Search for SUSY @ LEP

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On behalf of ~2000 LEP physicists

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What is the real conclusion of the myriad searches for signatures of susy particles done at LEP by Aleph, Delphi L3 and Opal

Why SUSY?

• Motivated mainly by need to keep the Higgs boson mass at the TeV scale;

• The only non-trivial extension of the Lorentz symmetry group. Combines internal with external symmetries;

• May give rise to dark matter;

• Local SUSY allows for a unification of gravity with the other interactions;

Not seen

Softly broken

>100 free parameters!

How can one look for such a thing??????

Particle Spectrum

Standard particles		SUSY states	SUSY particles	
electron	$e^{\pm}$	$\tilde{e}_L^{\pm}, \tilde{e}_R^{\pm}$	$\tilde{e}_L^{\pm}, \tilde{e}_R^{\pm}$	selectron
muon	$\mu^{\pm}$	$\tilde{\mu}_R^{\pm}, \tilde{\mu}_L^{\pm}$	$\tilde{\mu}_R^{\pm}, \tilde{\mu}_L^{\pm}$	smuon
tau	$\tau^{\pm}$	$\tilde{\tau}_R^{\pm}, \tilde{\tau}_L^{\pm}$	$\tilde{\tau}_1^{\pm}, \tilde{\tau}_2^{\pm}$	stau
neutrino	ν	$\tilde{\nu}_R, \tilde{\nu}_L$	$\tilde{\nu}_R, \tilde{\nu}_L$	sneutrino
quarks (u,d,s,c)		$\tilde{u}_R, \tilde{d}_R, \tilde{s}_R, \tilde{c}_R$ $\tilde{u}_L, \tilde{d}_L, \tilde{s}_L, \tilde{c}_L$	$\tilde{u}_R, \tilde{d}_R, \tilde{s}_R, \tilde{c}_R$ $\tilde{u}_L, \tilde{d}_L, \tilde{s}_L, \tilde{c}_L$	squarks
quarks (b,t)		$\tilde{b}_{R,}\tilde{b}_L, \tilde{t}_R, \tilde{t}_L$	$\tilde{b}_{1,}\tilde{b}_2, \tilde{t}_1, \tilde{t}_2$	sbottom,stop

Standard particles	SUSY states	SUSY particles	
$W^{\pm}, H^{\pm}$	$\tilde{W}^{\pm}, \tilde{H}^{\pm}$	$\chi_1^{\pm}, \chi_2^{\pm}$	chargino
$\gamma, Z^0, h^0, H^0, A^0$	$\tilde{\gamma}, \tilde{Z}^0, \tilde{h}^0, \tilde{H}^0, \tilde{A}^0$	$\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0,$	neutralino
g_i		$\tilde{g}_i$	gluino

SUSY tells us which are the couplings

But the symmetry breaking gives rise to an unknown mass hierarchy and mixings

MSSM

Since things are too complicated – one make some simplifying assumptions and reduce the model to a 'testeble' one.

Assume that all fermions have a common mass at the planck scale $m_{1/2}$

All bosons have common mass at the planck scale m_0

All trilinear interactions are equal – A

And the Higgs sector parameters:

$$\tan\beta = \frac{v_2}{v_1}$$

$$\mu$$

Under these assumptions one gets a well defines model which s easy to check in experiments.

MSSM Searches

Assume R parity conservation:

- Pair production
- Stable Lightest SUSY Particle (LSP)

In MSSM the LSP is the neutralino

Assuming one know the values of

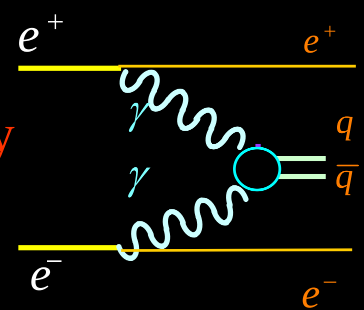
$$m_{1/2}, m_0, \tan\beta, A, \mu$$

One now knows what to look for and how to look for it.

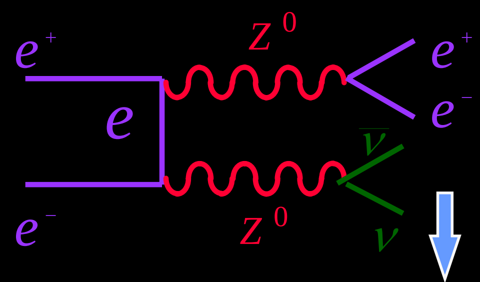
… but computations do not always agree

Background

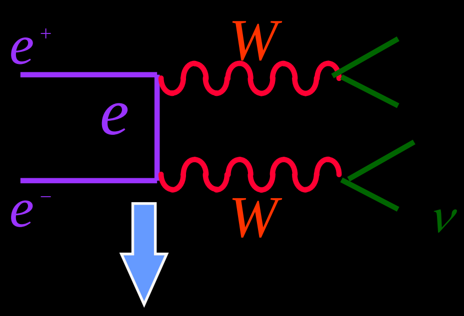
Two-photon processes have very big cross sections (~10s nb) but can be easily eliminated by p_T cut.



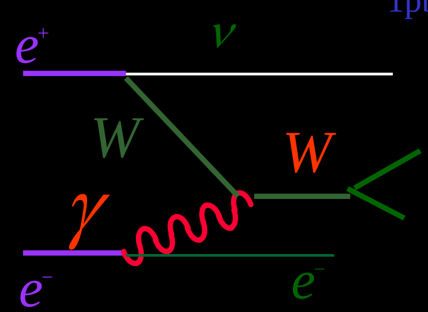
Four-fermion processes are very problematic background sources for LEP>1 physics, because they are irreducible



1pb

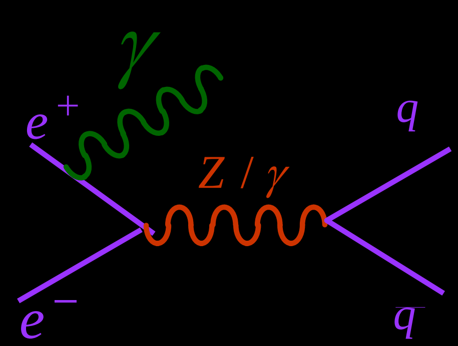


~20 pb

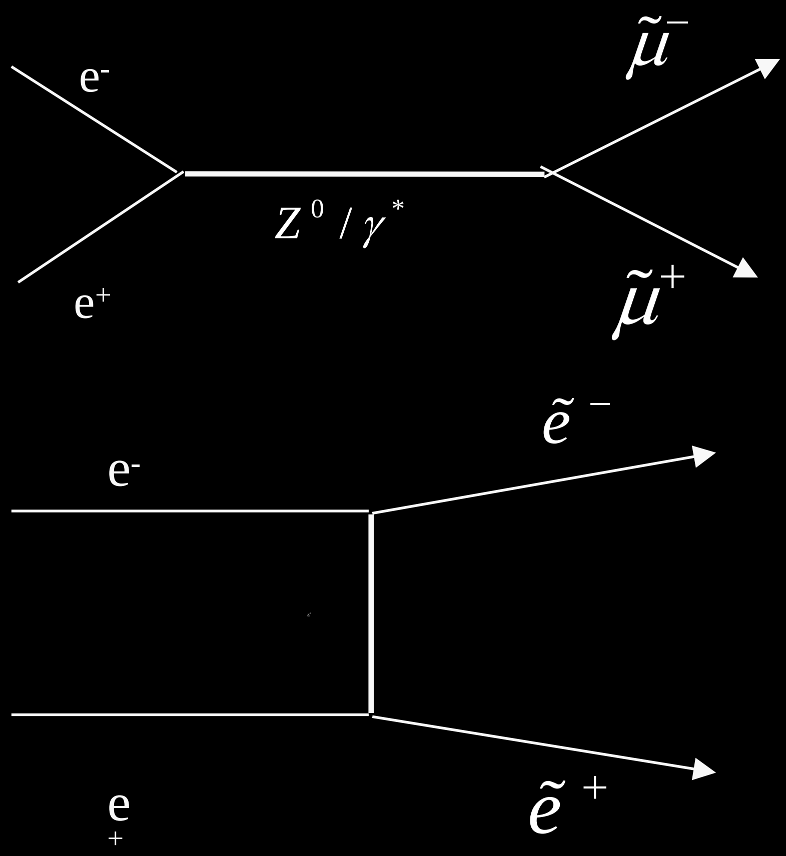


0.6pb

Radiative multihadronic events (~100 pb) and radiative di-lepton events (~40 pb) where the photon goes into the beam pipe are eliminated by cuts on energy flow in the beam direction or cuts on the missing momentum direction.



Slepton Production

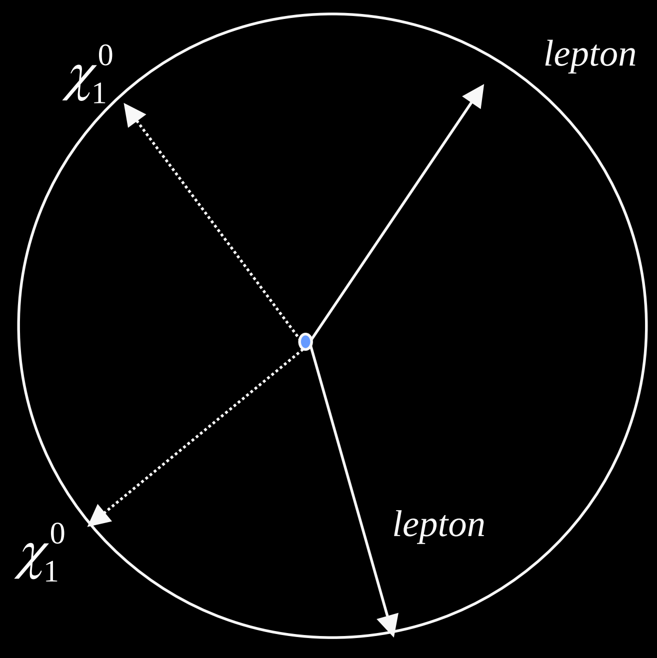


The Left handed sleptons were assumed to be beyond the reach of the experiment and the search (and limits) were set on the right handed ones which have lower production cross section (traditional LEP conservative approach).

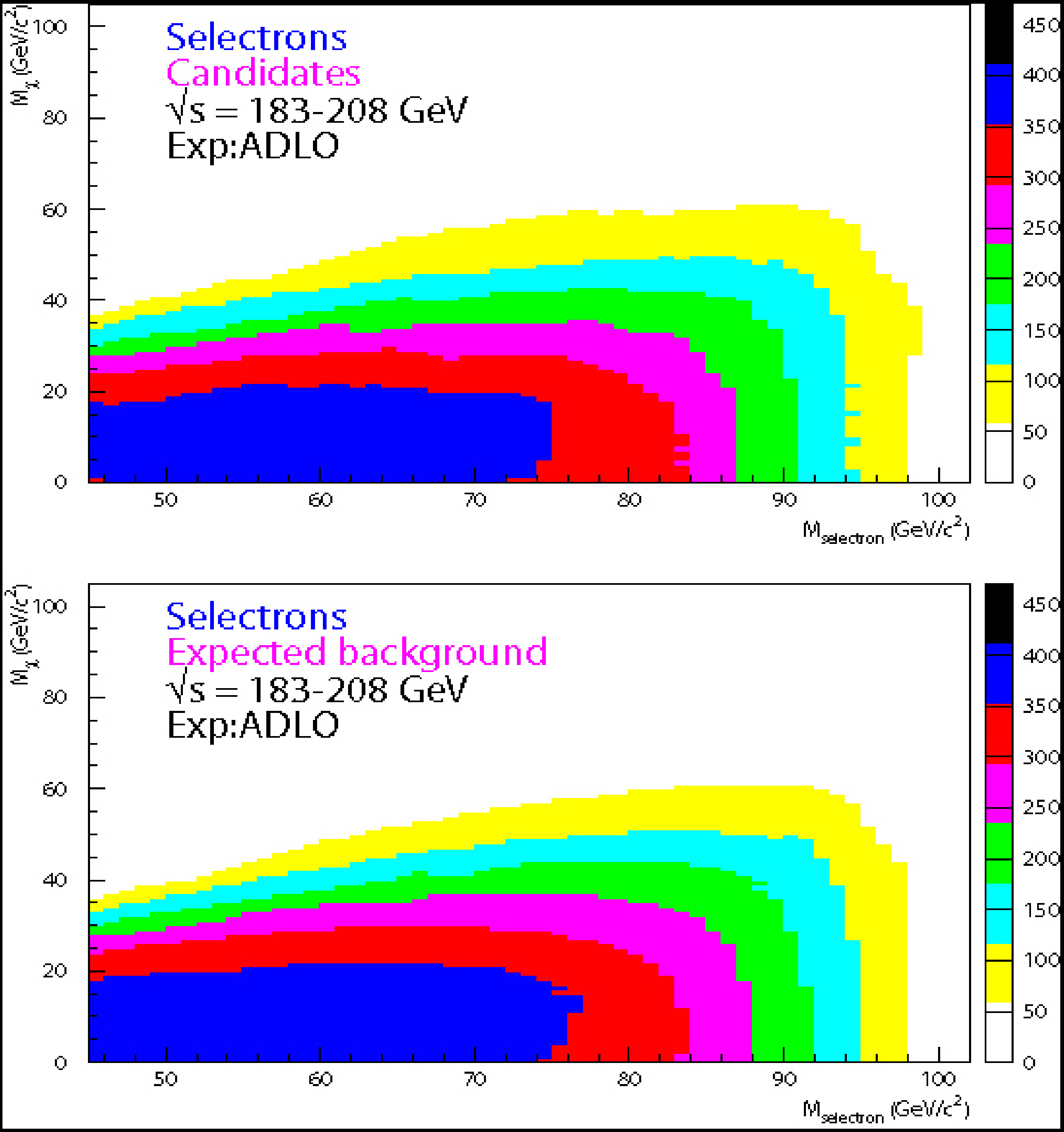
Slepton Searches

The dominant decay mode is $\tilde{l}^{\pm} \rightarrow \chi_1^0 l^{\pm}$

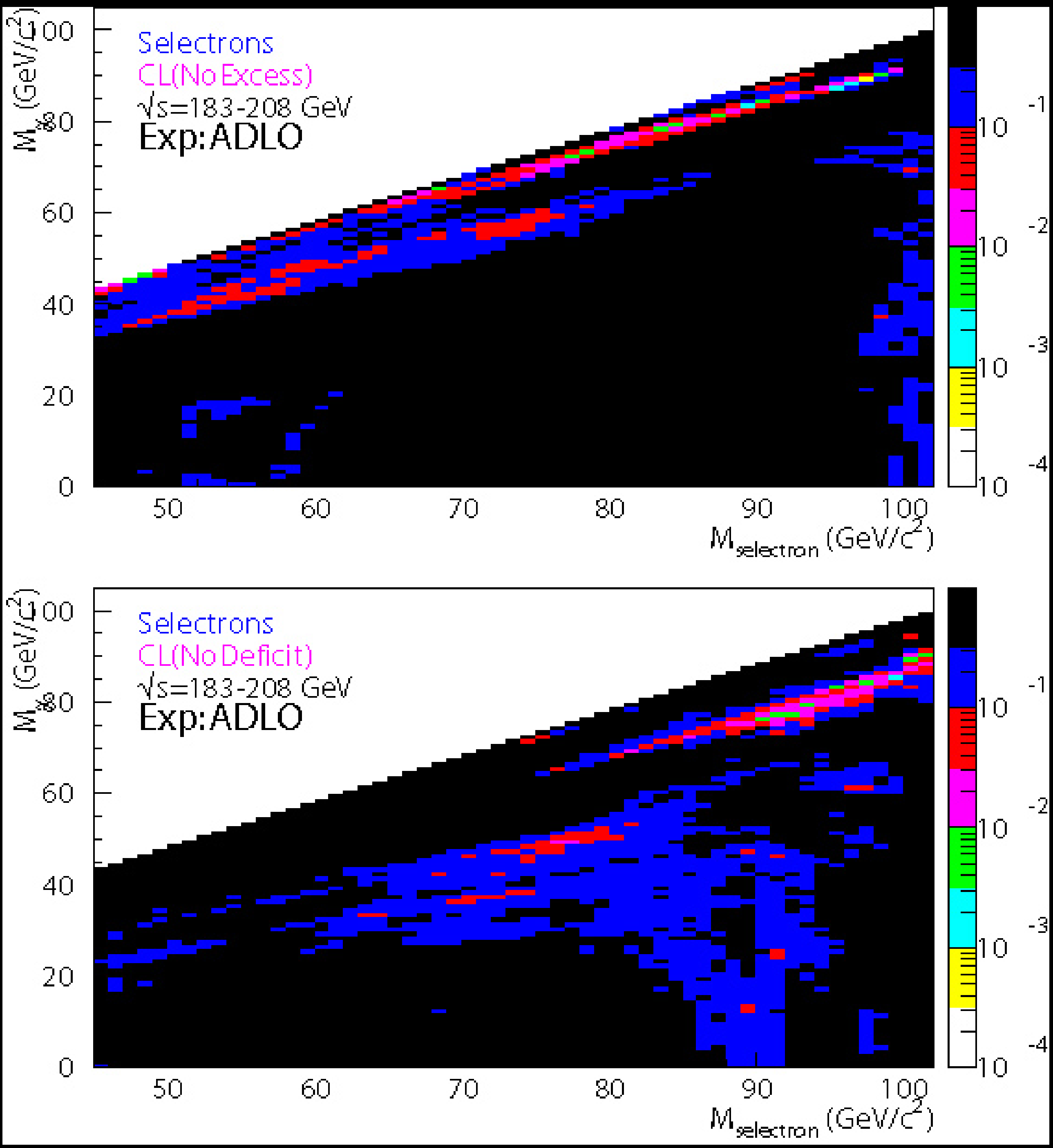
Which gives rise to *two acollinear lepton* final state



