

Search for long-lived particles at LEP

Marcello Fanti

University of Milano and INFN

References

The combined Aleph \oplus Delphi \oplus Opal \oplus L3 (aka ADLO) results are taken from :

http://lepsusy.web.cern.ch/lepsusy/www/stable_summer02/stable_208.html (stable particles, ADLO)

http://lepsusy.web.cern.ch/lepsusy/www/gmsb_summer02/lep.gmsb.html (gauge-mediated SUSY, ADLO)

... and references therein

More references:

ALEPH "Search for pair-production of long-lived heavy charged particles in e+e annihilation" arXiv:hep-ex/9706013v1

ALEPH "Search for gauge mediated SUSY breaking topologies in e+e collisions at centreofmass energies up to 209 GeV"
arXiv:hep-ex/0203024v2

DELPHI "Search for Heavy Stable and Long-Lived Particles in e+e Collisions at $\sqrt{s}=189$ GeV" arXiv:hep-ex/0103038v1

DELPHI "Search for supersymmetric particles in scenarios with a gravitino LSP and stau NLSP" arXiv:hep-ex/0103026v1

DELPHI "Search for an LSP gluino at LEP with the DELPHI detector" arXiv:hep-ex/0303024v1

OPAL "Search for Stable and Long-Lived Massive Charged Particles in e+e Collisions at $\sqrt{s} = 130 - 209$ GeV" arXiv:hep-ex/0305031v1

OPAL "Searches for Gauge-Mediated Supersymmetry Breaking Topologies in e+e Collisions at LEP2" arXiv:hep-ex/0507048v1

Introduction

Searches for heavy long-lived particles at LEP

LEP-1 phase at center-of-mass energy $\sqrt{s} = 91$ GeV
 LEP-1.5 ran at center-of-mass energies $\sqrt{s} = 130, 136$ GeV
 LEP-2 ran at center-of-mass energies $\sqrt{s} = 161 - 209$ GeV

Nominal $\sqrt{s}(GeV)$ bins	\mathcal{L} (pb^{-1})
133	10.7
161	10.0
172	10.4
183	56.3
189	172.3
192	29.0
196	72.5
200	74.0
202	37.0
205	87.4
207	133.5
Total	693.1

Several searches of pair-produced exotic particles were performed :

- charged or neutral
- over a wide lifetime range
- under quite general assumptions

Needless to say, **all searches gave negative results**

Results obtained at all \sqrt{s} were combined, assuming pair-production and cross-section evolution with \sqrt{s} as:

$$\sigma_{ee \rightarrow \tilde{l}\tilde{l}} \propto \frac{\beta^3}{s} \text{ for spin-0 particles} \quad \text{and} \quad \sigma_{ee \rightarrow \tilde{\chi}\tilde{\chi}} \propto \frac{\beta}{s} \left(1 - \frac{\beta^2}{3}\right) \text{ for spin-1/2 particles}$$

where $\beta = \sqrt{1 - \frac{4m_X^2}{s}}$ is the speed of pair-produced particles with mass m_X

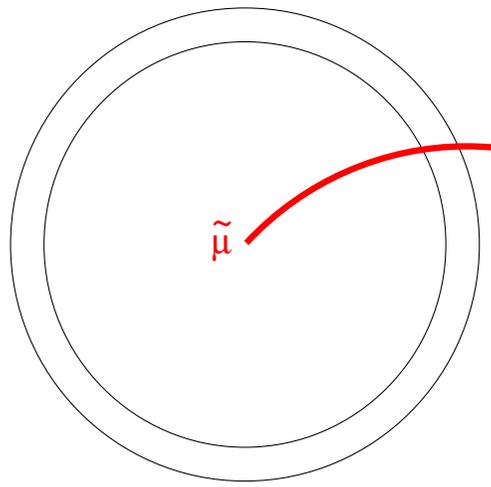
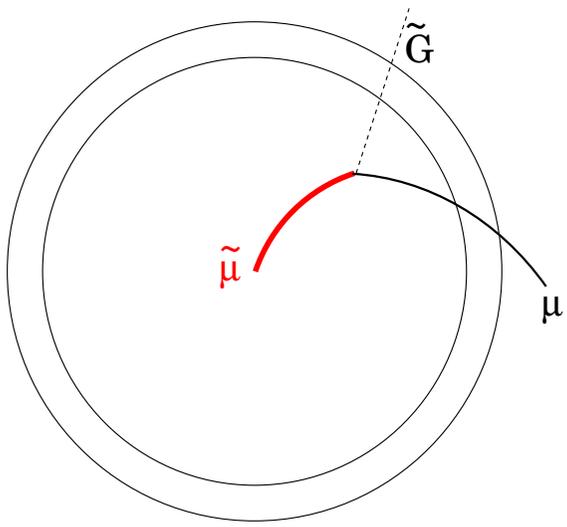
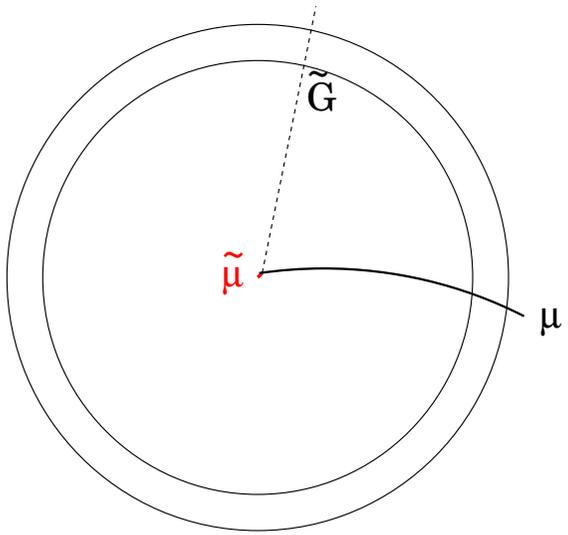
Charged heavy particles : signatures

decay mode: $\tilde{l} \rightarrow \tilde{G}l$ — lifetime τ_l is a free parameter

$\tau_l \lesssim 10^{-11} \text{ s}$

$10^{-11} \text{ s} \lesssim \tau_l \lesssim 10^{-7} \text{ s}$

$\tau_l \gtrsim 10^{-7} \text{ s}$



track + \vec{P}, \cancel{E}

track with large impact parameter
or track with a kink
+ \vec{P}, \cancel{E}

track with large ionization $\frac{dE}{dx}$

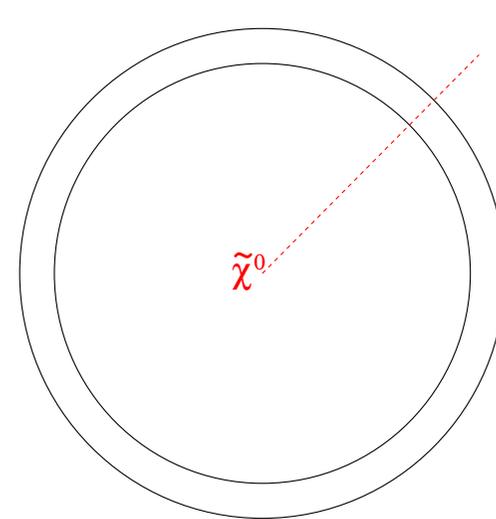
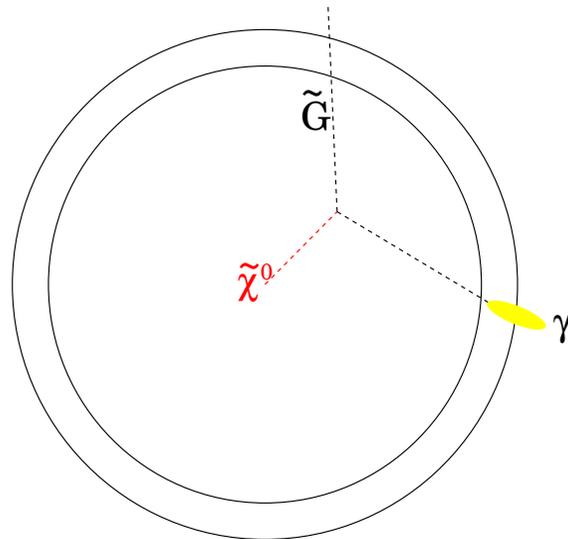
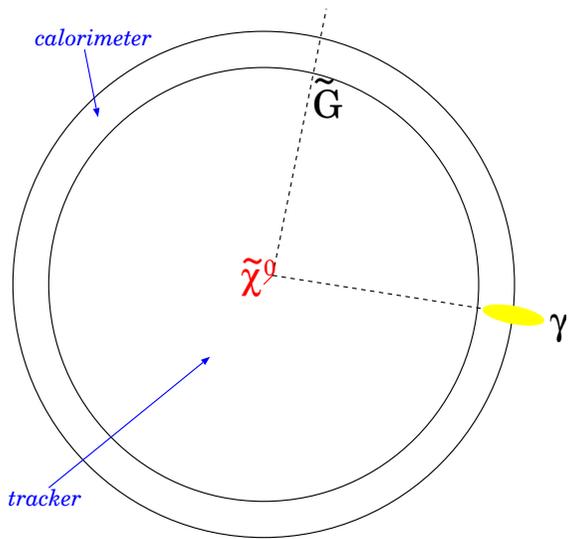
Neutral heavy particles : signatures

decay mode: $\tilde{\chi}^0 \rightarrow \tilde{G}\gamma$ — lifetime $\tau_{\tilde{\chi}}$ is a free parameter

$\tau_{\tilde{\chi}} \lesssim \dots$

$\dots \lesssim \tau_{\tilde{\chi}} \lesssim 10^{-8} \text{ s}$

$\tau_{\tilde{\chi}} \gtrsim 10^{-7} \text{ s}$



$\gamma + \vec{P}, \cancel{E}$

displaced $\gamma + \vec{P}, \cancel{E}$

\vec{P}, \cancel{E} (like SUGRA searches)

Interpretations

In all cases, signatures are striking

⇒ worth to pursue such searches even without a specific BSM physics theory in mind

Nonetheless, results could be interpreted in SUSY contexts

Gauge-mediated SUSY breaking (GMSB)

LSP is the **gravitino**, \tilde{G} — very light, spin-3/2 super-partner of the graviton

NLSP could be either **lightest neutralino**, $\tilde{\chi}^0$, or a **charged slepton**, $\tilde{\ell}$

Decay modes (respectively) : $\tilde{\chi}^0 \rightarrow \tilde{G}\gamma$ and $\tilde{\ell} \rightarrow \tilde{G}\ell$ with **unknown lifetime** τ_{NLSP}

Stable gluino

If \tilde{g} is the LSP, it is stable and hadronize ⇒ **R-hadrons** (neutral or charged)

SUSY with broken R-parity (RPV)

LSP is not stable anymore, could decay via RPV couplings ⇒ not necessarily neutral

again **lifetime** τ_{LSP} **is unknown** — depends on the strength of the RPV coupling, typically small (not covered here)

