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Search for Alternative SUSY at LEP

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Outline:

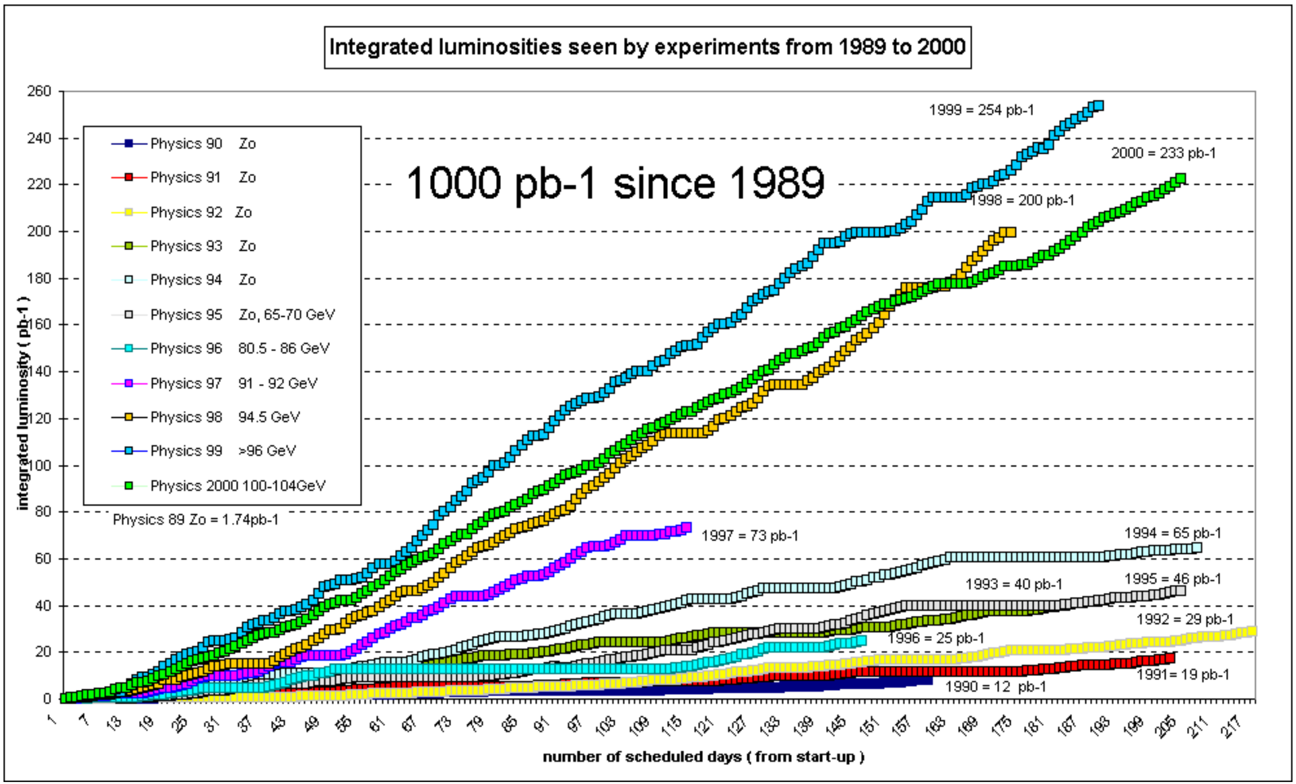
- Phenomenology: challenging topologies
- Searches for GMSB as f(NLSP)

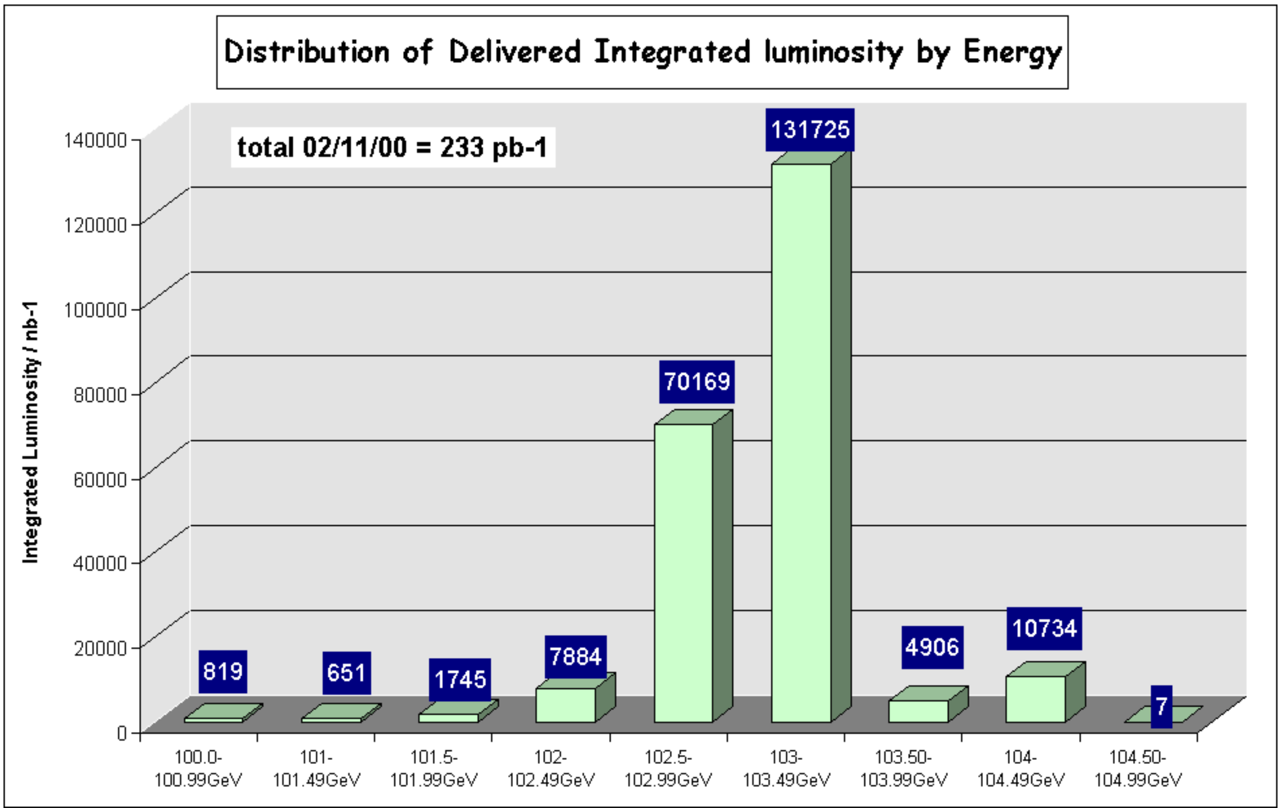
  —Topologies for $\tilde{\chi}_1^0$ NLSP Scenario

  —Topologies for $\tilde{\ell}$ NLSP Scenario
- Search for Sgoldstinos
- Summary and Conclusions

ps–file on `http://wwwinfo.cern.ch/~rembser/eps01_alternative.ps.gz`

The LEP Dataset





Introduction to GMSB

SUSY not discovered yet $\Rightarrow$ SUSY is a broken symmetry

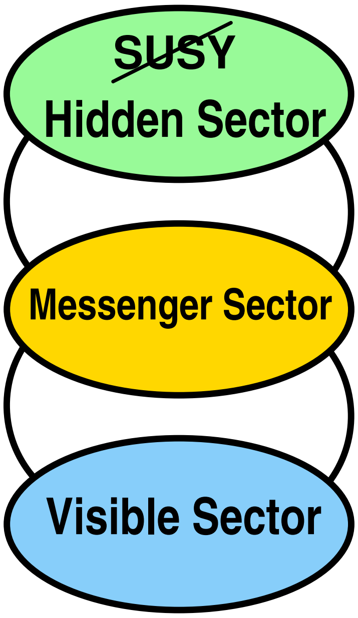
But: **the breaking mechanism is unknown.**

Via gravity: Large FCNC	Via gauge interactions: Flavour-blind $\longrightarrow$ No FCNC!

Gauge Mediated Supersymmetry Breaking

$\sqrt{F} \approx 10^{11}\,\mathrm{GeV}$

$10^3 < \sqrt{F} < 10^{10}\,\mathrm{GeV}$



$M_{\tilde{G}} \approx 2.5\,\mathrm{TeV}$

$M_{\tilde{G}} < 1\,\mathrm{GeV} \longrightarrow$ LSP

Only six new parameters in the minimal GMSB model:

$\sqrt{F}$	SUSY breaking scale
Λ	SUSY particle mass scale
M	Messenger particle mass scale
N	Number of sets of messenger particles
$\tan\beta$	Ratio of Higgs vacuum expectation values
Sign(μ)	Sign of Higgs sector mixing parameter

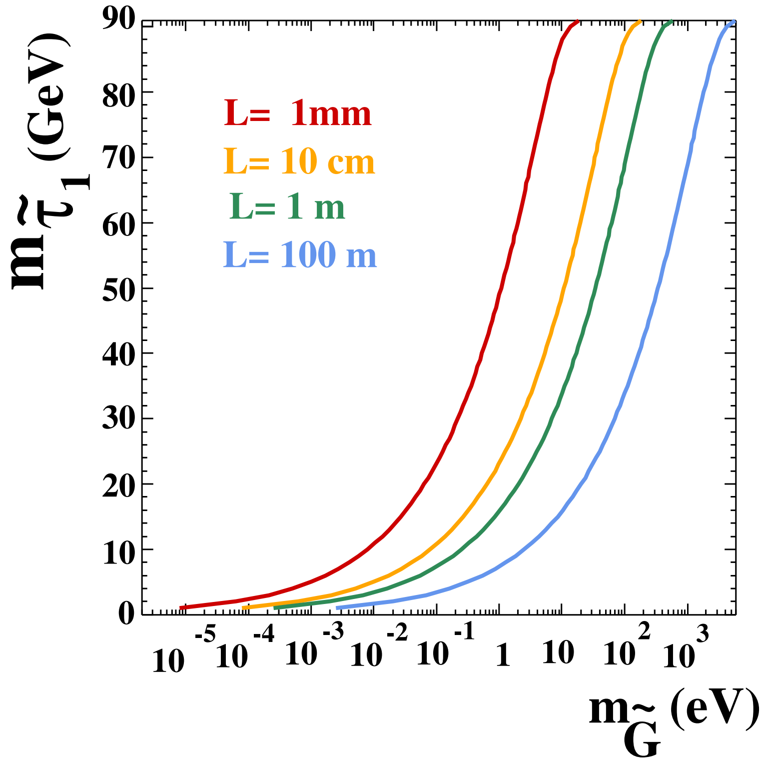
GMSB Phenomenology

- $\tilde{G}$ **is the LSP** , $m_{\tilde{G}} \lesssim \mathcal{O}$**(KeV) in minimal model.**
- $\tilde{\chi}_1^0$ **or** $\tilde{\ell}$ **(**$\tilde{\tau}$**) are the NLSP.**
- **Decay length of the NLSP depends on SUSY breaking scale** $\sqrt{F}$ $(\propto M_{\tilde{G}})$ **and NLSP mass:**

$$\boxed{c\tau_{\mathrm{NLSP}} \simeq \frac{0.01}{\kappa_\gamma}\left(\frac{100\mathrm{GeV}}{m_{\mathrm{NLSP}}}\right)^5\left(\frac{\sqrt{F}}{100\mathrm{TeV}}\right)^4 \mathrm{cm}}$$

