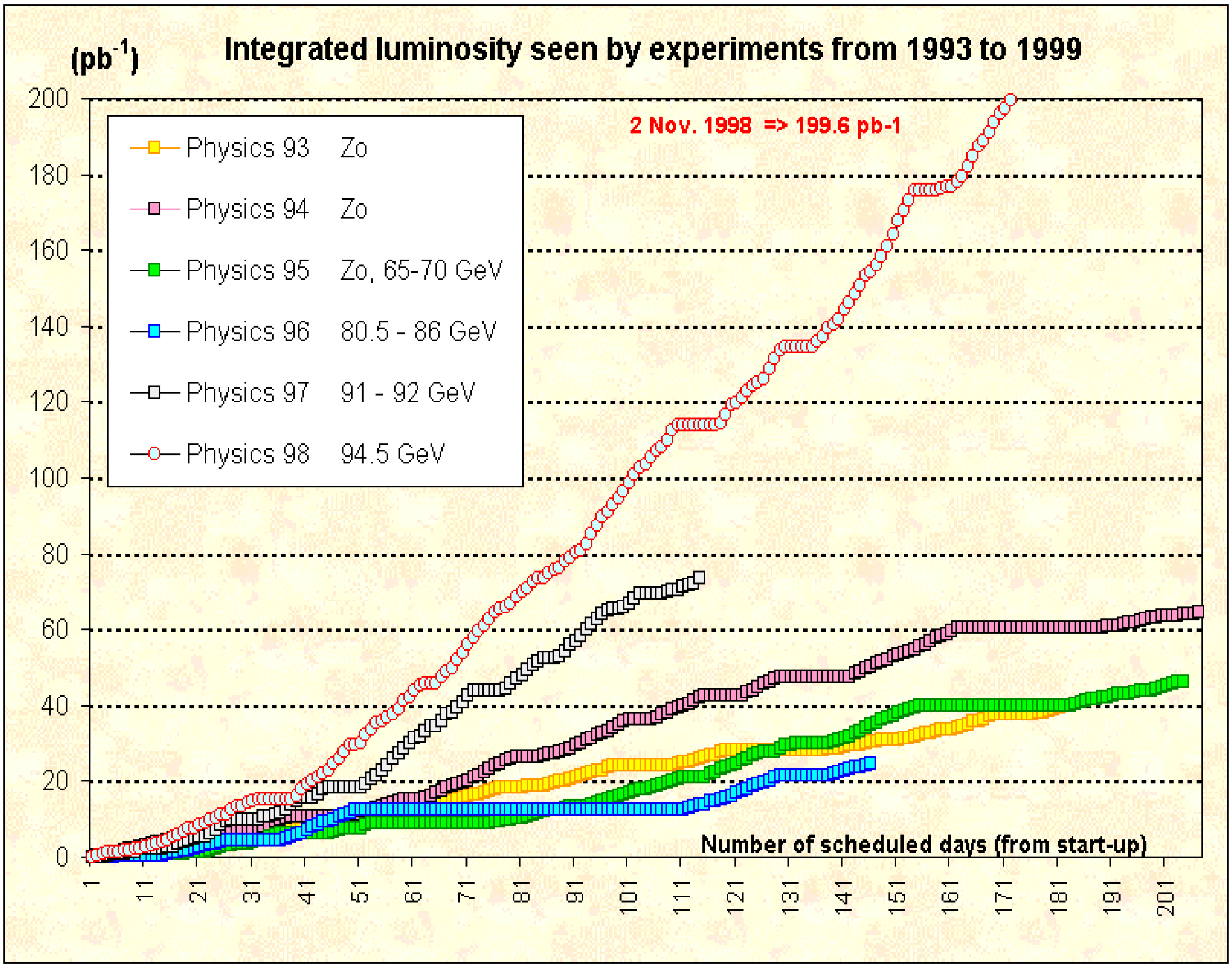
Searching for *Standard* SUSY at LEP2

Rob McPherson
University of Victoria, OPAL
On behalf of the LEP Collaborations

- *Standard* $\Rightarrow$ Gravity Mediated
  - no light Gravitino
- *Standard* $\Rightarrow$ R-Parity Conserving
  - Lightest SUSY particle (LSP) stable, weakly-interacting
  - Usually lightest neutralino, $\tilde{\chi}^0_1$ (*maybe* sneutrino, $\tilde{\nu}$)
- *Mostly* Look for Next-to-LSP decaying into LSP
  - Scalar Leptons, $\tilde{\ell}^+\tilde{\ell}^-$
  - Scalar Quarks, $\tilde{\mathrm{t}}\tilde{\mathrm{t}}$, $\tilde{\mathrm{b}}\tilde{\mathrm{b}}$
  - Gauginos, $\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^0_2\tilde{\chi}^0_1$ *etc. etc. etc.*
- LSP Massive? $\Rightarrow$ $\tilde{\chi}^0_1$ dark matter candidate

