7^{th} Topical Seminar on
The Legacy of LEP and SLC
Siena, 8-11 October 2001

Search for GMSB and AMSB




Outline

- Supersymmetry Breaking
- GMSB phenomenology
- GMSB searches results & interpretation
- AMSB
- Conclusions

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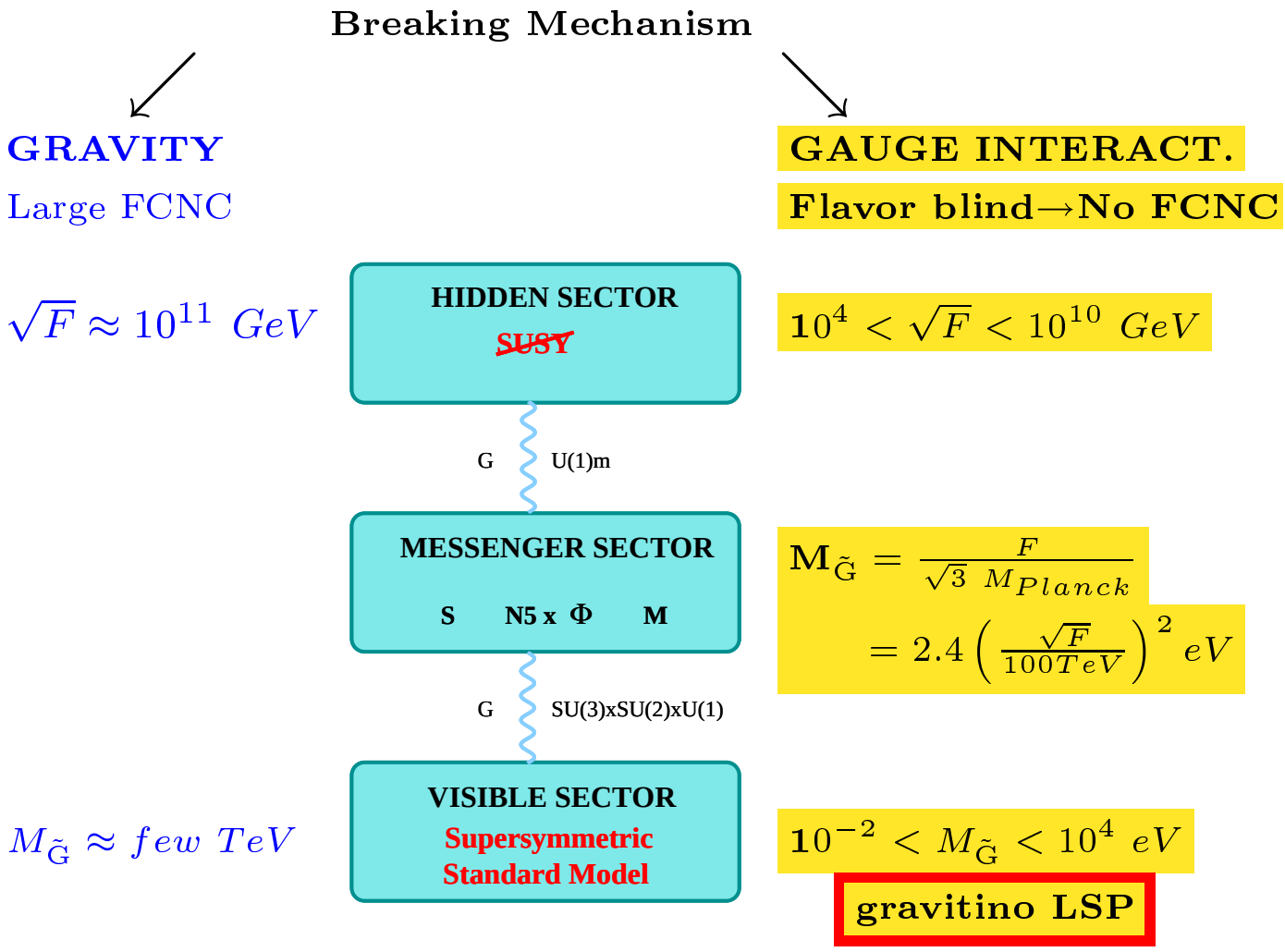
http://www.pp.rhul.ac.uk/~garcia/pubs/siena_gmsb.ps.gz

The LEP Dataset

Thanks LEP!

Breaking SUSY

SUSY is a broken symmetry: $m \neq \tilde{m}$



Gauge Mediated SUSY Breaking

Six new parameters to define GMSB models:

$\sqrt{F}$ SUSY breaking scale in the messenger sector

Λ universal mass scale of SUSY particles

N_5 number of messenger pairs

M_{mess} messenger mass scale

$\tan\beta$ ratio of Higgs vacuum expectation values

$sign(\mu)$ sign of Higgs sector mixing parameter

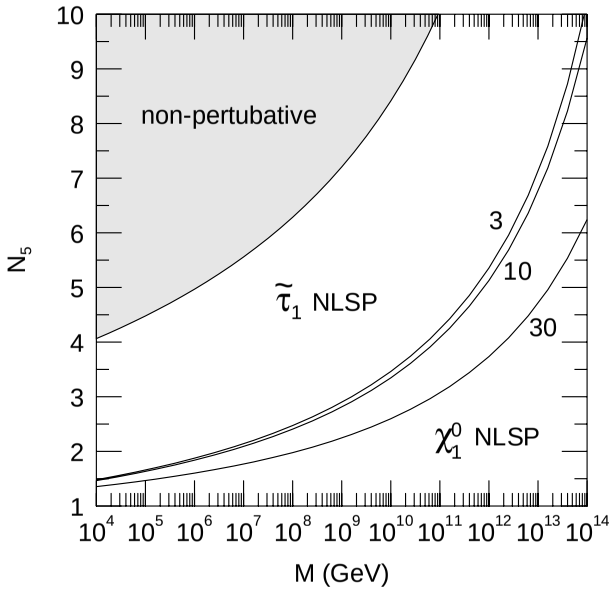
GMSB phenomenology

- $\tilde{G}$ is the LSP:

  10^{-2} eV $\lesssim M_{\tilde{G}} \lesssim$ 3 keV

- $$NLSP = \begin{cases} \chi & \rightarrow \gamma\tilde{G} \\ \tilde{\ell} & \rightarrow \ell\tilde{G} \end{cases}$$

- $\tilde{\tau}_R$ and $\tilde{\tau}_L$ mix $\Longrightarrow$ $\tilde{\tau}_1$ NLSP
  (large tan β)

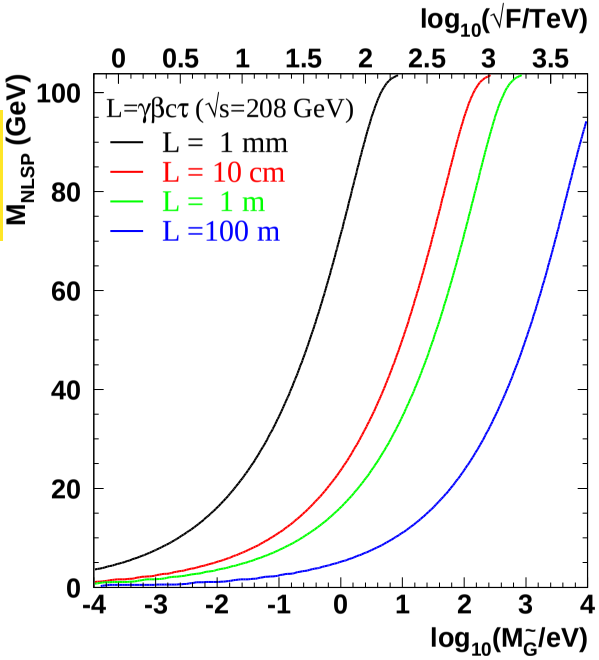


- Decay length of the NLSP:

$$c\tau \approx \frac{0.01}{\kappa_\gamma}\left(\frac{100GeV}{M_{NLSP}}\right)^5\left(\frac{\sqrt{F}}{100TeV}\right)^4 \text{ cm}$$

(κ_γ=1 for $\tilde{\ell}$ NLSP)

Signatures depend on the NLSP type and NLSP decay length



Many different topologies!

