Limit on the Mass of the Lightest Supersymmetric Particle from LEP

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Higgs and Supersymmetry:
Search & Discovery

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Outline

- Neutralino LSP scenarios
  - SUSY framework(s)
  - Method to derive the mass limit
  - Mass limits
- Gravitino LSP scenarios
  - Models with light gravitinos
  - From the photon spectrum to the mass limit
- Summary

LEP

ALEPH, DELPHI, L3, OPAL

Year	$\sqrt{s}$	$\mathcal{L}$ / Experiment
1989–1995	Z peak	$\approx 160\ \mathrm{pb}^{-1}$
1995	130–136 GeV	$\approx 6\ \mathrm{pb}^{-1}$
1996	161–172 GeV	$\approx 21\ \mathrm{pb}^{-1}$
1997	181–184 GeV	$\approx 56\ \mathrm{pb}^{-1}$
1998	189 GeV	$\approx 174\ \mathrm{pb}^{-1}$
1999	*192–200 GeV*	$\gtrsim 100\ \mathit{pb}^{-1}$
2000	*200+ϵ GeV*	

Results @ 189 GeV are
PRELIMINARY

SUSY Framework — MSSM

MSSM parameters

$M_1 \;\; M_2 \;\; M_3$	Gaugino masses
μ	Higgs mass parameter
$\tan\beta$	$= \frac{v_2}{v_1}$
m_{A}	Mass of CP–odd Higgs A
$M_{\tilde{l}} \;\; M_{\tilde{q}}$	Slepton and squark masses
$A_{\tilde{l}} \;\; A_{\tilde{q}}$	Trilinear couplings

Constrained MSSM

Unification of gaugino masses ➪ M_2

Unification of scalar masses ➪ m_0

Unification of trilinear couplings ➪ A_0

Free parameters: $\boxed{M_2,\ \mu,\ \tan\beta,\ m_0,\ A_0,\ m_{\mathrm{A}}}$

mSUGRA

Constrains parameter freedom to

$m_{1/2},\ \ m_0,\ \ \tan\beta,\ \ A_0,\ \ \text{sign}\,\mu$

R–Parity

$$R = (-1)^{3(B-L)+2S} = \begin{cases} +1 & \text{Particles} \\ -1 & \text{SUSY partners} \end{cases}$$

- R–parity conservation assumed

➤ Sparticles are produced in pairs and decay to their SM partner and the LSP

➤ LSP is stable and weakly interacting

  ↪ Lightest neutralino is LSP

  ↪ Candidate for cold dark matter

  ↪ LSP escapes detection

    ➠ No “direct” observation possible

    ➠ Missing energy signature

- R–parity violated ⇨ Visible decays into SM particles

Principle to Derive the Mass Limit on the LSP

Experimental search for various signatures of sparticle production

? nothing $\downarrow$ found ?

Cross section limits (model independent)

(C)MSSM, mSUGRA

$\downarrow$

Prediction of masses and couplings of all sparticles

Constraints on model parameters

$\downarrow$

Limits on sparticle masses

Neutralino Mass Matrix

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z\, s_\theta\, \cos\beta & m_Z\, s_\theta\, \sin\beta \\ 0 & M_2 & m_Z\, c_\theta\, \cos\beta & -m_Z\, c_\theta\, \sin\beta \\ -m_Z\, s_\theta\, \cos\beta & m_Z\, c_\theta\, \cos\beta & 0 & -\mu \\ m_Z\, s_\theta\, \sin\beta & -m_Z\, c_\theta\, \sin\beta & -\mu & 0 \end{pmatrix}$$

with $s_\theta = \sin\theta_W$ and $c_\theta = \cos\theta_W$

in the basis $\left(\tilde{B}, \tilde{W}^3, i\tilde{H}_1, i\tilde{H}_2\right)$

- $m_{\text{LSP}} \equiv m_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_i^0}(M_2, \mu, \tan\beta)\,, \quad i = 1 \ldots 4$
- Constraints on $M_2, \mu, \tan\beta$ ⇨ Mass limit on $m_{\tilde{\chi}_1^0}$

Sparticle Processes

$$\left.\begin{array}{l}\tilde{\chi}_1^+\,\tilde{\chi}_1^- \\ \tilde{\chi}_i^0\,\tilde{\chi}_j^0\end{array}\right\}\ \sigma = \sigma\left(M_2, \mu, \tan\beta, \boxed{m_0}\right)$$

$$\left.\begin{array}{l}\tilde{\mathrm{e}}\,\tilde{\mathrm{e}} \\ \tilde{\mu}\,\tilde{\mu} \\ \tilde{\tau}_1\,\tilde{\tau}_1 \\ \tilde{\mathrm{t}}_1\tilde{\mathrm{t}}_1 \\ \tilde{\mathrm{b}}_1\tilde{\mathrm{b}}_1\end{array}\right\}\ \sigma = \sigma\left(M_2, \mu, \tan\beta, \boxed{m_0}, (A_0)\right)$$

$$\left.\begin{array}{l}\mathrm{h\,Z} \\ \mathrm{h\,A}\end{array}\right\}\ \sigma = \sigma\left(m_{\mathrm{A}}, \tan\beta, (A_0, \mu), (m_0, M_2)\right)$$

- Scanning of whole parameter space
  If $\sigma_{\text{lim}} < \sigma_{\text{theory}} \rightarrow$ exclude point
- Collect all excluded points
- Search for point with lowest value of $m_{\tilde{\chi}_1^0}$ which is NOT excluded
- Voilà the $m_{\tilde{\chi}_1^0}$ limit

Rôle of m_0

- To have a general limit on

$$m_{\tilde{\chi}^0_1} = m_{\tilde{\chi}^0_1}(M_2, \mu, \tan\beta)$$

  exclusions on $M_2, \mu, \tan\beta$ must be valid for any m_0

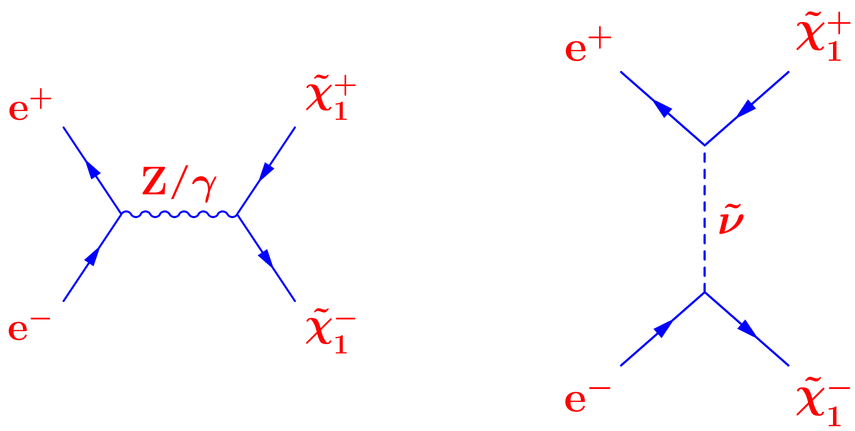
- $m_{\tilde{l},\tilde{q}} = m_{\tilde{l},\tilde{q}}(m_0, M_2, \tan\beta, \mu, A_0)$

High m_0

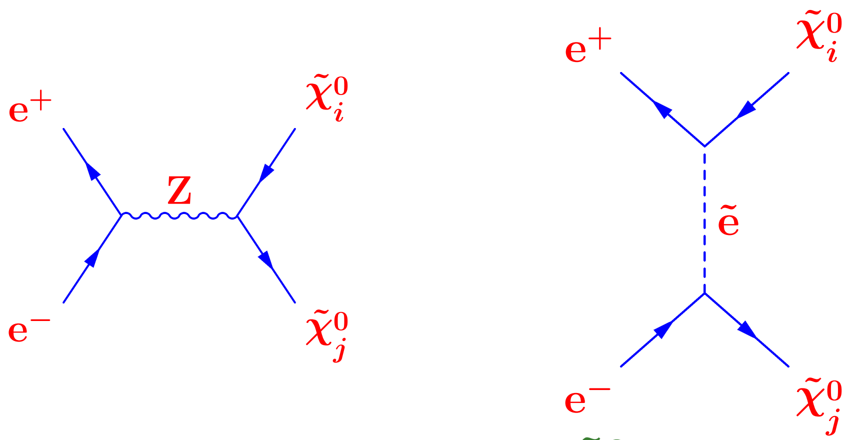
→ Scalar particles are beyond the kinematic reach

