*Beyond the Standard Model V*
*Balholm-Norway*
*April 29 - May 4*

# Sfermion searches at LEP 2

*Sylvie Braibant*
*Indiana University*

- *Introduction*
- *Stop and sbottom*
- *Selectron, smuon and stau*
- *R-Parity Violating (RPV) decays*
- *Long-lived heavy charged particles*
- *Conclusions*

*Chargino/Neutralino searches at LEP2:*
*see B. Orejudos's talk on Thursday.*

# Introduction: LEP 2 Data

## Data Sets Above the $Z^0$ - per expt.

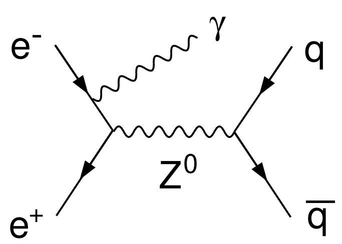
| Year | CM Energy (GeV) | Luminosity ($pb^{-1}$) | # of $Z/\gamma \to q\bar{q}$ | # of $Z/\gamma \to W^+W^-$ |
|---|---|---|---|---|
| Autumn 1995 | 130-136 | 5 | 350 | - |
| Summer 1996 | 161 | 10 | 300 | 30 |
| Autumn 1996 | 172 | 10 | 250 | 100 |

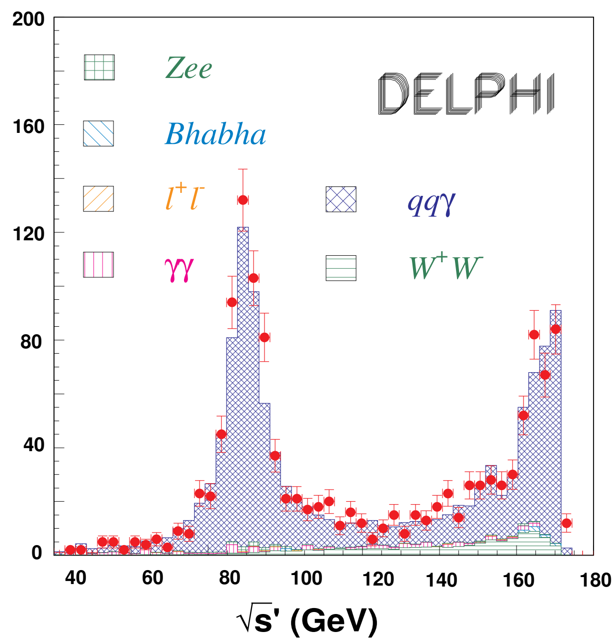
- *Highest energy available at an $e^+e^-$ collider*
- *Good opportunity to extend to a new frontier a lot of Searches*
- *Aim for 1997: $\sqrt{s}$ = 184 GeV- Factor ~5-10 in integrated luminosity*
- *1998 and beyond: 300-400 $pb^{-1}$ at $\sqrt{s}$ = 192 GeV*

# Introduction: Hermetic Detectors

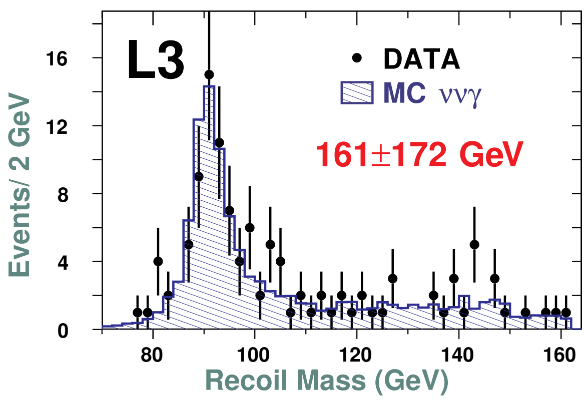
- Event topologies that could originate from SUSY signals:
  - Isolated Leptons (particle identification)
  - Acoplanar Jets (tracking, calorimetry)
  - Missing Energy (hermeticity)

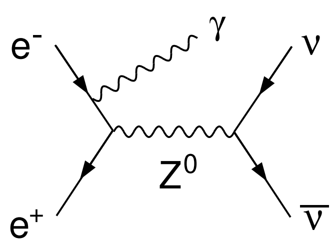
Good efficiency and resolution for the hadronic system



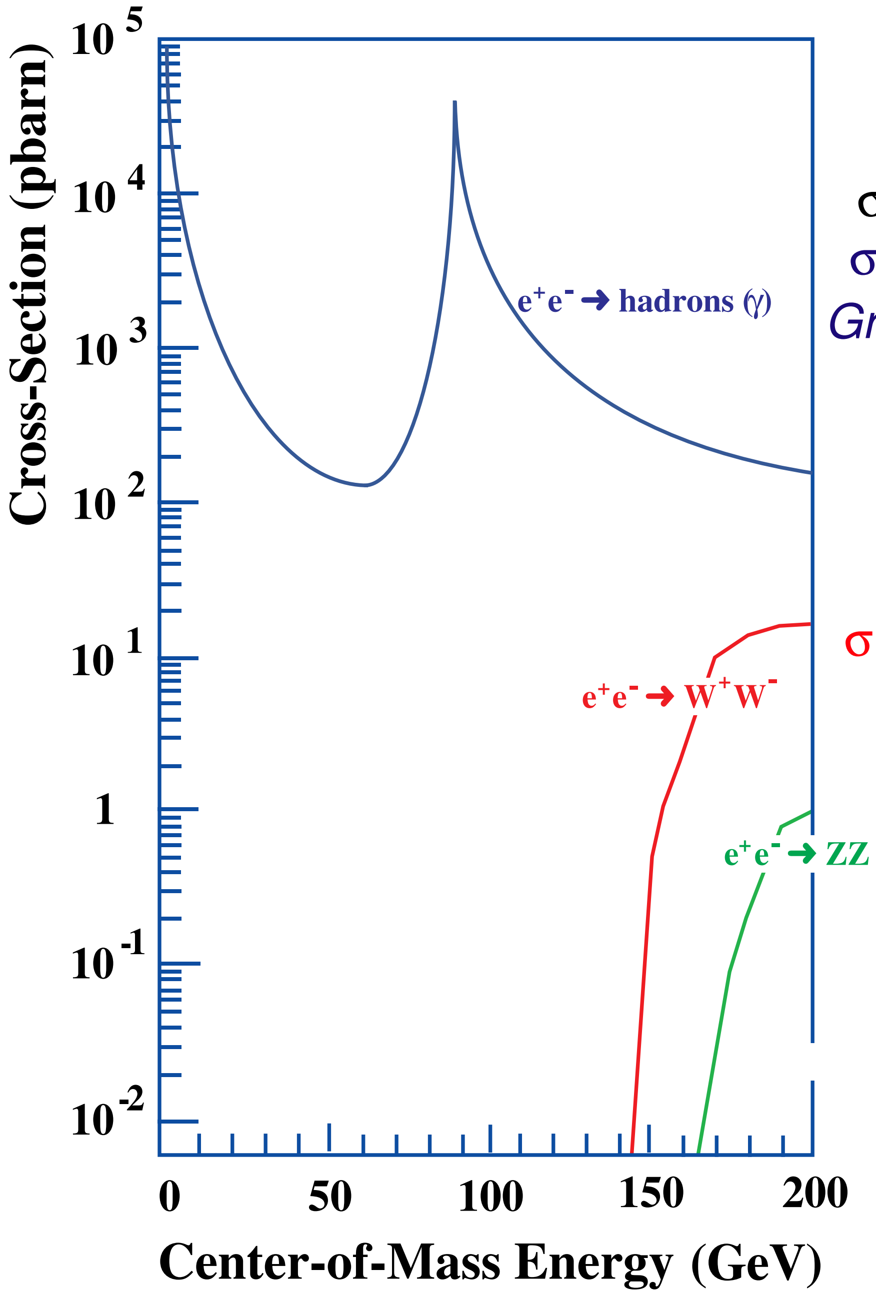




... and for γ 's and leptons: hermeticity for missing energy



# Introduction: Background for Searches




$\sigma\ (e^+e^- \rightarrow l\bar{l}\gamma) \sim 90$ pb

$\sigma\ (e+e- \rightarrow q\bar{q}\gamma) \sim 300$ pb

*Great reduction compared to LEP 1*

*Now Sizeable*

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

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

- *Four fermion processes, small cross section but difficult to eliminate*
- *Two photon processes $\gamma\gamma \rightarrow q\bar{q}$, $l\bar{l}$ large cross-section ($\sigma \sim 40$ nb) but can be greatly reduced*

# Introduction: SUSY

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

| 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 | |
| $\mu$ | 1/2 | - 1 | $\tilde{\mu}_L, \tilde{\mu}_R$ | 0 | smu | |
| $\tau$ | 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 | |
| $\gamma$ | 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 | $\pm 1$ | $\tilde{H}^\pm$ | 1/2 | charged Higgsino | charginos |
| $W^\pm$ | 1 | $\pm 1$ | $\tilde{W}^\pm$ | 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 | $\tilde{l}$<br>$\tilde{q}$<br>$H_1^0,H_2^0$<br>$H^\pm$ | $l$<br>q<br>$\tilde{\chi}_1^0 - \tilde{\chi}_4^0$<br>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ | $\gamma, Z^0$<br>$W^\pm$ |

***Subject of this talk***

# Introduction: MSSM

- **MSSM : Minimal Supersymmetric Standard Model**

- **Masses, $\sigma$ and BR from MSSM parameters:**
  - $M_2$: SU(2) gaugino mass at electroweak scales
  - tan $\beta$: ratio of VEV of Higgs doublets <V2>/<V1>
  - $\mu$: superpotential Higgsino mass
  - $m_0$: common mass of squarks and sleptons at the GUT scale (universal scalar mass)
  - $A_0$: trilinear scalar Yukawa-like coupling

- **R-Parity Conservation:**
  - A new multiplicative quantum number, $R_p$, is generally assumed to be conserved:

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

  - $\rightarrow$ SUSY particles must be produced in pairs
  - $\rightarrow$ a sparticle decays down to the LSP
  - $\rightarrow$ the LSP is stable $\rightarrow$ Missing energy.
  - Usually:LSP = $\tilde{\chi}^0_1$

# Introduction: MSSM

- **R-Parity Violation:**
  - $\rightarrow$ *Single sparticles can be produced*
  - $\rightarrow$ *LSP can decay*
  - $\rightarrow$ *Lightest sfermion can be the LSP*
  - *45 extra $\lambda$ couplings from explicit breaking of $R_p$ interactions parametrized in superpotential as:*

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

*$L^i_L$ and $Q^i_L$ are the SU(2)-doublet lepton and quark superfields and $E^i_R$, $U^i_R$ and $D^i_R$ are the singlet superfields*

# Introduction: MSSM Sfermion Sector

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

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

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

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

*Soft Susy-breaking masses*

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

$$a_f = \begin{cases} A_f - \mu \tan\beta \;\ldots\; f = e, d \\ A_f - \mu \cot\beta \;\ldots\; f = u \end{cases}$$

*Weak eigenstates $\rightarrow$ Mass eigenstates*

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

# Introduction: 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 quark and $\tau$ 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*

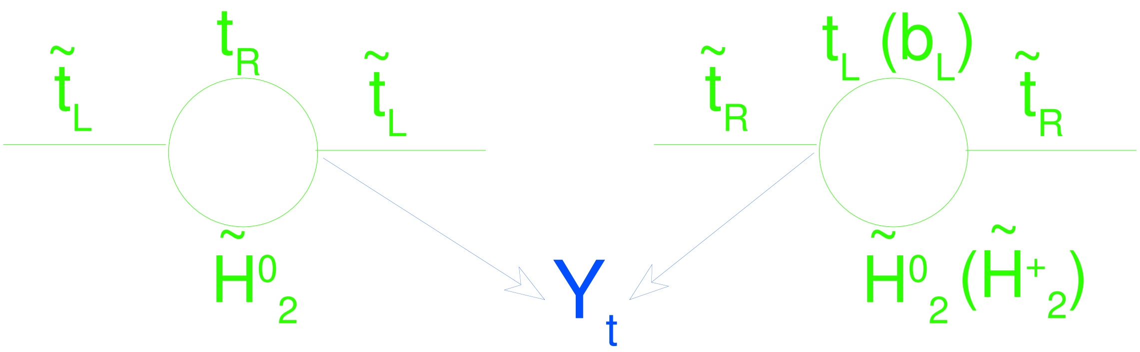
*$\tilde{t}_1$ can be the lightest charged SUSY particle*

