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SUSY Searches at LEP

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On behalf of the LEP experiments

Introduction

SUSY Searches with R-Parity conservation

Charginos, Neutralinos, Sleptons, Stop, Sbottom

SUSY Searches with R-Parity violation

Gauge-Mediated SUSY Searches

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 1997 ($\sqrt{s} \approx 183$ GeV and total integrated $L \approx 90$ pb^{-1})

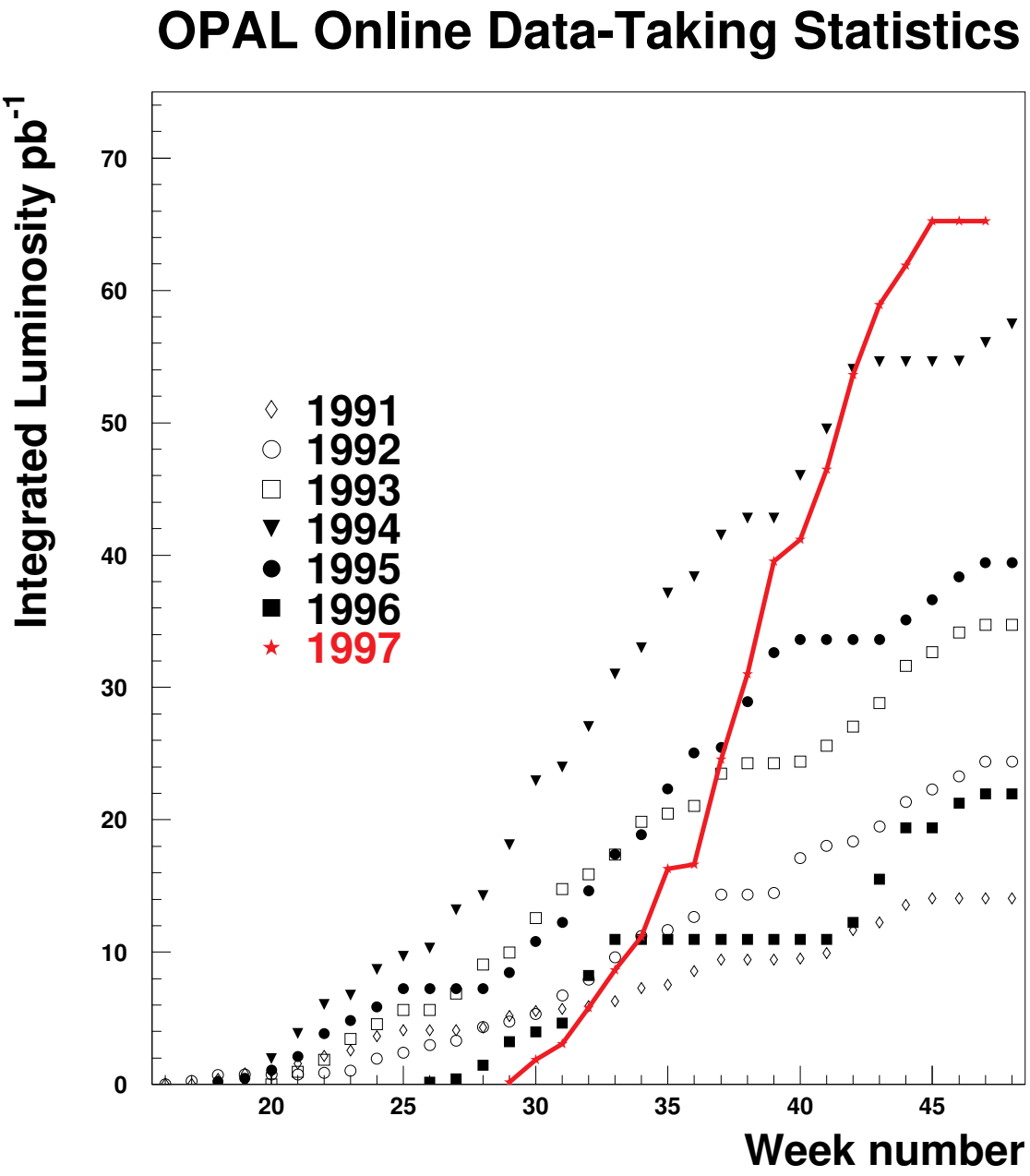
Note 4 : With LEP1 data basically all SUSY particles with $m < m_{Z^0} / 2$ have been excluded

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	~150
	200	1999	~100?
	200	2000	~100?

- Highest energies available at an e^+e^- collider
- Good opportunity to extend to a new frontier a lot of searches
- Aim for 1998: $\sqrt{s} \approx 189$ GeV with integrated $\mathcal{L} \approx 150\ pb^{-1}$
- 1999 and beyond: 200-300 pb^{-1} at $\sqrt{s} \approx 200$ GeV

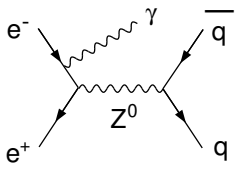
Introduction: The 1997 Run

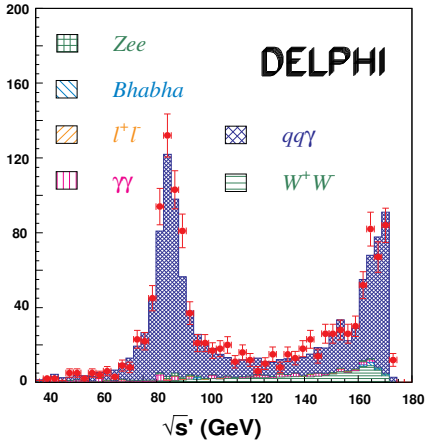


In 1997, OPAL logged a total of 65 pb $^{-1}$
(over 72 pb $^{-1}$ delivered)
57 pb $^{-1}$ @ 182.6 GeV
6 pb $^{-1}$ @ 130, 135 GeV
2 pb $^{-1}$ @ 91 GeV

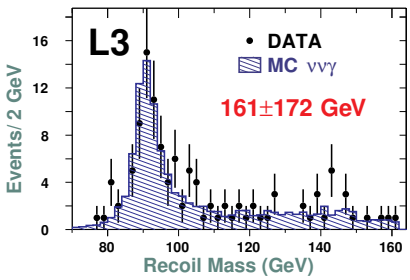
Introduction: Detectors

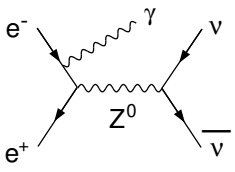
- ***Event topologies that could originate from SUSY signals:***
  - ***Isolated Leptons (particle identification)***
  - ***Acoplanar Jets (tracking, calorimetry)***
  - ***Missing Energy (hermeticity)***





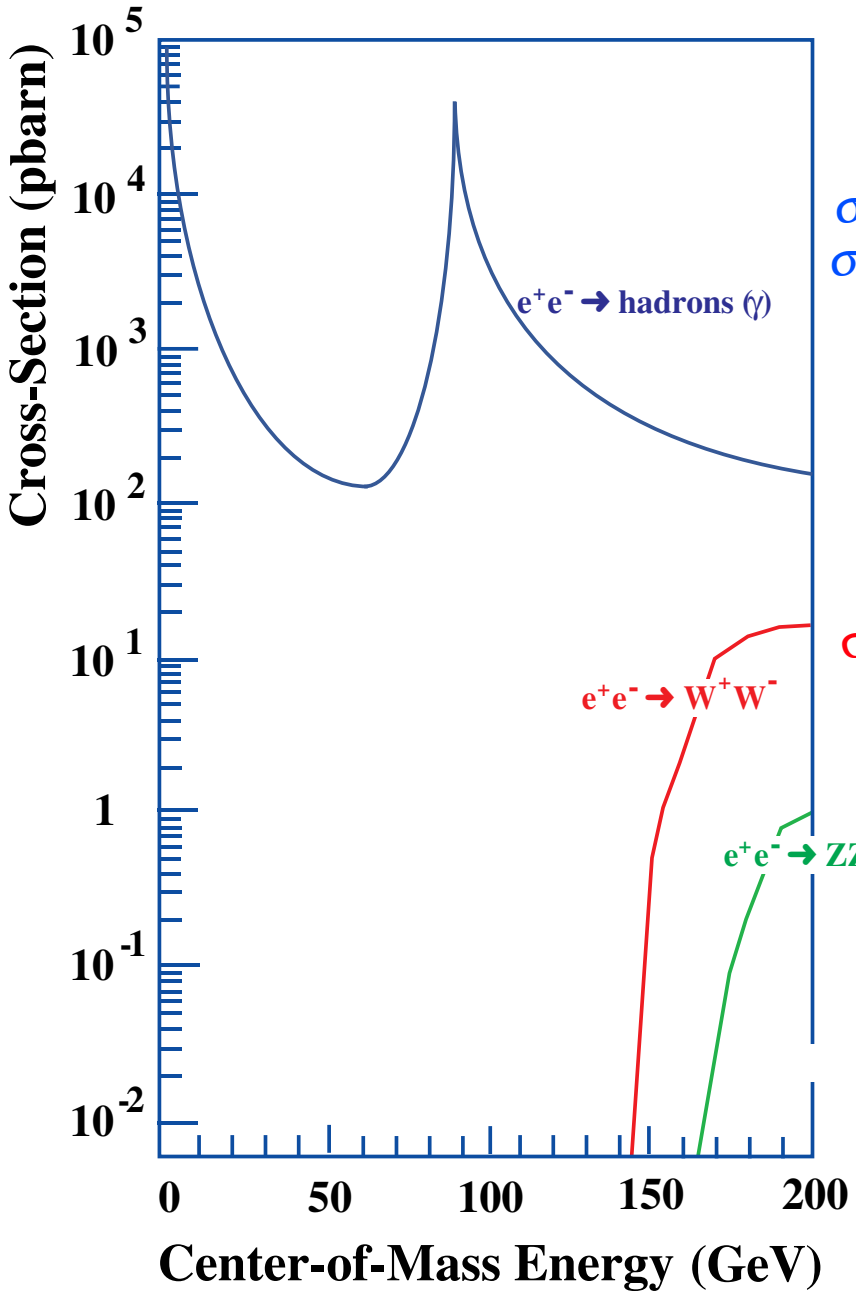
Good efficiency and resolution for the hadronic system





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

Introduction: Background for Searches



$\sigma(e^+e^- \to l\bar{l}\gamma) \sim 90$ pb
$\sigma(e^+e^- \to q\bar{q}\gamma) \sim 300$ pb
Great reduction compared to LEP 1

Now Sizeable
$\sigma(e^+e^- \to W^+W^-) \sim 3\text{-}15$ pb

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

- Four-fermion processes, small cross-section but difficult to eliminate
- Two-photon processes $\gamma\gamma \to q\bar{q}$, $l\bar{l}$ have large cross-section ($\sigma \sim 40$ 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	
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	
γ	1	0	$\tilde{\gamma}$	1/2	photino	
Z^0	1	0	$\tilde{Z}^0$	1/2	zino	neutralinos
H_1^0, H_2^0	0	0	$\tilde{H}_1^0, \tilde{H}_2^0$	1/2	neutral Higgsinos	($\tilde{\chi}_1^0$ - $\tilde{\chi}_4^0$)
$H^\pm$	0	± 1	$\tilde{H}^\pm$	1/2	charged Higgsino	charginos
$W^\pm$	1	± 1	$\tilde{W}^\pm$	1/2	wino	($\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$)
G	2	0	$\tilde{G}$	3/2	gravitino	

sfermions gauginos

	Spin		
	0	1/2	1
Particles and Sparticles	$\tilde{l}$ $\tilde{q}$ H_1^0, H_2^0 $H^\pm$	l q $\tilde{\chi}_1^0$ - $\tilde{\chi}_4^0$ $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	γ, 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 β , of the two Higgs doublets***

BUT

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

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
- $\tan\beta$: 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 :**

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

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

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

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

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

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

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

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:

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

S: Spin

L: Lepton Number

B: Baryon Number

$R_p = 1$ ***for SM particles***

$R_p = -1$ ***for SUSY particles***

	R_p	$\not{R}_p$
SUSY particles produced	***pairs***	***pairs or singly***
LSP is	$\tilde{\chi}_1^0$	***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

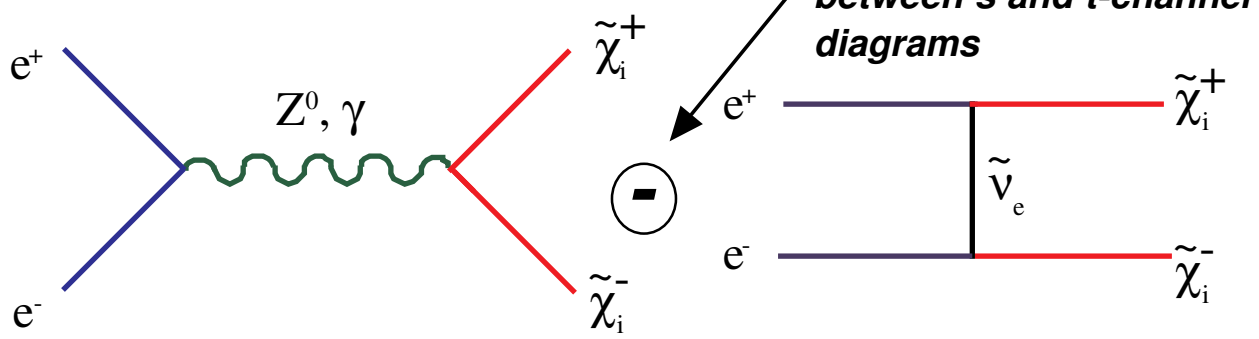
Gaugino Searches in R-parity Conserving scenarios

- **Charginos**
  - $\Delta m < 0.1$ GeV
  - $0.5 < \Delta m < 3$ GeV
  - Large Δm
- **Neutralinos**

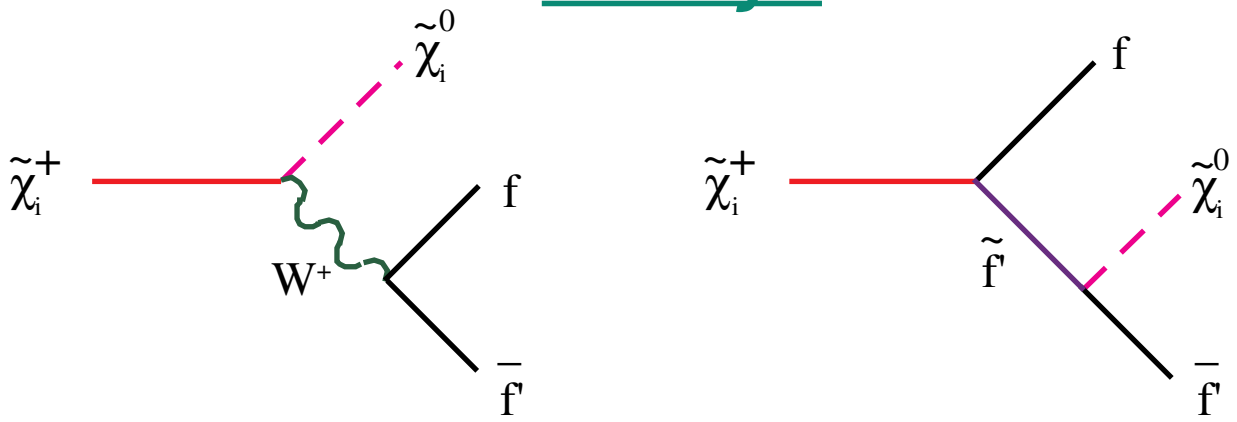
Chargino Production and Decays

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

Production



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

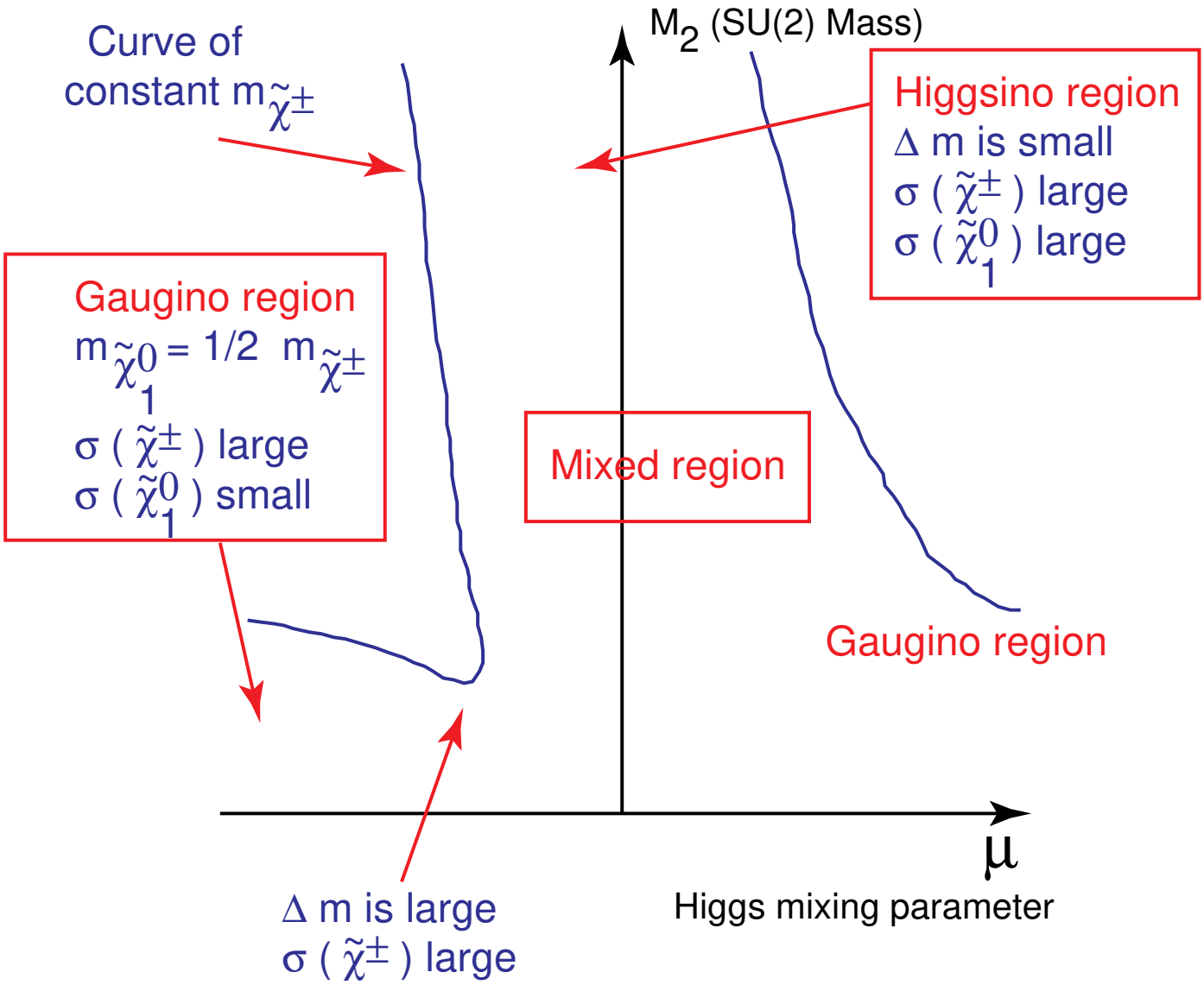
Experimentally the most important variable is:

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

Backgrounds

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

Guide to the (μ, M_2) Plane



Event properties depend on :

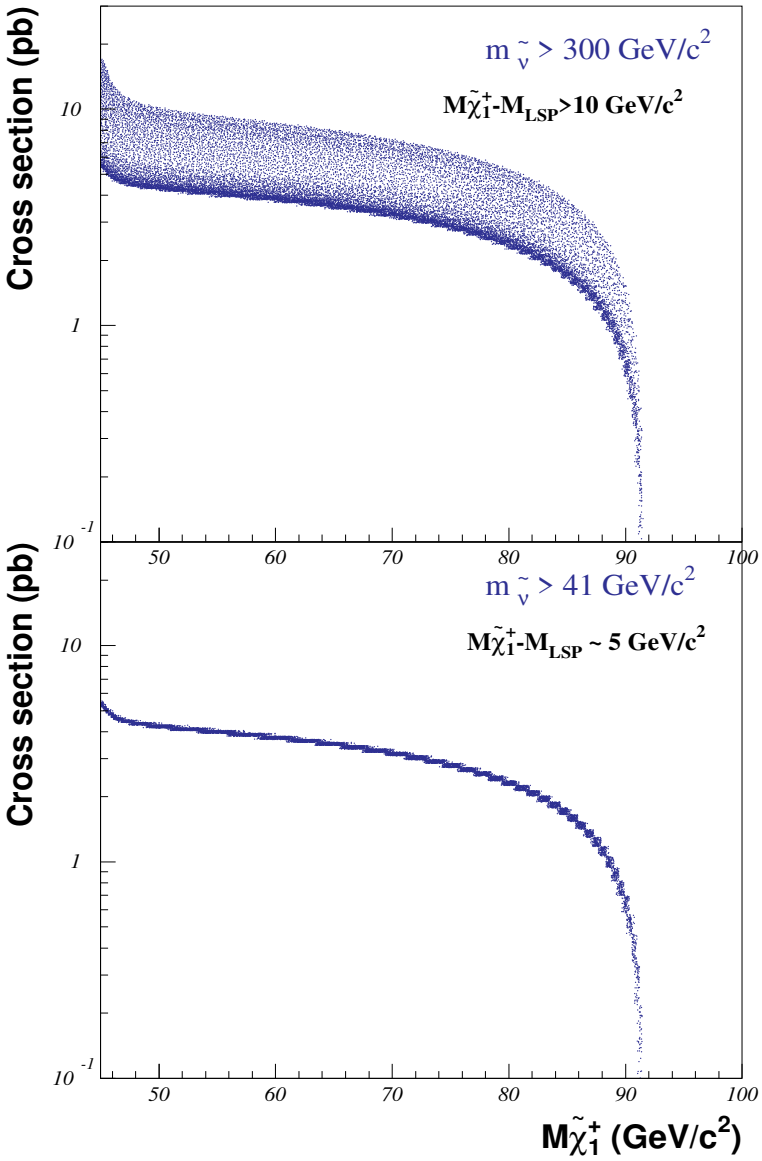
Δ m = Mass of parent sparticle - mass of LSP

Chargino Pair Production Cross-Sections

Expected cross-sections for chargino pair production at 183 GeV

Large cross-sections at LEP 2, σ ~1-18 pb

Scan $0 < M_2 < 800$ GeV and $-400 < \mu < 400$ GeV for $\tan\beta = 1$, 1.5 and 35