(κ_γ = Photino component of the $\tilde{\chi}_1^0$ = 1 for $\tilde{l}$)

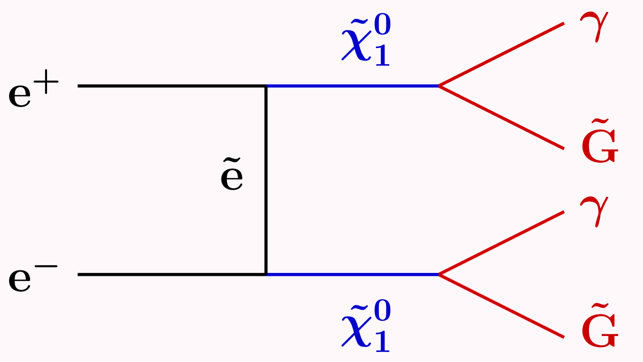
Example: $m_{\tilde{\tau}}$ versus $m_{\tilde{G}}$ for various decay lengths $\Longrightarrow$



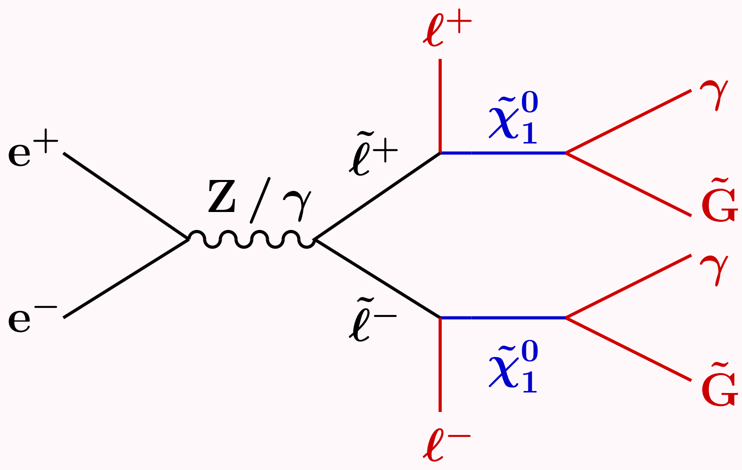
Wide range of NLSP lifetimes suggests to explore many different topologies!

Topologies in the Neutralino NLSP Scenario

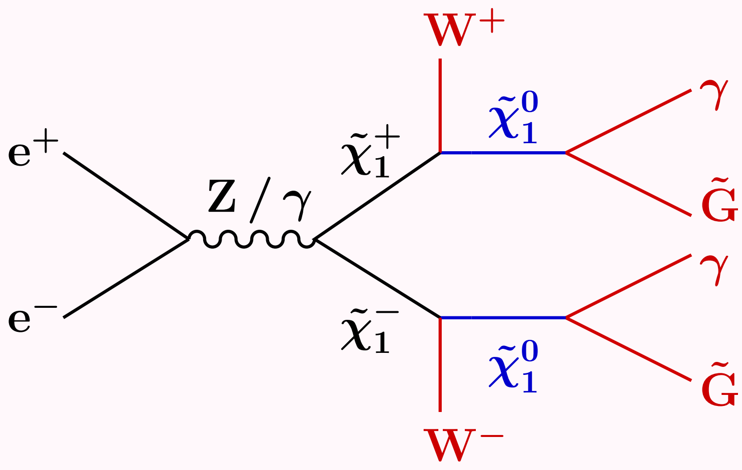
$c\tau \approx 0$	$\gamma\gamma + \not{E}$
$0 < c\tau < \infty$	$\gamma \quad + \not{E}$
$c\tau = \infty$	invisible



$c\tau \approx 0$	$\gamma\gamma + \ell^+\ell^- + \not{E}$
$0 < c\tau < \infty$	$\gamma \quad + \ell^+\ell^- + \not{E}$
$c\tau = \infty$	$\ell^+\ell^- + \not{E}$



$c\tau \approx 0$	$\gamma\gamma$ + 2jets + $\not{E}$
$0 < c\tau < \infty$	γ + 2jets + $\not{E}$
$c\tau = \infty$	2jets + $\not{E}$



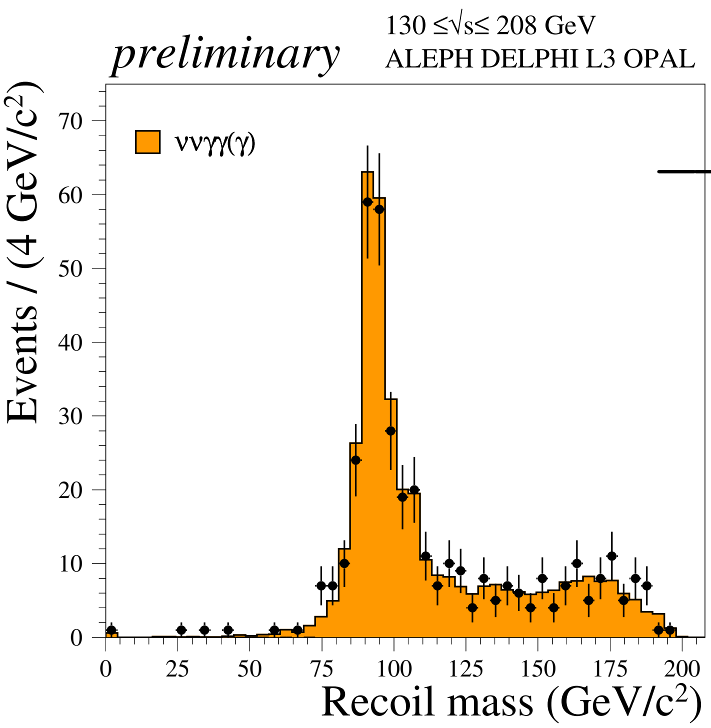
Photons and Missing Energy

- Searching for processes with
  two acoplanar photons pointing to the vertex and missing energy, indicative of

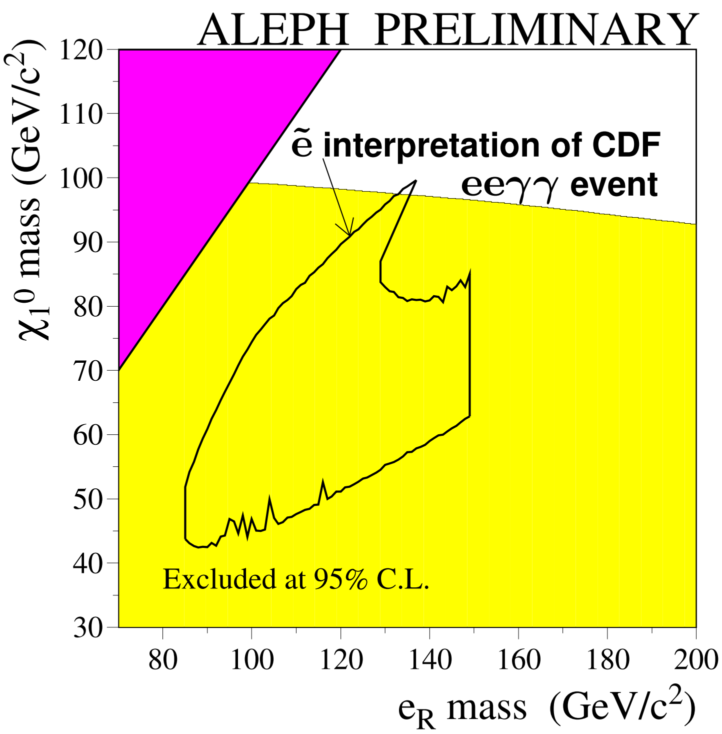
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \tilde{G}\gamma$$
$$\hookrightarrow \tilde{G}\gamma$$