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

*Correction are always <0 and proportional to $Y_t^2$*

*Because $m_t$ ~ 180 GeV → Large $Y_t$ is expected*

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



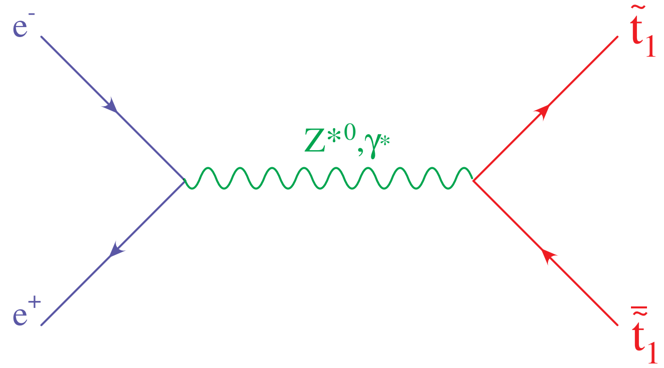

*2) L ↔ R mixing term contributes to off-diagonal components of the mass matrix:*

*large mass split (proportional to $m_t$)*

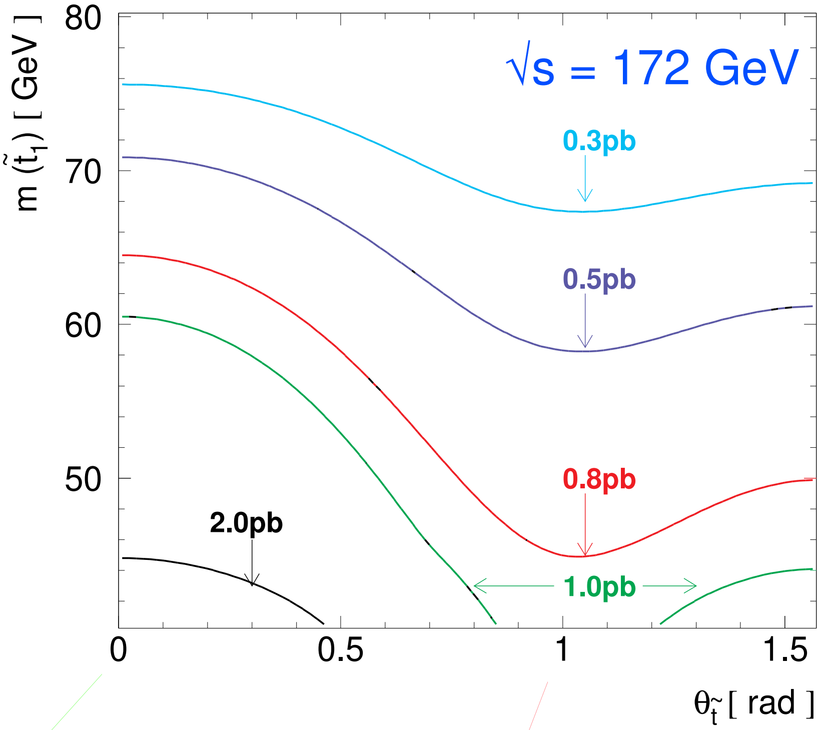
$$m^2_{\tilde{t}_{1,2}} = 1/2\,(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R}) \mp 1/2\sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4\,a_f^2\, m_f^2}$$

# 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 $\theta_{mix}$*




Incl. 1st order QCD correction

*1.57 rad = 90 °*

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

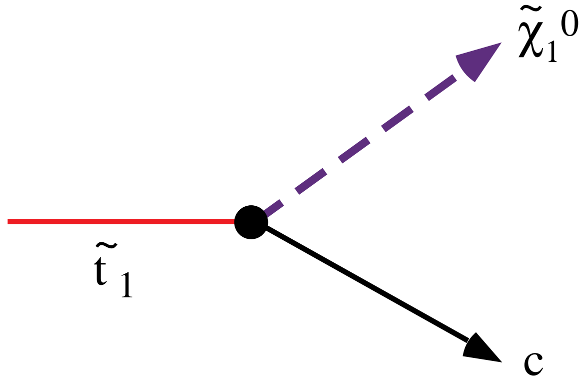
*If $\theta_{mix}$ = 0.98 rad (= 56 °), $\tilde{t}_1$ decouples from $Z^0$*

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

# Stop Quark Decays

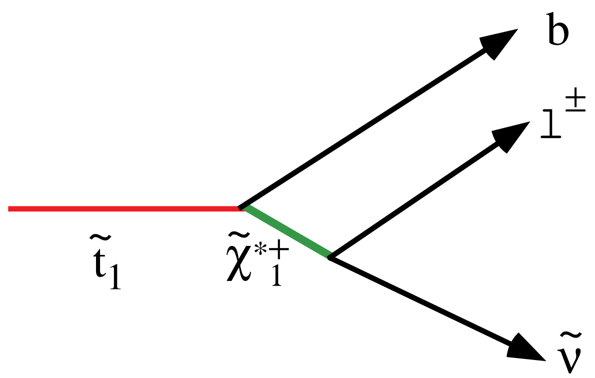
$$\tilde{t}_1 = \tilde{t}_L \cos\theta_{mix} + \tilde{t}_R \sin\theta_{mix}$$

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

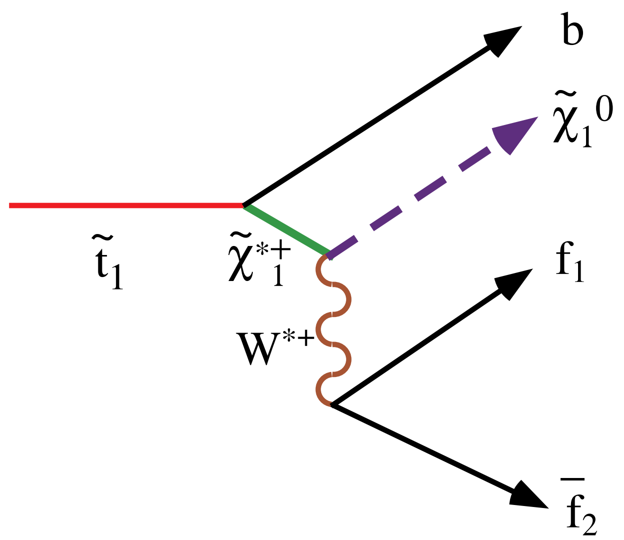



Two -body flavor changing decay:
$\Gamma = O\ (10\ eV)$

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




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




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

# Stop Quark Topology

*Because $\Gamma_{\tilde{t}_1} << \Lambda_{QCD}$: $\tilde{t}_1$-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.*

***<u>Topology for 2-body decay</u>***

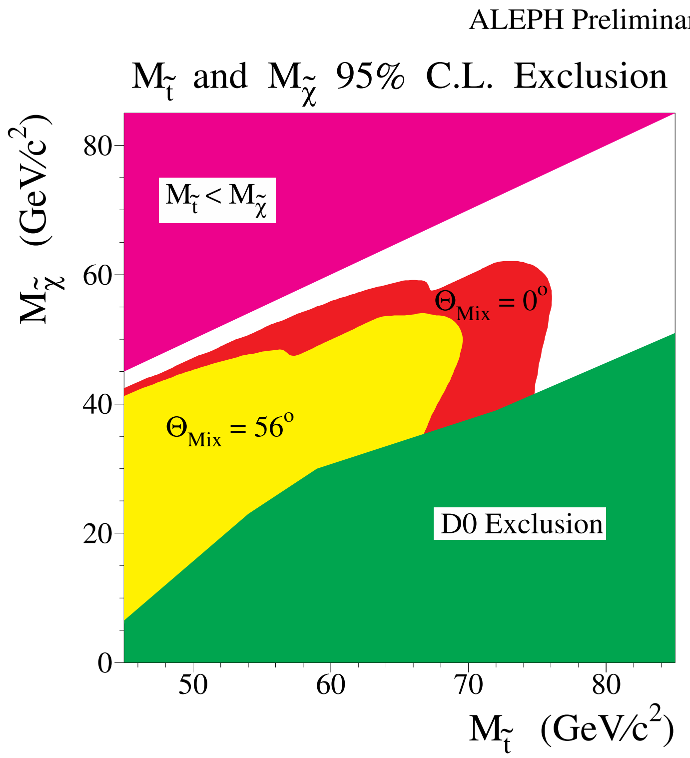
*Two acoplanar sharp jets and missing energy*

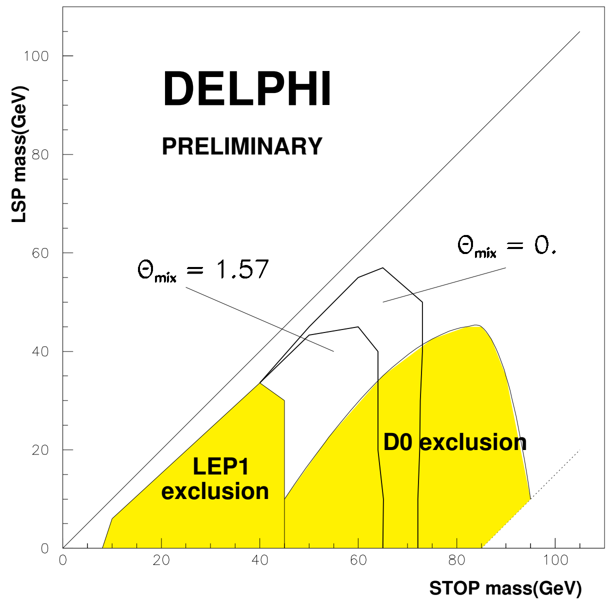
***<u>Topology for 3-body decay</u>***

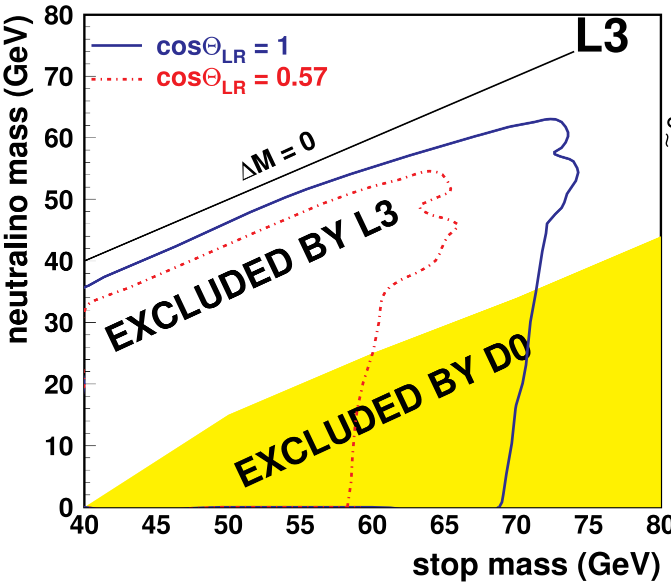
*Two acoplanar sharp jets, acoplanar lepton pair and missing energy*

