Unstoppable, Sbottomless Sfermion Searches

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on behalf of the Aleph, Delphi, L3 and Opal Collaborations

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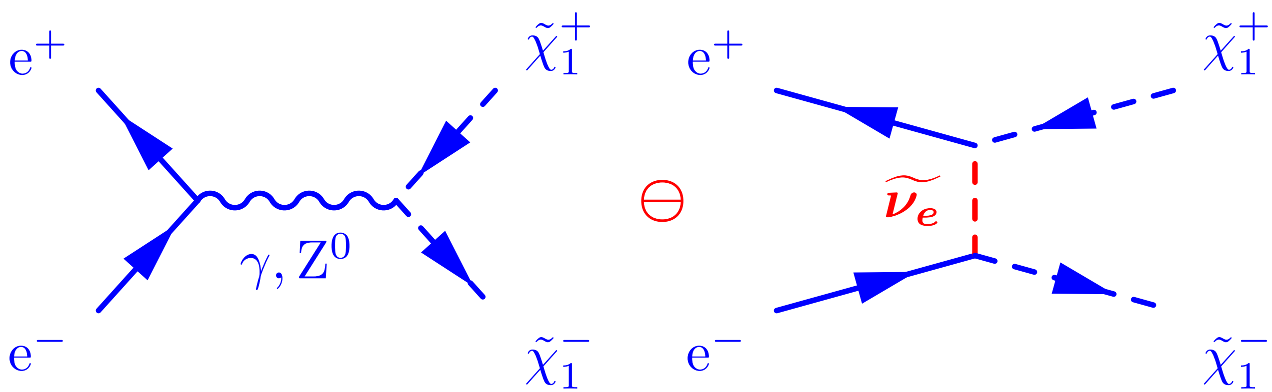
- Why look for sfermions?
- What happens if there are light $\tilde{f}$?
- Direct searches
- Where else could they be hiding?
- What do the results mean?

How do we usually search for Supersymmetry?

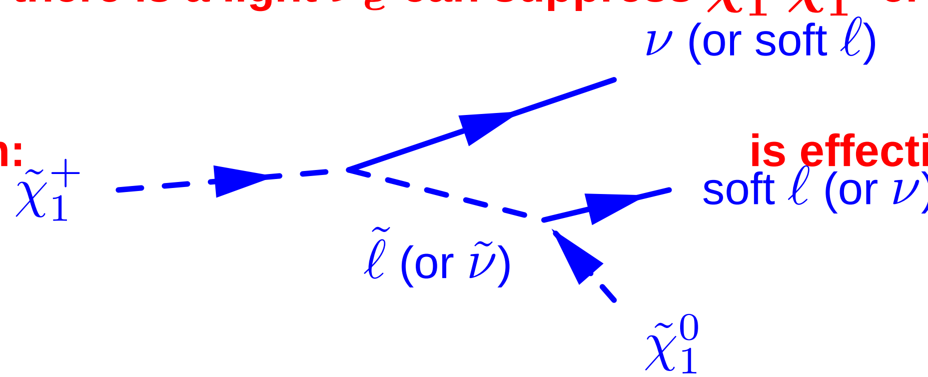
- all SUSY models predict scalar partners for the fermions
- also fermionic partners for gauge and Higgs bosons $\Rightarrow$ charginos and neutralinos
- often consider $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ to be lightest unstable SUSY particles, large cross-section

BUT:



$\longrightarrow$ destructive interference if there is a light $\tilde{\nu}_e$ can suppress $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ cross-section!

Light sleptons also a problem:



is effectively invisible.

SUSY and Light Sfermions

- SUSY models predict scalar partners for left- and right-handed Standard Model fermions
- in general, $\tilde{f}_L, \tilde{f}_R$ mix to form mass eigenstates (mixing $\propto$ *fermion* mass, ignore for $\tilde{\mathrm{e}}$, $\tilde{\mu}$)
- if they do not mix, $\tilde{f}_R$ eigenstate is lighter (for $\tan\beta \geq 1$)

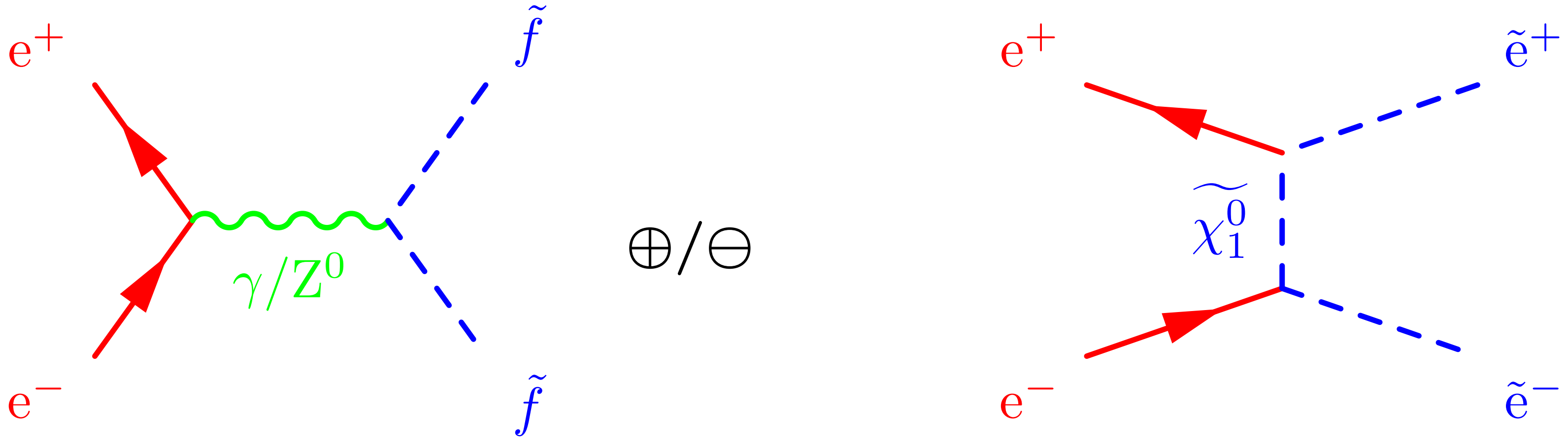
$$
\begin{aligned}
m^2_{\tilde{\ell}_R} &= m_0^2 + 0.15 m^2_{1/2} - m^2_{\mathrm{Z}^0} \cos 2\beta \sin^2\theta_W \\
m^2_{\tilde{\ell}_L} &= m_0^2 + 0.52 m^2_{1/2} - \frac{m^2_{\mathrm{Z}^0}}{2} \cos 2\beta (1 - 2\sin^2\theta_W) \\
m^2_{\tilde{\nu}} &= m_0^2 + 0.52 m^2_{1/2} + \frac{m^2_{\mathrm{Z}^0}}{2} \cos 2\beta
\end{aligned}
$$

- m_0 is common sfermion mass at GUT scale
- $m_{1/2}$ is common gaugino mass at GUT scale

What happens if there are light $\tilde{f}$?

