

7th TOPICAL SEMINAR ON
THE LEGACY OF LEP AND SLC
Siena, 8-11 October 2001

Search for GMSB and AMSB



Outline

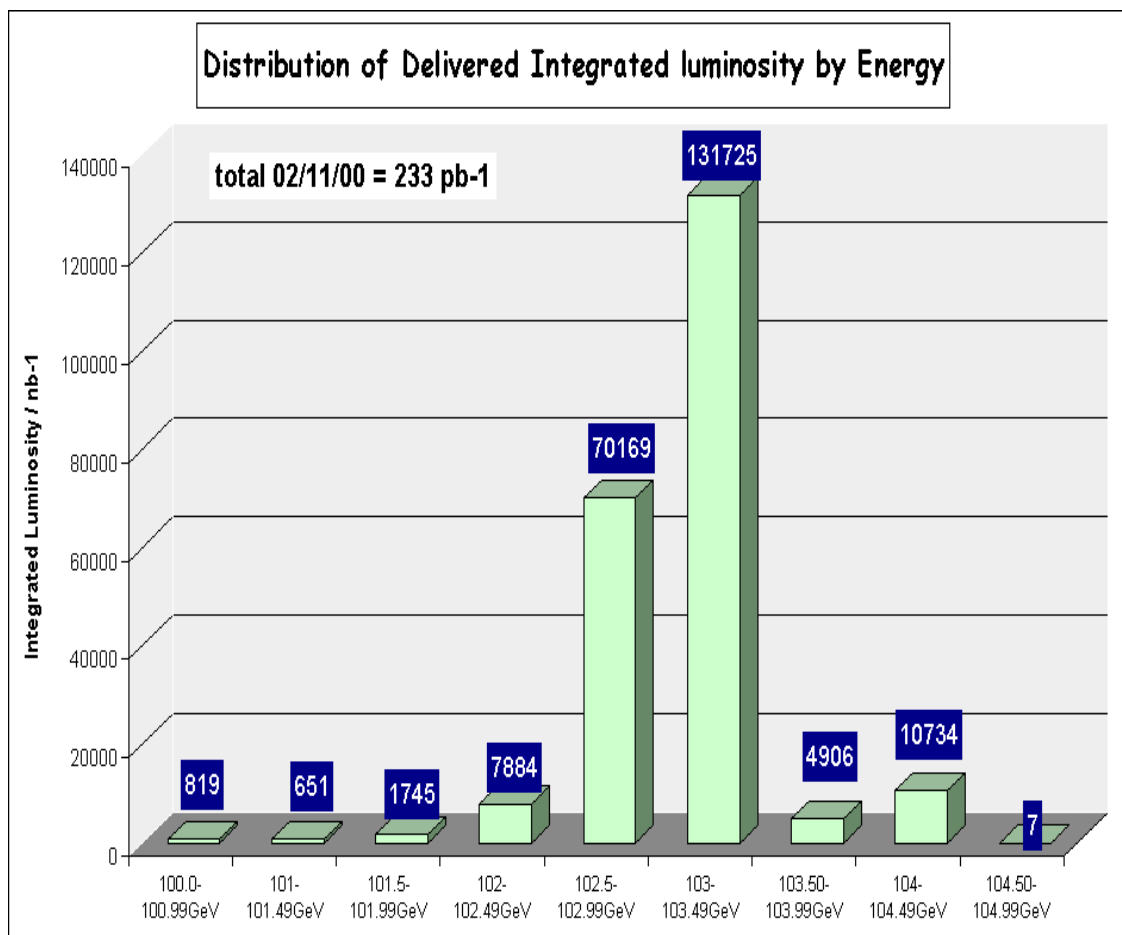
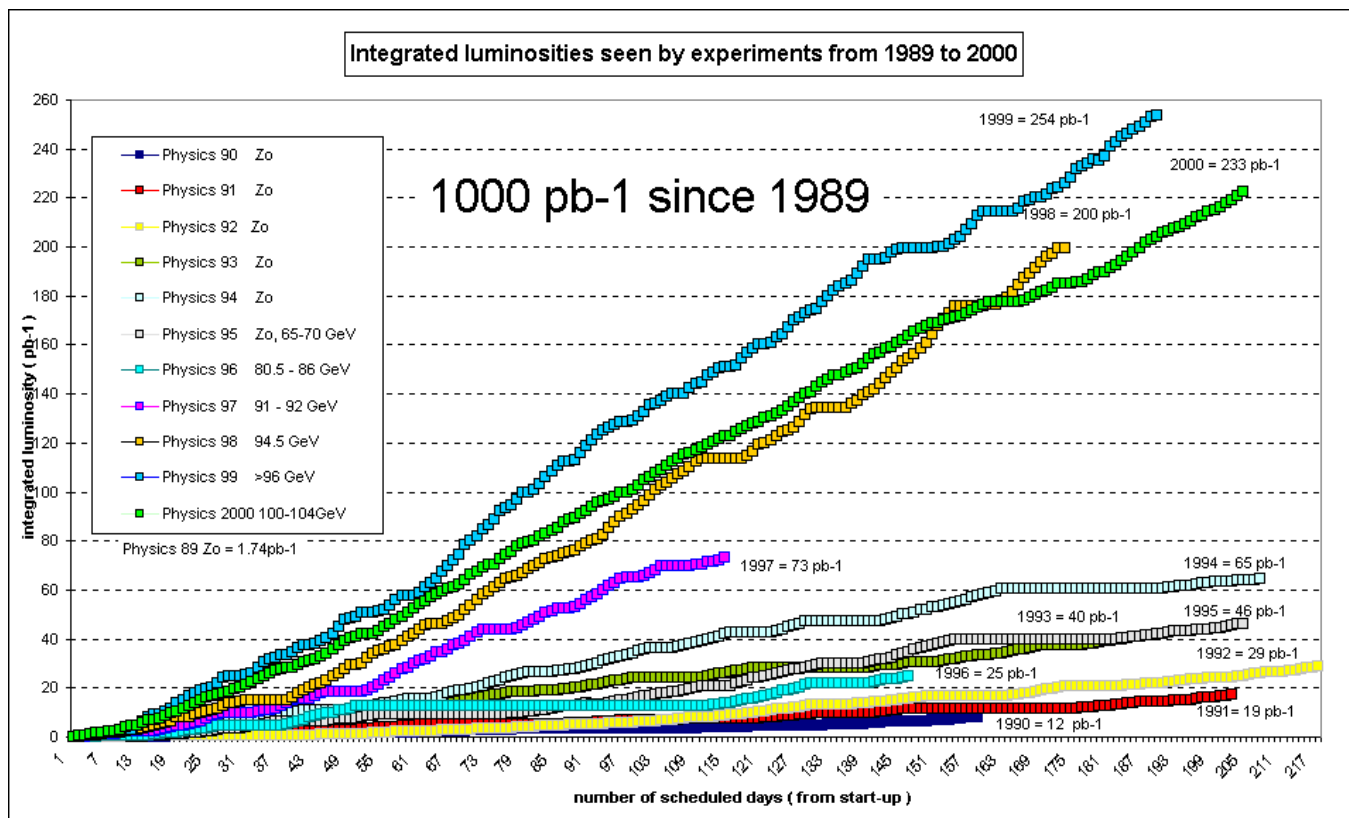
- Supersymmetry Breaking
- GMSB phenomenology
- GMSB searches results & interpretation
- AMSB
- Conclusions