→ Limit comes only from $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$ searches

Production of $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$



Destructive interference if $\tilde{\chi}_1^{\pm}$ is gaugino like

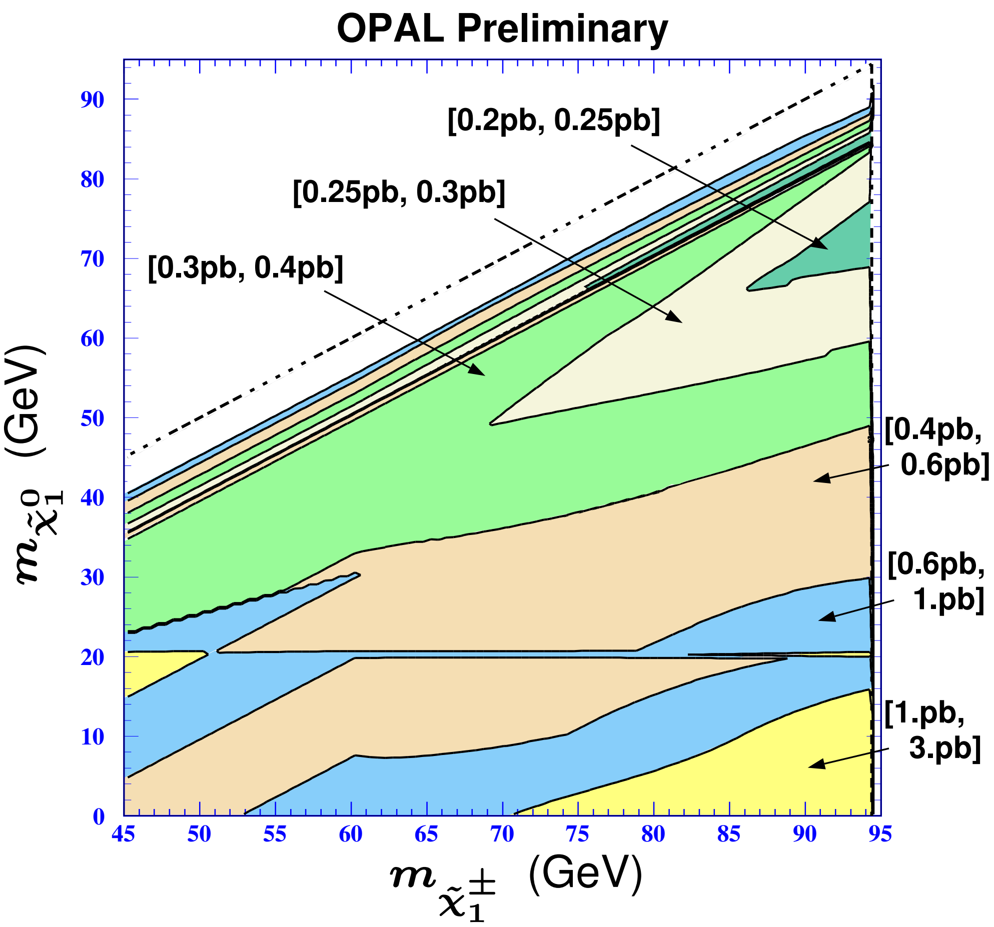


Constructive interference if $\tilde{\chi}^0$ is gaugino like

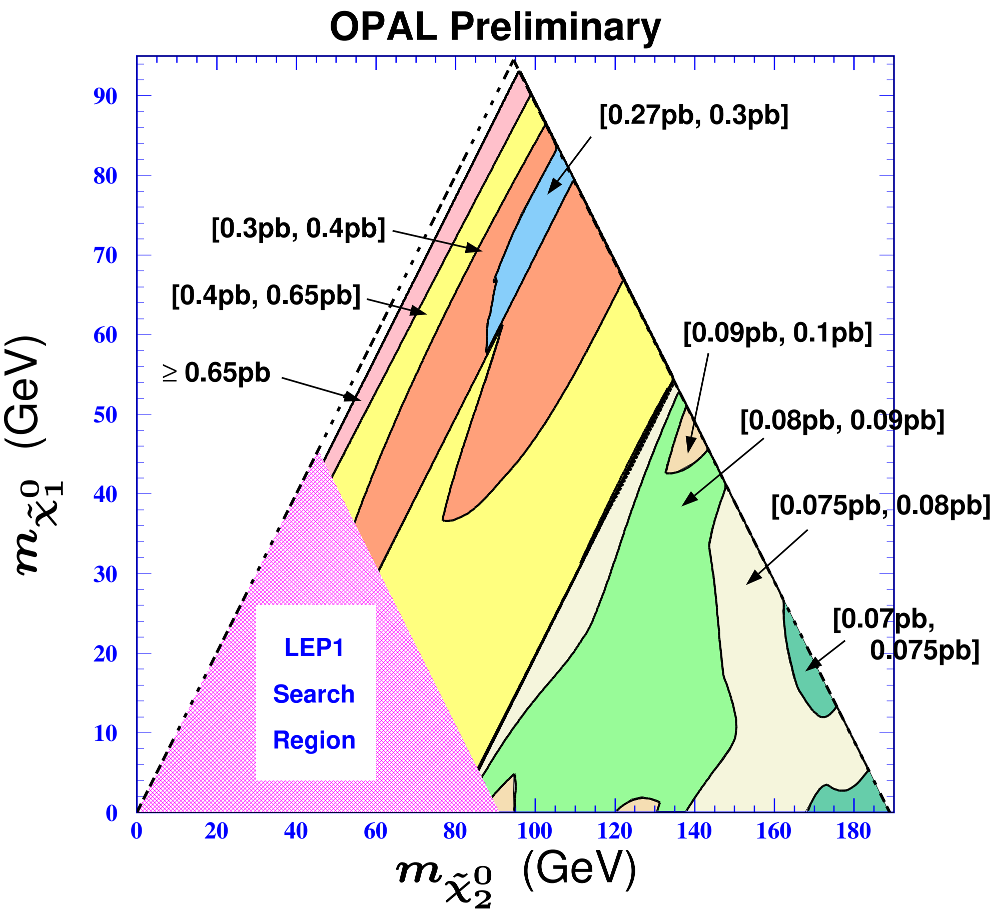
- Higgsino region $M_2 \gg |\mu|$
  No t–channel contribution
- Gaugino region $M_2 \ll |\mu|$, high m_0
  No t–channel contribution
- Gaugino region $M_2 \ll |\mu|$, low m_0
  t–channel contribution important

