Search for SUperSYmmetric Particles at LEP2

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- Introduction
- Chargino Neutralino and Sleptons
- Stop and Sbottom
- R-parity Violation
- Photons and Missing Energy
- Conclusion

SUPERSYMMETRY

Minimal Gauge Group and Minimal Particle Content

Particle	S–particle	Name
Fermions	Bosons	
$\ell = e, \mu, \tau, \nu$	$\tilde{\ell}_R, \tilde{\ell}_L$	slepton
$q = u, d, s, c, b, t$	$\tilde{q}_R, \tilde{q}_L$	squark
Bosons	Fermions	
g	$\tilde{g}$	gluino
γ	$\tilde{\gamma}$	photino
$W^{\pm}$	$\tilde{W}^{\pm}$	wino
Z	$\tilde{Z}$	zino
H_1°, H_2°	$\tilde{H}_1^{\circ}, \tilde{H}_2^{\circ}$	higgsino
$H^{\pm}$	$\tilde{H}^{\pm}$	higgsino
G	$\tilde{G}$	gravitino

Gaugino and Higgsino mix to form mass eigenstates
Charginos: $\tilde{\chi}^{\pm}_{1,2}$ Neutralinos: $\tilde{\chi}^{\circ}_{1,2,3,4}$

Minimal Supersymmetric Standard Model

- **MSSM parameters**

m_A	$\tan\beta$		
μ	A_t	A_b	mixing parameters (higgs,stop,sbottom)
M_1	M_2	M_3	gaugino mass parameters
$M_{\tilde{l}}$	$M_{\tilde{q}}$		slepton squark mass
$\ldots$			

- **Constrained MSSM**
  - M_1, M_2, M_3 unification at GUT scale $\Rightarrow m_{\frac{1}{2}}$
  - Scalar particle masses unification at GUT scale $\Rightarrow m_0$
    Scalar masses and gaugino masses are related
    (ex. $m_{\tilde{l}_R} = m_0^2 + 0.15\ m_{\frac{1}{2}}^{\ 2} + \cdots$)

Five Parameters left

$$\tan\beta \quad \mu \quad m_0 \quad m_{\frac{1}{2}} \quad A_0$$

Phenomenology

Particle-Sparticle have different masses

Susy must be broken

$\Rightarrow$ Gravity-mediated Susy Breaking (SUGRA)

- Heavy Gravitino
- Neutralino is the Lightest Susy Particle (LSP)

$\Rightarrow$ Gauge-Mediated Susy Breaking (GMSB)

- Gravitino (almost massless) is LSP
- Next-to-LSP $\tilde{\chi}^0_1 \rightarrow \tilde{\mathrm{G}}\gamma$ or $\tilde{\tau} \rightarrow \tilde{\mathrm{G}}\tau$

$\Rightarrow$ R parity conserved:

$R_P = (-1)^{3B+L+2S}$ =+1 P / -1 $\tilde{\mathrm{P}}$

- Susy particles are produced in pairs
- Susy particles decay in Susy particles
- The LSP is stable
  Good Dark Matter candidate
- LSP escapes the detection

Missing Momentum and Energy

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

Searches and Data Samples

- Susy R-parity conserved
- Susy R-Parity violated
- GMSB

Data Samples
Four LEP Experiments
ADLO

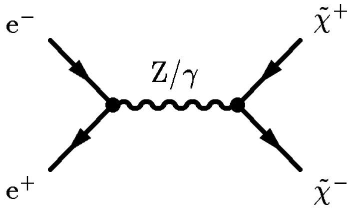
Year	$\sqrt{s}$	$\int \mathcal{L}dt$/expt
1995	130-136 GeV	6 pb^{-1}
1996	161-172 GeV	20 pb^{-1}
1997	181-184 GeV	57 pb^{-1}
1998	189 GeV	170 pb^{-1}

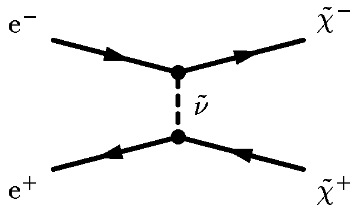
Results at 189 GeV are PRELIMINARY

SUSY Production and Decay

Chargino Production

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





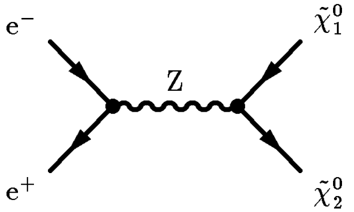
Chargino Decay

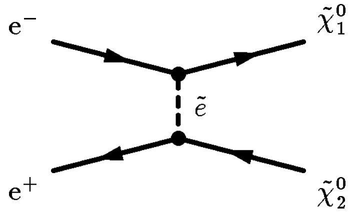
$$\tilde{\chi}_1^\pm \to \tilde{\chi}_i^0 q\bar{q}', \tilde{\chi}_i^0 l\nu$$

ll/hh/lh

Neutralino Production

$$e^+e^- \to \tilde{\chi}_i^\circ\tilde{\chi}_j^\circ$$





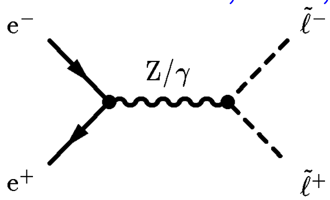
Neutralino Decay

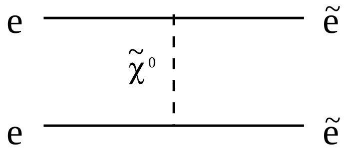
$$\tilde{\chi}_l^\circ \to \tilde{\chi}_k^\circ f\bar{f}$$

ll/hh

Slepton Production

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



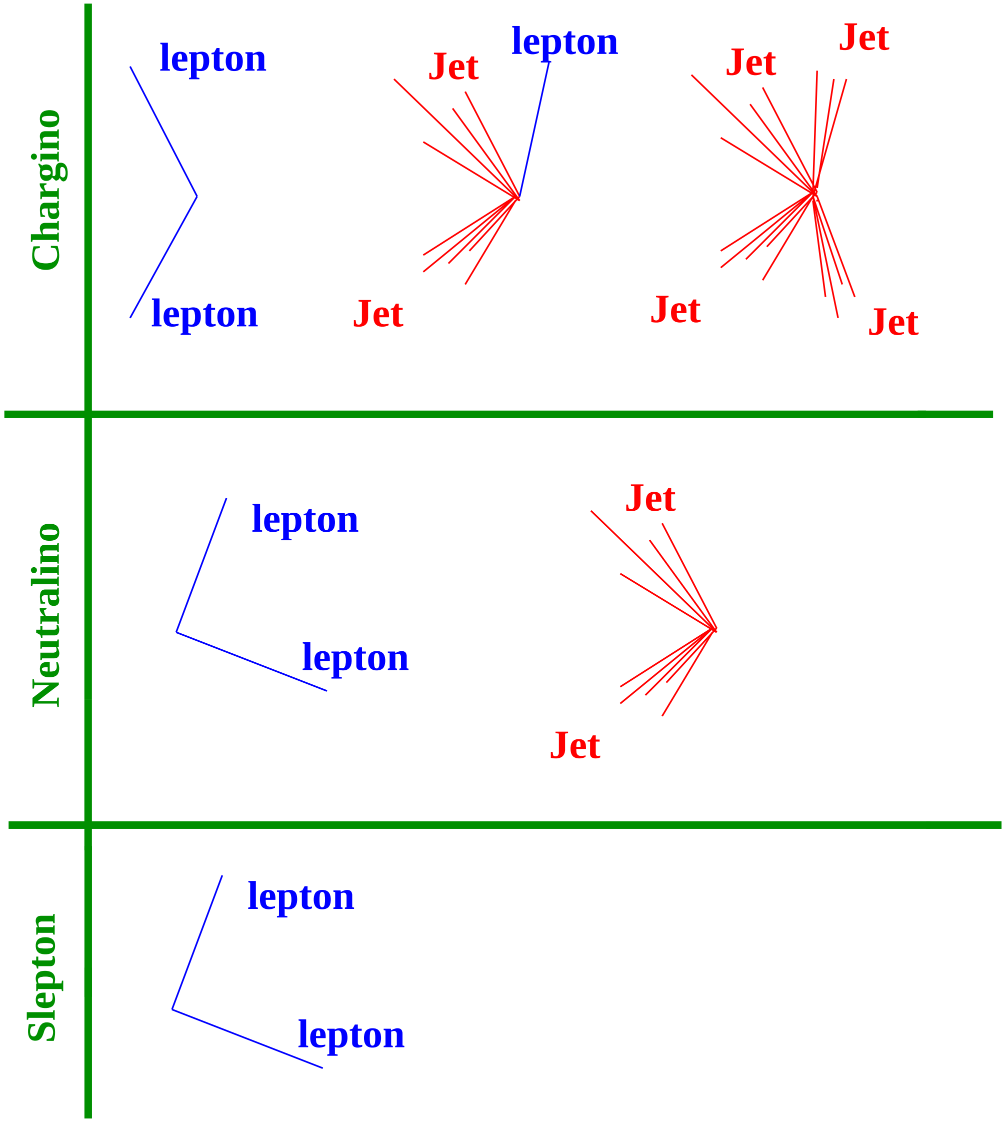


Slepton Decay

$$\tilde{\ell}^+ \to \ell^+\chi_i^\circ$$

ll

Typical SUSY Signatures

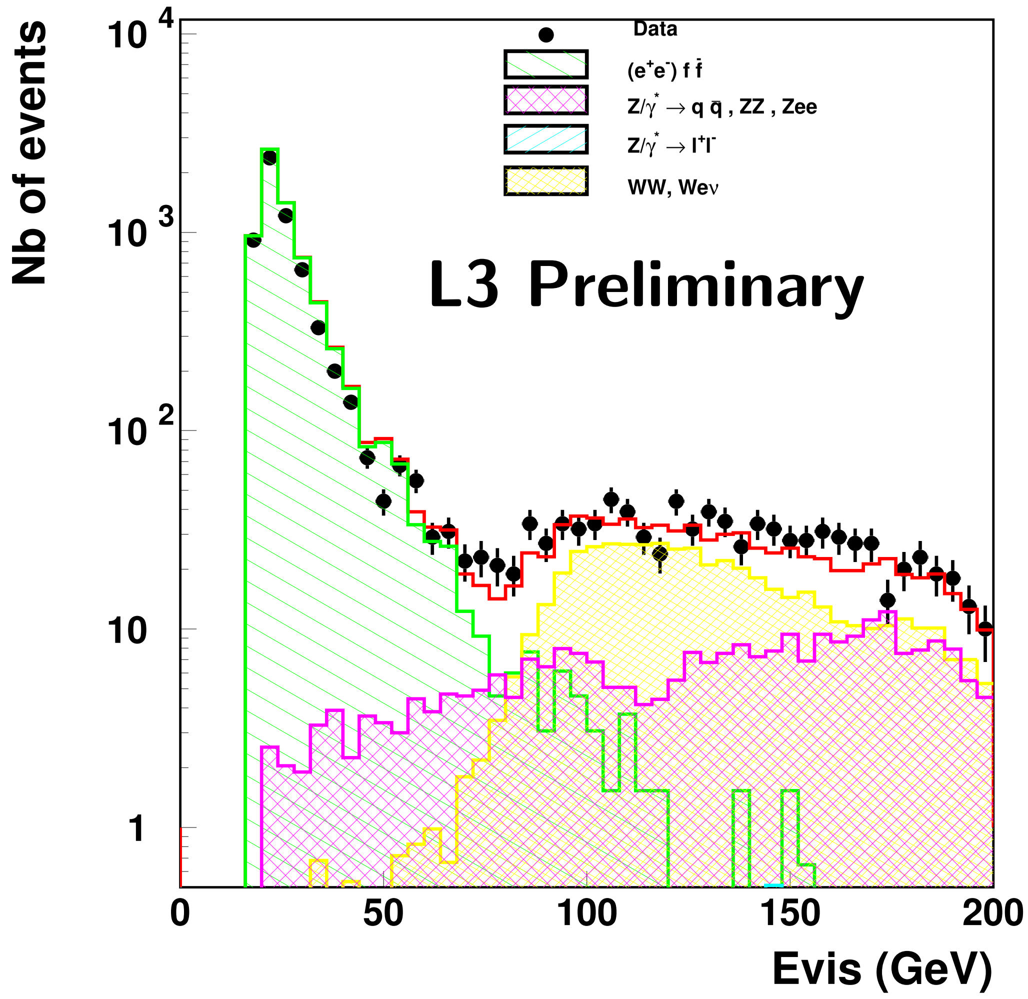


Signatures and Backgrounds

ΔM (≃ Visible Energy)	Background	Discriminating Variables
$>$50 GeV	WW ($\uparrow \sqrt{s}$) Weν ZZ	visible energy hadronic mass lepton momentum
≃ 30 GeV	Z/$\gamma^* \rightarrow f\bar{f}(\gamma)$	direction of missing momentum acoplanarity
3-10 GeV	Gamma-Gamma Physics	transverse missing momentum acoplanarity missing mass

Experimental Challenge

Hadronic channels at 189 GeV



Background cross sections

$e^+e^- f\bar{f}$	$f\bar{f}$	W^+W^-
17 nb	0.12 nb	17 pb
	ZZ	$We\nu$
	0.97 pb	2.9 pb