- main background: $\nu\bar{\nu}\gamma\gamma$

- **No evidence for an excess (ADLO: 384 events obs./388.7 exp.),**



→ **cross-section limits as function of $m_{\tilde{\chi}_1^0}$ below 0.02 pb.**



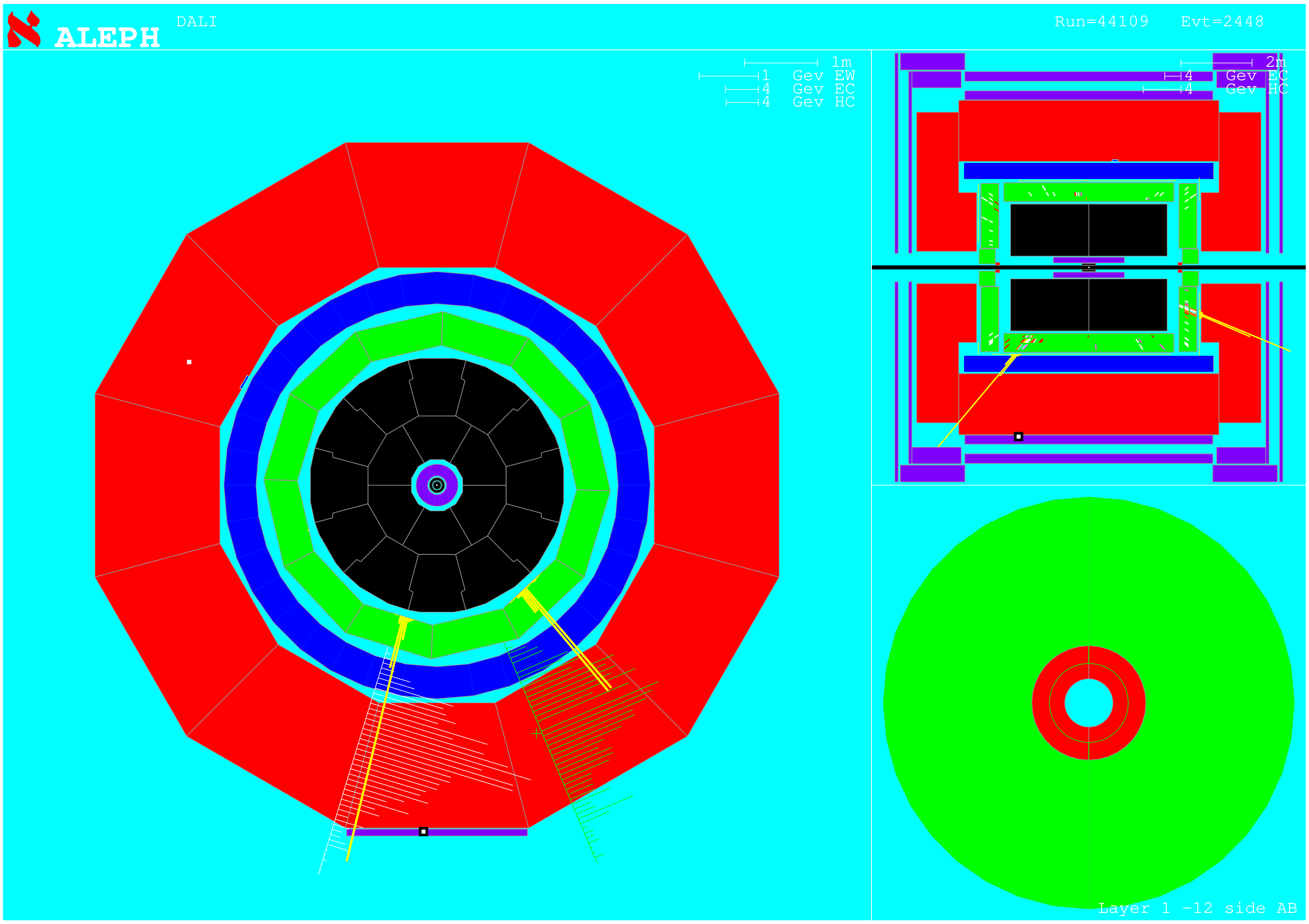
ZERO LIFETIME

Two Photons + Missing Energy: a Candidate

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

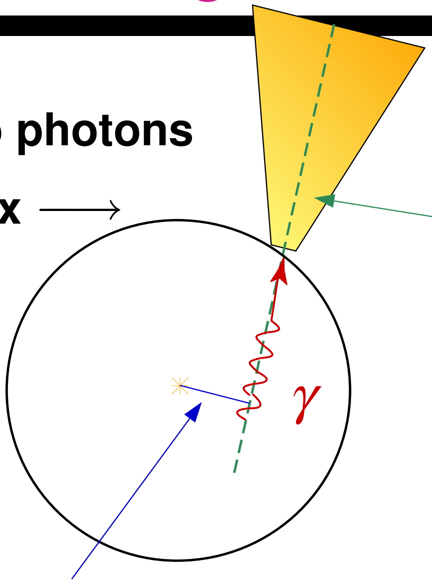
$$\hookrightarrow \tilde{G}\gamma$$

- Energy of photons: 45 GeV, 43 GeV
- Visible mass: 75 GeV
- Recoil mass: 82 GeV
- Impact parameters of photons: ~ 5 cm



Photons not pointing to the Vertex

- **Searching for one or two photons not pointing to the vertex** $\longrightarrow$

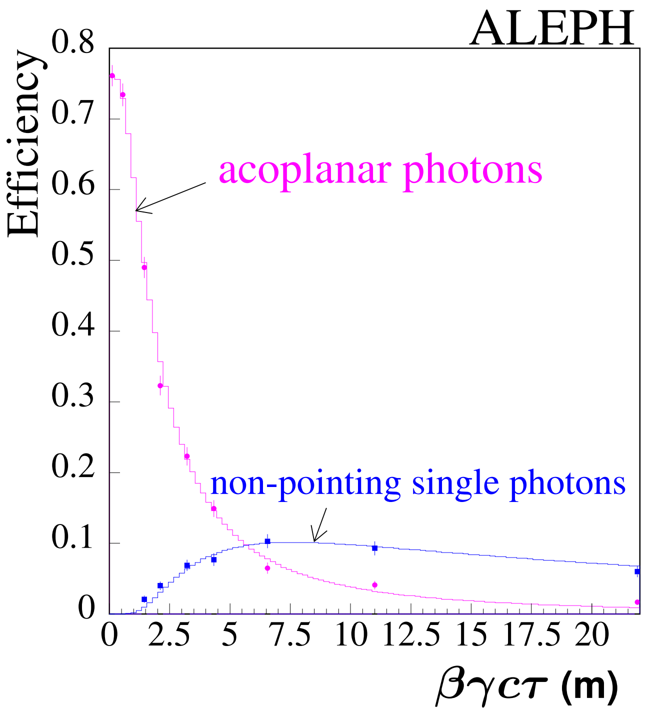


- calorimeter granularity provides reconstruction of **shower axis**

- require:
impact parameter > 40cm

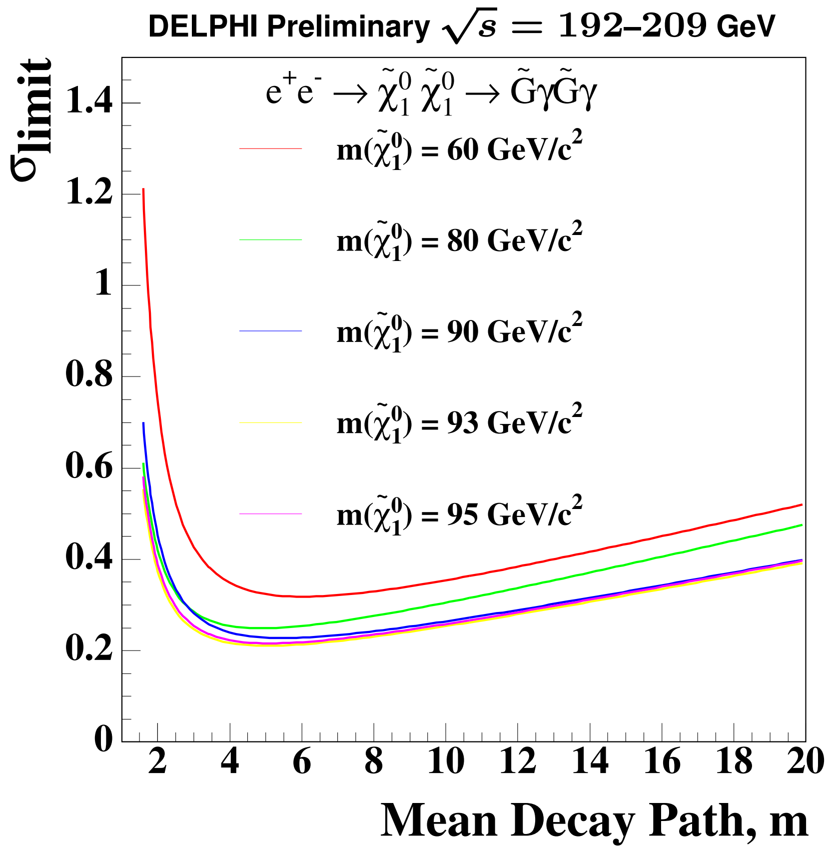
LONGER LIFETIME

- **Efficiencies** $\Rightarrow$



No evidence for an excess seen by DELPHI / ALEPH

$\longrightarrow$ **cross-section limits:**



Slepton Searches with $\tilde{\chi}_1^0$ NLSP

Signature:

$$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \to \tilde{\chi}_1^0\,\ell^-\ (\tilde{\chi}_1^0 \to \tilde{G}\gamma)\qquad \tilde{\chi}_1^0\,\ell^+\ (\tilde{\chi}_1^0 \to \tilde{G}\gamma)$$

Background:

- Bhabhas, $\gamma\gamma$, $\ell\ell$
- depends on lepton/photon energies, which are functions of

$$\Delta M = M_{\tilde{\ell}} - M_{\tilde{\chi}_1^0}$$

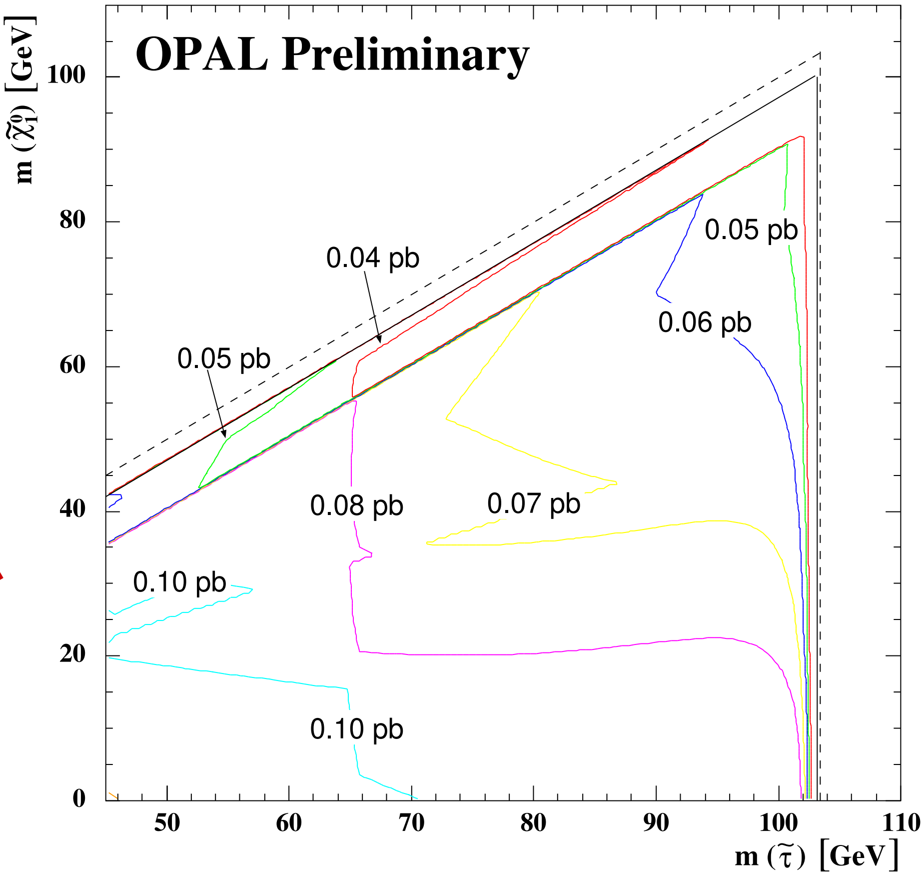
$\Longrightarrow$ **Analyses are optimised for three different ΔM regions**

- No evidence for an excess seen by individual experiments ...

