SUSY Searches at LEP

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On behalf of the LEP experiments

Introduction

MSSM Results

Searches with R-Parity Conservation

Charginos, Neutralinos, Sleptons, Stop, Sbottom

Searches with R-Parity Violation

λ, λ', λ''

GMSB: Gauge-Mediated SUSY Searches

Charginos, Neutralinos, Sleptons

Photonic Final States

Prospects

Conclusions

Introduction

- LEP2 Data Sets
- Detectors
- Backgrounds for Searches
- SUSY

Note 1 : no excess of sparticles seen at LEP2. I will only show limits valid at the 95 % C.L.

Note 2 : I cannot show all results from the 4 LEP experiments : I have chosen representative results from each Collaboration

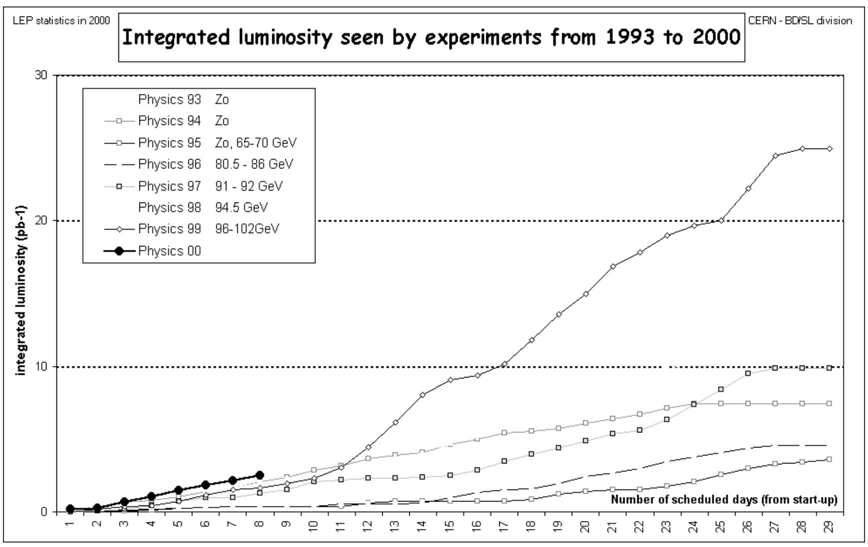
Note 3 : I will present a collection of preliminary results from data collected up to the end of 1999 (up to $\sqrt{s} \approx 202$ GeV and up to a total integrated $\mathcal{L} \approx 470$ pb^{-1})

Note 4 : With LEP1 data basically all SUSY particles with $m < m_{Z^0} / 2$ have been excluded

Introduction: LEP Data Sets

Phase	$\sqrt{s}$ (GeV)	Year	Int. $\mathcal{L}$ (pb $^{-1}$)
LEP 1	91	89-95	~160
LEP 1.5	130-140	1995/97	~10
LEP 2	161	1996	~10
	172	1996	~10
	183	1997	~60
	189	1998	~180
	192	1999	~30
	196	1999	~80
	200	1999	~80
	202	1999	~40
	206	2000	~200?

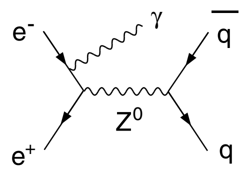
1999: very successfull year for LEP

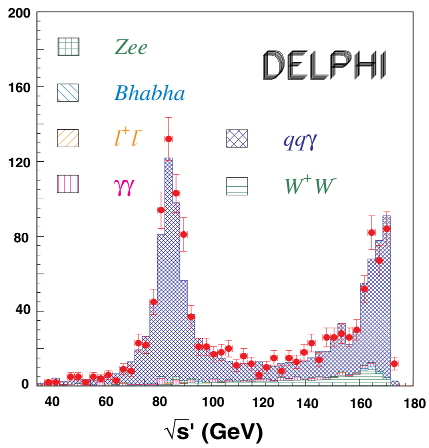


- **Highest energies available at an e^+e^- collider**
- **Good opportunity to extend to a new frontier a lot of searches**

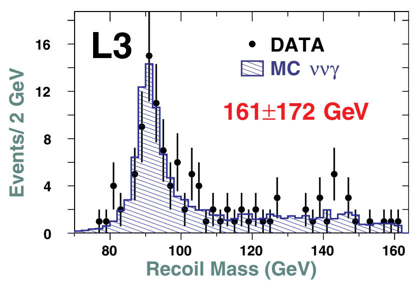
Introduction: Detectors

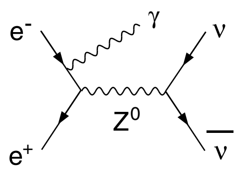
- **Event topologies that could originate from SUSY signals:**
  - *Isolated Leptons (particle identification)*
  - *Acoplanar Jets (tracking, calorimetry)*
  - *Missing Energy (hermeticity)*





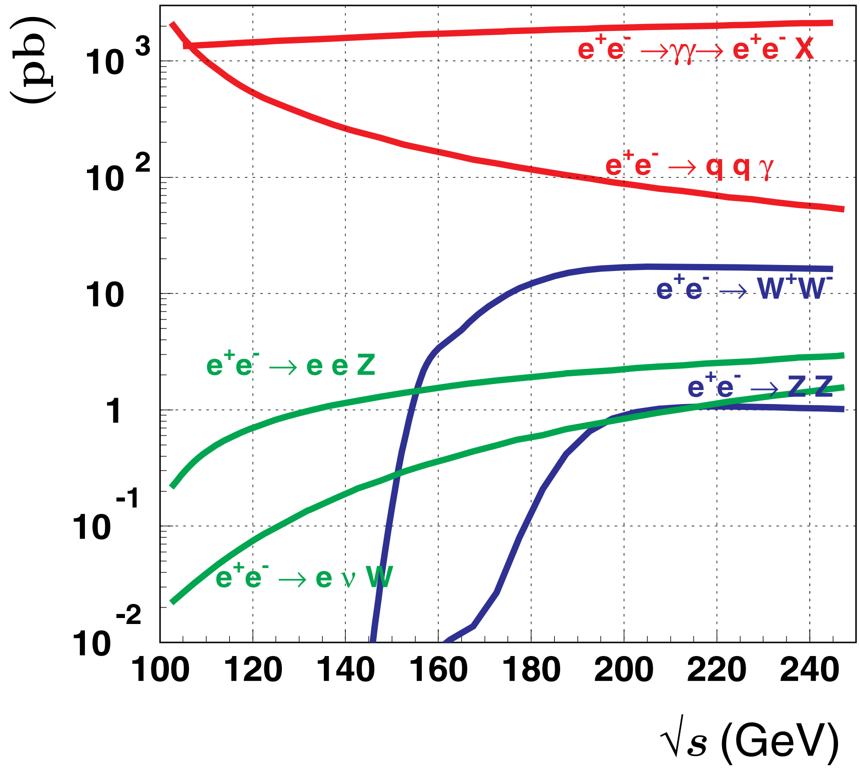
Good efficiency and resolution for the hadronic system





... and for γ's and leptons: hermeticity for missing energy

Introduction: Background for Searches



$\sigma\,(e^+e^- \rightarrow q\,\bar{q}\,\gamma) \sim 100$ pb

$\sigma\,(e^+e^- \rightarrow W^+W^-) \sim 15$ pb

$\sigma\,(e^+e^- \rightarrow ZZ) \sim 1$ pb

- *Four-fermion processes, small cross-section but difficult to eliminate*
- *Two-photon processes $\gamma\gamma \rightarrow q\,\bar{q}, \ell\,\bar{\ell}$ have large cross-sections (σ > 1 nb) but their contribution to the background can be greatly reduced*

Introduction: SUSY

In SUSY models all "normal" particles are accompanied by their supersymmetric partners, whose spin differs by 1/2.

SUSY Spectrum

Particles, $R = +1$			Sparticles, $R = -1$				
Particle	Spin	Charge	Sparticle	Spin	S-name	Mass eigenstates	
e	1/2	- 1	$\tilde{e}_L, \tilde{e}_R$	0	selectron		sfermions
μ	1/2	- 1	$\tilde{\mu}_L, \tilde{\mu}_R$	0	smu		
τ	1/2	- 1	$\tilde{\tau}_L, \tilde{\tau}_R$	0	stau		
$\nu = \nu_e, \nu_\mu, \nu_\tau$	1/2	0	$\tilde{\nu}$	0	sneutrino		
q = u,d,s,c,b,t	1/2	2/3, -1/3	$\tilde{q}_L, \tilde{q}_R$	0	squark		
g	1	0	$\tilde{g}$	1/2	gluino		gauginos
γ	1	0	$\tilde{\gamma}$	1/2	photino		
Z^0	1	0	$\tilde{Z}^0$	1/2	zino	neutralinos	
$H^0_1,\ H^0_2$	0	0	$\tilde{H}^0_1,\ \tilde{H}^0_2$	1/2	neutral Higgsinos	$(\tilde{\chi}^0_1 - \tilde{\chi}^0_4)$	
$H^\pm$	0	± 1	$\tilde{H}^\pm$	1/2	charged Higgsino	charginos	
$W^\pm$	1	± 1	$\tilde{W}^\pm$	1/2	wino	$(\tilde{\chi}^\pm_1,\ \tilde{\chi}^\pm_2)$	
G	2	0	$\tilde{G}$	3/2	gravitino		

	Spin		
	0	1/2	1
Particles and Sparticles	$\tilde{\ell}$ $\tilde{q}$ H^0_1, H^0_2 $H^\pm$	ℓ q $\tilde{\chi}^0_1 - \tilde{\chi}^0_4$ $\tilde{\chi}^\pm_1,\ \tilde{\chi}^\pm_2$	$\gamma,\ Z^0$ $W^\pm$

Why SUSY ??

Natural (no fine-tuning is necessary)

Important role in Grand Unification Theories (GUT's)

Allows Unification of gravity with other forces

Introduction: MSSM

- MSSM : Minimal Supersymmetric Standard Model is used to guide the analyses and to express the results in a predictive framework but more general cases are also studied

- Parametrization of SUSY Breaking mechanism via :
  - Gaugino masses, M_i (where i=1,2,3 for U(1), SU(2) and SU(3) gauge fields)
  - Scalar masses for Higgs and sfermion fields
  - Yukawa trilinear couplings, A_f , between sfermions and Higgs
  - Mass mixing parameter, μ , and ratio of vacuum expectation values, $\tan\beta$, of the two Higgs doublets

BUT

  - Too many free parameters : a constrained model is needed to substantially reduce the large number of unknown parameters and make predictions

Introduction: CMSSM

- *To constrain MSSM in supergravity inspired models (SUGRA), the SUSY parameters are assumed to be universal at the GUT scale:*
  - *all sfermions have a common mass, m_0*
  - *all gauginos have a common mass, $m_{1/2}$*
  - *all A-couplings are unifed, A_0*
- *The predicted mass spectra, σ and BR are mainly determined by the following 5 MSSM parameters:*

CMSSM

- M_1 and M_2 : U(1) and SU(2) gaugino mass parameters at the weak scale
- tan β : ratio of VEV of Higgs doublets <V2>/<V1>
- μ : mixing parameter of the two Higgs doublet fields
- m_0: common mass of squarks and sleptons at the GUT scale (universal scalar mass)
- A_0 : trilinear scalar Yukawa-like coupling

- *The gaugino and sfermions masses at the weak scale are determined by the RGE. M_2 is conventionally chosen as an independent parameter*

Introduction: CMSSM

- In CMSSM, the gaugino masses at the weak scale are :

$$M_2 = 0.82\, m_{1/2}$$
$$M_1 = 5/3 \tan^2\theta_w\, M_2$$
$$M_3 = \alpha_s / \alpha_{em} \sin^2\theta_w\, M_2$$

- ... and the squark, slepton and sneutrino masses at the weak scale are :

$$m^2_{\tilde{u}_R} \approx m_0^2 + 5.87\, m_{1/2}^2 - 0.16\, m_Z^2 \,|\cos 2\beta|$$

$$m^2_{\tilde{u}_L} \approx m_0^2 + 6.28\, m_{1/2}^2 - 0.35\, m_Z^2 \,|\cos 2\beta|$$

$$m^2_{\tilde{d}_R} \approx m_0^2 + 5.82\, m_{1/2}^2 - 0.08\, m_Z^2 \,|\cos 2\beta|$$

$$m^2_{\tilde{d}_L} \approx m_0^2 + 6.28\, m_{1/2}^2 - 0.42\, m_Z^2 \,|\cos 2\beta|$$

$$m^2_{\tilde{\ell}_R} \approx m_0^2 + 0.15\, m_{1/2}^2 - 0.23\, m_Z^2 \,|\cos 2\beta|$$

$$m^2_{\tilde{\ell}_L} \approx m_0^2 + 0.52\, m_{1/2}^2 - 0.27\, m_Z^2 \,|\cos 2\beta|$$

$$m^2_{\tilde{\nu}_L} \approx m_0^2 + 0.52\, m_{1/2}^2 - 0.50\, m_Z^2 \,|\cos 2\beta|$$

NB.: cannot be directly applied to the masses of the stop, sbottom, and stau since these are affected by large corrections due to the left-right mixing.

Introduction: R-parity

R-parity is a multiplicative quantum number defined as:

$$R_p = (-1)^{2S+3B+L}$$

This discrete multiplicative symmetry is introduced to avoid L and B violation

S: Spin

L: Lepton Number

B: Baryon Number

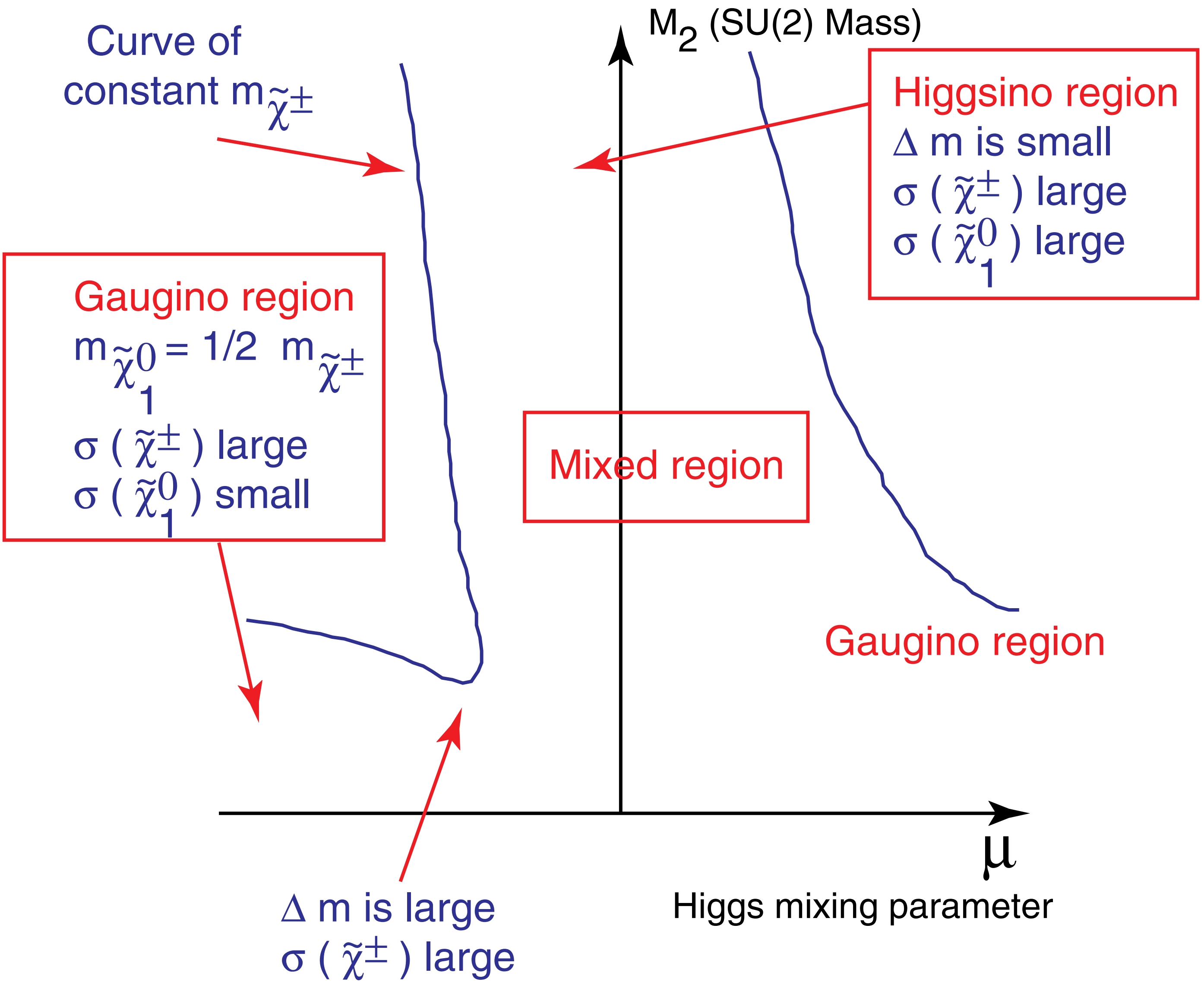
$R_p = 1$ for SM particles

$R_p = -1$ for SUSY particles

	R_p	$\cancel{R_p}$
SUSY particles produced	pairs	pairs or singly
LSP is	$\tilde{\chi}^0_1$	any sparticle
LSP	is stable	decays
Experimental signature	Missing E	Many