The LEP2 e^+e^- Collider

Stage	$\sqrt{s}$	Year	Luminosity
LEP 1	$\approx$ 91 GeV	1989-1995	175 pb^{-1}
LEP 1.5	130-140 GeV	1995	5 pb^{-1}
LEP 2	161 GeV	1996	10 pb^{-1}
	172 GeV	1996	10 pb^{-1}
	183 GeV	1997	55 pb^{-1}
	189 GeV	1998	150-180 pb^{-1}
	200 GeV !!!	1999/2000	$\sim$ 300 pb^{-1}



SUSY MODELS: guide the eye ...

Spin	0	1/2	1
	$\left.\tilde{\ell}^{\pm}_{L,R}\right\}\tilde{\ell}^{\pm}_{1,2}$	$\ell^{\pm}_{L,R}$	
	$\tilde{\nu}_L$	ν_L	
	$\left.\tilde{q}_{L,R}\right\}\tilde{q}_{1,2}$	$q_{L,R}$	
		$\tilde{g}$	g
	h^0, H^0, A^0	$\left.\begin{matrix}\tilde{\gamma}\\ \tilde{h}, \tilde{H}\\ \tilde{Z}^0\end{matrix}\right\}\tilde{\chi}^0_j$	γ Z^0
	$H^{\pm}$	$\left.\begin{matrix}\tilde{H}^{\pm}\\ \tilde{W}^{\pm}\end{matrix}\right\}\tilde{\chi}^{\pm}_i$	$W^{\pm}$

General MSSM

M_1, M_2, M_3	$U(1), SU(2), SU(3)$ Gaugino Masses
$m_{\tilde{f}}$	sfermion masses
$v, \tan\beta, m_{A^0}, \mu$	Higgs(ino) mass/mixing parameters
$A_U, A_D, A_L,$	Trilinear sfermion/higgs coupling matrices

105 new parameters, unsupressed FCNC, ...

(SUGRA) Constrain it $\Rightarrow$ CMSSM

M_2	EW-scale $SU(2)$ Gaugino Mass
	(GUT Unification gives M_1, M_3)
m_0	Common GUT-scale (Plank!) scalar mass
	(EW-scale masses from RGE's)
$\tan\beta$	v_2/v_1, Ratio of vev's of two higgs doublets
μ	Higgs mixing parameter
A_0	Common trilinear coupling

5'ish new parameters, FCNC *etc.* controllable

CMSSM: Unification, RGE's *etc.*

Gaugino mass unification:

$$
\begin{aligned}
M_2 &= 0.82\, m_{1/2} \\
M_1 &= 5/3\ \tan^2\theta_W\ M_2 \\
M_3 &= \alpha_s/\alpha_{EM}\ \sin^2\theta_W\ M_2
\end{aligned}
$$

Sfermion Masses:

$$
\begin{aligned}
m_{\tilde{\mathrm{u}}_\mathrm{R}} &\simeq m_0^2 + 5.87\, m_{1/2}^2 - 0.16\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta| \\
m_{\tilde{\mathrm{u}}_\mathrm{L}} &\simeq m_0^2 + 6.28\, m_{1/2}^2 - 0.35\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta| \\
m_{\tilde{\mathrm{d}}_\mathrm{R}} &\simeq m_0^2 + 5.82\, m_{1/2}^2 - 0.08\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta| \\
m_{\tilde{\mathrm{d}}_\mathrm{L}} &\simeq m_0^2 + 6.28\, m_{1/2}^2 - 0.42\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta| \\
m_{\tilde{\ell}_\mathrm{R}} &\simeq m_0^2 + 0.15\, m_{1/2}^2 - 0.23\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta| \\
m_{\tilde{\ell}_\mathrm{L}} &\simeq m_0^2 + 0.52\, m_{1/2}^2 - 0.27\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta| \\
m_{\tilde{\nu}_\mathrm{L}} &\simeq m_0^2 + 0.52\, m_{1/2}^2 - 0.50\, M_{\mathrm{Z}^0}^2\, |\cos 2\beta|
\end{aligned}
$$