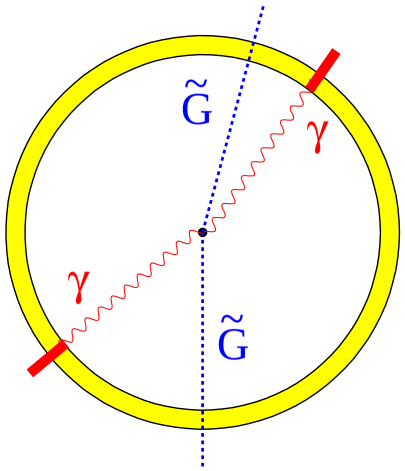
χ NLSP

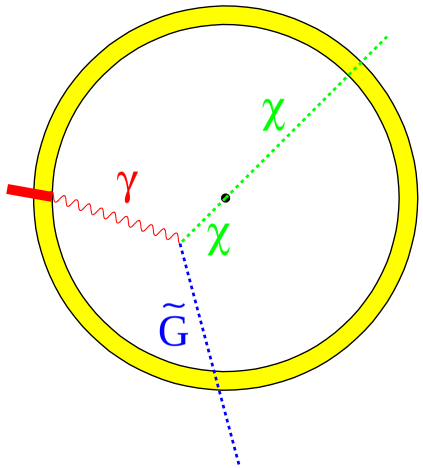
Short χ lifetime: $c\tau < 1\ cm$ ➡ **Two acoplanar γ**

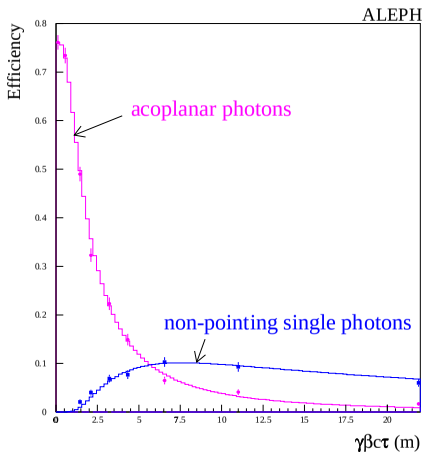
- Also $e^+e^- \to \tilde{\chi}_1^0\tilde{G} \to \gamma\tilde{G}\tilde{G}$ and $e^+e^- \to \tilde{G}\tilde{G}\gamma_{ISR} \Leftrightarrow M_{\tilde{G}} \sim 10^{-4}$ eV
- Suffer irreducible bkg: $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$
- MC generators: KK, KoralZ, NUNUGPV

Medium χ lifetime: $c\tau \sim \ell_{detector}$ ➡ **Non pointing γ(s)**

- Require impact parameter > 40 cm
- Impact parameter reconstructed from the EM shower axis
- Bkg: $\nu\bar{\nu}\gamma(\gamma)$ + cosmic rays → bremsstrahlung from out-of-time muons





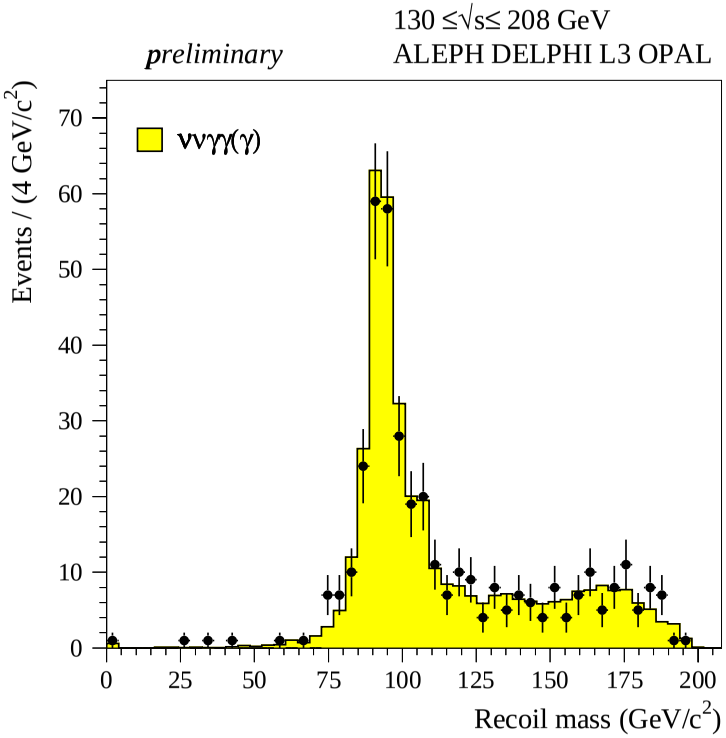


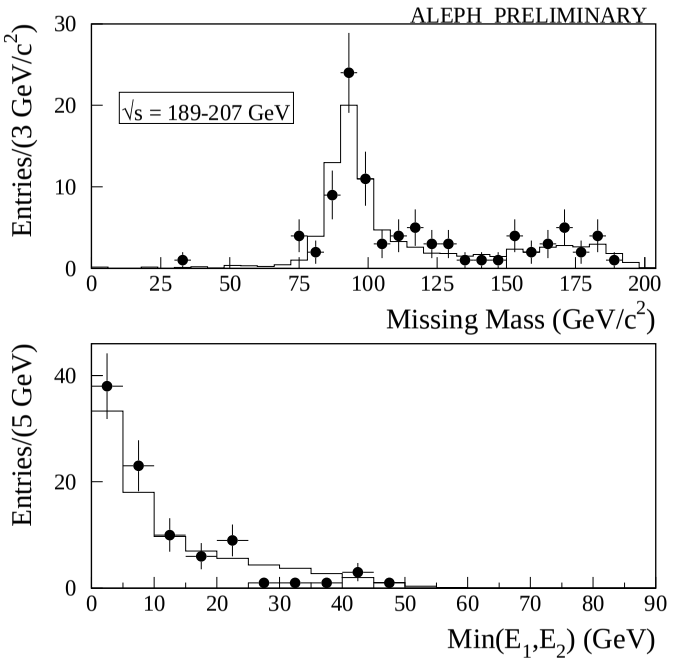
☞ If $c\tau > \ell_{detector}$: Indirect limits from 'standard' $\tilde{\ell}$ and $\tilde{\chi}^{\pm}$ searches

