International Conference on High Energy Physics
Amsterdam, Netherlands (July 24 - 31, 2002)

Exotic SUSY Signatures at LEP

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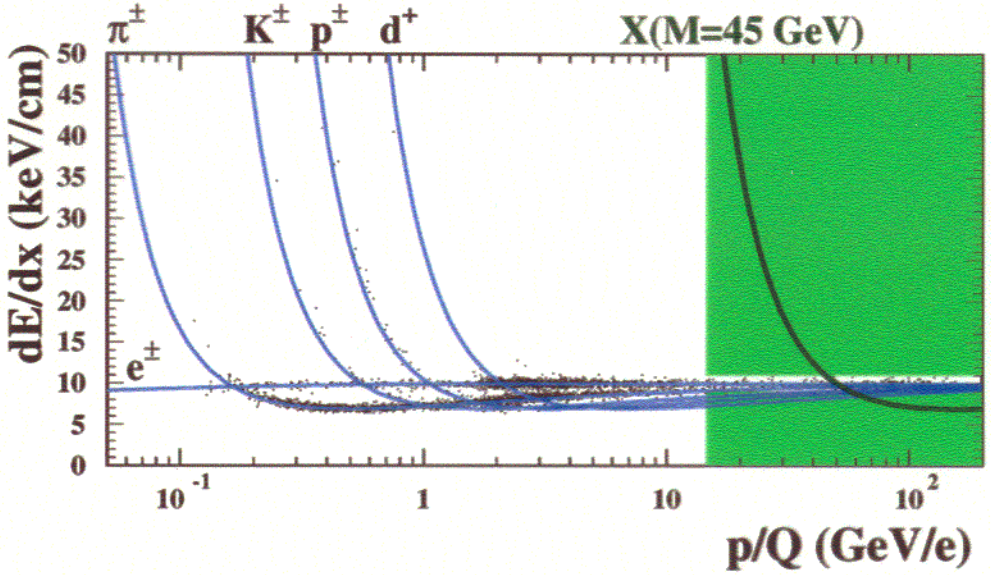
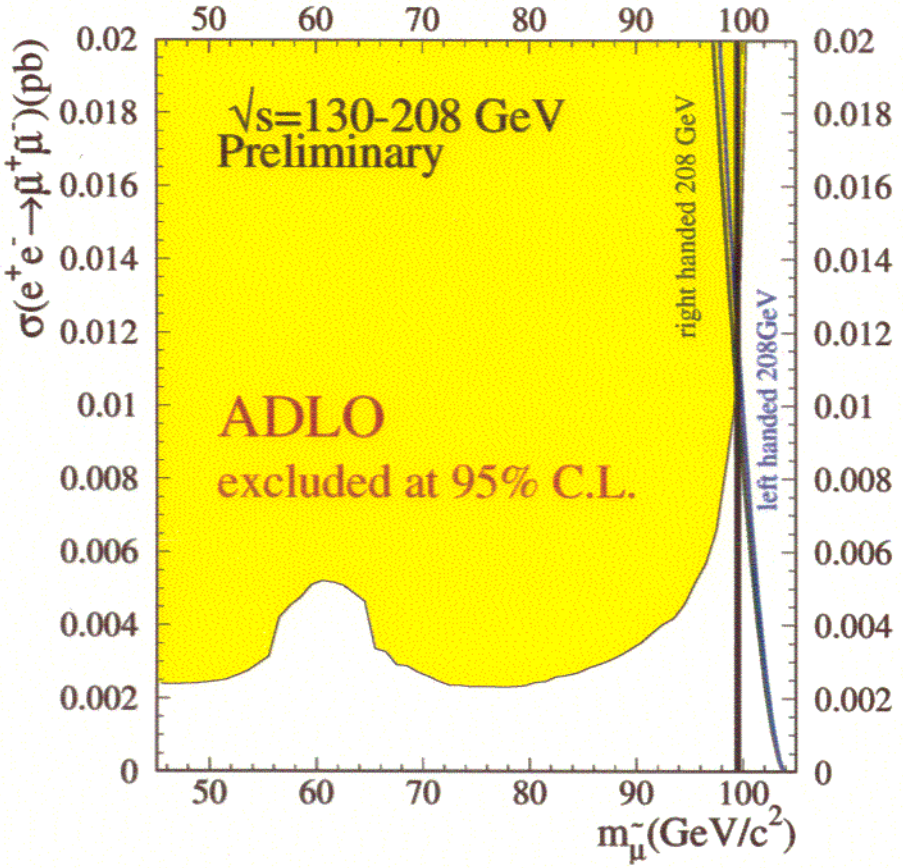
- Searches for signatures of models with different **l**ightest **S**USY **p**article (**LSP**)
  - ◇ Models with Gauge-mediated Supersymmetry breaking (GMSB):
    - — gravitino LSP
    - — gluino LSP
  - ◇ Models with Anomaly-mediated Supersymmetry breaking (AMSB):
    - — neutralino LSP
    - — sneutrino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

⇒ 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:





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

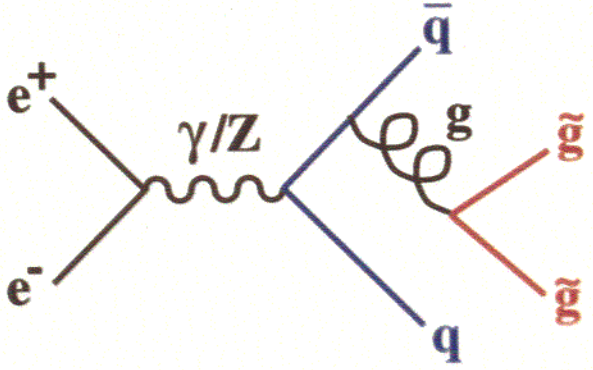
$m_{\tilde{\tau},\,\tilde{\mu}} > 99.4\ (99.6)$ GeV/c²

⇒ stable charginos with $m_{\tilde{\nu}} > 41.\ (500.)$ GeV/c²:

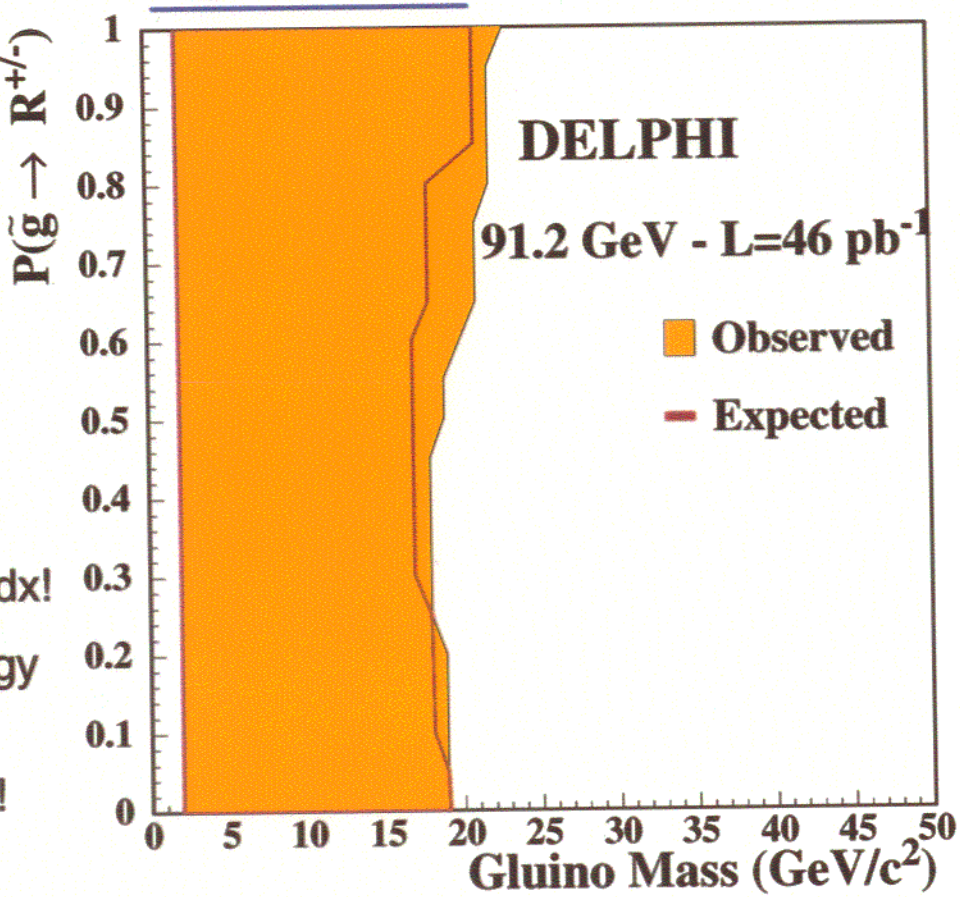
$m_{\tilde{\chi}_1^{\pm}} > 101.5\ (102.5)$ GeV/c²

Alternative Signatures ⇒ Search for Stable Gluinos

Gluino production at LEP 1:



LEP 1 data: no excess ⇒



- Gluino forms R-hadron.

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

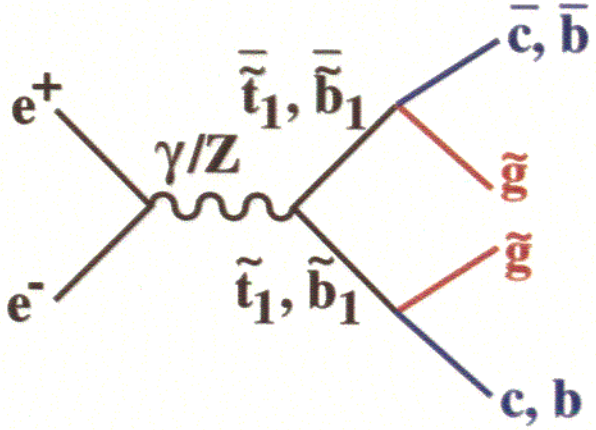
  Neutral R-hadron, R^0: can deposit enough energy to escape "missing energy" signature ⇒ analysis using relaxed cuts on missing energy!

