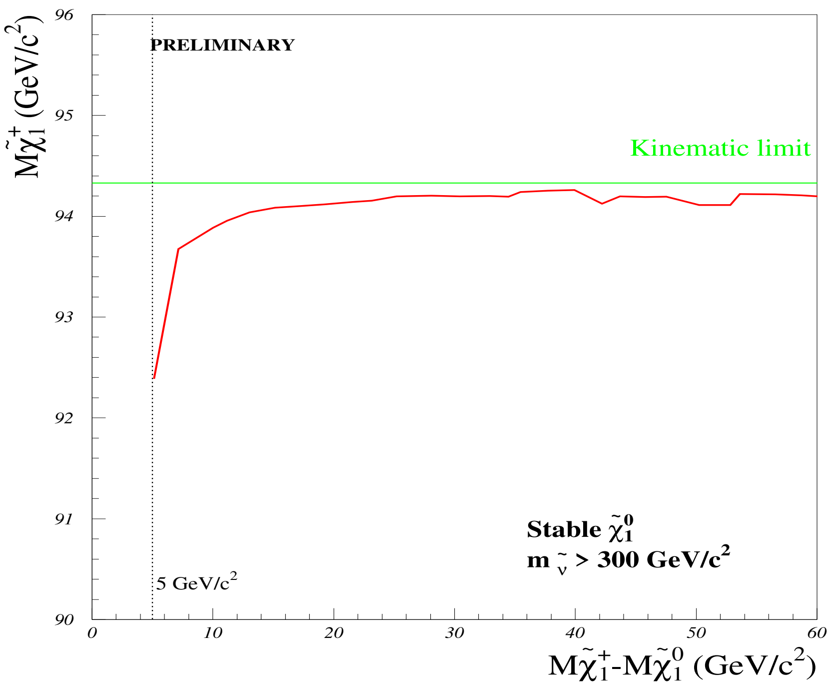
Upper Cross Section Limits

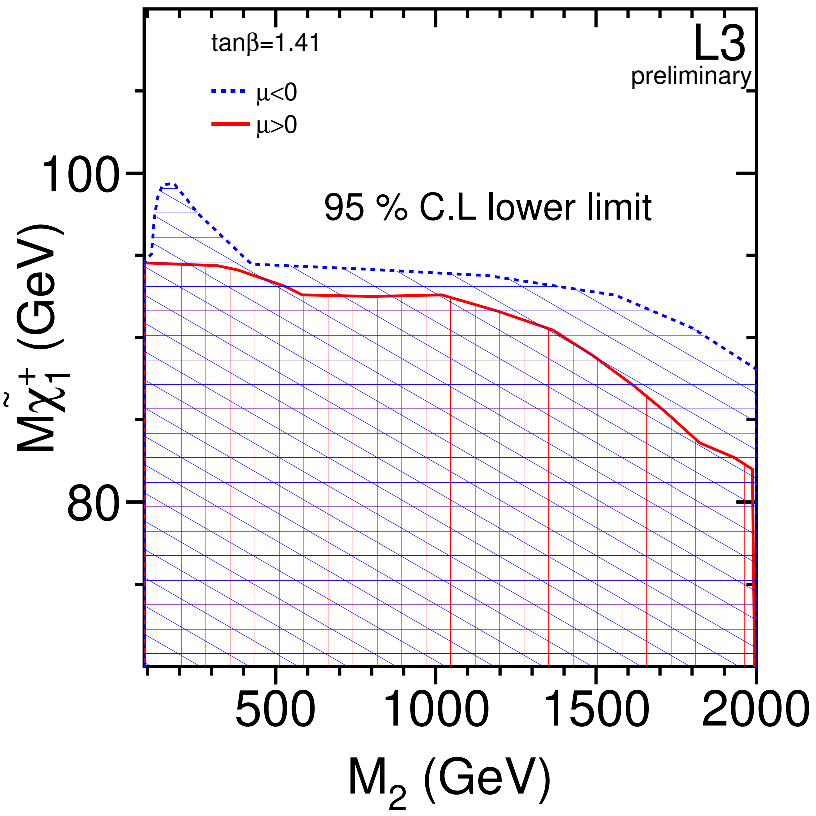




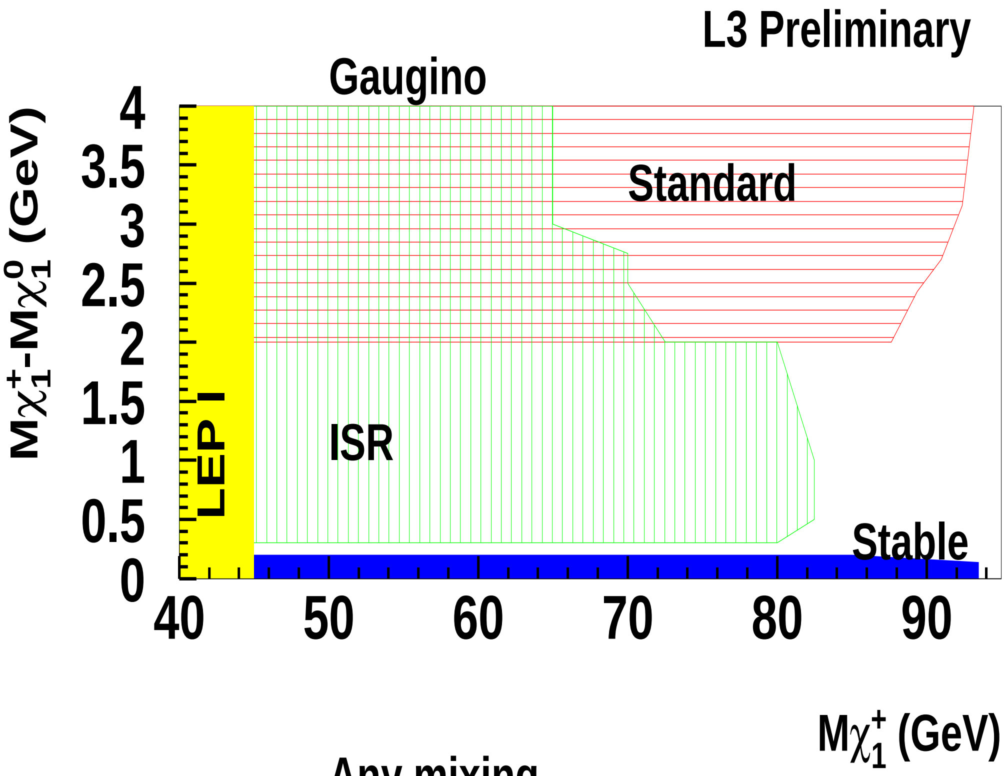
Dependence on ΔM

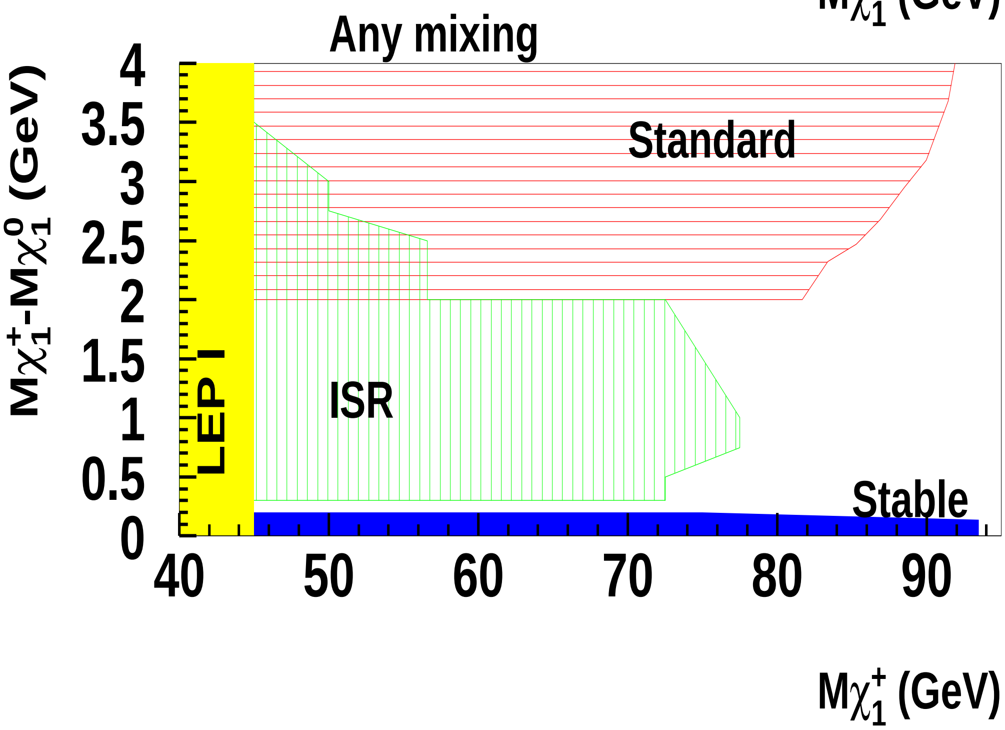
DELPHI $\tilde{\chi}_1^+\tilde{\chi}_1^-$ limits at 189 GeV





Chargino Mass Limits at 189 GeV





Summary and Outlook

- No evidence for any SUSY particle up to now at LEP
- improved limits for sleptons and squarks by combining the data of the four experiments
- best start of LEP this year - 200 pb reachable but different energies
- all four experiments have improved their analyses significantly

SUSY-2000 :
200 GeV and GOOD LUMINOSITIES

let's work and see.....