International Conference on High Energy Physics

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Exotic SUSY Signatures at LEP

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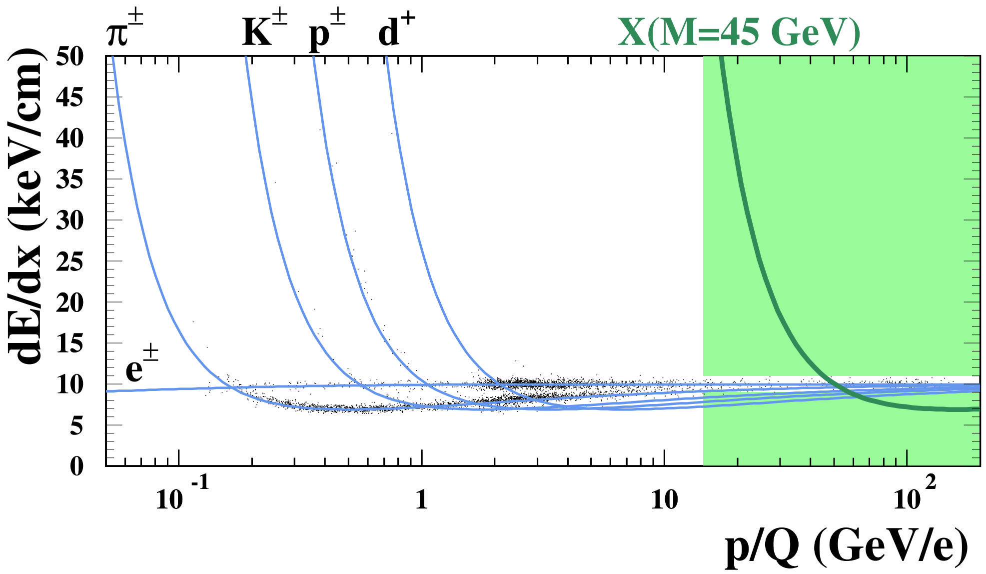
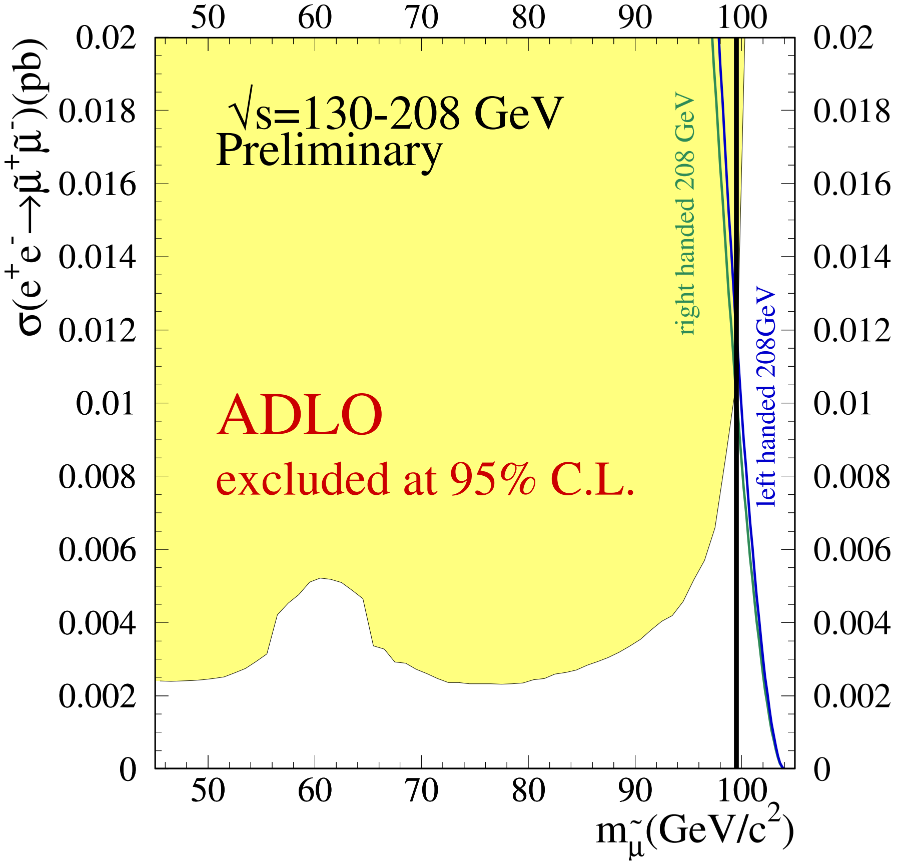
- Searches for signatures of models with different **l**ightest **S**USY **p**article (**LSP**)
  - ◇ Models with Gauge-mediated Supersymmetry breaking (GMSB):
    - — gravitino LSP
    - — gluino LSP
  - ◇ Models with Anomaly-mediated Supersymmetry breaking (AMSB):
    - — neutralino LSP
    - — sneutrino LSP
    - — stau LSP
  - ◇ String motivated models:
    - — gluino LSP

$\Rightarrow$ Many topologies and search methods depending on the nature of the LSP and the **n**ext-to-**l**ightest **S**USY **p**article (**NLSP**).

Search for Heavy Stable Charged Particles

- Search for pair produced heavy stable charged particles:
  - ◇ candidate for LSP in AMSB ($\tilde{\tau}$)
  - ◇ candidate for stable NLSP in AMSB ($\tilde{\chi}^{\pm}$)
  - ◇ candidate for stable NLSP in GMSB ($\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$)
- Main tool: search for particles with anomalously high or low ionisation energy loss (dE/dx) in the tracking chambers:





$\Rightarrow$ right (left) handed $\tilde{\tau}$, $\tilde{\mu}$:

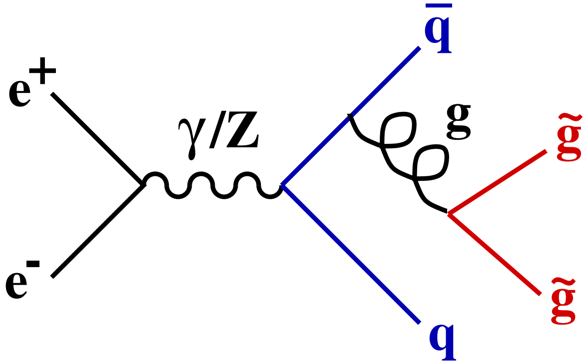
$$\mathbf{m}_{\tilde{\tau},\,\tilde{\mu}} > 99.4\ (99.6)\ \mathbf{GeV/c^2}$$

$\Rightarrow$ stable charginos with $m_{\tilde{\nu}}$ >41. (500.) GeV/c^2:

$$\mathbf{m}_{\tilde{\chi}_1^{\pm}} > 101.5\ (102.5)\ \mathbf{GeV/c^2}$$

Alternative Signatures ⇒ Search for Stable Gluinos

Gluino production at LEP 1:



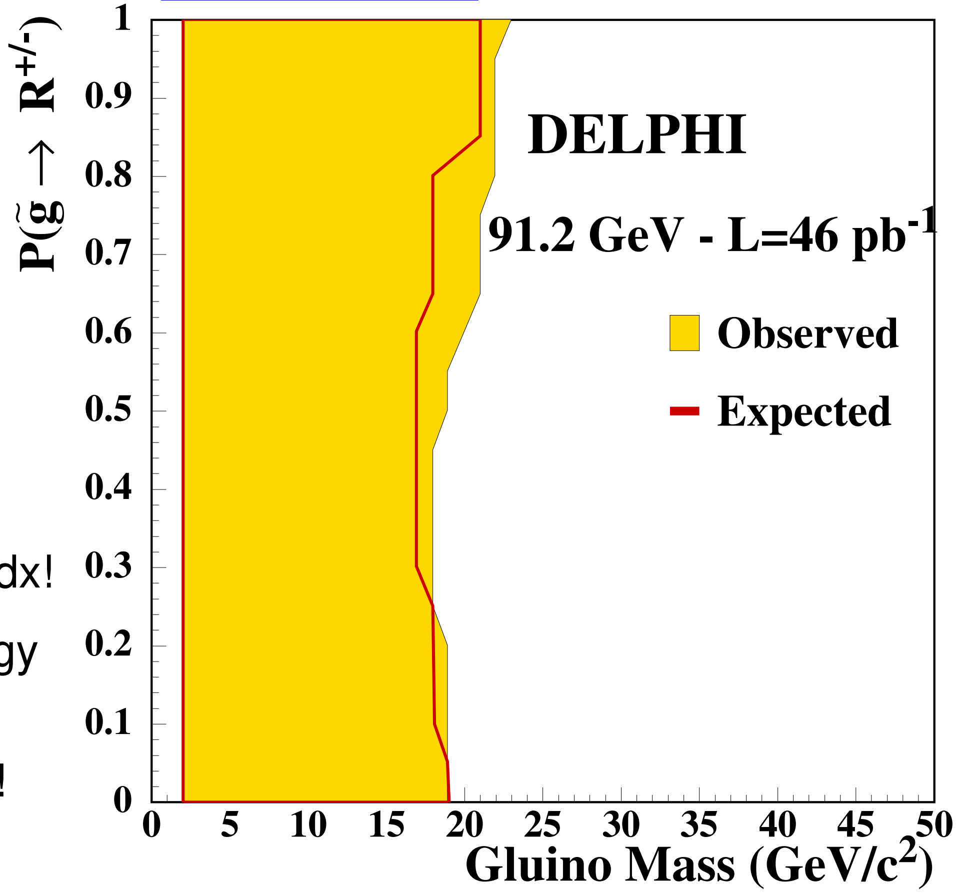
- Gluino forms R-hadron.

  Charged R-hadron, $R^{\pm}$: look for anomalous dE/dx!

  Neutral R-hadron, R^0: can deposit enough energy to escape "missing energy" signature ⇒ analysis using relaxed cuts on missing energy!