Results from searches assuming R_p-conservation are not valid in scenarios assuming R_p-violation

Guide to the (μ, M_2) Plane



Event properties depend on :

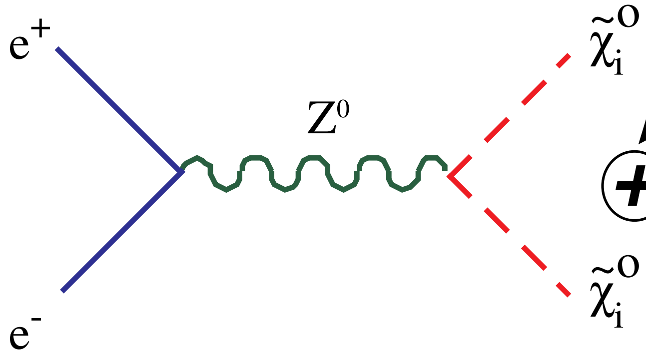
Δ m = Mass of parent sparticle - mass of LSP

Gaugino Searches in R-parity Conserving scenarios

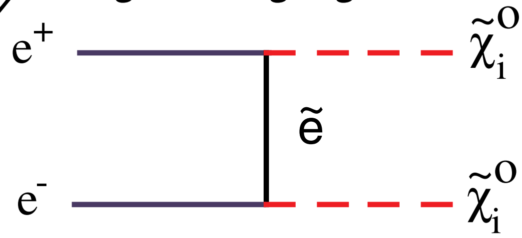
- Neutralinos
- Charginos
  - Large Δm
  - Small Δm
    - $0.15 < \Delta m < 3$ GeV
    - $\Delta m < 0.2$ GeV

Neutralino Production and Decays

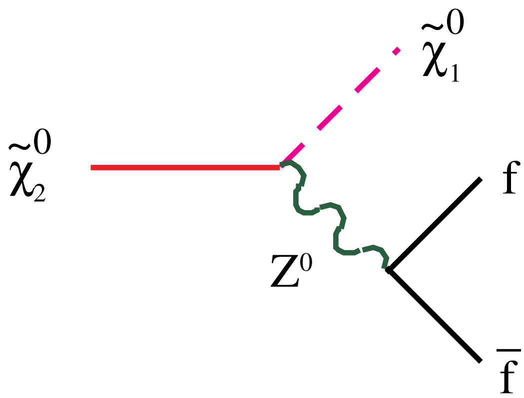
Production

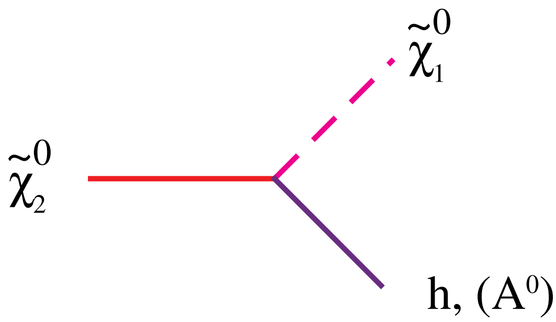


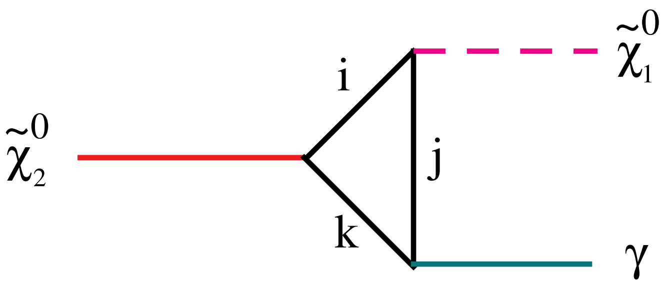
Constructive interference between s and t-channel diagrams if gaugino-like



Decays







$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\, f\bar{f}$$

$$\rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\, \gamma$$

Topologies

Acoplanar jets and missing energy

Acoplanar leptons and missing energy

Single photon events

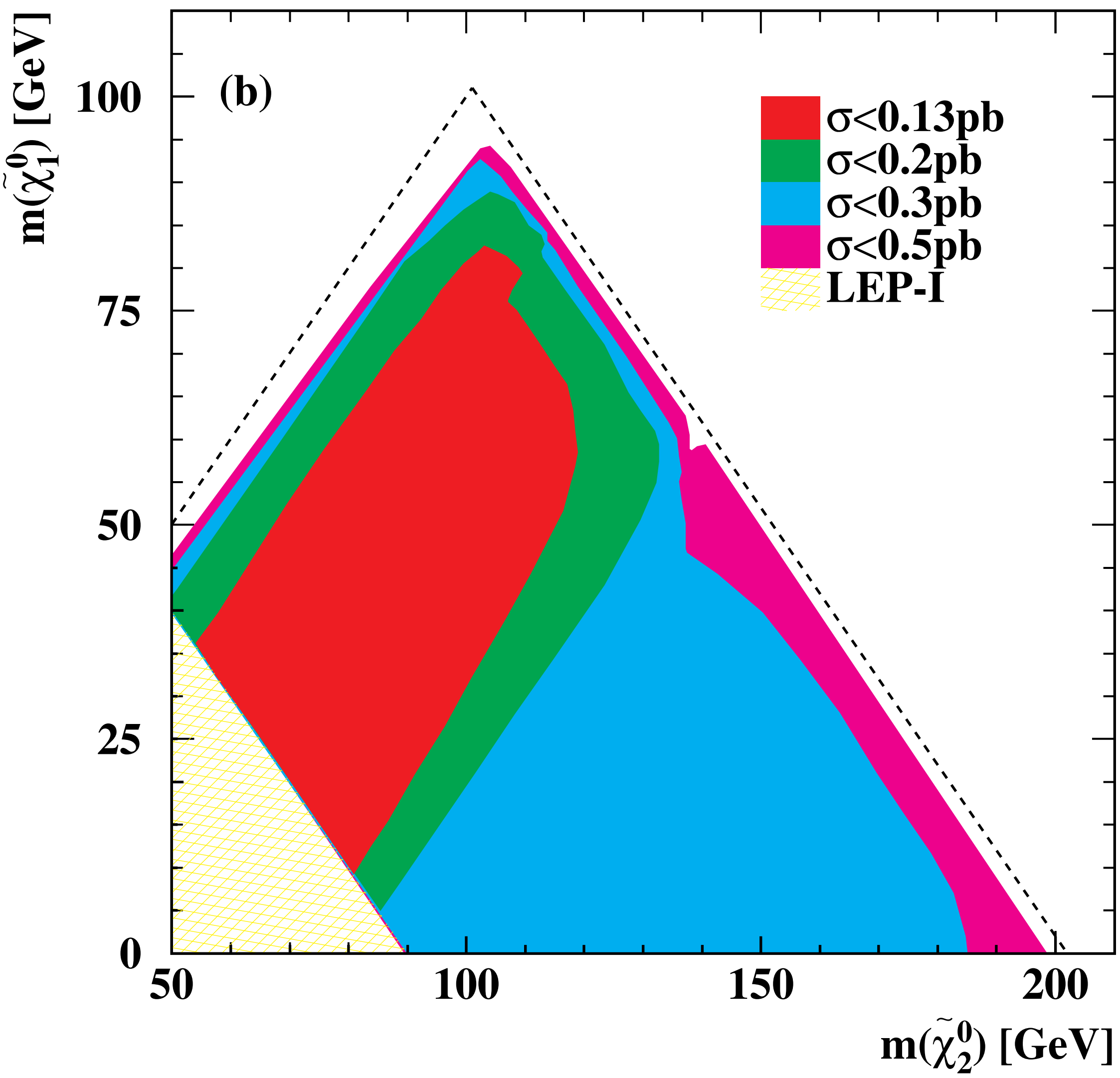
Neutralino Searches: Large Δ m

E.g. OPAL: 2 topologies x 4 Δ m regions

Nch < 4

Nch > 4

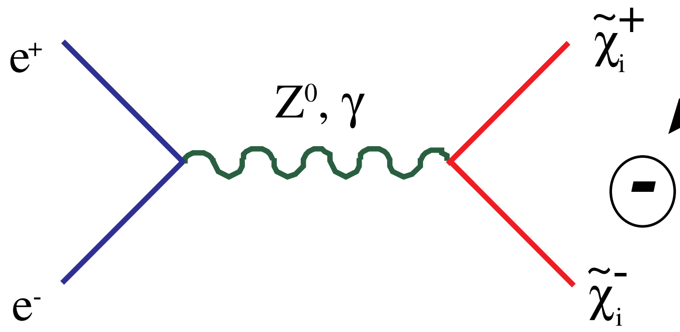
Δ m < 10 GeV
10 GeV < Δ m < 30 GeV
30 GeV < Δ m < 80 GeV
Δ m > 80 GeV



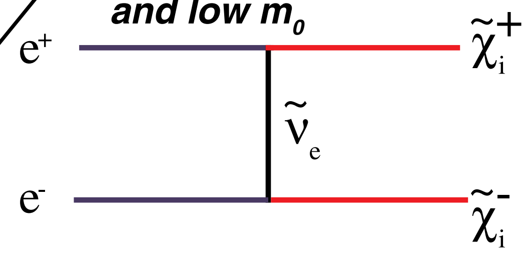
Chargino Production and Decays

Mixtures of $\widetilde{W}^{\pm}$ and $\widetilde{H}^{\pm}$

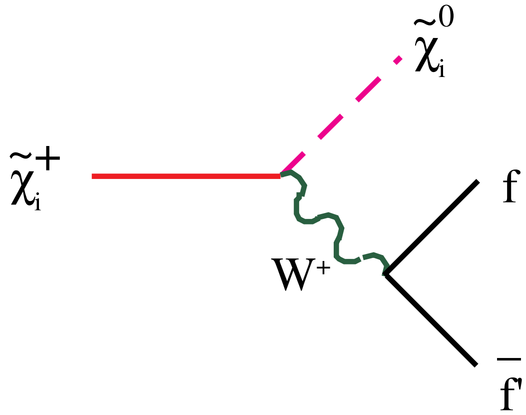
Production

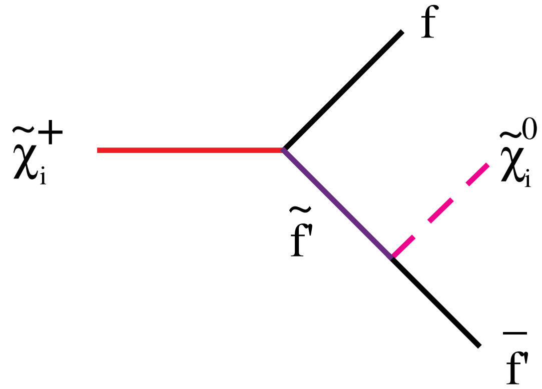


Destructive interference between s and t-channel diagrams if gaugino-like and low m_0



Decays





If sfermion is a light sneutrino: enhances the leptonic BR

Topologies

Acoplanar jets and missing energy

Jets and isolated lepton plus missing energy

Acoplanar leptons and missing energy

Experimentally the most important variable is:

$$\Delta m = m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}$$

Backgrounds

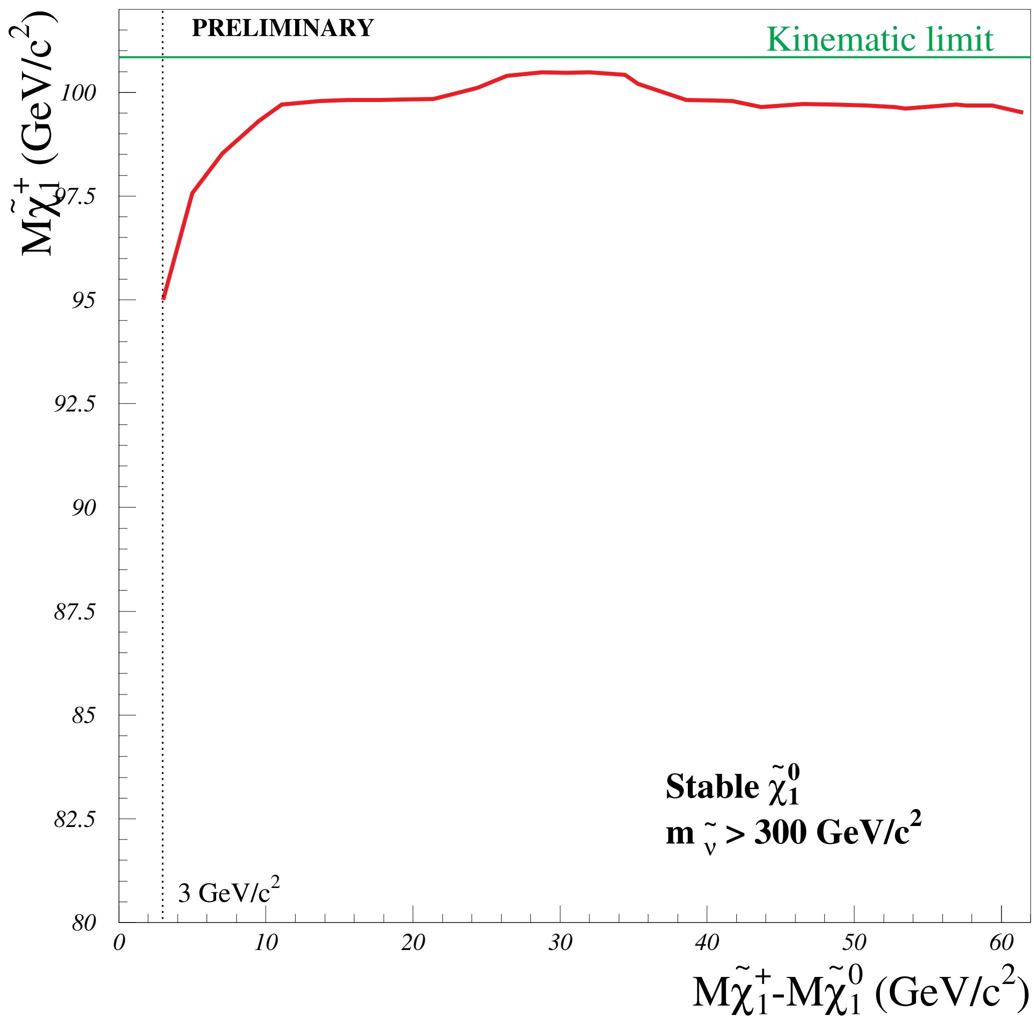
Small Δm	**$\gamma\gamma$ processes**
Large Δm	**WW**