... limits $\Longrightarrow$

upper limits on $\tilde{\tau}/\tilde{\chi}_1^0$ production cross-section at 95% CL

ZERO LIFETIME

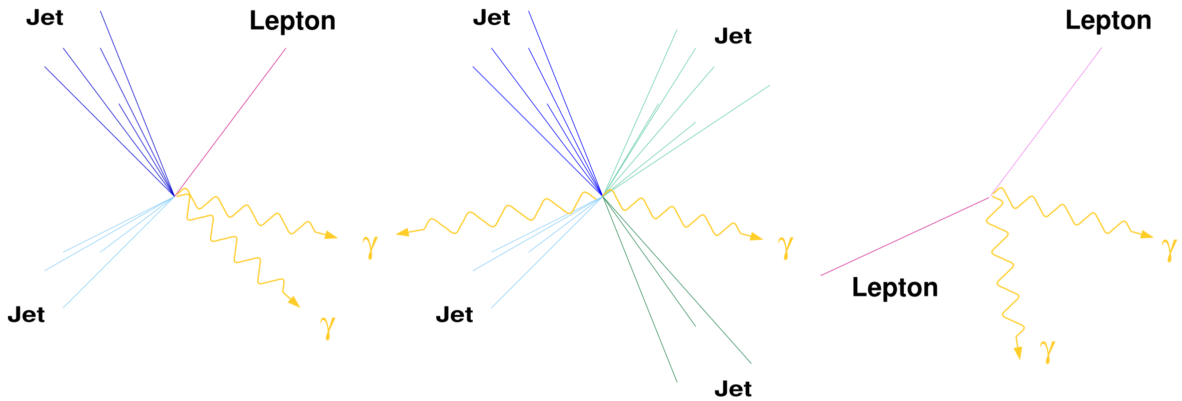


Chargino Searches with $\tilde{\chi}_1^0$ NLSP

- **Process to search for**

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^{(*)+}\tilde{\chi}_1^0 W^{(*)-}\tilde{\chi}_1^0 \rightarrow W^{(*)+}\ \tilde{G}\gamma\, W^{(*)-}\ \tilde{G}\gamma$$

- **Topologies** (high multiplicity, low multiplicity)**:**



- **background composition** depends on lepton, photon energies, which are functions of $\Delta M = M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$

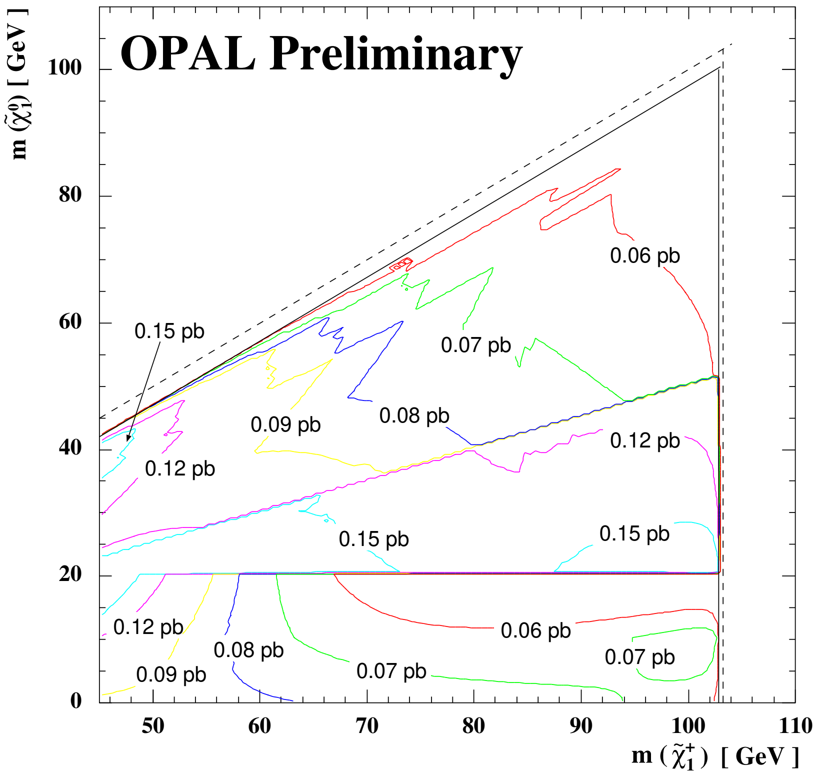
$\Longrightarrow$ Analyses are separately optimised for different ΔM regions

upper limits on $\tilde{\chi}_1^+/\tilde{\chi}_1^0$ production cross-section at 95% CL

- No excess found in data

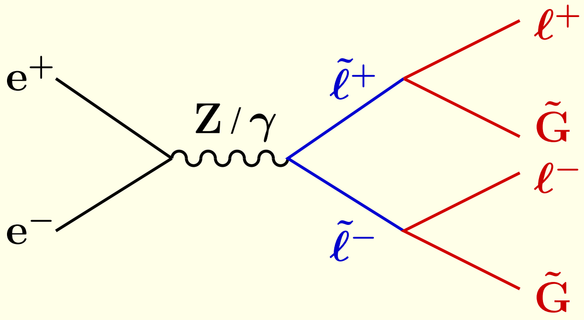
ZERO LIFETIME

$\Rightarrow$

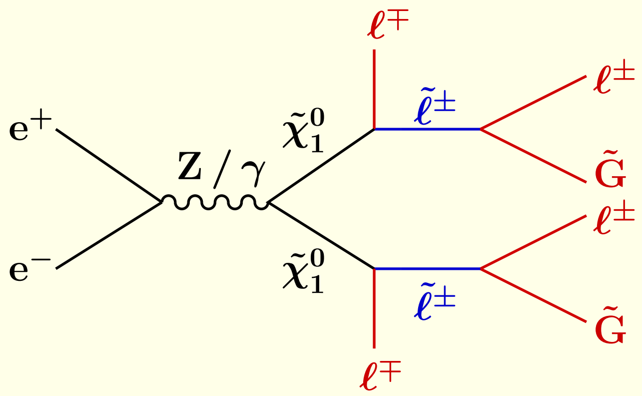


Topologies in the Slepton NLSP Scenario

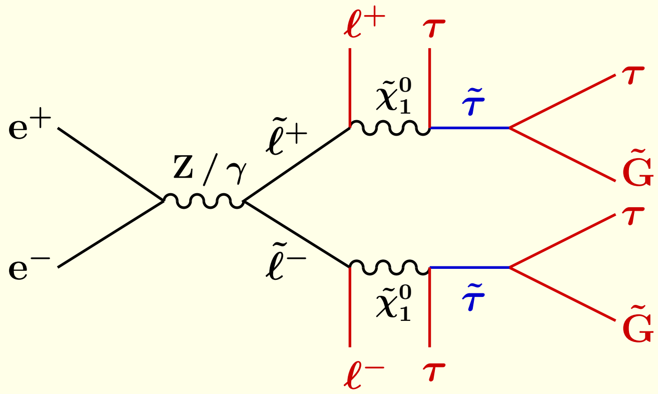
$c\tau \approx 0$	$\ell^+\ell^-$ + $\not\!\!E$
$0 < c\tau < \infty$	2 kinked tracks
$c\tau = \infty$	2 stable particles



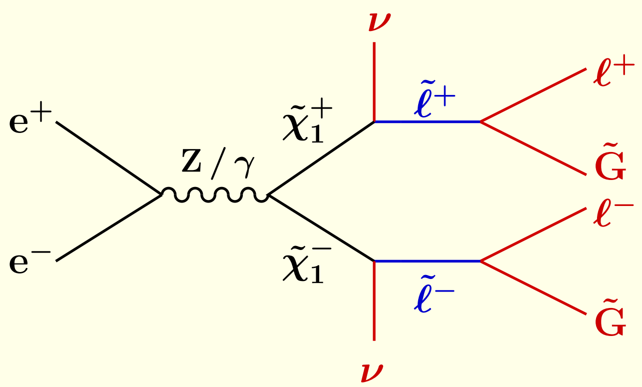
$c\tau \approx 0$	$\ell^+\ell^-$ + $\ell^+\ell^-$ + $\not\!\!E$
$0 < c\tau < \infty$	$\ell^+\ell^-$ + 2 kinked tracks
$c\tau = \infty$	$\ell^+\ell^-$ + 2 stable particles



$c\tau \approx 0$	$\ell\tau\,\ell\tau + \tau\tau + \not\!\!E$
$0 < c\tau < \infty$	$\ell\tau\,\ell\tau$ + 2 kinked tracks
$c\tau = \infty$	$\ell\tau\,\ell\tau$ + 2 stable particles



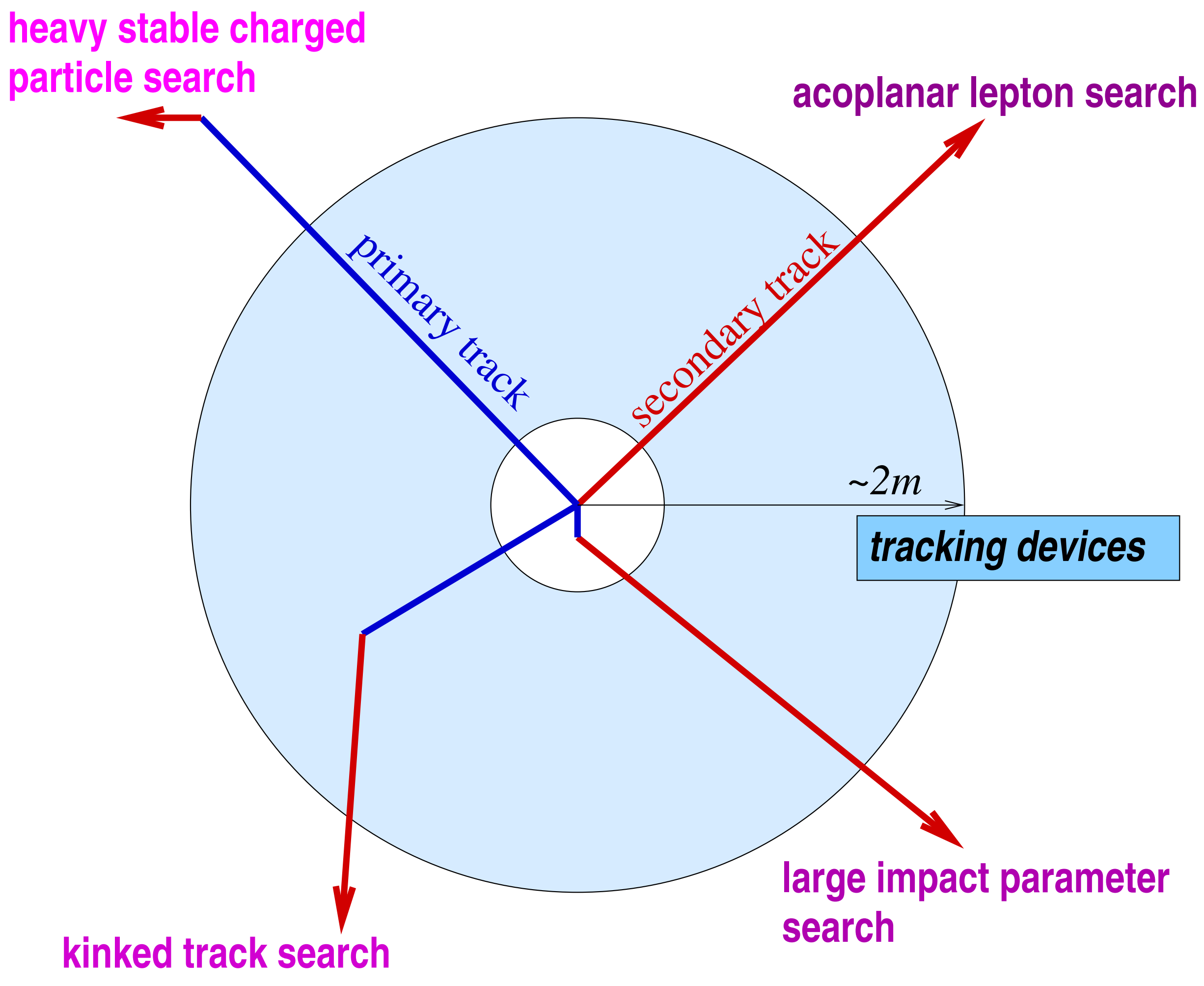
$c\tau \approx 0$	$\ell^+\ell^-$ + $\not\!\!E$
$0 < c\tau < \infty$	2 kinked tracks + $\not\!\!E$
$c\tau = \infty$	2 stable particles + $\not\!\!E$