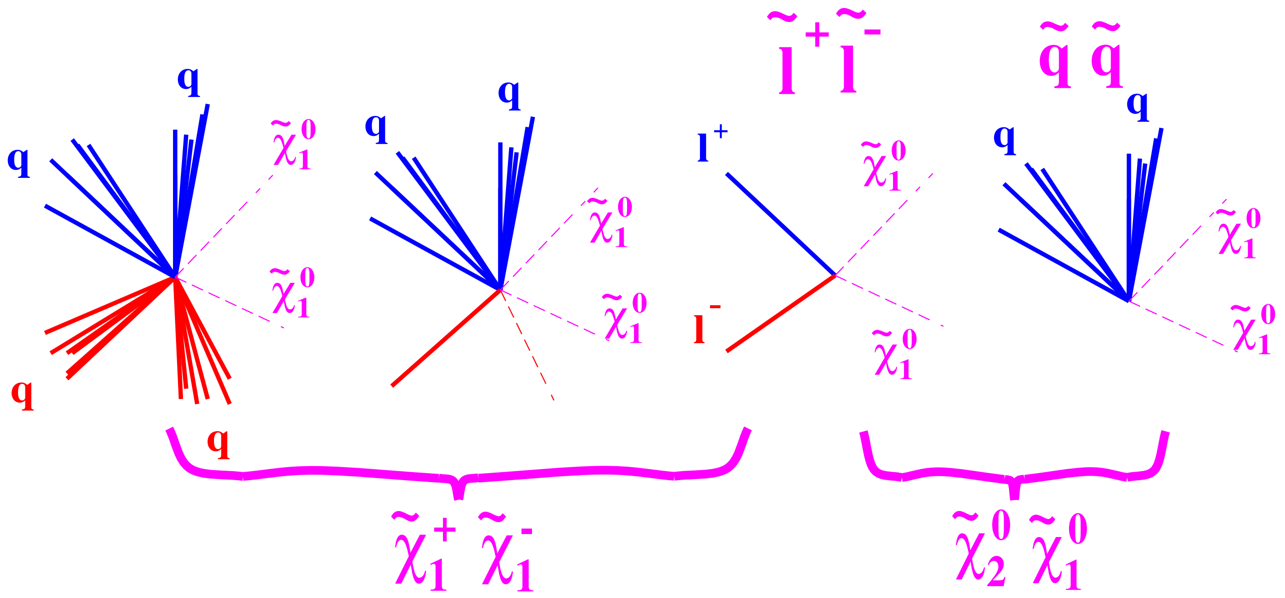
Actually:

- Mass eigenstates mixtures of L and R
- Important for $\tilde{\mathrm{t}}$
- Also for $\tilde{\mathrm{b}}$, $\tilde{\tau}$ if $\tan\beta$ large