- Search for $\mathrm{q\bar{q}R^{\pm}R^{\mp}}$, $\mathrm{q\bar{q}R^{\pm}R^{0}}$, $\mathrm{q\bar{q}R^{0}R^{0}}$ ⇒

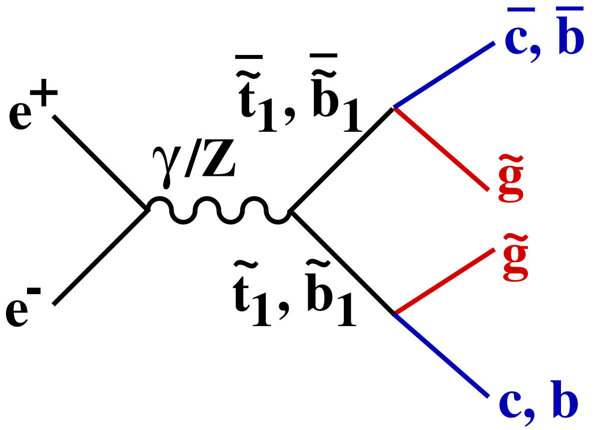
LEP 1 data: no excess ⇒



$2\ \mathrm{GeV} < M_{\tilde{g}} < 18\ \mathrm{GeV}$

Search for Gluinos at LEP 2

Gluino production at LEP 2:



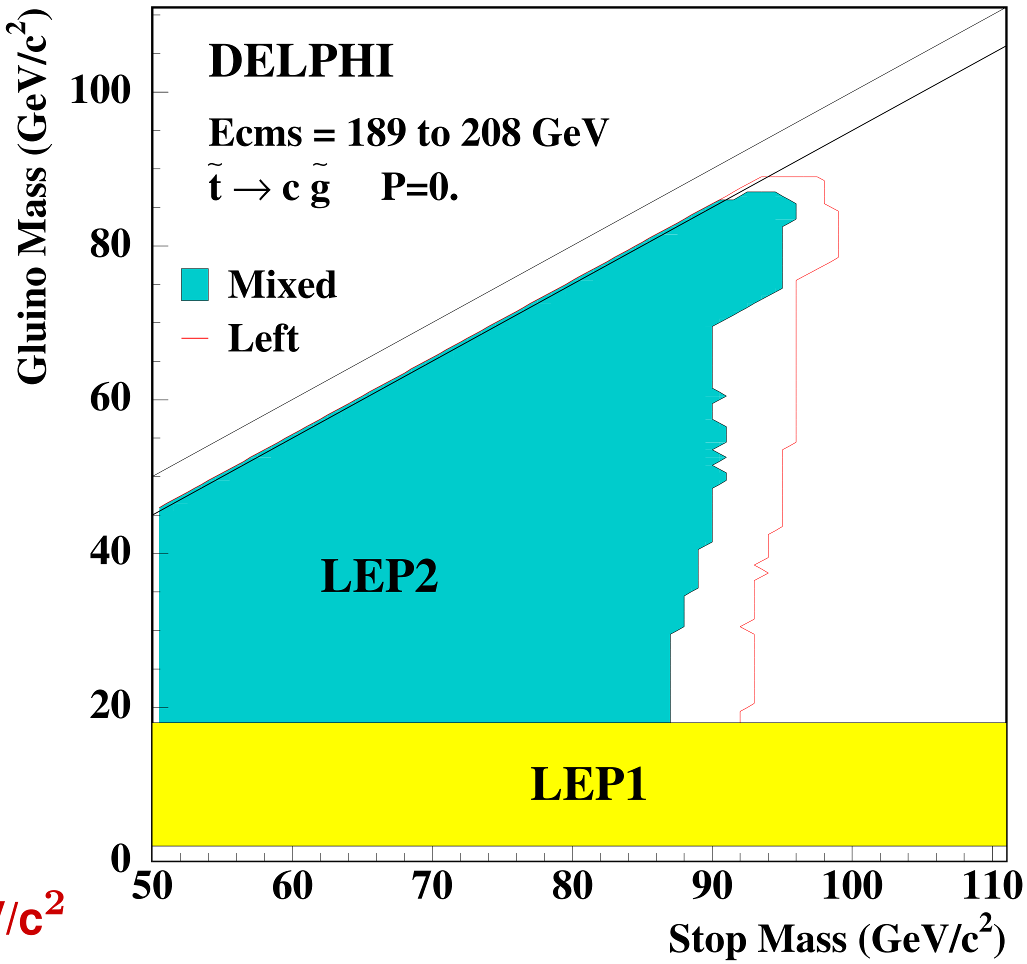
- Topology: two jets, two R-hadrons

LEP 2 data: no excess $\Rightarrow$

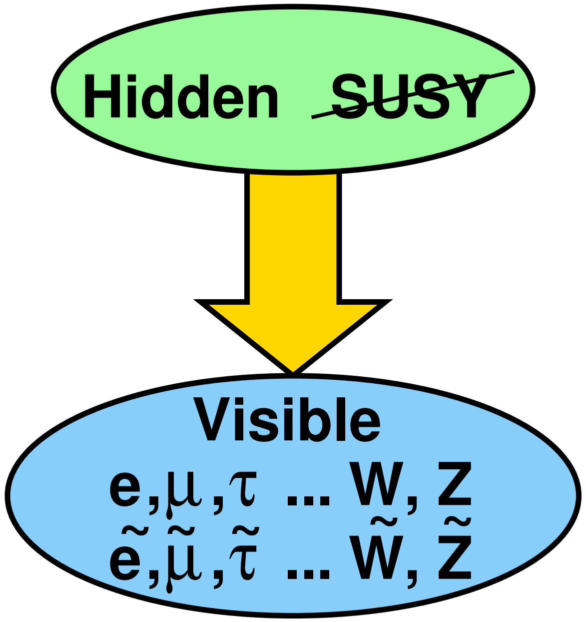
$$M_{\tilde{t}} > 87 \text{ GeV/c}^2$$

for $M_{\tilde{g}} < 2$ GeV and $\Delta M = M_{\tilde{t}} - M_{\tilde{g}} \geq 10$ GeV/c^2

(similar analysis for $\tilde{b} \rightarrow b\tilde{g}$: $M_{\tilde{b}} > 82$ GeV/c^2)



AMSB Phenomenology



Anomaly mediated:

SUSY breaking communicated to visible sector via superconformal anomaly

- LSP: $\tilde{\chi}_1^0$ ($\tilde{\mathrm{W}}$), $\tilde{\nu}$ or $\tilde{\tau}$
- $\tilde{\chi}_1^0$ / $\tilde{\chi}_1^{\pm}$ are mass degenerate

Four parameters to define minimal AMSB models:

◇ m$_{3/2}$: gravitino mass

◇ m$_0$: common scalar mass parameter

◇ tan(β): ratio of Higgs vacuum expectation values

◇ sign(μ): sign of Higgs sector mixing parameter

Constraints on AMSB Particle Mass Spectrum (1)

Scan over AMSB parameters (ISAJET)

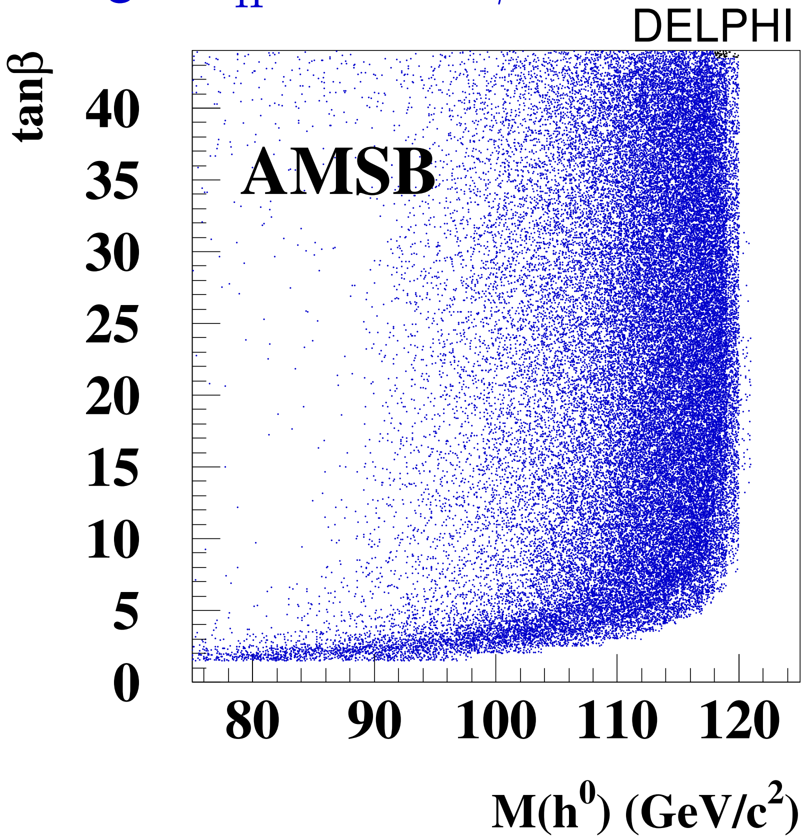
($1 < m_{3/2} < 50$ TeV/c^2, $0 < m_0 < 1000$ GeV/c^2,
$1.5 < \tan\beta < 45$, pos./neg. μ)

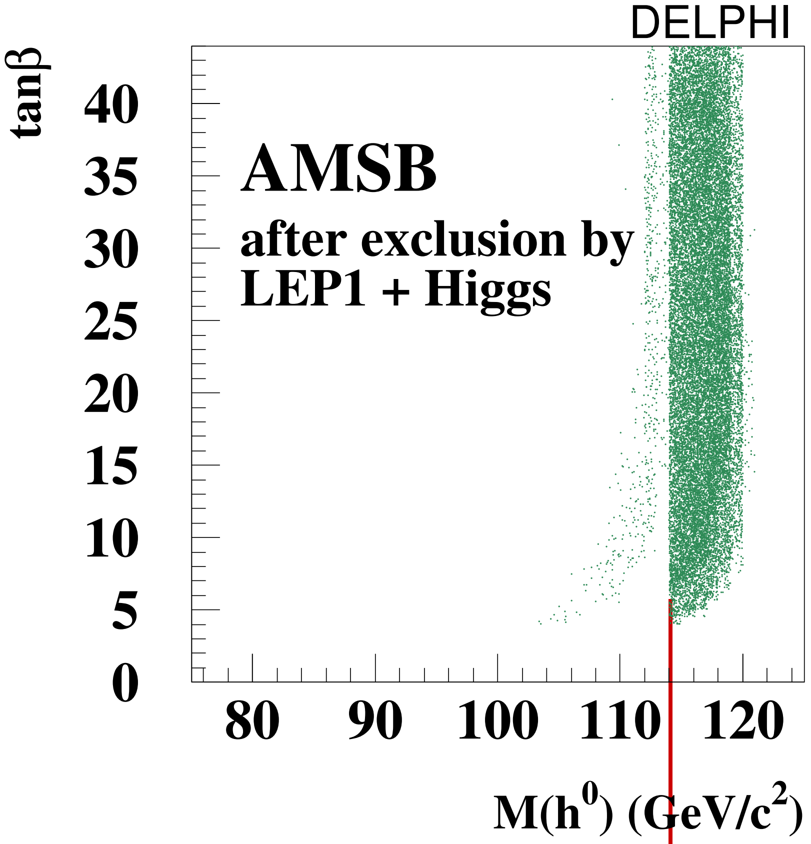
$\Rightarrow$ SUSY particle mass spectra.

e.g. M_{h^0} vs $\tan\beta$:

Including results of Higgs/LEP1 searches

- SM Higgs + invisible Higgs decays
  $(h^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0,\ \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\nu}\tilde{\nu})$
- LEP1: $\tilde{\chi}_1^\pm$ / $\tilde{\nu}$ exclusions