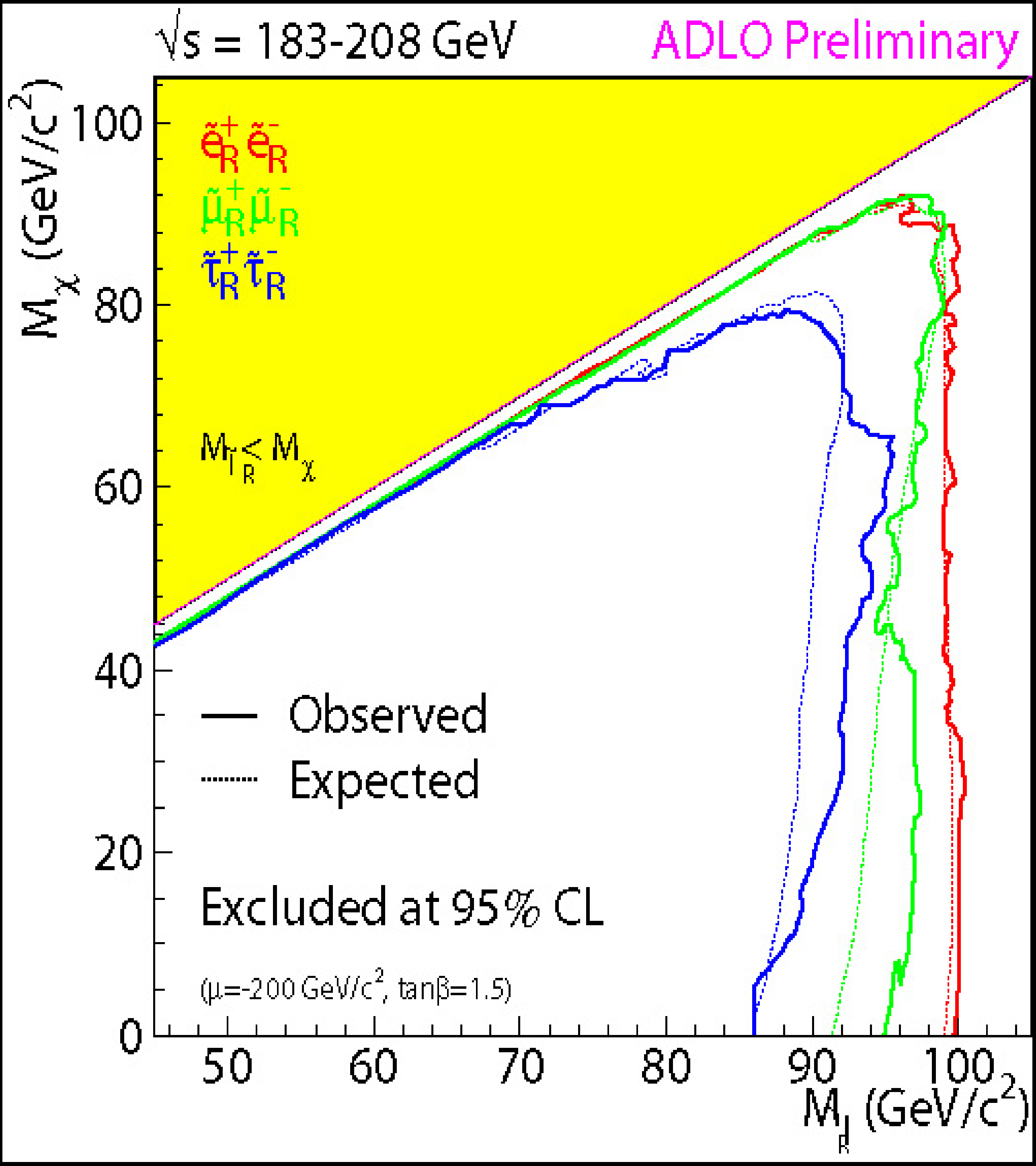
Comparing Data With Expectations



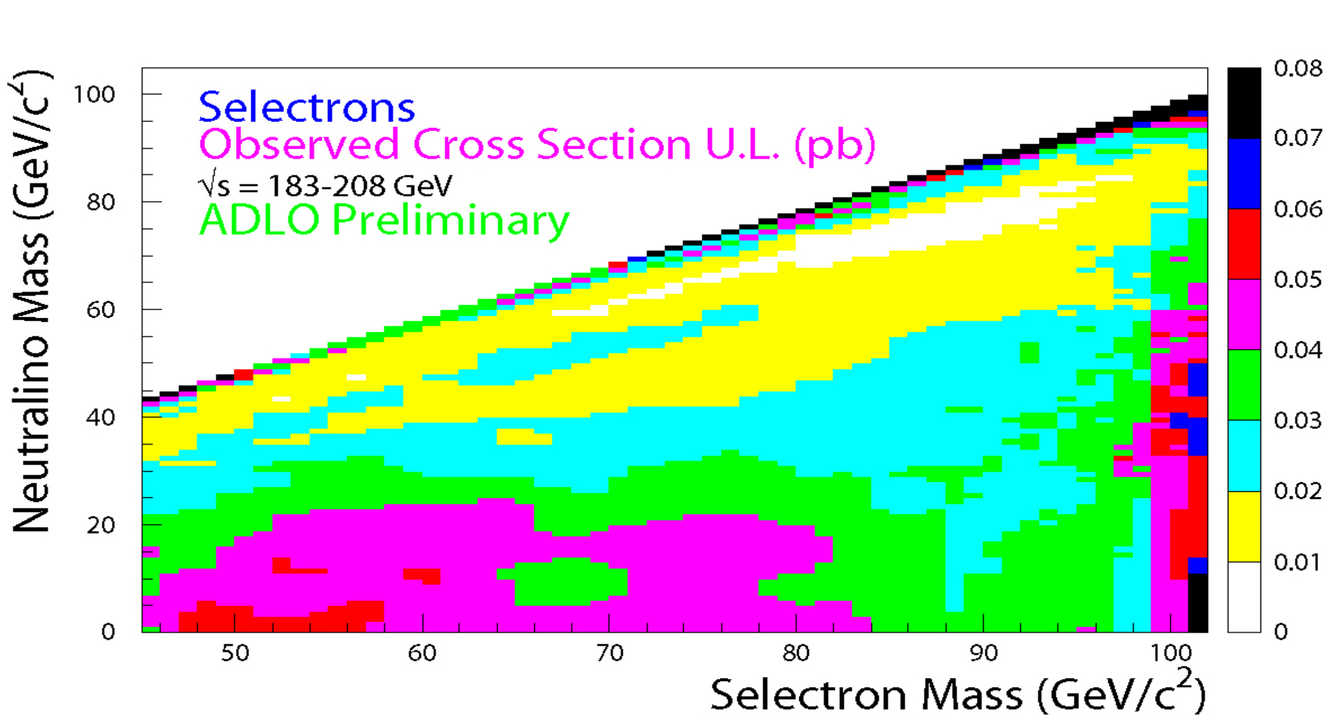
Looking for Excess

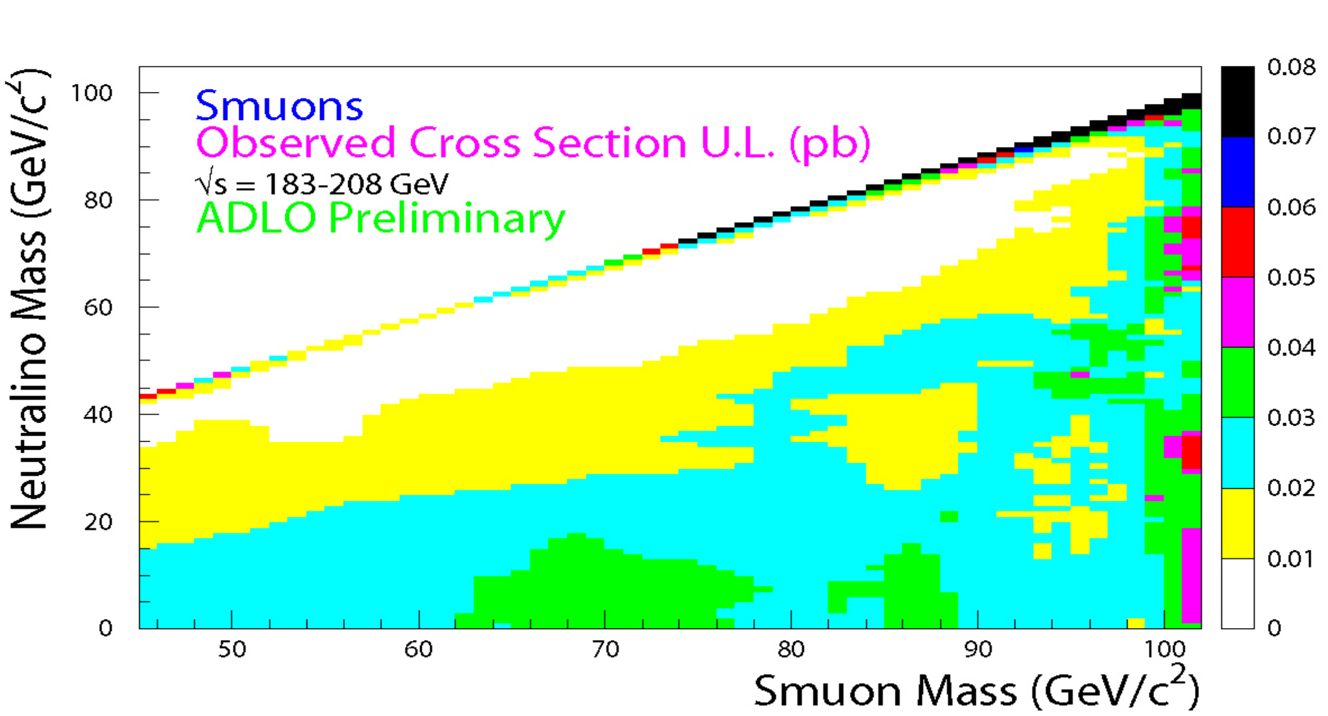


Limits on Sleptons Masses

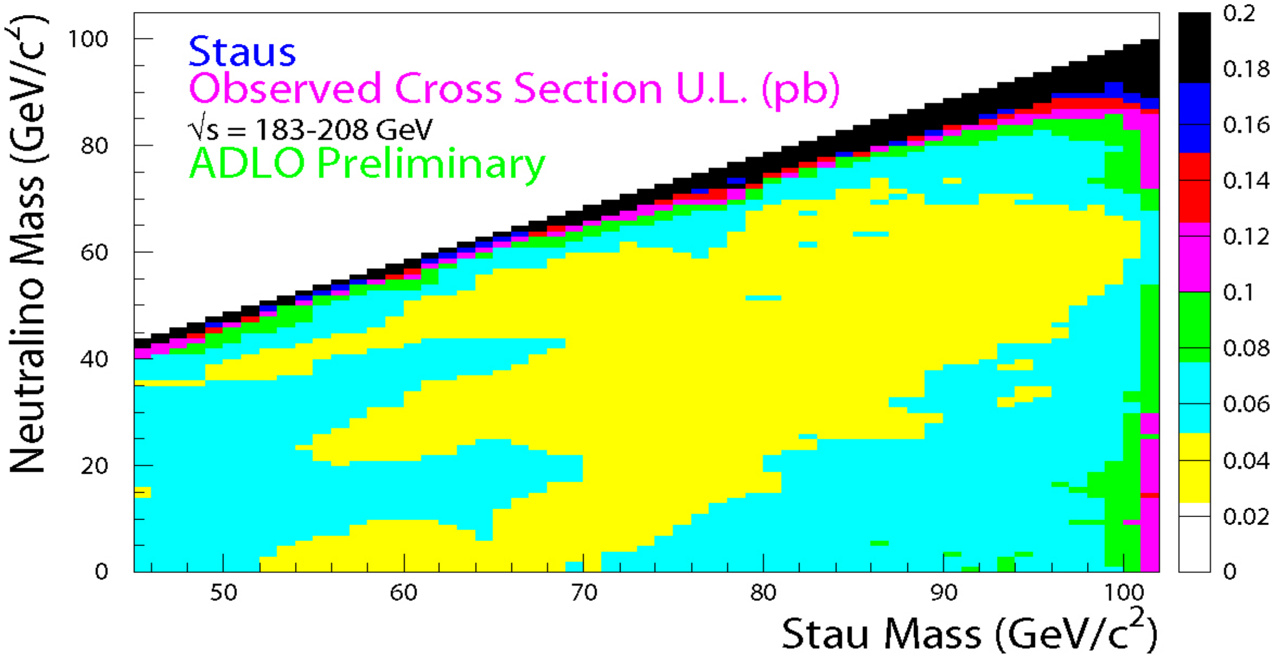


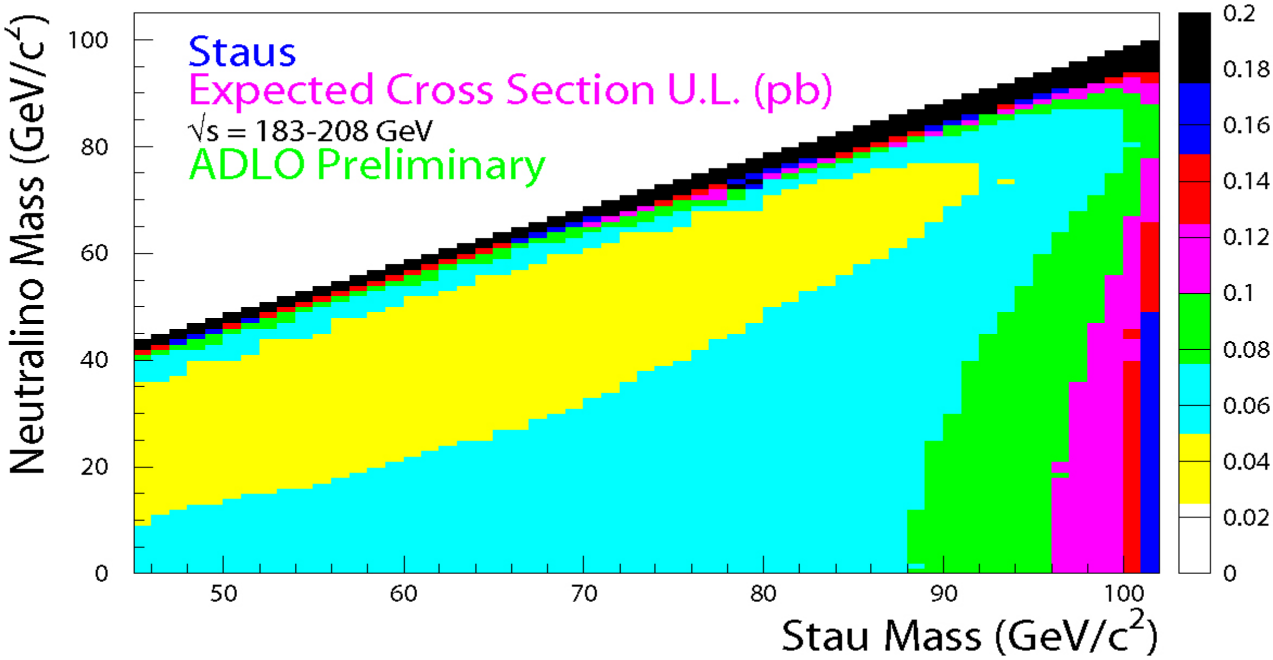
Sleptons Cross-Section





Stau Cross-Section





More on two leptons

In some regions of the parameter space the $\tilde{l}^{\pm} \rightarrow \chi_2^0 l^{\pm} \rightarrow \gamma l$ mode is possible leading to *two acollinear leptons and two photons* final satate

The t-channel exchange in the selectron production can give rise to $\tilde{e}_L \tilde{e}_R$ and one might encounter a situation in which

$$\Delta m \equiv m_{\tilde{e}_R} - m_{\chi_1^0} \approx 0$$

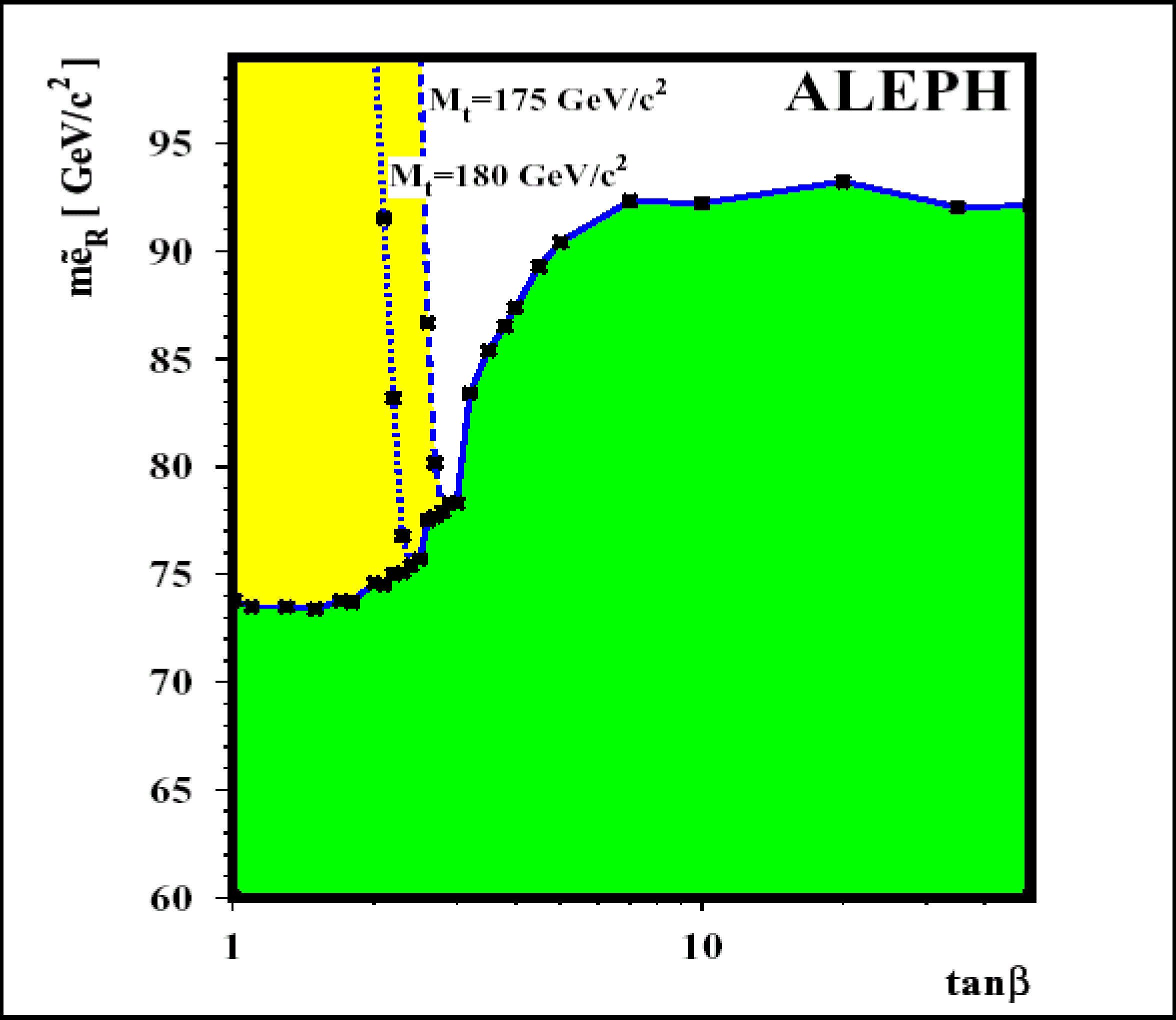
Which gives rise to a *single electron* final state.

First List

So even the simplest possible process of slepton production requires the following searches:

- Single electron;
- two acollinear leptons;
- two leptons and a photon;
- two leptons and two photons.

Absolute Limit on Selectrons



$$m_{\tilde{e}} > 73 GeV$$

The Chargino

- The charginos are the mixture of the super-partners of the W and the charged Higgs bosons.

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & -\mu \end{pmatrix}$$

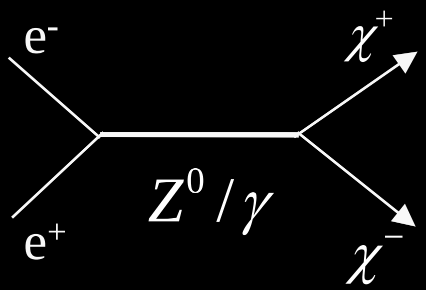
When $M_2 \gg \mu$ the chargino consists of mainly Higgsino and when $M_2 \ll \mu$ mainly of W-ino

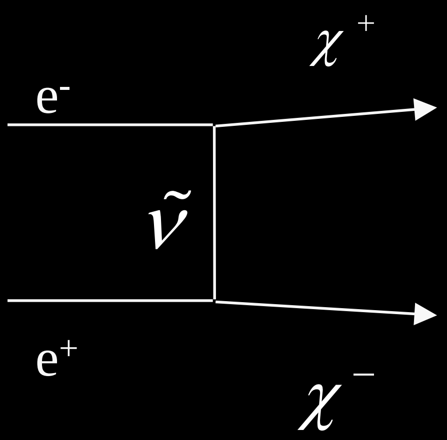
The lightest chargino ($\chi_1^{\pm}$) is expected to be one of the lightest SUSY charged particles having mass given by:

$$m^2_{\chi^{\pm}_{1,2}} = \frac{1}{2}\left\{M_2^2 + 2M_W^2 + \mu^2\right\} \mp$$

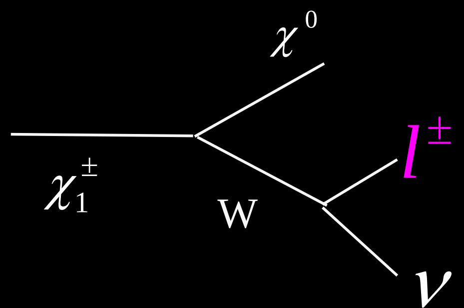
$$\left[\left(M_2^2-\mu^2\right)^2 + 4M_W^4\cos^2 2\beta + 4M_W^2\left(M_2^2+\mu^2\right) - 2M_2\mu\sin^2\beta\right]^{0.5}$$

