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Search for SUSY with Gravitino LSP at LEP

Christoph Rembser

CERN, Switzerland

Outline:

- Phenomenology: challenging topologies
- Searches as f(NLSP)
  - —Topologies for $\tilde{\chi}_1^0$ NLSP Scenario
  - —Topologies for $\tilde{\ell}$ NLSP Scenario
- Summary and Outlook

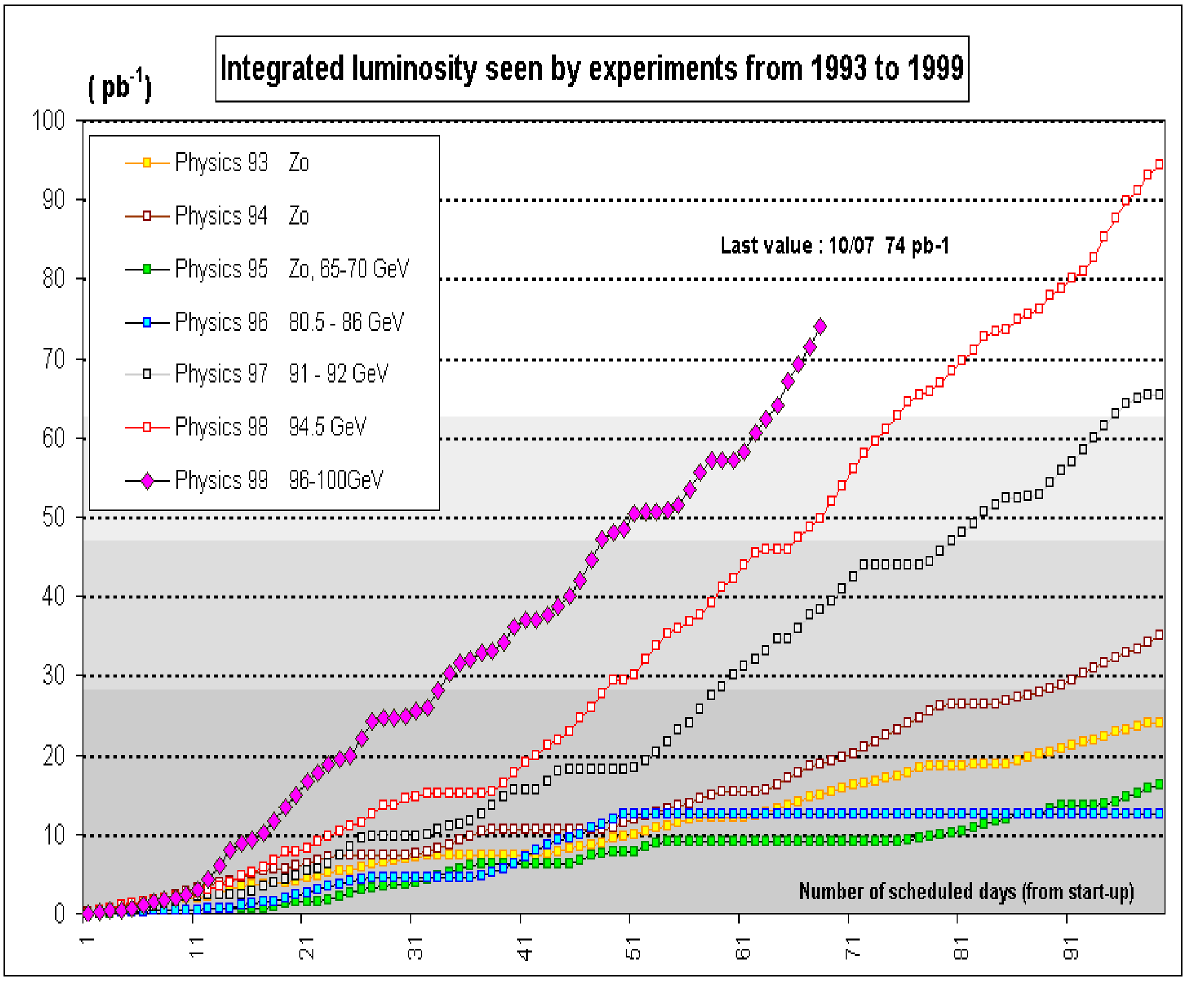
ps–file on `http://wwwinfo.cern.ch/~rembser/eps99_gmsb.ps.gz`

LEP2 Running

Luminosities collected by each individual experiment

ALEPH, DELPHI, L3 or OPAL

Stage	$\sqrt{s}$	Year	Luminosity
LEP 1	$\approx$ 91 GeV	1989-1995	175 pb^{-1}
LEP 1.5	130-140 GeV	1995	5 pb^{-1}
LEP 2	161 GeV	1996	10 pb^{-1}
	172 GeV	1996	10 pb^{-1}
	183 GeV	1997	55 pb^{-1}
	189 GeV	1998	150-180 pb^{-1}



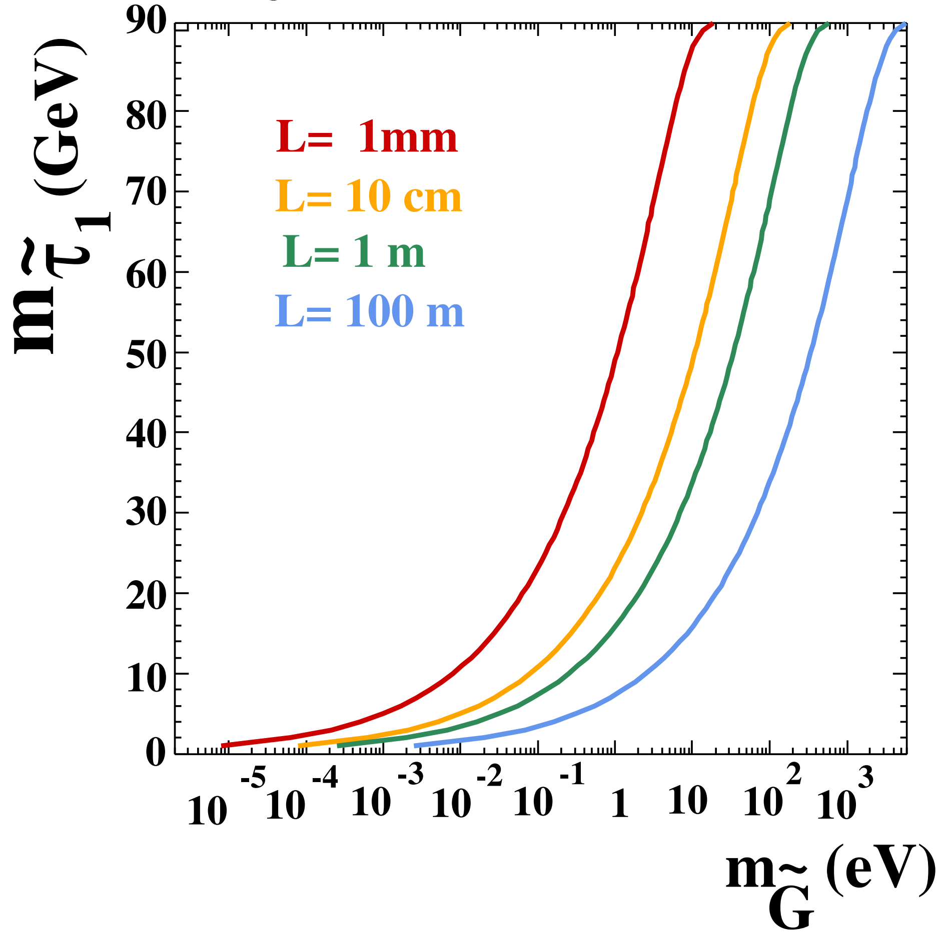
Light Gravitino Scenarios

Very general light gravitino scenarios:

- $\tilde{G}$ is the LSP $m_{\tilde{G}} \lesssim \mathcal{O}(KeV)$.
- $\tilde{\chi}_1^0$ or $\tilde{\tau}_1$ are the NLSPs.
- Decay length of the NLSP depends on $\tilde{\mathrm{G}}$ mass and NLSP mass:

$$L_{(\mathrm{NLSP})} \sim \sqrt{\frac{E^2}{m^2_{NLSP}} - 1} \left(\frac{\mathrm{GeV}}{m_{NLSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{\mathrm{eV}}\right)^2 \mathrm{cm}$$

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



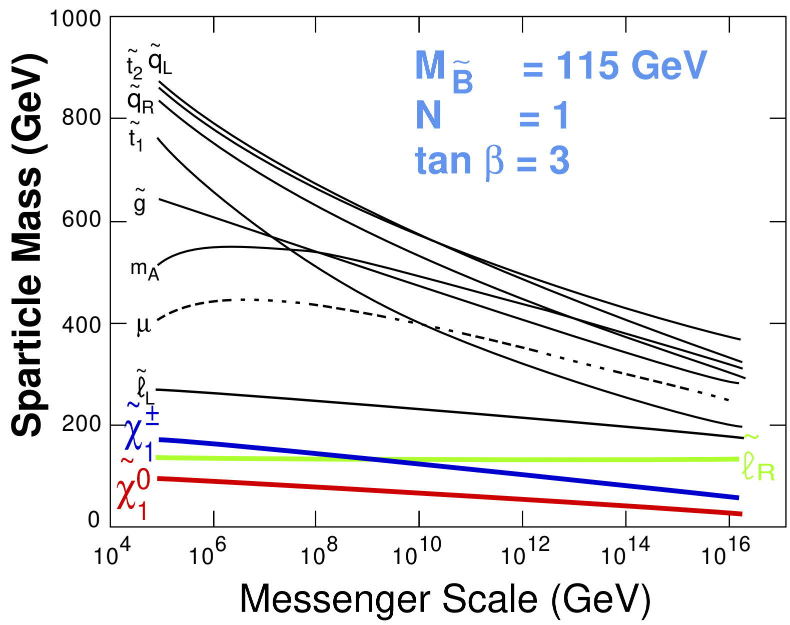
Wide range of NLSP lifetimes suggests to explore many different final topologies!

Gauge-Mediated SUSY Breaking

Parameters of Minimal Model	
$\sqrt{F}$	SUSY breaking scale (or $m_{\tilde{G}}$)
M	Messenger scale
N	Number of sets of messenger particles
Λ	Sparticle mass scale
$\tan\beta$	Ratio of the vacuum expectation values of the two Higgs doublets
μ	SUSY-conserving Higgs mass parameter

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

Example GMSB mass spectra
(Dimopoulos *et al.*, hep-ph/9609434):



NLSP

$\tilde{\chi}_1^0 \to \gamma\tilde{\mathrm{G}}$

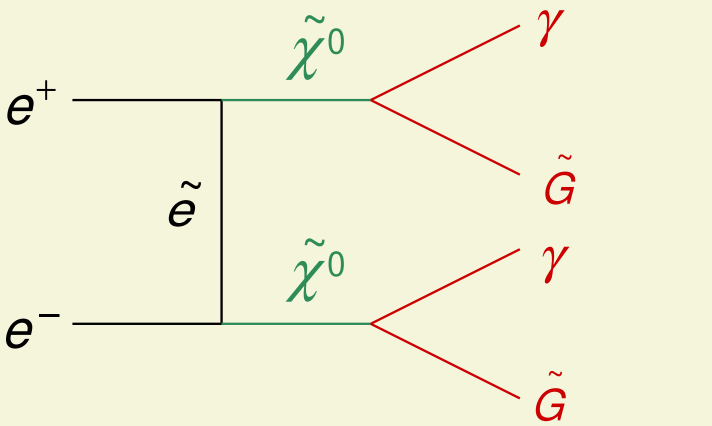
$\tilde{\ell}_{\mathrm{R}}^{\pm} \to \ell^{\pm}\tilde{\mathrm{G}}$