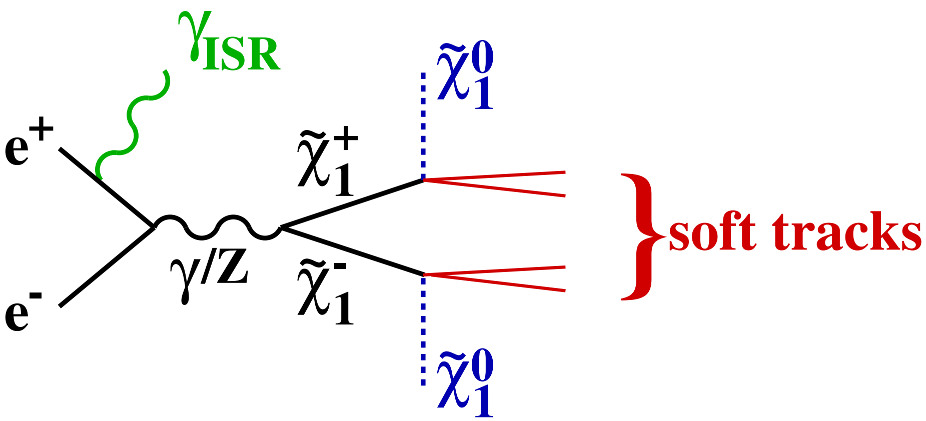


114.1 GeV/c^2
(D: SM Higgs result)

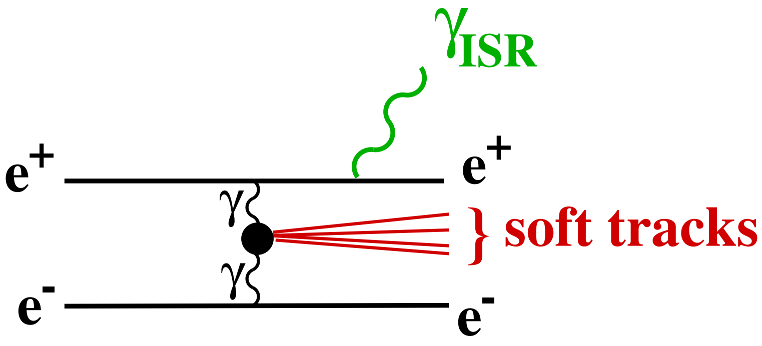
Searches for Mass Degenerate $\tilde{\chi}_1^{\pm}$/ $\tilde{\chi}_1^0$

$\tilde{\chi}_1^{\pm}$: $M_\pi < \Delta M < 5$ GeV $\Rightarrow$ ISR

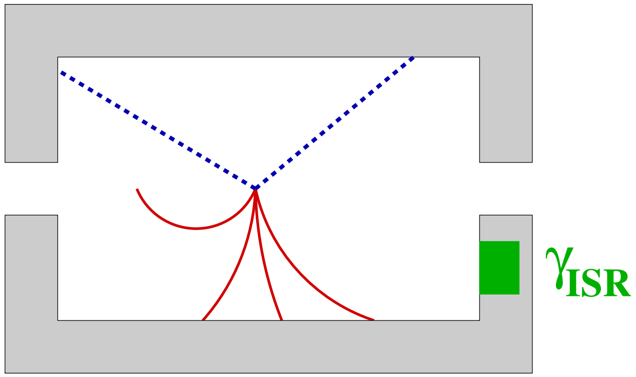
- **Signal**: big cross-section

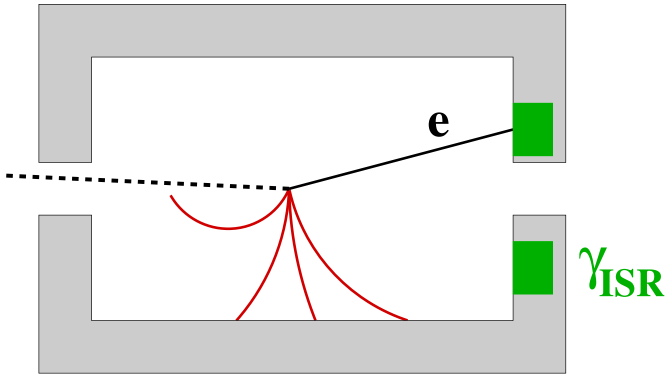


- **Background**: enormous cross-section



Analysis: tag γ with soft tracks, veto e





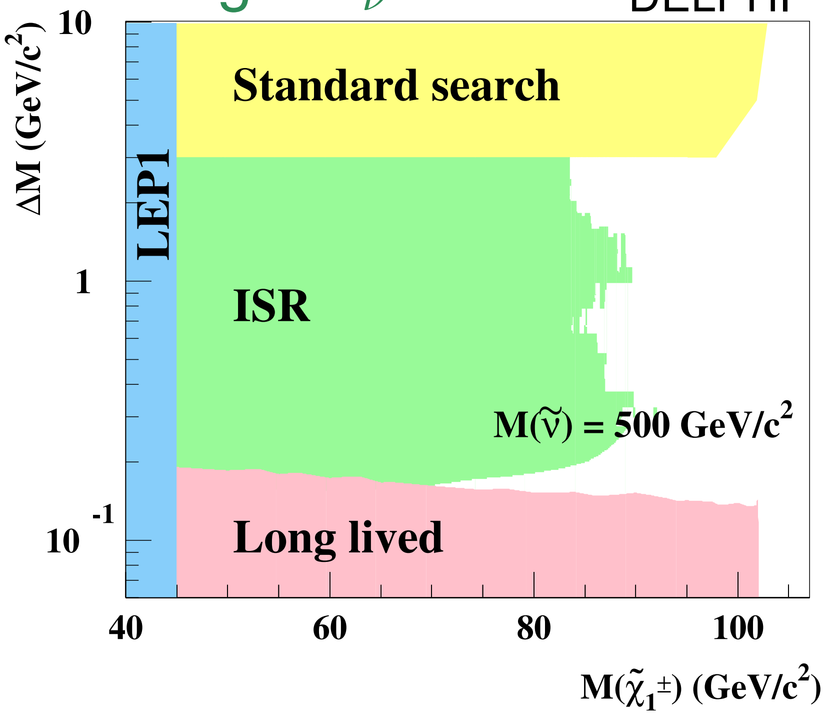
Results of Small Δ M Searches

Combined with

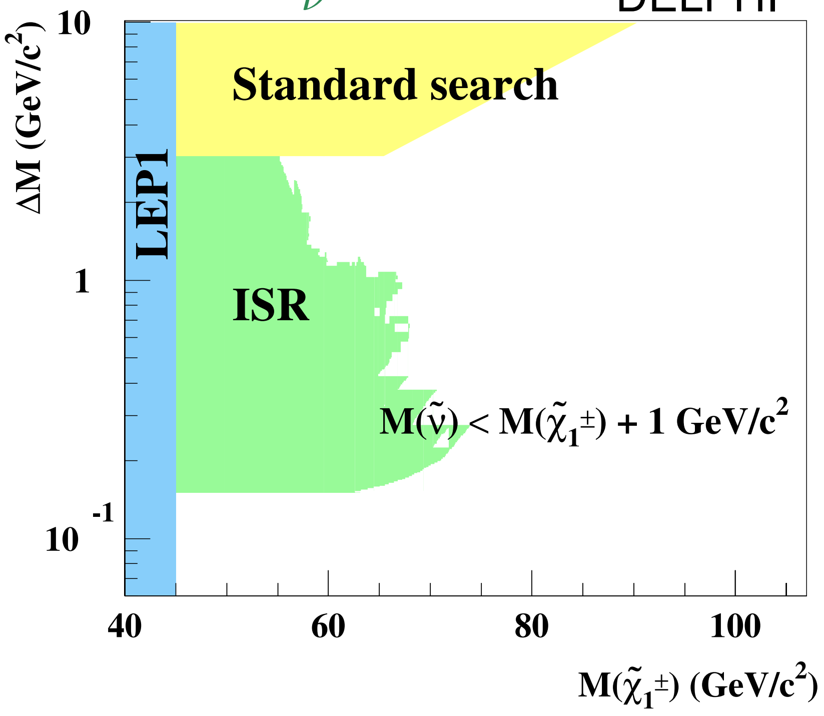
- MSSM (“standard”) $\tilde{\chi}_1^{\pm}$ search
- search for heavy stable charged particles $\Rightarrow$

Results depend on M$_{\tilde{\nu}}$, for light M$_{\tilde{\nu}}$: $\tilde{\chi}_1^{\pm} \longrightarrow \tilde{\nu}\ell^{\pm}$ possible