- Optimized analysis different ΔM

SUSY R_P Conserved

Inclusive Searches - Example: L3 at 189 GeV

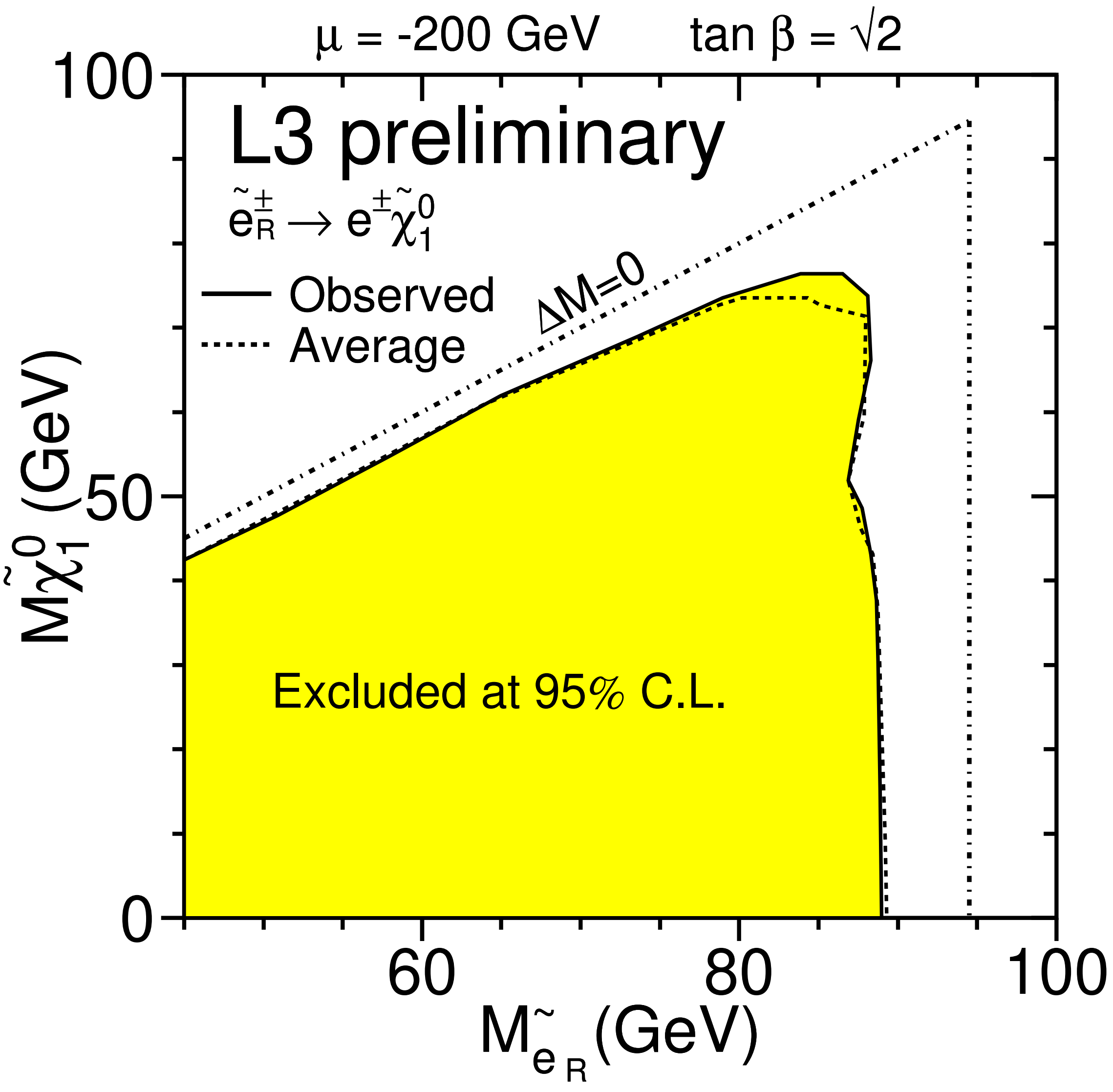
	Low ΔM		Medium ΔM		High ΔM		.OR.	
	N_{data}	N_{exp}	N_{data}	N_{exp}	N_{data}	N_{exp}	N_{data}	N_{exp}
$\tilde{\chi}^{\pm}$	11	8.51	7	3.69	7	11.1	24	22.1
$\tilde{\mathrm{e}}$	0	2.19	1	0.60	4	3.44	5	6.04
$\tilde{\mu}$	2	0.50	2	0.71	5	4.77	7	5.48
$\tilde{\tau}$	6	1.51	4	3.46	3	5.50	11	7.60
.OR.	17	12.4	11	6.94	15	19.8	38	34.4

No Excess

- Limits on production cross sections
- Limits on masses in MSSM framework

Selectron - L3

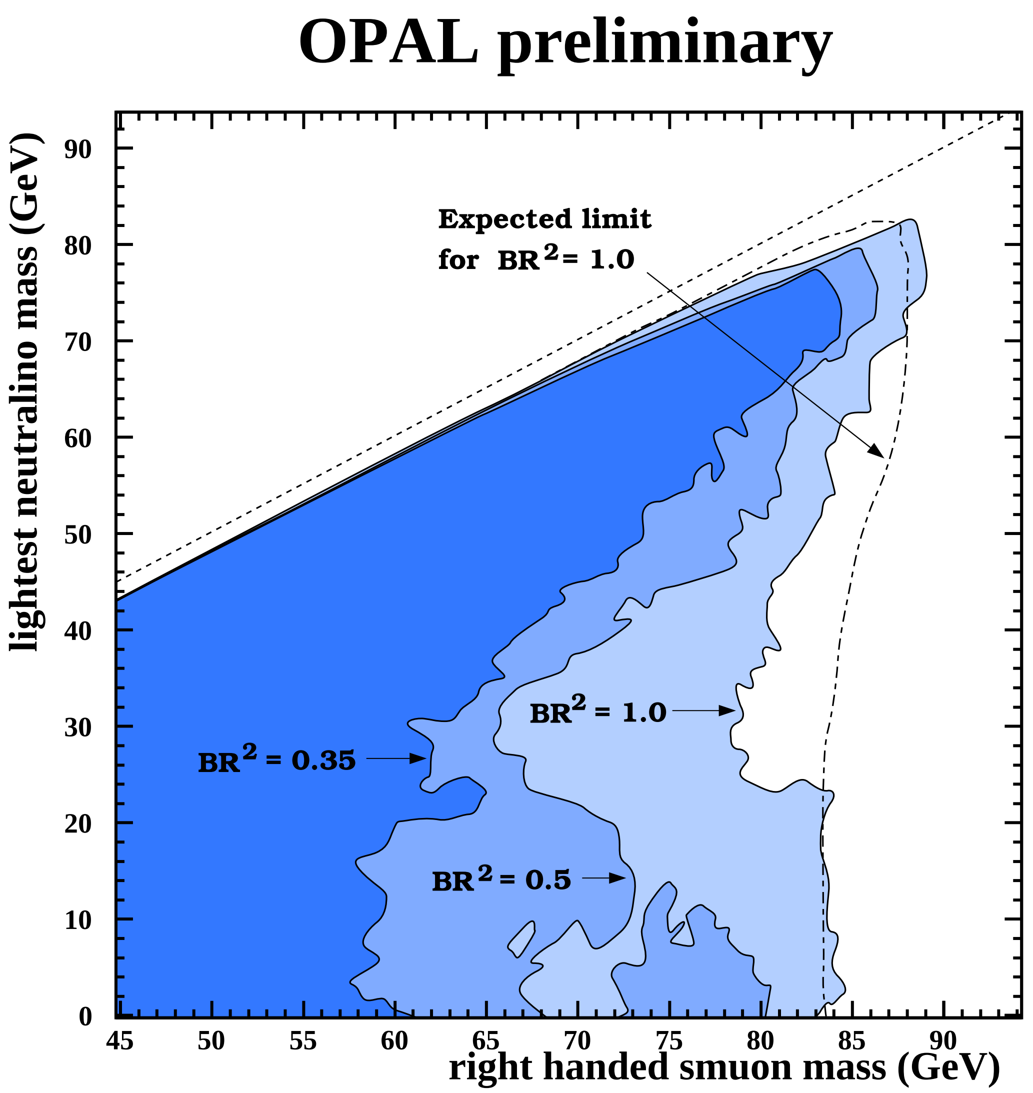
Excluded regions in $(M_{\tilde{\chi}^0_1}, M_{\tilde{\ell}})$ plane



$M_{\tilde{e}_R} > 87$ **GeV**

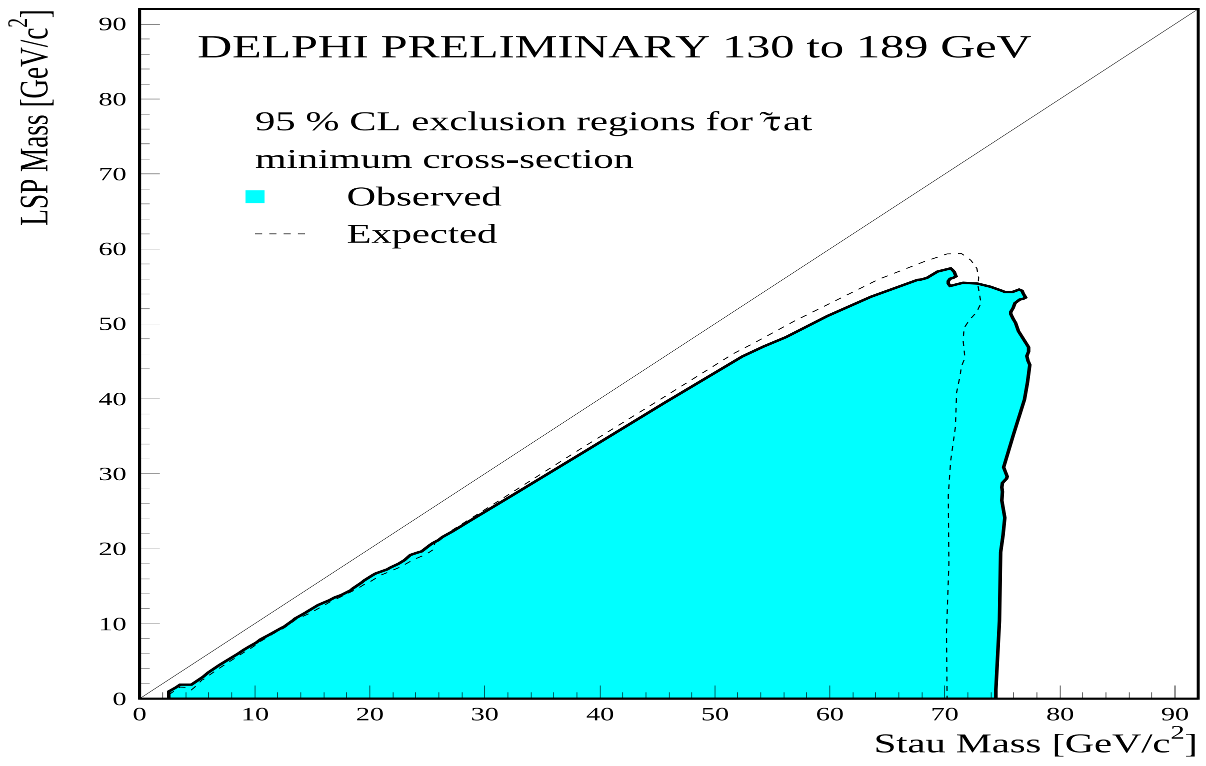
Smuon - OPAL

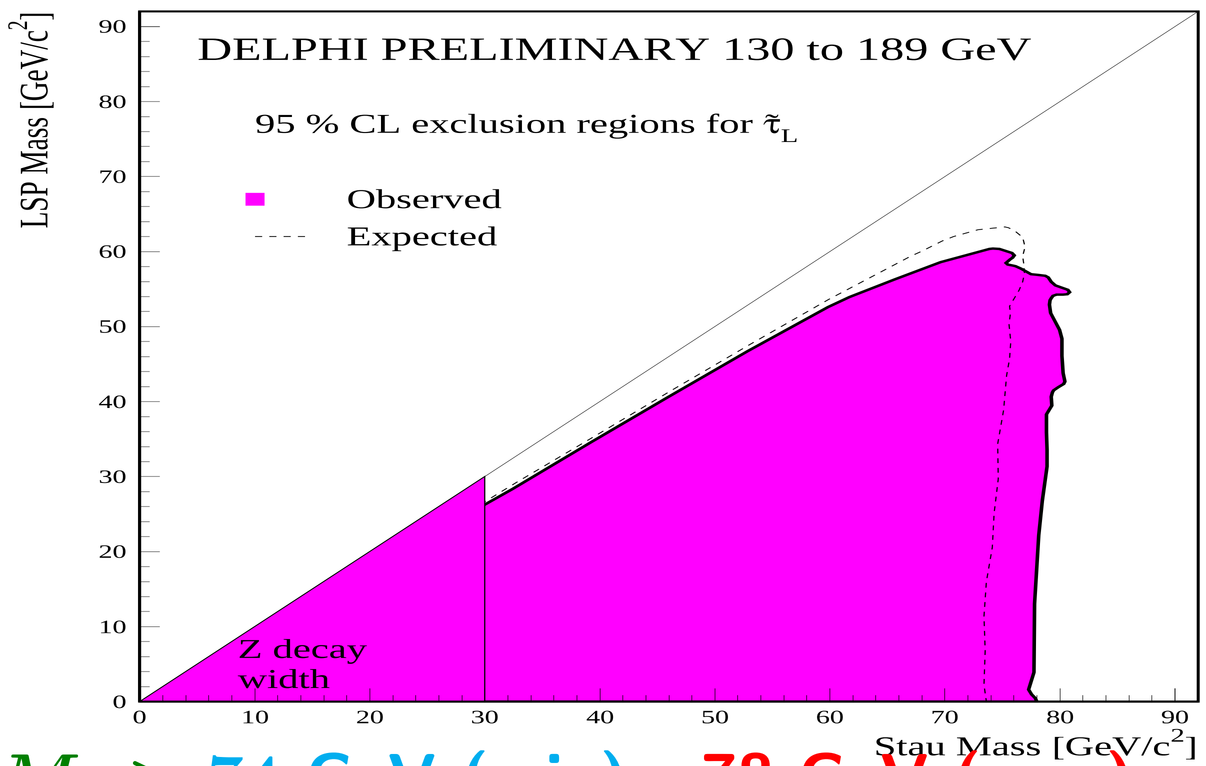
Limits as a function of branching ratio $\mathrm{BR}(\tilde{l}^{\pm} \rightarrow l^{\pm}\tilde{\chi}_1^0)$