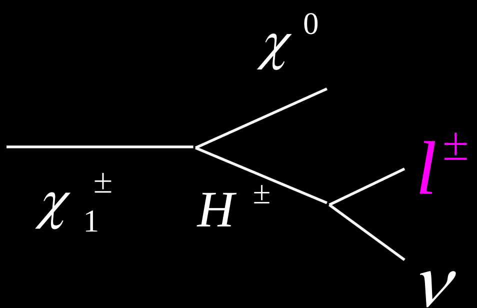
Chargino Production and Decay

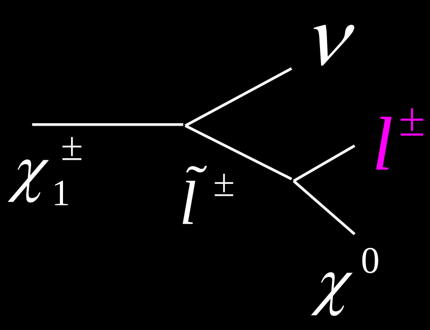


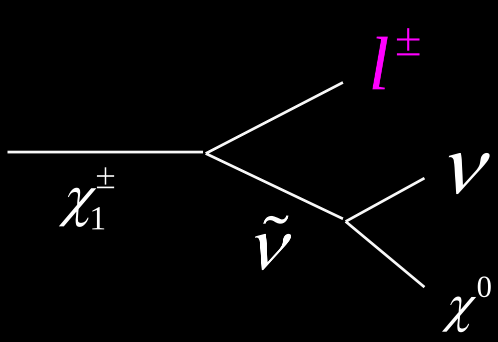


Destructive interference



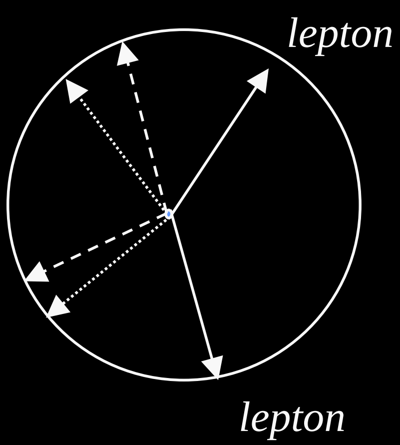


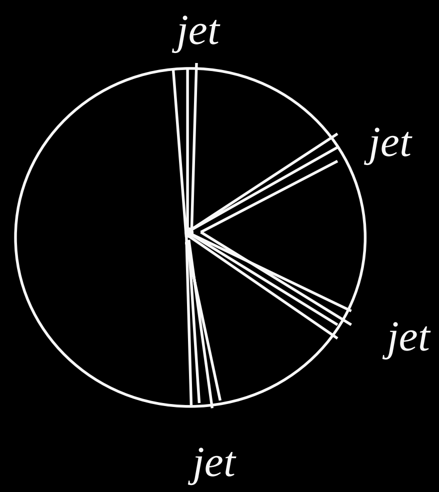


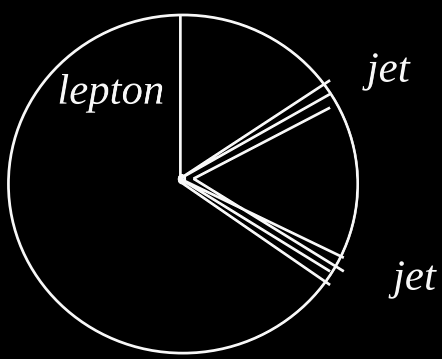


+ the corresponding hadronic modes

Experimental Signatures







$$\Delta M \equiv m_{\chi_1^\pm} - m_{\chi_1^0}$$

More About Chargino

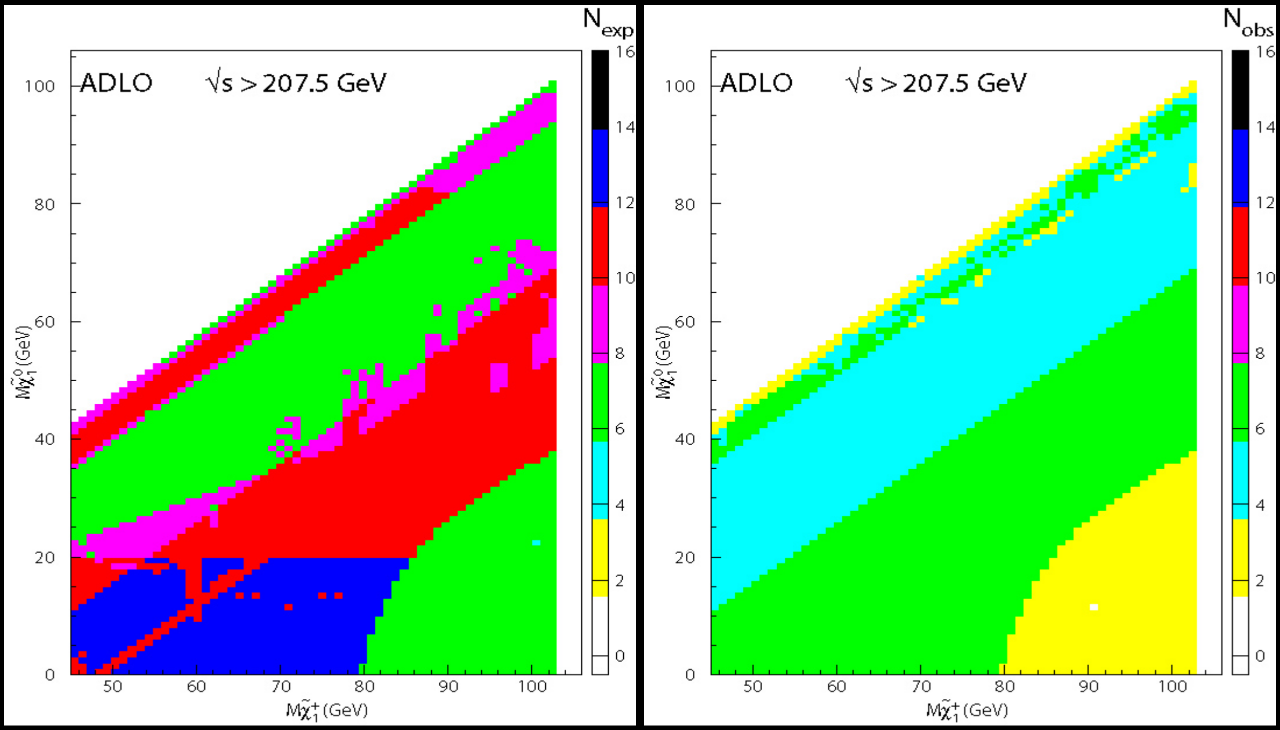
But what does one do when $\Delta m \equiv m_{\chi_1^\pm} - m_{\chi_1^0}$

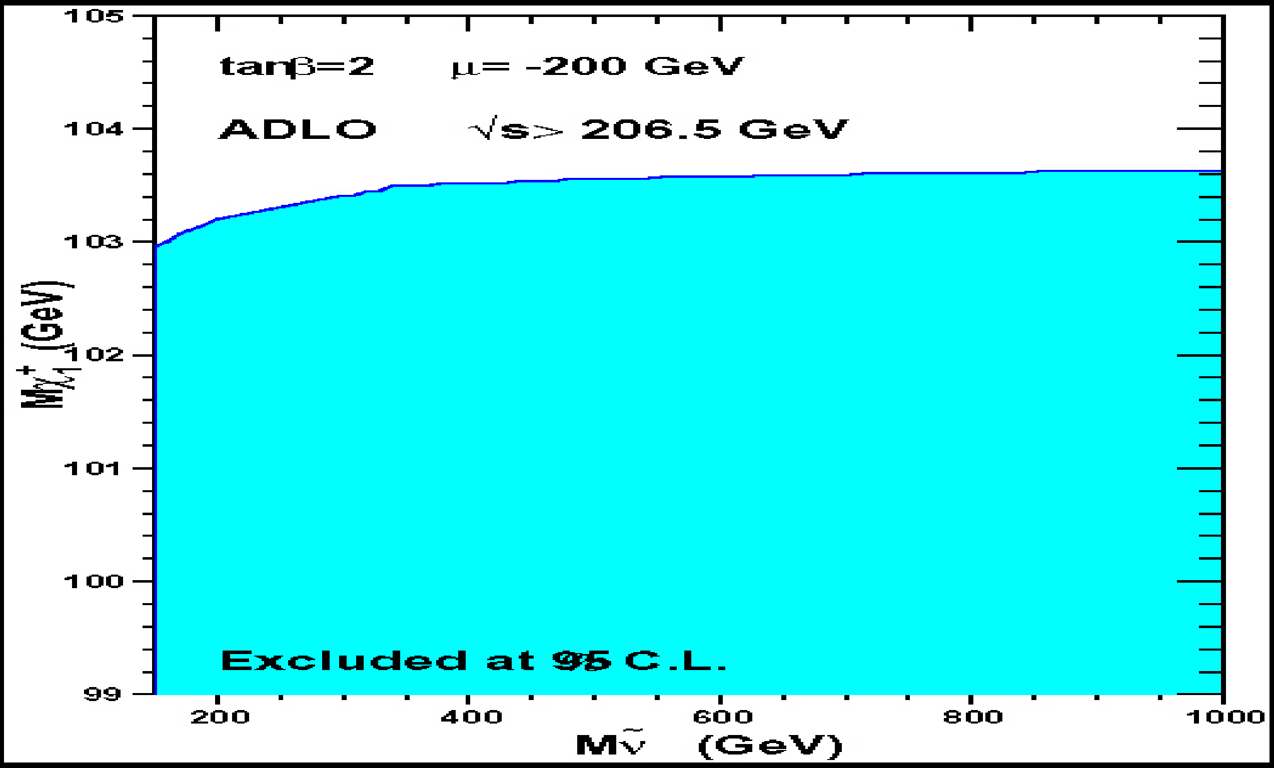
Is very small? This happens naturally in AMSB models and in some corner of MSSM

•Can lead to *stable pair of charged particles*

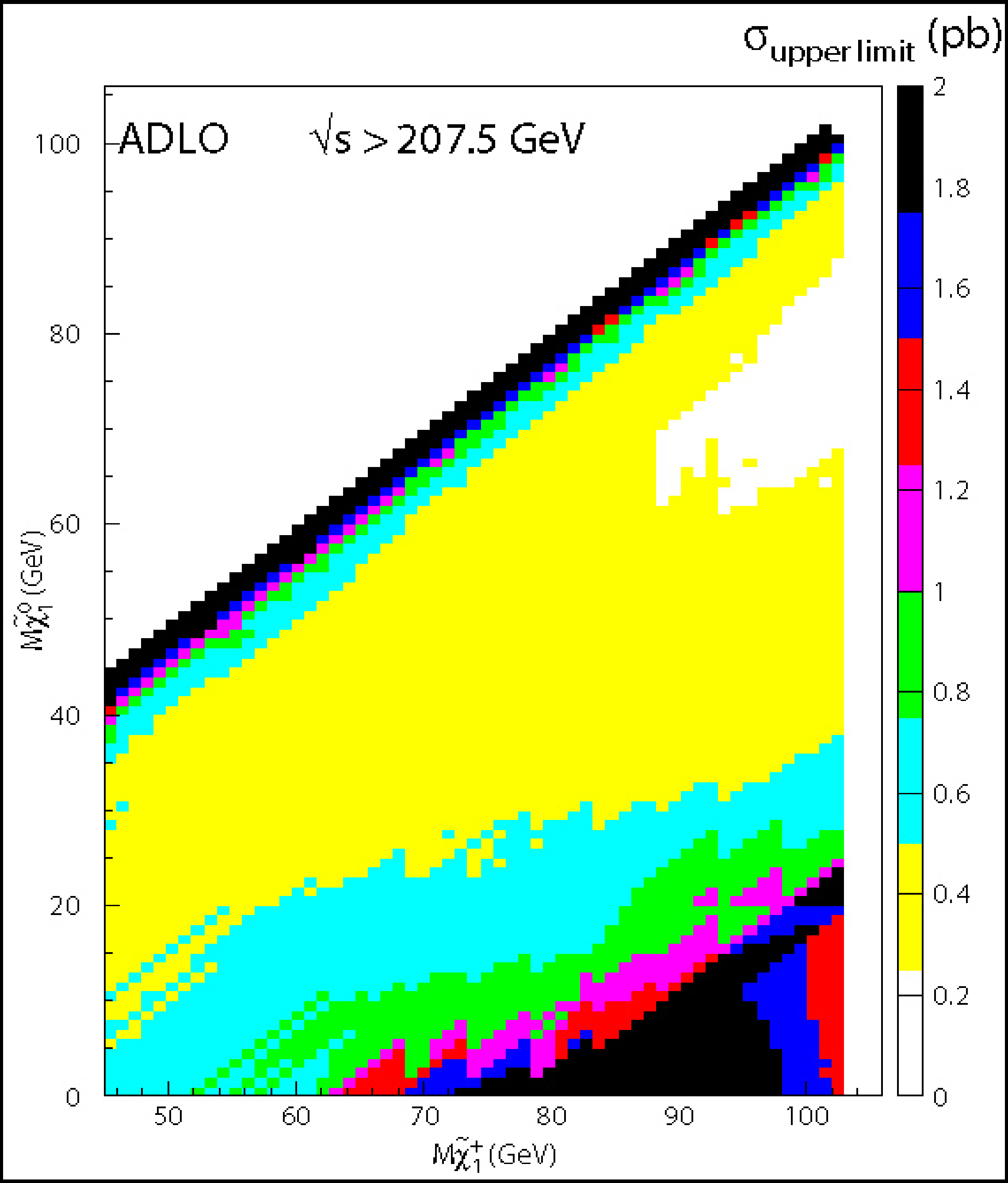
• or if the decay happens in the detector and the decay products are insufficient to trigger one can use the ISR and look for *single photon* final state or *high p_t photon accompanied by some soft activity*

Chargino Results

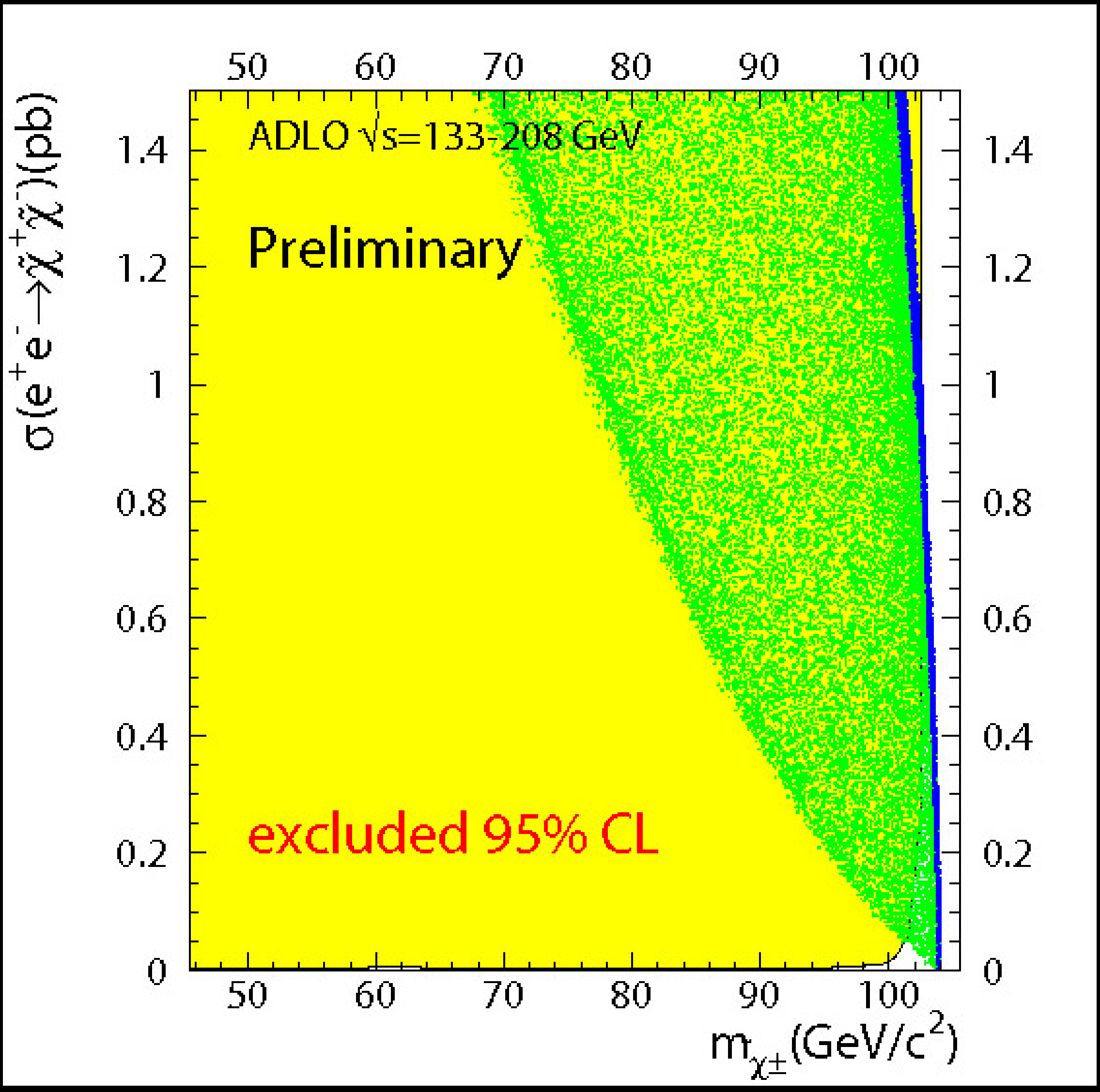




Chargino Cross-Section



Stable Chargino

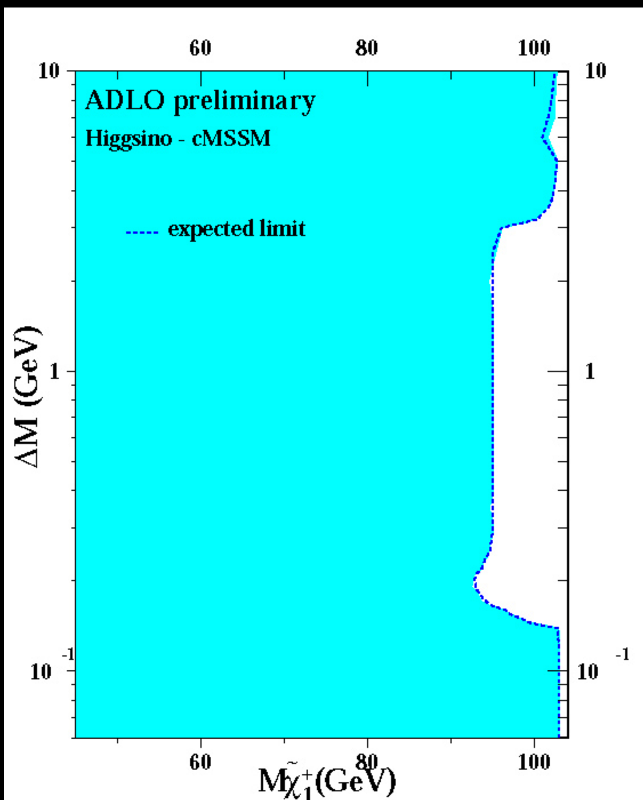


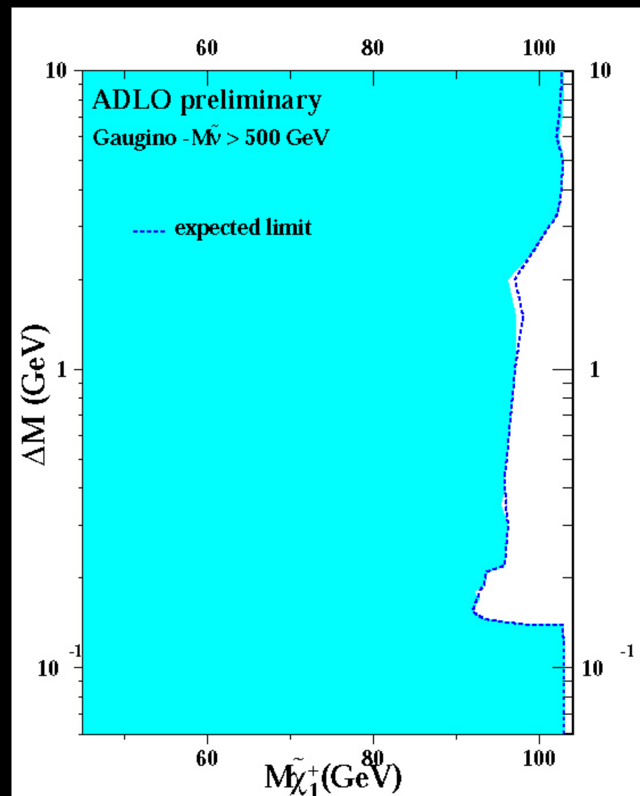
Second List

The search for the chargino includes the following channels:

- Single photon;
- A photon + some activity;
- Two stable particles;
- two acollinear leptons;
- two jets a lepton and missing energy;
- 4 jets + missing energy.

Absolute limit





Higgsino case

Gaugino case

$$m_{\chi_1^\pm} > 91.9 GeV$$

LSP in MSSM (Neutralino)

- Check the existence of a solution (theory);
- Is the solution consistent with the Z width?
- Is the solution consistent with the Higgs boson search?
- Does it give rise to a stable stau which is already excluded?