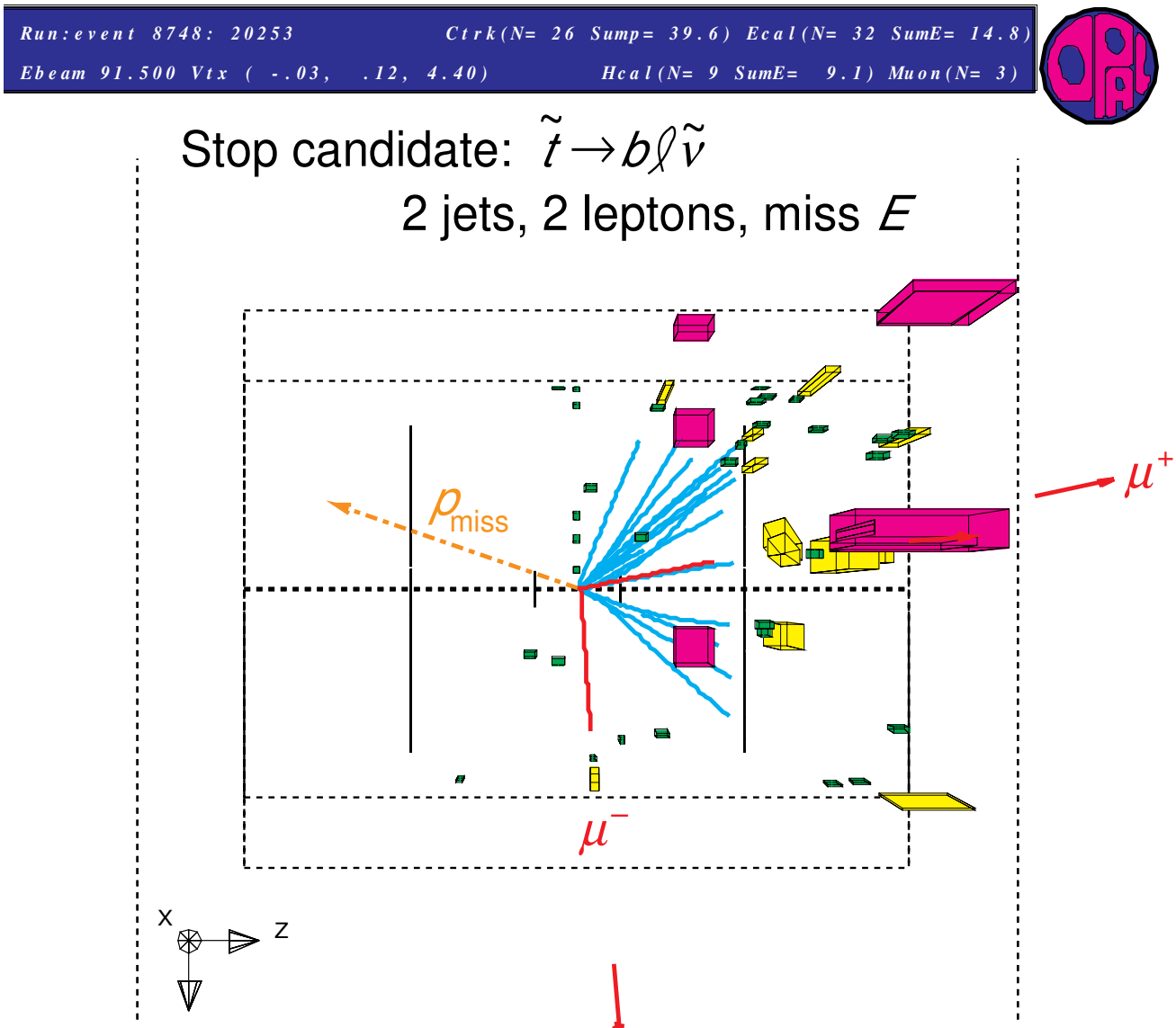
Large Δ m (Gaugino Region)

Non-degenerate scenario where a heavy sneutrino is assumed

Small Δ m (Higgsino Region)

Degenerate scenario where a light sneutrino is assumed: the chargino is Higgsino-like yielding a strong suppression of its production via sneutrino exchange so that the pair production cross-section is similar to the case of a heavy sneutrino

Candidate



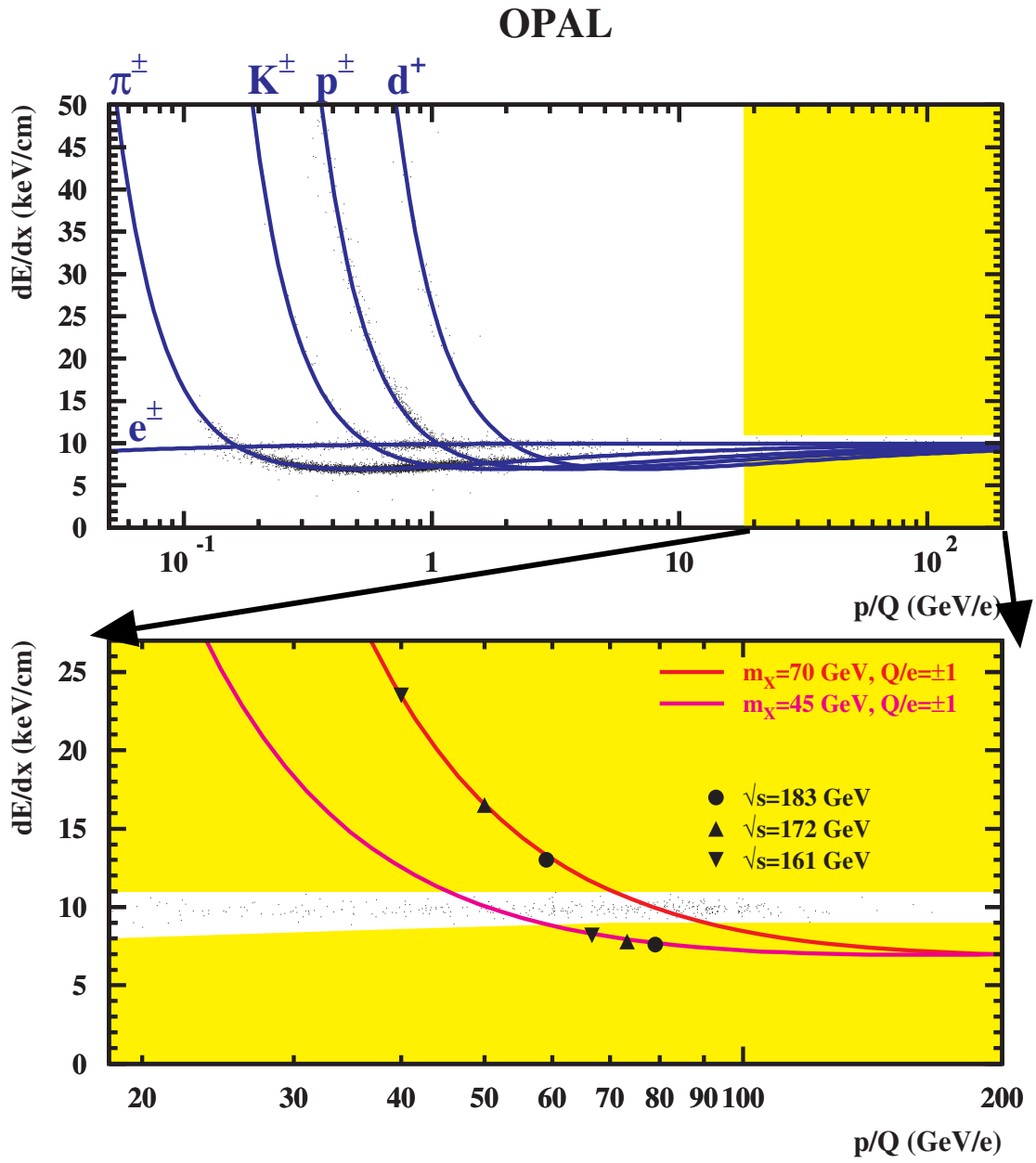
But consistent with background, eg could be WW

Chargino Searches: $\Delta m < 0.1$ GeV

Search for long-lived heavy charged particles

Topology

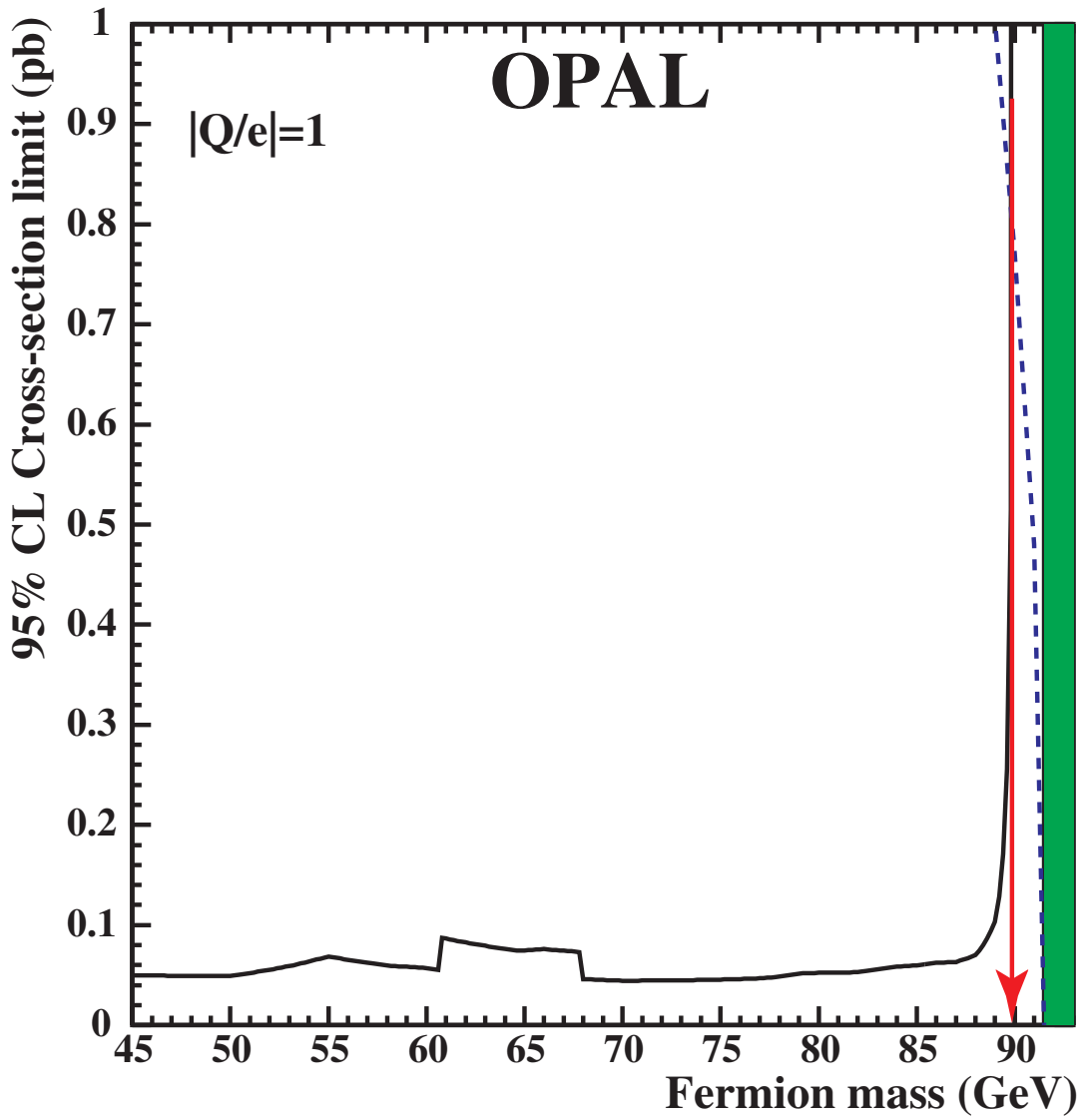
Two back-to-back tracks with very large *dE/dx* (ALEPH, DELPHI and OPAL). DELPHI also used their RICH data.



Chargino Searches: $\Delta m < 0.1$ GeV

No signal observed → limit on pair production cross-section of long-lived charged particles.

$\sqrt{s} \approx$ 130-136, 161, 172 and 183 GeV



Long-lived charginos are excluded for masses below 89.5 GeV

Chargino Searches: $0.5 < \Delta$ m < 3 GeV

Search for charginos with small mass difference with the lightest neutralino

Topology

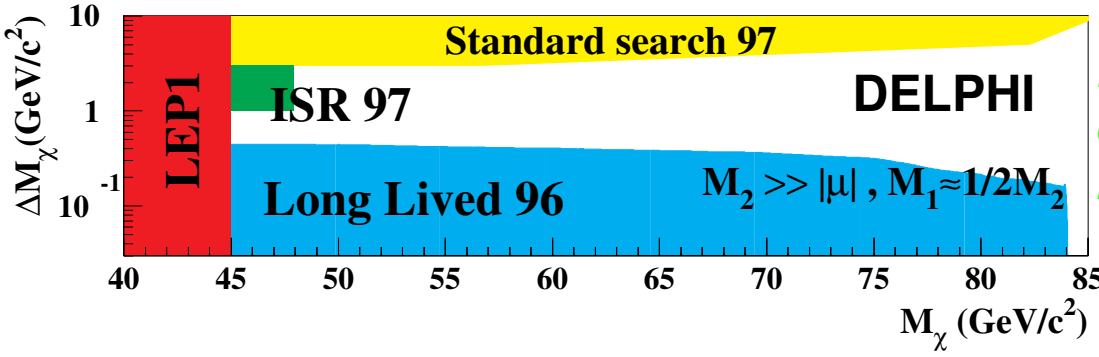
Signal events would have very small visible energy. Require an energetic ISR photon. Detection efficiency very low (few percent)

Search for ISR photons + X

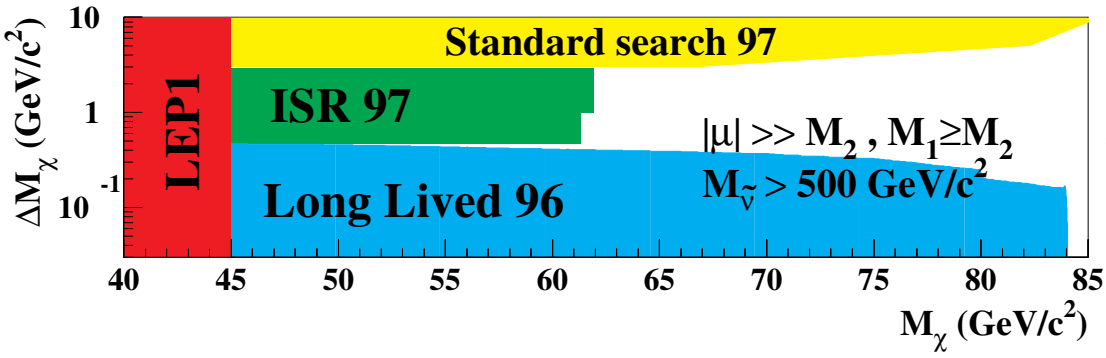
No excess observed → mass limits on the mass of the charginos in three different scenarios

Chargino Searches: $0.5 < \Delta m < 3$ GeV

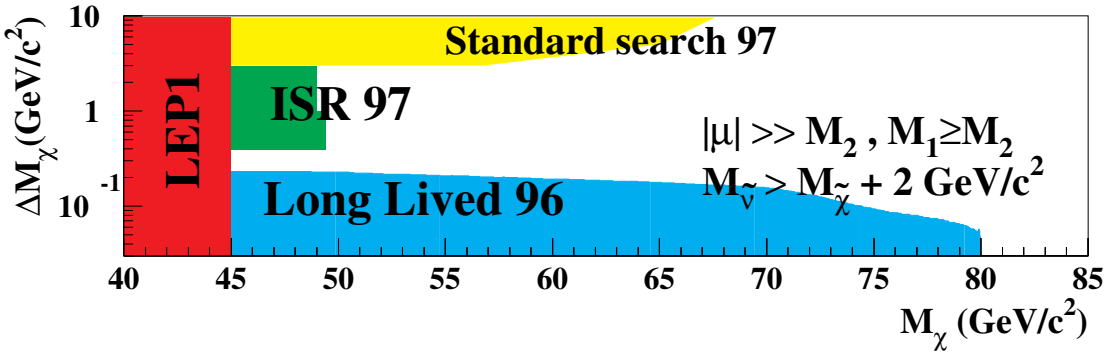
$\sqrt{s} \approx$ 130-136, 183 GeV (1997)



Lightest chargino is higgsino-like



Lightest chargino is gaugino-like and $m_{\tilde{\nu}} >$ 500 GeV

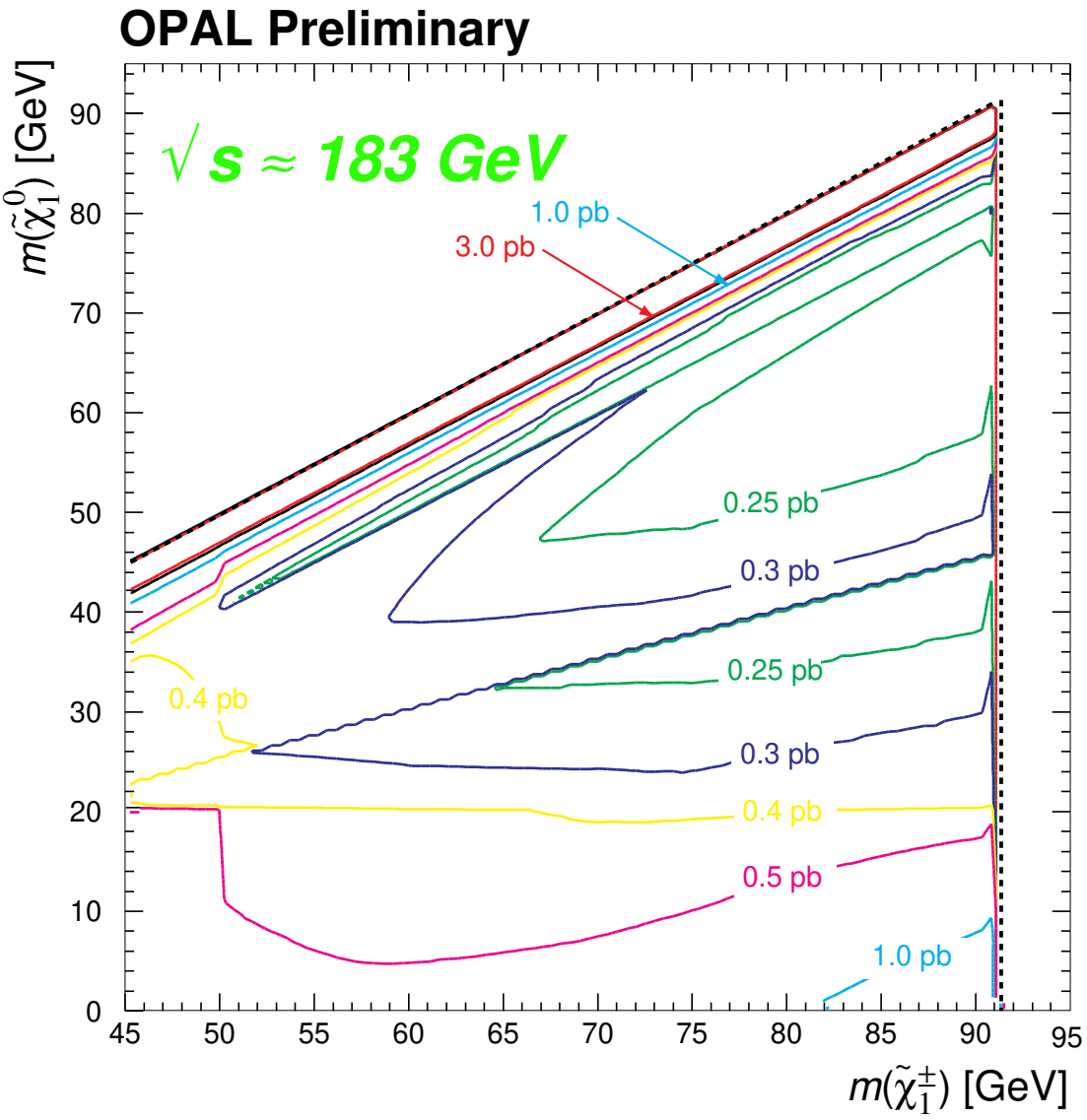


Lightest chargino is gaugino-like and $m_{\tilde{\nu}} > m_{\tilde{\chi}_1^\pm}$

	$\lvert\mu\rvert \ll M_2$	$\lvert\mu\rvert \gg M_2$ $M(\tilde{\nu}) > 500$ GeV/c^2	$\lvert\mu\rvert \gg M_2$ Any $M(\tilde{\nu}) > M(\tilde{\chi}_1^\pm)$
$0.5 < \Delta(M) < 1.0$ GeV/c^2	-	61.3 GeV/c^2	49.4 GeV/c^2
$1.0 < \Delta(M) < 3.0$ GeV/c^2	47.9 GeV/c^2	61.9 GeV/c^2	49.0 GeV/c^2

Chargino Searches: Large Δm

95 % C.L. limits on chargino pair production cross-section

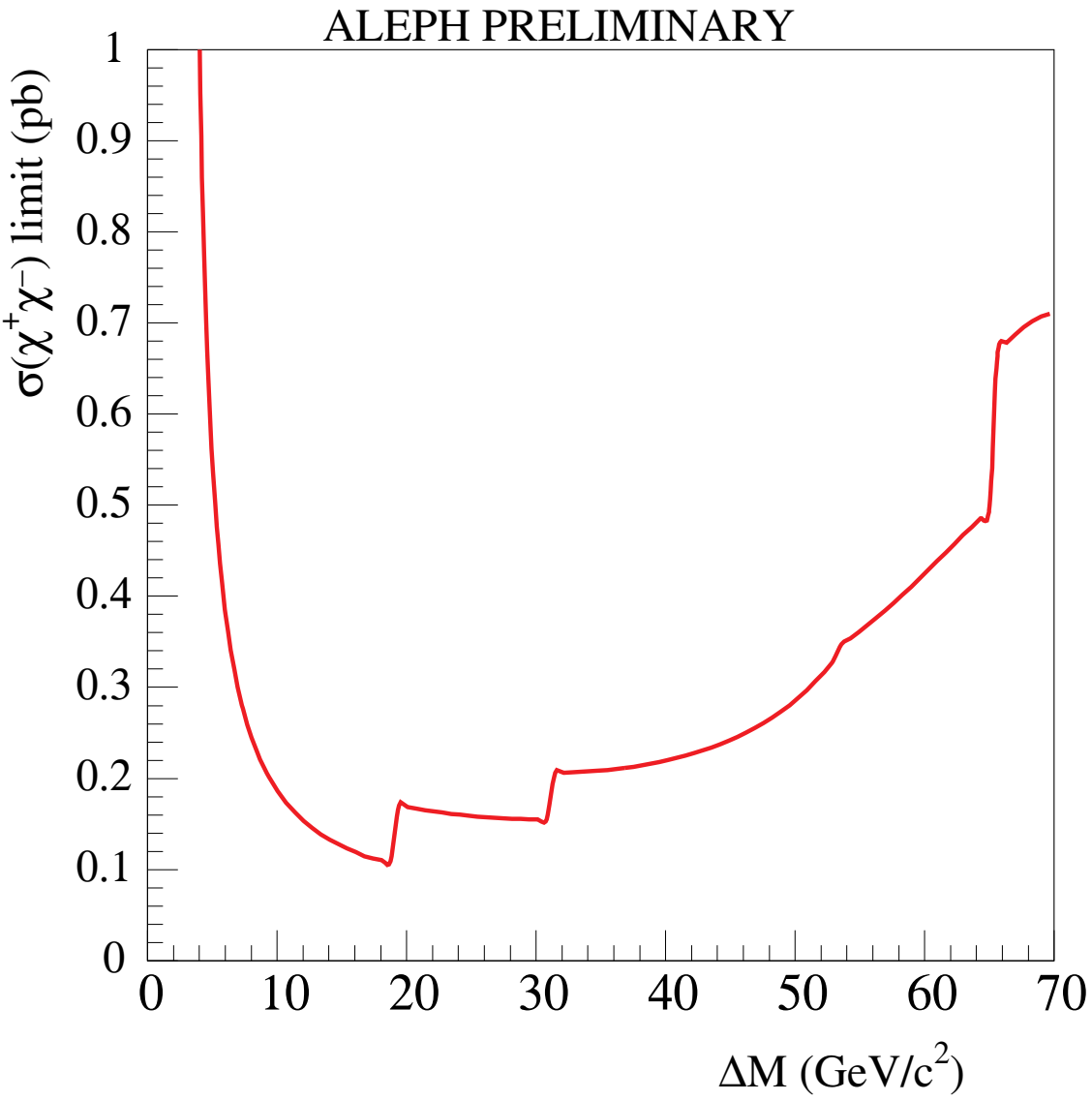


If $5 < \Delta m < 80$ GeV and σ is larger than 0.6 pb, the lightest chargino is excluded at 95% C.L. up to the kinematical limit