χ NLSP: No lifetime

Topology: two acoplanar photons pointing to the vertex and $\not\!\!E$

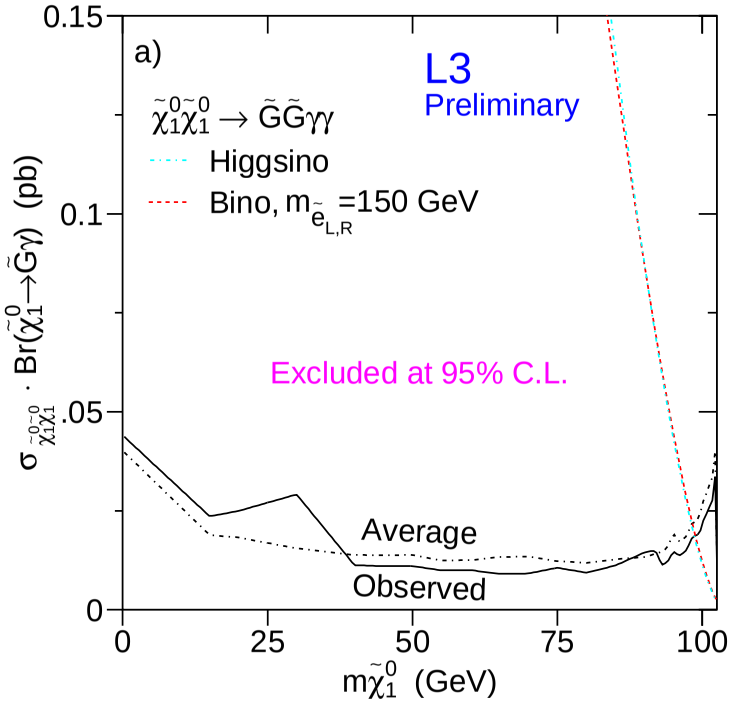
- Events with no charged tracks (except from conversions) and significant $\not\!\!E$
- Use as discriminant: recoil mass against the photon system
- Good agreement in total number of events:
  384 observed / 388.7 expected (ADLO)

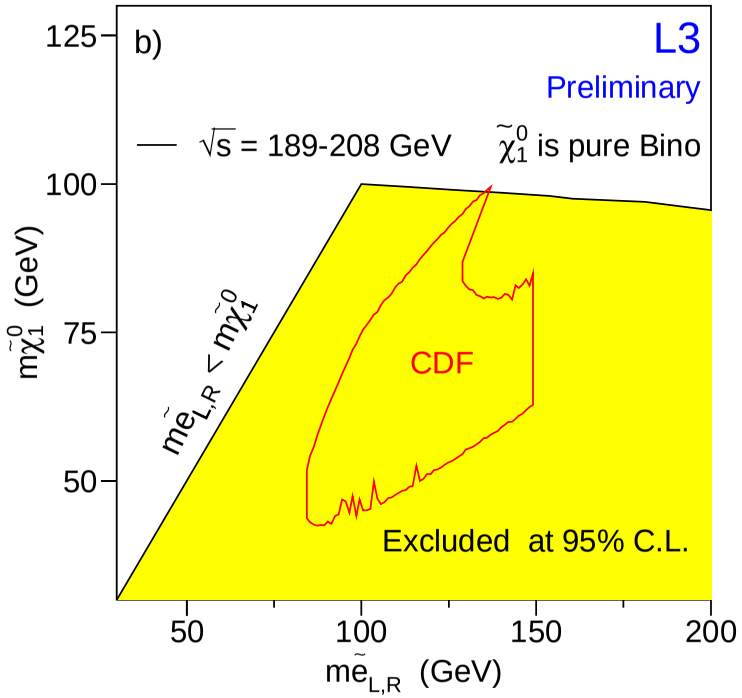




χ NLSP: No lifetime – Results

- No evidence for an excess $\Longrightarrow$ $m_{\tilde{\chi}_1^0} \gtrsim 99\ GeV/c^2$
- SUSY interpretation of the CDF event ruled out by LEP:
  Event: $2e{+}2\gamma{+}\not{E}$ (SM exp. $< 10^{-3}$ events)
  GMSB explanation: $q\bar{q} \rightarrow \tilde{e}\tilde{e} \rightarrow ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\gamma\gamma\tilde{G}\tilde{G}$
  Exploit t-channel dependence on $m_{\tilde{e}_R}$ for $\tilde{\chi}_1^0$ pairs @ LEP2

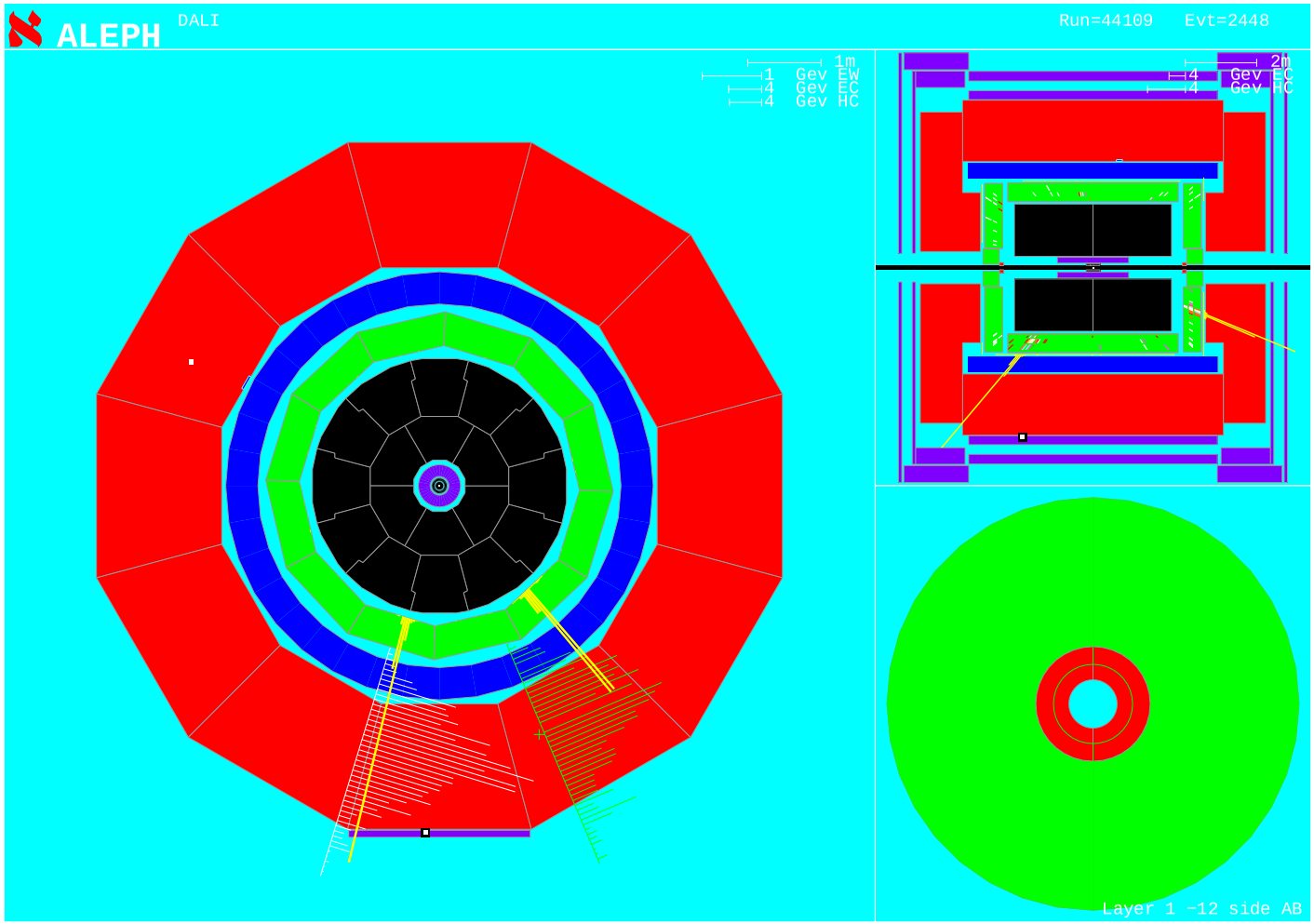




χ NLSP: No lifetime – a candidate

2 photon candidate ($\sqrt{s} = 189\ GeV$): $e^+e^- \rightarrow \tilde{\chi}_1^0\ \tilde{\chi}_1^0 \rightarrow \gamma\tilde{\mathrm{G}}\ \gamma\tilde{\mathrm{G}}$