Slepton Searches with $\tilde{\ell}$ NLSP

The mean decay length of the slepton (primary track) can be

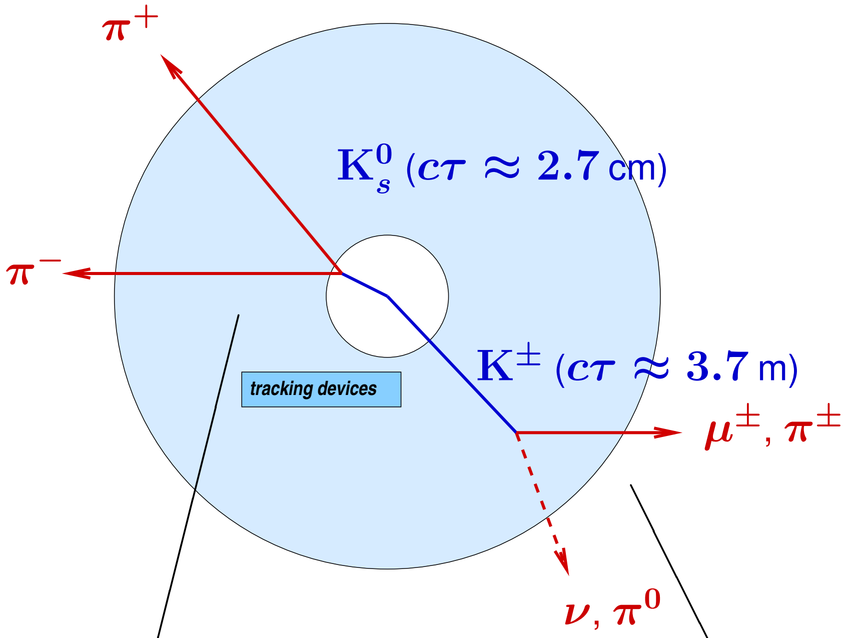
- mean decay length $\lesssim \mathcal{O}(1\,\mathrm{cm})$
  $\Longrightarrow$ **search for acoplanar lepton pairs**
- $\mathcal{O}(1\,\mathrm{cm}) \lesssim$ mean decay length $\lesssim \mathcal{O}(40\,\mathrm{cm})$
  $\Longrightarrow$ **search for tracks with large impact parameters**
- $\mathcal{O}(10\,\mathrm{cm}) \lesssim$ mean decay length $\lesssim \mathcal{O}(2\,\mathrm{m})$
  $\Longrightarrow$ **search for kinked tracks**
- $\mathcal{O}(2\,\mathrm{m}) \lesssim$ mean decay length
  $\Longrightarrow$ **search for tracks with anomalous ionisation energy loss**

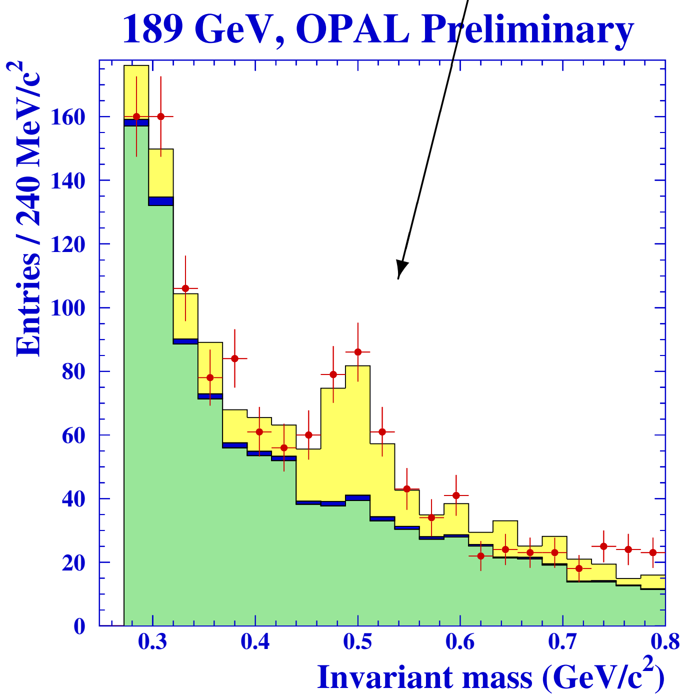


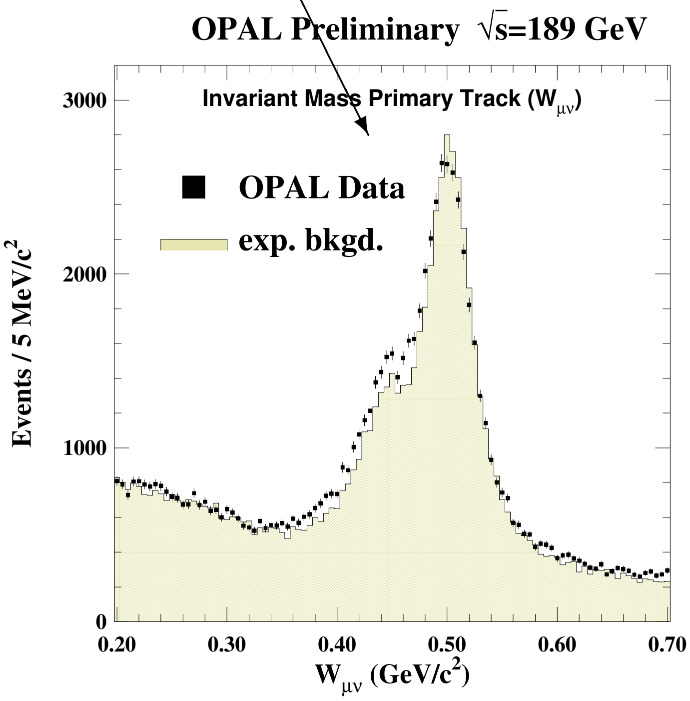
Very good conditions at LEP

→ large impact parameter search: **sensitive to decay of K_s^0**

→ kinked track search: **sensitive to decay of $K^{\pm}$**







large impact parameter search

$|d_0| < 5$ cm

kinked track search

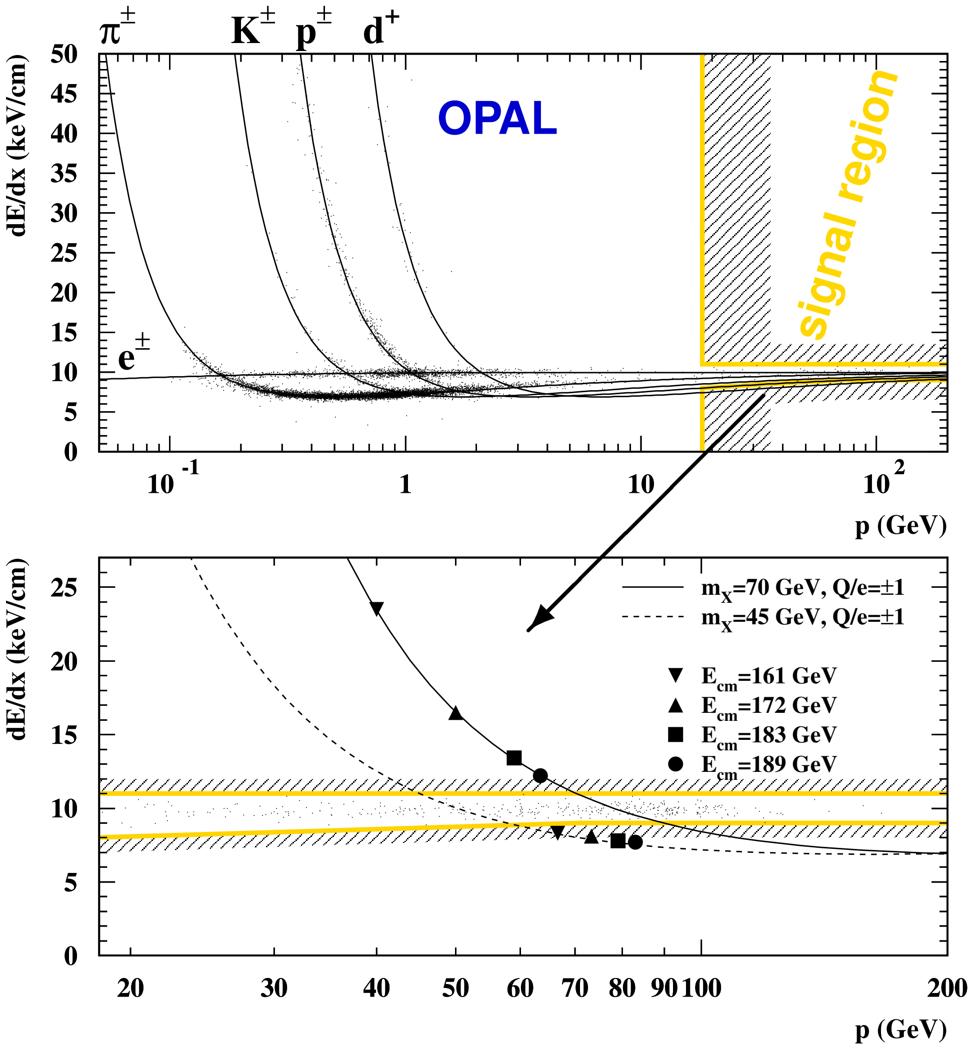
all kinks

◇ **well modelled SM background and precise tracking detectors**

Search for Stable Sleptons

Process: $e^+e^- \longrightarrow \tilde{\ell}^+\tilde{\ell}^- \quad (c\tau \longrightarrow \infty)$

Powerfull search tool is dE/dx: no background from SM physics processes in most of the search region + high efficiency ($\approx 95\,\%$)

