Search for SUSY at LEP2

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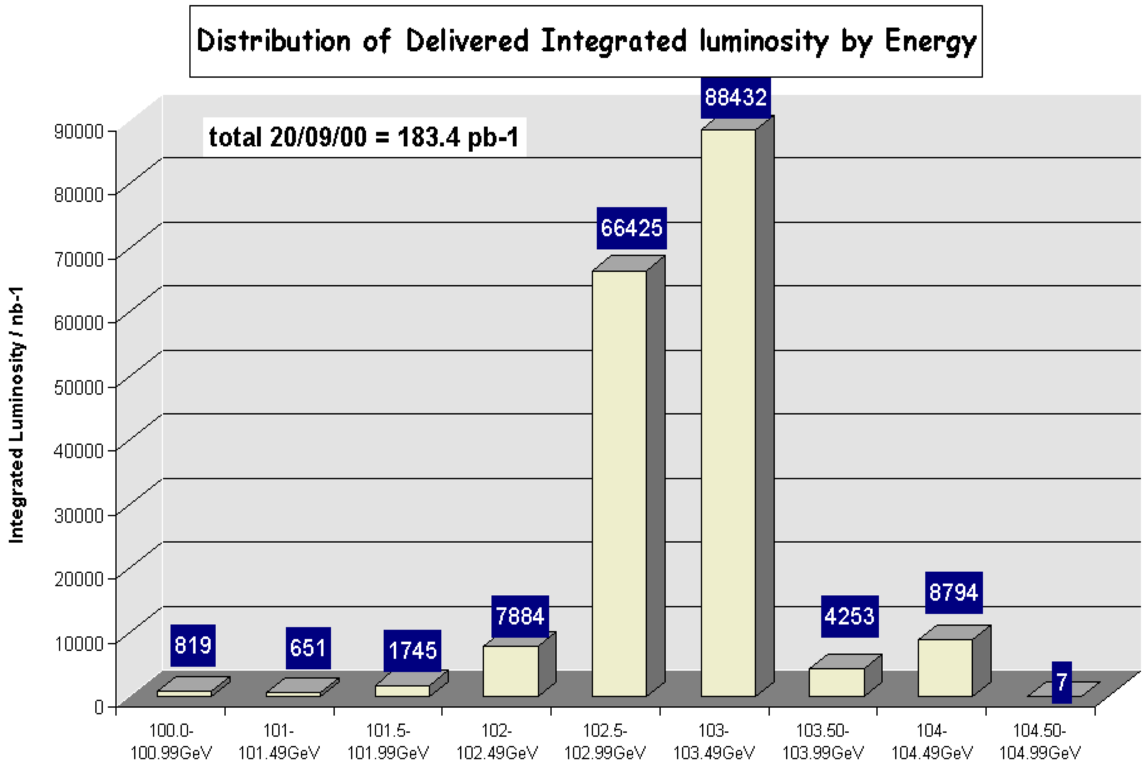
For the LEP Collaborations

- Introduction
- LEP SUSY searches in the context of MSSM
- Search for Gauge Mediated SUSY Breaking models
- Conclusion

LEP2 dataset

ALEPH, DELPHI, L3, OPAL

Year	$\sqrt{s}$	$\mathcal{L}$/Experiment
1995	130-136 GeV	$\approx 6pb^{-1}$
1996	161-172 GeV	$\approx 21pb^{-1}$
1997	181-184 GeV	$\approx 56pb^{-1}$
1998	189 GeV	$\approx 170pb^{-1}$
1999	192-202 GeV	$\approx 240pb^{-1}$
2000	203-209 GeV	$\approx 170{+}pb^{-1}$



All results are obtained with 1999, 2000 data and are PRELIMINARY

MSSM framework

- Constrained MSSM
  - Unification of gaugino masses
  - Unification of scalar masses
  - Unification of trilinear couplings
  - Parameters left with
    - M_2 SU(2) gaugino mass at EW scale
    - m_0 common scalar mass at GUT scale
    - $tan\beta$ $= \frac{v_2}{v_1}$
    - μ Higgs mass parameter
    - A_0 common trilinear coupling
    - m_A mass of CP-odd higgs A
- Assume R-parity conservation
  - LSP is stable and weakly interacting
    - Lightest neutralino is LSP
    - LSP escapes detection
      $\Rightarrow$ missing energy signature
  - Sparticles are produced in pairs and decay to their SM partner and the LSP

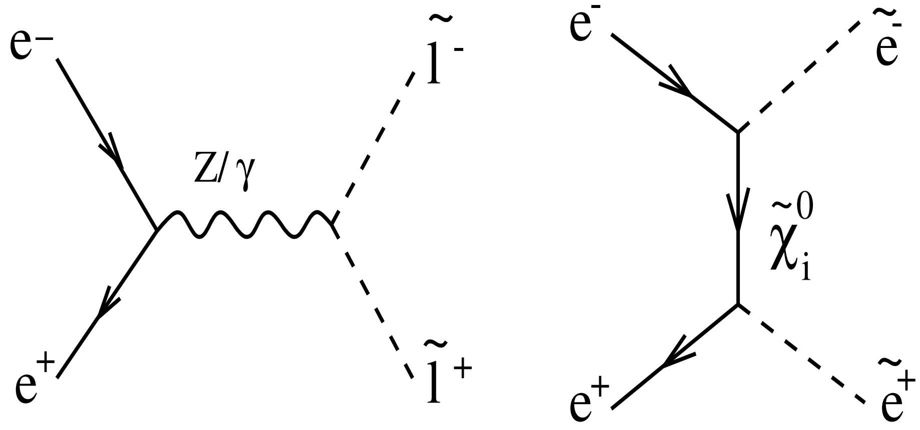
MSSM sparticle searched at LEP

- Sleptons
  $\tilde{e}^+\tilde{e}^-, \tilde{\mu}^+\tilde{\mu}^-, \tilde{\tau}_1^+\tilde{\tau}_1^-$
- Squarks
  $\tilde{t}_1^+\tilde{t}_1^-, \tilde{b}_1^+\tilde{b}_1^-$
- Charginos and Neutralinos
  $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_i^0\tilde{\chi}_j^0$

- Major decay mode
  $\tilde{f} \to f\tilde{\chi}_1^0$, except for stop $\tilde{t} \to c\tilde{\chi}_1^0$
  $\tilde{\chi}_1^\pm \to W^{\pm *}\tilde{\chi}_1^0 \to f\bar{f}'\tilde{\chi}_1^0$
  $\tilde{\chi}_i^0 \to Z^*\tilde{\chi}_1^0 \to f\bar{f}\tilde{\chi}_1^0$
- Cascade decays may also be important
  $\tilde{f} \to f\tilde{\chi}_2^0$, $\tilde{t} \to bl\tilde{\nu}$
  $\tilde{\chi}_1^\pm \to W^{\pm *}\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm \to \tilde{l}\nu(l\tilde{\nu})$
  $\tilde{\chi}_i^0 \to Z^*\tilde{\chi}_2^0$, $\tilde{\chi}_i^0 \to \tilde{l}l$, $\tilde{\chi}_i^0 \to \tilde{\nu}\nu$,

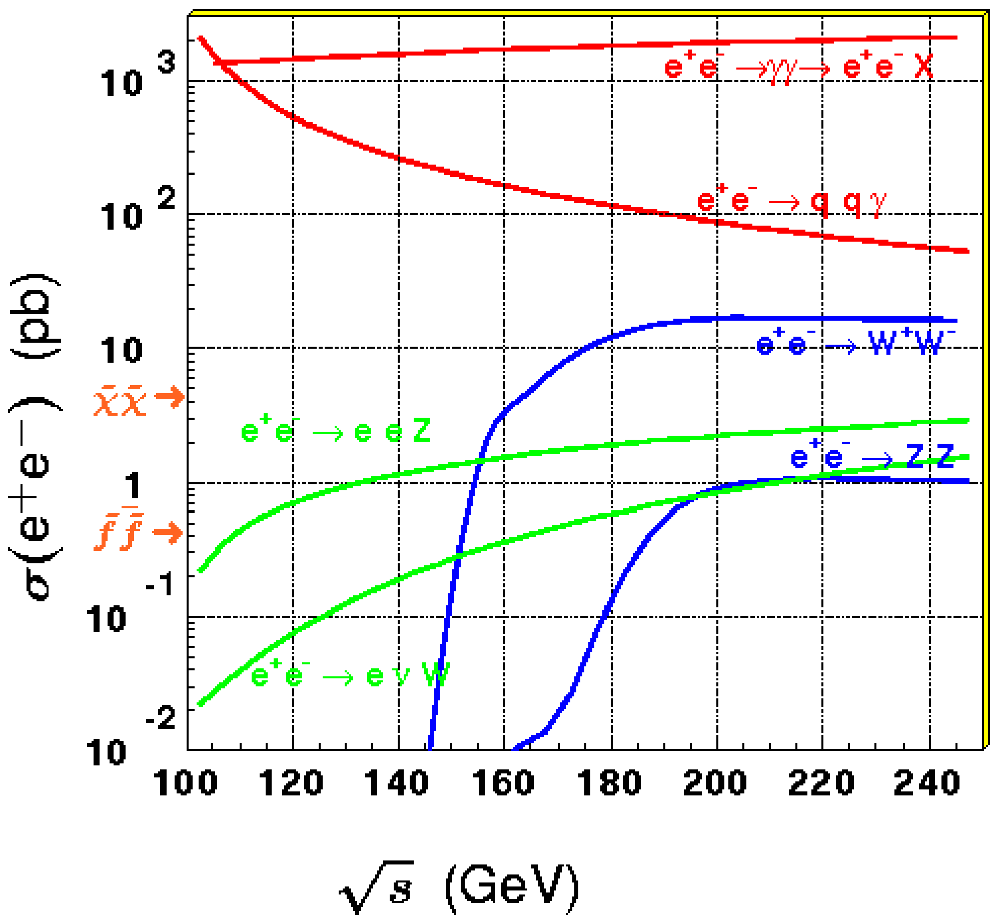
- Event signature
  $[\, lepton(s),\ jet(s)\,] + E_{missing}$
  Important kinematic variable
  $\Delta M = M_{sparticle} - M_{LSP}$

MSSM Sleptons



$$e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow l^+l^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

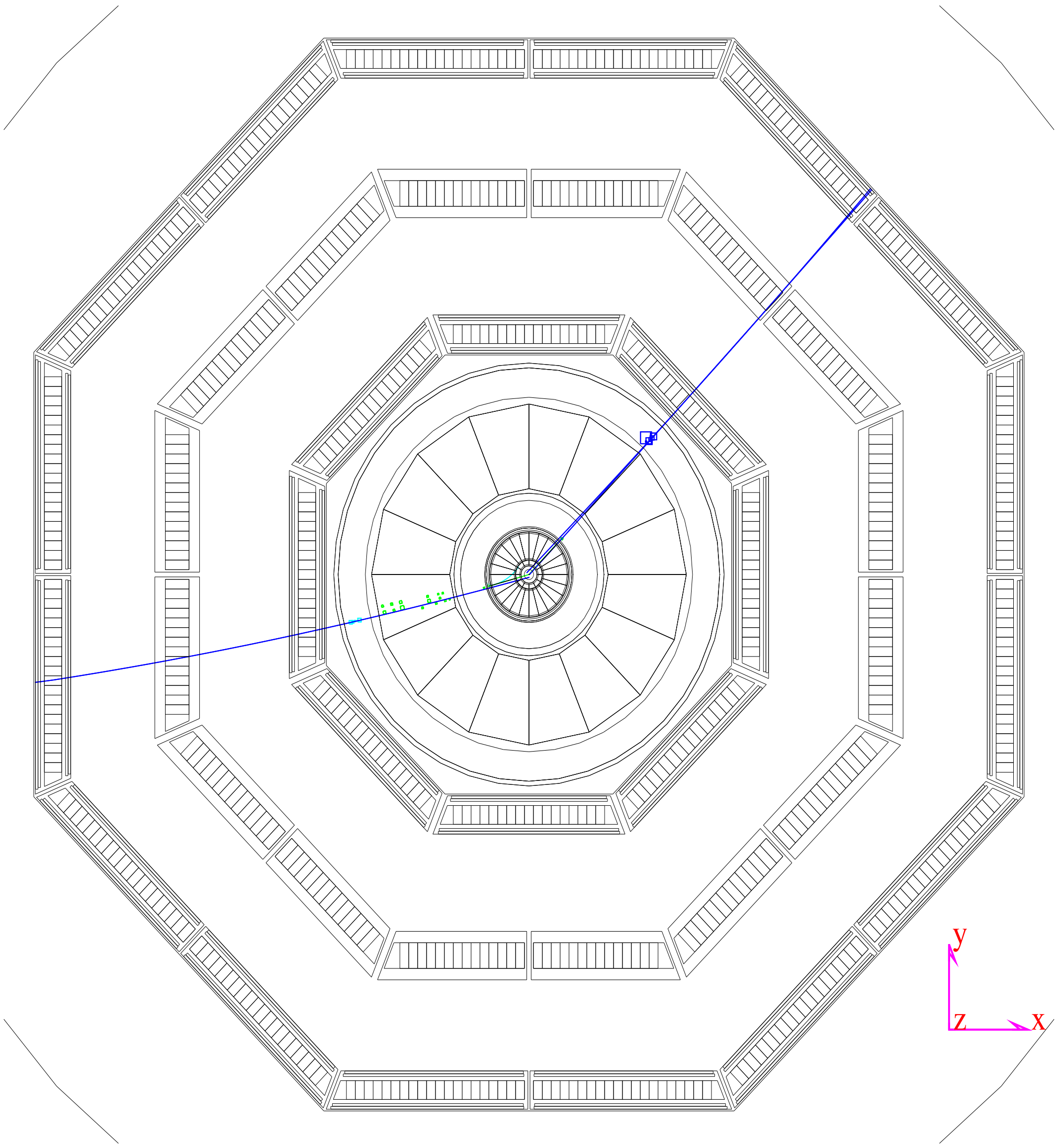
$$\Rightarrow Acoplanaleptons + E_{missing}$$