Arán García-Bellido



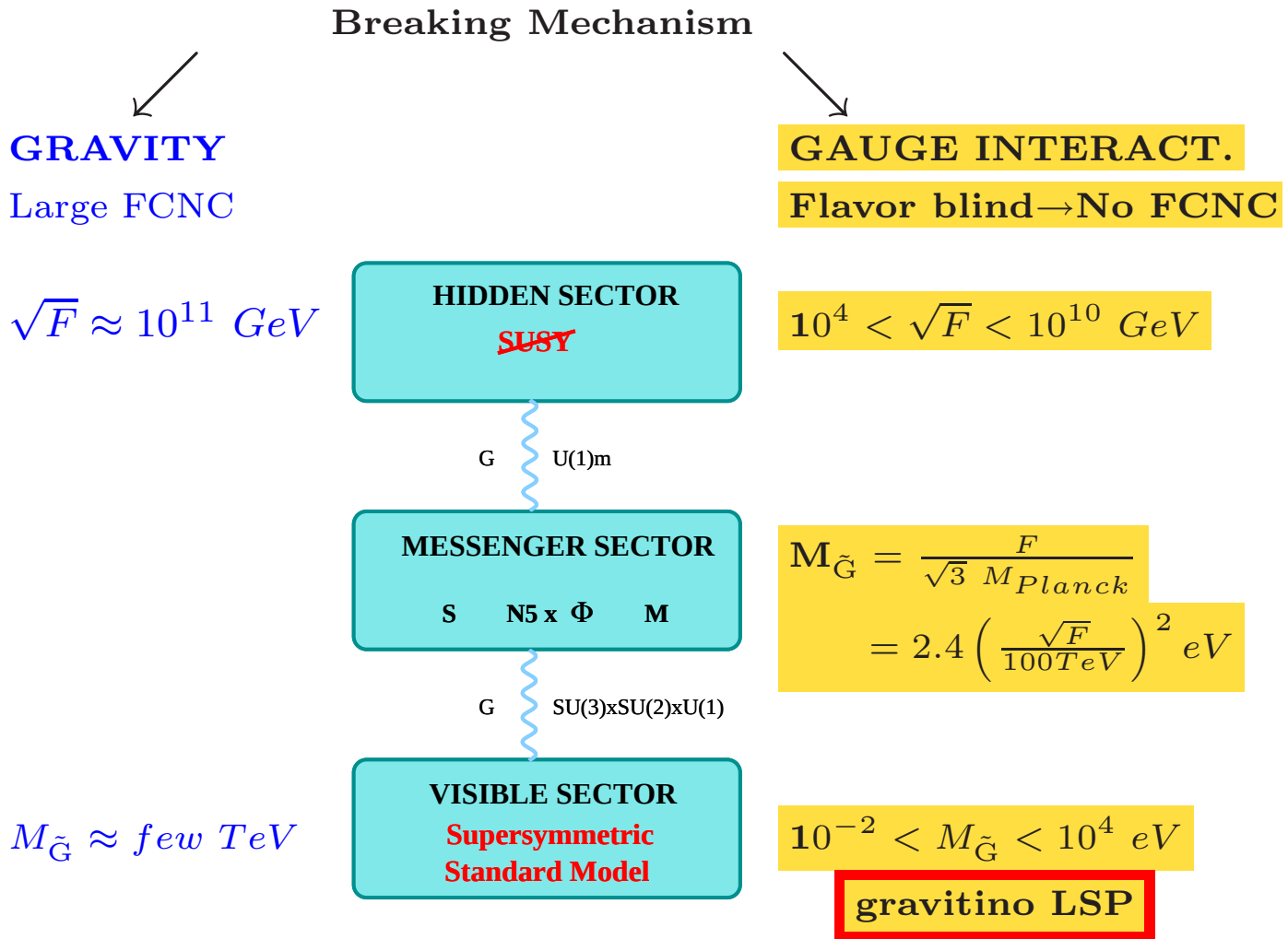
The LEP Dataset



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

$\text{sign}(\mu)$ sign of Higgs sector mixing parameter

GMSB phenomenology

- $\tilde{G}$ is the LSP:
- $10^{-2} \text{ eV} \lesssim M_{\tilde{G}} \lesssim 3 \text{ keV}$
-
- $$NLSP = \begin{cases} \chi & \rightarrow \gamma \tilde{G} \\ \tilde{\ell} & \rightarrow \ell \tilde{G} \end{cases}$$
- $\tilde{\tau}_R$ and $\tilde{\tau}_L$ mix $\Rightarrow \tilde{\tau}_1$ NLSP (large $\tan \beta$)
- Decay length of the NLSP:

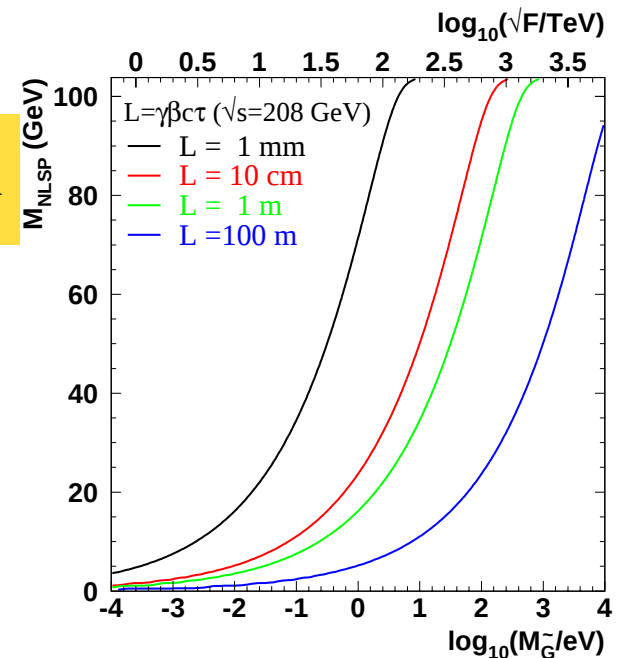
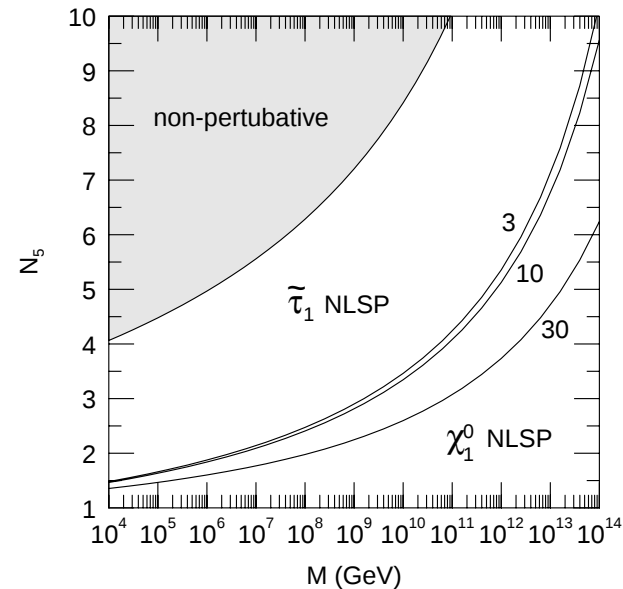
$$c\tau \approx \frac{0.01}{\kappa_\gamma} \left(\frac{100 \text{ GeV}}{M_{NLSP}} \right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \text{ cm}$$

($\kappa_\gamma = 1$ for $\tilde{\ell}$ NLSP)

Signatures depend on the NLSP type and NLSP decay length



Many different topologies!