Parameters $\leftrightarrow$ Search Channels

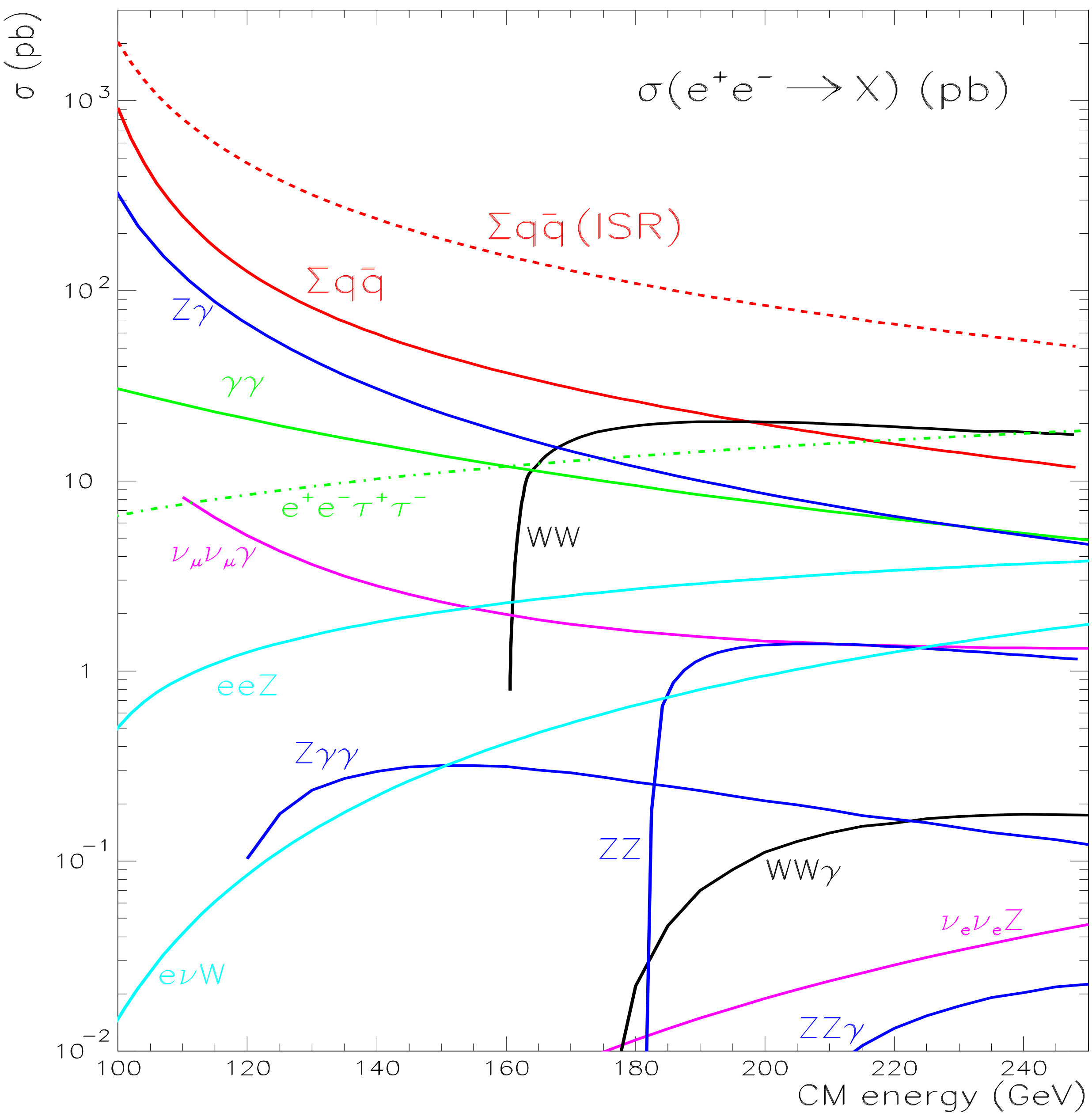
$\mu << M_2$	$\mu >> M_2$		
Higgsino Region	Gaugino Region		
no $\tilde{\nu}$ coupling	Large $m_0, m_{\tilde{f}}$	Small $m_0, m_{\tilde{f}}$	
			Large $\tilde{q}$ Mix
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$		$\tilde{\ell}^+\tilde{\ell}^-$	$\tilde{t}\tilde{t}$, $\tilde{b}\tilde{b}$

Primary Search Topologies



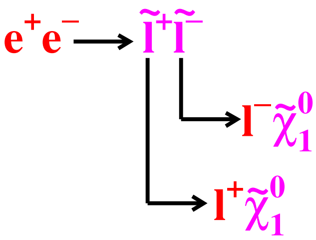
- Select events with significant missing energy
- Categorize using
  - hadronic jets
  - charged leptons
  - Event Visible Energy, jet/lepton energies
- Depend Strongly on $\Delta M = M_{\mathrm{SUSY}} - M_{\mathrm{LSP}}$

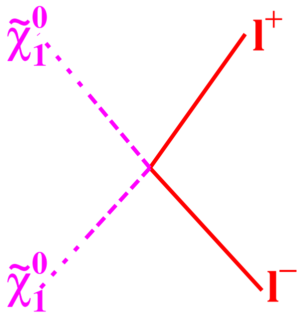
Background from the SM



- 4-Fermion, especially $\mathrm{W^+W^-}$
  - $\sigma \sim$ 20 pb
  - Large visible energy (large ΔM region)
- $\mathrm{e^+e^- \to e^+e^-\gamma^{(*)}\gamma^{(*)} \to e^+e^-f\bar{f}}$
  - σ *enormous* (say $\sim$ 100-10000 pb)
  - Small visible energy (small ΔM region)