Cross Section Limits

189 GeV

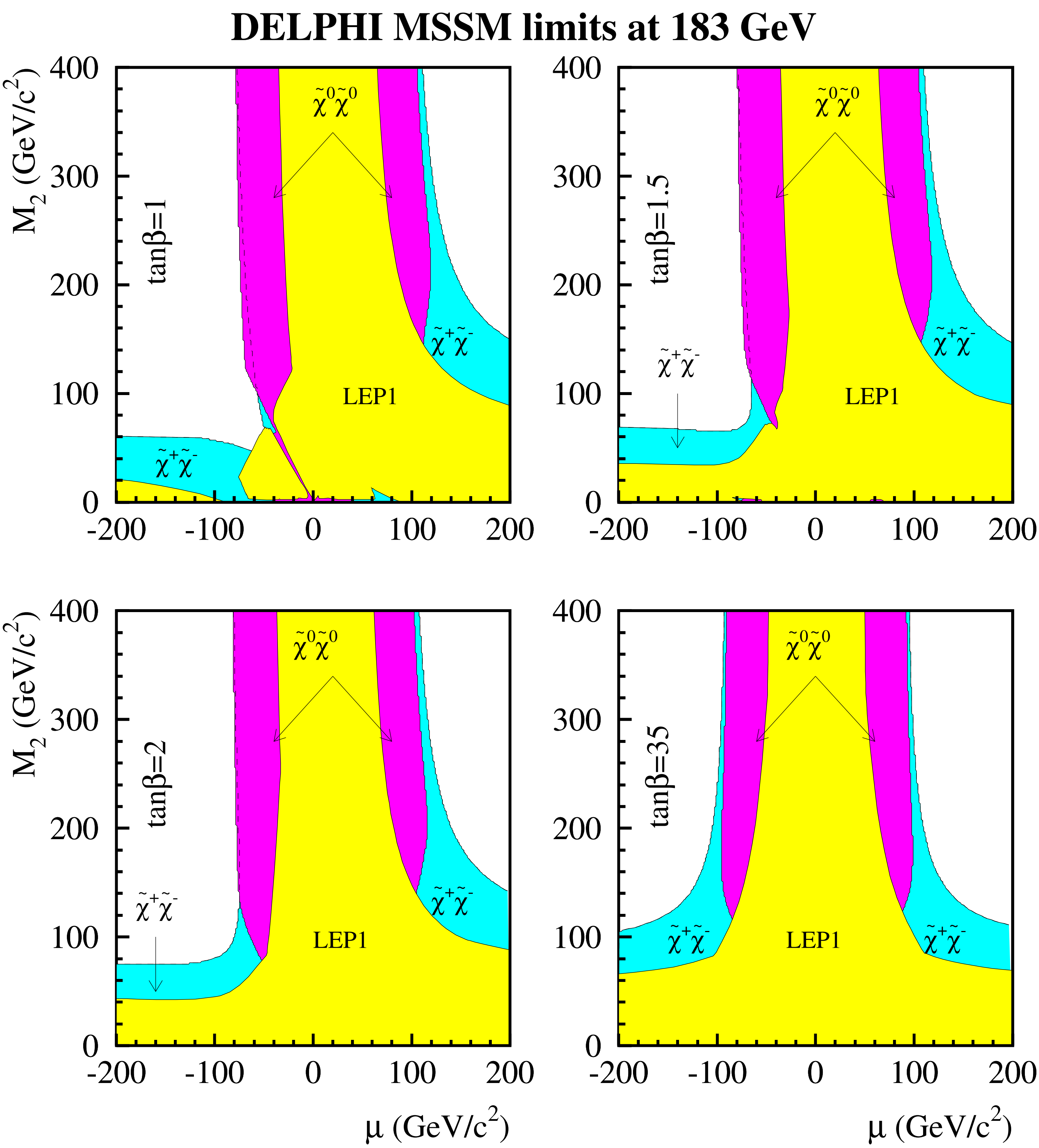


Assuming 100% $\tilde{\chi}^\pm_1 \rightarrow W^* \tilde{\chi}^0_1$



Assuming 100% $\tilde{\chi}^0_2 \rightarrow Z^* \tilde{\chi}^0_1$

$m_0 = 1000$ GeV

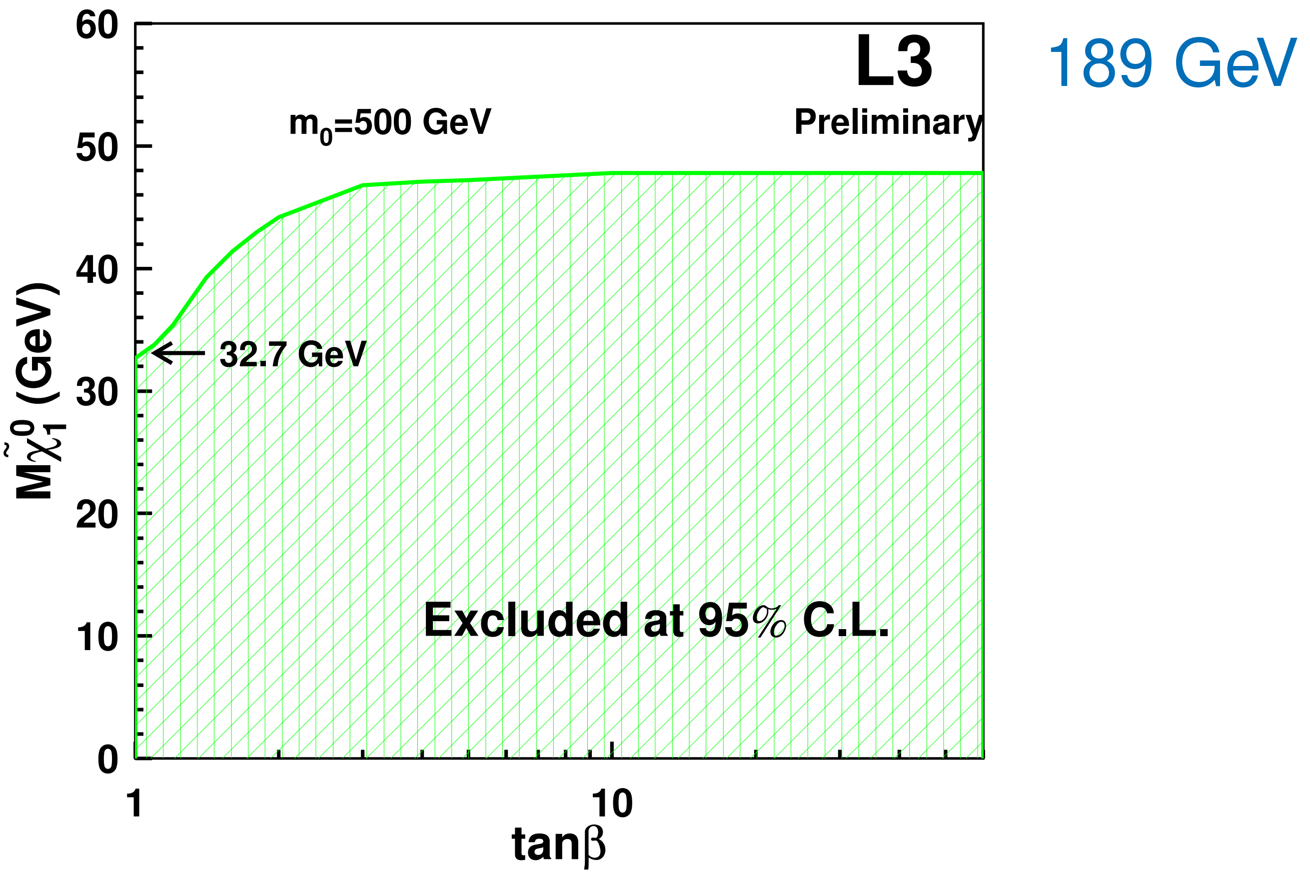


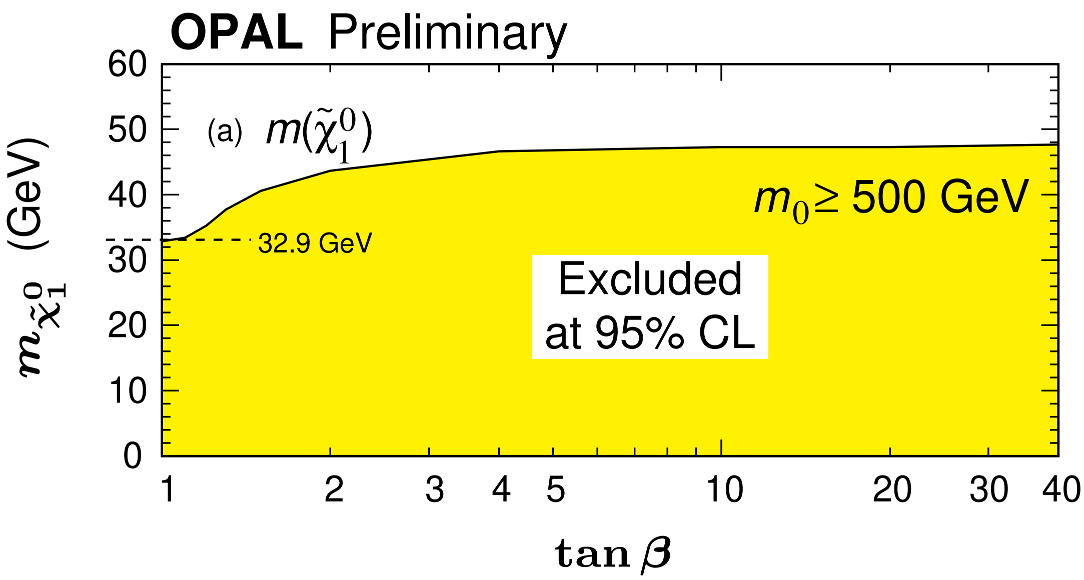
Main contribution to exclusion contour from $\tilde{\chi}_1^{\pm}$ search

Scan ranges

	M_2	$\lvert\mu\rvert$	$\tan\beta$	m_0
ALEPH	0 – 1000 GeV	0 – 2000 GeV	1 – 50	40 GeV – 500 GeV
DELPHI	0 – 500 GeV	0 – 400 GeV	1 – 10	1000 GeV
L3	0 – 2000 GeV	0 – 2000 GeV	1 – 60	10 GeV – 500 GeV
OPAL	0 – 2000 GeV	0 – 500 GeV	1 – 40	0 – 500 GeV

Limits on $m_{\tilde{\chi}^0_1}$ for high m_0





ALEPH: $m_{\tilde{\chi}^0_1} > 32.3$ GeV @ 189 GeV Prel.