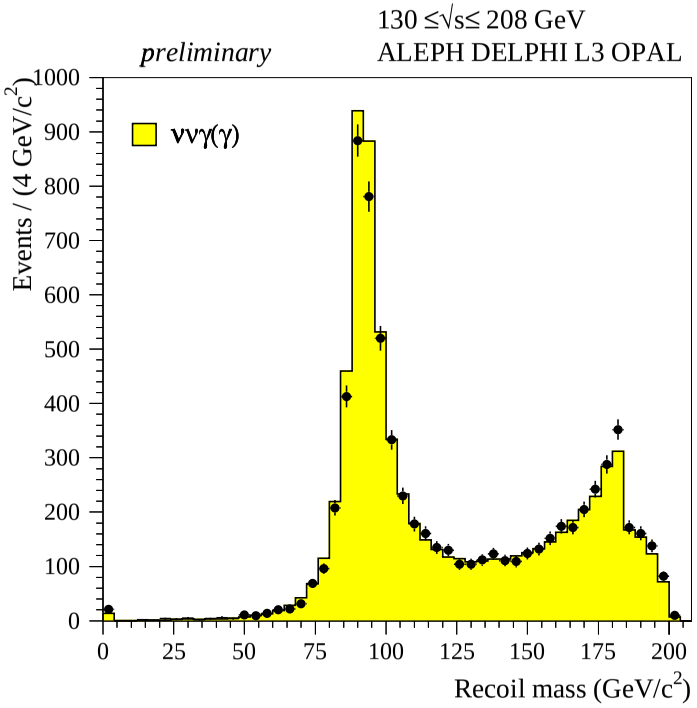
- Energy of photons: 45 and 43 GeV
- Visible mass: 75 GeV
- Recoil mass: 82 GeV
- Impact parameters: $\sim$ 5 cm

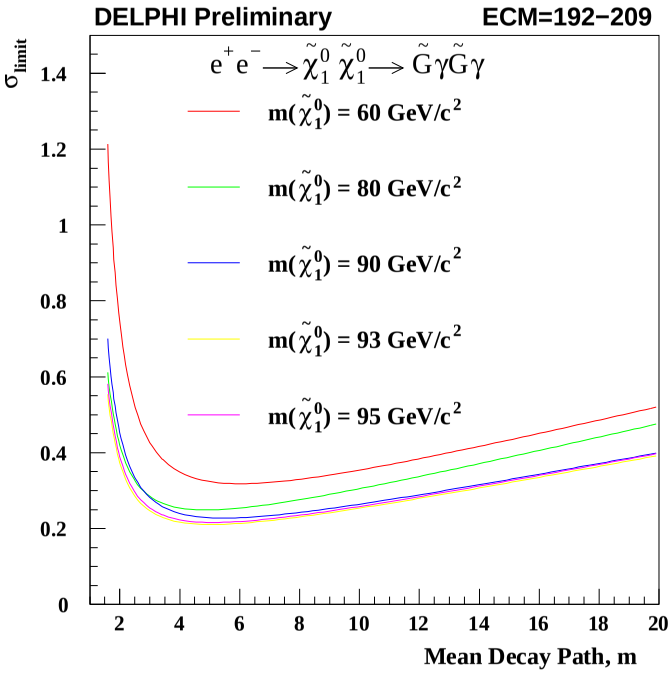


χ NLSP: Medium lifetime

Topology: Non pointing photon(s)
(unlikely that both χ decay inside the detector)

- Reconstruct impact parameter from EM shower axis
- Small deviations in the shape of the recoil mass distribution ...
- But good agreement in total number of events:
  7364 observed / 7502 expected (ADLO)





$\tilde{\ell}$ NLSP

Short $\tilde{\ell}$ lifetime: $c\tau < 1\ cm$ ➡ **2 acoplanar $\ell + \not{E}$**

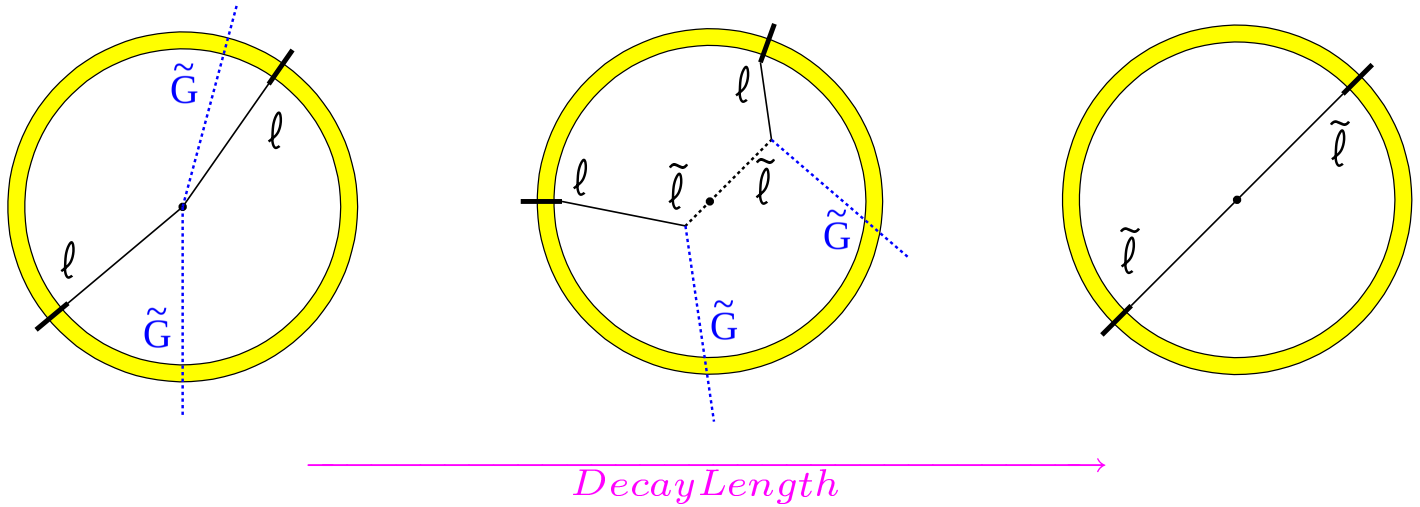
- Major bkg.: WW production, $\gamma\gamma$ processes

Medium $\tilde{\ell}$ lifetime: $c\tau \sim \ell_{detector}$ ➡ **kinks + large IP**

- Look for large Impact Parameter tracks ($1 \lesssim L \lesssim 40\ cm$) and kinked tracks ($10 \lesssim L \lesssim 200\ cm$)
- Major bkg.: cosmic rays, $\gamma\gamma$ and decays of K^0_s (large IP) and $K^{\pm}$ (kinks)

Long $\tilde{\ell}$ lifetime: $c\tau > \ell_{detector}$ ➡ **Heavy Stable Ch. part.**