- $e^+e^- f\bar{f}$ is major background at low ΔM
- WW and WWeν are main backgrounds at high ΔM

A smuon candidate from L3

Run # 755104 Event # 1194 Total Energy : 69.31 GeV



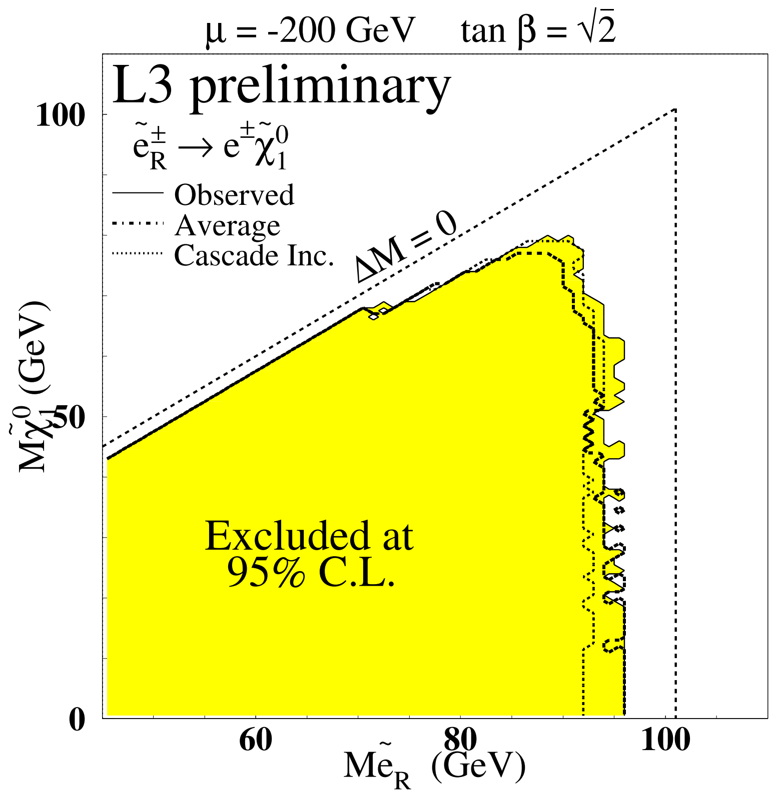
Transverse Imbalance : .6543		**Longitudinal Imbalance :** .1887	
Thrust : .9814	**Major :** .1428	**Minor :** .0013	
Event DAQ Time : *990708 84421*			

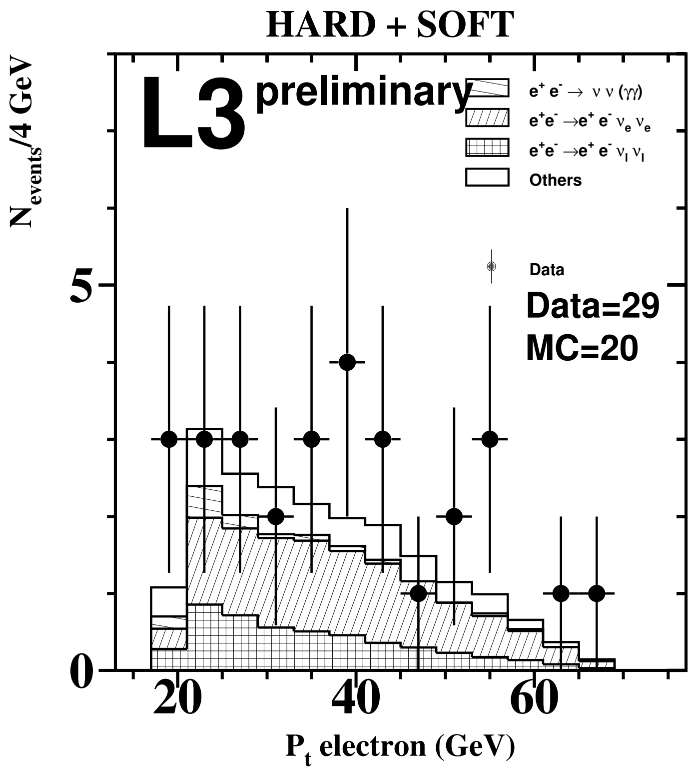
MSSM Sleptons

$\tilde{e}_R^+\tilde{e}_R^- \longrightarrow e^+e^- + E_{missing}$
Data till 1999

In 1999 data:

$N_{(data)}$ 60
$N_{(MC)}$ 56.2
$\varepsilon =$ 5 - 60%





To cover low ΔM
$(M_{\tilde{e}_R} - M_{\tilde{\chi}_1^0})$ region

$\tilde{e}_L^\pm\tilde{e}_R^\mp \longrightarrow$
$e^\pm + soft\ sys. + E_{missing}$
In 1999 data:

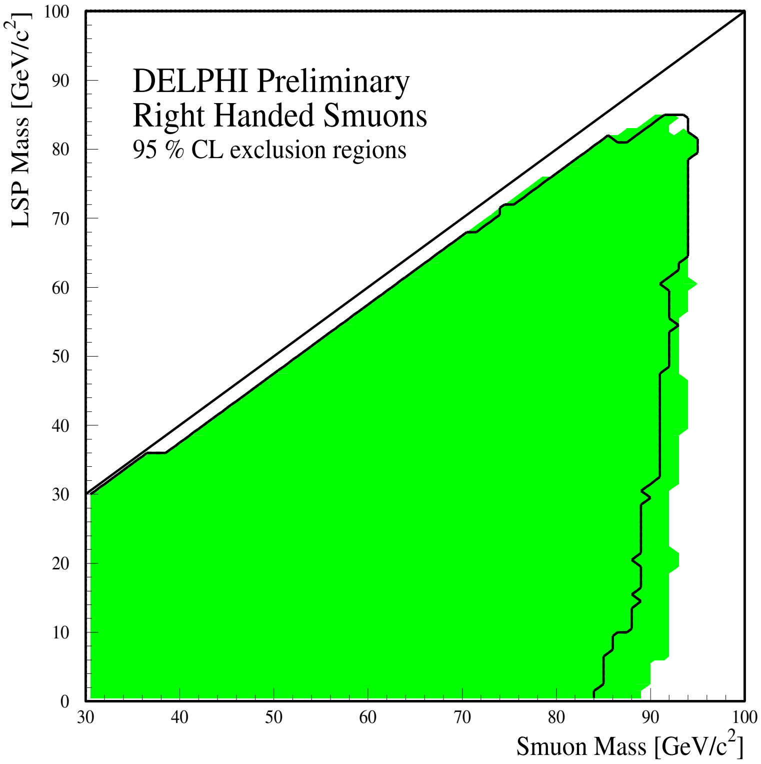
$N_{(data)}$ 29
$N_{(MC)}$ 20.

MSSM Sleptons

$\tilde{\mu}^+_R \tilde{\mu}^-_R \rightarrow \mu^+ \mu^- + E_{missing}$
Include $93.7 pb^{-1}$ data from year 2000

In 2000 data:

$N_{(data)}$ 4
$N_{(MC)}$ 7.6

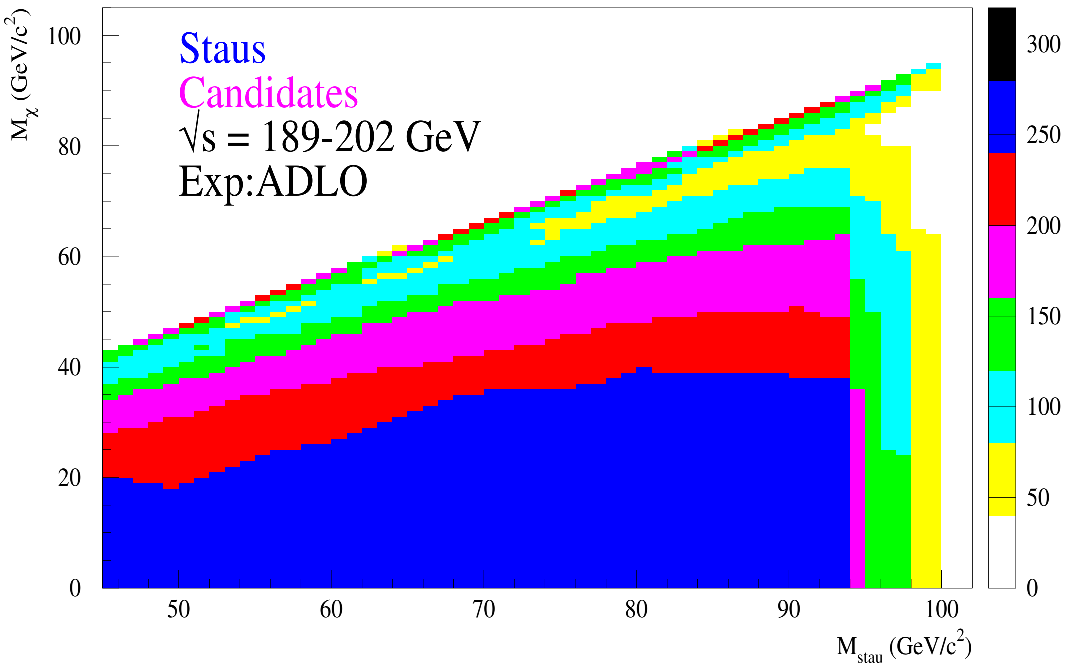


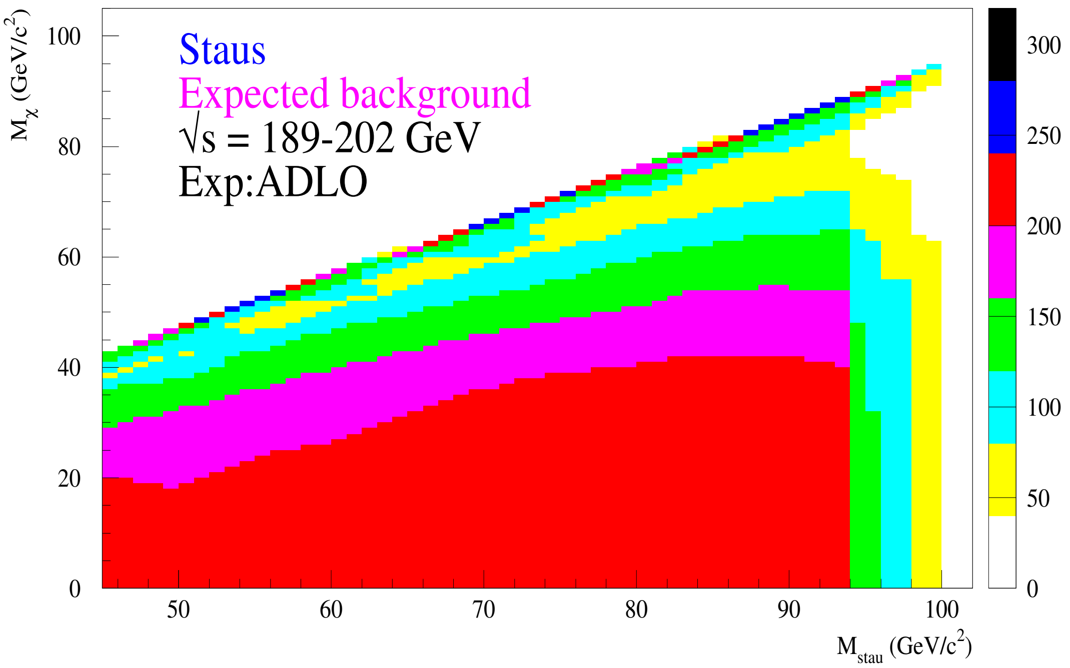
LEP combined 1999

Channel	$M_{\tilde{l}}(obtained) >$	$M_{\tilde{l}}(expected) >$
$\tilde{e}_R$	95 GeV	95 GeV
$\tilde{\mu}_R$	92 GeV	87 GeV