$m_0, m_{1/2}$ both small:

- t-channel $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production may cause negative interference so may NOT see charginos!
- or light sleptons or sneutrinos can mean charginos decay almost invisibly
- BUT (if light enough) have direct production of $\tilde{f}\bar{\tilde{f}}$ pairs:

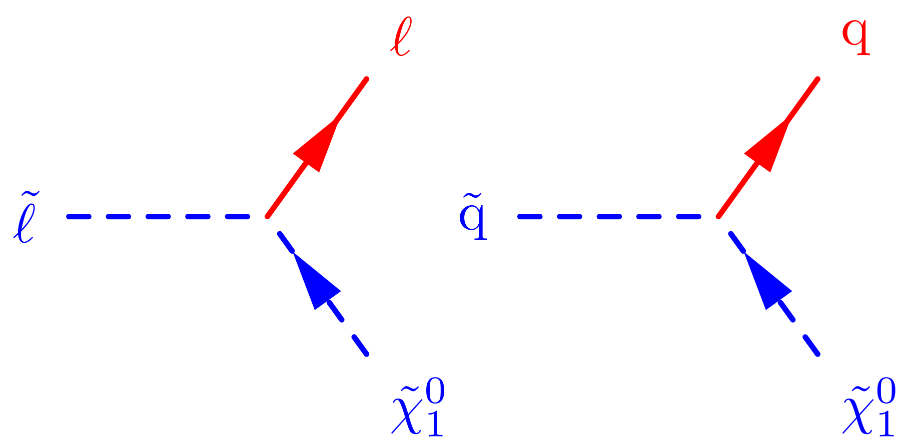


- s-channel cross-section for $\tilde{f}_R\bar{\tilde{f}}_R$ smaller than for $\tilde{f}_L\bar{\tilde{f}}_L \longrightarrow$ limits on $\tilde{f}_R\bar{\tilde{f}}_R$ conservative

Direct Searches for Sfermion Pair Production

RP-Conserving Signatures for Slepton and Squark Decay:

- $\tilde{f} \to f\tilde{\chi}_1^0$
- sleptons: $\ell^+\ell^- + E_T^{\rm miss}$
- squarks (excluding $\tilde{t}$): $q\bar{q}' + E_T^{\rm miss}$
  - generally $\tilde{\rm t}_1, \tilde{\rm b}_1$ assumed to be lightest squarks – see stop/sbottom talk

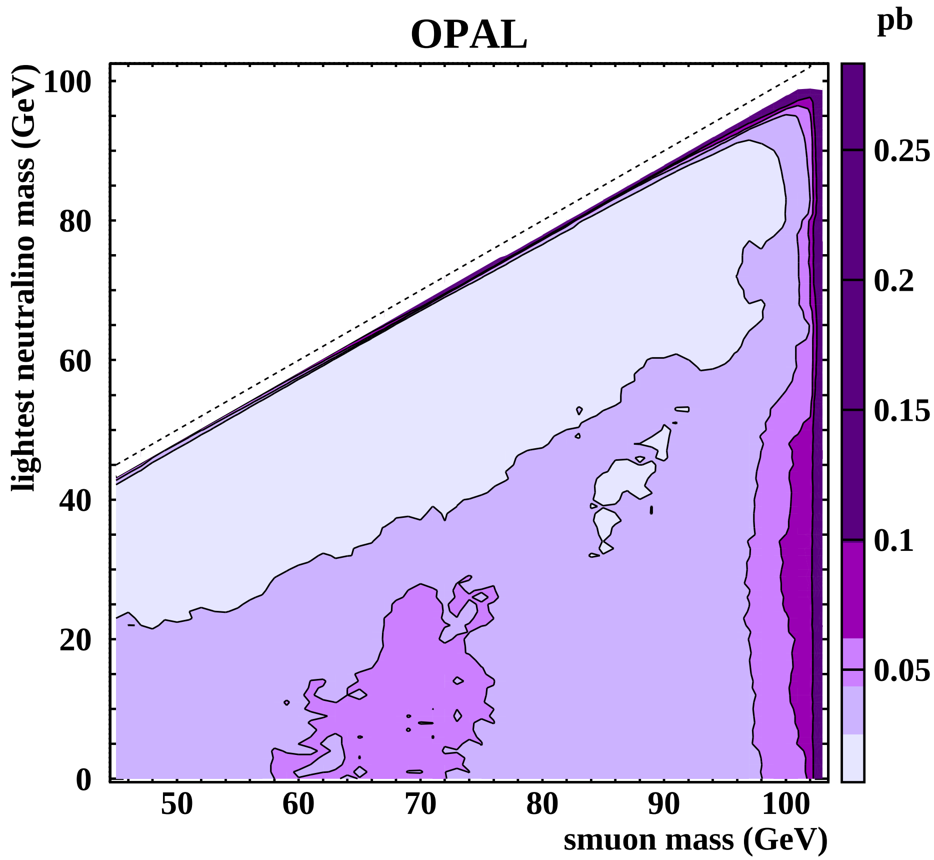


Searches for Promptly Decaying Pair-Produced Sleptons

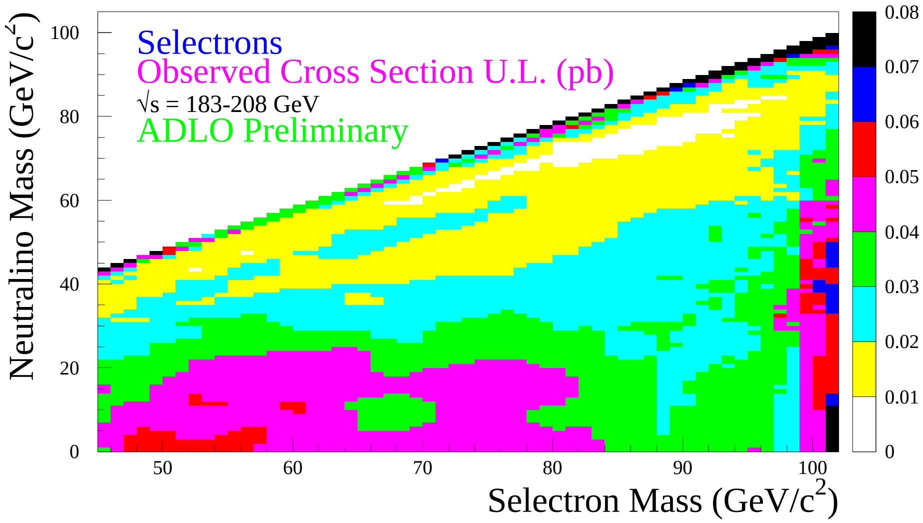
Example: $\tilde{\mu}^+\tilde{\mu}^-$ search at OPAL