Then compare the predictions with the observations of the following channels:

$$\tilde{e}_R \tilde{e}_R \to e e \chi_1^0 \chi_1^0$$

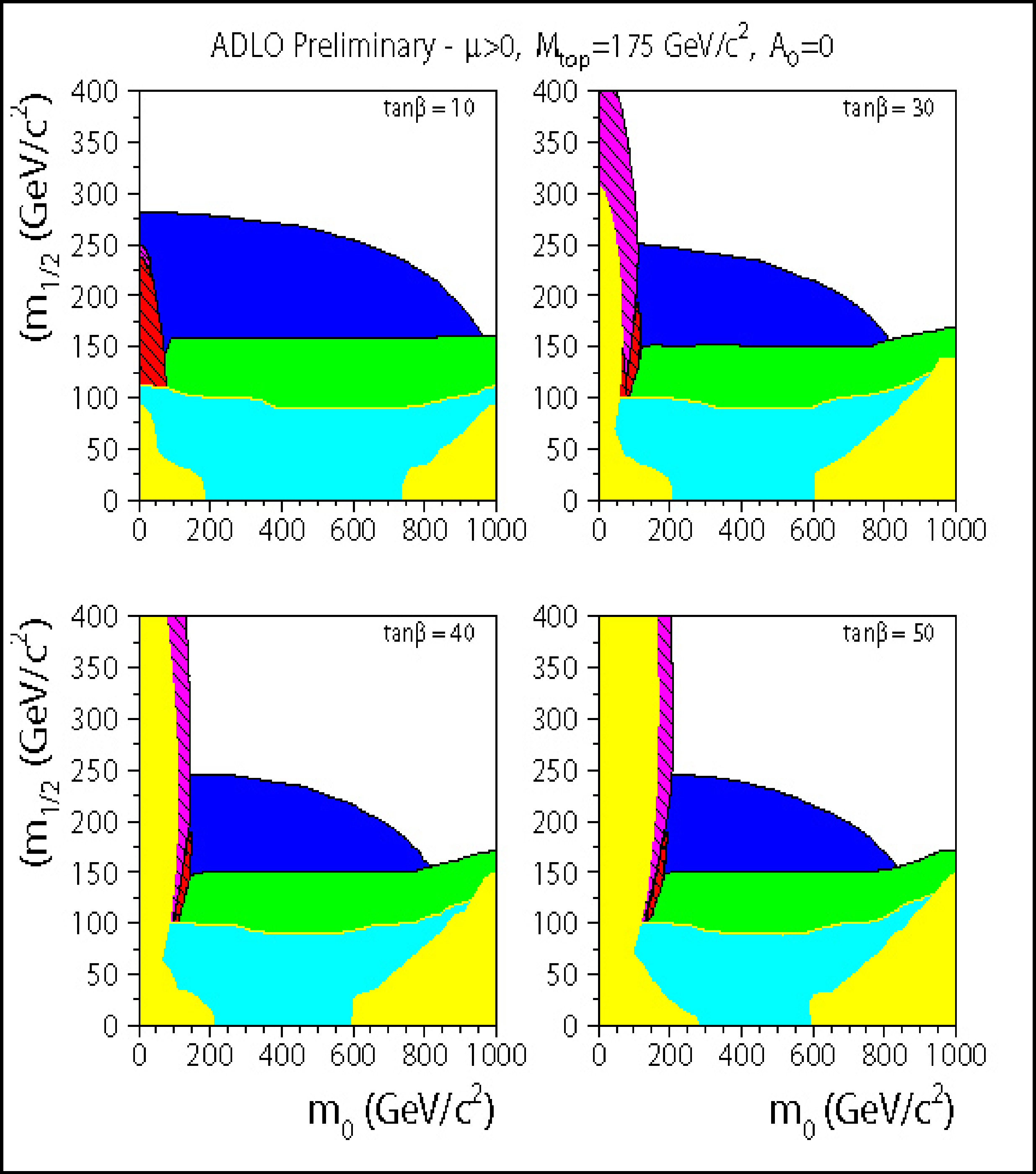
$$\tilde{\tau}_1 \tilde{\tau}_1 \to \tau \tau \chi_1^0 \chi_1^0$$

$$\chi_1^+ \chi_1^- \to l^+ l^- \nu \bar{\nu} \chi_1^0 \chi_1^0 \qquad +\text{Had}$$

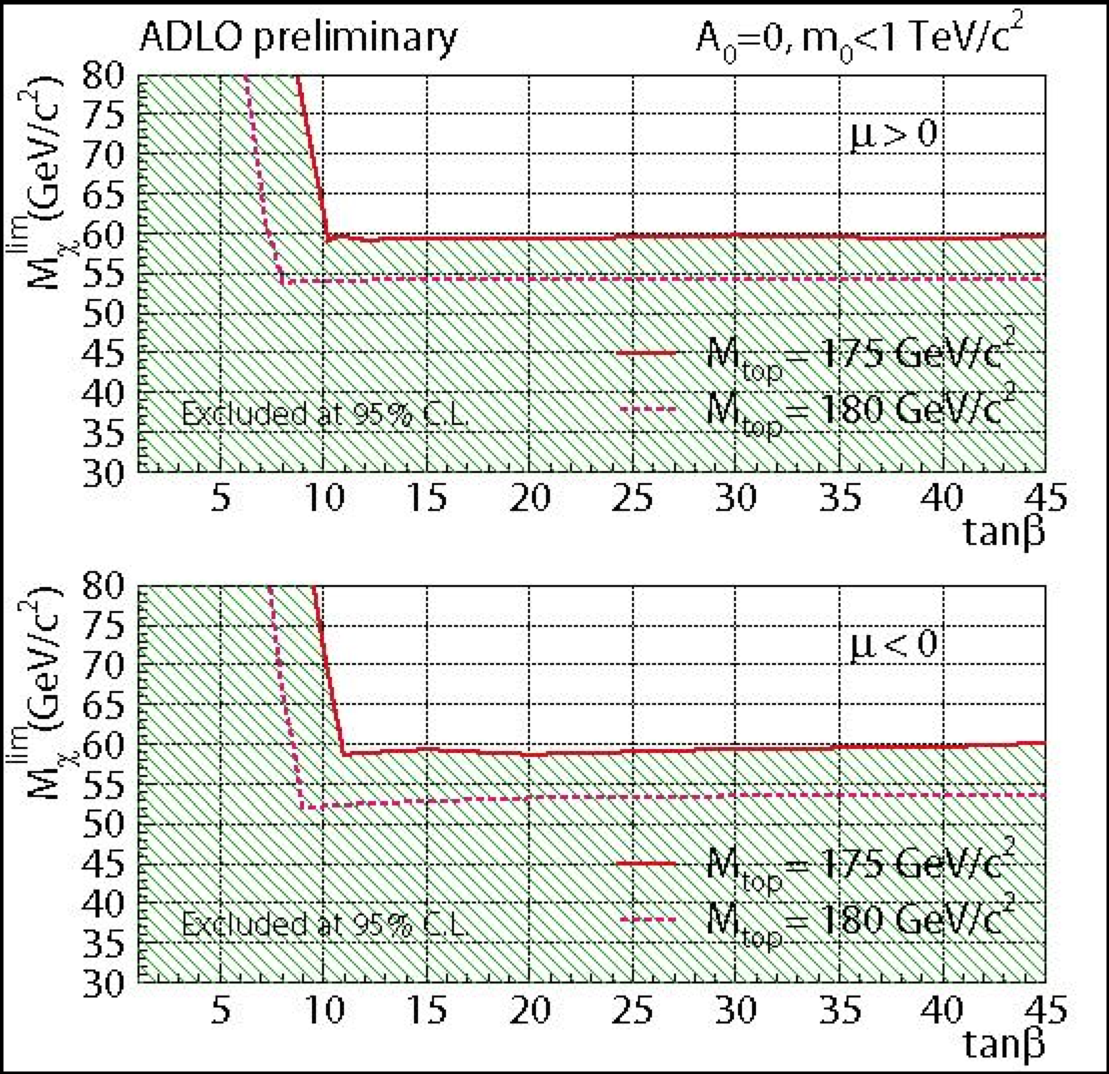
$$\chi_1^0 \chi_2^0 \to \tau^+ \tau^- \chi_1^0 \chi_1^0$$

$$\chi_2^0 \chi_2^0 \to \tau^+ \tau^- \tau^+ \tau^- \chi_1^0 \chi_1^0$$

Neutralino Results



Mass Limits

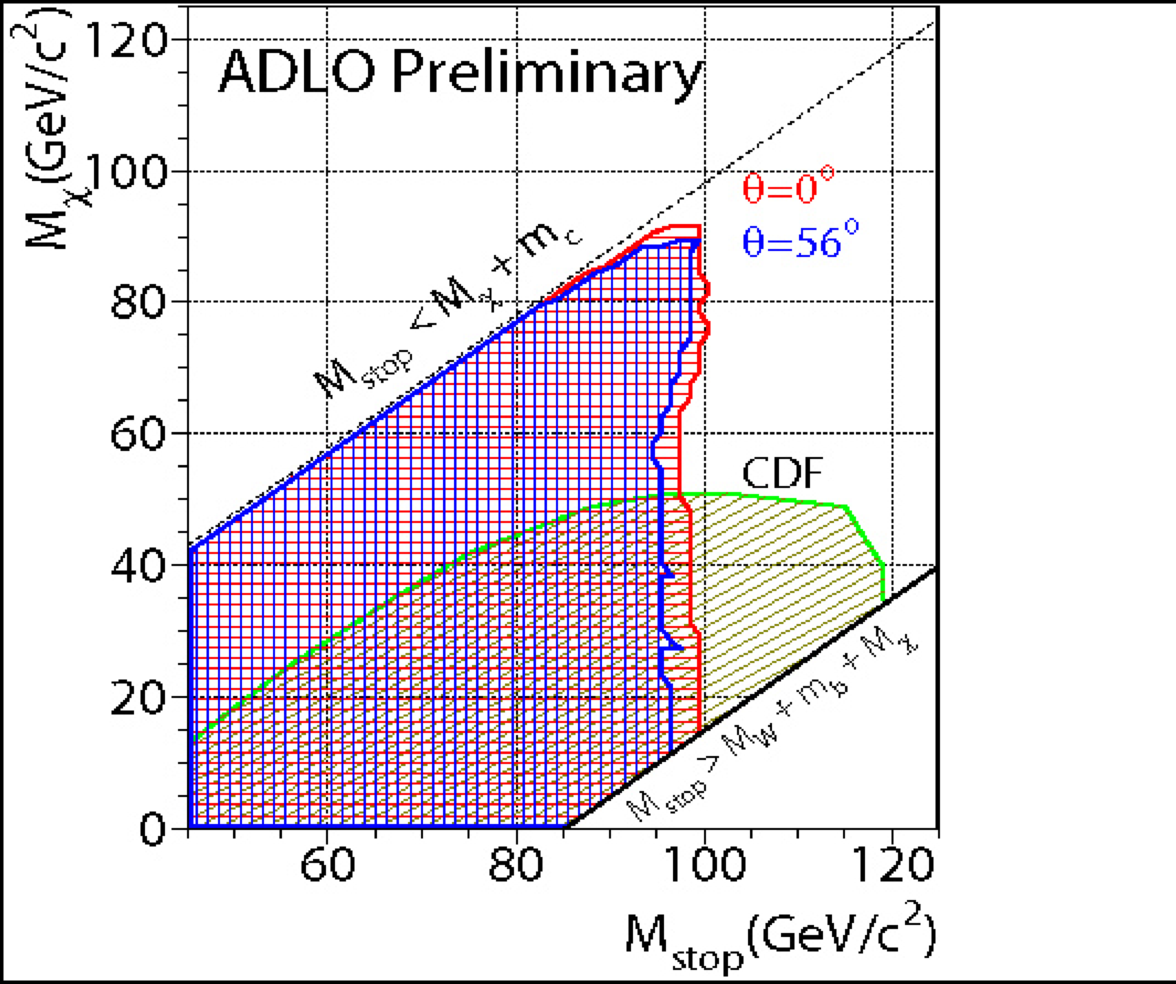


Mu	M_{top}=175	M_{top}=180
Positive	59.0	53.9
Negative	58.6	52.0

Squarks

Lightest are s-top and s-botom

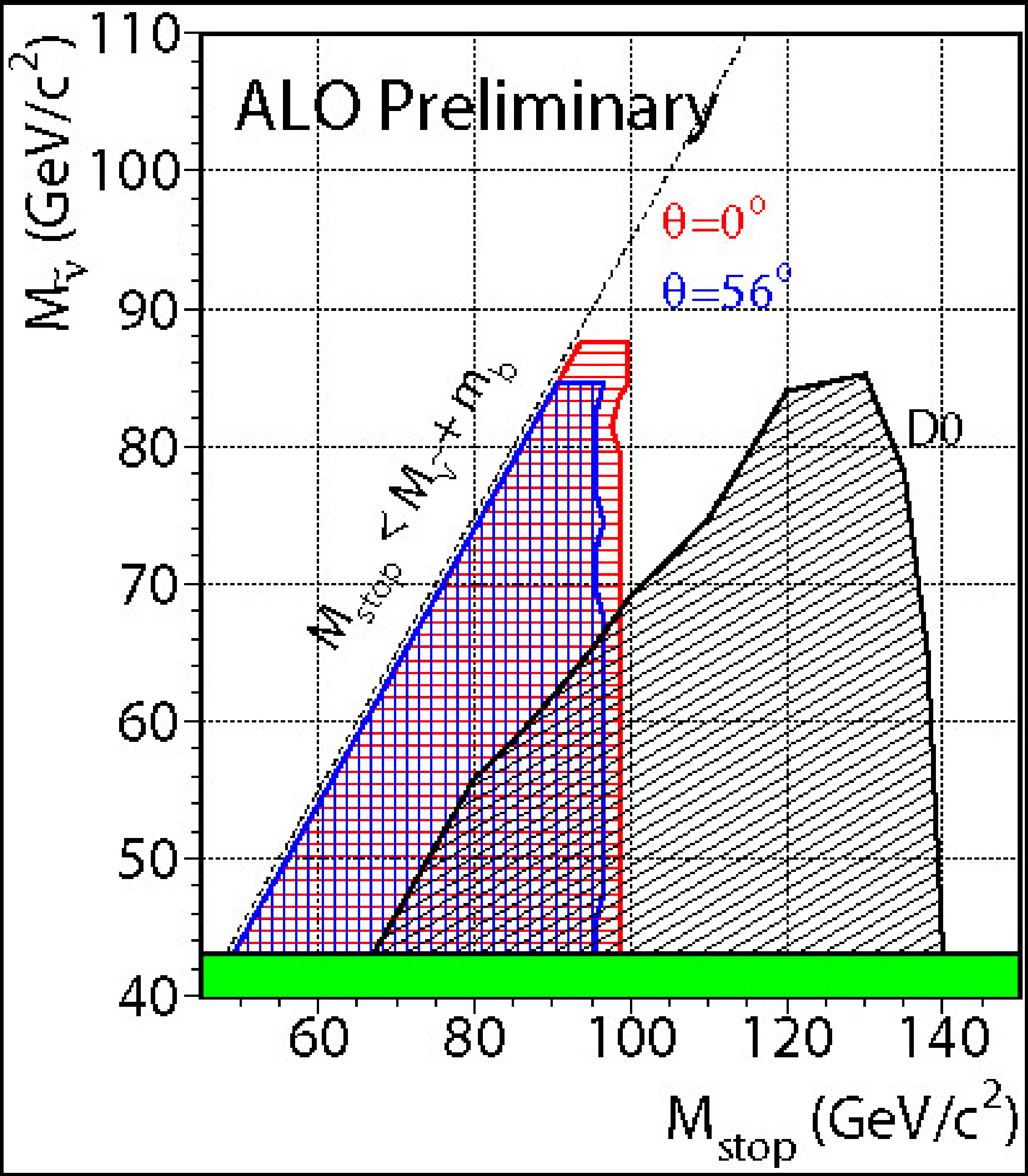
Look at stop->charm-neutralino *two acollinear jets*



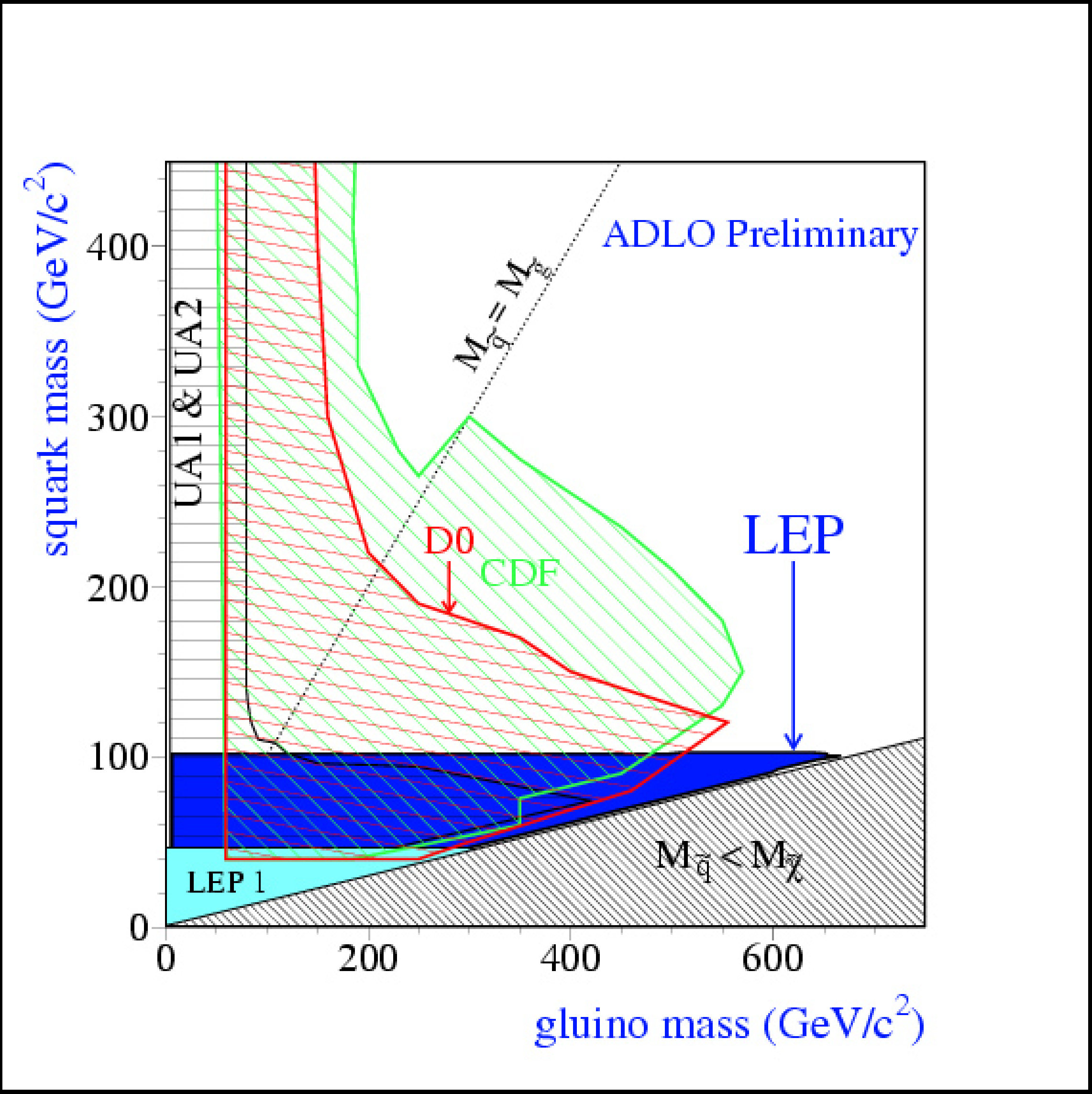
Similar study is done for $\tilde{b} \to b\chi_1^0$

Stop Leptonic Decay

Search through $\tilde{t} \rightarrow bl\tilde{\nu}$

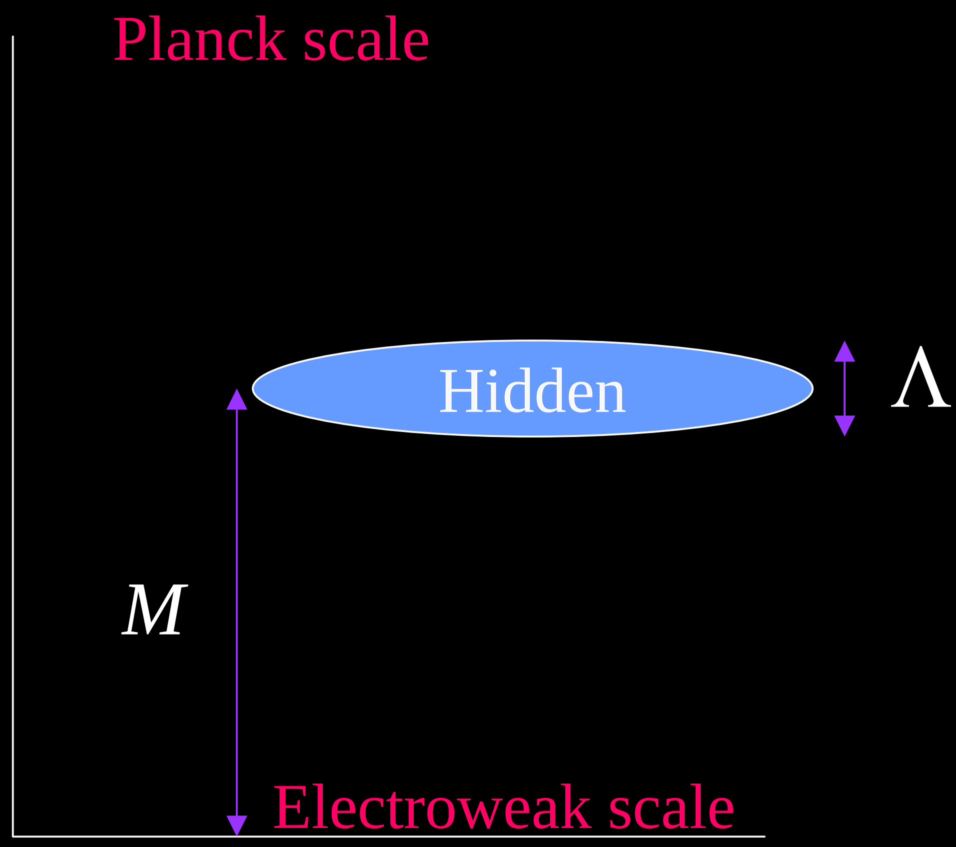


Squarks & Gluino



GMSB

Basic idea: SUSY is softly broken somewhere between the Planck and Electroweak scale. The breaking occurs in a 'hidden' sector and is mediated down via ordinary gauge bosons.



Phenomenology depends mainly on Λ and $\tan\beta$

Basic Phemenology

The LSP in GMSB is always the Gravitino which is basically massless.