Stau - DELPHI

Limits on Stau production





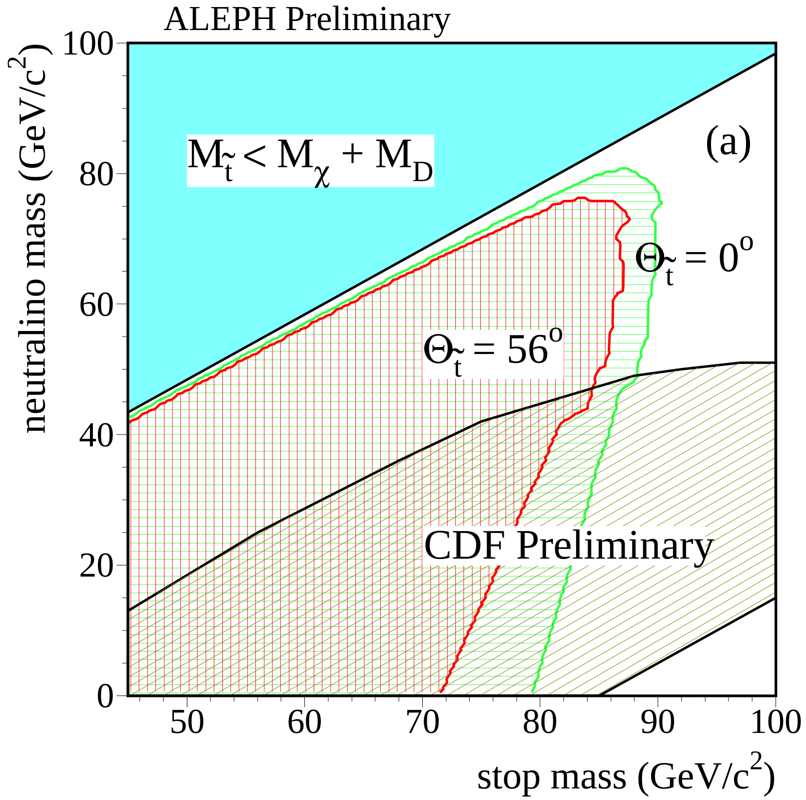
$M_{\tilde{\tau}} >$ 74 GeV (min) - 78 GeV (max)

Stop and Sbottom

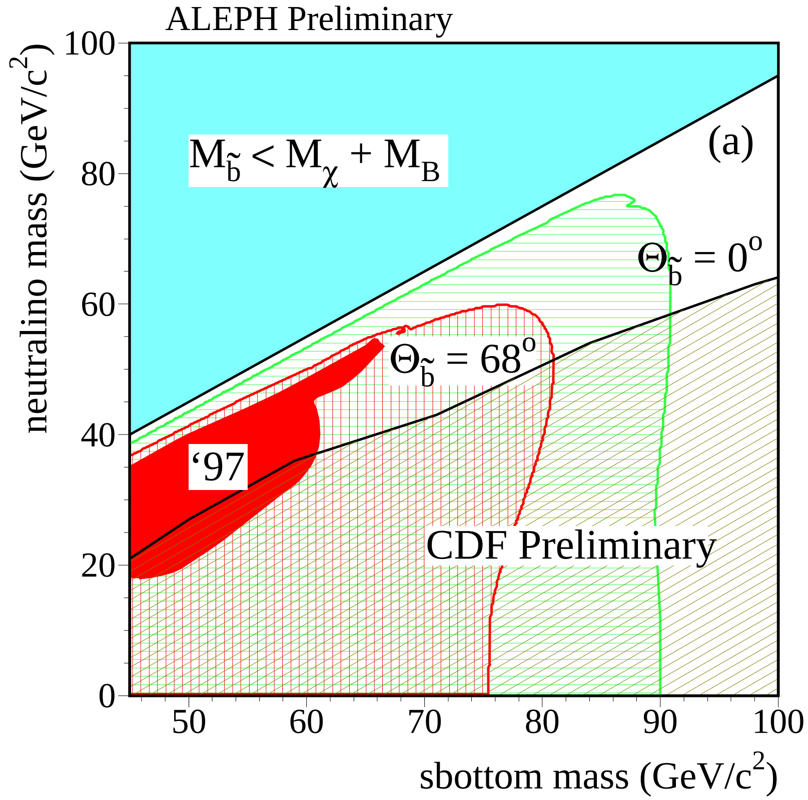
Squark masses expected to be large except for Stop and Sbottom (mixing)

- $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ $\tilde{t} \rightarrow bl\tilde{\nu}$ $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ $\Rightarrow$ **Acoplanar (c,b) jets with/without leptons**

$\tilde{t} \rightarrow c\tilde{\chi}_1^0$



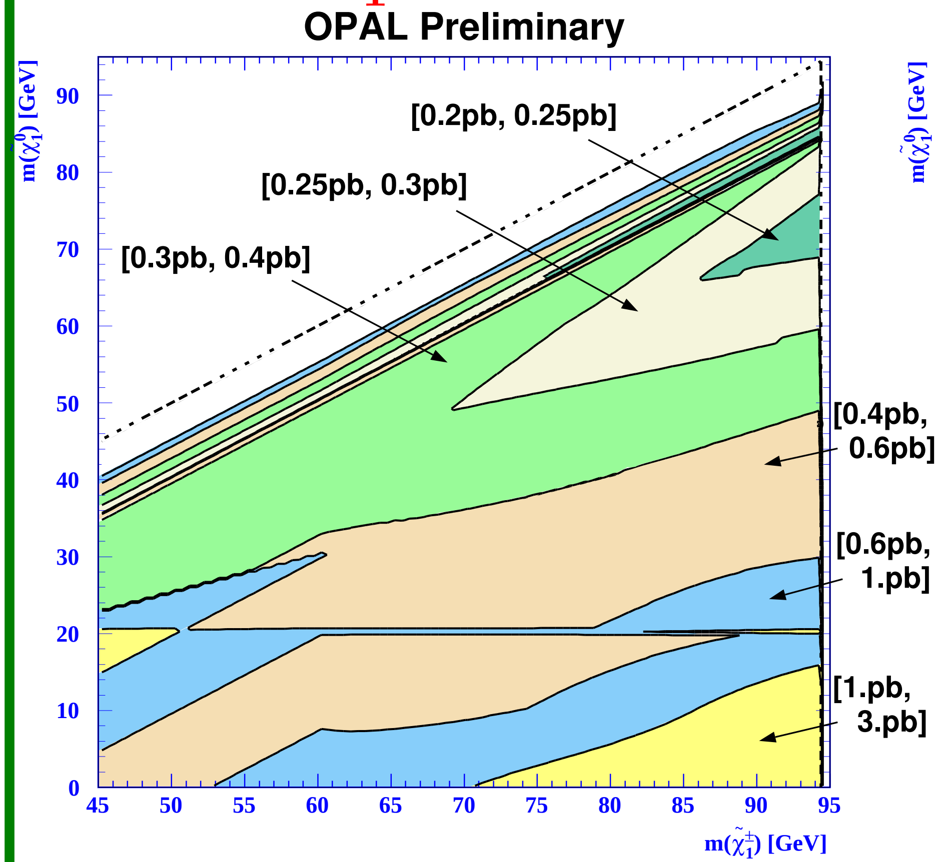
$\tilde{b} \rightarrow b\tilde{\chi}_1^0$



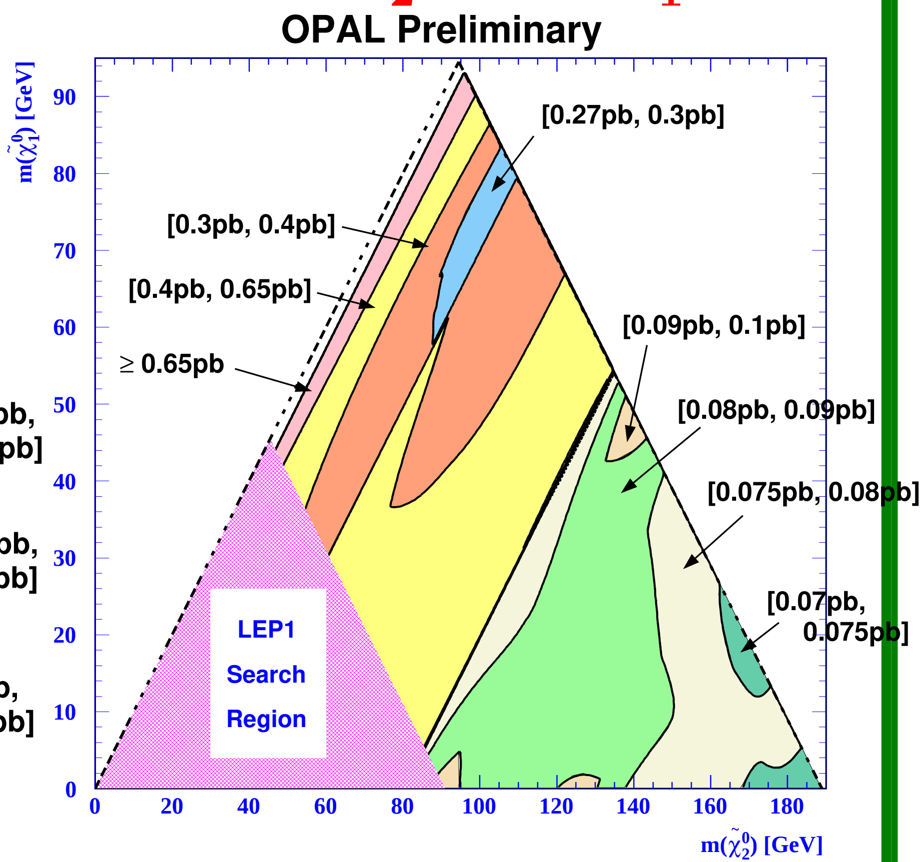
Chargino-Neutralino Searches

Limit on production cross section Assuming 100%

$\tilde{\chi}_1^+ \rightarrow W^* \tilde{\chi}^0$

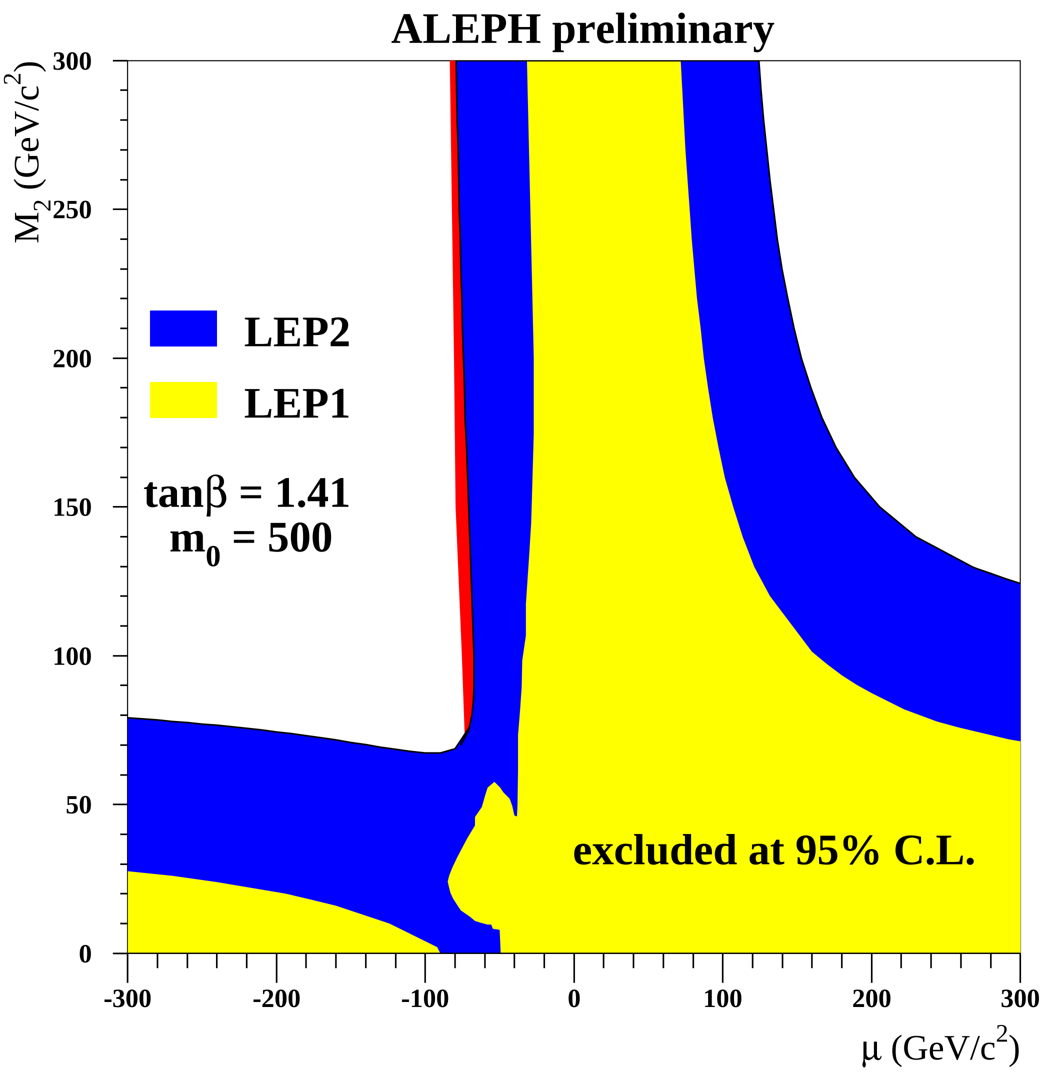


$\tilde{\chi}_2^0 \rightarrow Z^* \tilde{\chi}_1^0$



Chargino-Neutralino Searches

Limit on MSSM parameters:



Exclusion from different searches

Searches Regions

⇒Higgsino Region - $M_2 >> |\mu|$

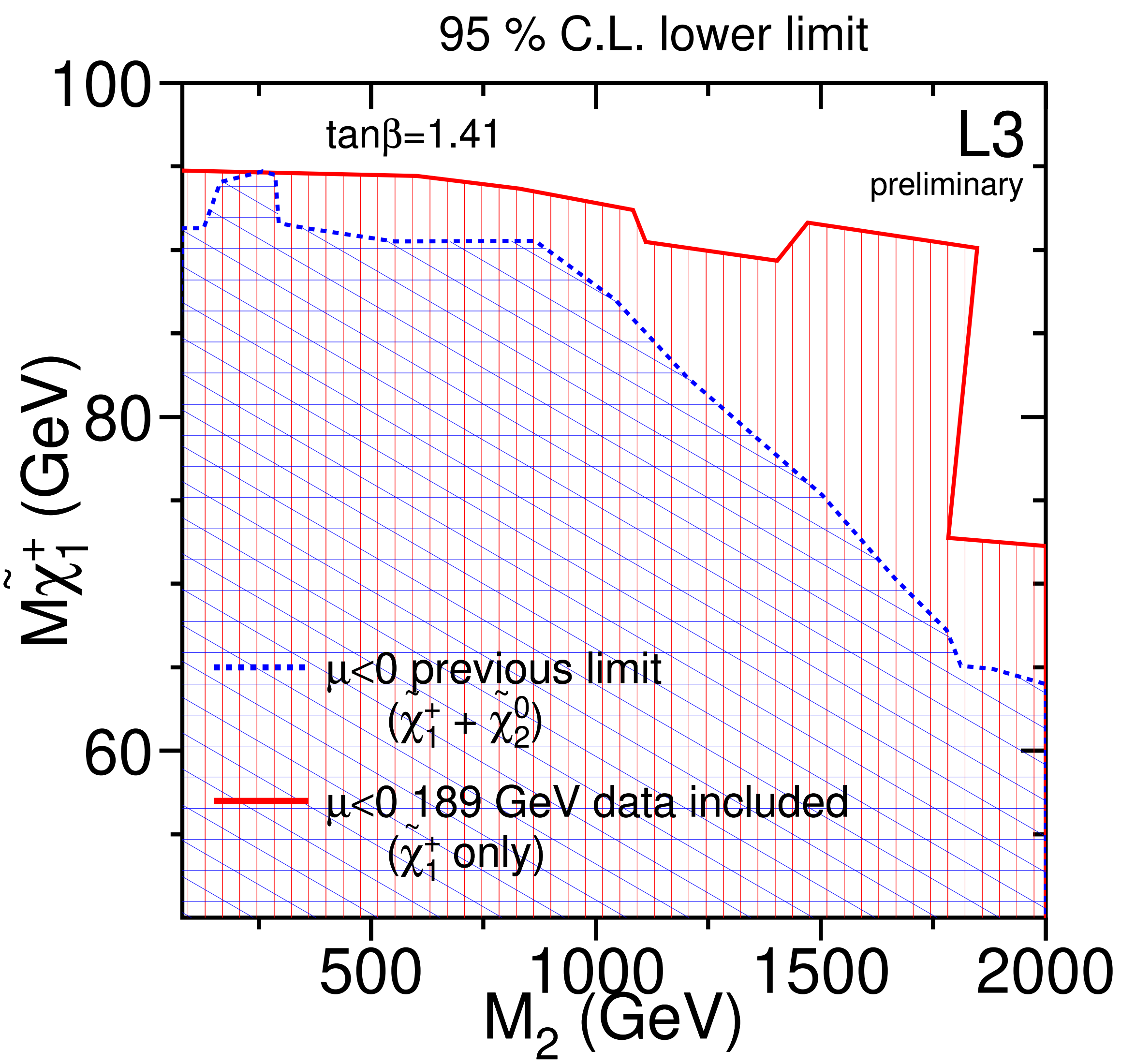
- Large Sneutrino masses
- **Contribution from Charginos and Neutralinos**

⇒Gaugino Region - $M_2 << |\mu|$

- High m_0
  - Large Sneutrino masses
  - No t-channel $\tilde{\nu}$ exchange
  - **Contribution from Charginos**
- Low m_0
  - Small Sneutrino masses
  - t-channel $\tilde{\nu}$ exchange destructive interference
  - **Contribution from Sleptons** (mainly)

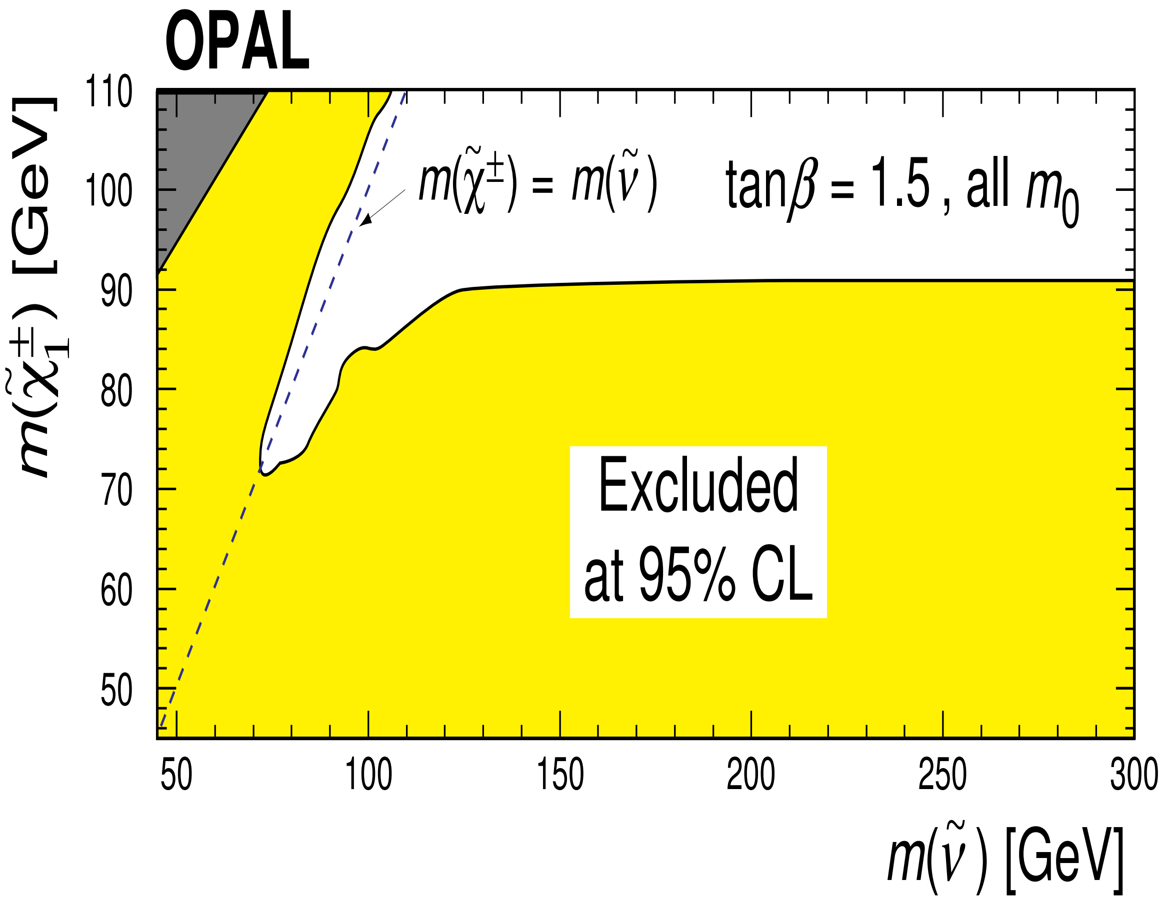
Chargino

Limit on Chargino Mass
Higgsino region
Low ΔM ($\Delta M \leq 10$ GeV $\simeq M_2 \geq 400$ GeV)



Chargino

Limit on Chargino Mass
Gaugino region - 183 GeV data



Contributions from different searches:

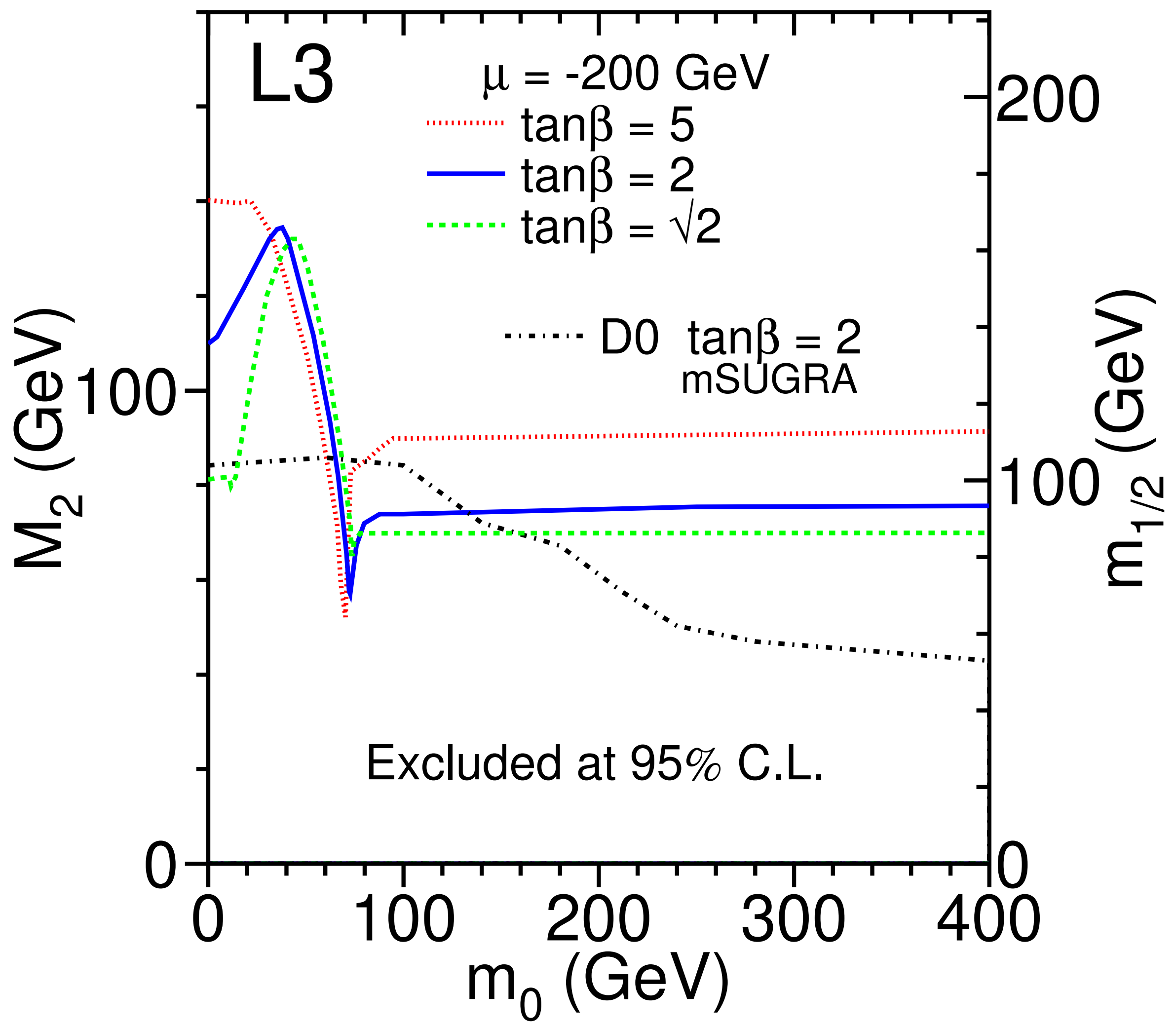
- $M_{\tilde{\nu}} > 120$ **GeV: chargino**
- $M_{\tilde{\nu}} \simeq M_{\tilde{\chi}_1^\pm}$**: sleptons**
- $M_{\tilde{\nu}} < M_{\tilde{\chi}_1^\pm}$**: sleptons and neutralino**

$M_{\tilde{\chi}_1^+} > 94.4$ GeV ($m_{\tilde{\nu}} > 300$ GeV)
using 189 GeV data