NLSP $c\tau =$

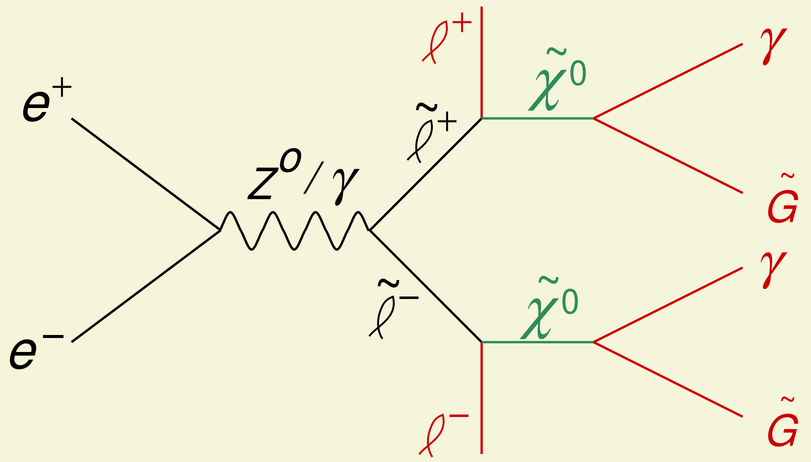
1 μm–10^{11} km

GMSB Scenarios with $\tilde{\chi}_1^0$ NLSP

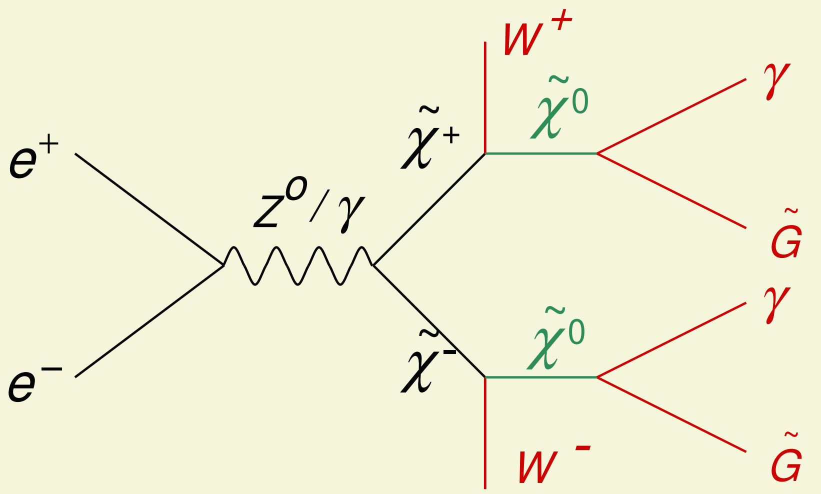
$c\tau \sim 0$:	$\gamma\gamma \quad + \not{E}_T$
$0 < c\tau < \infty$:	$\gamma \quad + \not{E}_T$
$c\tau < \infty$:	$+ \not{E}_T$



$c\tau \sim 0$:	$\gamma\gamma \;\; \ell^-\ell^+ + \not{E}_T$
$0 < c\tau < \infty$:	$\gamma \;\; \ell^-\ell^+ + \not{E}_T$
$c\tau < \infty$:	$\ell^-\ell^+ + \not{E}_T$



$c\tau \sim 0$:	$\gamma\gamma$ jets / $\ell^\pm + \not{E}_T$
$0 < c\tau < \infty$:	γ jets / $\ell^\pm + \not{E}_T$
$c\tau < \infty$:	jets / $\ell^\pm + \not{E}_T$



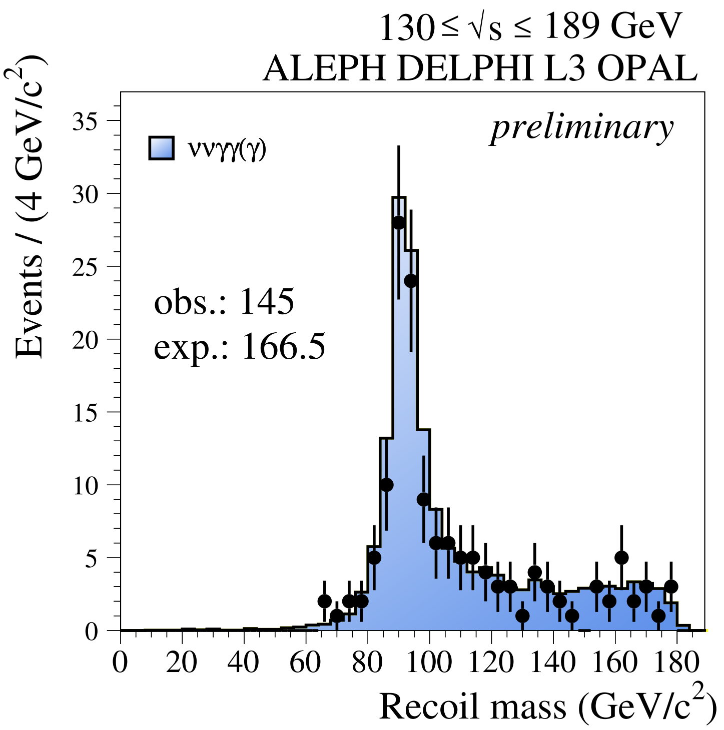
Photons and Missing Energy

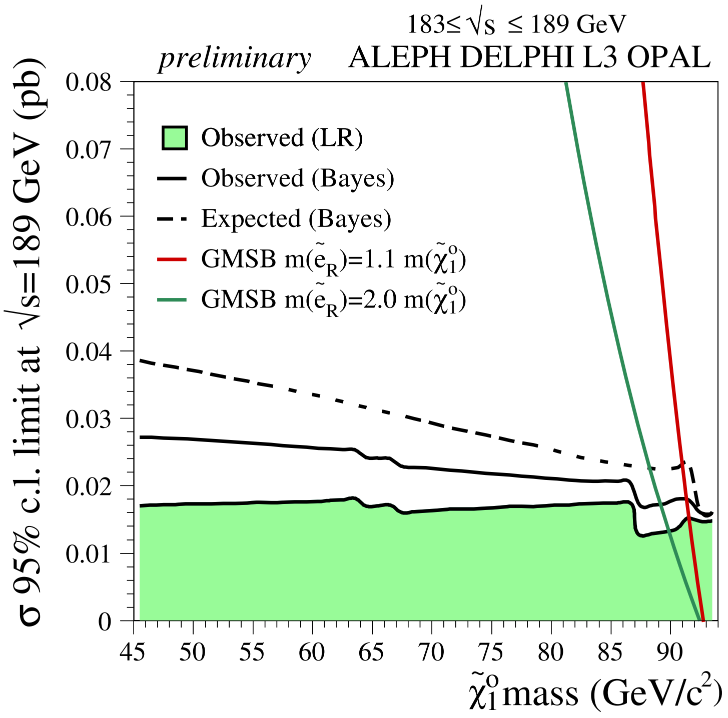
- Searching for processes with acoplanar, two photons pointing to the vertex and missing energy, indicative of

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

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

- **No evidence for an excess,**
- **ADLO set limits as function of $m_{\tilde{\chi}_1^0}$ below 0.02 pb.**



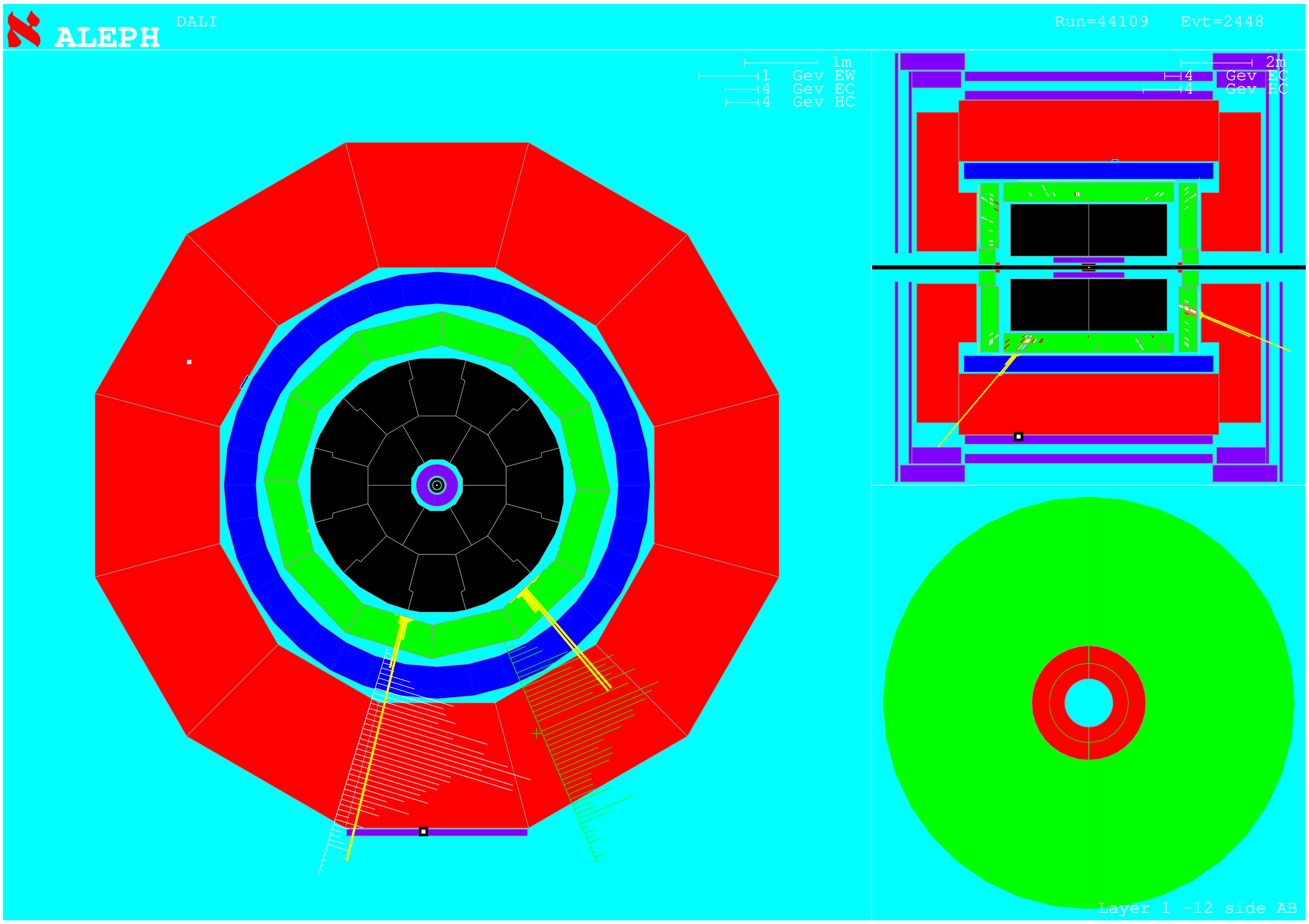


ZERO LIFETIME

Two Photons + Missing Energy: a Candidate

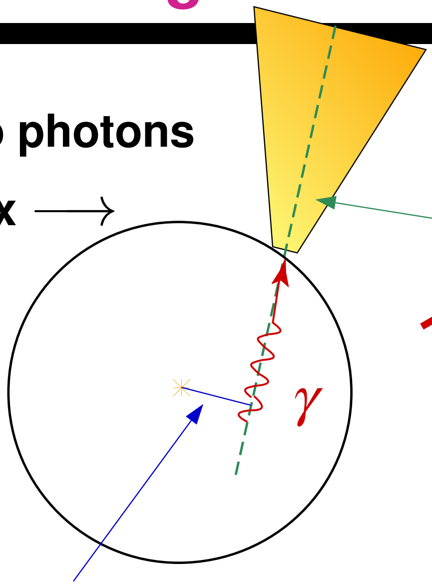
Candidate for
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \tilde{G}\gamma$$
$$\hookrightarrow \tilde{G}\gamma$$

- 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

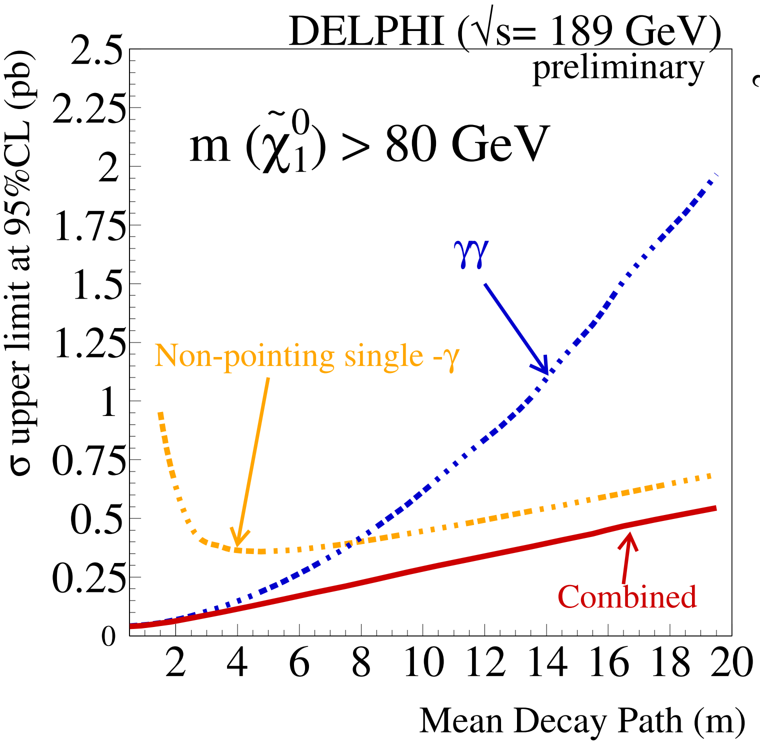
- **Searching for one or two photons not pointing to the vertex** $\longrightarrow$

