SUSY searches at LEP2

with the L3 experiment

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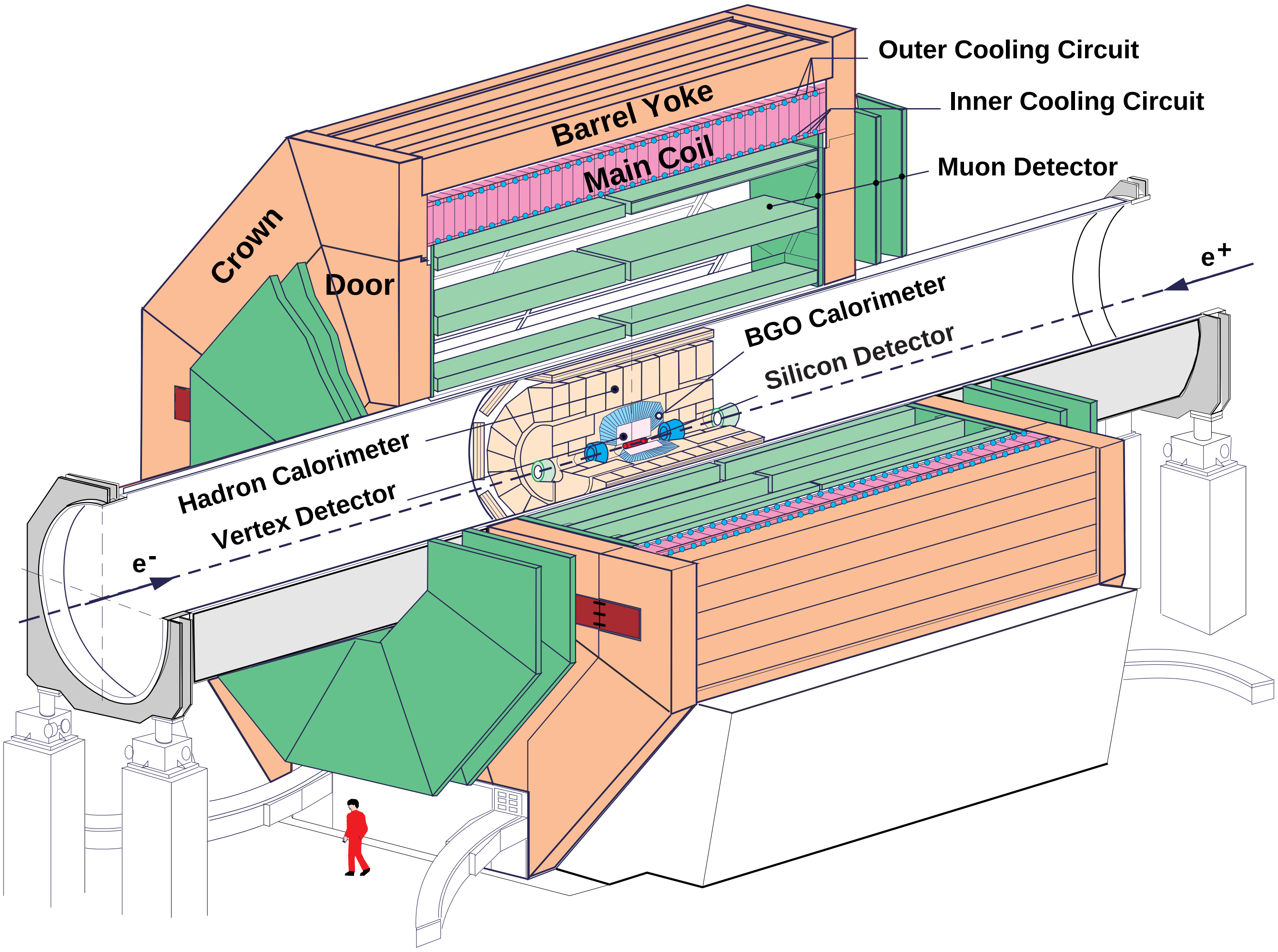
LEPI measurements have given an extraordinary confirmation of the validity of the STANDARD MODEL.
But, despite of this, it is generally believed that this theory is still not the final theory of the fundamental particle interactions.

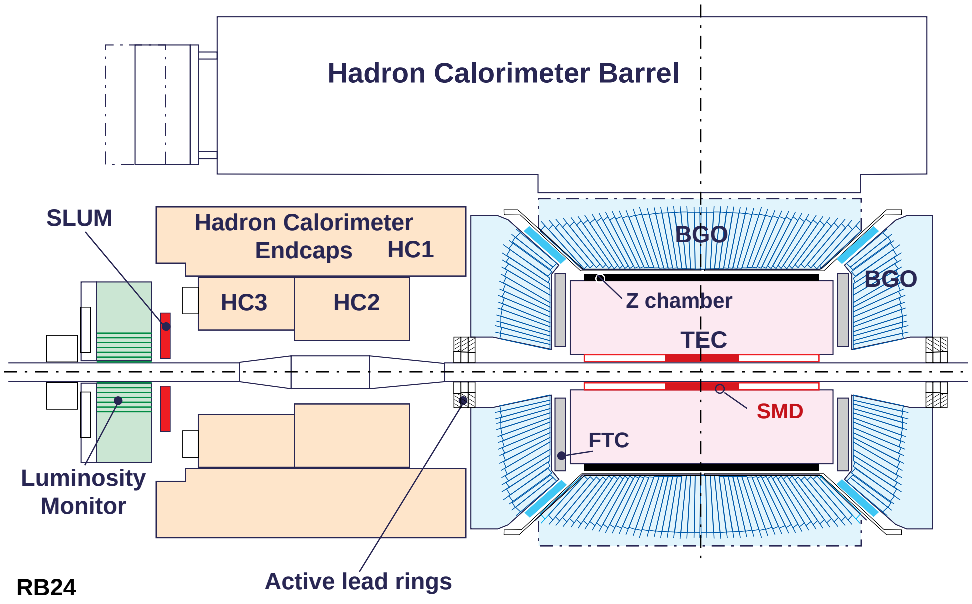
One of the most attractive possibilities of extending the Standard Model is provided by SUPERSYMMETRY.
Therefore the searches for SUSY particles play a fundamental role at LEP 200.

In this talk I will report on the searches of supersymmetric particles at LEP by the L3 collaboration at $\sqrt{s} = 130, 136$ GeV in late 1995 and $\sqrt{s} = 161$ and $\sqrt{s} = 172$ GeV in 1996.

- Supersymmetric particles, production and decays;
- SUSY signature;
- results and limits;
- interpretation in the MSSM;
- conclusions.

L3 Detector


Outer Cooling Circuit
Inner Cooling Circuit
Muon Detector
Barrel Yoke
Main Coil
Crown
Door
BGO Calorimeter
Silicon Detector
Hadron Calorimeter
Vertex Detector
e+
e-


Hadron Calorimeter Barrel
SLUM
Hadron Calorimeter
Endcaps HC1
HC3
HC2
BGO
BGO
Z chamber
TEC
SMD
FTC
Luminosity
Monitor
RB24
Active lead rings

SUSY is a symmetry which predicts, as major phonomenological consequence, the existence of a partner for each of the ordinary Standard Model particles with spin different by 1/2. The symmetry is broken because the partners have not the same mass.
The mass of SUSY particles are expected to be ≤ 1 TeV.

The minimal extension of the Standard Model compatible with the supersymmetry is the Minimal Supersymmetric Standard Model (MSSM) which is based, as the SM, on the $SU(3) \times SU(2) \times U(1)$ gauge symmetry group, but requires at least two Higgs doublets that respectvely couple to the $T_3 = 1/2$ and $T_3 = -1/2$ fermions.

The MSSM contains all the known particles and their superpartners:

Particle	Spin	S–particle	Spin	Name
$\ell = e, \mu, \tau, \nu$	1/2	$\tilde{\ell}_R, \tilde{\ell}_L$	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°, H_2°	0	$\tilde{H}_1^{\circ}, \tilde{H}_2^{\circ}$	1/2	higgsino
$H^{\pm}$	0	$\tilde{H}^{\pm}$	1/2	higgsino

Particles and S–particles have egual couplings and quantum numbers.

Gaugino and Higgsino Mass Eigenstates

- Super–partners of the $W^{\pm}$ and the charged Higgs bosons mix to form two charged fermion mass eigenstates:

$$\text{Charginos: } \tilde{\chi}^{\pm}_{1,2}$$

- Super–partners of the Z, γ and the neutral Higgs bosons give four neutral fermion mass eigenstates:

$$\text{Neutralinos: } \tilde{\chi}^{\circ}_{1,2,3,4}$$

Slepton and Squark Mass Eigenstates

- The scalar mass eigenstates are given by mixture of the Left and Right fermion partners. The mixing is assumed to be proportional to the corresponding fermion Yukawa coupling.
  Large mass eigenstates splitting in the case of the Stop quark.

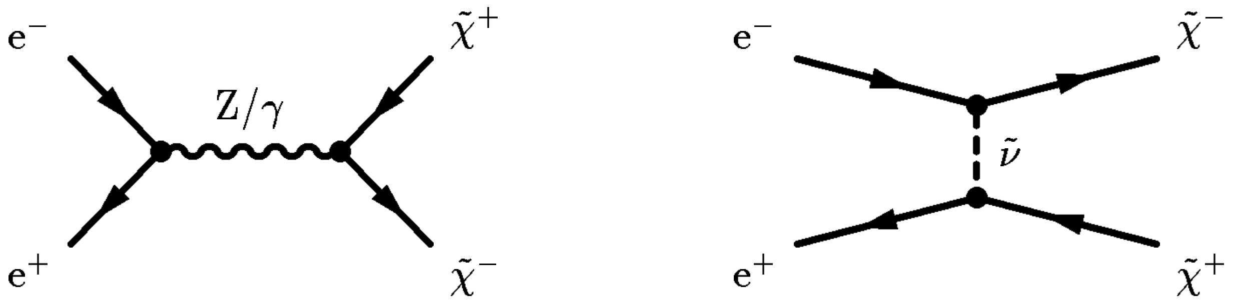
$$\begin{aligned} \tilde{t}_1 &= \tilde{t}_L \cos\theta_{LR} + \tilde{t}_R \sin\theta_{LR} \\ \tilde{t}_2 &= -\tilde{t}_L \sin\theta_{LR} + \tilde{t}_R \cos\theta_{LR} \end{aligned}$$

The stop could be the lightest charged particle.