Contribution from Sleptons

Excluded domains from Chargino/Neutralino and Slepton

183 GeV data



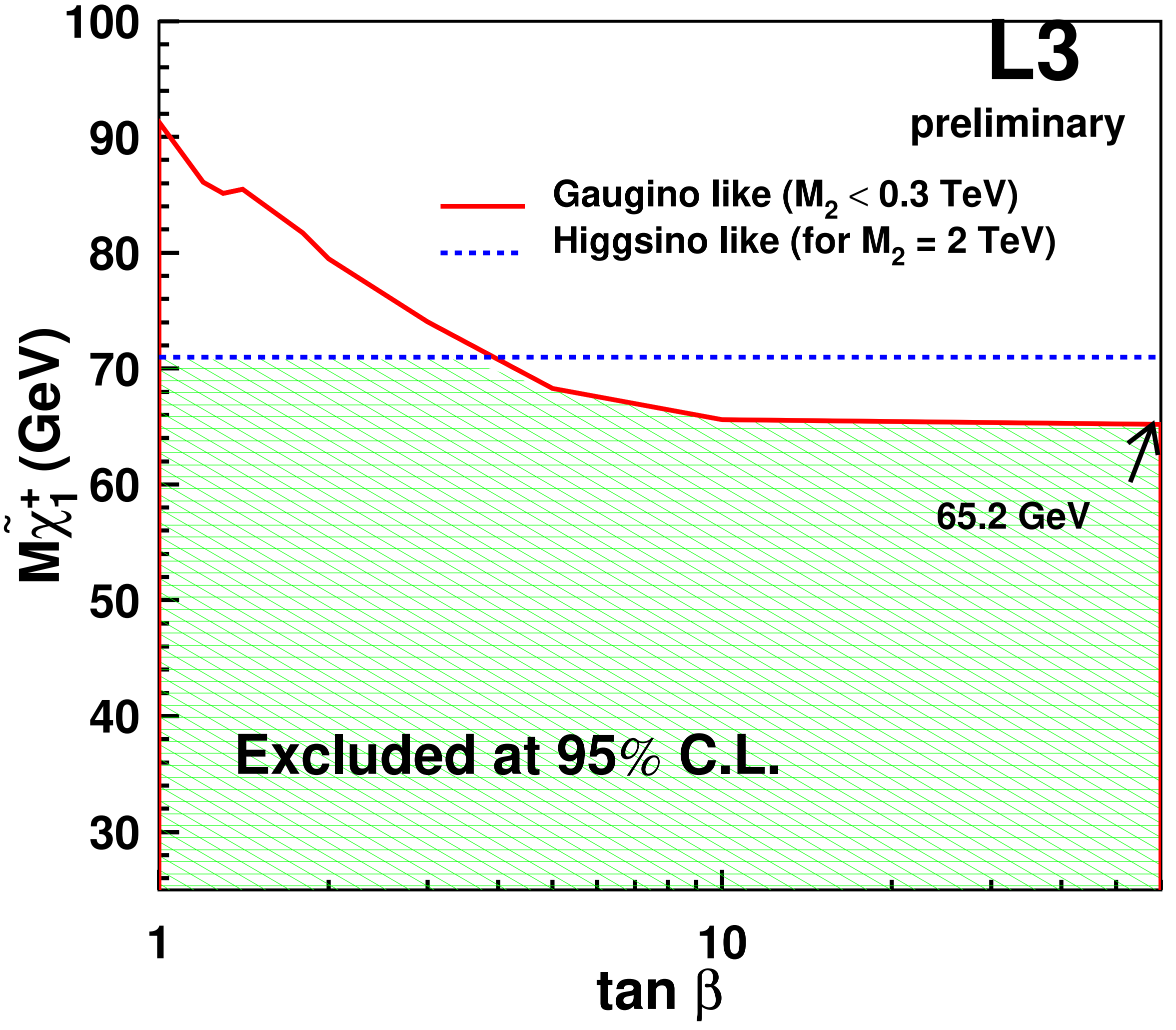
$m_0 \leq 70$ **GeV** $\Rightarrow$ **Slepton searches**

$m_0 \geq 70$ **GeV** $\Rightarrow$ **Chargino Neutralino**

Chargino: MSSM Limits

Limit on Chargino Mass
INDEPENDENT OF MSSM PARAMETERS

Include slepton searches
extend the limit for any m_0



$M_{\tilde{\chi}_1^+} > 65.2$ **GeV**

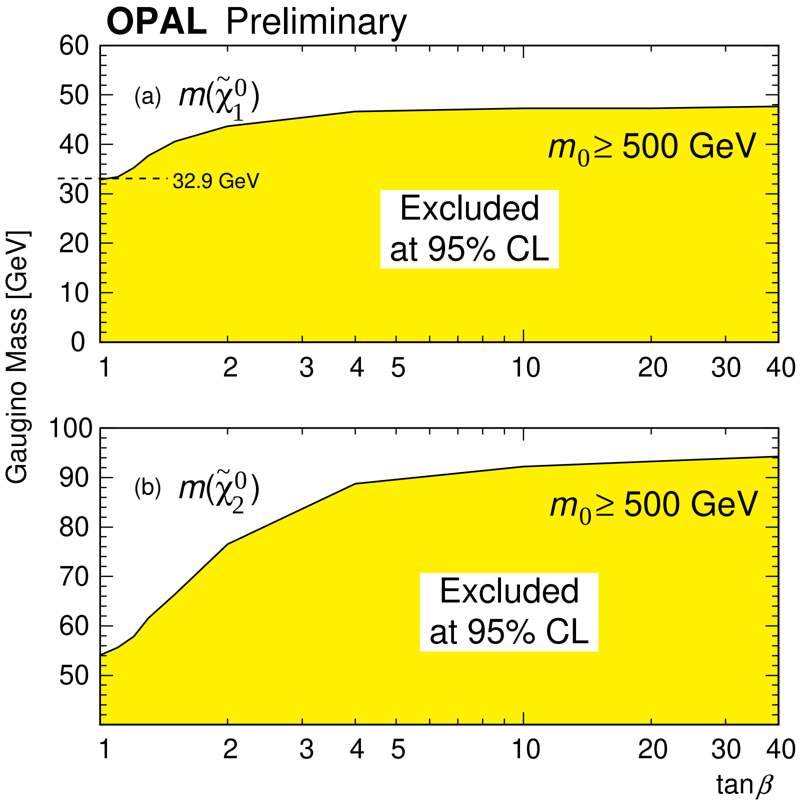
any m_0 - any $\tan\beta$

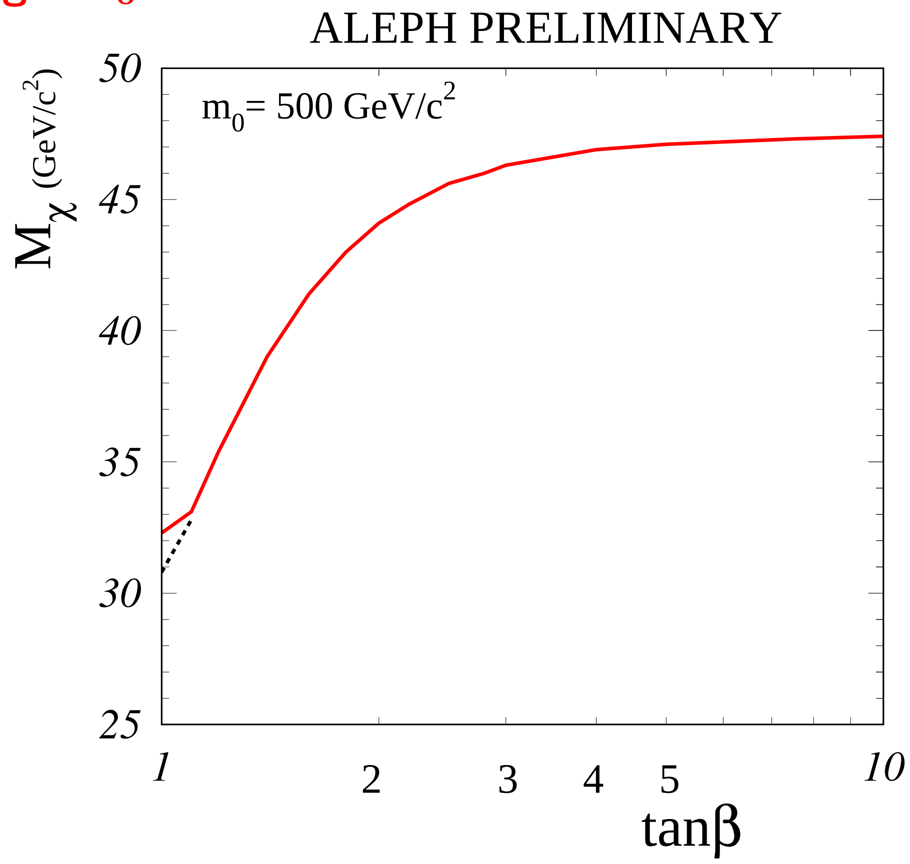
Neutralino

Limit on Lightest Neutralino Mass

Using MSSM mass relations and including $\tilde{\chi}^0_i \tilde{\chi}^0_k$ processes

Large m_0





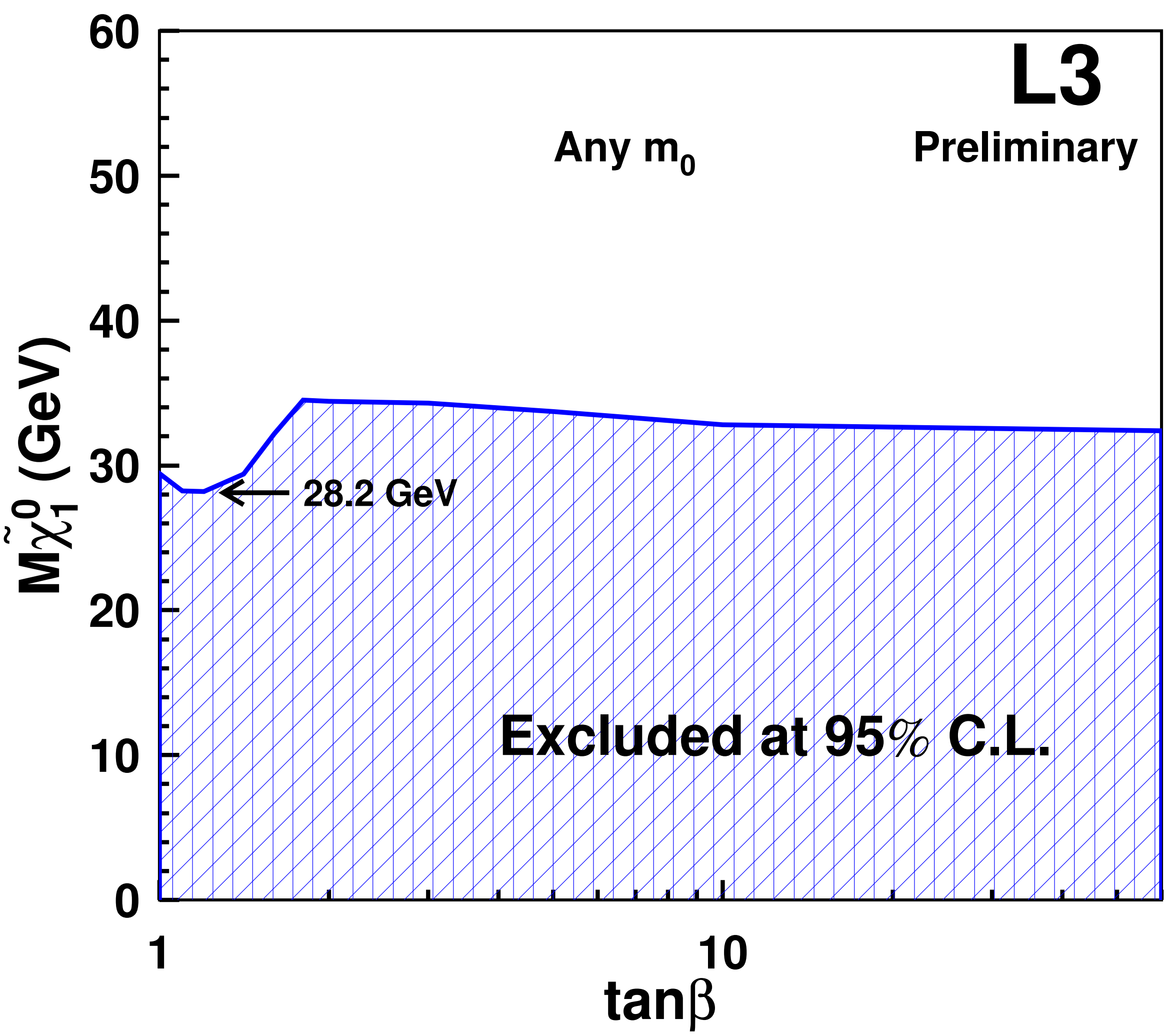
$M_{\tilde{\chi}^0_1} > 32.9$ **GeV** $\qquad$ $M_{\tilde{\chi}^0_1} > 32.3$ **GeV**

(for $m_0 \geq 500$ GeV)

Neutralino: MSSM Limits

Limit on Lightest Neutralino Mass
independent of m_0, $\tan\beta$

Combining $\tilde{l}, \tilde{\chi}^0, \tilde{\chi}_1^+$



$M_{\tilde{\chi}_1^0} > 28.2$ GeV

any m_0 - any $\tan\beta$

R-Parity Violation

SUSY with R-Parity Violation

Terms in the superpotential

$\lambda_{ijk} L_i L_j \bar{E}_k +$	9	ΔL	$\tilde{\chi}^0_1 \rightarrow l_i^- l_j^+ \nu_k$
$\lambda'_{ijk} L_i Q_j \bar{D}_k +$	27	ΔL	
$\lambda''_{ijk} \bar{U}_i \bar{U}_j \bar{D}_k$	9	ΔB	$\tilde{\chi}^0_1 \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k$

Constraint on some of the couplings to prevent fast proton decay

Consequences of R-Parity violation:

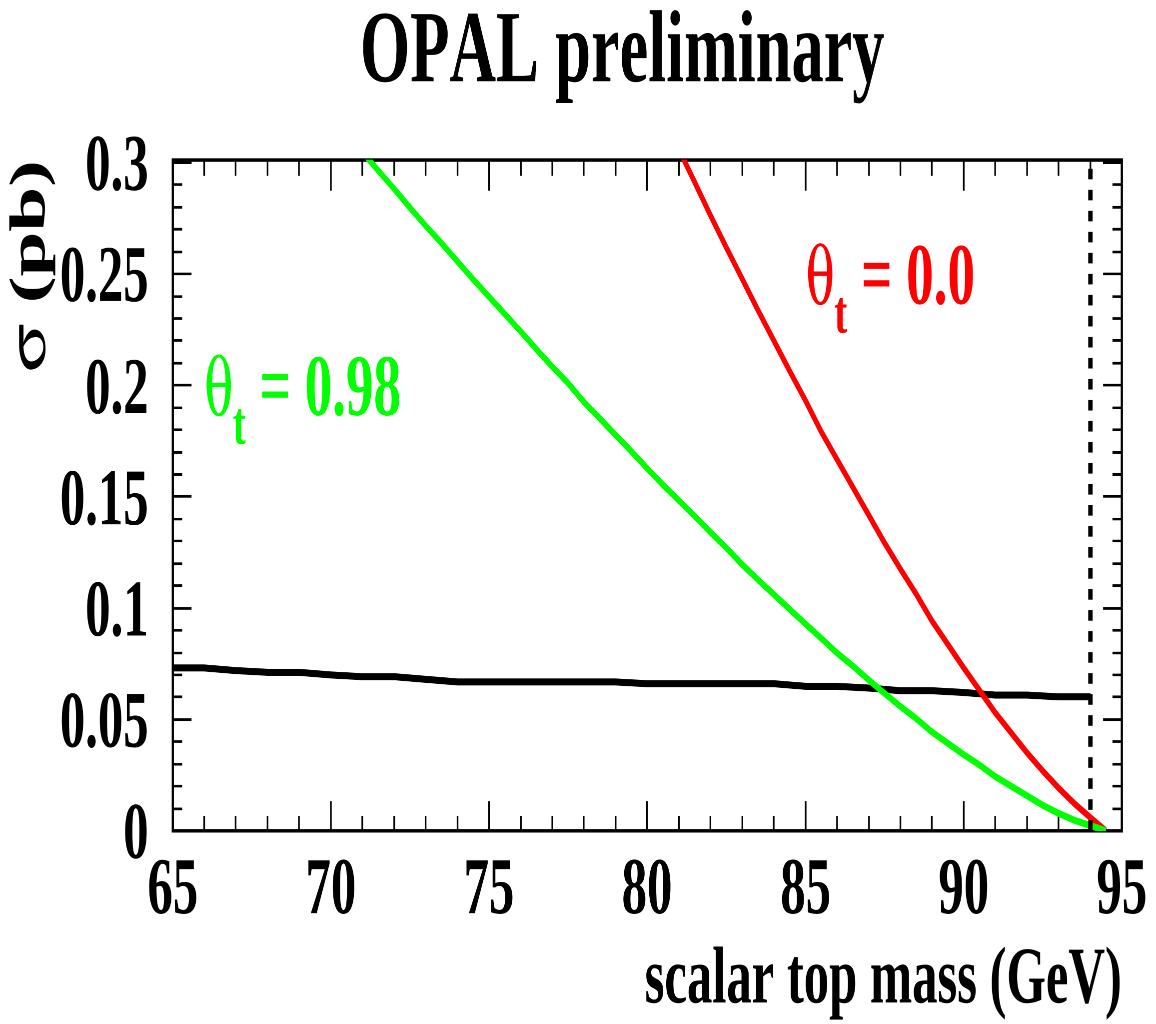
- SUSY particles can be singly produced
- LSP can decay
  - Missing energy signal replaced by large multiplicity, leptons and/or jets
  - higher sensitivity compared to R_P conserved SUSY
- A single term is generally assumed to dominate
- R_P violation searches in chargino/neutralino/slepton/squark

RPV - Stop

R-parity violating decay: $\tilde{t} \rightarrow q(e, \mu)$

Final state jet-jet-lepton-lepton

Limit on production cross section



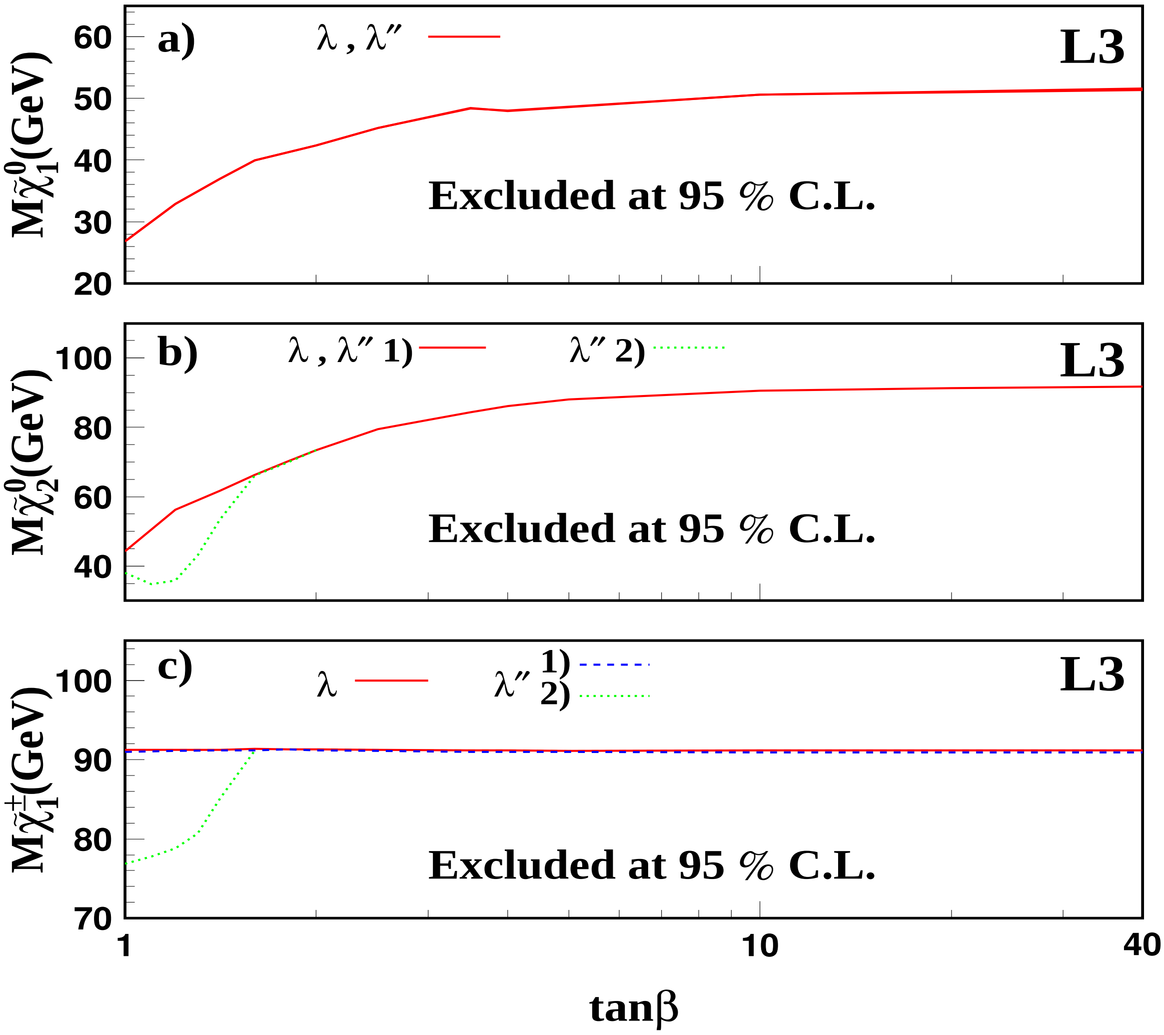
$M_{\tilde{t}} > 90.5$ **GeV** $(\theta_{\tilde{t}} = 0)$

RPV - Chargino and Neutralino

Chargino and Neutralino $\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_2^0$

Decay: $\tilde{\chi}_2^0 \to Z^*\tilde{\chi}_1^0,\ \tilde{\chi}_1^+ \to W^*\tilde{\chi}_1^0$
$\tilde{\chi}_1^0 \to f_1\tilde{f}_1 \to f_1 f_2 f_3$

183 GeV



	$M_{\tilde{\chi}_1^\pm}$	$M_{\tilde{\chi}_1^0}$
183 GeV Data	91.1 GeV	26.8 GeV
Prelim. 189 GeV Data	94.4 GeV	30.6 GeV

GMSB at LEP

Gauge Mediated Symmetry Breaking
Gravitino $\tilde{\mathrm{G}}$ is the Lightest Susy Particle

- **NLSP is $\tilde{\chi}_1^0$:**
  $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{\mathrm{G}} \quad \tilde{\mathrm{X}} \rightarrow \tilde{\chi}_1^0 X \rightarrow \gamma\tilde{\mathrm{G}} X$
  Standard topologies (Missing Energy) + Photon(s) $\rightarrow$ improved sensitivity

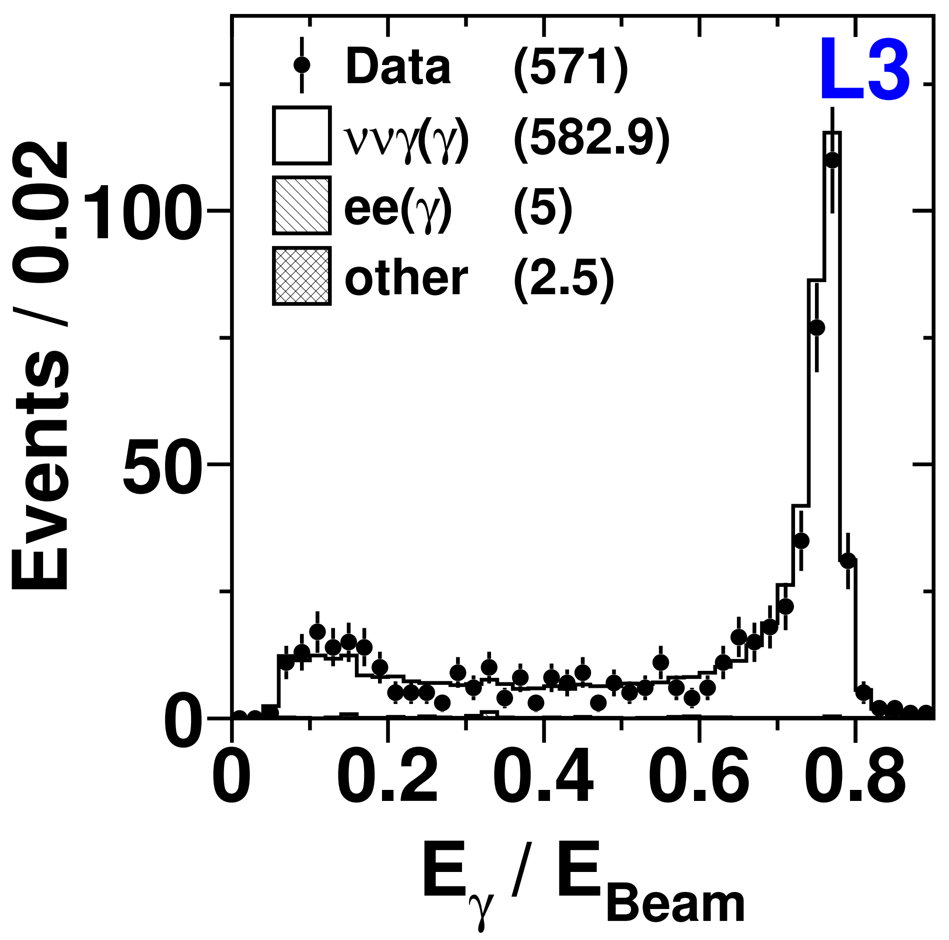
- **NLSP is $\tilde{\tau}$:**
  $\tilde{\tau} \rightarrow \tau\tilde{\mathrm{G}} \quad \tilde{\mathrm{X}} \rightarrow \tilde{\tau}(\tau, \nu_\tau) \rightarrow \tau\tilde{\mathrm{G}}(\tau, \nu_\tau)$
  High τ multiplicity