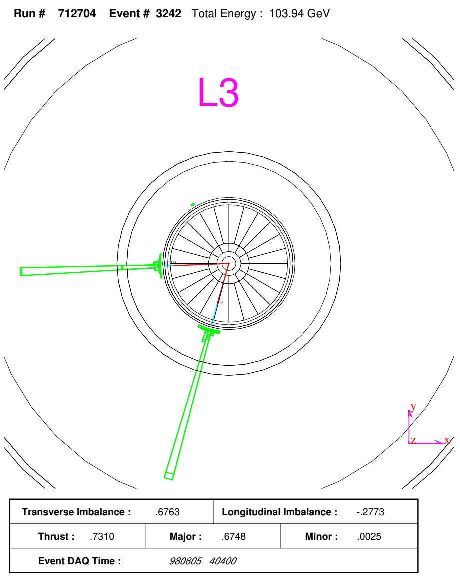
Scalar Lepton Searches



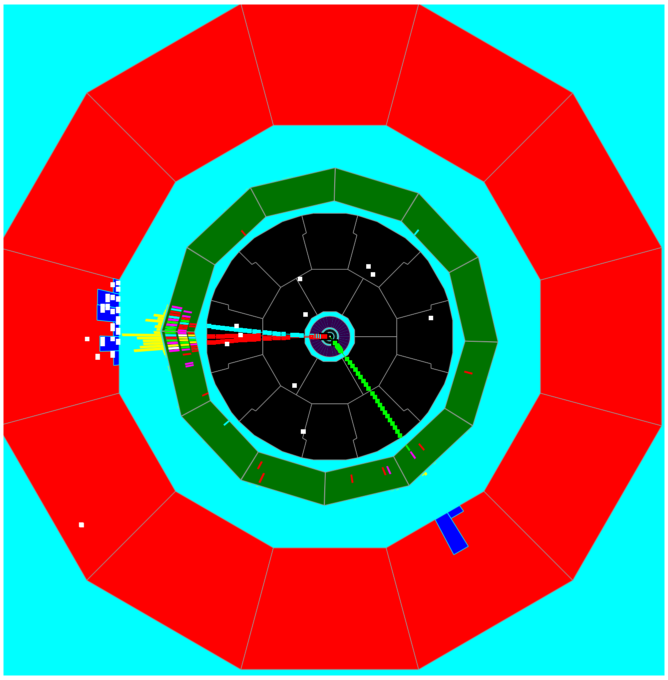


- Acoplanar lepton pair
- Missing E_T

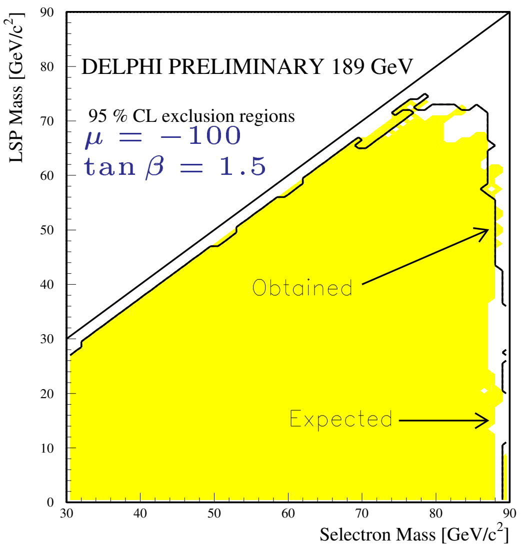
Many Candidates:



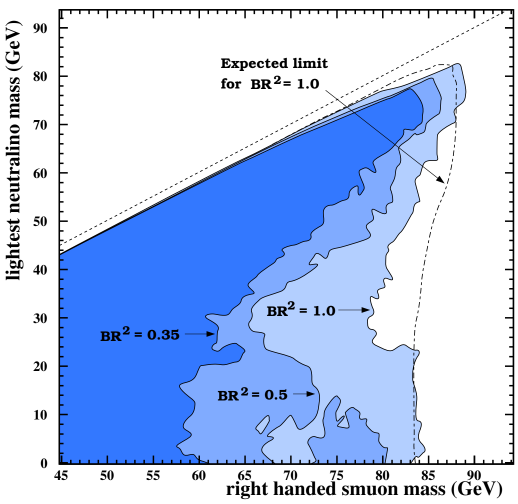
ALEPH



But consistent with SM backgrounds$\Rightarrow$ Limits:



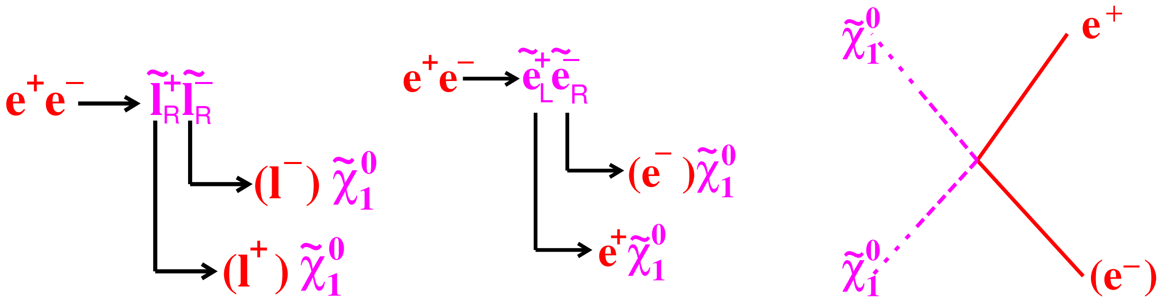
OPAL preliminary



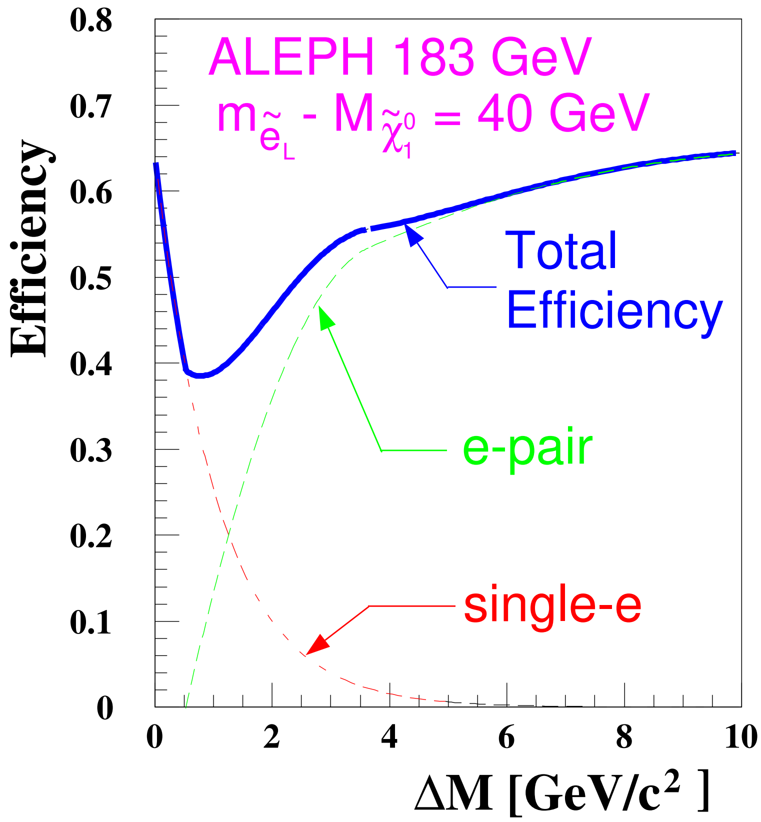
Slepton Loophole

$$m_{\tilde{\ell}_{\mathrm{R}}} - M_{\tilde{\chi}^0_1} \sim 0$$

$\tilde{\ell}^+_R \tilde{\ell}^-_R$ Invisible	$m_{\tilde{\ell}_{\mathrm{L}}} - M_{\tilde{\chi}^0_1} > 3\ \mathrm{GeV} \Rightarrow \tilde{\mathrm{e}}^+_L \tilde{\mathrm{e}}^-_R$?



- Select single electrons with nothing else
- Significant visible energy
- Significant transverse momentum