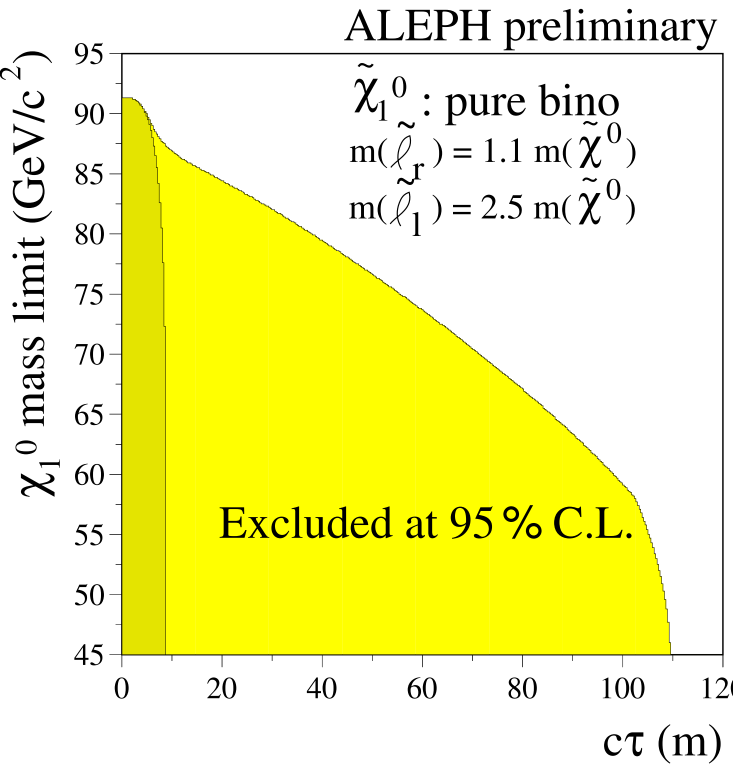


- calorimeter granularity provides reconstruction of **shower axis**
- require: **impact parameter** > 40cm

NON-ZERO LIFETIME

- **ALEPH** expects 0.8 events and observes none ($\sqrt{s} = 161$ GeV–189 GeV)
- **DELPHI** expects 7.9 events and observes 6 ($\sqrt{s} = 133$ GeV–189 GeV)



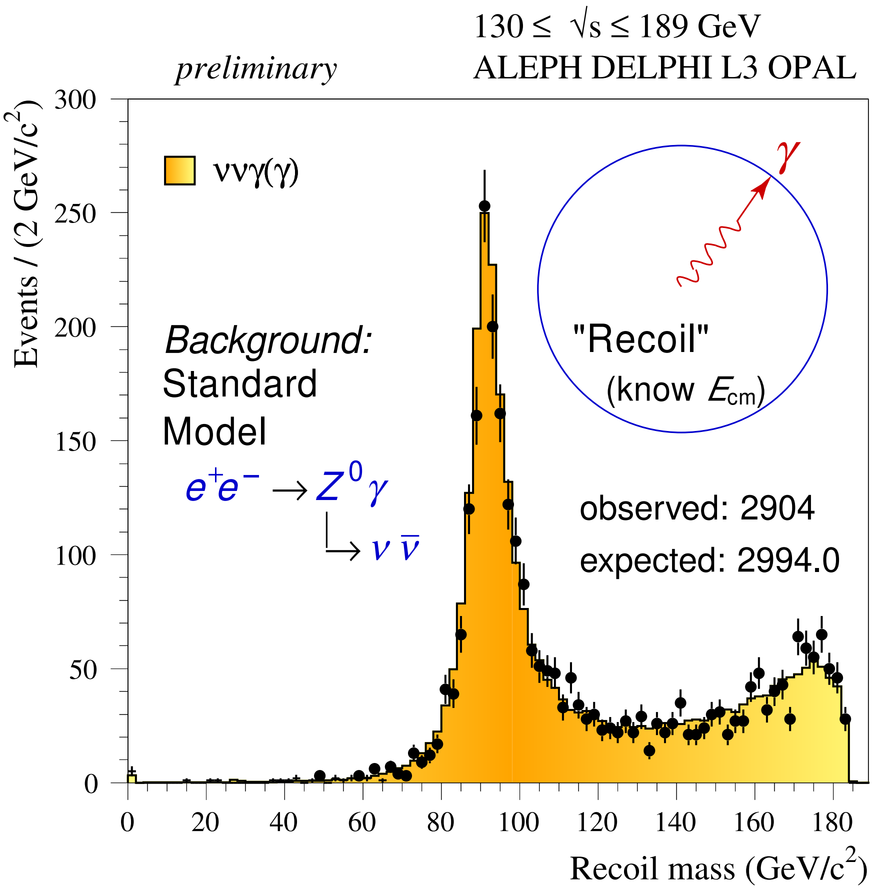


Single Photon and Missing Energy

Search for $e^+e^- \to \tilde{G}\tilde{G}\gamma$

in Ultra-Light Gravitino Scenario $\Rightarrow m_{\tilde{G}} \lesssim \mathcal{O}(10^{-4}$ eV)

(not naturally GMSB)



No anomalous production of single–photon events has been observed by the experiments $\Longrightarrow$

ADL set a 95% C.L. lower limit on the gravitino mass:

	ALEPH	DELPHI	L3
$m_{\tilde{G}} >$	$10 \cdot 10^{-6}$ eV	$8.9 \cdot 10^{-6}$ eV	$8.9 \cdot 10^{-6}$ eV

(based on Brignole, Feruglio & Zwirner, Nuc. Phys. B516(1998) 13)

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

Signature:

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

Background:

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

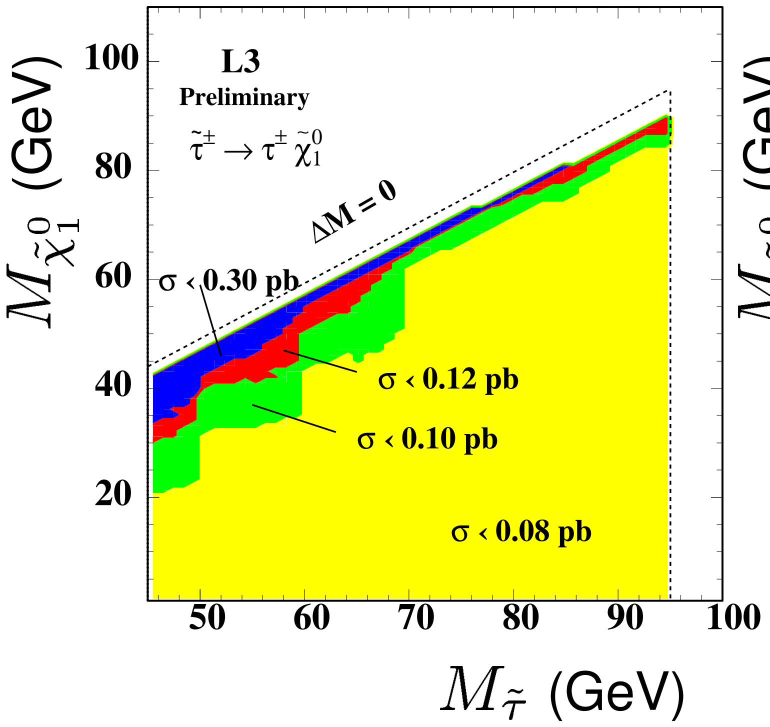
$$\Delta M = M_{\tilde{\ell}} - M_{\tilde{\chi}_1^0}$$

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

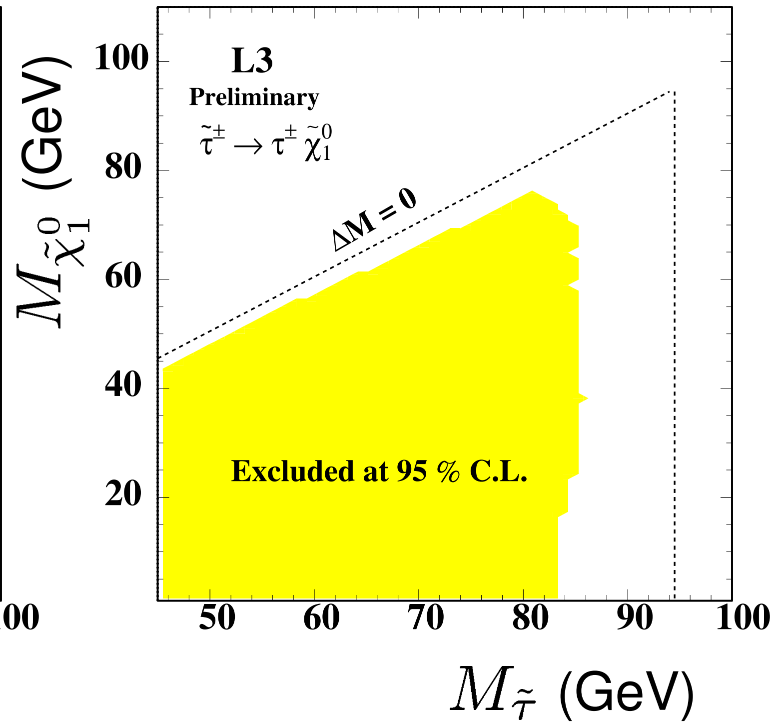
- No evidence for an excess seen by individual experiments ...