Chargino Searches: Large Δ m

E.g. DELPHI: 4 topologies x 6 Δ m regions

Standard searches are not sensitive at low Δ m

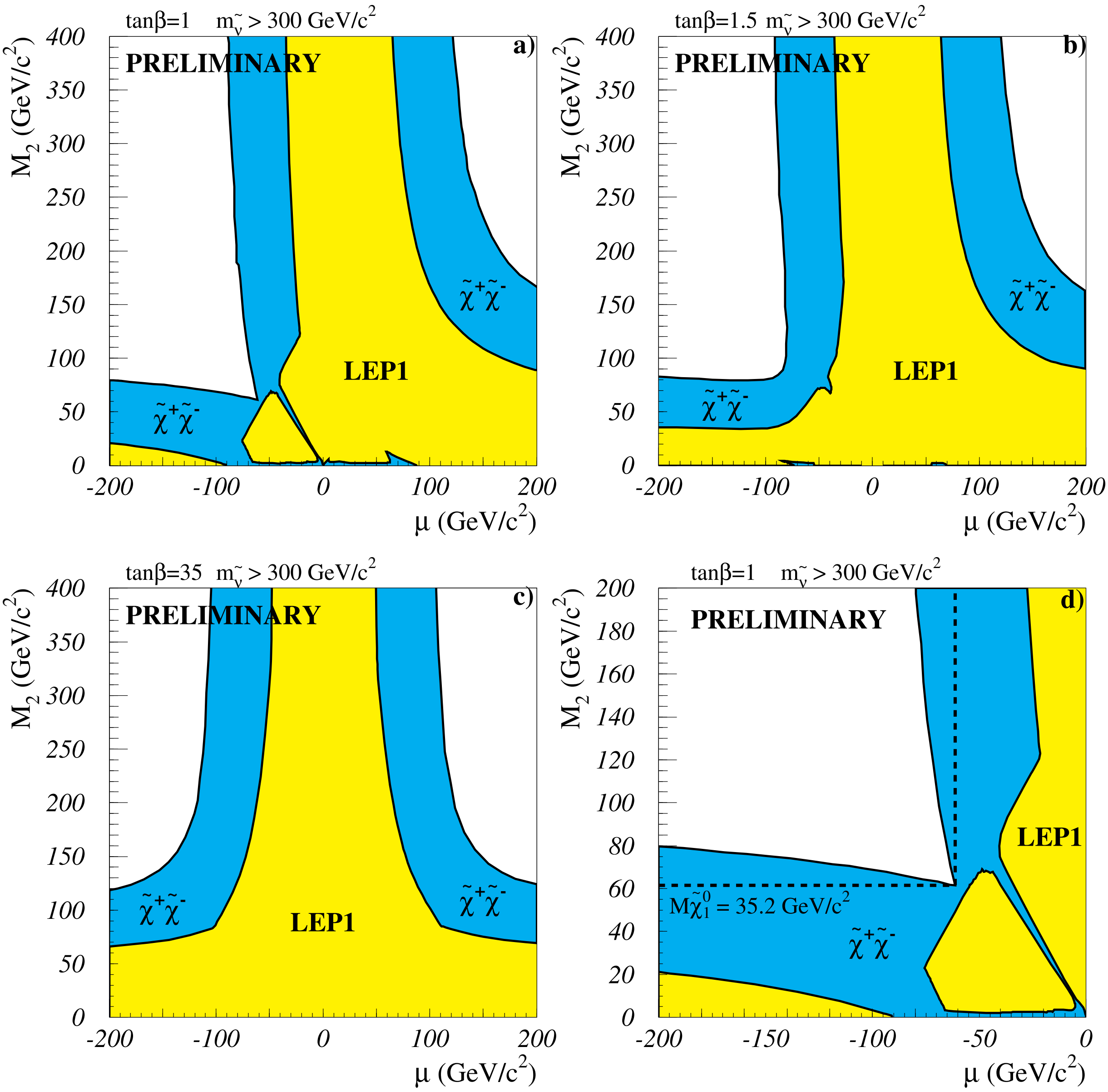
DELPHI $\tilde{\chi}_1^+\tilde{\chi}_1^-$ limits at 202 GeV



Chargino Searches: Large Δ m

Limits in CMSSM

DELPHI MSSM limits at 202 GeV



Chargino Searches: Small Δm

Search for charginos with small mass difference with the lightest neutralino

Standard searches have no sensitivity at low Δm

$$\boxed{0.15 < \Delta m < 3 \text{ GeV}}$$

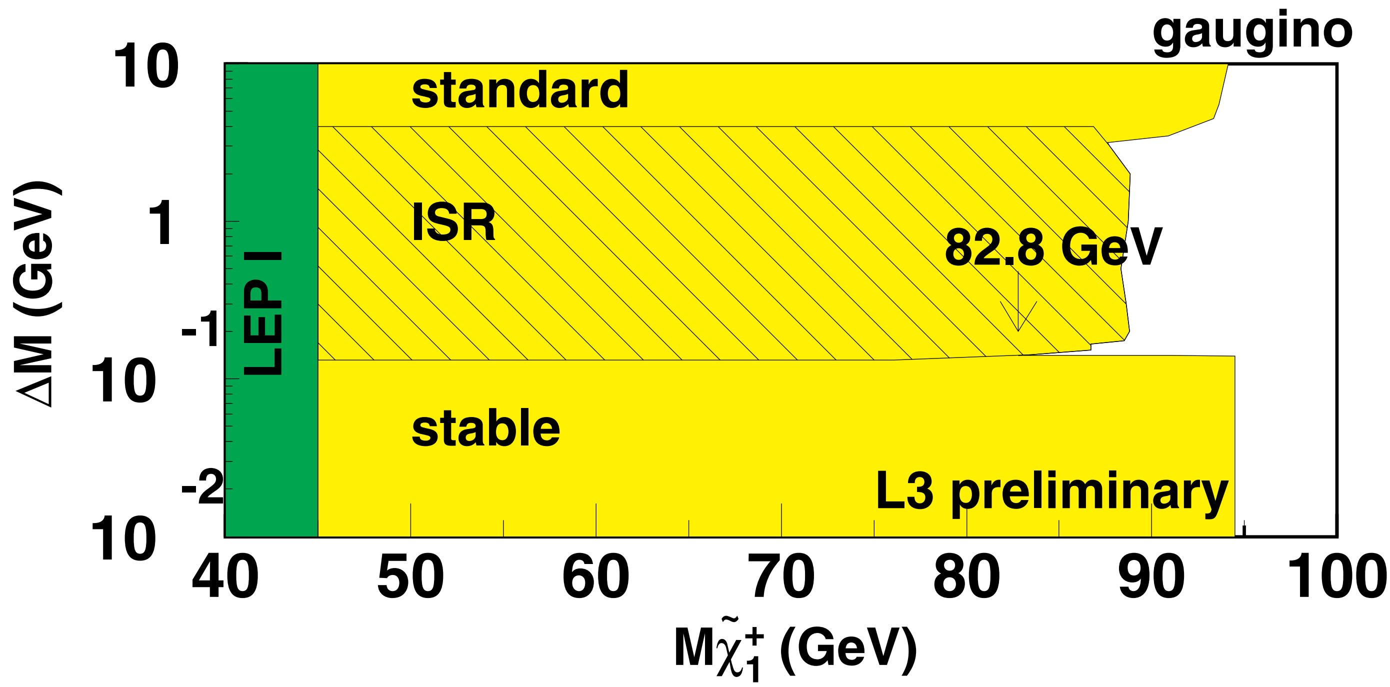
Signal events would have very small visible energy. Require an energetic ISR photon. Detection efficiency very low (few percent)

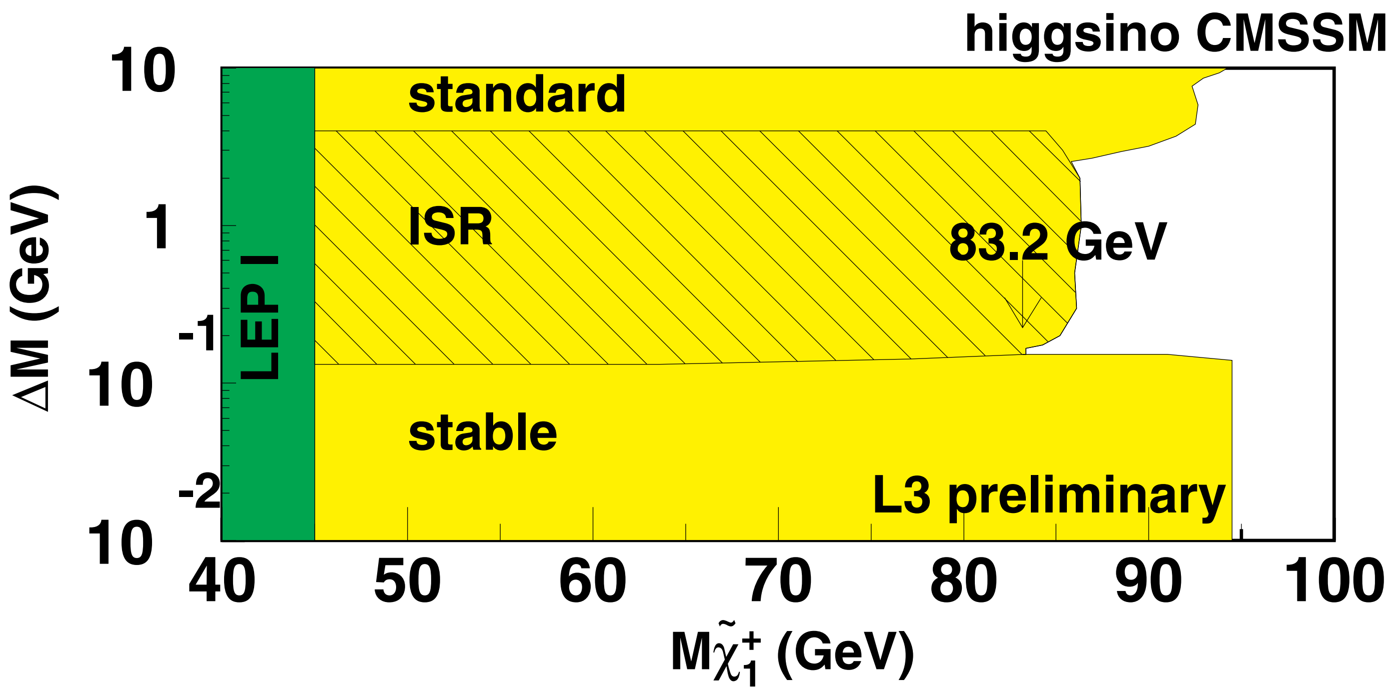
Search for ISR photons + X

$$\boxed{\Delta m < 0.2 \text{ GeV}}$$

Searches for charged heavy stable particles

Chargino Searches: Small Δ m



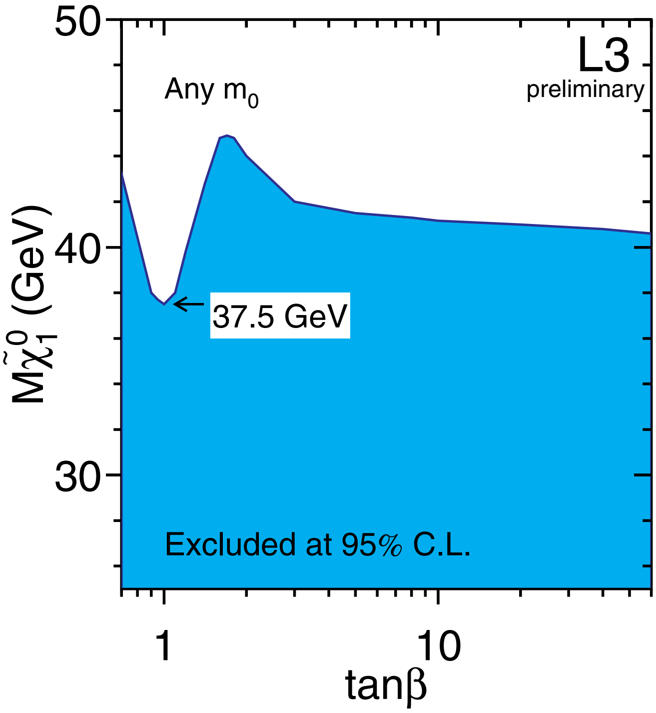


Gaugino Searches: Mass Limits

Charginos are excluded up to the kinematic limit over a large portion of the MSSM (~100 GeV).

L3: Parameter scans → model independent limit on chargino mass:

$$m_{\tilde{\chi}^{\pm}_1} > 80.5 \text{ GeV}$$



ALEPH:	$m_{\tilde{\chi}^0_1} > 36.8$ GeV	$m_o > 500$ GeV
DELPHI:	$m_{\tilde{\chi}^0_1} > 35.2$ GeV	heavy sneutrino
L3:	$m_{\tilde{\chi}^0_1} > 37.5$ GeV	any m_o
OPAL:	$m_{\tilde{\chi}^0_1} > 35.7$ GeV	$m_o > 500$ GeV

Sfermion Searches

Sfermions Searches in R-parity Conserving scenarios

- **MSSM Sfermion Sector**
  - Stop
  - Sbottom
  - Sleptons
    - Selectrons
    - Smuons
    - Staus

MSSM Sfermion Sector

Quarks and leptons have scalar partners: one for each chirality state: ($\tilde{f}_L$, $\tilde{f}_R$)

$$\mathcal{M}^2_{\tilde{f}} = \begin{pmatrix} m^2_{\tilde{f}_L} & a_f m_f \\ a_f m_f & m^2_{\tilde{f}_R} \end{pmatrix}$$

$$m^2_{\tilde{f}_L} = M^2_{\tilde{F}_L} + m_f^2 + (\text{D-term})_L$$

$$m^2_{\tilde{f}_R} = M^2_{\tilde{F}_R} + m_f^2 + (\text{D-term})_R$$

Soft Susy-breaking masses

$$(\text{D-term})_{L,R} = (I^3_{L,R} - Q_f \sin^2\theta_W) \cos 2\beta \, m^2_Z$$

$$a_f = A_f - \mu \tan\beta \;\ldots\; f = e, d$$
$$A_f - \mu \cot\beta \;\ldots\; f = u$$

Weak eigenstates $\rightarrow$ *Mass eigenstates*

$(\tilde{f}_L, \tilde{f}_R) \rightarrow (\tilde{f}_1, \tilde{f}_2)$

MSSM Sfermion Sector

For the first two generations, $\tilde{f}_L$ and $\tilde{f}_R$ are mass eigenstates (Yukawa-coupling effects can be neglected)

Important for 3rd generation: large t, b quarks and τ masses $\rightarrow$ respective right and left sfermions mix

$\rightarrow$ Large Yukawa coupling Y_f and large mixing can make one mass ($\tilde{f}_1$) eigenstate light!

$$m^2_{\tilde{f}_{1,2}} = 1/2\,(m^2_{\tilde{f}_L} + m^2_{\tilde{f}_R}) \mp 1/2 \sqrt{(m^2_{\tilde{f}_L} - m^2_{\tilde{f}_R})^2 + 4\, a^2_f\, m^2_f}$$

$$\tilde{f}_1 = \tilde{f}_L \cos\theta_{mix} + \tilde{f}_R \sin\theta_{mix}$$

$$\theta_{mix} = f\,(m_f, \text{SUSY parameters})$$

Stop Quark Mass

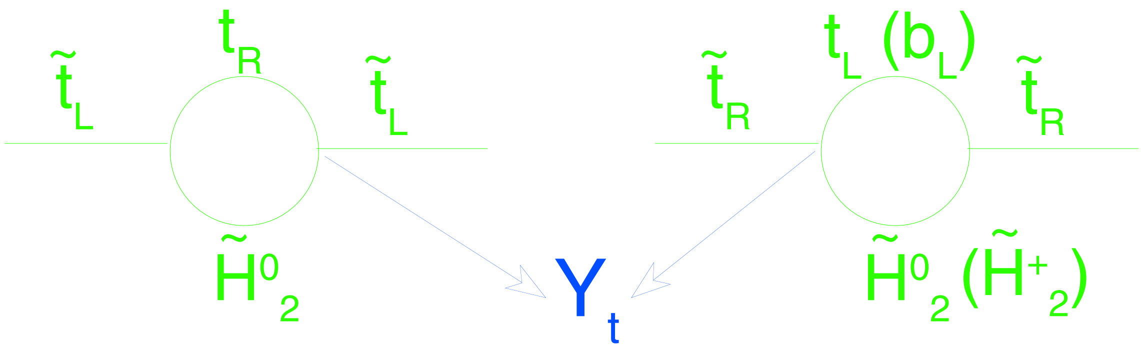
$\tilde{t}_1$ can be the lightest charged SUSY particle

1) Sizeable Radiative correction to $m_{\tilde{t}}$:

Correction is always negative and proportional to Y_t^2

Because $m_t \sim 180$ GeV $\rightarrow$ Large Y_t is expected

$$Y_t = m_t / (\sqrt{2}\, m_W \sin\beta\ )$$



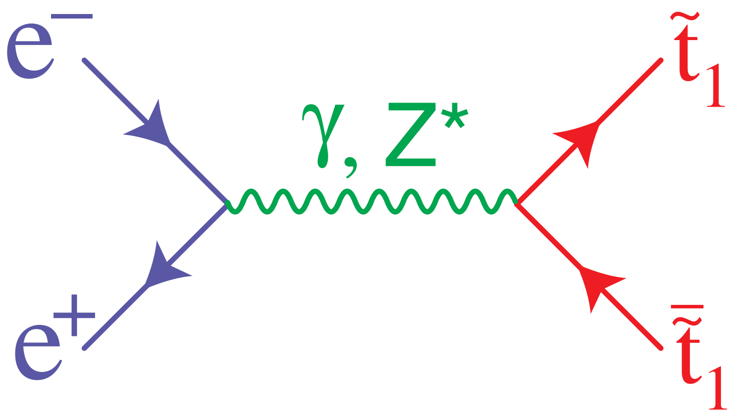
2) L $\leftrightarrow$ R mixing term contributes to off-diagonal components of the mass matrix: large mass split (proportional to m_t)

$$m^2_{\tilde{t}_{1,2}} = 1/2\,(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}) \mp 1/2\sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4\,a^2_f m^2_f}$$

Stop Quark Production

$\tilde{t}_1$ can be the lightest charged SUSY particle

$$\tilde{t}_1 = \tilde{t}_L \cos\theta_{mix} + \tilde{t}_R \sin\theta_{mix}$$



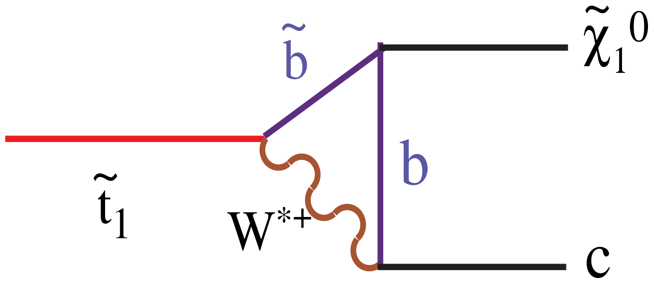
Because $\tilde{t}_1$ is L-R mixing state, $\tilde{t}_1$-coupling to Z^0 depends on θ_{mix}