- Two back to back particles: highly ionising tracks

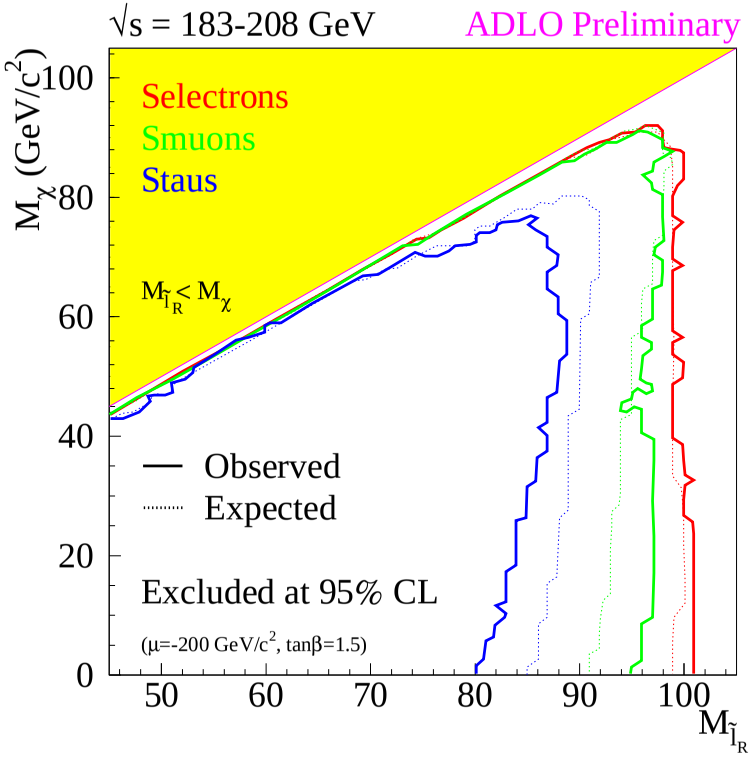


$\tilde{\ell}$ NLSP: Prompt decay

Topology: $e^+e^- \rightarrow \tilde{\ell}^+_R\tilde{\ell}^-_R \rightarrow \ell^+\ell^-\ \tilde{\mathrm{G}}\tilde{\mathrm{G}}$

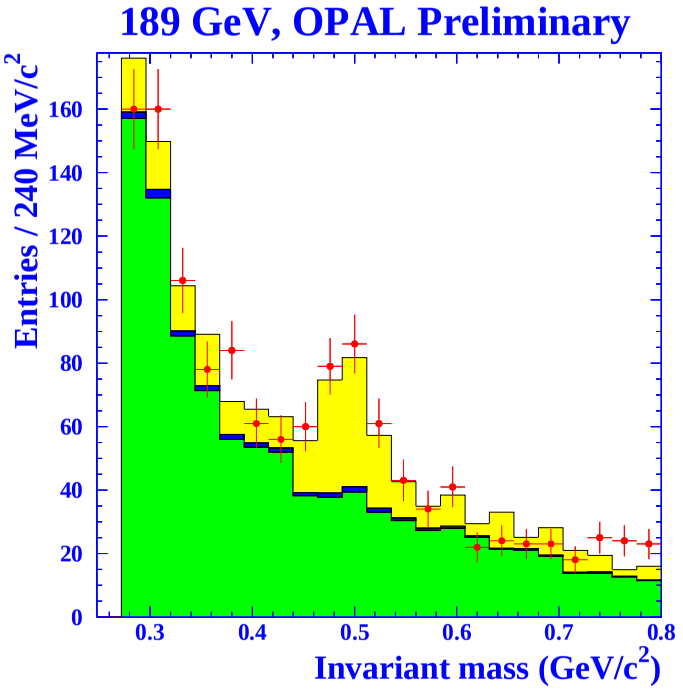
- Identical to $\tilde{\ell}^+_R\tilde{\ell}^-_R \rightarrow \ell^+\ell^-\ \tilde{\chi}^0_1\tilde{\chi}^0_1$ with $m_{\tilde{\chi}^0_1} \sim 0$ in SUGRA
- Search for two identified leptons and $\not{E}$
- No excess seen ... $\Longrightarrow$ put limits:

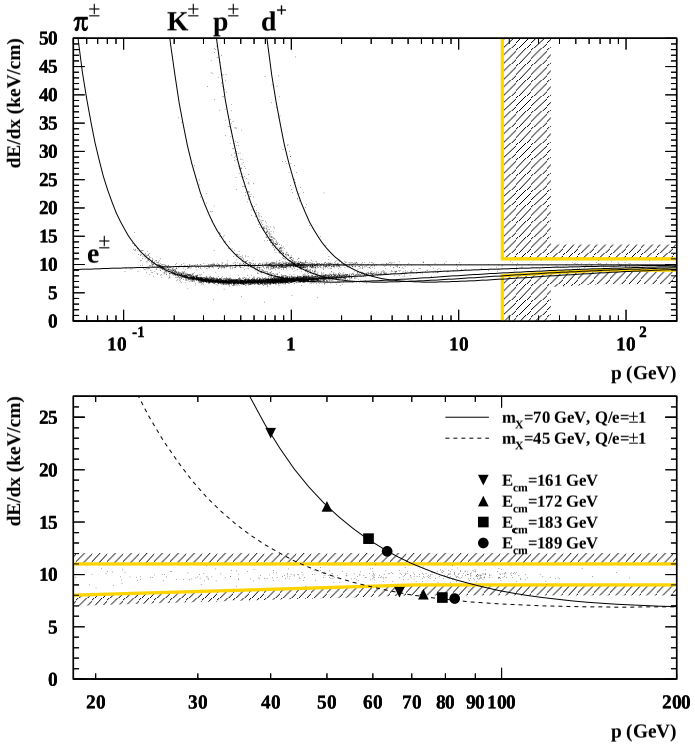
lower limits @ $m_\chi = 0$			
	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$
obs	100.5	95.4	80.0
exp	99.1	91.0	85.1



$\tilde{\ell}$ NLSP: Medium and long lifetime

- Slepton decays before reaching tracking devices $\longrightarrow$ large IP
  - ★ Require at least one (non-tau) track with $|d_0| > 1\ cm$
- Slepton decays in the tracking chamber $\longrightarrow$ kinked track
  - ★ Use kink angle and energy veto to discern from hard bremsstrahlung and hadronic interactions: $\pi^{\pm} \rightarrow \mu^{\pm}\nu$, $K^{\pm} \rightarrow \mu^{\pm}\nu$ or $\pi^{\pm}\pi^{0}$
- Heavy Stable Charged Particles (weakly interacting)
  - ★ High efficiency ($\sim 90\%$) & very low SM bkg