Chargino production

$$\boxed{e^+e^- \rightarrow \tilde{\chi}_i^+\tilde{\chi}_i^-}$$

Chargino pair production proceeds via *s–channel* Z or γ exchange and via *t–channel* $\tilde{\nu}$ exchange



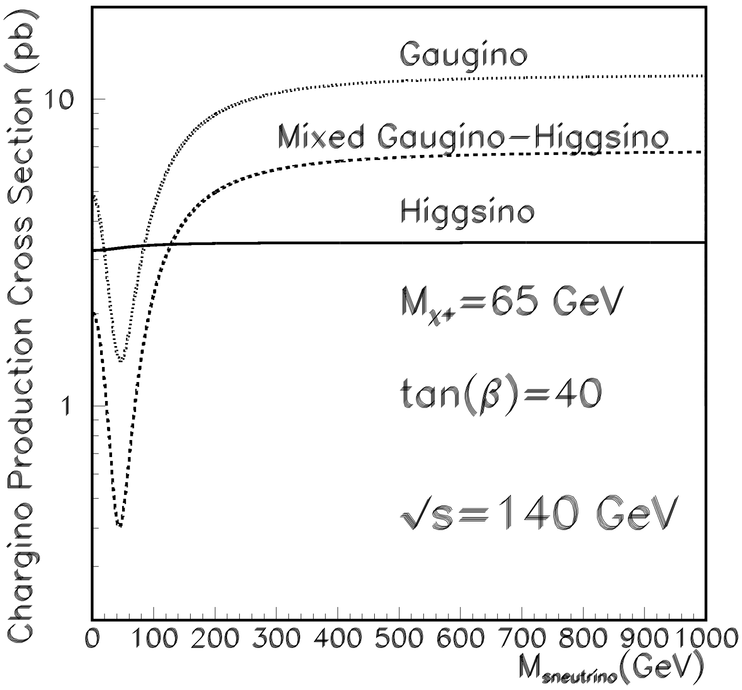
The interference between the two diagrams is destructive

Chargino cross section

The Chargino cross section is strongly dependent on the mass of the sneutrino.

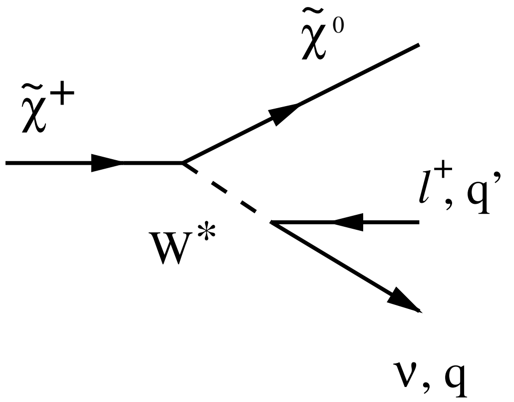
If the Gaugino component is dominant the destructive interference reduces the cross section for $m_{\tilde{\nu}} \leq 200$ **GeV.**

If the Higgsino component is dominant the cross section is independent from $m_{\tilde{\nu}}$



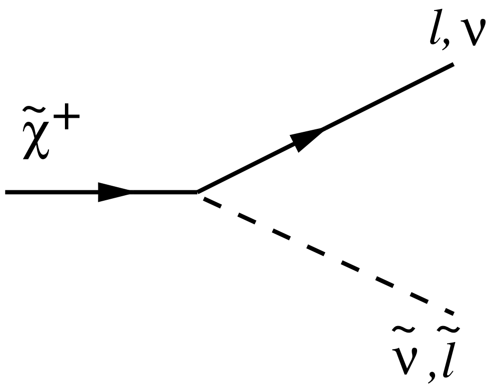
Chargino decays

If the $H^{\pm}$, $\tilde{\ell}$ and $\tilde{\nu}$ masses are very large, the main decay channel is via virtual W: $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}_1^{\circ} f \bar{f}'$.



If the $\tilde{\ell}$ and $\tilde{\nu}$ masses are comparable with m_W, the chargino decays via virtual slepton or sneutrino and the leptonic branching ratio is enhanced.

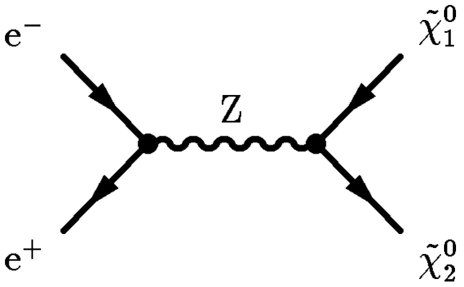
If the decay $\tilde{\chi}^{\pm} \rightarrow \ell\tilde{\nu}, \tilde{\ell}\nu$ is kinematically allowed, the leptonic branching ratio is dominant (2 body).

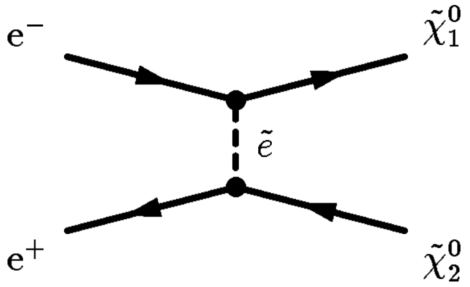


Neutralino production

$$\boxed{e^+e^- \rightarrow \tilde{\chi}^\circ_i \tilde{\chi}^\circ_j}$$

Neutralino pair production proceeds via *s–channel* Z exchange and via *t–channel* $\tilde{e}$ exchange.



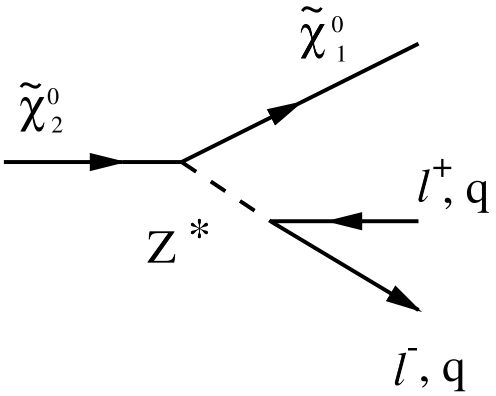


The Z couples only to the Higgsino components of the neutralinos, whereas the selectron couples only to the Gaugino components.

$\Rightarrow$ Greater cross section for neutralinos with dominant Higgsino component. Only if $m_{\tilde{e}} \simeq m_Z$ the Gaugino dominant neutralinos have sizeable cross section.

Neutralino decays

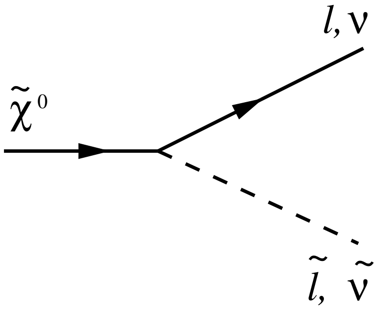
If the slepton masses are very large, the dominant neutralino decay channel is via virtual Z: $\tilde{\chi}^\circ_2 \to \tilde{\chi}^\circ_1 f \bar{f}$.



When the $\tilde{\ell}$ and $\tilde{\nu}$ masses are comparable with the Z mass, the neutralino decays also via virtual slepton, enhancing the leptonic branching ratio.

If $m_{\chi^\circ_2} < m_{\chi^\pm_1}$ the decay $\tilde{\chi}^\circ_2 \to \tilde{\chi}^\pm_1 f \bar{f}'$ is allowed (cascade).

If the $\tilde{\nu}$ and $\tilde{\ell}$ are lighter than the $\tilde{\chi}^\circ_2$ the 2 body decays are dominant.

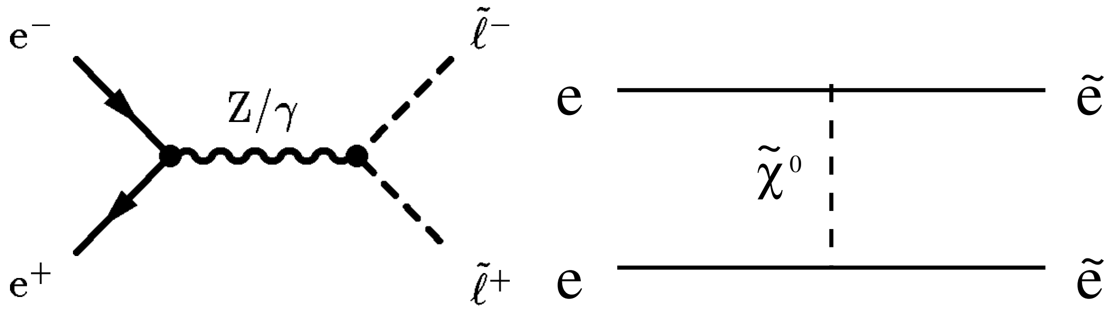


Slepton production and decay

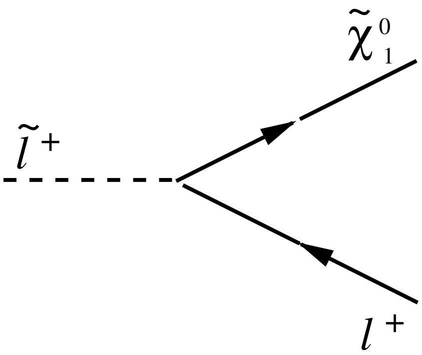
$$\boxed{e^+e^- \rightarrow \tilde{\ell}^+_{R,L}\tilde{\ell}^-_{R,L}}$$

Slepton pair production proceeds in the *s–channel* via Z or γ exchange and, only for the selectrons, in the *t–channel* via χ°_i exchange.