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

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

Search for Gluinos at LEP 2

Gluino production at LEP 2:



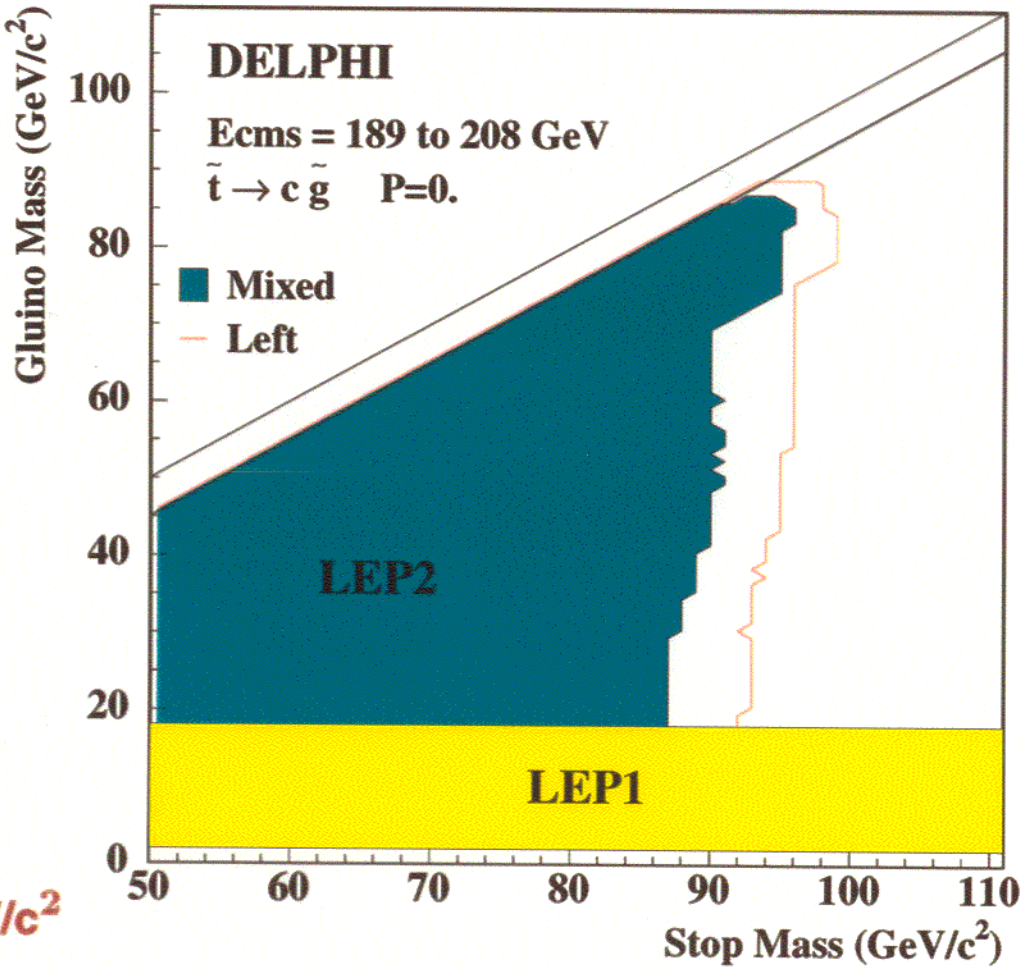
- Topology: two jets, two R-hadrons

LEP 2 data: no excess $\Rightarrow$

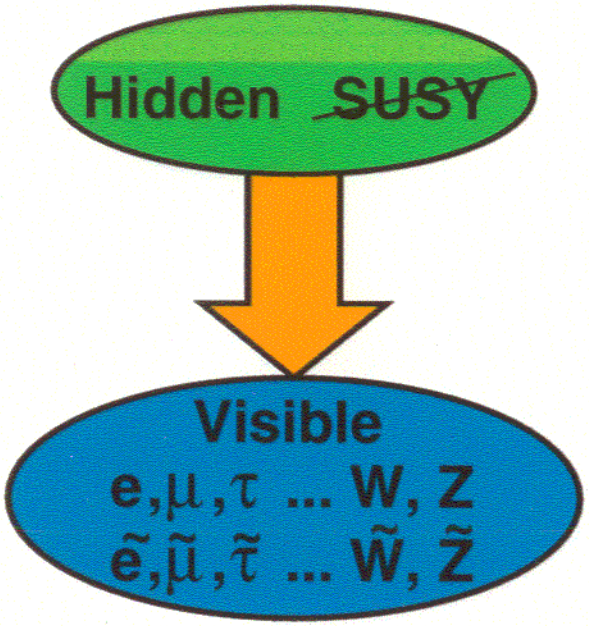
$$M_{\tilde{t}} > 87 \text{ GeV/c}^2$$

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

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

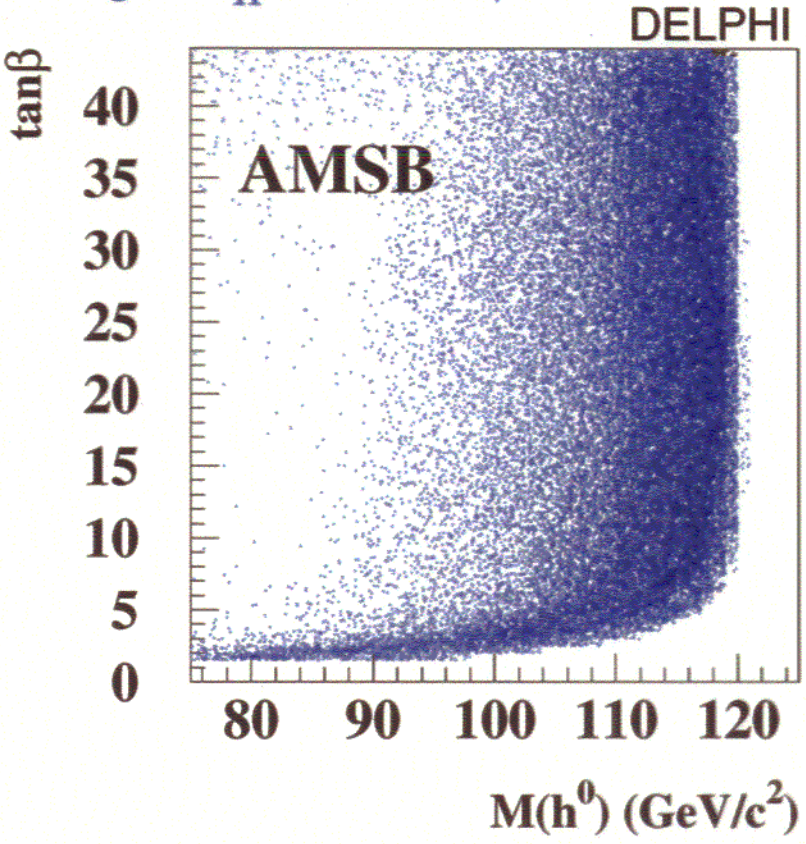
Constraints on AMSB Particle Mass Spectrum (1)

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)

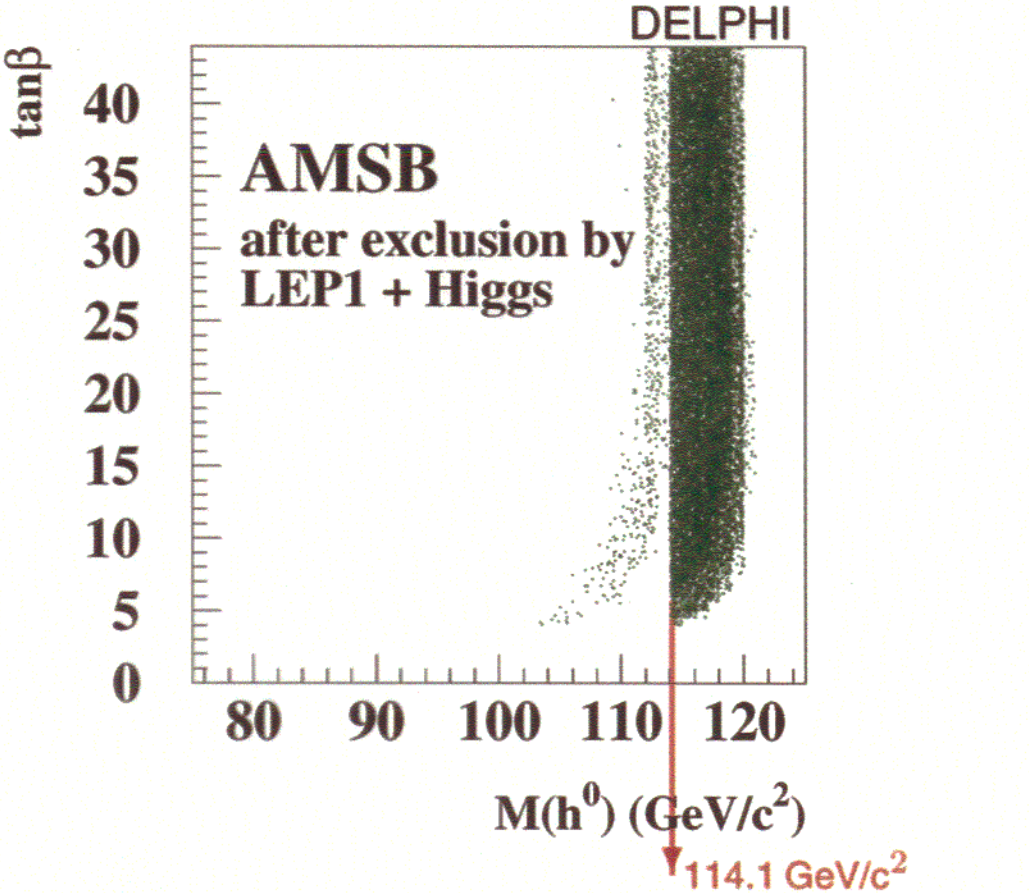
$\Rightarrow$ SUSY particle mass spectra.