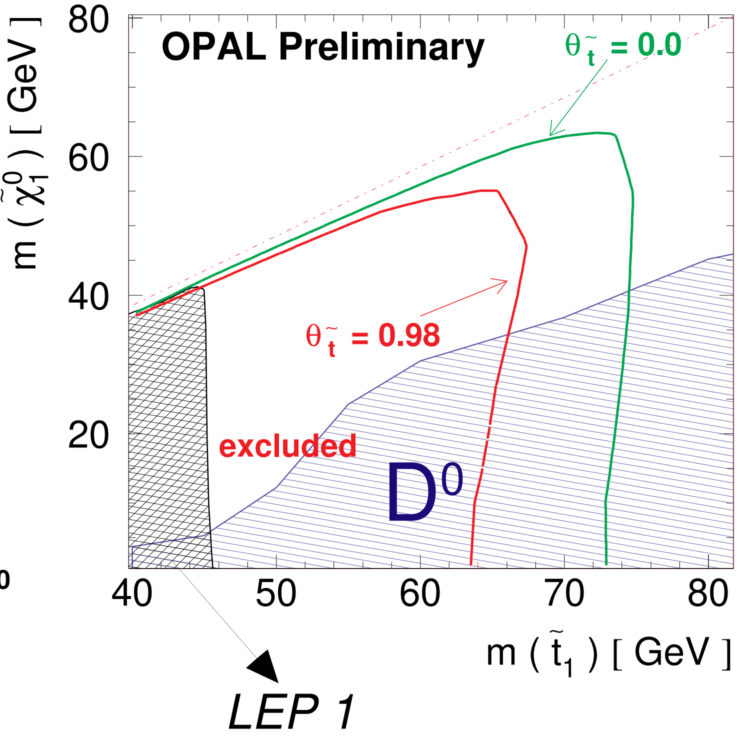
# Stop Quark Results

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



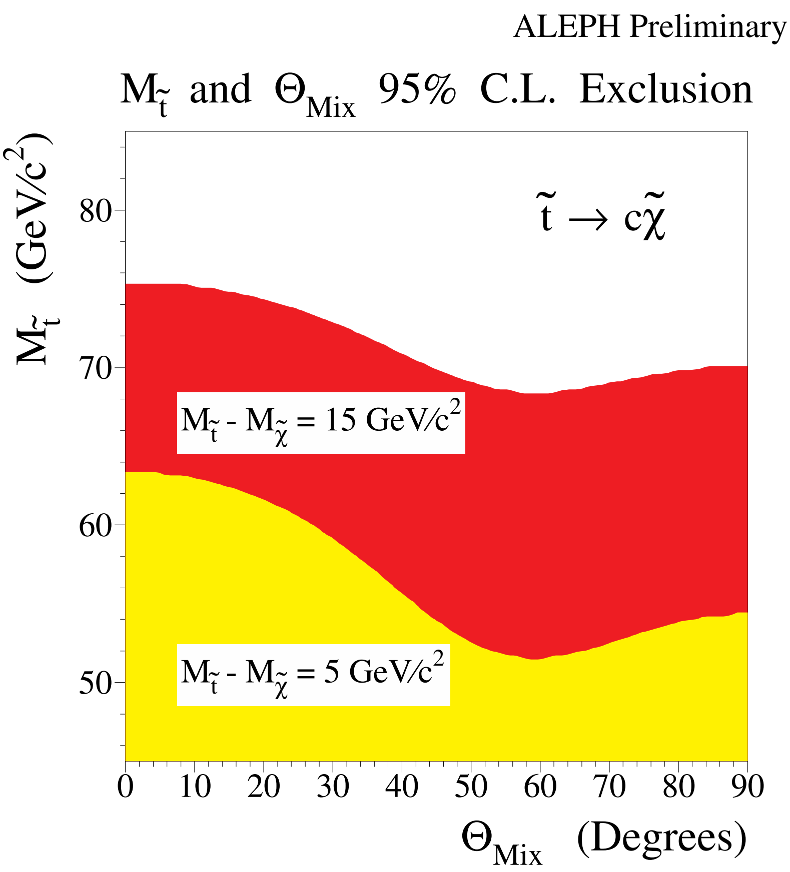



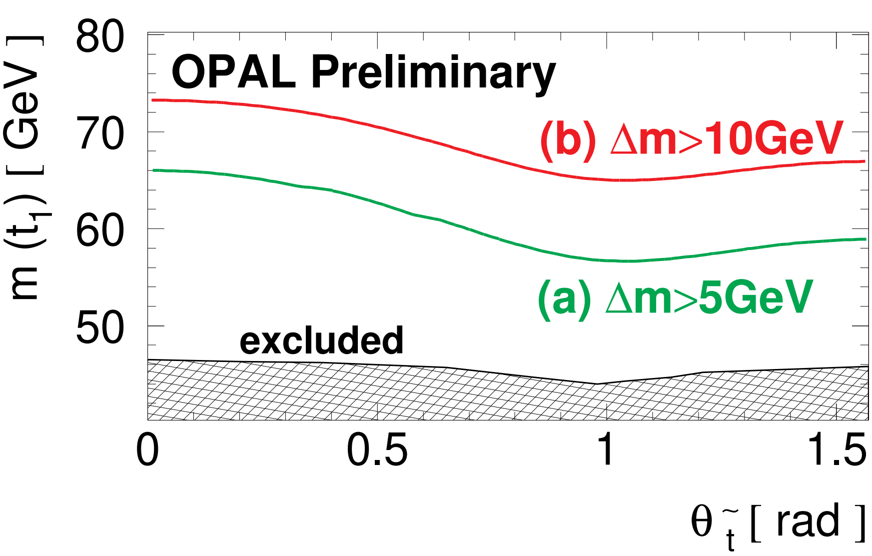
# Stop Quark Results

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




*For $\theta_{mix} = 56^o$ and $\Delta m = 5$ GeV:*

***$m_{\tilde{t}_1} > 52$ GeV***



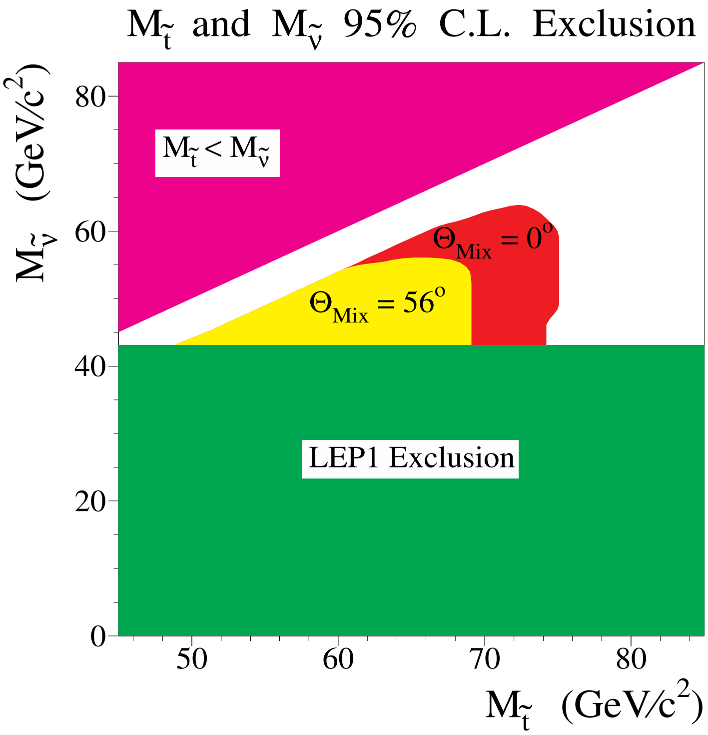

*For $\theta_{mix} = 56^o$ and $\Delta m > 5$ GeV:*

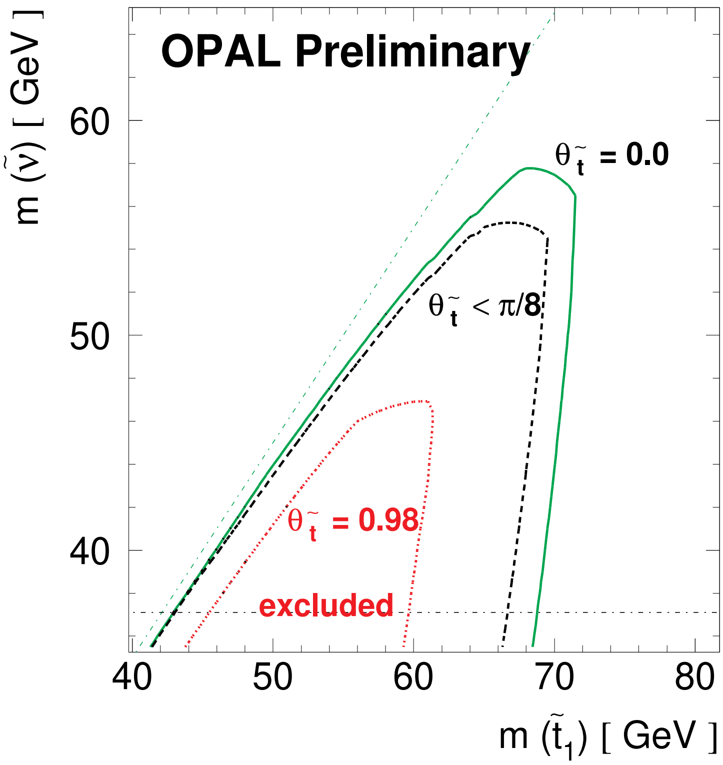
***$m_{\tilde{t}_1} > 56.7$ GeV***

# *Stop Quark Results*

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

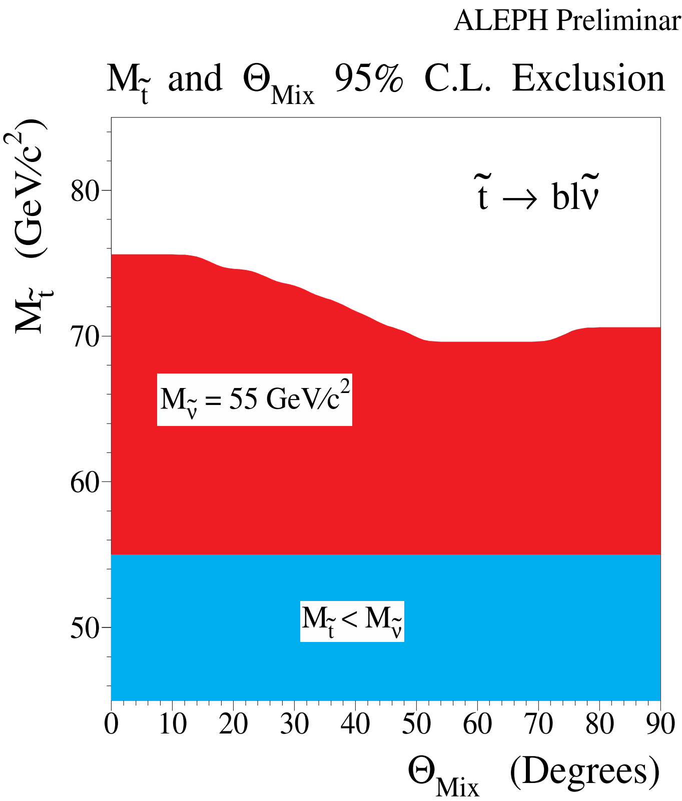
ALEPH Preliminary



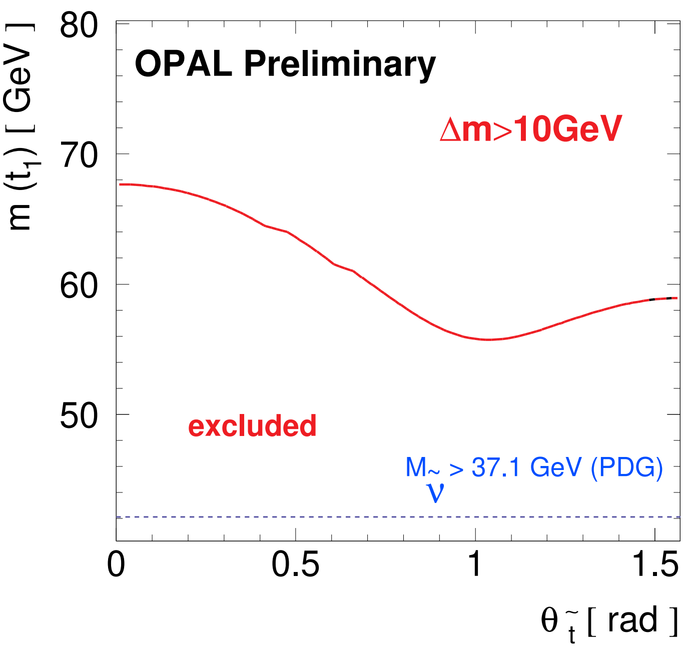
# Stop Quark Results

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




**For $\theta_{mix} = 56^o$ and $m_{\tilde{\nu}} = 55$ GeV:**

**$m_{\tilde{t}_1} > 70$ GeV**




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

**$m_{\tilde{t}_1} > 55.8$ GeV**

# Sbottom Quark

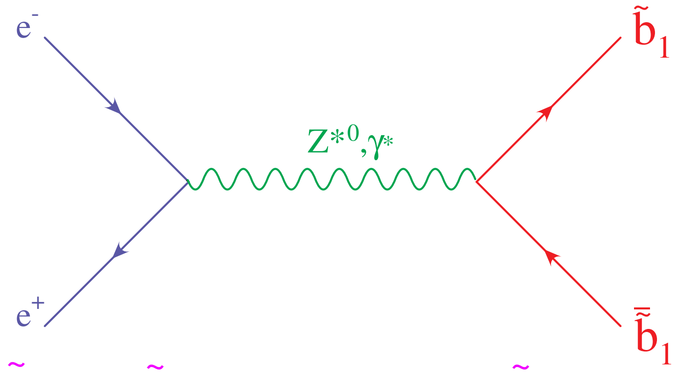
*1) $Y_b = m_b / (\sqrt{2}\, m_W \sin\beta)$ is also sizeable $\rightarrow$ Sizable Radiative correction to $m_{\tilde{b}}$*