... limits $\Longrightarrow$ ZERO LIFETIME

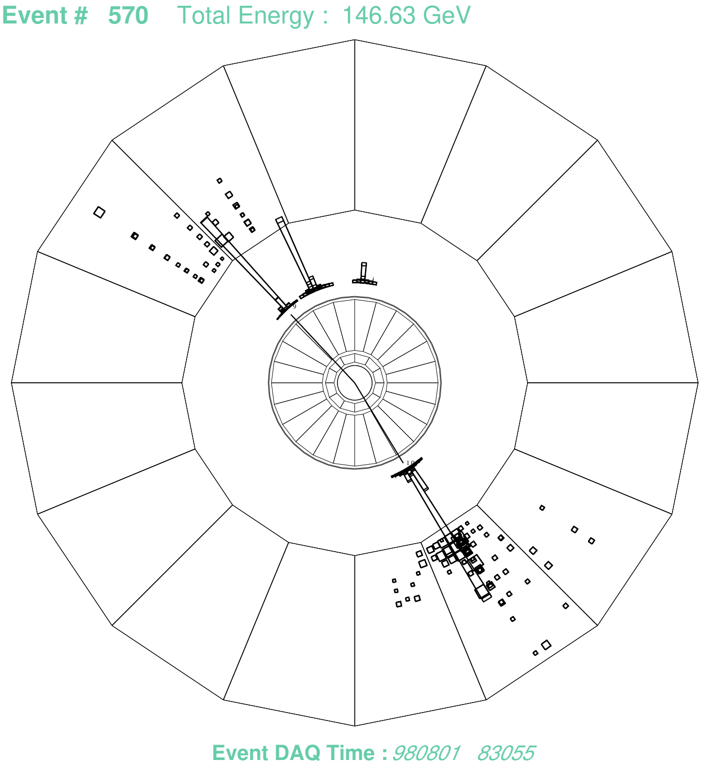
upper limits on σ at 95% CL



upper limits on $\tilde{\tau}$ mass 95% CL

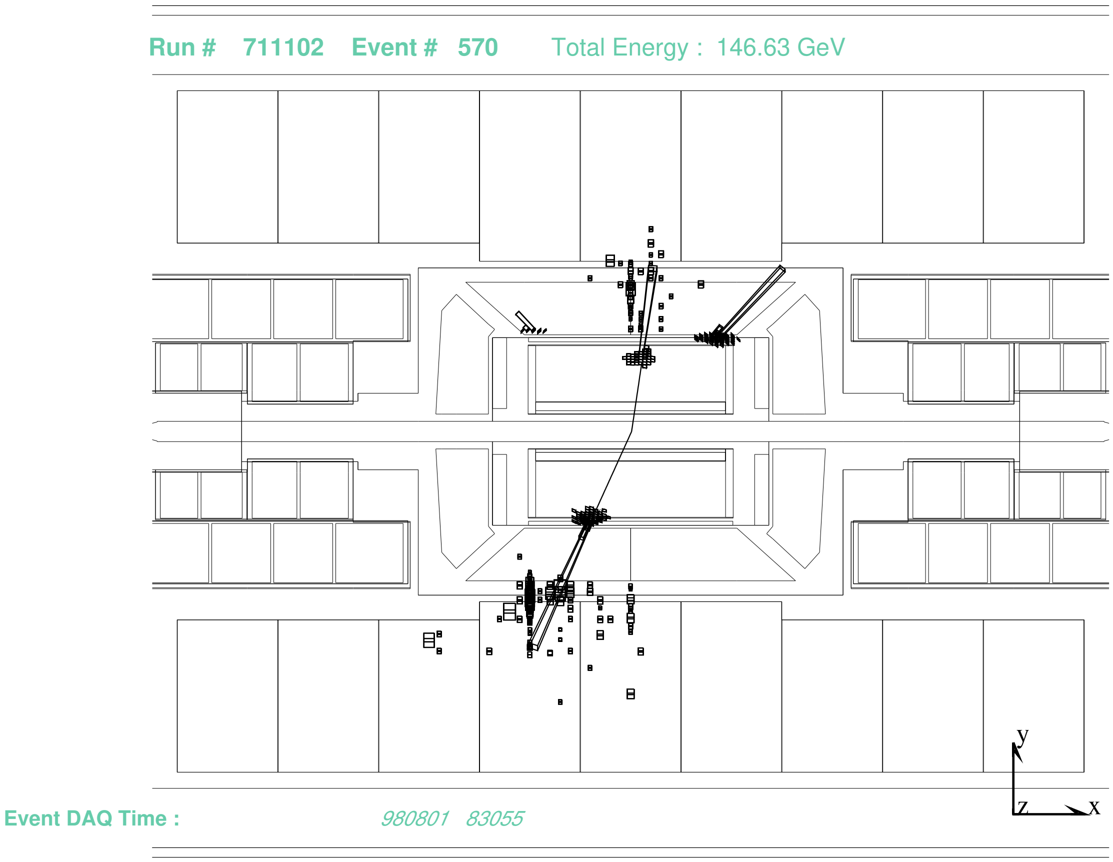


Candidate for Slepton Searches ($\tilde{\chi}^0_1$ NLSP)



Candidate for

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



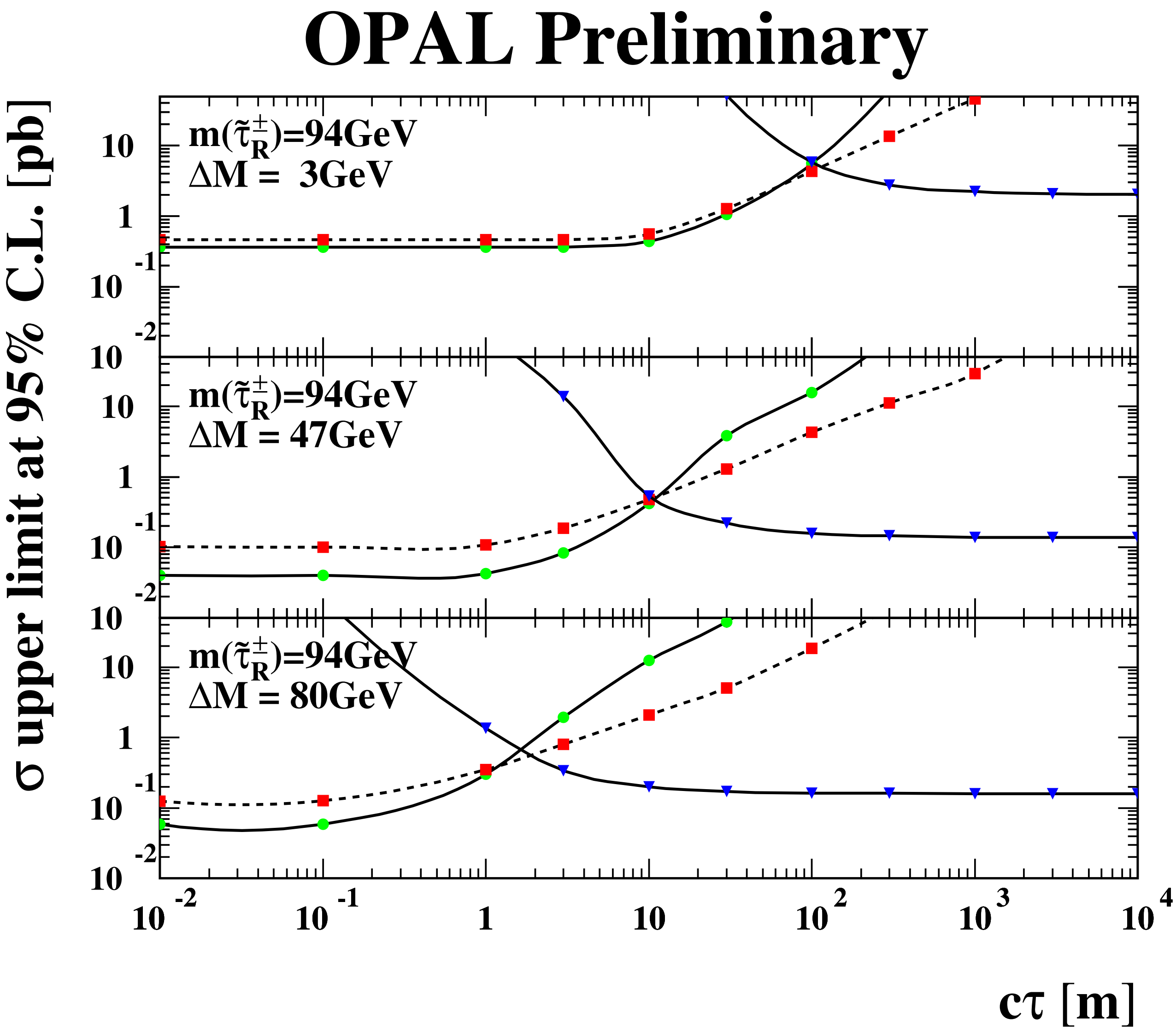
Slepton Search depending on $\tilde{\chi}^0_1$ Lifetime

- for longer lifetime of the $m_{\tilde{\chi}^0_1}$:

  decay $\tilde{\chi}^0_1 \rightarrow \tilde{G}\gamma$ outside the detector volume $\Longrightarrow$ NON-ZERO LIFETIME

Type of analysis: missing energy +

● $\tau^+\tau^-\gamma\gamma$ ⟶ ■ $\tau^+\tau^-\gamma$ ⟶ ▼ $\tau^+\tau^-$

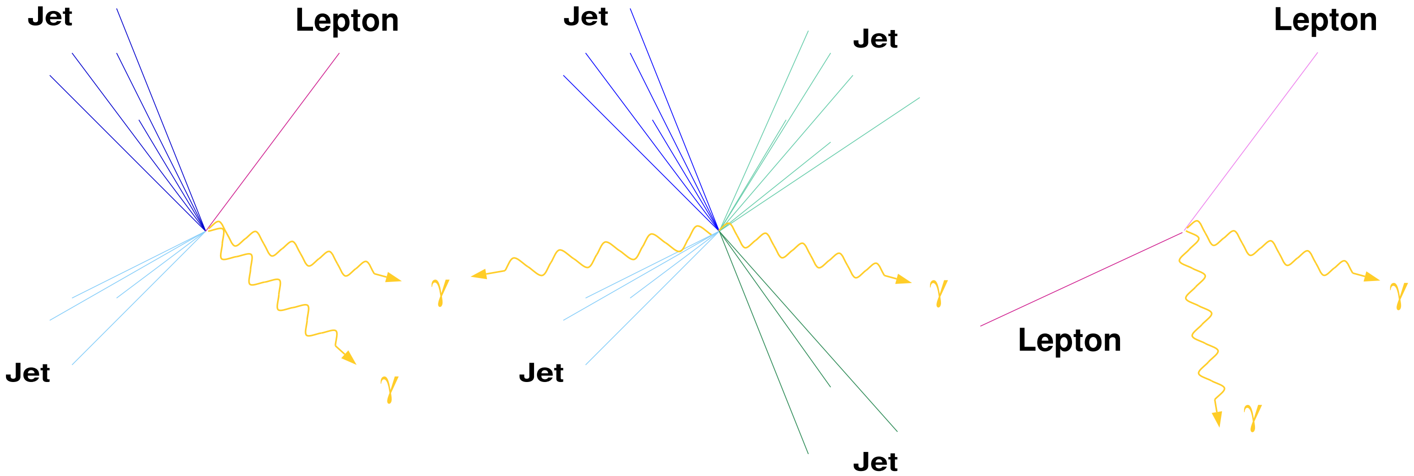


Chargino Searches with $\tilde{\chi}_1^0$ NLSP

- **Process to search for**

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

- **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 separatly optimised for different ΔM regions (D:5, O:4 regions)

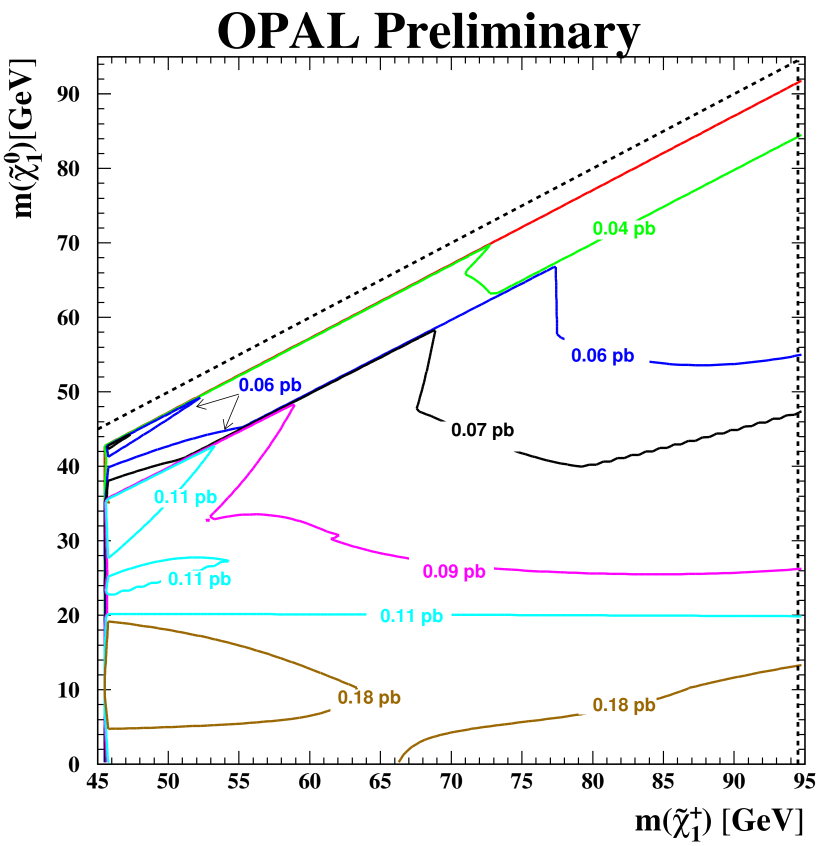
- No excess found in data ($\sqrt{s} = 189$ GeV) by DELPHI and OPAL