The process $e^+e^- \rightarrow \tilde{e}^\pm_L e^\mp_R$ receives only the *t–channel* contribution.



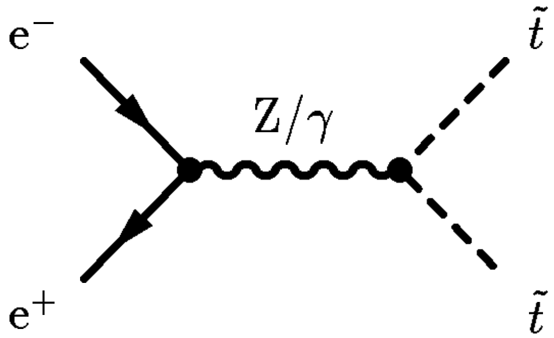
The main decay channel is $\tilde{\ell} \rightarrow \ell\tilde{\chi}^\circ_1$.



Stop production and decay

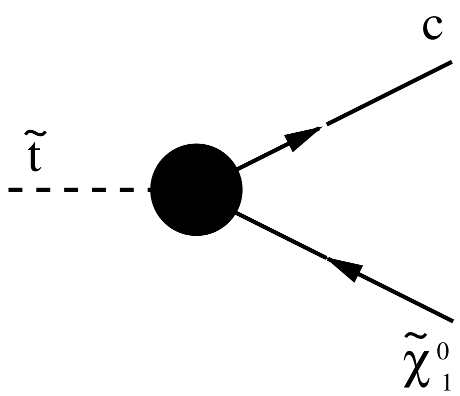
$$\boxed{e^+e^- \rightarrow \tilde{t}_1^+\tilde{t}_1^-}$$

Stop pair production is mediated by Z or γ exchange in the *s–channel*.



The cross section is proportional to the mixing angle θ_{LR} and the maximum value is for $\cos\theta_{LR} = 1$.

The main decay is trough the process $\tilde{t}_1 \rightarrow \tilde{\chi}_1^{\circ} c$.



R parity conserved

$\Rightarrow$ Susy particles are produced in pairs

$\Rightarrow$ Susy particles decay in Susy particles

$\Rightarrow$ The lightest Susy particle (LSP) is stable

χ_1° is the LSP

$\Rightarrow$ χ_1° is neutral and colorless and escapes the detection

Missing Momentum and Energy

is the Susy footprint.

Definition: $\Delta M \equiv M_{sp} - M_{lsp}$

Three different final state topologies in the:

- HH – Acoplanar jets
- LH – Acoplanar jets + isolated lepton
- LL – Acoplanar leptons

The main experimental signature is large Transverse Momentum, large Missing Energy and Missing Mass and large Acoplanarity due to the neutralinos and eventually neutrinos.

If ΔM is small the visible energy in the detector is reduced.

$\Rightarrow$ Trigger efficiency is very important.

We performed separate analyses for different ΔM regions and different topologies.

Background

All the physical processes with Missing Energy are background for SUSY searches.

Missing Energy due to the neutrinos or to undetected particles going in the beam–pipe or in regions not covered by the detector.

The main bkgd sources are:

- Two photons physics: $e^+e^- \to e^+e^- f\bar{f}$

  MC simulation not very precise.

  Huge cross section divergent with $M_{\gamma\gamma}$.

- *s–channel* electroweak processes: $e^+e^- \to Z/\gamma^* \to f\bar{f}(\gamma)$

  Mainly $Z/\gamma^* \to \tau\tau$ and radiative return of the Z.

- W pairs production: $e^+e^- \to WW$

  Small cross section at $\sqrt{s} = 161$ GeV.

- *t–channel* electroweak processes: $e^+e^- \to We\nu, Z/\gamma^* Z/\gamma^*, Zee$

  Small cross sections.

Small ΔM

Two photons physics is the dominant bkgd. Discriminating variables:

- Transverse missing momentum
- Direction of the missing momentum
- Missing mass
- Acoplanarity

Small angle physics detectors required.

Large ΔM

The dominant source of bkgd is WW physics. It is similar to the signal when χ_1° is very light. Discriminating variables:

- hadronic mass
- visible energy
- lepton momentum

The Analysis

Our analysis is based on a sample of data collected by L3 during the run in November 1995 ($\sqrt{s} = 130, 136$ GeV) and in the summer ($\sqrt{s} = 161$ GeV) and autumn 1996 ($\sqrt{s} = 172$ GeV) .

The integrate luminosities collected are:

$\sqrt{s}$	$\int \mathcal{L}\mathrm{d}t$	$\sqrt{s}$	$\int \mathcal{L}\mathrm{d}t$
130 GeV	2.75 pb^{-1}	161 GeV	10.5 pb^{-1}
136 GeV	2.27 pb^{-1}	172 GeV	10.7 pb^{-1}

Signal Generators: (Matrix of points in $M_{sp} - M_{lsp}$ plane)

SUSYGEN – chargino, neutralino and slepton production;

DFGT – chargino production with spin correlations;

EGLO – stop production.

Background Generators:

KORALW – WW production;

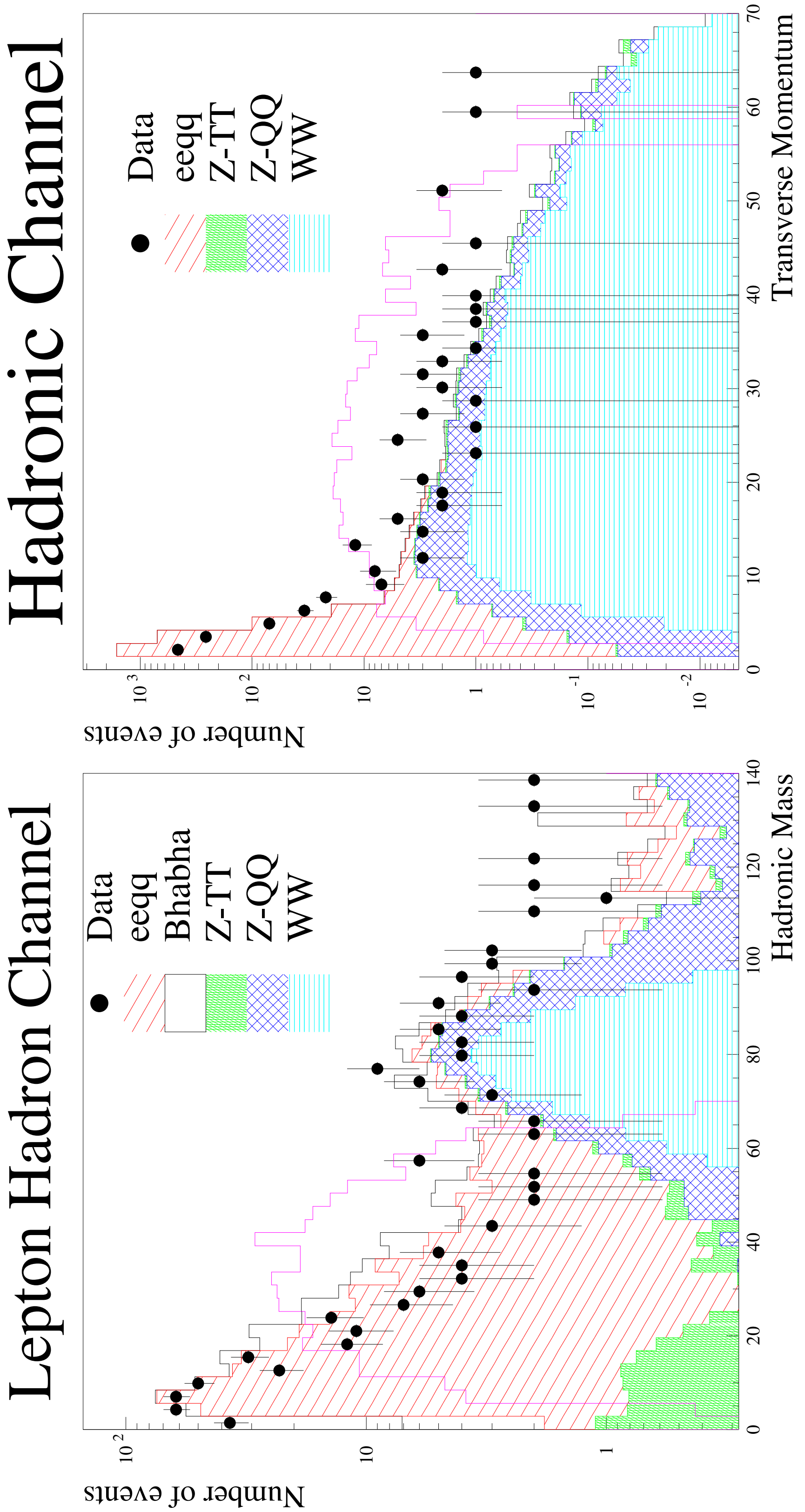
EXCALIBUR – four fermions processes;

PHYTHIA – two photons, $Z \rightarrow q\bar{q}$, *t–channel* processes;

KORALZ – $Z \rightarrow \mu^+\mu^-, \tau^+\tau^-$;

PHOJET – hadronic two photons processes;

DIAG36 – leptonic two photons processes.