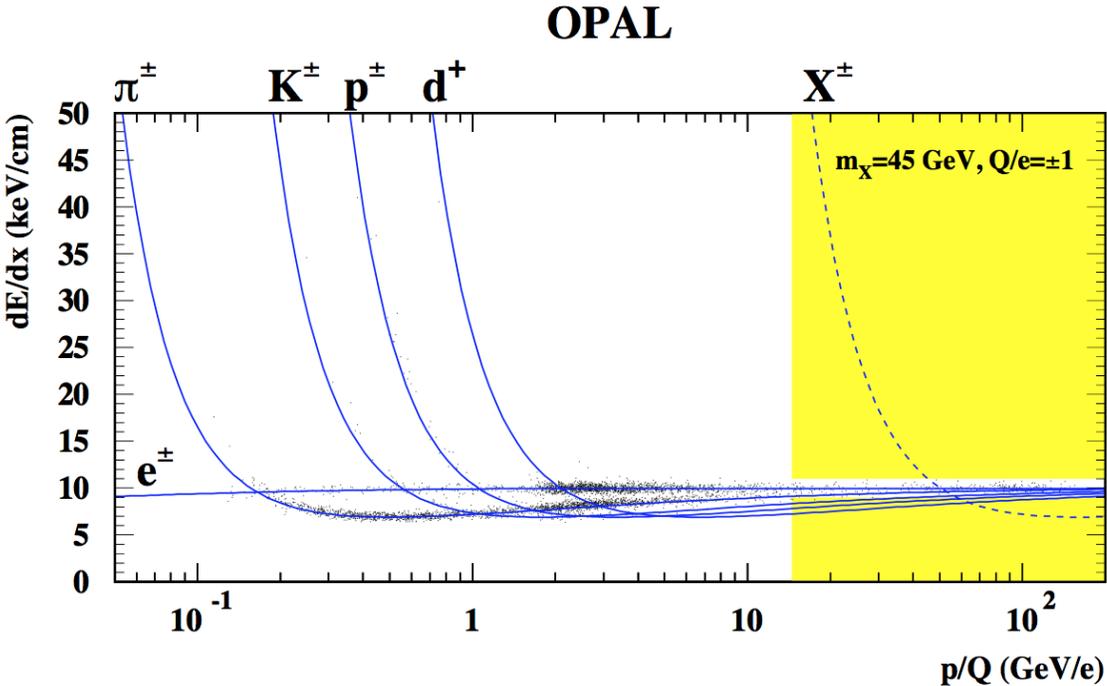
In the following:

⇒ give model-independent exclusions

⇒ provide interpretation in GMSB and stable gluino contexts

Heavy stable charged particles

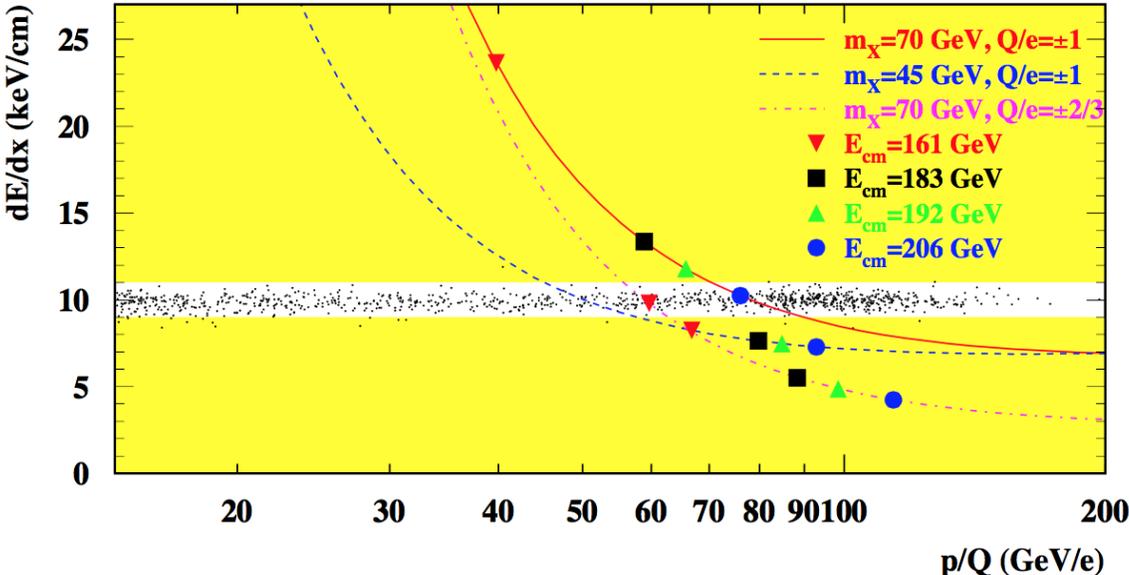
Ionization energy loss for stable charged particles



(a)

Combined measurement of $\frac{p}{Q}$ and $\frac{dE}{dx}$ allows discrimination of particles' masses

Exclude intermediate $\frac{dE}{dx}$ region, populated by high- p ordinary charged particles

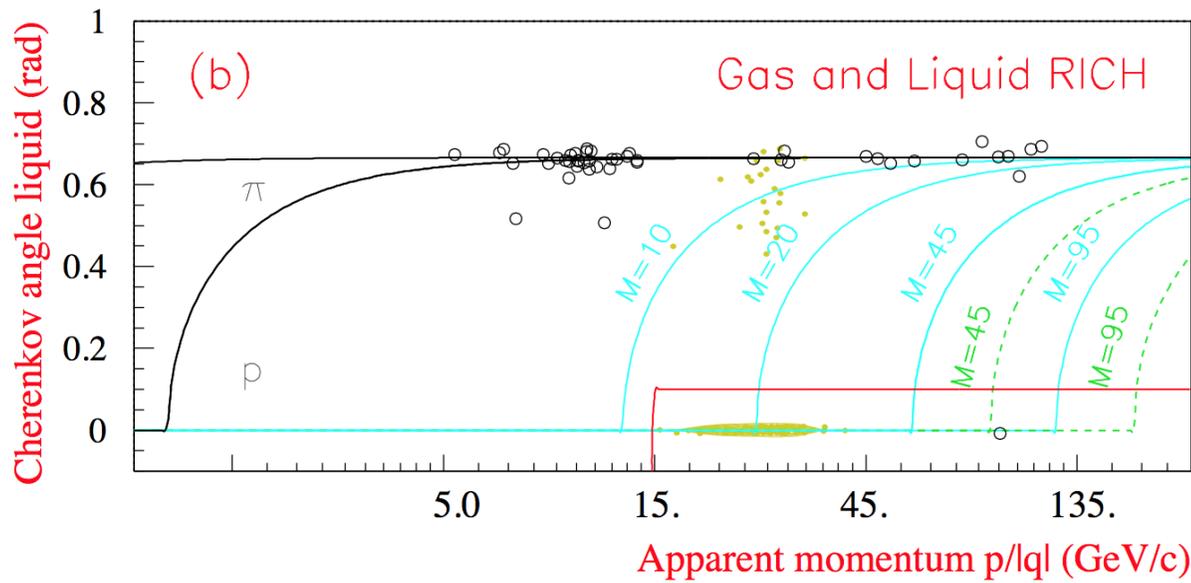
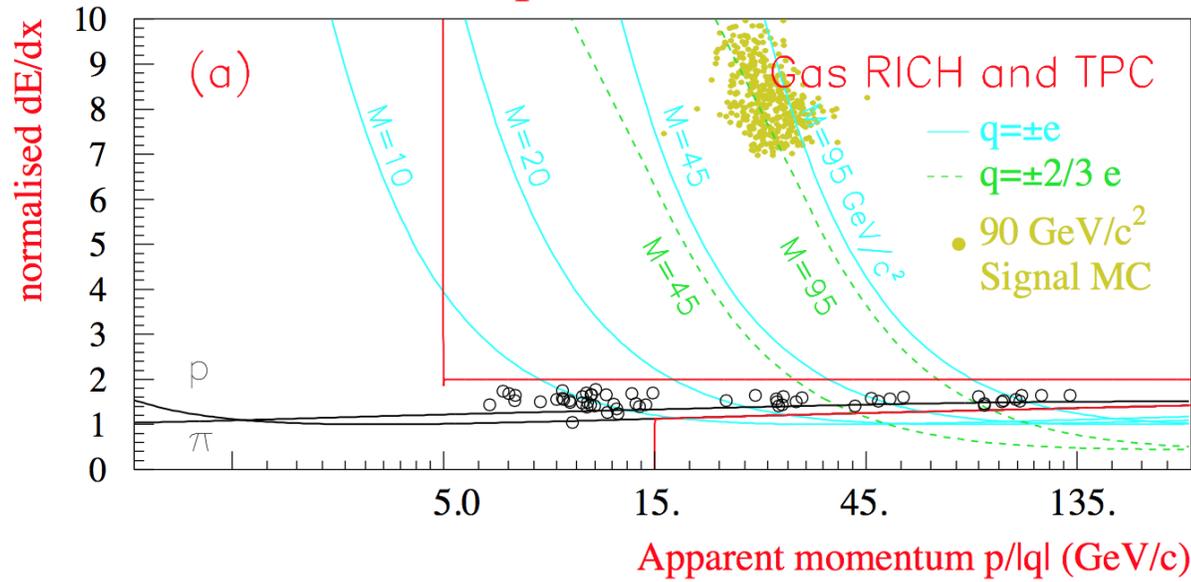


(b)

Pair-produced particles have fixed momentum $p_X = \sqrt{\frac{s}{4} - m_X^2}$
 \Rightarrow for given \sqrt{s} may fall in the intermediate $\frac{dE}{dx}$ region
 (see e.g. case $\sqrt{s} = 206$ GeV and $m_X = 70$ GeV)