$\longrightarrow$

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

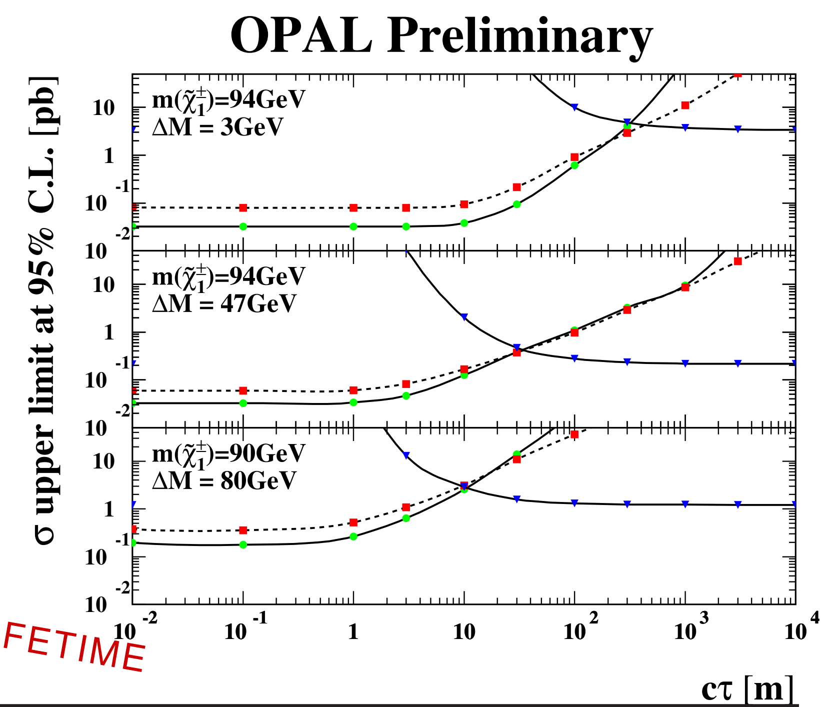
Limits at 95% C.L. for the production cross section of $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^\pm_1 \to W^{(*)\pm}\tilde{\chi}^0_1$, followed by prompt decays $\tilde{\chi}^0_1 \to \tilde{G}\gamma$:

ZERO LIFETIME



same limits for specific points in the mass plane for different $\tilde{\chi}^0_1$ lifetimes $\longrightarrow$

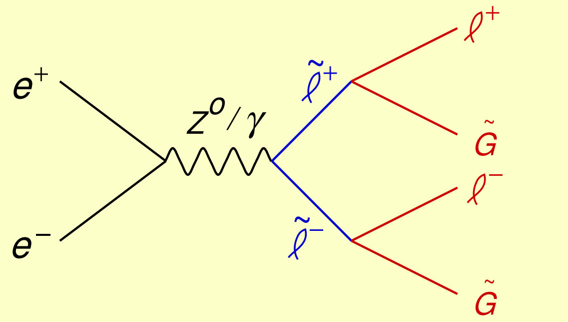
(requiring ● 2 photons
■ 1 photons
▼ no photons)



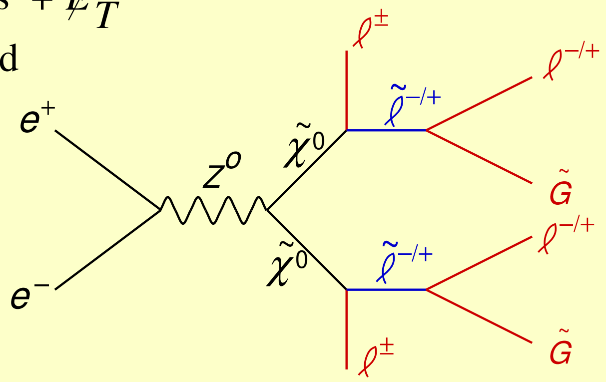
NON-ZERO LIFETIME

GMSB Scenarios with $\tilde{\ell}$ NLSP

$c\tau \sim 0$:	$\ell^- \ell^+ + \not{E}_T$
$0 < c\tau < \infty$:	$2 \times$ Kinked Tracks $+ \not{E}_T$
$c\tau < \infty$:	$2 \times$ Stable Charged

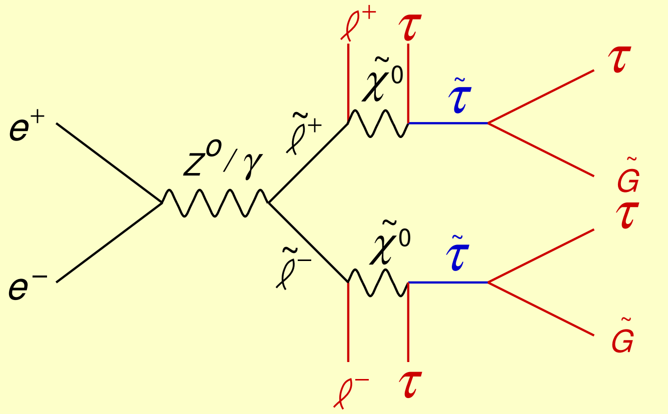


$c\tau \sim 0$:	$4 \times \ell^\pm + \not{E}_T$
$0 < c\tau < \infty$:	$2 \times \ell^\pm + 2 \times$ Kinked Tracks $+ \not{E}_T$
$c\tau < \infty$:	$2 \times \ell^\pm + 2 \times$ Stable Charged



$c\tau \sim 0$:	$\tau^{+/-} \quad \tau^{+/-} + (\ell^{+/-}\tau^{-/+} \quad \ell^{+/-}\tau^{-/+}) + \not{E}_T$
$0 < c\tau < \infty$:	$2 \times$ Kinked Tracks $+ (\ell^{+/-}\tau^{-/+} \quad \ell^{+/-}\tau^{-/+}) + \not{E}_T$
$c\tau < \infty$:	$2 \times$ Stable Charged $+ (\ell^{+/-}\tau^{-/+} \quad \ell^{+/-}\tau^{-/+}) + \not{E}_T$

$\tilde{\tau}^\pm$ NLSP ($\tan\beta > 10$)

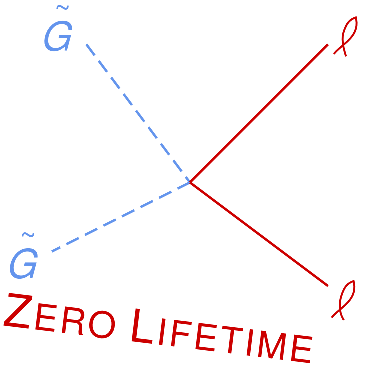


Slepton Searches with $\tilde{\ell}$ NLSP

Similar to search for

- $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \to (\ell^+\tilde{\chi}^0_1)(\ell^-\tilde{\chi}^0_1)$, sleptons in grav. med. SUSY

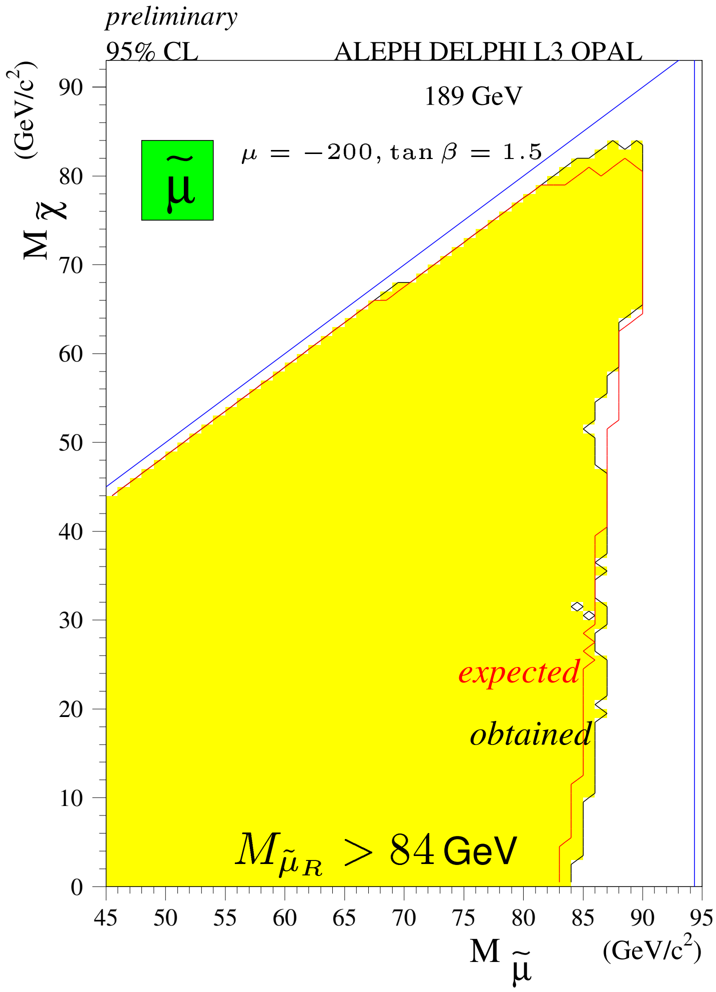
$$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \to (\ell^+\tilde{G})(\ell^-\tilde{G})$$

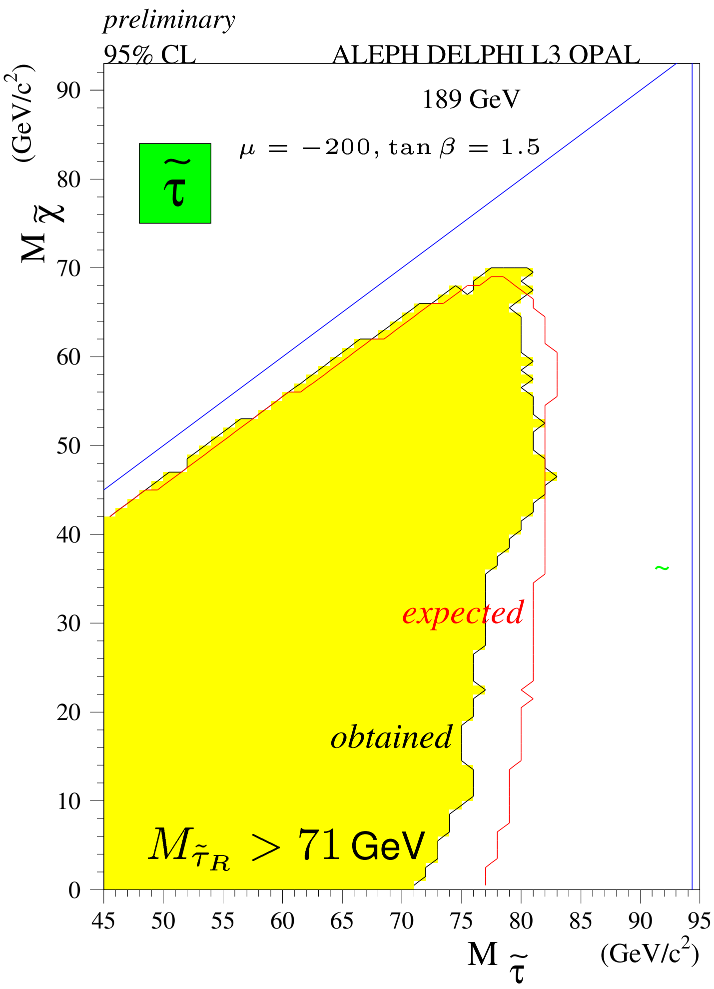


- acoplanar lepton pair
- missing E_T

...consistent with SM backgrounds $\Rightarrow$

limits (extracted from MSSM search)





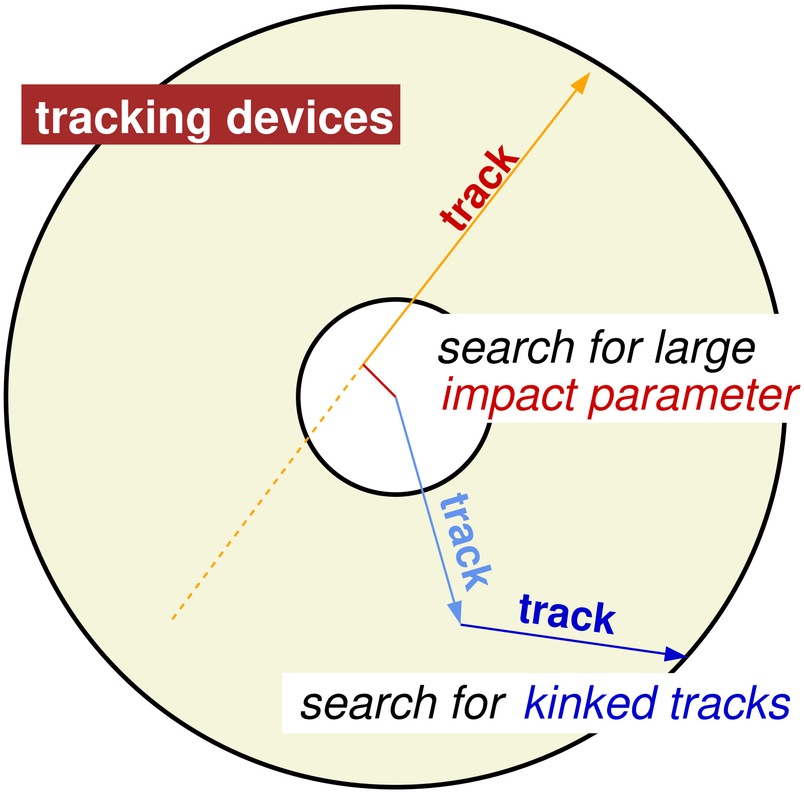
Sleptons Decaying in Flight

- $\tilde{\ell}$ decays before reaching the tracking devices
  ($\mathcal{O}$(1 mm) $\lesssim$ Mean Decay Length $\lesssim$ $\mathcal{O}$(40 cm))