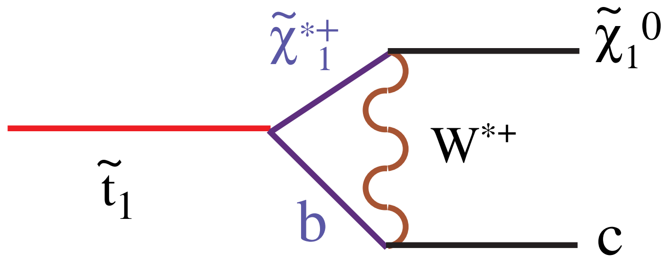
If θ_{mix} = 0.98 rad (= 56 ^{0}),
$\tilde{t}_1$ decouples from Z^0

Stop Quark Decays

$\tilde{t}_1 = \tilde{t}_L \cos\theta_{mix} + \tilde{t}_R \sin\theta_{mix}$

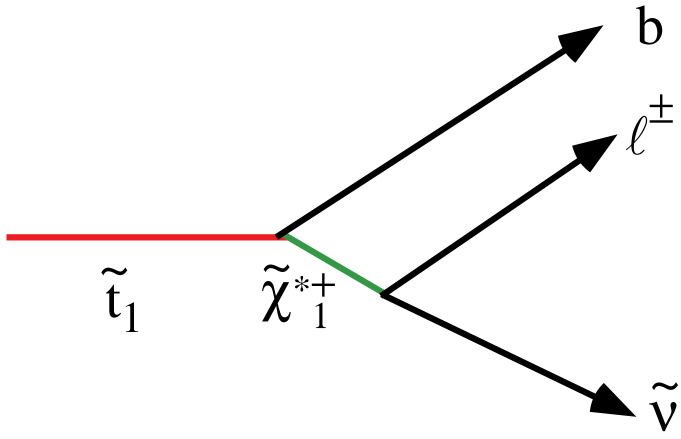
$\tilde{t}_1$ could be the lightest charged SUSY particle



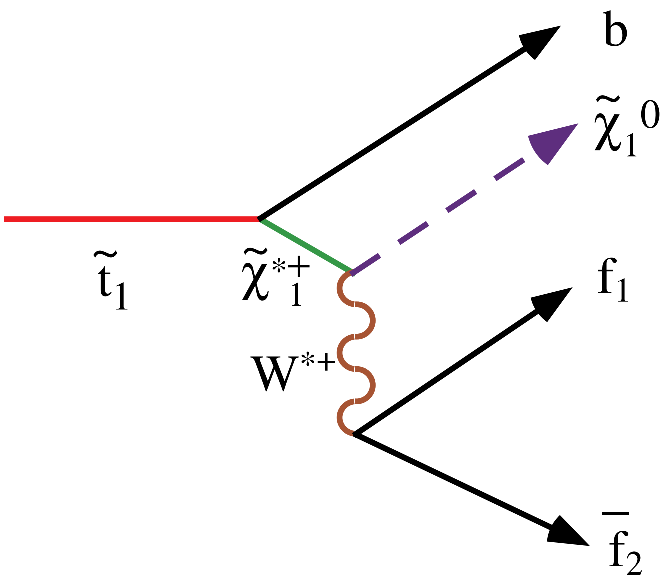


(If chargino is heavy:

$\tilde{t}_1 \rightarrow \tilde{\chi}_1^{\pm}$ b is forbidden)



Three-body decay:
$\Gamma = \mathcal{O}$(10 keV)
If kinematically accessible: dominant mode.
Larger than two-dody decay if $m_{\tilde{\chi}_1^{\pm}} < 200$ GeV

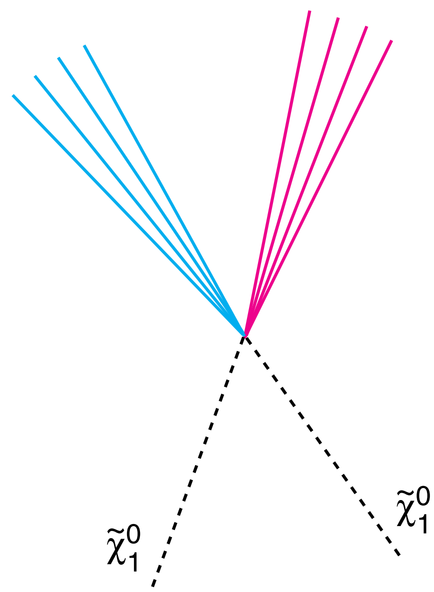


Four-body decay:
$\Gamma = \mathcal{O}$(0.01 eV)
Kinematically suppressed
$\rightarrow$ NEGLECTED

Stop Quark Topology

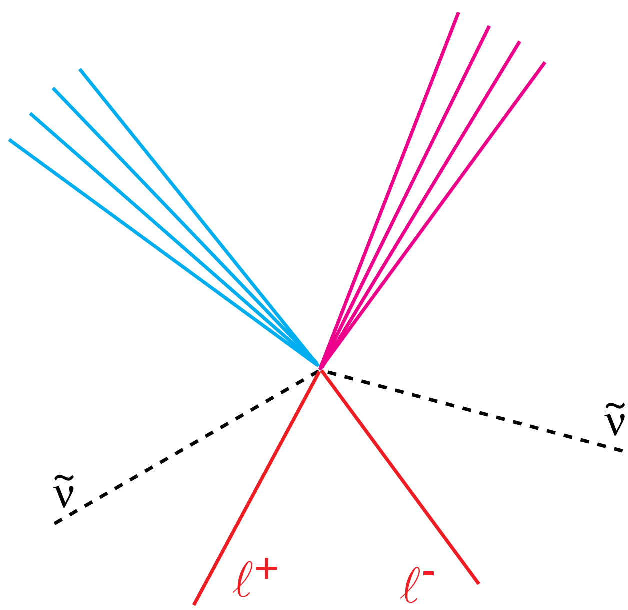
Because $\Gamma << \Lambda_{QCD}$: $\tilde{t}_1$-quark makes $\tilde{t}_1$-hadron before it decays.

Since fragmentation of $\tilde{t}_1$, c, b is hard and $\tilde{t}_1$-hadron is strongly boosted: the jets are expected to be sharp.



Topology for 2-body decay

Two acoplanar sharp jets and missing energy

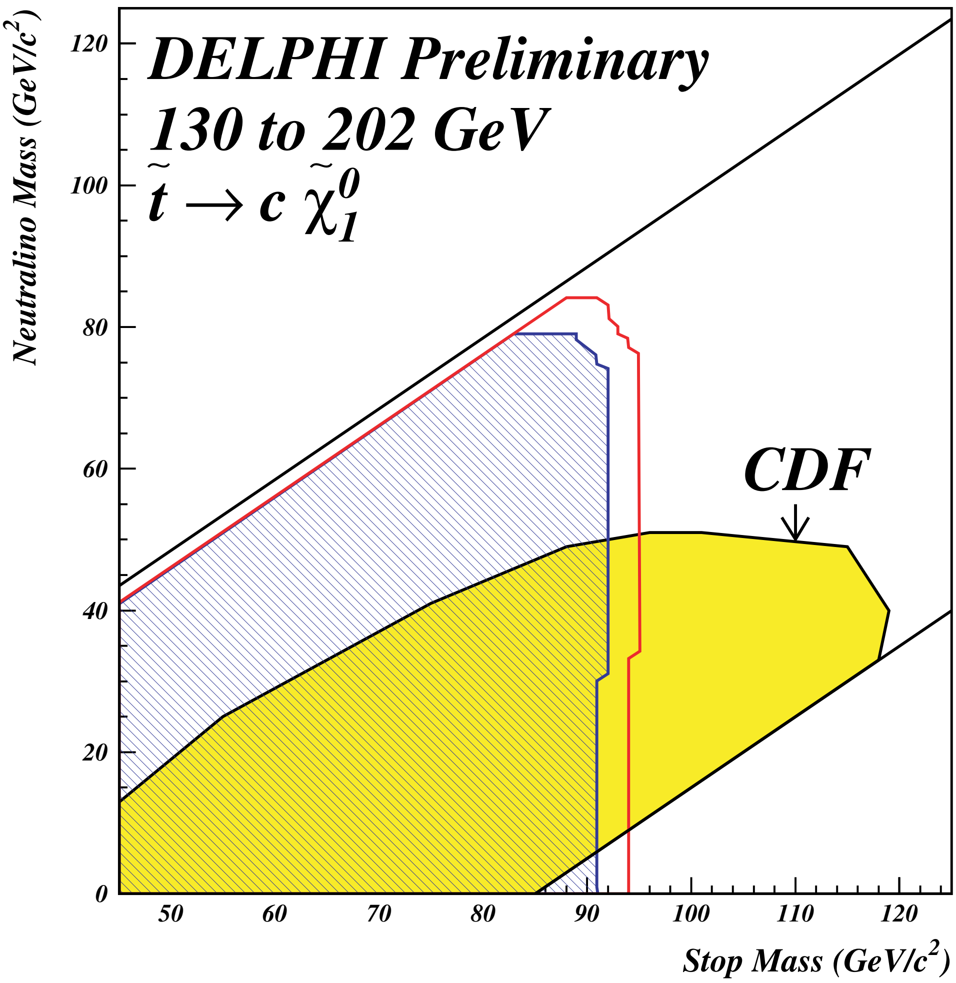


Topology for 3-body decay

Two acoplanar sharp jets, acoplanar lepton pair and missing energy

Stop Quark Results

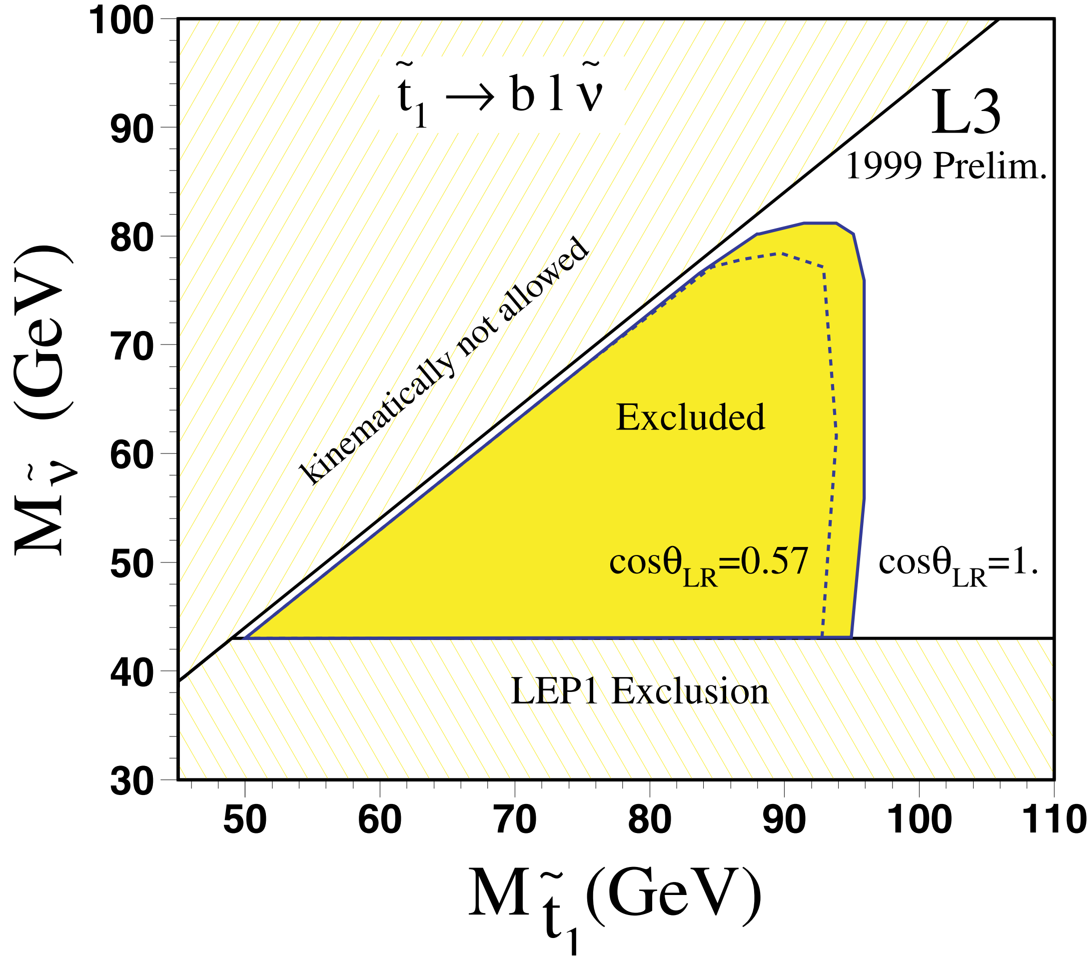
Two-body decay



	Observed	Expected	$m_{\tilde{t}} >$	
ALEPH:	8 and 2	6.5 and 1.9	87 GeV	$6 < \Delta m < 40$ GeV min. σ
DELPHI:	6	9.97	91 GeV	$\Delta m > 20$ GeV min. σ
L3:	19	17.3	87 GeV	$\Delta m > 17$ GeV min. σ
OPAL:	4	8.6	91.8 GeV	$\Delta m > 10$ min. σ

Stop Quark Results

Three-body decay



	Observed	Expected	$m_{\tilde{t}} >$	
ALEPH:	2	1.3	88 GeV	$\Delta m > 10$ GeV min. σ
L3:	0	0.72	92 GeV	$\Delta m > 17$ GeV min. σ
OPAL:	3	2	89.8 GeV	$\Delta m > 10$ GeV min. σ

Sbottom Quark Mass

1) $Y_b = m_b / (\sqrt{2}\, m_W \sin\beta)$ is also sizeable
$\rightarrow$ Sizeable radiative correction to $m_{\tilde{b}}$

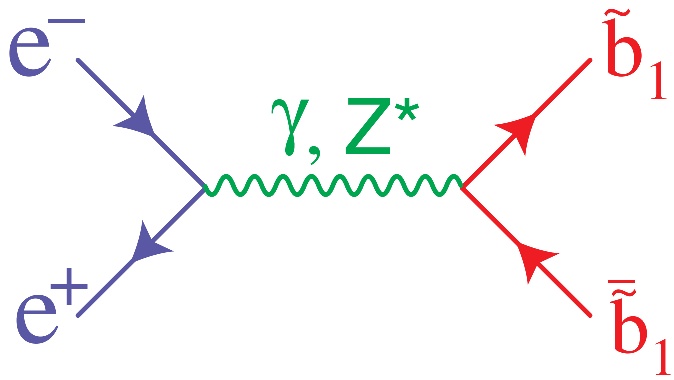
2) L $\leftrightarrow$ R mixing term contributes to off-diagonal components of the mass matrix.

$$m^2_{\tilde{b}_{1,2}} = 1/2\,(m^2_{\tilde{b}_L} + m^2_{\tilde{b}_R}) \mp 1/2\sqrt{(m^2_{\tilde{b}_L} - m^2_{\tilde{b}_R})^2 + 4\,a^2_f m^2_f}$$

Large mass split if large a $\leftrightarrow$ large tan β
$\tilde{b}_1$ can be light if tan $\beta \sim 40$

Sbottom Quark Production

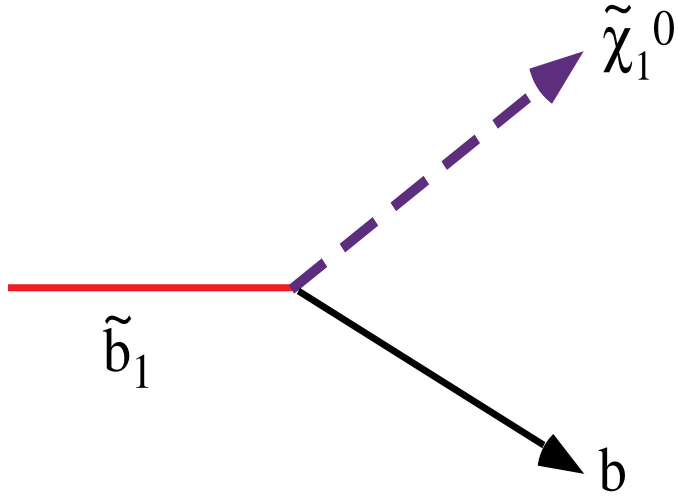
$\tilde{b}_1 = \tilde{b}_L \cos\theta_{mix\text{-}b} + \tilde{b}_R \sin\theta_{mix\text{-}b}$