Ionization energy loss and Cherenkov rings

DELPHI slepton searches at 189 GeV



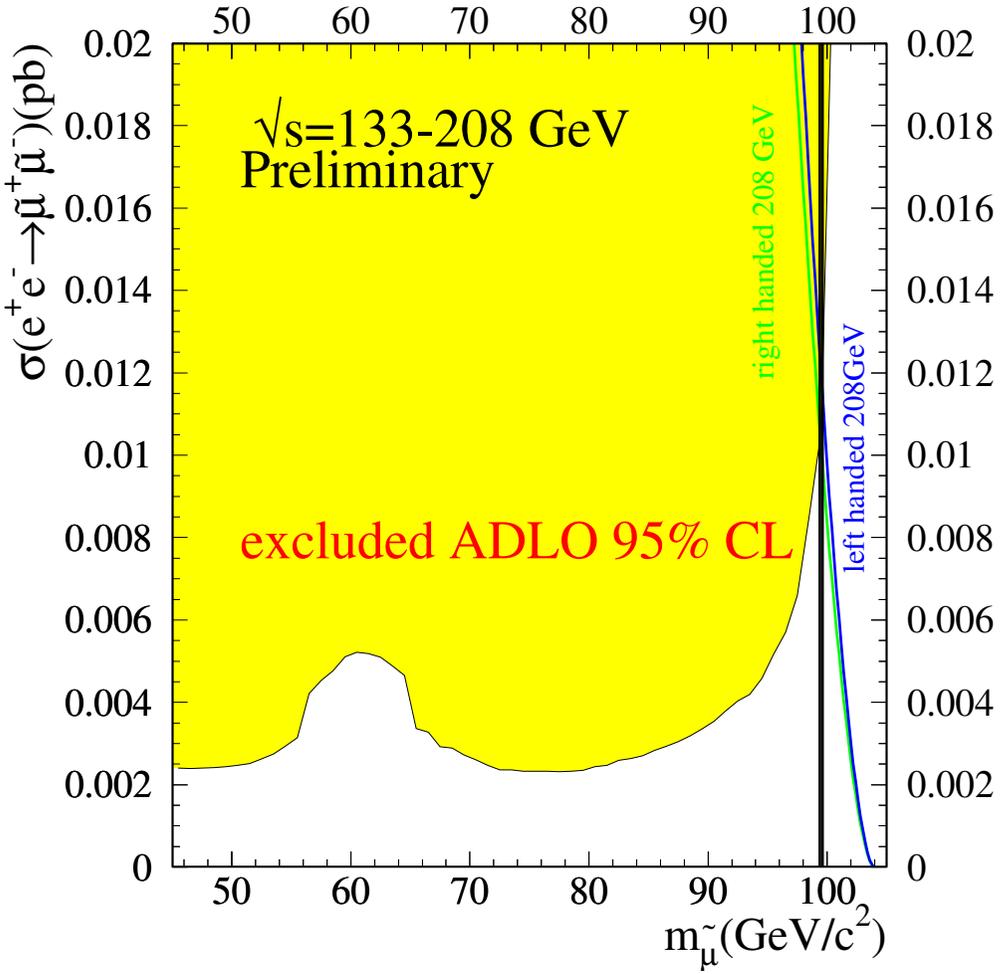
Anomalous $\frac{dE}{dx}$ and

~ no Cherenkov rings

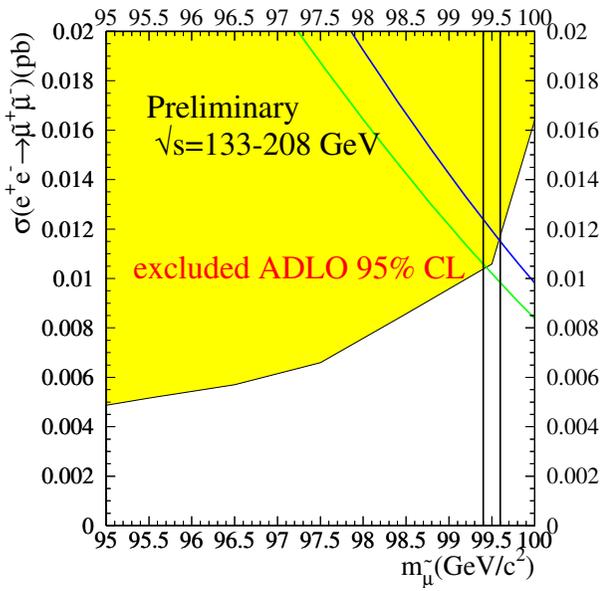
expected for heavy stable charged particles

ADLO combination for stable scalar particles

model-independent combined cross-section limit
 @ $\sqrt{s} = 208$ GeV



Comparing cross-section limits
 with predicted $\sigma_{\tilde{\mu}\tilde{\mu}}$ @ $\sqrt{s} = 208$ GeV [SUSYGEN]
 allows to put limits on stable $\tilde{\mu}$ mass



If stable $\tilde{\mu}$ exist, they must have mass:

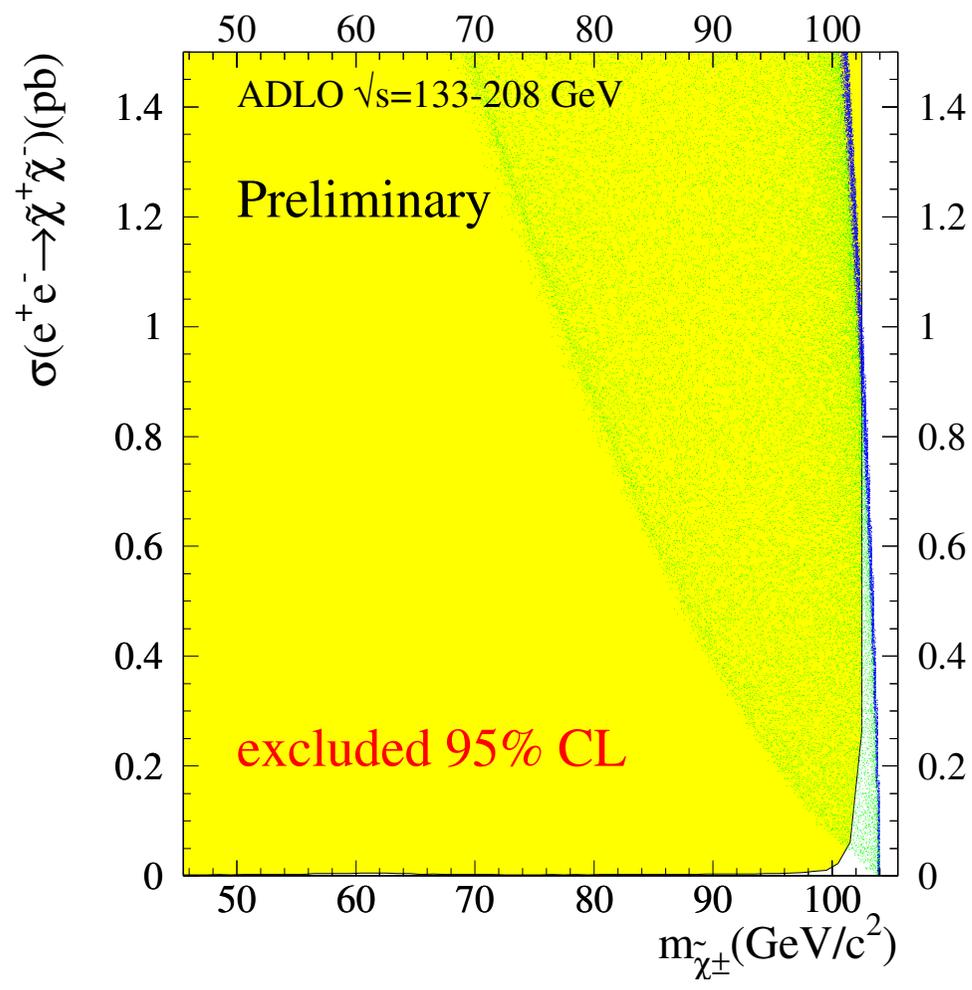
$$\tilde{\mu}_R > 99.4 \text{ GeV}$$

$$\tilde{\mu}_L > 99.6 \text{ GeV}$$

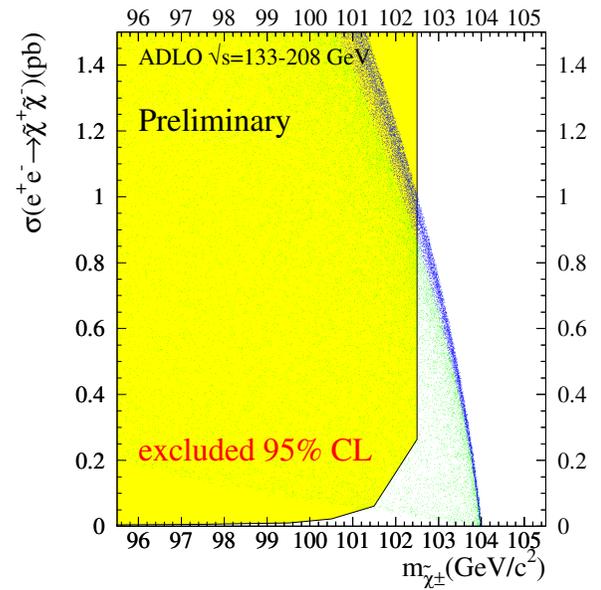
[The “bump” at $m_\chi \approx 60$ GeV due to dE/dx curve crossing the intermediate region]

ADLO combination for stable spin-1/2 particles

model-independent combined cross-section limit
 @ $\sqrt{s} = 208$ GeV



Scattered points (blue/green) represent a scan over the MSSM parameters space [SUSYGEN]
 (blue: $m_{\tilde{\nu}} > 500$ GeV ; green: $m_{\tilde{\nu}} < 500$ GeV)
 Points falling in the yellow region are experimentally excluded.



This translates into mass limits for stable $\tilde{\chi}^{\pm}$:

$$\begin{aligned} \tilde{\chi}^{\pm} &> 102.5 \text{ GeV} && \text{for } m_{\tilde{\nu}} > 500 \text{ GeV} \\ \tilde{\chi}^{\pm} &> 101.2 \text{ GeV} && \text{for } m_{\tilde{\nu}} < 500 \text{ GeV} \end{aligned}$$

Gauge-mediated SUSY breaking

Few basics of GMSB

Parameters

	description	scanned interval
\sqrt{F}	VEV of scalar messenger	—
Λ	scale of SUSY masses	[5;150] TeV (in steps of 1 TeV)
N	number of messengers' families	{1, 2, 3, 4, 5}
M	messengers' mass	{ $1.01 \cdot \Lambda$, 250 TeV, 10^6 TeV }
$\tan \beta$	ratio of VEVs of two Higgs doublets	[1;50] (in steps of 0.2)
$\text{sign}(\mu)$	sign of Higgs sector mixing	{-1; +1}

Gravitino mass: $m_{\tilde{g}} = \frac{F}{\sqrt{3} M_{\text{Pl}}} = 2.4 \left(\frac{\sqrt{F}}{100 \text{ TeV}} \right)^2 \text{ eV}$ — $M_{\text{Pl}} = 2.4 \cdot 10^{18} \text{ GeV}$ being the reduced Planck mass

from cosmological constraints: $m_{\tilde{g}} \lesssim 1 \text{ keV}$ — i.e. $100 \text{ TeV} \lesssim \sqrt{F} \lesssim 2000 \text{ TeV}$