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

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

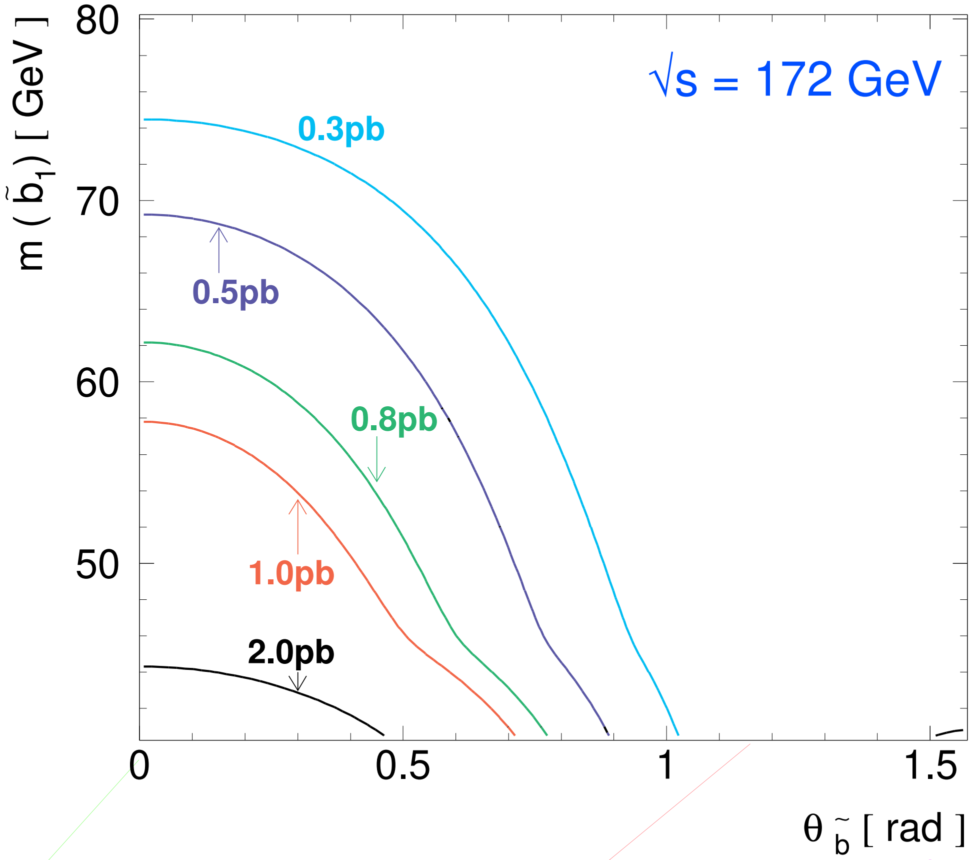
*Large mass split if large a $\leftrightarrow$ large tan $\beta$*
*$\tilde{b}_1$ can be light if tan $\beta$ ~ 40*

# 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 $\theta_{mix}$



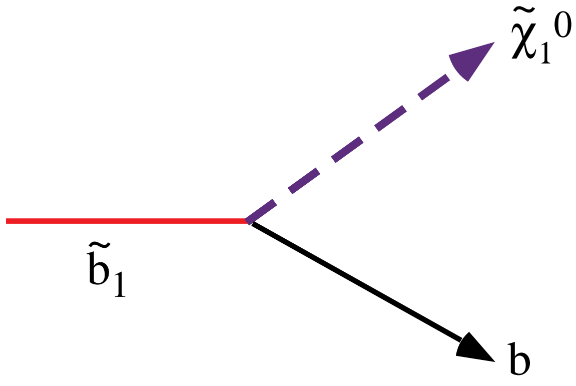

1.57 rad = 90 °

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

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

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

# Sbottom Quark Decay




Two -body decay:
$\Gamma = O\ (50\ \text{MeV})$

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

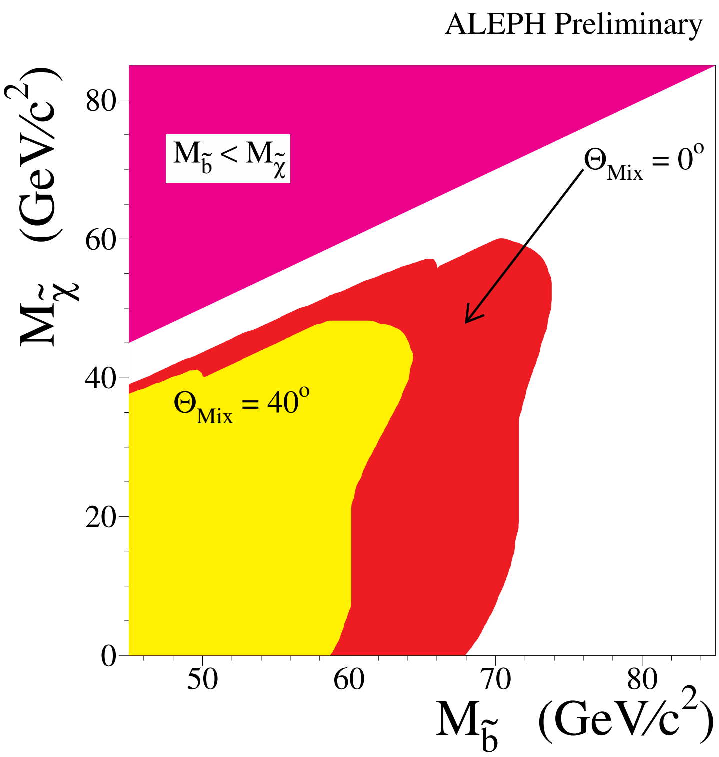
*Since fragmentation of $\tilde{b}_1$, c, b is hard and $\tilde{b}_1$-hadron is strongly boosted: the jets are expected to be sharp.*

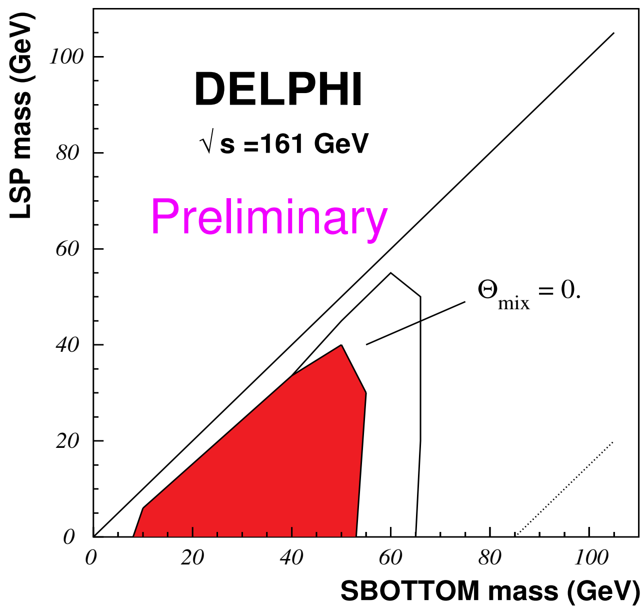
***<u>Topology</u>***

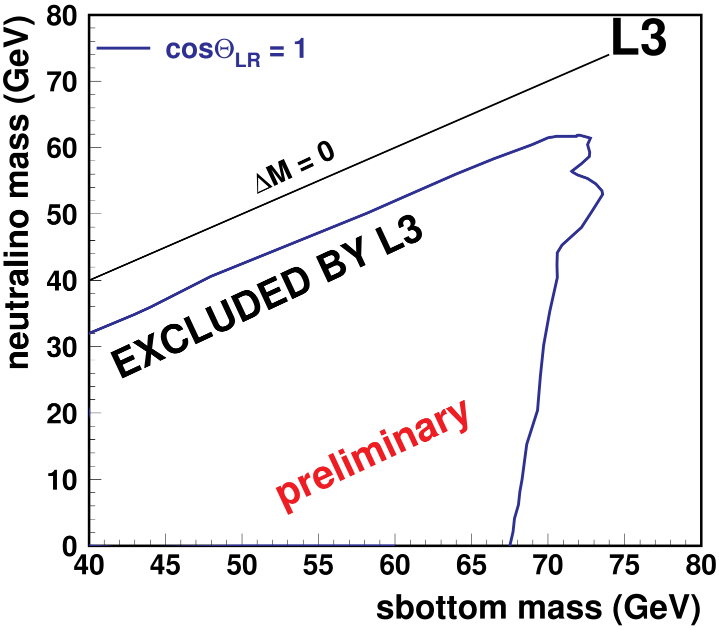
*Two acoplanar sharp jets and missing energy*

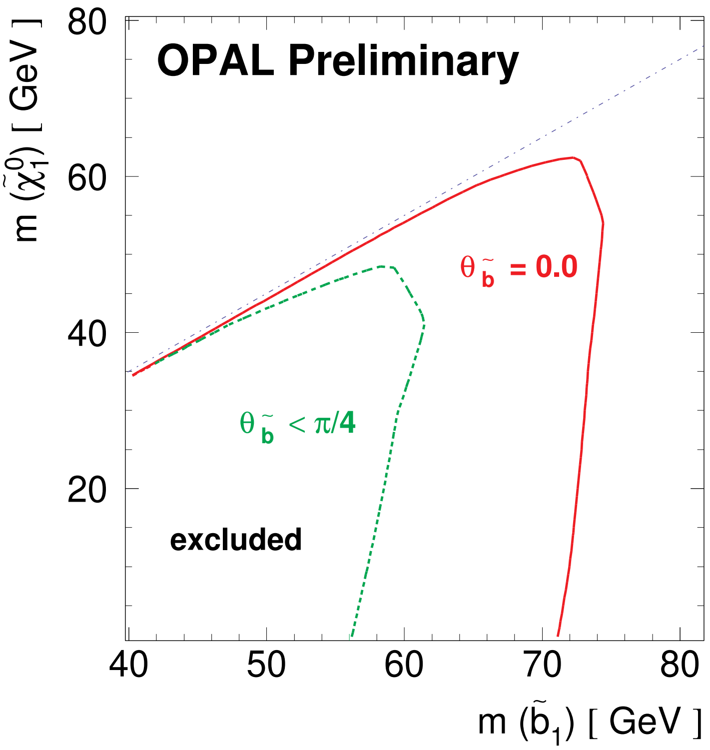
SIMILAR TO $\tilde{t}_1 \rightarrow \tilde{\chi}^0_1\, c$

