Ehud Duchovni, Orsay March 2001

Search For Non-MSSM SUSY Models

- R Parity Violation (RPV)
- Gauge Mediated (GMSB)
- Spontaneous RPV
- Sgoldstino
- LSP gluino

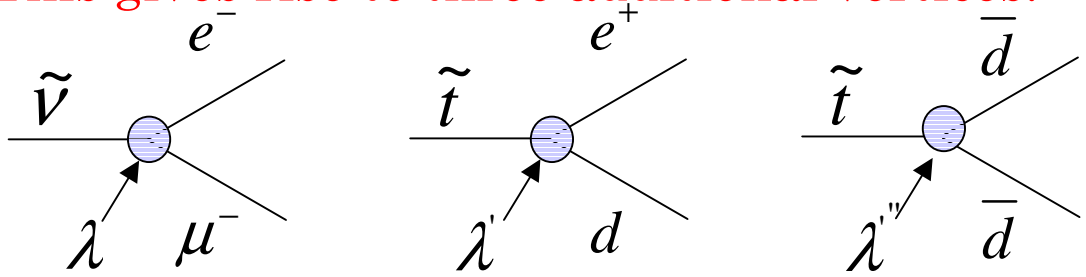
R-parity Violation

- The most general SUSY super potential contains terms like:

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

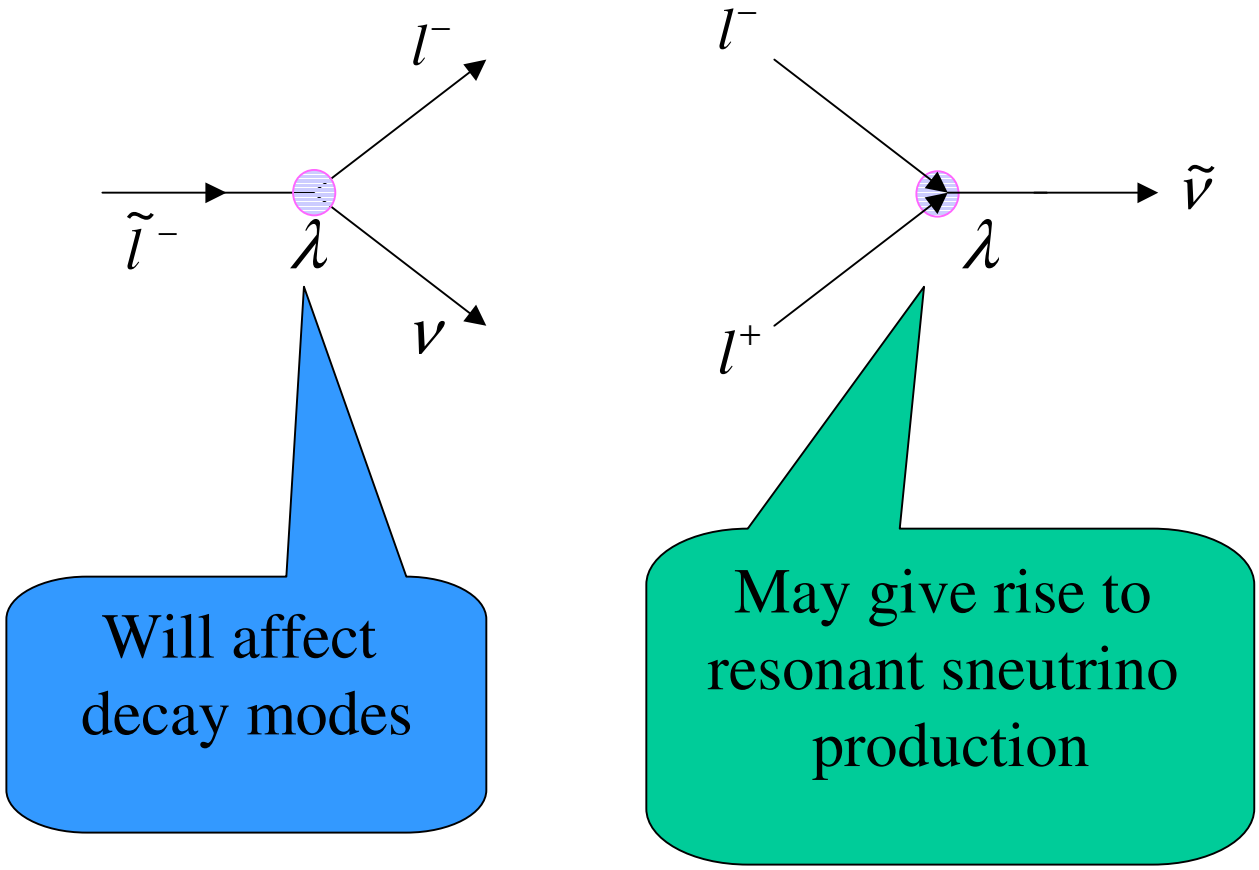
where	L_L	Lepton doublet	(1,2,1/2)
	Q_L	quark doublet	(3,2,1/6)
	D_R	down-type quark singlet	(3,1,1/3)
	U_R	up-type quark singlet	(3,1,-2/3)
	E_R	down-type lepton singlet	(1,1,1)
	$\lambda, \lambda', \lambda''$	Yukawa couplings	
		generation indices	

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

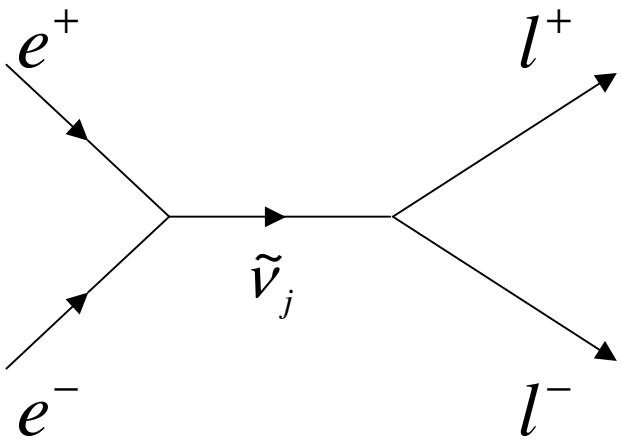
The $\lambda_{ijk} L_L^i L_L^j \overline{E_R^k}$ Term



This vertex violates L conservation!

There are 9 possible λ_{ijk} corficients

Resonant Sneutrino Production



$\lambda_{1j1} * \lambda_{kjk}$

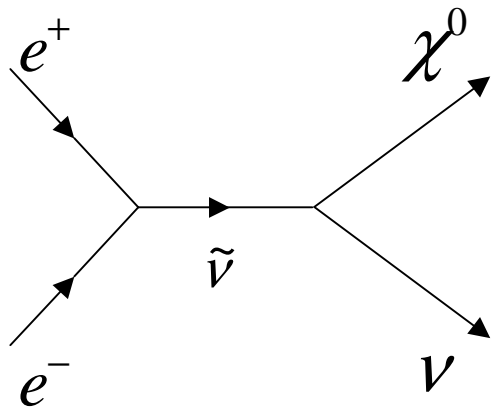
Should give rise to large peak in di-lepton production at CMS energy.

Have some sensitivity to lower masses through 'return photon' emission.

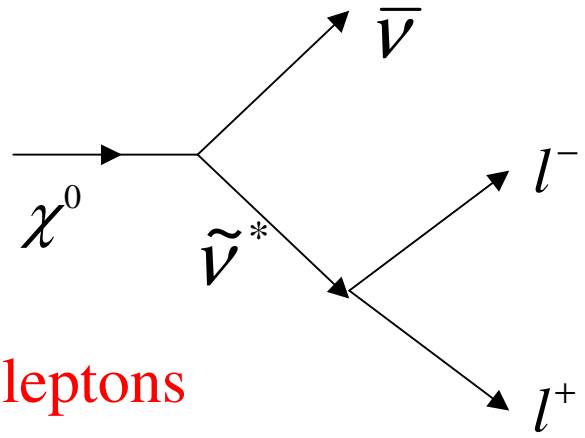
Also some sensitivity to higher masses due to off-the-mass-shell sneutrino production.

Resonant Sneutrino Production

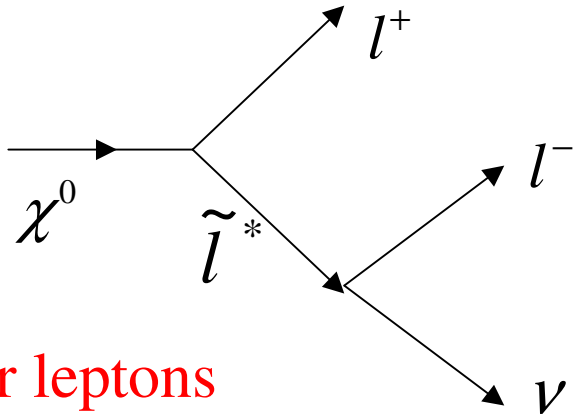
Suppose one has this production process



The neutralino can decay through:

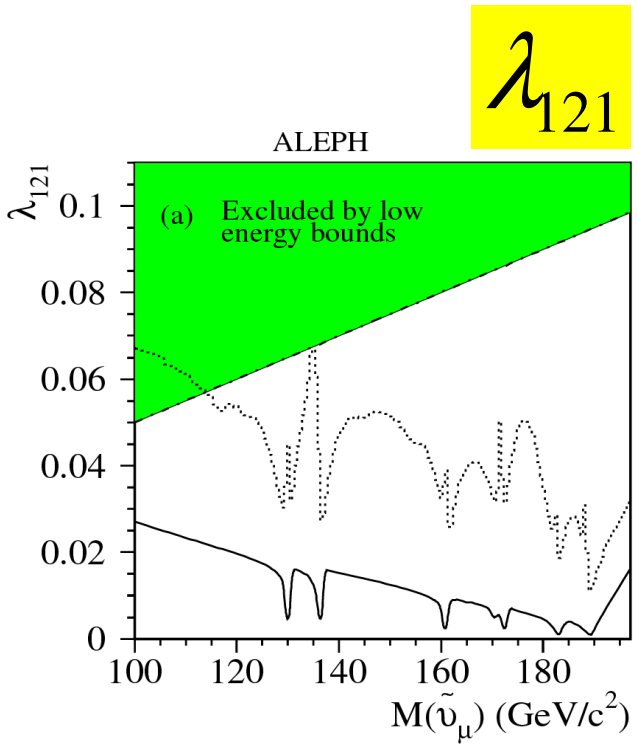


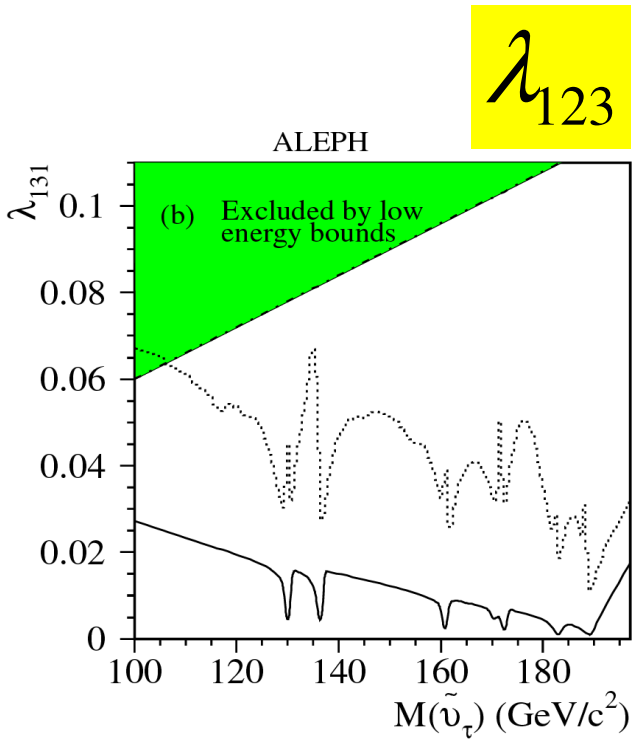
→ Two acollinear leptons



→ Also two acollinear leptons

Results on λ_{ijk}





Limits on λ_{121} and λ_{131} as a function of the $\tilde{\nu}_\mu$ and $\tilde{\nu}_\tau$ mass. Based on ~400pb^{-1} of data up to 201.6 GeV.