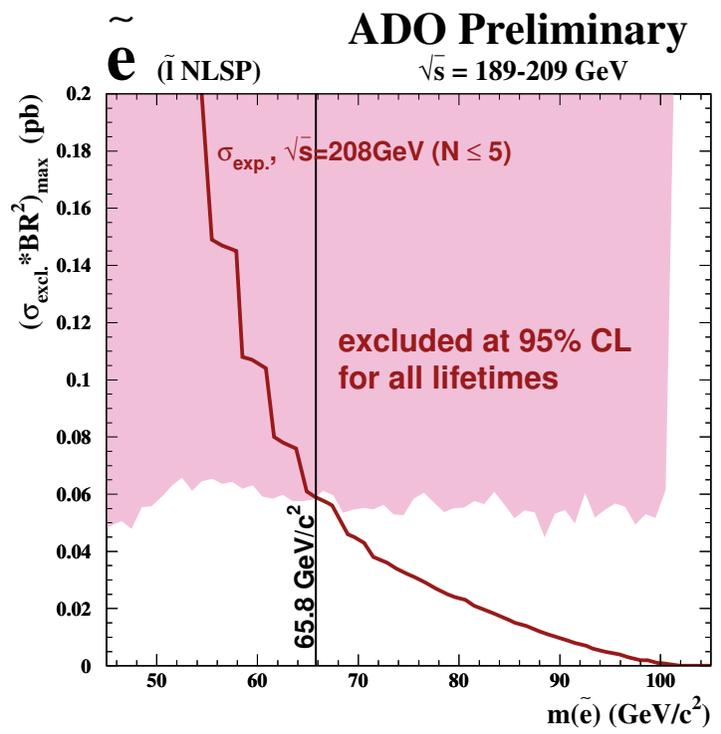
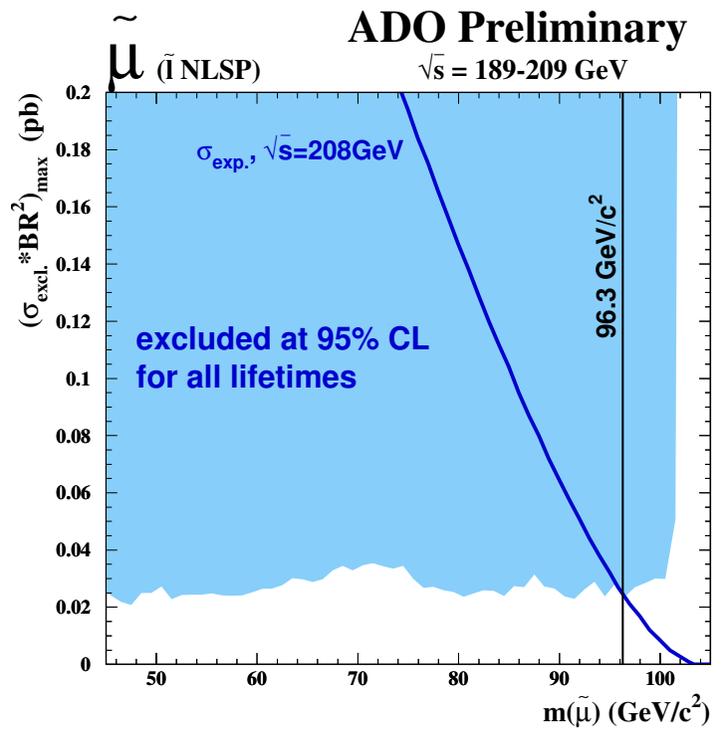
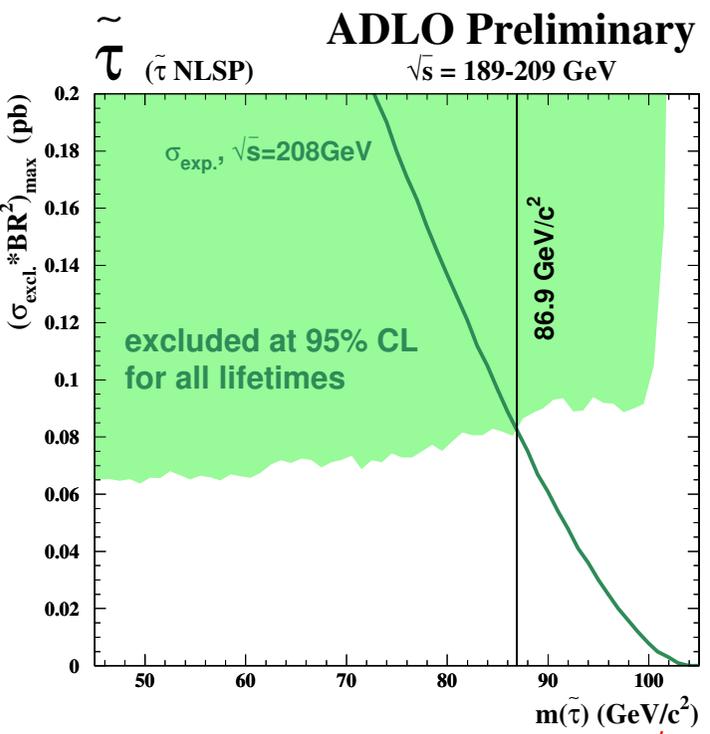
NLSP lifetime: $c\tau_{\text{NLSP}} = \left(\frac{100 \text{ GeV}}{m_{\text{NLSP}}} \right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \text{ cm}$

NLSP nature:

$\tilde{\tau}_1$ or $\tilde{\mu}, \tilde{e}$ ("co-NLSP")	acoplanar $ll + \vec{\cancel{P}}_T \oplus$ tracks with large impact parameter \oplus tracks with kinks \oplus highly ionizing tracks
$\tilde{\chi}^0$	acoplanar $\gamma\gamma + \vec{\cancel{P}}_T \oplus$ non-pointing $\gamma(s) \oplus (\tilde{\chi}^\pm, \tilde{\ell}$ searches with $\tilde{\chi}^0$ in decay chain)

ADLO: lifetime-independent limits on sleptons

Compute from data upper limit $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]^{excl} (m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$ for each $m_{\tilde{\ell}}, \tau_{\tilde{\ell}}$
 Get maximum upper limit $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]_{max}^{excl} (m_{\tilde{\ell}}) \equiv \text{MAX} \{ [\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]^{excl} (m_{\tilde{\ell}}, \tau_{\tilde{\ell}}) \}$



Compute from theory $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]^{th} (m_{\tilde{\ell}})$ for each $m_{\tilde{\ell}}$.
 Exclude mass value $m_{\tilde{\ell}}$ if $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]^{th} (m_{\tilde{\ell}}) > [\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]_{max}^{excl} (m_{\tilde{\ell}})$

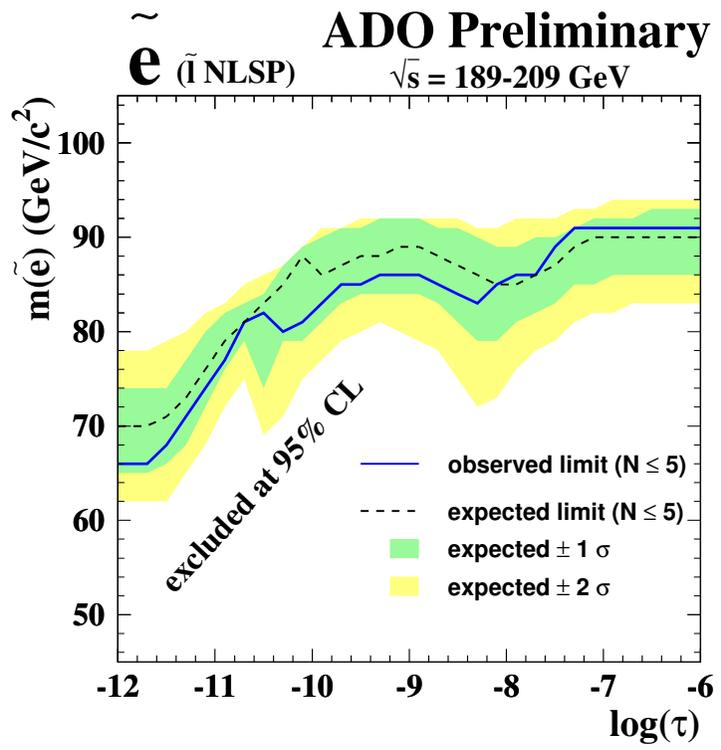
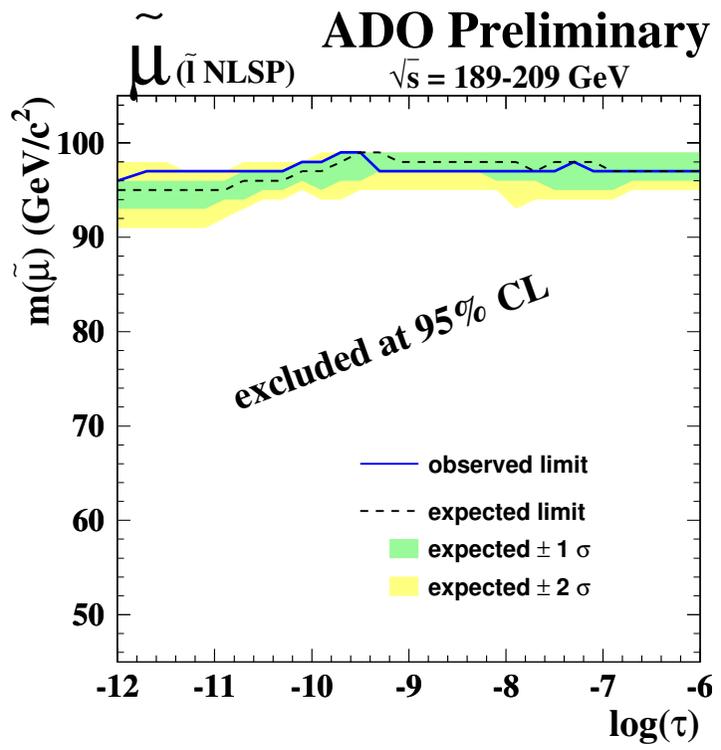
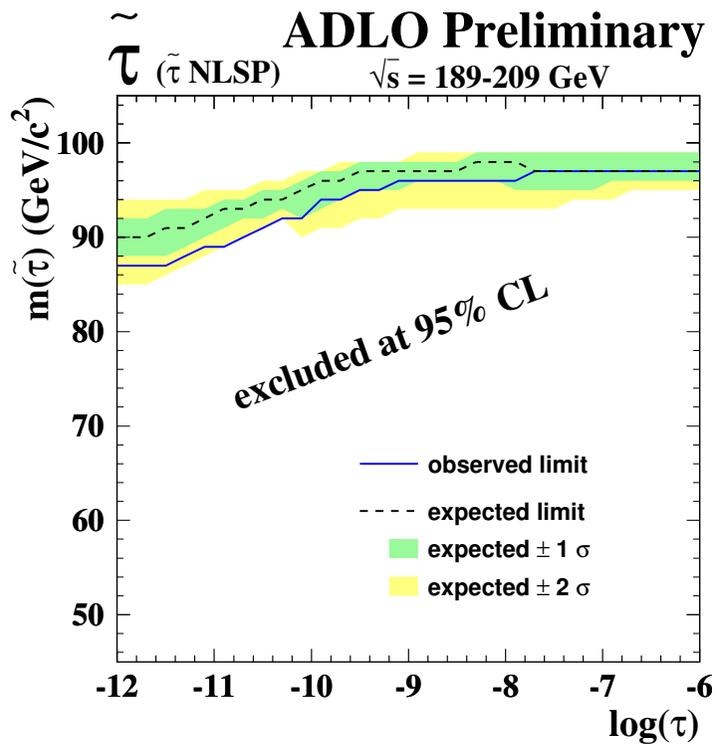
ADLO: lifetime vs mass limits on sleptons

Compute from data upper limit $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]^{excl} (m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$ for each $(m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$ point.

Compute from theory the minimal $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]_{min}^{th} (m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$ for each $(m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$ point.