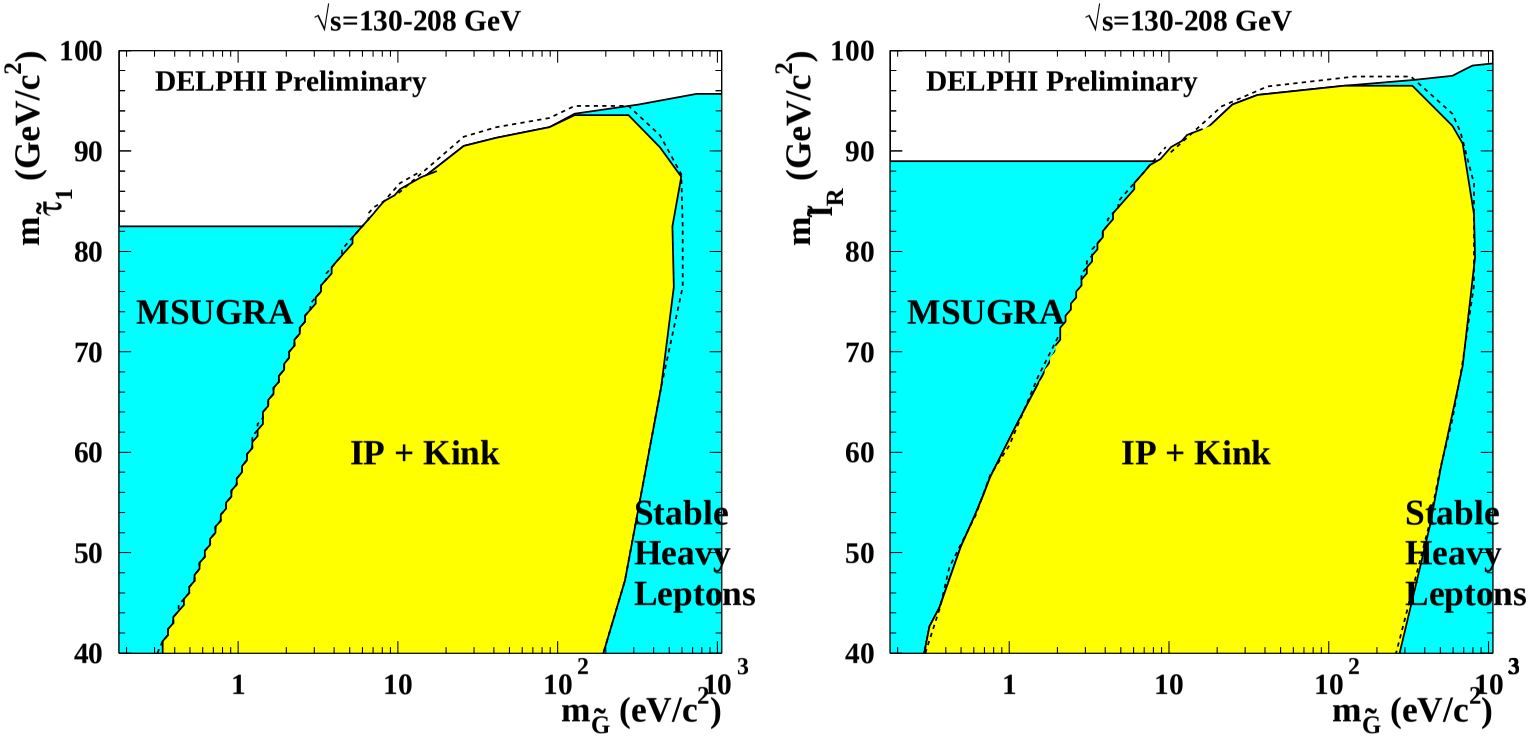




$\tilde{\ell}$ NLSP: Combined results

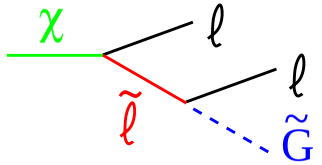
No excess in any channel $\Longrightarrow$
produce $\tilde{\ell}$ mass limit independent of lifetime (or $m_{\tilde{G}}$)
Two possibilitites: $\tilde{\tau}_1$ NLSP and $\tilde{\ell}$ co-NLSP

	A	D	L	0
$m_{\tilde{\tau}_1}$	79	82.2	63.5	84.6
$m_{\tilde{\ell}_R}$	91.7	89	84	93.8



$\tilde{\ell}$ NLSP: Cascade decays

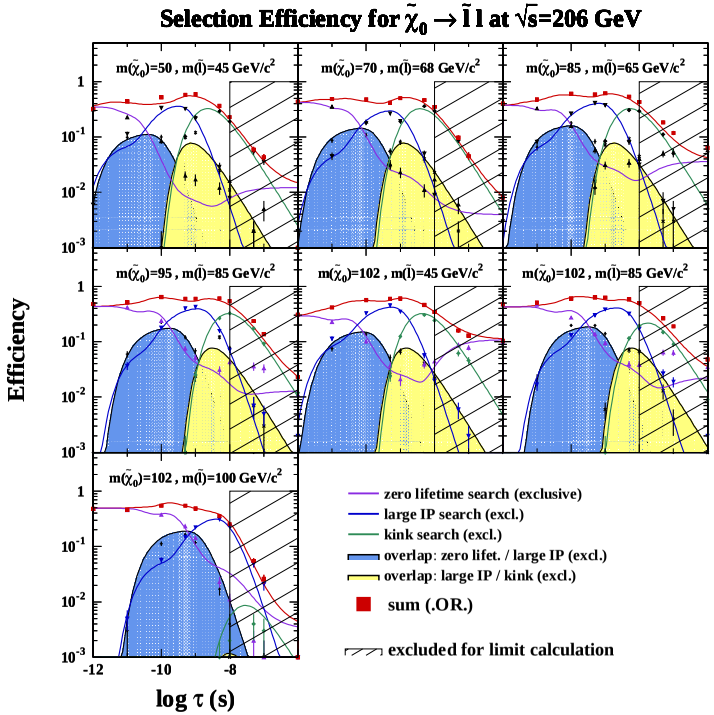
Study $e^+e^- \rightarrow \chi\chi$ with

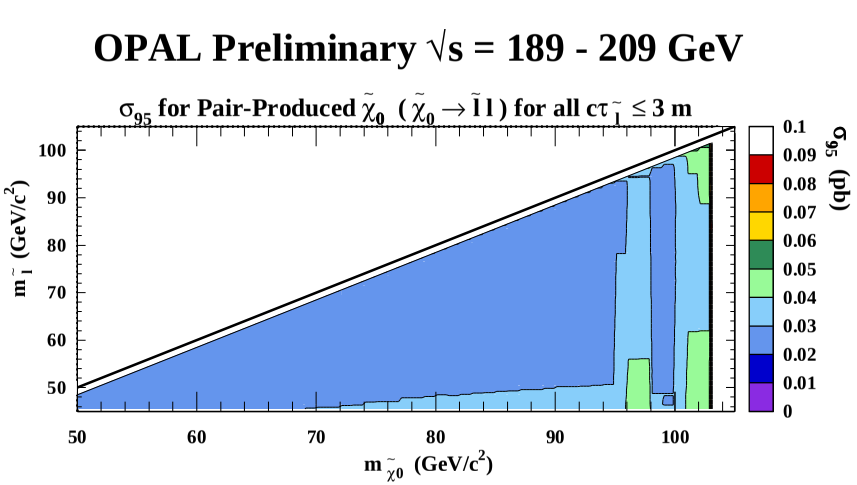


to benefit from larger ($\times$ 2) cross section

Topology: Final state with 4 lepton/tau + $\not{E}$

- Search for two energetic and two soft ℓ
  - ★ also new searches with lifetime: kinks or large IP
- χs decay independently $\rightarrow$ six selections: $\tilde{e}\tilde{e}$, $\tilde{\mu}\tilde{\mu}$, $\tilde{\tau}\tilde{\tau}$, $\tilde{e}\tilde{\mu}$, $\tilde{e}\tilde{\tau}$, $\tilde{\mu}\tilde{\tau}$
  - ★ Strong dependence on $\Delta M = m_{\chi} - m_{\tilde{\ell}}$
- No excess $\Rightarrow$ 95% C.L. limits on production cross section:





Other possibilities (DO)

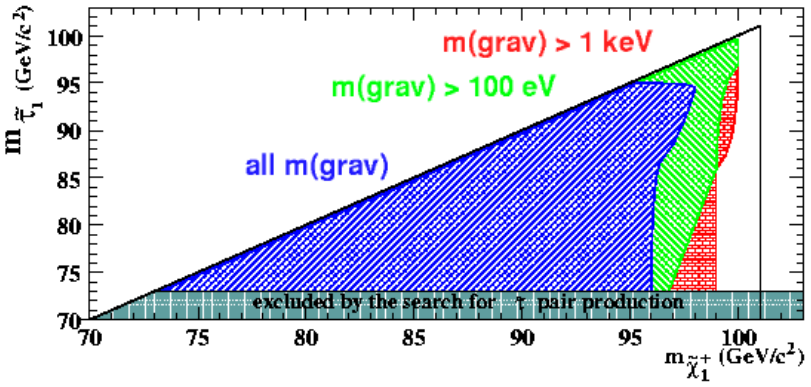
Charginos with $\tilde{\ell}$ NLSP: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\ell}^+\tilde{\ell}^-\nu\bar{\nu} \to \ell^+\ell^-\tilde{G}\tilde{G}\nu\bar{\nu}$