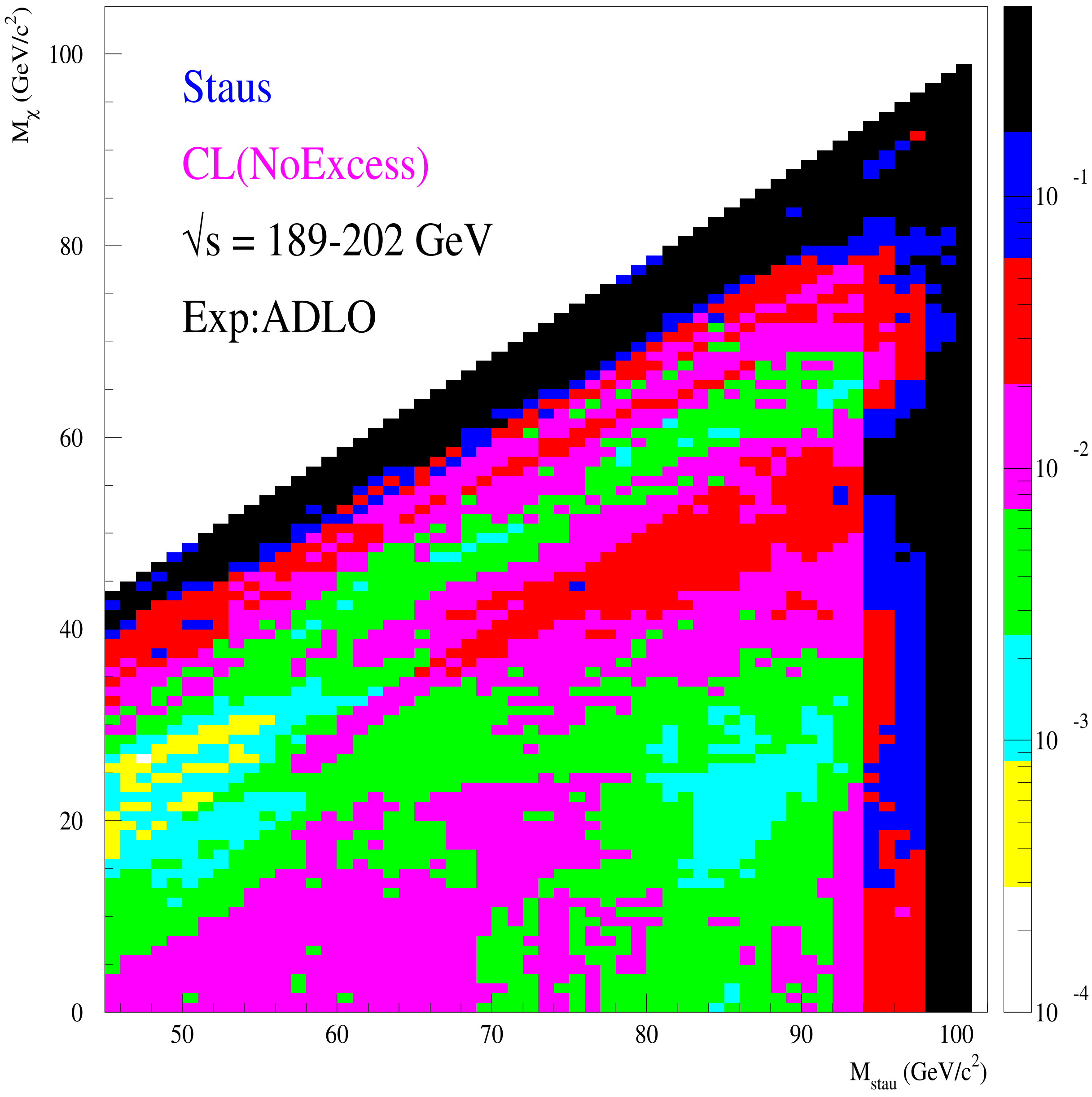
MSSM Sleptons

The preliminary combined stau result shows an excess spread over all the experiments, for LEP energies between 189GeV and 202GeV





MSSM Sleptons

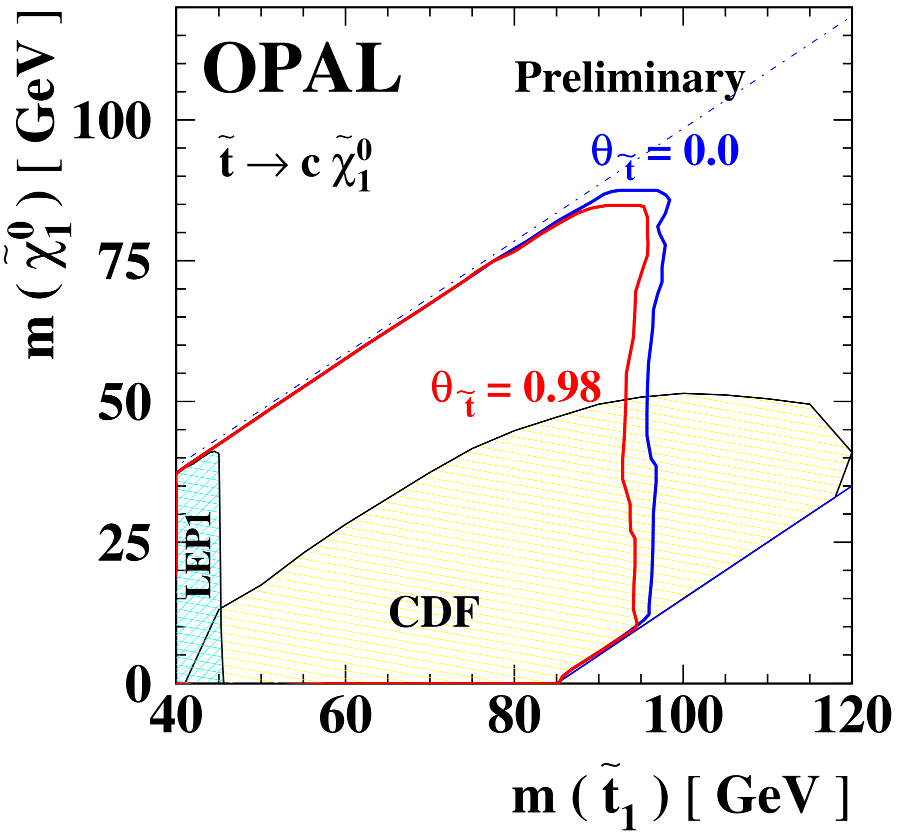


The multichannel CL (assume no excess) for an upward fluctuation of the background is 0.2%, at high $M_{\tilde{\tau}}$

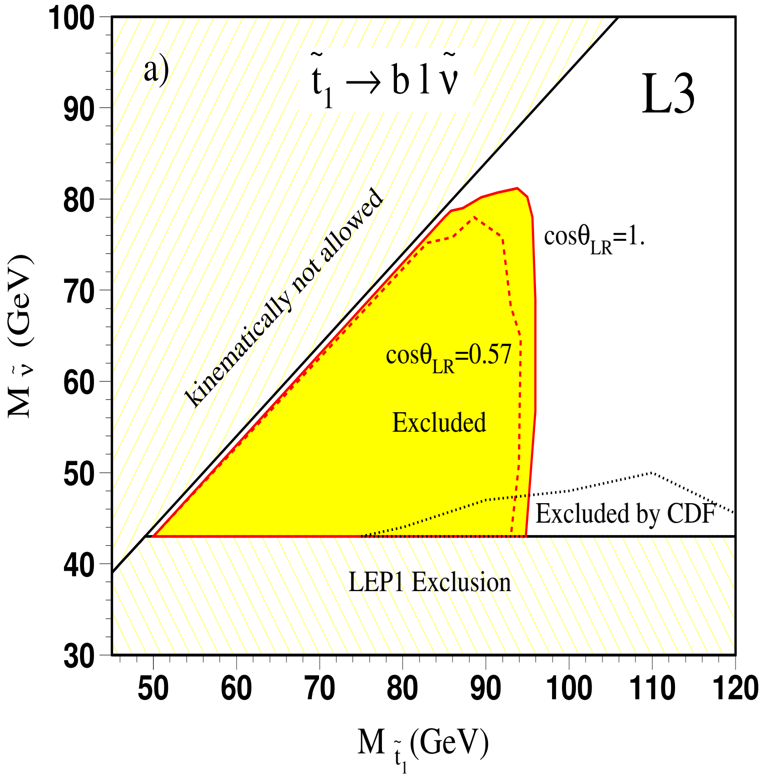
MSSM Squarks

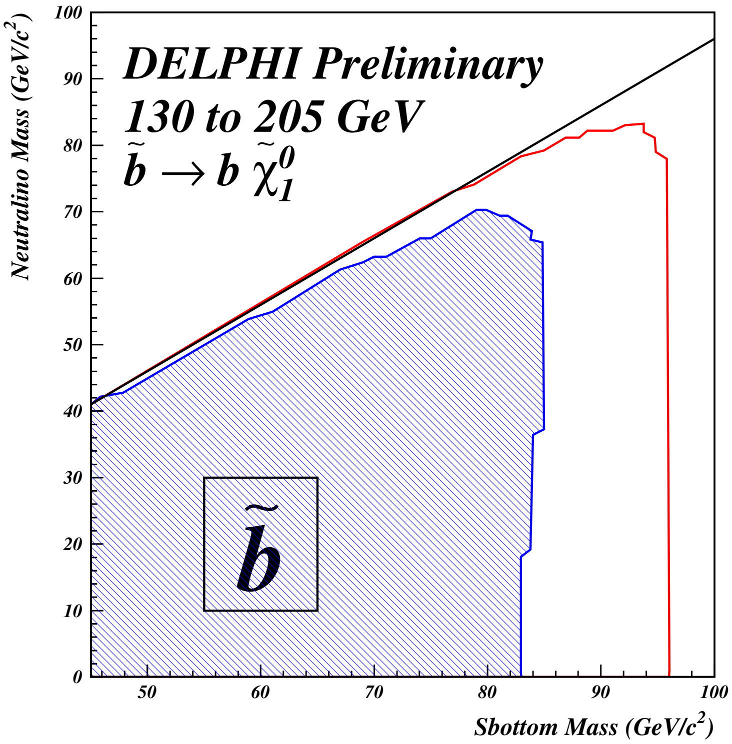
- $\tilde{t}_1\,\bar{\tilde{t}}_1 \rightarrow c\,\tilde{\chi}_1^0\,\bar{c}\,\tilde{\chi}_1^0$
- $\tilde{t}_1\,\bar{\tilde{t}}_1 \rightarrow b\,\ell^+\,\tilde{\nu}\,\bar{b}\,\ell^-\,\tilde{\nu}, \quad \ell = e, \mu, \tau$
- $\tilde{b}_1\,\bar{\tilde{b}}_1 \rightarrow b\,\tilde{\chi}_1^0\,\bar{b}\,\tilde{\chi}_1^0$

Exclusion contours for $\tilde{t}, \tilde{b}$, at minimal and maximal cross-sections



MSSM Squark

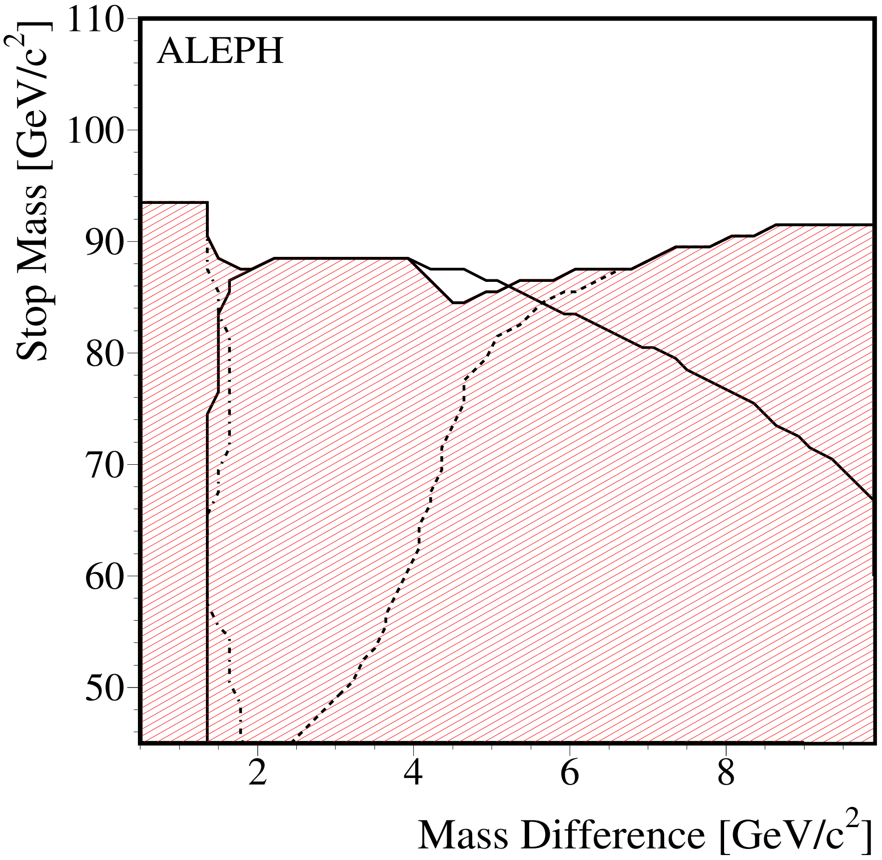

a)
$\tilde{t}_1 \rightarrow b\, l\, \tilde{\nu}$
L3
kinematically not allowed
$\cos\theta_{LR}$=1.
$\cos\theta_{LR}$=0.57
Excluded
Excluded by CDF
LEP1 Exclusion
$M_{\tilde{\nu}}$ (GeV)
$M_{\tilde{t}_1}$(GeV)


DELPHI Preliminary
130 to 205 GeV
$\tilde{b} \rightarrow b\, \tilde{\chi}^0_1$
$\tilde{b}$
Neutralino Mass (GeV/c^2)
Sbottom Mass (GeV/c^2)

MSSM Squark

When $M_{\tilde{t}_1}$ almose degenerate with LSP

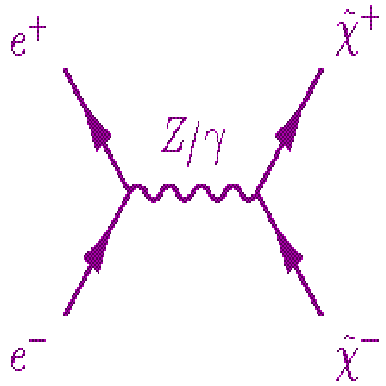
- $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0,\ u\tilde{\chi}_1^0$
- $\tilde{t}_1$ life time can be long
  - $\Delta M \geq 3GeV$ "standard $\not{E}$ searches"
  - $\Delta M \sim 1.5 - 3GeV$ impact parameter
  - $\Delta M \leq 1.5GeV$ anomalous ionization