$\Longrightarrow$ **Search for large impact parameter**

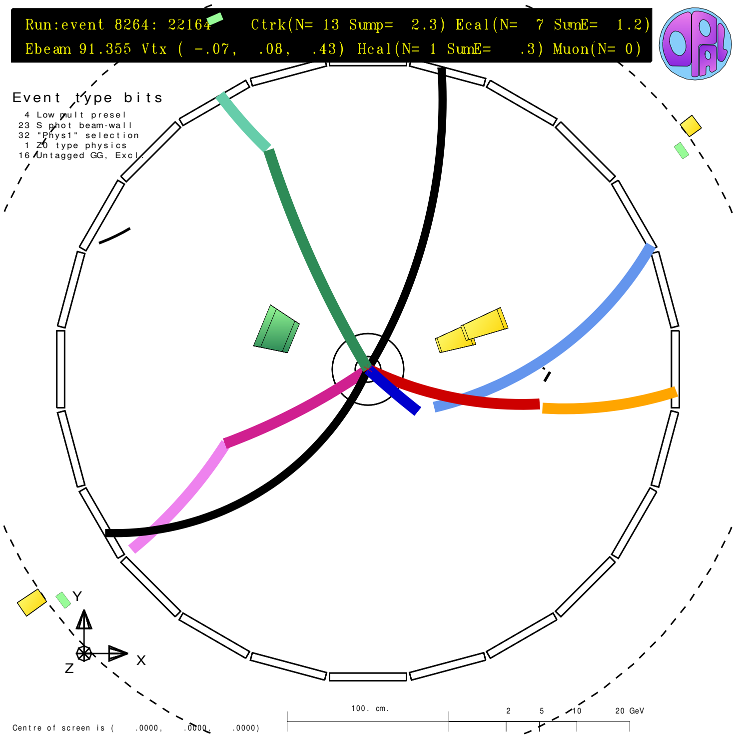
- $\tilde{\ell}$ decays inside the tracking devices
  ($\mathcal{O}$(10 cm) $\lesssim$ Mean Decay Length $\lesssim$ $\mathcal{O}$(2 m))

$\Longrightarrow$ **Search for tracks with kinks**

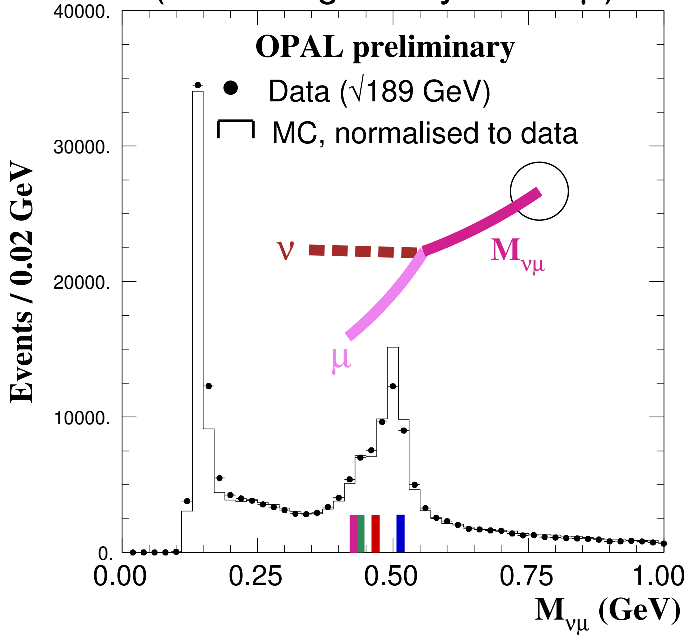


Kinked Track Search

- **Main backgrounds:** Bremsstrahlung, interactions with the detector material, badly reconstructed tracks, 2 photon production of long lived particles
- **Not a slepton candidate, but nice:**
  (particles seen by the detector: $K^+K^-\pi^+K^+K^-\pi^-$)



Invariant mass of all primary kink tracks (assuming decay into ν μ)

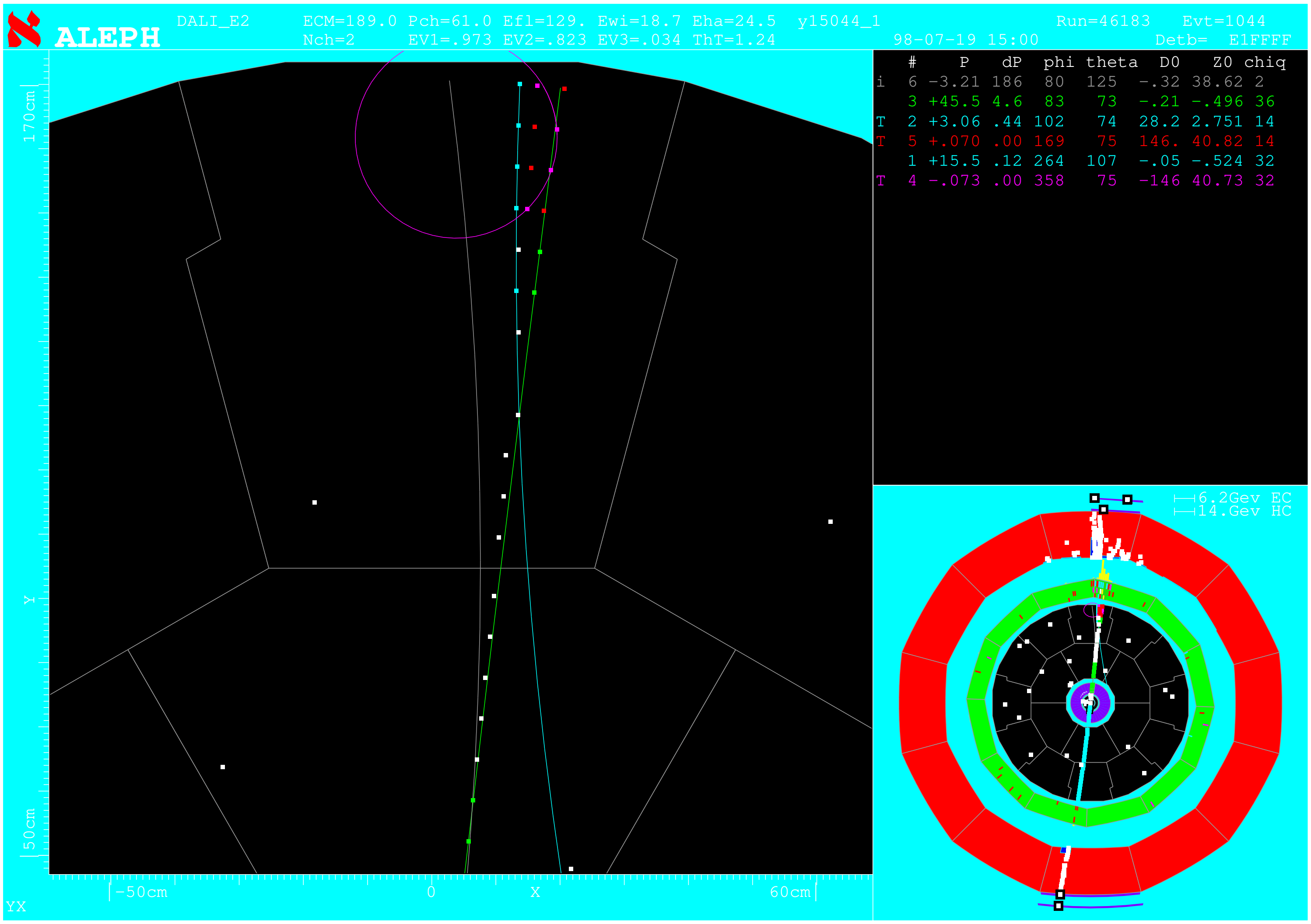


- **Results for this search by individual experiments:**

Experiment	√s (GeV)	Expected bg.	Observed
ALEPH (IP + kink)	161-189	2	1 + 1
DELPHI (IP + kink)	189	4.5 + 1.4	4 + 1
OPAL (kink)	189	0.4	0

Kinked Track Candidate

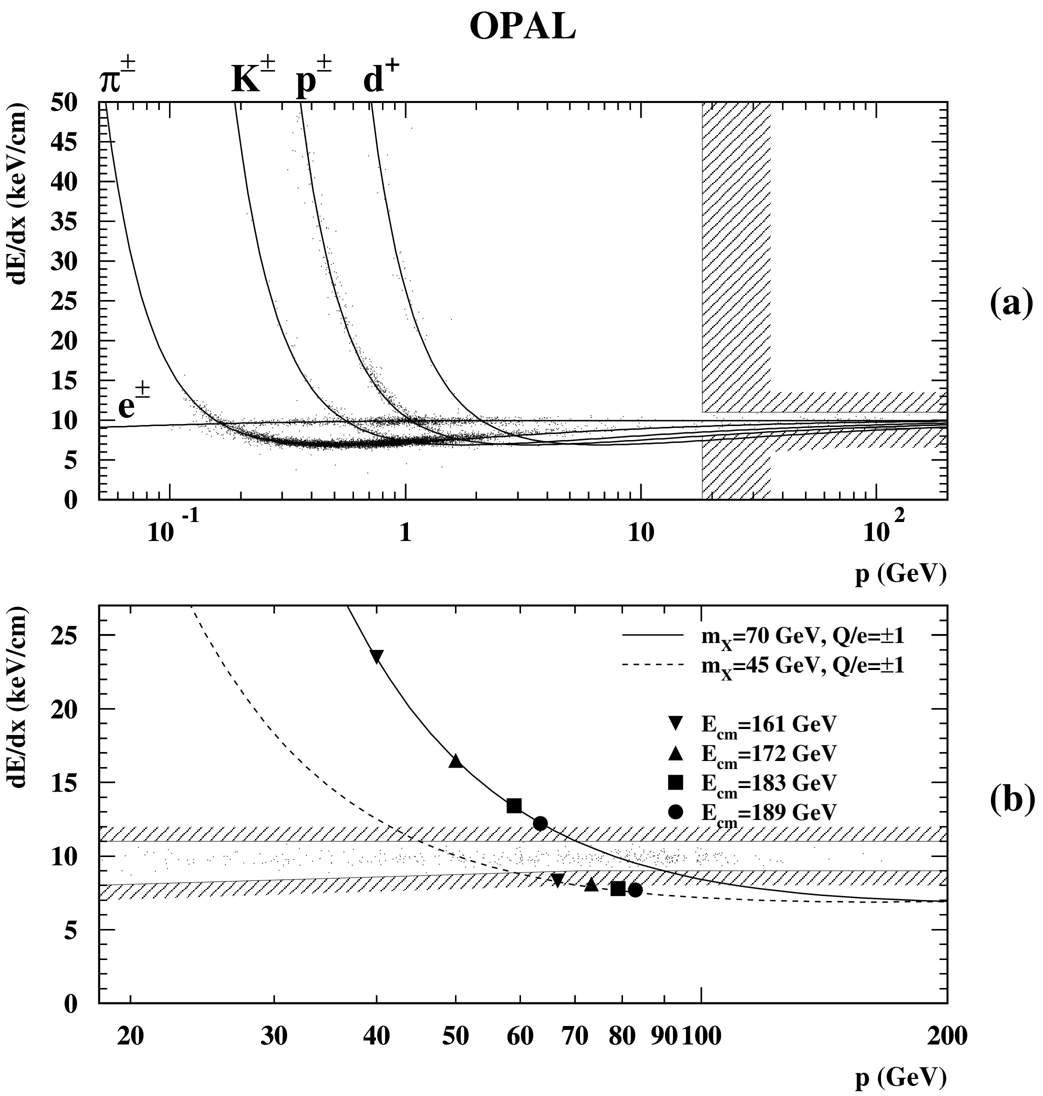
- Invariant mass assuming massless decay particles: 1.88 GeV
- Angle between tracks: $8.8\,^{\circ}$
- Back-to-back track: μ
- Missing momentum: $31.$ GeV