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



Including results of Higgs/LEP1 searches

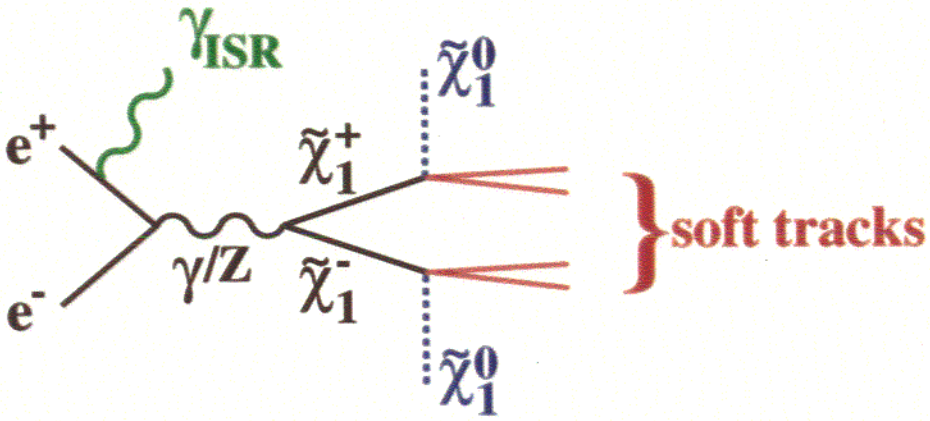
- SM Higgs + invisible Higgs decays
  ($h^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\nu}\tilde{\nu}$)
- LEP1: $\tilde{\chi}_1^\pm$ / $\tilde{\nu}$ exclusions



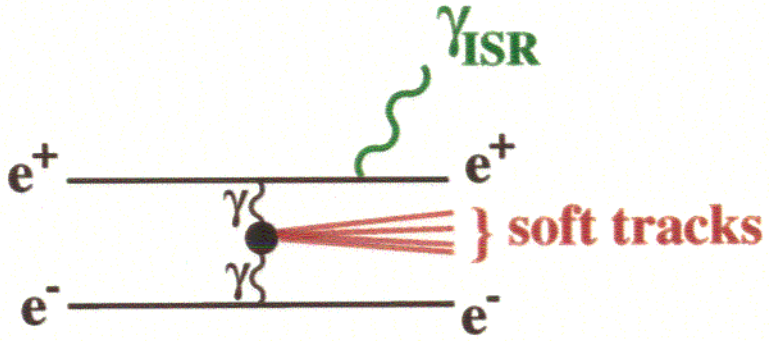
Searches for Mass Degenerate $\tilde{\chi}_1^{\pm}$/ $\tilde{\chi}_1^0$

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

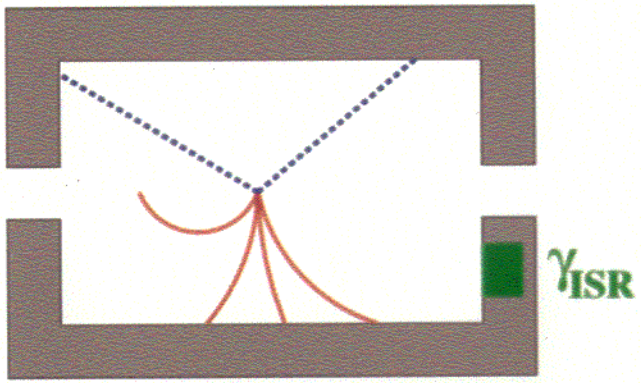
- Signal: big cross-section

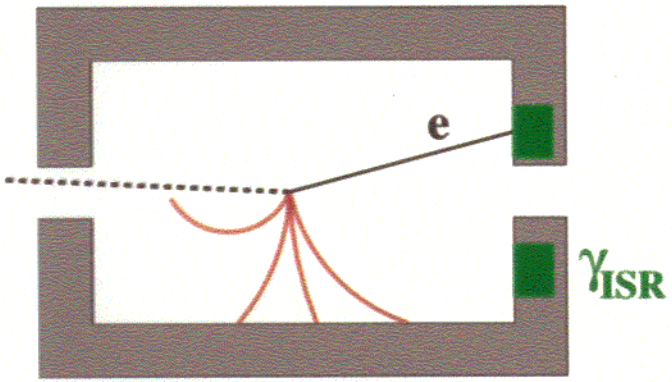


- Background: enormous cross-section



Analysis: tag γ with soft tracks, veto e





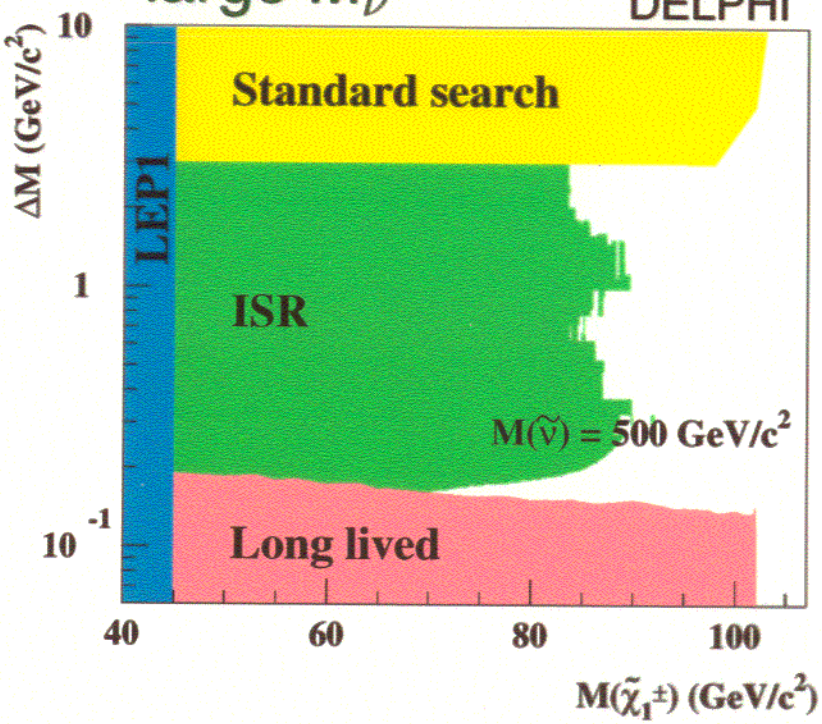
Results of Small Δ M Searches

Combined with

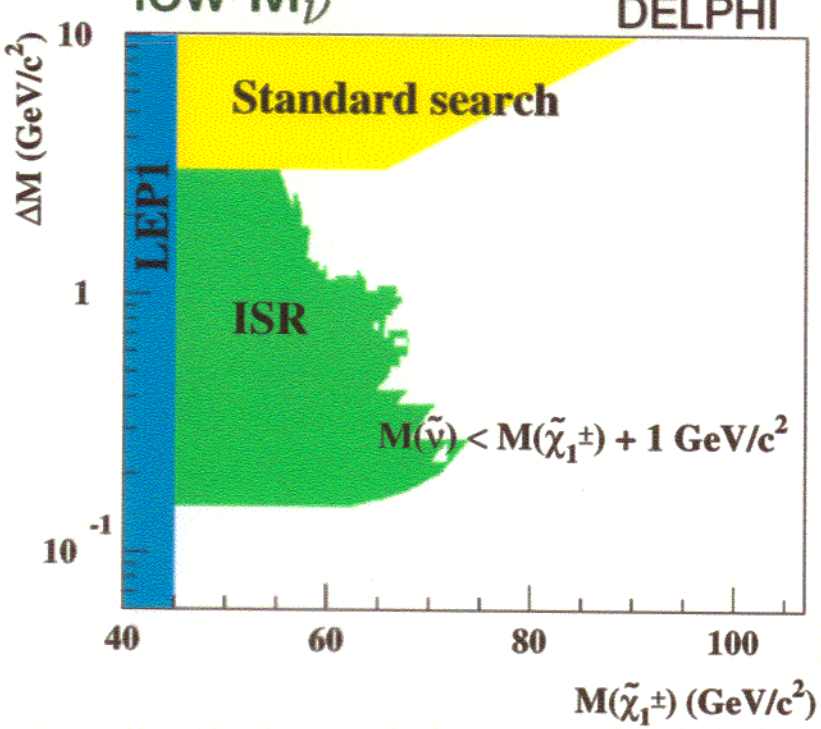
- MSSM ("standard") $\tilde{\chi}_1^{\pm}$ search
- search for heavy stable charged particles ⇒

Results depend on $M_{\tilde{\nu}}$, for light $M_{\tilde{\nu}}$: $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\nu}\ell^{\pm}$ possible