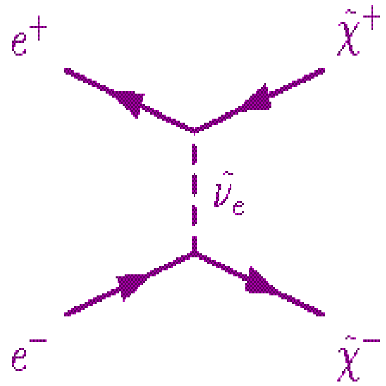


$$\mu = -100GeV, \quad tan\beta = 1.5$$

MSSM Charginos & Neutralinos

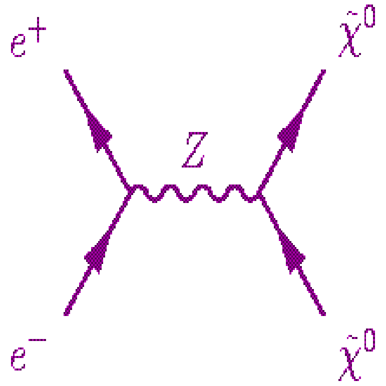
Chargino

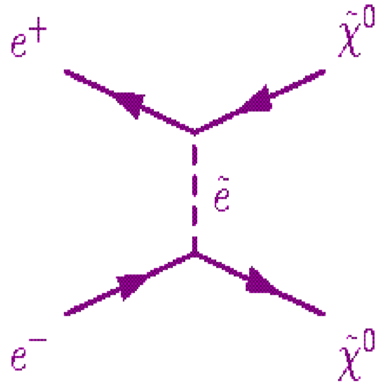




$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 W^* \rightarrow \tilde{\chi}_1^0 f \bar{f}'$$

Neutralinos





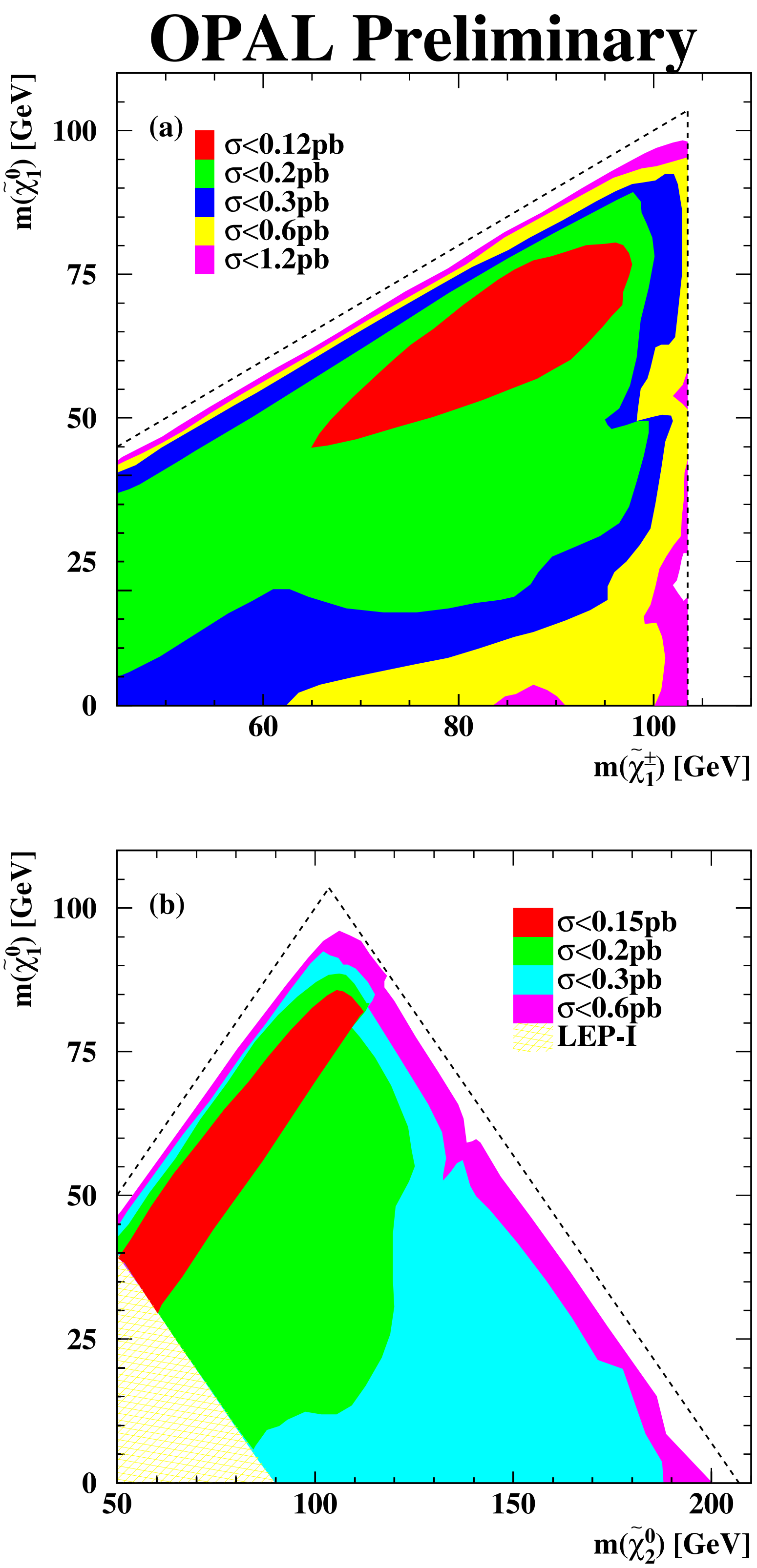
$$\tilde{\chi}_j^0 \rightarrow \tilde{\chi}_k^0 Z^* \rightarrow \tilde{\chi}_k^0 f \bar{f},\ with\ j > k$$

Looking for

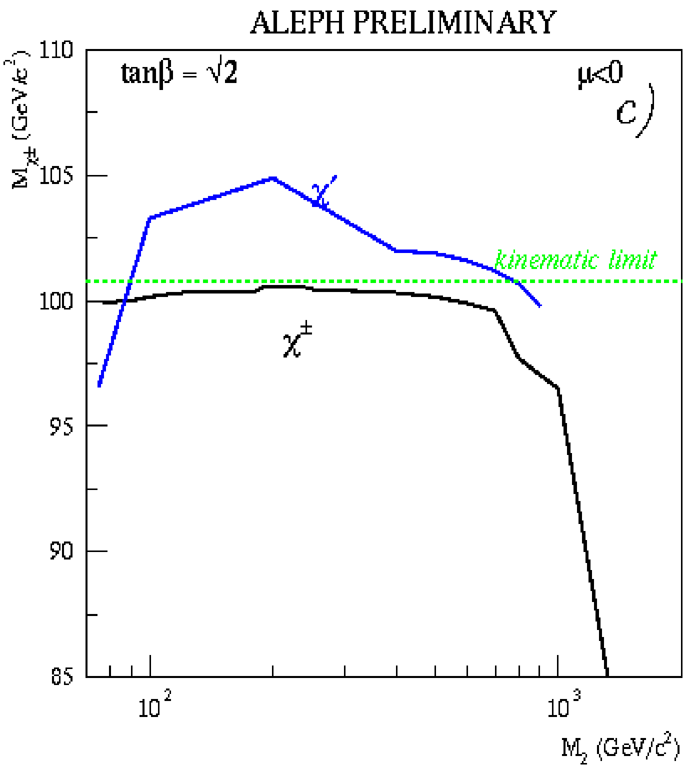
acoplanar leptons
multiple jets

jets + isolated lepton
two acoplanar jets

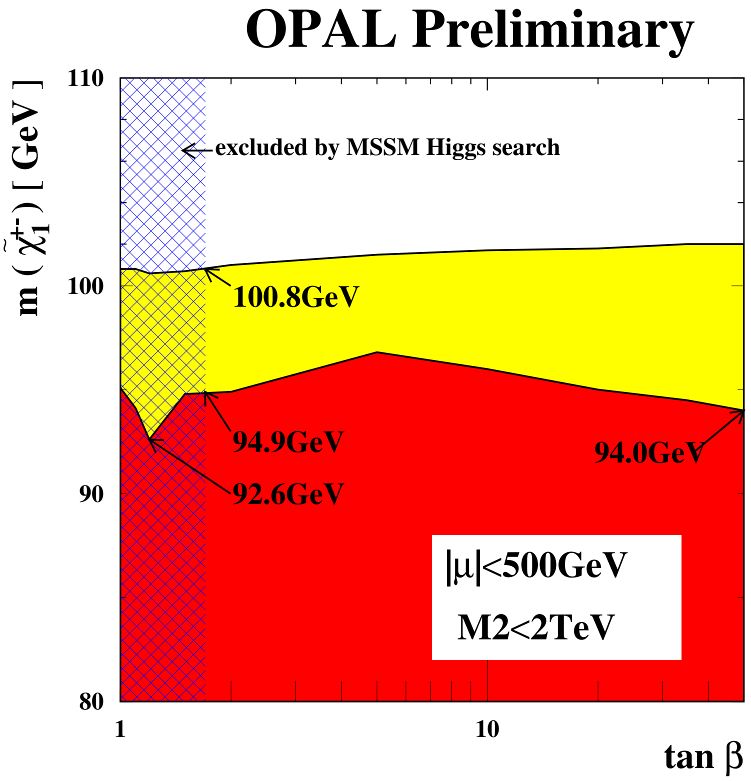
MSSM Charginos & Neutralinos



MSSM Charginos & Neutralinos



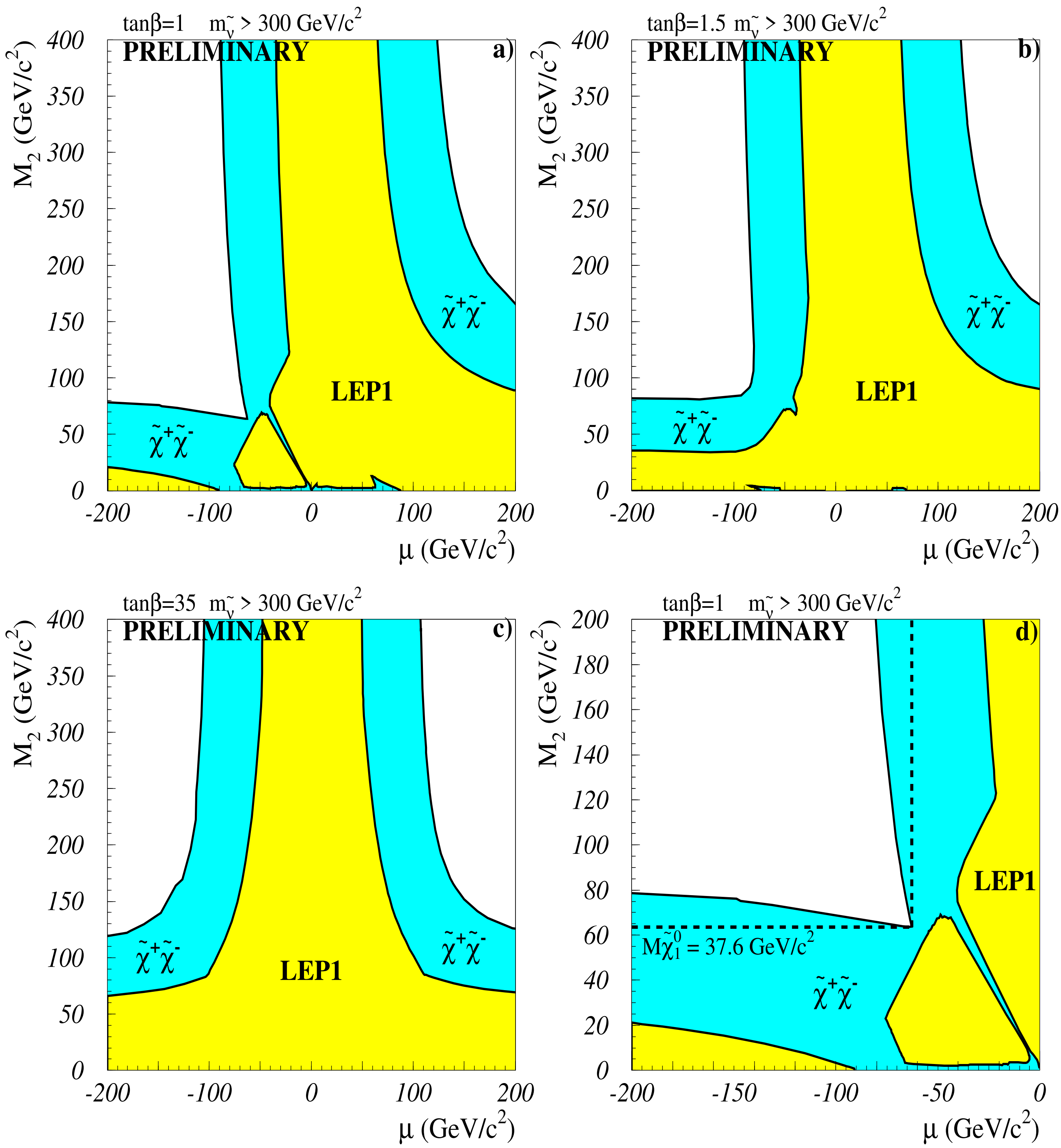
chargino mass limit from direct searches, indirect searches