Because $\tilde{b}_1$ is L-R mixing state, $\tilde{b}_1$-coupling to Z^0 depends on θ_{mix}

If $\theta_{mix\text{-}b} = 1.17$ rad (= 67 ^{0}),
$\tilde{b}_1$ decouples from Z^0

Sbottom Quark Decay



Two -body decay:
$\Gamma = O$**(50 MeV)**

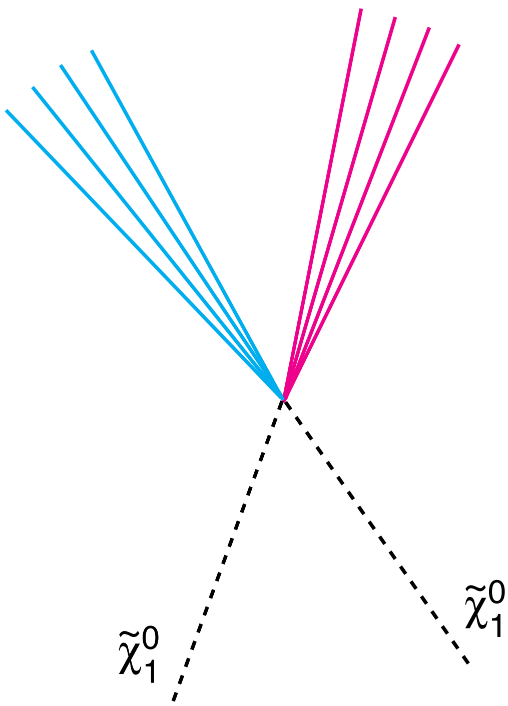
Because $\Gamma << \Lambda_{QCD}$***:*** $\tilde{b}_1$ ***- quark makes*** $\tilde{b}_1$***-hadron before it decays.***

Since fragmentation of $\tilde{b}_1$***, c, b is hard and*** $\tilde{b}_1$***-hadron is strongly boosted: the jets are expected to be sharp.***

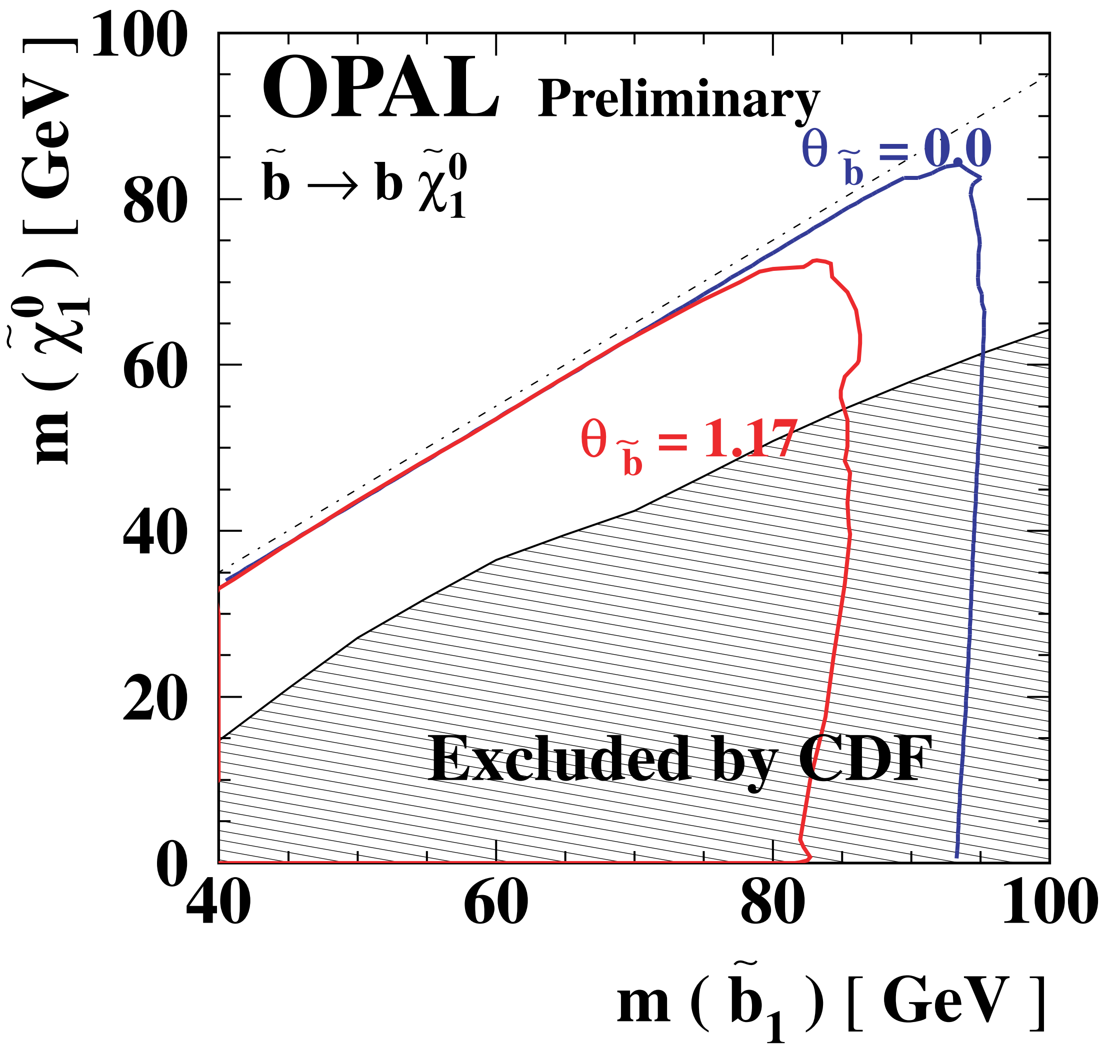
Topology

Two acoplanar sharp jets and missing energy

SIMILAR TO $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 c$



Sbottom Quark Results

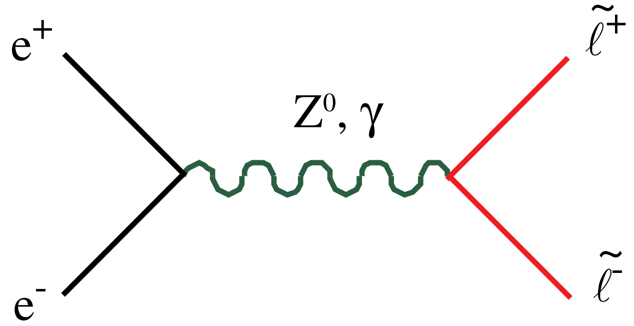


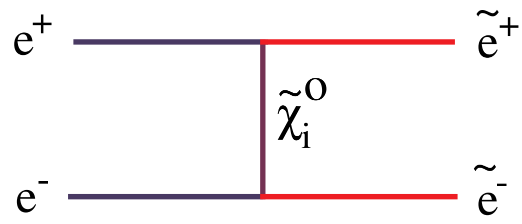
	Observed	Expected	$m_{\tilde{b}} >$	
ALEPH:	1	1.8	84 GeV	$\Delta m > 15$ GeV min. σ
DELPHI:	6	7.75	81 GeV	$\Delta m > 15$ GeV min. σ
L3:	0	1.9	66.5 GeV	$\Delta m > 10$ GeV min. σ
OPAL:	3	8.6	81.9 GeV	$\Delta m > 10$ GeV min. σ

Slepton Production and Decay

Production

$e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$

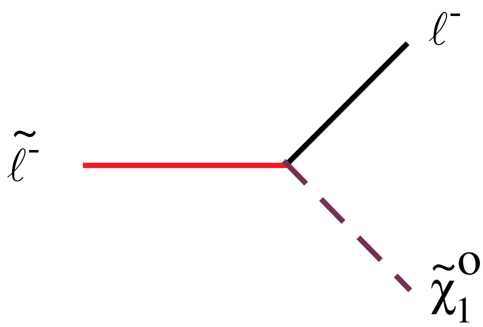




Smuon σ smaller due to s-channel only

Selectron σ higher due to t-channel

Decays



Topology

Two acoplanar leptons of the same family and missing energy

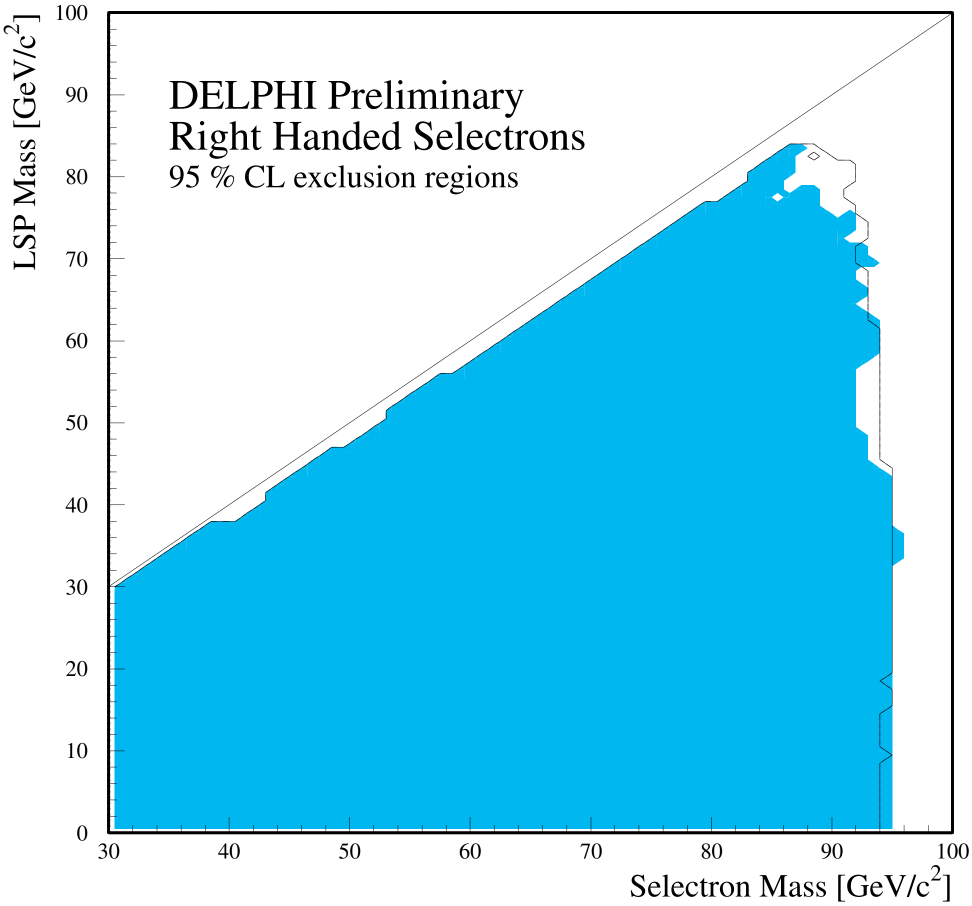
For Stau: non-negligible Yukawa coupling; the lighter state τ_1 is a mixing state of τ_L and τ_R. But cross-section dependence is not strong.

$\tau_1 = \tilde{\tau}_L \cos\theta_{mix\text{-}\tau} + \tilde{\tau}_R \sin\theta_{mix\text{-}\tau}$

If $\theta_{mix\text{-}\tau} = 0.822$ rad $(= 47^0)$, $\tilde{\tau}_1$ decouples from Z^0

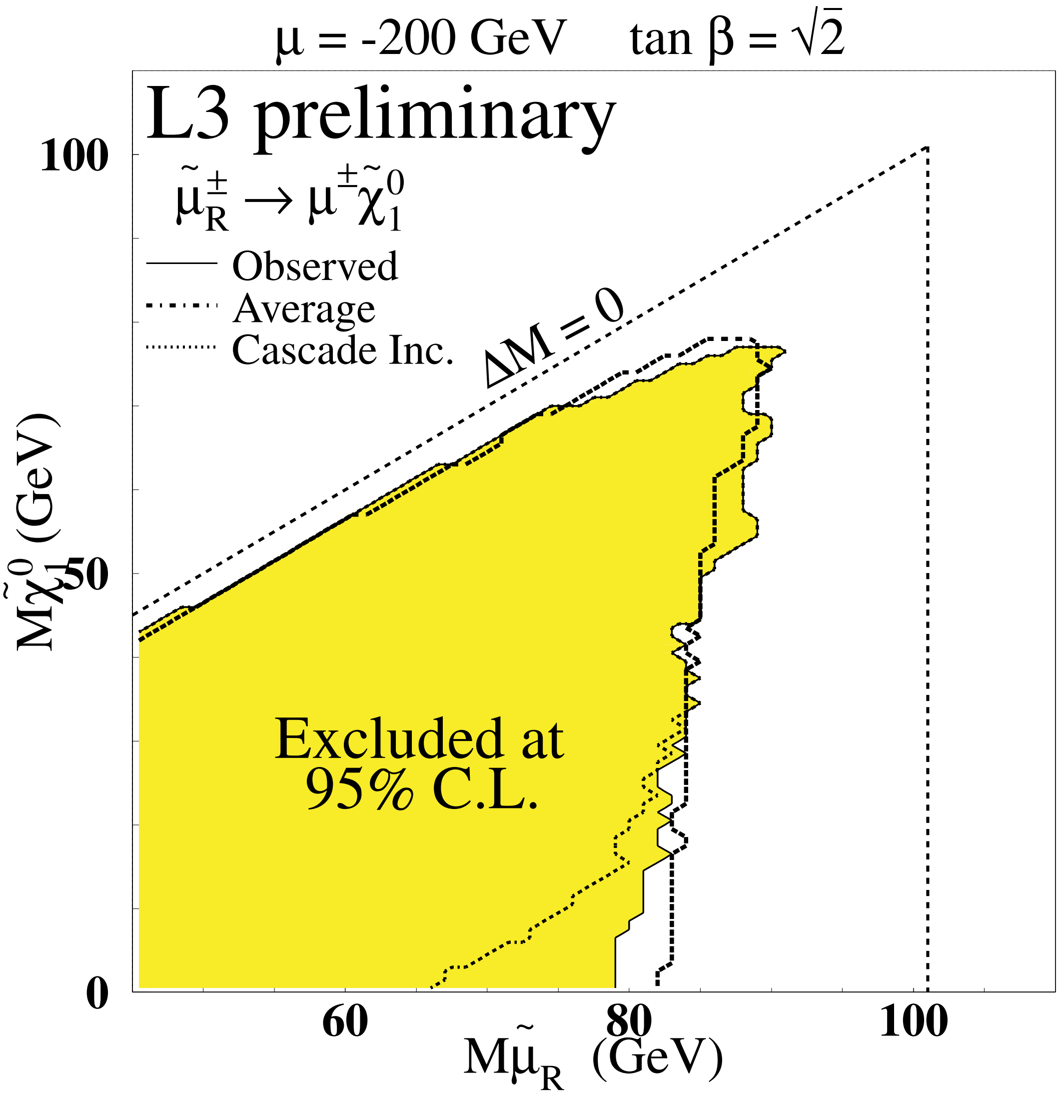
Selectron Results

$\tan\beta$ = 1.5 , μ=200 GeV



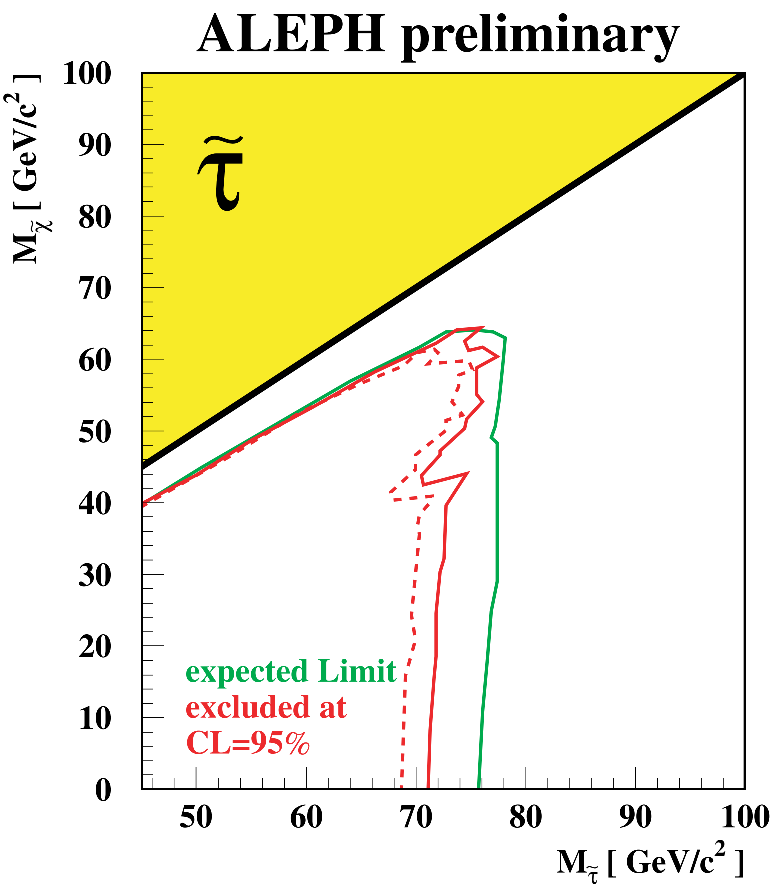
	Observed	Expected	$m_{\tilde{e}}$ >	
ALEPH:	42	48.1	92 GeV	Δ m > 10 GeV
DELPHI:	68	59.3	95 GeV	large Δ m
L3:	24	24.5	92 GeV	Δ m > 17 GeV
OPAL:	48 (ee)	51.2 (ee)	σ limit	