large $M_{\tilde{\nu}}$



low $M_{\tilde{\nu}}$



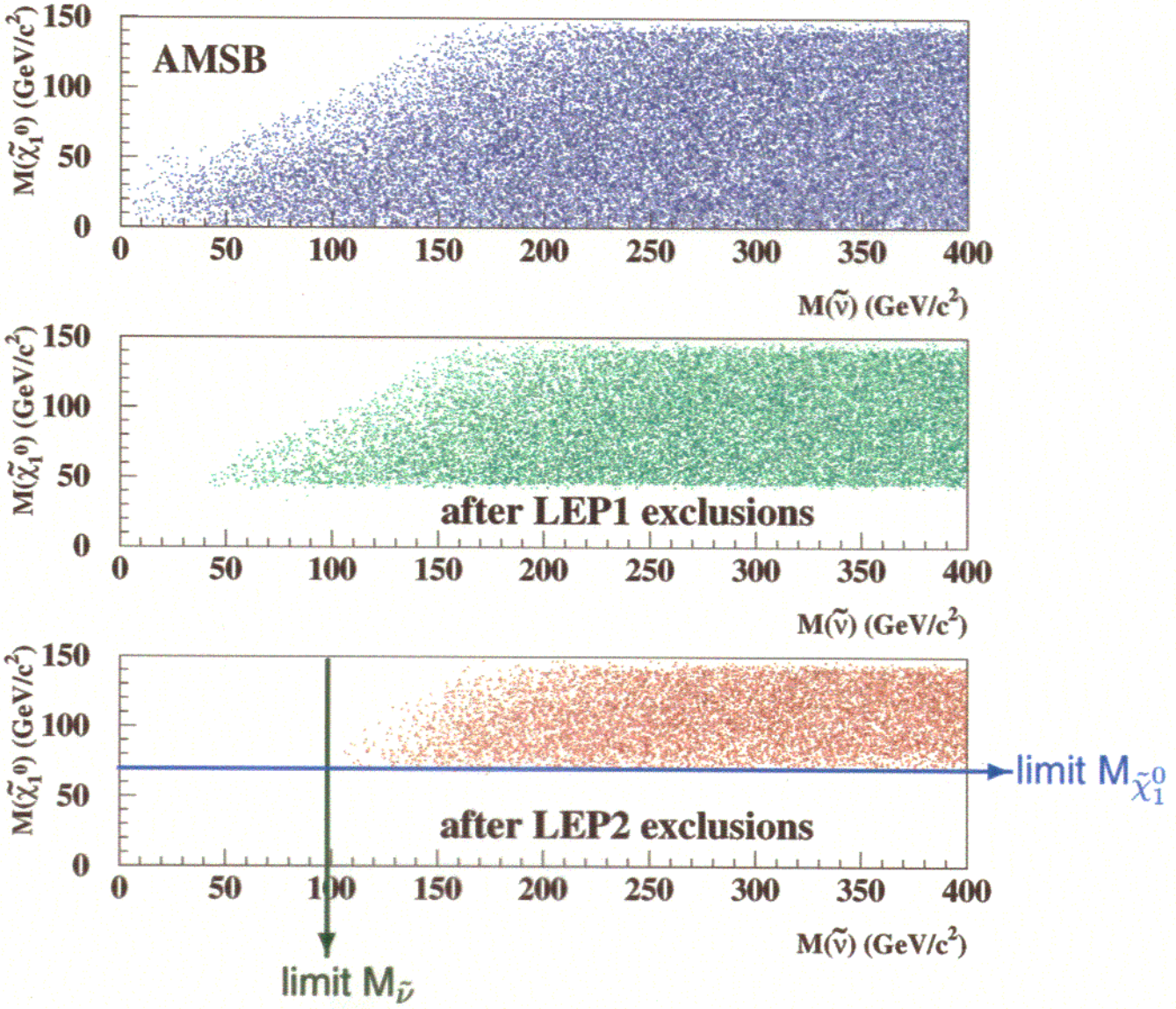
AMSB: Exclusions on LSP Masses

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

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

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



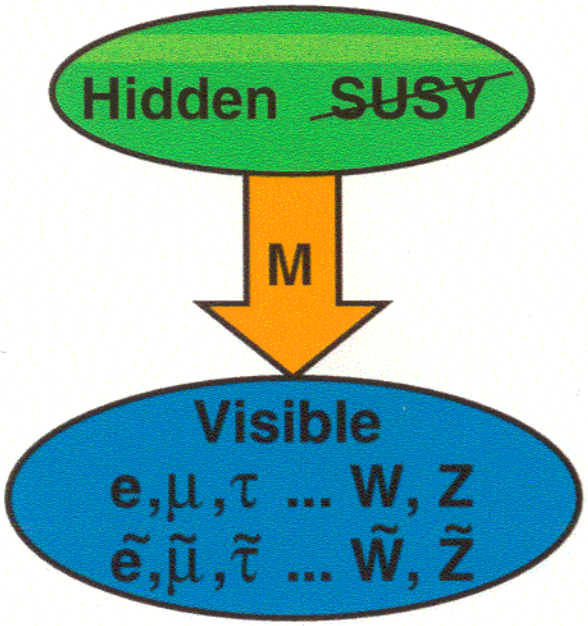
SUSY Breaking (Mediation)

Gravity

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

$M \sim M_P \sim 10^{18}$ GeV

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



Gauge

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

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

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

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

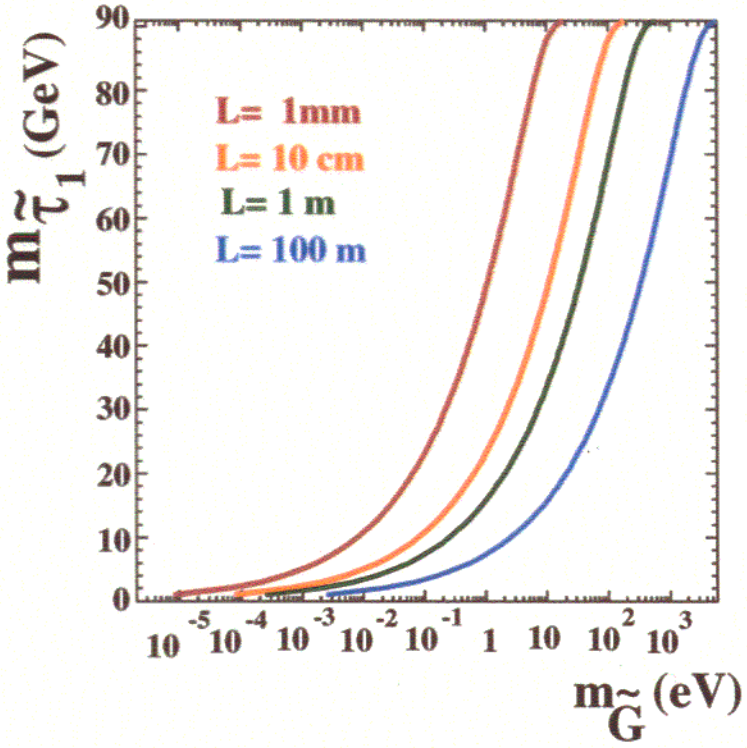
GMSB Phenomenology

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

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

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

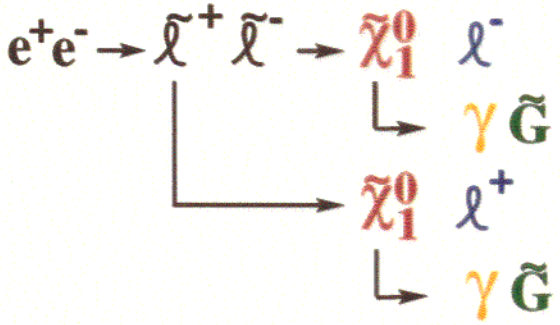
Example: $m_{\tilde{\tau}_1}$ versus $m_{\tilde{G}}$ for various decay lengths ($L=\beta\gamma c\tau_{\text{life}}$):

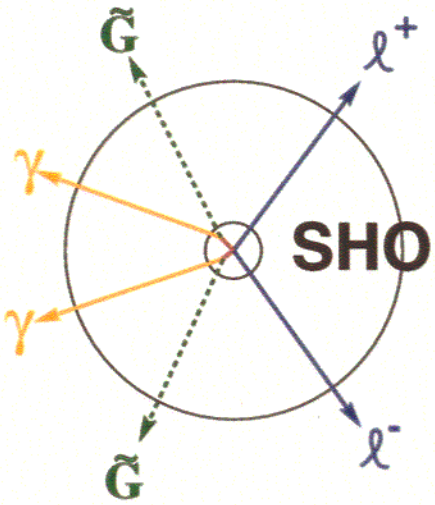


Wide range of NLSP lifetimes means we must explore many different topologies!

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

Signatures:

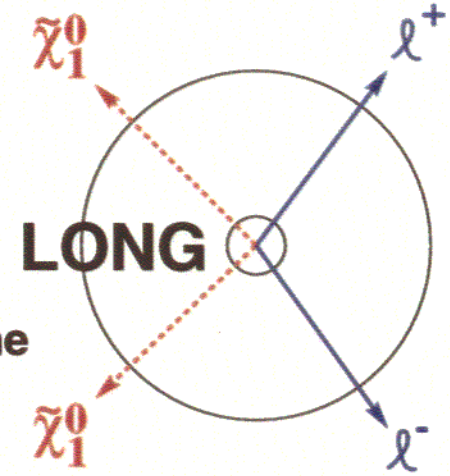




SHORT

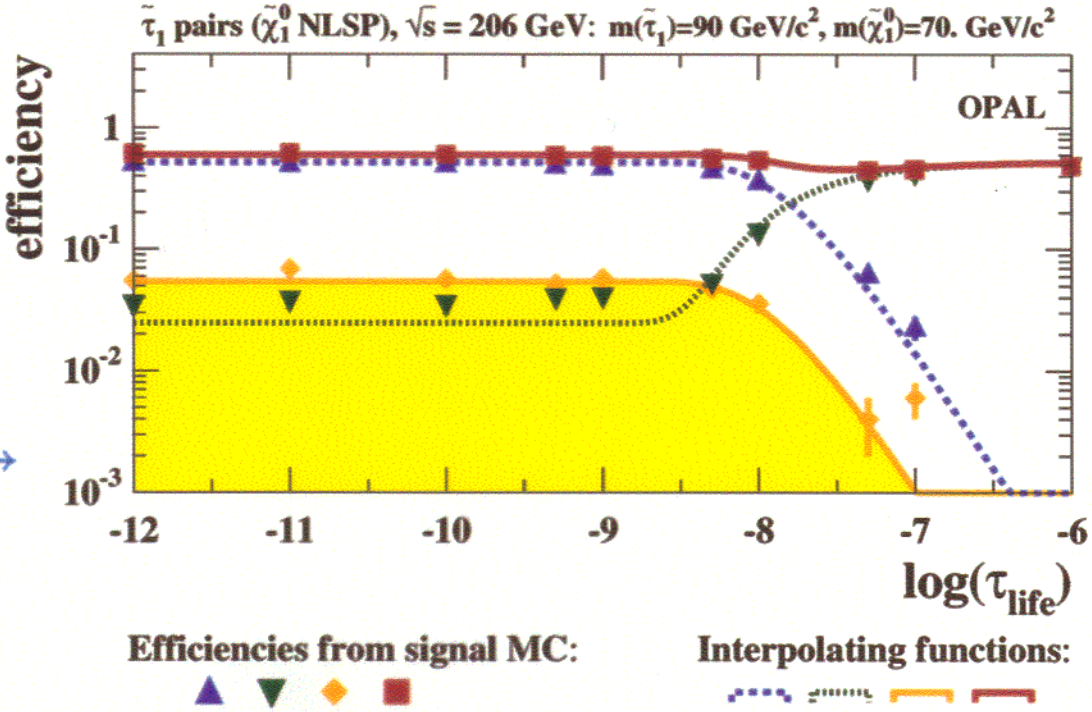
neutralino lifetime

LONG

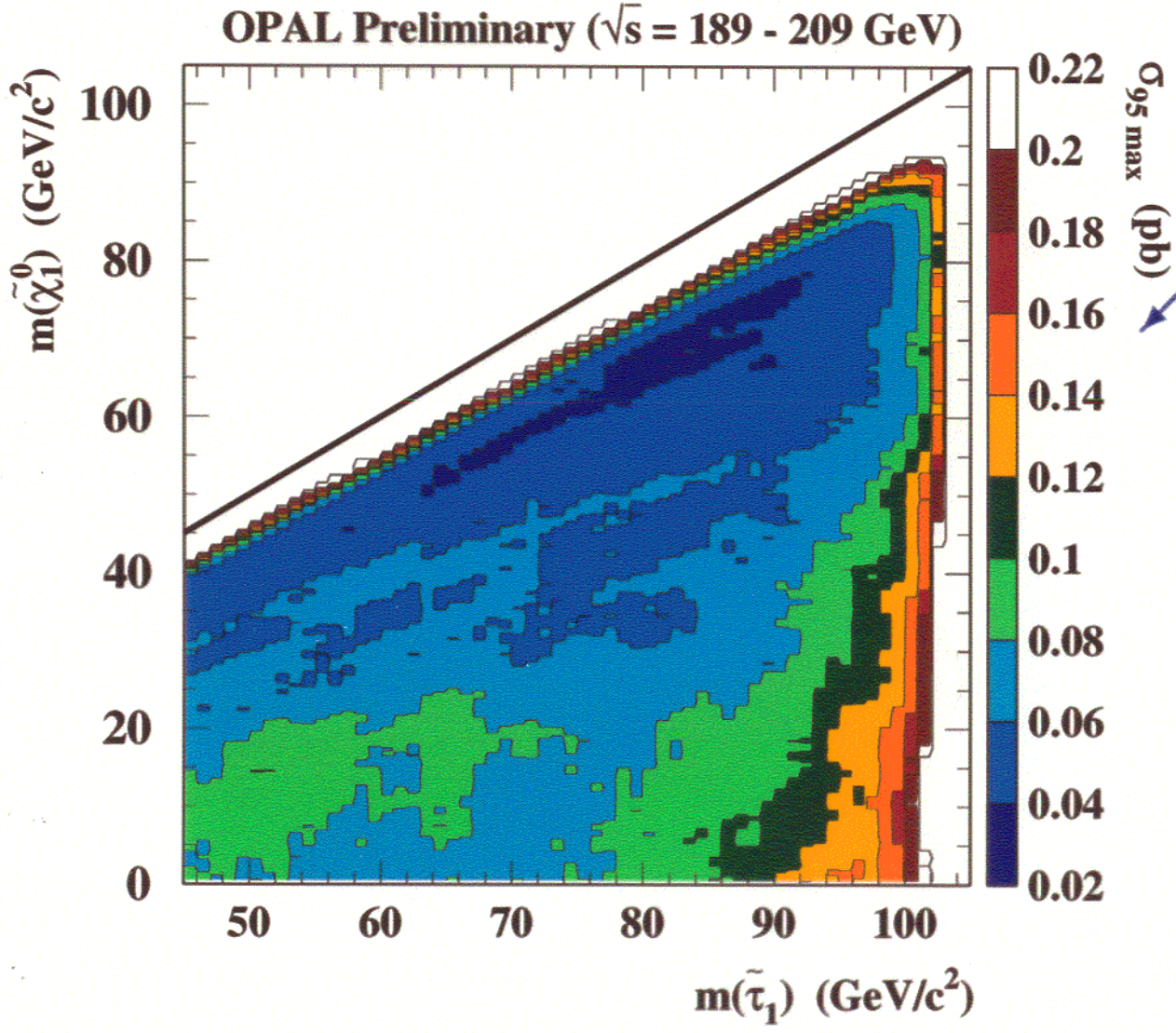


- Combination of analyses sensitive to different lifetime regimes of the NLSP.
- Efficiency depends on $m_{\tilde{\ell}}$, $\tau_{\mathrm{life}(\tilde{\ell})}$, $m_{\tilde{\chi}_1^0}$ and $\sqrt{s}$.
- Example:

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

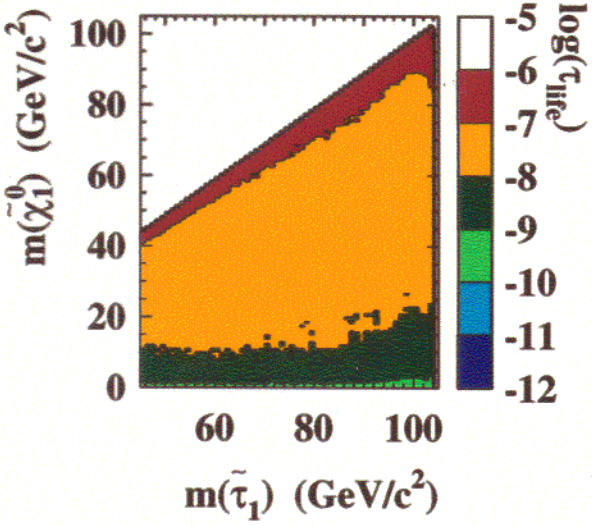


Limits on $\tilde{\tau}_1$ Pair Production ($\tilde{\chi}_1^0$ NLSP)



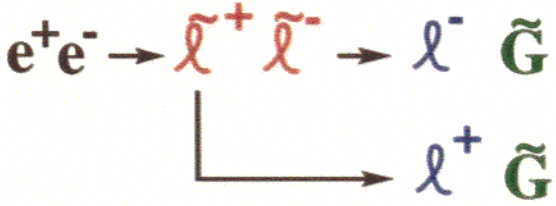
Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\tau}_1$ pairs ($\tilde{\chi}_1^0$ NLSP), valid for any $\tilde{\chi}_1^0$ lifetime ($\sigma_{\text{excluded}} \sim$ 0.04 – 0.15 pb).

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

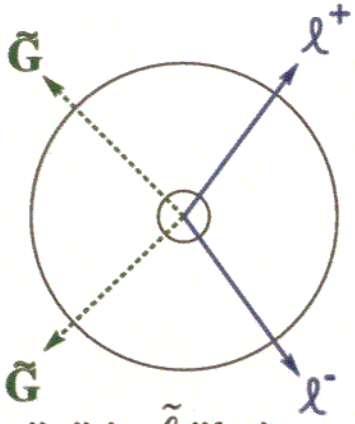


GMSB: Slepton Searches ($\tilde{\tau}$ NLSP/$\tilde{\ell}$ co-NLSP)

Signatures:

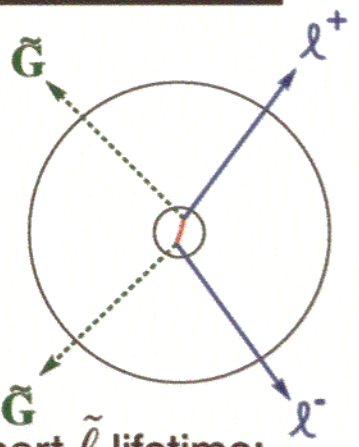


- Combination of analyses sensitive to different lifetime regimes of the NLSP.
- Efficiency depends on $m_{\tilde{\ell}}$, $\tau_{\mathrm{life}(\tilde{\ell})}$ and $\sqrt{s}$.



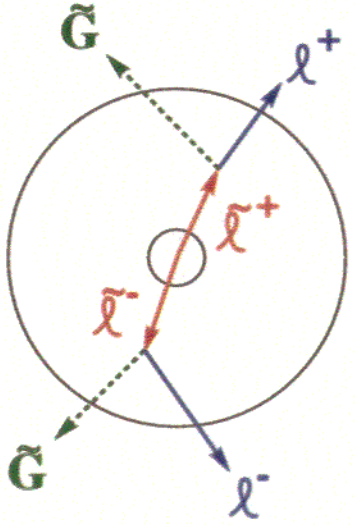
negligible $\tilde{\ell}$ lifetime:

acoplanar lepton search



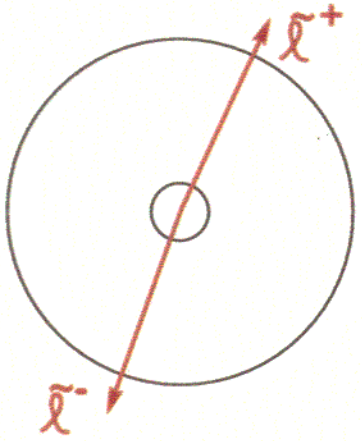
short $\tilde{\ell}$ lifetime:

search for tracks with large impact parameter



medium $\tilde{\ell}$ lifetime:

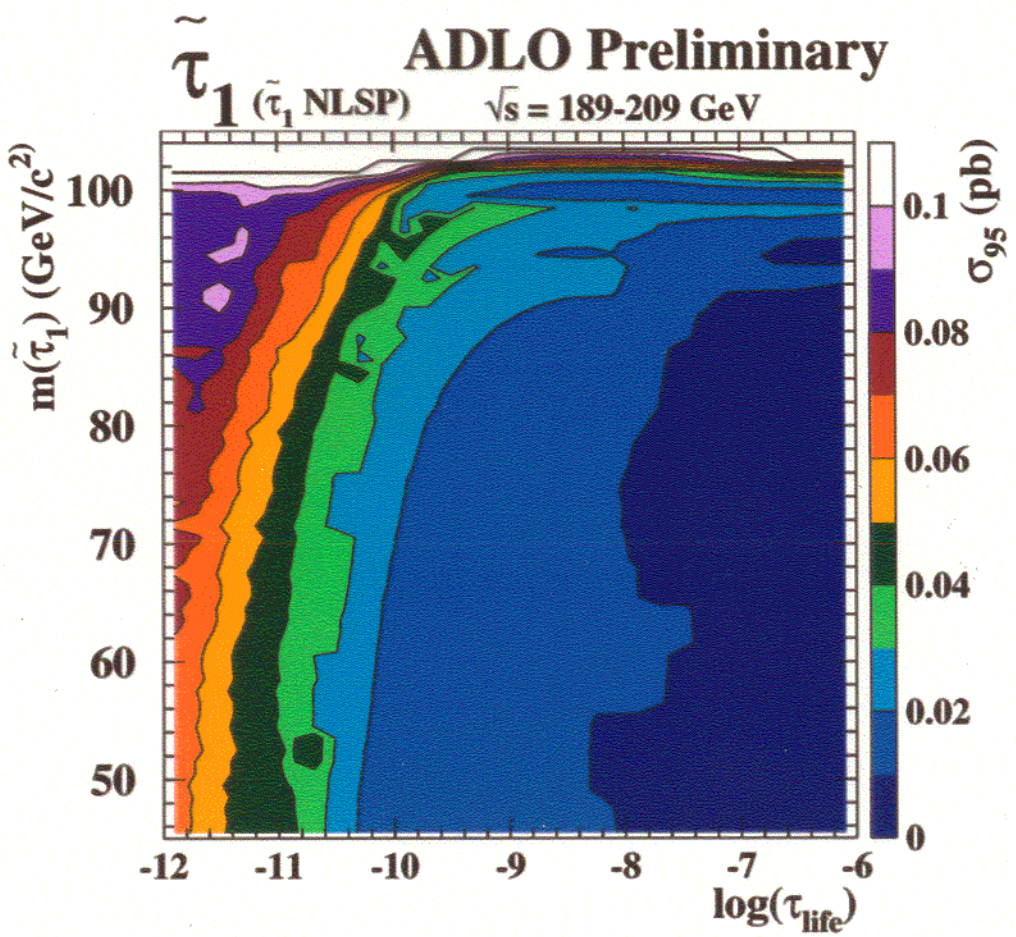
search for kinked tracks



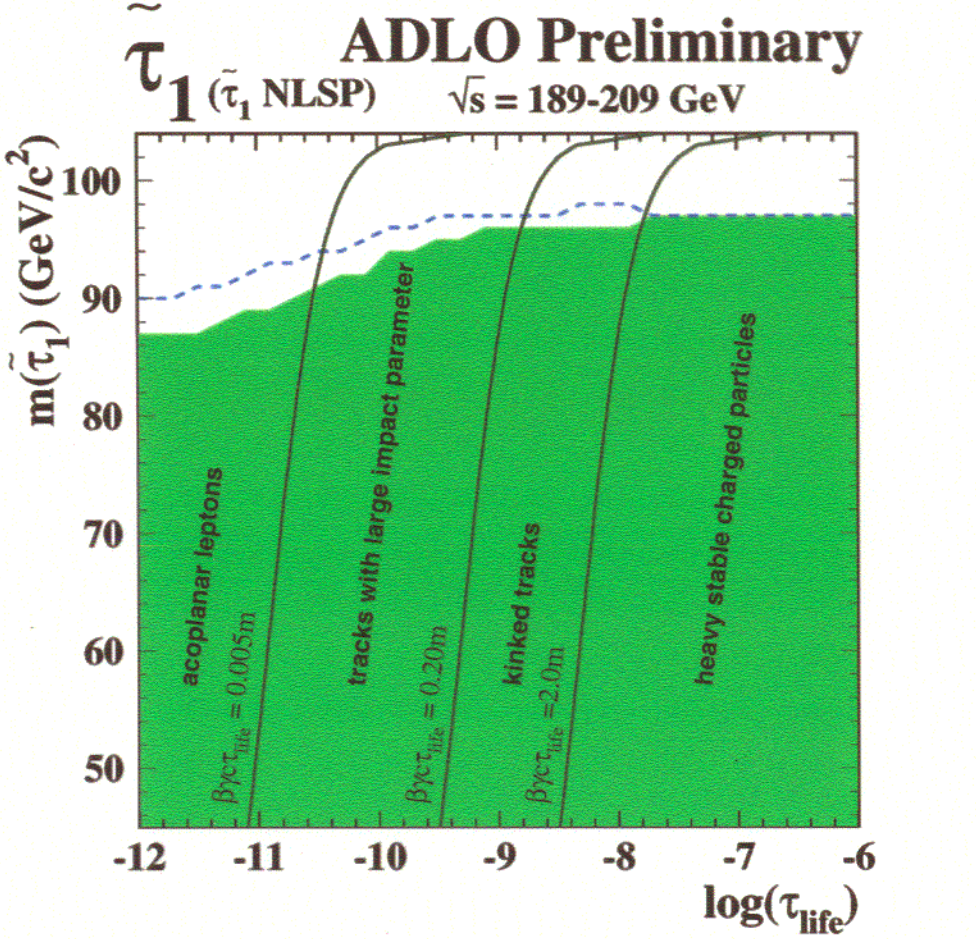
long $\tilde{\ell}$ lifetime:

search for heavy stable charged particles

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



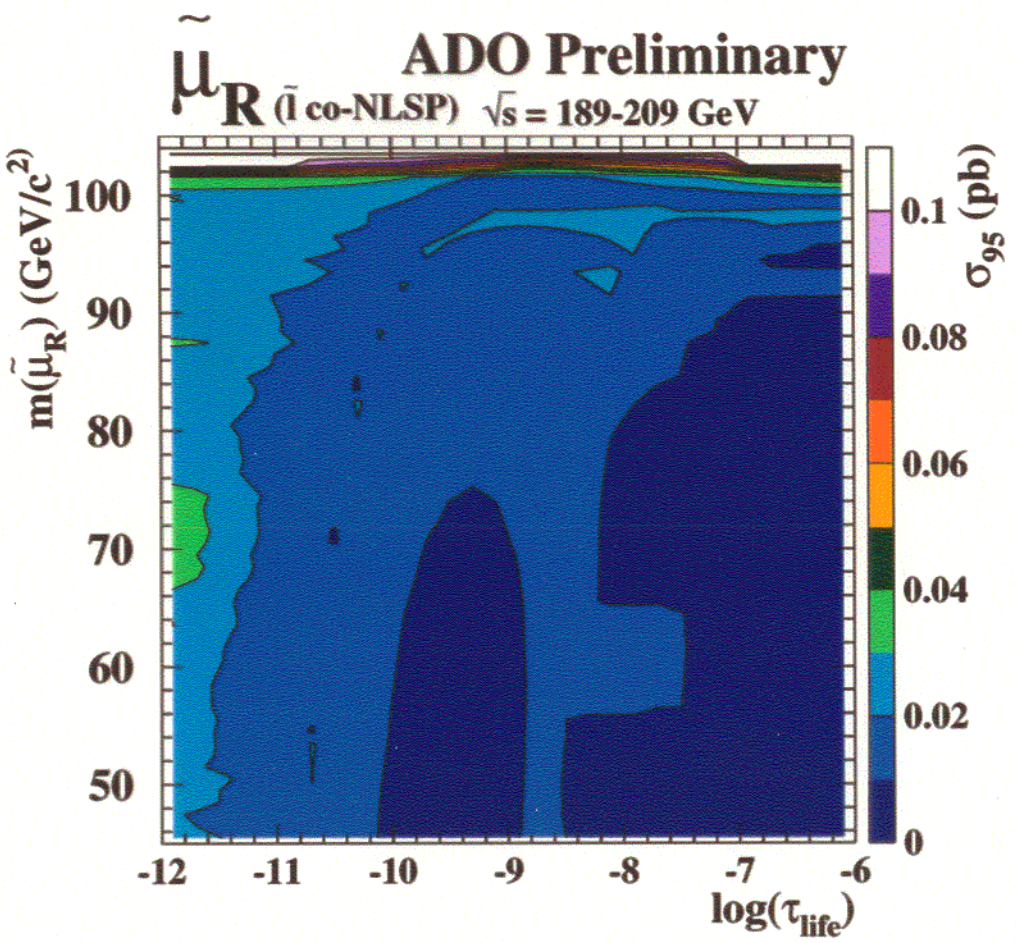
Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\tau}_1$ pairs ($\tilde{\tau}_1$ NLSP) as a function of $\tilde{\tau}_1$ lifetime ($\sigma_{\text{excluded}} \sim 0.01 - 0.1$ pb).