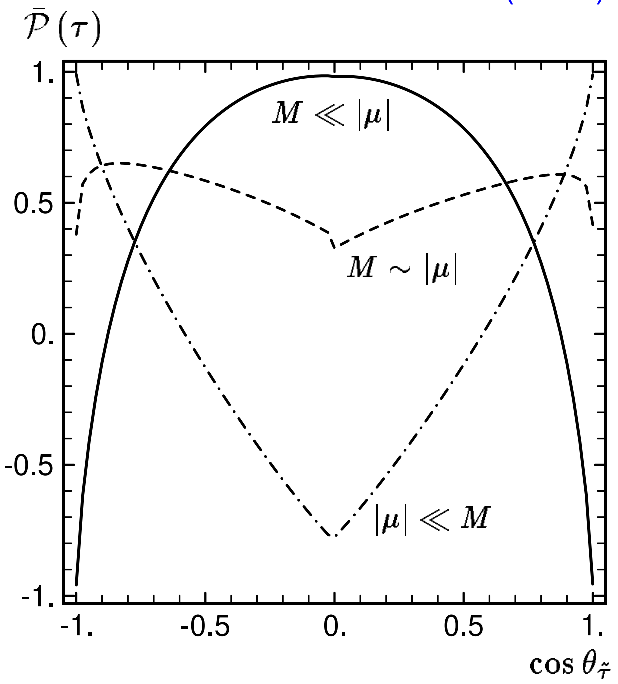


Data: 5 Events

Background: 6.6 Events

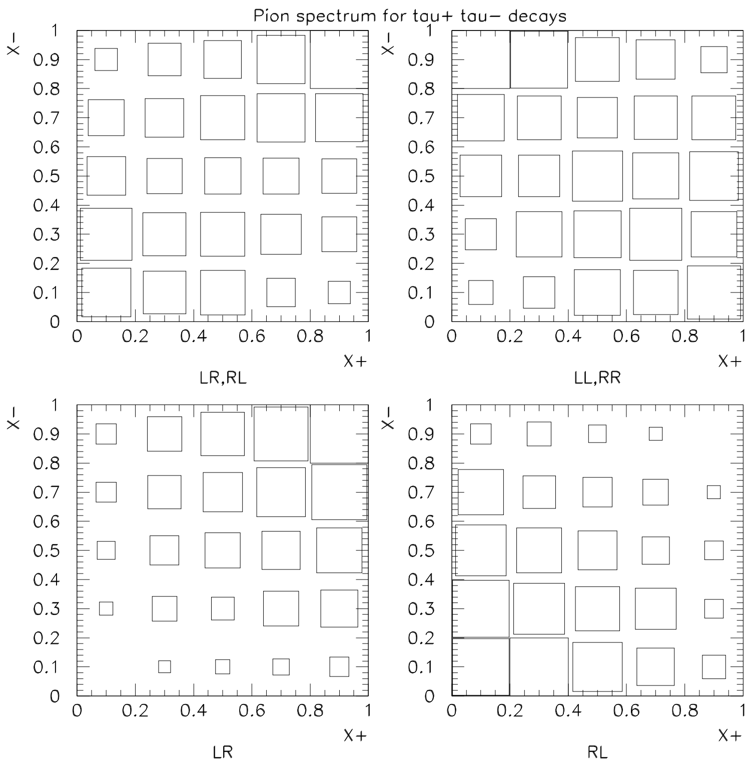
Uniquely Stau Loophole

Bartl *et al.* ZPC73(1997)



- $\mathcal{P}_\tau$ from $\tilde{\tau}_1 \to \tilde{\chi}_1^0$
- $-1 \leq \mathcal{P}_\tau \leq 1$!!

Example: 100% $\tau \to \pi$ decays (G.W. Wilson, Manchester U.)



τ^+, τ^- Polarization

$x^\pm = P_{\pi^\pm}/P_{\tau^\pm}$

But $P_{\pi^\pm}$ used

For BG reduction!

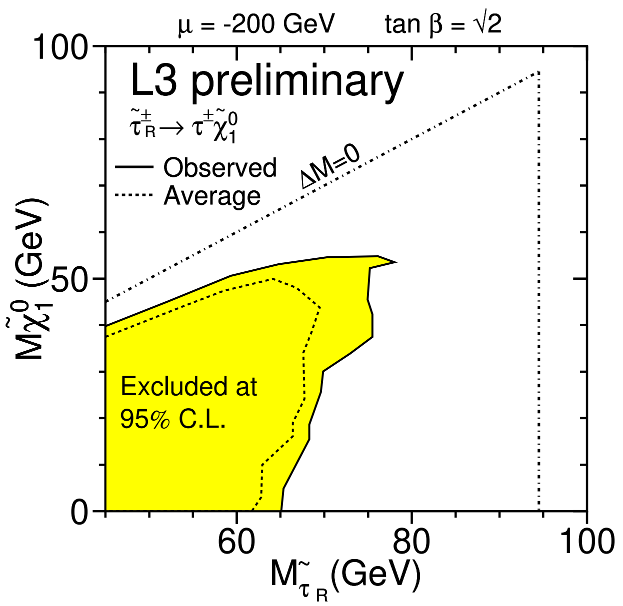
Effect under study $\Rightarrow$ Handle with care ...