Smuon Results



	Observed	Expected	$m_{\tilde{\mu}} >$	
ALEPH:	39	43.4	85 GeV	$\Delta m > 10$ GeV
DELPHI:	13	19.2	86 GeV	large Δm
L3:	48	40.1	80 GeV	large Δm
OPAL:	57 ($\mu\mu$)	53.8 ($\mu\mu$)	σ limit	

Stau Results



	Observed	Expected	$m_{\tilde{\tau}} >$	
ALEPH:	46	34.2	68 GeV	Δ m > 10 GeV min. σ
DELPHI:	25	19.2	74 GeV	Δ m > 20 GeV min. σ
L3:	41	33.7	70 GeV	Δ m > 10 GeV right-handed stau
OPAL:	107 (eμ)	95.8 (eμ)	σ limit	

RPV Superpotential

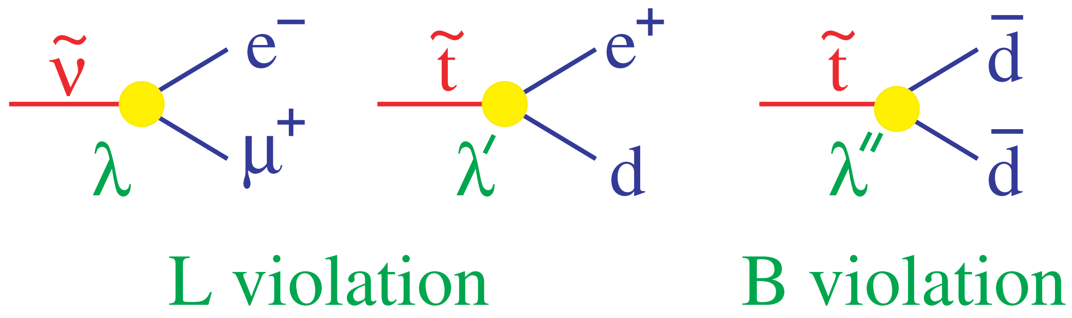
$$W = \lambda_{ijk} L_L^i L_L^j \overline{E}_R^k + \lambda'_{ijk} L_L^i Q_L^j \overline{D}_R^k + \lambda''_{ijk} \overline{U}_R^i \overline{D}_R^j \overline{D}_R^k$$

L violation B violation

(bilinear term $\varepsilon_i L_i H_u$ rotated away)

with

L_L:	lepton doublet superfield
Q_L:	quark doublet superfield
E_R:	lepton singlet superfield
D_R:	down-quark type singlet superfield
U_R:	up-quark type singlet superfield
λ , λ' , λ'' :	Yukawa couplings
i, j, k :	generation indices



Due to symmetry $i < j$ for λ_{ijk}

$j < k$ for λ''_{ijk}

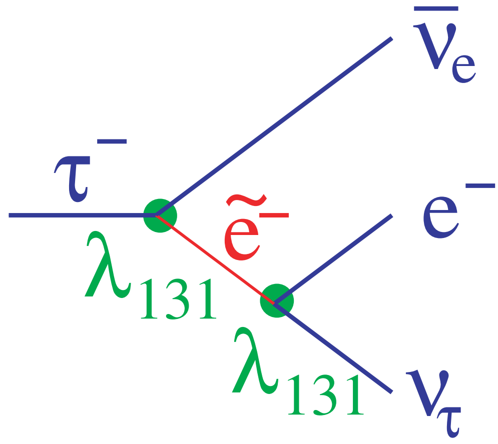
$\longrightarrow$ 45 (9 + 27 + 9) independent couplings

RPV: Experimental Limits

R_p–violation leads to several measurable effects e.g.

- lepton universality violation
- fast proton decay

Non observation of these effects sets limits on the size of the λ-couplings



H. Dreiner: hep-ph/9707435
G. Bhattacharyya: hep-ph/9709395

λ	λ'			λ''
(121) 0.04	(111) 0.0003	(211) 0.03	(311) 0.1	(121) 10^{-10}
(122) 0.04	(112) 0.01	(212) 0.03	(312) 0.1	(131) 10^{-5}
(123) 0.04	(113) 0.01	(213) 0.03	(313) 0.1	(132) 1.25
(131) 0.05	(121) 0.04	(221) 0.13	(321) 0.36	(221) 1.25
(132) 0.05	(122) 0.02	(222) 0.13	(322) 0.36	(231) 1.25
(133) 0.001	(123) 0.04	(223) 0.13	(323) 0.26	(232) 1.25
(231) 0.05	(131) 0.04	(231) 0.22	(331) 0.26	(321) 0.43
(232) 0.05	(132) 0.04	(232) 0.22	(332) 0.26	(331) 0.43
(233) 0.05	(133) 0.001	(233) 0.22	(333) 0.12	(332) 0.43

limits for sparticle mass of 100 GeV

More stringent limits on product of two λ–couplings

– non observation of proton decay:

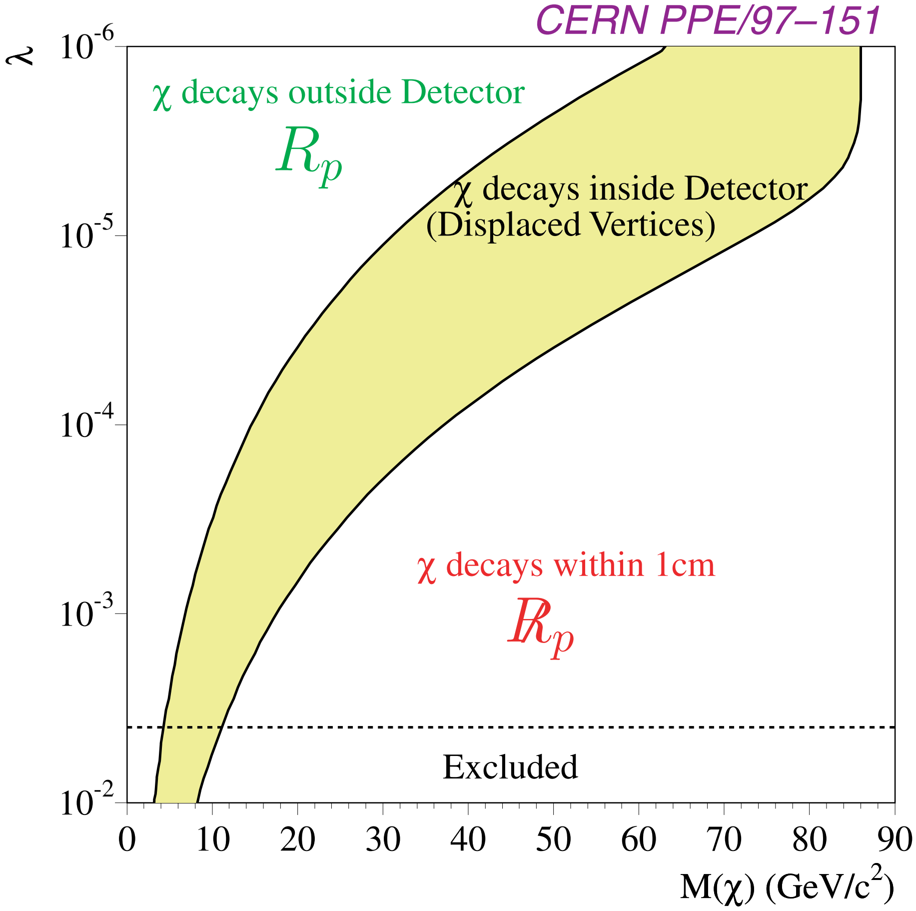
$$\lambda'_{11k} \cdot \lambda''_{11k} < 10^{-23}$$

$\longrightarrow$ assume exactly one λ-coupling is different from 0

RPV: Gaugino Decay Width

Decay width of photino like $\tilde{\chi}^0_1$

CERN PPE/97–151



$$\boxed{\Gamma = \lambda^2 \frac{\alpha}{128\pi^2} \frac{(m_{\tilde{\chi}^0_1})^5}{(m_{\tilde{f}})^4}}$$

$m_{\tilde{f}}$: virtual sfermion mass

Decay width depends strongly on $\tilde{\chi}^0_1$ matrix

For negligible LSP lifetime: mean path of flight is < 1 cm

$$\rightarrow \lambda > 10^{-4}\text{-}10^{-5}$$

RPV: Sfermion Decay Width

$$\Gamma(\tilde{f} \rightarrow f_1 f_2) = \frac{A}{16\pi}\lambda^2 m_{\tilde{f}}$$

A : colour factor (1 or 3)

$m_{\tilde{f}}$: sfermion mass

$\rightarrow \lambda > 10^{-7}$ for decays at vertex

At LEP, couplings down to 10^{-7} have been probed for

- sparticle masses up to the beam energy
- decays at or close to the interaction point

Smaller couplings lead to:

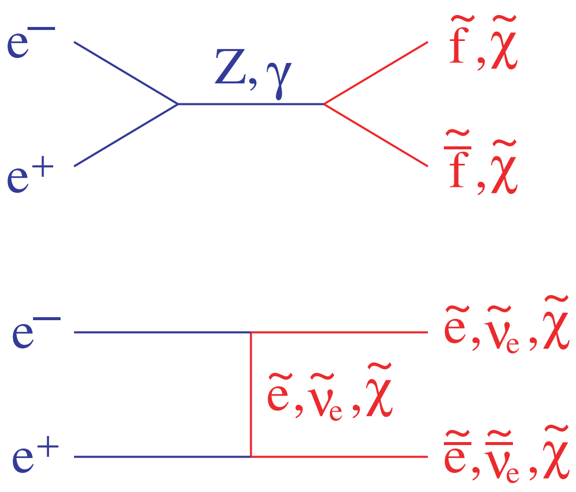
- displaced vertices
- decay outside detector = R_p conversation

Combining all three types of topologies
(decay at vertex, displaced vertices, decay outside detector)

$\rightarrow$ all values of λ-couplings could be probed

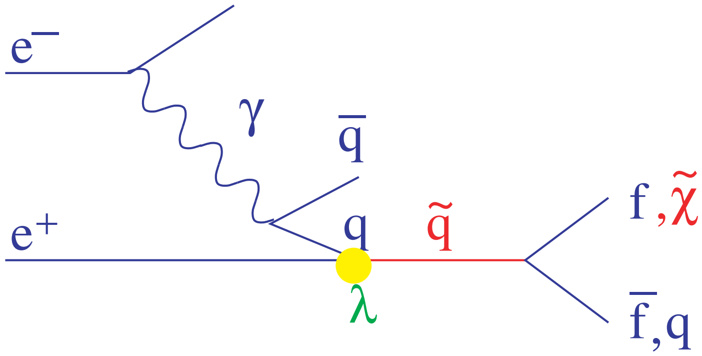
RPV: Production Mechanisms

Pair -production



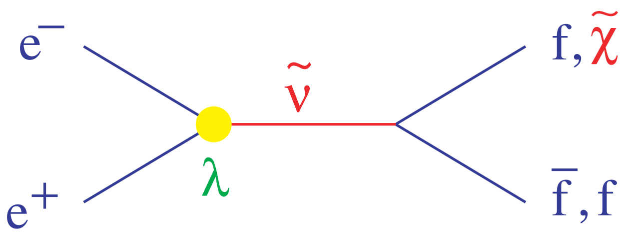
masses up to beam energy

Single production



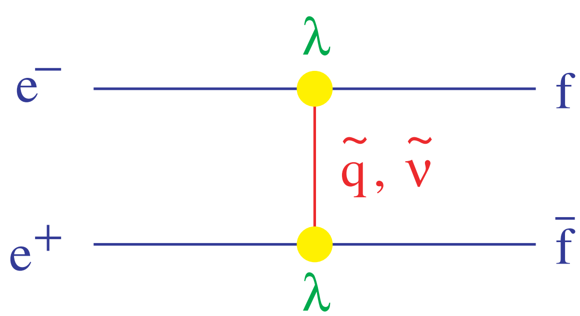
masses up to $\sqrt{s}$

s–channel resonance



masses up to $\sqrt{s}$

t–channel exchange



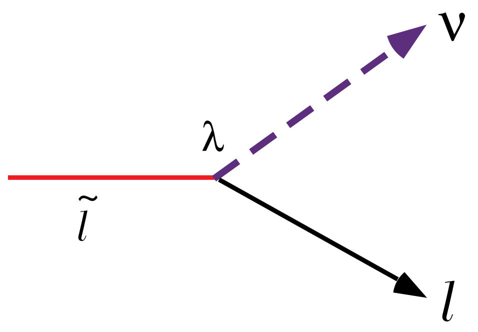
masses up to $2 \times \sqrt{s}$

RPV Slepton Searches

Pair produced $e^+e^- \rightarrow \tilde{l}^+\tilde{l}^-$

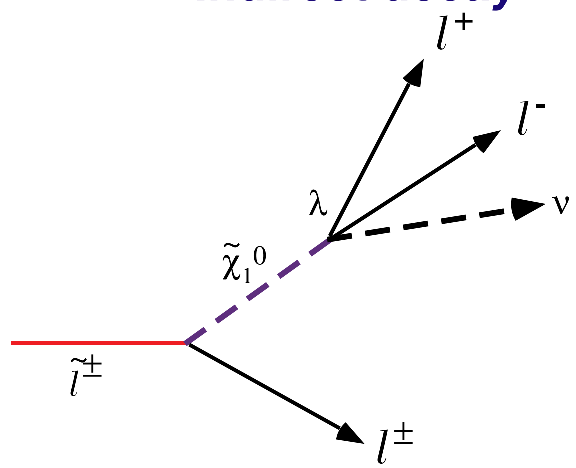
λ Coupling

Direct decay



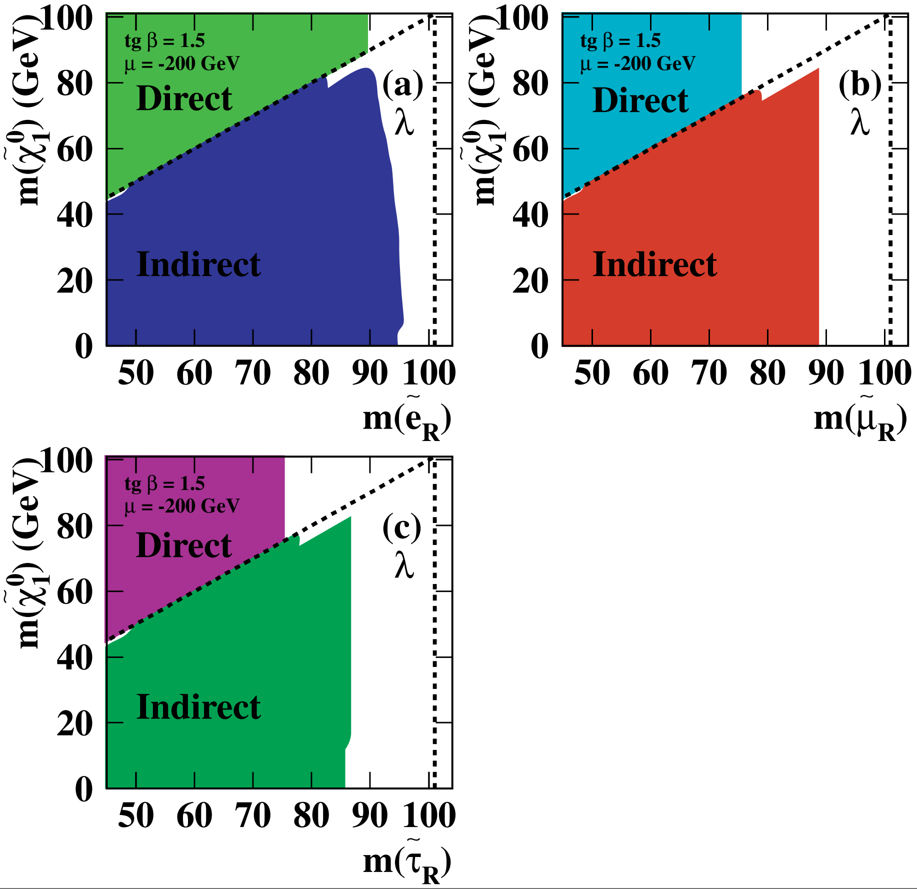
Final states:
2 charged leptons + E_{mis}