- Look for $2\,\ell + \not{E}$ like in SUGRA. Different kinematics in lifetime case
- $m_{\tilde{\chi}_1^\pm} > 95.2\ GeV/c^2$ at 95% C.L. for $\Delta M \geq 0.3\,GeV/c^2$

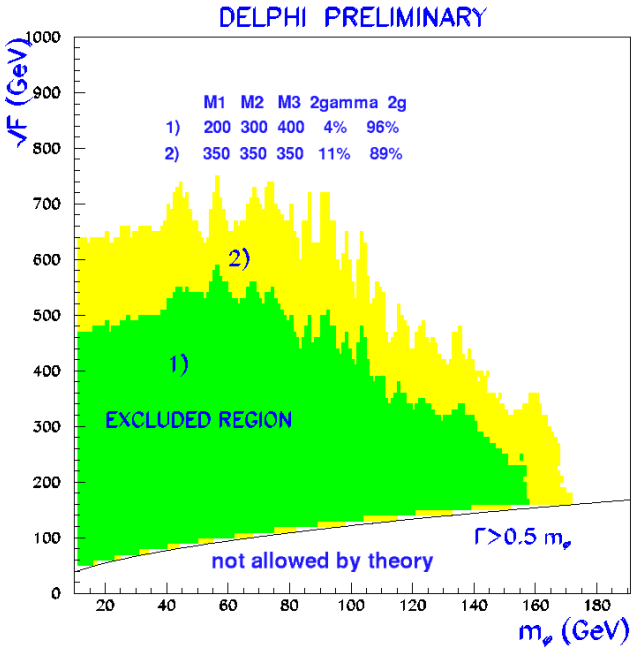
Sgoldstinos $e^+e^- \to S\gamma \to \begin{matrix}\gamma\gamma\gamma \\ gg\gamma\end{matrix}$

- For ultralight $\tilde{G}$ ($\Leftrightarrow$ $\sqrt{F}$ very small) $\to$ $\tilde{G}$ is mainly goldstino
- Search for its heavy SUSY partner: Sgoldstino S (+ monochr. γ)
- Not seen $\Rightarrow$ exclude $\sqrt{F} - m_S$ plane for different gaugino mass values

DELPHI $\sqrt{s}$=189-202



DELPHI $\sqrt{s}$=189-208



GMSB Interpretation

Perform scan over parameter space, eg:

Combine:

- ★ all lifetimes
- ★ all topologies
- ★ LEP1 searches
- ★ MSSM $\tilde{\ell}$ & $\tilde{\chi}^{\pm}$

$10^4 < M_{mess} < 10^{12}$ GeV

$0.1 < M_{\tilde{G}} < 10^5$ eV

$1 < \Lambda < 90$ TeV

$1.5 < \tan\beta < 40$

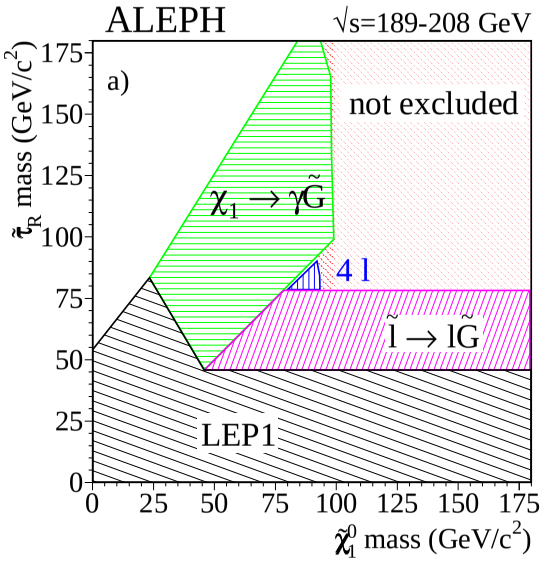
$1 < N_5 < 5$

sign(μ)=± 1

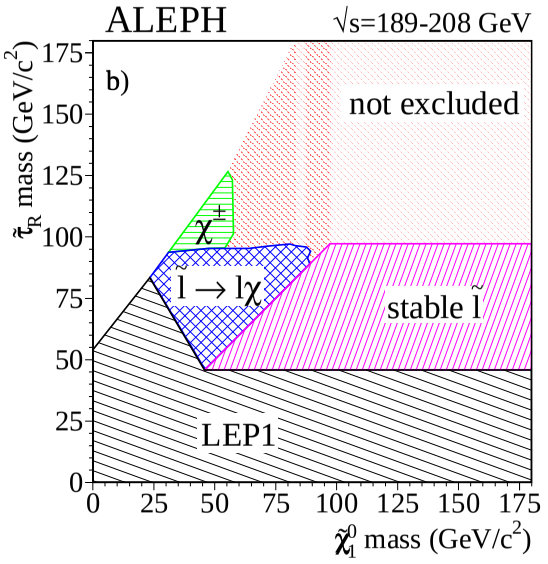
Absolute (indirect) lower mass limit on the NLSP:

$M_{NLSP} > 54\ GeV/c^2$ (independent of lifetime)

short lifetimes ($m_{\tilde{G}} \leq 10$ eV)



long lifetimes ($m_{\tilde{G}} \geq 1$ keV)



GMSB Interpretation

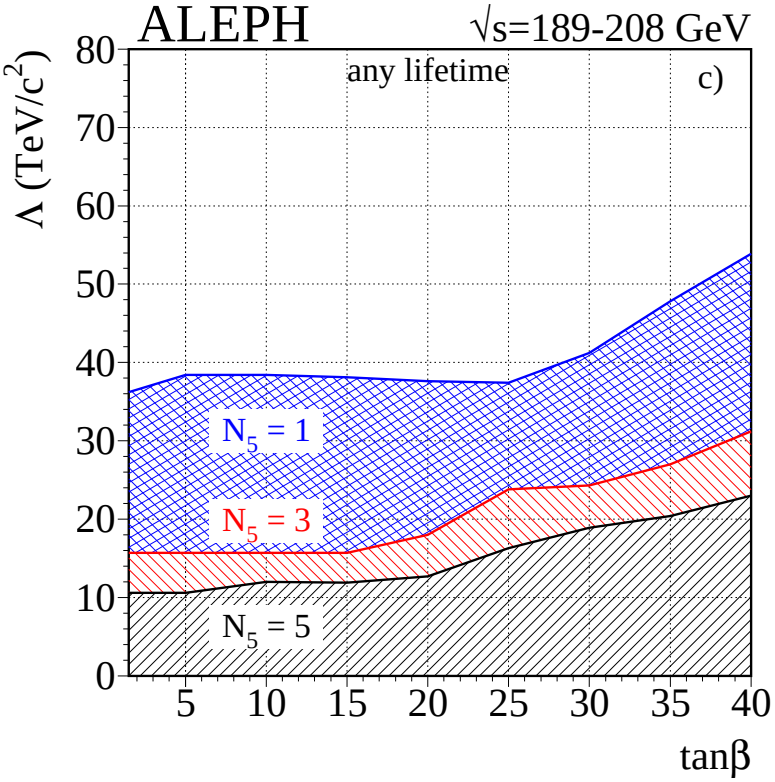
Gaugino and sfermion masses depend on Λ and N_5