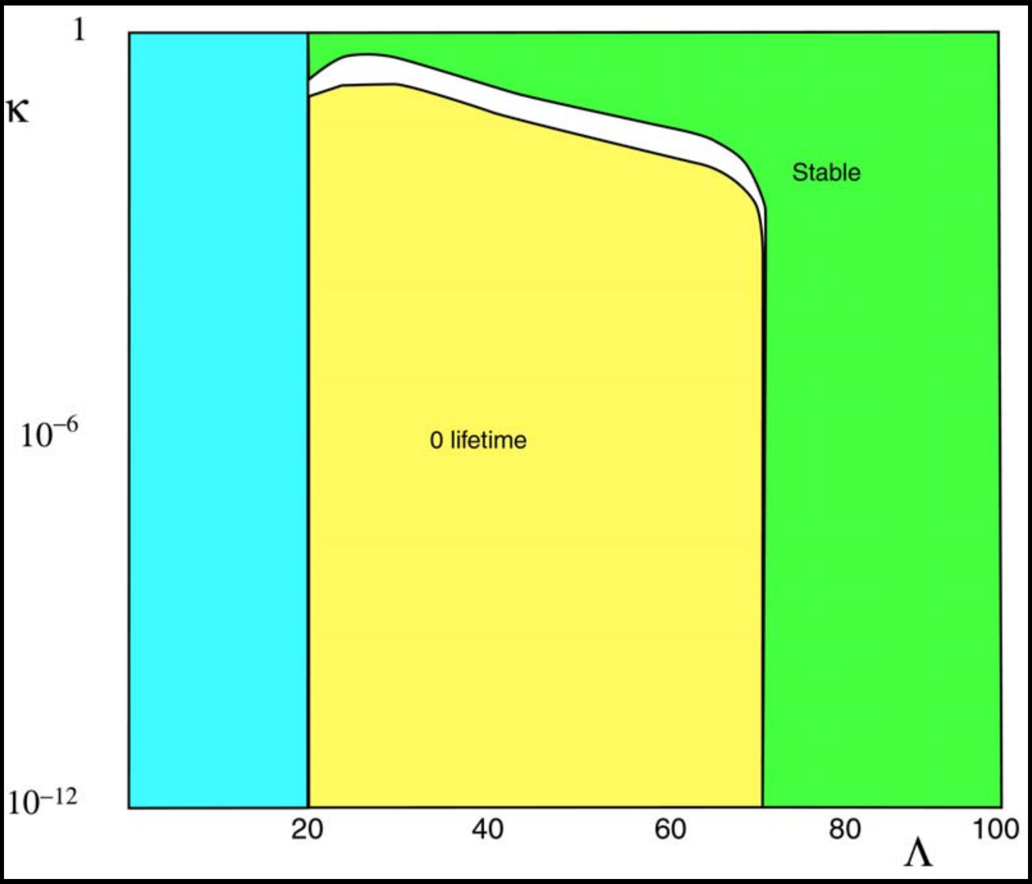
$$m_G = F / \kappa \left[\sqrt{3} M_P \right]$$

Colored sparticles, due to their extra gauge coupling, are heavier than the non-colored ones. Consequently the NLSP is either the neutralino or the sleptons (stau or all together).

The effective coupling of the NLSP to the gravitino depends on an additional free coefficient of the model, (κ). Variations of this coefficient can lead to 3 different cases namely:

- Quasi stable NLSP
- 0-lifetime NLSP
- NLSP with decay distance comparable to the size of the detector.

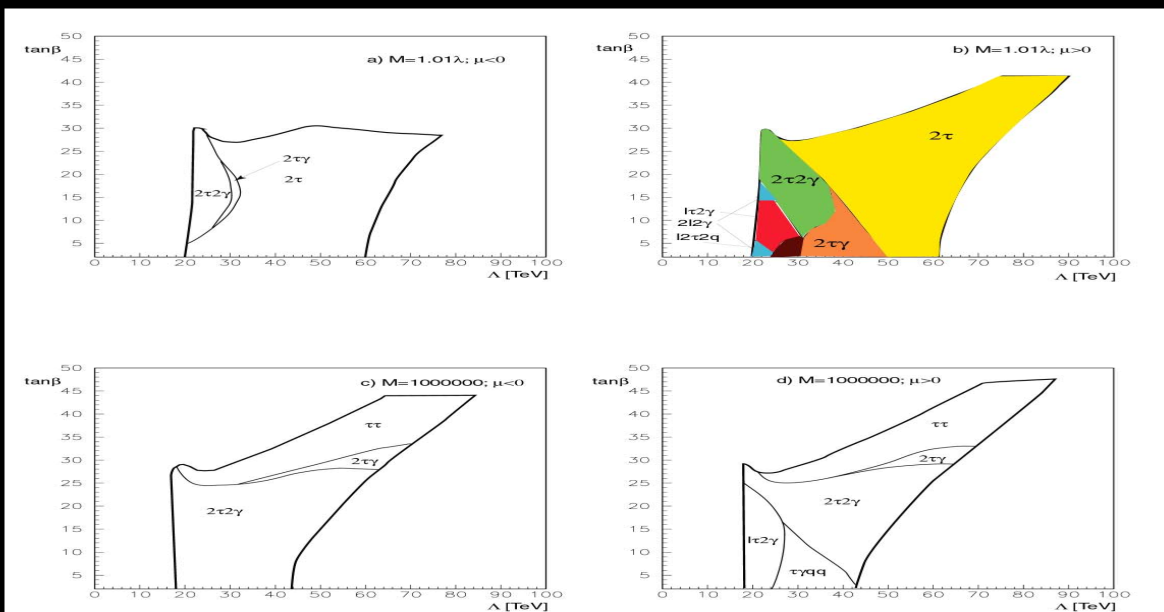
Life-times in GMSB

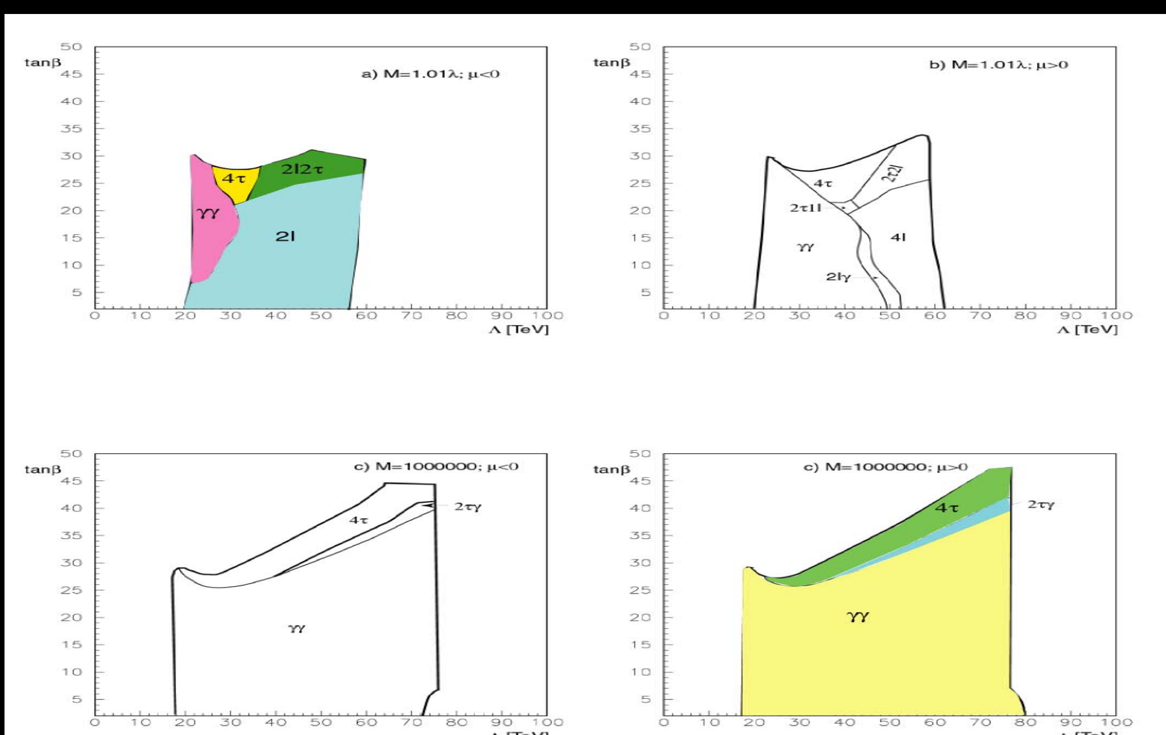


Either in the 'stable' or in the '0-life-time' situation

What Shall One Look For?

Very Rich phenomenology:



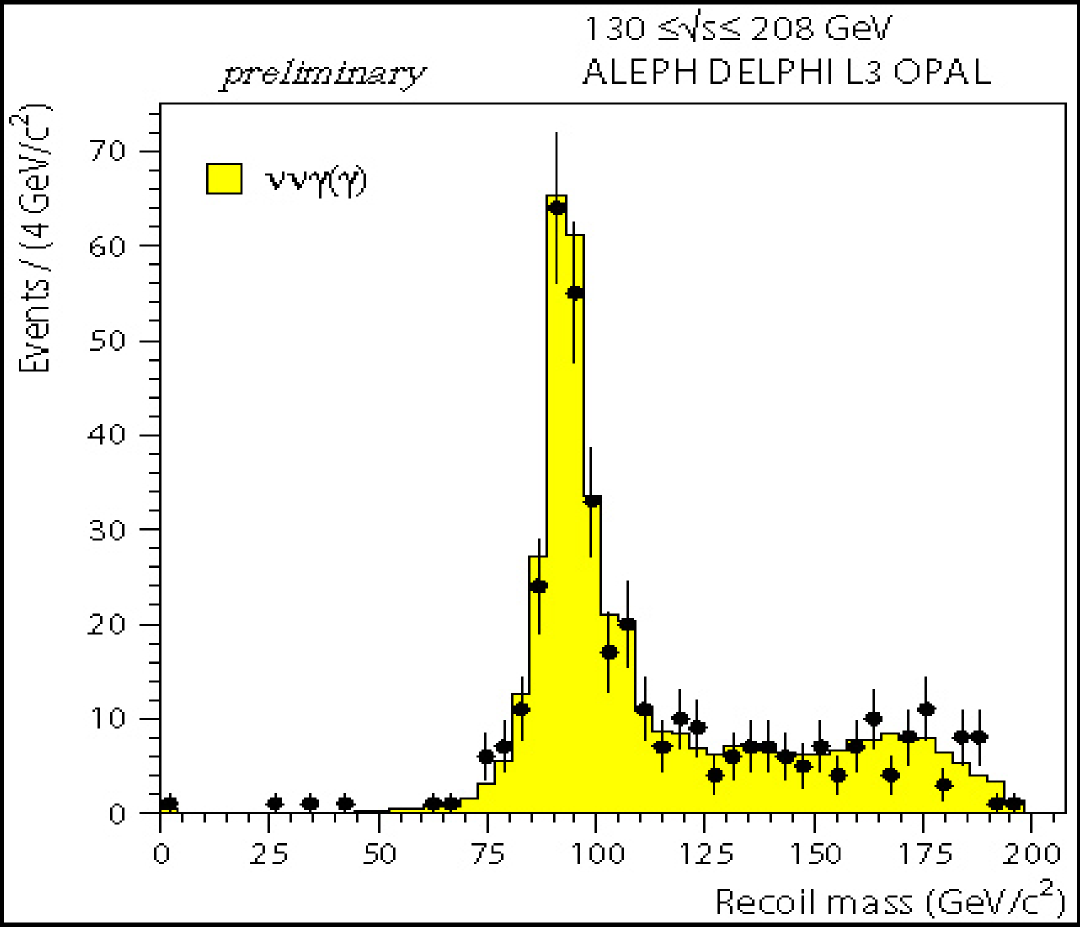


Neutralino Pair Production

The dominant decay mode of the neutralino is:

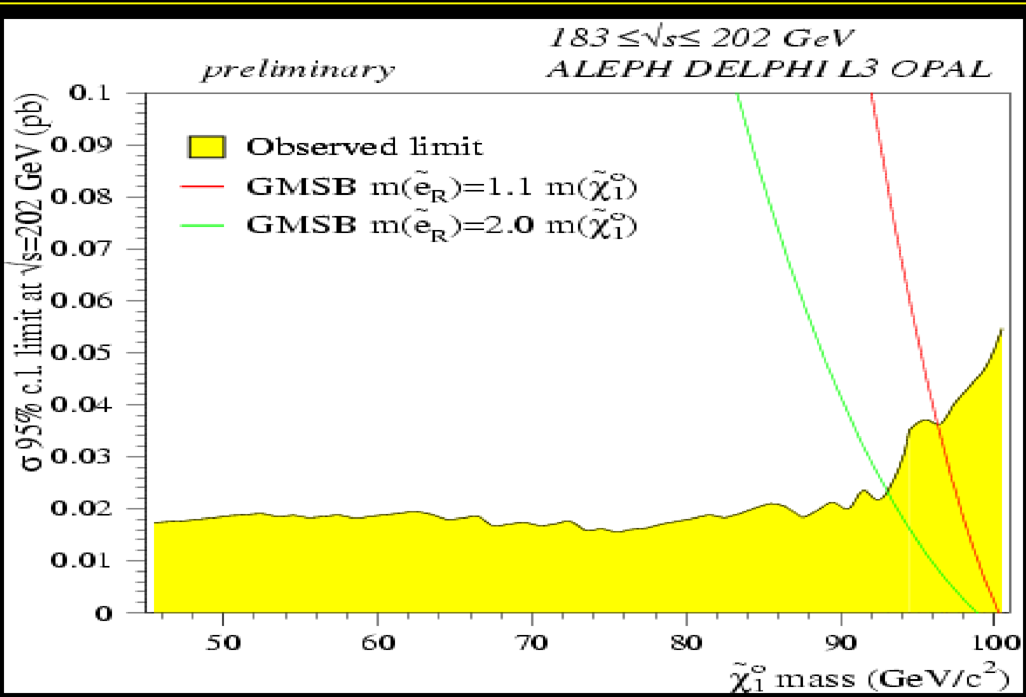
$$\chi_1^0 \rightarrow \gamma G_R$$

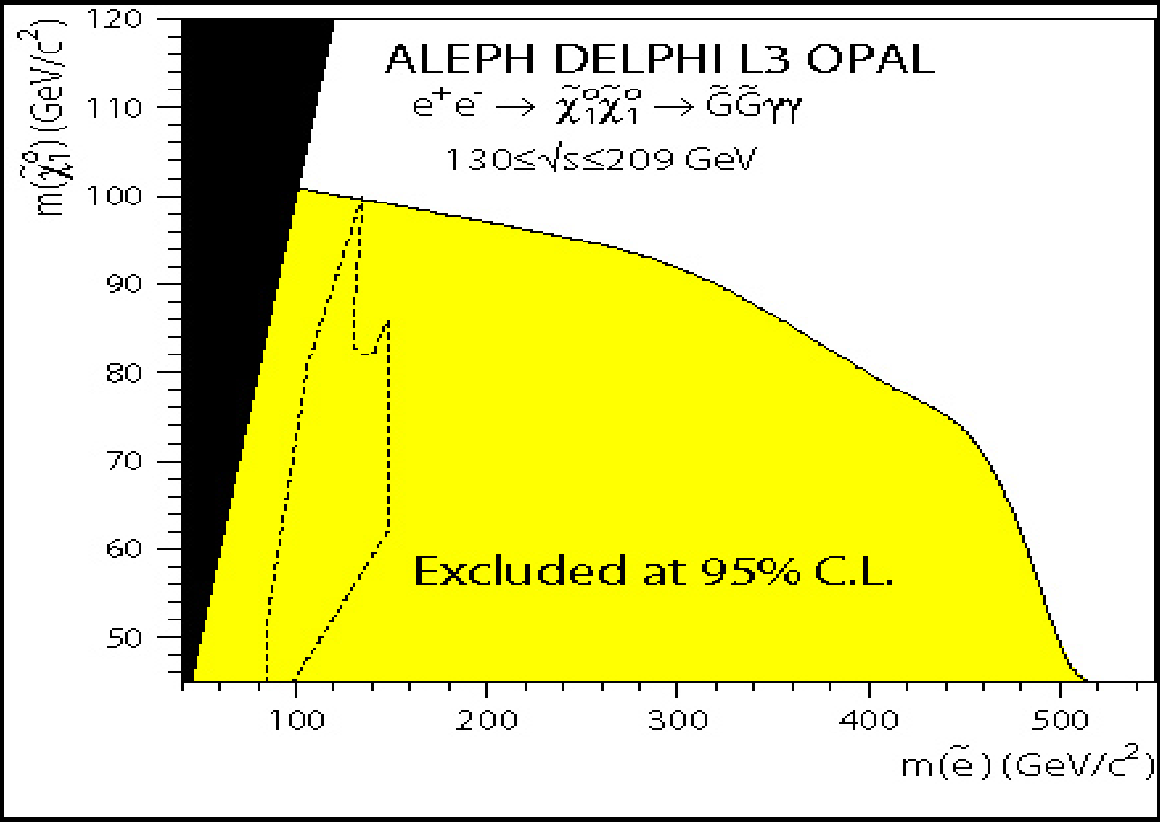
Such a decay can give rise to *di-photons* which are not back-to-back due to the gravitinos



Expect from SM 404 evts See 387.