Chargino Searches: Large Δ m

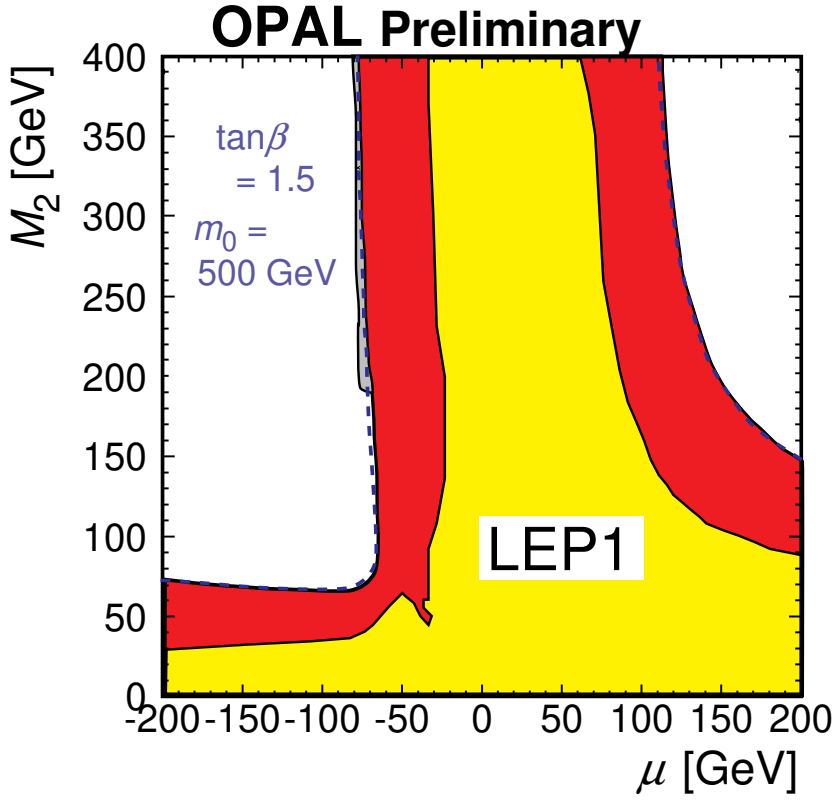
95 % C.L. limits on chargino pair production cross-section for a 91 GeV chargino as a function of Δ m

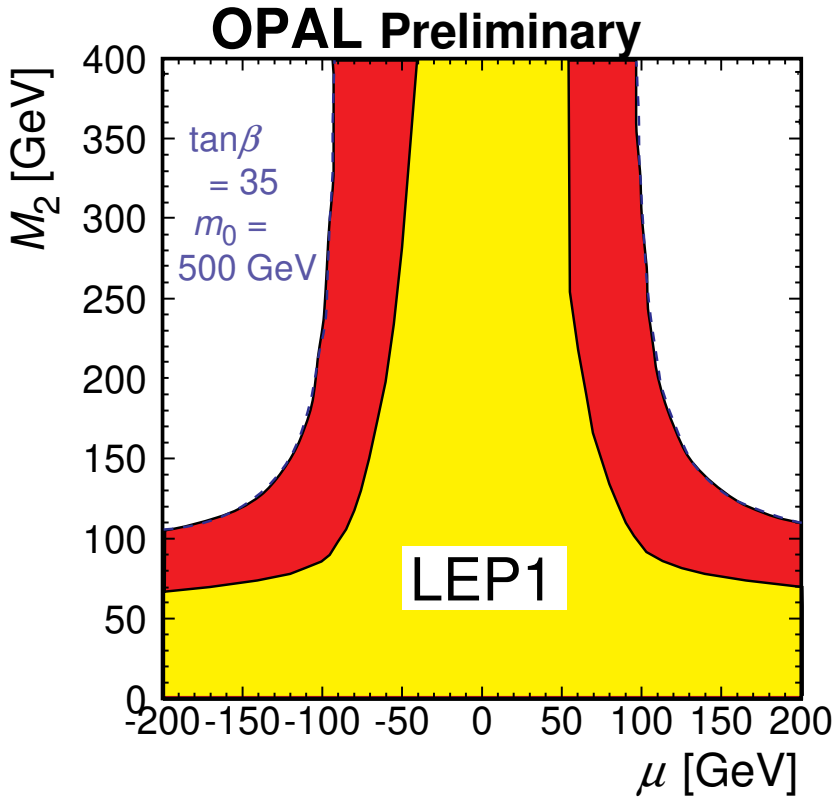
$\sqrt{s} \approx 183$ GeV



Limits in the (μ , M_2) Plane

$\sqrt{s} \approx 183$ GeV

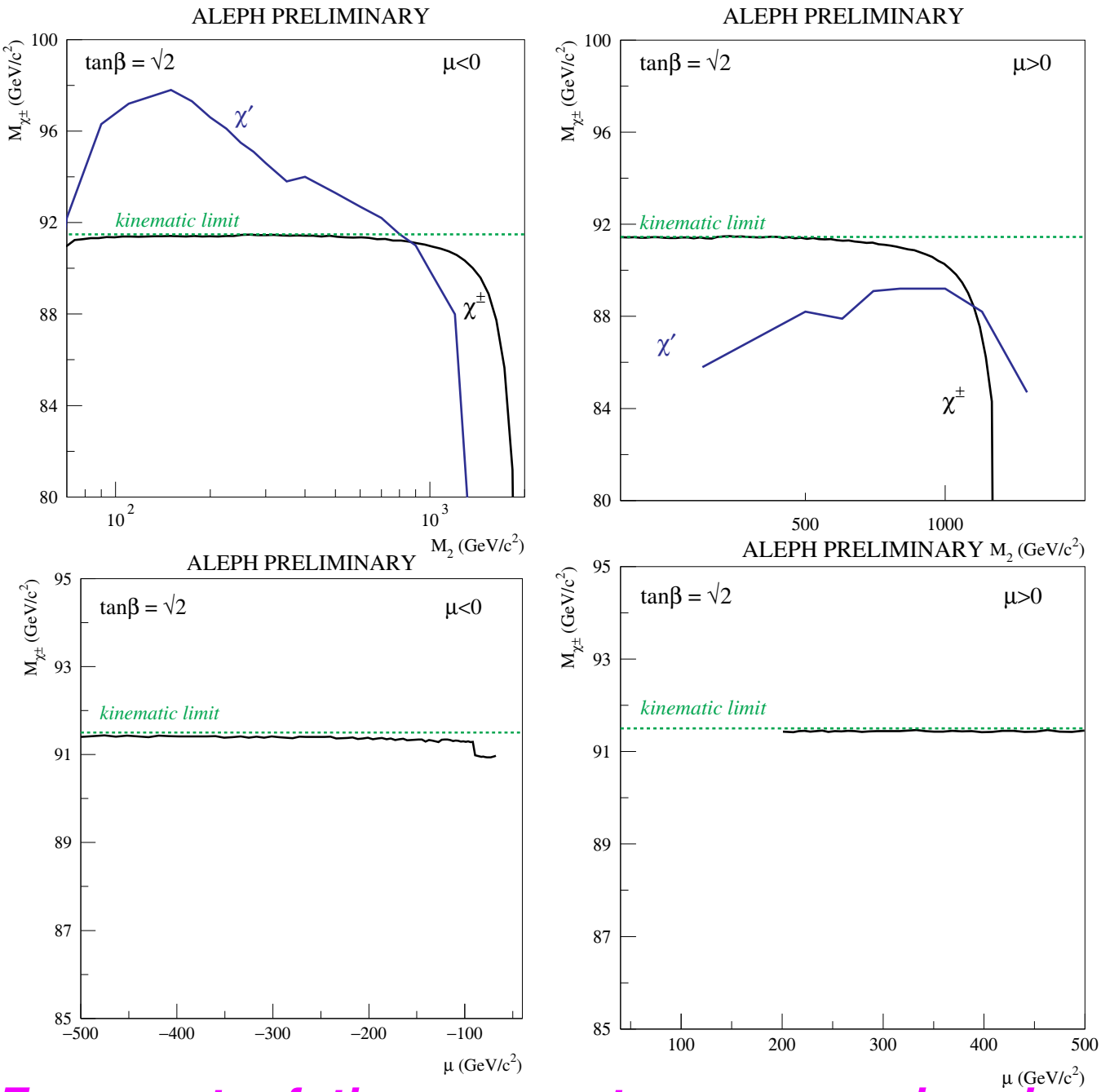




Chargino Mass Limits in the MSSM

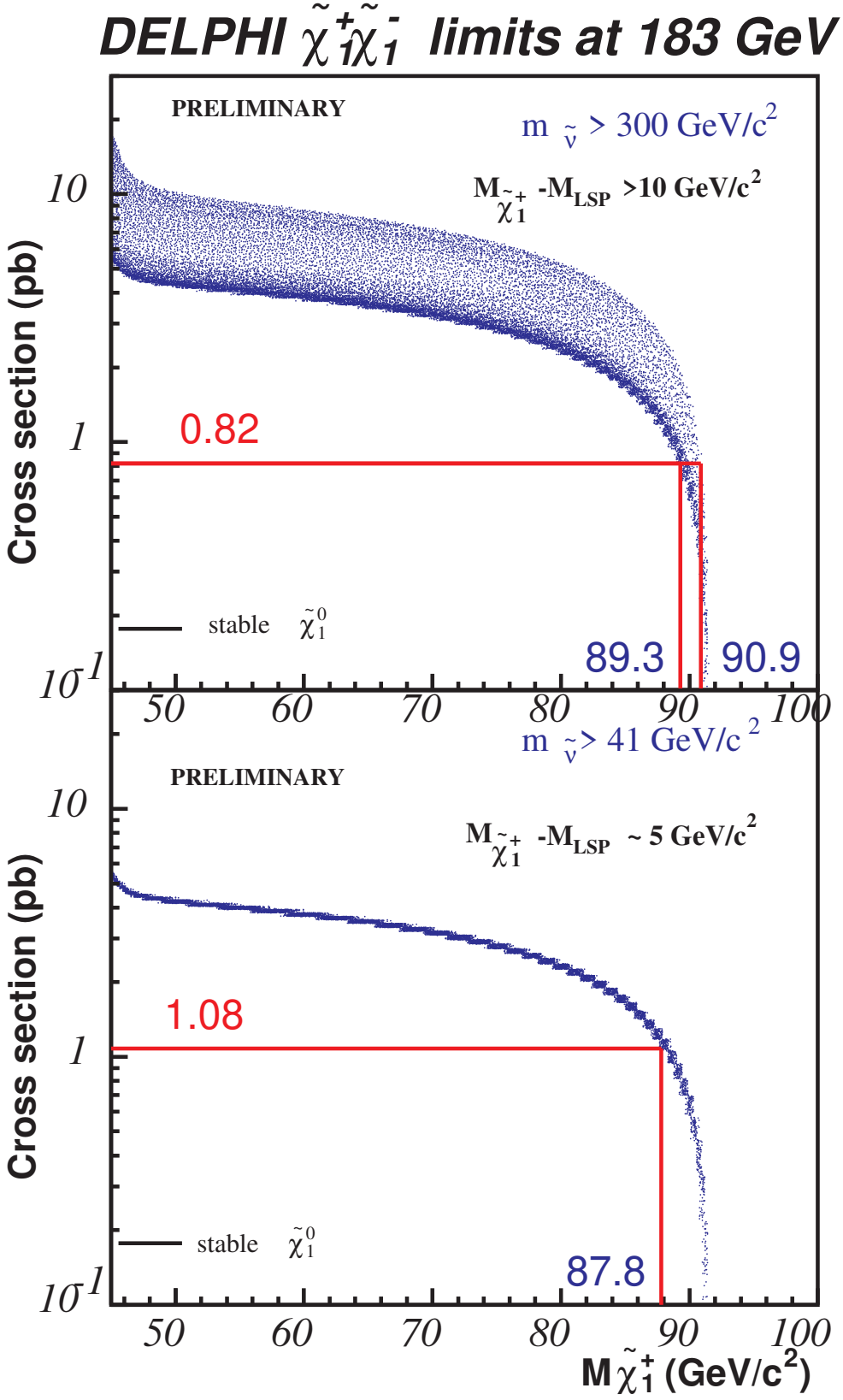
Exclusion regions in the (μ , M_2) plane can be translated into mass limits

$\sqrt{s} \approx 183$ GeV



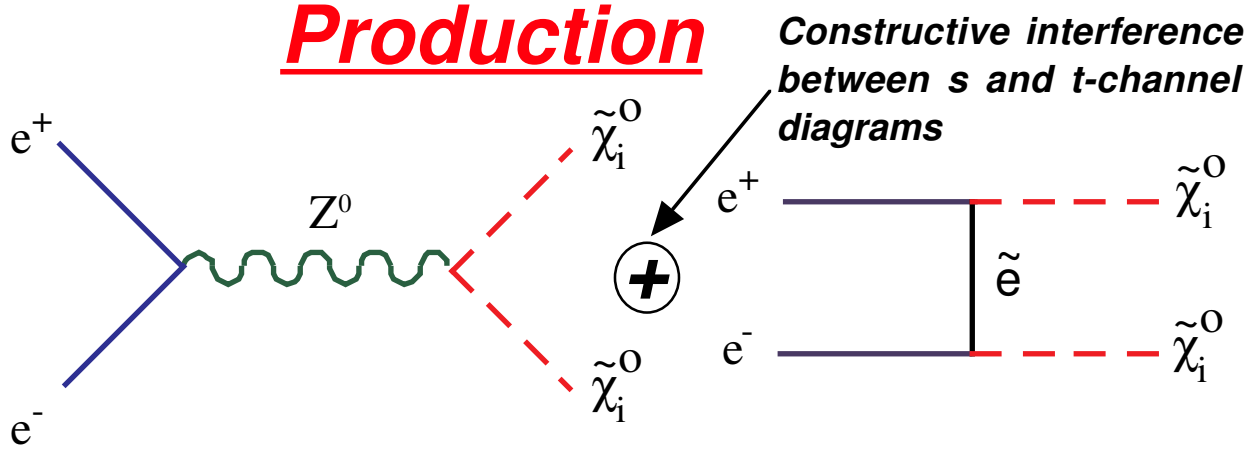
For most of the parameter space, chargino masses within 1 GeV of the kinematical limit are excluded at the 95 % C.L.

Chargino Mass Limits in the MSSM

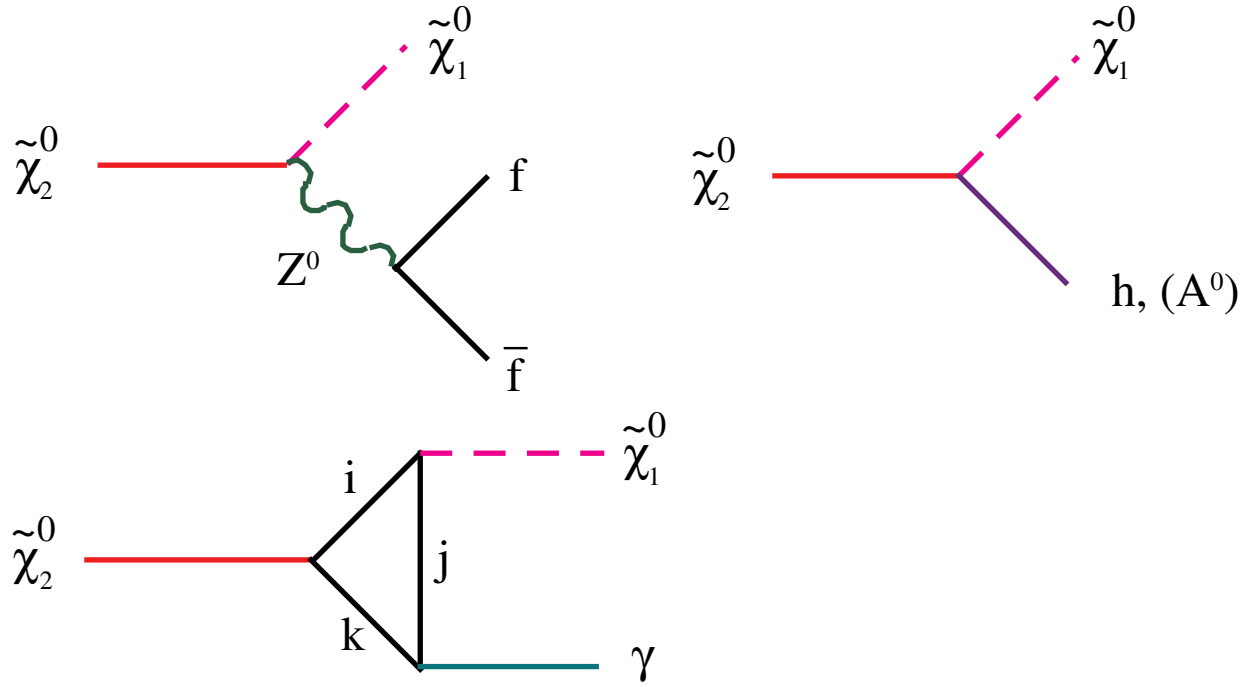


Neutralino Production and Decays

Production



Decays



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

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

Large cross-sections at LEP 2, up to σ ~ 7 pb

Topologies

Acoplanar jets and missing energy

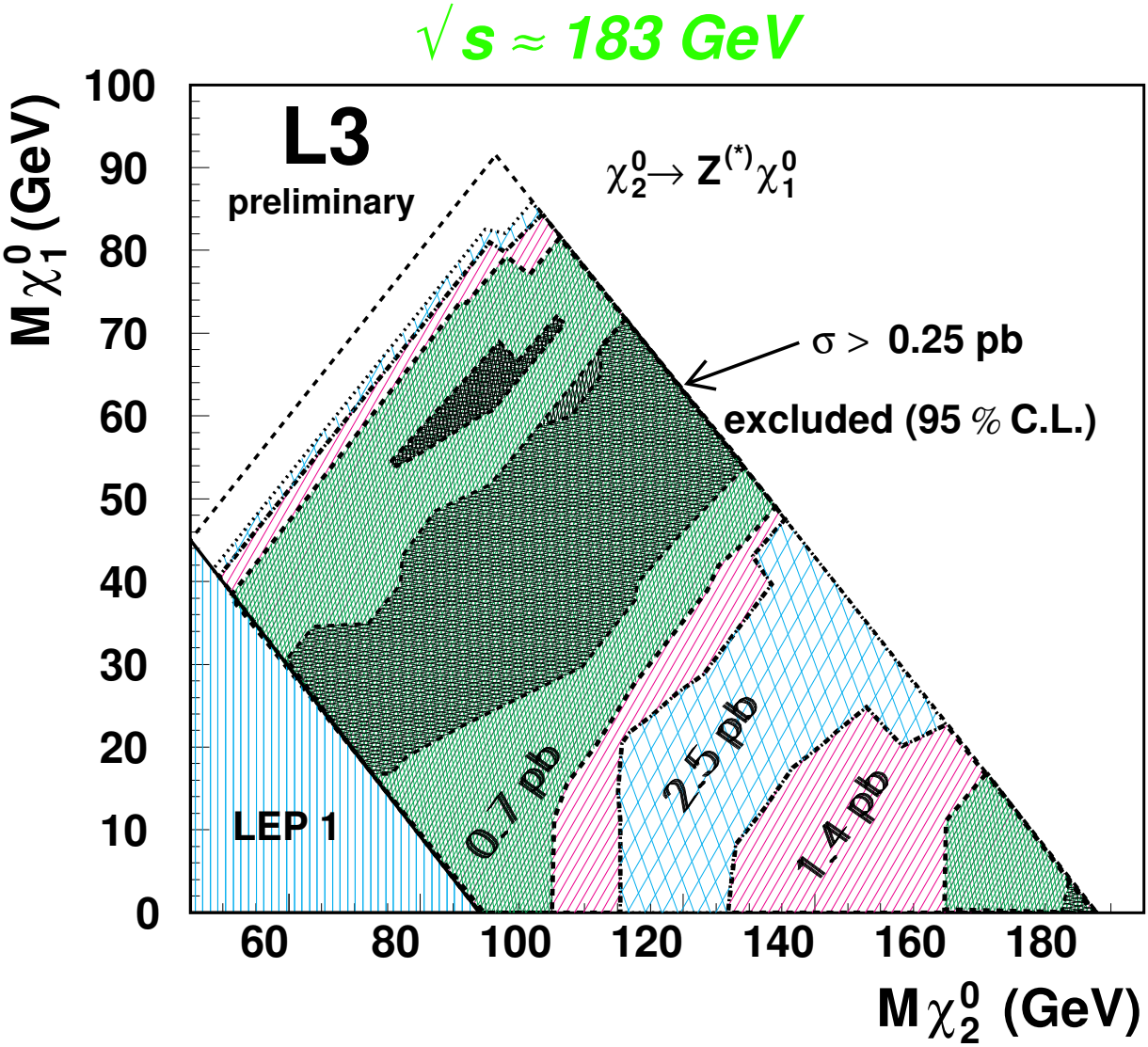
Jets and isolated lepton plus missing energy

Acoplanar leptons and missing energy

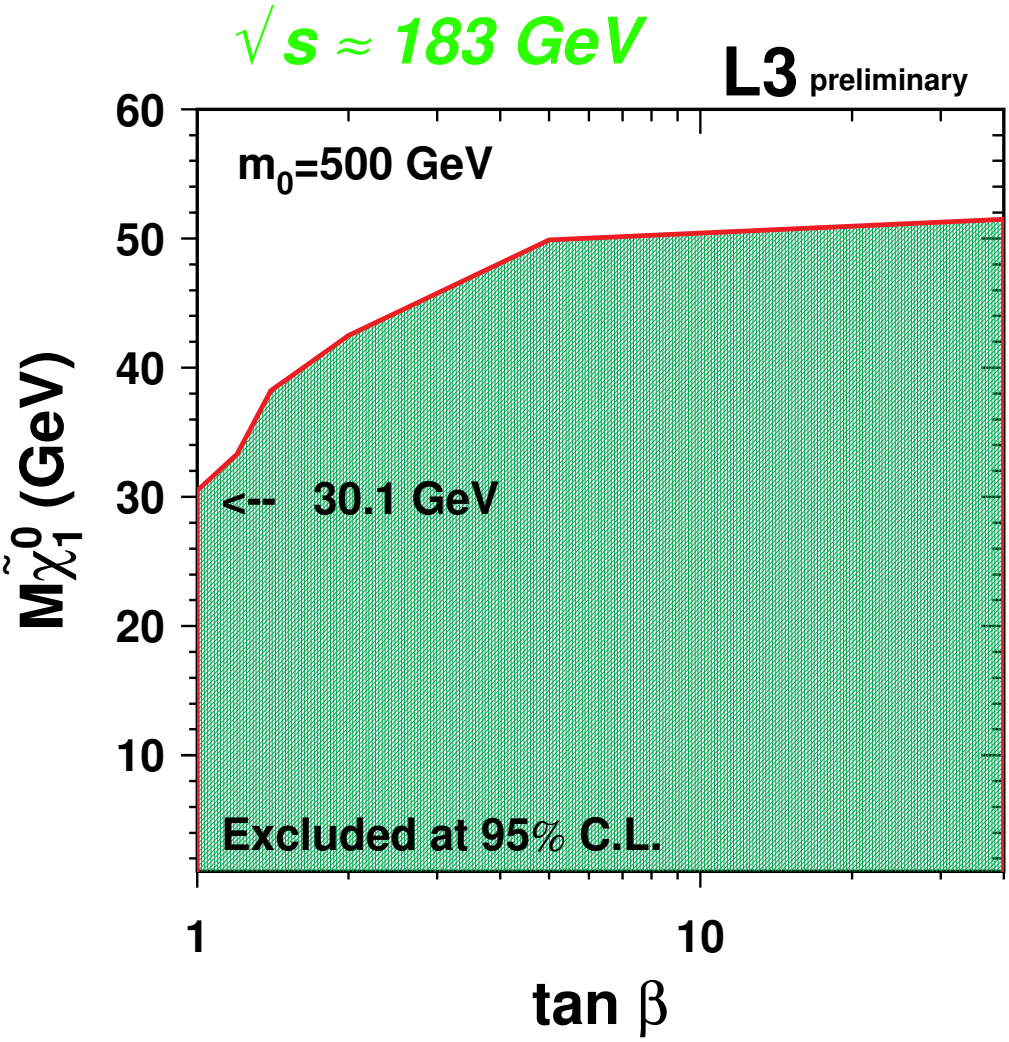
Single photon events

Neutralino Searches

95 % C.L. limits on neutralino pair production cross-section



Neutralino Mass Limits in the MSSM



For any tan β :

ALEPH : m $\tilde{\chi}_1^0$ > 30.1 GeV for m_0 > 200 GeV

DELPHI : m $\tilde{\chi}_1^0$ > 28.1 GeV for m_0 > 1 TeV

L3 : m $\tilde{\chi}_1^0$ > 30.1 GeV for m_0 > 200 GeV

OPAL : m $\tilde{\chi}_1^0$ > 30.1 GeV for m_0 > 500 GeV

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: ($\tilde{f}_L$, $\tilde{f}_R$)

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

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

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

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 3 rd 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!