# Sbottom Quark Results

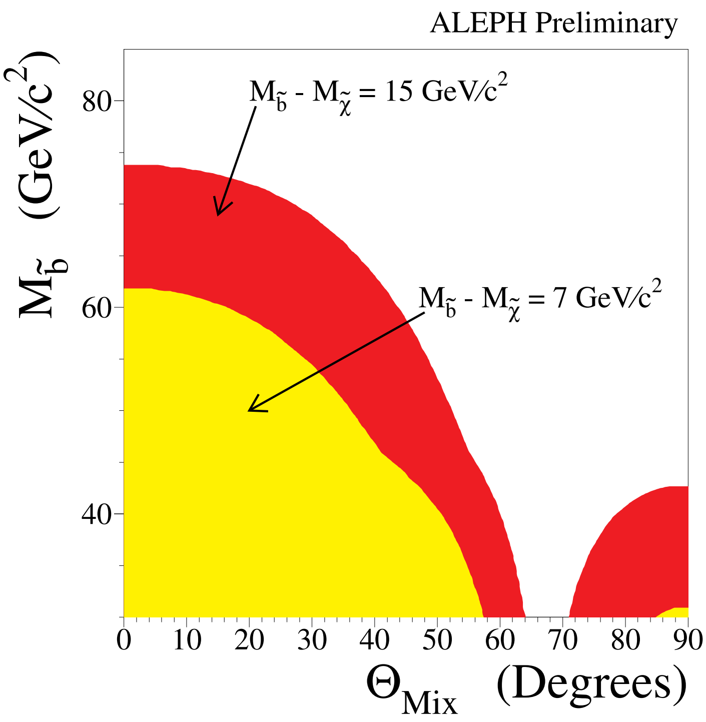


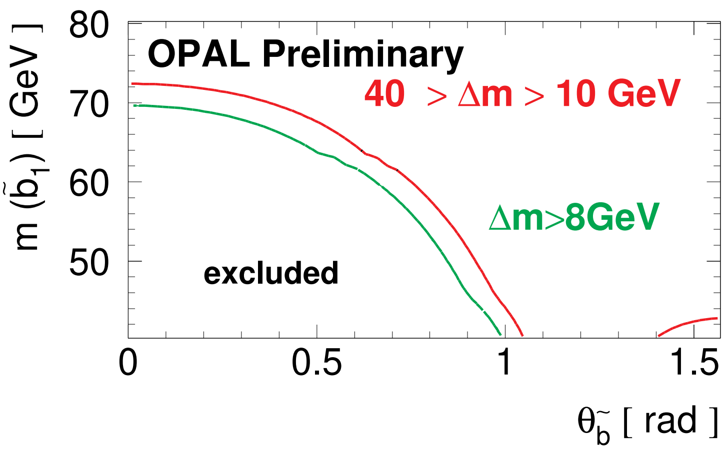



# Sbottom Quark Results

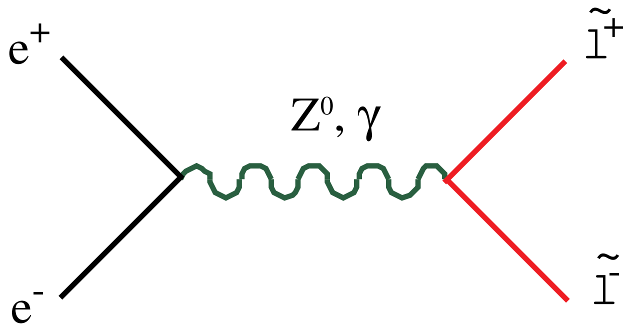


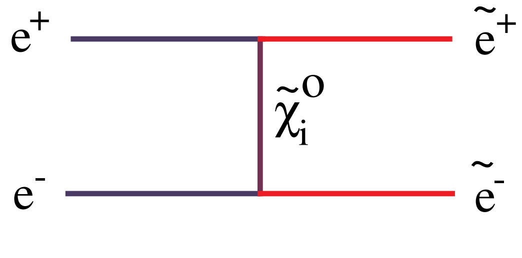



# Slepton Production and Decay

## Production

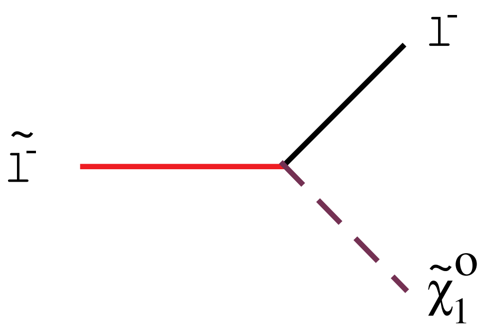
$e^+e^- \rightarrow \tilde{l}^- \tilde{l}^+$




*If R-parity is conserved : pair production*

## Decays




### Topology

*Two acoplanar leptons of the same family and missing energy*

*Assume that $\tilde{\chi}_1^o$ is the LSP.*
*If R-parity is conserved: $\tilde{\chi}_1^o$ does not decay*

*At 172 GeV, the expected the cross-section are:*

$\sigma\,(e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-) \sim 0.4 - 4\ pb$

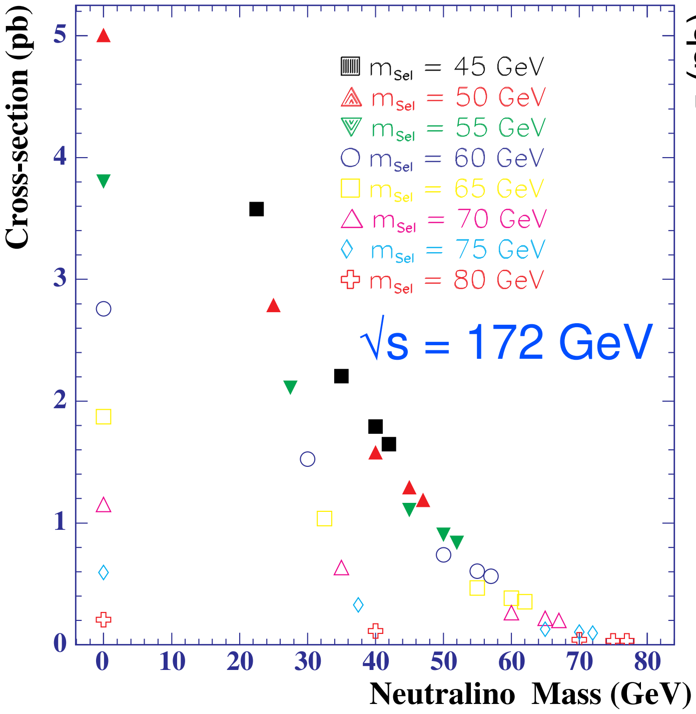
$\sigma\,(e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-) \sim 0.1 - 0.5\ pb$

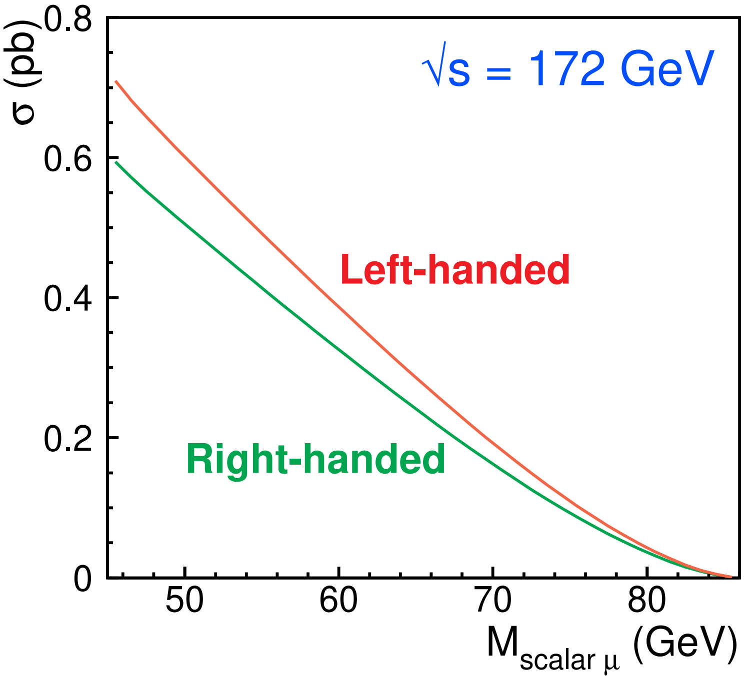
$\sigma\,(e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}) \sim 0.1 - 0.5\ pb$

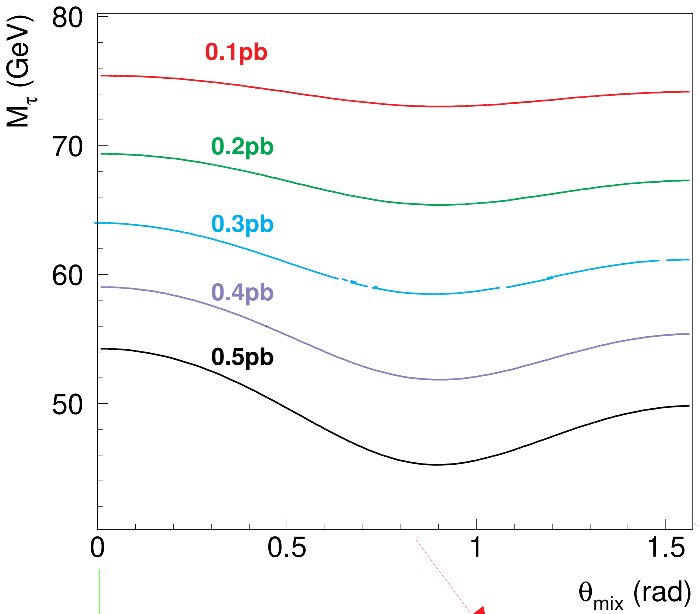
# *Slepton Pair Production Cross-Sections*