DELPHI: $m_{\tilde{\chi}^0_1} > 29.1$ GeV @ 183 GeV

L3: $m_{\tilde{\chi}^0_1} > 32.7$ GeV @ 189 GeV Prel.

OPAL: $m_{\tilde{\chi}^0_1} > 32.9$ GeV @ 189 GeV Prel.

Low m_0

- Light sleptons

– $\tilde{\chi}_1^\pm$ cross section is smaller due to the destructive interference of s and t–channel

– Leptonic branching ratio of $\tilde{\chi}_1^\pm$ is enhanced

➜ Smaller detection efficiency (large W background) or (almost) invisible decay if $\tilde{\chi}_1^\pm \to \tilde{\nu} l^\pm$ & $|m_{\tilde{\chi}_1^\pm} - m_{\tilde{\nu}}|$ small

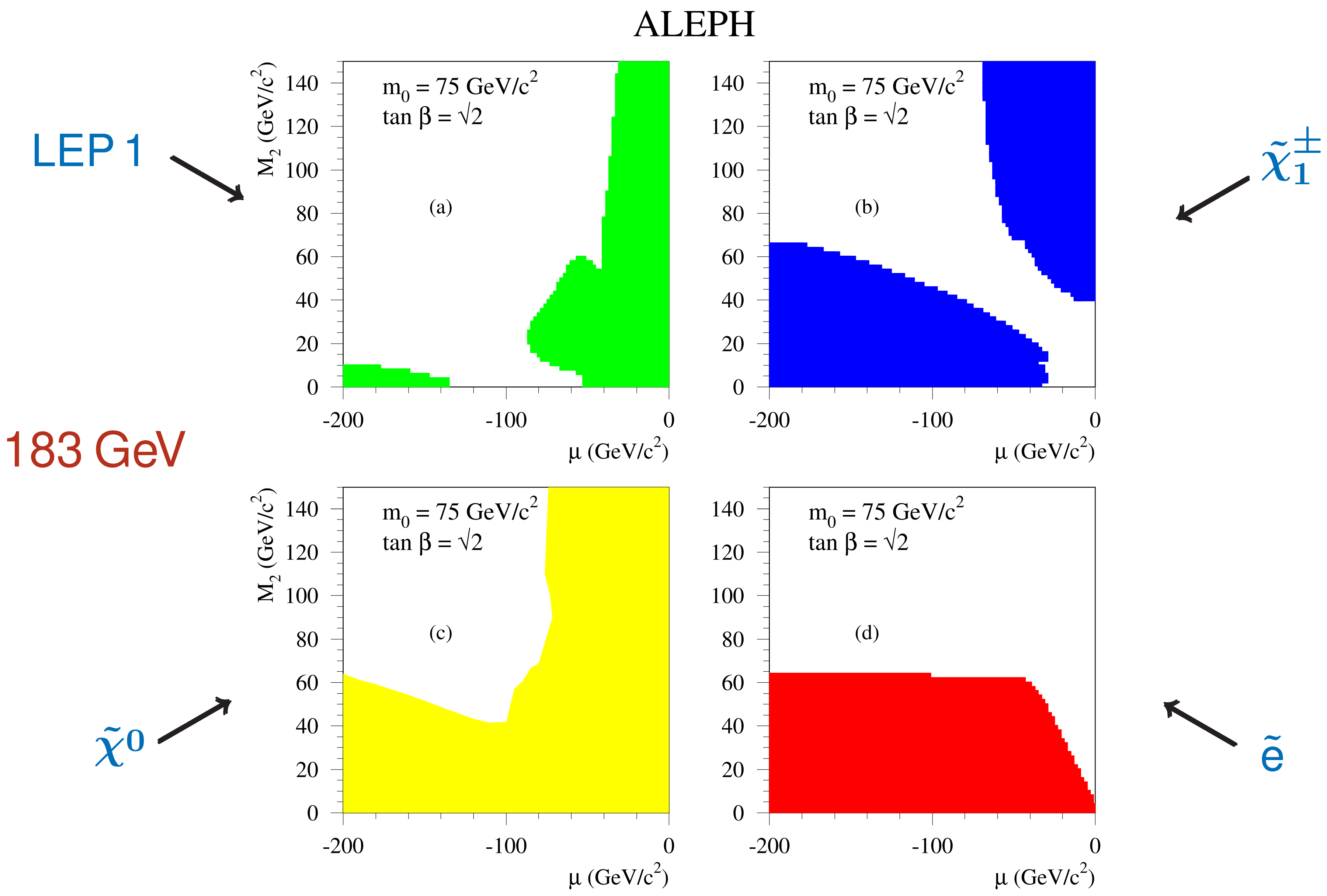
+ $\tilde{\chi}_i^0 \tilde{\chi}_j^0$ cross section(s) can be larger

– Many $\tilde{\chi}^0$ combinations have to be taken into account ($\tilde{\chi}_1^0 \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \tilde{\chi}_2^0$, $\tilde{\chi}_1^0 \tilde{\chi}_3^0$, $\tilde{\chi}_2^0 \tilde{\chi}_3^0$)