Hadronic Channel
Data
eeqq
Z-TT
Z-QQ
WW
Number of events
Transverse Momentum
Lepton Hadron Channel
Data
eeqq
Bhabha
Z-TT
Z-QQ
WW
Number of events
Hadronic Mass

Analysis strategy

In our analysis we aim at finding any evidence of SUSY particles.

In order to have a large signal efficiency and to detect any small discrepancy between data and Monte Carlo we applied some "loose" selections during the data taking

We have defined 15 selections for the HH, LH, LL topologies and for the Small, Medium and Large ΔM regions:

- 9 selections for chargino and neutralino
- 3 selections for the sleptons
- 3 selections for the stop

No evidence for SUSY has been found.

All the analysis have been tightened and optimised in order to derive the best limits on the production cross section of the SUSY particles.

Optimisation procedure

The optimisation procedure varies all the cuts over the Monte Carlo variables simultaneously in order to maximise the signal efficiency and the background rejection.

Minimisation of the Sensitivity function:

$$S = \frac{\Sigma_n k_n P_b(n)}{\varepsilon}$$

ε is the efficiency for a given set of cuts.

k_n is the 95% C.L. Poisson upper limit for n events seen.

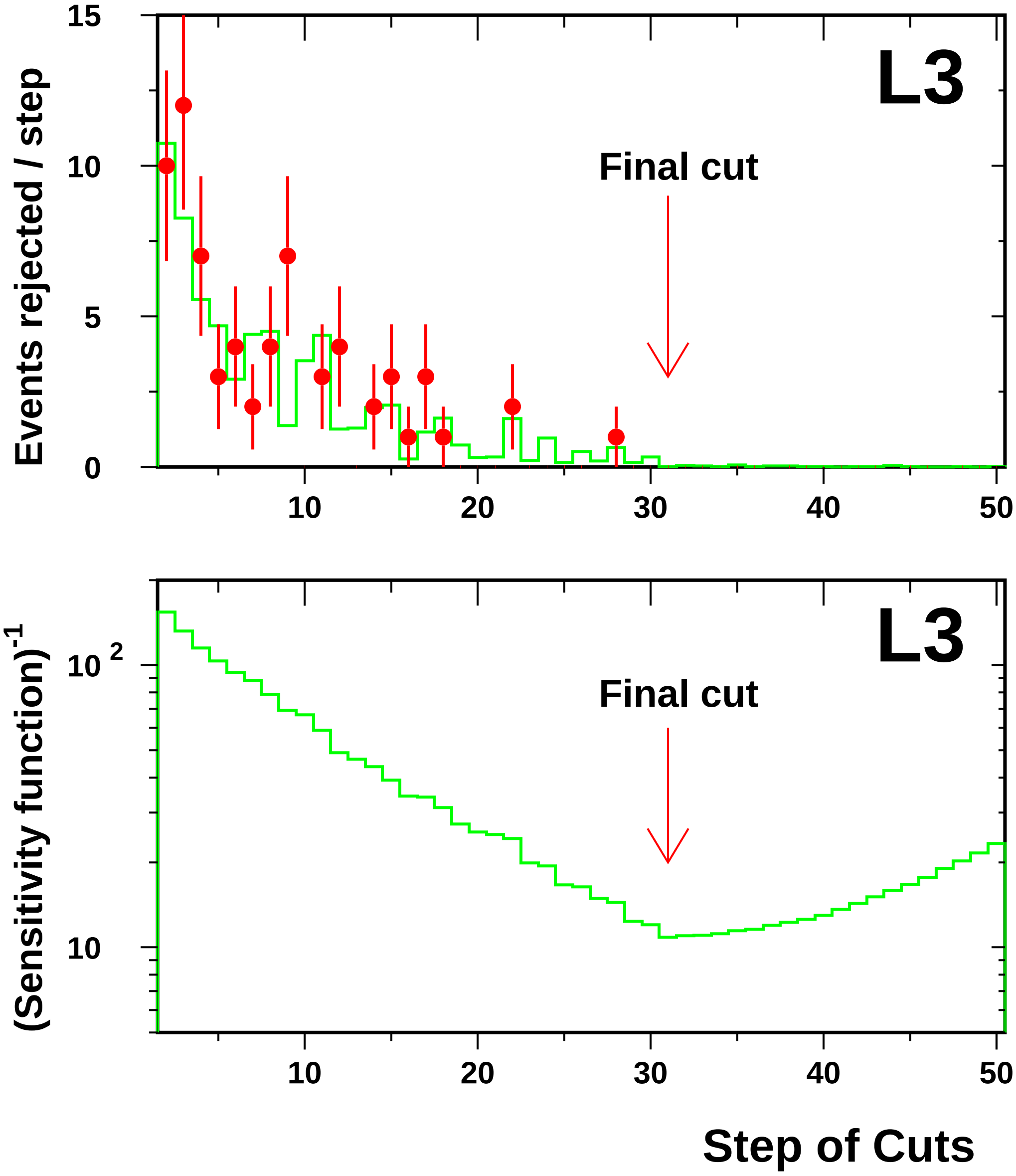
$P_b(n)$ is the Poisson distribution with n events seen and b bkgd events expected.

- First step: Separate optimisation of each selection.
- Second step: The selections are applied in Logical OR. The combination of selections giving a minimum of the Sensivity function are chosen.

The Analysis

Example at $\sqrt{s} = 130$ GeV.

Number of events rejected (data vs. MC) and the Sensitivity function in any of the step of the minimisation. The final cut corresponds to the minimum of the Sensitivity function.



Results

All the selections:

Events selected:

130–134 GeV	0
161 GeV	1
172 GeV	7
Total	8

Total Background events selected: 7.6 (sub. 4.2)

Main sources: WW in the large ΔM region and two photons in the small ΔM region (not subtracted).

Chargino - Neutralino selection:

events selected = 5

background = 3.7 (sub. = 1.2)

Stop selection

events selected = 1

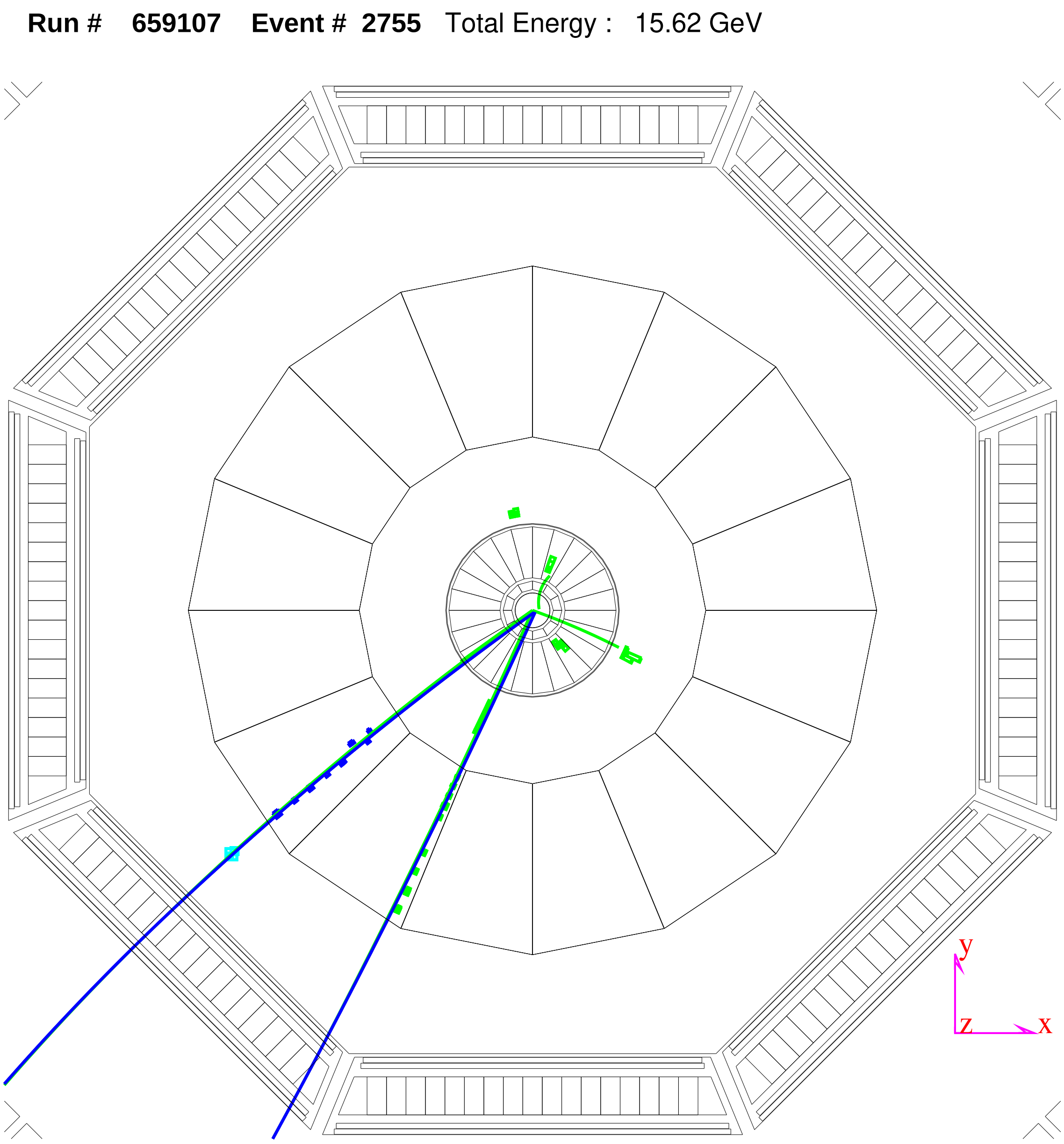
background = 1.5 (sub. = 0.9)

Slepton selection

events selected = 4 (selectrons)

background = 3.5 (sub. = 2.8)