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

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.*

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

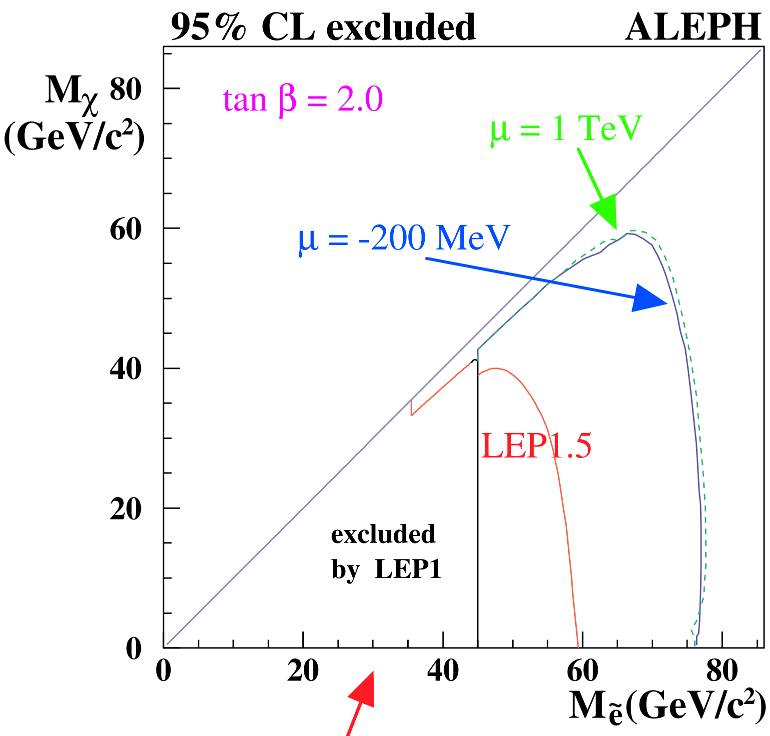
*1.57rad = 90°*

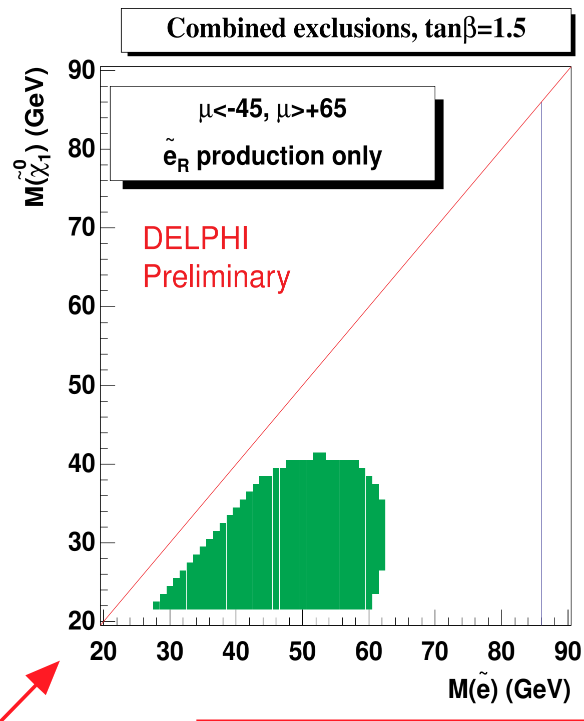
$\tilde{\tau}_1 = \tilde{\tau}_R$

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

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

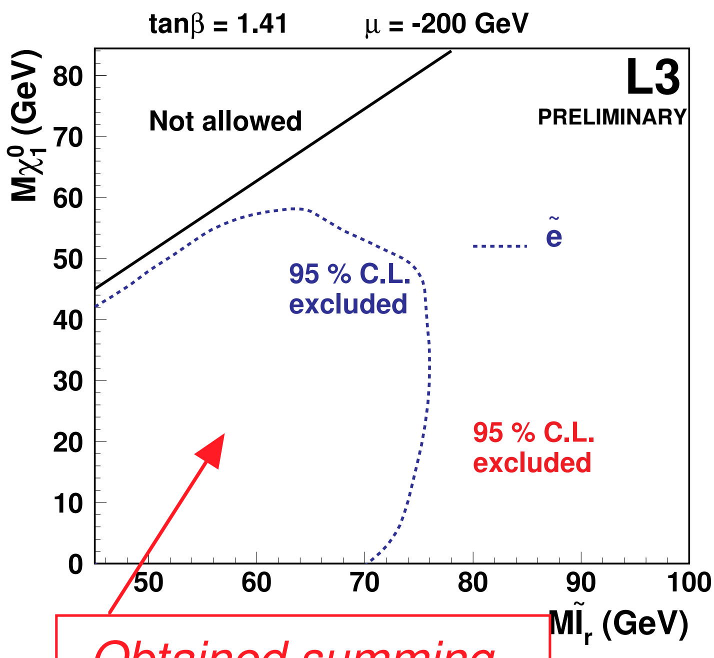
# Selectron Results

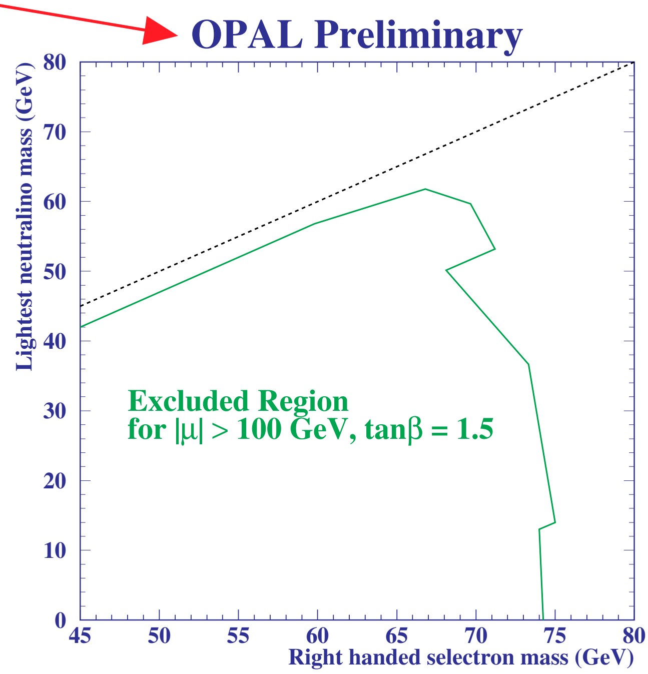



$\sigma\ (e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-)$ *only*

*Common $m_o$ at the GUT scale*

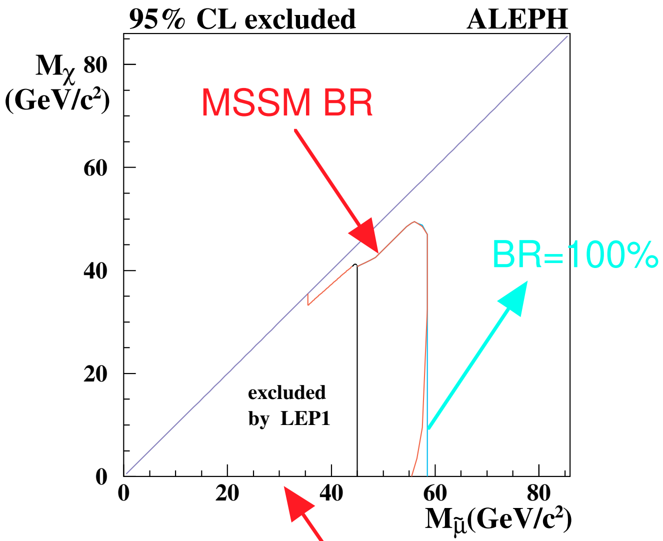


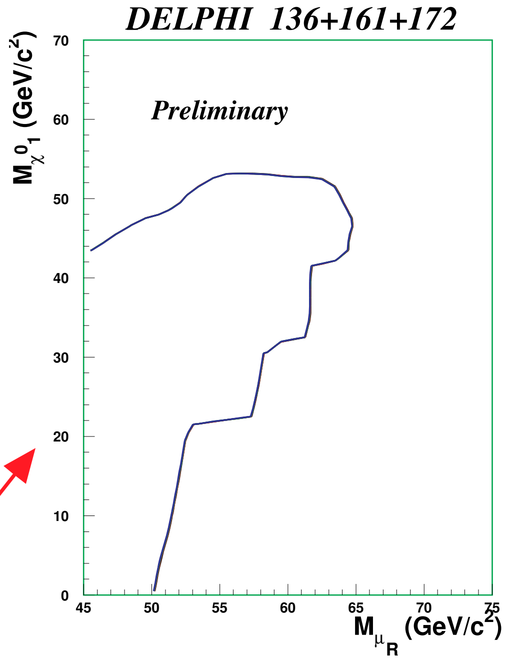




*Obtained summing $\tilde{e}_R\tilde{e}_R$, $\tilde{e}_L\tilde{e}_L$ and $\tilde{e}_L\tilde{e}_R$ cross-sections*

*NO common $m_o$ at the GUT: mass degeneracy*

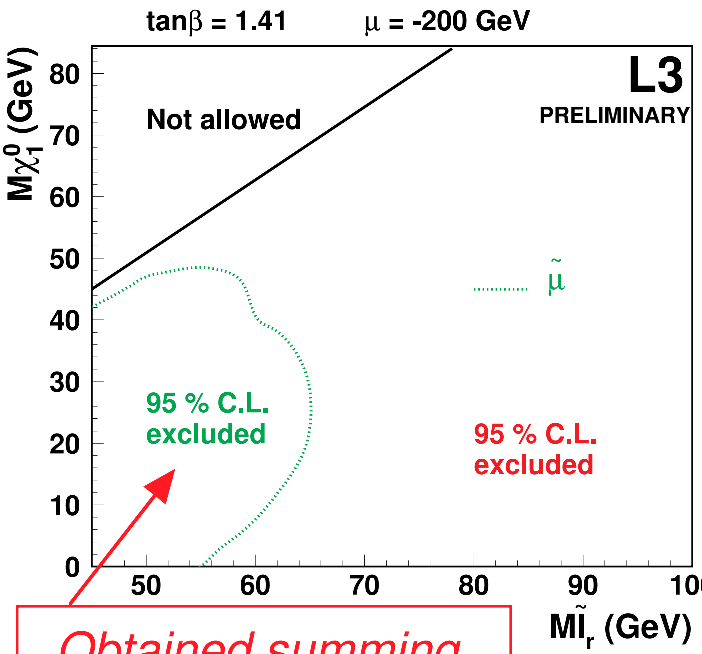
# Smuons Results

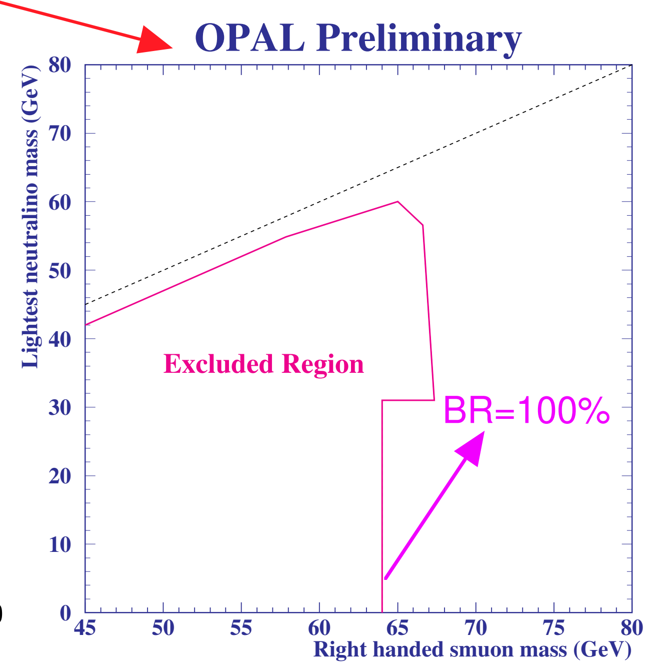



$\sigma\,(e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-)$ *only*

*Common $m_o$ at the GUT scale*

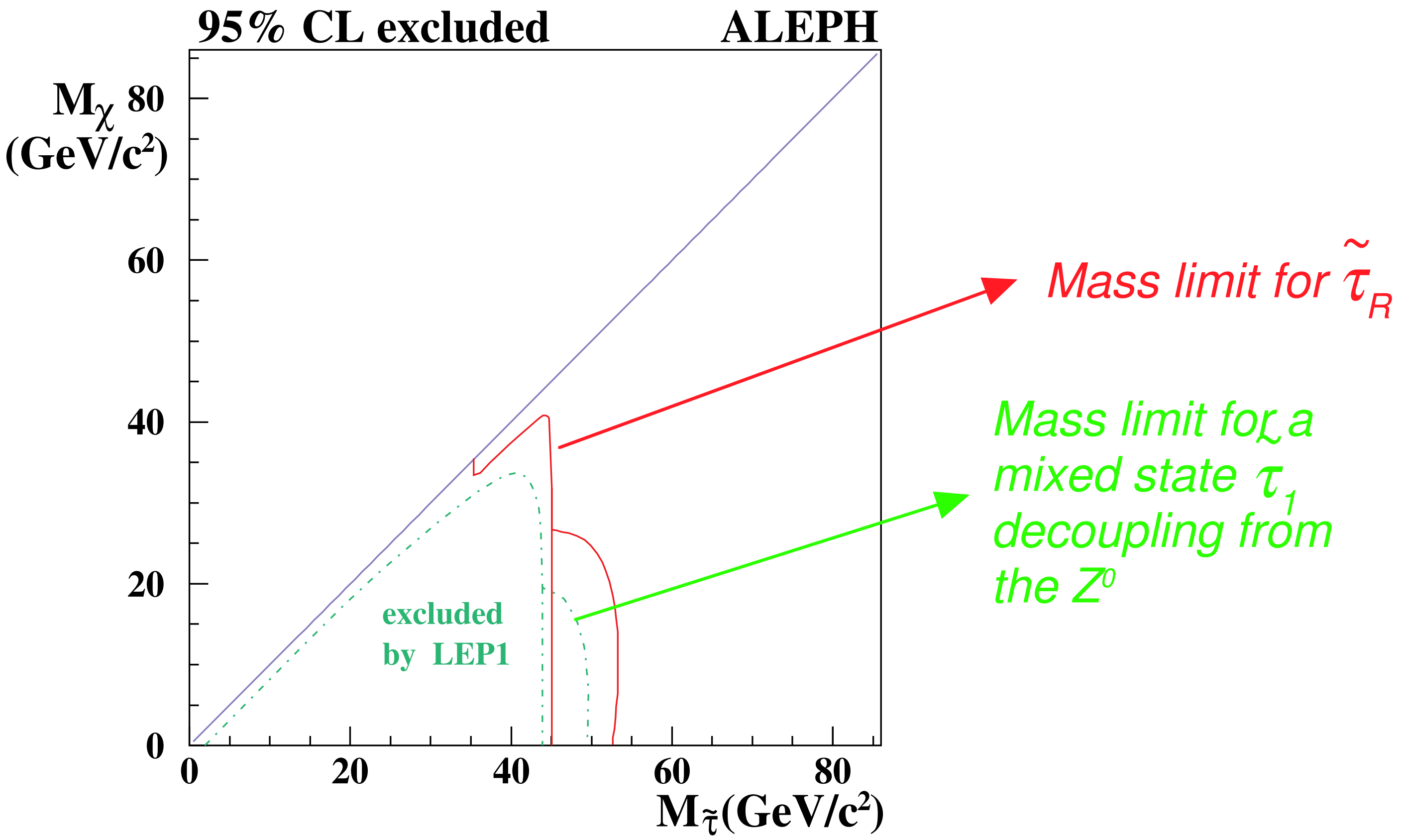


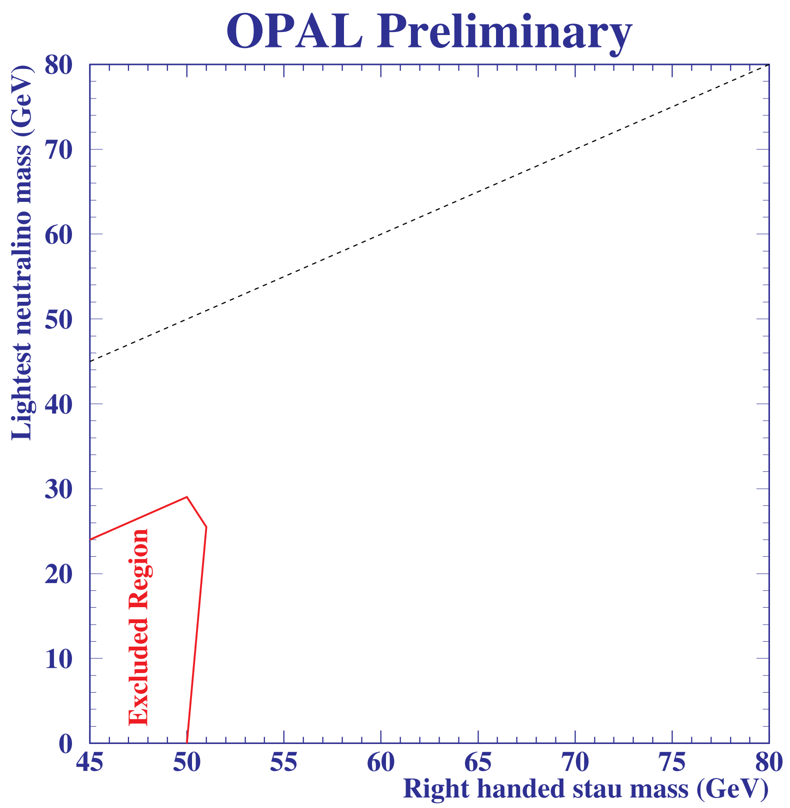




*Obtained summing $\tilde{\mu}_R\tilde{\mu}_R$ and $\tilde{\mu}_L\tilde{\mu}_L$ cross-sections*