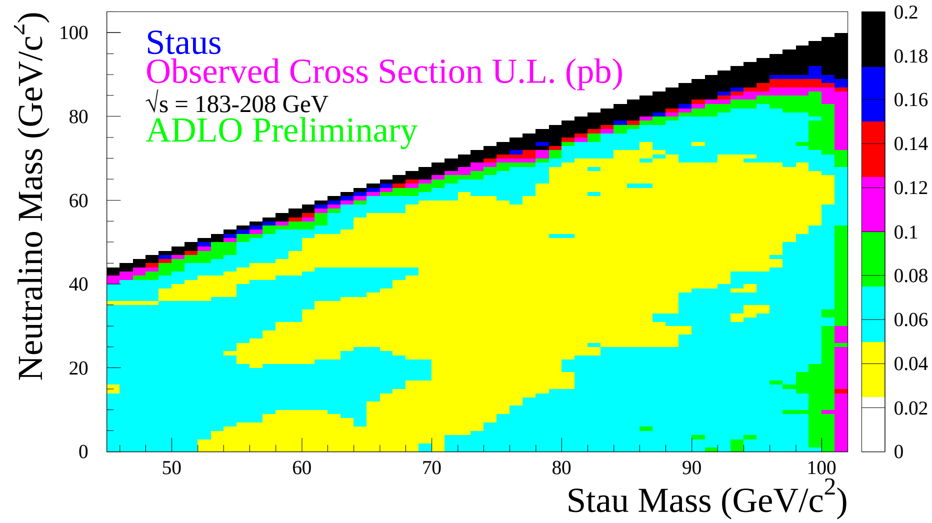
- Require 2 (or 1) isolated ℓ candidates, $E_{\mathrm{t}}^{\mathrm{miss}}$ and nothing else (possibly some forward activity or a γ)
- ID lepton candidates – require at least 1 $\mu^\pm$, nothing compatible with $\mathrm{e}^\pm$
- Construct likelihood, compare with MSSM $\tilde{\mu}^+\tilde{\mu}^-$ signal for a grid of kinematically allowed $(M_{\tilde{\mu}}, M_{\tilde{\chi}_1^0})$
- If no hint of signal, use extended max LH technique to find σ_s below which 95% of LH function for data lies

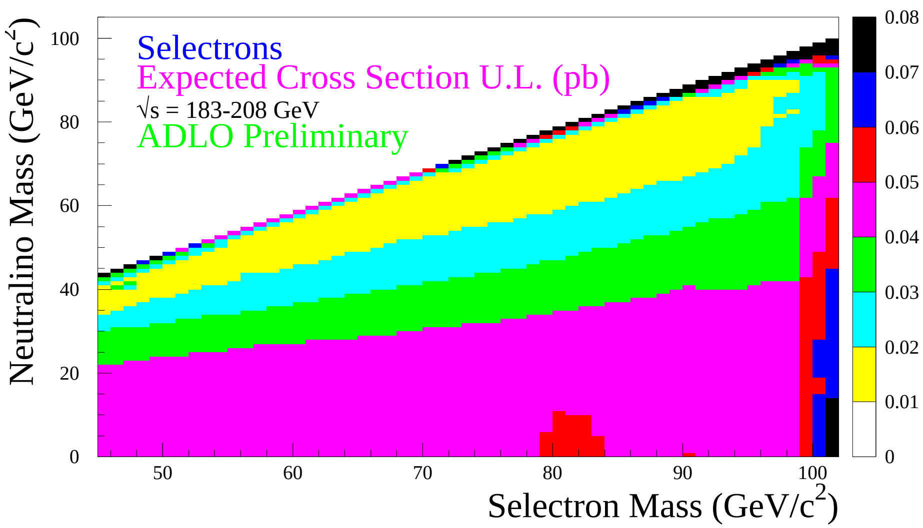
95% CL cross-section limits:

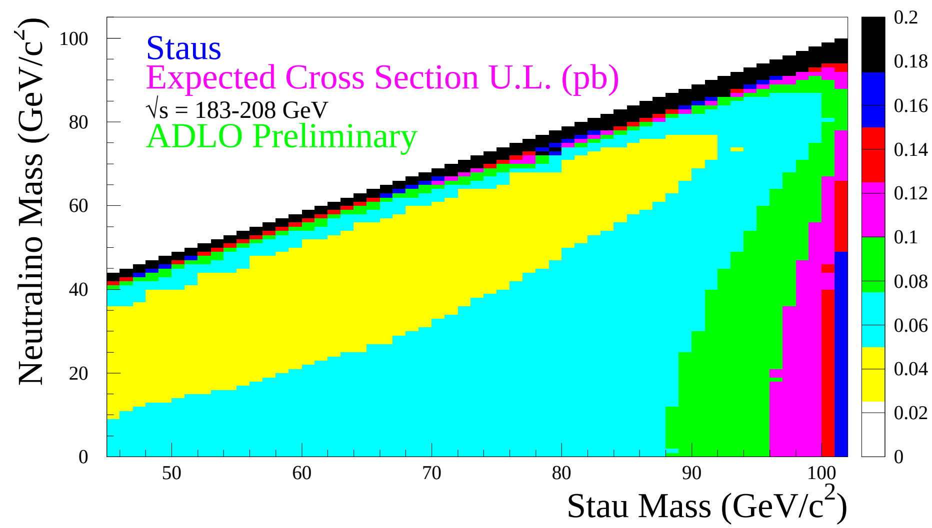


Selectron and Stau Cross-Section Limits



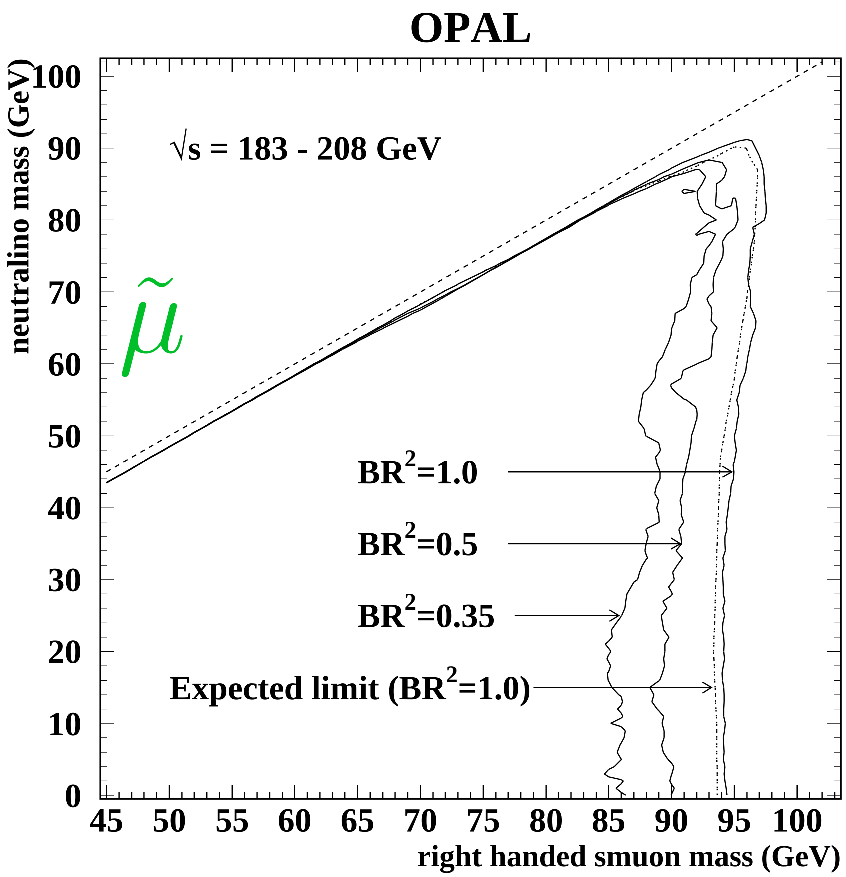


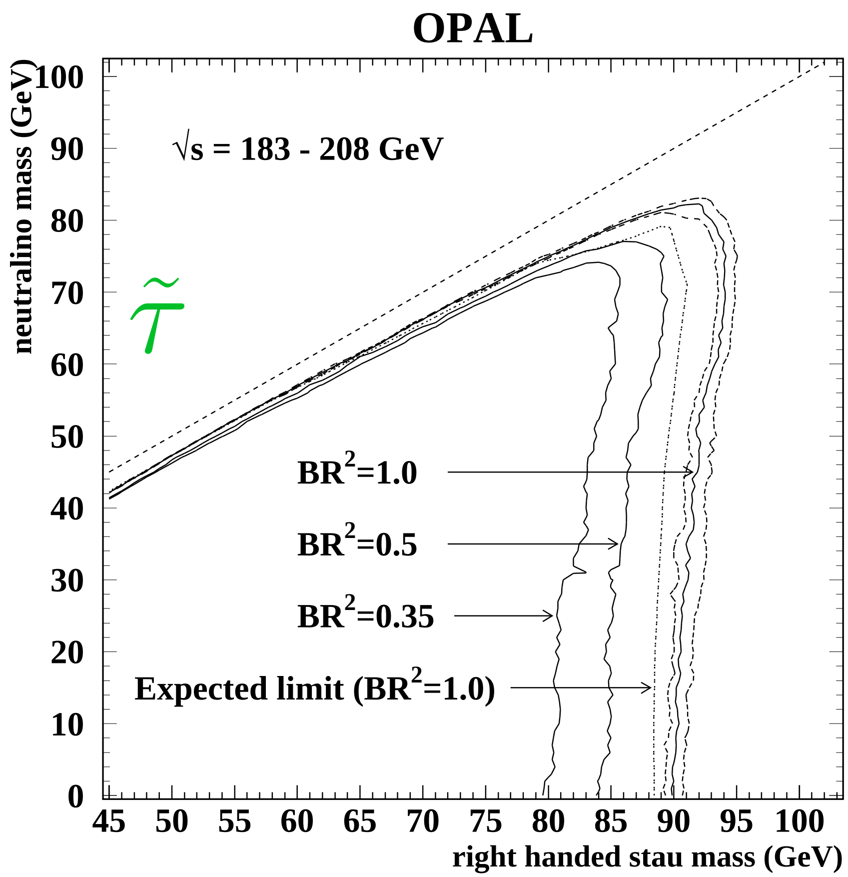




Model-Independent Mass Limits from Standard Slepton Searches

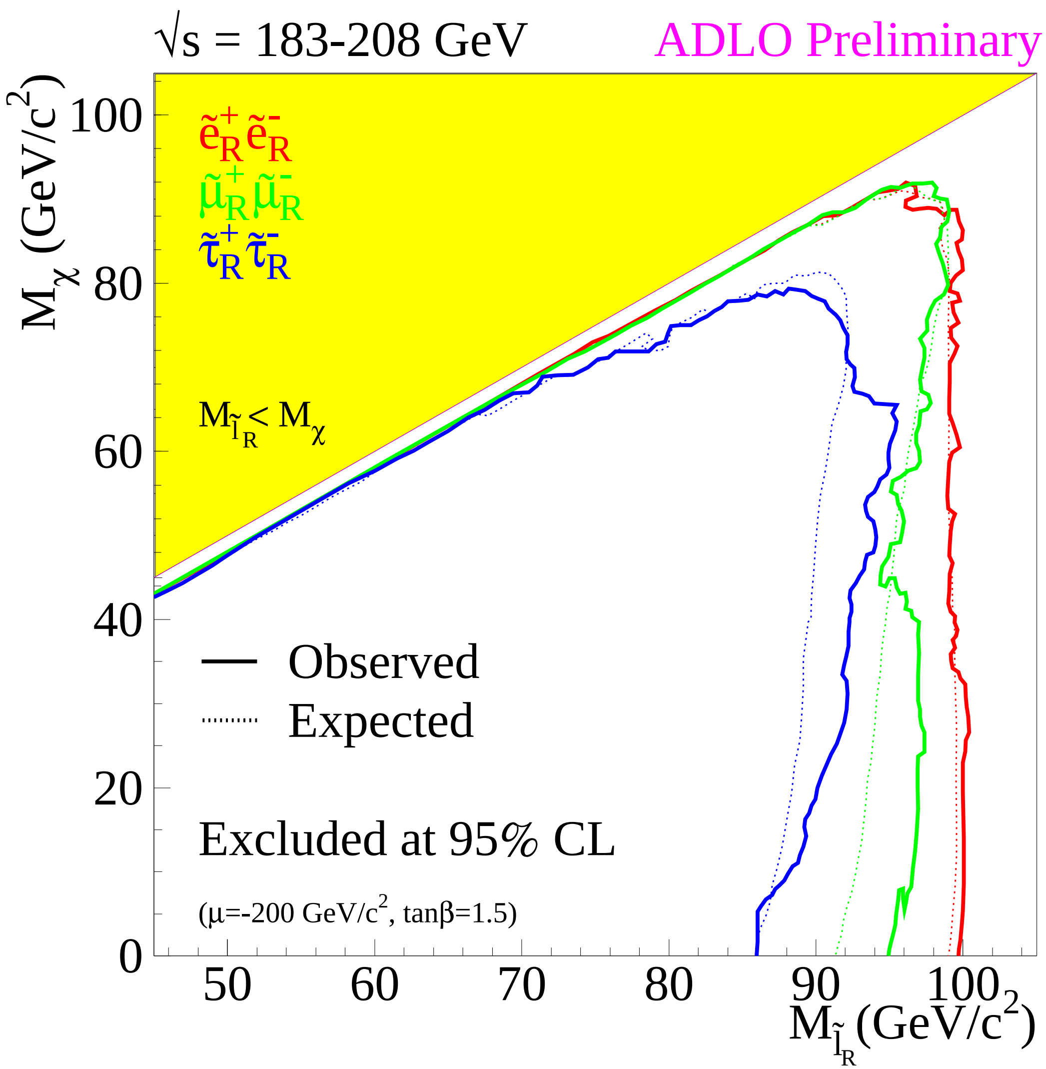
Can set model-independent limits for $\tilde{\ell}_R$ produced in purely s-channel processes:





BR($\tilde{\ell}_R \rightarrow \ell\tilde{\chi}^0_1$) is model-dependent. For $\tilde{\tau}$ mixing, multiply $\sigma_{\tilde{\tau}_R\tilde{\tau}_R}$ by $\sigma_{\tilde{\tau}_1\tilde{\tau}_1}/\sigma_{\tilde{\tau}_R\tilde{\tau}_R}$

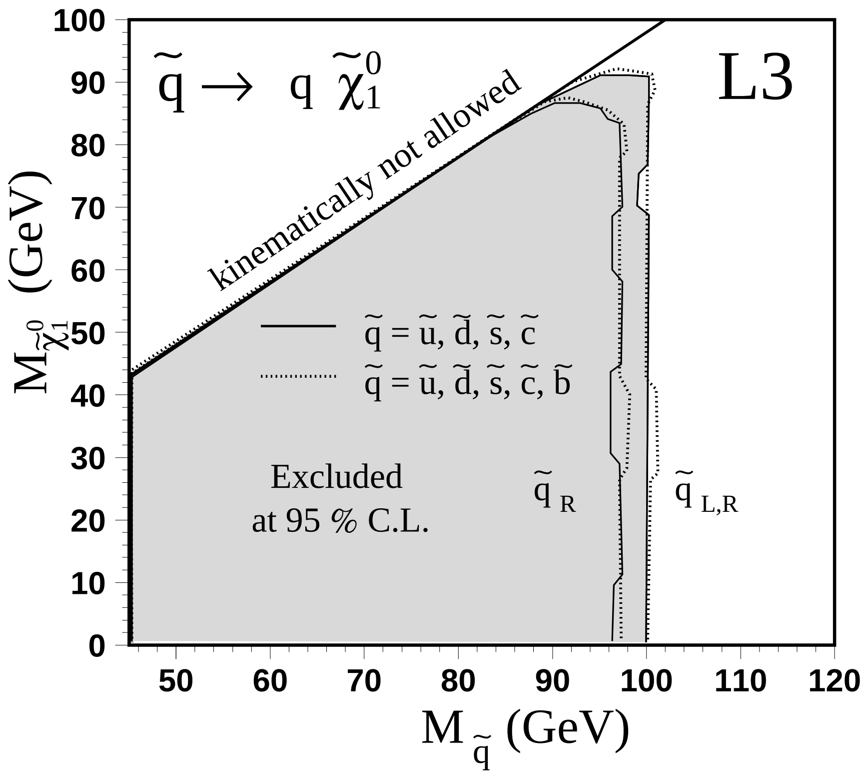
Standard Searches Interpreted as Mass Limits in Constrained MSSM

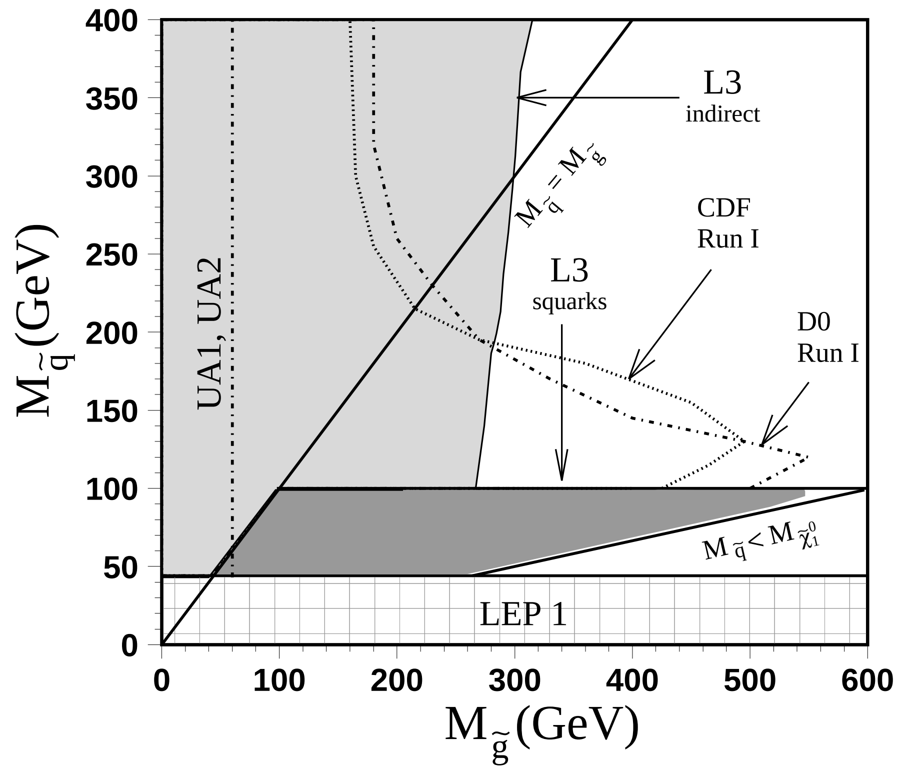


Slepton	Limit at $M_{\tilde{\chi}^0_1} =$	
	40 GeV	0 GeV
$\tilde{e}_R$	99.4	99.6
$\tilde{\mu}_R$	96.5	94.9
$\tilde{\tau}_R$	92.5	85.9
$\tilde{\tau}_{Z^0 \text{ decoupling}}$	91.7	85.0

...for $\mu = -200$ GeV, $\tan\beta = 1.5$

Searches for Mass-Degenerate Squarks





... a reinterpretation of $\tilde{\mathrm{t}}$ searches; right-hand plot assumes GUT-level gaugino unification.