Indirect decay



Final states:
6 charged leptons + E_{mis}

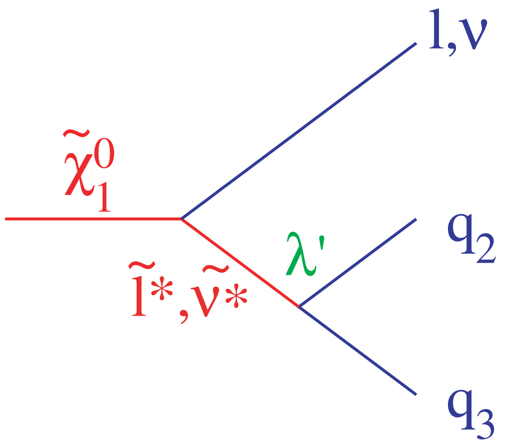
OPAL Preliminary



RPV Chargino/Neutralino Searches

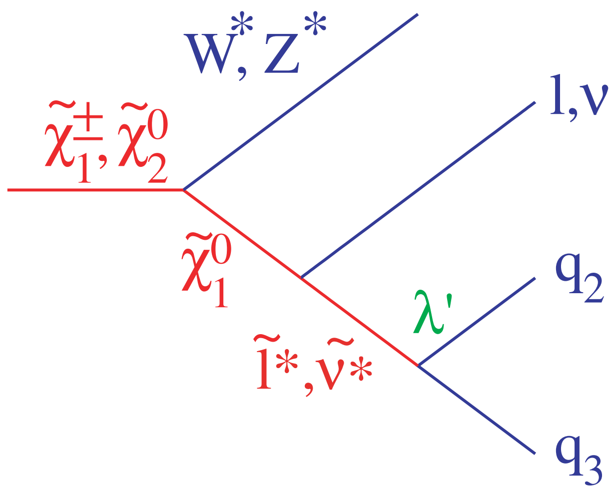
λ' Coupling

Direct decay

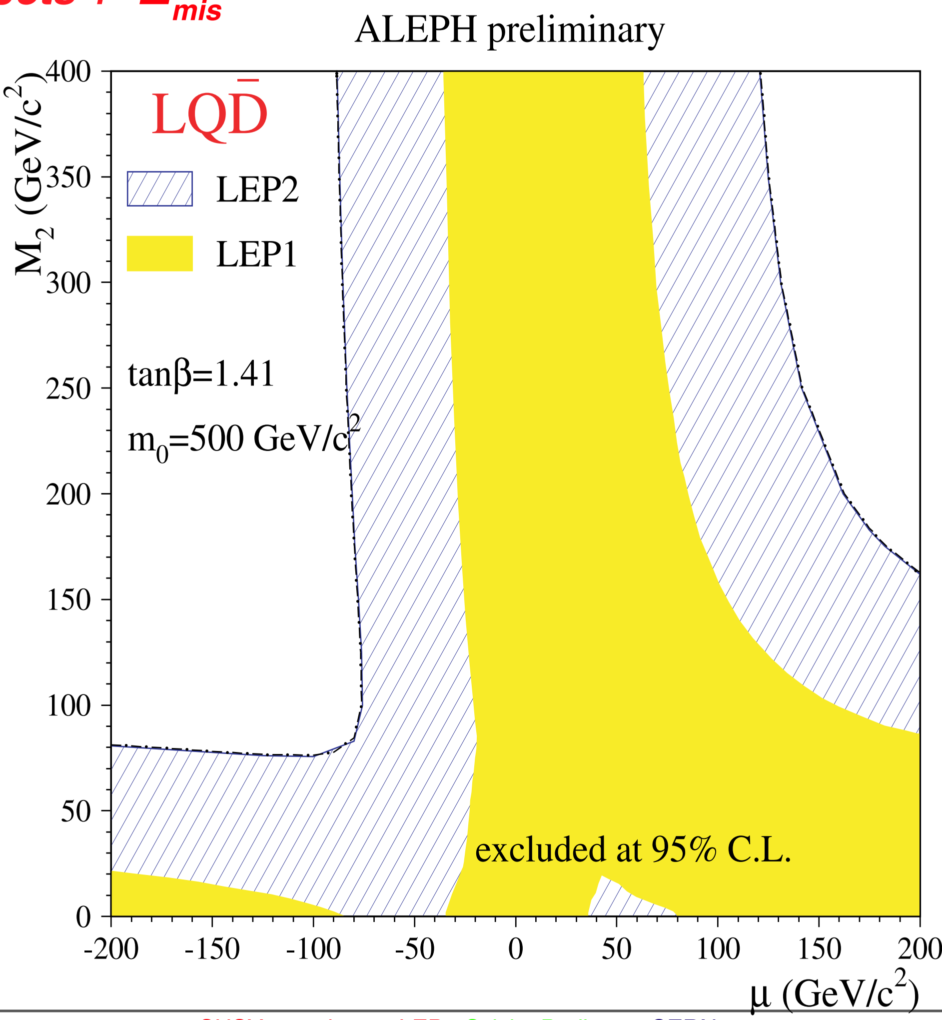


Final states:
Jets + leptons
Jets + E_{mis}

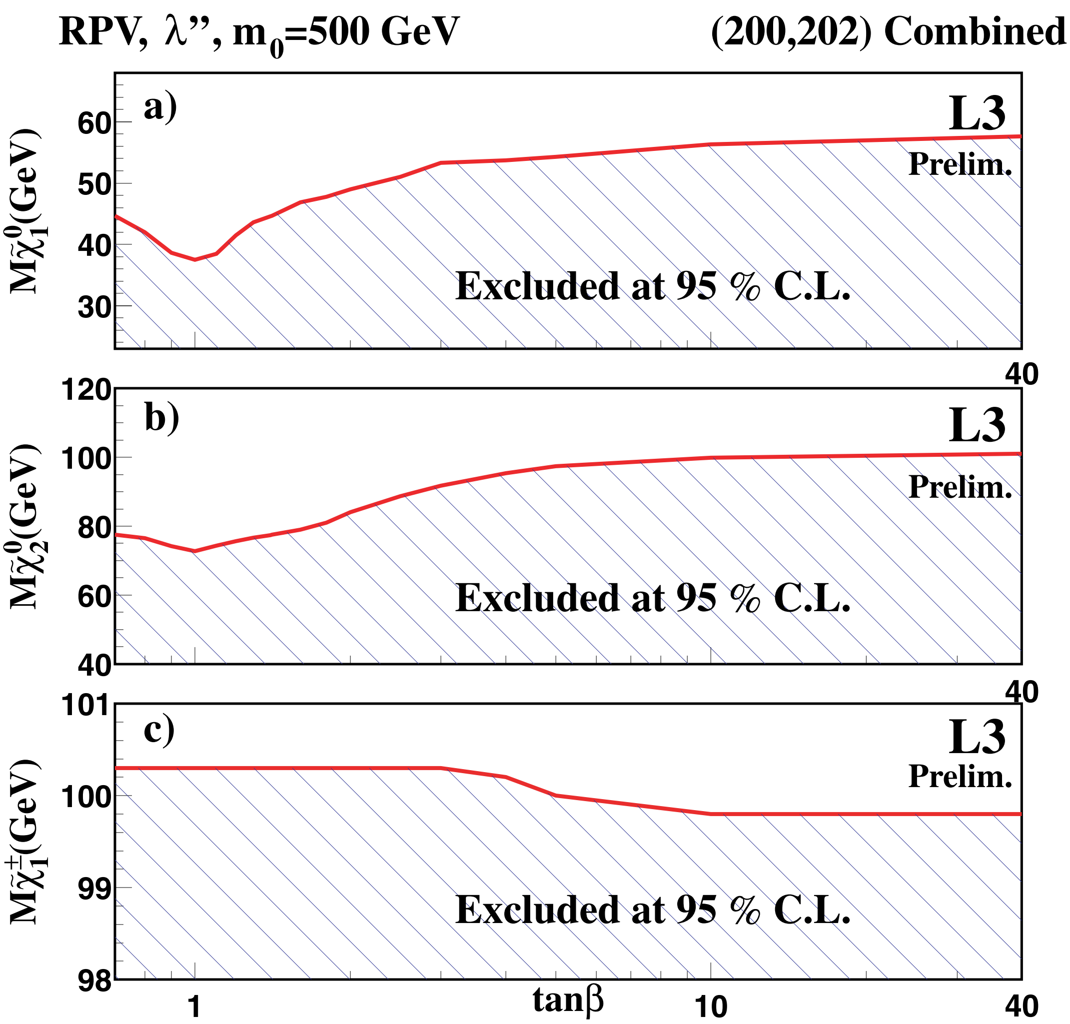
Indirect decay



Final states:
Jets + leptons (+ E_{mis})



RPV Chargino/Neutralino Searches

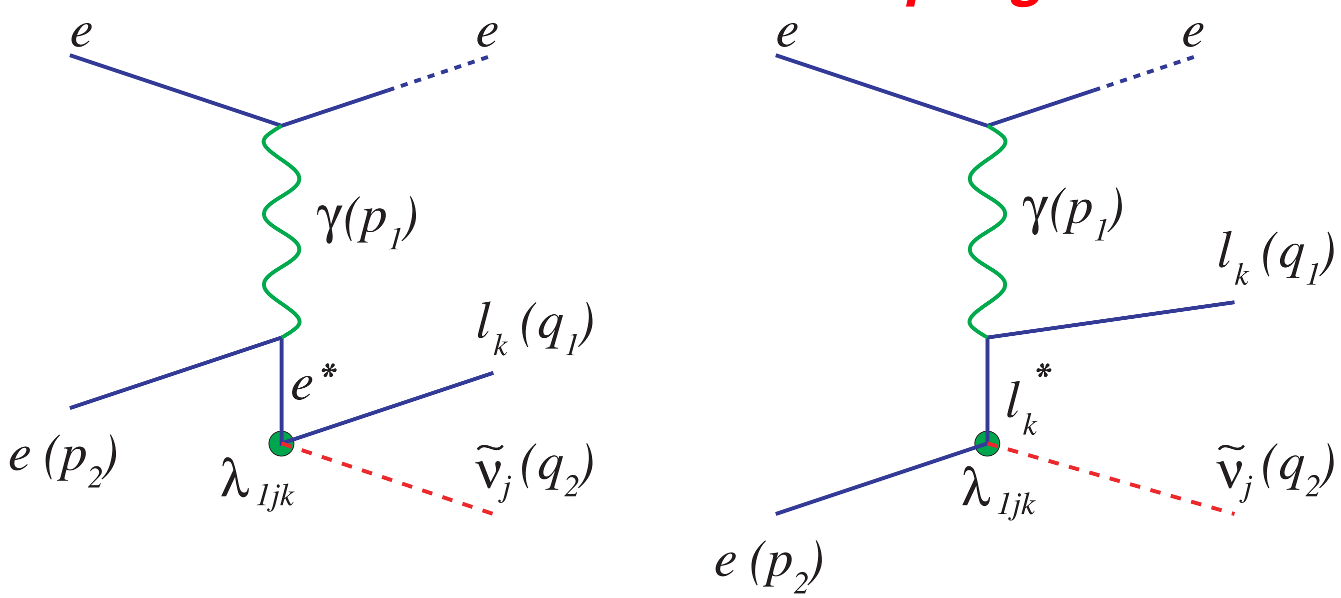


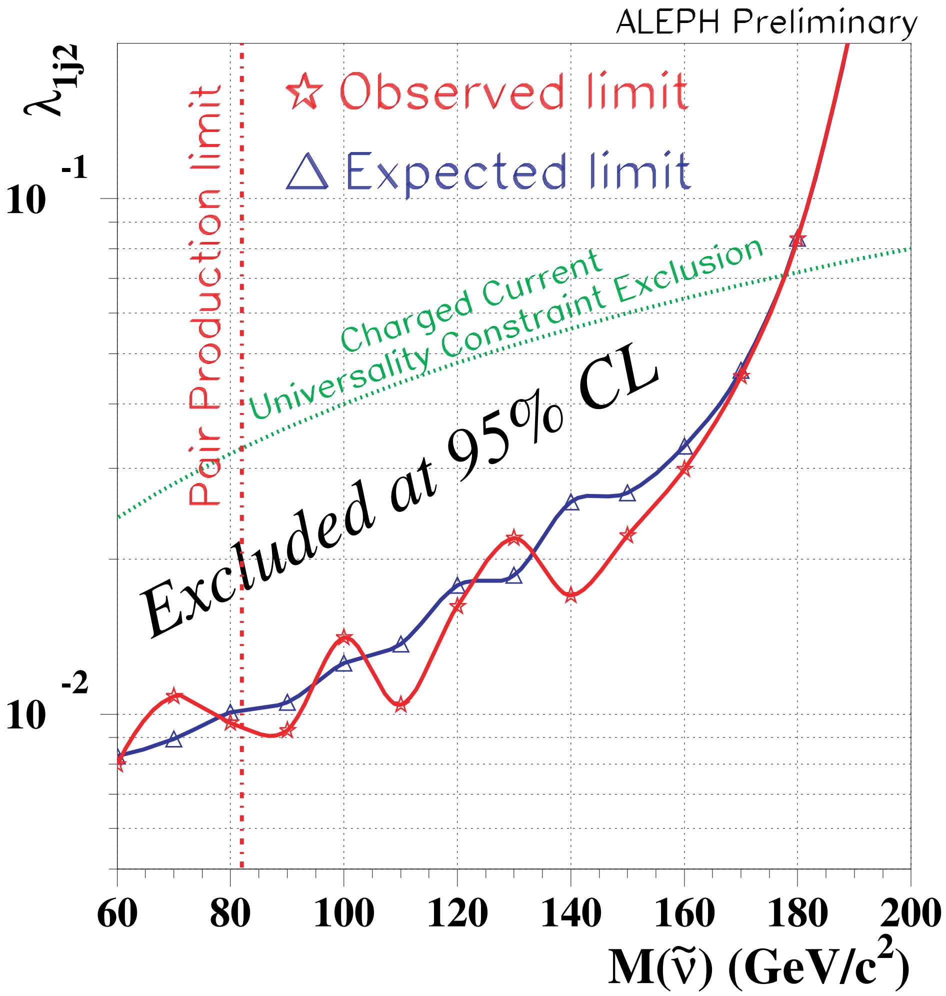
$$m_{\tilde{\chi}_1^0} > 37.5 \text{ GeV}$$

Reached sensitivity is absolutely comparable to the one in R-parity conserving searches

RPV Sneutrino Search

New search with λ coupling





Gauge-Mediated SUSY Breaking

In these models, gauge interactions, rather than gravity, are responsible for SUSY breaking

Phenomenology

- ***The LSP is a Goldstone fermion: the Goldstino, $\tilde{G}$: $m_{\tilde{G}} \leq 1$ keV;***
- ***The NLSP (Next-to-Lightest SUSY Particle) is either the lightest neutralino, $\tilde{\chi}^0_1$, or a charged slepton, $\tilde{\ell}^\pm_R$; these would decay:***
  - $\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$
  - $\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{G}$
- ***The NLSP lifetime, τ_{NLSP} , ranges between 0 and $+\infty$, leading to many different topologies.***

GMSB: Topologies

"Small" τ_{NLSP}

- *The NLSP decays near the interaction point, therefore:*
- *Missing energy due to $\tilde{G}$'s.*
- *If the NLSP is $\tilde{\chi}^0_1$:*
  - *Isolated, energetic photons.*
- *If the NLSP is $\tilde{\ell}^{\pm}$:*
  - *Isolated leptons.*

"Large" τ_{NLSP}

- *The NLSP decays outside the detector.*
- *If the NLSP is $\tilde{\chi}^0_1$:*
  - *Back to "standard" SUSY searches.*
- *If the NLSP is $\tilde{\ell}^{\pm}$:*
  - *Heavy charged "stable" particles.*

"Intermediate" τ_{NLSP}

- *The NLSP may decay inside the detector, but far from the interaction point.*
- *If the NLSP is $\tilde{\chi}^0_1$:*
  - *Displaced photons.*
- *If the NLSP is $\tilde{\ell}^{\pm}$:*
  - *Tracks with a "kink" at the decay point.*