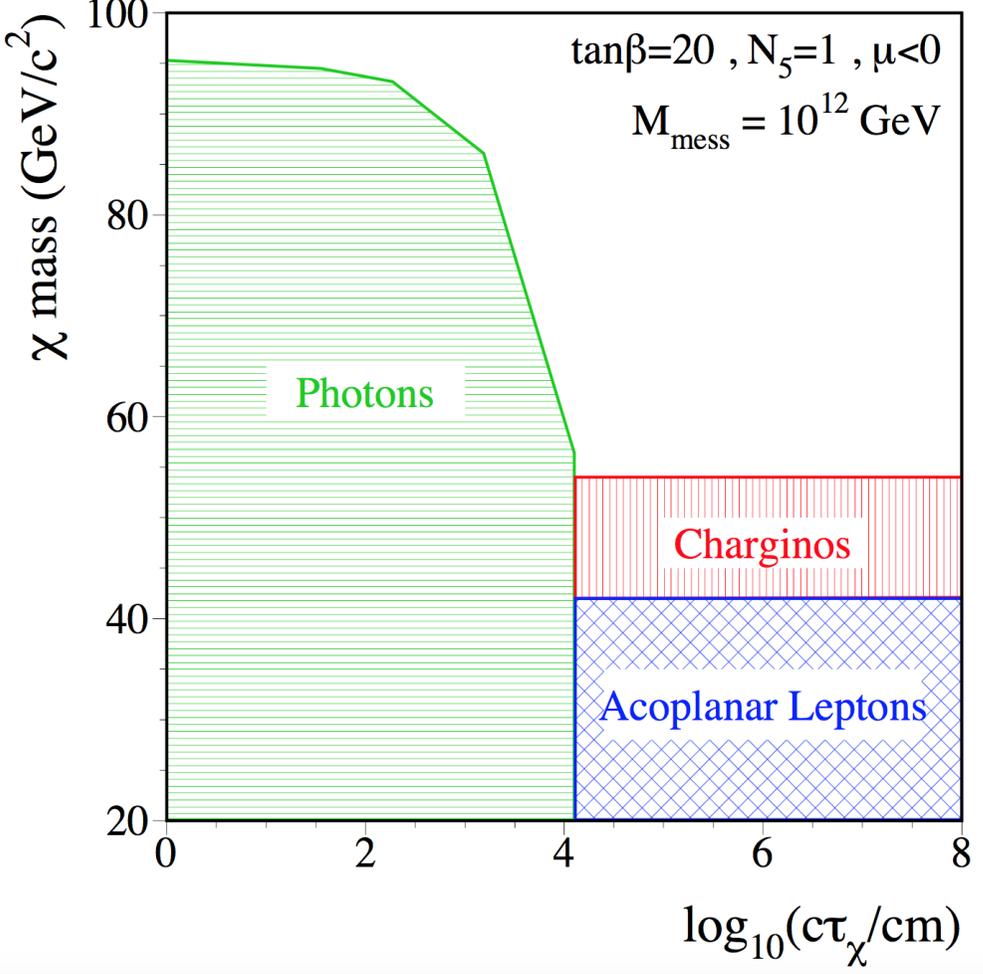
[the minimization is taken scanning the parameters space for the point providing smallest $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]$

Exclude $(m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$ point if $[\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]_{min}^{th} (m_{\tilde{\ell}}, \tau_{\tilde{\ell}}) > [\sigma_{\tilde{\ell}\tilde{\ell}} \cdot (BR)^2]^{excl} (m_{\tilde{\ell}}, \tau_{\tilde{\ell}})$

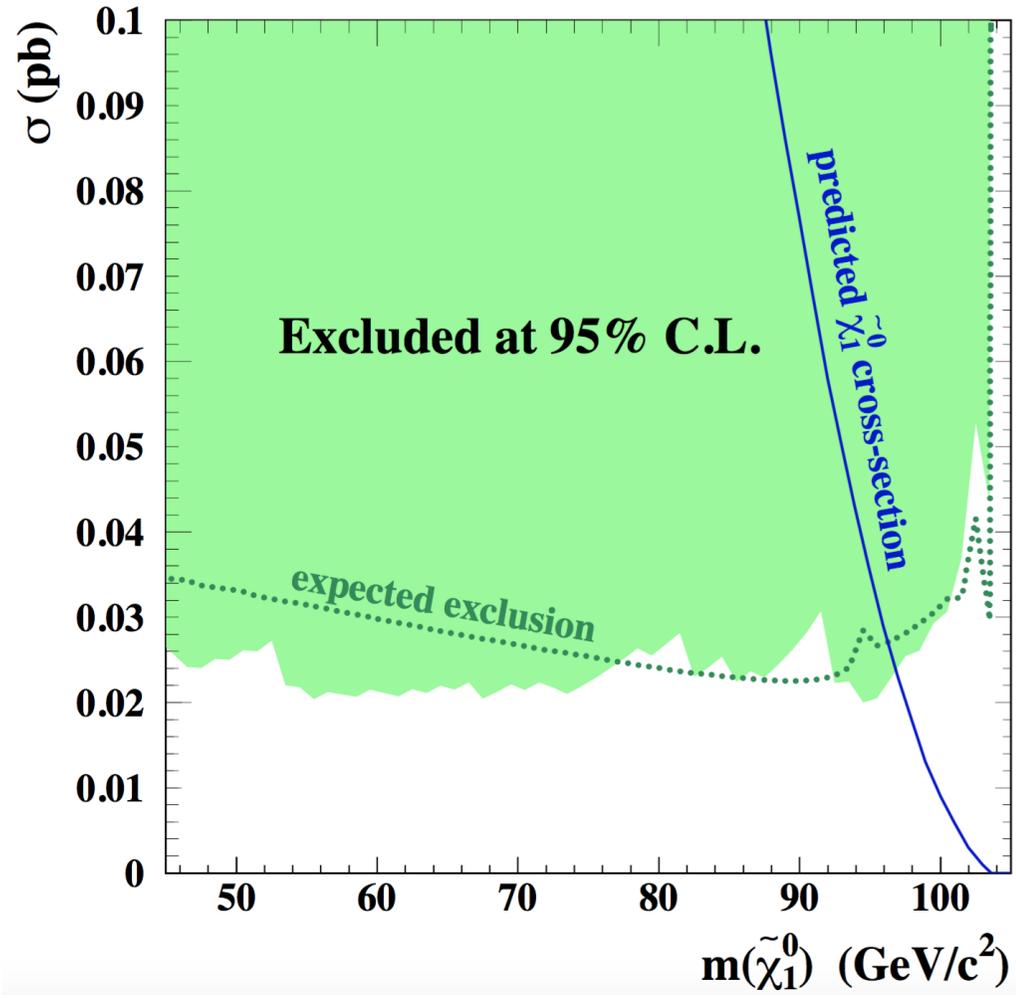


Neutralino searches

ALEPH



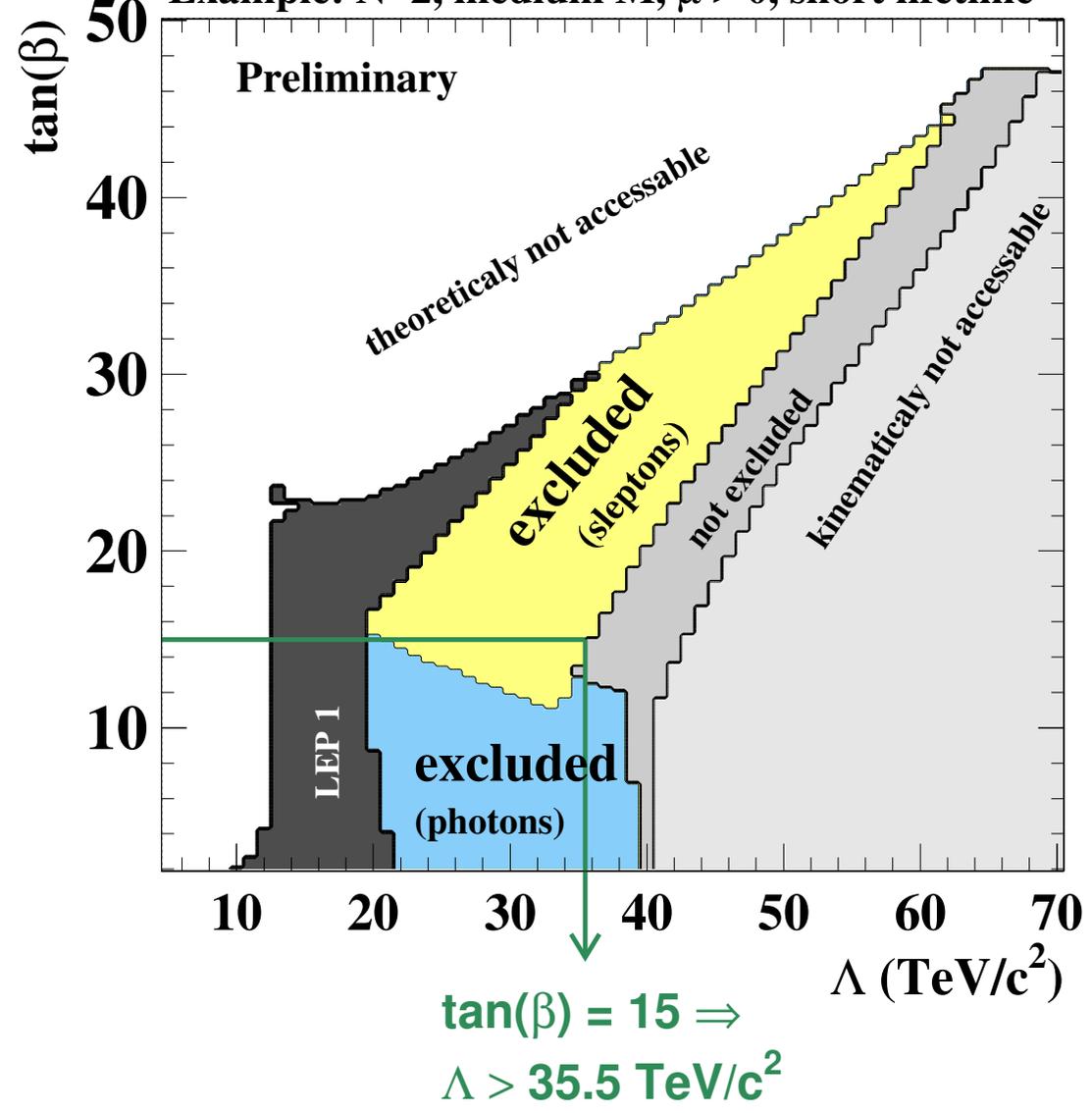
OPAL



Exclusions in GMSB parameters space

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

Example: $N=2$, medium M , $\mu > 0$, short lifetime



Gluino as LSP

Search for stable gluinos

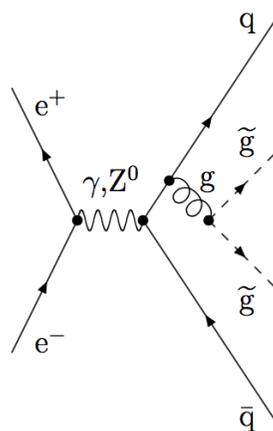
If gluino is the LSP it would be stable and hadronize, producing charged or neutral R-hadrons, R^\pm , R^0

@ LEP1: $e^+e^- \rightarrow Z \rightarrow q\bar{q}\tilde{g}\tilde{g}$

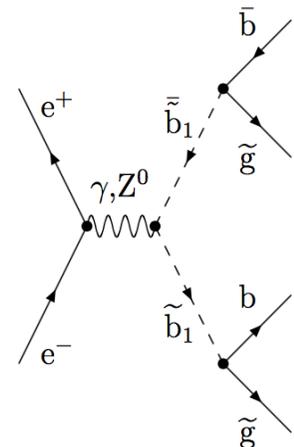
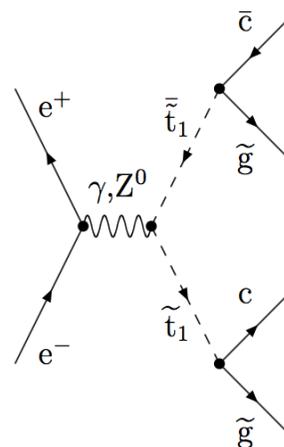
@ LEP2:
 $e^+e^- \rightarrow Z \rightarrow \tilde{t}\tilde{t} \rightarrow c\bar{c}\tilde{g}\tilde{g}$
 $e^+e^- \rightarrow Z \rightarrow \tilde{b}\tilde{b} \rightarrow b\bar{b}\tilde{g}\tilde{g}$

... and $\tilde{g} \rightarrow R^0$ or R^\pm
 $P \stackrel{\text{def}}{=} \text{Prob}(\tilde{g} \rightarrow R^\pm)$

@ LEP1



@ LEP2



Experimental signatures multihadronic events characterized by:

$\tilde{g}\tilde{g} \rightarrow R^\pm R^0$ or $R^\pm R^\pm$

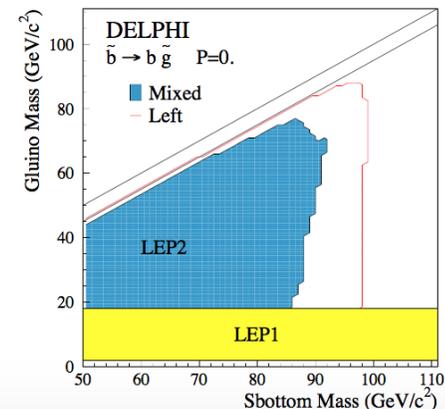
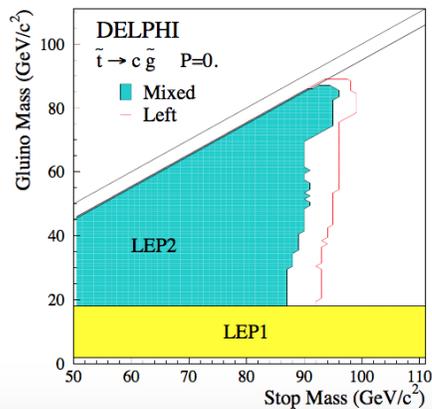
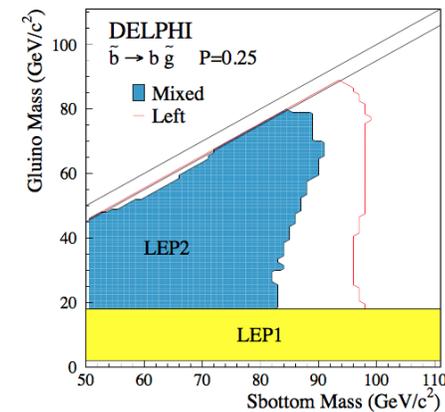
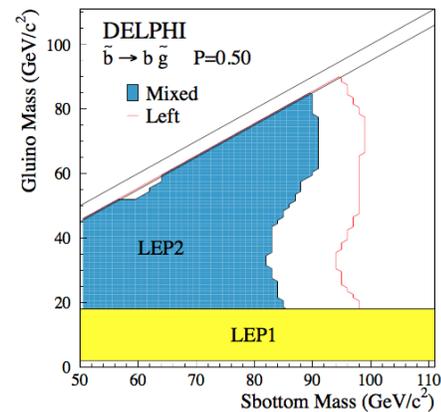
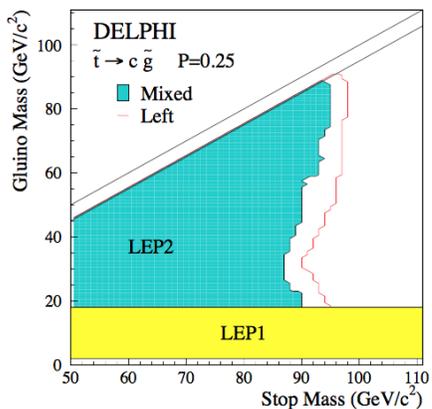
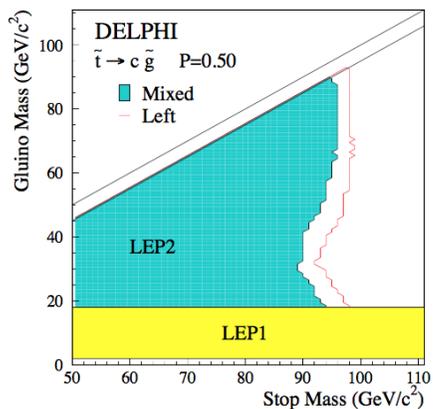
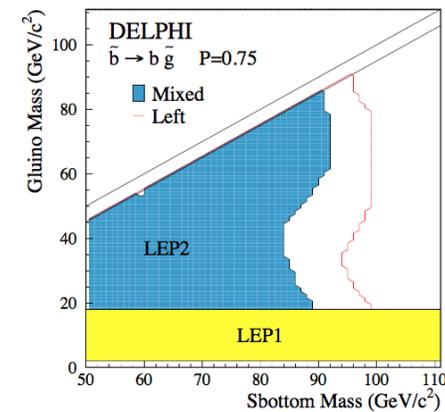
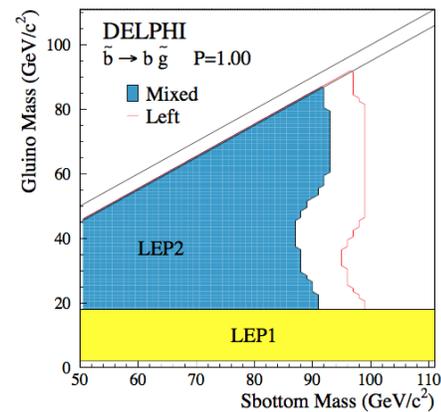
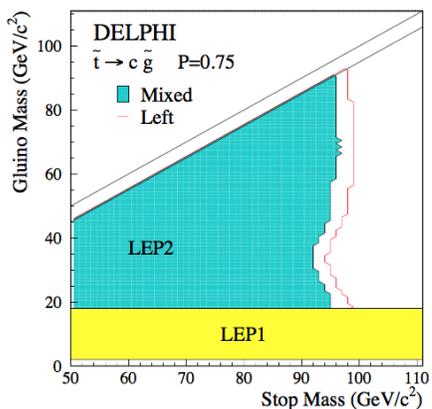
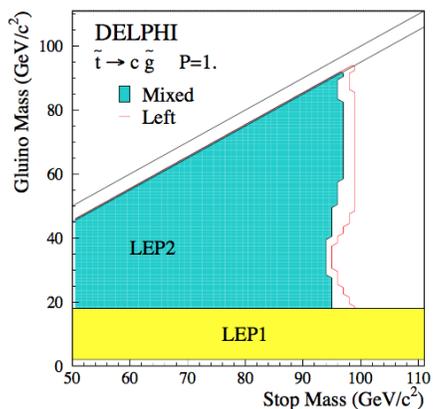
\Rightarrow track(s) with anomalous $\frac{dE}{dx}$

$\tilde{g}\tilde{g} \rightarrow R^0 R^0$

\Rightarrow 2 acollinear jets, sizable \cancel{E} , low visible mass

\Rightarrow @ LEP-2, also a neural net based on several event variables (kinematics, shape) and flavour tagging

Stable gluino exclusion from LEP1+LEP2



Conclusions ?

LEP didn't find new physics ...
... but LHC will keep hunting for years
so, no time for conclusions, yet

Thanks for your attention!

Additional Material

Cross-sections for pair-production

Assumptions on how cross-sections scale with \sqrt{s} and change with polar angle θ

spin-0

$$\frac{d\sigma^{(\text{spin-0})}}{d\Omega} \propto \frac{\beta^3}{s} \sin^2 \theta$$

spin-1/2

$$\frac{d\sigma^{(\text{spin-1/2})}}{d\Omega} \propto \frac{\beta}{s} [1 + \cos^2 \theta + (1 - \beta^2) \sin^2 \theta]$$

(both valid for s -channel production)
(for spin-1/2, assuming pure V-couplings with vector bosons)

These assumptions are used

- to combine results at all \sqrt{s}
- to compute η -dependent efficiencies, for any spin hypothesis

If NLSP is a charged slepton $\tilde{\ell}$

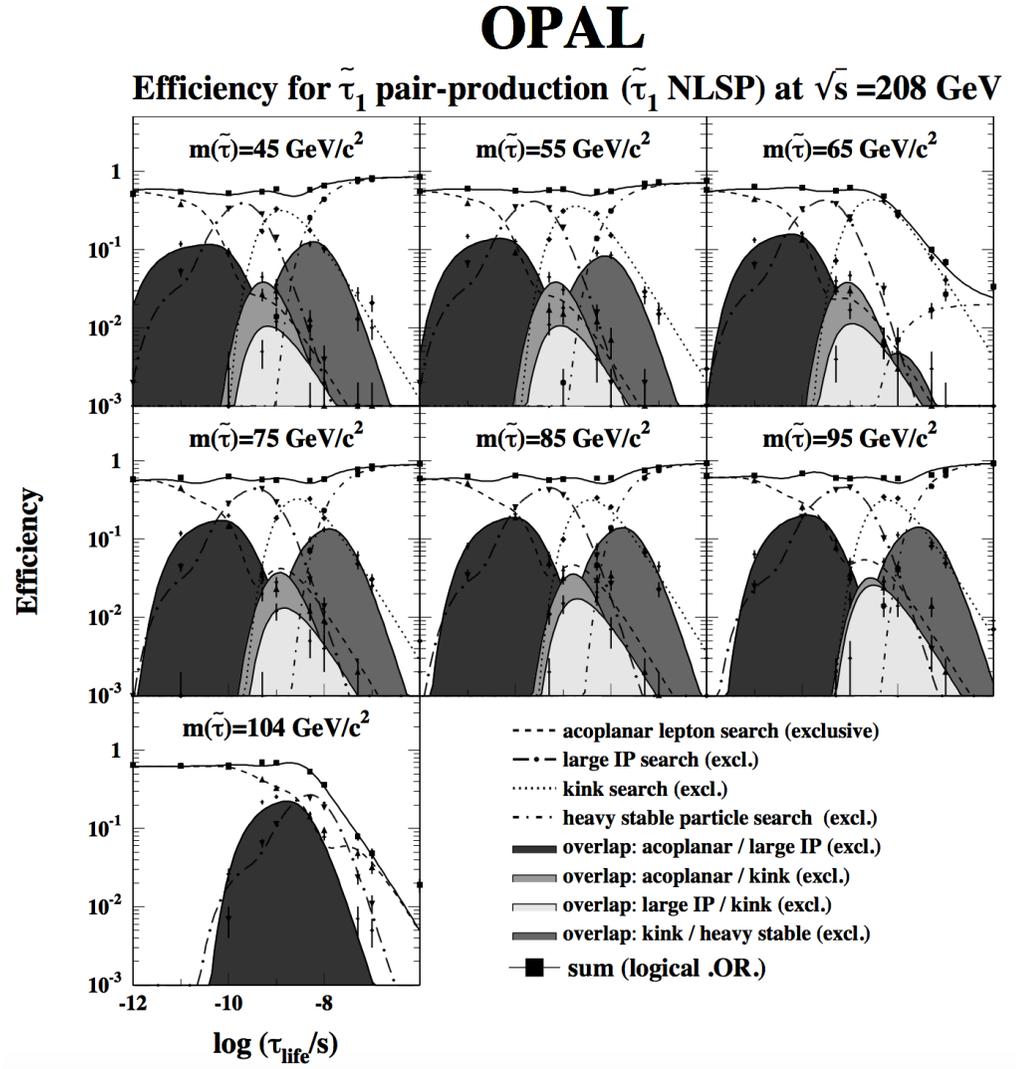
NLSP can be:

- $\tilde{\tau}_1$
- $\tilde{\mu}, \tilde{e}$ (degenerate with $\tilde{\tau}_1$, "co-NLSP")