Photons and missing energy

Single photon and missing energy

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

189 GeV - PRELIMINARY

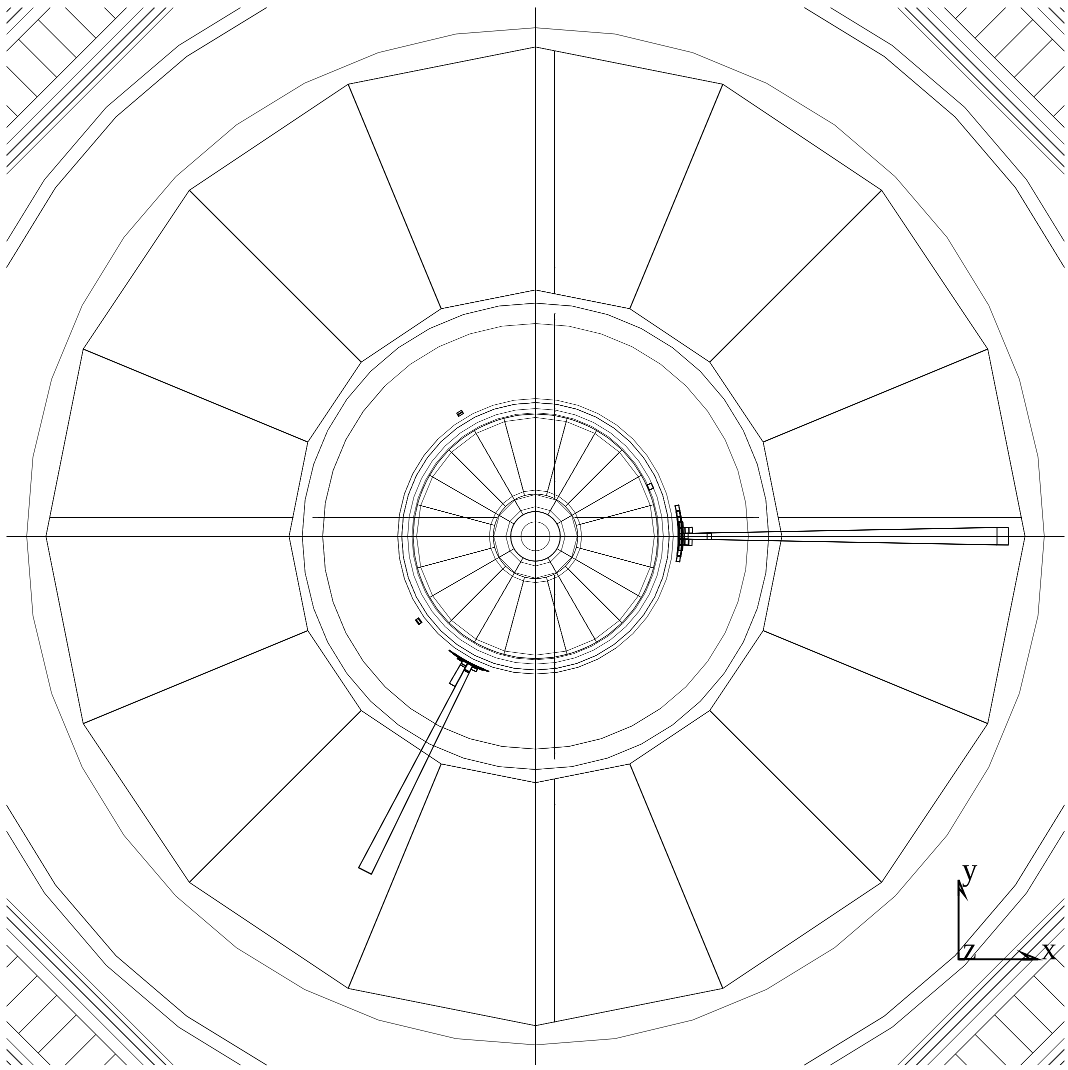


Good agreement with Standard Model

- cross section measurement $\sigma(e^+e^- \rightarrow \nu\bar{\nu}\gamma)$
- limits on new physics

Photons and missing energy

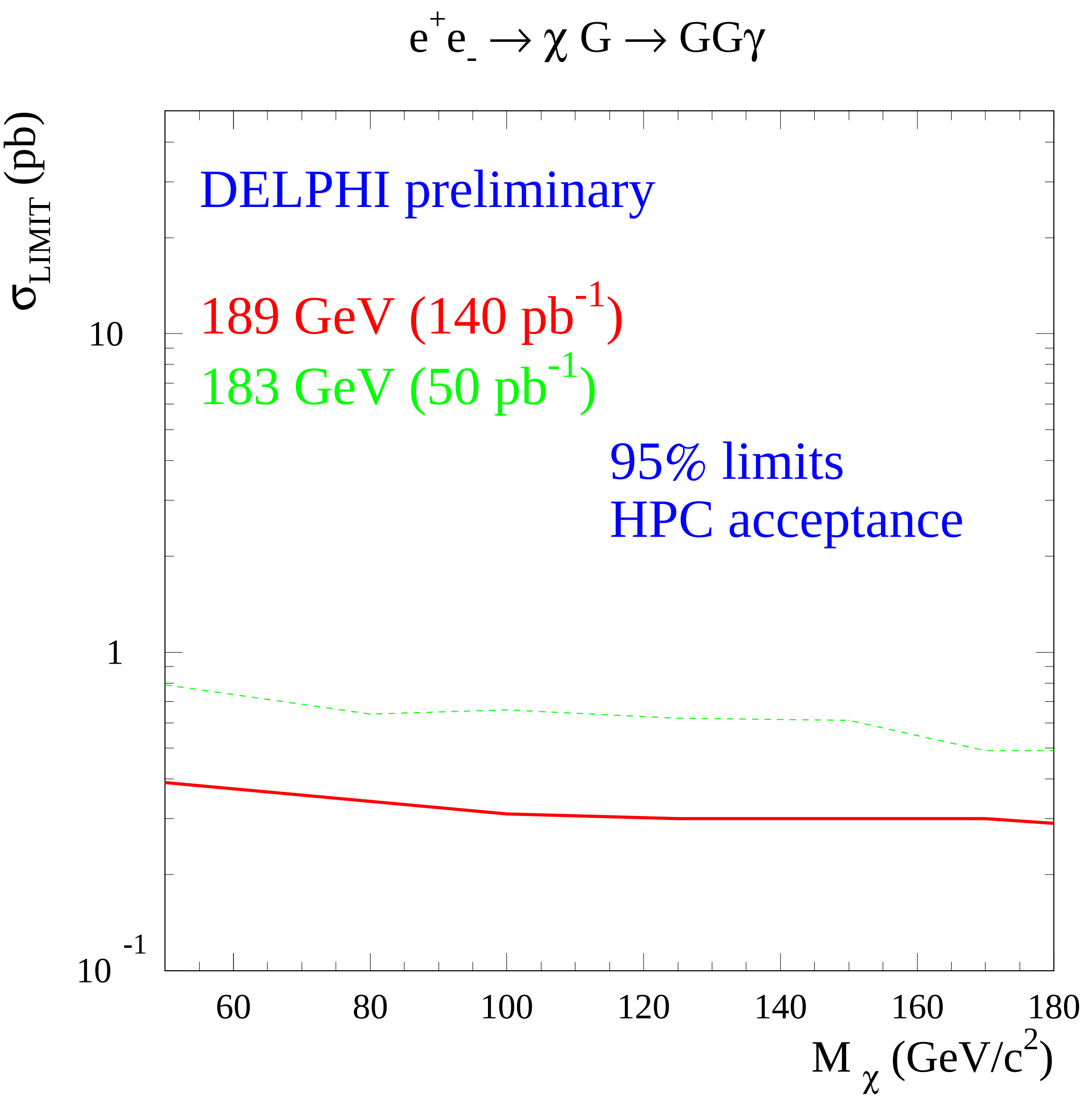
Run # 712608 Event # 2857 Total Energy : 87.75 GeV



Photons and missing energy

Single photon final states: Upper limit on cross section

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

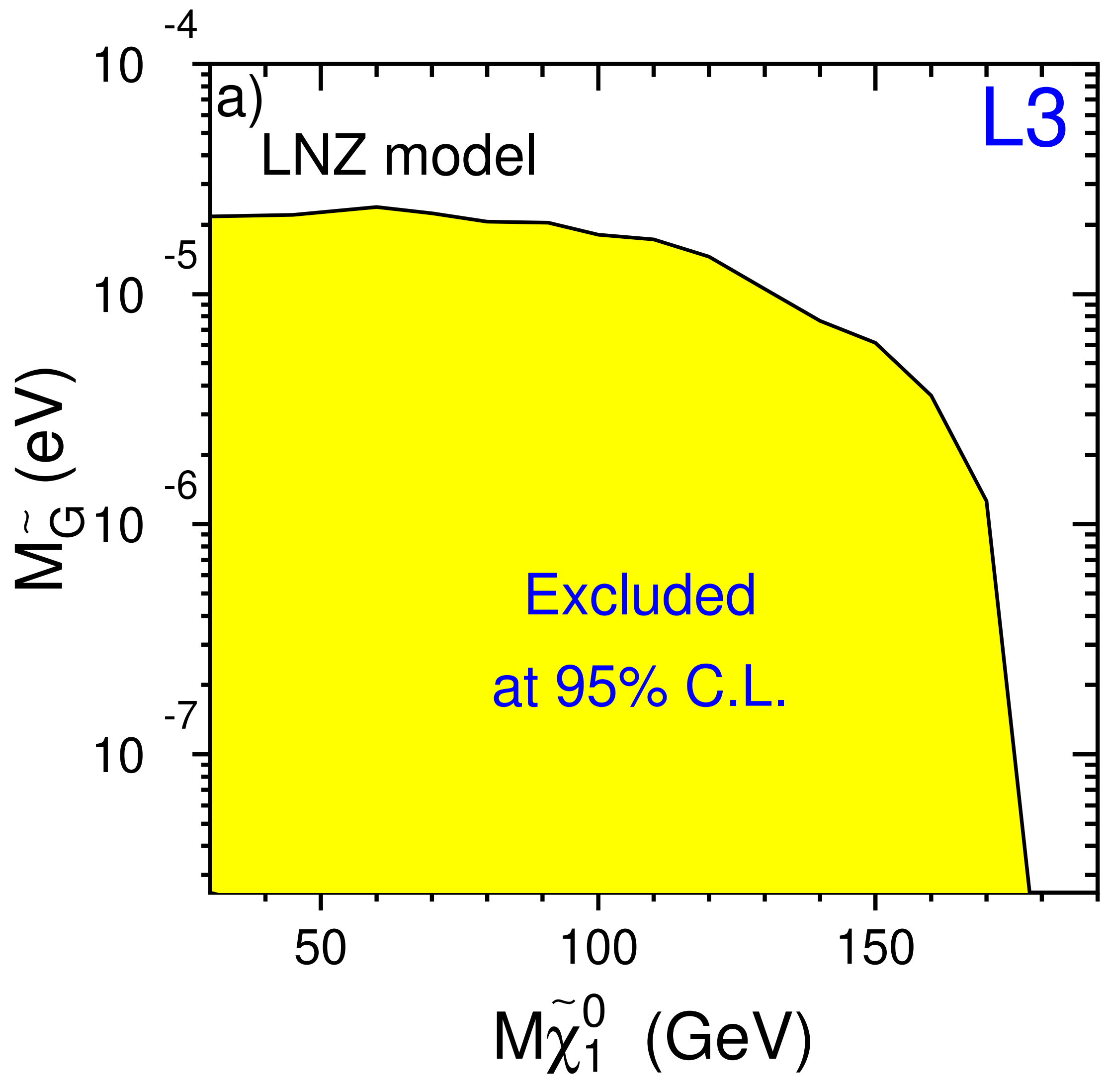


Photons and missing energy

Single photon final states

- LNZ models (no scale SUGRA)
- Superlight $\tilde{G}$ and NLSP $\tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$

183 GeV Data

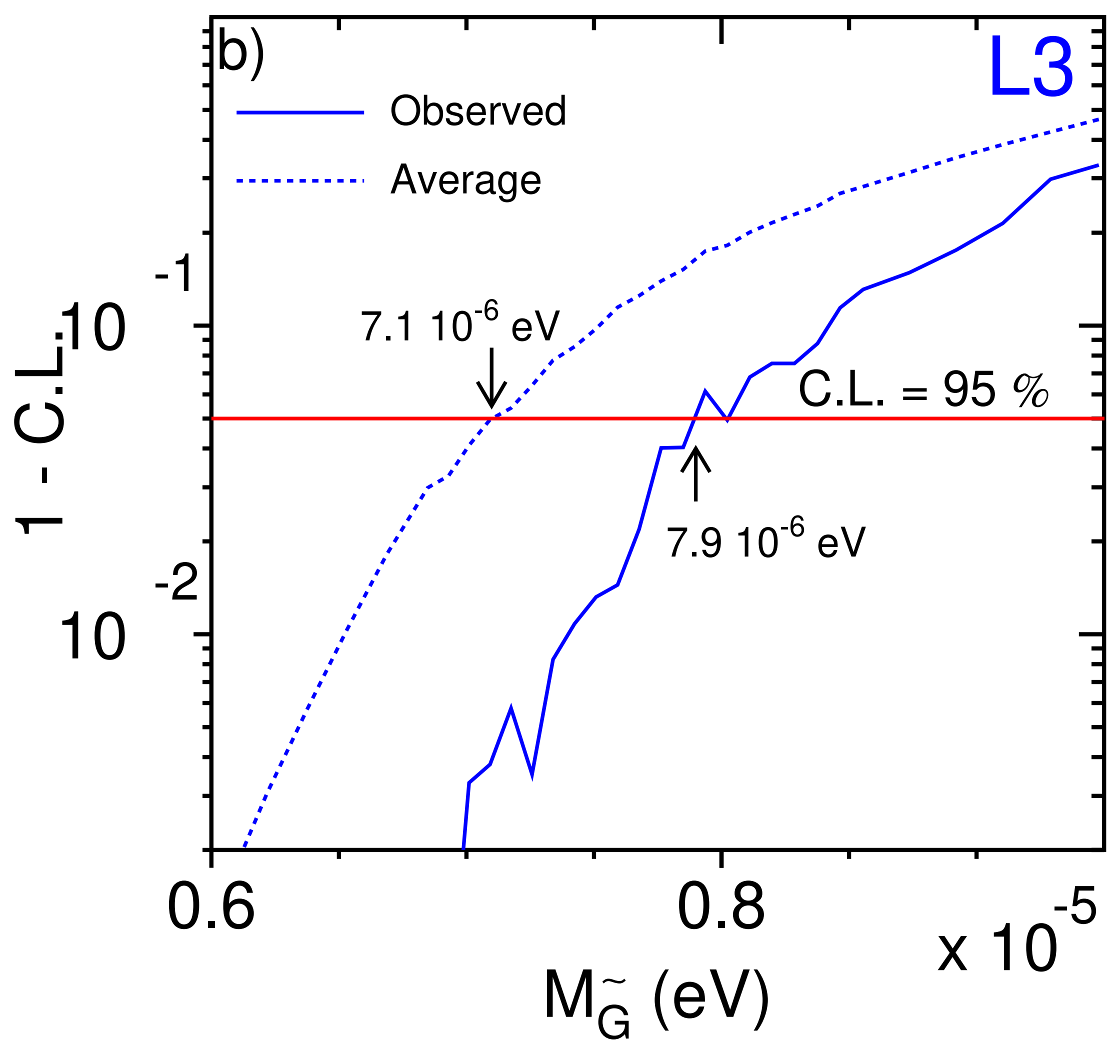


Photons and missing energy

Single photon final states

- Superlight gravitino $e^+e^- \to \tilde{G}\tilde{G}\gamma$
- cross section dominated by ISR (BFZ)