chargino mass limit for $m_0 \geq 500GeV$, all m_0 values

MSSM Charginos & Neutralinos

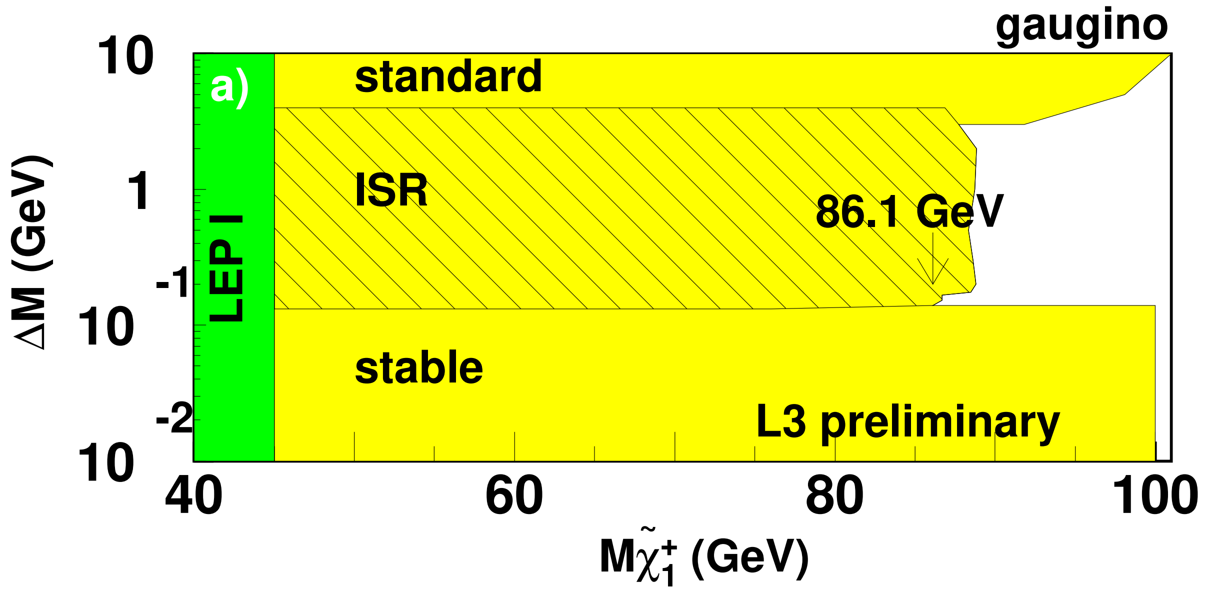
DELPHI MSSM limits at 205.32 GeV

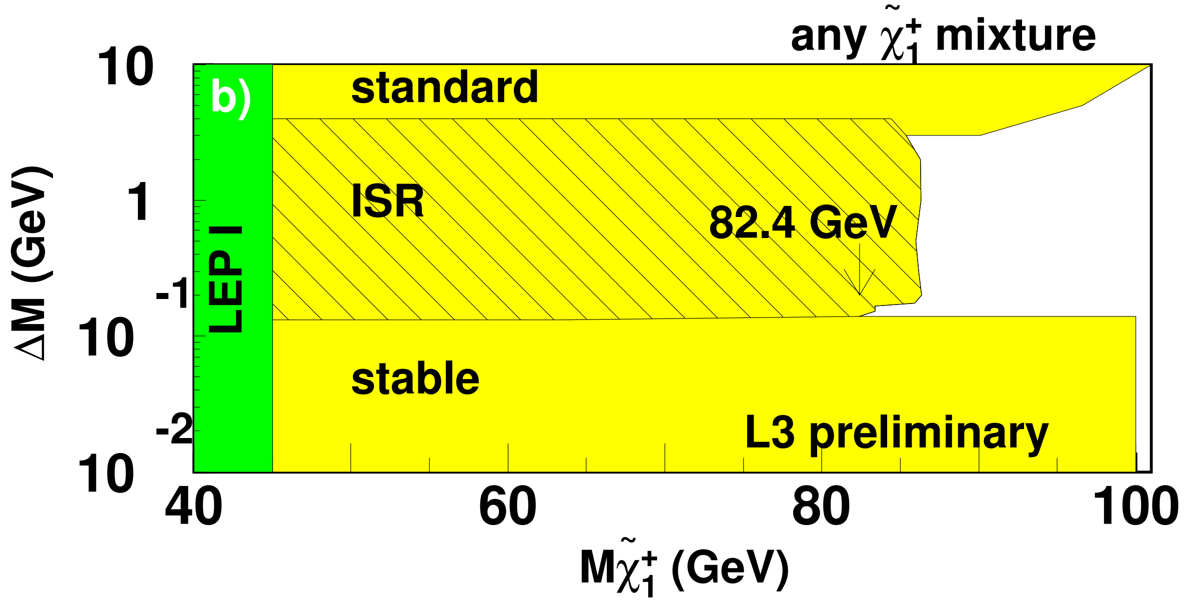


MSSM Charginos & Neutralinos

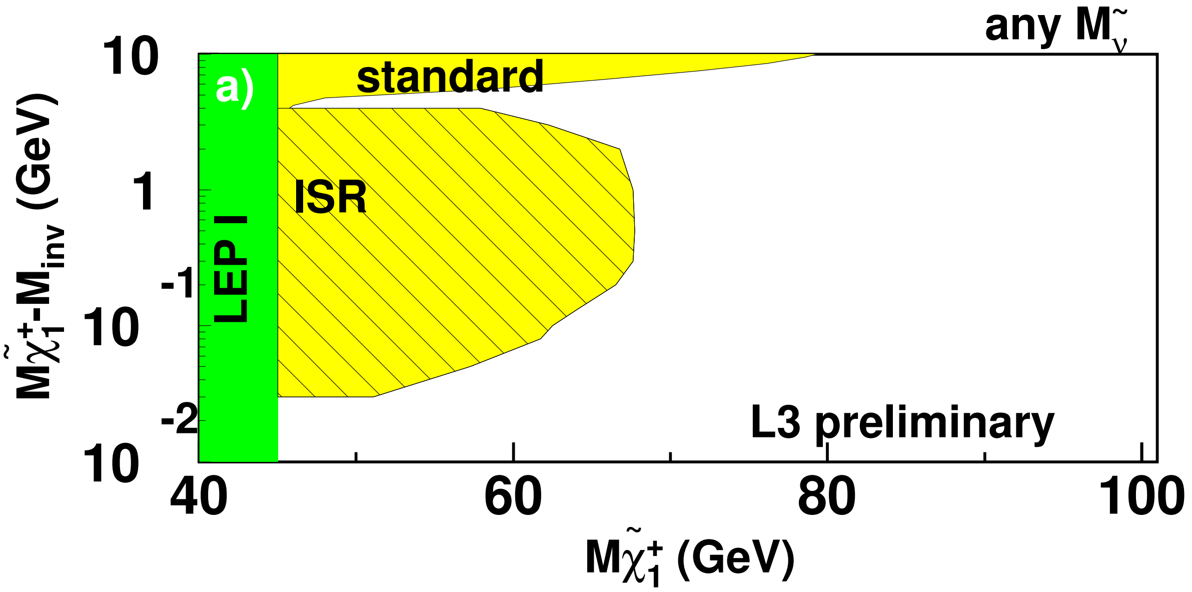
Chargino Mass almost degenerate with LSP

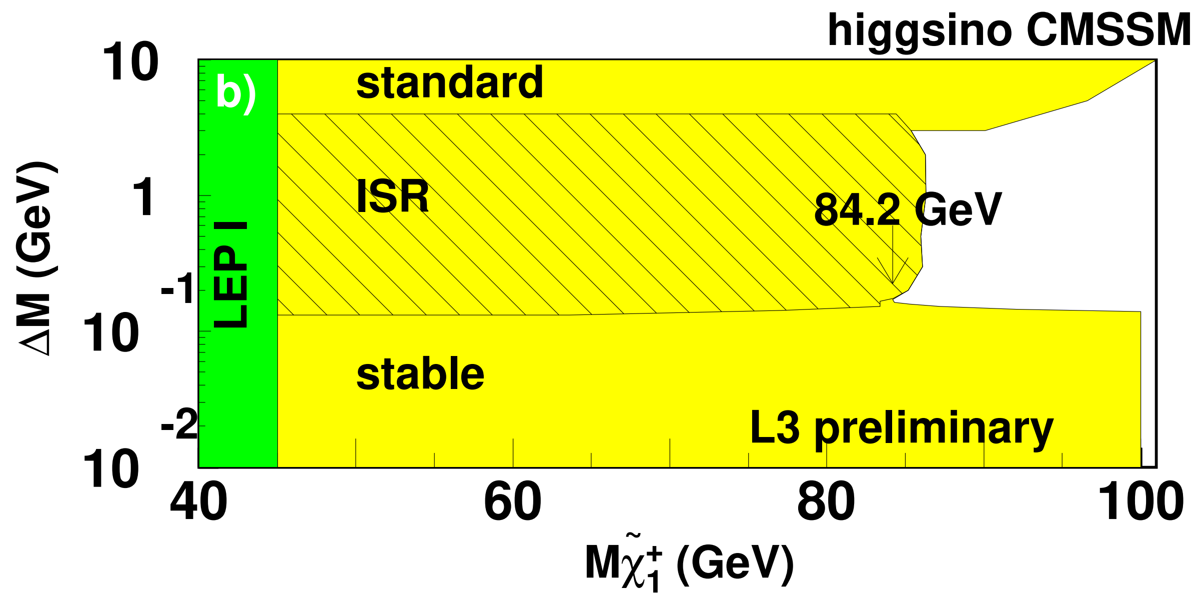
$$e^+e^- \to \gamma\tilde{\chi}_1^+\tilde{\chi}_1^- \to \gamma\tilde{\chi}_1^0\tilde{\chi}_1^0 X$$





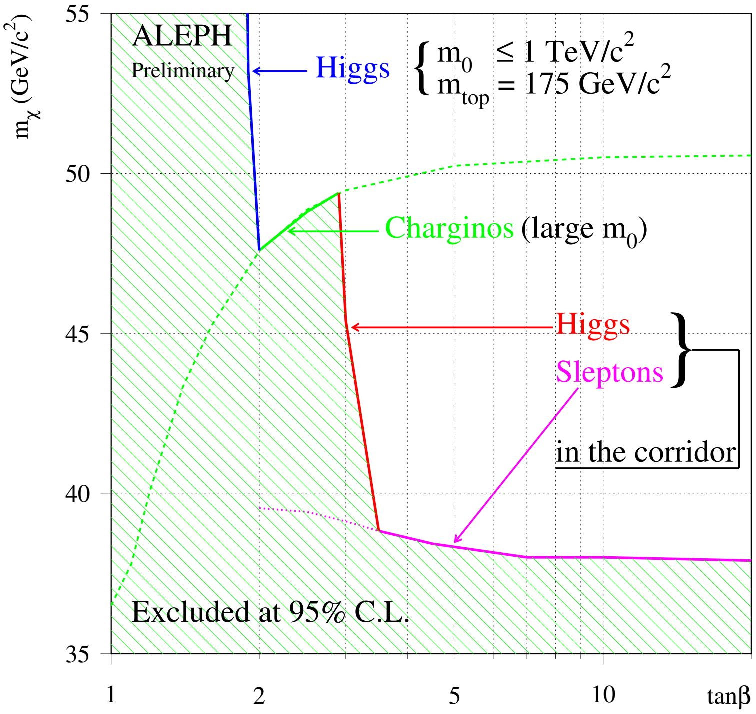
MSSM Charginos & Neutralinos





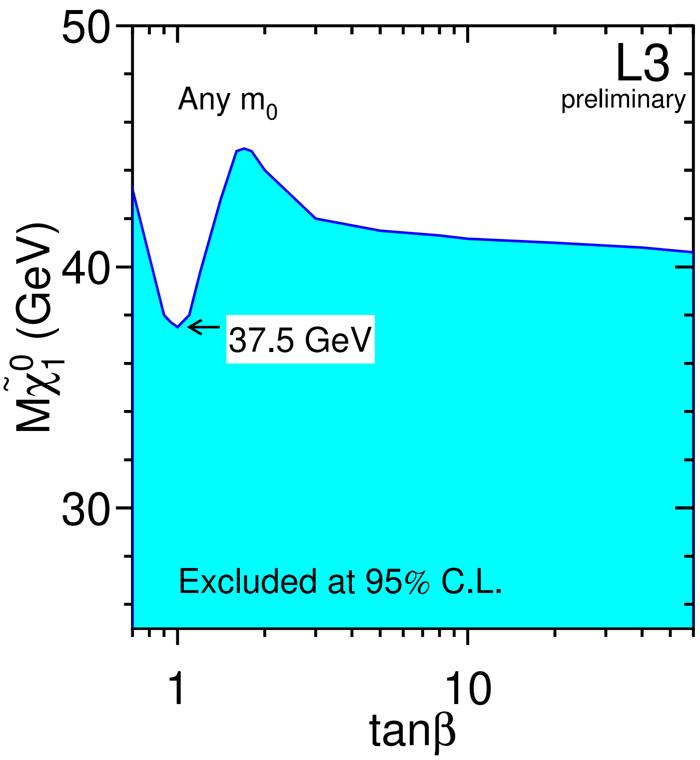
Allows to set limit on $M_{\tilde{\chi}_1^\pm}$ for any ΔM
in case of heavy scalar particles

MSSM LSP



ALEPH

Employing $\tilde{\chi}_1^+\tilde{\chi}_1^-$, slepton and Higgs searches



L3

Employing $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_i^0\tilde{\chi}_j^0$, and slepton searches

Introduction to $\not R_p$

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

Normal particles: $R_p = +1$ SUSY particles: $R_p = -1$

- R_p conserved

  Stable LSP, SUSY particles are paired produced

- R_p violated

  LSP not stable, may decay into normal particles
  Single SUSY particle production

R_p violating term in superpotential:

$$W_R = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- $\lambda_{ijk}, \lambda'_{ijk}$ terms violate lepton quantum number
- λ'' terms violate baryon quantum number
- suppose dominant coupling is strong enough
  $\Rightarrow$ negligible decay length

Chargino and Neutralino

Direct decay

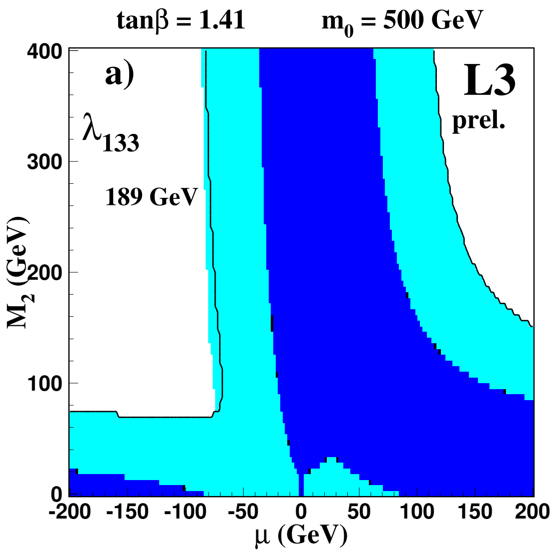
	λ	$\lambda^{'}$	$\lambda^{''}$
$\tilde{\chi}_1^0$	$\nu l l$	lqq or νqq	qqq
$\tilde{\chi}_1^{\pm}$	lll or $l\nu\nu$	lqq or νqq	qqq
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	$4l+\not{E}$	$2l+4jets$ or $(1l+)4jets+\not{E}$	$6jets$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$(2,4)l+\not{E}$ or $6l$	$2l+4jets$ or $(1l+)4jets+\not{E}$	$6jets$