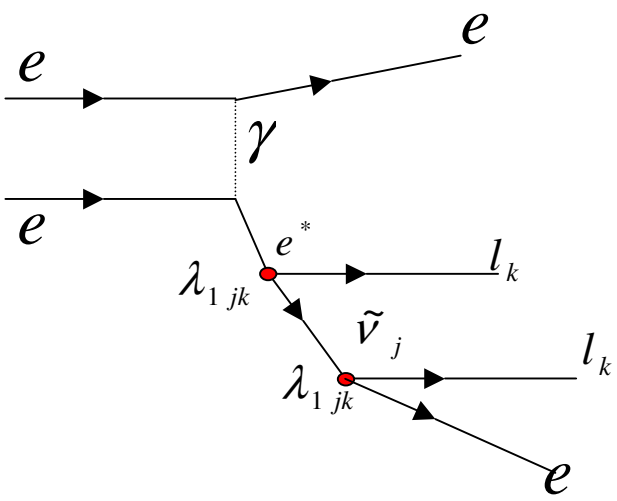
Other limits on both couplings for $\tilde{m}$=100 (2σ only):

$\lambda_{121} < 0.05 \frac{m_{\tilde{\nu}}}{100GeV}$ charged current universality

$\lambda_{131} < 0.06 \frac{m_{\tilde{\nu}}}{100GeV}$ Tau decay

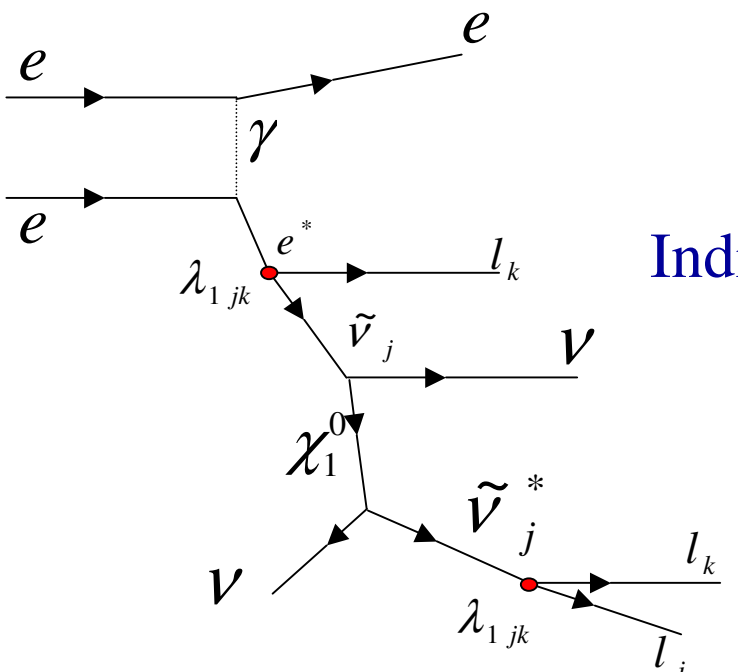
Single Sneutrino Via $e\gamma$

Different process that can give rise to a single sneutrino production are:



Direct decay

or



Indirect decay

Sensitive to: $\lambda_{121}, \lambda_{131}, \lambda_{122}, \lambda_{123}, \lambda_{132}, \lambda_{133}, \lambda_{231}$

More Results on λ_{ijk}

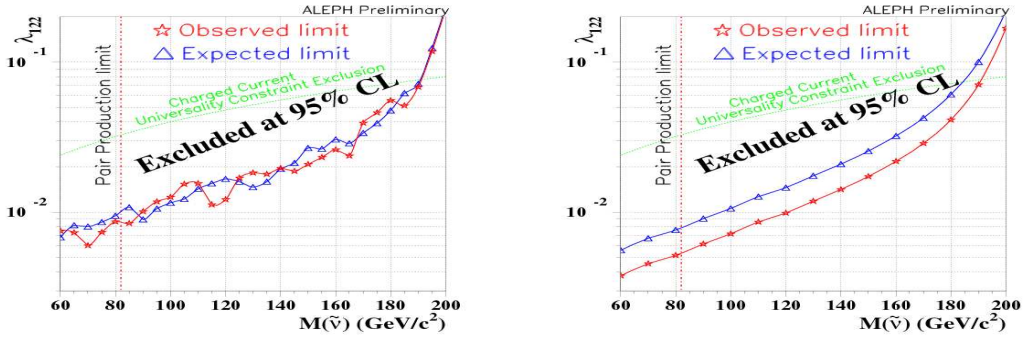


Figure 6: Observed and expected 95% CL limits on the λ_{1j2} coupling: (left) direct decay, (right) indirect decay. The limits given by the low energy bounds and the pair production search are indicated.

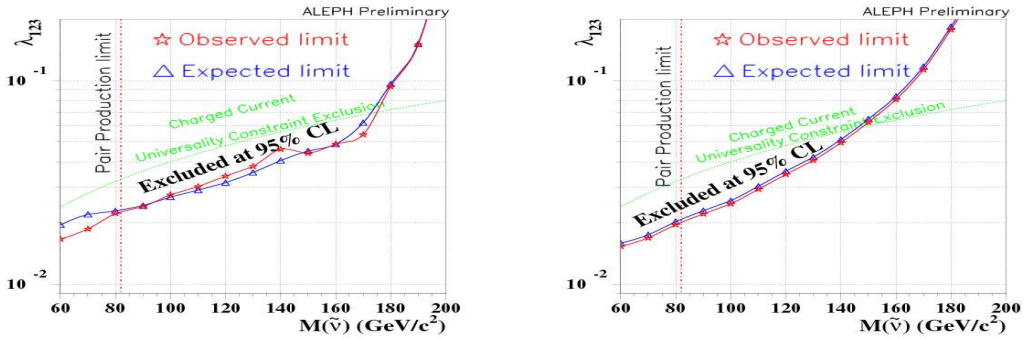
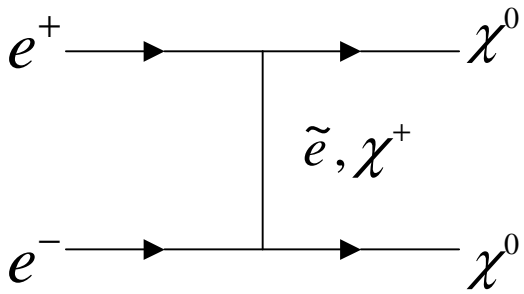


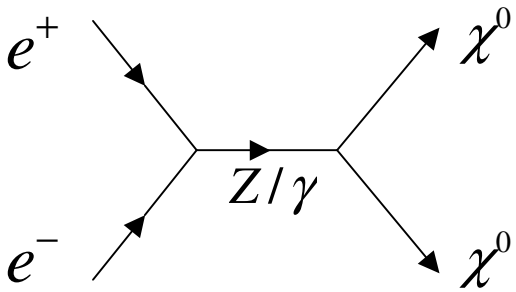
Figure 7: Observed and expected 95% CL limits on the λ_{123} coupling: (left) direct decay, (right) indirect decay. The limits given by the low energy bounds and the pair production search are indicated.

Coupling	Low Energy	Direct	Indirect
122	0.04	0.013(190)	0.007(190)
123	0.04	0.028(175)	0.025(148)
132	0.05	0.013(192)	0.012(187)
133	0.003	0.028	
231	0.05	0.013(192)	0.016(180)

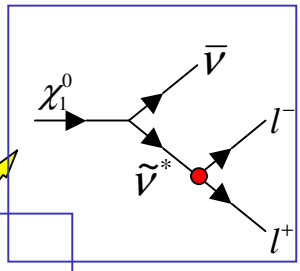
Search for neutralinos Decaying Through the LLE Term

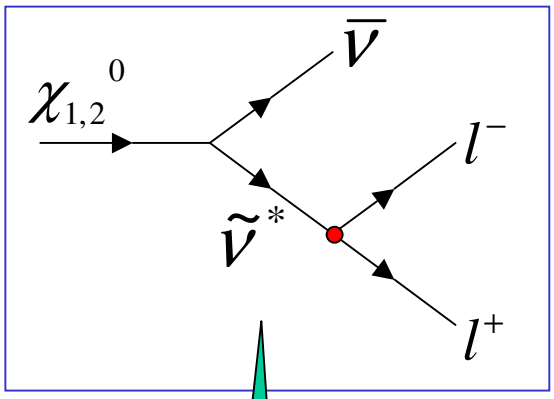
One can produce a pair of charginos/neutralinos in the 'usual' way followed by RPV decay.

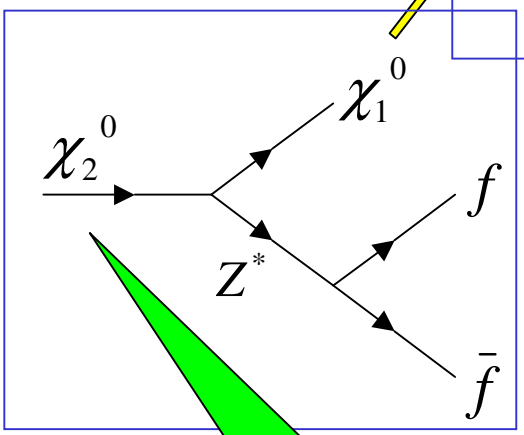




Coupled with an LLE RPV decay







2 leptons

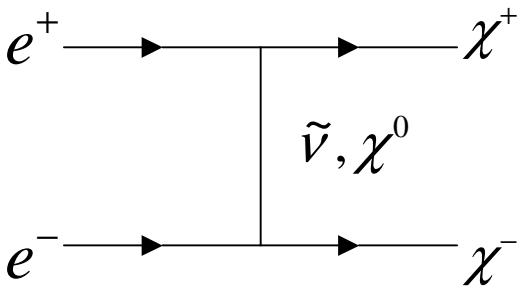
2+2 leptons/

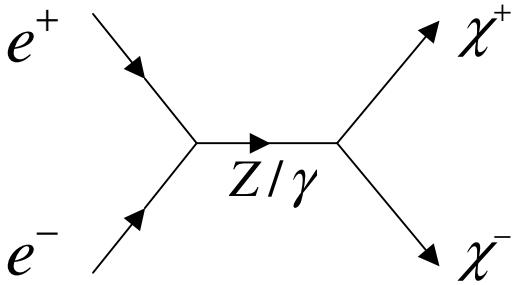
2 lept + 2 jets/

2 lept + miss

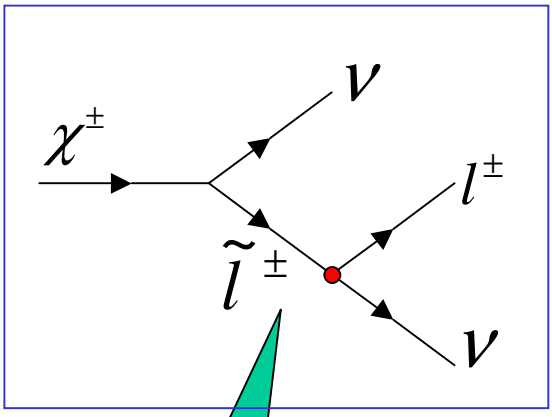
Search for charginos Decaying Through the LLE Term

Similar production processes

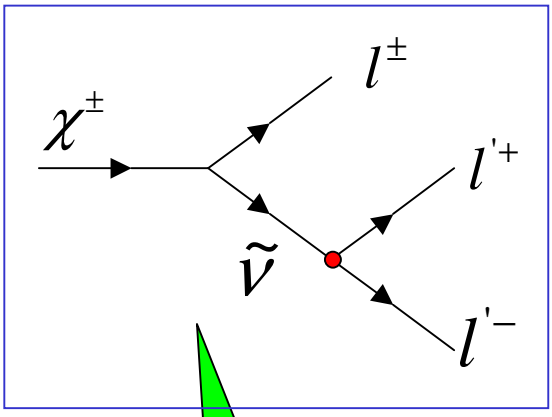




…and similar LLE decay modes:



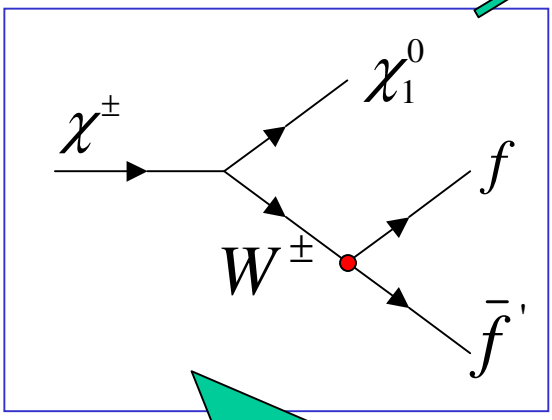
Lepton + missing energy

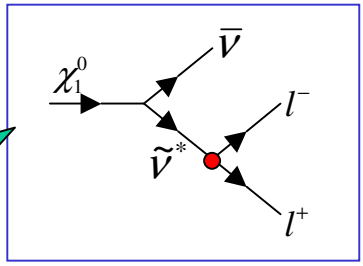


2+1 leptons

And Both Together

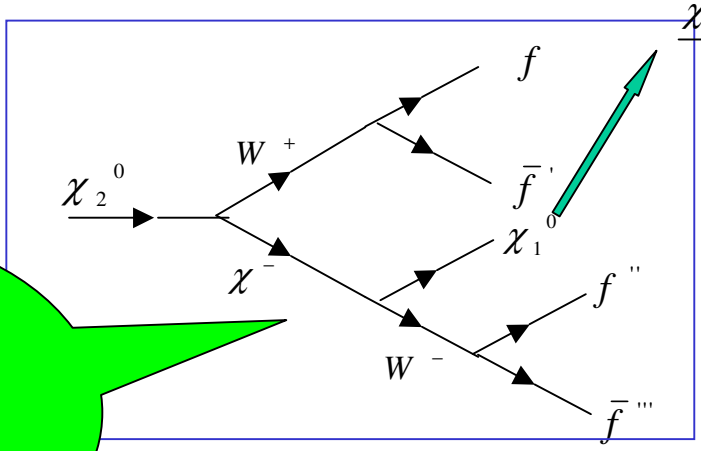
From chargino pair production:

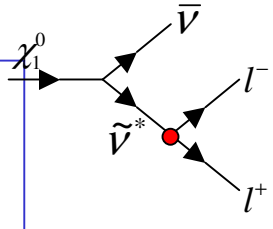




2 leptons+missing energy+2 jets or:
2+1 leptons + missing energy

χ_2^0 production





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

So What Should One Search for?