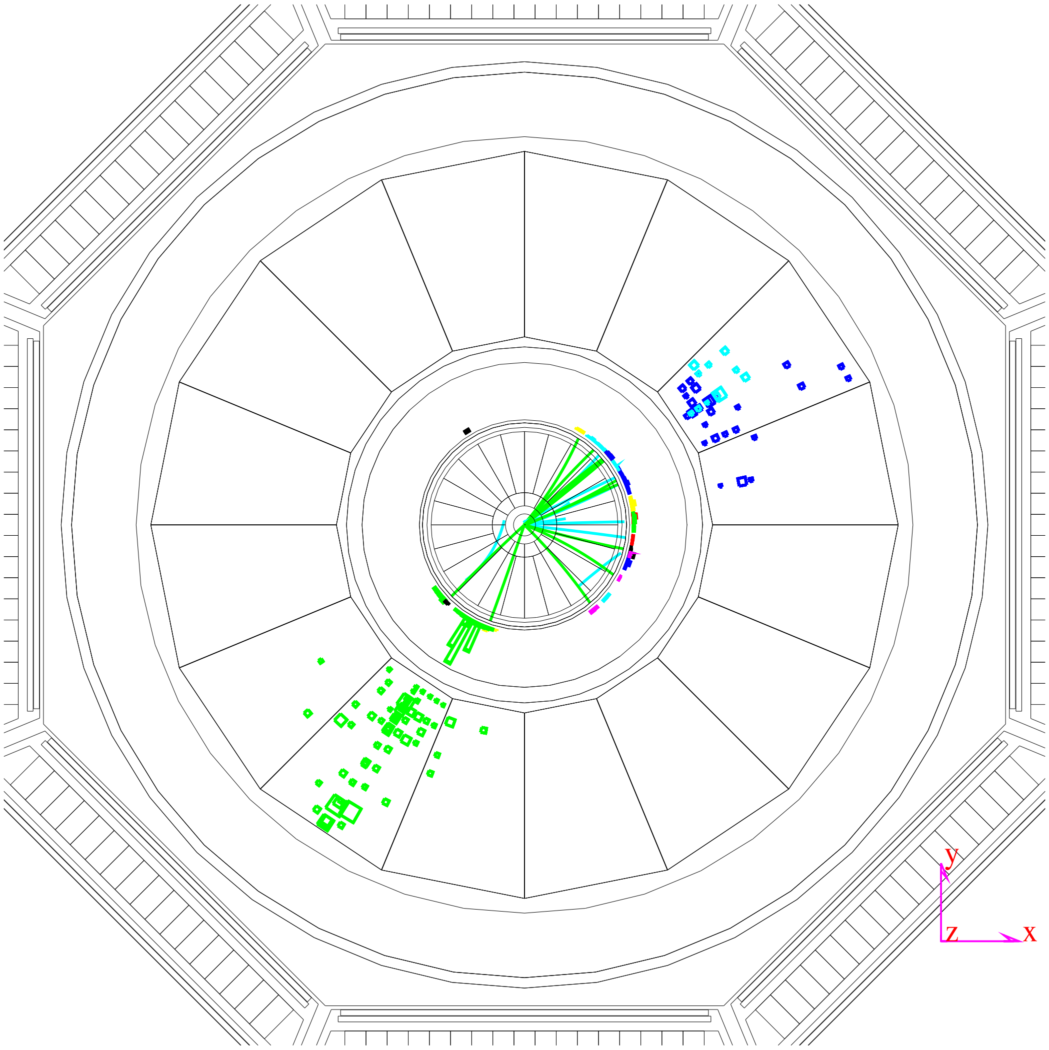
Small ΔM candidate



Transverse Imbalance :	.7119		**Longitudinal Imbalance :**	-.5913	
Thrust :	.9346	**Major :**	.2578	**Minor :**	.0634
Event DAQ Time :	*960724 152459*				