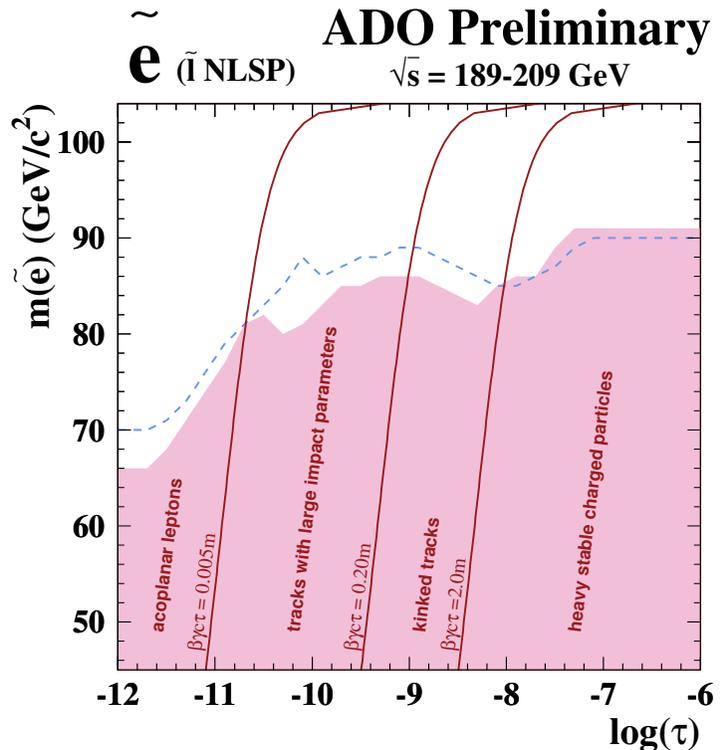
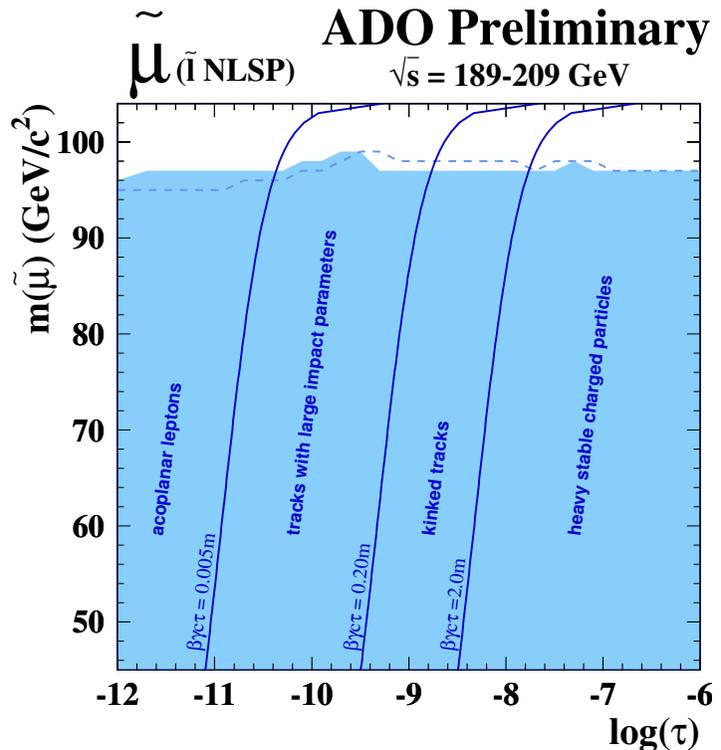
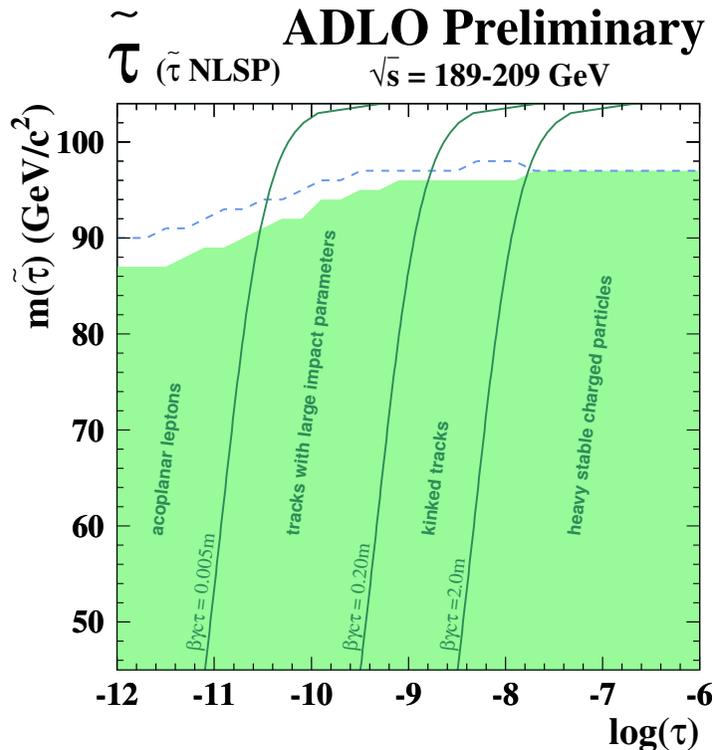
Combine 4 searches (depending on lifetime)

- acoplanar $ll + \vec{P}_T$
- tracks with large impact parameter
- tracks with kink
- highly ionizing tracks

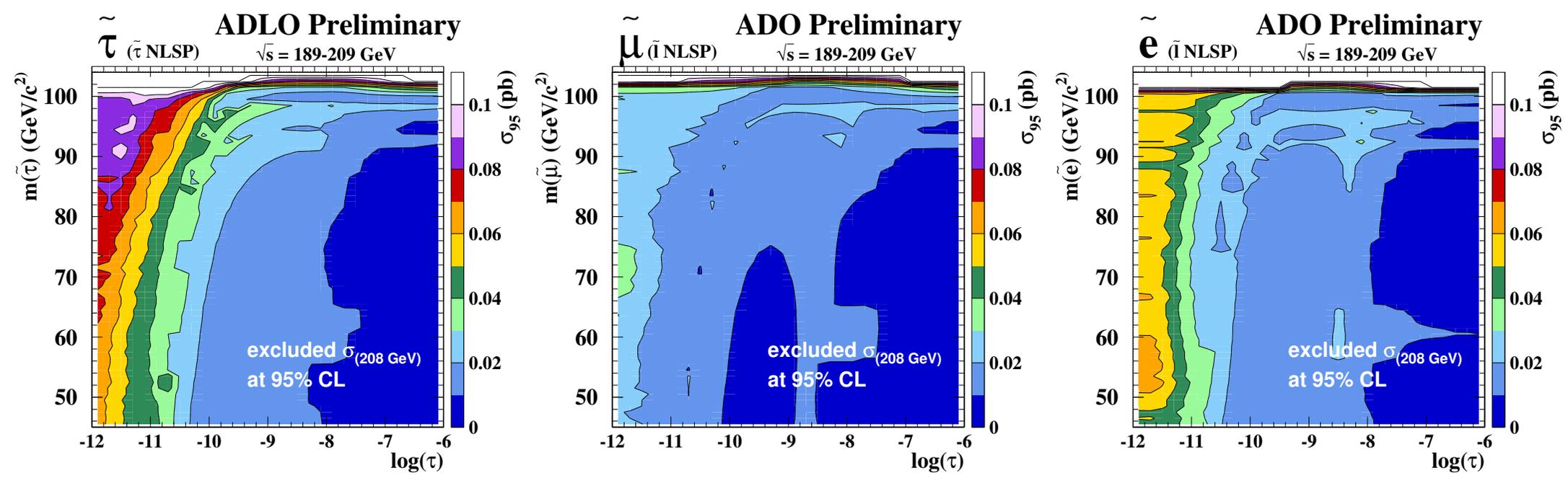
and account for overlaps



ADLO: searches for slepton pairs

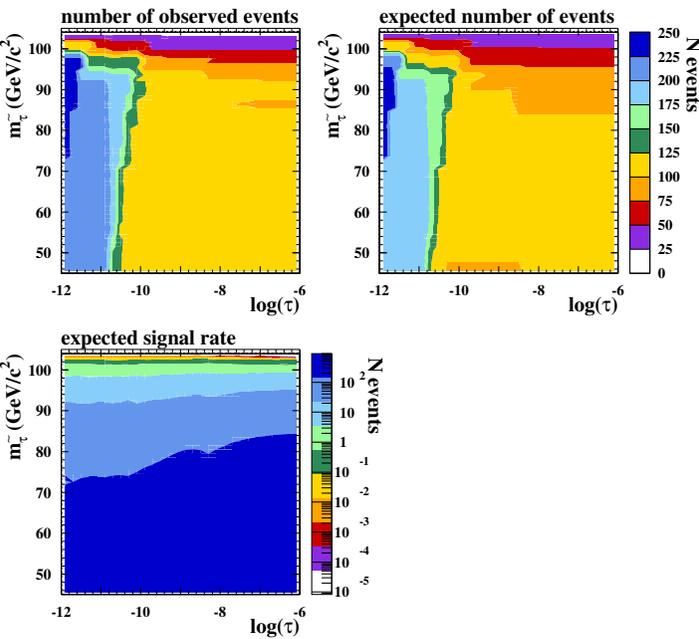


ADLO: searches for slepton pairs

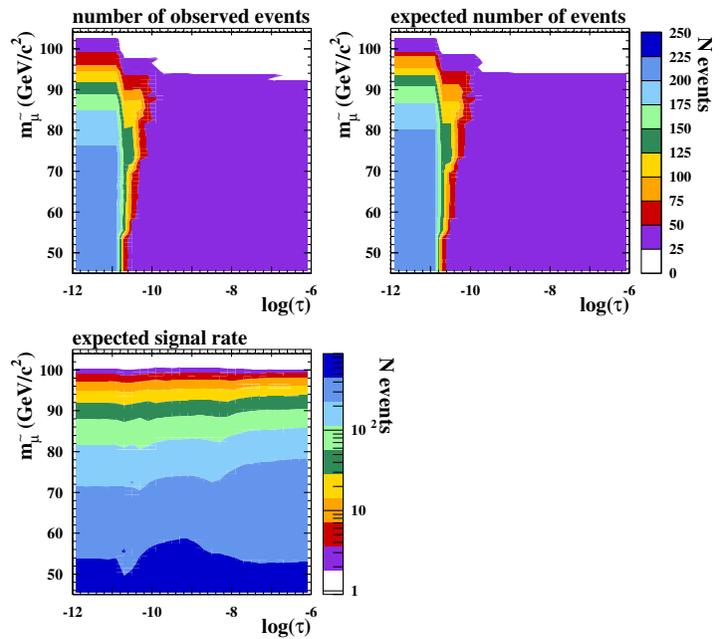


ADLO: searches for slepton pairs

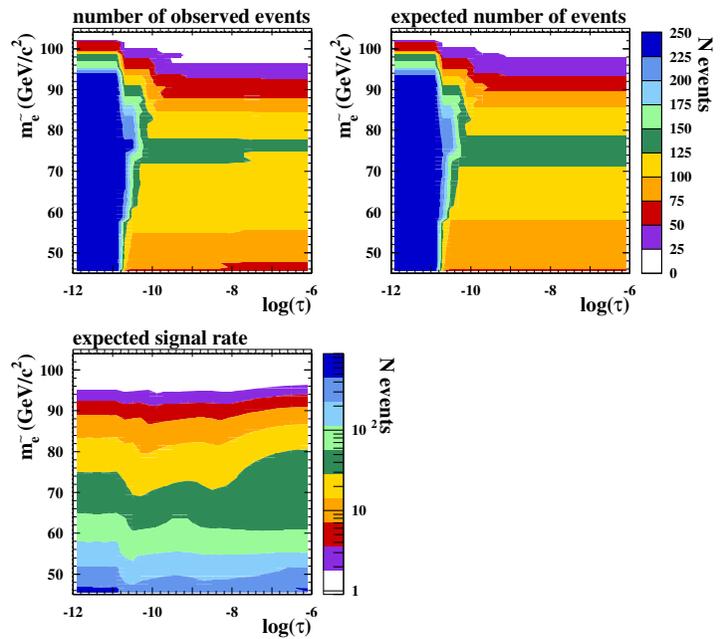
ADLO Preliminary, $\tilde{\tau}$ ($\sqrt{s} = 189 - 209$ GeV)