χ NLSP

Short χ lifetime: $c\tau < 1 \text{ cm}$

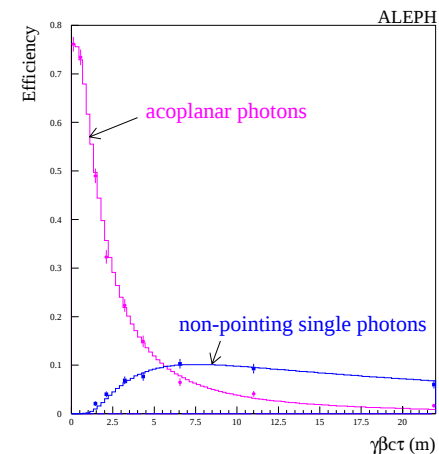
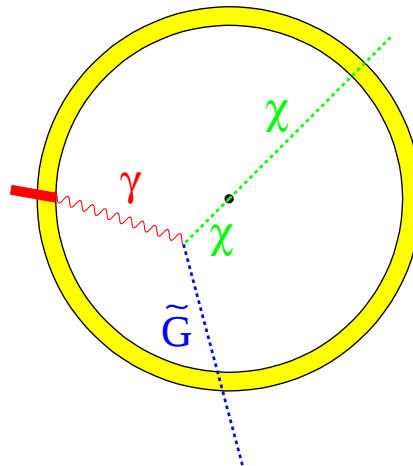
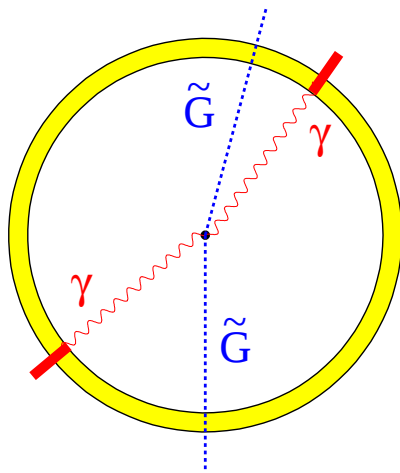
➔ **Two acoplanar γ**

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

Medium χ lifetime: $c\tau \sim \ell_{detector}$

➔ **Non pointing $\gamma(s)$**

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

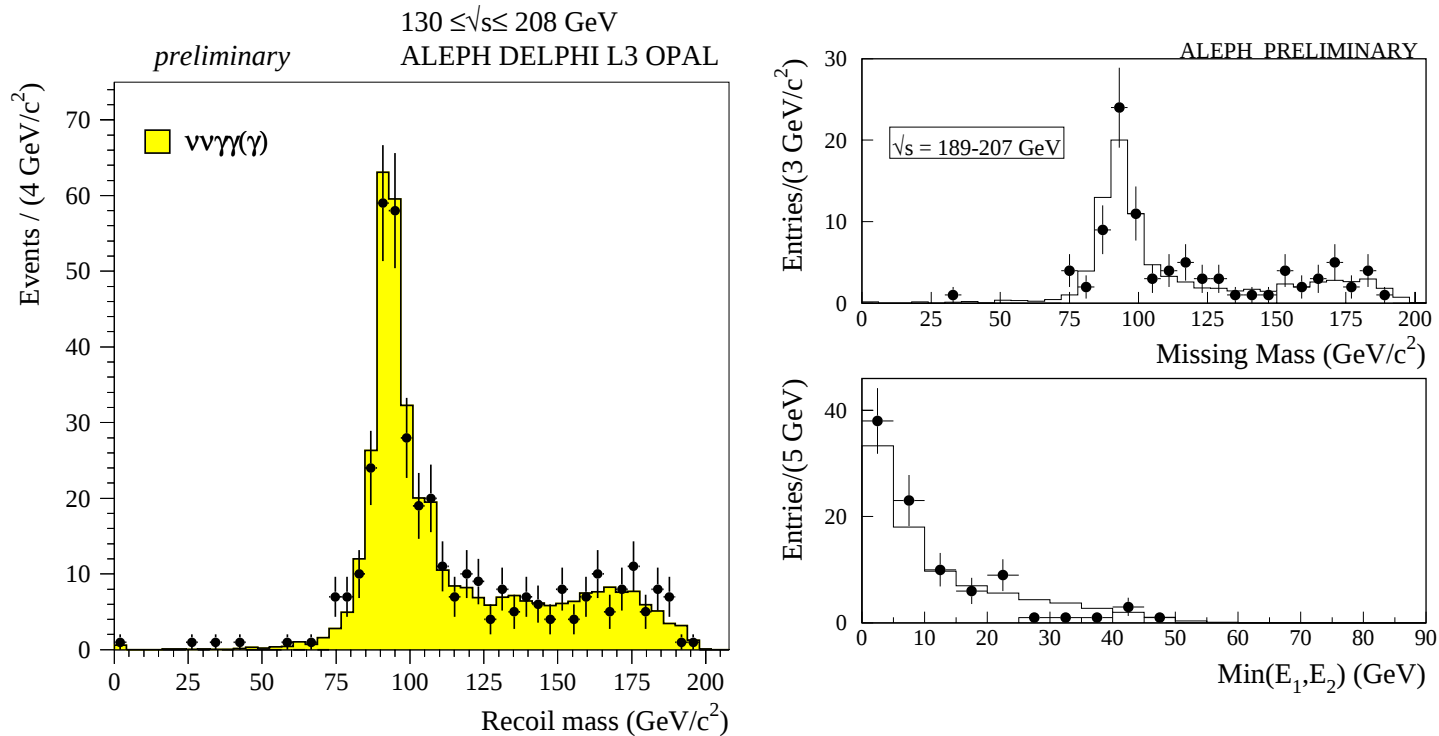


☞ If $c\tau > \ell_{detector}$: Indirect limits from ‘standard’ $\tilde{\ell}$ and $\tilde{\chi}^\pm$ searches

χ NLSP: No lifetime

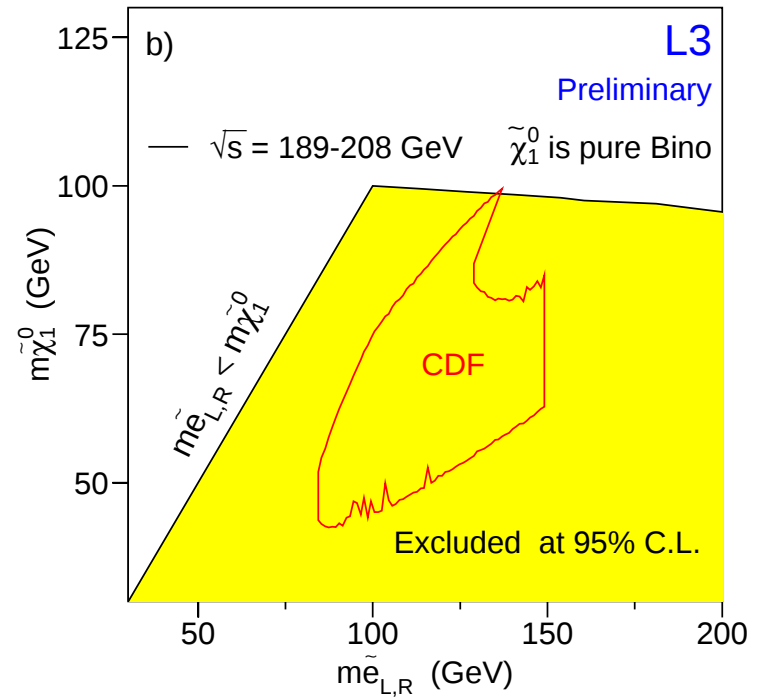
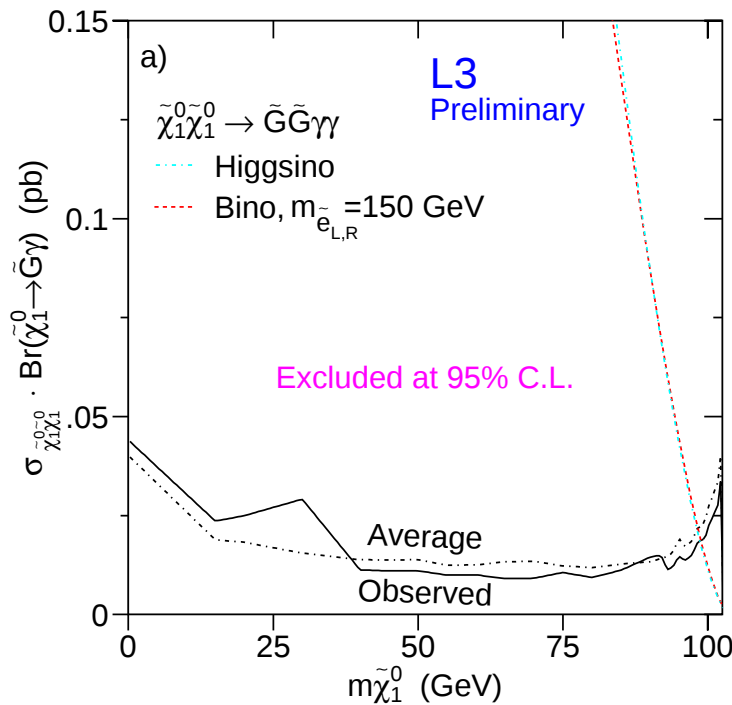
Topology: two acoplanar photons pointing to the vertex and $\cancel{E}$