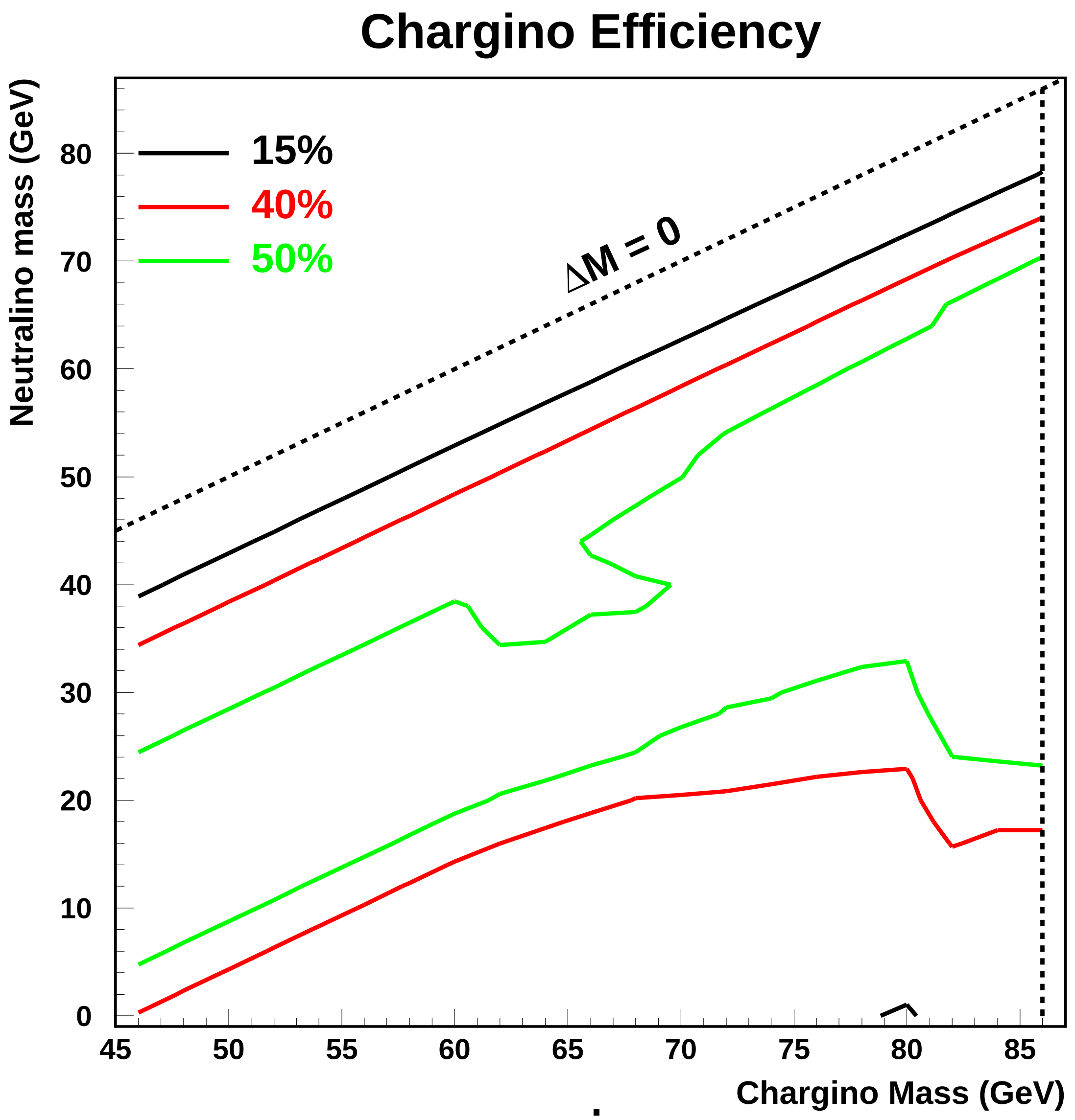
Large ΔM candidate

Run # 663209 Event # 216 Total Energy : 87.44 GeV



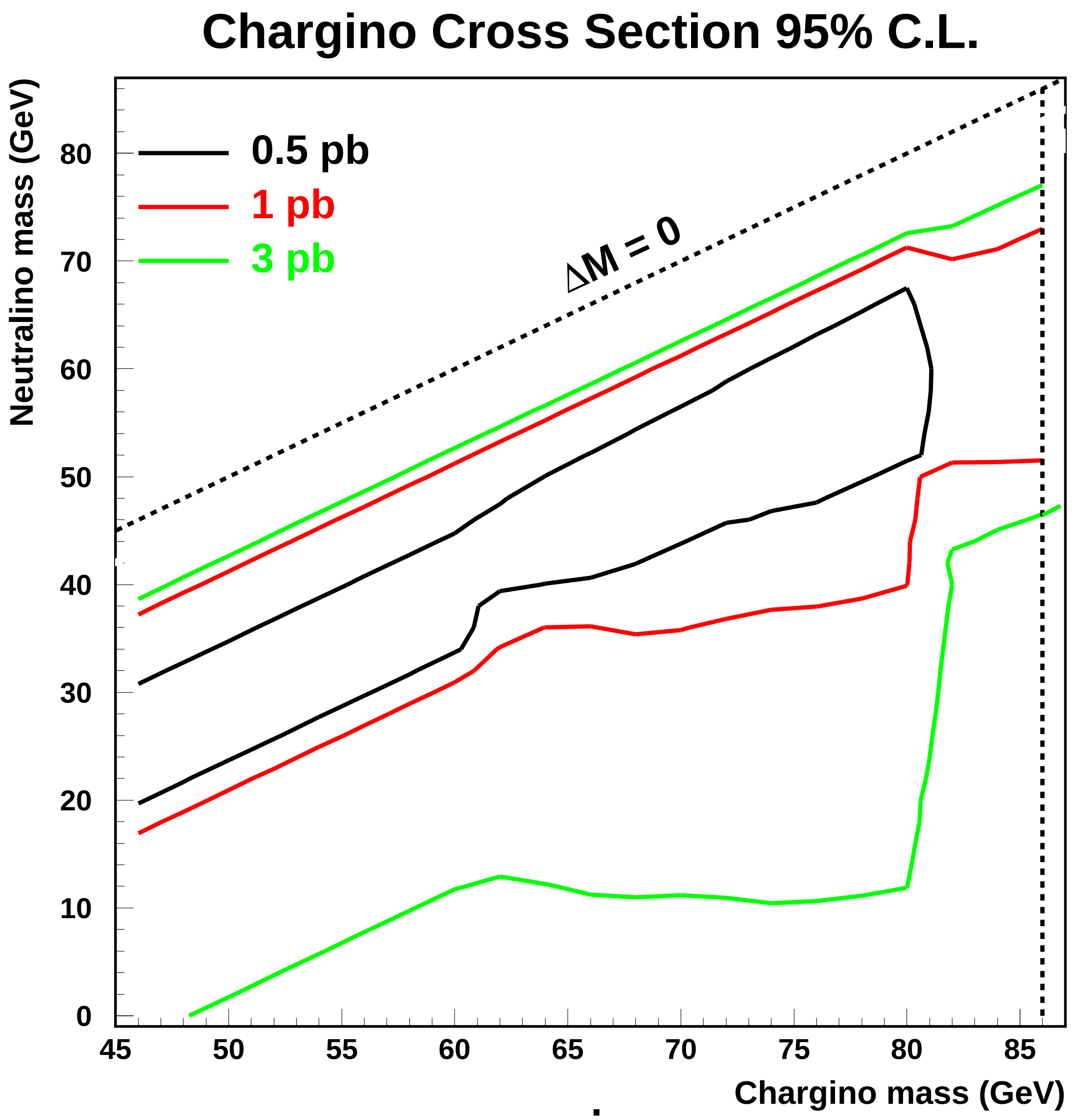
Transverse Imbalance :	.5962	**Longitudinal Imbalance :**	-.2075
Thrust : .9263	**Major :** .2290	**Minor :** .0566	
Event DAQ Time :	*961019 184441*		

L3 PRELIMINARY 172 GeV



L3 PRELIMINARY

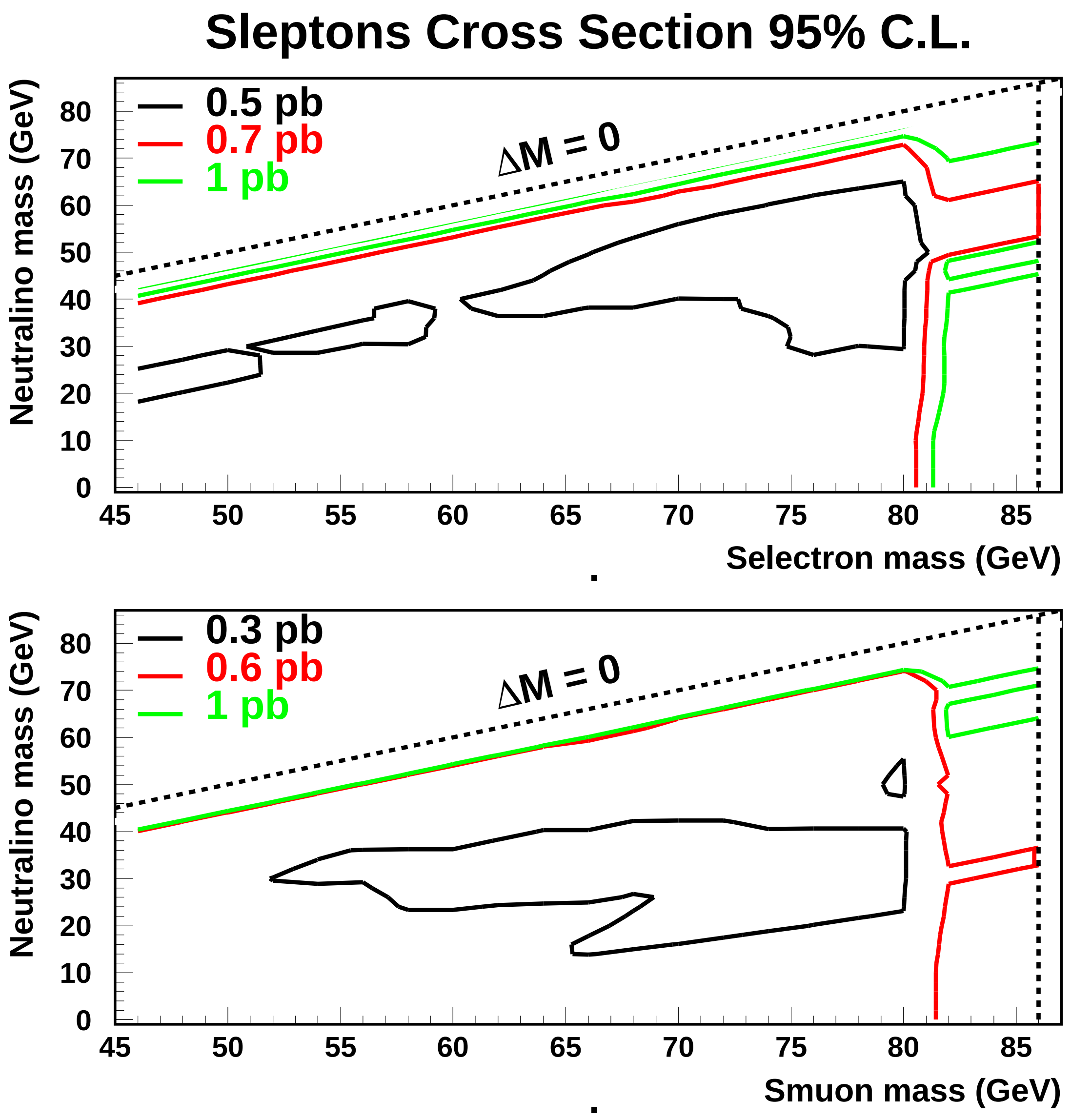
130–136 GeV, 161 GeV and 172 GeV results combined



It is assumed 100% $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{\circ} W^{\pm}$.

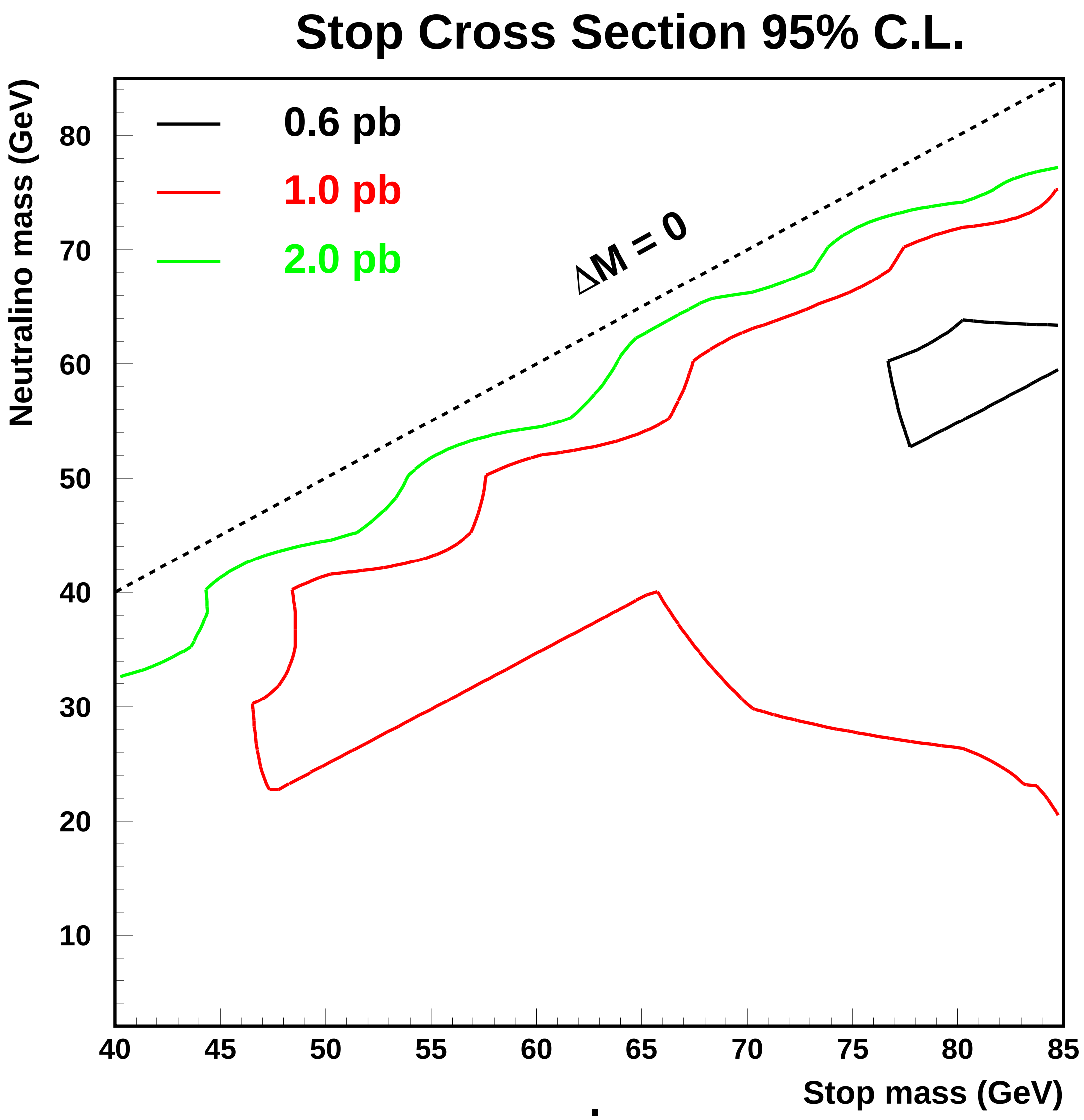
L3 PRELIMINARY

130–136 GeV, 161 GeV and 172 GeV results combined



Results

L3 PRELIMINARY 172 GeV



Limit in the MSSM frame

All masses and couplings of the Supersymmetric particles are dependent on the free parameter of the MSSM:

- M_1, M_2, M_3 – the SUSY breaking masses associated to $U(1)$, $SU(2)$, $SU(3)$;
- μ – the supersymmetric higgsino mass term;
- $\tan\beta = v_2/v_1$ – the ratio of the vacuum expectation values of the two higgs field;
- m_0 – the common sfermion mass at the GUT scale.