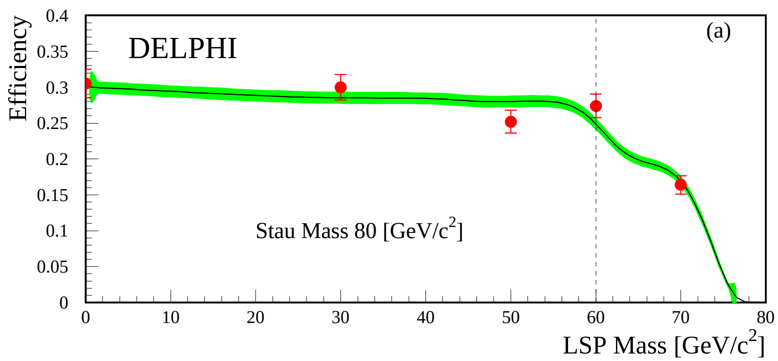
Indirect limit on $M_{\tilde{\mathrm{g}}}$ is from limit on M_2 from $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$ searches.

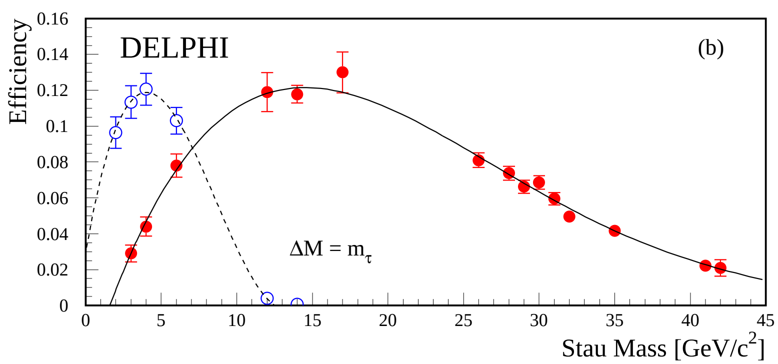
How could light sleptons hide from direct searches?

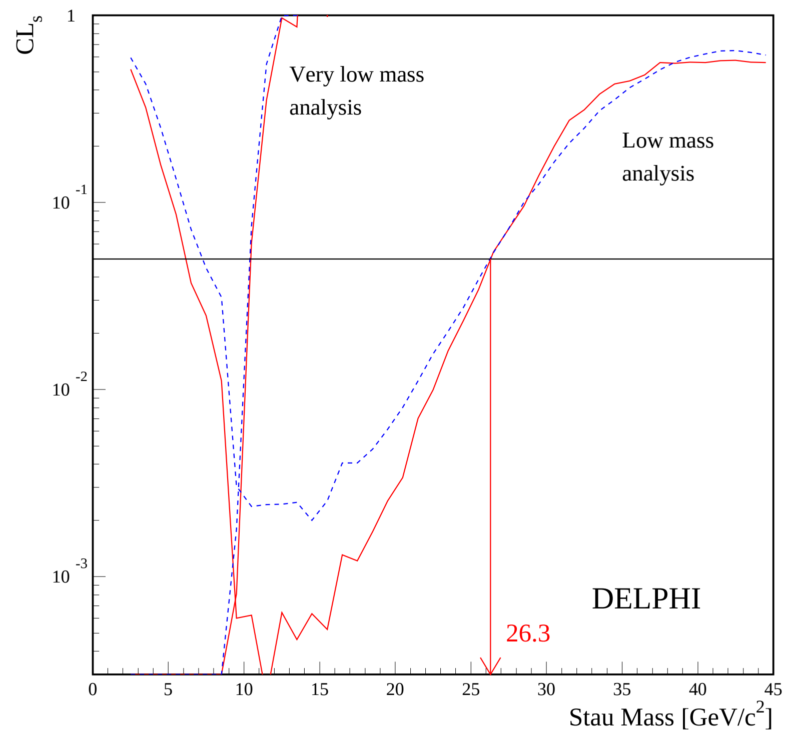
- different models can predict different final states:
  - MSSM with gravity mediated SUSY breaking: $\tilde{f} \rightarrow f\tilde{\chi}_1^0$: fermions and missing energy
  - GMSB: $\tilde{f} \rightarrow f'\mathrm{NLSP}(\tilde{\chi}_1^0, \tilde{\tau}, \tilde{\ell}, \ldots) \rightarrow f\tilde{G}\gamma, f\tilde{G}\tau, f\tilde{G}\ell, \ldots$
  - RPV: $\tilde{f} \rightarrow$ just about anything (maybe no E_{miss}, *many* fermions in final state
- Lifetime: *eg.* GMSB – final state depends on NLSP identity and lifetime, generally extra photons or leptons (see GMSB talk)
- Unexpected decays: *eg.* RPV (see RPV talk)
- Masses nearly degenerate with LSP: $\tilde{\mathrm{e}}_R\tilde{\mathrm{e}}_L$ single electron / unequal mass searches
- $\tilde{\tau}$ mixing $\rightarrow$ decoupling from Z^0, LEP 1 constraints do not apply: special light $\tilde{\tau}$ searches

Staus: Mixing, Decoupling

Search for low mass $\tilde{\tau}$ which decouples from Z^0: $M_{\tilde{\tau}} > 26.3$ GeV ($\Delta M > m_\tau$)