$\chi_1^0 \chi_1^0$ – *production*

2+2 leptons + missing energy

$\chi_2^0 \chi_2^0$ – *production*

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.

$\chi_1^+ \chi_1^-$ – *production*

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

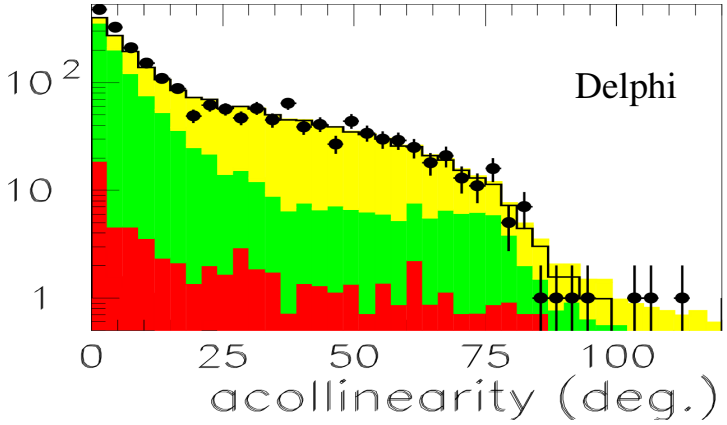
2+2 leptons + E_{miss} + W^+ & W^- decay products.

Search

Look for deviations from SM predictions in any of these channels (not really).

See beautiful agreement between data and SM predictions.

(e.g. acollinearity angle btwn leptons)

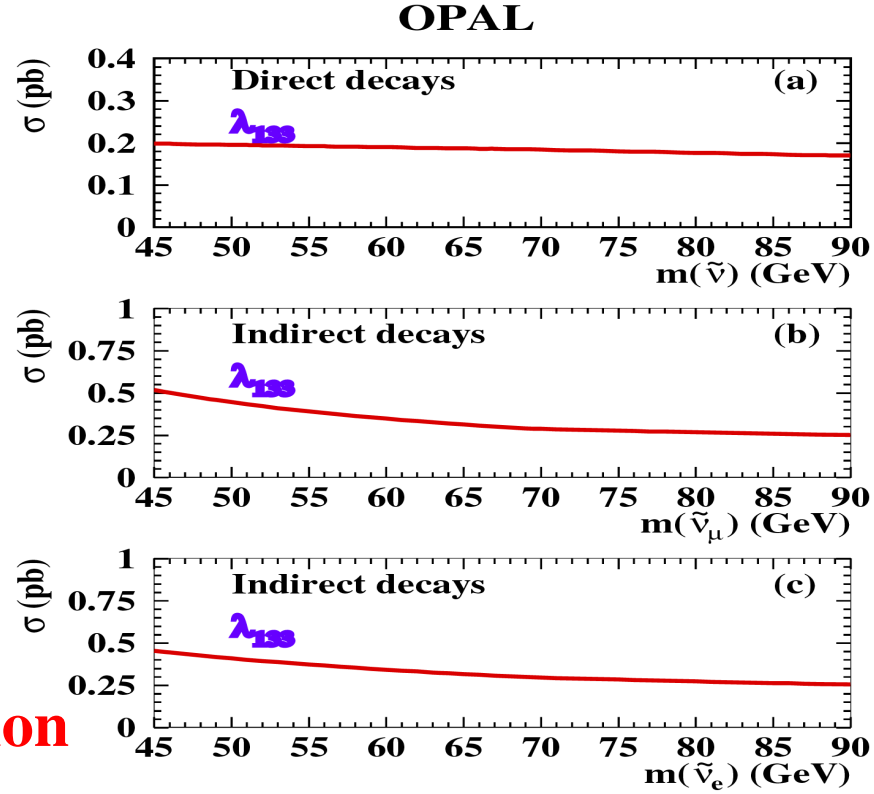


Get upper limit

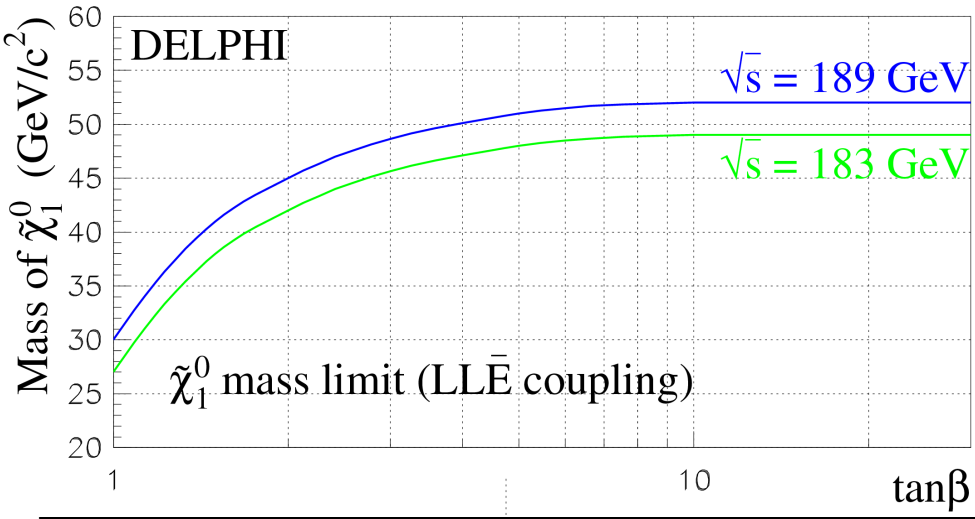
Topological

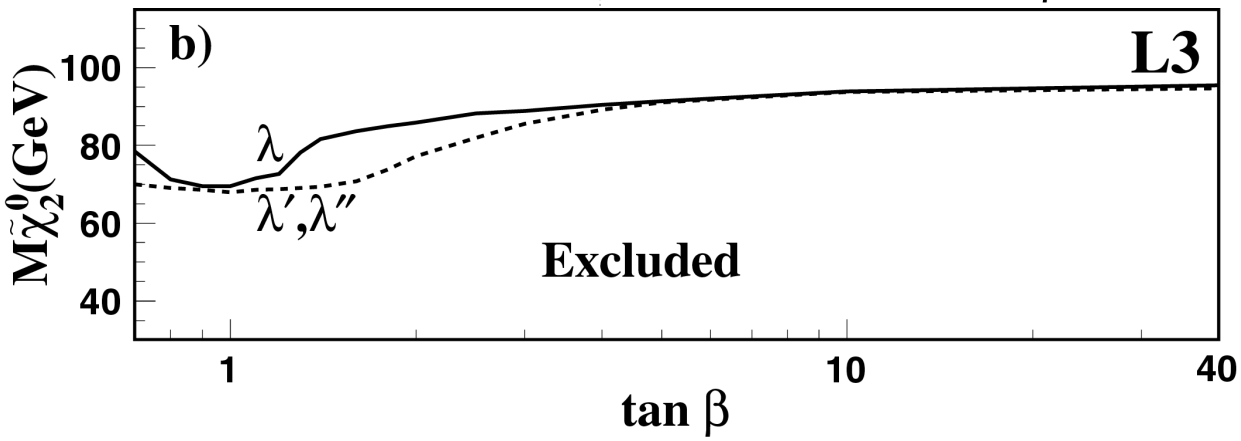
final states

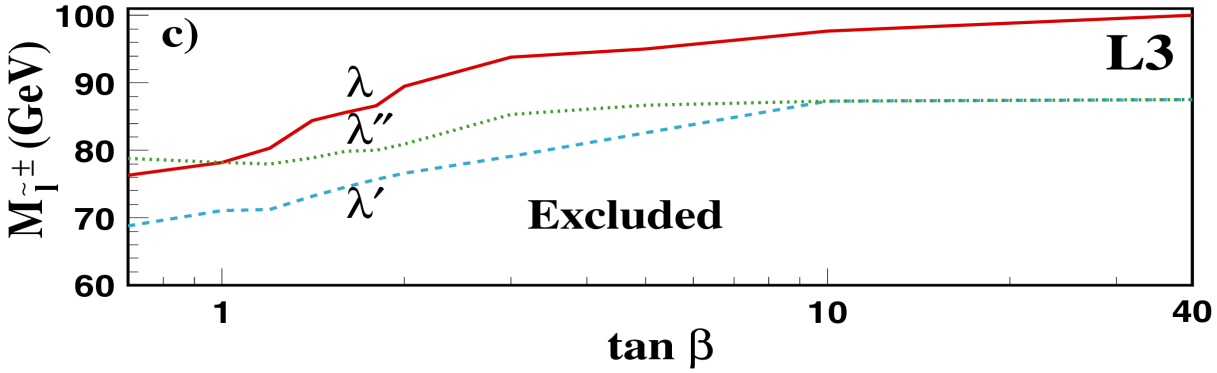
interpretation



Results on Neutralino Pair Production



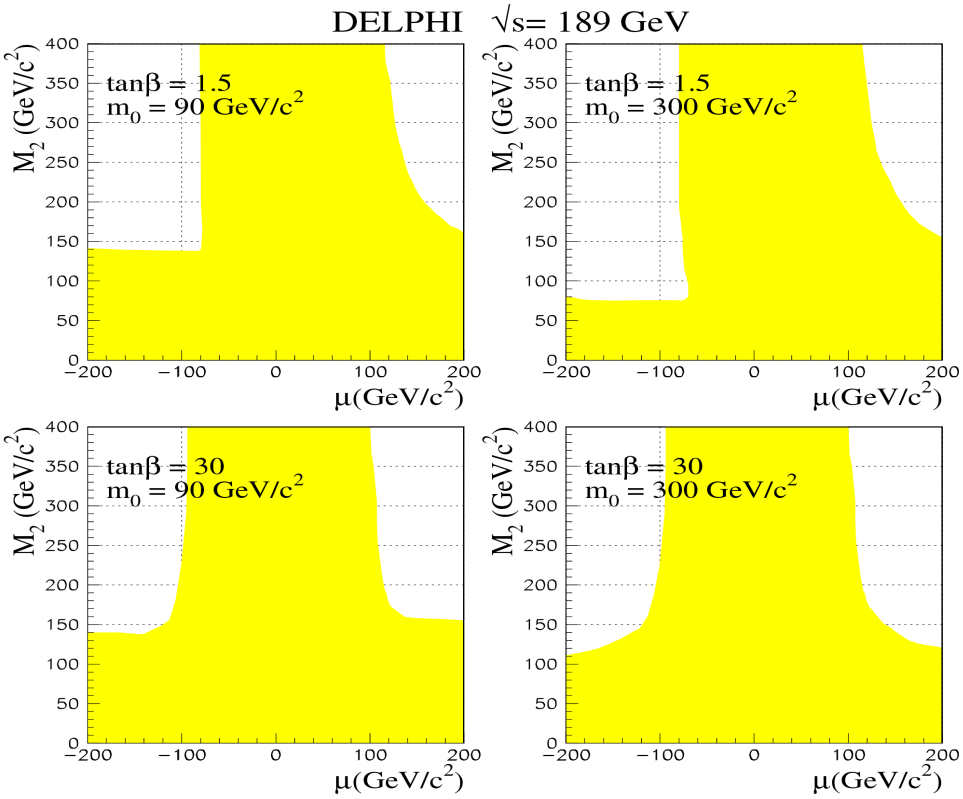




176pb^{-1} @ 189GeV, all m_2, m_0=500

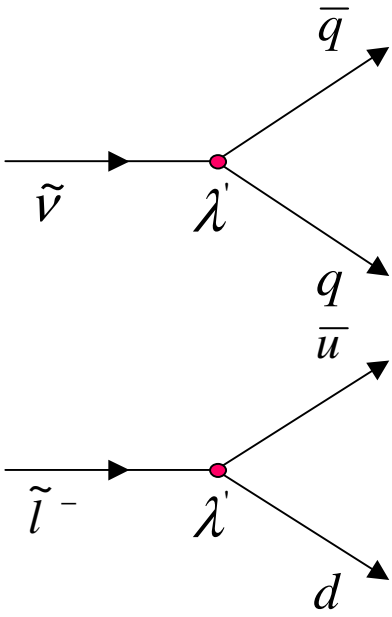
Results on Chargino Pair Production

$m_{\chi_1^0} > 32.6 GeV$	$m_{\tilde{e}_R} > 96 GeV$
$m_{\chi_2^0} > 69.5 GeV$	$m_{\tilde{\mu}_R} > 87 GeV$
$m_{\chi_3^0} > 99.3 GeV$	$m_{\chi_1^\pm} > 103 GeV$
$m_{\tilde{\nu}} > 141.2 GeV$	א