The GUT relation between the gaugino mass parameters

$$M_1 = \frac{5}{3} M_2 \tan^2\theta_W$$

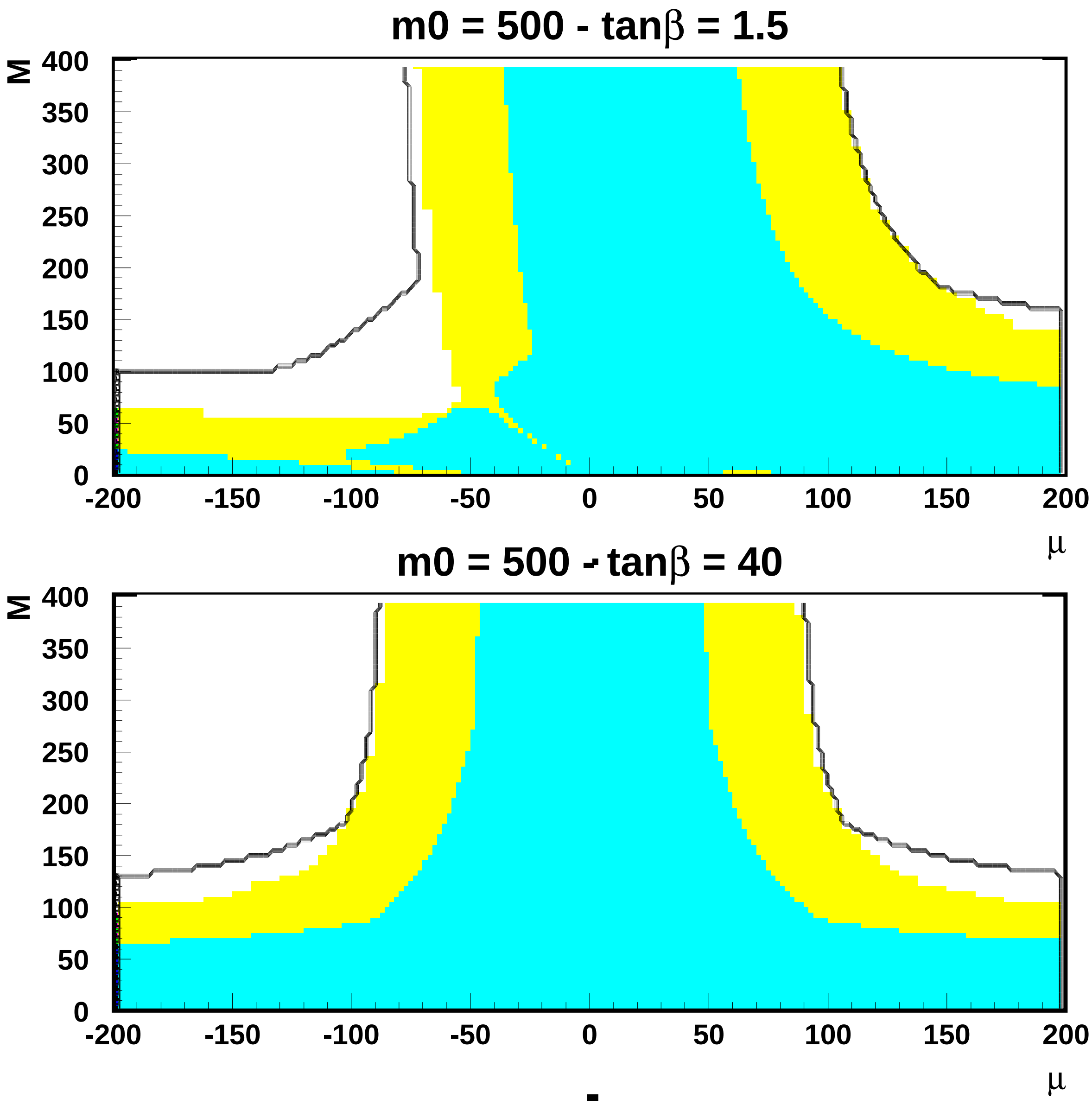
is assumed at the electroweak scale.

The sfermion masses are dependent on the parameter m_0.

L3 PRELIMINARY

130–136 GeV, 161 GeV and 172 GeV results combined

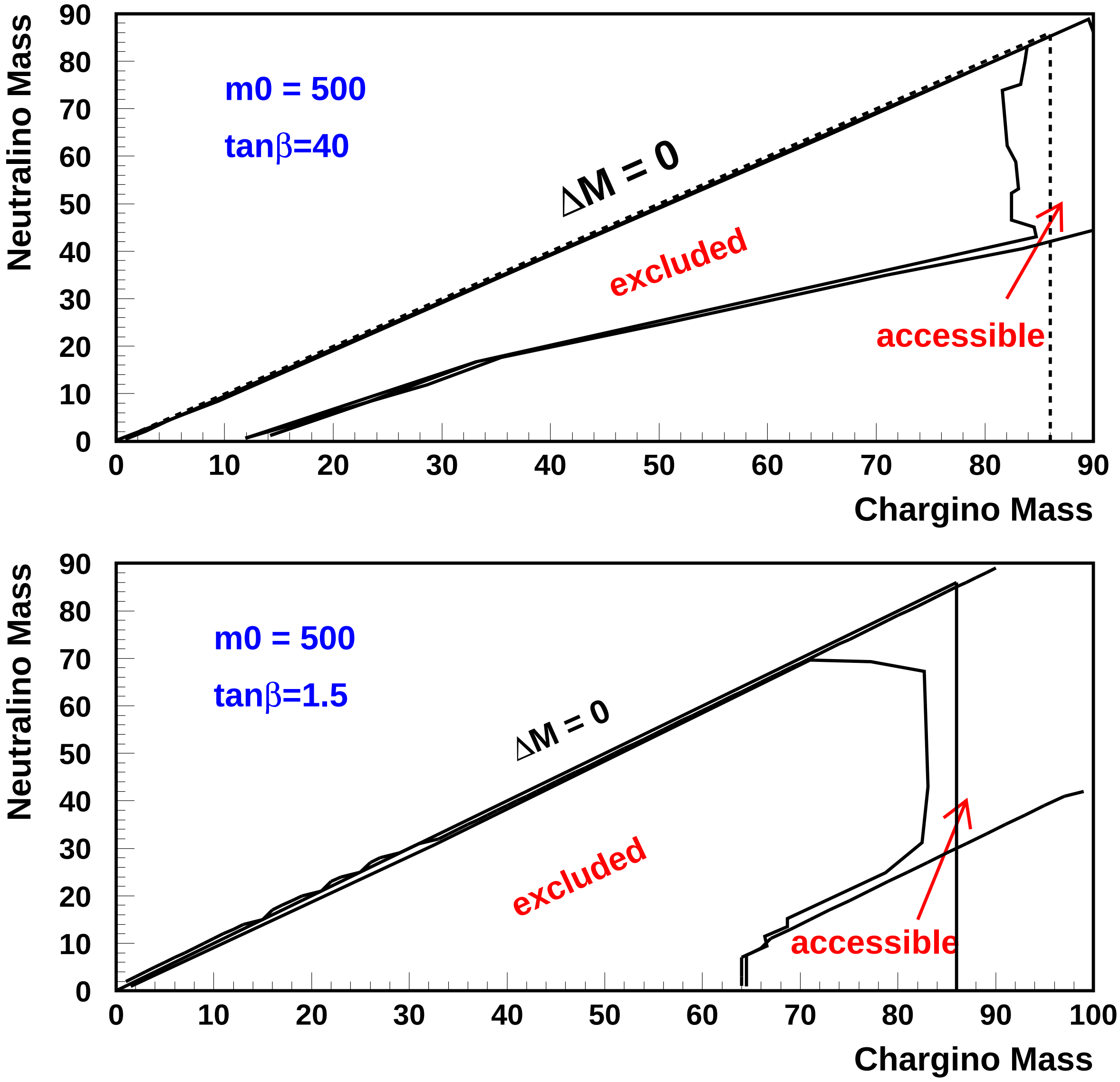
Chargino, neutralino and slepton selections included