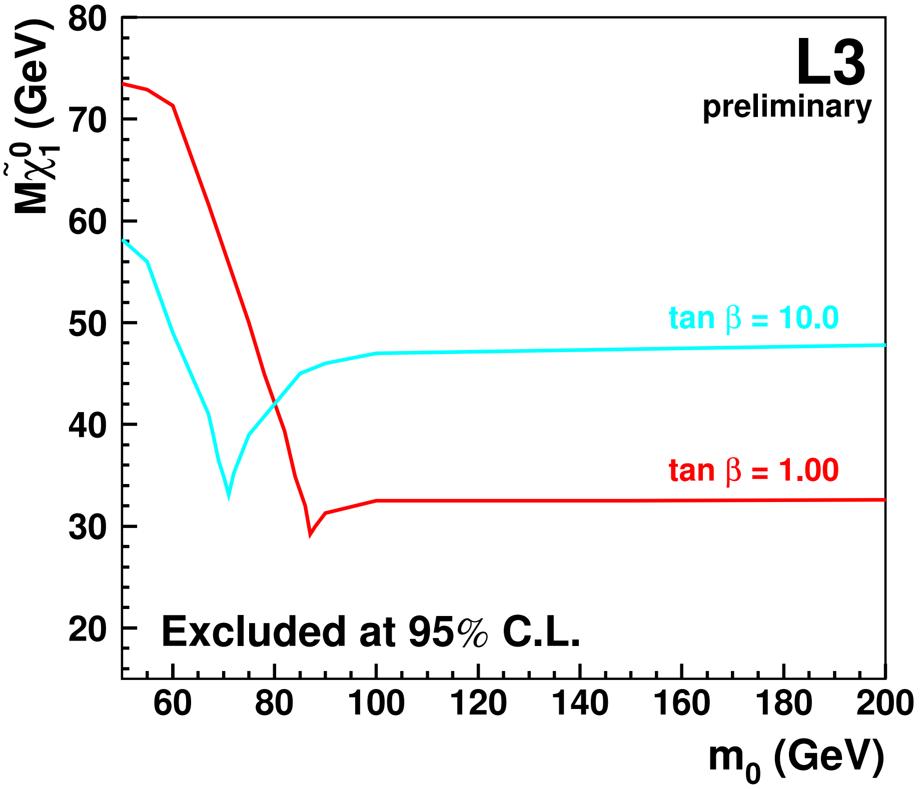
➜ All final states are considered

+ Slepton searches

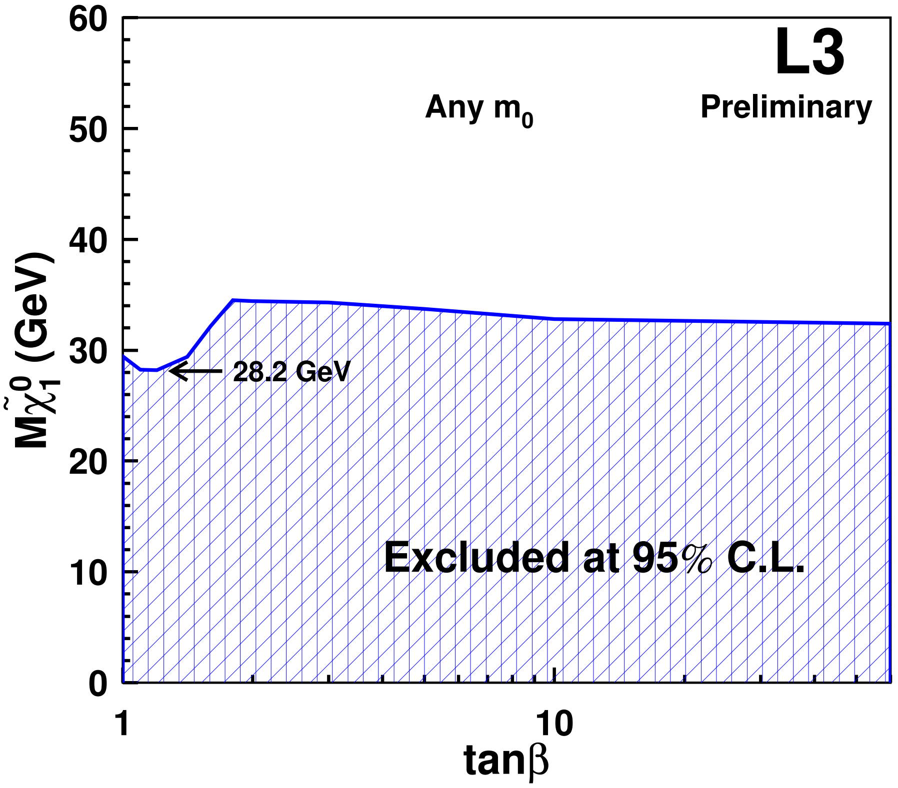
Contributions to $M_2 - \mu$ Exclusion



Limits on $m_{\tilde{\chi}_1^0}$ for any m_0



189 GeV

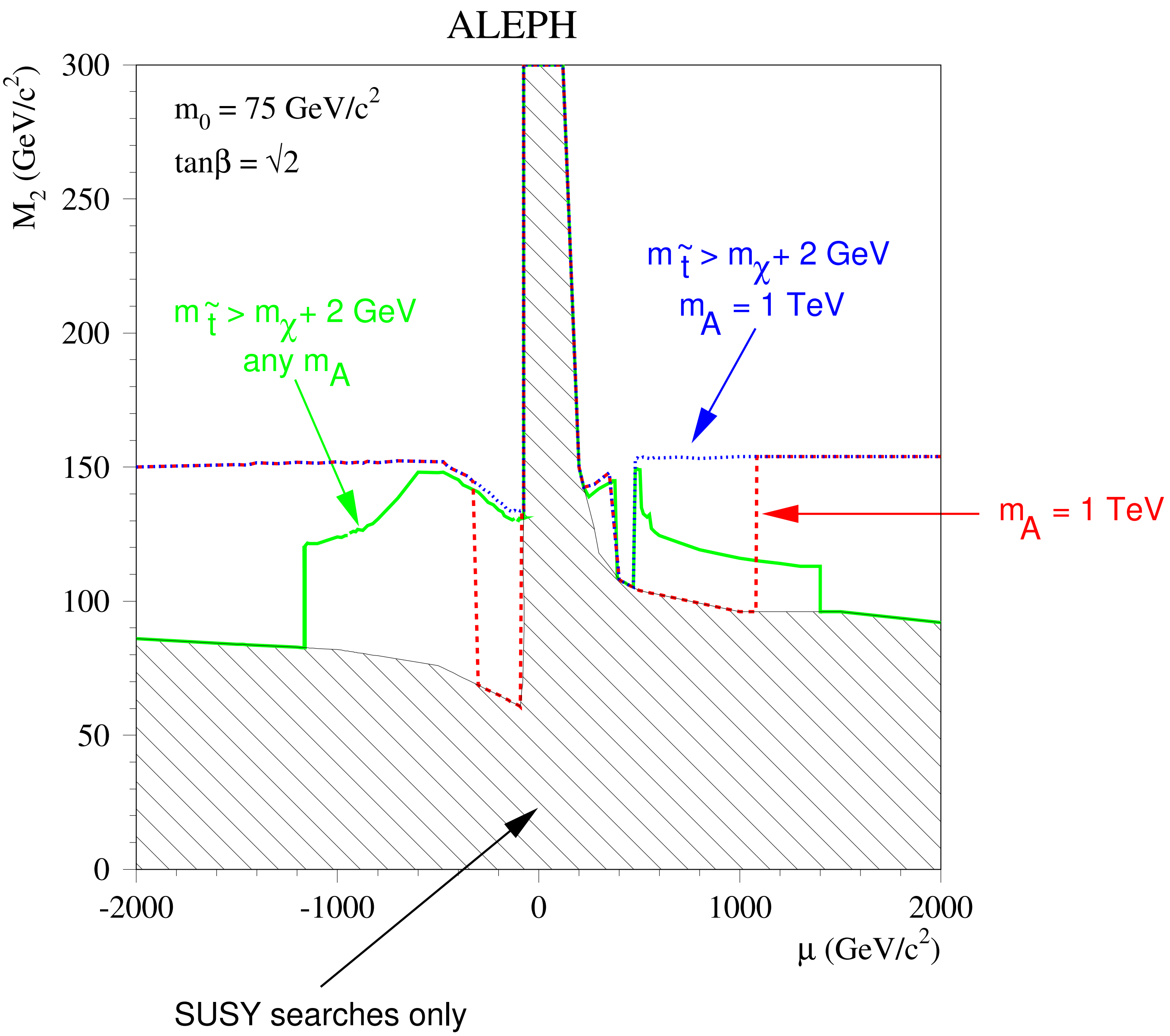


ALEPH:	$m_{\tilde{\chi}_1^0} > 32.3$ GeV	@ 189 GeV Prel.
L3:	$m_{\tilde{\chi}_1^0} > 28.2$ GeV	@ 189 GeV Prel.
OPAL:	$m_{\tilde{\chi}_1^0} > 24.2$ GeV	@ 183 GeV