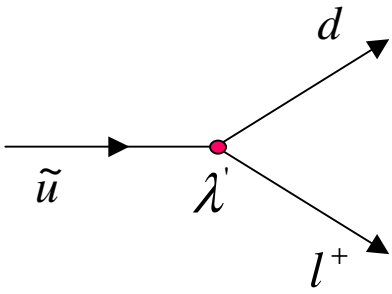


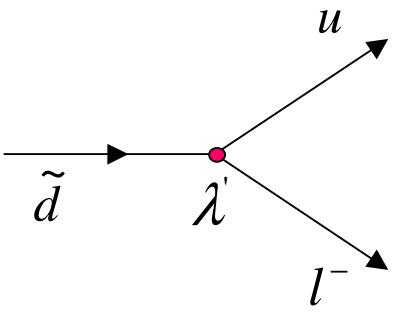
The $\lambda'_{ijk}\ L^i_L Q^j_L \overline{D^k_R}$ Term

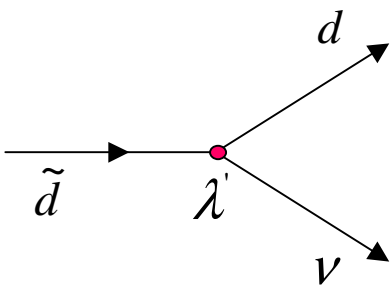
Slepton LQD decay:



Squarks LQD decay:





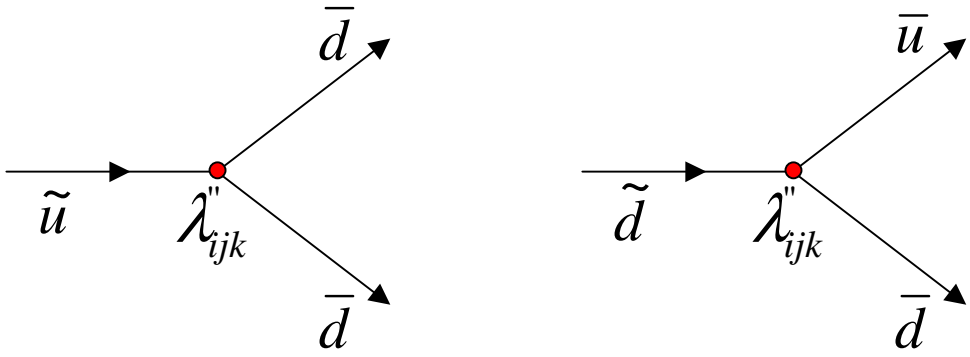


This vertex violates L conservation!

(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

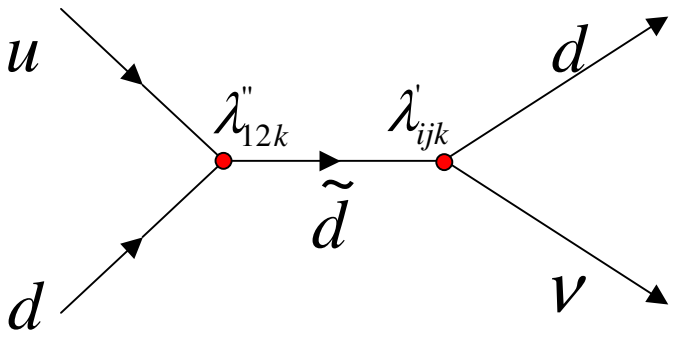
Quite a few limits on the relevant Yukawa couplings exist. In particular, from proton decay experiments one can deduce that:

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

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!

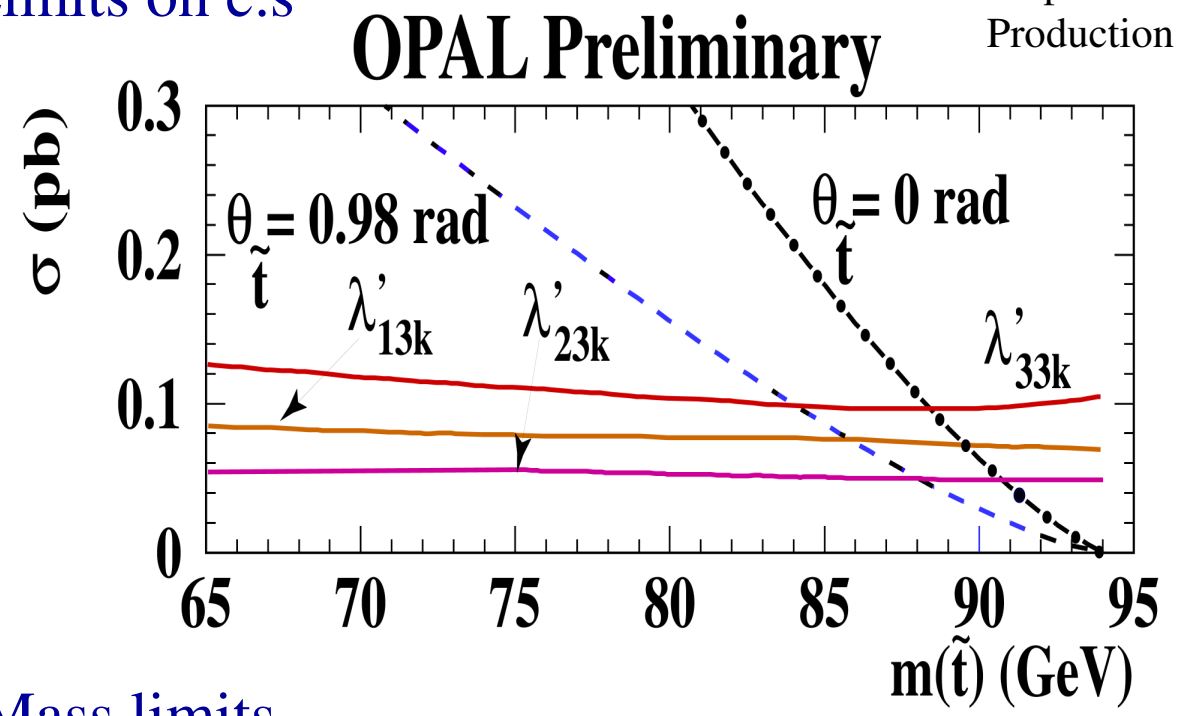
Production and Decay		Coupling	Analysis Name	Section
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-\rightarrow$	$\ell qq\ \ell qq$	λ' direct	ℓ + jets	5.1.3
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-\rightarrow$	$\ell qq\ \nu qq$	λ' direct	ℓ + jets	5.1.3
$\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-\rightarrow$	$\nu qq\ \nu qq$	λ' direct	$\not\perp$ 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	$>\not\perp$ 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	$>\not\perp$ 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	$>\not\perp$ 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	$>\not\perp$ jets	5.3.2
	$[\ell\nu][qq](qqq)(qqq)$	λ'' indirect	$>\not\perp$ jets	5.3.2
	$[qq][qq](qqq)(qqq)$	λ'' indirect	$>\not\perp$ jets	5.3.2