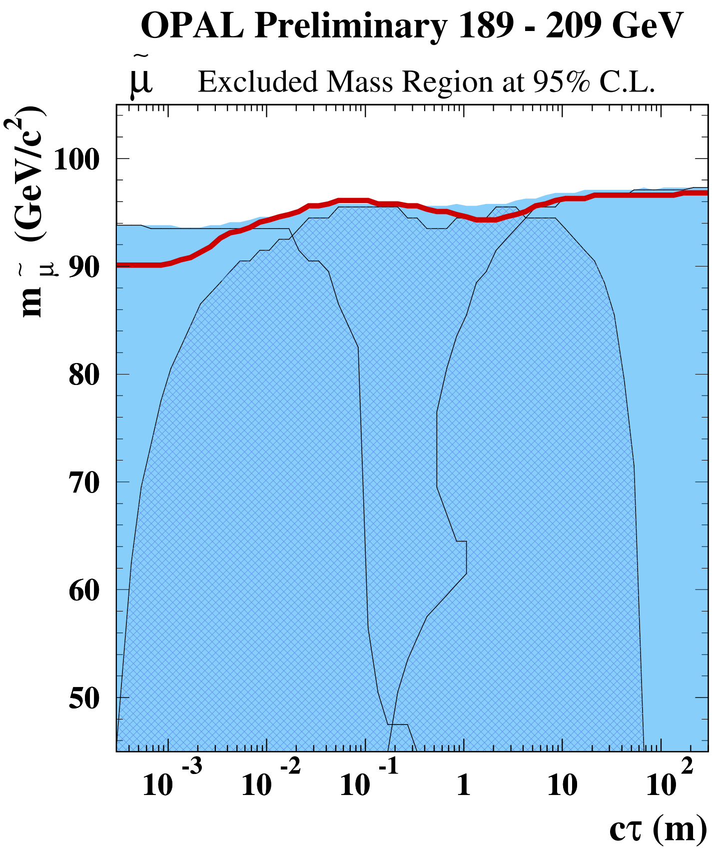


Results given by individual experiments:

Dataset	ALEPH $\geq 189\,\mathrm{GeV}$	DELPHI $\geq 192\,\mathrm{GeV}$	OPAL $\geq 189\,\mathrm{GeV}$
Expected	2.3	1.0	0.6
Observed	1	0	0
$M_{\mu_R} >$	97.0 GeV	97.1 GeV	98.0 GeV

Limits for $\tilde{\ell}$ with Lifetime

- Combining searches in various regions of $\tilde{\ell}$ lifetime $\longrightarrow$



limit on $M_{\tilde{\mu}_R}$

(slepton co-NLSP scenario)

$m_{\tilde{\mu}} > 93.8$ GeV

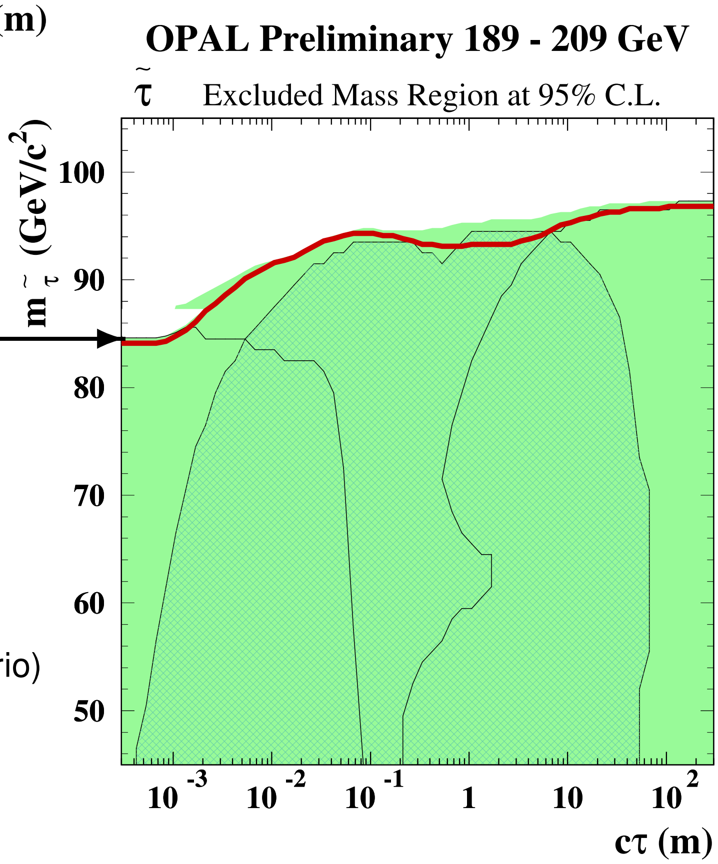
- red line: expected limit
- hatched region: large impact parameter and kinked track search

ALL LIFETIMES

limit on $M_{\tilde{\tau}_1}$

(slepton co–NLSP scenario)

$m_{\tilde{\tau}} > 84.6$ GeV



Other results:

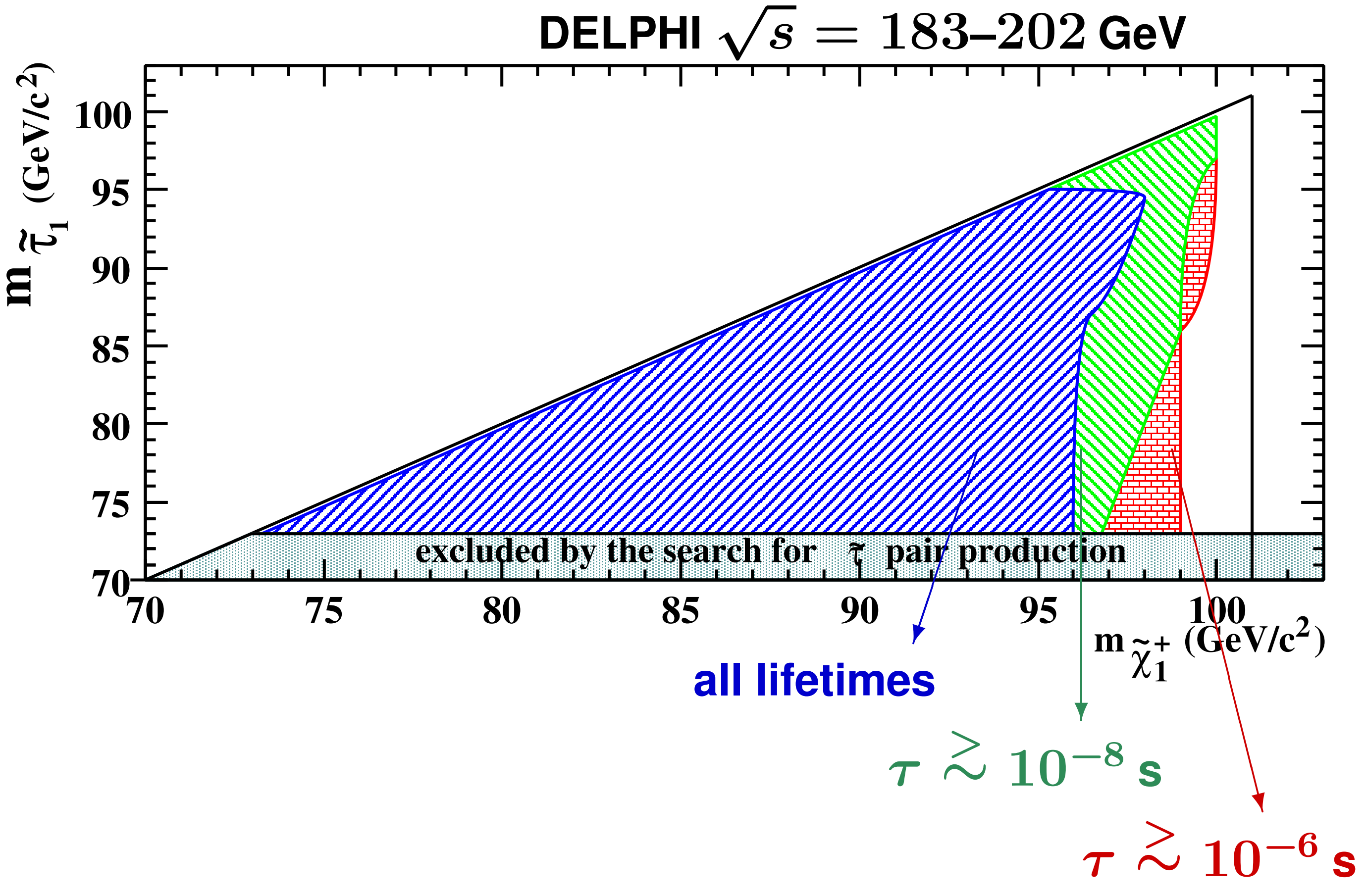
$m_{\tilde{e}} > 73.0$ GeV

$m_{\tilde{\tau}} > 84.0$ GeV ($\tilde{\tau}$ NLSP scenario)

Chargino Searches with $\tilde{\tau}$ NLSP

$$e^+e^- \longrightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \longrightarrow \tilde{\tau}_1^+\tilde{\tau}_1^-\nu_\tau\bar{\nu}_\tau \longrightarrow \tau^+\tau^-\tilde{G}\tilde{G}\nu_\tau\bar{\nu}_\tau$$

- Assumption: $\tilde{\tau}_1$ (lightest mass eigenstate produced by $\tilde{\tau}_R$ and $\tilde{\tau}_L$ mixing) is NLSP
- Again: looking for 2 leptons (τ's)
- Combination of results of different lifetime analyses $\longrightarrow$



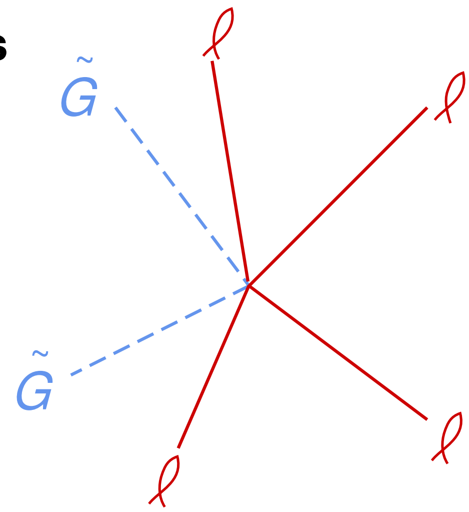
$\Longrightarrow$ $\boxed{M_{\tilde{\chi}_1^\pm} > 95.2 \text{ GeV}}$ at 95% C.L. ($\Delta M \geq 0.3$ GeV)

ALL LIFETIMES

Search for $\tilde{\chi}_1^0$ Pair Production

- **Process:** $e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \longrightarrow \tilde{\ell}\ell\tilde{\ell}\ell \longrightarrow \ell\tilde{G}\ell\ell\tilde{G}\ell$