large M$_{\tilde{\nu}}$



low M$_{\tilde{\nu}}$



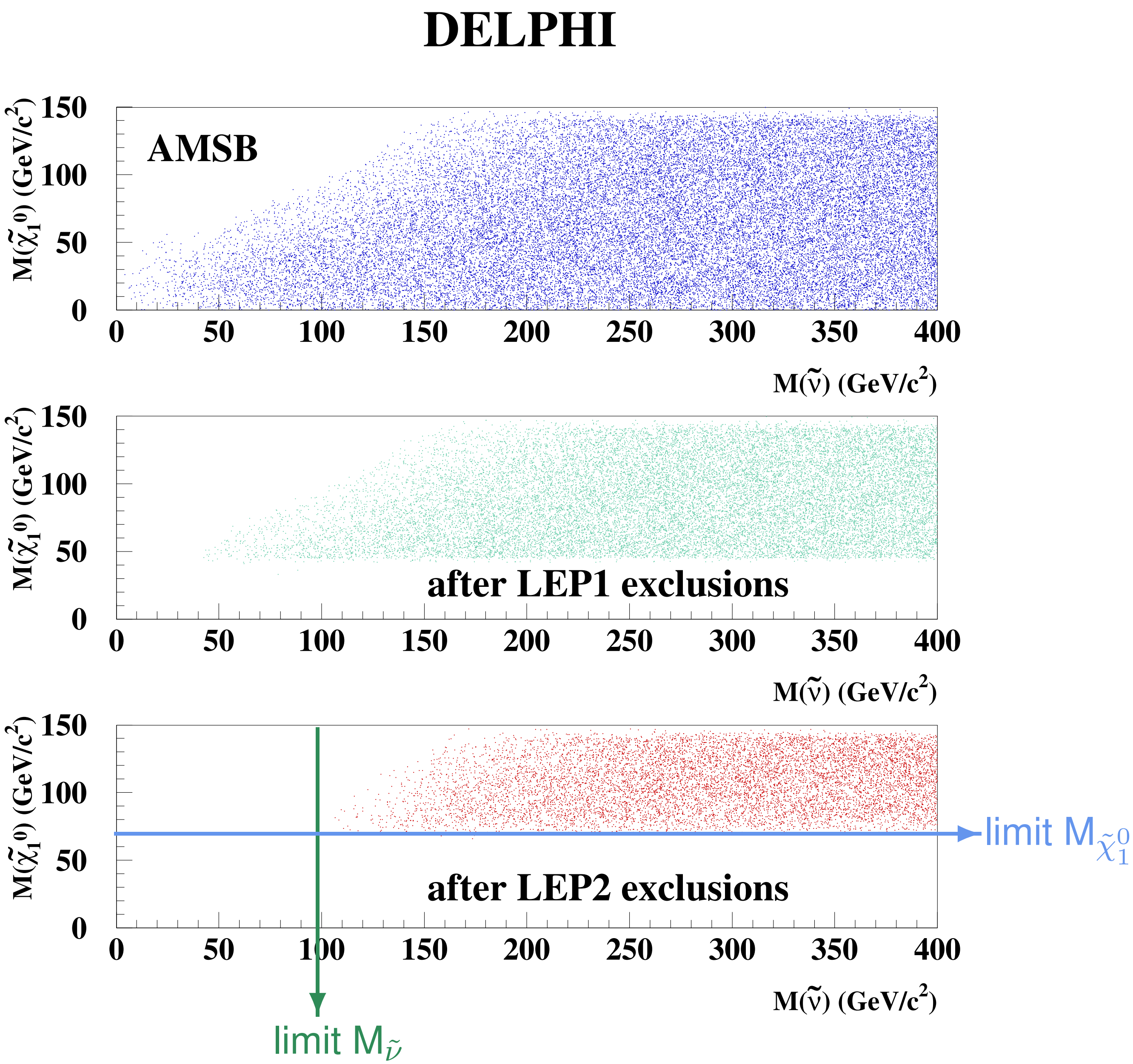
AMSB: Exclusions on LSP Masses

Limits on $\tilde{\chi}_1^0$ / $\tilde{\nu}$ LSP

- LEP1: $\tilde{\chi}_1^\pm$ / $\tilde{\nu}$ exclusions
- Higgs searches
- searches for $\tilde{\chi}_1^\pm$ / $\tilde{\chi}_1^0$ (low Δ M)
- searches for leptonic $\tilde{\chi}_1^\pm$ decays

$M_{\tilde{\chi}_1^0} > 68$ GeV/c^2

$M_{\tilde{\nu}} > 98$ GeV/c^2



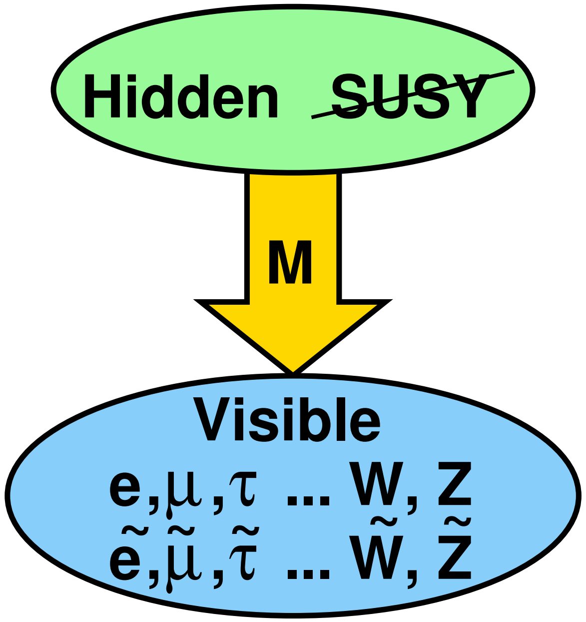
SUSY Breaking (Mediation)

Gravity

$\sqrt{\mathrm{F}} \sim 10^{11}$ GeV

M$\sim$ M$_{\mathrm{P}} \sim 10^{18}$ GeV

- FCNC problems
- Heavy $\tilde{\mathrm{G}}$
- $\tilde{\chi}_1^0$ LSP, CDM candidate



Gauge

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

$10^3 <$ M$< 10^{15}$ GeV

- no severe FCNC
- Light $\tilde{\mathrm{G}}$
- $\tilde{\mathrm{G}}$ LSP, lose CDM candidate

Five parameters to define minimal GMSB models:

◇ Λ: scale of SUSY breaking

◇ M: messenger mass scale

◇ N: number of messenger fields

◇ tan(β): ratio of Higgs vacuum expectation values

◇ sign(μ): sign of Higgs sector mixing parameter

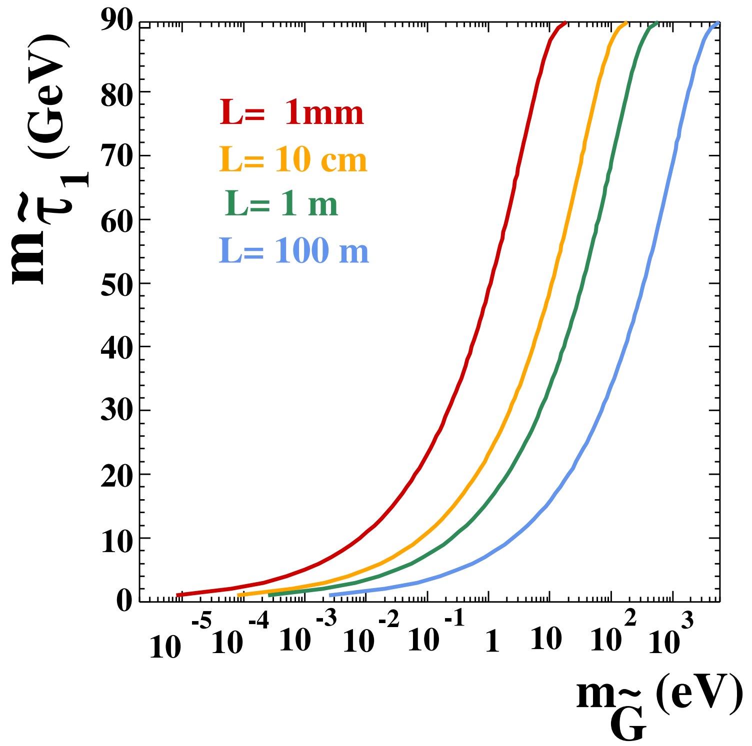
GMSB Phenomenology

- $\tilde{G}$ is the lightest SUSY particle (LSP), $m_{\tilde{G}} \lesssim \mathcal{O}(\text{keV})$ in minimal model.
- $\tilde{\chi}^0_1$ or $\tilde{\tau}_1$ ($\tilde{\ell}$) are the next-to-lightest SUSY particle, the NLSP (co-NLSP).
- Lifetime $\tau_{\rm life}$ of the NLSP depends on SUSY breaking scale $\sqrt{F}$ ($\propto$M$_{\tilde{G}}$) and NLSP mass:

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

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

Example: m$_{\tilde{\tau}_1}$ versus m$_{\tilde{G}}$ for various decay lengths (L=$\beta\,\gamma\,c\,\tau_{\rm life}$):



Wide range of NLSP lifetimes means we must explore many different topologies!

GMSB: Searches for Sleptons ($\tilde{\chi}^0_1$ NLSP)

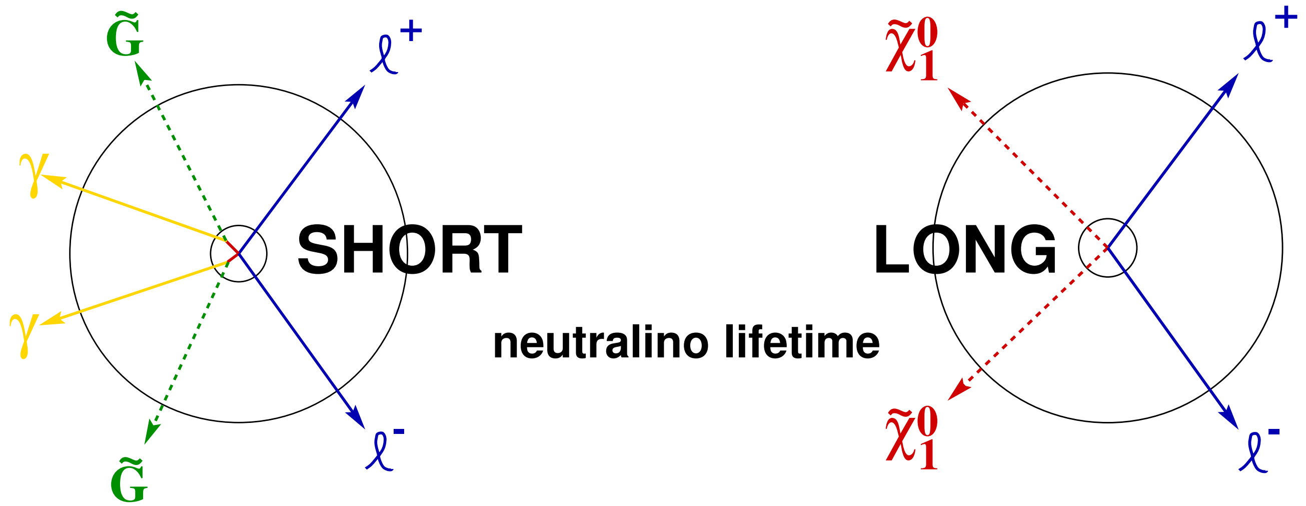
Signatures:

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

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

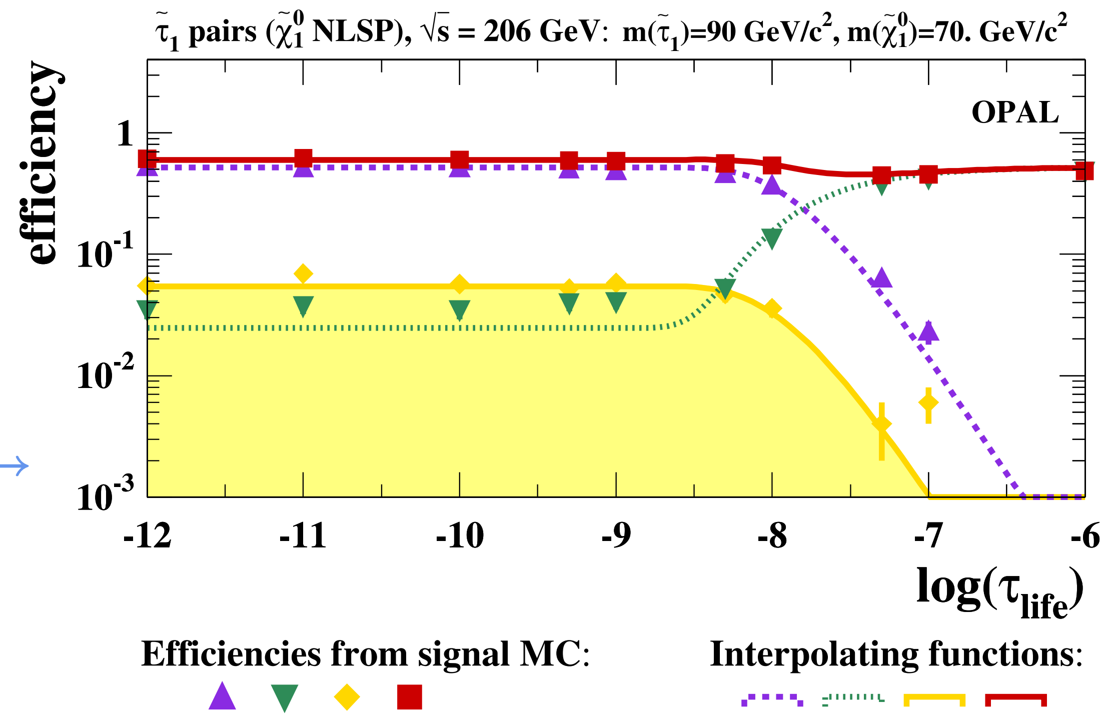
$\quad\quad\quad\quad \to \tilde{\chi}^0_1 \; \ell^+$