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

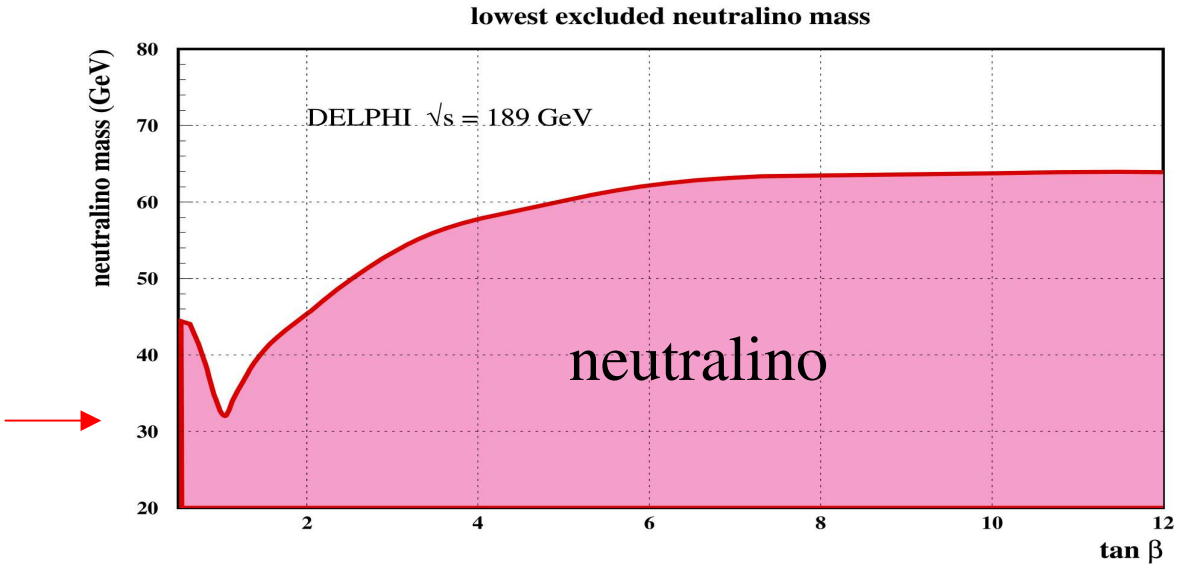
Results on the λ' and λ'' Terms

Limits on c.s

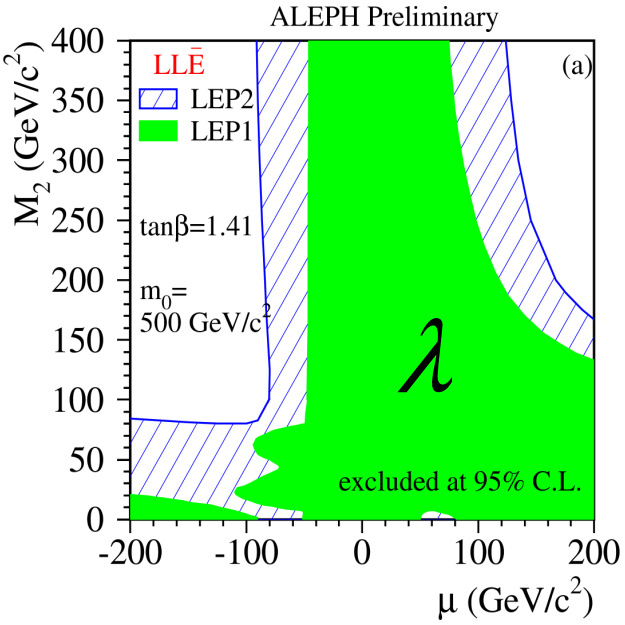
Stop Pair Production

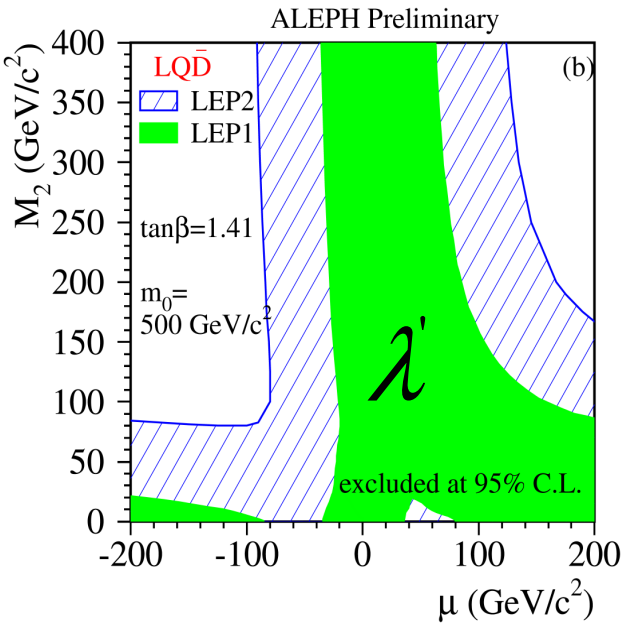


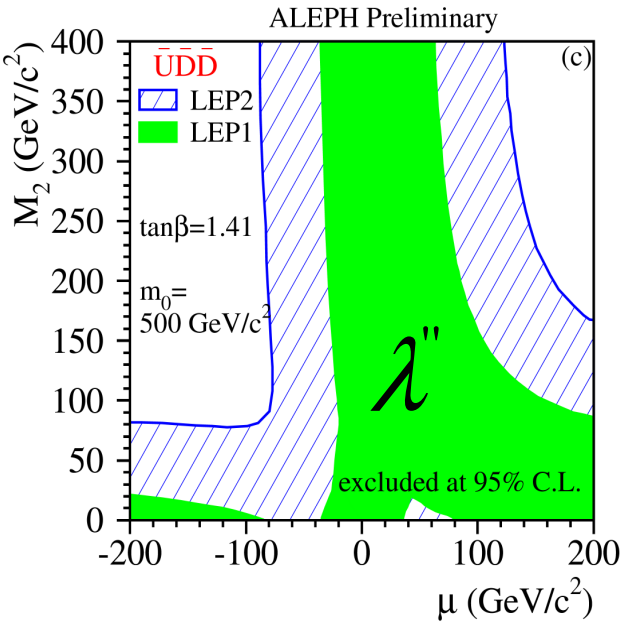
Mass limits



Interpretation in the MSSM Framework







Based on all the data up to 208 GeV

Bounds on Masses

In the framework of MSSM one can set lower mall limits on various sparticles:

(indirect) א

sparticle	LLE	LQD	UDD
$\tilde{t}_1$	91	85	71.5
$\tilde{b}_1$	90	80	71.5
$\tilde{e}_R$	96	93	94
$\tilde{\mu}_R$	96	90	85
$\tilde{\tau}_R$	95	76	X
$\tilde{\nu}_e$	98	91	88
$\tilde{\nu}_{\mu,\tau}$	89	78	65

And from direct decays:

$$m_{\tilde{\nu}_\mu} > 79GeV \qquad m_{\tilde{u}_L} > 82.5GeV$$

$$m_{\tilde{\mu}_L} > 81GeV \qquad m_{\tilde{d}_L} > 77.0GeV$$

$$m_{\tilde{t}_L} > 97GeV$$

Search for Spontaneous R-Parity Violation

Delphi:

Assume RP as an exact Lagrangian symmetry, broken spontaneously through the Higgs mechanism (non-zero vev for 3^{ed} generation sneutrino).

=> Stable massles Majoron (J) (R-odd).

- Look for chargino pair production (only s cha)
- consider the decay $\chi^{\pm} \rightarrow \tau^{\pm} J$

in addition to the 'standard' ones:

$$\chi^{\pm} \rightarrow \nu_{\tau} W^{\pm} \rightarrow \nu_{\tau} q\bar{q}', \nu_{\tau} l^{\pm} \nu_{l}$$

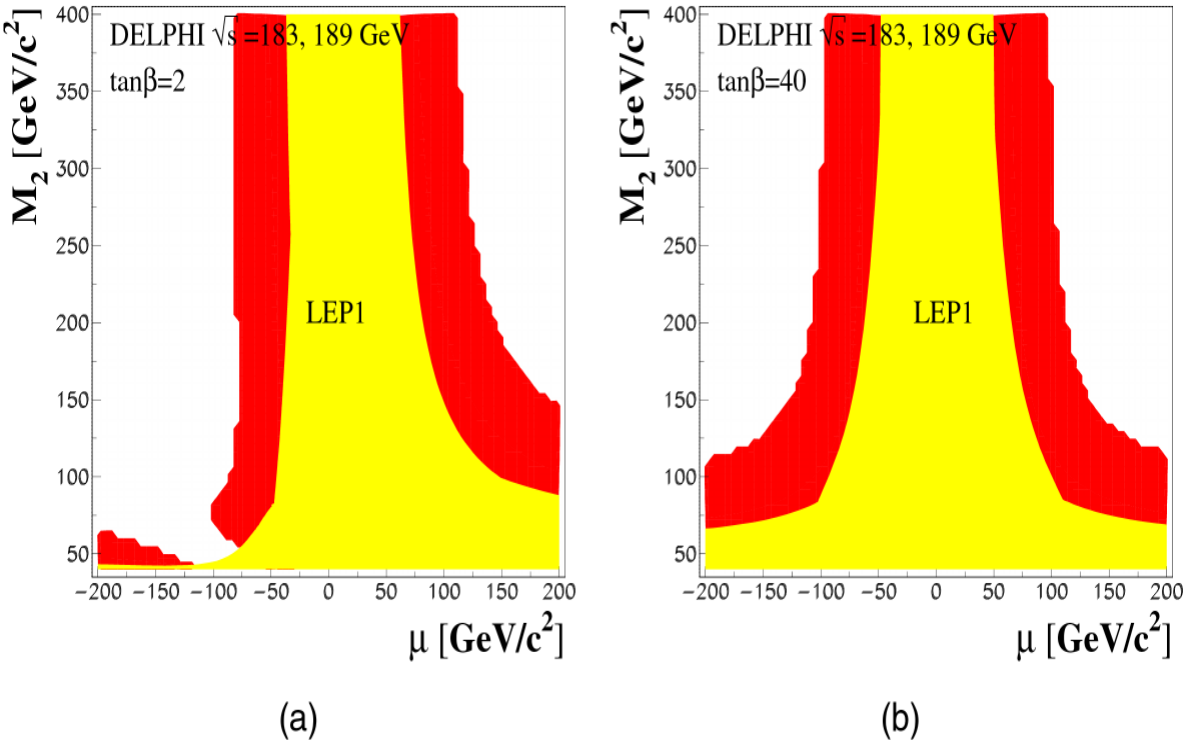
$$\chi^{\pm} \rightarrow \chi_1^0 W^{\pm} \rightarrow \chi_1^0 q\bar{q}', \chi_1^0 l^{\pm} \nu_{l}$$

The Br is a function of the RPV parameter. The 2-body tends to dominate.

Look for acollinear tau pairs

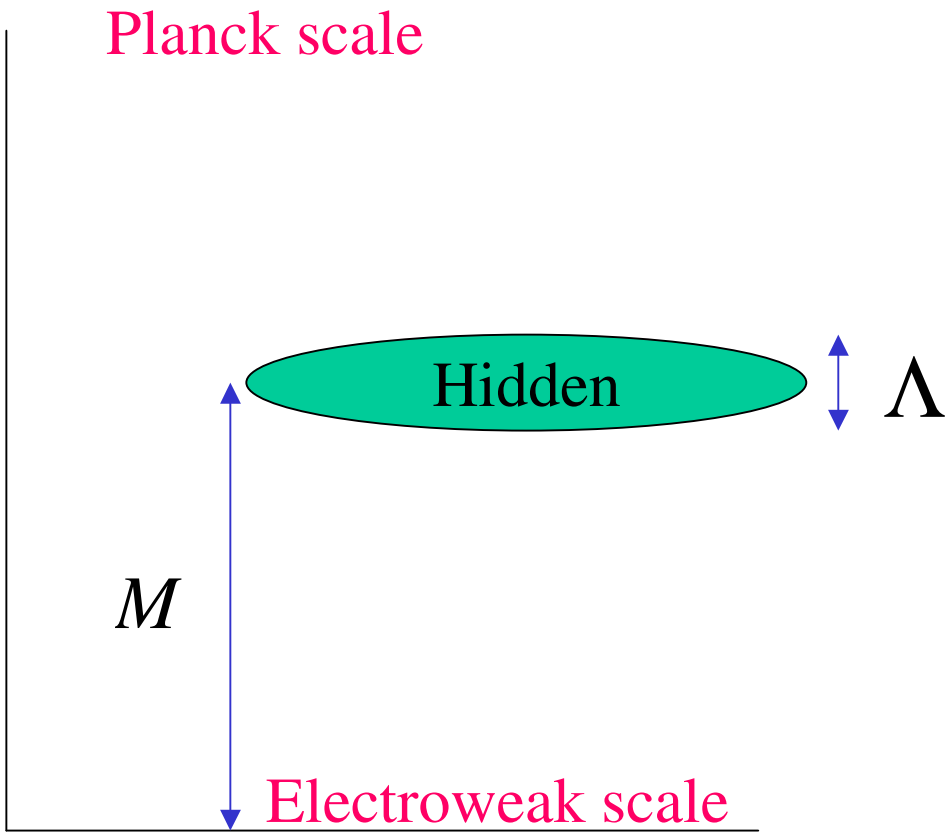
Spontaneous RRRResults

Expect from SM 15.9 events.
See 15 events.



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.

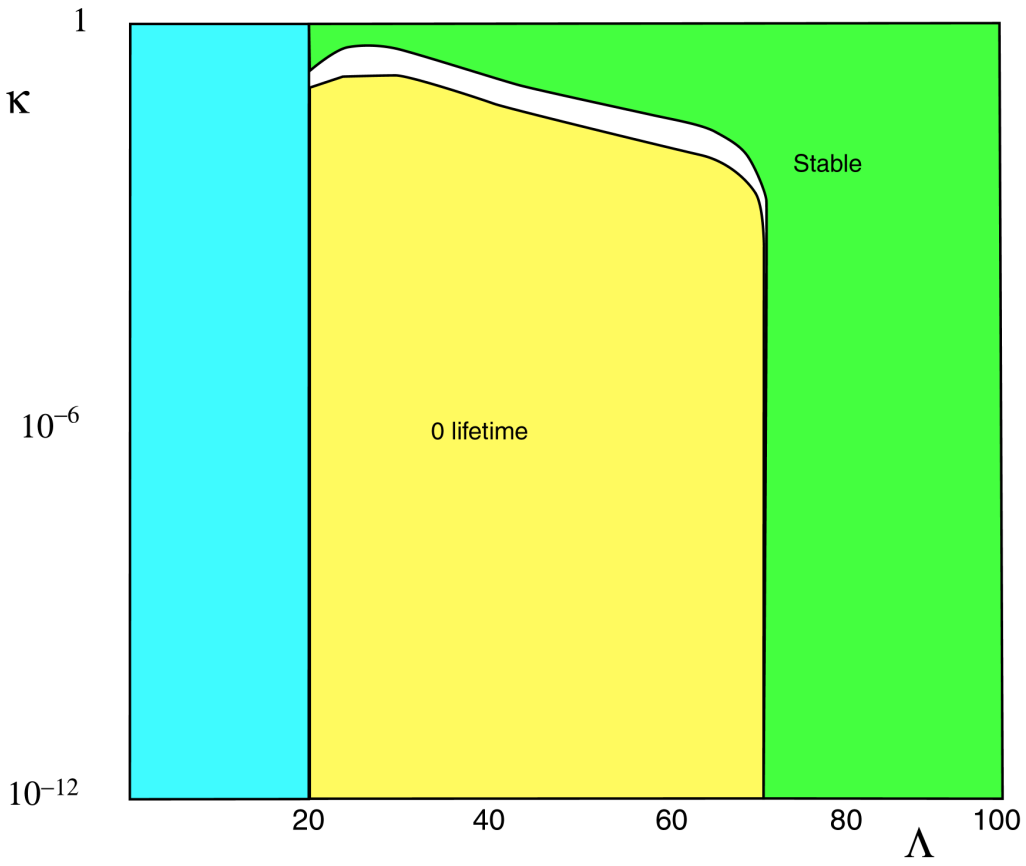
$$m_G = F / \kappa\left[\sqrt{3}M_P\right]$$

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

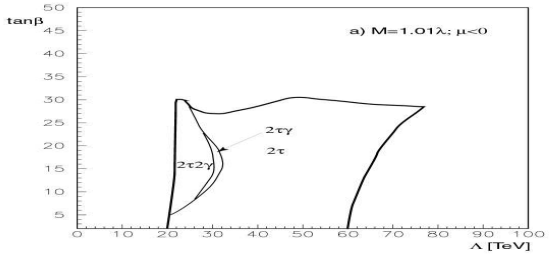


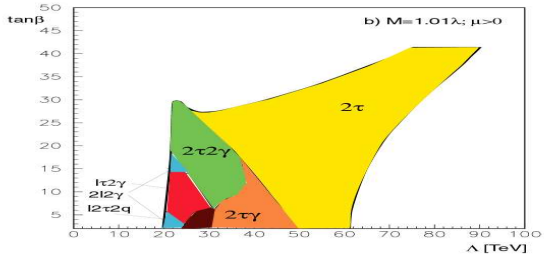
Either in the ‘stable’ or in the ‘0-life-time’ situation

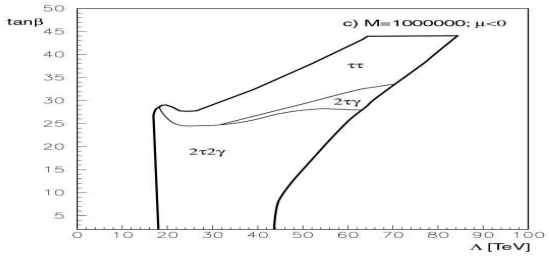
What Shall One Look For?