*NO common $m_o$ at the GUT: mass Degeneracy*

# Stau Results

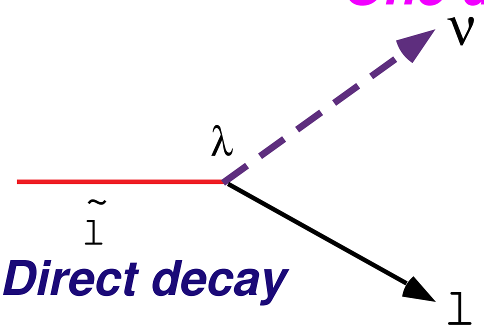


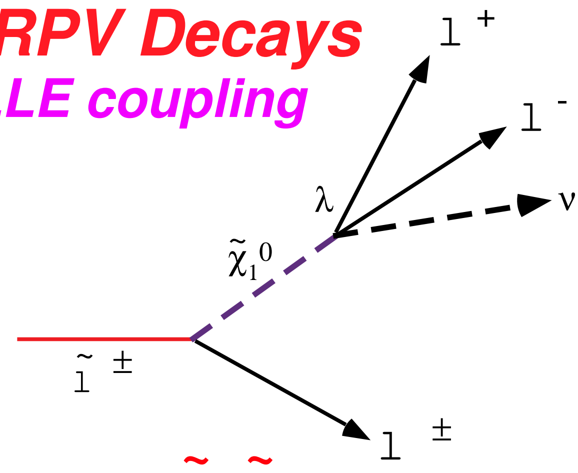



# RPV Searches

## Charged slepton RPV Decays

### One dominant LLE coupling




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

**Final states:**
**2 leptons + 2 neutrinos**
**Lower $\varepsilon$, Higher background**

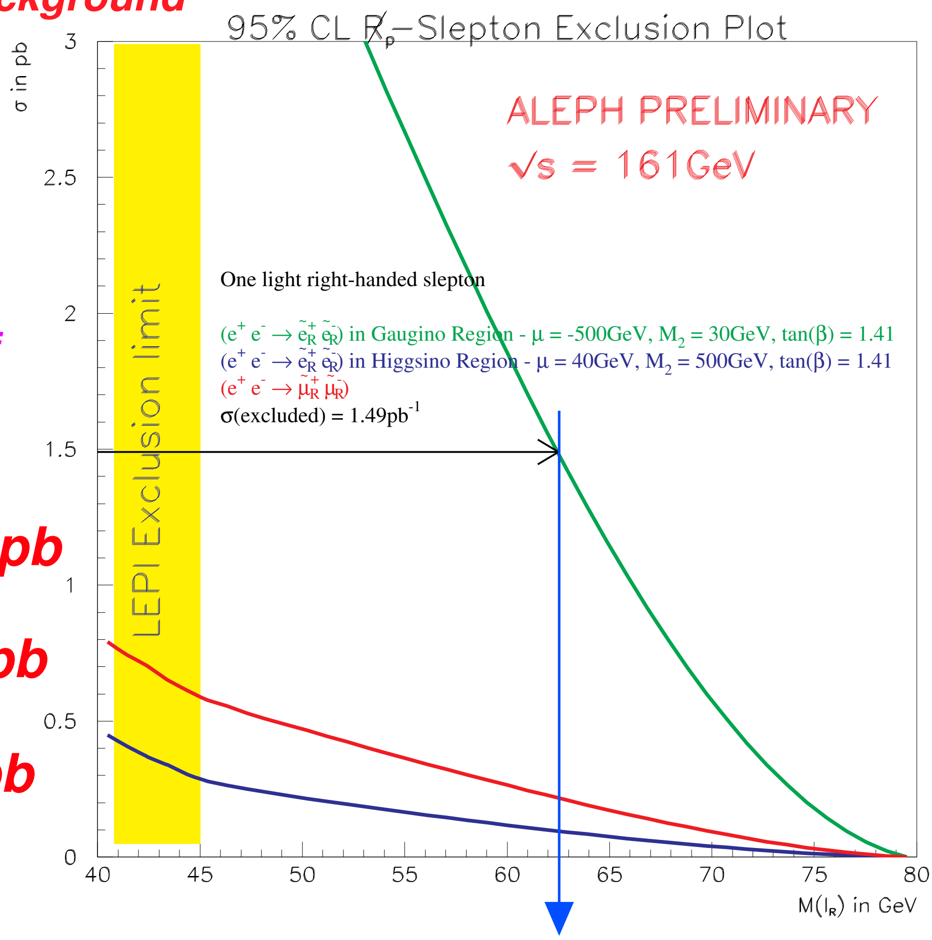
**Multi-lepton Final state:**
**Higher $\varepsilon$, Lower background**

**Conservative approach: Use Br(direct) = 100 % and most unfavourable case (to be independent of the generation indices)**

$\sigma_{excl}(\tilde{e}_R^+\tilde{e}_R^-) < 1.49$ pb

$\sigma_{excl}(\tilde{\mu}_R^+\tilde{\mu}_R^-) < 1.53$pb

$\sigma_{excl}(\tilde{\tau}_R^+\tilde{\tau}_R^-) < 1.53$pb

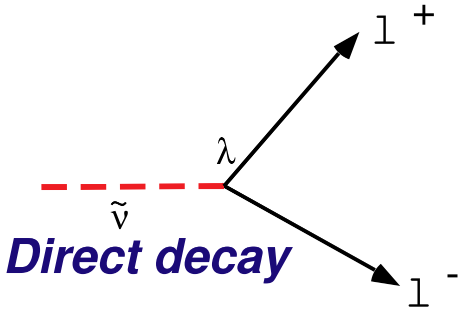


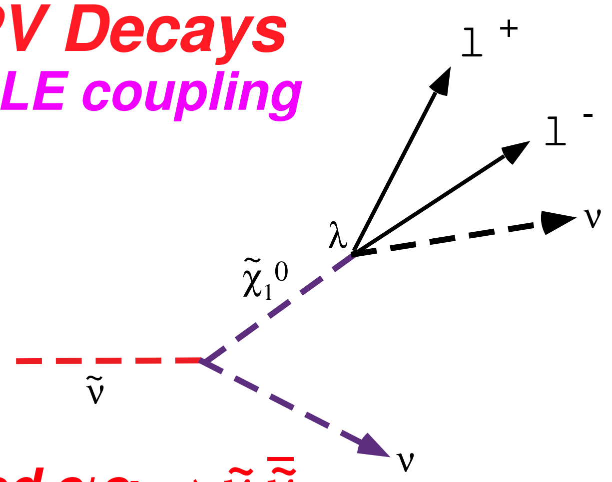

**In the gaugino region:**
**$m_{\tilde{e}_R} > 62.7$ GeV**

# RPV Searches

## Sneutrino RPV Decays

### One dominant LLE coupling

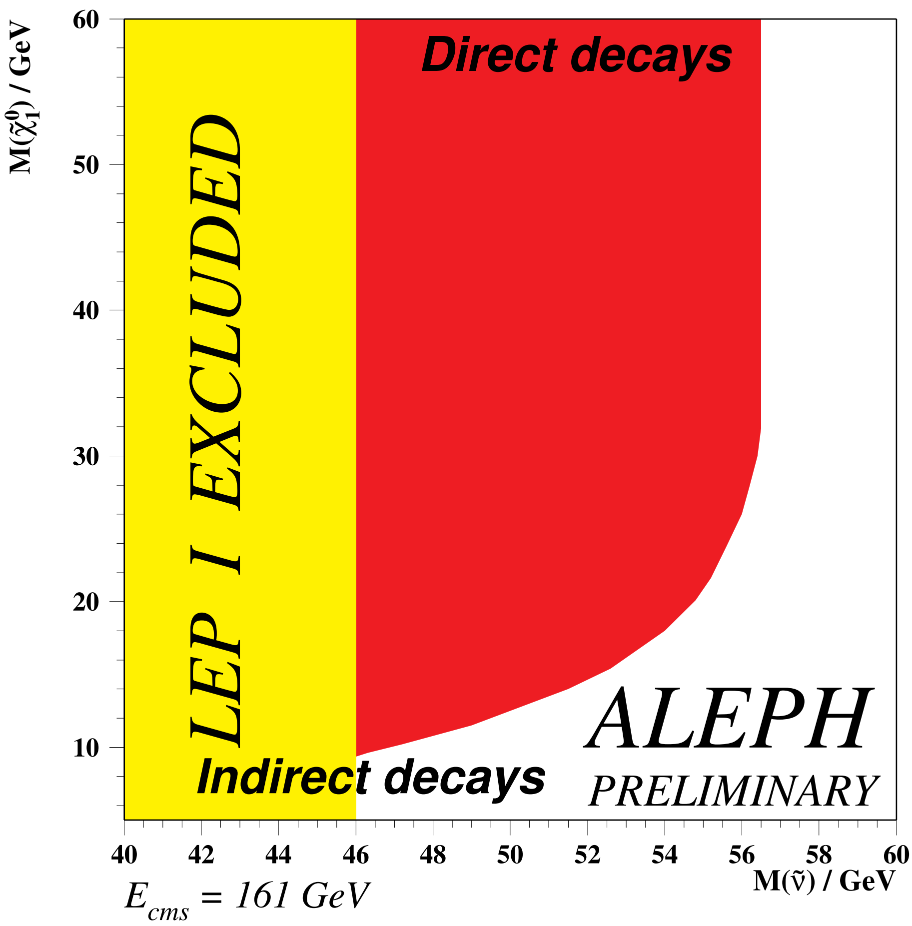



**Pair produced $e^+e^- \rightarrow \tilde{\nu}\,\bar{\tilde{\nu}}$**

| Final states: 4 leptons | Final state: 4 leptons + 2 Neutrinos |
|---|---|

$\tilde{\nu}$ **All Decays : 122 coupling** ***(No $\tau$ in the final state)***



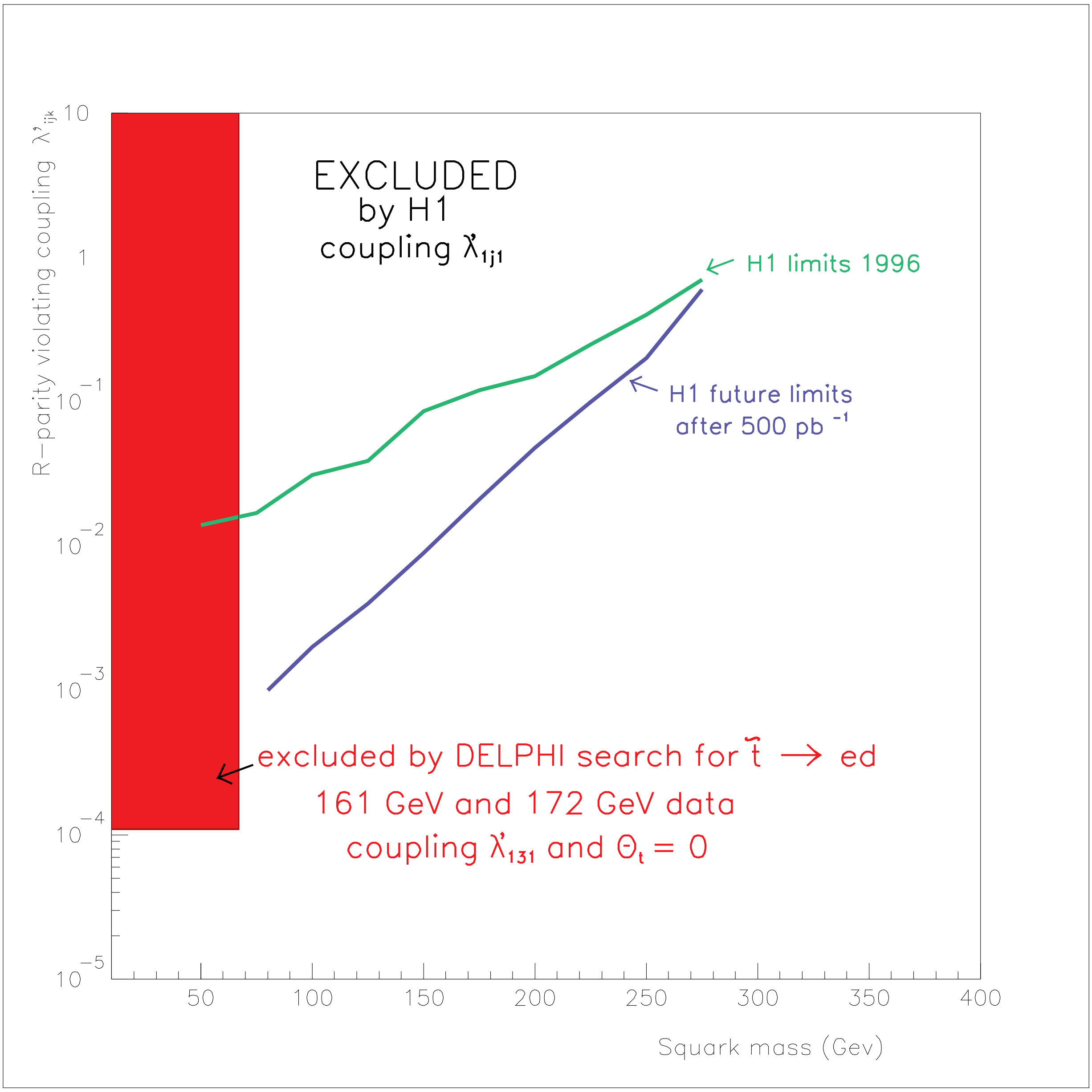

*Valid for any sneutrino type since the cross-section for $\tilde{\nu}_\tau$ pair production has been used. The cross -section for pair produced $\tilde{\nu}_e$ is higher due to positive interference from the t-channel*