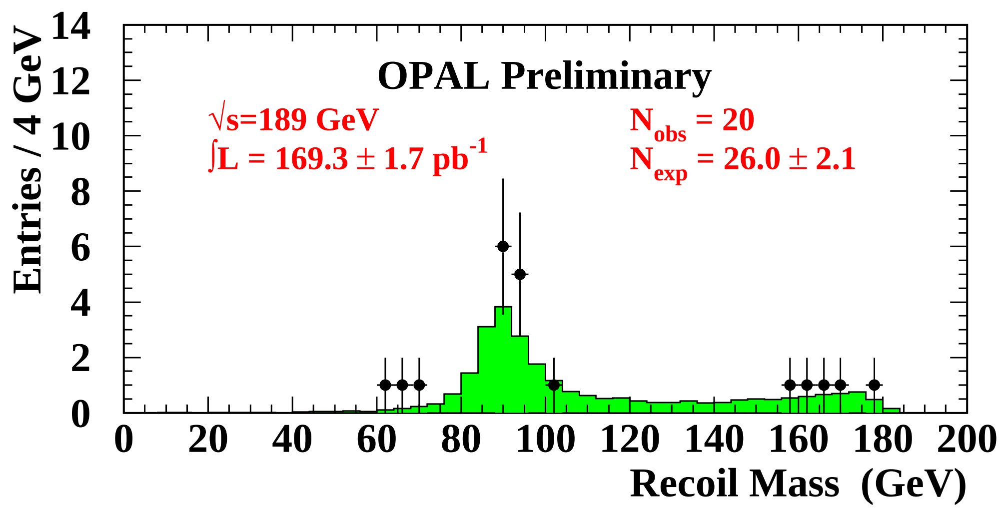
Likelihood fit to energy spectrum 183 GeV Data



- $M_{\tilde{G}} > 7.9\ 10^{-6}$ eV

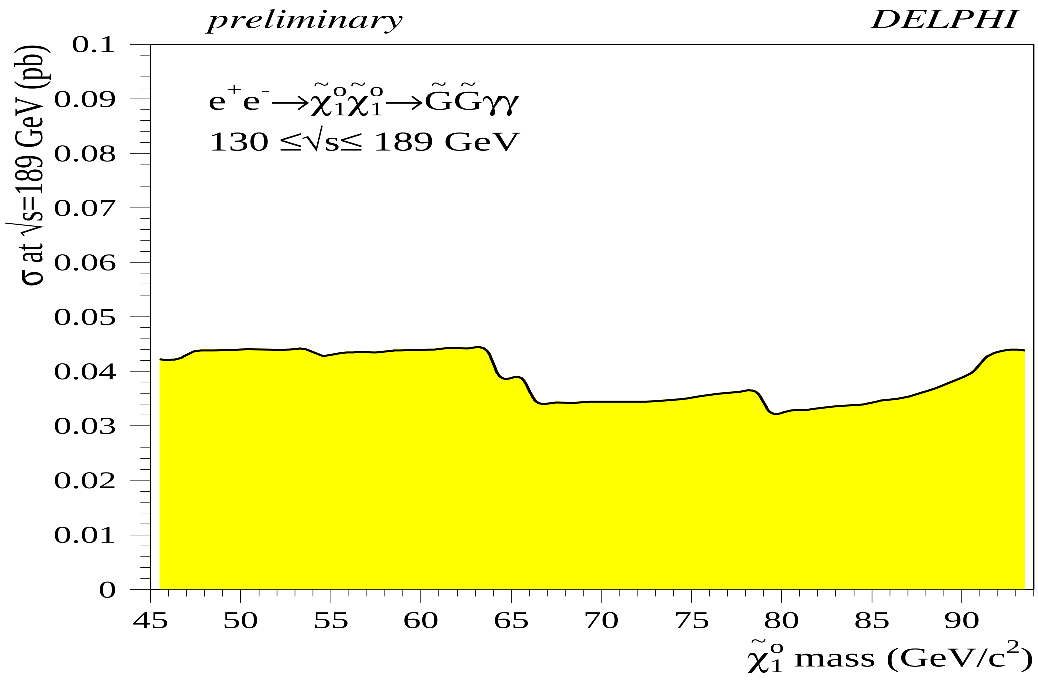
Photons and missing energy

Multiphoton final states:



Upper limit on cross sections

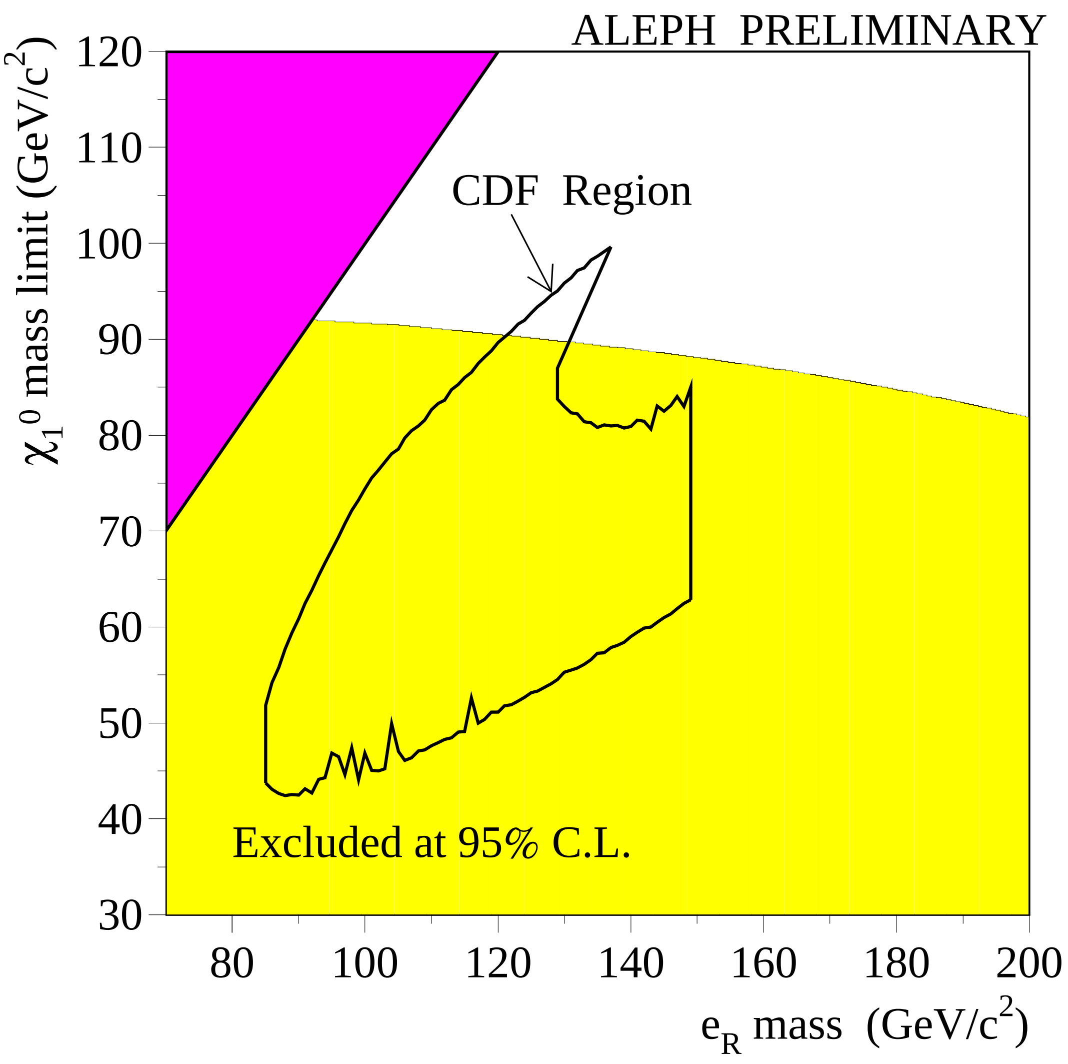
- $e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$



Photons and missing energy: GMSB

GMSB: multiphoton final states

- **Interpretation of the CDF event**
  $q\bar{q} \rightarrow \tilde{e}_R\tilde{e}_R \rightarrow ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\gamma\tilde{G}\gamma\tilde{G}$
- **LEP:** $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$



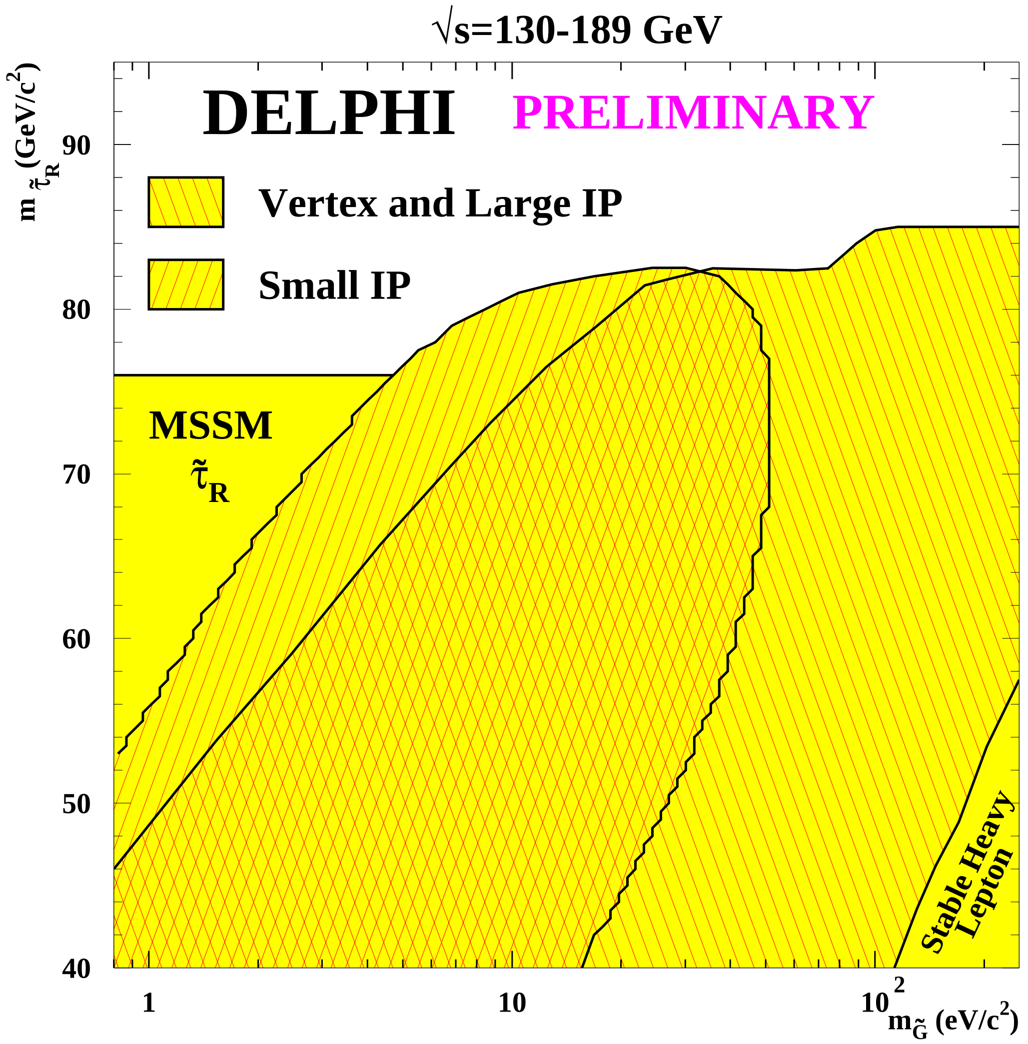
Comparison of LEP data with regions favoured by CDF event within GMSB model

GMSB stau

GMSB: $\tilde{\tau}$ is the NLSP

$\tilde{\tau} \rightarrow \tilde{G}\tau \quad \tilde{\chi}_1^0 \rightarrow \tilde{\tau}\tau$

Massive $\tilde{G}$: decay length $L \simeq M_{\tilde{l}}^{-5}\, M_{\tilde{G}}^{2}$



Conclusions

- No indication for SUSY
- Large domain of models is covered
- Standard SUSY
  - Lightest chargino excluded up to kinematc limit (94.4 GeV) in most of the parameter space
  - Independent of MSSM parameters

$M_{\tilde{\chi}_1^\pm} > 65.2$ GeV (L3 - 189 GeV PRELIMINARY)

$M_{\tilde{\chi}_1^0} > 27$ GeV (ALEPH - 183 GeV)
28.2 GeV (L3 - 189 GeV PRELIMINARY)
24.2 GeV (OPAL - 183 GeV)

- RPV searches give similar/better results
- GMSB

$M_{\tilde{G}} > 8.3\ 10^{-6}$ eV (ALEPH - 183 GeV)
$8.7\ 10^{-6}$ eV (DELPHI - 189 GeV PRELIM.)
$7.9\ 10^{-6}$ eV (L3 - 183 GeV)

- New Data and New Energies to come

1999 $\sqrt{s} \simeq$ (192-196-200) GeV