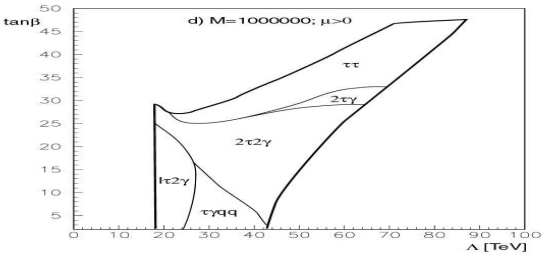
Very Rich phenomenology:

$\tau\tau$

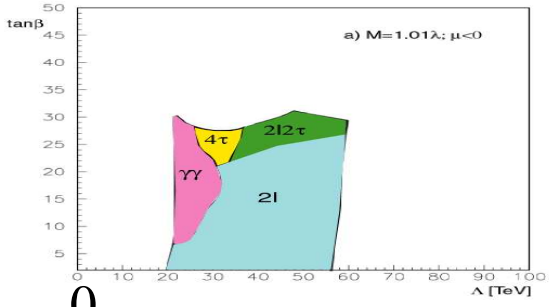


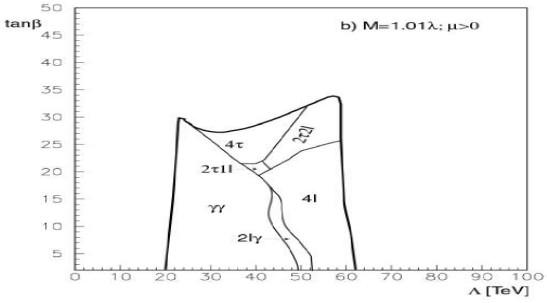


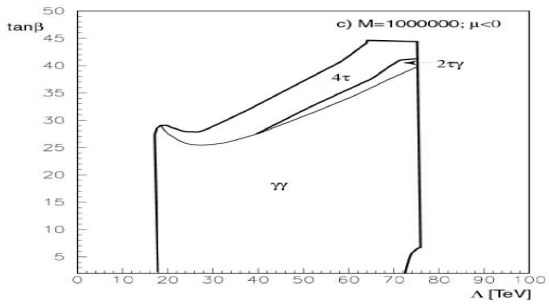


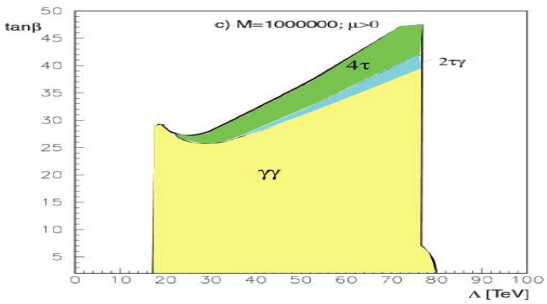


$\chi_1^0\chi_1^0$









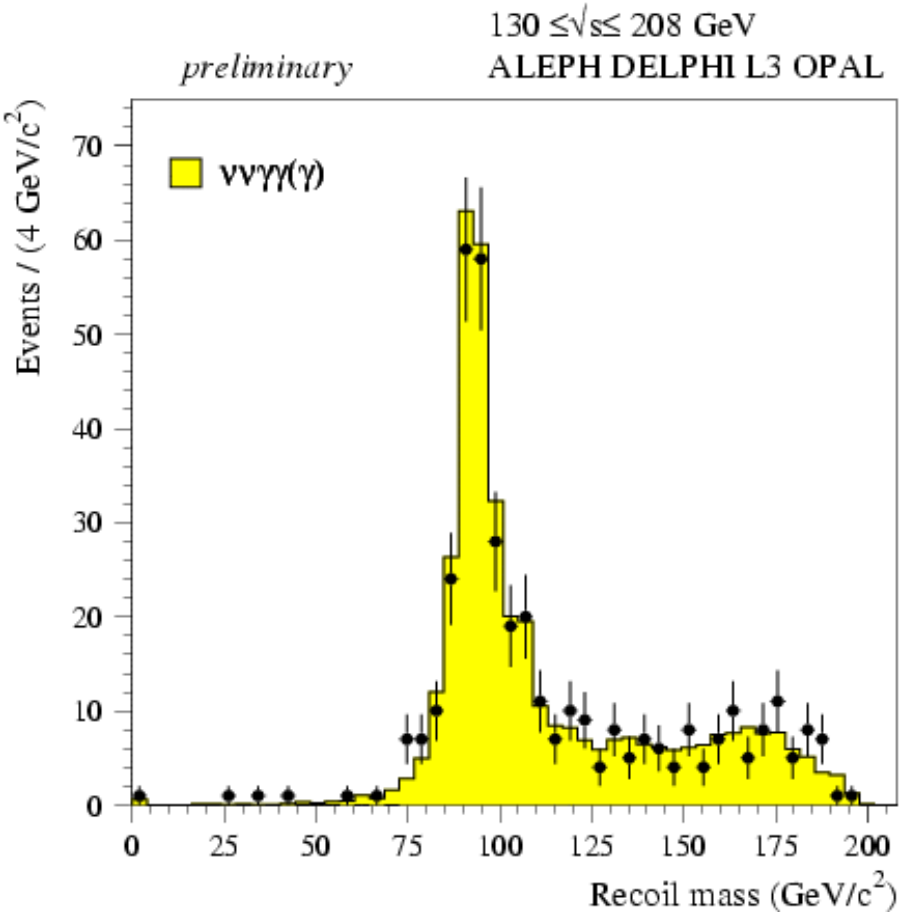
Neutralino Pair Production

The dominant decay mode of the neutralino is:

$$\chi_0^1 \rightarrow \gamma G_R$$

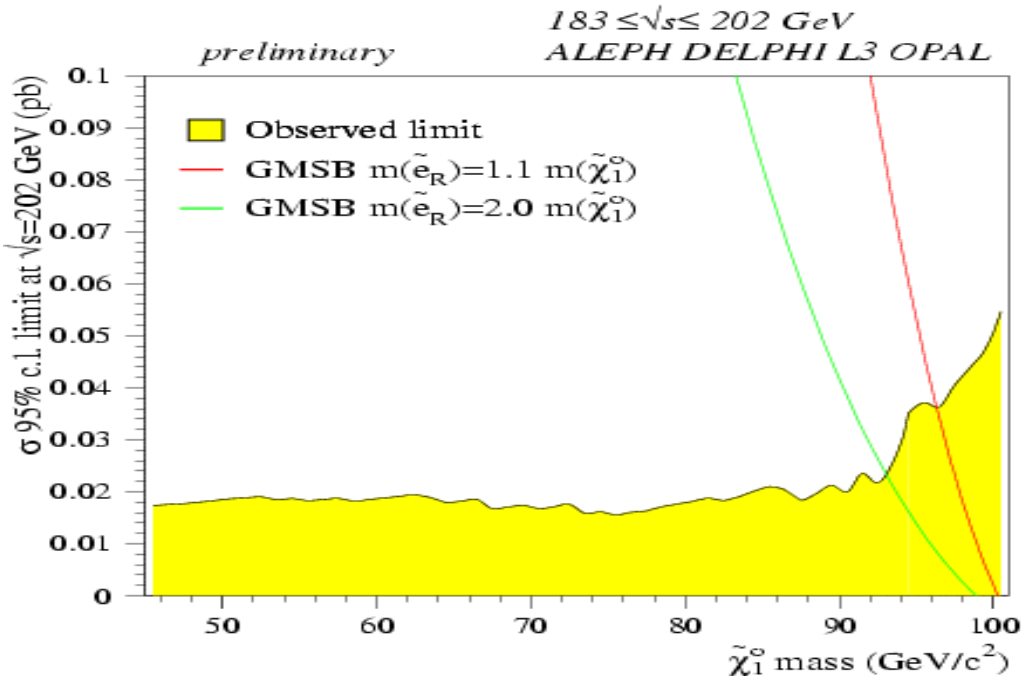
Such a decay can give rise to di-photons which are not back-to-back due to the gravitinos

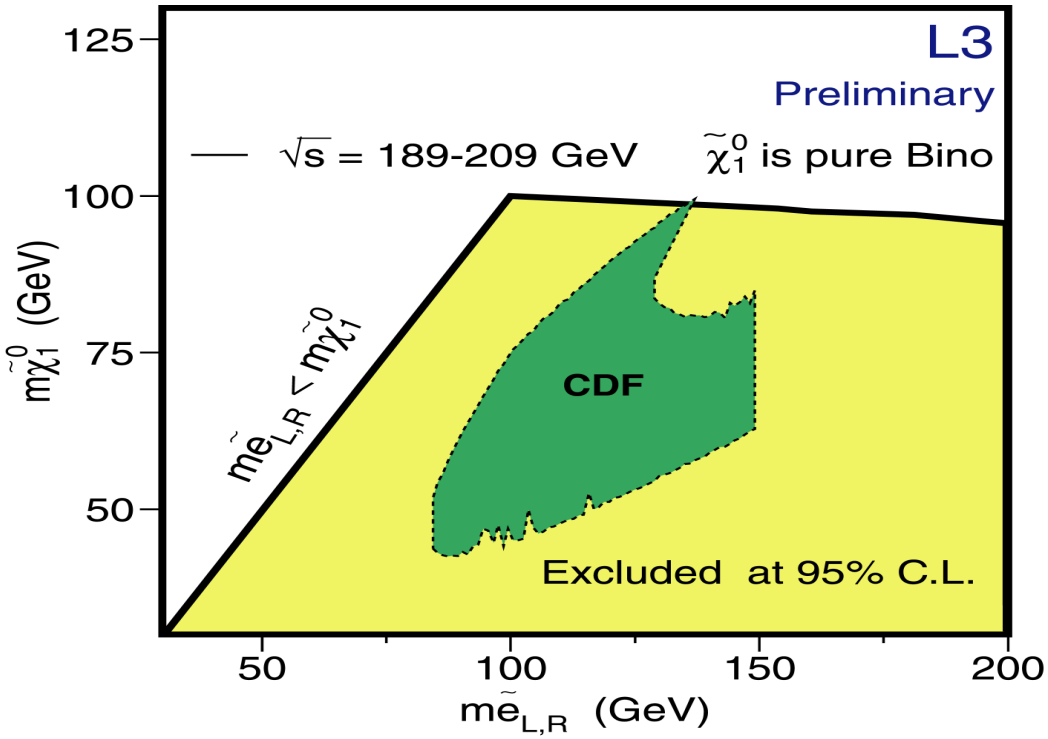
Grand Unification



Expect from SM 388.7 evts See 384.