# RPV Searches

## Stop RPV decays

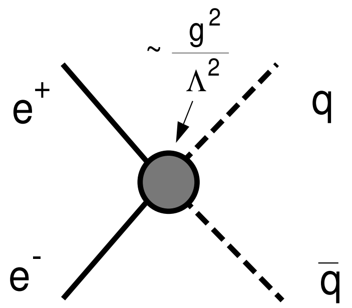
***Stop decay with violation of R-parity can be induced by terms of the form LQD with the coupling constant $\lambda'$ in the superpotential.***

***Give rise to decays:*** $\tilde{t}_1 \rightarrow e\, d$

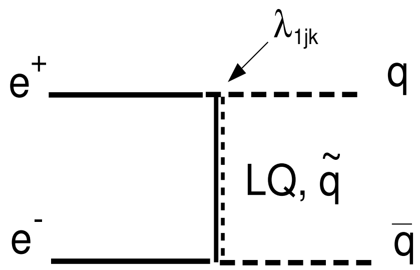


# *RPV Searches*

***Limits based on measured $\sigma(e^+e^- \to \text{hadrons})$***




**contact interaction**




**LeptoQuark**

**R-parity breaking SUSY**

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\rm SM} + \frac{g^2}{\Lambda^2}\left.\frac{d\sigma}{d\Omega}\right|_{\rm Interf.} + \frac{g^4}{\Lambda^4}\left.\frac{d\sigma}{d\Omega}\right|_{\rm New\ Physics}$$

# RPV Searches

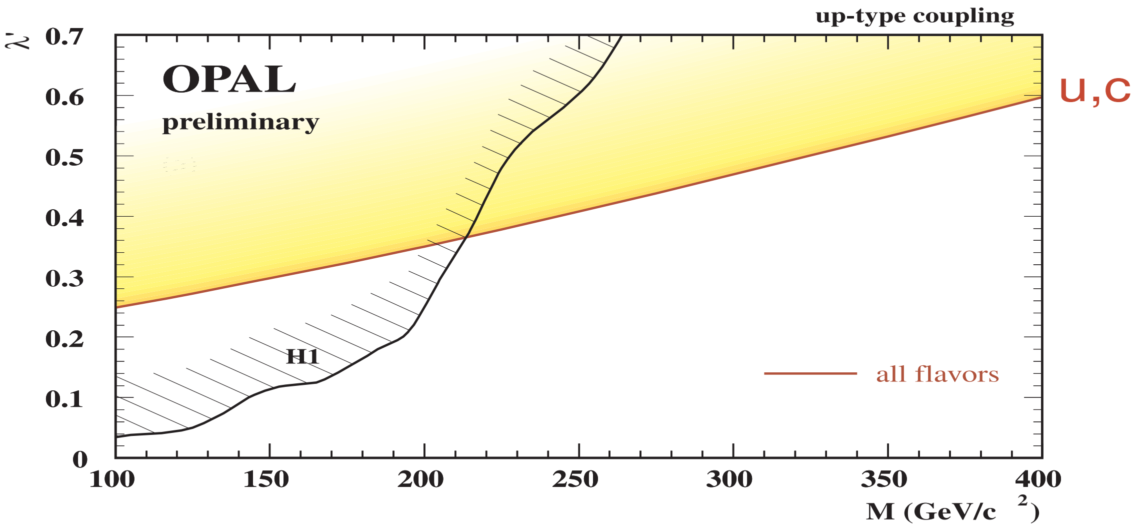
## $e\,\tilde{q}\,q$ coupling

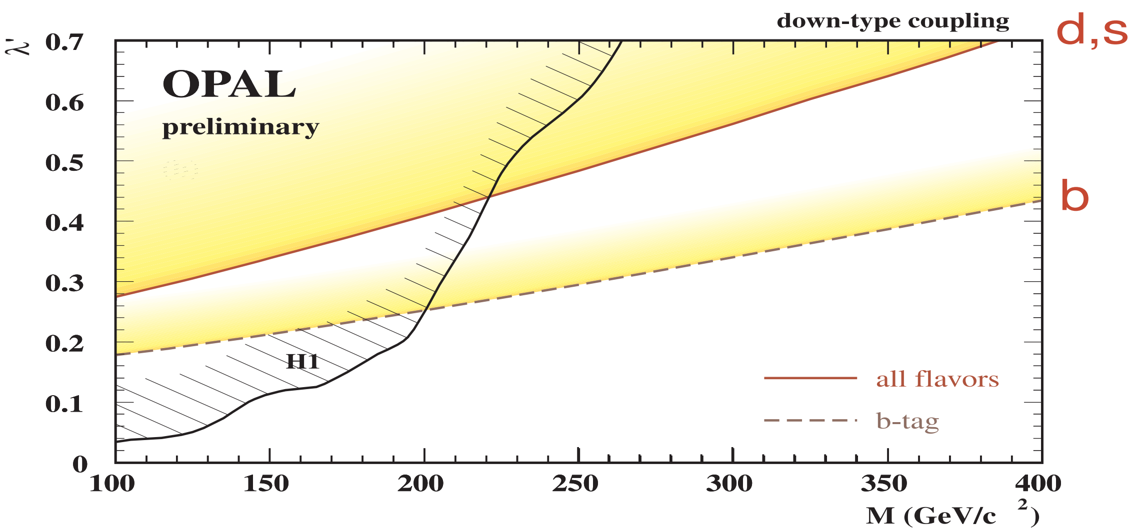
$\lambda' = \lambda'_{1jk}$

$k \rightarrow q$ family

$j \rightarrow \tilde{q}$ family

$1 \rightarrow e$ = first family



# 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:***

$$\tilde{l}^{\pm} \rightarrow l^{\pm} \tilde{G}$$

***with a lifetime dependent on the SUSY-breaking energy scale $\sqrt{F}$ :***

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

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

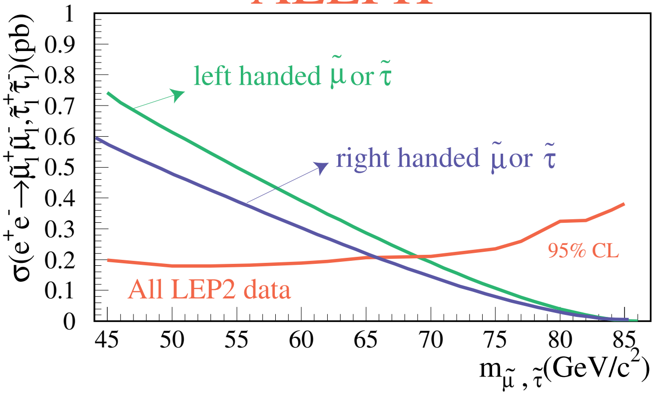
***Long-lived charged SUSY particles also exists in the context of SUSY models if there is a high mass degeneracy with the LSP and also in RPV SUSY models if the couplings are small.***

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

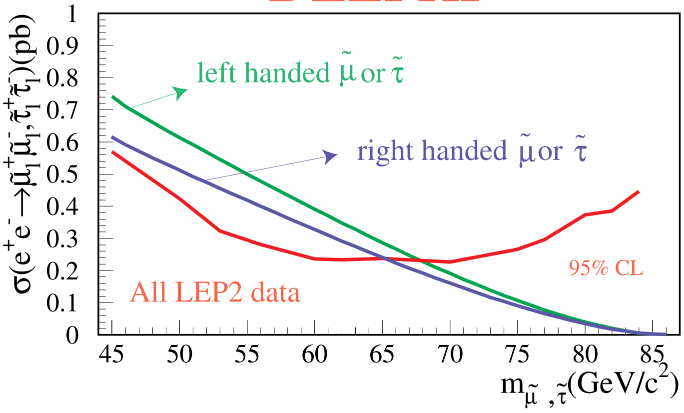
# *Long-lived heavy charged particles*

## *Combined LEP SUSY working group*

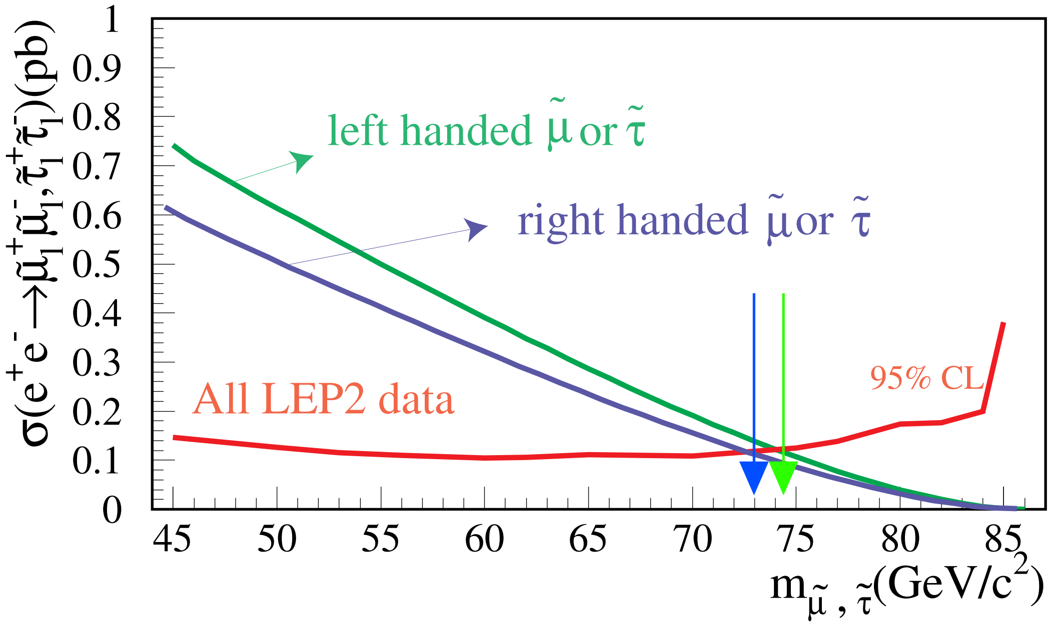
ALEPH




DELPHI




ALEPH-DELPHI combined




***Model independent 95% confidence level upper limit on the production cross-section of 0.1-0.4 pb for masses between 45 and 86 GeV***

***Assuming MSSM:***

$$m_{\tilde{\mu}_R^\pm, \tilde{\tau}_R^\pm} > 73 \text{ GeV}$$

$$m_{\tilde{\mu}_L^\pm, \tilde{\tau}_L^\pm} > 74.5 \text{ GeV}$$

# Conclusions

*The four LEP collaborations have searched for sfermions at LEP 2 energies. Some candidates were selected by the analyses but their number is compatible with the expected background from Standard Model processes.*

*No experimental evidence of sfermion production yet $\rightarrow$ exclusion limits have been greatly improved compared to LEP1 results.*

*With the next run at $\sqrt{s}$ = 184 GeV this summer, all these searches will be significantly improved in a few weeks of running time.*

*Many thanks to my OPAL colleagues (especially S. Asai), W. de Boer , A. Lipniacka and L. Pape (DELPHI), B. Orejudos, M. Schmitt, P. Vangemmeren and V. Buescher (ALEPH) , M. Pieri and S. Rosier (L3)*