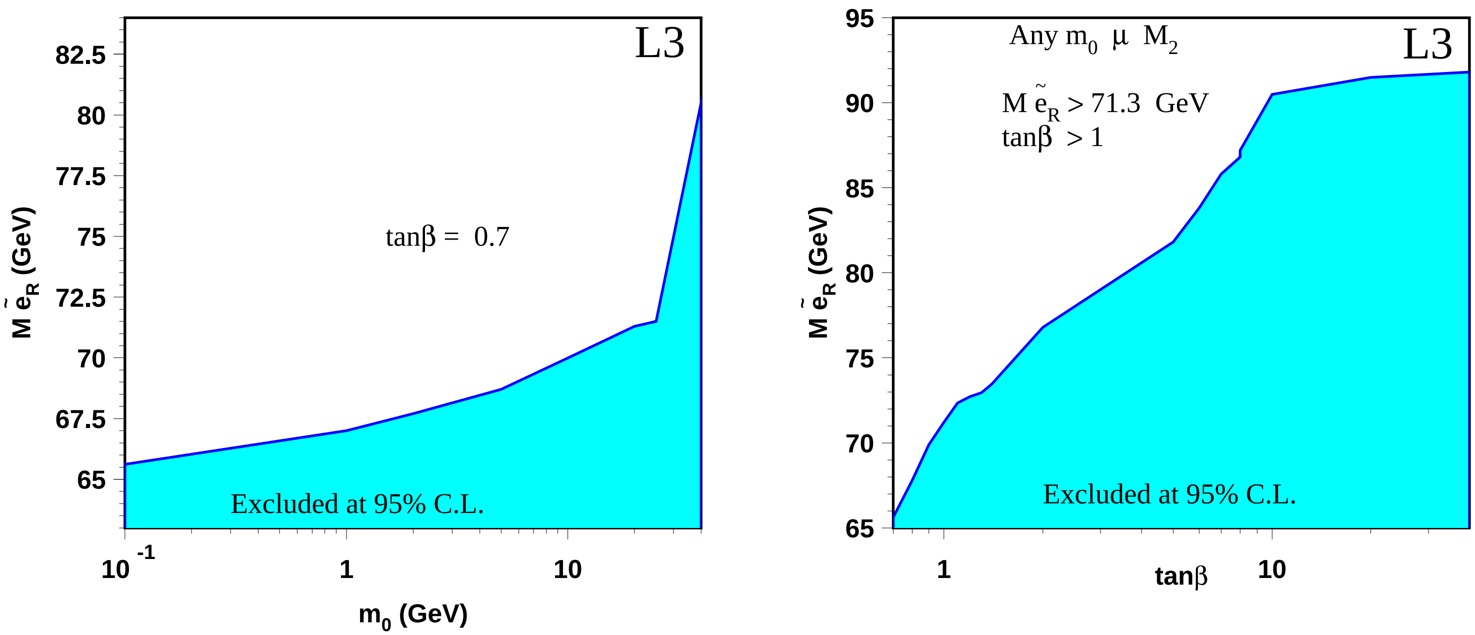


- "low mass": 10 GeV $< M_{\tilde{\tau}} < 45$ GeV and "very low mass":2 GeV $< M_{\tilde{\tau}} < 10$ GeV
- signature: 2 τ in the barrel, harder than 2-photon, softer than 2-fermion

Selectrons: $\tilde{e}^+_R \tilde{e}^-_L$

- Only s-channel for $\tilde{\mu}, \tilde{\tau} \longrightarrow$ can have only $\tilde{\mu}^+_L \tilde{\mu}^-_L$, $\tilde{\mu}^+_R \tilde{\mu}^-_R$, $\tilde{\tau}^+_L \tilde{\tau}^-_L$, $\tilde{\tau}^+_R \tilde{\tau}^-_R$
- $\tilde{e}$ can also be produced in t-channel $\longrightarrow$ can have $\tilde{e}^+_L \tilde{e}^-_L$, $\tilde{e}^+_R \tilde{e}^-_R$ AND $\tilde{e}^+_R \tilde{e}^-_L$, $\tilde{e}^+_L \tilde{e}^-_R$

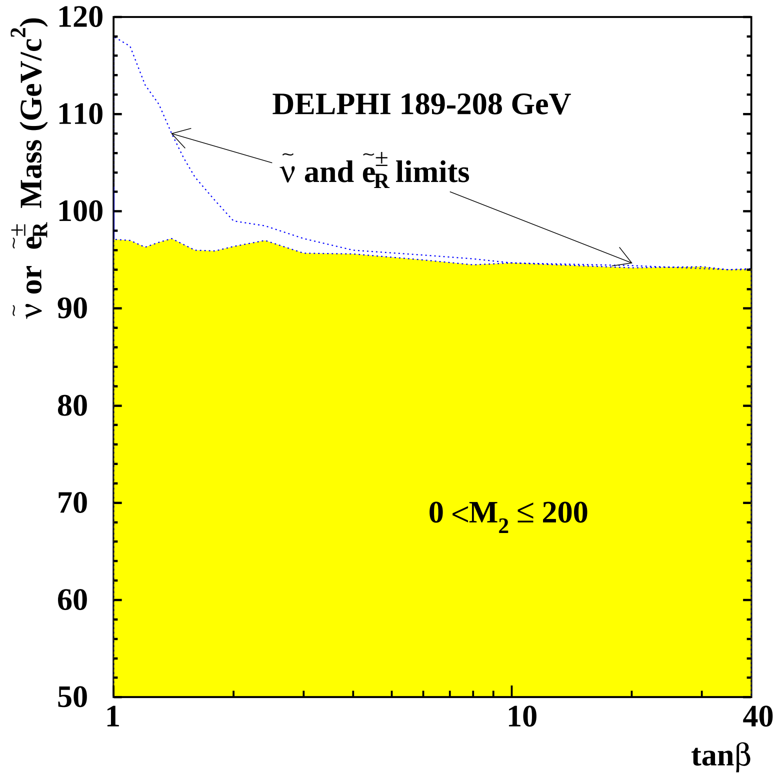
$M_{\tilde{e}_L} \neq M_{\tilde{e}_R}$, so do Unequal Mass Search (OPAL) or, if decay products of $\tilde{e}_R$ very soft, dedicated Single Electron Search (L3, Aleph) to plug hole at small $M_{\tilde{e}_R} - M_{\tilde{\chi}^0_1}$

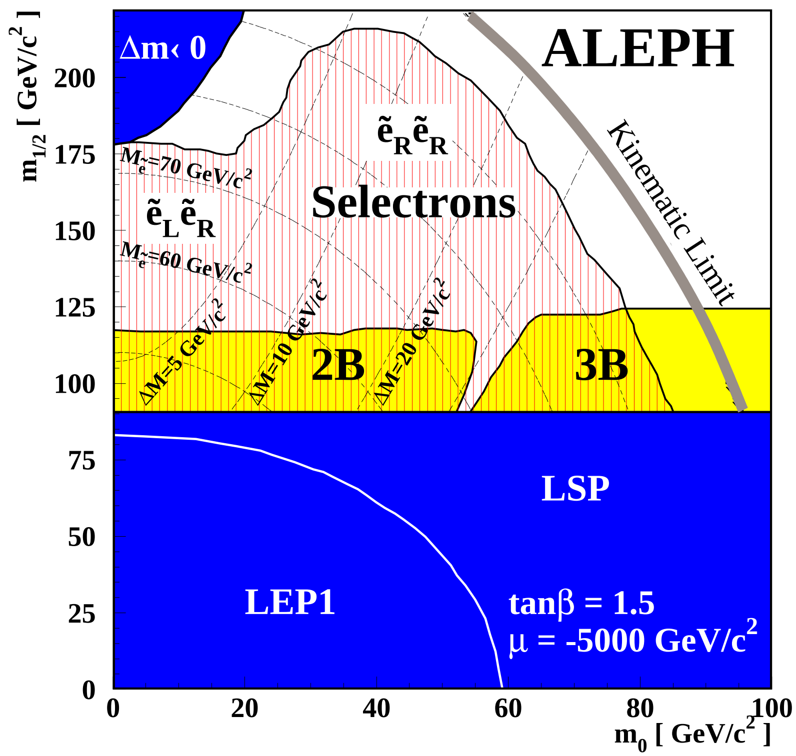


Limits based only on $\tilde{e}^+\tilde{e}^-$ searches.