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

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

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

Stop Quark

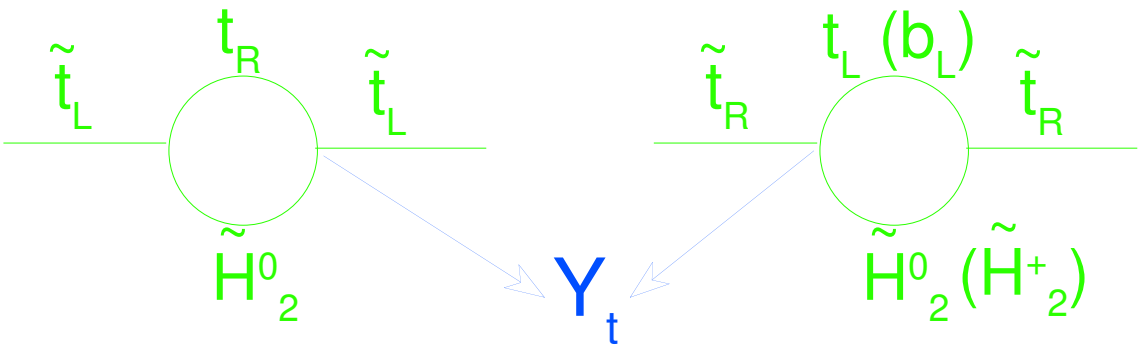
$\tilde{t}_1$ can be the lightest charged SUSY particle

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

Correction is always negative and proportional to Y_t^2

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

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

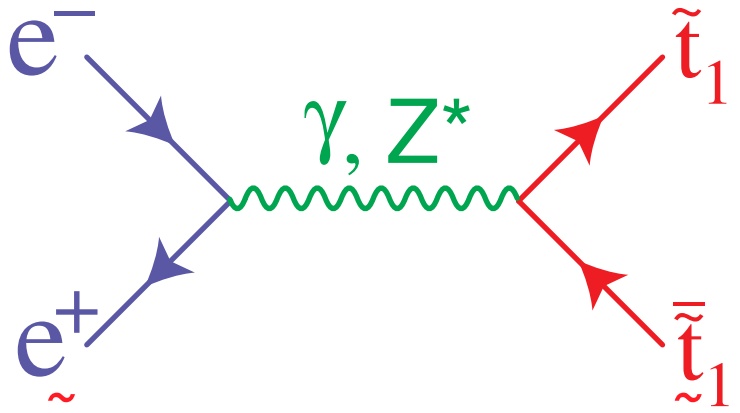


2) L $\leftrightarrow$ R mixing term contributes to off-diagonal components of the mass matrix: large mass split (proportional to m_t)

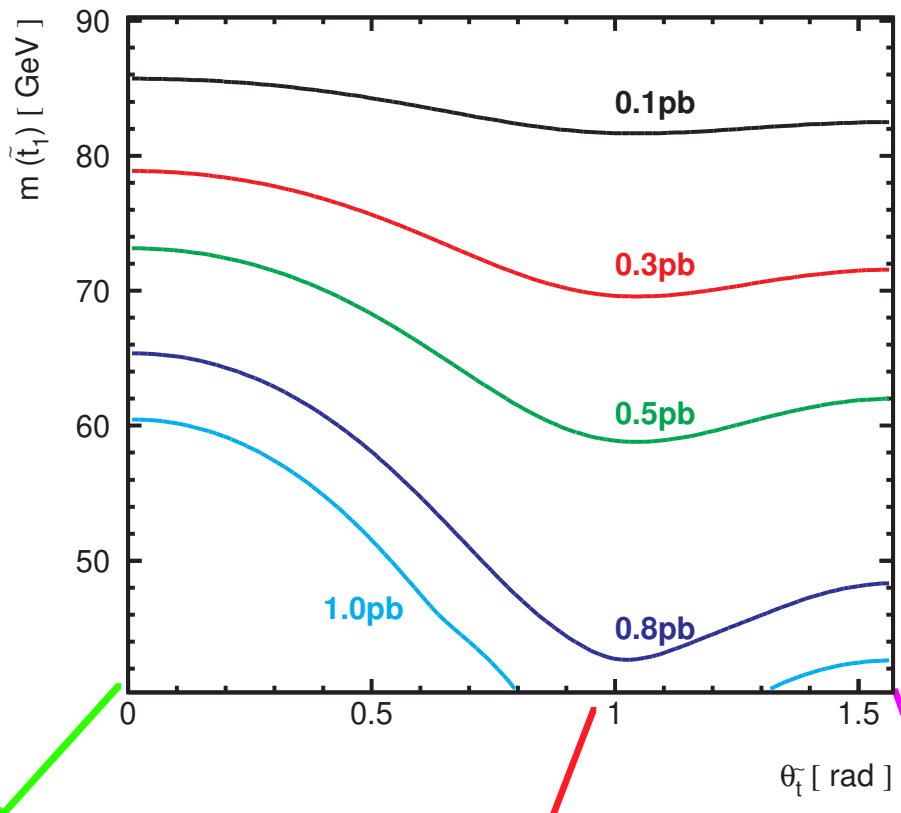
$$m^2_{\tilde{t}_{1,2}} = 1/2\,(\, m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}\,) \;\mp\; 1/2\,\sqrt{(\, m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4\, a^2_f m^2_f}$$

Stop Quark Production

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



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



$\tilde{t}_1 = \tilde{t}_L$

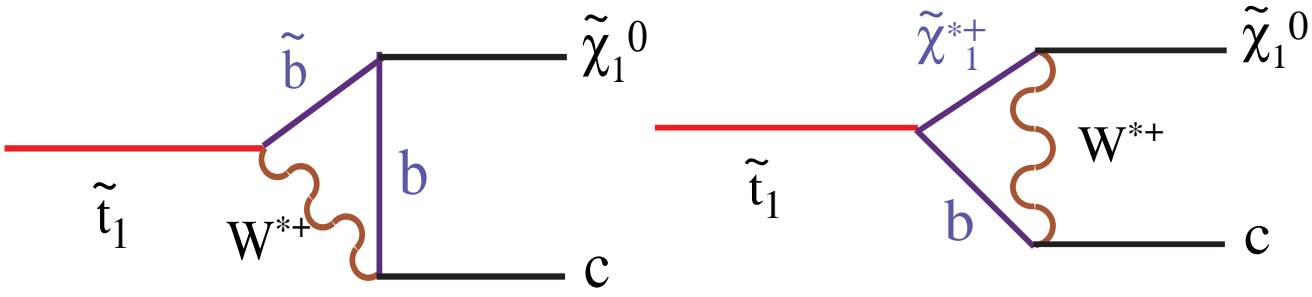
If $\theta_{mix} = 0.98$ rad (= 56 ^{0}), $\tilde{t}_1$ decouples from Z^0

1.57 rad = 90 ^{0}
$\tilde{t}_1 = \tilde{t}_R$

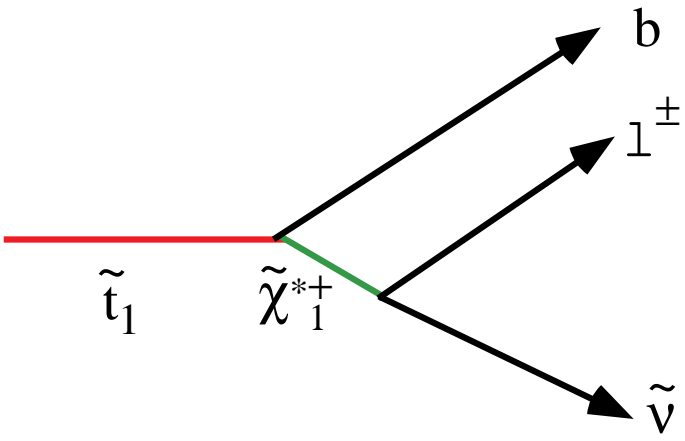
Stop Quark Decays

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

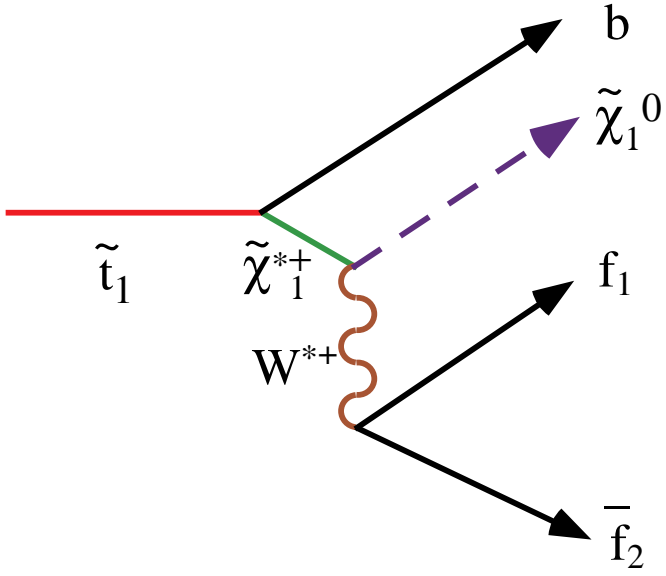
$\tilde{t}_1$ could be the lightest charged SUSY particle



(If chargino is heavy: $\tilde{t}_1 \rightarrow \tilde{\chi}_1^{\pm}$ b is forbidden)



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



Four-body decay:
$\Gamma \sim O$ (0.01 eV)
Kinematically suppressed
$\rightarrow$ NEGLECTED

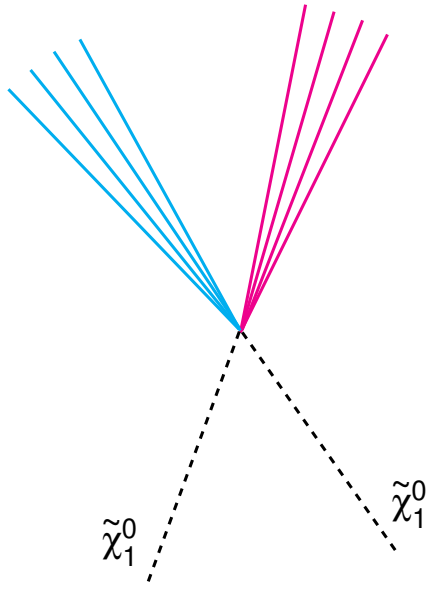
Stop Quark Topology

Because Γ << Λ_{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.

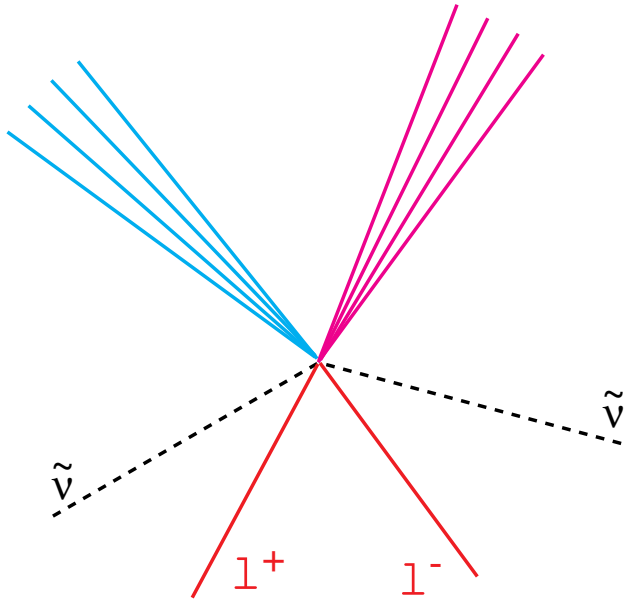
Topology for 2-body decay

Two acoplanar sharp jets and missing energy



Topology for 3-body decay

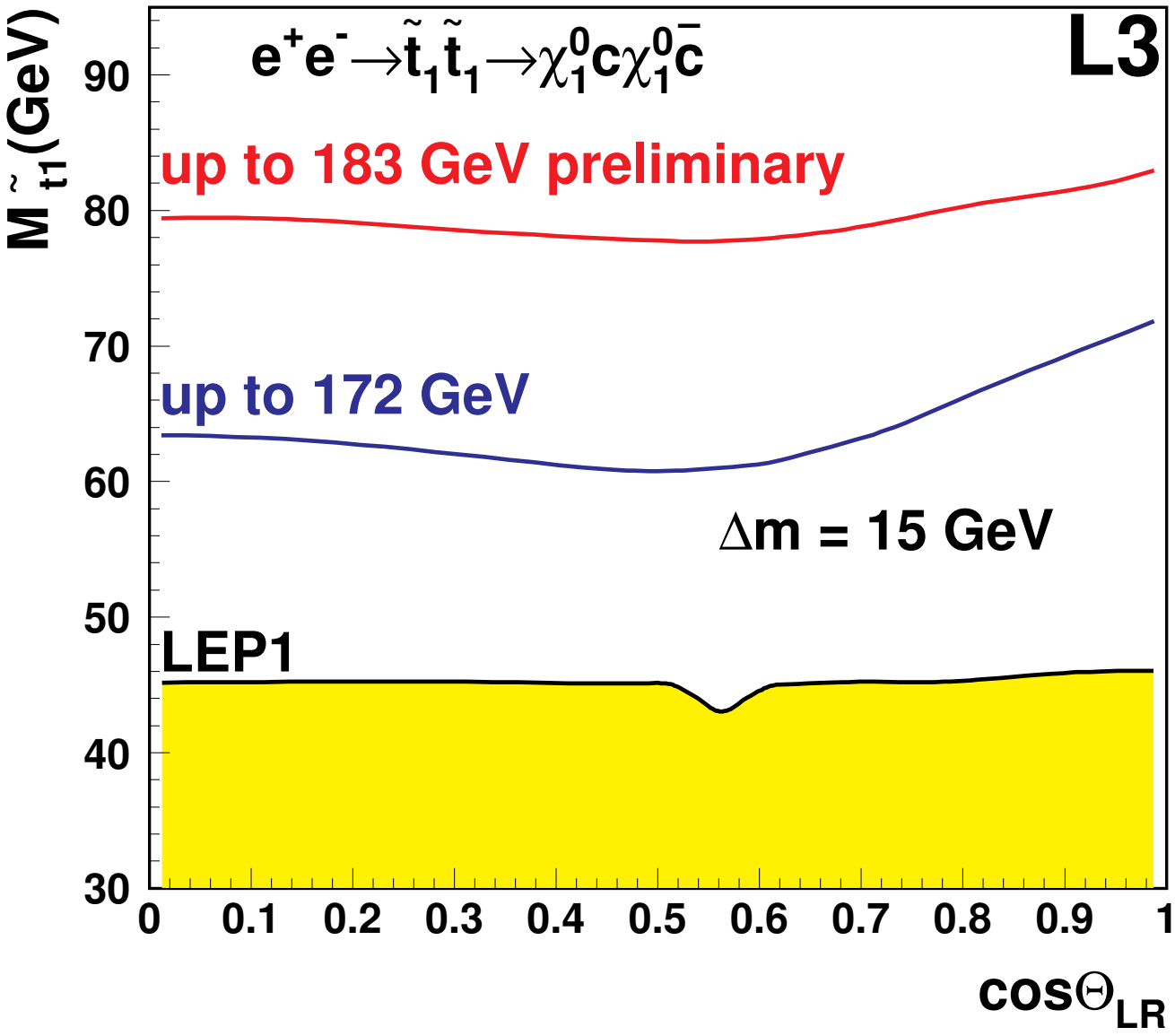
Two acoplanar sharp jets, acoplanar lepton pair and missing energy



Stop Quark Results

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

$\sqrt{s} \approx$ 161, 172 and 183 GeV



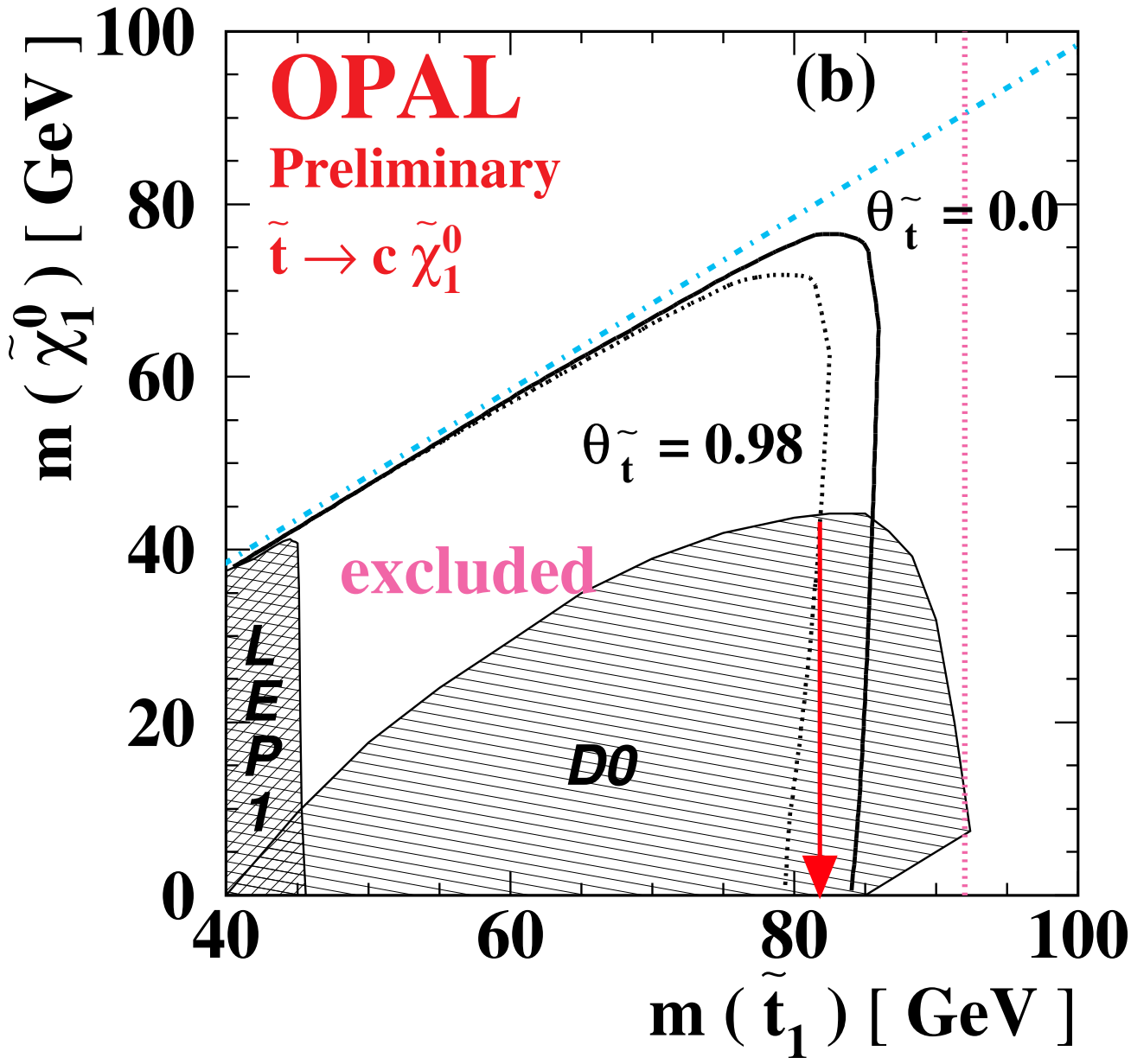
For $\theta_{mix} = 56°$ and $\Delta m > 10$ GeV:

$m_{\tilde{t}_1} > 75$ GeV

Stop Quark Results

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

$\sqrt{s} \approx 130, 136, 161, 172$ and 183 GeV



For $\theta_{mix} = 56°$ and $\Delta m > 10$ GeV:

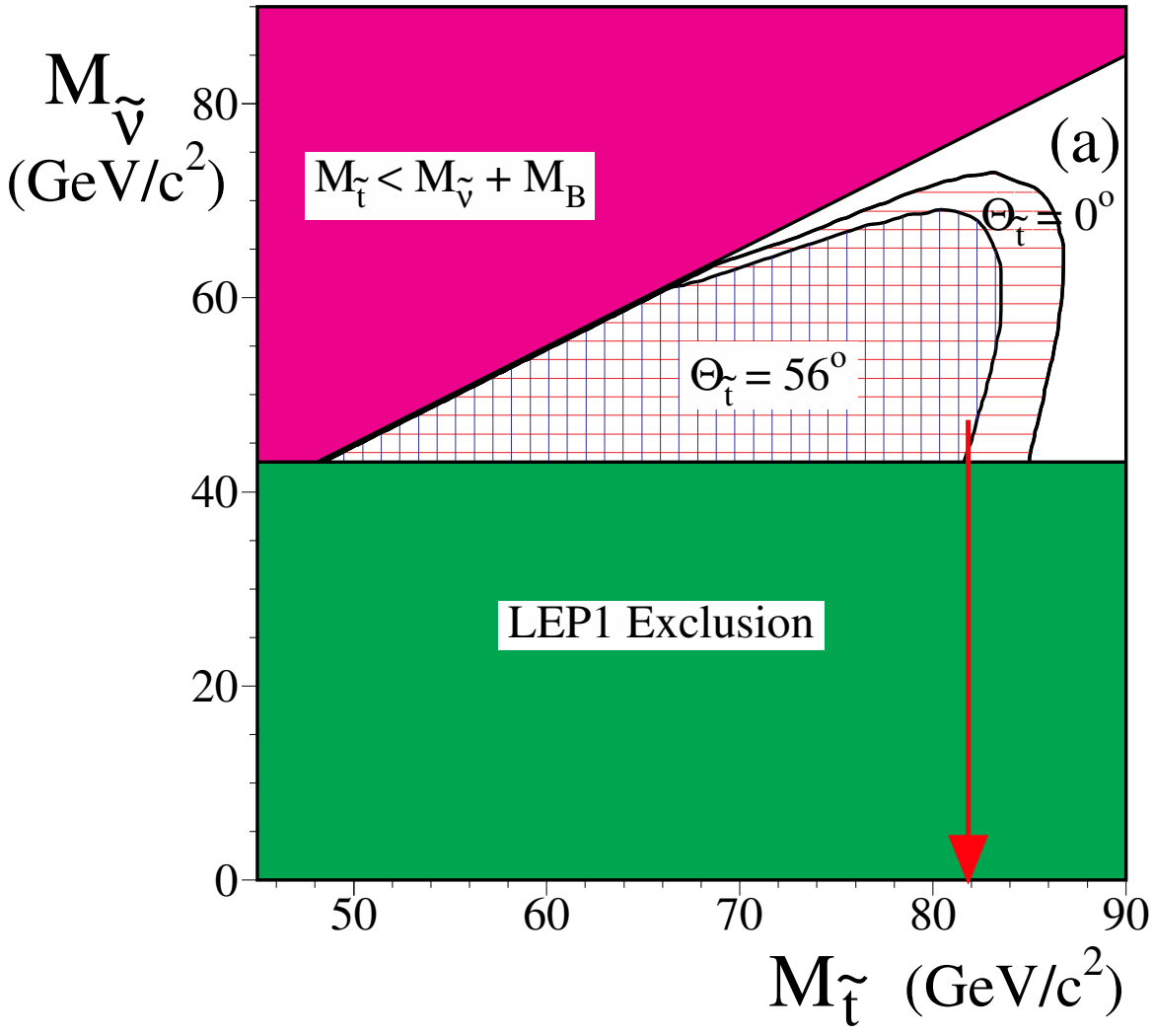
$m_{\tilde{t}_1} > 81.3$ GeV

Stop Quark Results

$\tilde{t}_1 \rightarrow l^+ b \tilde{\nu}$

$\sqrt{s} \approx 183$ GeV

ALEPH PRELIMINARY $M_{\tilde{t}}$ and $M_{\tilde{\nu}}$ 95% C.L. Exc



For $\theta_{mix} = 56^o$ and $\Delta m > 10$ GeV:

$m_{\tilde{t}_1} > 82$ GeV

Sbottom Quark

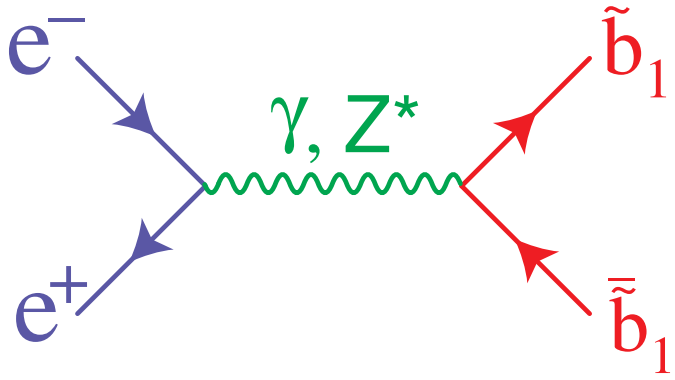
1) $Y_b = m_b / (\sqrt{2}\, m_W \sin\beta)$ is also sizeable
$\rightarrow$ Sizeable Radiative correction to $m_{\tilde{b}}$