Search for Stable Sleptons

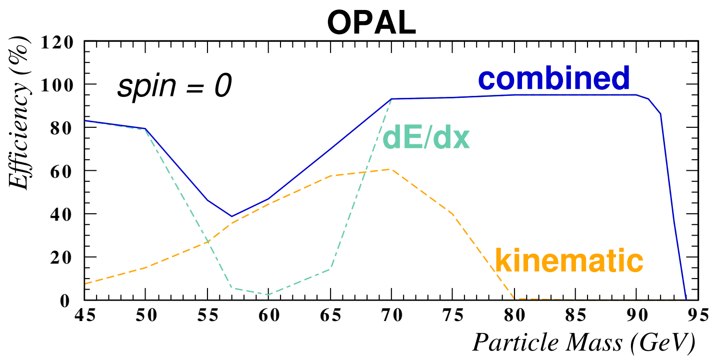
Process: $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \quad (c\tau \to \infty)$

Powerfull search tool is dE/dx: no background from other physics processes in most of the search region $\Longrightarrow$



- search based on kinematics is designed for region of $0.5 \lesssim M_{\tilde{\ell}}/E_{Beam} \lesssim 0.7$

$\Longrightarrow$

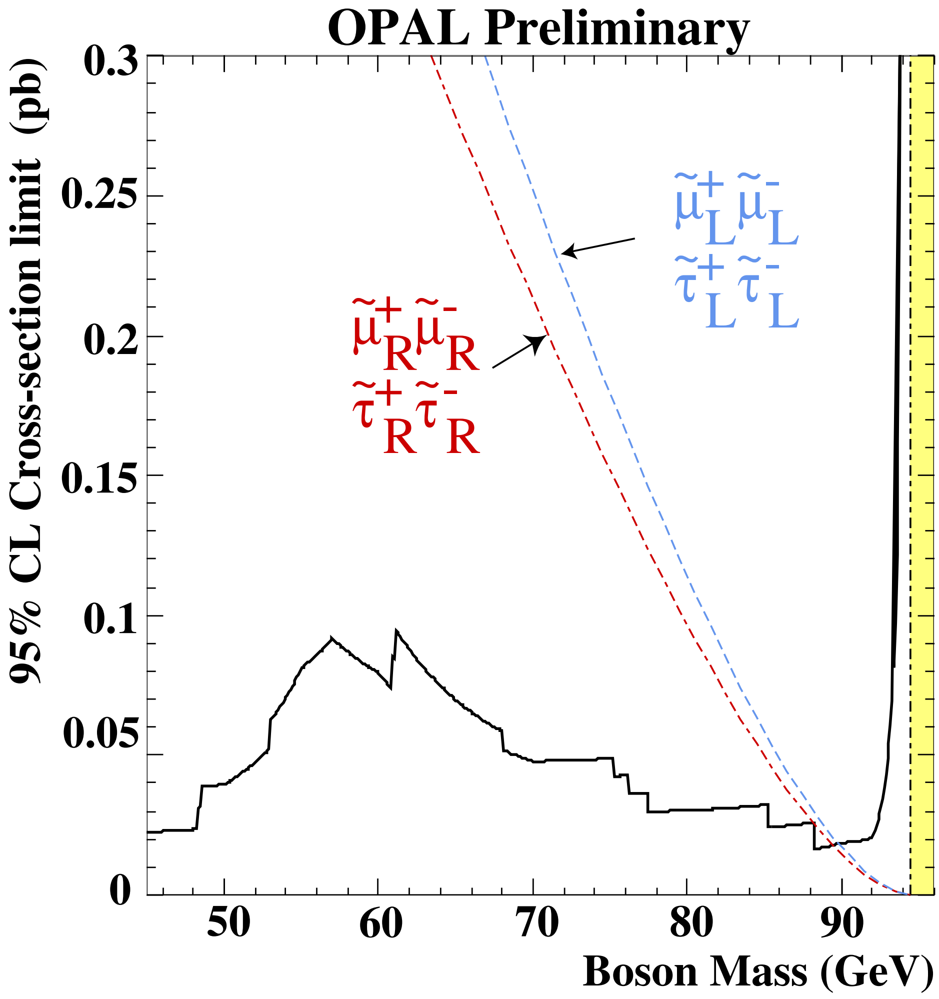


Limits for Stable Sleptons

Results given by individual experiments (up to $\sqrt{s} = 189$ GeV):

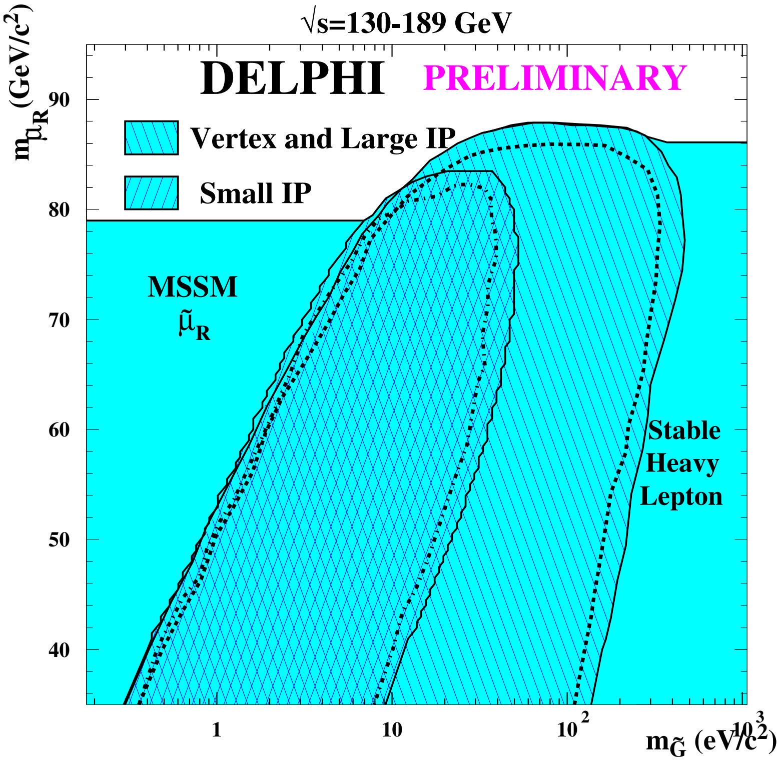
	ALEPH	DELPHI	L3	OPAL
Expected	0.9	1.7	4.4	4.7
Observed	3	1	4	7
$\mu_R >$	88.6	87.0		88.0

(LEP combined limit up to $\sqrt{s} = 183$ GeV: $l_R > 86.5$ GeV)



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

- Combining searches in various regions of $\tilde{\ell}$ lifetime $\longrightarrow$ limits as function of lifetime/gravitino mass:



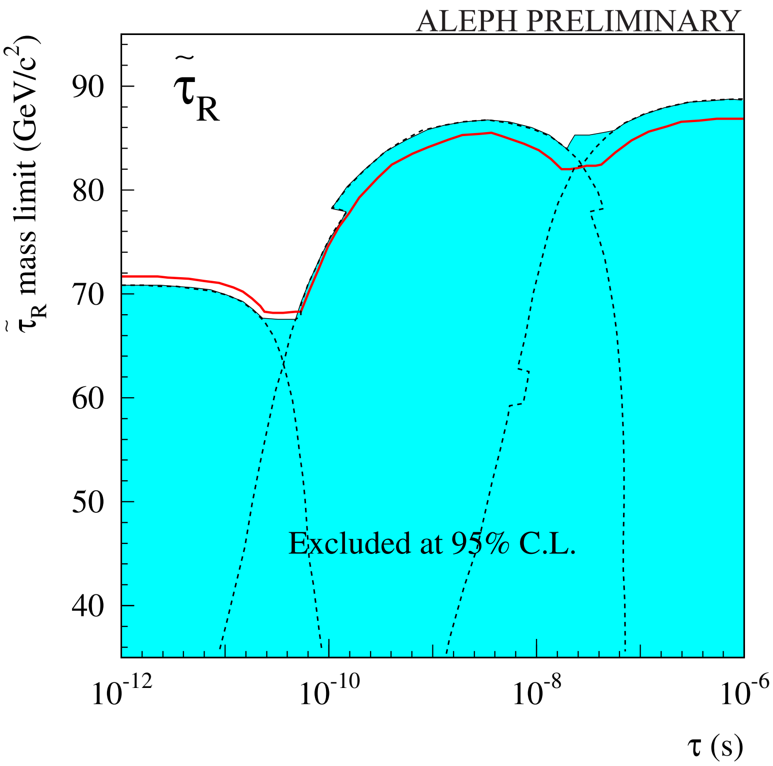
95% C.L. limit on $M_{\tilde{\mu}_R}$

- dashed line: expected limit
- positive-slope hatched: impact parameter search
- negative-slope hatched: kinked track search

ALL LIFETIMES

95% C.L. limit on $M_{\tilde{\tau}_R}$

- red line: expected limit



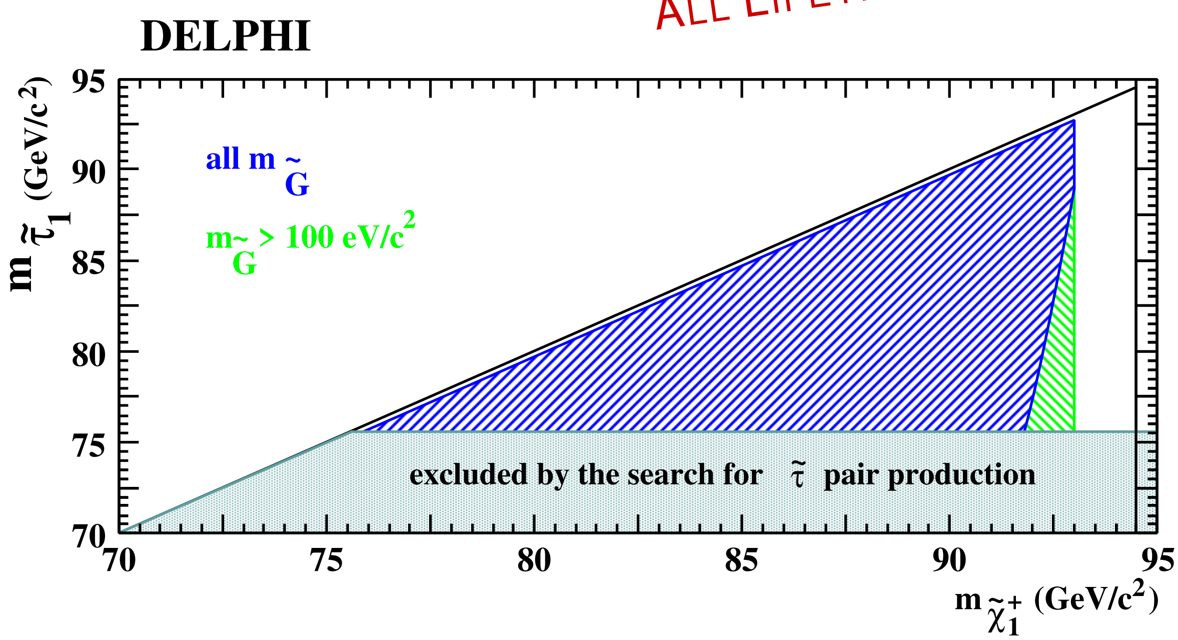
Chargino Searches with $\tilde{\tau}$ NLSP

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

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

- DELPHI observes 36 candidates (38.9 expected)