- Events with no charged tracks (except from conversions) and significant $\cancel{E}$
- 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

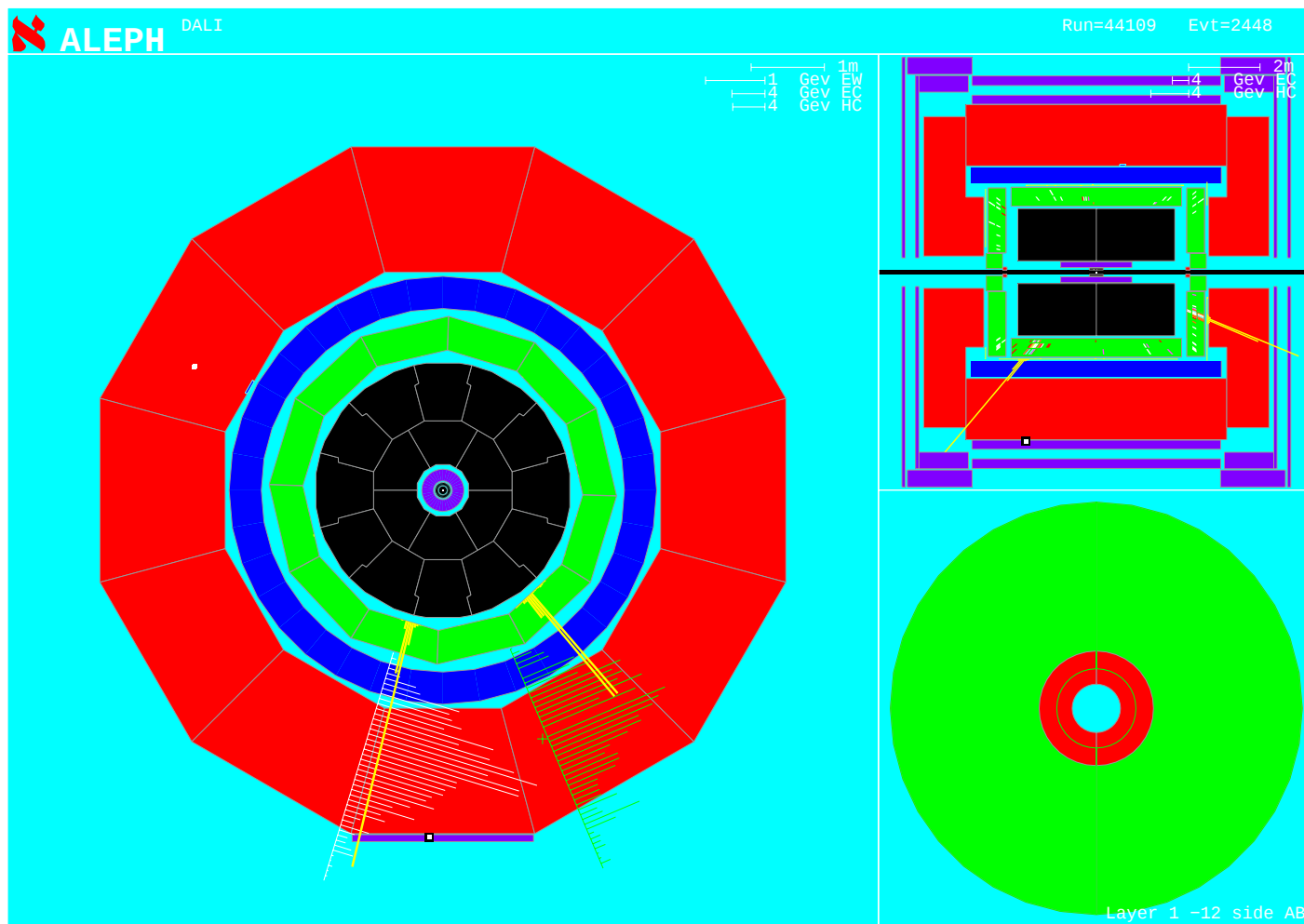
- No evidence for an excess $\Rightarrow m_{\tilde{\chi}_1^0} \gtrsim 99 \text{ GeV}/c^2$
- SUSY interpretation of the CDF event ruled out by LEP:
 Event: $2e+2\gamma+\cancel{E}$ (SM exp. $< 10^{-3}$ events)
 GMSB explanation: $q\bar{q} \rightarrow \tilde{e}\tilde{e} \rightarrow ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\gamma\gamma\tilde{G}\tilde{G}$
 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 ($\sqrt{s} = 189 \text{ GeV}$): $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \gamma \tilde{G}$

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

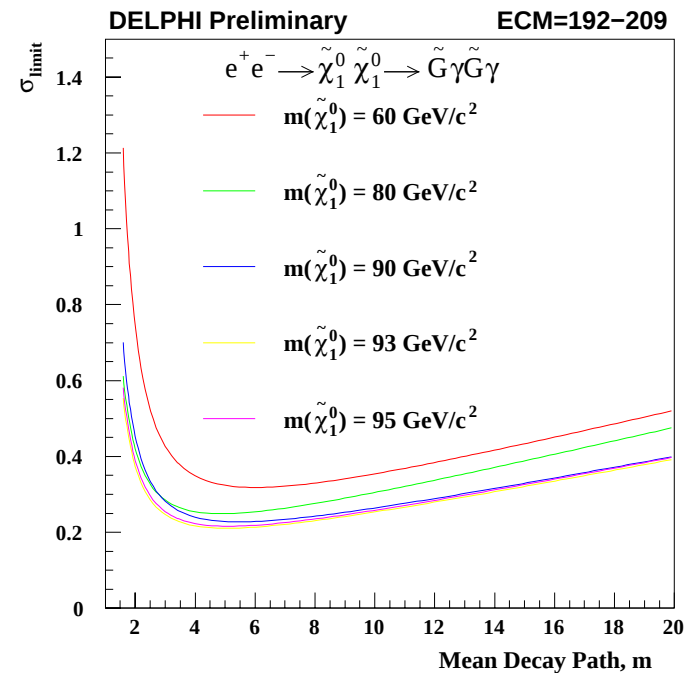
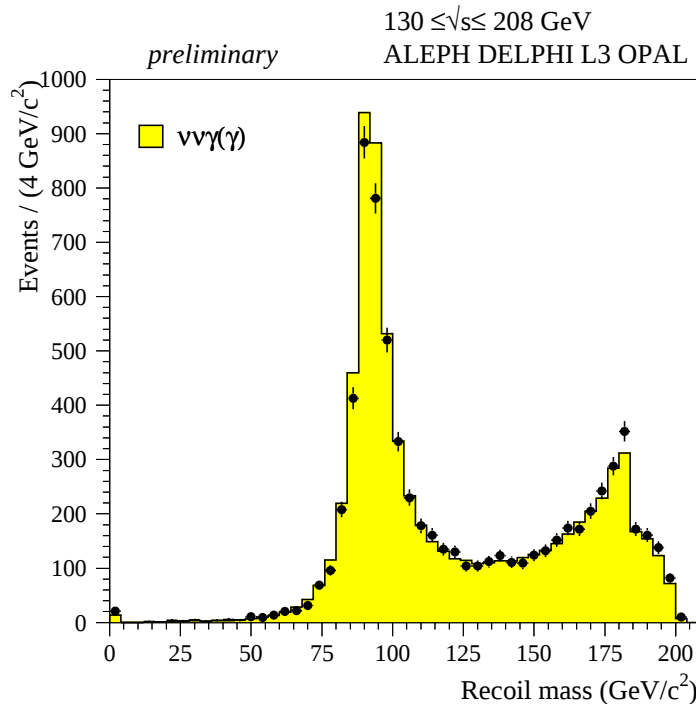