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

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

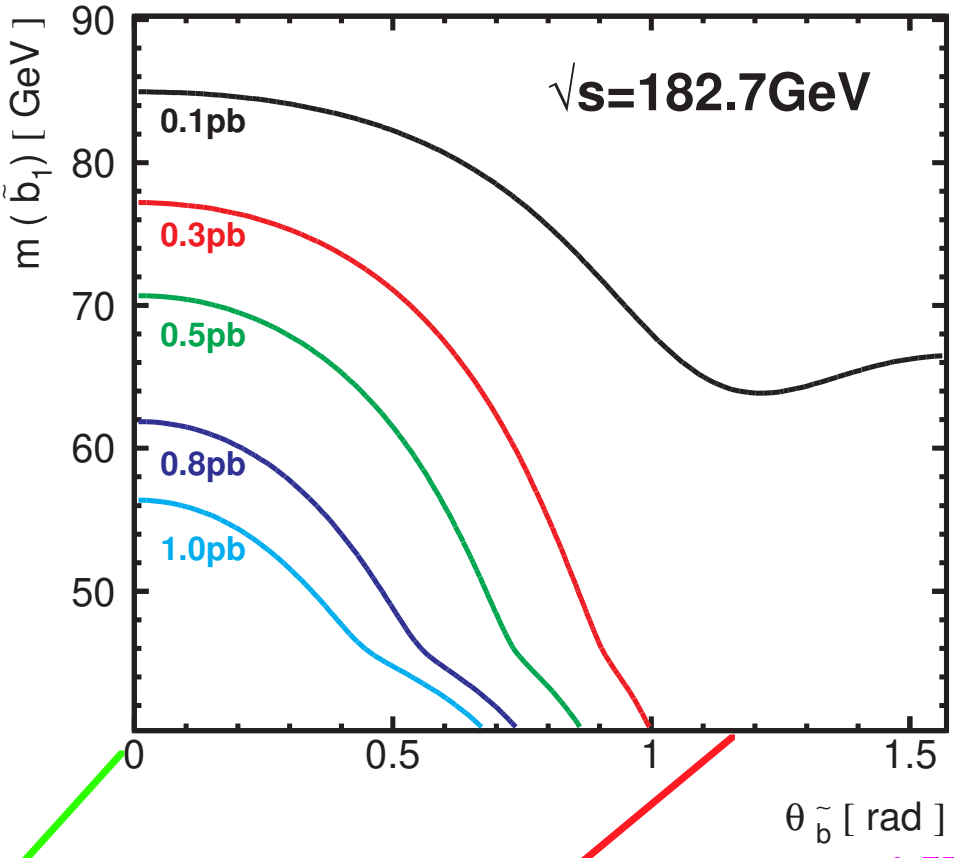
Large mass split if large a $\leftrightarrow$ large tan β
$\tilde{b}_1$ can be light if tan β ~ 40

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}



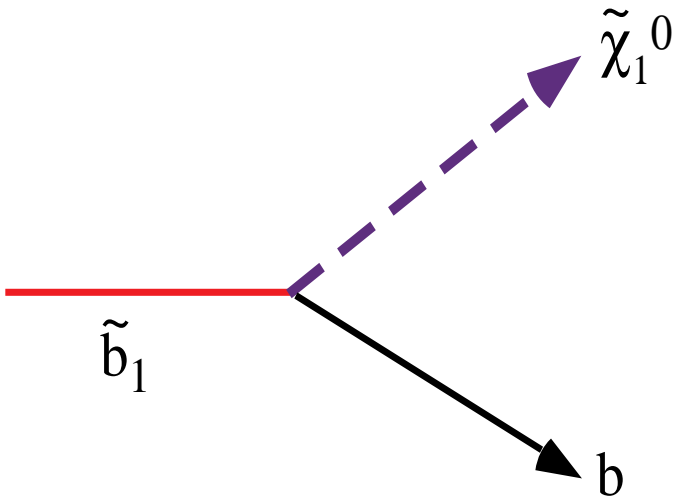
$\tilde{b}_1 = \tilde{b}_L$

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

1.57 rad = 90 °

$\tilde{b}_1 = \tilde{b}_R$

Sbottom Quark Decay



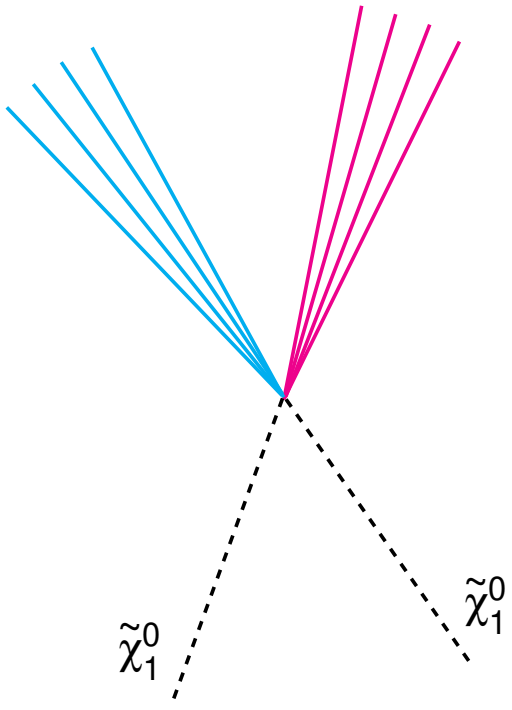
Two -body decay:
Γ=0 (50 MeV)

Because Γ << Λ_{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

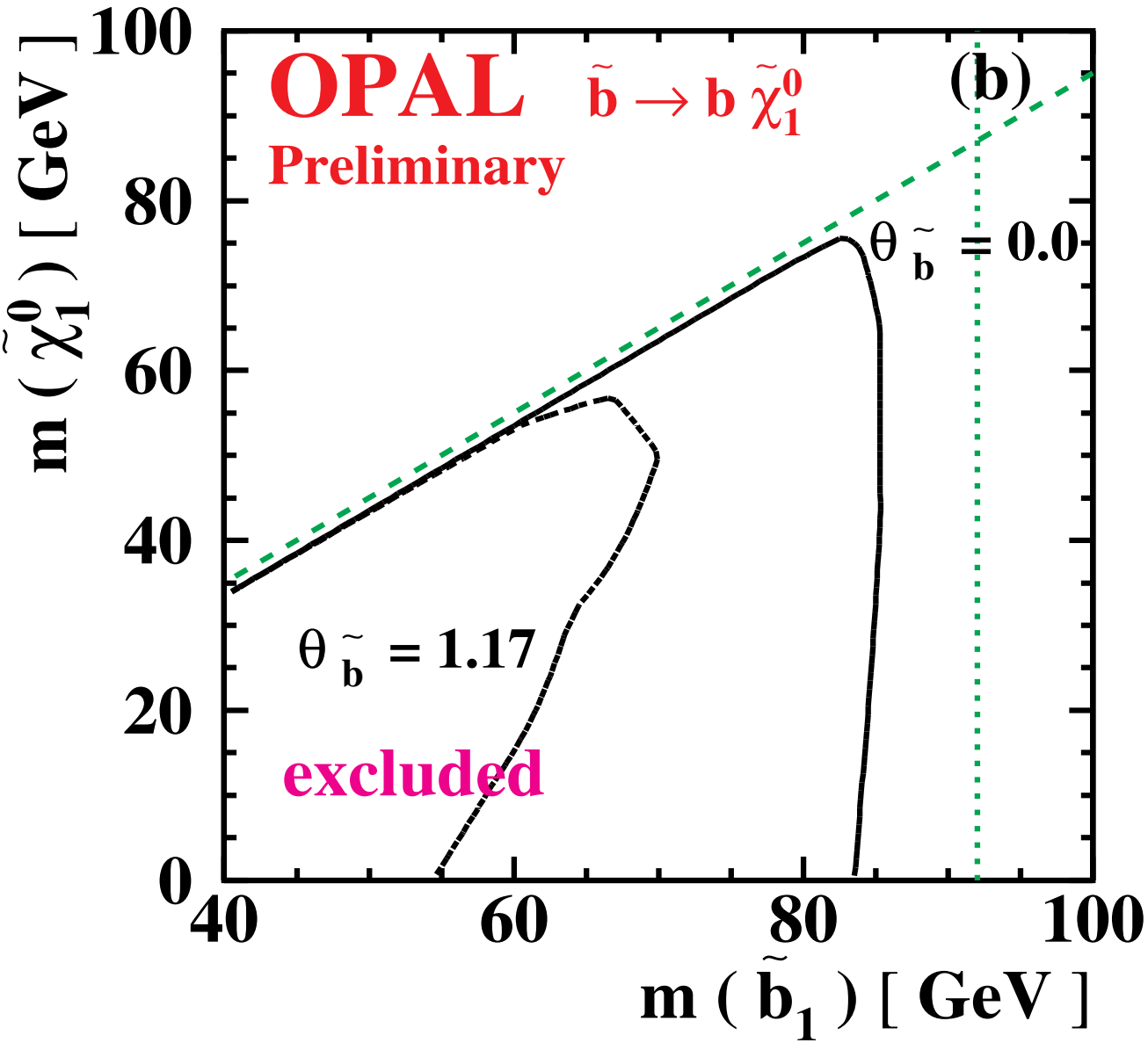
Two acoplanar sharp jets and missing energy



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

Sbottom Quark Results

$\tilde{b}_1 \rightarrow \tilde{\chi}^0_1 b$



For $\theta_{mix} = 0°$ and $\Delta m > 7$ GeV:

$m_{\tilde{b}_1} > 82.7$ GeV

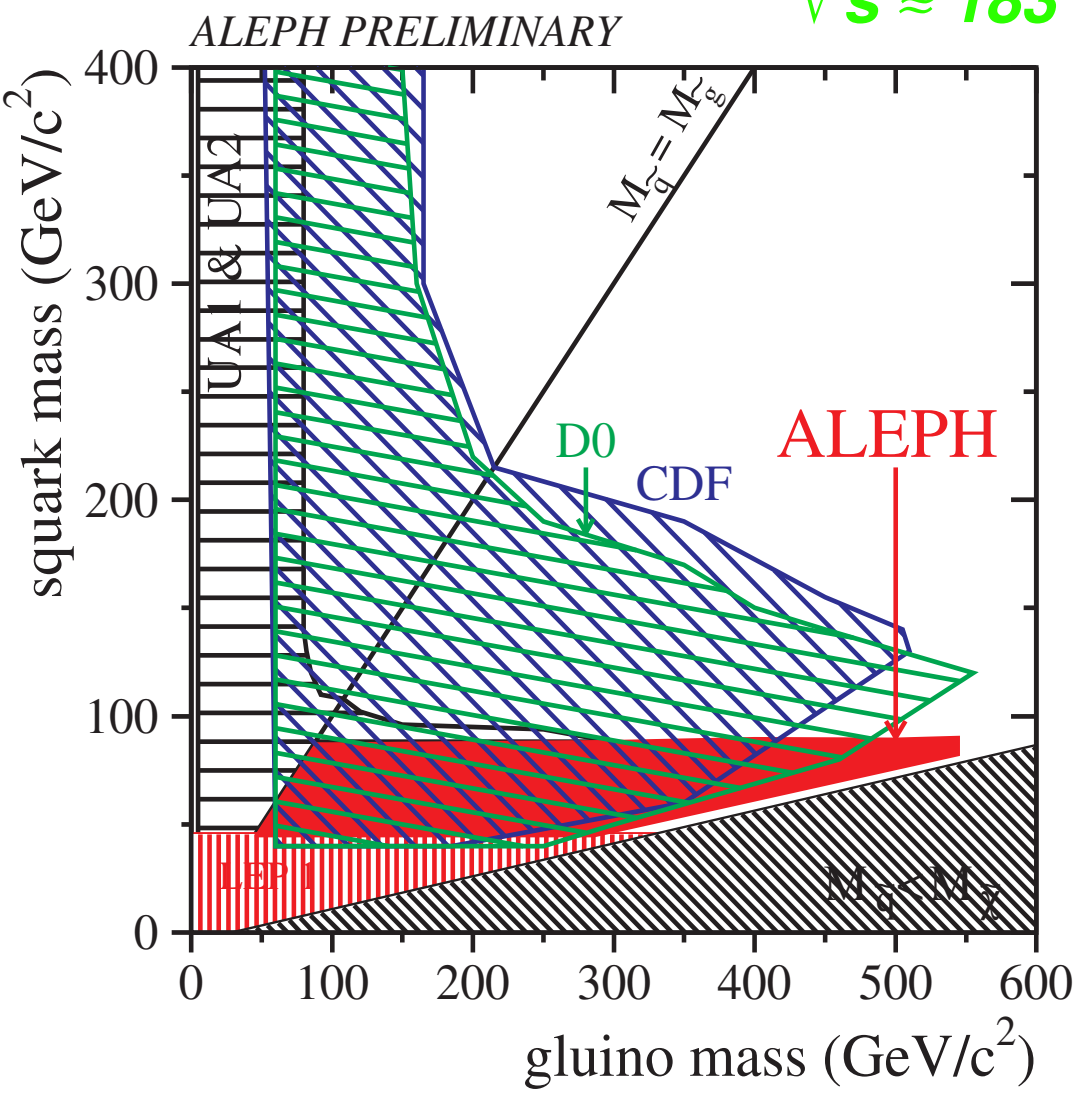
Degenerate Squark Results

Susy partners of the light quarks are generally expected in the MSSM to be heavy, i.e., beyond the LEP2 reach. But their masses receives large negative corrections from gluino loops.

Decay similar to sbottom $\tilde{q}_1 \rightarrow \tilde{\chi}^0_1 q$

Limits on u d s c b squarks assuming they are mass degenerate (ALEPH)

$\sqrt{s} \approx 183$ GeV



Stop and Sbottom Mass Limits Summary

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

ALEPH	74 GeV	$10 < \Delta m < 40$ GeV
DELPHI	70 GeV	massless $\tilde{\chi}^0_1$
L3	75 GeV	$\Delta m >$ 10 GeV
OPAL	81 GeV	$\Delta m >$ 10 GeV

$\tilde{t}_1 \rightarrow l^+ b \tilde{\nu}$

ALEPH	82 GeV	$\Delta m >$ 10 GeV
OPAL	79.2 GeV	$\Delta m >$ 10 GeV

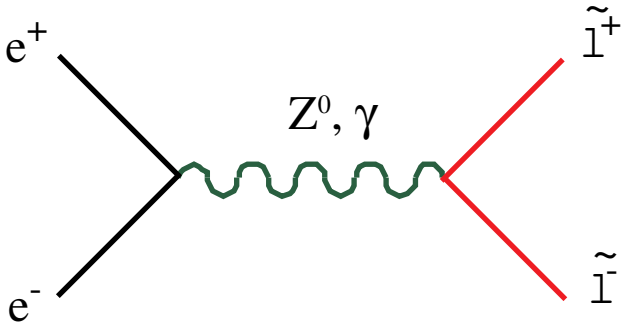
$\tilde{b}_1 \rightarrow \tilde{\chi}^0_1 b$

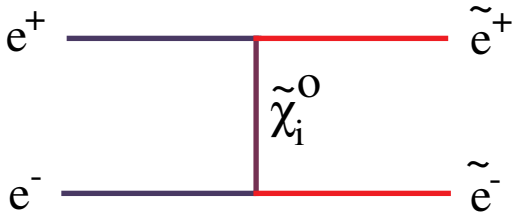
ALEPH	79 GeV	$\Delta m >$ 10 GeV
OPAL	84 GeV	$\Delta m >$ 10 GeV

Slepton Production and Decay

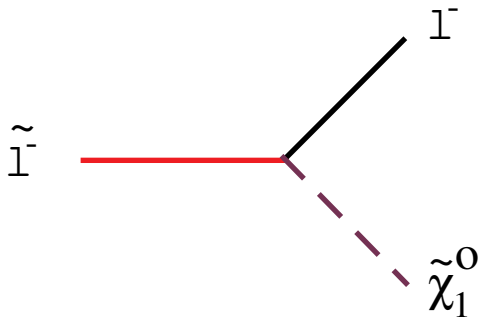
Production

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





Decays



Topology

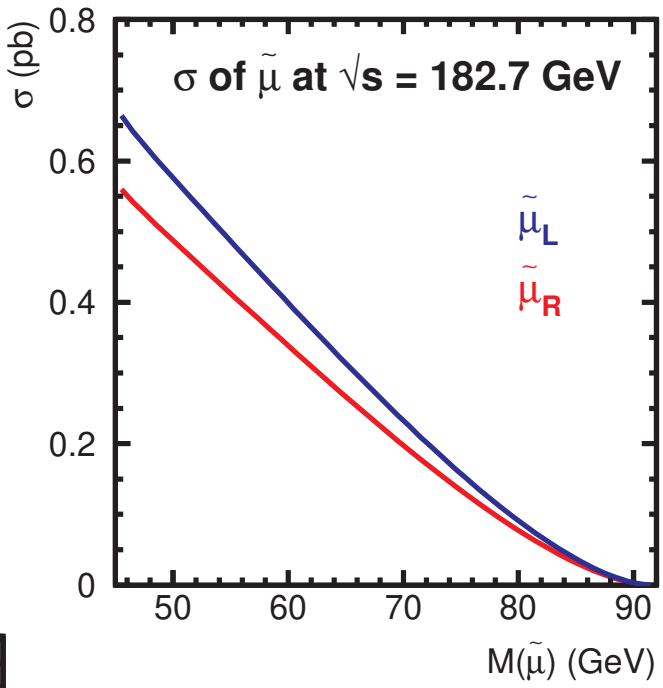
Two acoplanar leptons of the same family and missing energy

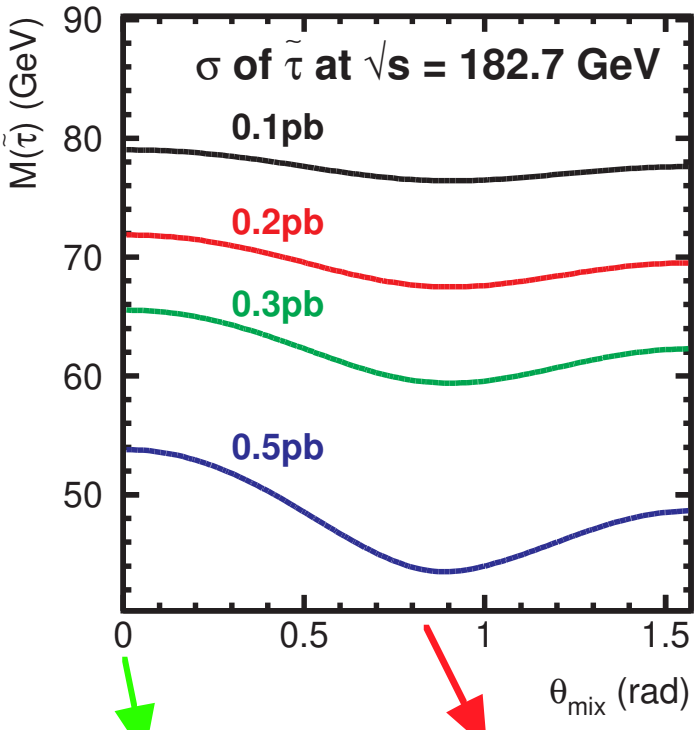
Slepton Pair Production Cross-Sections

Selectron σ higher due to t-channel (μ = -200 GeV and tan β =1.5)

$\sqrt{s}$ = 182.7 GeV

Smuon σ smaller due to s-channel only





For Stau: non-negligible Yukawa coupling; the lighter state $\tilde{\tau}_1$ is a mixing state of $\tilde{\tau}_L$ and $\tilde{\tau}_R$. But cross-section dependence is not strong.

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

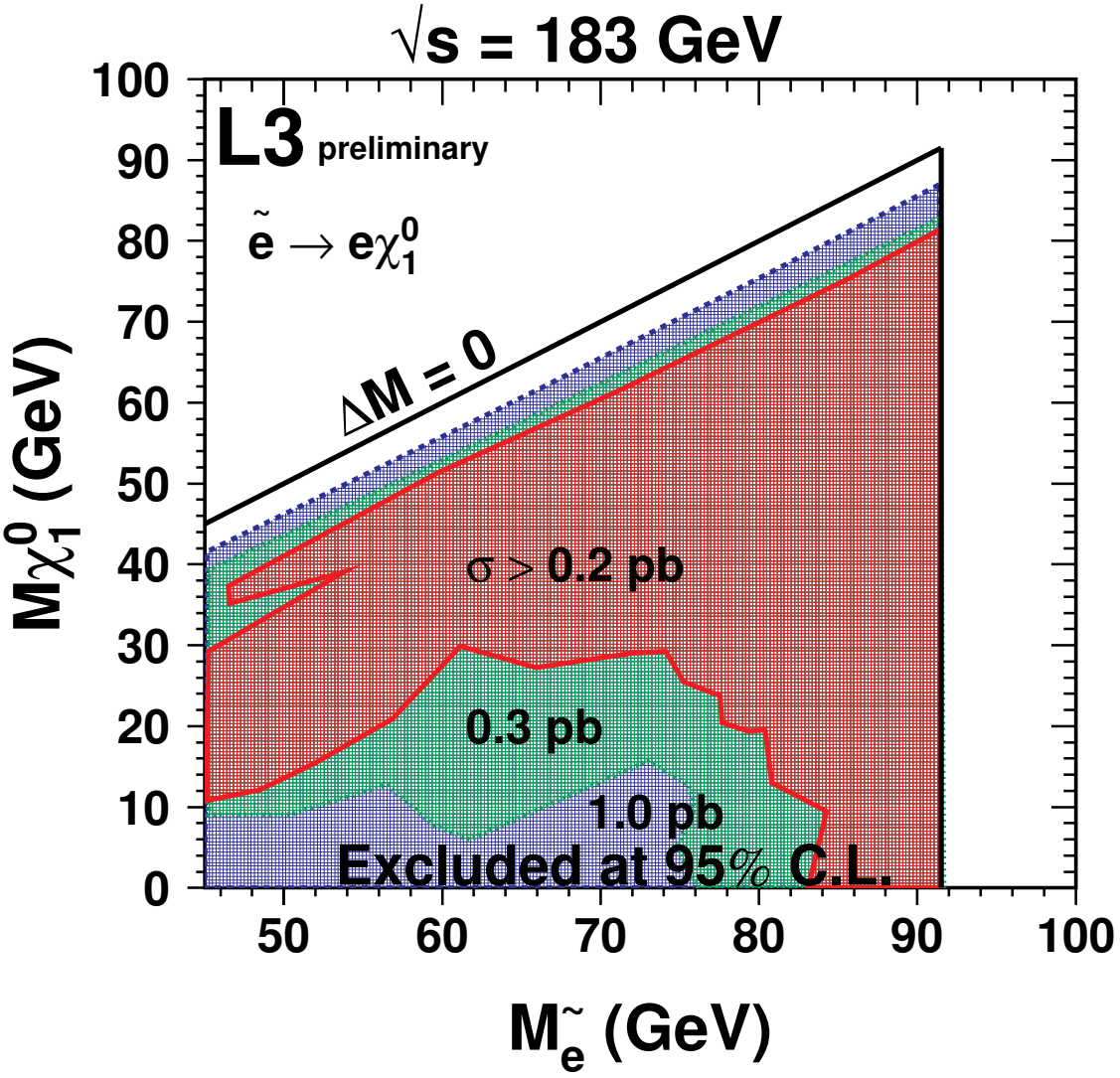
1.57rad = 90 ° $\tilde{\tau}_1 = \tilde{\tau}_R$

$\tilde{\tau}_1 = \tilde{\tau}_L$

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

Slepton Cross-Section Limits

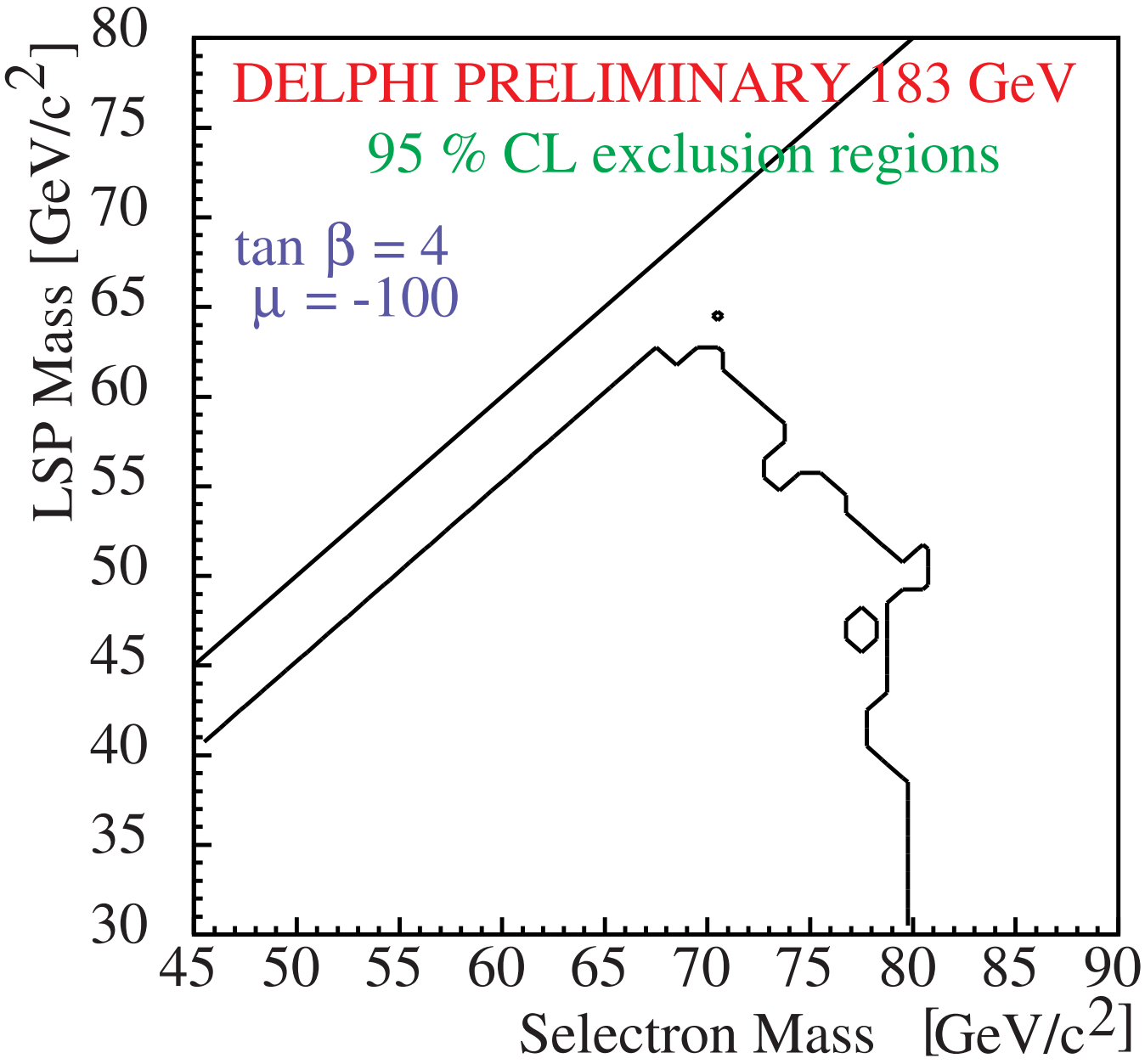
Selectrons



Similar plots for smuons and staus.