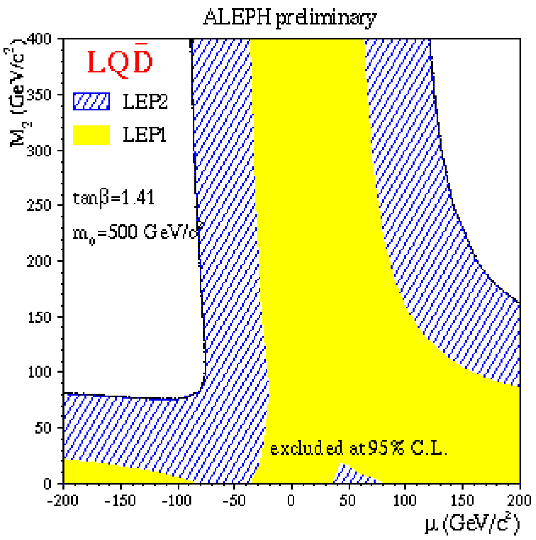
Indirect decay

$$\tilde{\chi}_j^0 \rightarrow \tilde{\chi}_1^0 Z^* \Rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 finalstate + 2Z^* products$$
$$\tilde{\chi}_j^{\pm} \rightarrow \tilde{\chi}_1^0 W^* \Rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 finalstate + 2W^* products$$

No signigicant excess found

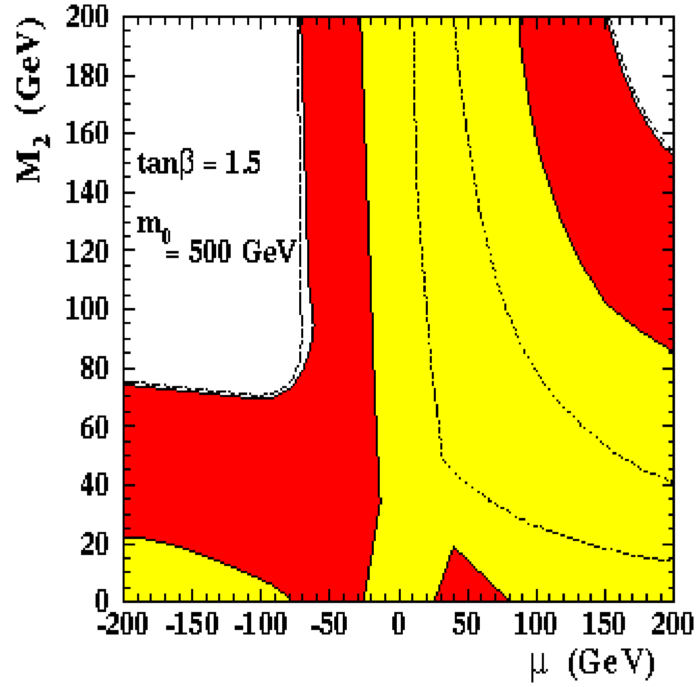
L3 λ ALEPH $\lambda^{'}$



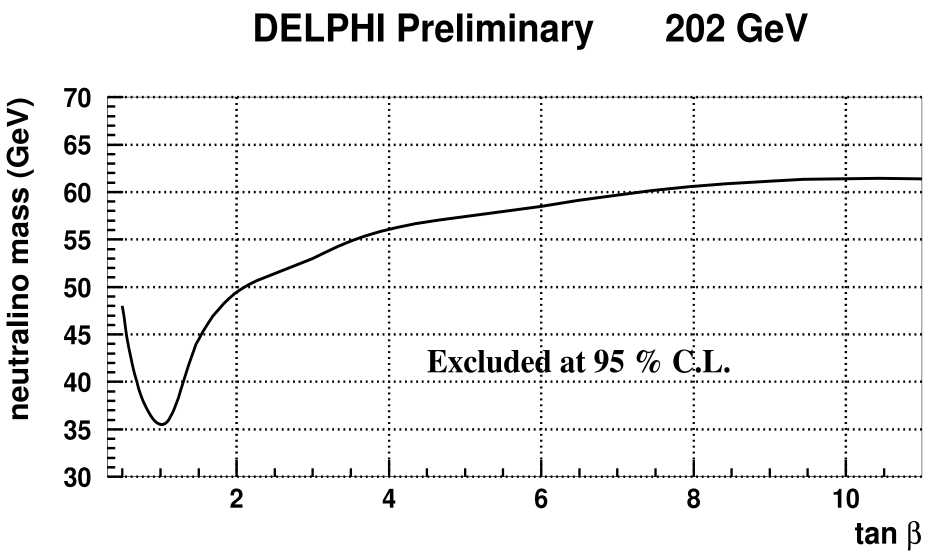


Chargino and Neutralino

OPAL λ''



$\tilde{\chi}_1^0$ limit obtained from λ'' term



Sfermion pair production

Direct decay

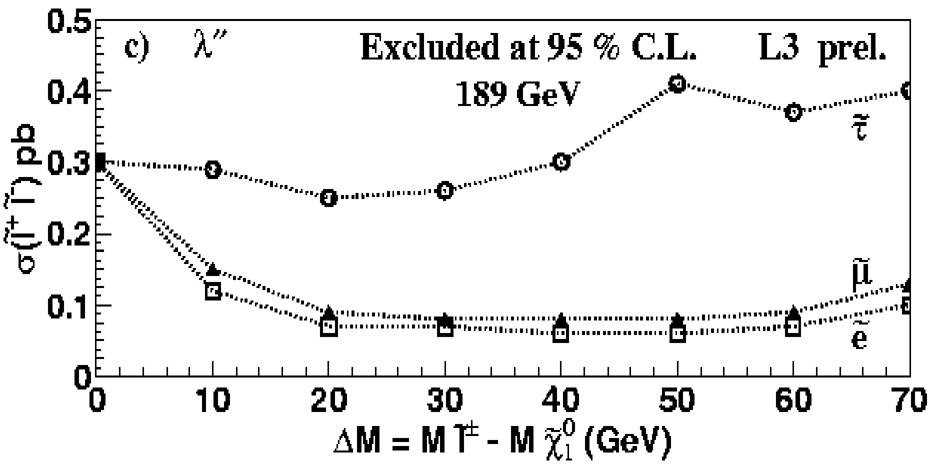
	λ	λ'	λ''
$\tilde{\nu}$	ll	qq	-
$\tilde{l}$	νl	qq	-
$\tilde{q}$	-	νq or lq	qq
$\tilde{\nu}\tilde{\nu}$	$4l$	$4jets$	-
$\tilde{l}\tilde{l}$	$2l+\not{E}$	$4jets$	-
$\tilde{q}\tilde{q}$	-	$2l+2jets$ or $2jets+\not{E}$	$4jets$

Indirect decay

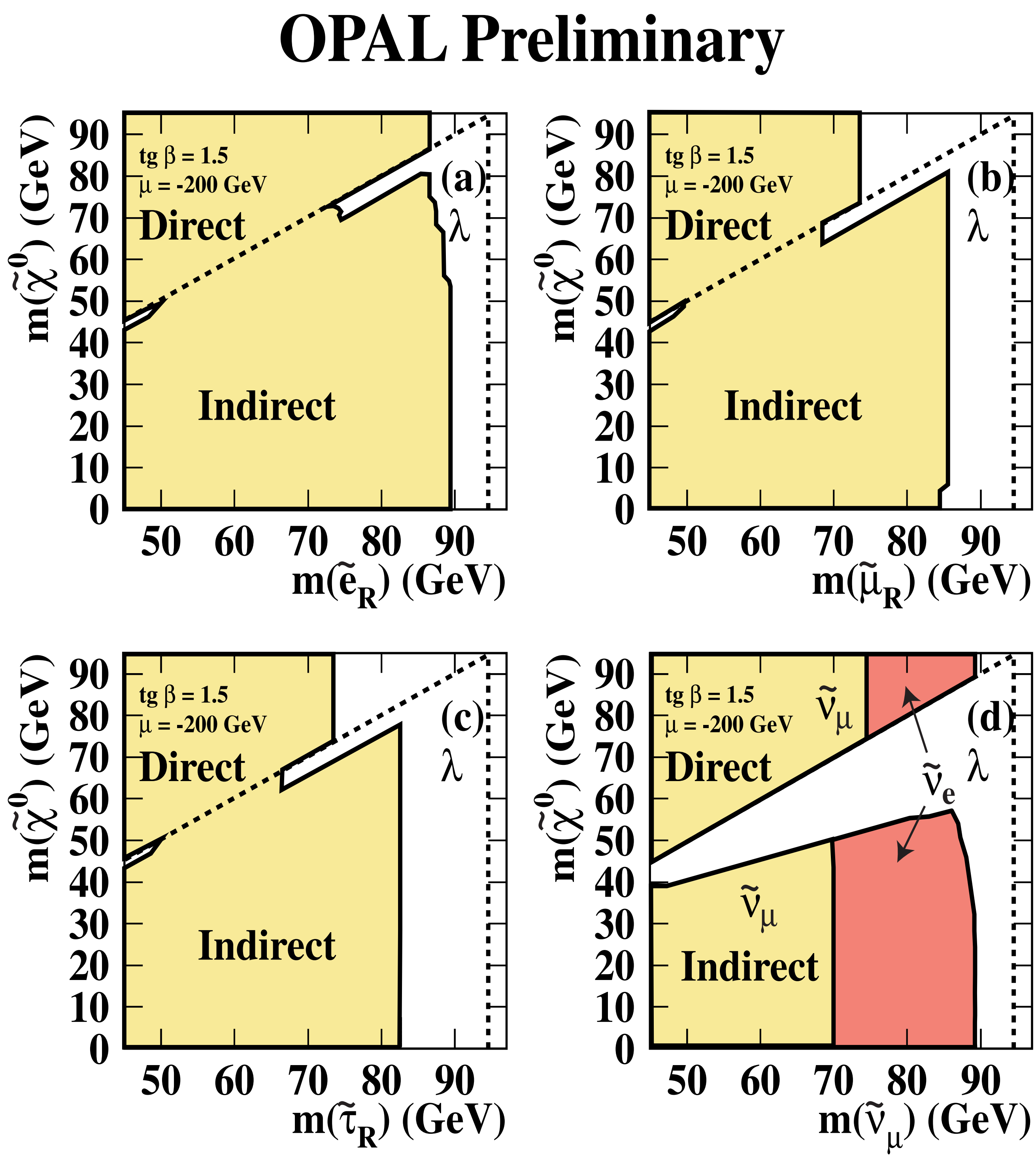
$\tilde{\nu} \rightarrow \nu\tilde{\chi}_1^0$ $\tilde{l} \rightarrow l\tilde{\chi}_1^0$ $\tilde{q} \rightarrow q\tilde{\chi}_1^0$

No signigicant excess found

L3 λ'' indirect searches

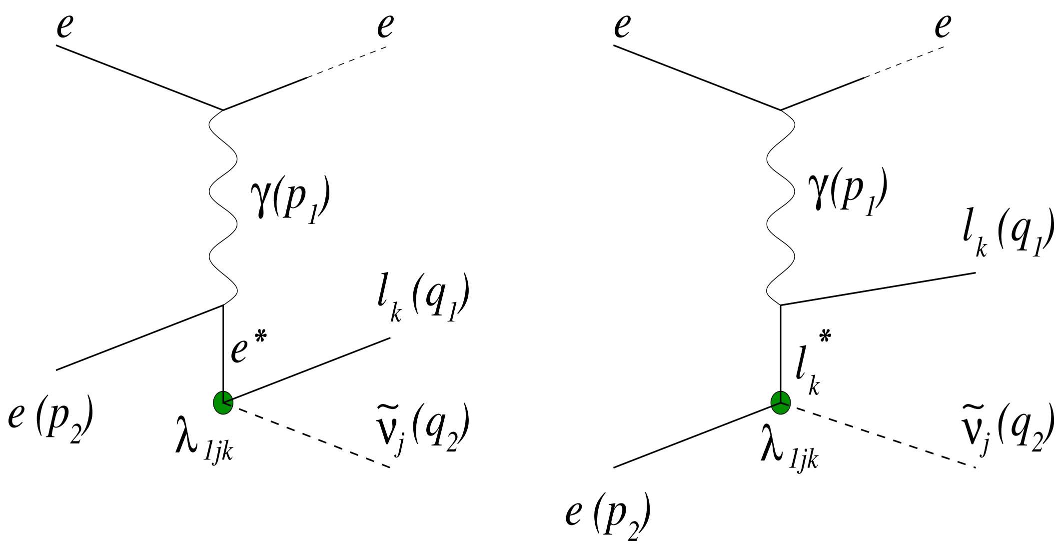


Sfermion pair production

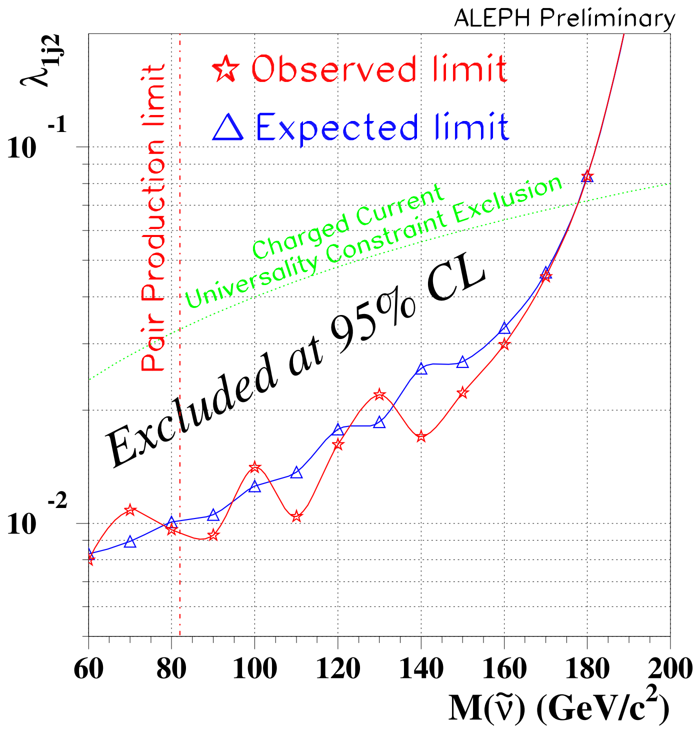


Single sparticle production

$$e\gamma \to \tilde{\nu} l$$



Production and decay through λ_{1j2}: $\tilde{\nu} \to e\mu$
$\Rightarrow$ final state: $e\mu^+\mu^-$