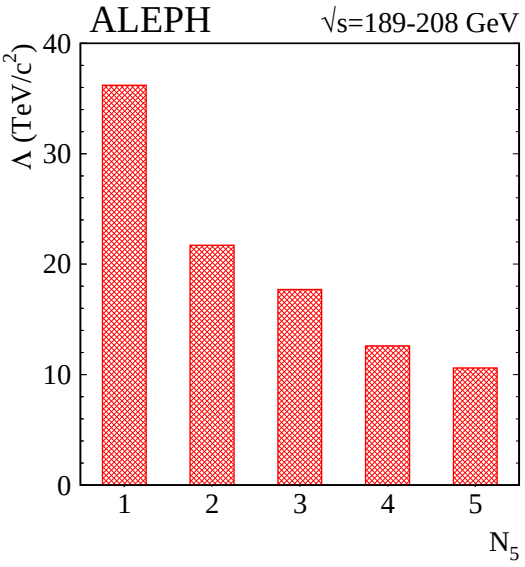
$M_\lambda \propto N_5\Lambda$

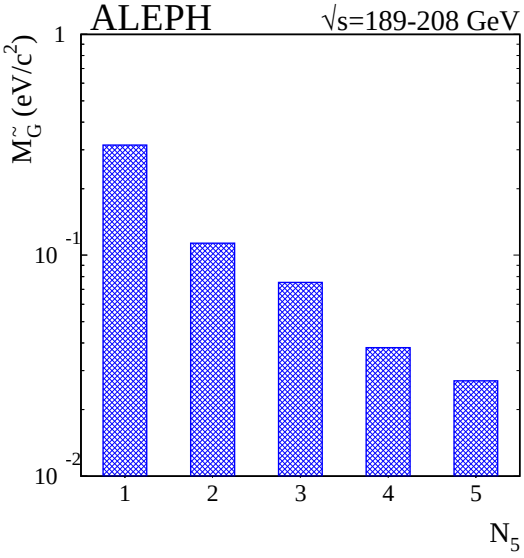
$M^2_{\tilde{f}} \propto N_5\Lambda^2$

→ Λ controls the mass scale of SUSY particles

→ Set a model dependent limit on Λ :







$\Lambda > 10\ TeV/c^2$ → $M_{\tilde{G}} > 0.024\ eV/c^2$

AMSB

SUSY Breaking is mediated by anomalies in gravity

★ No need for Messenger Sector + FCNC suppressed for free

AMSB is very predictive: $\mathbf{m_{3/2}}$, $\mathbf{m_0}$, $\tan\beta$ **and sign**(μ)

Furthermore: $\mathrm{M}_i^{AMSB} \sim m_{3/2}\frac{\alpha_i}{4\pi}$ while $\mathrm{M}_i^{SUGRA} \sim m_{3/2}$

- Chargino nearly mass degenerate with the lightest neutralino
- $\boxed{\mathbf{m}_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0}}$ can occur if:
  - ★ $M_2 \lesssim M_1 \ll |\mu| \rightarrow \mathrm{m}_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} \sim M_2 \rightarrow$ gaugino-like
  - ★ $|\mu| \ll M_{1,2} \rightarrow \mathrm{m}_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} \sim |\mu| \rightarrow$ higgsino-like
  - ★ $M_1 \gg M_2$
- Problem: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$X (with X very soft system)
  - ★ trigger efficiency very low & huge $\gamma\gamma$ background
- Solution: require an **ISR** $\gamma \Rightarrow e^+e^- \rightarrow \gamma\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \gamma\tilde{\chi}_1^0\tilde{\chi}_1^0 X$
  - ★ trigger event by the energetic ISR γ, and get rid of $\gamma\gamma$ events by:
  - ★ imposing $\mathrm{E}_T(\gamma_{ISR}) \gtrsim \sqrt{s}\frac{\sin\theta_{min}}{1+\sin\theta_{min}}$ and no low-angle beam electron

  (θ_{min} = minimum polar angle to detect electron)

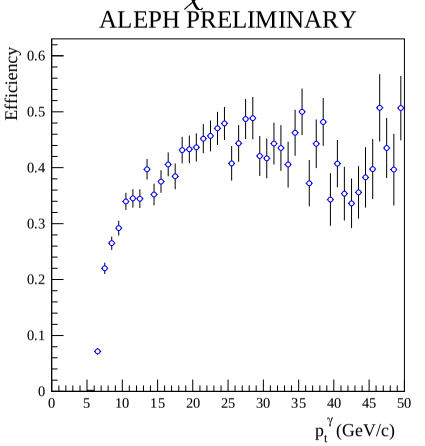
AMSB – Results

lower 95% C.L. limit on $m_{\tilde{\chi}^{\pm}}$ for heavy $\tilde{\nu}$

	A	D	L	O
gaugino	91	74	87.6	91
higgsino	89	82	84.7	-

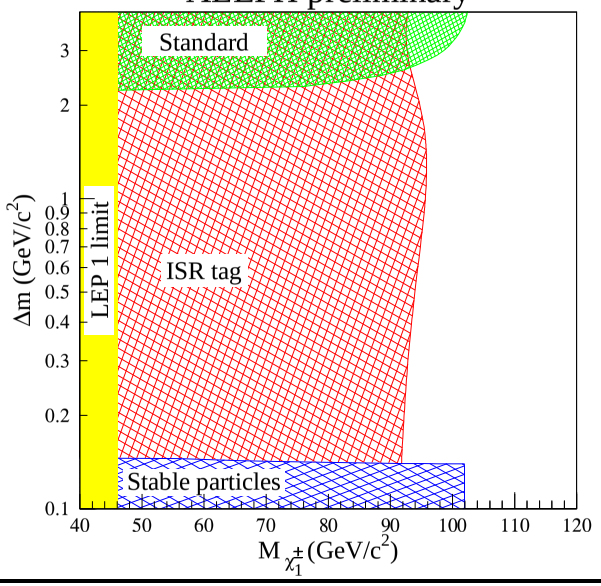
Eff @ 189 GeV

p_t^{γ} $(46 < m_{\tilde{\chi}^{\pm}} < 91$ GeV)



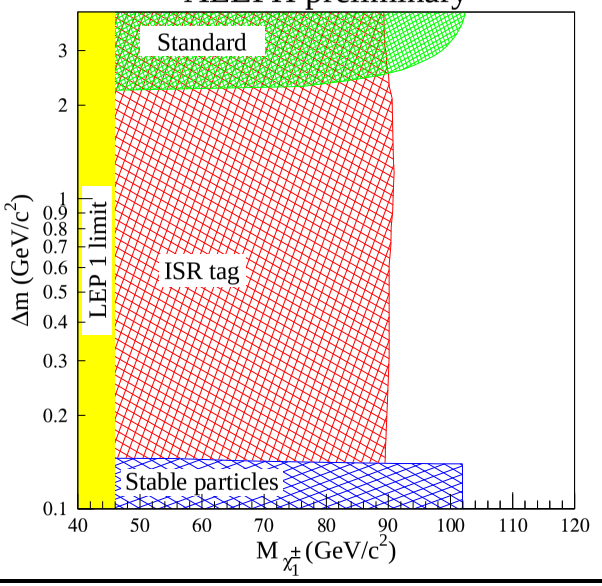
Gaugino region

$\sqrt{s}$=189-209 GeV



Higgsino region

$\sqrt{s}$=189-209 GeV



Conclusions

- No hint for alternative SUSY at LEP
- Many different topologies have been studied up to the highest energies in GMSB and AMSB scenarios (some not mentioned here)
- Now covering all lifetimes and most of the parameter space
- (almost) Independent limits on the NLSP mass and the gravitino mass are set
- Still working on final results and GMSB LEP combination to come soon
- Many thanks to the LEP collaborations and the LEP SUSY WG for their help