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

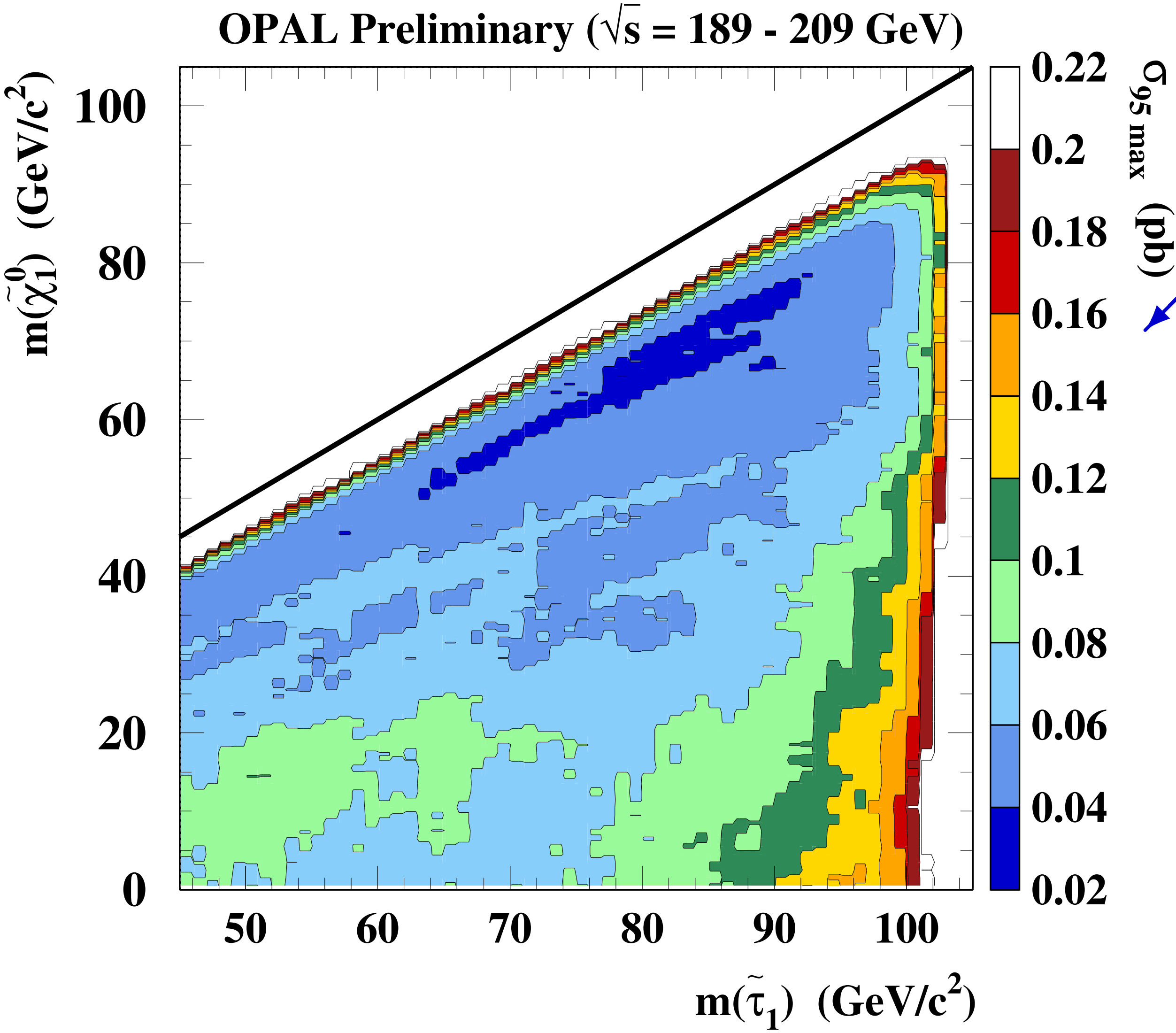


- Combination of analyses sensitive to different lifetime regimes of the NLSP.
- Efficiency depends on $m_{\tilde{\ell}}, \tau_{\text{life}(\tilde{\ell})}, m_{\tilde{\chi}^0_1}$ and $\sqrt{s}$.
- Example:

  efficiencies for $\tilde{\tau}_1$ pair production $\longrightarrow$

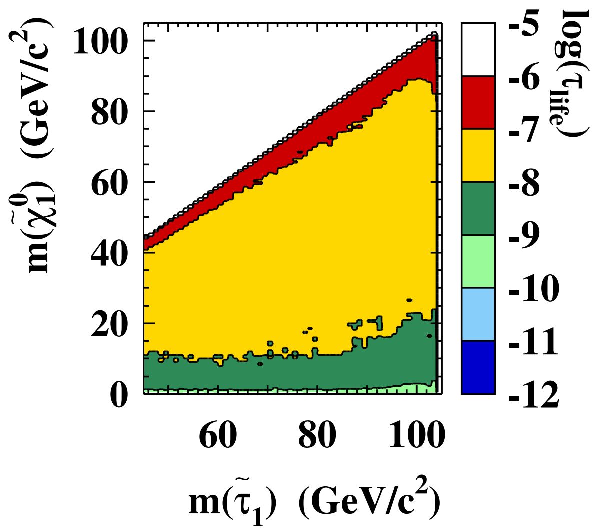


Limits on $\tilde{\tau}_1$ Pair Production ($\tilde{\chi}_1^0$ NLSP)



Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\tau}_1$ pairs ($\tilde{\chi}_1^0$ NLSP), valid for any $\tilde{\chi}_1^0$ lifetime ($\sigma_{\text{excluded}} \sim$ 0.04 – 0.15 pb).

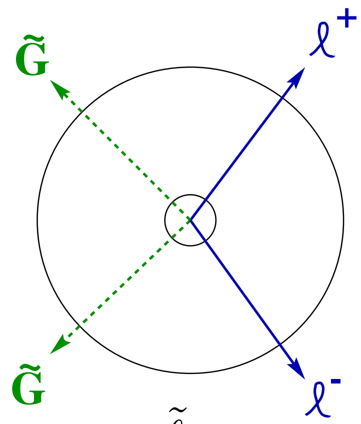
$\tilde{\chi}_1^0$ lifetime at the highest excluded cross-section.



GMSB: Slepton Searches ($\tilde{\tau}$ NLSP/$\tilde{\ell}$ co-NLSP)

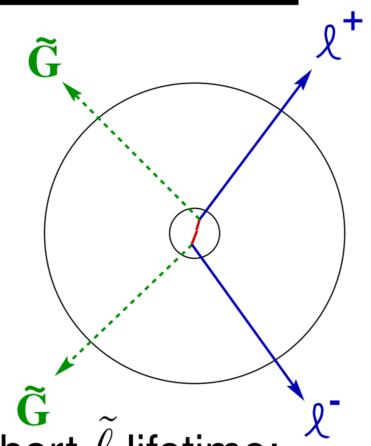
Signatures:

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



negligible $\tilde{\ell}$ lifetime:

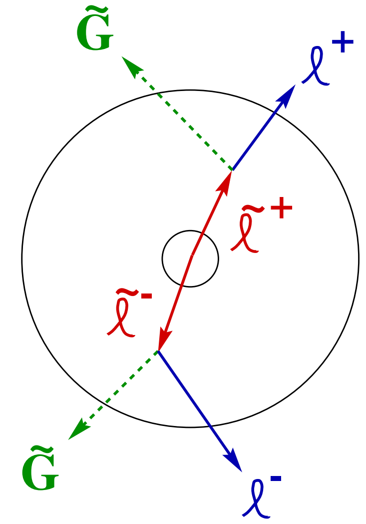
acoplanar lepton search



short $\tilde{\ell}$ lifetime:

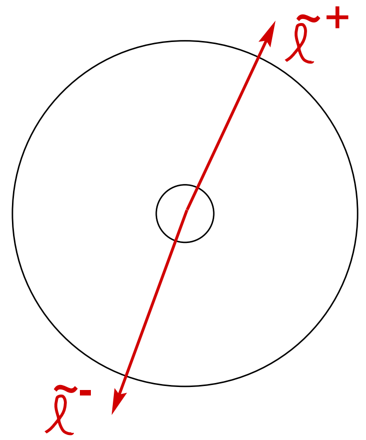
search for tracks with large impact parameter

- Combination of analyses sensitive to different lifetime regimes of the NLSP.
- Efficiency depends on $m_{\tilde{\ell}}$, $\tau_{\mathrm{life}(\tilde{\ell})}$ and $\sqrt{s}$.



medium $\tilde{\ell}$ lifetime:

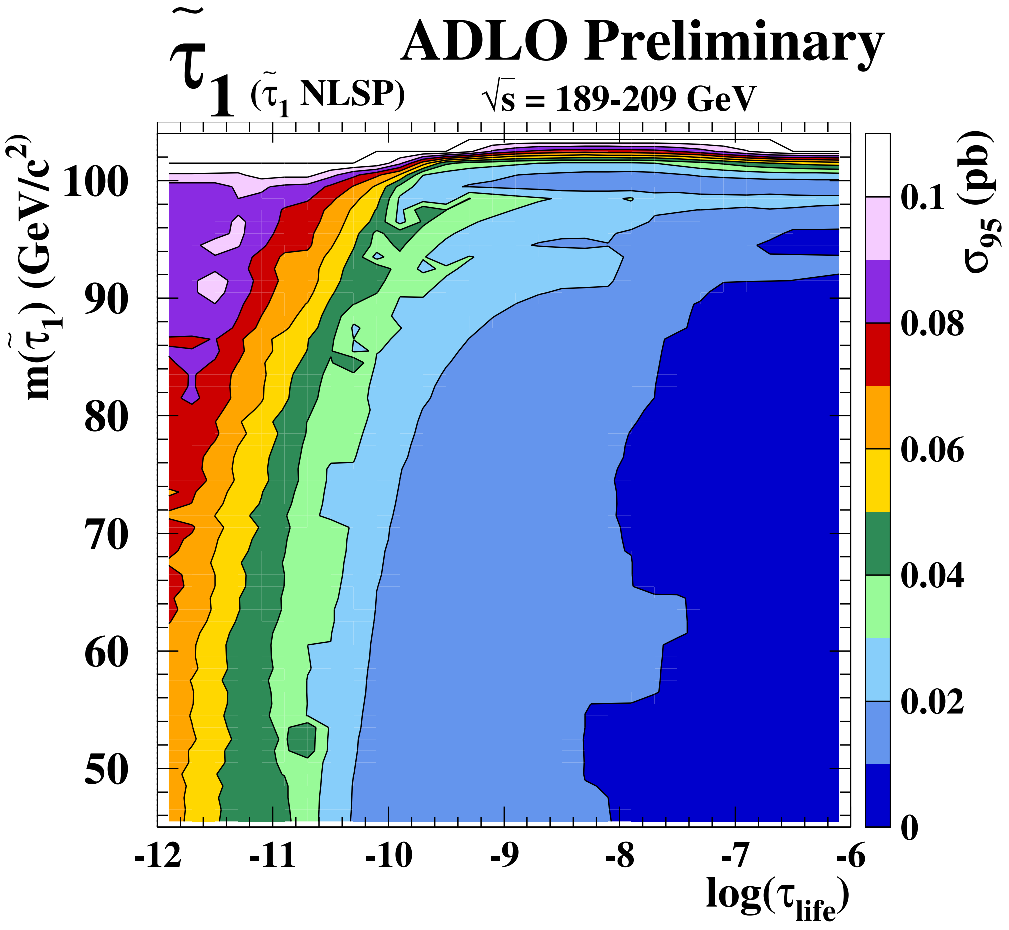
search for kinked tracks

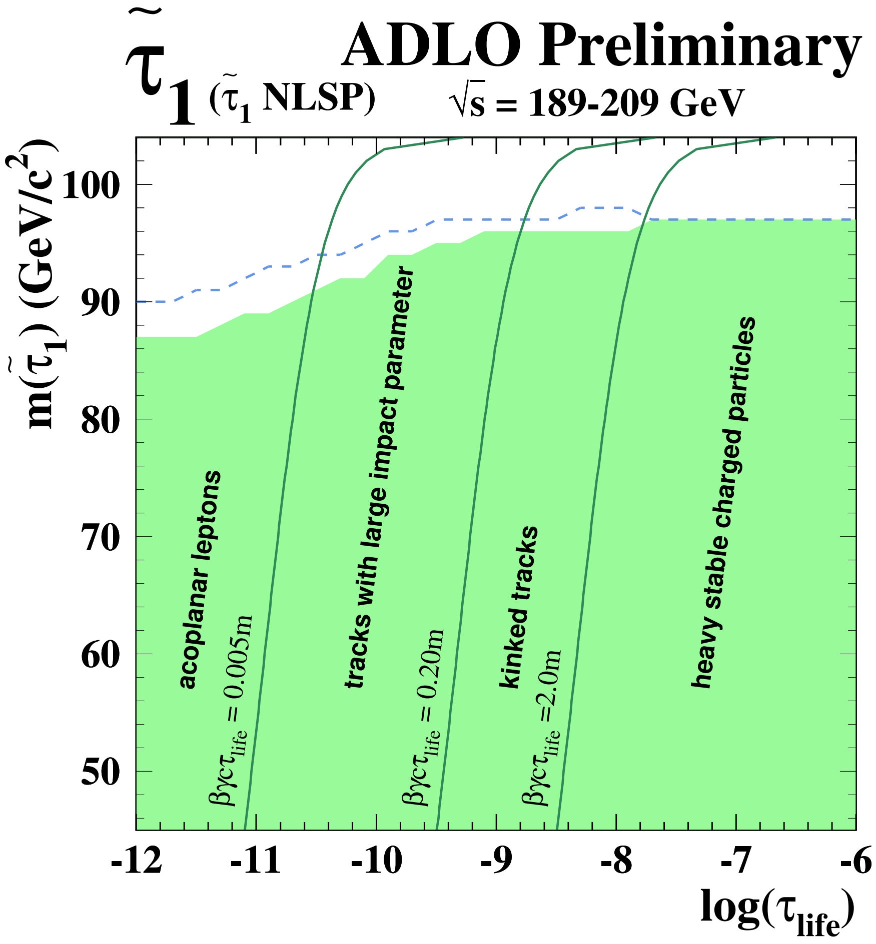


long $\tilde{\ell}$ lifetime:

search for heavy stable charged particles

GMSB: Limits on Pair Produced Staus ($\tilde{\tau}_1$ NLSP)



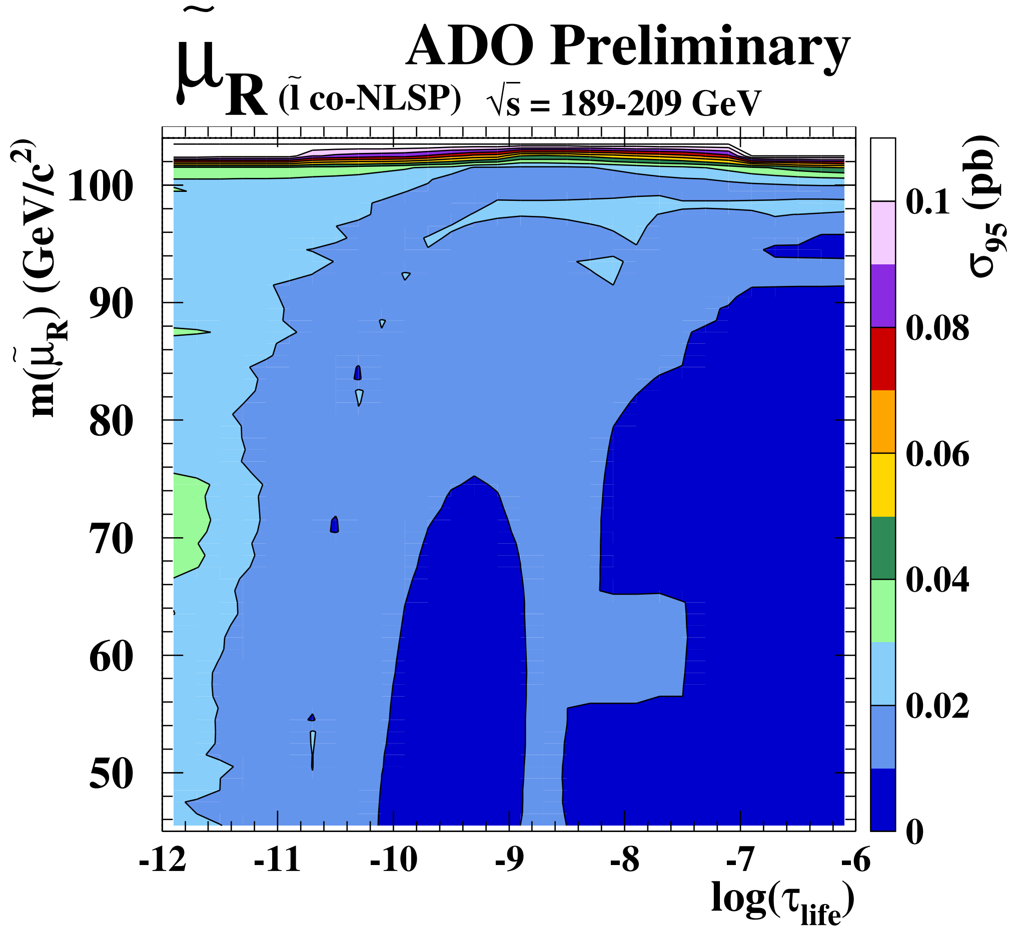


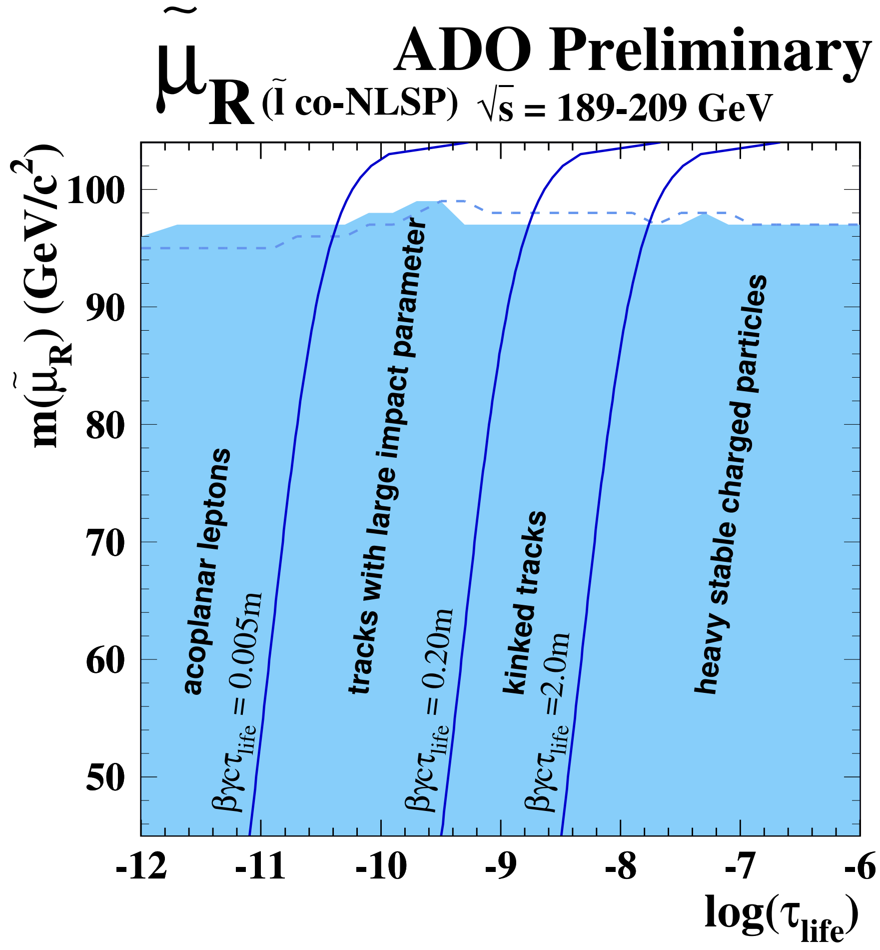
Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\tau}_1$ pairs ($\tilde{\tau}_1$ NLSP) as a function of $\tilde{\tau}_1$ lifetime ($\sigma_{\text{excluded}} \sim$ 0.01 – 0.1 pb).