GMSB phenomenology

- SUSY breaking scale $\sqrt{F}$ at much lower energy
- $\tilde{G}$ is the LSP, and is very light $\Rightarrow E_{missing}$
- Possible NLSP, that might appear at LEP
  - neutralino NLSP
  - stau NLSP
  - slepton co-NLSP
  - neutralino stau co-NLSP

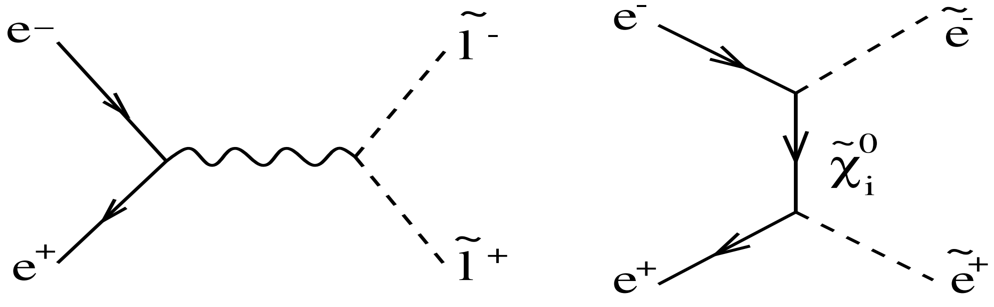
- Assume R-parity is conserved

$\Downarrow$

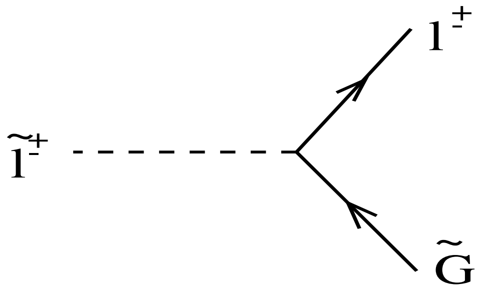
Search for neutralino and sleptons, especially stau

Some indirect searches are performed too

GMSB slepton NLSP



(a)



(b)

Event signature

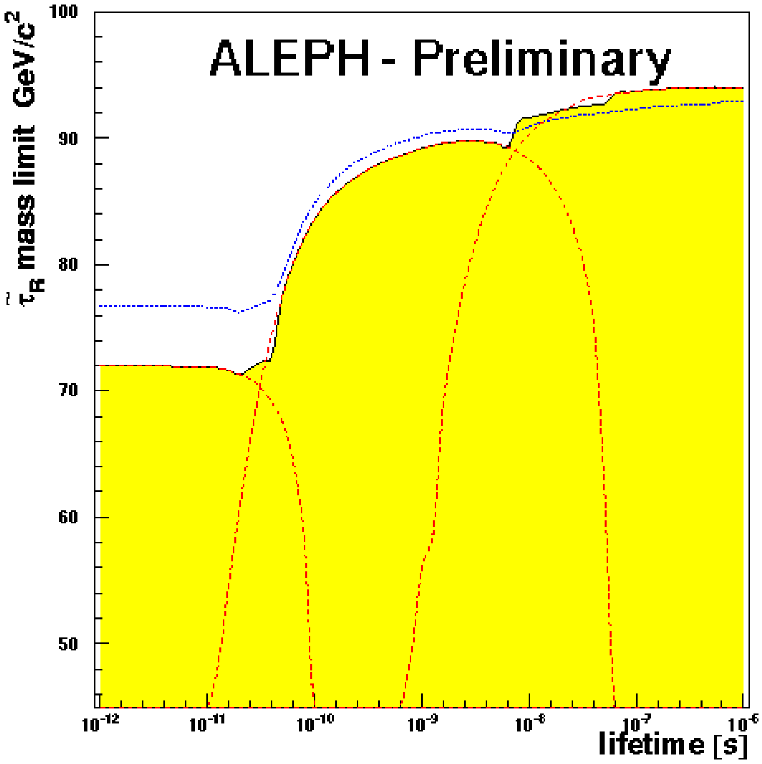
$$e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow \tilde{G}\tilde{G}l^+l^-$$

- $\tilde{G} \Rightarrow E_{missing}$
- Decay lengh of slepton strongly depends on $m_{\tilde{G}}$

Decay Length		Event Signature
Short	1mm	Acoplanar leptons
Medium	1mm - 1m	large impact parameter or kinks
Long	$\geq$ 1m	heavy stable charged particles

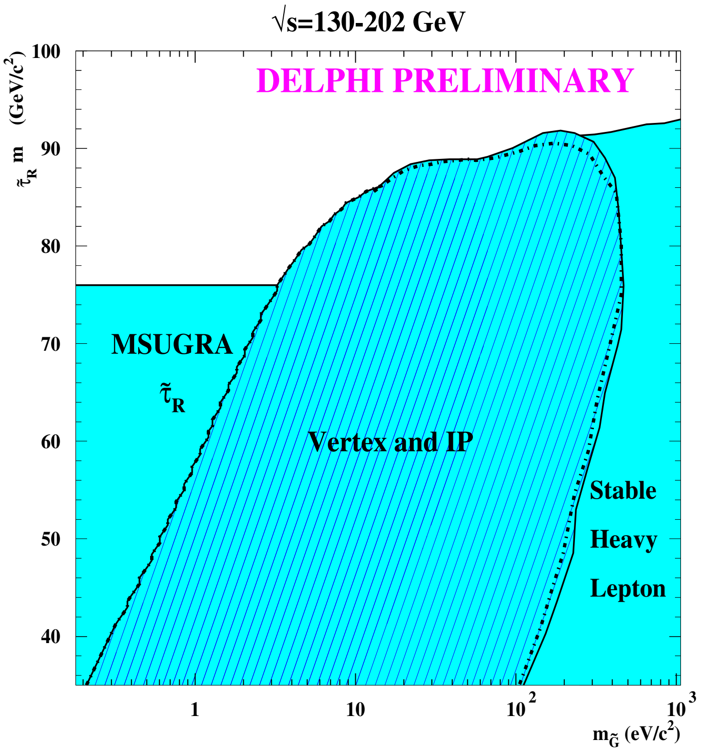
GMSB slepton NLSP

$$e^+e^- \to \tilde{\tau}\tilde{\tau} \to \tilde{G}\tilde{G}\tau\tau$$



ALEPH

$M_{\tilde{\tau}} > 71.3$ GeV
for any decay length



DELPHI

$M_{\tilde{\tau}} > 76$ GeV
for any decay length

GMSB neutralino NLSP

- NLSP decay $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$
- direct searches
  - $e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$, $e^+e^- \rightarrow \tilde{G}\tilde{G}\gamma_{ISR}$
  - $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$
  - suffer from irreducible background
    $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$

Decay Length		Event Signature
Short	$<$ 1cm	single photon, acoplanar photons
Medium	$>$ 1cm	non pointing photon(s)

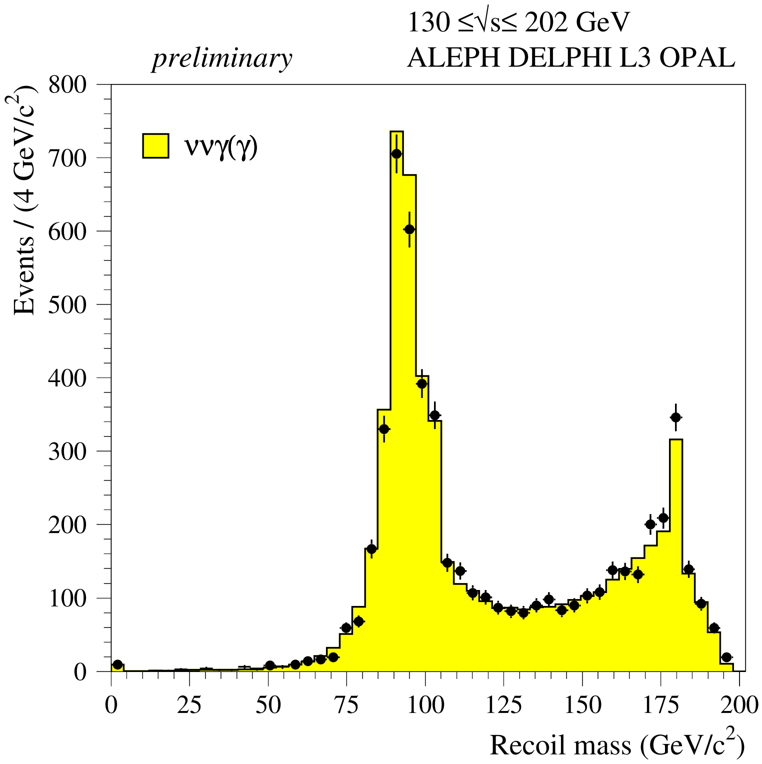
- indirect searches
  - $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^*$
    $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{G}\tilde{G}\gamma\gamma$+2W decay prod.
  - $\tilde{l} \rightarrow l\tilde{\chi}_1^0$
    $e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow \tilde{G}\tilde{G}\gamma\gamma l^+l^-$
  - $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$
    $e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$+Z decay products
  - photon tag provide high efficiency