Implications



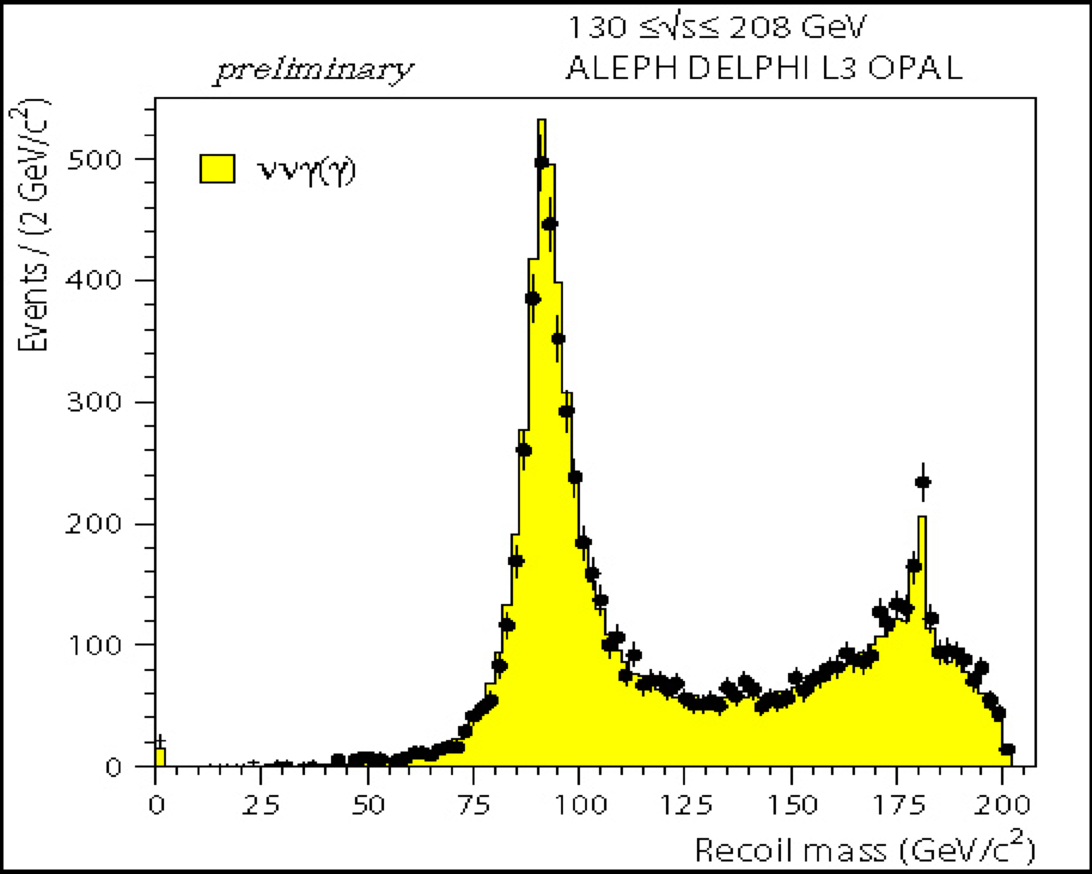


Single Photon

$$e^+e^- \rightarrow \chi_1^0\tilde{G} \rightarrow \gamma\tilde{G}\tilde{G}$$

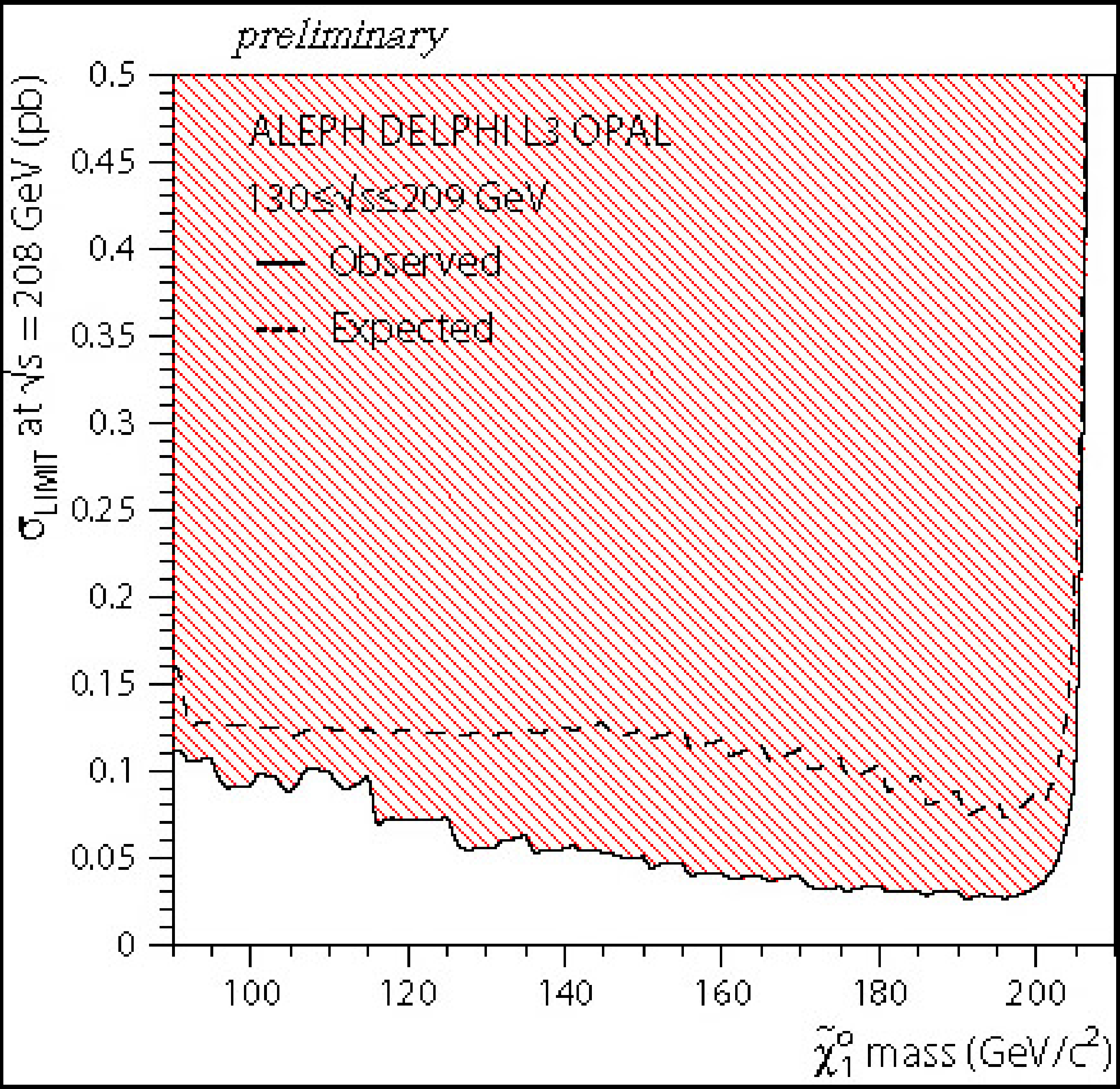
$$e^+e^- \rightarrow \chi_2^0\chi_1^0 \rightarrow \gamma\tilde{G}\tilde{G}$$

Also in case of a long-lived neutralino one of the neutralinos might decay inside and the other outside of the detector. In such a case one looks for single-photon events.

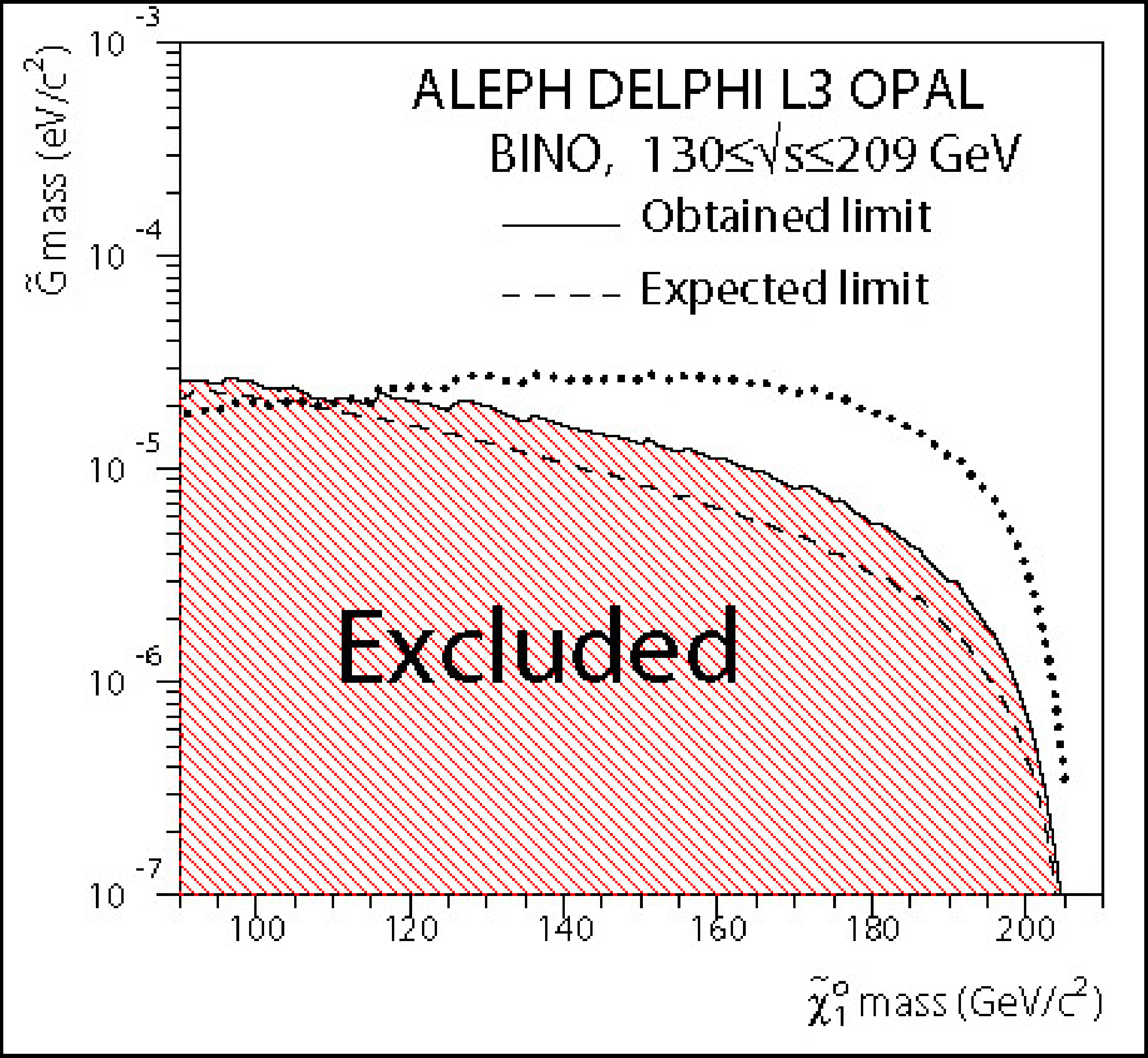


Expect 7676 events observe 7561.

Cross-section Limits



Interpretation



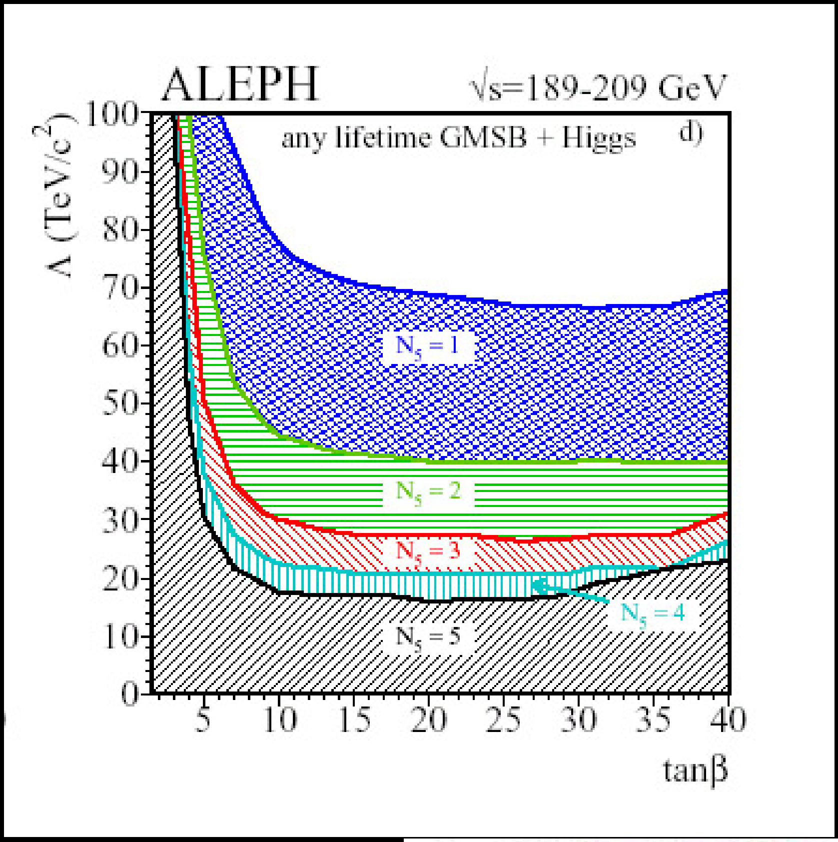
for $m_{\tilde{e}_L} = m_{\tilde{e}_R} = 150 GeV$

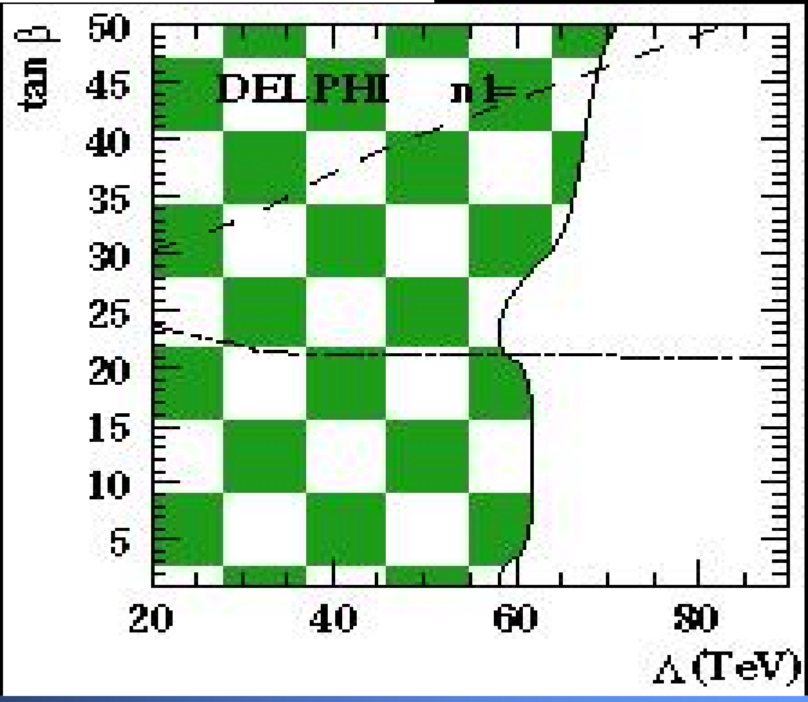
And Another List

For GMSB studies one looks at:

- one photon
- Two photons;
- two non pointing photons;
- Two …
- 4 tau;
- 2tau + 2 leptons;
- 4 leptons;
- 2 kinked leptons (high d_0) + 2 others;
- 6 leptons;
- 2 kiked leptons (high d_0) + 4 others;
- 2 leptons + 2 photons;
- Jets + photon ….

General Limit





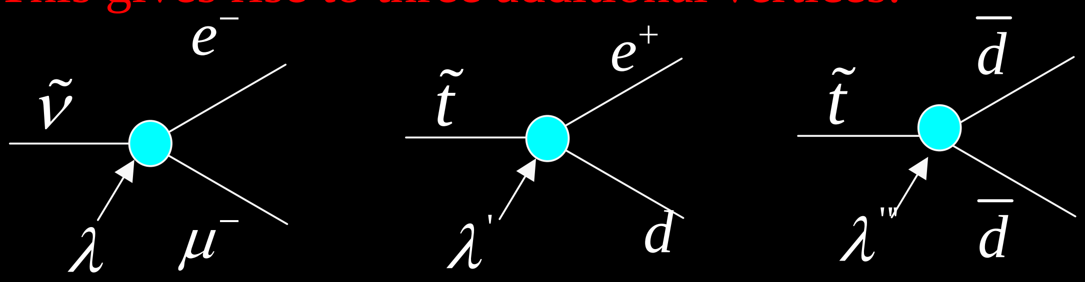
R Parity Violation

- The most general SUSY super potential contains terms like:

$$W = \lambda_{ijk} L_L^i L_L^j \overline{E_R^k} + \lambda'_{ijk} \; L_L^i Q_L^j \overline{D_R^k} + \lambda''_{ijk} \; \overline{U}_R^i \overline{D}_R^j \overline{D_R^k}$$

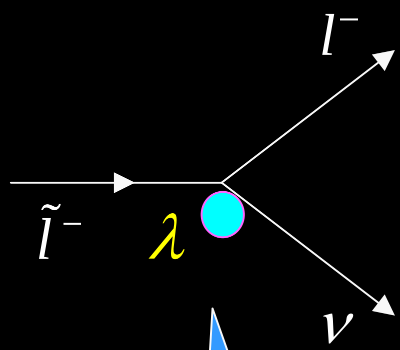
where	L_L	Lepton doublet	(1,2,1/2)
	Q_L	quark doublet	(3,2,1/6)
	D_R	down-type quark singlet	(3,1,1/3)
	U_R	up-type quark singlet	(3,1,-2/3)
	E_R	down-type lepton singlet	(1,1,1)
	$\lambda, \lambda', \lambda''$	Yukawa couplings	
	i, j, k	generation indices	

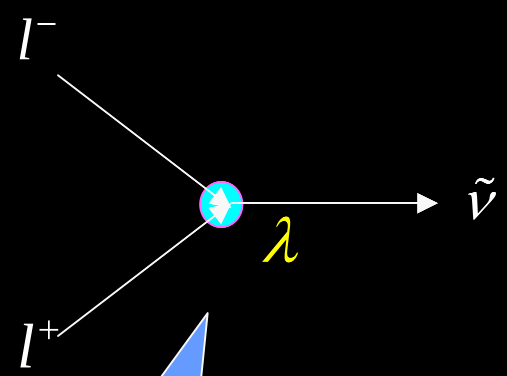
This gives rise to three additional vertices:



Due to symmetries ($\lambda_{ijk} = -\lambda_{jik}, \lambda''_{ijk} = -\lambda''_{ikj}$) there are 'only' 45 (9+27+9) independent Yukawa couplings

The $\lambda_{ijk} L_L^i L_L^j \overline{E_R^k}$ Term





Will affect decay modes

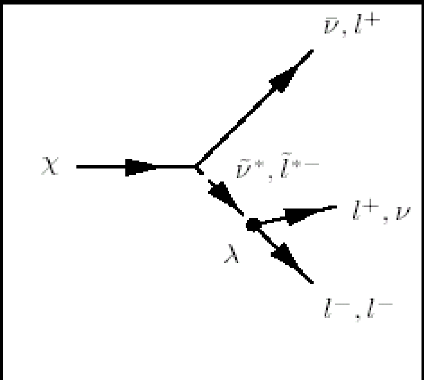
May give rise to resonant sneutrino production

This vertex violates L conservation!

There are 9 possible λ_{ijk} corficients

Working Assumptions:

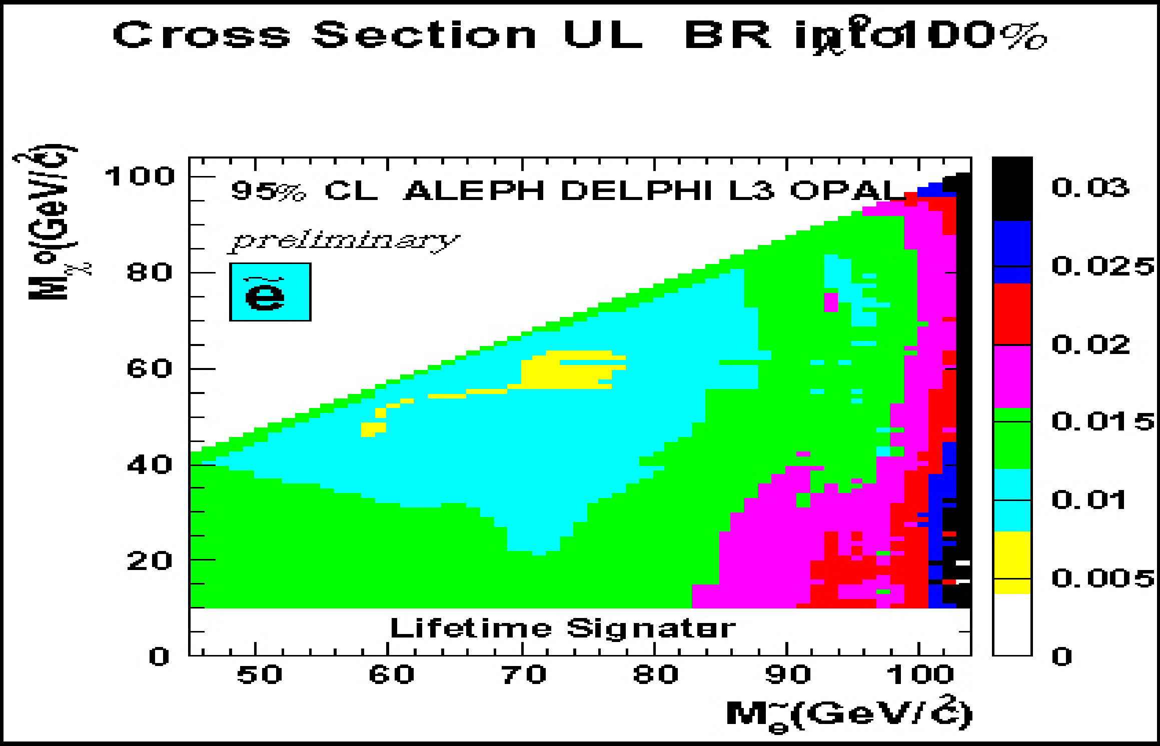
- Only one coupling differ from zero;
- It is not ‘very’ weak;
- Look at pair production of sleptons;
- Assume sleptons to decay the neutralino (LSP) (i.e.assume MSSM!);
- Assume M(neuralino)>10GeV;
- Assume M(slepton)-M(LSP)>3GeV;