MSSM Selector Mass Limit

$\sqrt{s} \approx 183$ GeV

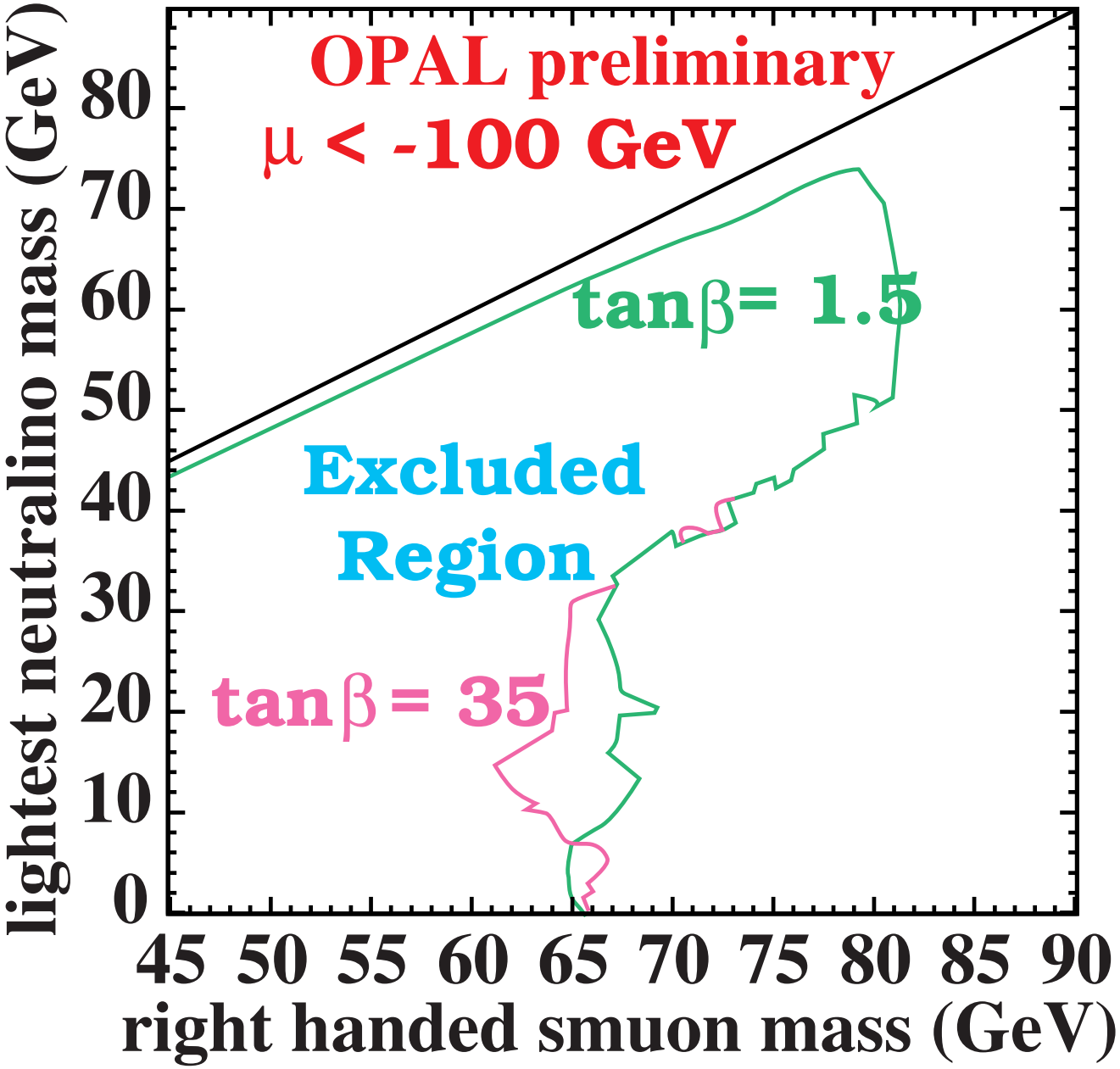


In the MSSM, lower mass limit on right-handed selectrons at the 95% C.L. is :

77 GeV when $m_{\tilde{\chi}_1^0} < 50$ GeV

MSSM Smuon Mass Limit

$\sqrt{s} \approx$ 130-136, 161, 172 and 183 GeV

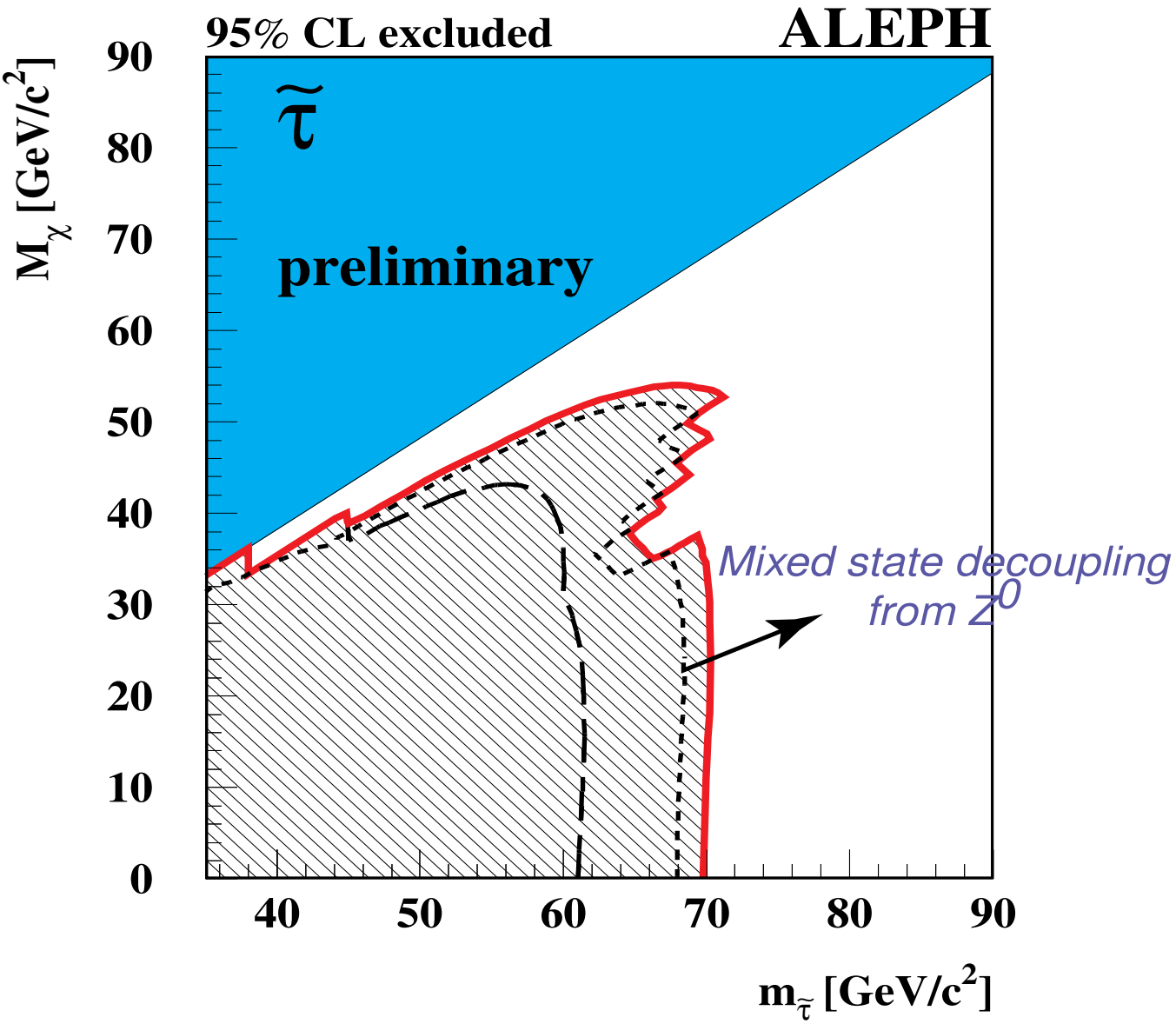


In the MSSM, lower mass limit on right-handed smuons at the 95% C.L. is :

65 GeV when Δ m > 3 GeV

MSSM Stau Mass Limit

$\sqrt{s} \approx$ 161, 172 and 183 GeV



In the MSSM, lower mass limit on right-handed staus at the 95% C.L. is :

65 GeV when Δ m > 15 GeV

Slepton Mass Limits Summary

Collab.	Limit (95 % C.L.)	Condition
Right-handed Smuons		
ALEPH	71 GeV	$\Delta m >$ 5 GeV
DELPHI	66 GeV	$m\,\tilde{\chi}^0_1 <$ 65 GeV $\Delta m >$ 5 GeV
L3	69 GeV	$\Delta m >$ 15 GeV
OPAL	65 GeV	$\Delta m >$ 3 GeV
Right-handed Selectrons		
ALEPH	81 GeV	$\Delta m >$ 10 GeV μ = - 200 GeV tanβ = 2
DELPHI	77 GeV	$m\,\tilde{\chi}^0_1 <$ 50 GeV μ = - 100 GeV tanβ = 4
L3	80 GeV	$\Delta m >$ 15 GeV μ = - 200 GeV tanβ = 1.41
OPAL	78 GeV	$\Delta m >$ 2 GeV $\mu <$ - 100 GeV tanβ = 1.5
Right-handed Staus		
ALEPH	65 GeV	$\Delta m >$ 15 GeV
DELPHI	60 GeV	$m\,\tilde{\chi}^0_1 <$ 35 GeV $\Delta m >$ 10 GeV
OPAL	66 GeV	$\Delta m >$ 20 GeV

Long-lived Heavy Charged Particles

Most SUSY searches assume the LSP is neutral and weakly interacting and that all SUSY particles ultimately decay with a very short lifetime into the LSP plus standard particles.

HOWEVER the possibility of SUSY long-lived charged particles is favoured by some models.

For instance, in gauge-mediated SUSY models, if the slepton is the next-to-lightest supersymmetric particle (NLSP), it can decay into a standard lepton and a gravitino which is assumed to be the LSP with a lifetime dependent on the SUSY-breaking energy scale $\sqrt{F}$:

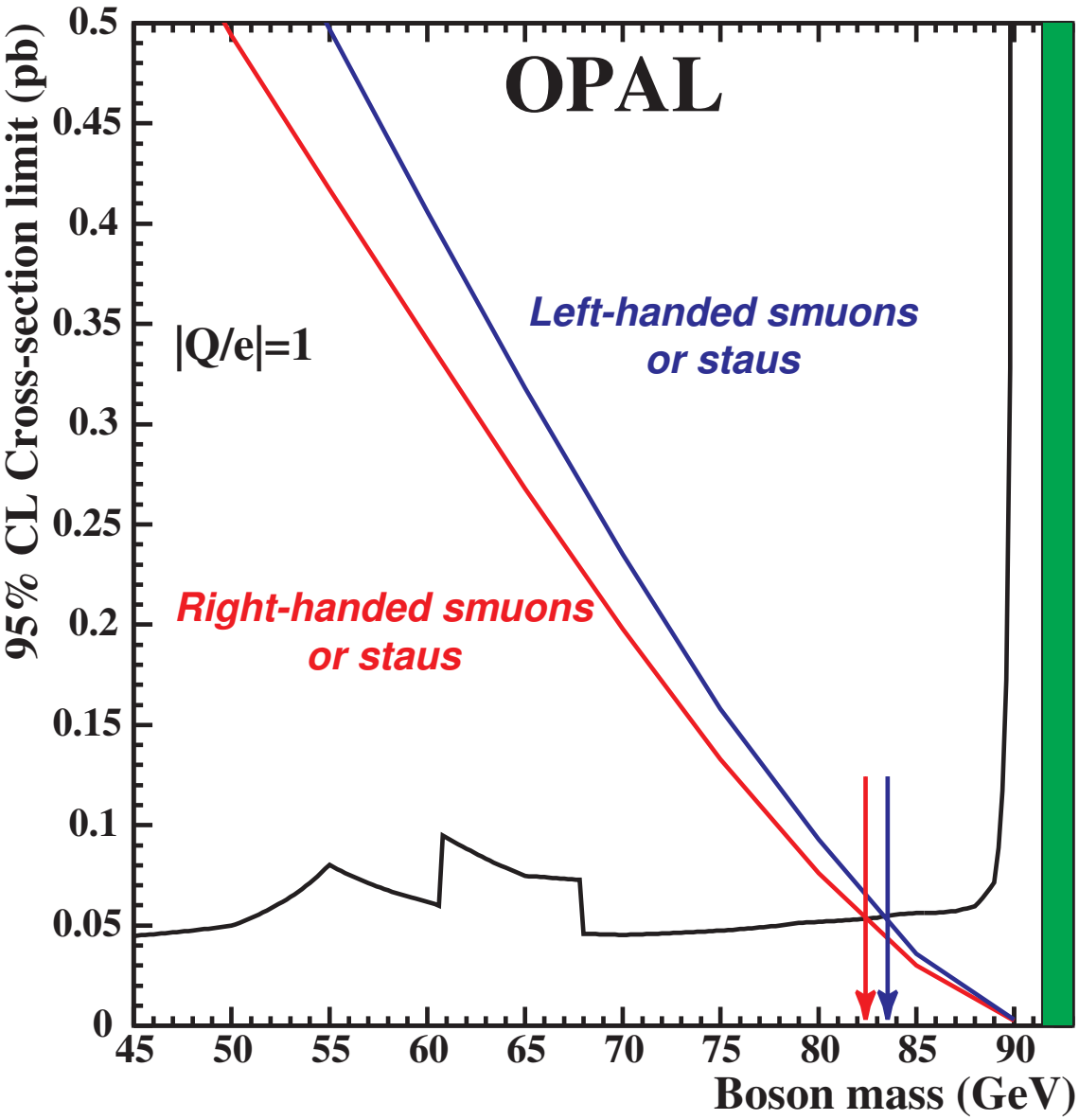
$$c\tau = (130\ \mu m)\ (\ 100\ GeV/m_1\ )^5\ (\ \sqrt{F}\ /100\ TeV)^4$$

If $\sqrt{F}$ >> a few thousand TeV, a 70 GeV slepton has a decay length greater than 10 meters, which corresponds to the typical size of a LEP experiment detector.

Long-lived charged SUSY particles also exist in the context of SUSY models if there is a high mass degeneracy with the LSP and also in RPV SUSY models if the couplings are small.

The selection is based on the specific ionization loss measurements (dE/dx) . DELPHI also uses the particle ID provided by the RICH detectors.

Long-lived Heavy Charged Particles



95% C.L. upper limit on the production cross-section of 0.05-0.1 pb for masses between 45 and 89.5 GeV

Assuming MSSM:

$m_{\tilde{\mu}_R^{\pm}, \tilde{\tau}_R^{\pm}} > 82.5$ GeV

$m_{\tilde{\mu}_L^{\pm}, \tilde{\tau}_L^{\pm}} > 83.5$ GeV

R-parity Violation

45 extra λ couplings from explicit breaking of R_p interactions parametrized in superpotential as:

$$W = \lambda_{ijk} L^i_L L^j_L \bar{E}^k_R + \lambda'_{ijk} L^i_L Q^j_L \bar{D}^k_R + \lambda''_{ijk} \bar{U}^i_R \bar{D}^j_R \bar{D}^k_R$$

L^i_L : the SU(2)-doublet lepton superfield

Q^i_L : the SU(2)-doublet quark superfield

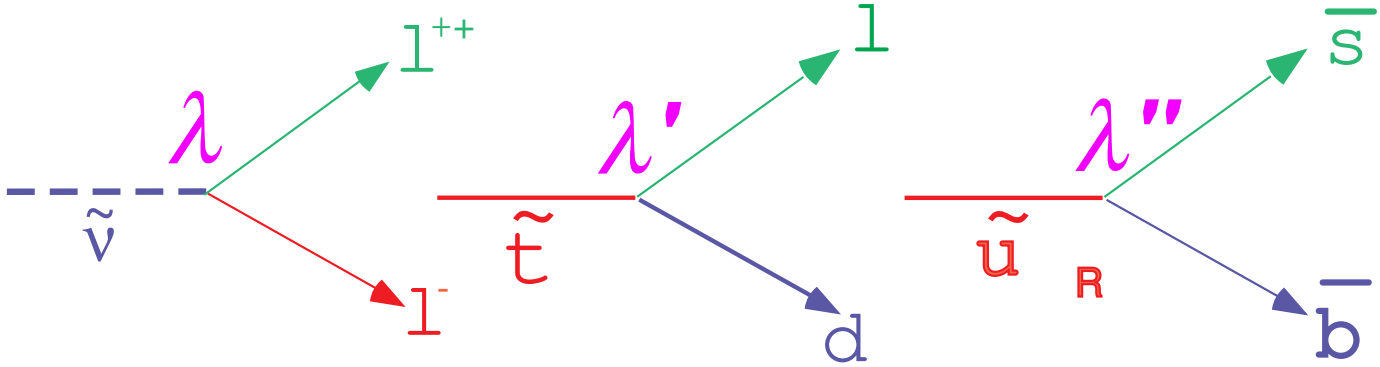
E^i_R: the lepton singlet superfield

U^i_R : the up-type quark singlet superfield

D^i_R : the down-type quark singlet superfield

Due to symmetry, $\lambda_{ijk} = -\lambda_{ijk}$ and $\lambda''_{ijk} = -\lambda''_{ijk}$

9 + 27 + 9 = 45 independent couplings



L-Violation **B -Violation**

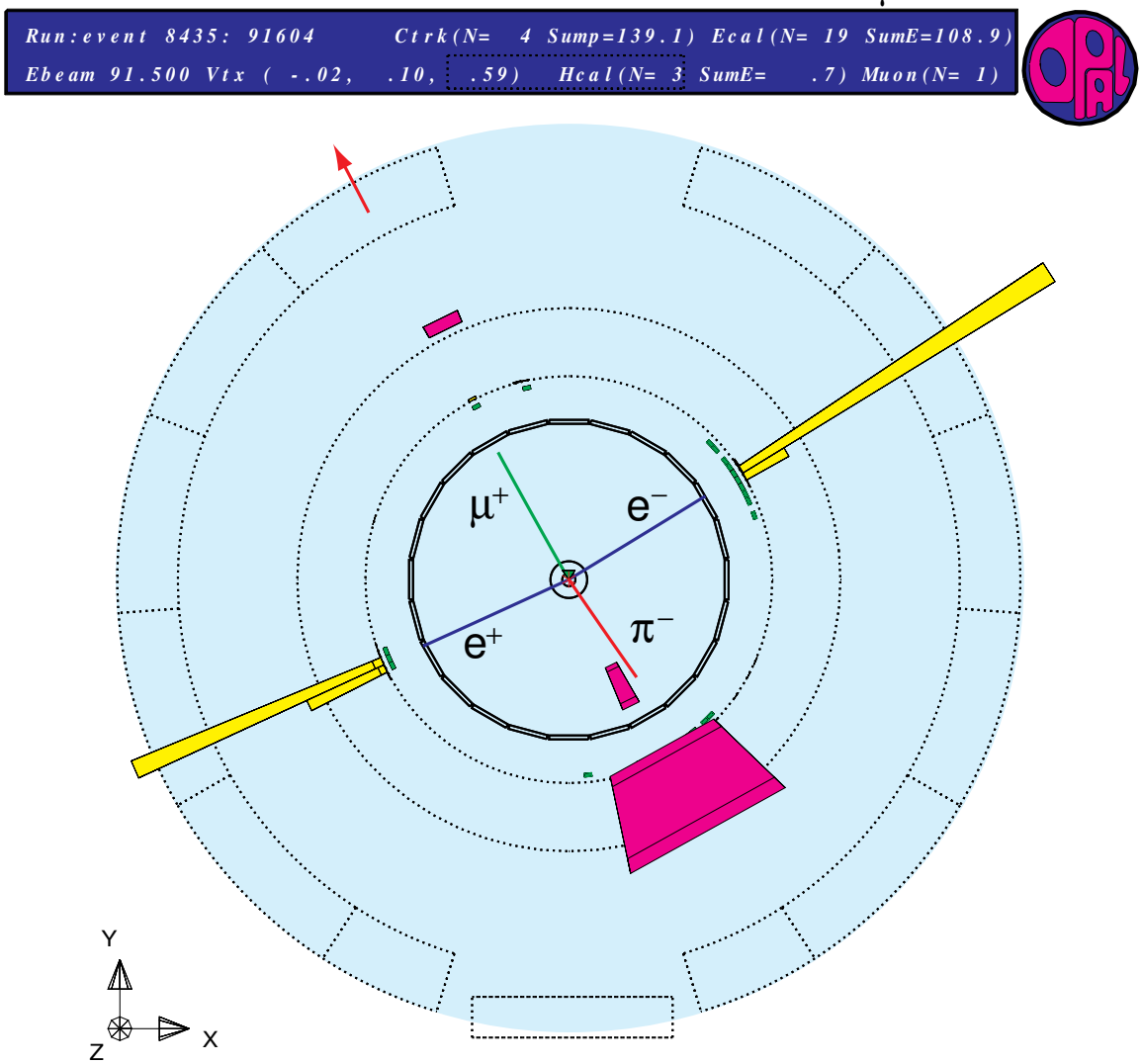
Candidate

$< E_{beam} >$ = 91.3 GeV $\Rightarrow$ just above ZZ threshold.