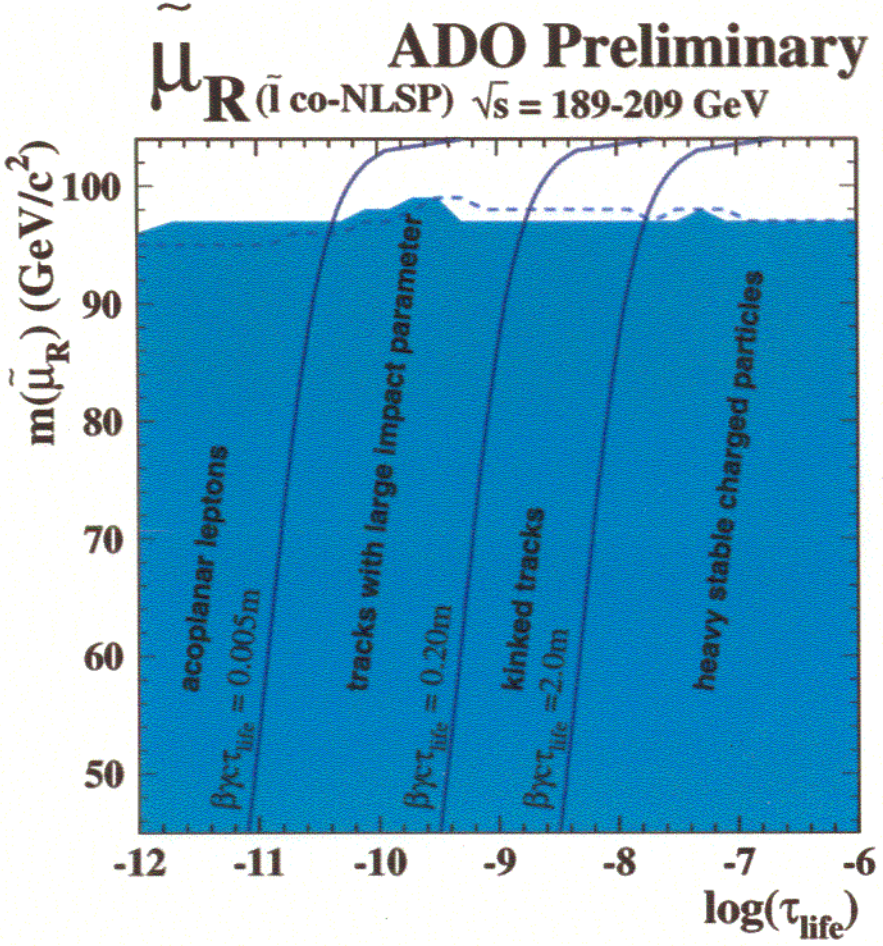
Excluded $\tilde{\tau}_1$ masses ($\tilde{\tau}_1$ NLSP) as a function of $\tilde{\tau}_1$ lifetime (87 – 97 GeV/c^2).
Dashed line: expected limit (90 – 97 GeV/c^2).

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

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 ($\sigma_{\text{excluded}} \sim 0.01 - 0.04$ 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).

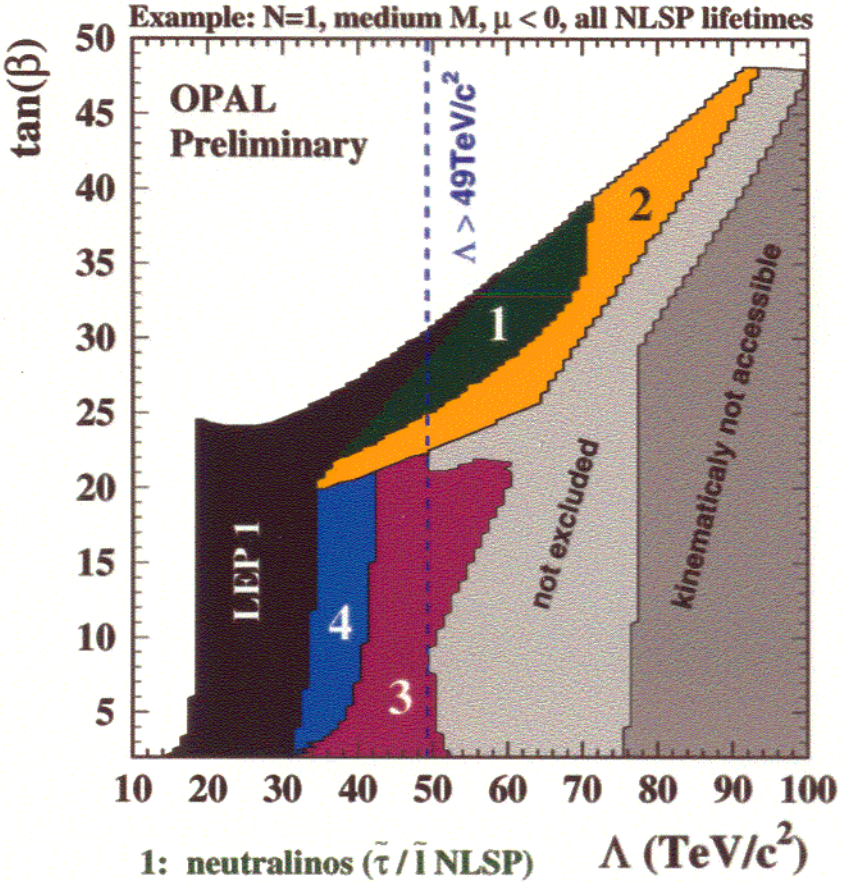
$$\Rightarrow m_{\tilde{\mu}_R} > 96 \text{ GeV/c}^2 \text{ for all } \tilde{\mu}_R \text{ lifetimes}$$

Scan of the GMSB Parameters (all NLSP Lifetimes)

Combination with other GMSB searches

$\Rightarrow$ search for pair production of:

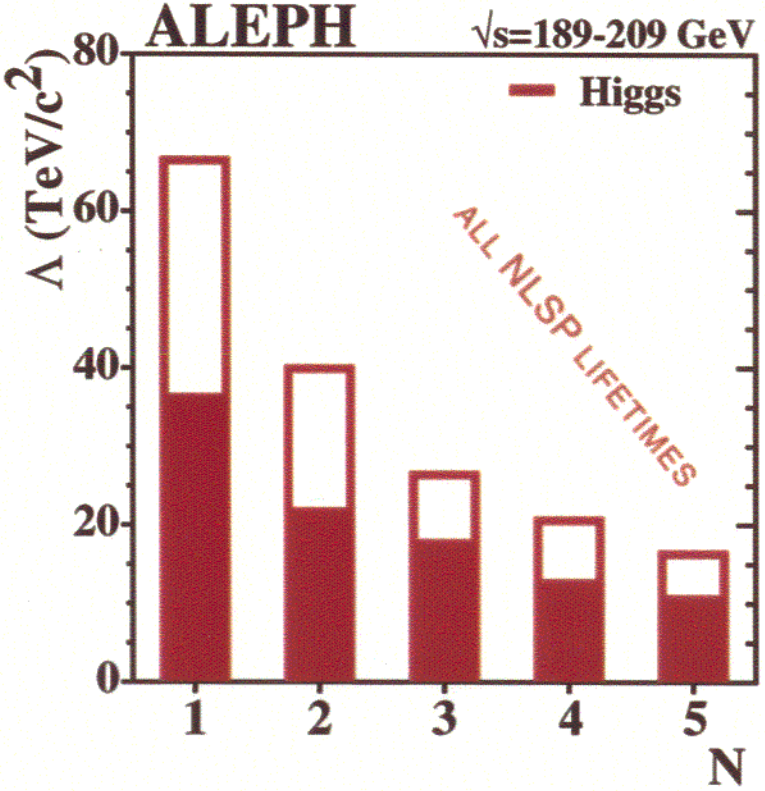
$\tilde{\chi}_1^0$ ($\tilde{\tau}$ NLSP / $\tilde{\ell}$ co-NLSP), $\tilde{\chi}_1^\pm$ ($\tilde{\chi}_1^0$ NLSP).



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



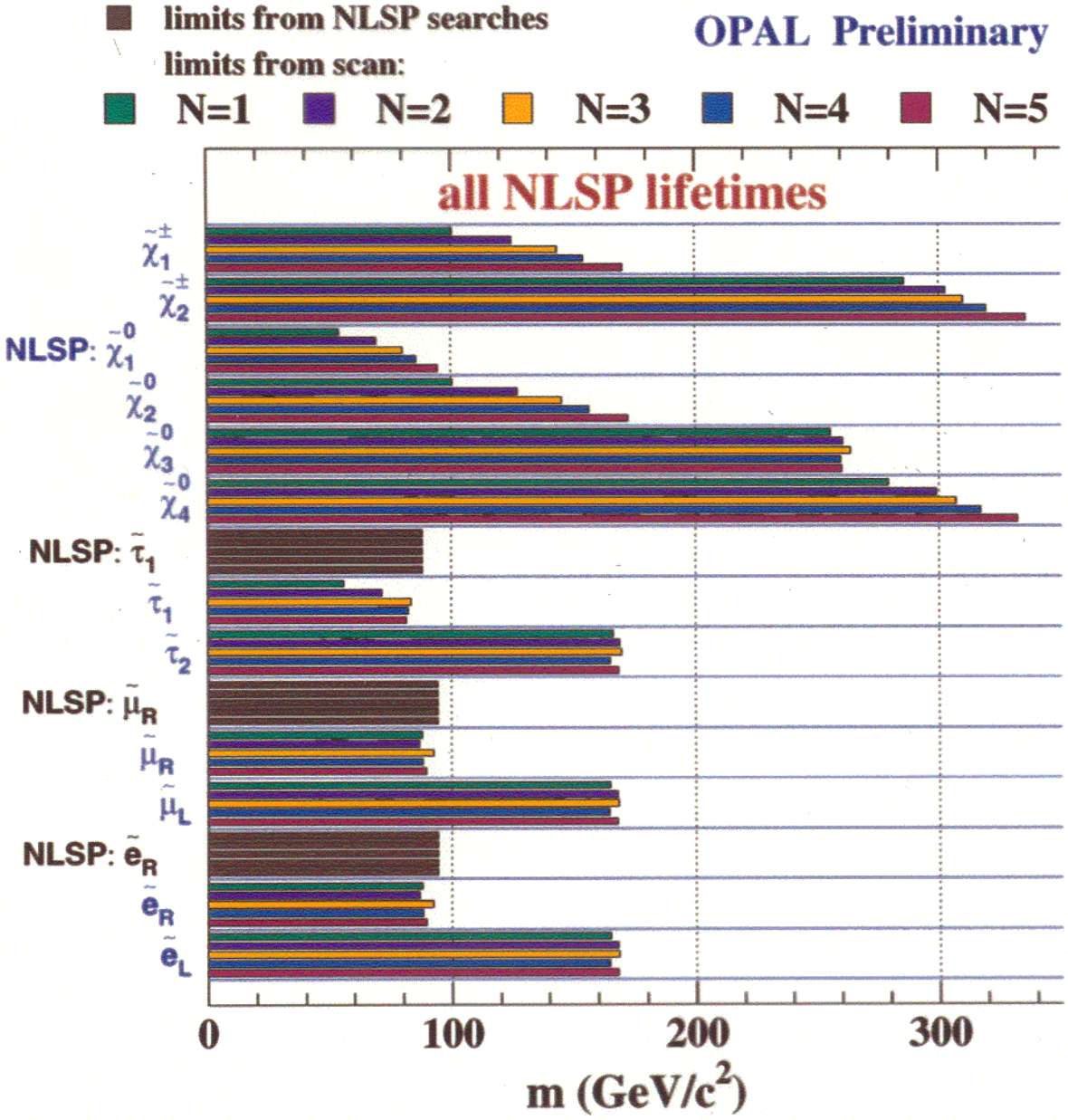
ALEPH: $\Lambda > 10$ TeV/c^2 for N$\leq$5