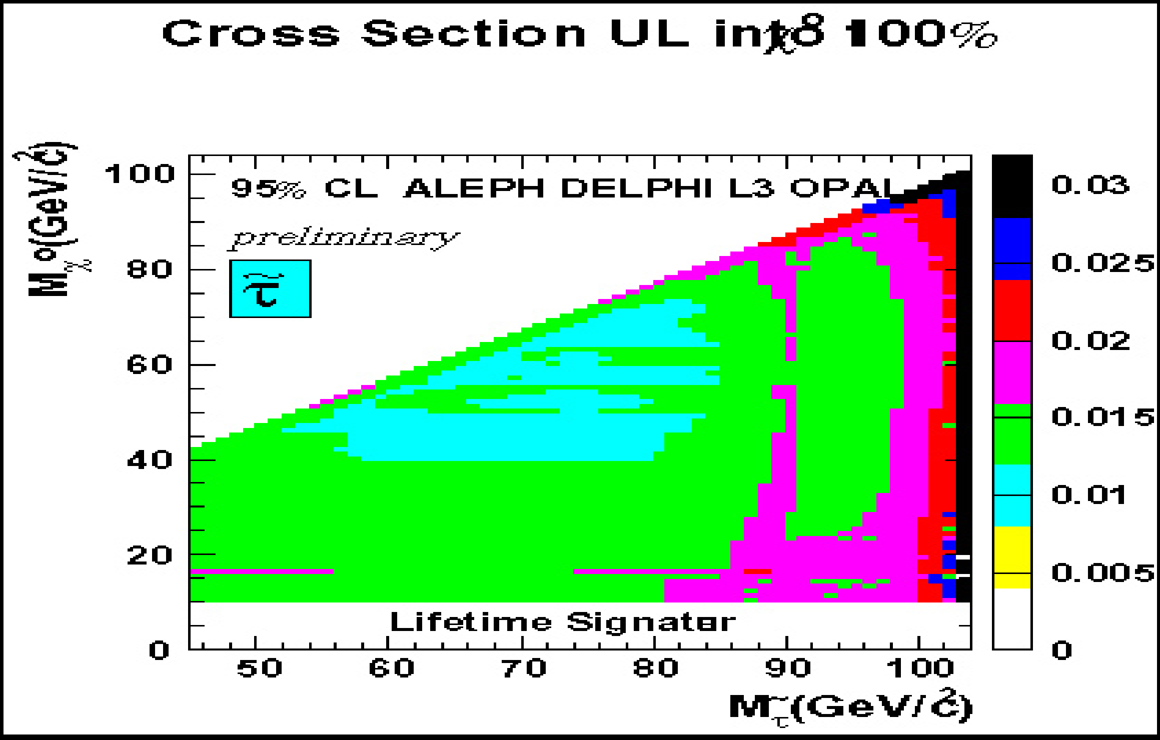


Compute upper limits on the prodction cross-section

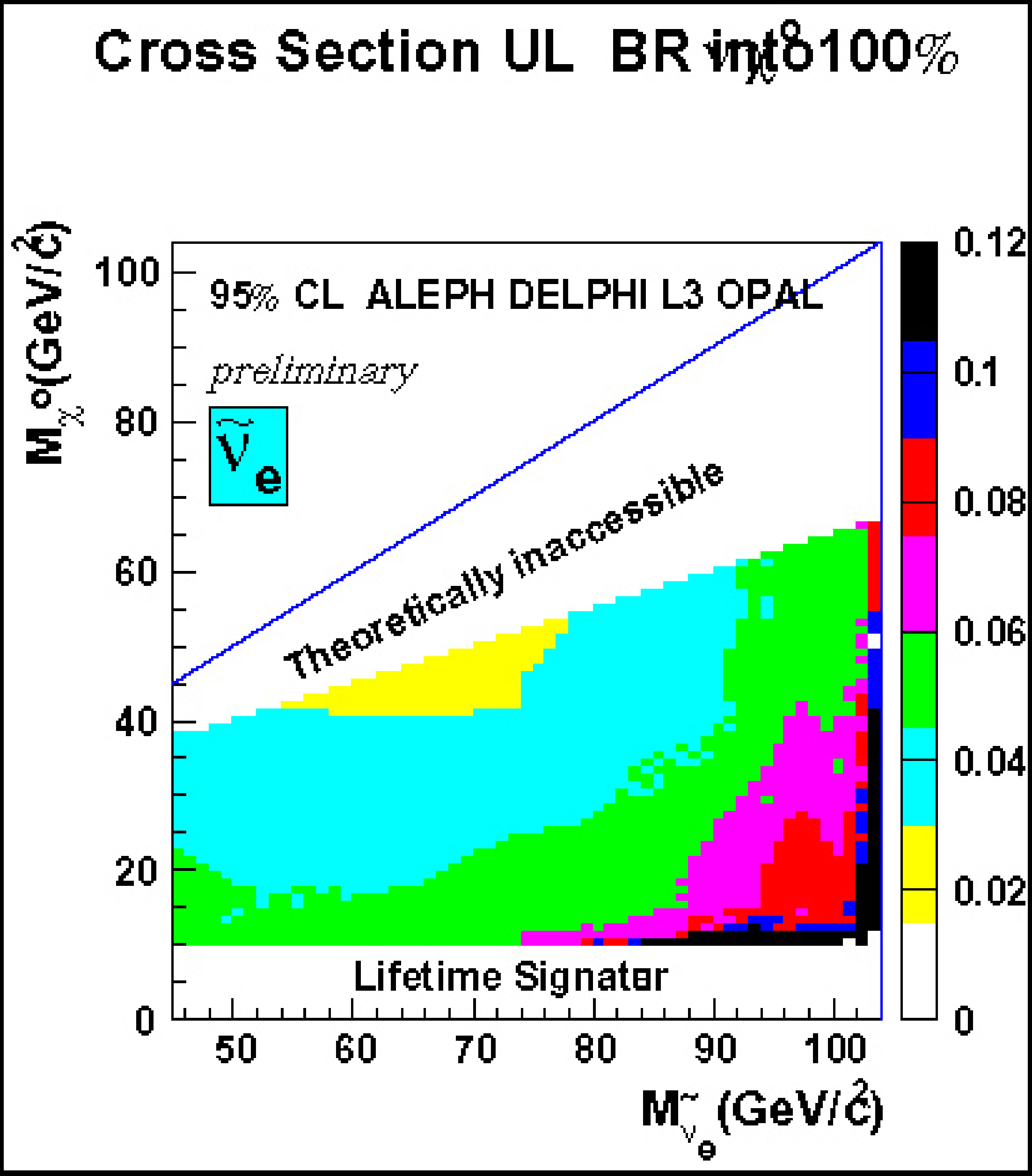
Derive mass limits in the framework of MSSM

Cross-section Limits

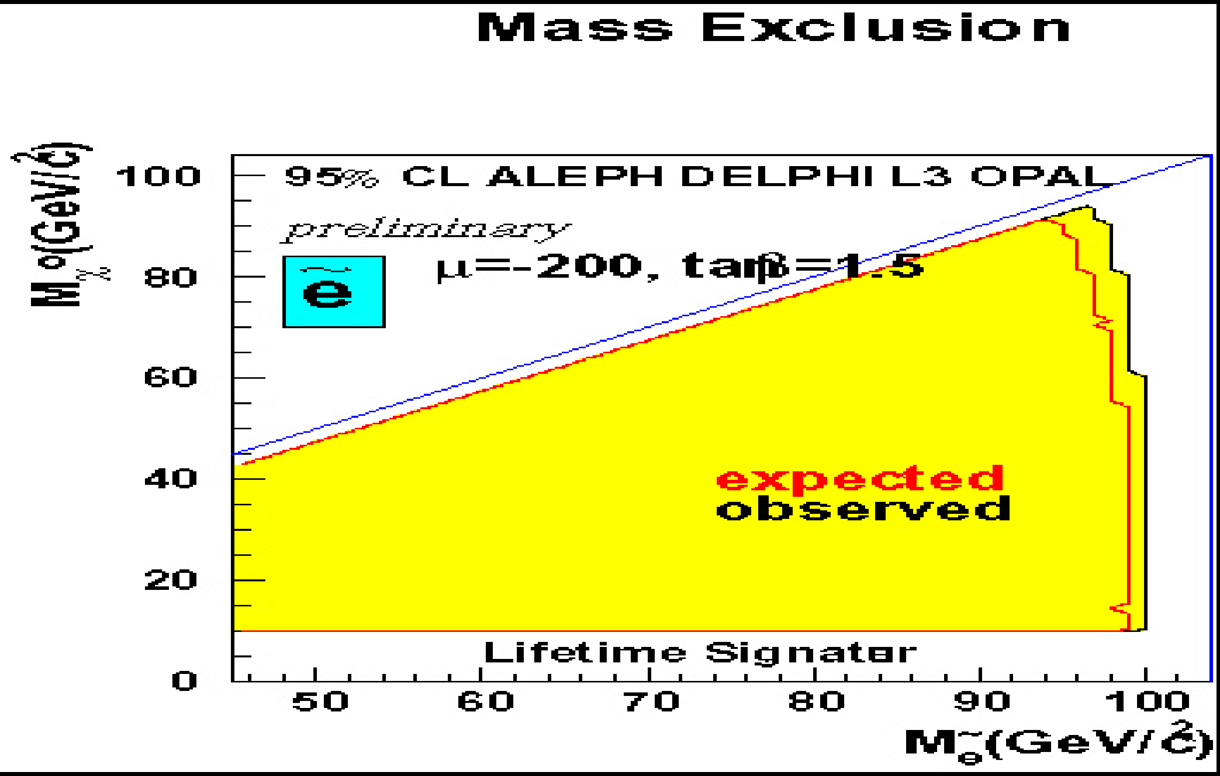




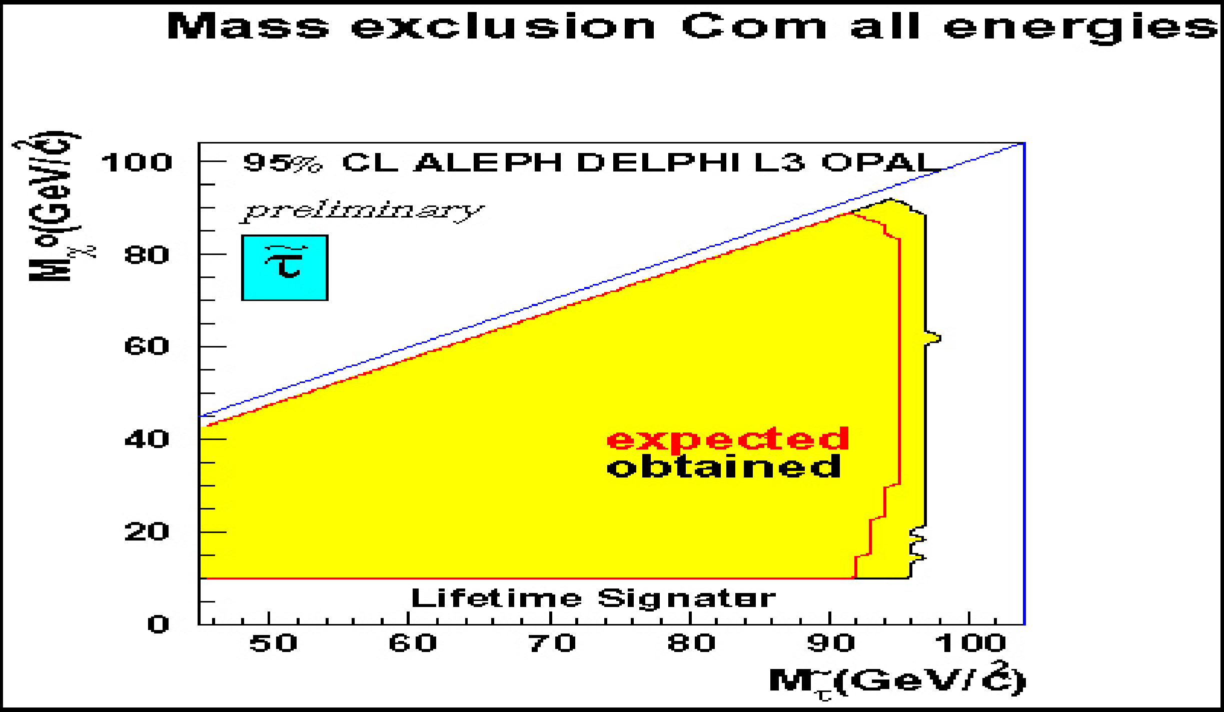
More Cross-sections



Mass Limits

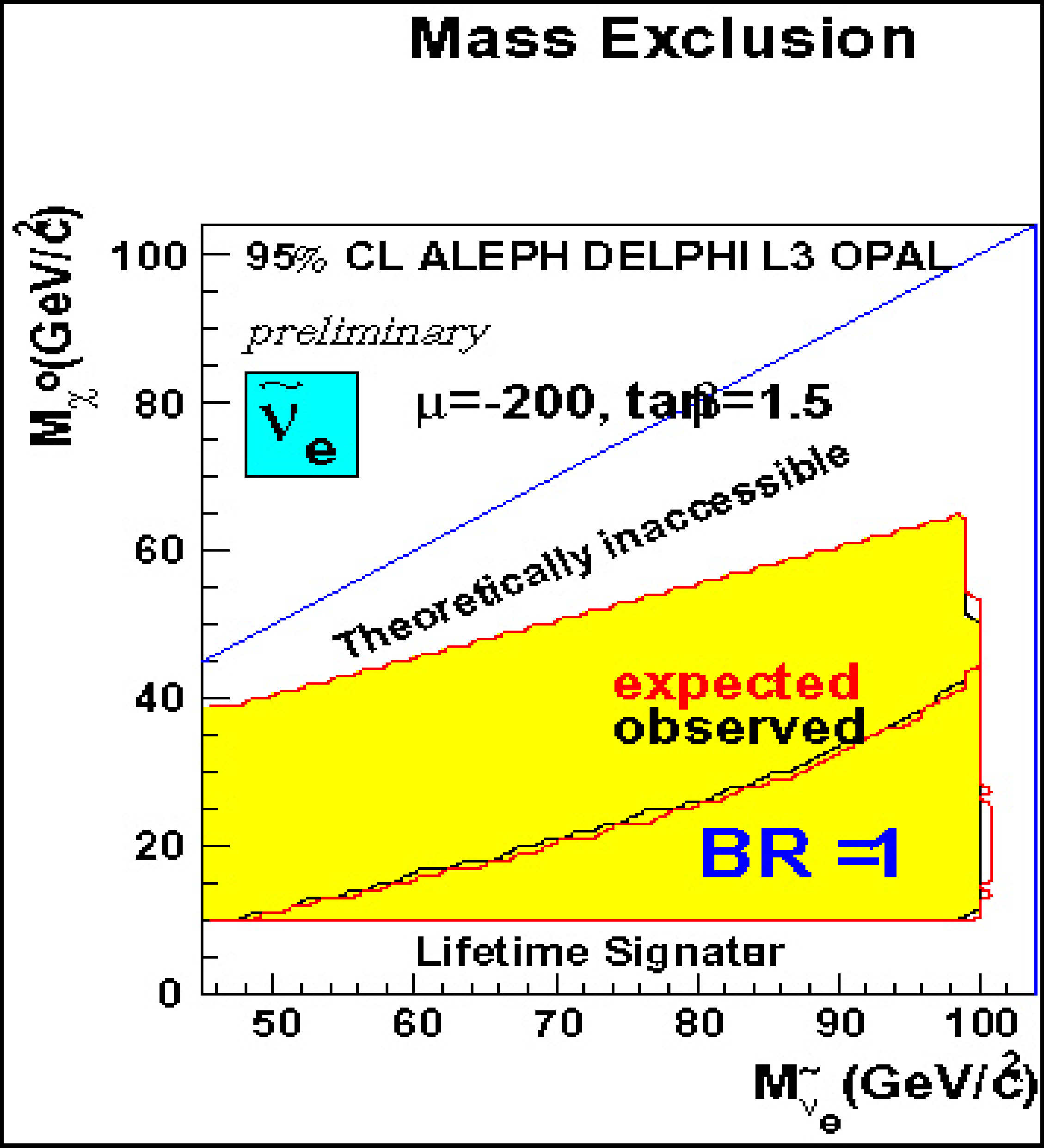


Mass Exclusion
95% CL ALEPH DELPHI L3 OPAL
preliminary
μ=-200, tanβ=1.5
expected
observed
Lifetime Signatur



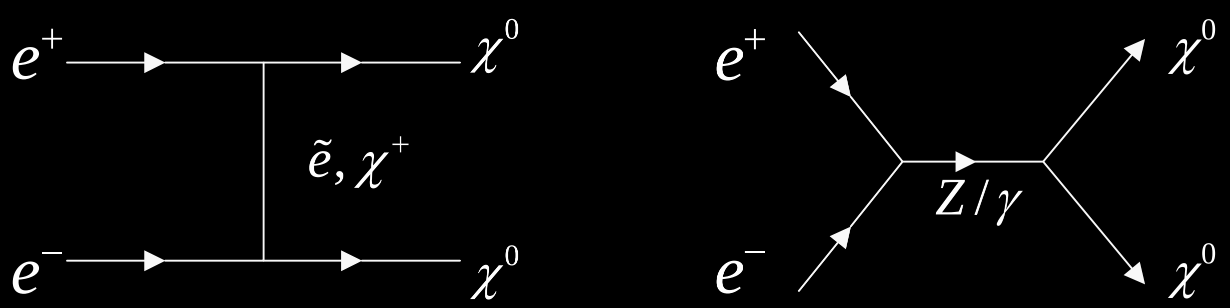
Mass exclusion Com all energies
95% CL ALEPH DELPHI L3 OPAL
preliminary
expected
obtained
Lifetime Signatur

More Mass Limits

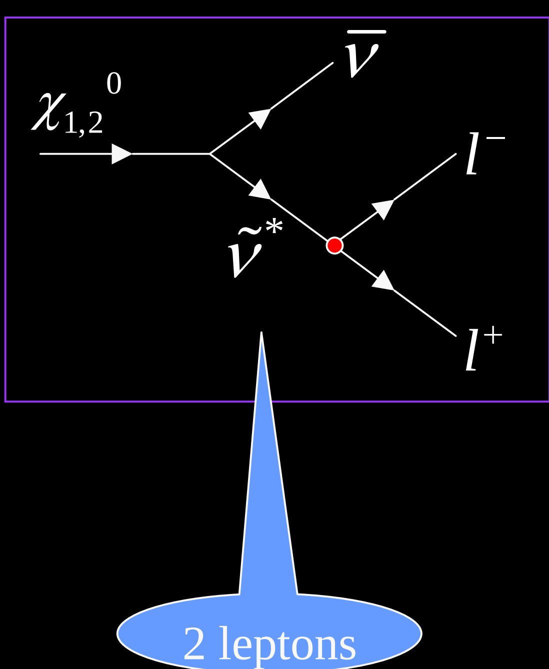


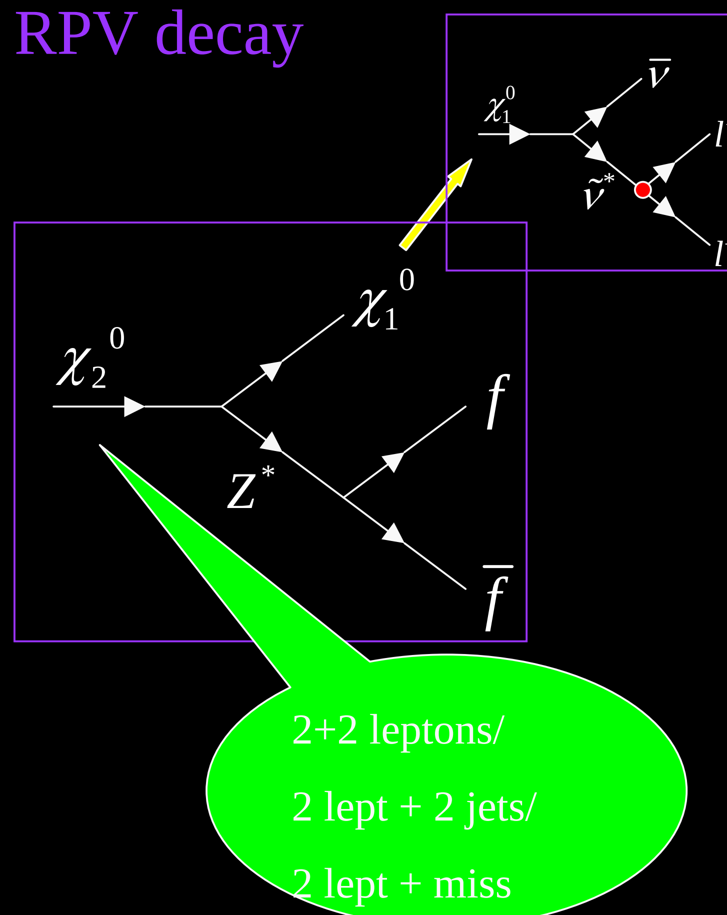
Search for neutralinos Decaying Through the LLE Term

One can produce a pair of charginos/neutralinos in the 'usual' way followed by RPV decay.