$e^+e^- \rightarrow Z^0Z^0 \rightarrow e^+e^- \tau^+\tau^-$

$\tau^- \rightarrow \pi^- X$

$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$



Mass (e^+e^-) = 89.5 +/- 3.4 GeV

Mass (recoil) = 90.7 +/- 3.1 GeV

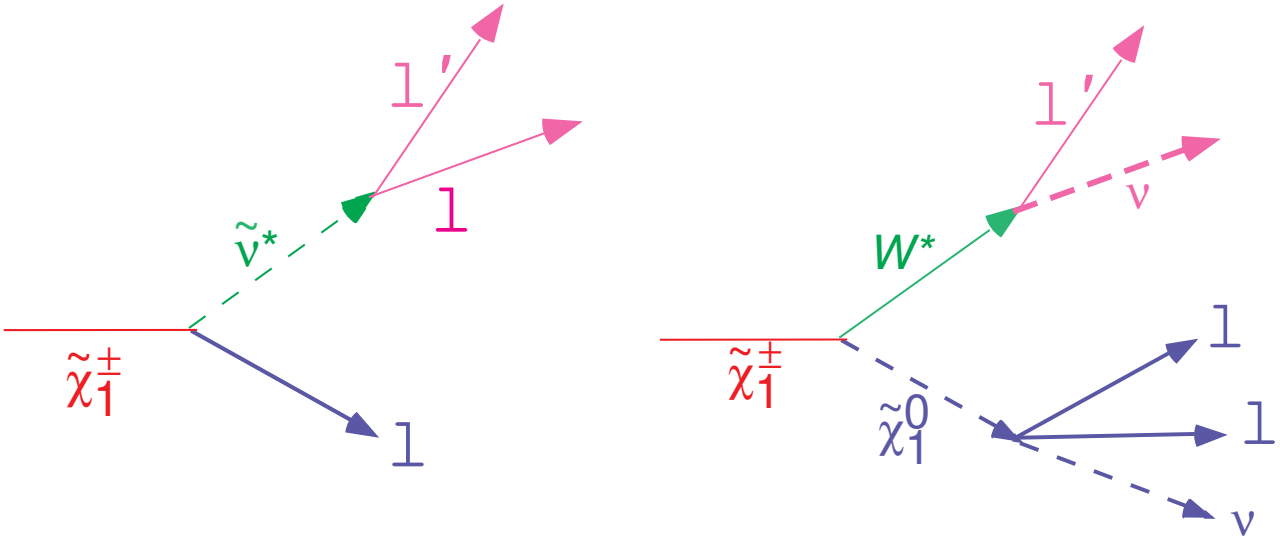
Expectation from ZZ:

channel	N_{exp}	N_{obs}
eeqq, $\mu\mu$qq	0.7	0
$llll$	0.1	1

RPV Chargino Searches

One dominant LLE coupling

λ coupling



Pair production

Direct Decays

Indirect Decays

Final states: 6 charged leptons and no missing energy

Final states: 6 charged leptons and missing energy

RPV Chargino Results

Valid for any of the possible 9 λ

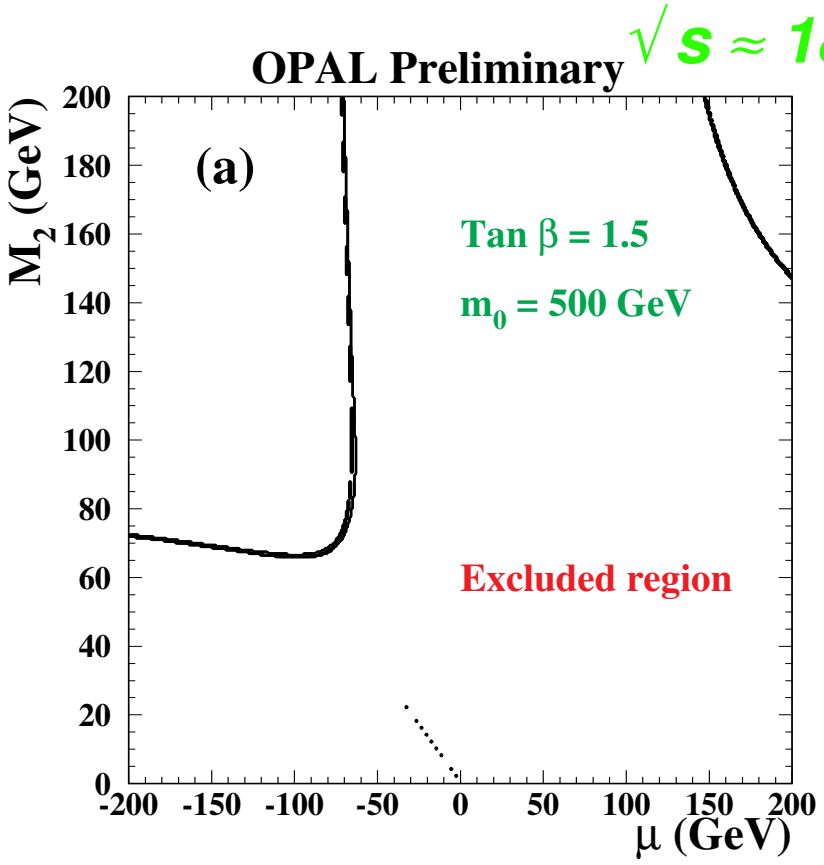
OPAL excludes a cross-section greater than 0.2 pb at the 95 % C.L.

MSSM mass limits:

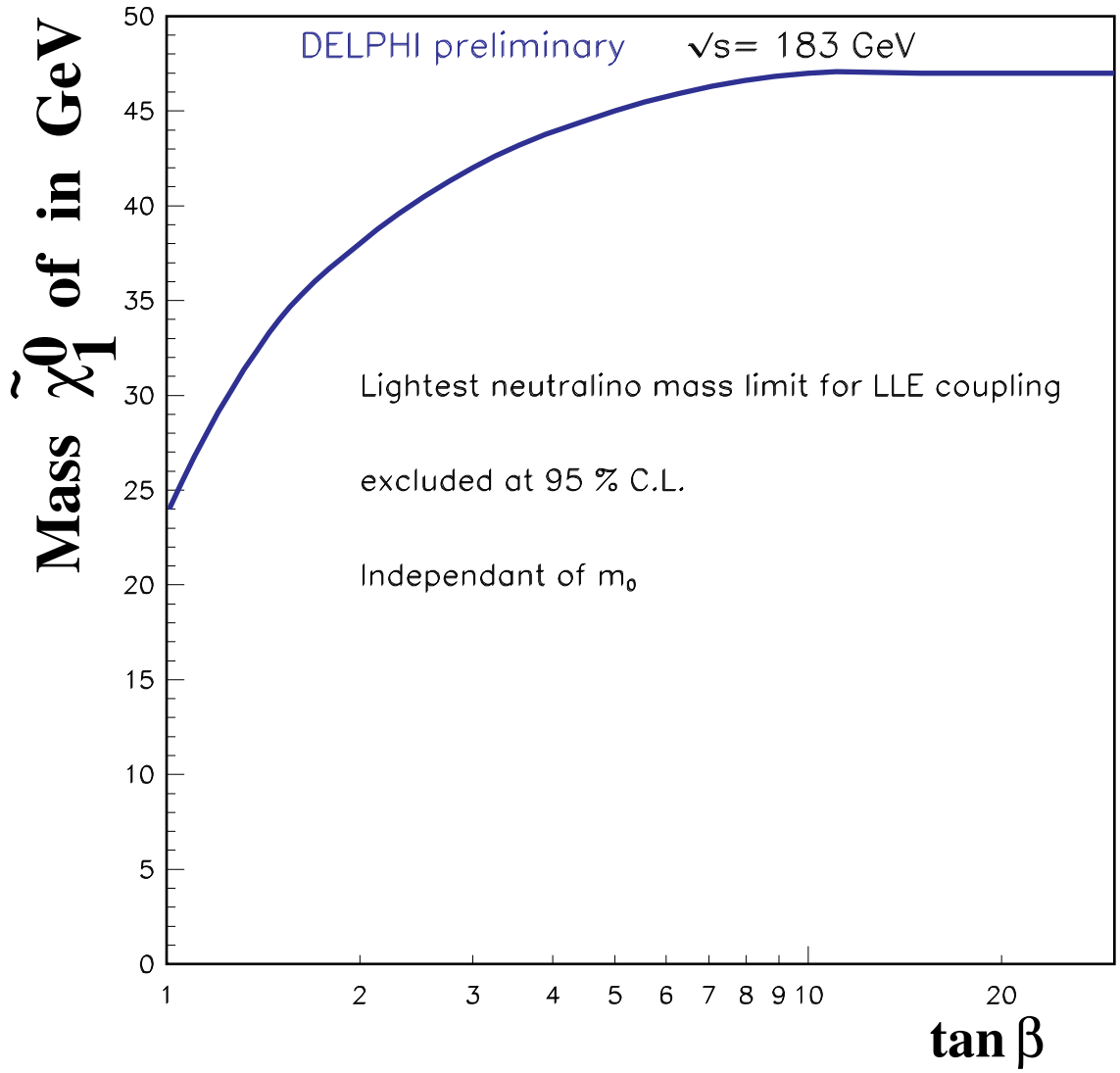
Direct Decays: $m_{\tilde{\chi}^{\pm}_1} > 90$ GeV at the 95 % C.L.

Indirect Decays: $m_{\tilde{\chi}^{\pm}_1} > 88$ GeV at the 95 % C.L.

(using a branching ratio of $W^* \rightarrow l\nu = 10.8\%$ per lepton flavour)



RPV Neutralino Results



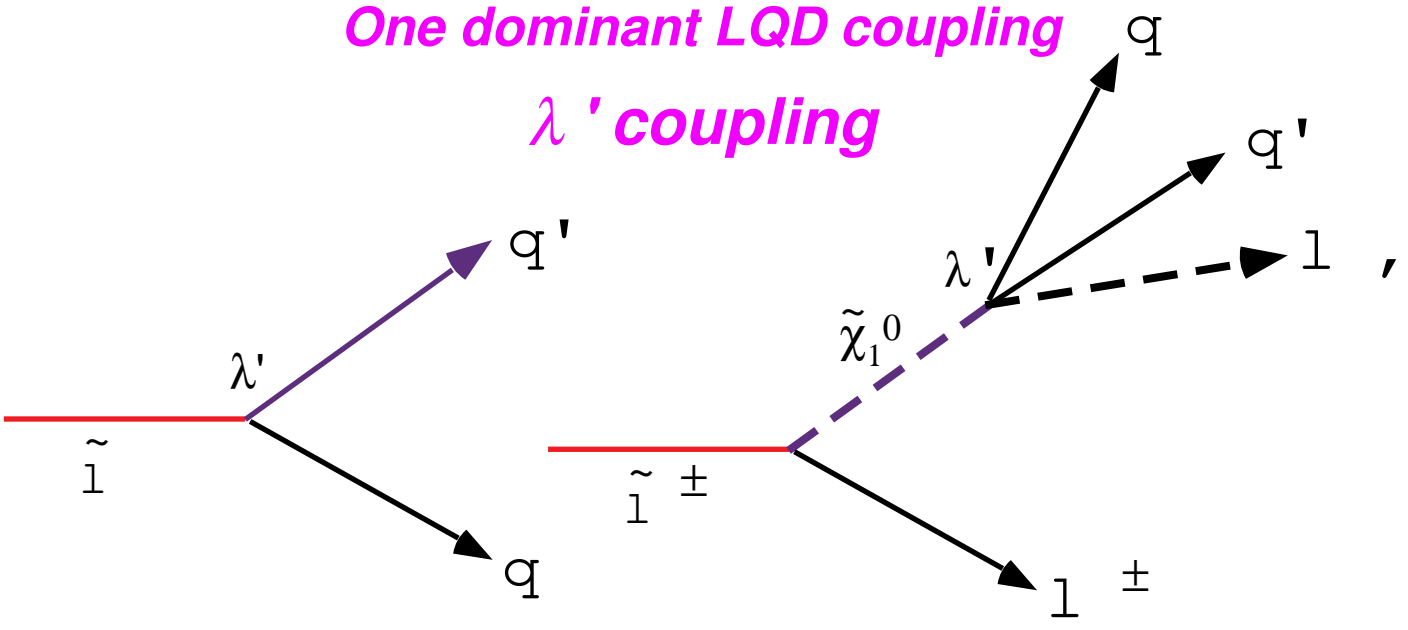
For any tan β :

$m_{\tilde{\chi}_1^0}$ > 24 GeV at 95 % C.L.

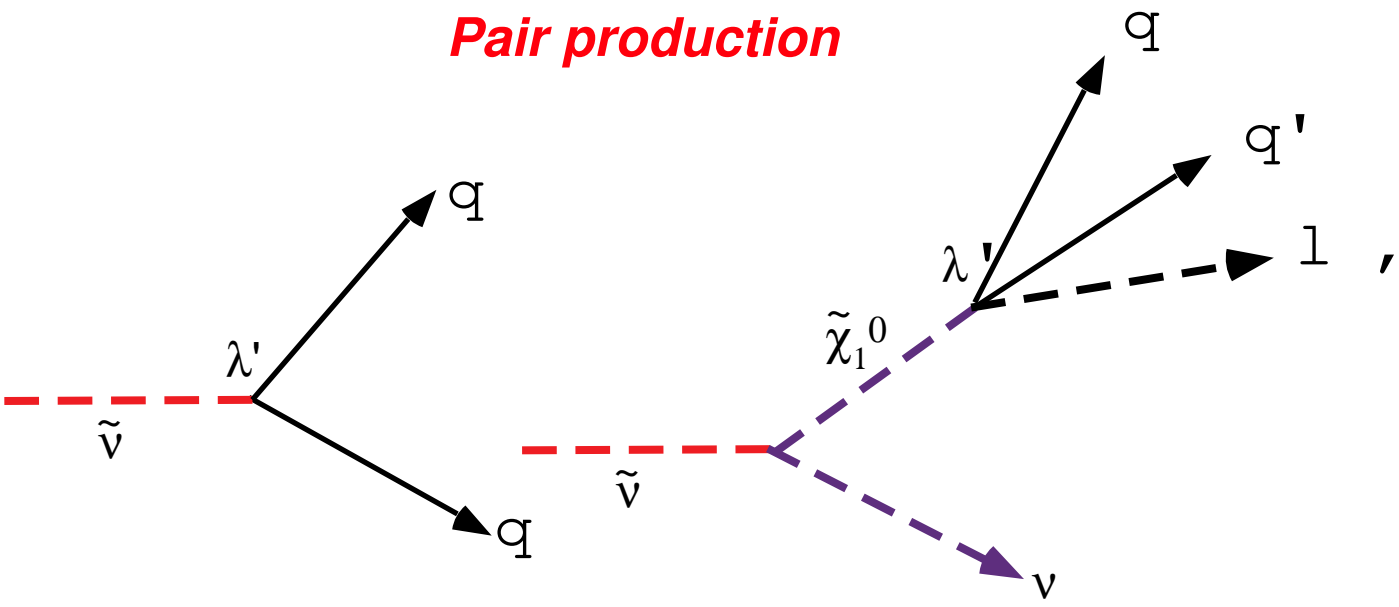
RPV Slepton Searches

One dominant LQD coupling

λ' coupling



Pair production



Direct decays

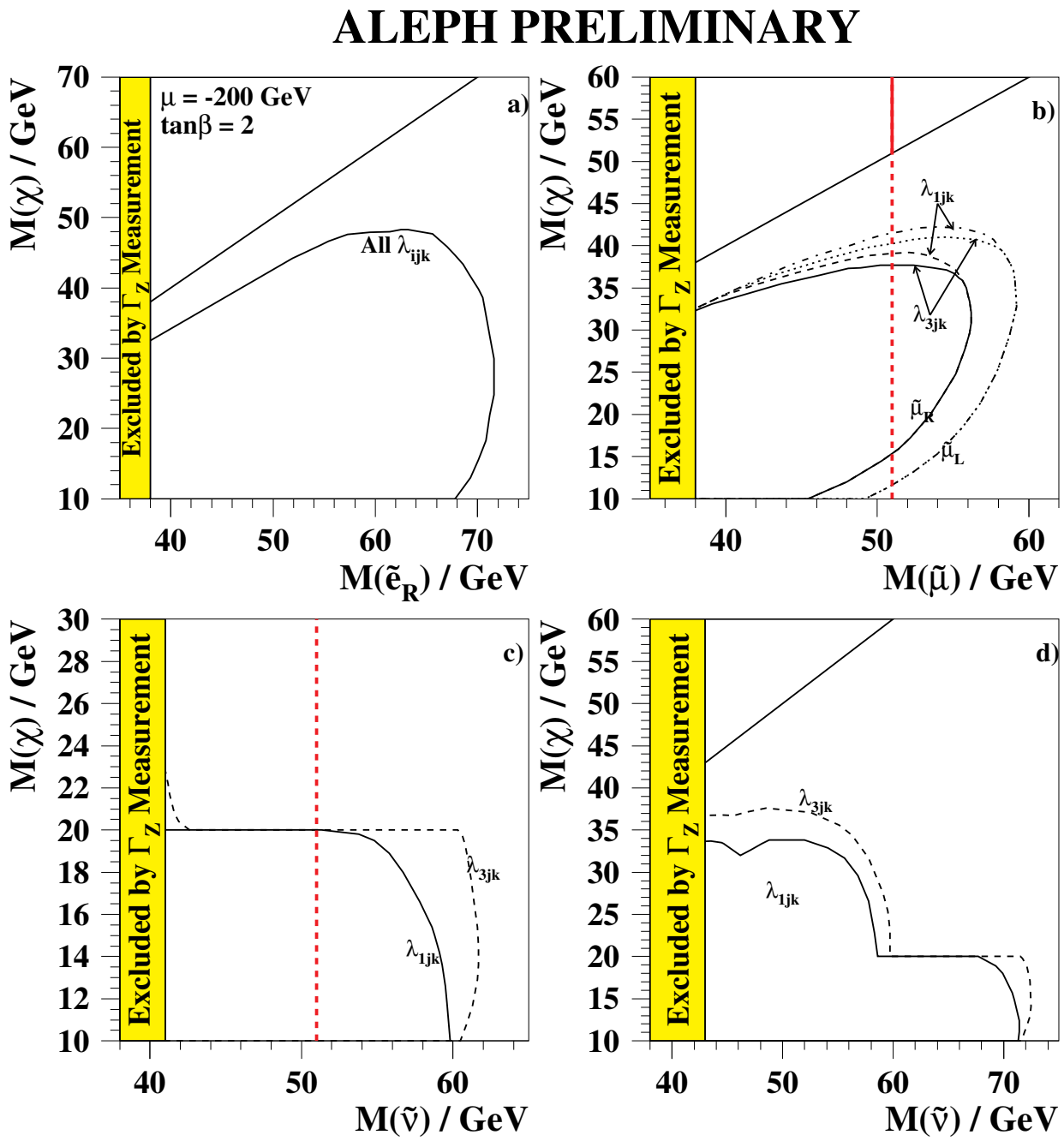
Final states:
4 jets

Indirect decays

Final states:
multi-jets + leptons

RPV Slepton Results

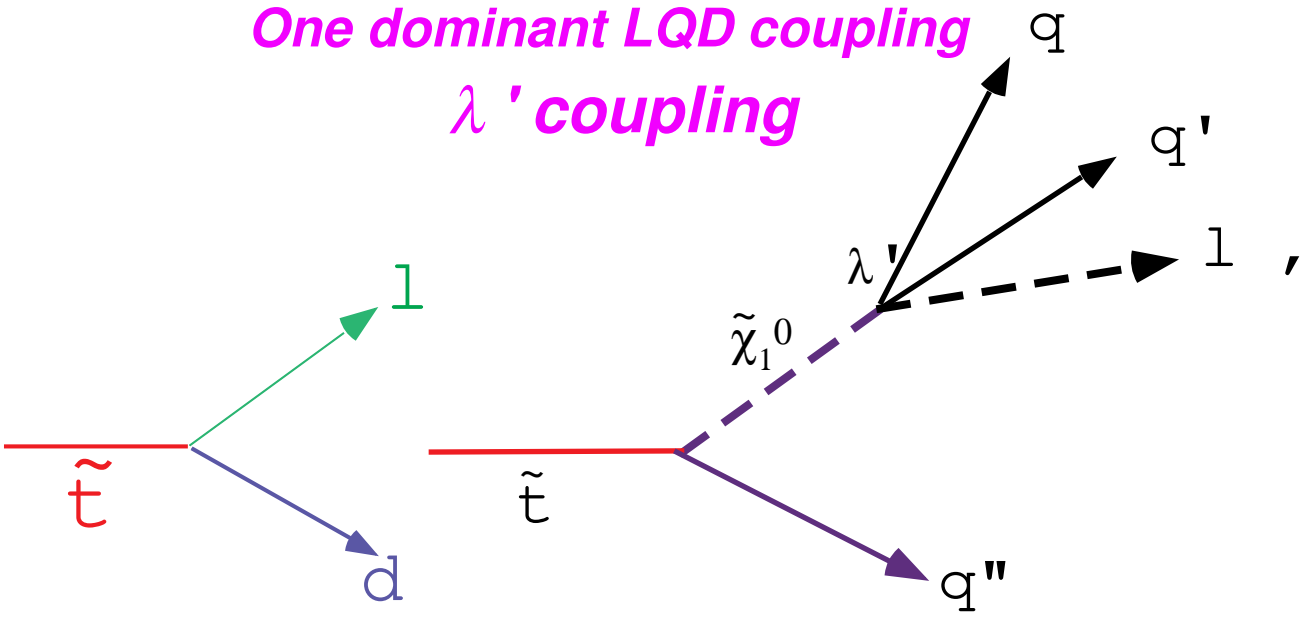
$\sqrt{s} \approx$ 130-136, 161, 172 GeV