Excluded $\tilde{\tau}_1$ masses ($\tilde{\tau}_1$ NLSP) as a function of $\tilde{\tau}_1$ lifetime (87 – 97 GeV/c^2). Dashed line: expected limit (90 – 97 GeV/c^2).

$\Rightarrow m_{\tilde{\tau}_1} > 87$ GeV/c^2 for all $\tilde{\tau}_1$ lifetimes

GMSB: Limits on Pair Produced Smuons ($\tilde{\ell}$ co-NLSP)





Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\mu}_R$ pairs ($\tilde{\ell}$ co-NLSP) as a function of $\tilde{\mu}_R$ lifetime ($\sigma_{\mathrm{excluded}} \sim$ 0.01 – 0.04 pb).

Excluded $\tilde{\mu}_R$ masses ($\tilde{\ell}$ co-NLSP) as a function of $\tilde{\mu}_R$ lifetime (96 – 99 GeV/c^2).
Dashed line: expected limit (95 – 99 GeV/c^2).

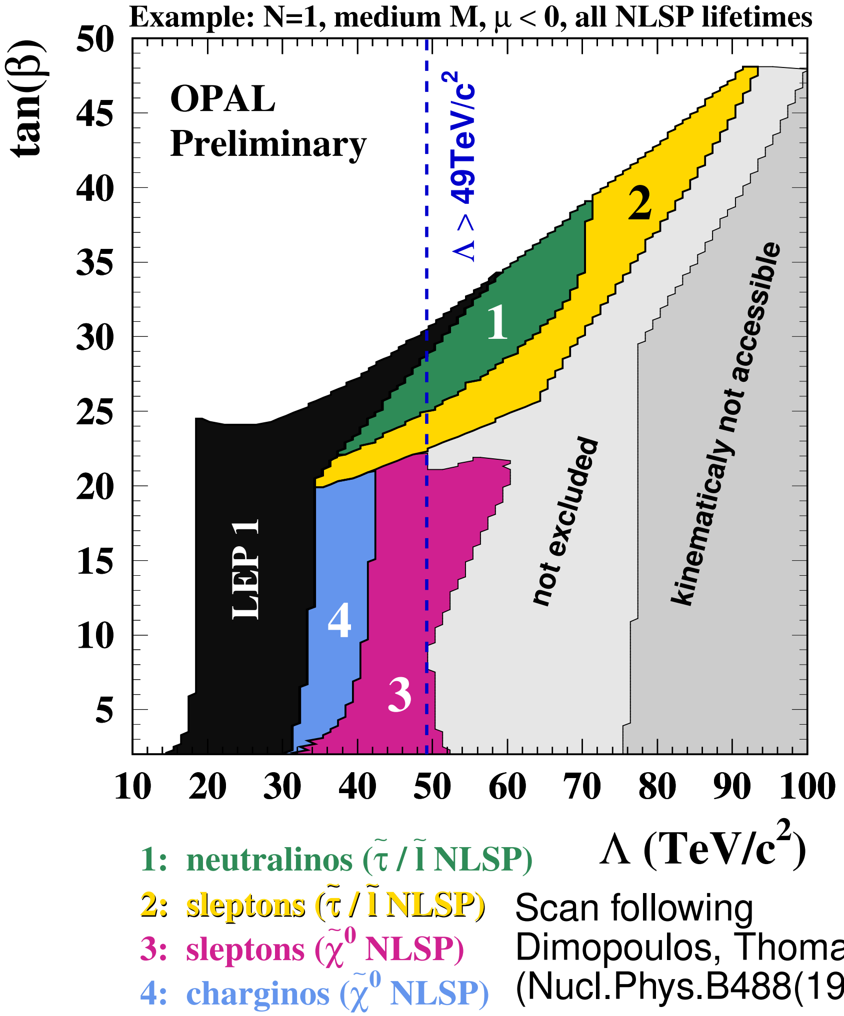
$\Rightarrow m_{\tilde{\mu}_R} > 96$ **GeV/c^2 for all $\tilde{\mu}_R$ lifetimes**

Scan of the GMSB Parameters (all NLSP Lifetimes)

Combination with other GMSB searches

$\Rightarrow$ search for pair production of:

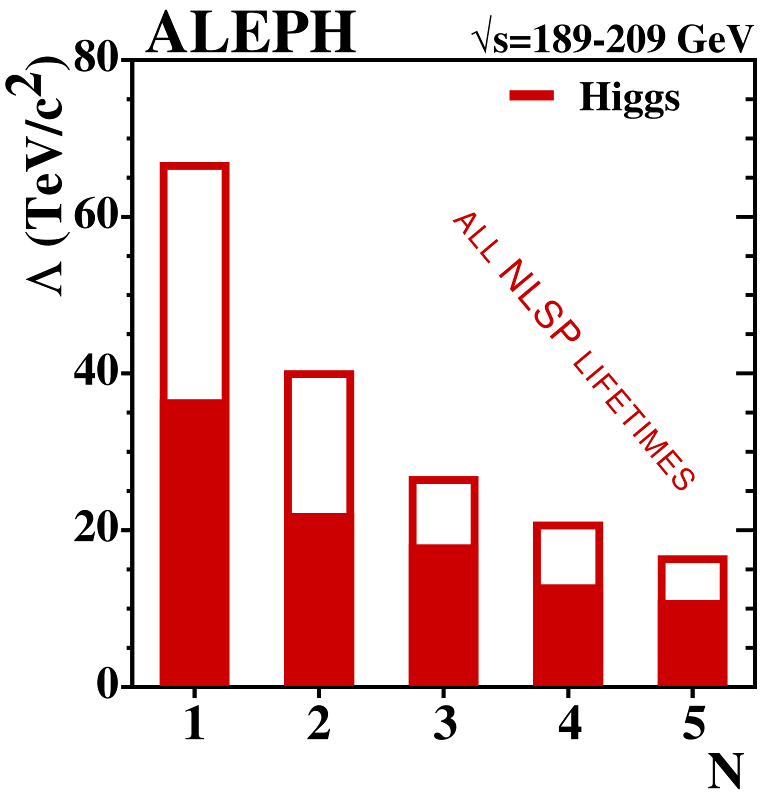
$\tilde{\chi}_1^0$ ($\tilde{\tau}$ NLSP / $\tilde{\ell}$ co-NLSP), $\tilde{\chi}_1^{\pm}$ ($\tilde{\chi}_1^0$ NLSP).



Scan following Dimopoulos, Thomas, Wells (Nucl.Phys.B488(1997)39)

Scanning minimal GMSB model (N, M, Λ, tan β, sign(μ)):

Limit on SUSY particle mass scale Λ



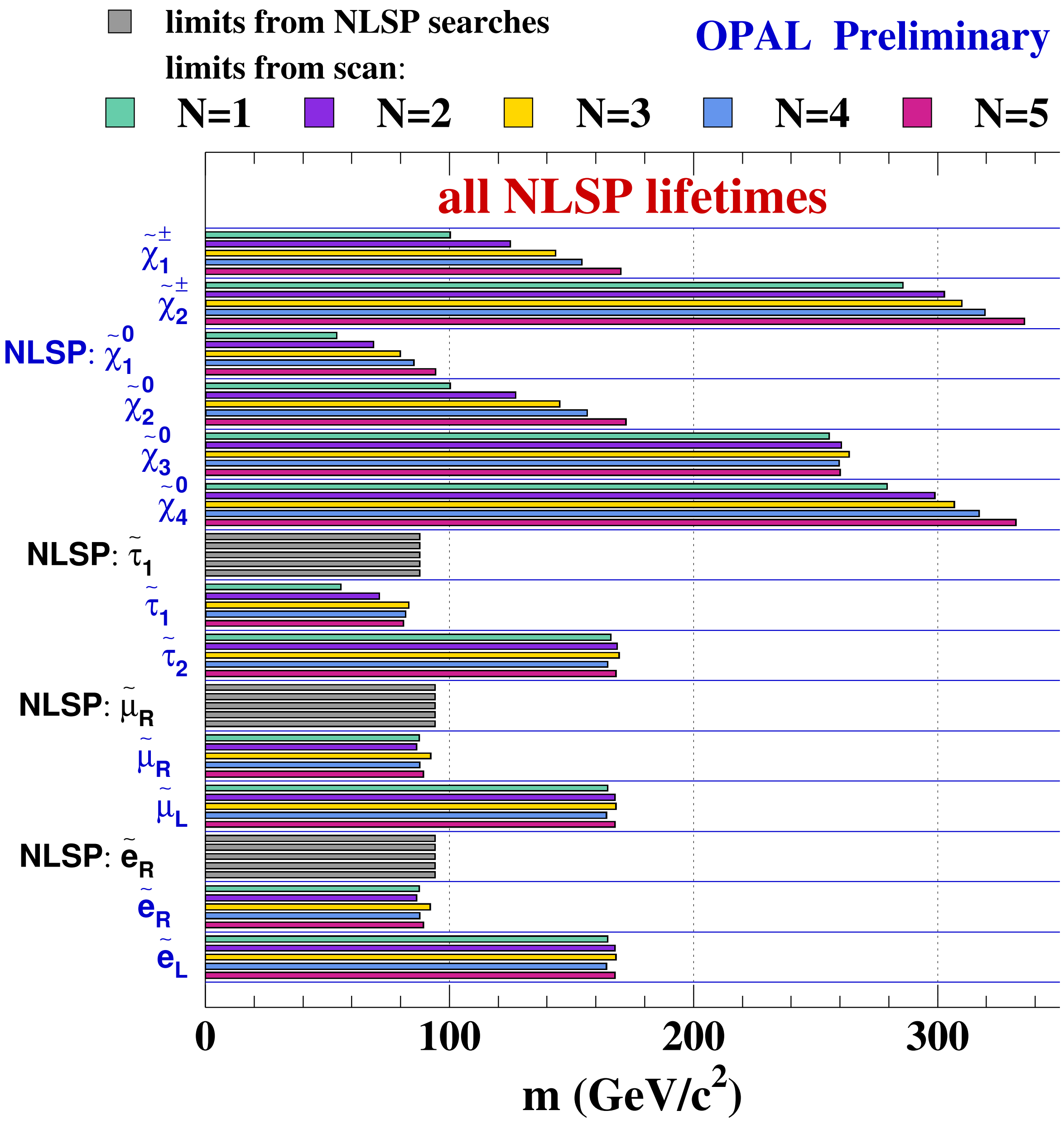
ALEPH: Λ $>$10 TeV/c^2 for N$\lesssim$5

(Λ $>$16 TeV/c^2 incl. Higgs constraints)