χ NLSP: Medium lifetime

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: $c\tau < 1 \text{ cm}$ $\Rightarrow$ 2 acoplanar $\ell + \cancel{E}$

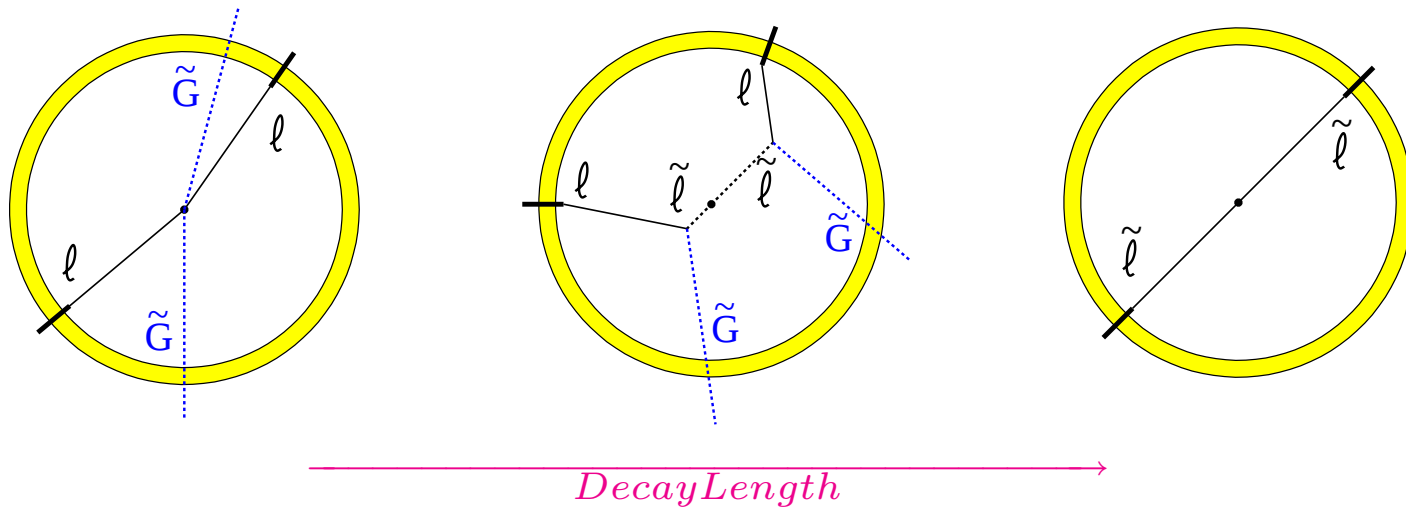
- Major bkg.: WW production, $\gamma\gamma$ processes

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

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

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

- Two back to back particles: highly ionising tracks

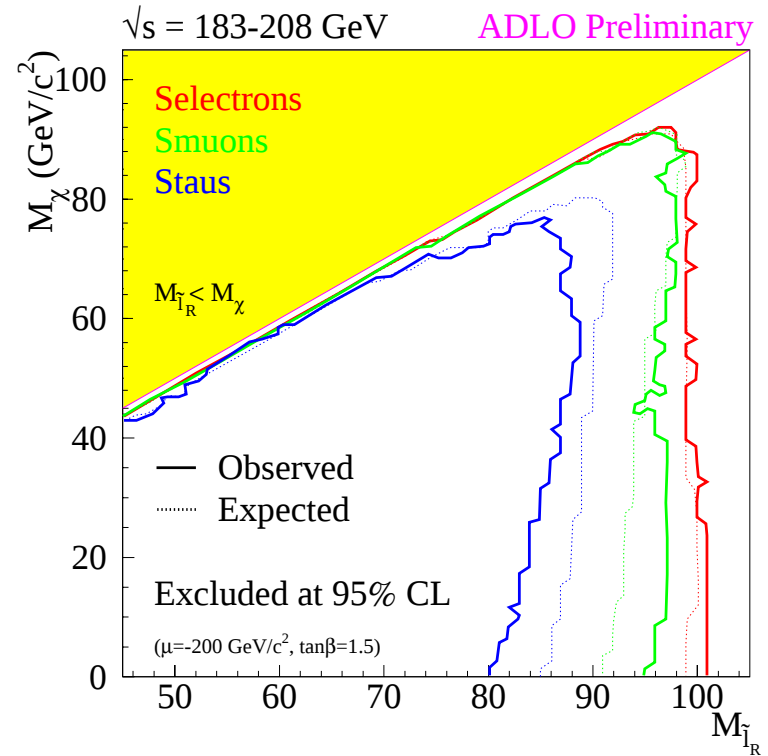


$\tilde{\ell}$ NLSP: Prompt decay

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

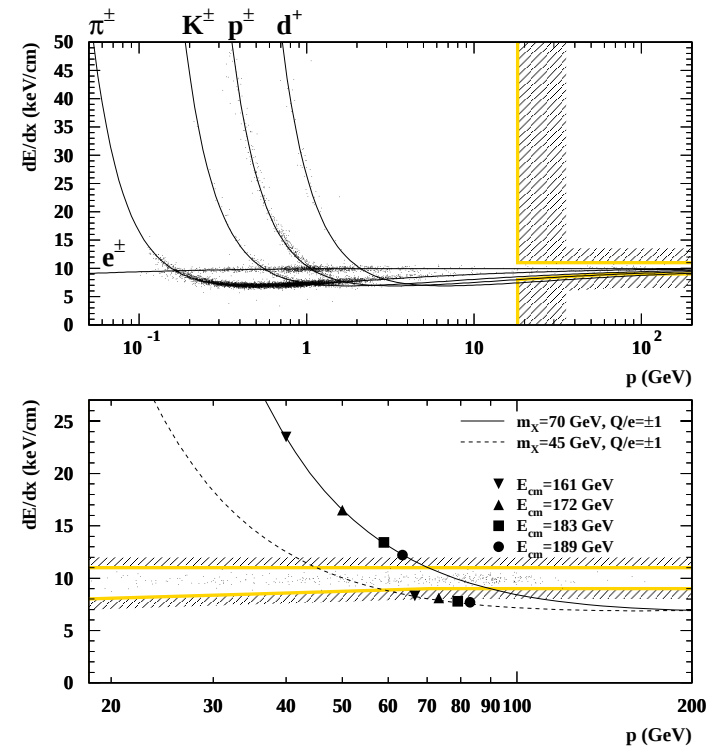
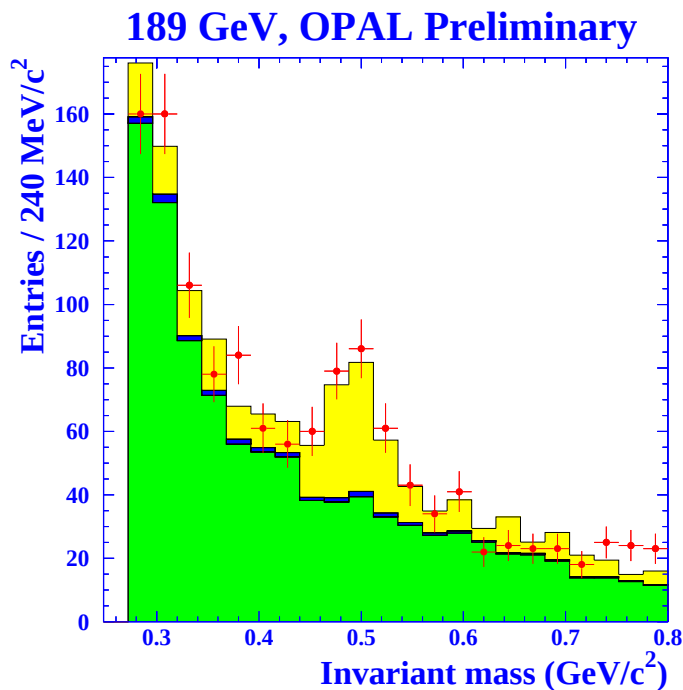
- Identical to $\tilde{\ell}_R^+ \tilde{\ell}_R^- \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$ with $m_{\tilde{\chi}_1^0} \sim 0$ in SUGRA
- Search for two identified leptons and $\cancel{E}$
- No excess seen ... $\Rightarrow$ put limits:

	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 $|d_0| > 1 \text{ cm}$
- 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



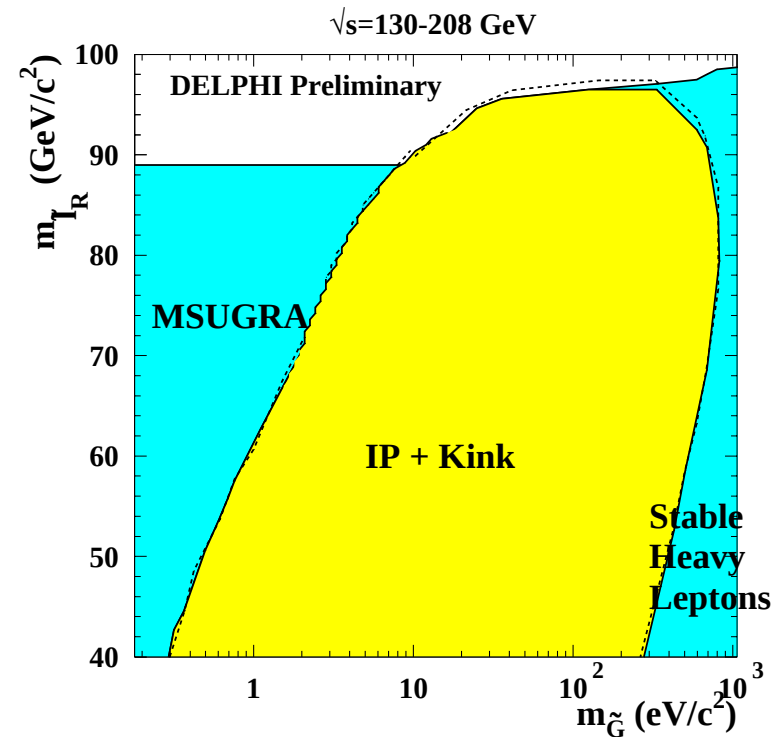
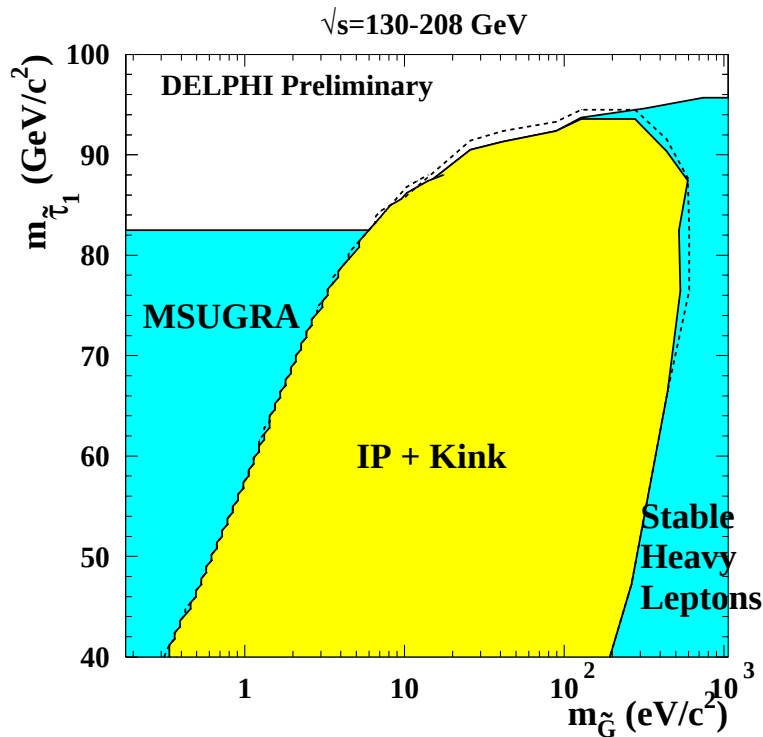
$\tilde{\ell}$ NLSP: Combined results

No excess in any channel $\Rightarrow$

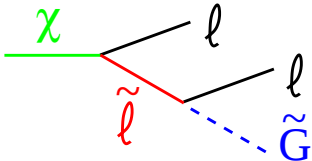
produce $\tilde{\ell}$ mass limit independent of lifetime (or $m_{\tilde{G}}$)

Two possibilities: $\tilde{\tau}_1$ 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

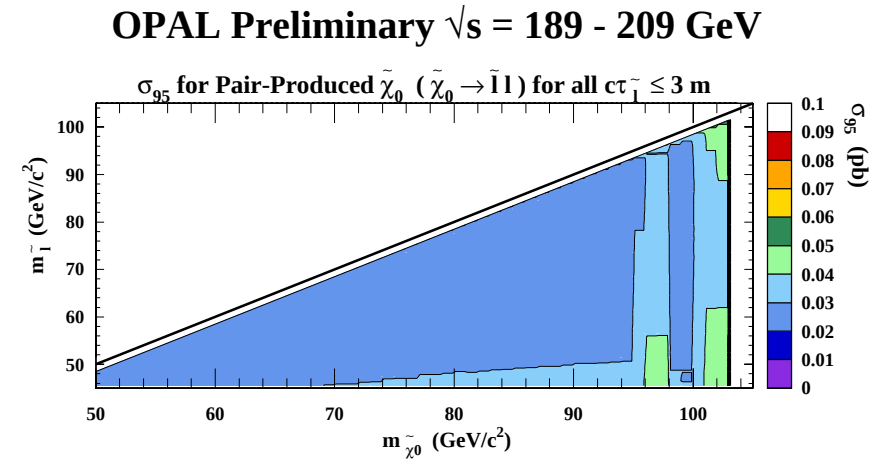
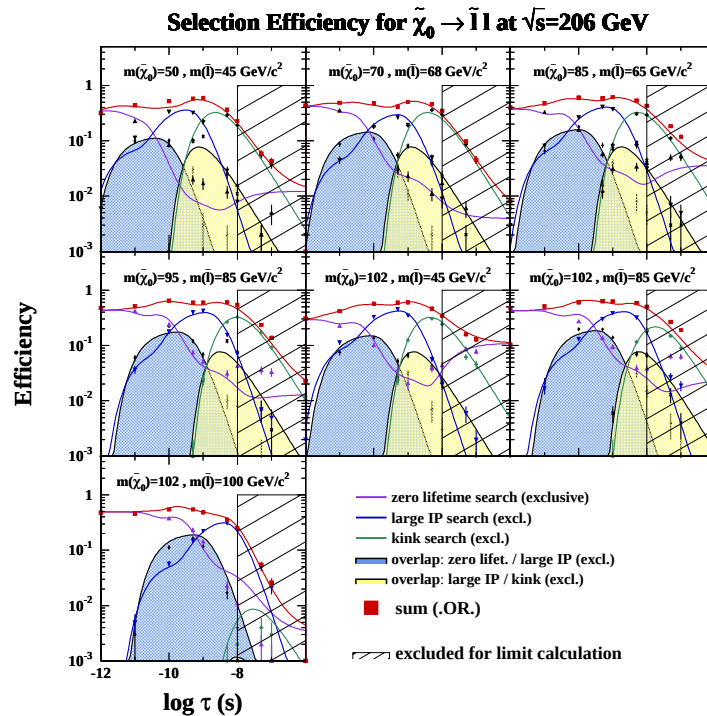