Constrained MSSM Results from Combining Searches

Combine $\tilde{\ell}$, $\tilde{\chi}^0$ searches (for $M_{\tilde{e}_R} - M_{\tilde{\chi}^0_1} >$ 10 GeV, $|\mu| < 1$ TeV, $1 \leq \tan\beta \leq 40$ & no mass splitting in $\tilde{\tau}/\tilde{t}$ family)





$\tilde{\chi}^+\tilde{\chi}^-, \tilde{e}^+\tilde{e}^-$ searches $\Rightarrow$ minimum $M_{\tilde{e}_R}$, independent of $M_{\tilde{e}_R} - M_{\tilde{\chi}^0_1}$

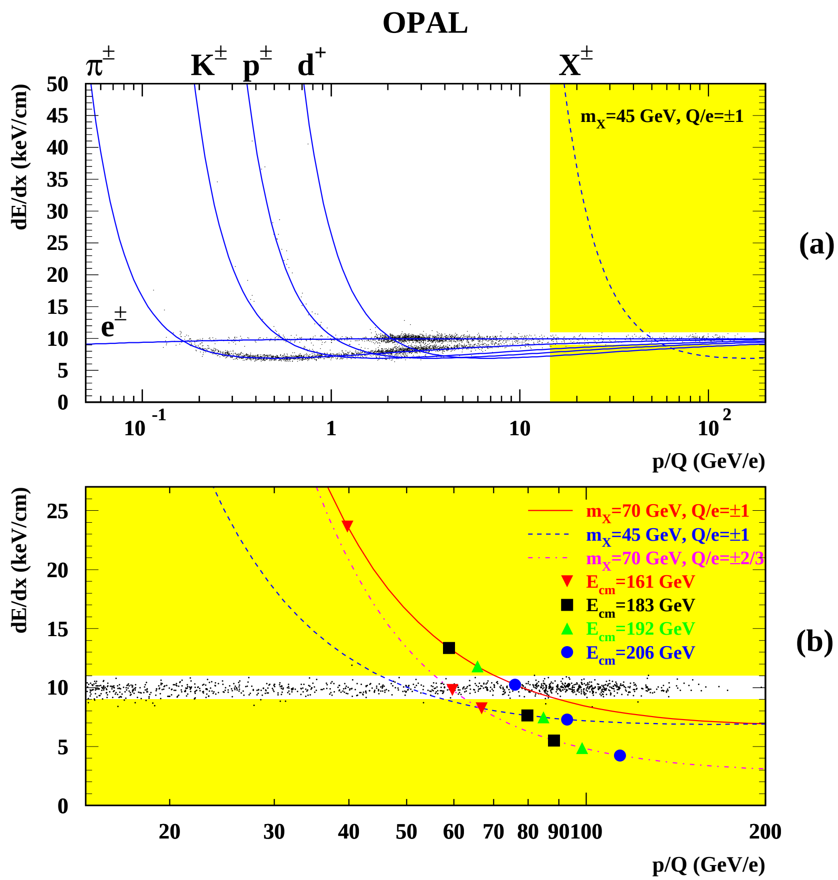
Lifetime

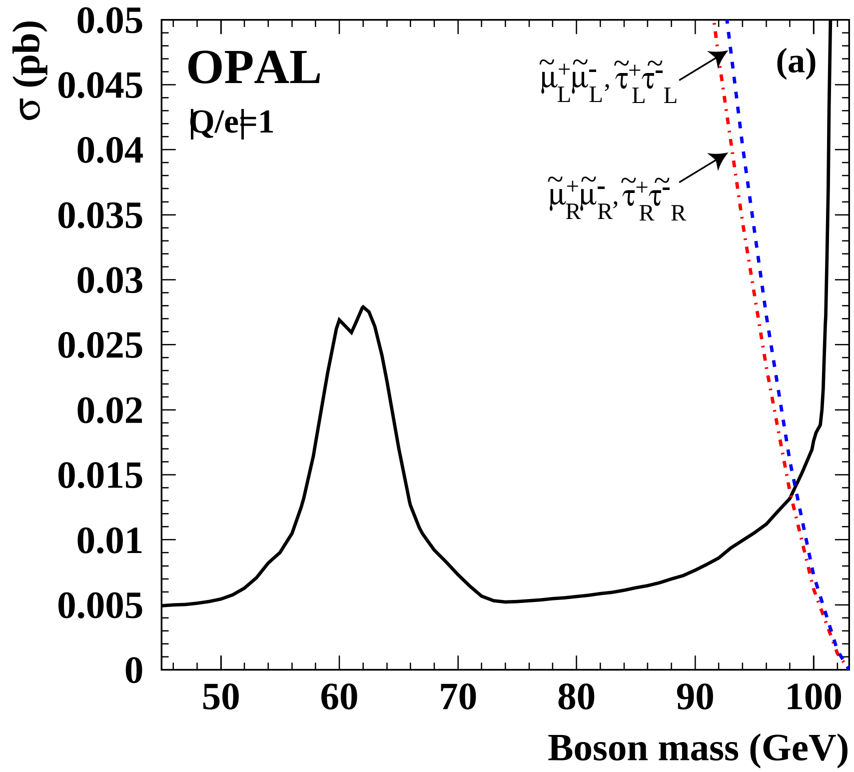
Dedicated searches for small mass differences between $\tilde{f}$ and $\tilde{\chi}^0_1$ (or GMSB scenarios with stable or quasi-stable NLSP) with $\tilde{f}$ decaying in detector volume or outside it:

- Standard acoplanar lepton pair searches (covered above)
- small ΔM searches (partly covered above – single $\mathrm{e}^{\pm}$ analysis, low mass $\tilde{\tau}$,...)
- displaced vertices (see GMSB talk)
- kinked tracks (see GMSB talk)
- heavy stable charged particles (next slide)

Searches for Heavy Stable Charged Particles

Look for anomalous dE/dx.





Combine many $\sqrt{s}$ to dilute efficiency hole. 95% CL limit for $\tilde{\mu}_R, \tilde{\tau}_R$: 98.0 GeV

Conclusions

$\tilde{\mathrm{e}}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{\mathrm{q}}$

- data are consistent with Standard Model
- no evidence for $\tilde{\ell}, \tilde{\mathrm{q}}$ seen at LEP
- absolute limits in Constrained MSSM:

  eg. $M_{\tilde{\mathrm{e}}_R} > 73$ GeV (Aleph)
- absolute limits on slepton masses in more general MSSM:

  eg. $M_{\tilde{\tau}_R} > 26$ GeV if $M_{\tilde{\tau}_R} > M_\tau$ (Delphi)
- constraints on m_0, $m_{1/2}$ contribute to LSP limits
- not easy to look for $\tilde{\ell}$ at other existing colliders

  (but nice $\tilde{\mathrm{q}}$ searches at TeVatron)
- pretty good prospects from the LHC?

$\tilde{\mathrm{e}}$ $\tilde{\mu}$ $\tilde{\tau}$ $\tilde{\mathrm{q}}$