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

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

OPAL: $\Lambda > 15$ TeV/c^2 for N$\leq$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⟶ Neutralino Searches ($\tilde{\chi}_1^0$ NLSP)

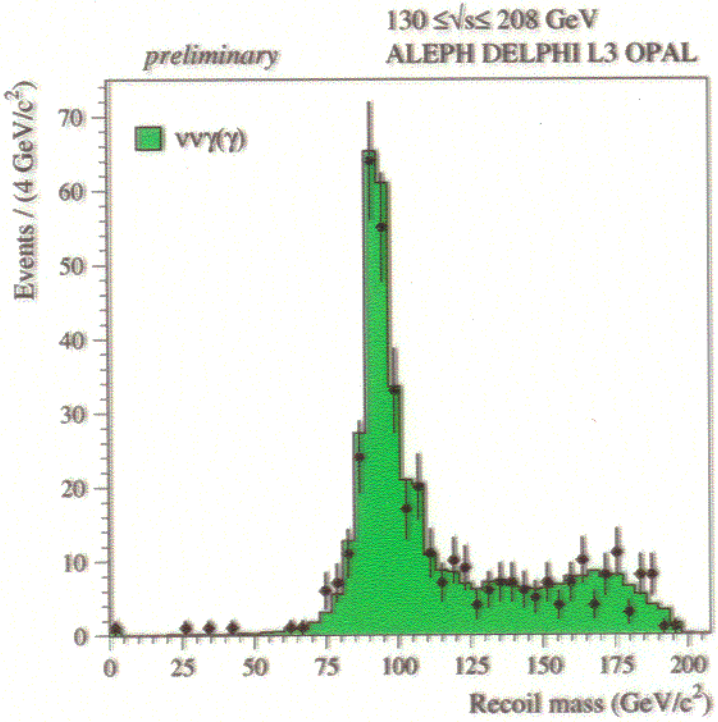
Signature:

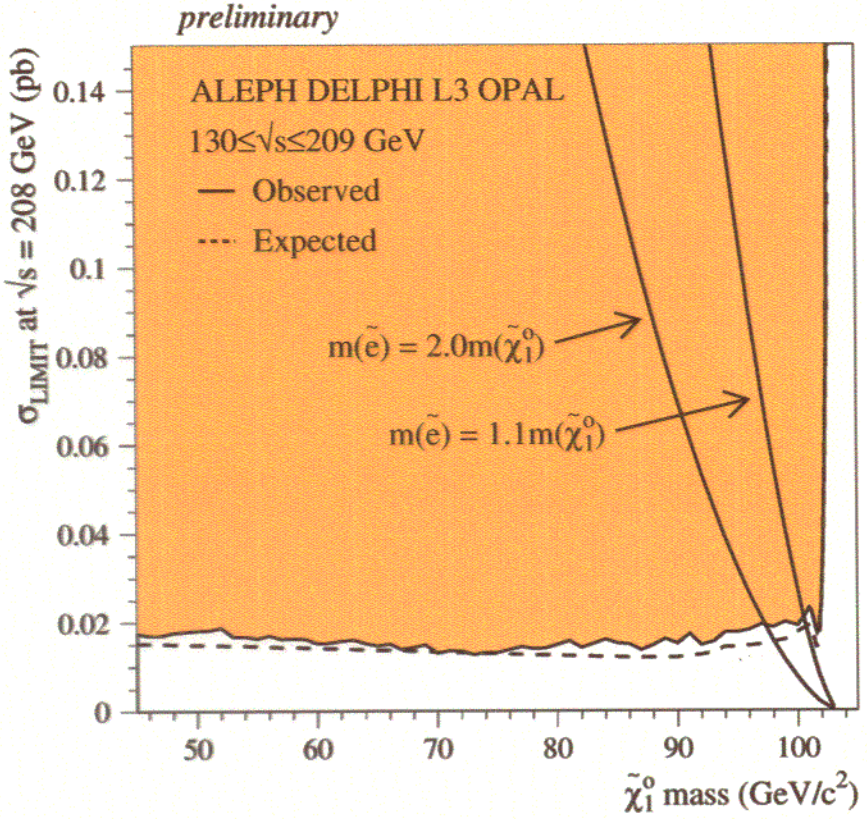
$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma \tilde{G}$

$\hookrightarrow \gamma \tilde{G}$

⇒ Search for acoplanar photon pairs.

ADLO: 387 events observed/ 403.9 expected





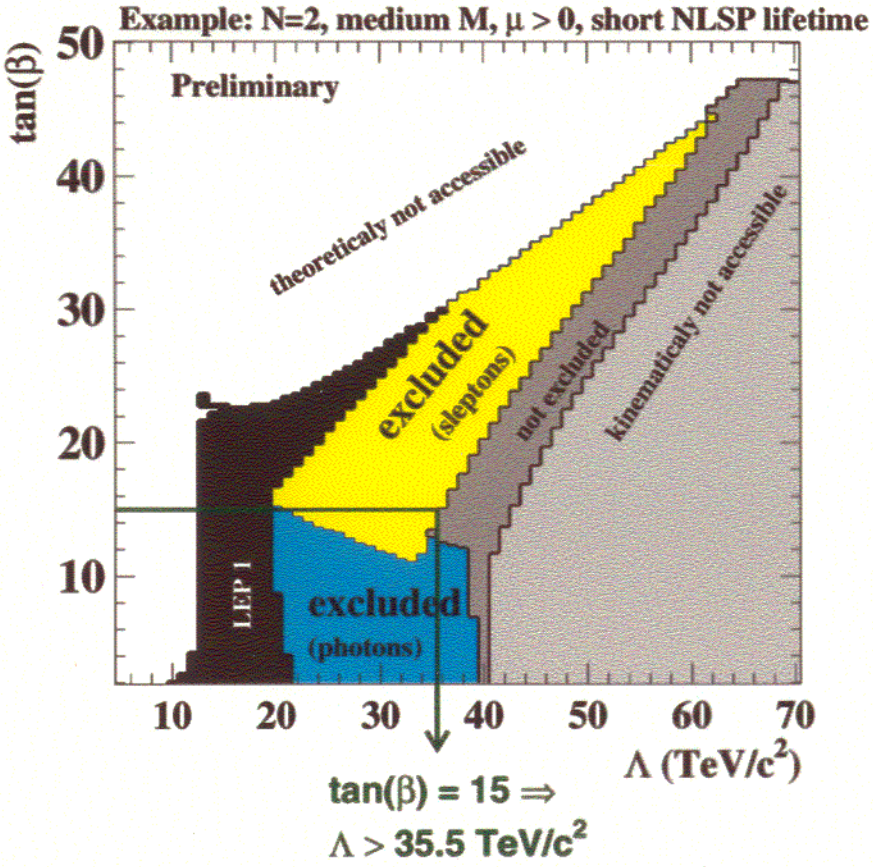
Excluded cross-section at $\sqrt{s} = 208$ GeV for $\tilde{\chi}_1^0$ pairs ($\tilde{\chi}_1^0$ NLSP) (~0.02 pb).

GMSB: Prospects

ADLO, short NLSP lifetime

(no Higgs results included)

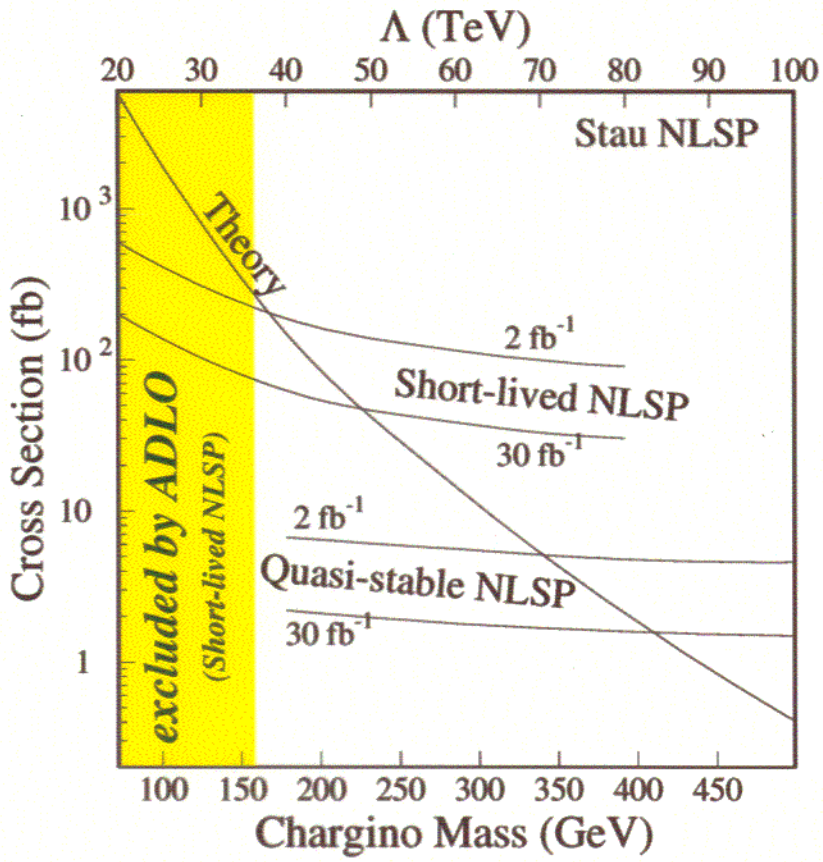
Scan in GMSB parameter space following
Dimopoulos, Thomas, Wells, Nucl. Phys. B488 (1997) 39



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.