$\Rightarrow m_{\tilde{G}}$ $>$0.024 (0.061) eV/c^2

OPAL: Λ $>$15 TeV/c^2 for N$\lesssim$5

GMSB: Constraints on Masses of SUSY Particles



NLSP mass limit (all NLSP lifetimes):

$\tilde{\chi}_1^0$ NLSP:

ALEPH: $m_{\tilde{\chi}_1^0} > 54$ GeV/c^2

> 77 GeV/c^2 incl. Higgs

OPAL: $m_{\tilde{\chi}_1^0} > 54$ GeV/c^2

$\tilde{\tau}_1$ NLSP:

ADLO: $m_{\tilde{\tau}_1} > 87$ GeV/c^2

$\tilde{\ell}$ co-NLSP:

ADLO: $m_{\tilde{\ell}} > 94$ GeV/c^2

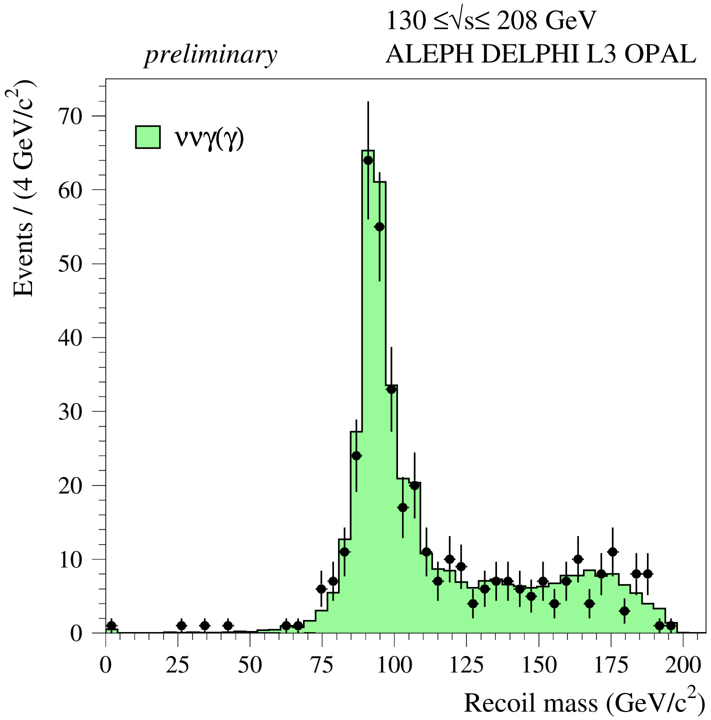
GMSB: Short NLSP Lifetime$\longrightarrow$ Neutralino Searches ($\tilde{\chi}^0_1$ NLSP)

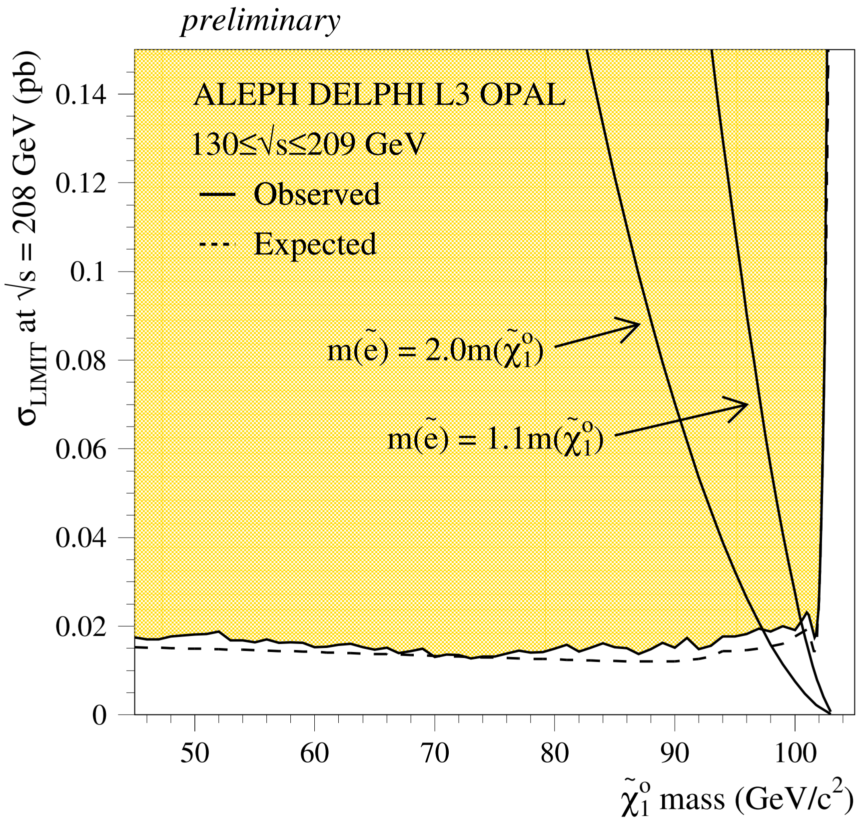
Signature:

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

$\Rightarrow$ Search for acoplanar photon pairs.

ADLO: 387 events observed/ 403.9 expected





Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\chi}^0_1$ pairs ($\tilde{\chi}^0_1$ NLSP) ($\sim$0.02 pb).

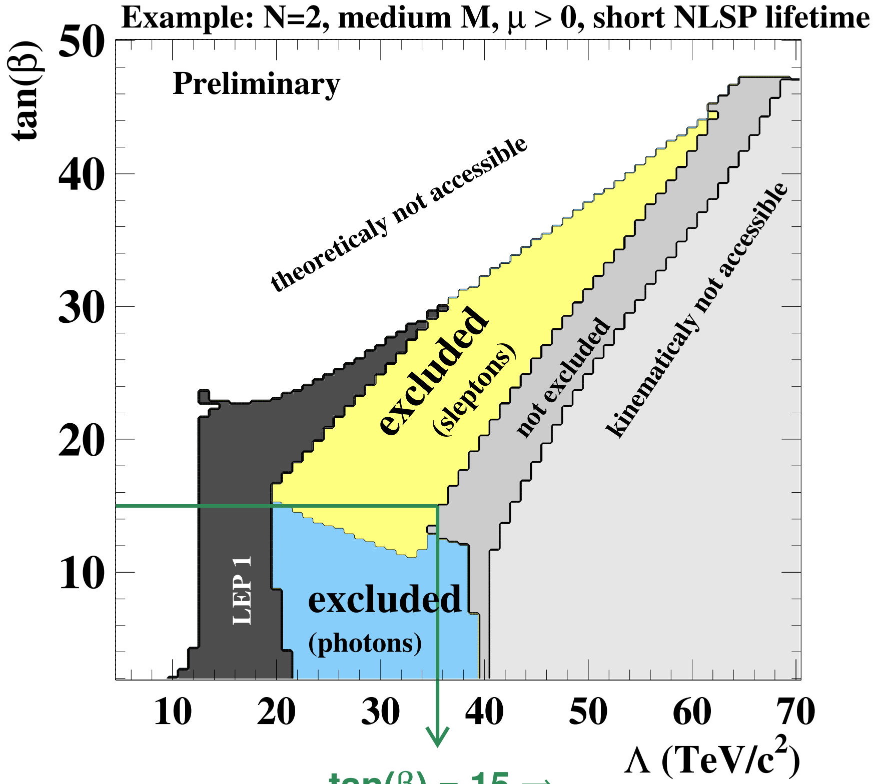
GMSB: Prospects

ADLO, short NLSP lifetime

(no Higgs results included)

Scan in GMSB parameter space following

Dimopoulos, Thomas, Wells, Nucl. Phys. B488 (1997) 39



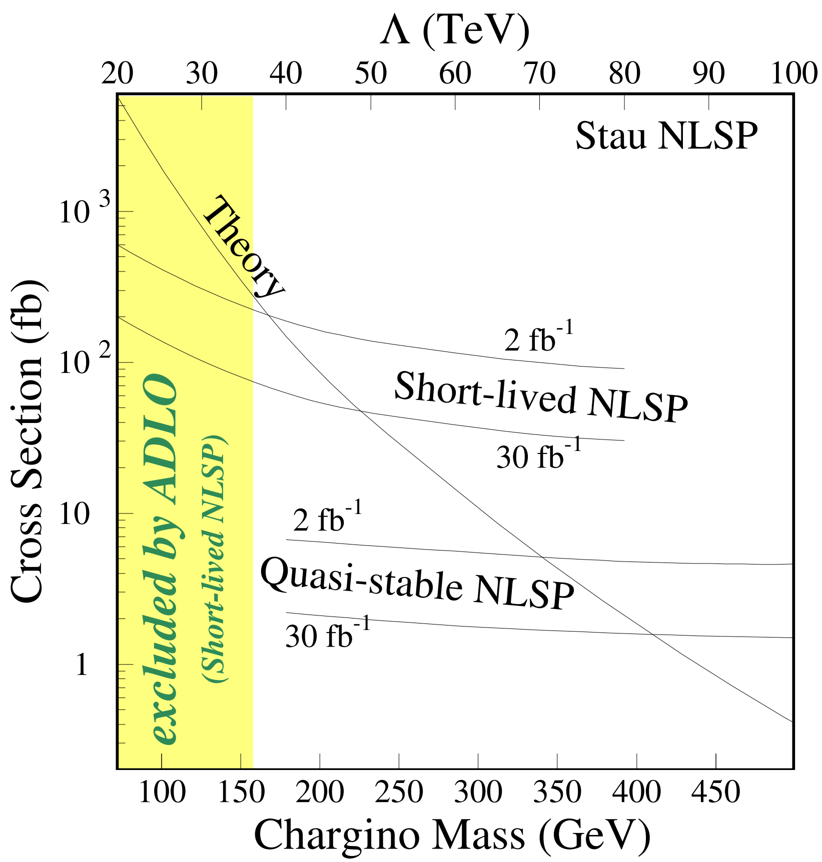
tan(β) = 15 ⇒

$\Lambda >$ 35.5 TeV/c^2

TEVATRON, prospects

J. Quian, hep-ph/9903548 v2:

$$N = 2,\ \frac{M}{\Lambda} = 3,\ tan\beta = 15,\ \mu > 0$$



Conclusions

- A broad spectrum of searches for SUSY particles has been covered by the four LEP experiments.
  - ◇ Standard modes $\Rightarrow$ Null results $\Rightarrow$ New models $\Rightarrow$ New searches
  - ◇ e^+e^- environment allowed searches for many “exotic SUSY” modes with many LSP / NLSP types.
  - ◇ No hints of a signal.
  - ◇ Constraints on M_{LSP} and M_{NLSP}.
  - ◇ Combination of all LEP SUSY results with LEP Higgs results $\Rightarrow$ stronger constraints (t.b.d.)
- Must look for LSP / NLSP beyond our kinematic limit.