Including Higgs Searches

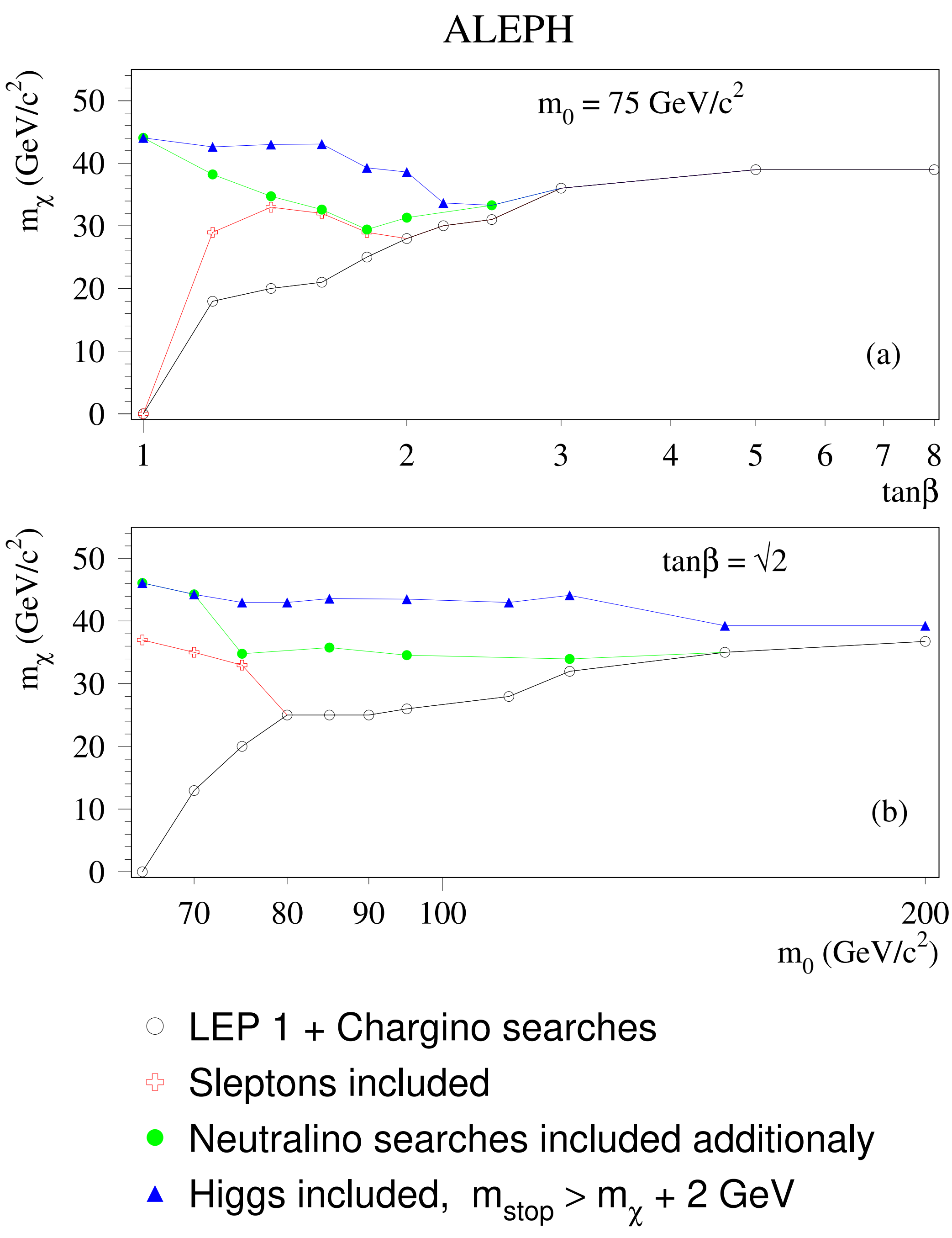
- Additional parameter m_A to define the Higgs sector
- The stop mass enters via one-loop contribution to the Higgs phenomenology
- Stop search limits have been used as constraint
- A_t has been scanned

183 GeV



$m_{\tilde{\chi}_1^0}$ Limit with Higgs

183 GeV

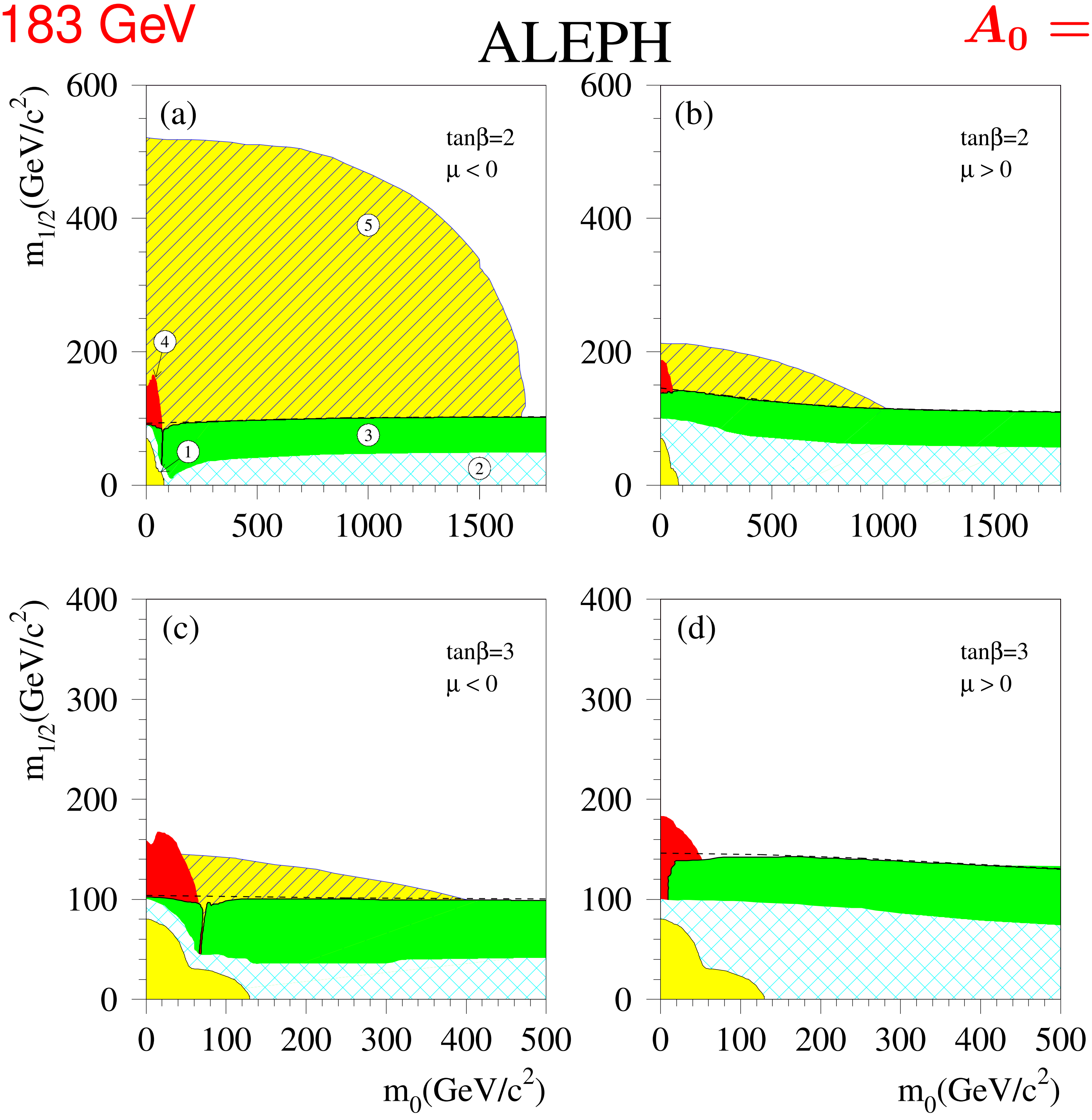


- With Higgs: Limit valid for $m_{\tilde{t}} > m_{\tilde{\chi}_1^0} + 2$ GeV
- Improvement for lower $\tan\beta$ and m_0 values
- ALEPH limit independent of $\tan\beta$, m_0 is not affected

- Further unification constraints remove m_A and μ (up to sign ambiguity) as free parameters