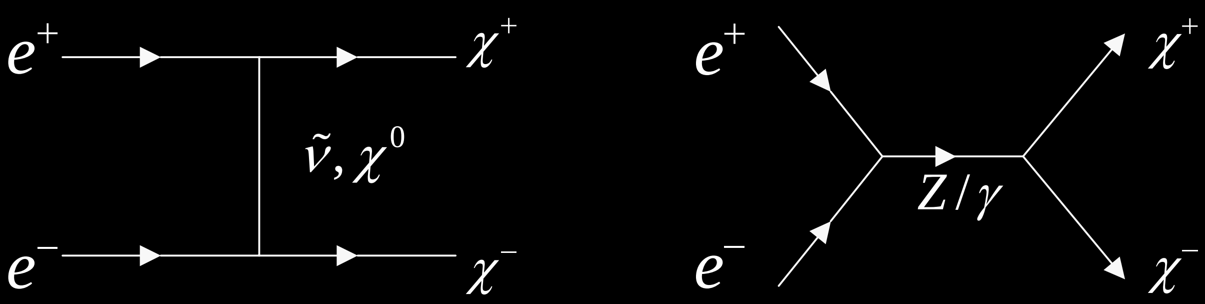
Coupled with an LLE RPV decay



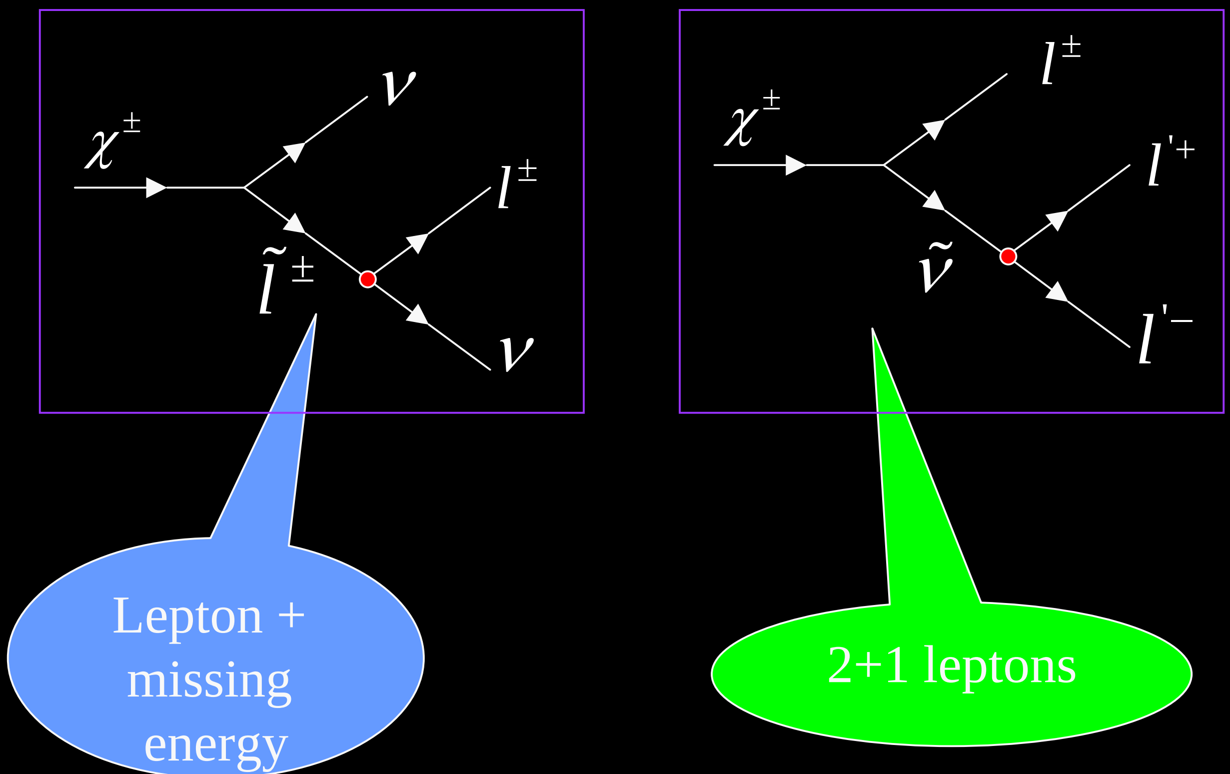


Search for charginos Decaying Through the LLE Term

Similar production processes

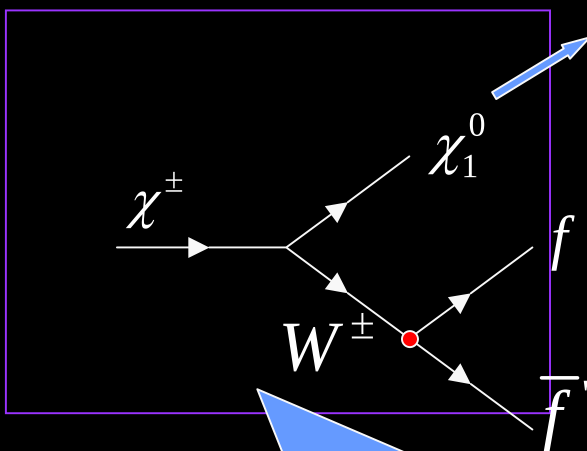


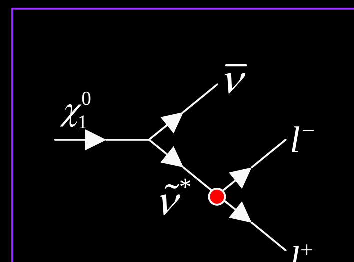
…and similar LLE decay modes:



And Both Together

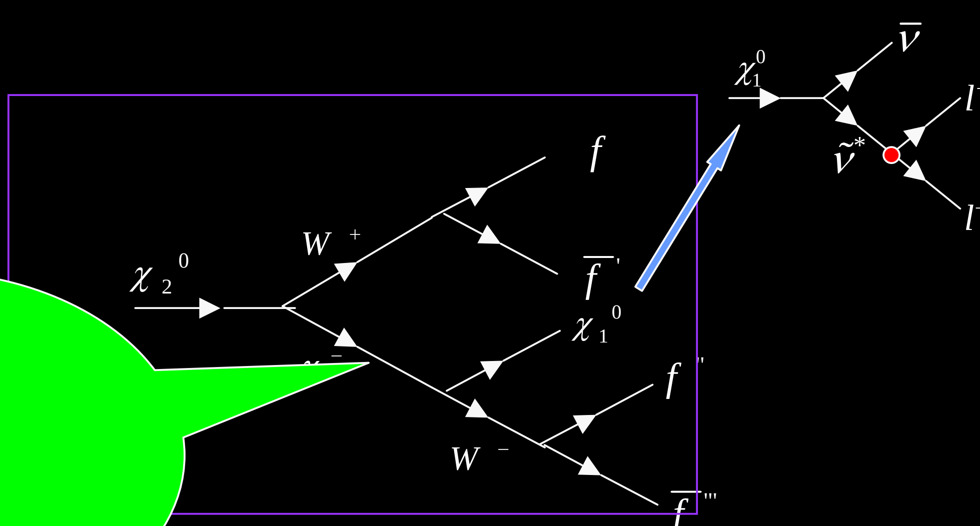
From chargino
pair production:





2 leptons+missing energy+2 jets or:
2+1 leptons + missing energy

production



2 lept+miss
+(4 jets or
2 jets + lept or
1+1 lept)

So What Should One Search for?

2+2 leptons + missing energy

2+2 leptons + E_{miss}, or

2+2 leptons + E_{miss} + Z^* decay products, or

2+2 leptons _E_{miss} + $2Z^*$ decay products, or

2+2 leptons +E_{miss} + W^+ & W^- decay products, or

2+2 leptons + E_{miss} + Z,W & W decay products,or

2+2 leptons + E_{miss} + 4W decay producs.

1+1 leptons + E_{miss} or

2+1+1 leptons + E_{miss} or

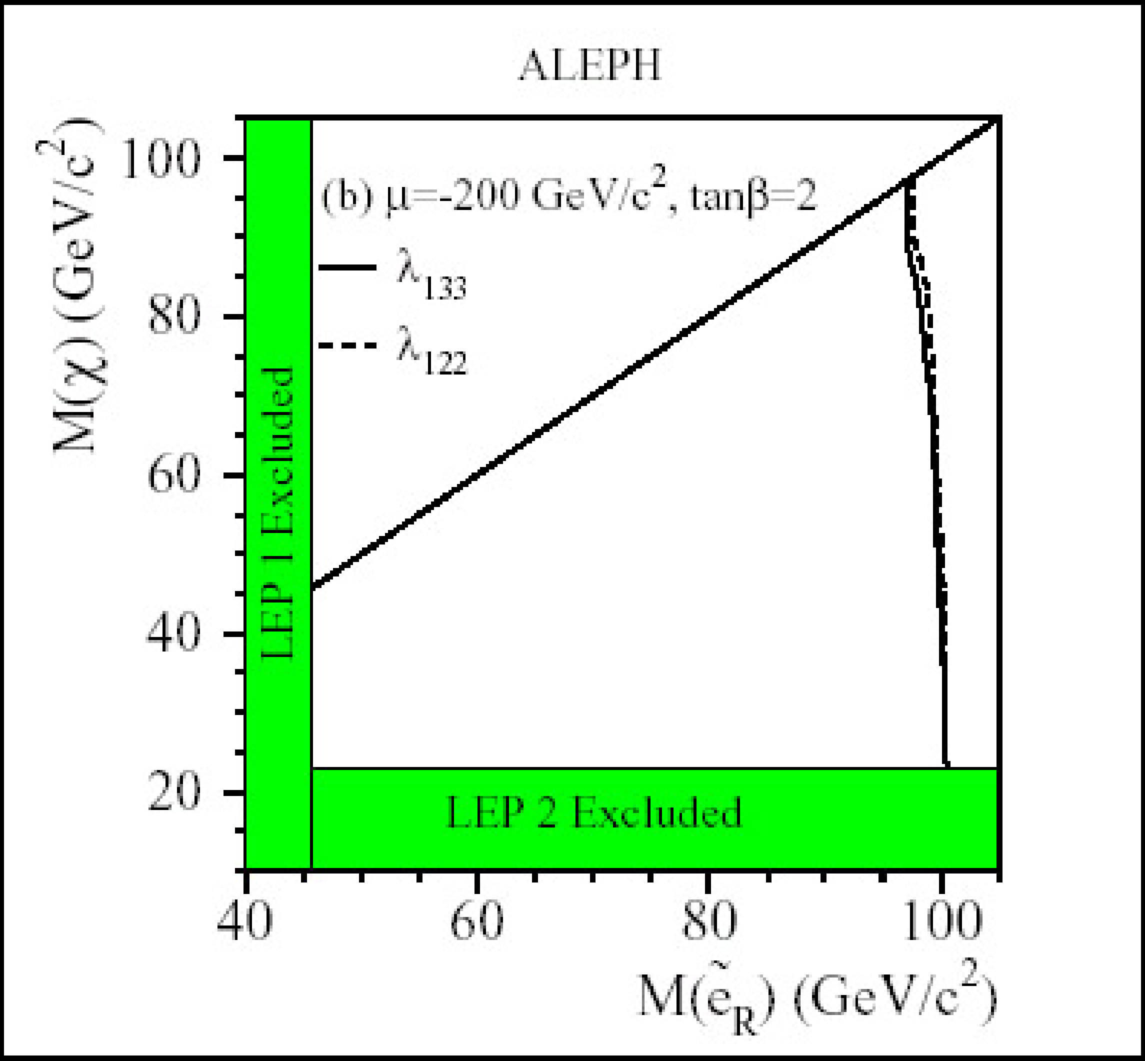
2+2+1+1 leptons, or

2+1 leptons + E_{miss} + W decay products, or

2+2+1 leptons + E_{miss} + W decay products, or

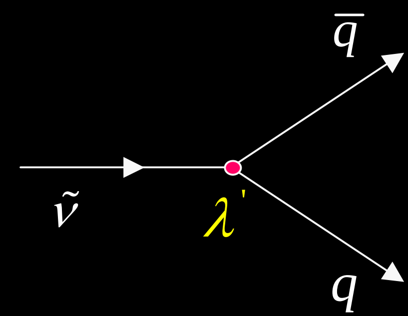
2+2 leptons + E_{miss} + W^+ & W^- decay products.

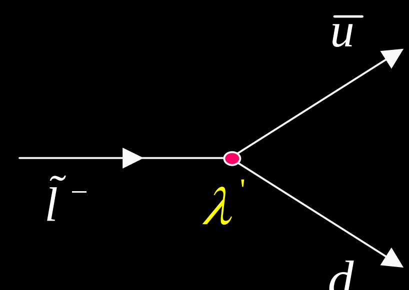
Typical Results



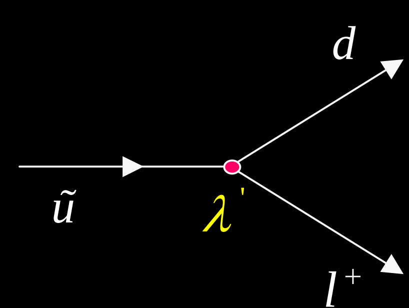
The $\lambda'_{ijk} L_L^i Q_L^j \overline{D_R^k}$ Term

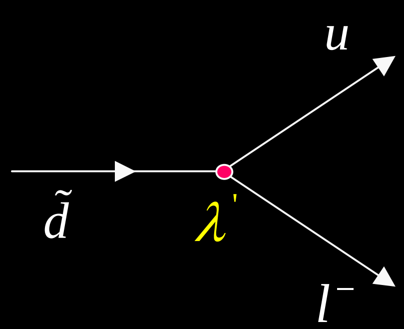
Slepton LQD decay:

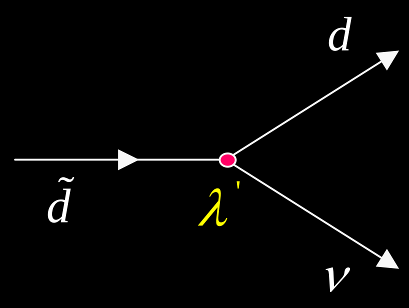




Squarks LQD decay:







Calico Jack Rackham

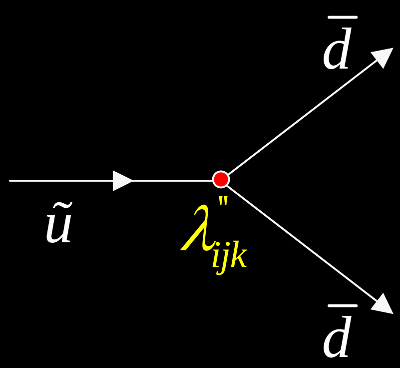
This vertex violates L conservation!

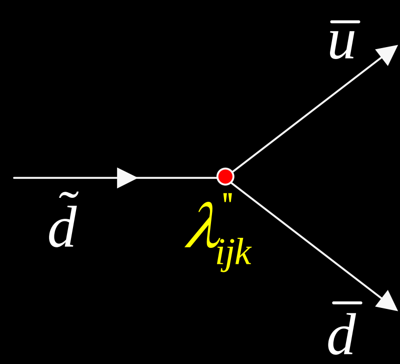
(27 Yukawa couplings)

The $\lambda''_{ijk}\,\overline{U}^i_R\,\overline{D}^j_R\,\overline{D}^k_R$ Term

This vertex violates B conservation!

('only' 9 Yukawa couplings)





Some limits already exist:

$\lambda''_{112} < 10^{-6}$	Double nucleon decay
$\lambda''_{113} < 10^{-4}$	Neutron oscillations
$\lambda''_{231,232,233} < 0.50$	LEP 1
$\lambda''_{123,131,132,133} < 1.25$	Pert. Uni.

Existing Limits on Products

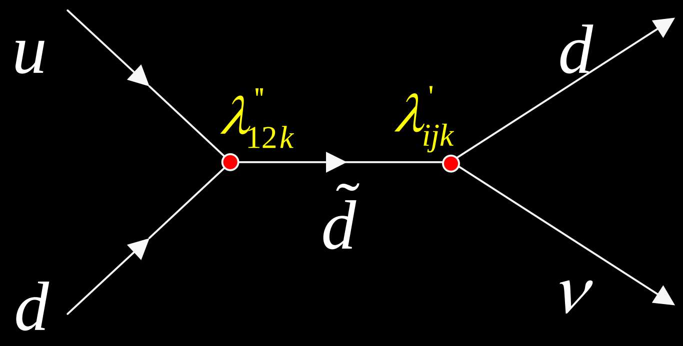
Quite a few limits on the relevant Yukawa couplings exist. In particular, from proton decay experiments one can deduce that:

$$\lambda'_{11k} * \lambda''_{11k} \leq 10^{-25} - 10^{-27}\, \tilde{d}^2_{kR}$$

In addition one gets that:

$$\lambda'_{ijk} * \lambda''_{lmn} \leq 10^{-7} - 10^{-9}$$

While such limits are well above LEP sensitivity range (O(10^{-5})), very few limits on individual Yukawa couplings exist and they are typically at the level of 0.01.



Expected Signatures

One can look for RPV through pair production of squarks, gauginos and sleptons. One can look for direct RPV violation (sparticle decays via RPV) or indirect (first some RC decays and RPV at the end).

The number of possible signatures exceeds even the number of Yukawa couplings!

Production and Decay		Coupling	Analysis Name	Section
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow$	$\ell qq\ \ell qq$	λ' direct	ℓ + jets	5.1.3
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow$	$\ell qq\ \nu qq$	λ' direct	ℓ + jets	5.1.3
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow$	$\nu qq\ \nu qq$	λ' direct	4 jets + E_{miss}	5.2.1
$\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^* W^* \tilde{\chi}_1^0\ \tilde{\chi}_1^0 \rightarrow$	$[\ell^+\nu][\ell^-\nu](\ell qq)(\ell qq)$	λ' indirect	ℓ + jets	5.1.3
	$[\ell^+\nu][\ell^-\nu](\ell qq)(\nu qq)$	λ' indirect	ℓ + jets	5.1.3
	$[\ell\nu][qq](\ell qq)(\ell qq)$	λ' indirect	ℓ + jets	5.1.3
	$[\ell\nu][qq](\ell qq)(\nu qq)$	λ' indirect	ℓ + jets	5.1.3
	$[\ell\nu][qq](\nu qq)(\nu qq)$	λ' indirect	> 4 jets + E_{miss}	5.3.1
	$[qq][qq](\ell qq)(\ell qq)$	λ' indirect	ℓ + jets	5.1.3
	$[qq][qq](\ell qq)(\nu qq)$	λ' indirect	ℓ + jets	5.1.3
	$[qq][qq](\nu qq)(\nu qq)$	λ' indirect	> 4 jets + E_{miss}	5.3.1
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow$	$qqq\ qqq$	λ'' direct	> 4 jets	5.3.2
$\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^* W^* \tilde{\chi}_1^0\ \tilde{\chi}_1^0 \rightarrow$	$[\ell^+\nu][\ell^-\nu](qqq)(qqq)$	λ'' indirect	> 4 jets	5.3.2
	$[\ell\nu][qq](qqq)(qqq)$	λ'' indirect	> 4 jets	5.3.2
	$[qq][qq](qqq)(qqq)$	λ'' indirect	> 4 jets	5.3.2

Look at f.s. containing as many as 10 jets!

More Channels

Physics process	E . (%)	Data	Tot. bkg MC	Data > 206 GeV	MC > 206 GeV
$\tilde{e}^+ \tilde{e}$					
4 jets + 2 e + 2 e	38.6 – 69.0	13	13.3 ± 0.6 ± 0.5	2	2.5 ± 0.3 ± 0.3
4 jets + 2 e + 2 μ	25.0 – 53.0	2	2.6 ± 0.3 ± 0.2	0	0.7 ± 0.1 ± 0.1
4 jets + 2 e + 2	5.6 – 25.4	14	12.7 ± 0.6 ± 0.7	5	2.7 ± 0.3 ± 0.2
4 jets + 2 e + e	17.4 – 39.7	16	17.6 ± 0.7 ± 0.6	2	3.3 ± 0.3 ± 0.3
4 jets + 2 e + μ	20.9 – 52.2	16	12.3 ± 0.6 ± 0.6	4	2.8 ± 0.3 ± 0.4
4 jets + 2 e +	2.3 – 11.6	7	7.3 ± 0.5 ± 0.4	1	1.5 ± 0.2 ± 0.2
4 jets + 2 e + 2	6.0 – 17.0	6	5.8 ± 0.4 ± 0.2	2	1.4 ± 0.3 ± 0.1
$\tilde{\mu}^+ \tilde{\mu}$					
4 jets + 2 μ + 2 e	34.1 – 54.0	2	1.6 ± 0.2 ± 0.1	0	0.2 ± 0.1 ± 0.0
4 jets + 2 μ + 2 μ	52.0 – 78.8	4	2.9 ± 0.3 ± 0.3	2	0.7 ± 0.1 ± 0.2
4 jets + 2 μ + 2	8.8 – 31.9	2	3.6 ± 0.3 ± 0.2	0	0.7 ± 0.1 ± 0.1
4 jets + 2 μ + e	25.3 – 52.1	5	4.4 ± 0.3 ± 0.4	0	1.0 ± 0.2 ± 0.3
4 jets + 2 μ + μ	29.8 – 51.2	4	3.6 ± 0.3 ± 0.3	2	0.9 ± 0.2 ± 0.2
4 jets + 2 μ +	5.8 – 21.5	2	2.3 ± 0.2 ± 0.1	0	0.4 ± 0.1 ± 0.0
4 jets + 2 μ + 2	14.7 – 34.9	6	3.8 ± 0.3 ± 0.2	0	0.8 ± 0.1 ± 0.0
˜ + ˜					
4 jets + 2 + 2 e	18.8 – 51.5	9	9.4 ± 0.5 ± 0.3	1	1.9 ± 0.3 ± 0.1
4 jets + 2 + 2 μ	19.3 – 55.5	7	8.8 ± 0.4 ± 0.7	0	2.2 ± 0.2 ± 0.5
4 jets + 2 + 2	6.7 – 21.7	53	46.0 ± 1.1 ± 1.6	6	9.3 ± 0.6 ± 0.6
4 jets + 2 + e	4.2 – 16.3	15	12.1 ± 0.6 ± 0.4	1	2.1 ± 0.3 ± 0.2
4 jets + 2 + μ	3.8 – 13.5	12	12.8 ± 0.5 ± 0.6	1	2.8 ± 0.3 ± 0.4
4 jets + 2 +	7.7 – 21.1	26	24.9 ± 0.8 ± 0.9	6	5.1 ± 0.4 ± 0.5
4 jets + 2 + 2	2.9 – 8.0	83	66.3 ± 1.2 ± 0.9	16	13.6 ± 0.6 ± 0.2

Conclusion

An incredible amount of work has been invested in the search for every conceivable final state. Nothing has been seen.

Had there been pair production of SUSY particles with mass below LEP beam energy – we would have seen it!

In the framework of MSSM the lower mass limit on the

LSP is 58.6 GeV.

Chargino > 91.9 Gev

Selectron > 73 GeV

It the Framework of GMSB:

$\Lambda > 17 TeV$ for N=4