GMSB: Neutralino NLSP

Neutralino Searches

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

2 energetic photons and missing energy

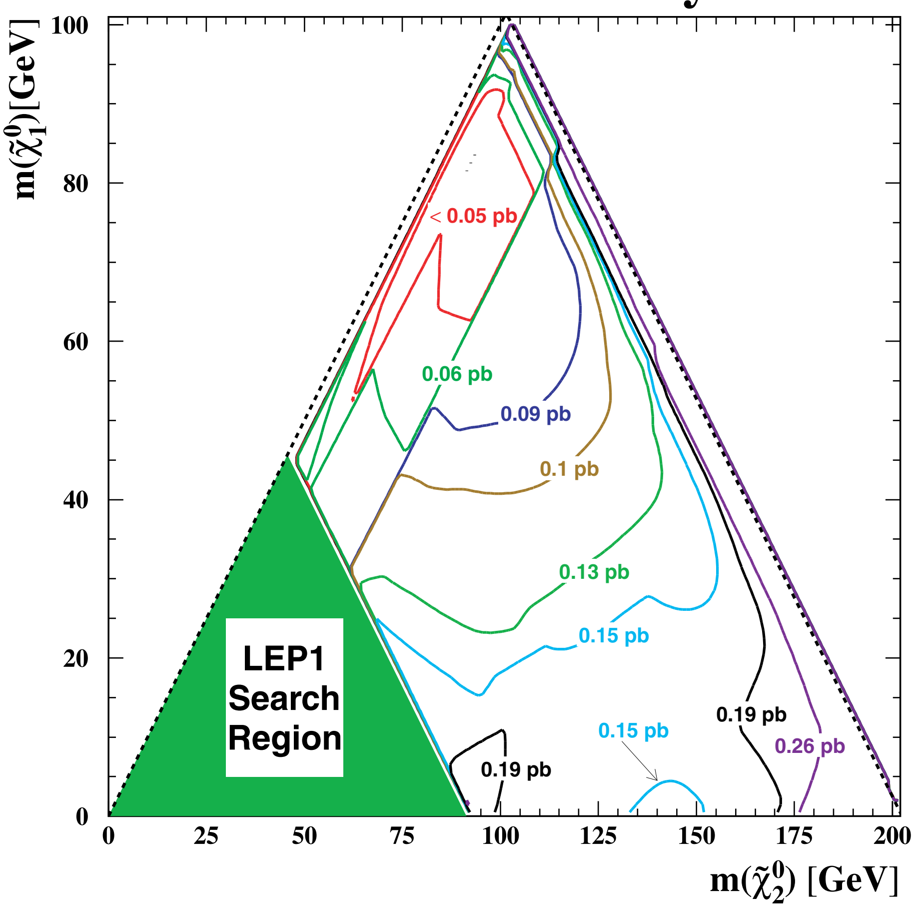
$e^+e^- \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1$ $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 Z^{(*)}$ $\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$

2 energetic photons plus jets and/or isolated leptons and missing energy

Ex.: OPAL: 2 topologies x 4 Δ m regions

Assuming a zero lifetime

OPAL Preliminary



GMSB: Neutralino NLSP

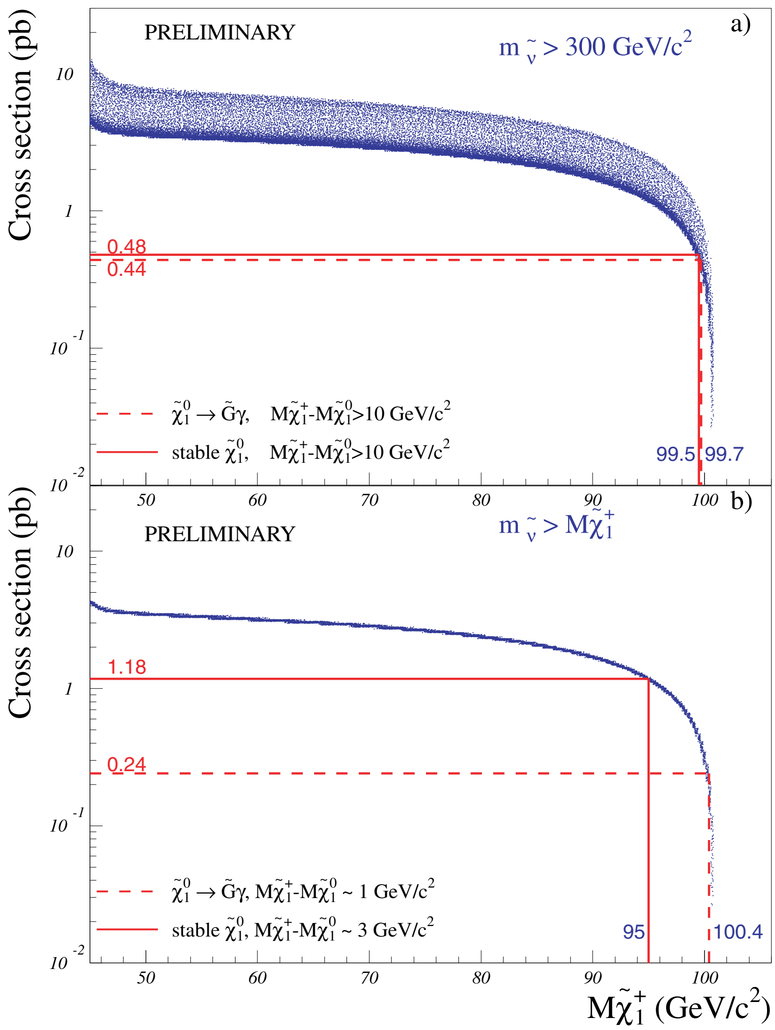
Chargino Searches

$e^+e^- \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^-_1$ $\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 W^{(*)\pm}$ $\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$

2 energetic photons plus jets and/or isolated leptons plus missing energy

Improvement at low ΔM thanks to the presence of photons

DELPHI $\tilde{\chi}^+_1\tilde{\chi}^-_1$ limits at 202 GeV



$m_{\tilde{\chi}^\pm_1} > 99.7$ GeV

Degenerate case
$\Delta M = 1$ GeV

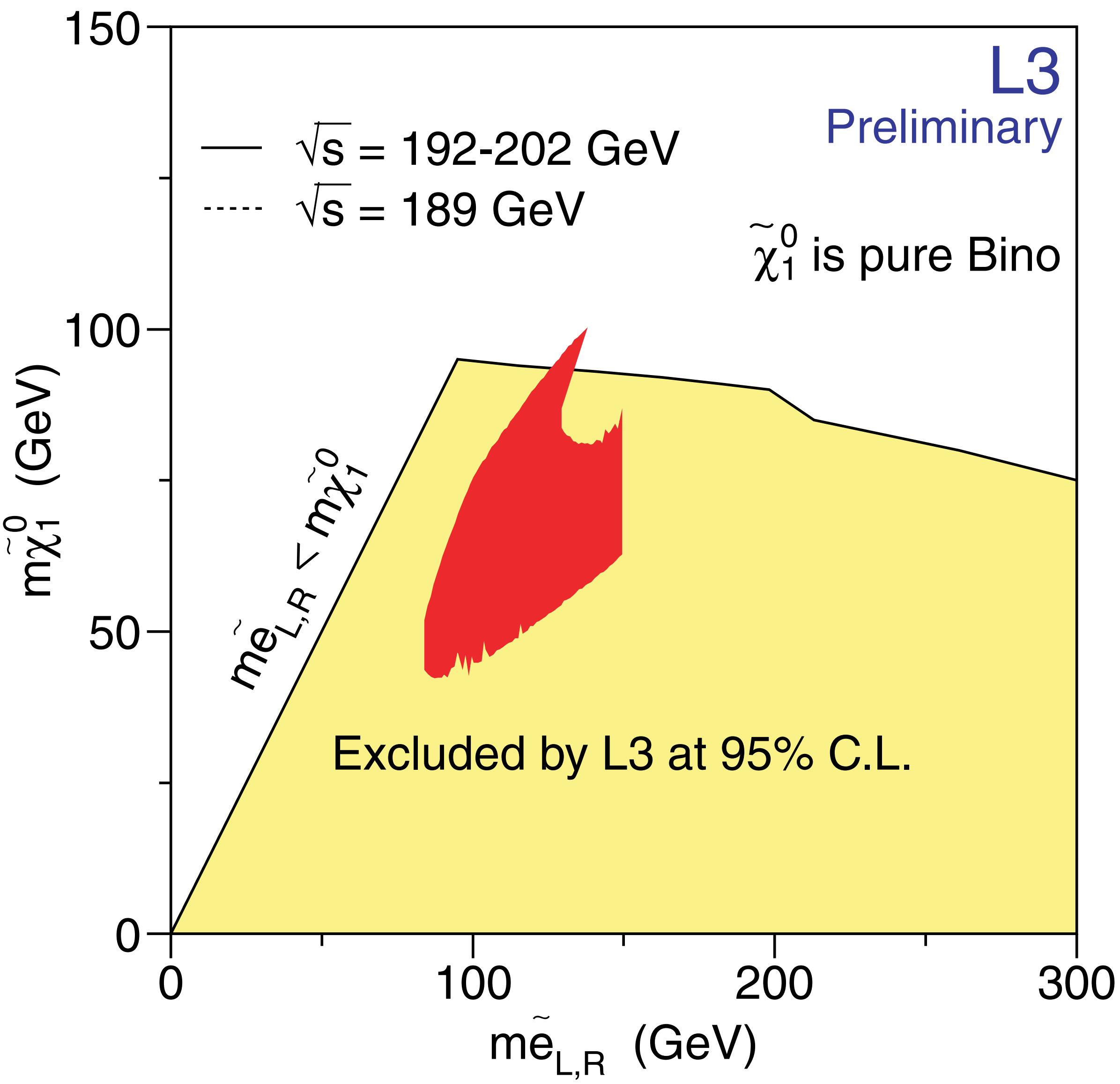
$m_{\tilde{\chi}^\pm_1} > 100.4$ GeV

GMSB: Neutralino NLSP

Slepton Searches

$$e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1 \rightarrow e^+e^-\gamma\,\tilde{G}\,\gamma\,\tilde{G}$$

Searches for events with more than 2 photons



Interpretation in SUSY models with a gravitino LSP of CDF event is almost ruled out

GMSB: Slepton NLSP

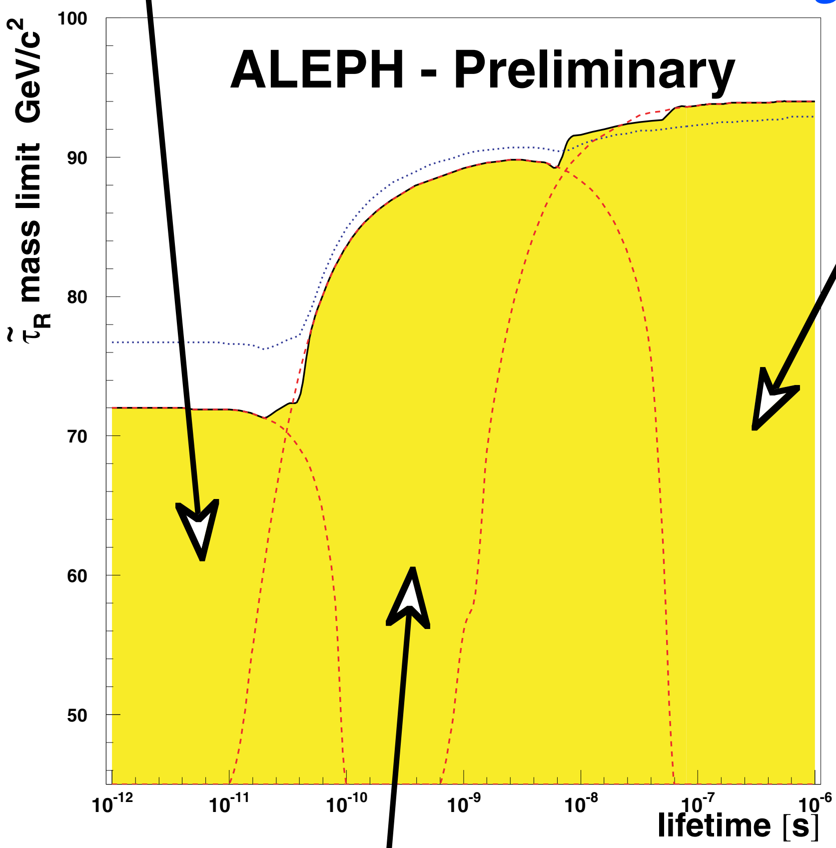
Stau Searches

$$e^+e^- \to \tilde{\tau}^+\tilde{\tau}^+ \to \tau\,\tilde{G}\,\tau\,\tilde{G}$$

Lifetime dependent analysis

Zero lifetime:
Search for prompt decays: acoplanar lepton search

Long lifetime:
Searches for heavy stable charged particles



Intermediate lifetime
Searches for tracks with significant impact parameter
Searches for kinks

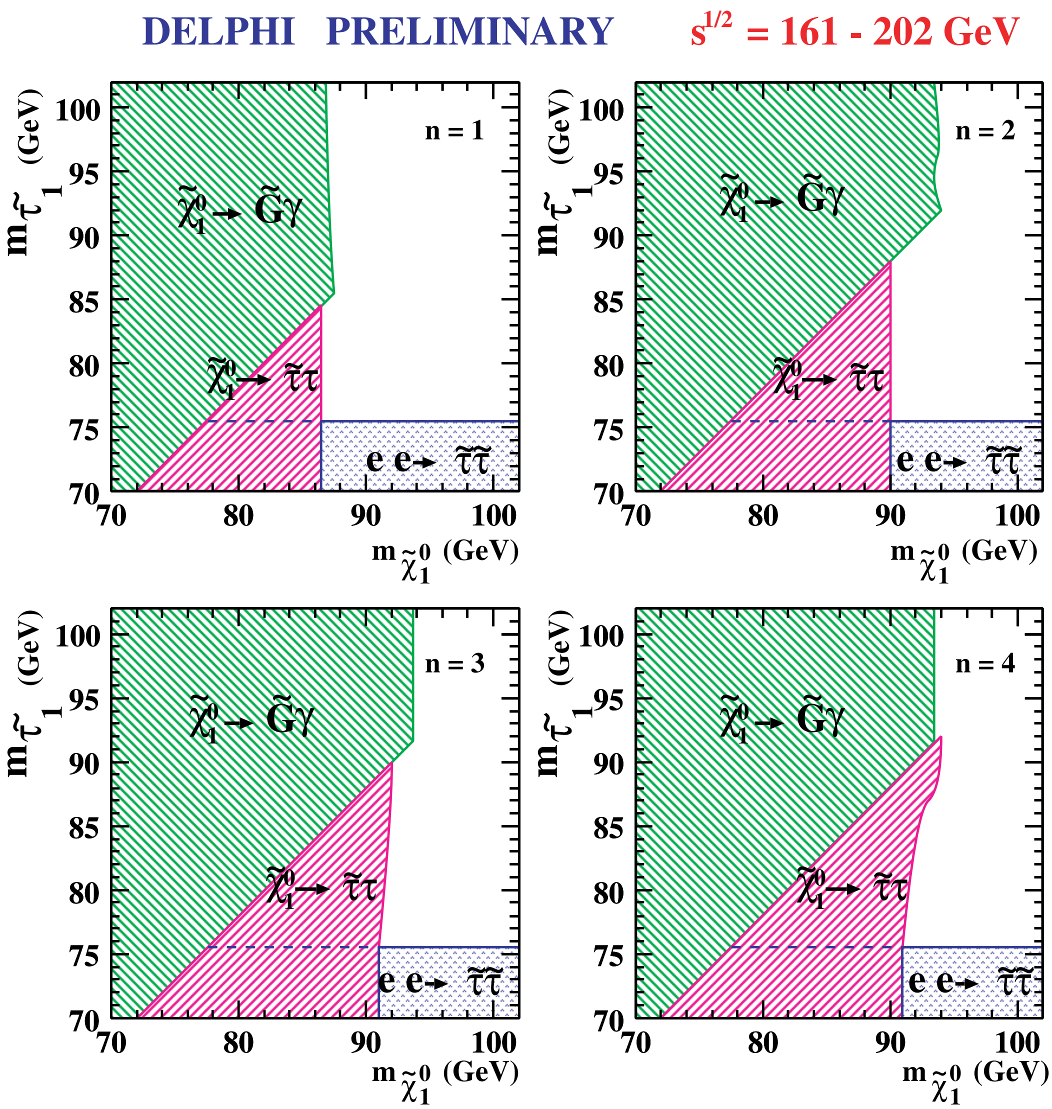
GMSB: Slepton NLSP

Neutralino Searches

Search in the context of a light gravitino scenario

$e^+e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$ $\chi^0_1 \rightarrow \tau\,\tilde{\tau}$ $\tilde{\tau} \rightarrow \tau\,\tilde{G}$

4 taus + missing energy



$m_{\tilde{\chi}^0_1} > 86$ GeV if $m_{\tilde{G}} < 1$ GeV

Prospects

Aim for 2000: $\sqrt{s} \approx 206$ GeV with integrated $\mathcal{L} \approx 200\ pb^{-1}$

Run has successfully started

Run at the highest possible energy

... and with the lowest loss in integrated luminosity

Combination of results of the 4 LEP experiments by the LEP SUSY working group

Conclusions

- *Many searches for physics beyond the SM have been performed with the data available from LEP 2. The four LEP collaborations have searched for several SUSY particles in different scenarios (CMSSM, RPV, GMSB). Some candidates were selected by the analyses but their number is compatible with the expected background from SM processes.*
- *So far, no excess of events in any of the presented topologies has been observed → limits on charginos, neutralinos and several other SUSY particles have been derived.*
- *LAST YEAR OF LEP RUNNING: let's hope to discover sparticle production in 2000 !*