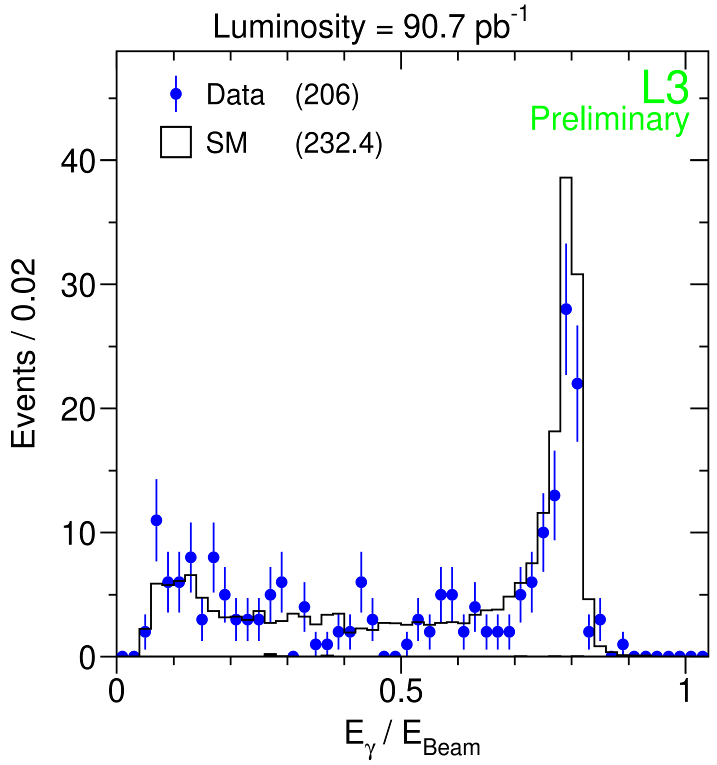
GMSB single photon

$$e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$$

LEP SUSY working group

ADLO combined





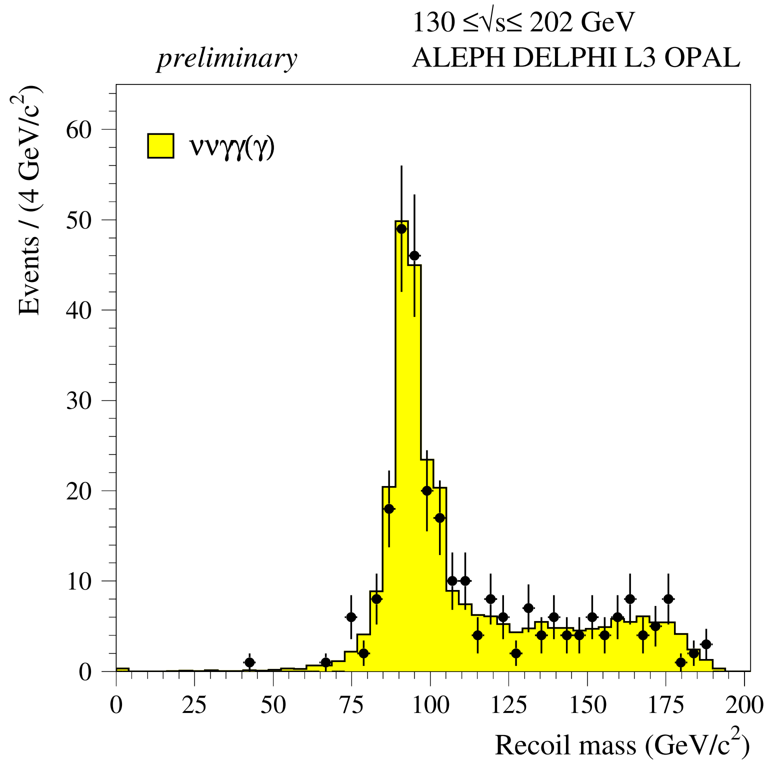
L3

update

$\sqrt{s} \sim$ **205 GeV**

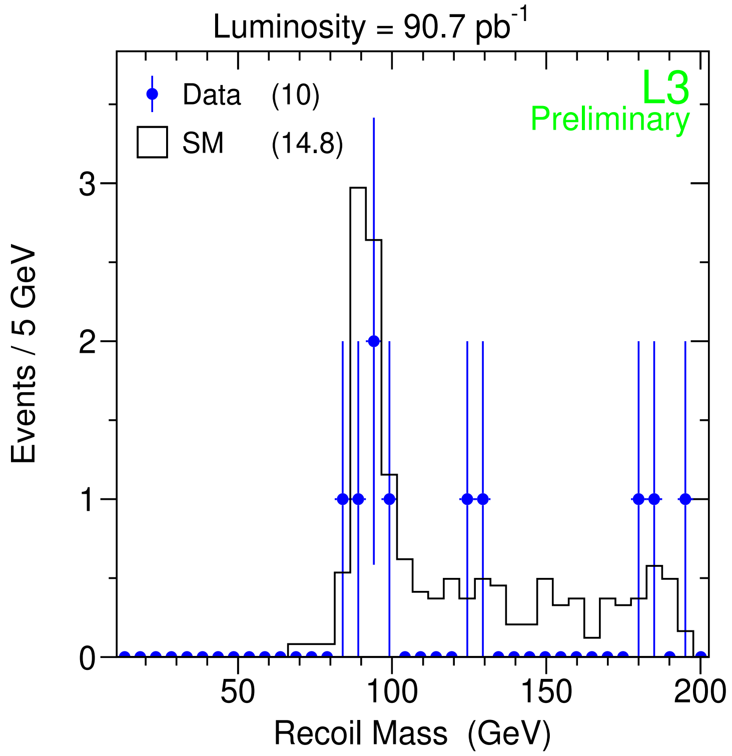
GMSB two photon

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma\gamma$$



LEP SUSY working group

ADLO combined



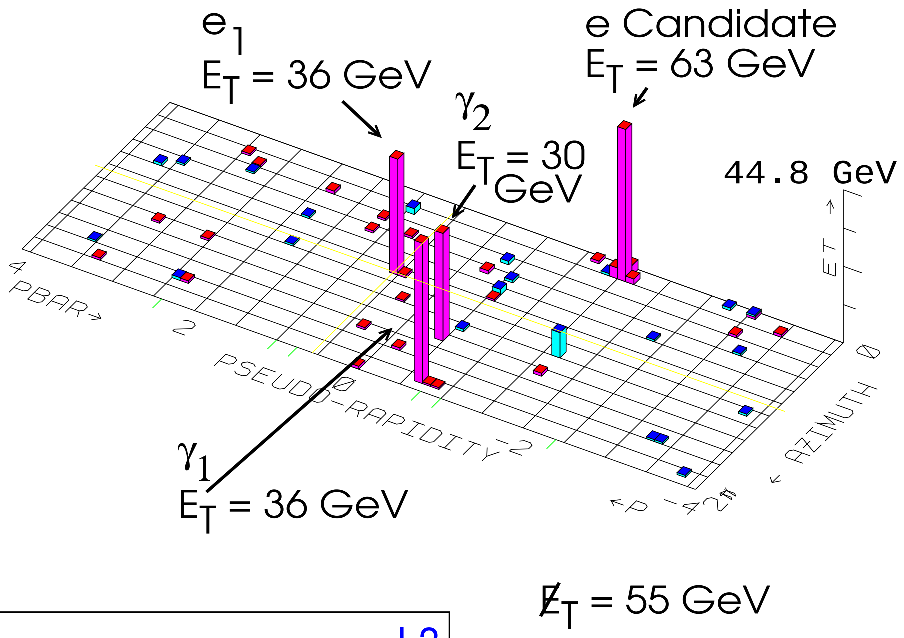
L3

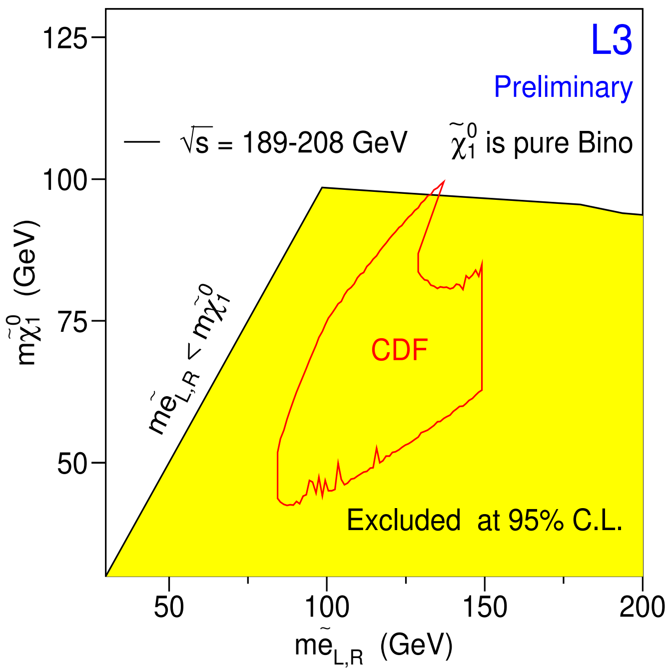
update

$\sqrt{s} \sim$ **205 GeV**

CDF event

- two energetic photons + two energetic leptons + missing energy, very low SM expectation
- can be explained by GMSB models
  $q\bar{q} \to \tilde{e}\tilde{e} \to ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ee\gamma\gamma\tilde{G}\tilde{G}$





L3

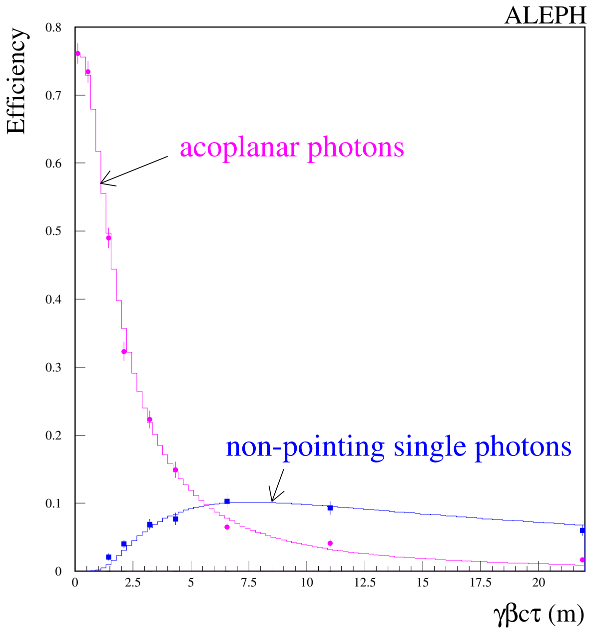
comparison with CDF event

GMSB non-zero lifetime

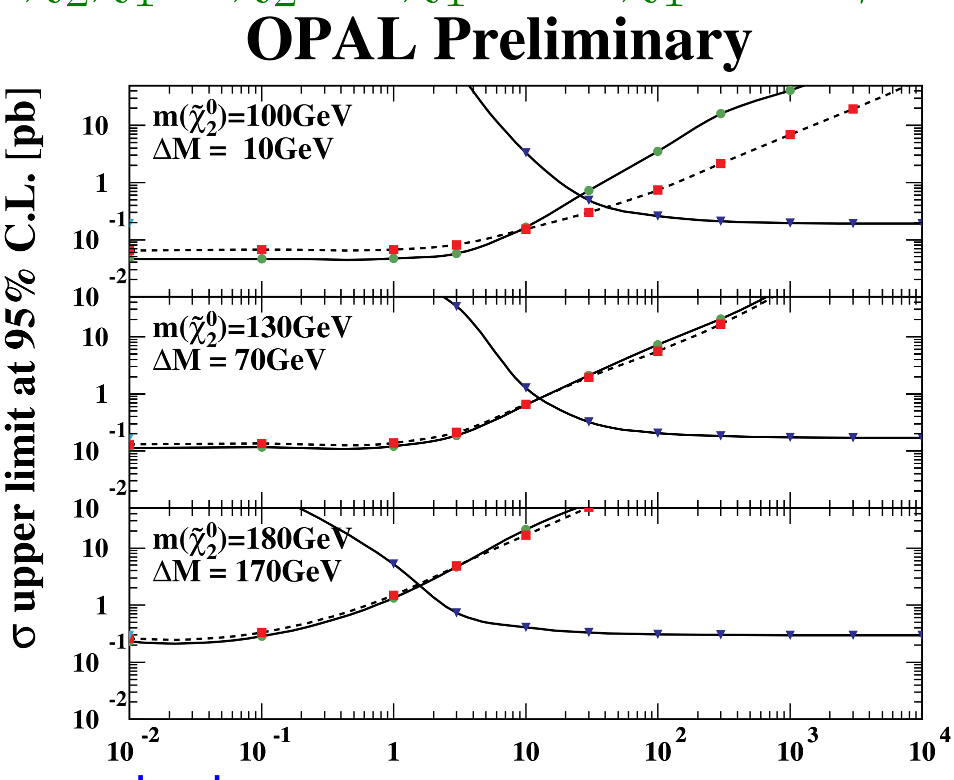
$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma\gamma$$

ALEPH

photon with large impact parameter

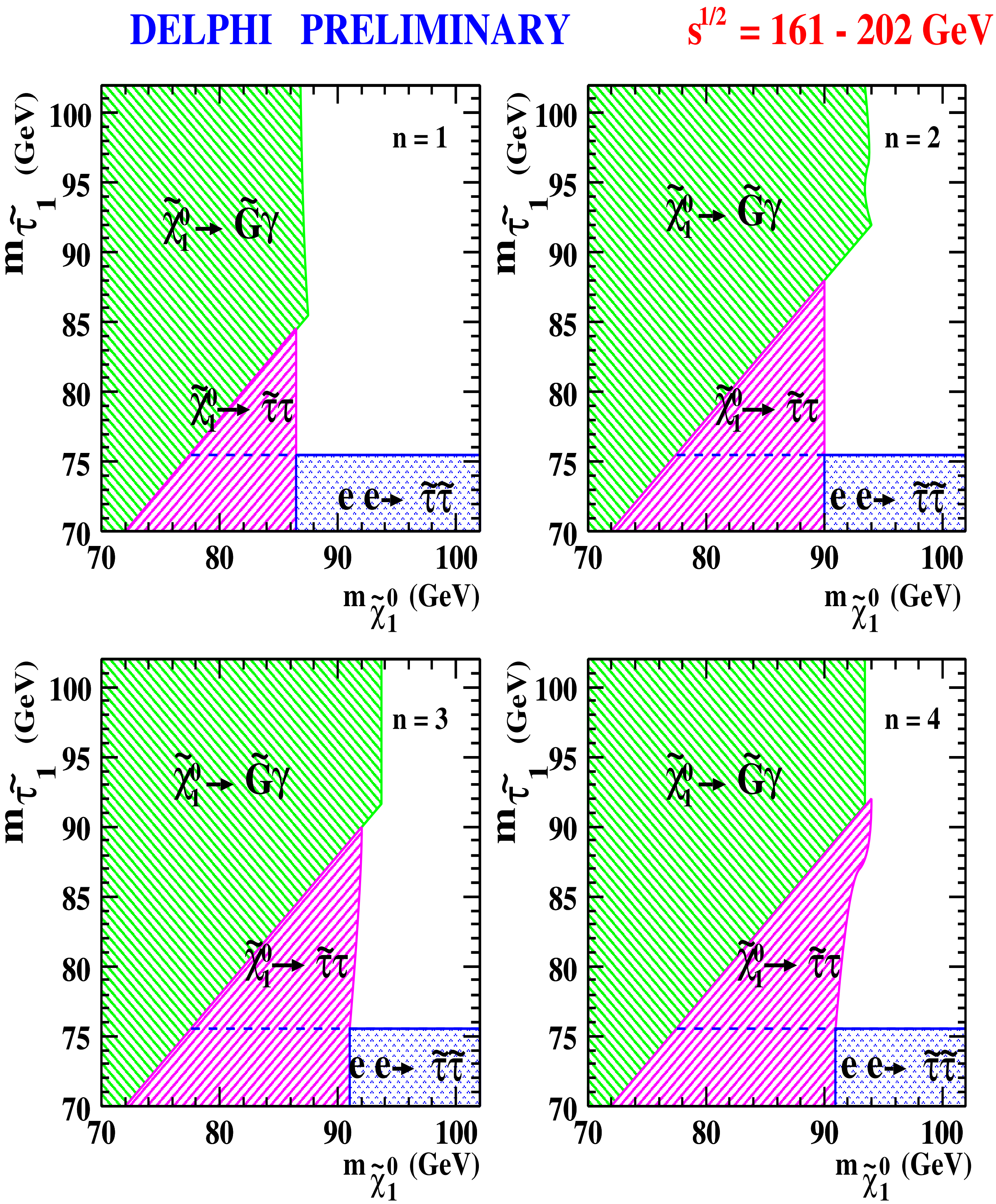


$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^* \quad \tilde{\chi}_1^0 \to \tilde{G}\gamma$$



OPAL cascade decay

GMSB interpretation



Conclusions

- SUSY searches in various scenarios have been performed by the 4 LEP experiments
  - MSSM
  - R-parity violation
  - GMSB models

- No evidence for SUSY particle production has been found

- New limits have been set on sparticle masses and SUSY parameters for all scenarios