L3 PRELIMINARY

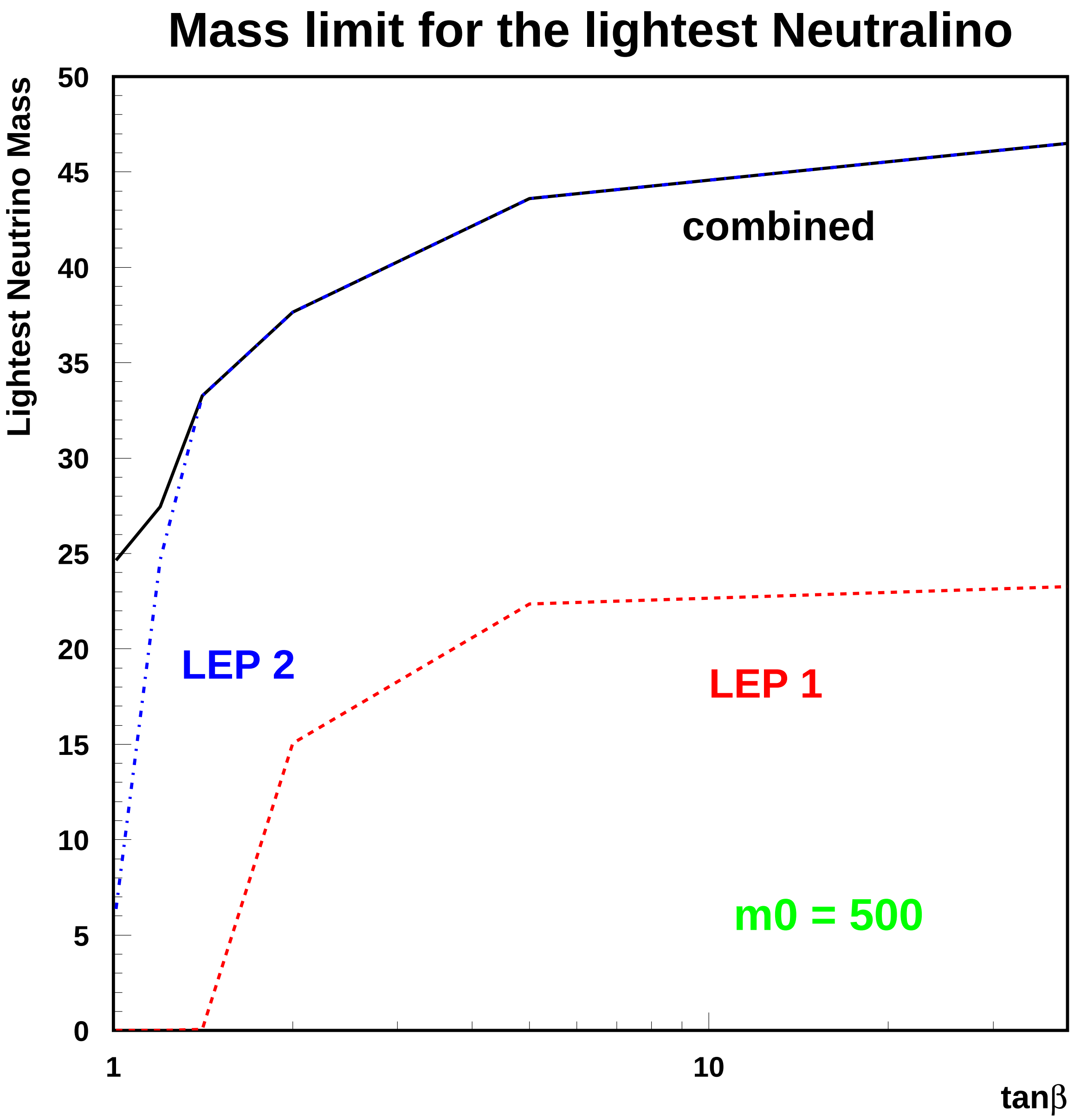
130–136 GeV, 161 GeV and 172 GeV results combined

95% C.L. excluded region



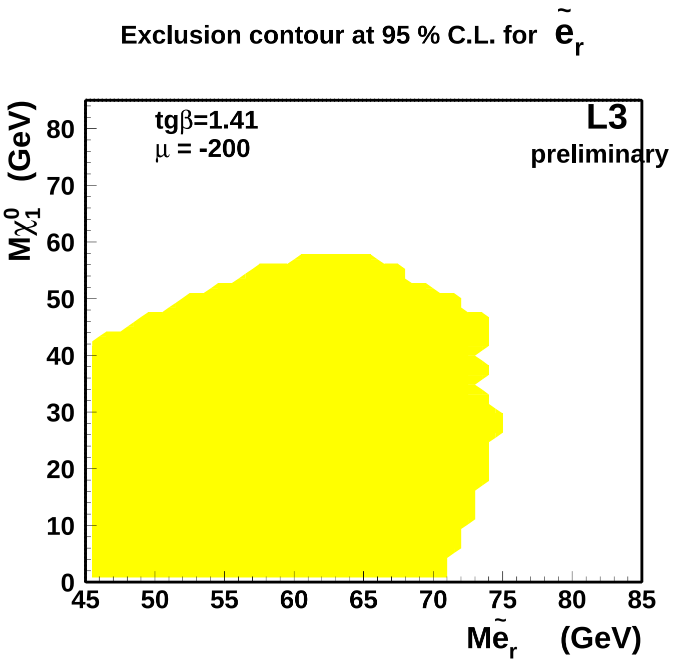
L3 PRELIMINARY

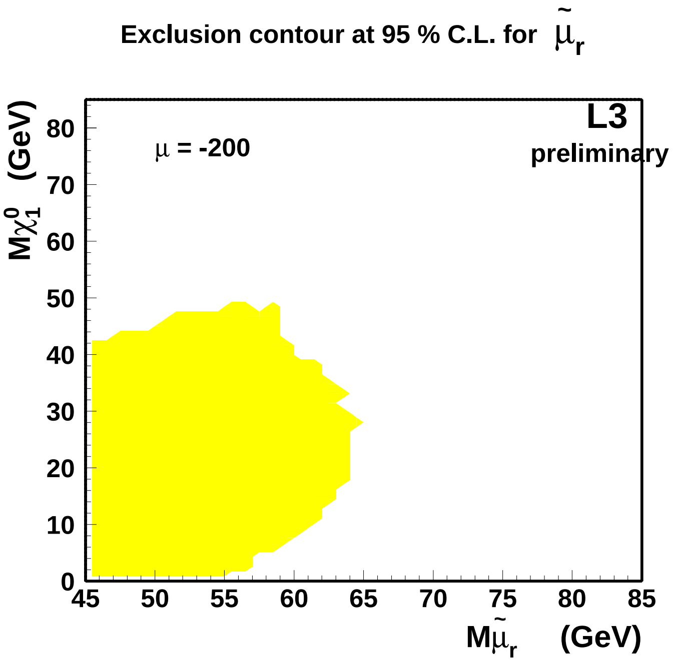
130–136 GeV, 161 GeV and 172 GeV results combined



L3 PRELIMINARY

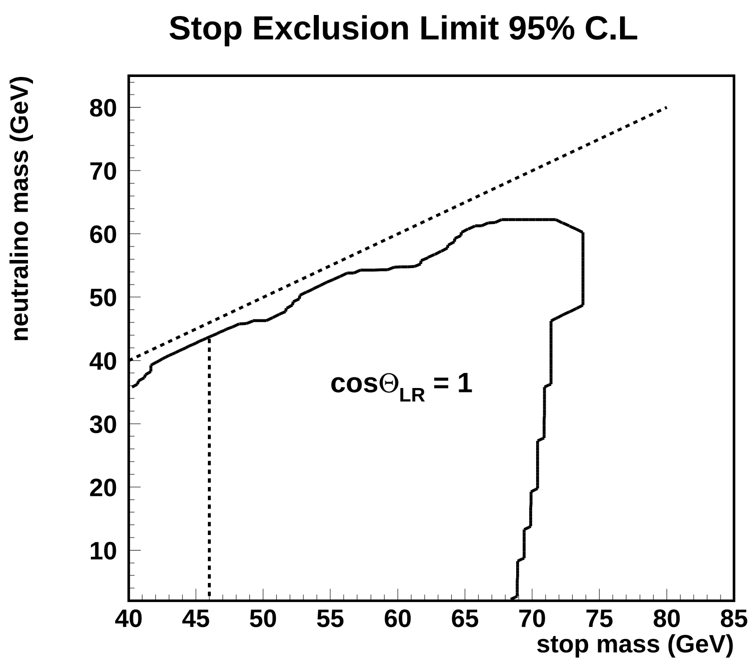
130–136 GeV, 161 GeV and 172 GeV results combined

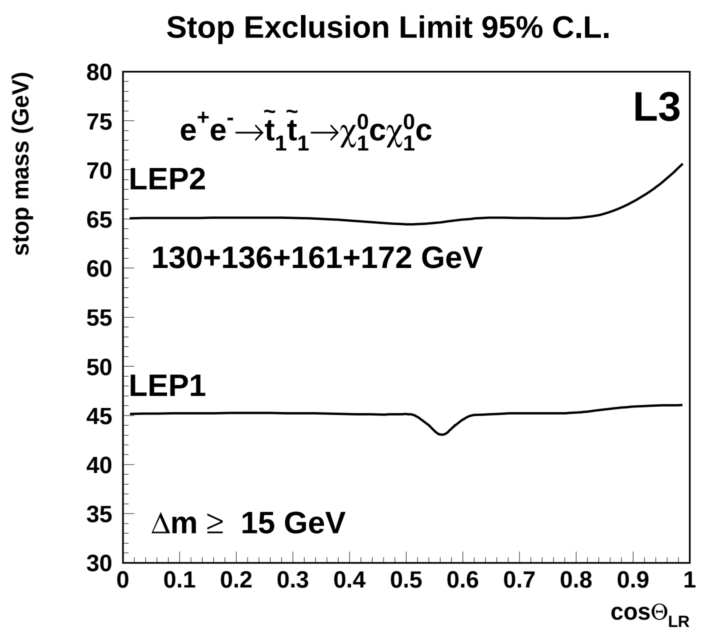




L3 PRELIMINARY

130–136 GeV, 161 GeV and 172 GeV results combined





Conclusions

The data collected by L3 in the LEP2 runs have shown no evidence of Supersymmetric particles.

- Model independent limits on the production cross section.
- Improved mass limits.
- New excluded regions in the SUSY parameter space.

Next run at $\sqrt{s} > 180$ GeV in summer 1997

SUSY searches are not over !!!!!