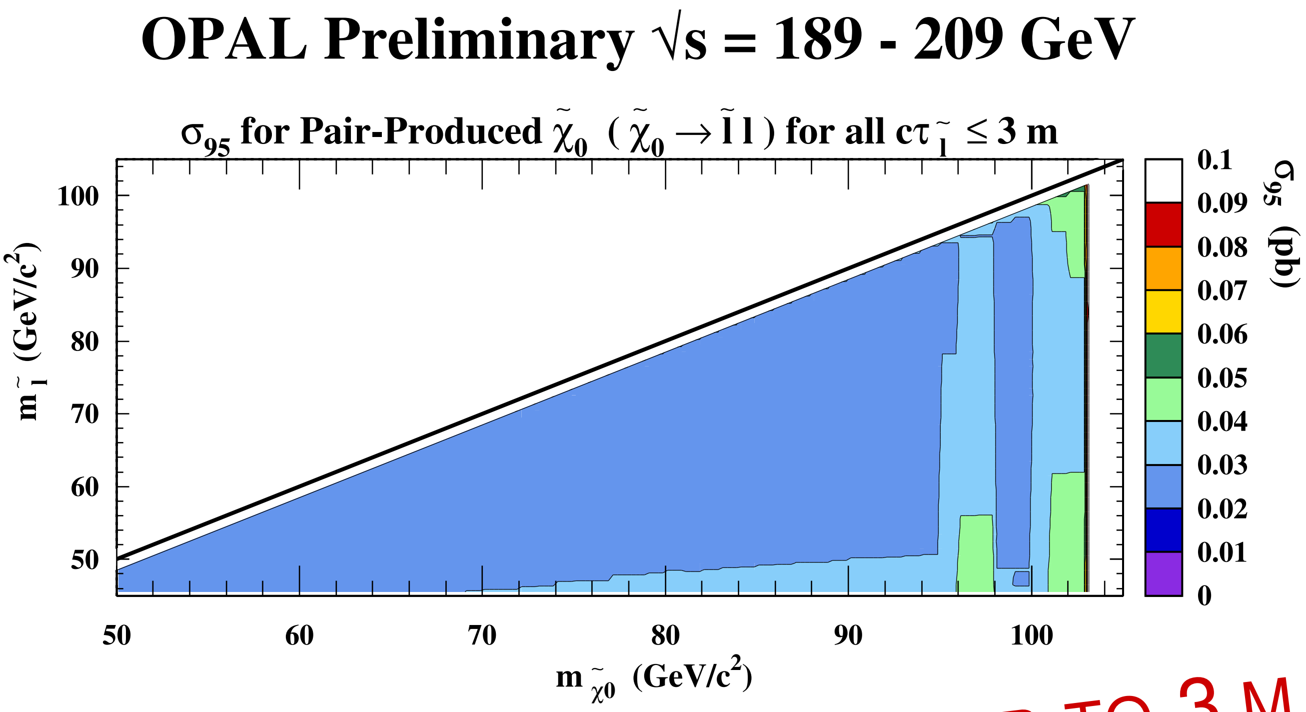
- **Search for 4 lepton final states**



- Combination of results of different lifetime analyses $\longrightarrow$

No excess of events compared to expected SM background

$\Rightarrow$ 95% C.L. limits on production cross section:



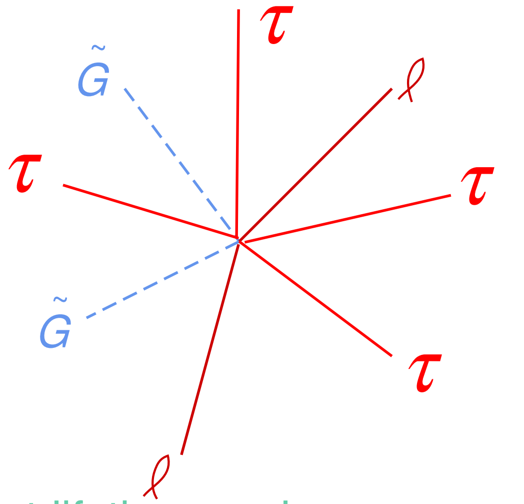
DECAY LENGTH UP TO 3 M

$\tilde{e}^+\tilde{e}^-$ and $\tilde{\mu}^+\tilde{\mu}^-$ Production with $\tilde{\tau}$ NLSP

- If $\tilde{\chi}^0_1$ too heavy and $m_{\tilde{\tau}} < m_{\tilde{\mu}}, m_{\tilde{e}} \Longrightarrow$

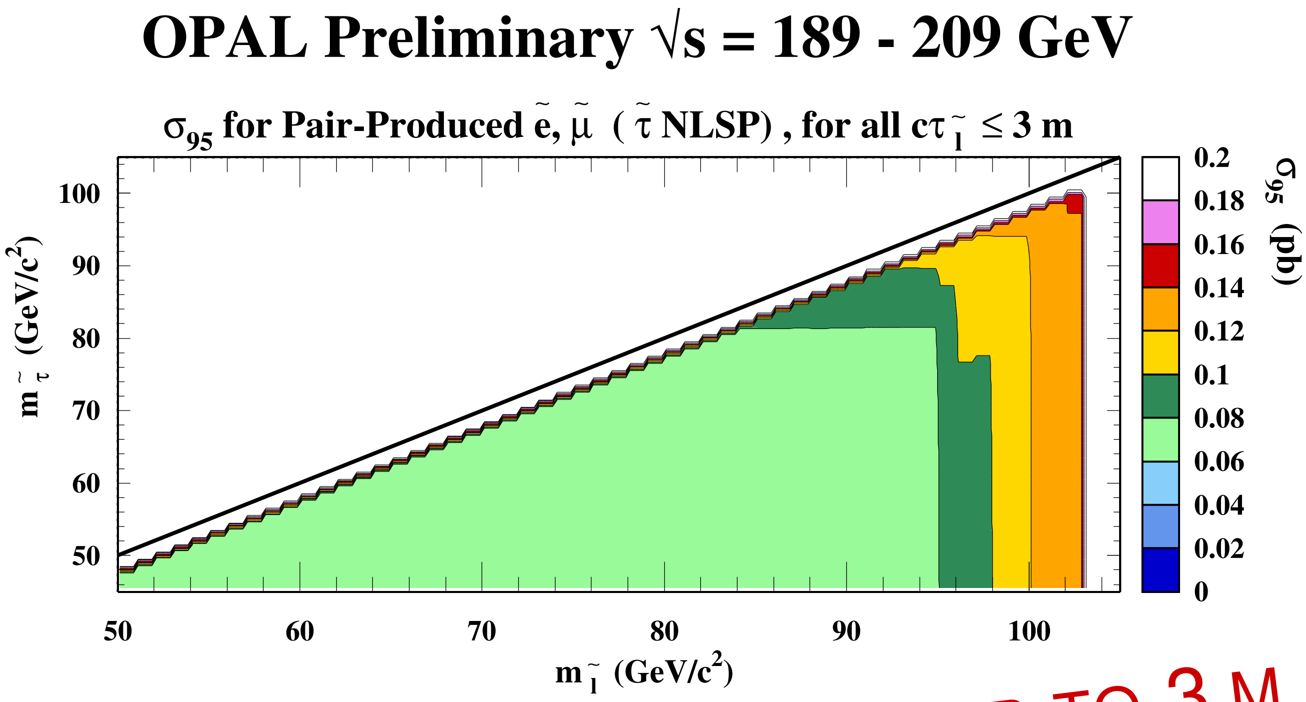
$$e^+e^- \longrightarrow \tilde{\ell}\tilde{\ell} \longrightarrow (\ell\tilde{\tau}\tau)(\ell\tilde{\tau}\tau) \longrightarrow (\ell\tau\tau\tilde{G})(\ell\tau\tau\tilde{G})$$

- Search for 6 lepton final states



- Combination of results of different lifetime analyses $\longrightarrow$

No excess of events compared to expected SM background
...Limits at the 95% C.L. for the production cross-section:



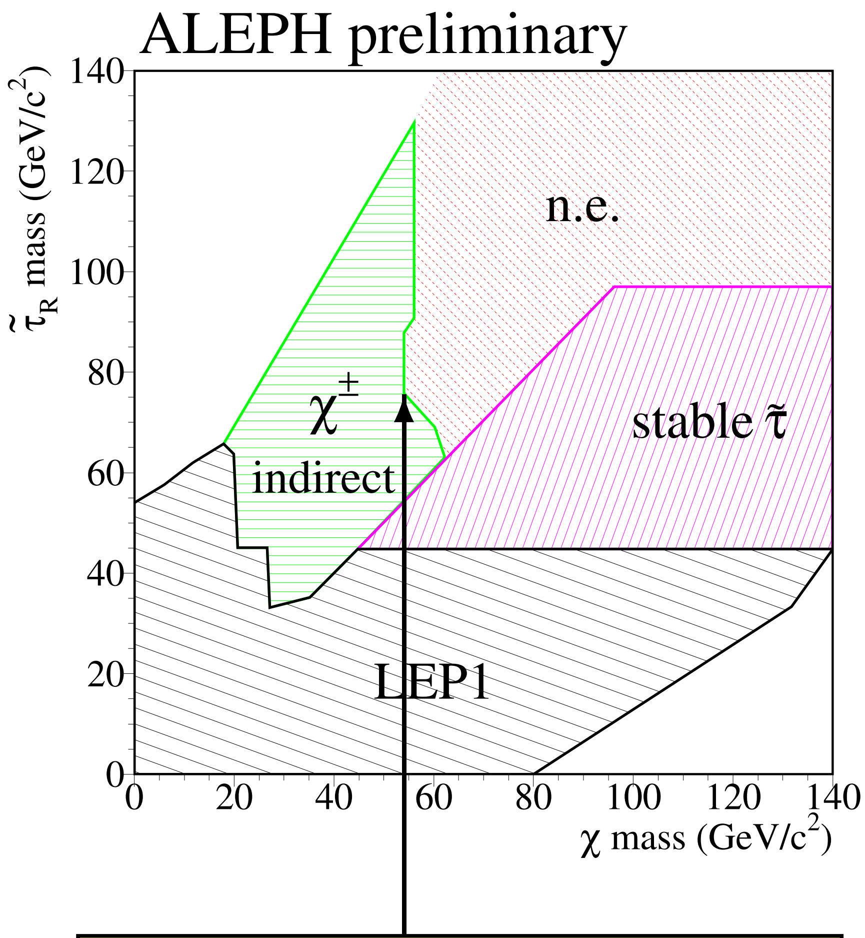
DECAY LENGTH UP TO 3 M

GMSB Interpretation

A)

★ **Regions excluded by different analyses**

Most conservative: long lifetime searches, *as stable* $\tilde{\chi}^0_1$ *invisible*:



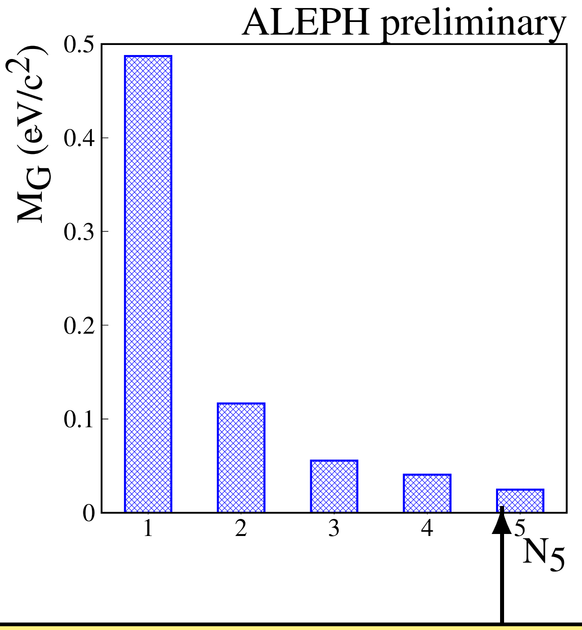
$M_{\mathrm{NLSP}} > 54.0$ **GeV at 95% C.L.**

B)

★ **For lowest NLSP mass:**

★ **Scan mGMSB parameter space, e.g.**

$$10 \text{ TeV} < M < 10^9 \text{ TeV}$$
$$1 \text{ TeV} < \Lambda < \min(\sqrt{F}, M)$$
$$1.3 < \tan\beta < 38$$
$$1 < N < 5$$
$$\text{sign}(\mu) = \pm 1$$



$M_{\tilde{G}} > 0.024$ **eV at 95% C.L.**

An Additional Possibility: Sgoldstinos

$\sqrt{F}$ very small $\longrightarrow$ ultralight gravitino

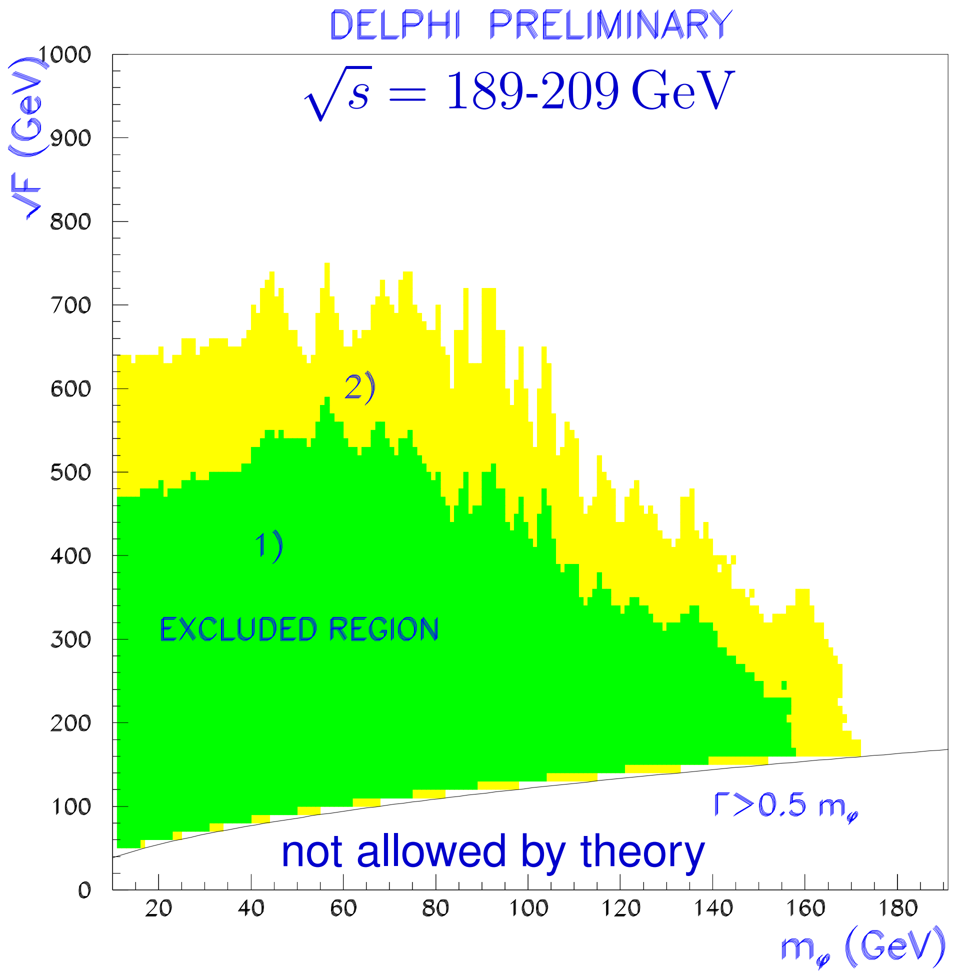
- gravitino has dominant goldstino component

$\Rightarrow$ search for its heavy supersymmetric partner, the sgoldstino S

Processes: $\mathrm{e}^+\mathrm{e}^- \longrightarrow S\gamma \longrightarrow \gamma\gamma\gamma$

$\longrightarrow gg\gamma$ (jet jet γ)

Search by DELPHI: no signal $\Rightarrow$ exclusion in $\sqrt{F}$–m_S

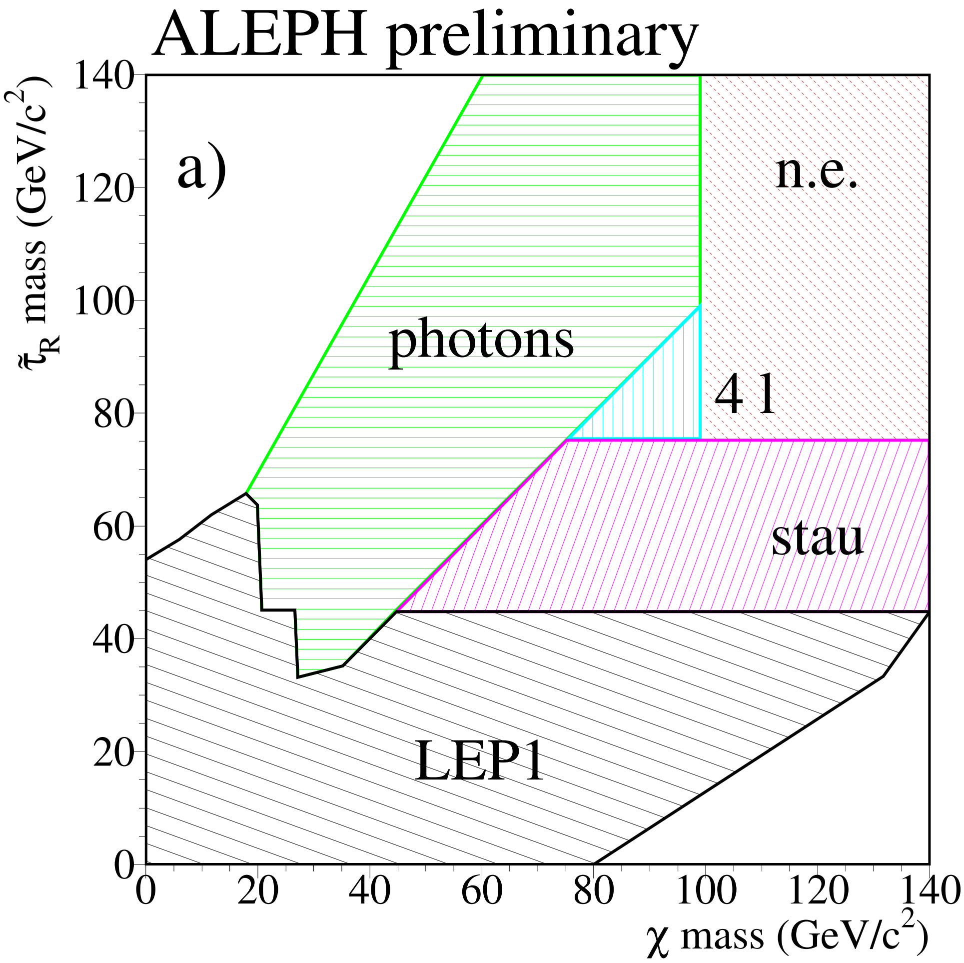


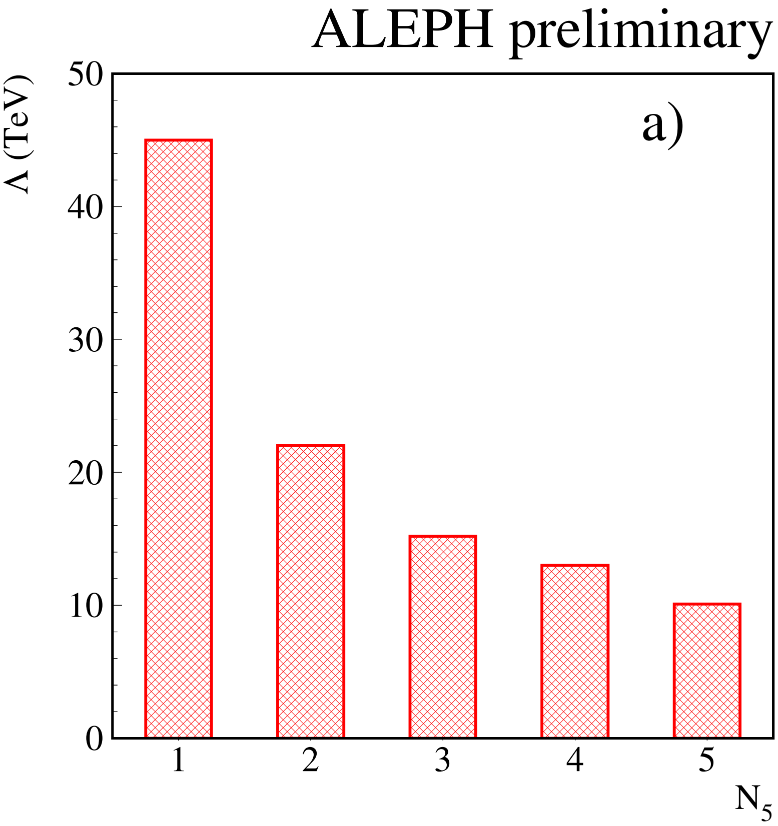
1) and 2): two sets of gaugino mass parameters

Summary and Conclusions

- Motivated by alternative SUSY models, a large number of final states have been studied by the four LEP collaborations.
- No signal detected but ...
- ... still unexcluded parameter space in SUSY models.
- In GMSB, limits on the NLSP mass and the gravitino mass have been set.
- More results still to come:
  analyses of individual experiments as well as combined results of the LEP collaborations.

Backup: Excluded GMSB Regions





Backup: OPAL Lifetime Efficiencies

Selection Efficiency for $\tilde{\tau}$ Pairs at $\sqrt{s}$ =208.1 GeV