$\tilde{\ell}$ NLSP: Cascade decays

Study $e^+e^- \rightarrow \chi\chi$ with  to benefit from larger
($\times 2$) cross section

Topology: Final state with 4 lepton/tau + $\cancel{E}$

- Search for two energetic and two soft ℓ
★ also new searches with lifetime: kinks or large IP
- χ s 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)

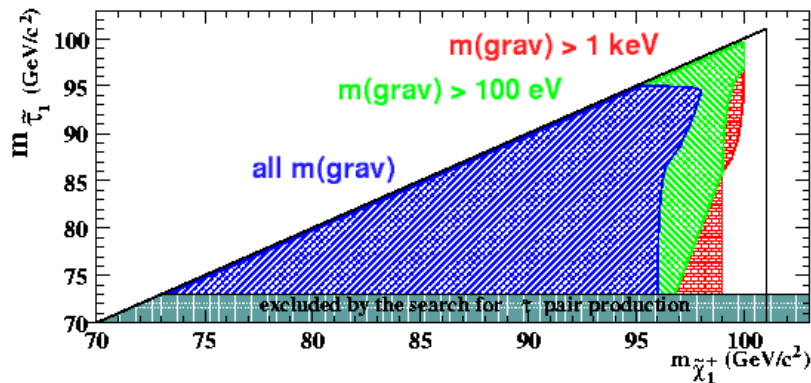
Charginos with $\tilde{\ell}$ NLSP: $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^- \nu \bar{\nu} \rightarrow \ell^+ \ell^- \tilde{G} \tilde{G} \nu \bar{\nu}$

- Look for $2\ell + \cancel{E}$ like in SUGRA. Different kinematics in lifetime case
- $m_{\tilde{\chi}_1^\pm} > 95.2 \text{ GeV}/c^2$ at 95% C.L. for $\Delta M \geq 0.3 \text{ GeV}/c^2$

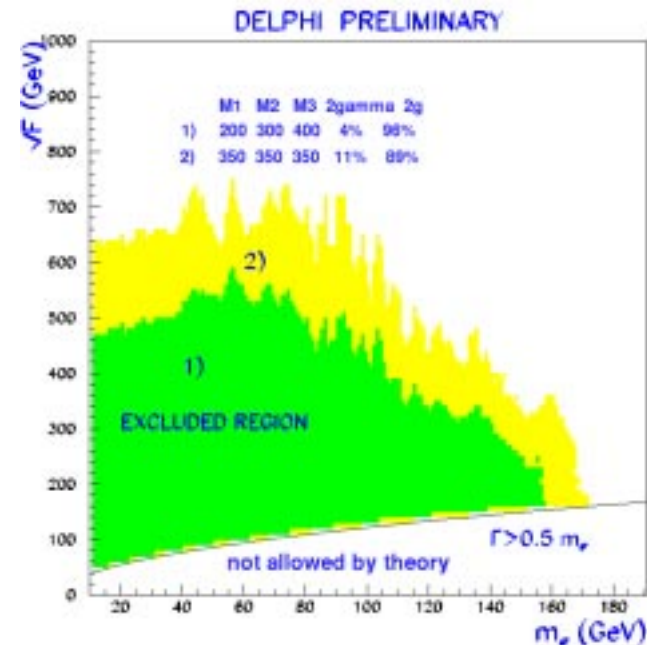
Sgoldstinos $e^+e^- \rightarrow S\gamma \rightarrow \begin{matrix} \gamma\gamma\gamma \\ gg\gamma \end{matrix}$

- For ultralight $\tilde{G}$ ($\Leftrightarrow \sqrt{F}$ very small) $\rightarrow \tilde{G}$ 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 $\sqrt{s}=189\text{-}202$



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



GMSB Interpretation

Perform scan over parameter space, eg:

Combine:

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

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

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

$$1 < \Lambda < 90 \text{ TeV}$$

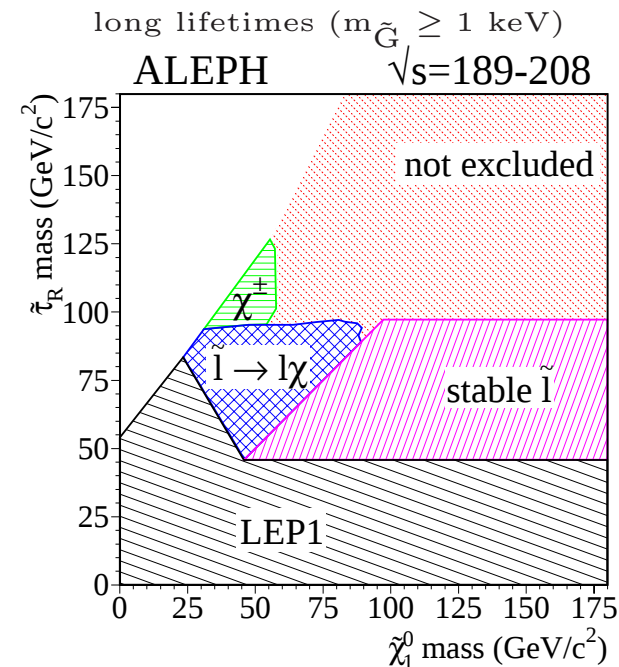
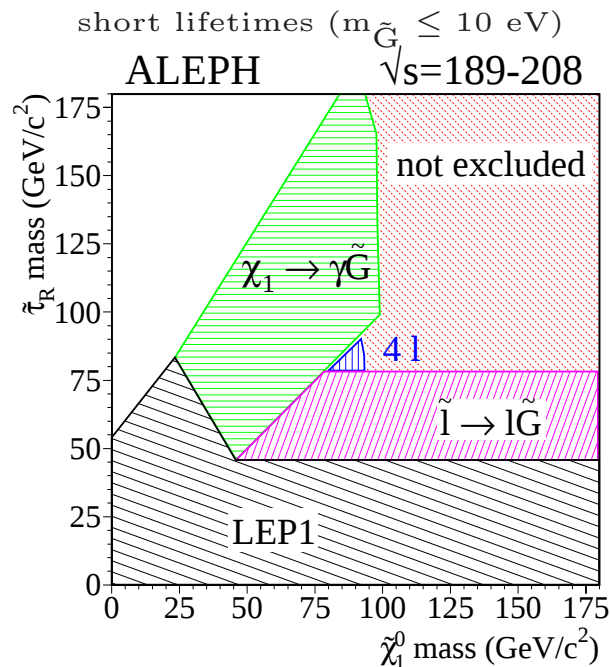
$$1.5 < \tan \beta < 40$$

$$1 < N_5 < 5$$

$$\text{sign}(\mu) = \pm 1$$

Absolute (indirect) lower mass limit on the NLSP:

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



GMSB Interpretation

Gaugino and sfermion masses depend on Λ and N_5

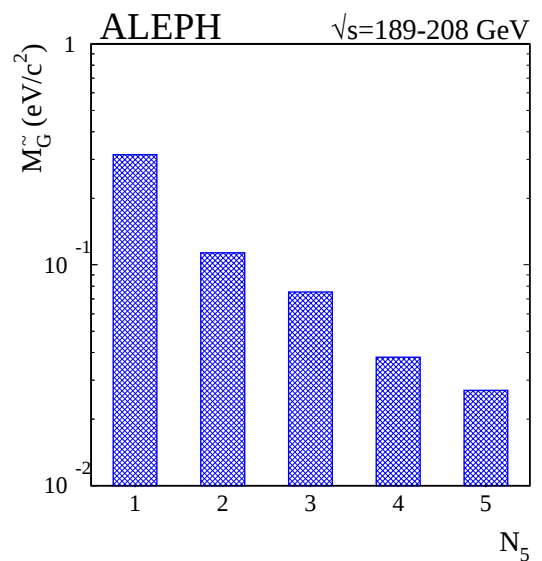
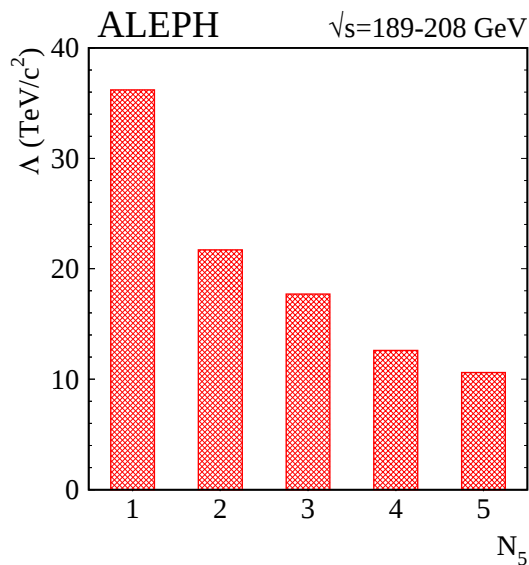
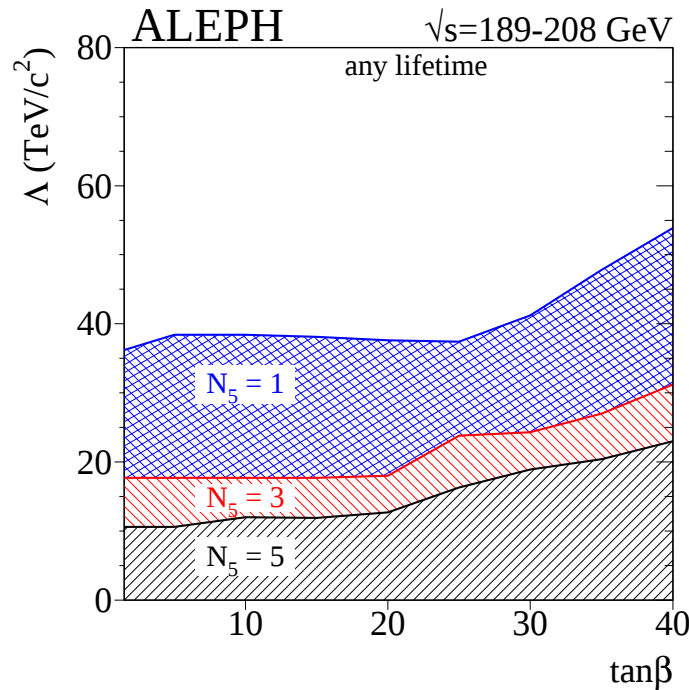
$$M_\lambda \propto N_5 \Lambda$$

$$M_f^2 \propto N_5 \Lambda^2$$



Λ controls the mass scale of SUSY particles

Set a model dependent limit on Λ :



$$\Lambda > 10 \text{ TeV}/c^2$$



$$M_{\tilde{G}} > 0.024 \text{ eV}/c^2$$

AMSB

SUSY Breaking is mediated by anomalies in gravity

★ No need for Messenger Sector + FCNC suppressed for free

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

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

- Chargino nearly mass degenerate with the lightest neutralino
- $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0}$ can occur if:
 - ★ $M_2 \lesssim M_1 \ll |\mu| \rightarrow m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} \sim M_2 \rightarrow$ gaugino-like
 - ★ $|\mu| \ll M_{1,2} \rightarrow m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} \sim |\mu| \rightarrow$ 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 $E_T(\gamma_{ISR}) \gtrsim \sqrt{s} \frac{\sin \theta_{min}}{1 + \sin \theta_{min}}$ and no low-angle beam electron
(θ_{min} = minimum polar angle to detect electron)

AMSB – Results

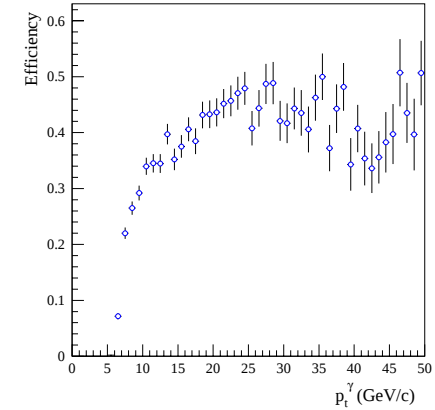
lower 95% C.L. limit on $m_{\tilde{\chi}^\pm}$ for heavy $\tilde{\nu}$

	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)

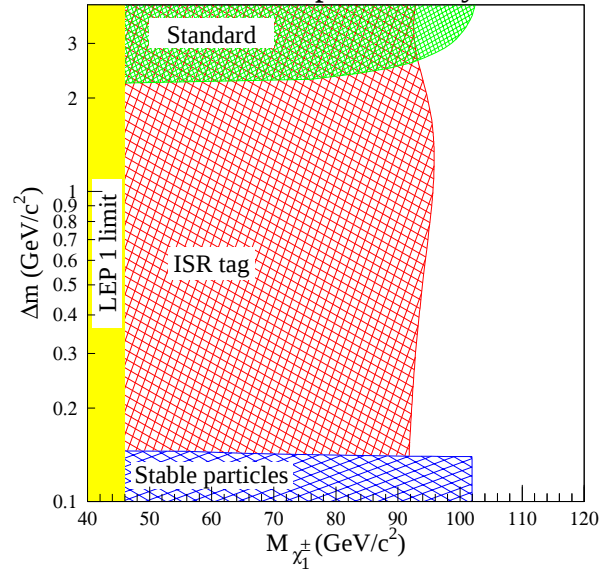
ALEPH PRELIMINARY



Gaugino region

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

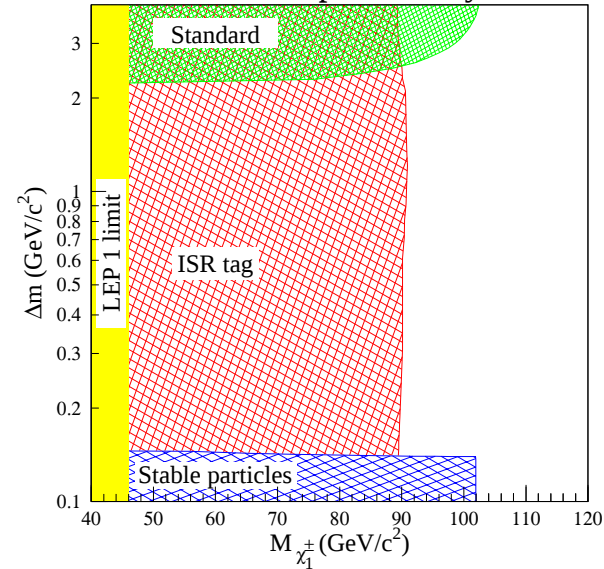
ALEPH preliminary



Higgsino region

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

ALEPH preliminary



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