183 GeV

$A_0 = 0$

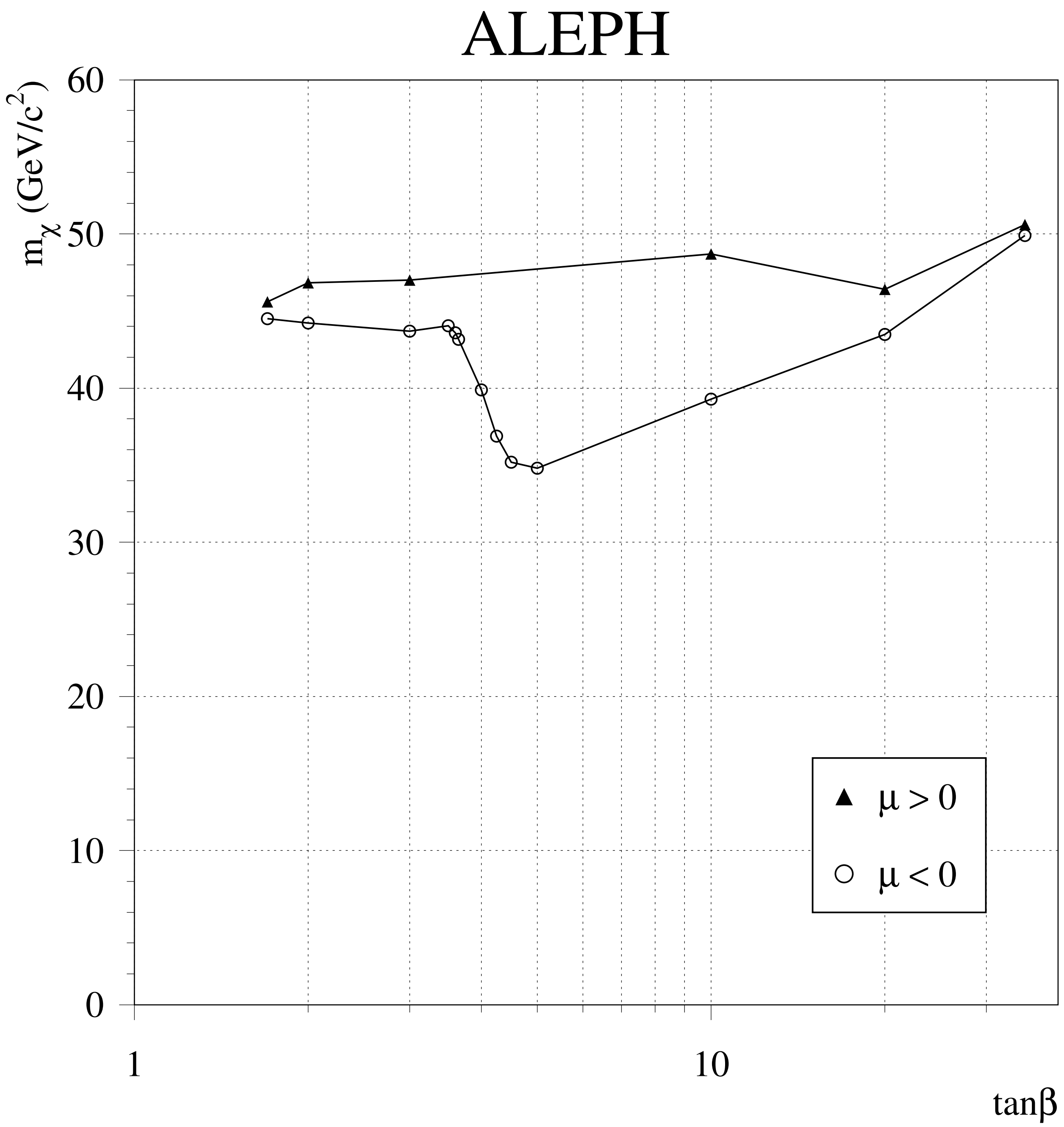


① Theoretically forbidden ② Z width @ LEP 1

③ Chargino searches ④ Slepton searches

⑤ Higgs searches

183 GeV $A_0 = 0$



$$m_{\tilde{\chi}_1^0} > 35 \text{ GeV} \quad \text{for } A_0 = 0$$

$$m_{\tilde{\chi}_1^0} > 29 \text{ GeV} \quad \text{for any } A_0$$

$$m_{\tilde{\mathrm{G}}} = \frac{F}{\sqrt{3}\, m_{\mathrm{P}}}$$

F SUSY breaking scale

$m_{\mathrm{P}} = 2.4 \times 10^{18}$ GeV reduced Planck mass

2 Approaches

- Treatment of F as free parameter, *i.e.* no assumption about mechanism of SUSY breaking
  - $\tilde{\mathrm{G}}$ can be arbitrarily light
- Choose a specific model like
  - GMSB (= Gauge-Mediated Supersymmetry Breaking)
    - 2×10^{-2} eV $\lesssim m_{\tilde{\mathrm{G}}} \lesssim 1000$ eV
    - No direct $\tilde{\mathrm{G}}$ production at colliders
    - $\tilde{\mathrm{G}}$ only produced via NLSP decay
  - No-Scale SUGRA, LNZ (= Lopez Nanopoulos Zichichi)
    - $\tilde{\mathrm{G}}$ can be superlight

$$m_{\tilde{\mathrm{G}}} = \frac{F}{\sqrt{3}\, m_{\mathrm{P}}}$$

- Gravitino mass is disconnected from sparticle production

  But: Grip on $m_{\tilde{\mathrm{G}}}$ via direct production

  ✗ $\mathrm{e}^+\mathrm{e}^- \longrightarrow \tilde{\chi}_1^0\, \tilde{\mathrm{G}} \longrightarrow \tilde{\mathrm{G}}\, \tilde{\mathrm{G}}\, \gamma$

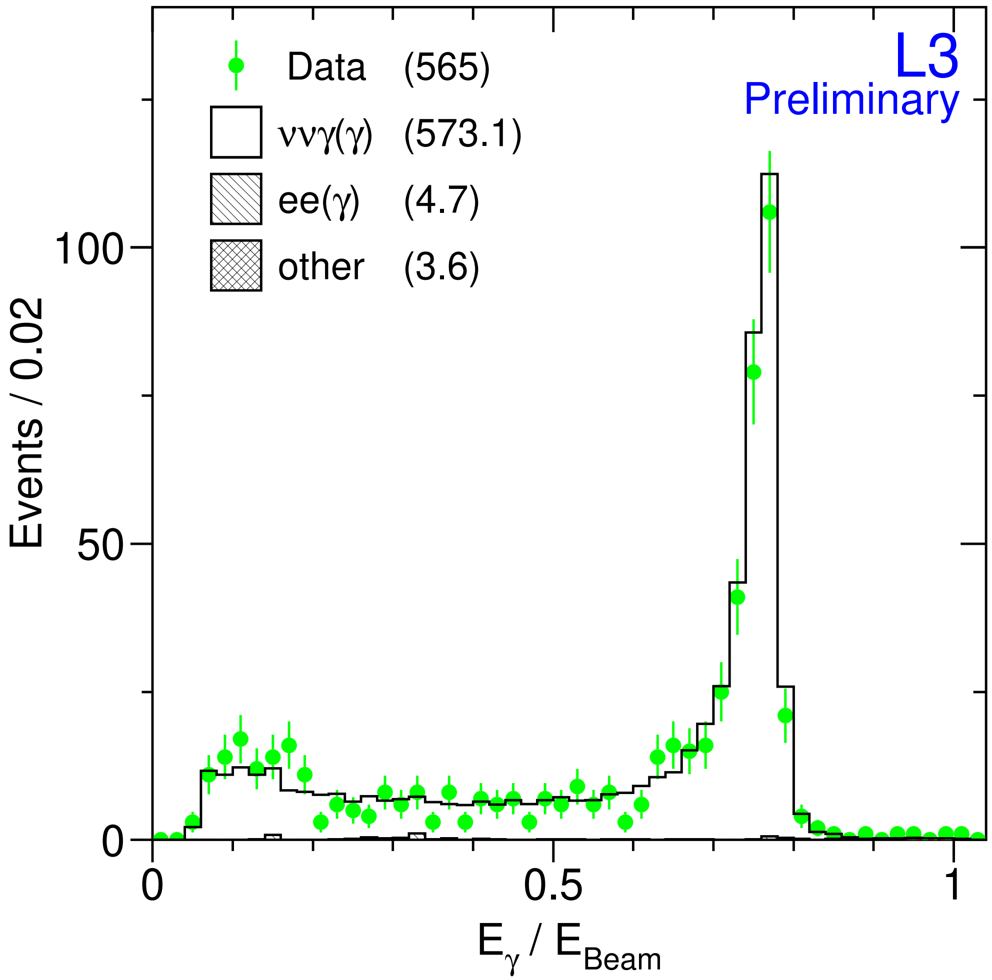
  ✗ $\mathrm{e}^+\mathrm{e}^- \longrightarrow \tilde{\mathrm{G}}\, \tilde{\mathrm{G}}\, \gamma$