RPV Stop and Sbottom Searches

One dominant LQD coupling

λ' coupling



Pair production

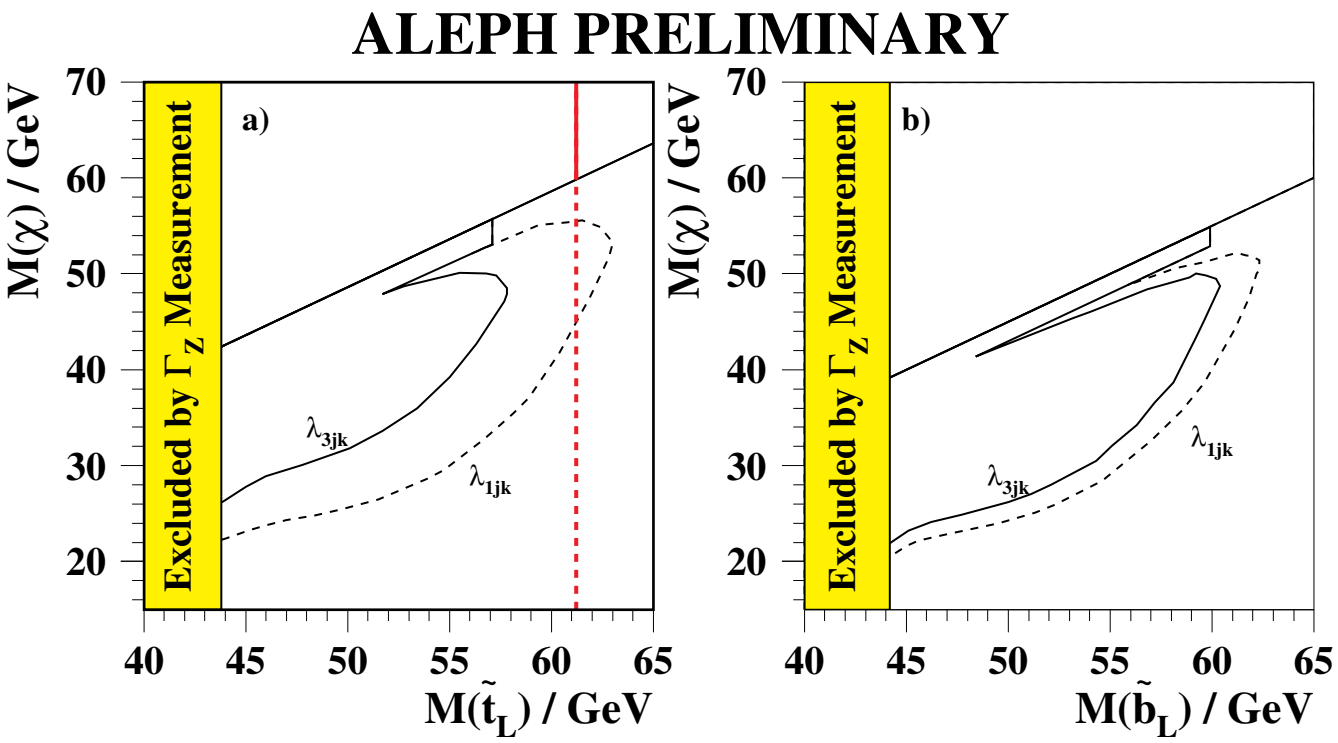
Direct Decays

Final states: 2 charged leptons and 2 jets

Indirect Decays

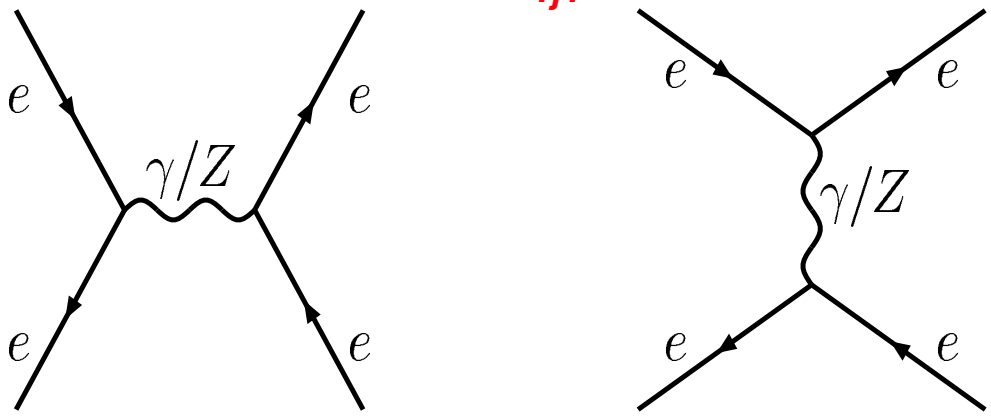
Final states: multi-jets plus leptons

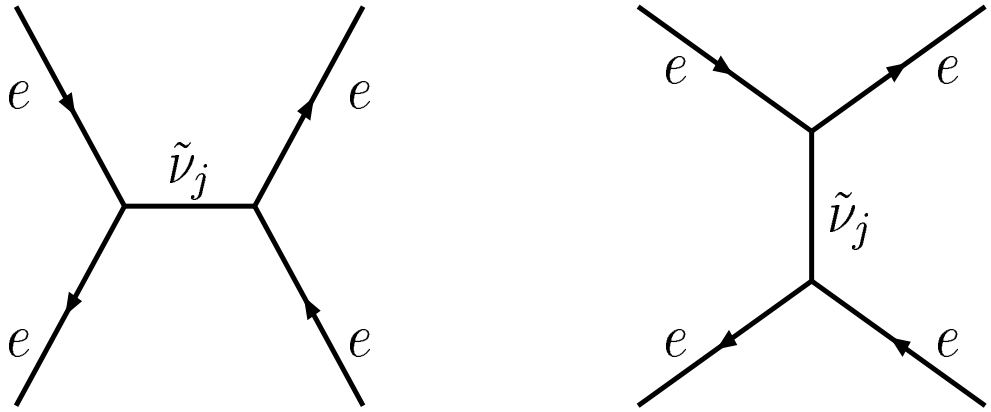
RPV Stop and Sbottom Results



RPV s- and t-channel Resonance

Bhabha scattering including the exchange of a sneutrino in the s- and t-channels (λ_{1j1})

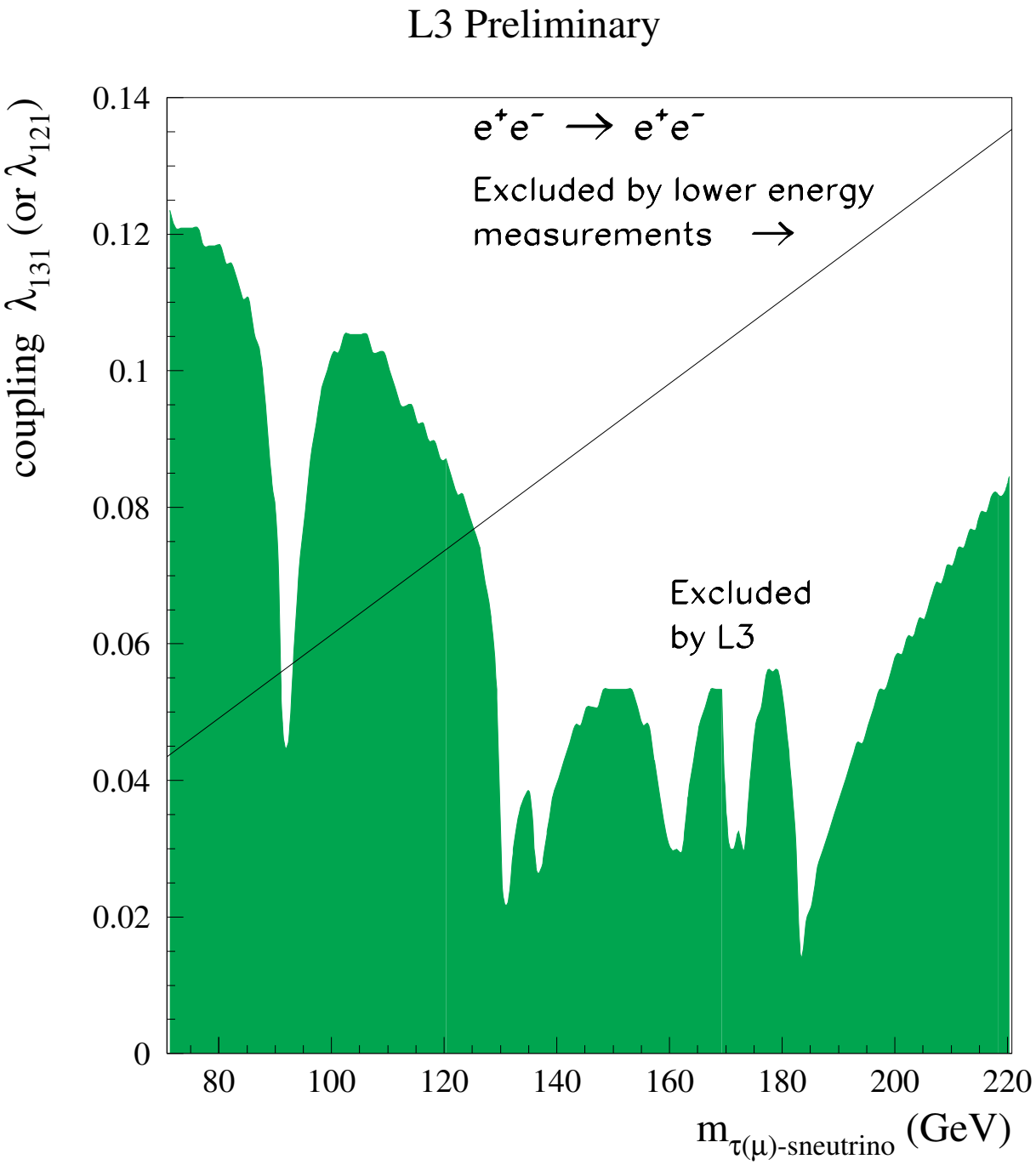




Limits from cross-section measurements

S- and t-Channel Results

$\sqrt{s} \approx 91$ -183 GeV



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, $\tilde{l}^{\pm}_R$; these would decay:***
  - $\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$
  - $\tilde{l}^{\pm} \rightarrow l^{\pm} \tilde{G}$
- ***The NLSP lifetime, τ_{NLSP} , ranges between 0 and $+\infty$, leading to many different topologies.***

Introduction to GMSB

"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 $\tilde{l}^{\pm}$:
  - 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 $\tilde{l}^{\pm}$:
  - 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 $\tilde{l}^{\pm}$:
  - Tracks with a "kink" at the decay point.

GMSB Introduction

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

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

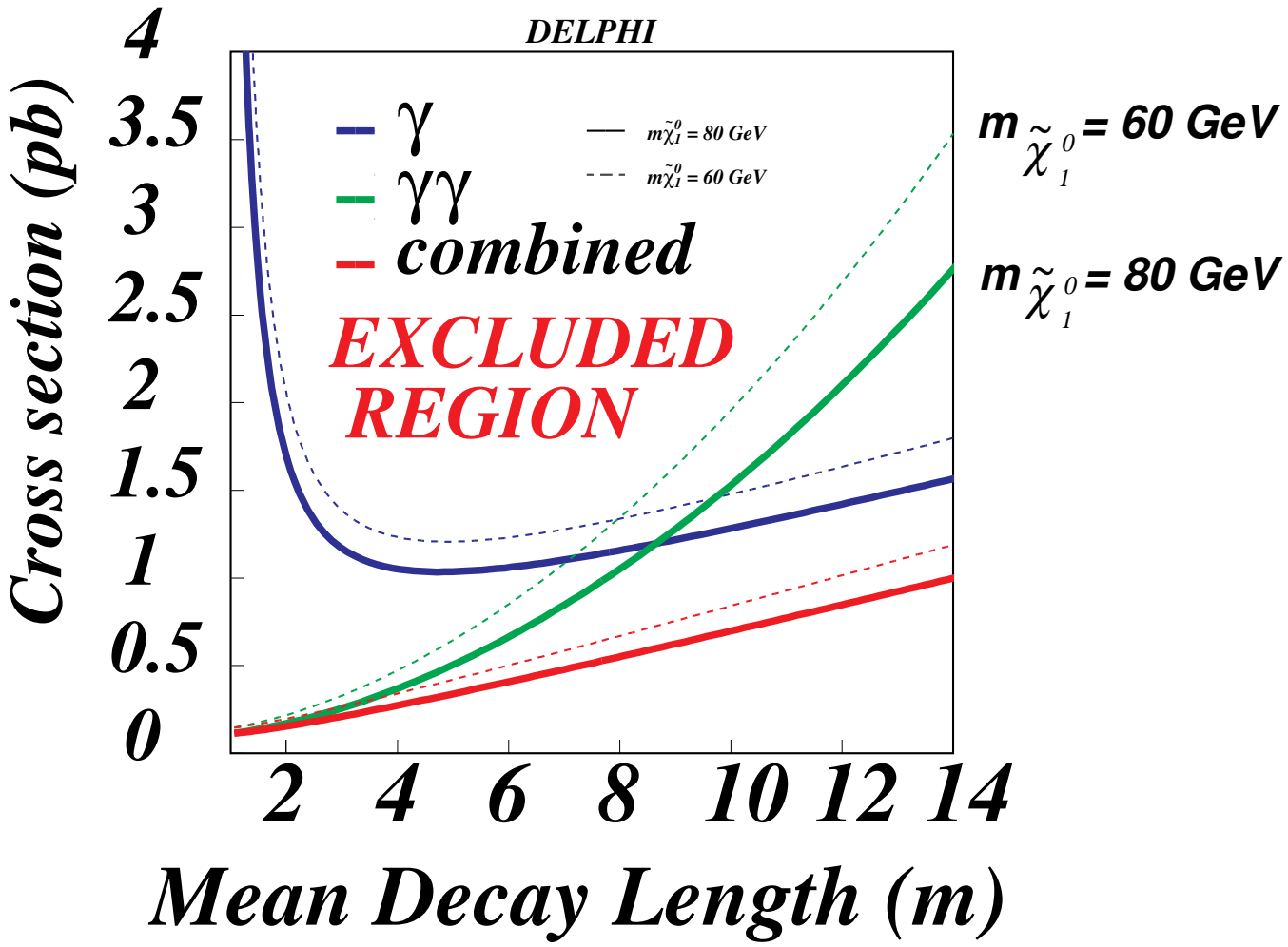
Search for Photonic Final States

Upper limits at the 95 % C.L. for the process:

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

as a function of the neutralino decay length

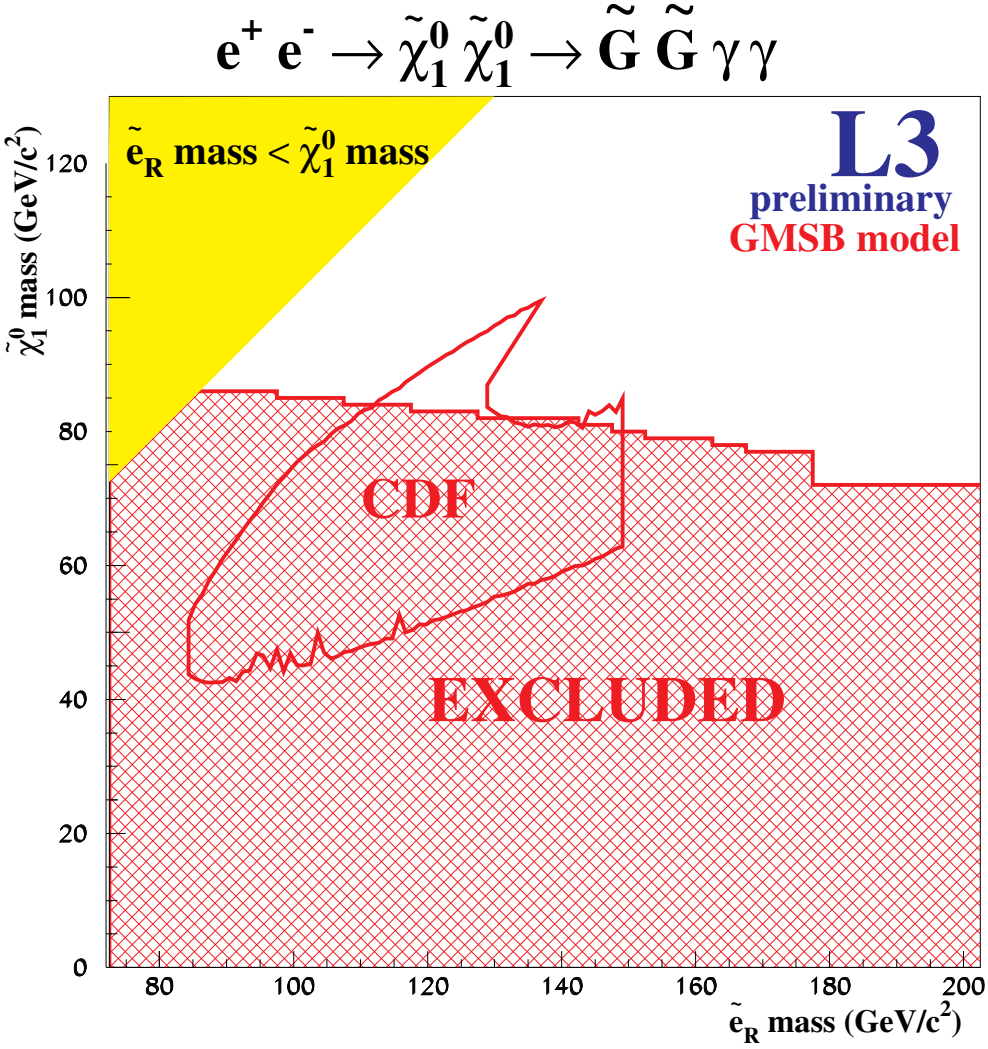
$\sqrt{s} \approx 183$ GeV



Search for Photonic Final States

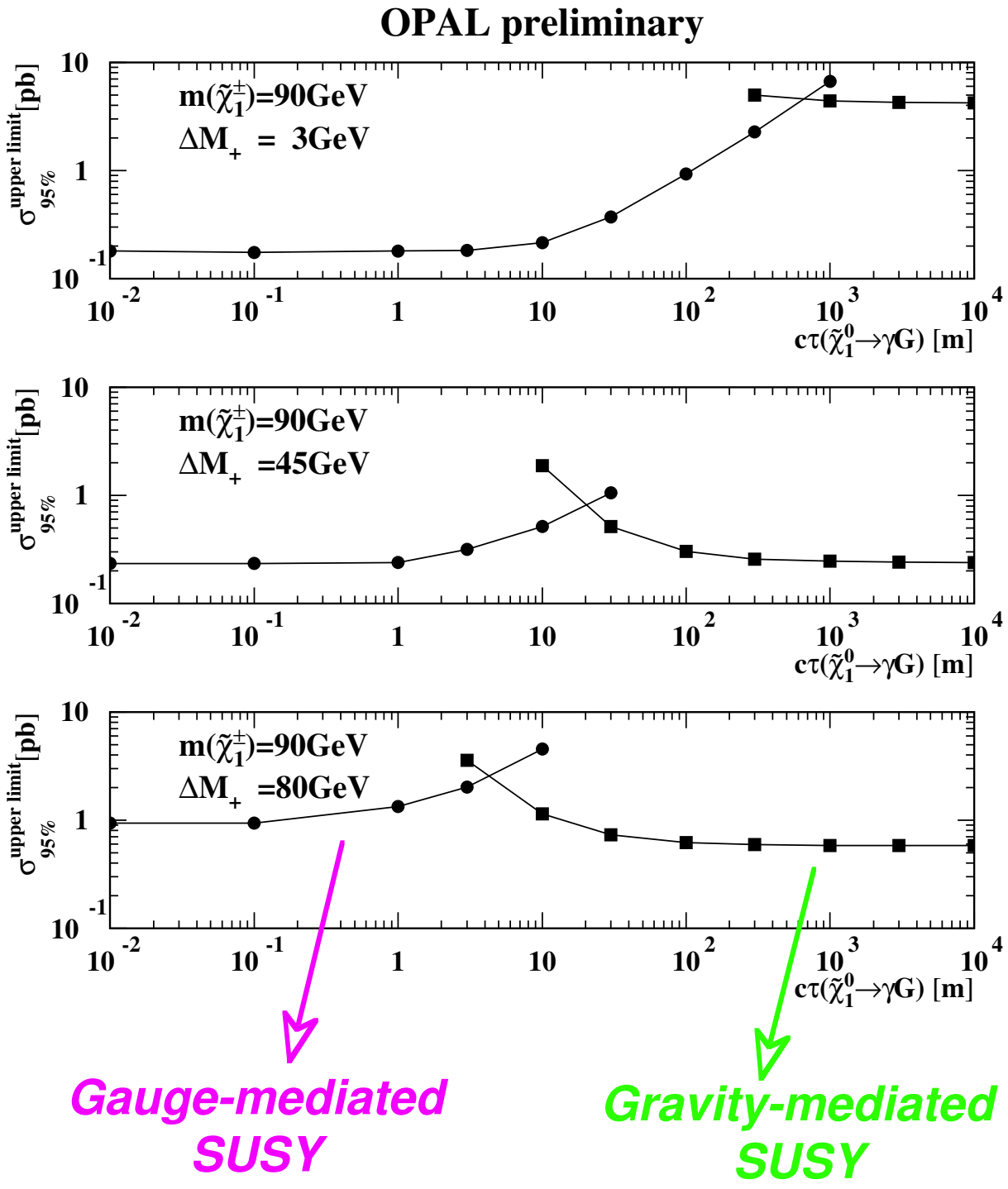
Topology: events with 2 photons and missing energy

$\sqrt{s} \approx 183$ GeV



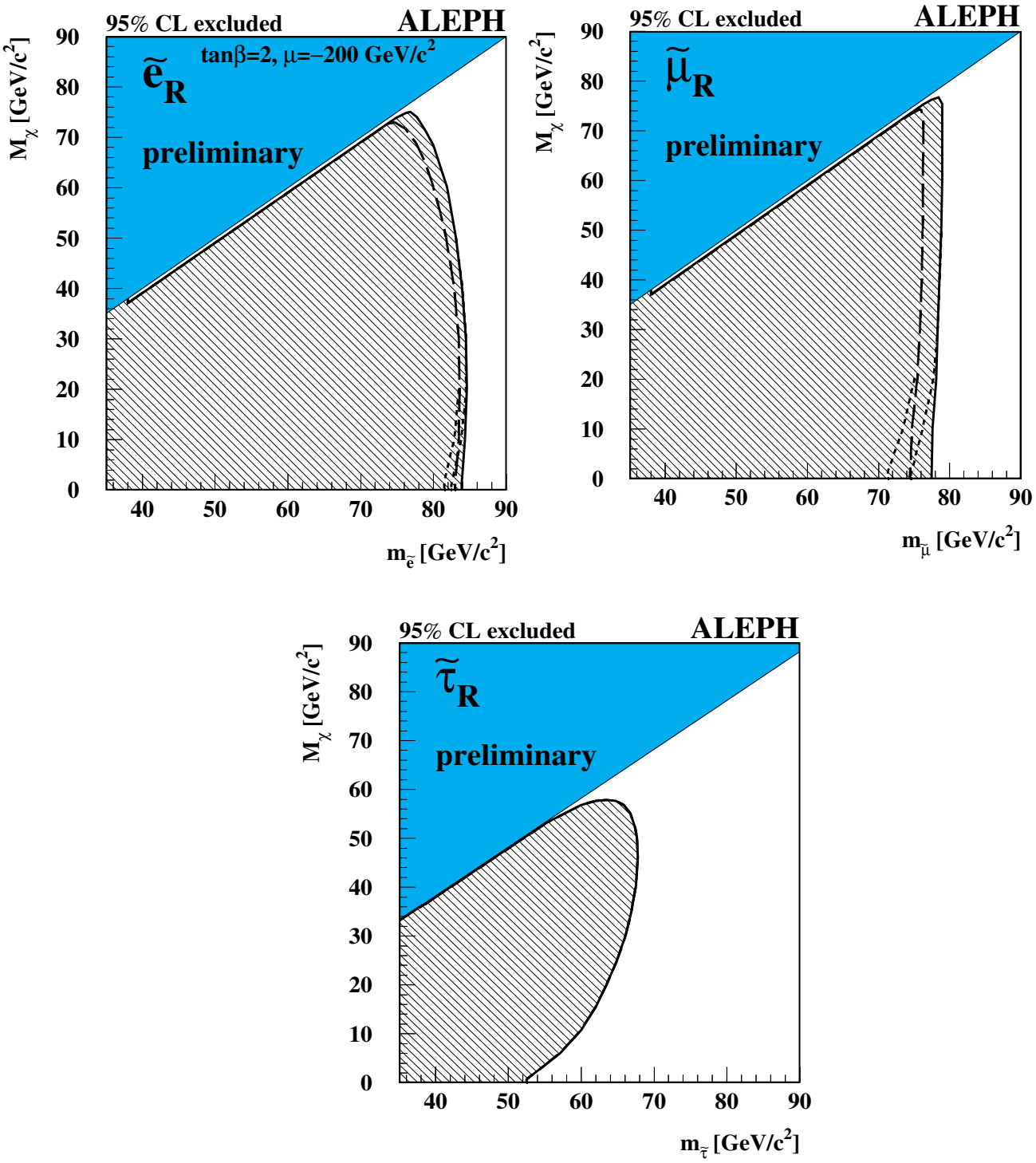
GMSB Chargino Searches

Upper limits on the chargino production cross-sections in GMSB models with neutralino NLSP versus the neutralino lifetime



GMSB Slepton Searches

Mass limits for right-handed sleptons in GMSB models with neutralino NLSP



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. 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. These limits greatly improve the limits obtained with LEP data at the Z^0 peak.*
- *With more LEP data let's hope to finally discover something!*

Symbols Library

$\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$

$\tilde{\nu}_L$ $\tilde{\nu}_L$ $\tilde{\nu}_L$ $\tilde{\nu}_L$

$\tilde{l}_L$ $\tilde{l}_L$ $\tilde{l}_L$ $\tilde{l}_L$

$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$

$\tilde{t}_1$ $\tilde{t}_1$ $\tilde{t}_1$ $\tilde{t}_1$

$\cos\theta_{mix}$ → → →

l^+ l^+ l^+ l^+

$\tilde{\nu}$ $\tilde{\nu}$ $\tilde{\nu}$ $\tilde{\nu}$

$\tilde{u}_L$ $\tilde{u}_L$ $\tilde{u}_L$ $\tilde{u}_L$

$\tilde{u}_R$ $\tilde{d}_R$ $\tilde{d}_L$

$\sigma(e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-)$