ALL LIFETIMES

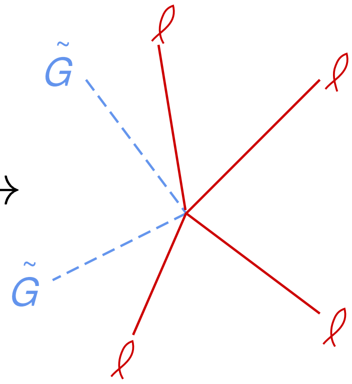


$\Longrightarrow M_{\tilde{\chi}_1^\pm} > 91.8$ GeV 95% C.L. ($\Delta M \geq 0.3$ GeV) for all $M_{\tilde{\mathrm{G}}}$

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

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

- **Search for 4 lepton final states** $\to$

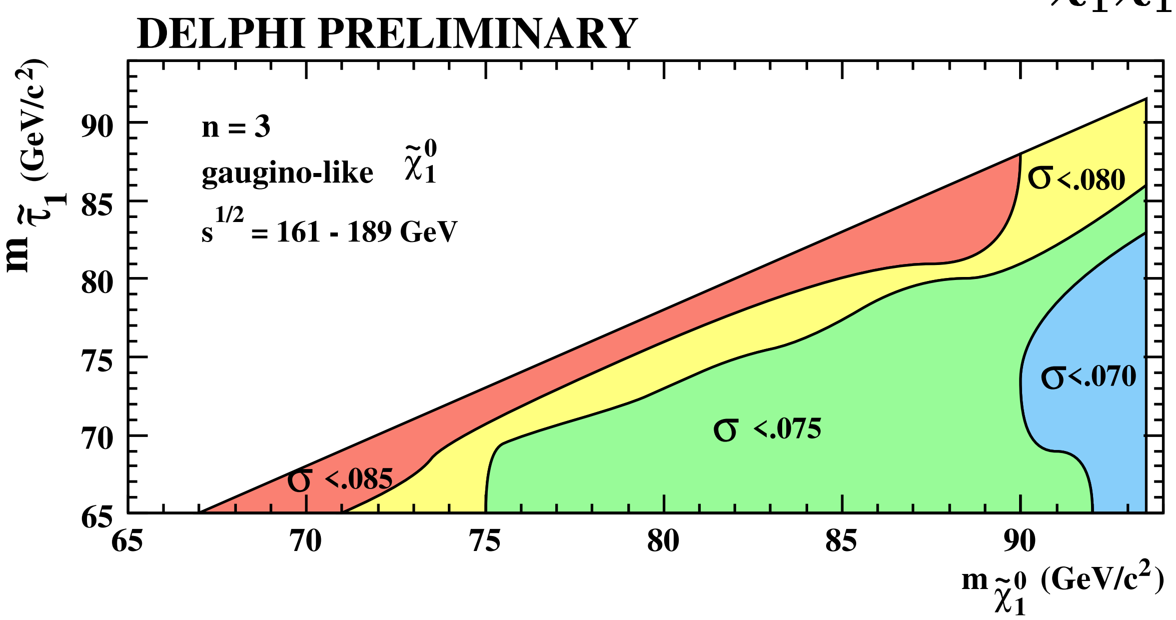


- **Search results for individual experiments:**

Experiment	√s (GeV)	Expected bg.	Observed
ALEPH $\tilde{e},\tilde{\mu},\tilde{\tau}$	189	0.1 - 5.1	0 - 4
DELPHI $\tilde{\tau}$	161-189	1.9	3
OPAL $\tilde{e},\tilde{\mu},\tilde{\tau}$	189	1.9	2

- **95% C.L. limits on production cross section for**

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



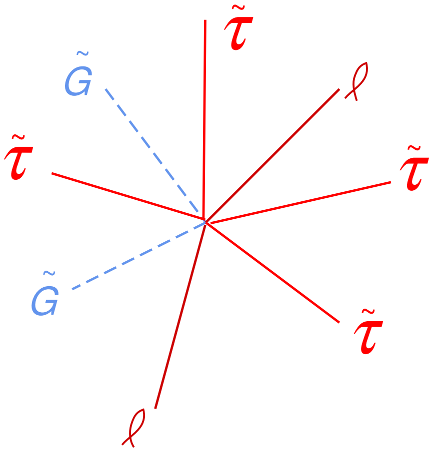
ZERO LIFETIME

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

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

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

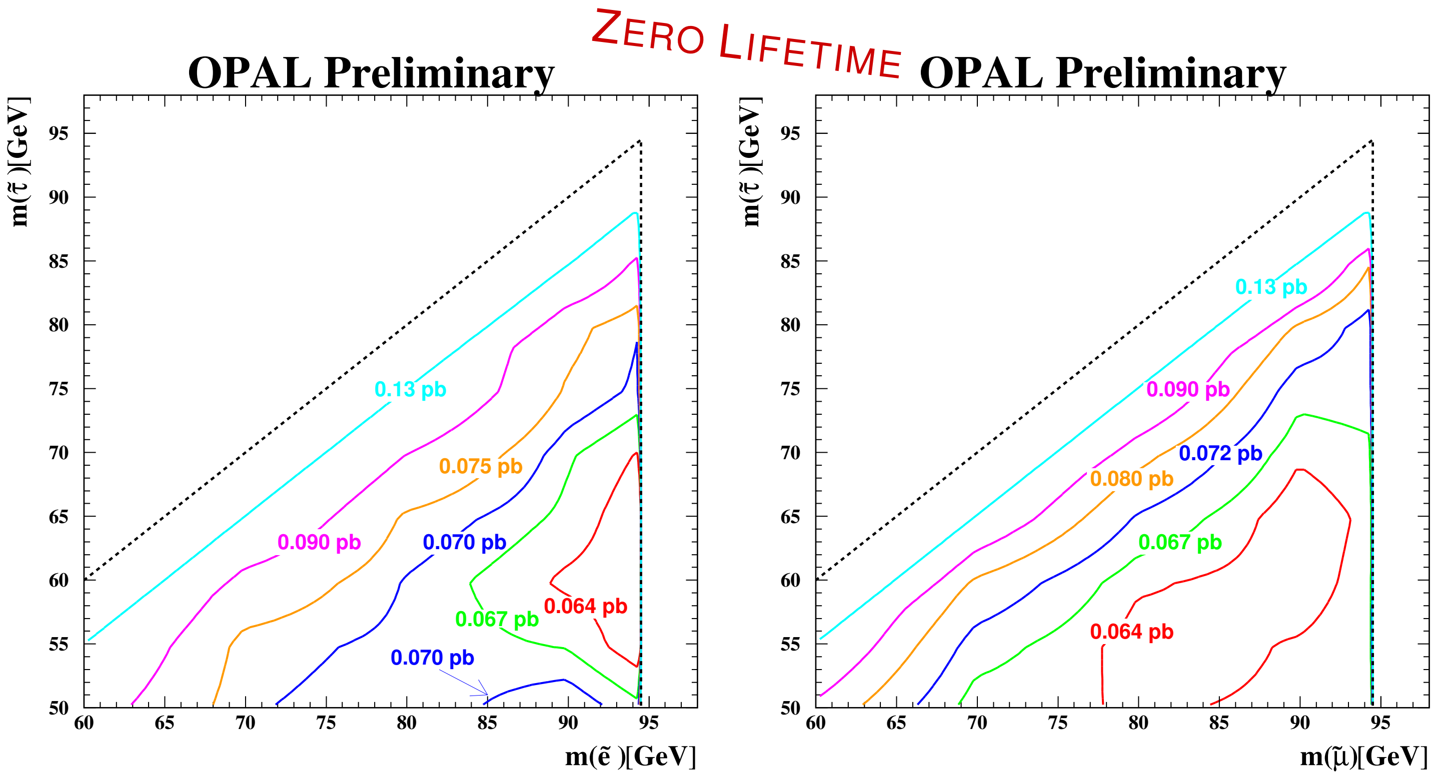
- Search for six leptons $\longrightarrow$



- **OPAL:**

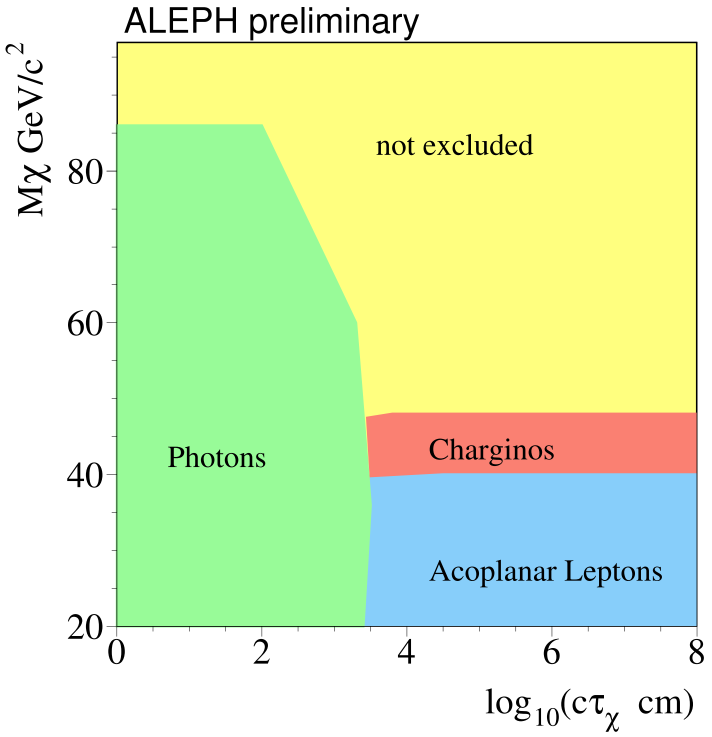
  5 events seen, with 5.2 expected from SM sources ($\sqrt{s} = 189$ GeV)

...Limits at the 95% C.L. for the production cross-section:



Model Dependent Interpretation

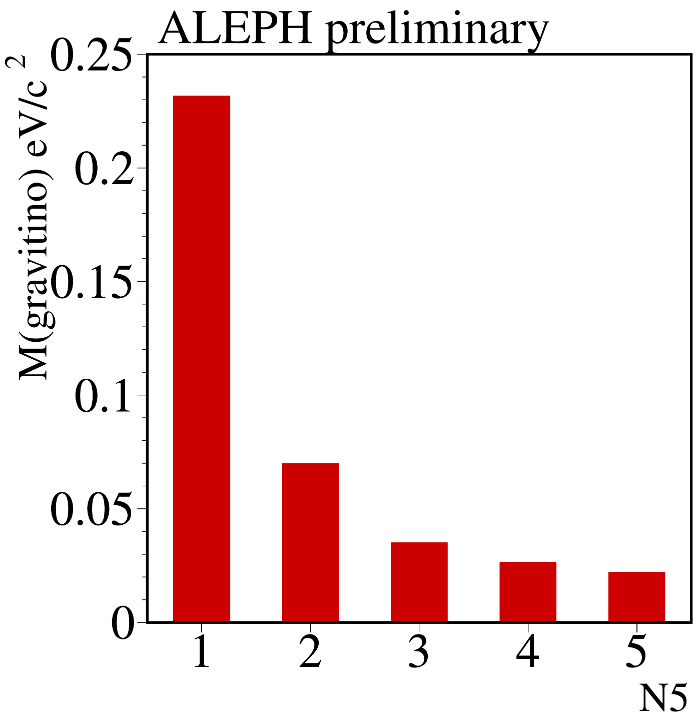
Model: Dimopoulos et al., Phys.Rev. D54(1996)3283



Regions excluded at 95% C.L. for

- N5 = 1
- $M_{mess} = 10^{12}$
- $\tan\beta = 20$
- negative μ

($\tilde{\chi}^0_1$ most likely NLSP, light $\tilde{\tau}$; $m_{\tilde{\tau}} < m_{\tilde{e}}, m_{\tilde{\mu}}$)



Summary and Outlook

- LEP ran very well at $\sqrt{s} \sim 189$ GeV in 1998 ...
- ... but no indication for New Physics yet (unfortunatly!) .
- All observed phenomena are well described by the Standard Model.
- A broad spectrum of *conventional* new particle searches plus a large number of novelties inspired by theory, are actively pursued at LEP2.
- New final topologies are searched for: displaced vertices, kinked tracks, displaced photons, multilepton final states, etc
- Results are interpreted in varios models, existing limits have been extended.
- Hopefully to come soon from the four Collaborations: complete study of all possible topologies with displaced vertices; systematic study of schemes used.
- LEP has turned on very well in 1999, looking forward to $\sqrt{s} \sim 200$ GeV !!
- ... And remaining ready for the unexpected