Limits Based on di-photon Events

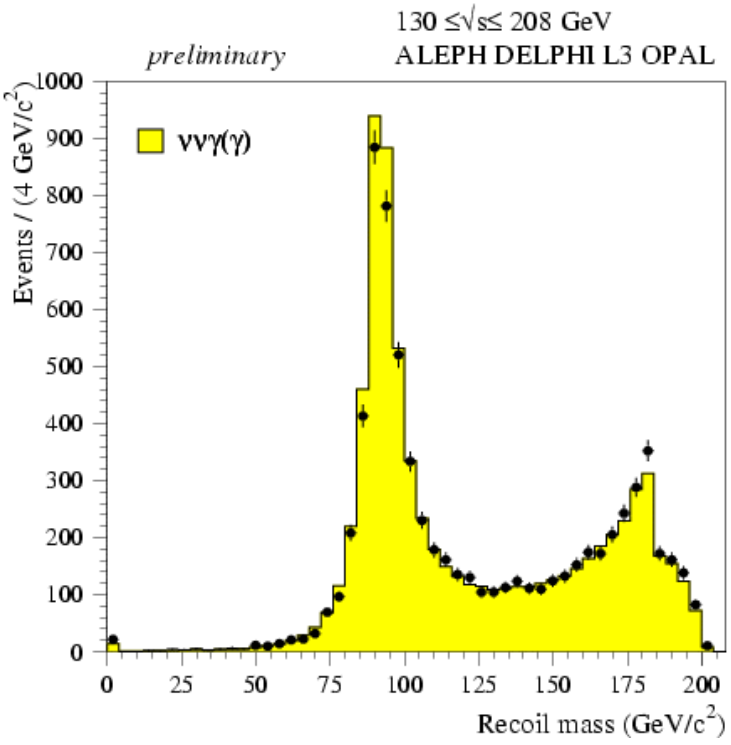




Single Photon Events

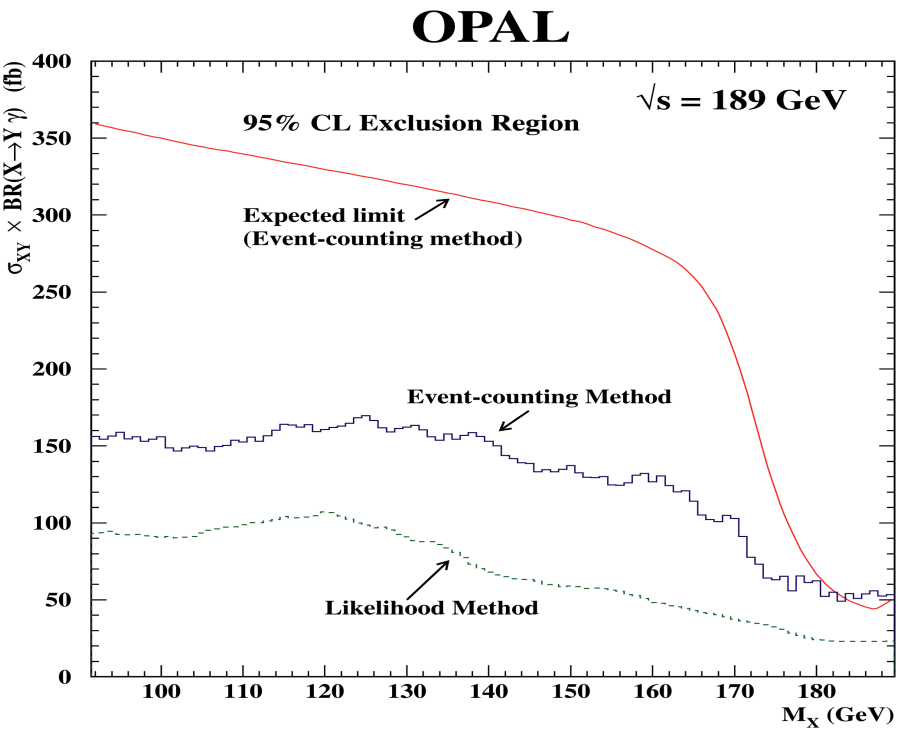
In case of a long-lived neutralino one of the neutralinos might decay inside and the other outside of the detector. In such a case one looks for single-photon events.

Grand Unification



Good agreement in number. Some problem in shape. No indication for a signal

Limits Based on One Photon Events



LNZ

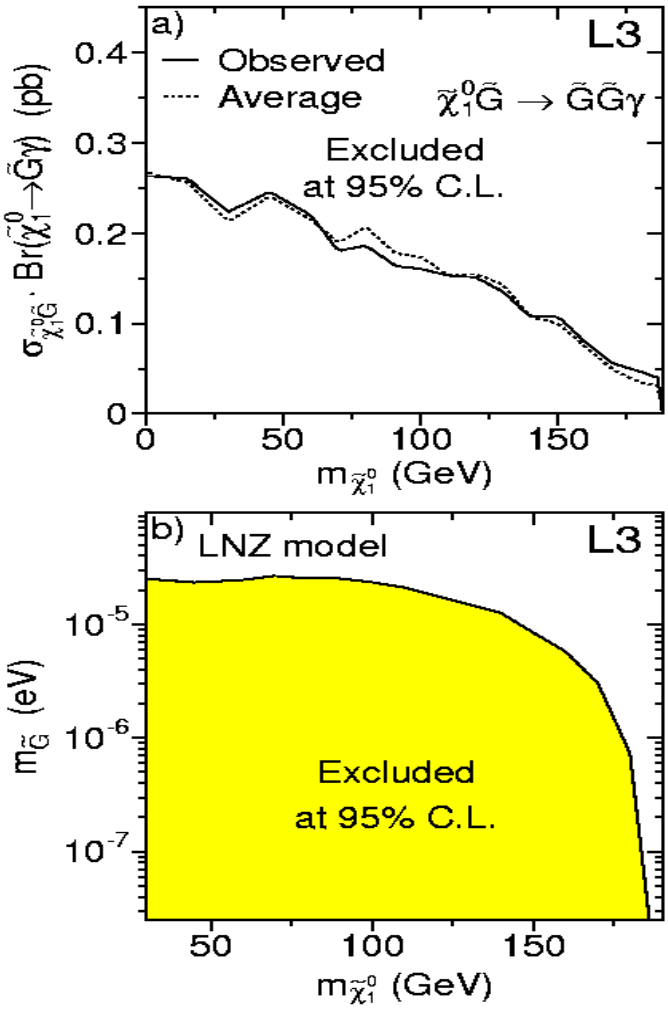
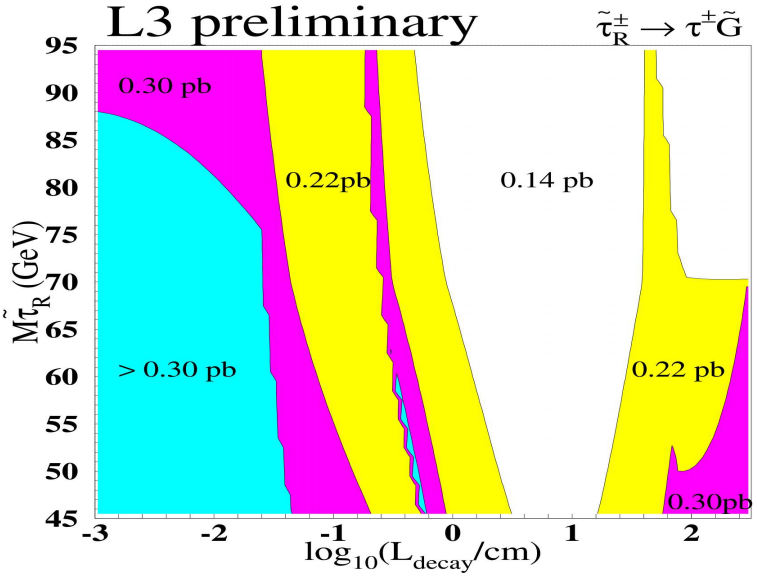
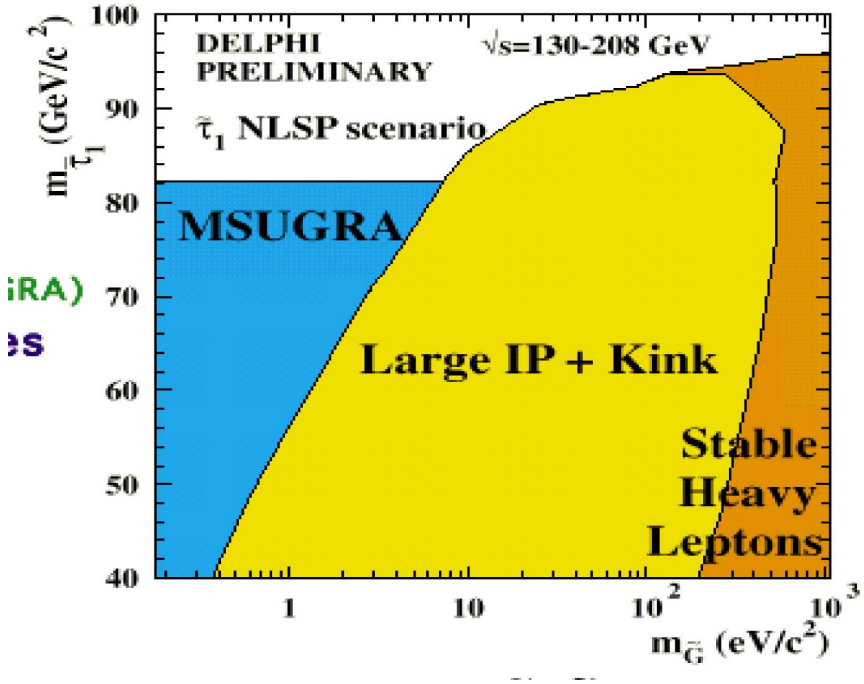


Figure 5: (a) Upper limits on the production cross section for the process $e^+e^- \rightarrow \tilde{G}\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma$ and average limit obtained using Monte Carlo trials with background only. (b) Region excluded in the LNZ model in the plane $m_{\tilde{G}}$ versus $m_{\tilde{\chi}_1^0}$.

Stau Pair Production





M_{stau}>82 GeV

General Limits On GMSB

Consider 3 ‘typical cases:

- High M (M=1,000,000 TeV)
- Low M (M=250 TeV)
- Extra low M (M=1.01Λ)