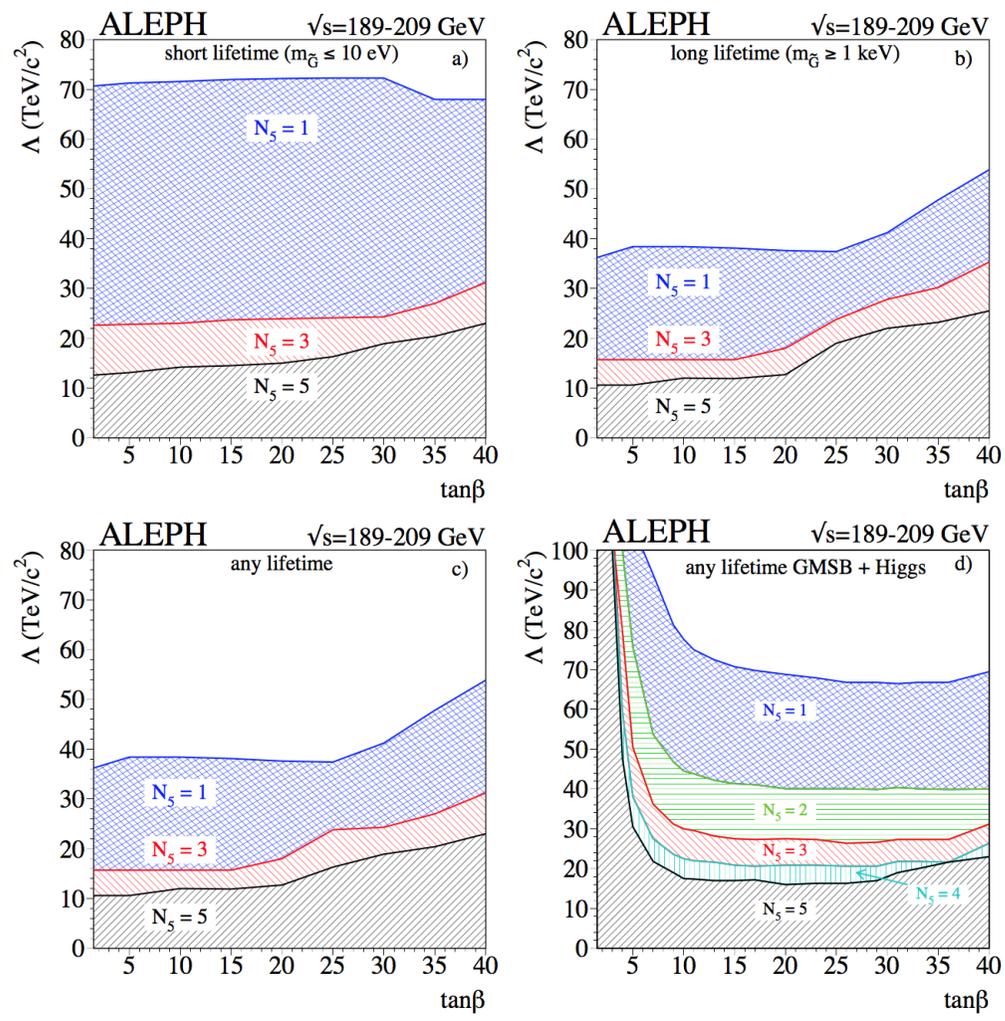
ADO Preliminary, $\tilde{\mu}$ ($\sqrt{s} = 189 - 209$ GeV)



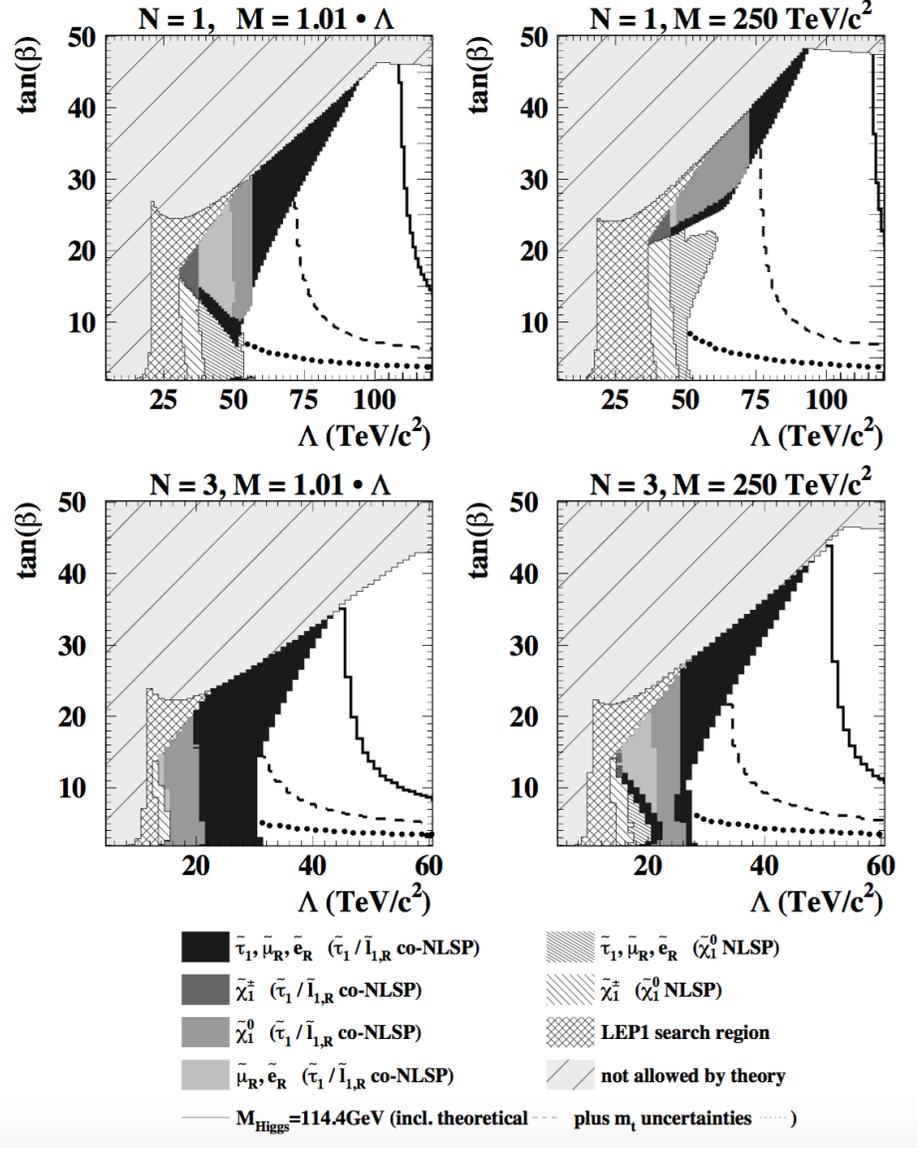
ADO Preliminary, \tilde{e} ($\sqrt{s} = 189 - 209$ GeV)



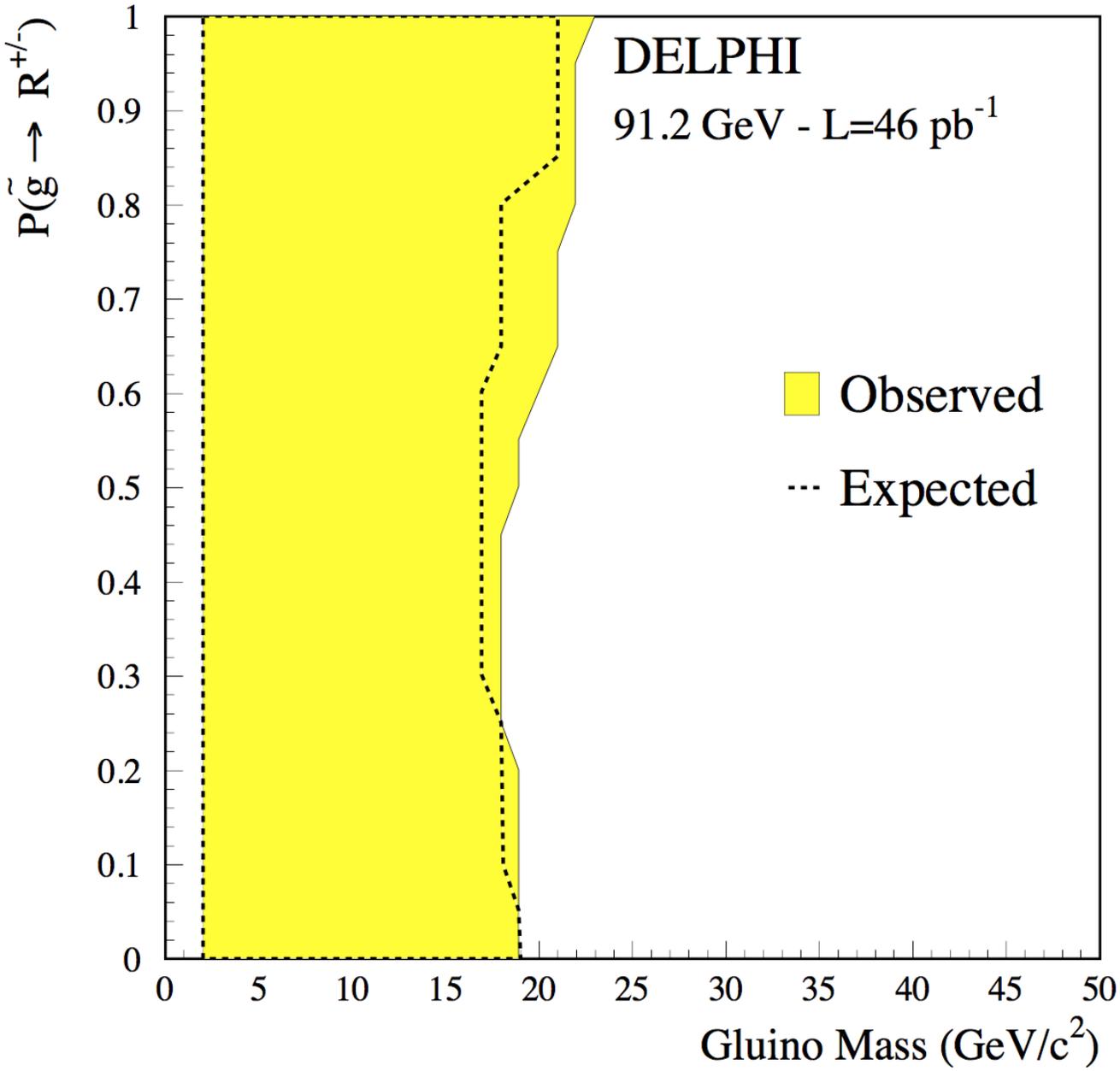
Exclusions in GMSB parameters space



OPAL



Stable gluino exclusion from LEP1



mass limit nicely stable vs $P \equiv \text{Prob}(\tilde{g} \rightarrow R^{\pm})$

minimal exclusion: $m_{\tilde{g}} > 18 \text{ GeV}$

best exclusion: $m_{\tilde{g}} > 23 \text{ GeV}$
for $P = 1$