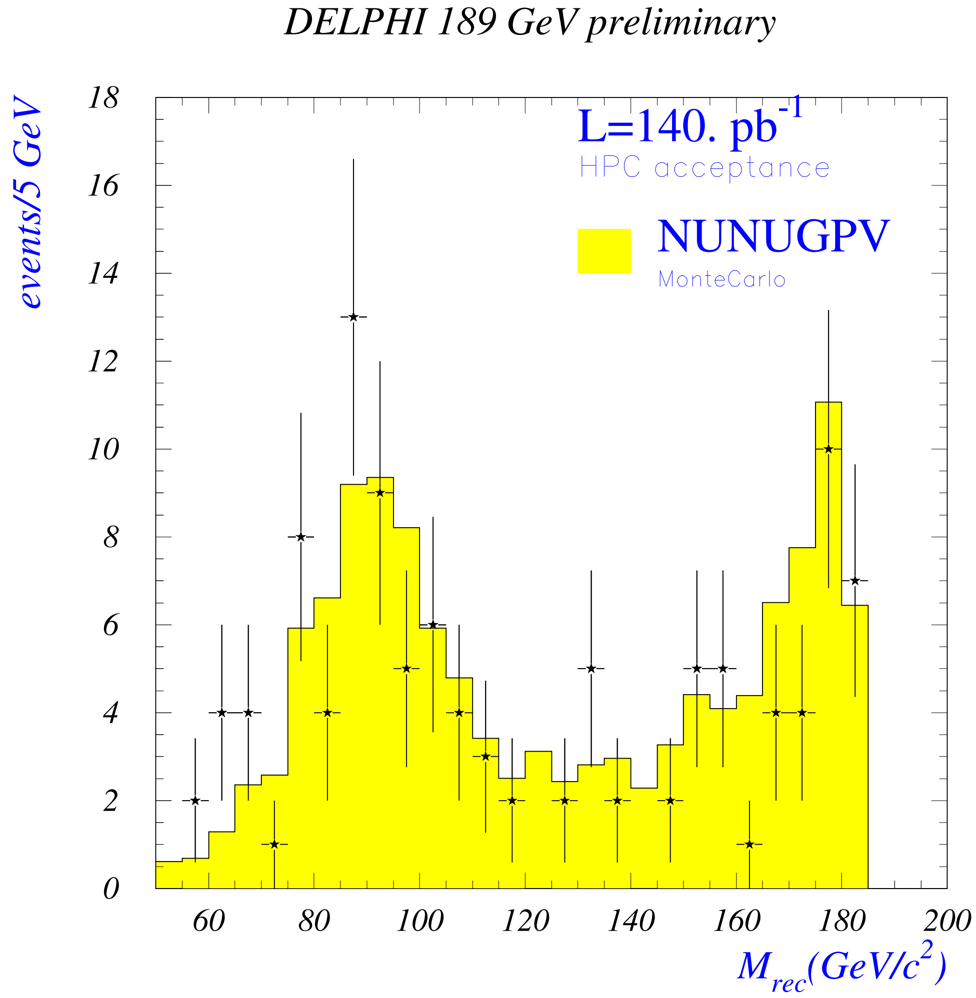
  Cross section is sizable only for superlight $\tilde{\mathrm{G}}$
  → not in GMSB

- Study of single photon events

Single Photon Spectra

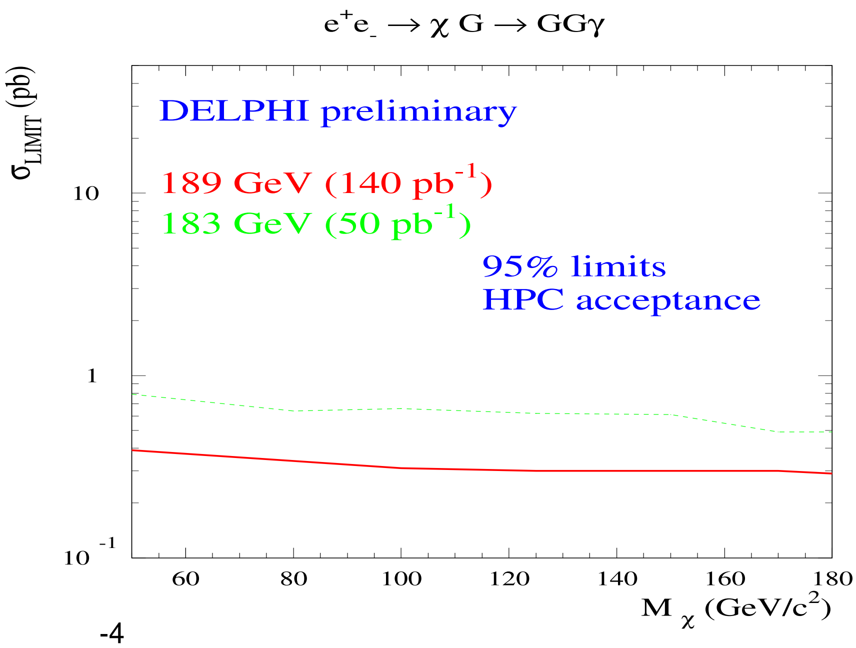
189 GeV

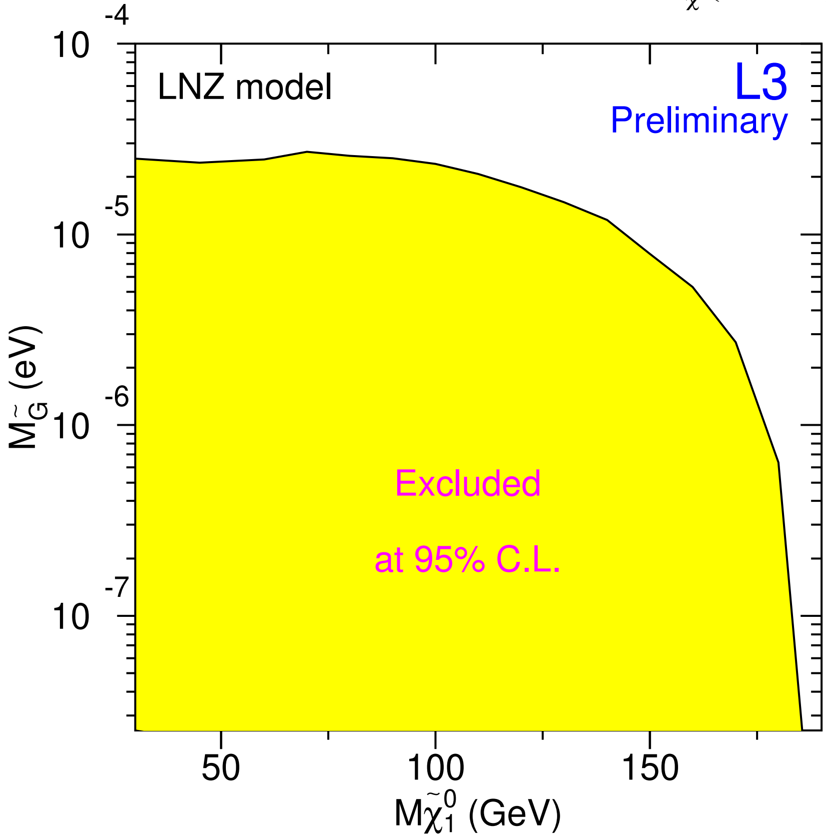




Gravitino Limits

189 GeV





$\boxed{e^+e^- \to \tilde{G}\,\tilde{G}\,\gamma}$ — If the other sparticles are heavy

ALEPH:	$m_{\tilde{G}} > 11 \times 10^{-6}$ eV	@ 189 GeV Prel.
DELPHI:	$m_{\tilde{G}} > 8.7 \times 10^{-6}$ eV	@ 189 GeV Prel.
L3:	$m_{\tilde{G}} > 9.8 \times 10^{-6}$ eV	@ 189 GeV Prel.

Summary

$\tilde{\chi}_1^0$ LSP

Any m_0

ALEPH:	$m_{\tilde{\chi}_1^0} > 32.3$ GeV	@ 189 GeV Prel.
L3:	$m_{\tilde{\chi}_1^0} > 28.2$ GeV	@ 189 GeV Prel.
OPAL:	$m_{\tilde{\chi}_1^0} > 24.2$ GeV	@ 183 GeV

End of LEP expectation: $\mathcal{O}(40$ GeV$)$

mSUGRA

ALEPH: $m_{\tilde{\chi}_1^0} > 29$ GeV @ 183 GeV

$\tilde{G}$ LSP

Other sparticles heavy

ALEPH:	$m_{\tilde{G}} > 11 \times 10^{-6}$ eV	@ 189 GeV Prel.
DELPHI:	$m_{\tilde{G}} > 8.7 \times 10^{-6}$ eV	@ 189 GeV Prel.
L3:	$m_{\tilde{G}} > 9.8 \times 10^{-6}$ eV	@ 189 GeV Prel.