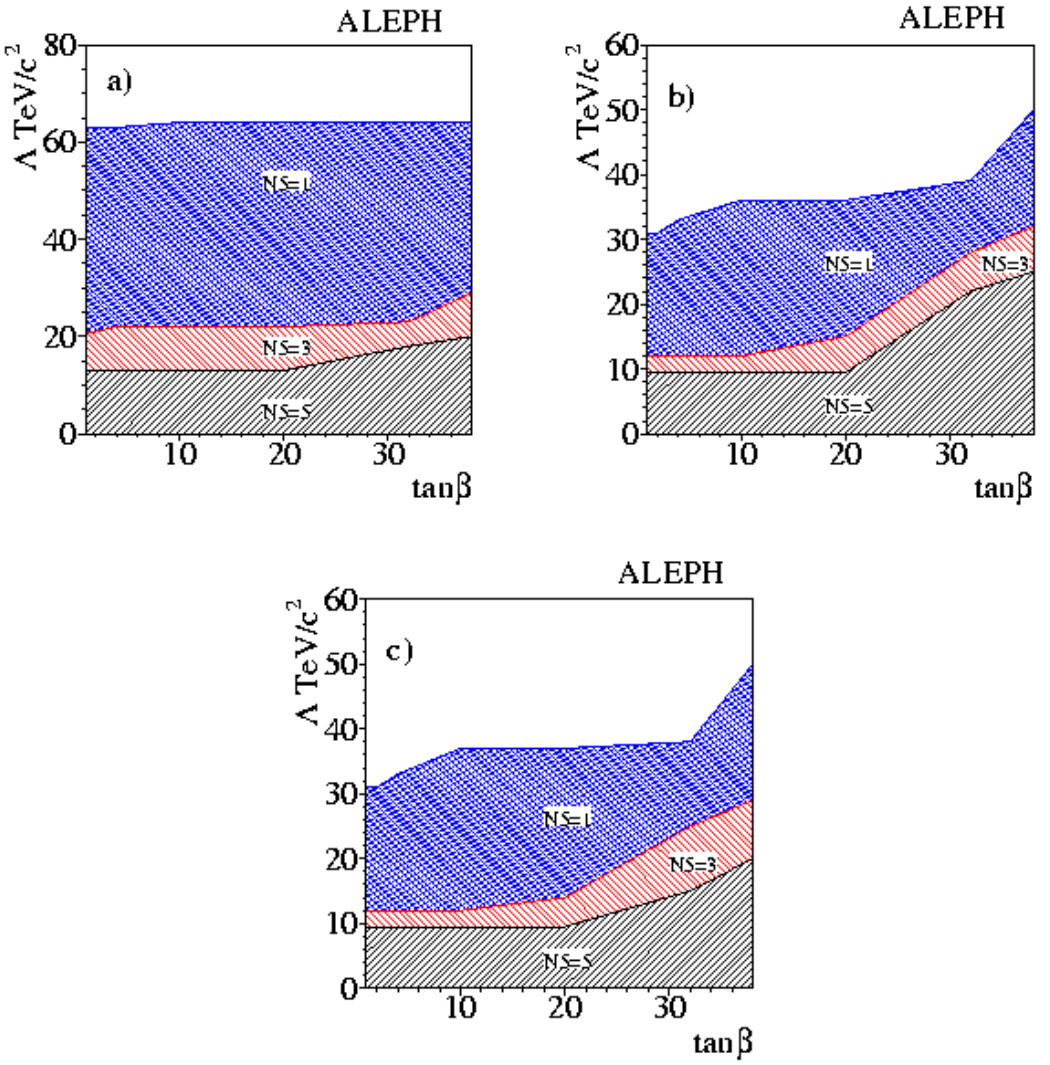
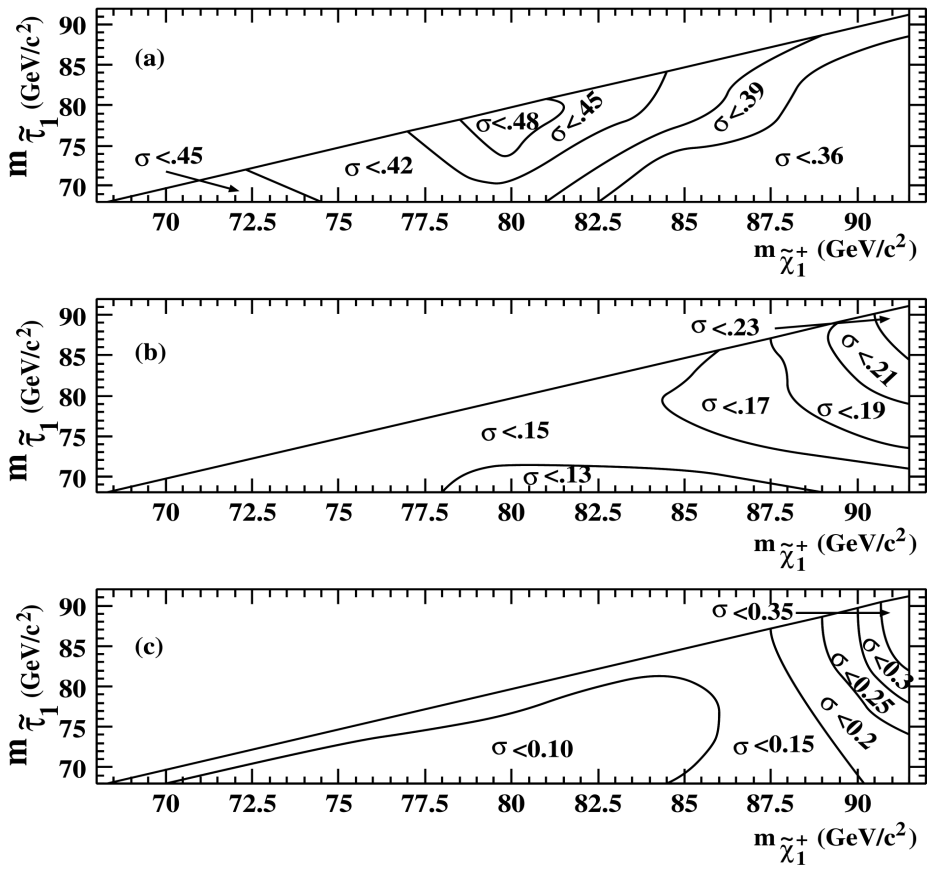
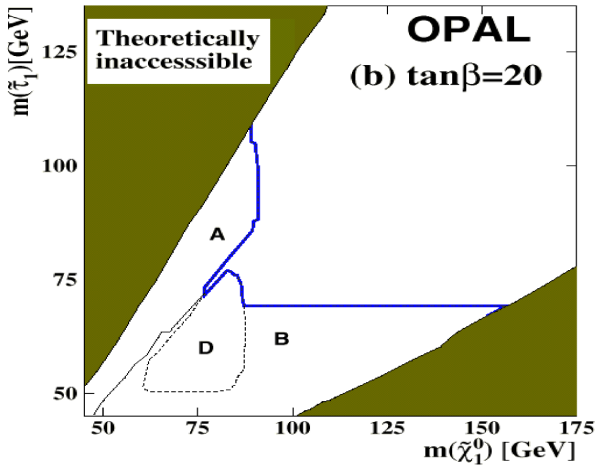


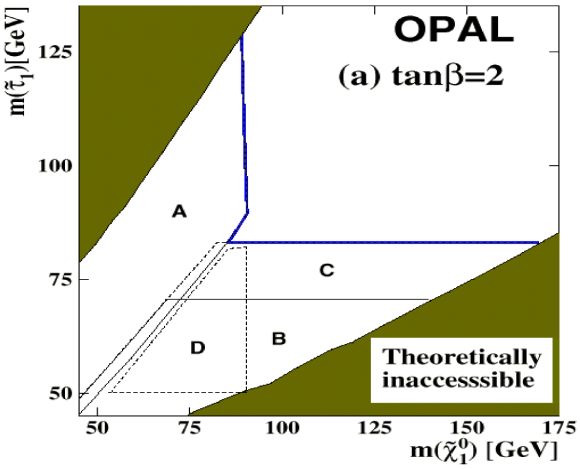
Figure 7: Region excluded at 95 % confidence level in the Λ-tan β plane for (a) short, (b) long and (c) any NLSP lifetimes.

$$\Lambda > 62 TeV\,(N = 1)$$

Different View







Search for Sgoldstino

Physicists break everything (my wife).

The spontaneous breaking of susy symmetry give rise to a goldstone boson. This boson should have also a supersymmetric partner, namely, the sgoldstino. Perazzi, Ridolfi and Zwirner

The relevant sparticle S (P) can be produced through: $e^+e^- \rightarrow S\gamma$
And the most likely S decay mode is into two photons or two gluons.

Both S and P have even R parity.

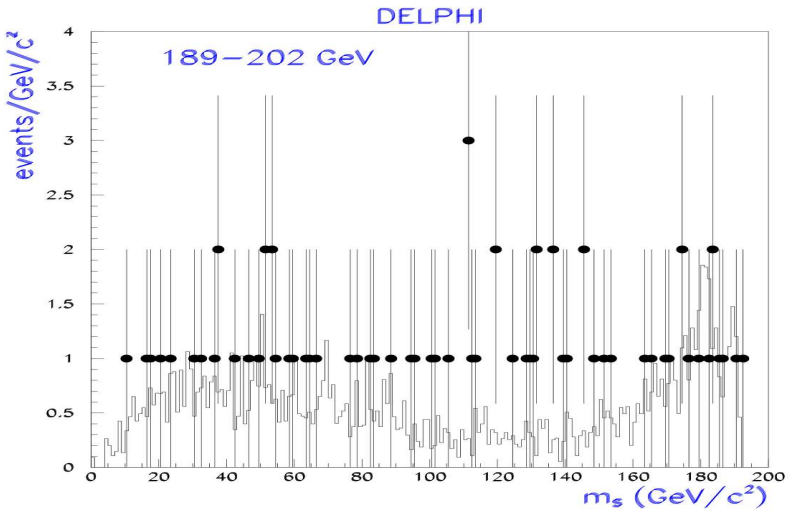
Look for:

3 photons (one monochromatic)

A monochromatic photon + 2 jets

Sgoldinoless Results

380pb^{-1} were analyzed by Delphi.



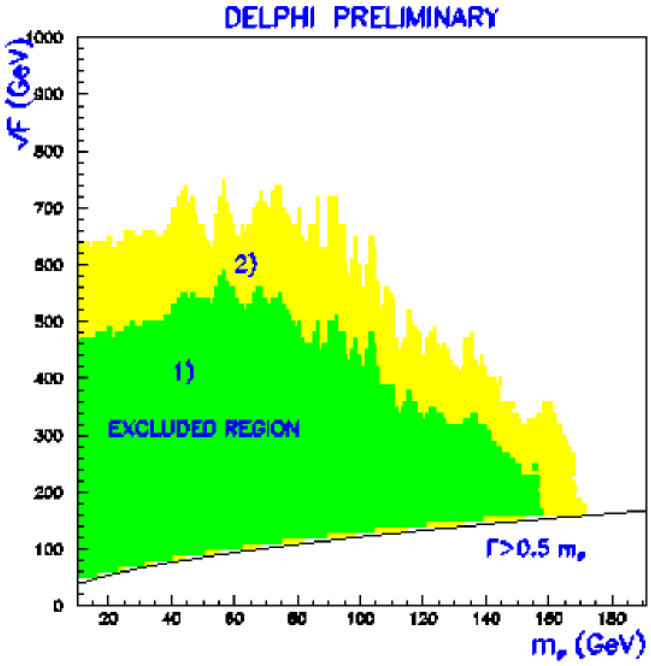


Figure 7: Exclusion region at the 95% Confidence Level in m_ϕ, $\sqrt{F}$ plane for the two sets of parameters of Table 1 and using all DELPHI data between 189 and 208 GeV.

Search for an LSP Gluino

Common wisdom teaches us that:

$\frac{m_1}{g_1^2} = \frac{m_2}{g_2^2} = \frac{m_3}{g_3^2}$ and $m_1 : m_2 : m_3 \approx 1 : 2 : 7$

And hence the gluino is usually heavy.
However, some model exist in which the gluino is the LSP [H. Baer, Chenug, Gunion].

In such a model the gluino is a stable particle (R is not broken) and can form 'R hadrons'.

3 processes were studied by Delphi:

$e^+e^- \to \tilde{t}\bar{\tilde{t}} \to c\bar{c}\tilde{g}\tilde{g}$

$e^+e^- \to \tilde{b}\bar{\tilde{b}} \to b\bar{b}\tilde{g}\tilde{g}$

$e^+e^- \to q\bar{q}g \to q\bar{q}\tilde{g}\tilde{g}$

The resulted 'R-hadrons ($\tilde{g}\tilde{g}$, $\tilde{g}u\bar{u}$,...$\tilde{g}u\bar{d}$,...) are identified by their abnormal dE/dX

LSP Gluino Results

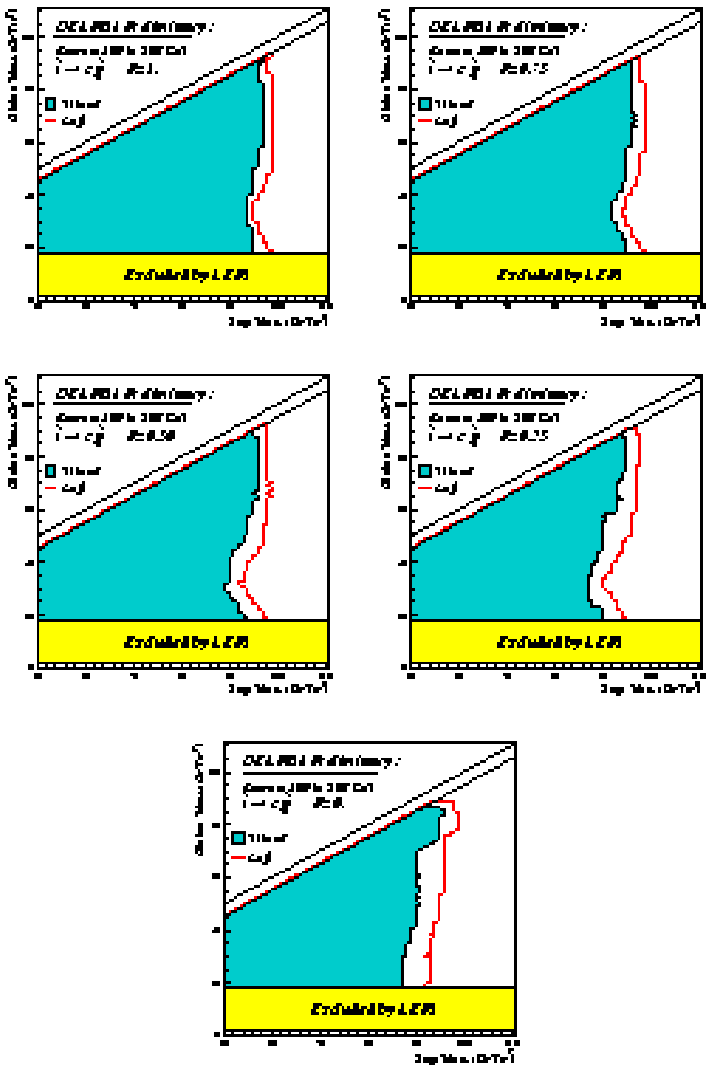


Figure 17: Results of the LEP2 susy analysis: excluded region at 95% confidence level in the plane $(m_{\tilde{g}}, m_{\tilde{\chi}})$. The shaded region corresponds to the exclusion for purely left susy, and the line to exclusion obtained for susy at the Z^0 decoupling. Excluded regions are given for different values of P_L the probability that the gluino hadronizes to charged R-hadrons: 0, 0.25, 0.5, 0.75 and 1.

Conclusion

A very extensive effort has been done by all LEP collaborations in an attempt to find non-MSSM SUSY signatures.

The search includes simple topologies like single photons as well as complex ones with many jets, leptons and missing energy.

In the absence of a positive signal various limits have been established.

We don't give up! We will be back with the Tevatron/LHC/NLC/FMC…..