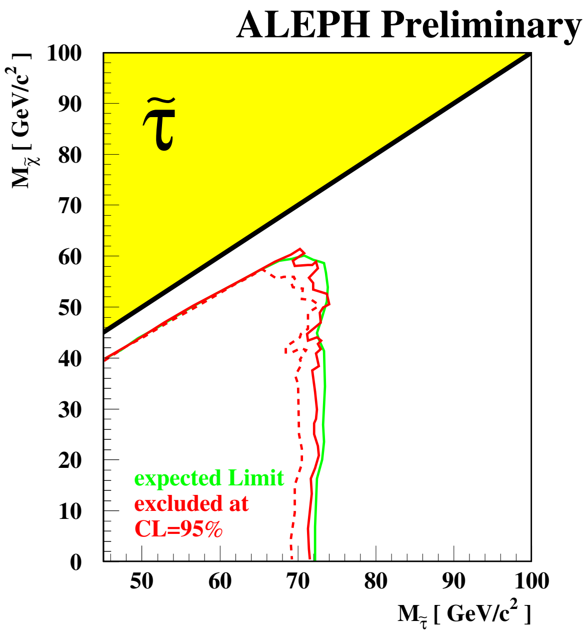
Another Stau Loophole?

- $\tilde{\tau}_R, \tilde{\tau}_L$ mix to form the physical mass eigenstates, $\tilde{\tau}_1, \tilde{\tau}_2$

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

- Mixing big for large $\tan\beta$
- Can decouple $\tilde{\tau}_1$ from Z^0





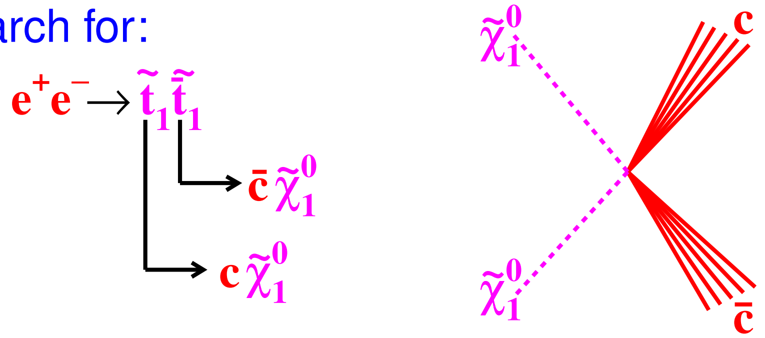
Slepton Mass Limits

189 GeV	$m_{\tilde{e}_R}$	$m_{\tilde{\mu}_R}$	$m_{\tilde{\tau}_R}$
ALEPH	>88 GeV $\Delta M > 10\,\mathrm{GeV}, \tan\beta = 2$	>80 GeV $\Delta M > 10\,\mathrm{GeV}$	>67 GeV $\Delta M > 10\,\mathrm{GeV}$
DELPHI	>87 GeV $\Delta M > 10\,\mathrm{GeV}, \tan\beta = 1.5$	>73 GeV $\Delta M > 5\,\mathrm{GeV}$	>74 GeV $\Delta M > 15\,\mathrm{GeV}$
L3	>87 GeV $\Delta M > 10\,\mathrm{GeV}, \tan\beta = \sqrt{2}$	>77 GeV $\Delta M > 5\,\mathrm{GeV}$	>65 GeV $\Delta M > 10\,\mathrm{GeV}$
OPAL	>77 GeV $\Delta M > 5\,\mathrm{GeV}, \tan\beta = 1.5$	>78.4 GeV $\Delta M > 2\,\mathrm{GeV}$	>69.4 GeV $\Delta M > 10\,\mathrm{GeV}$

Stop & Sbottom Searches

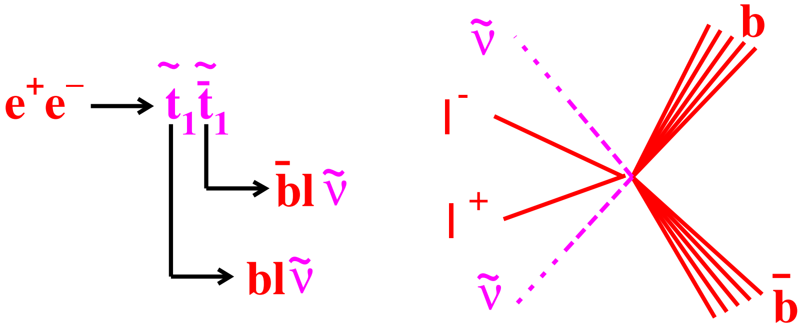
- Loop corrections to $m_{\tilde{t}}$
  $\Rightarrow \tilde{t}_R, \tilde{t}_L$ expected to be lightest of the squarks
- Mix to form the physical mass eigenstates, $\tilde{t}_1, \tilde{t}_2$
  $$\tilde{t}_1 = \cos\theta_{\tilde{t}}\tilde{t}_L + \sin\theta_{\tilde{t}}\tilde{t}_R$$
- For large m_{top} : $\tilde{t}_1$ can be light.

Search for:

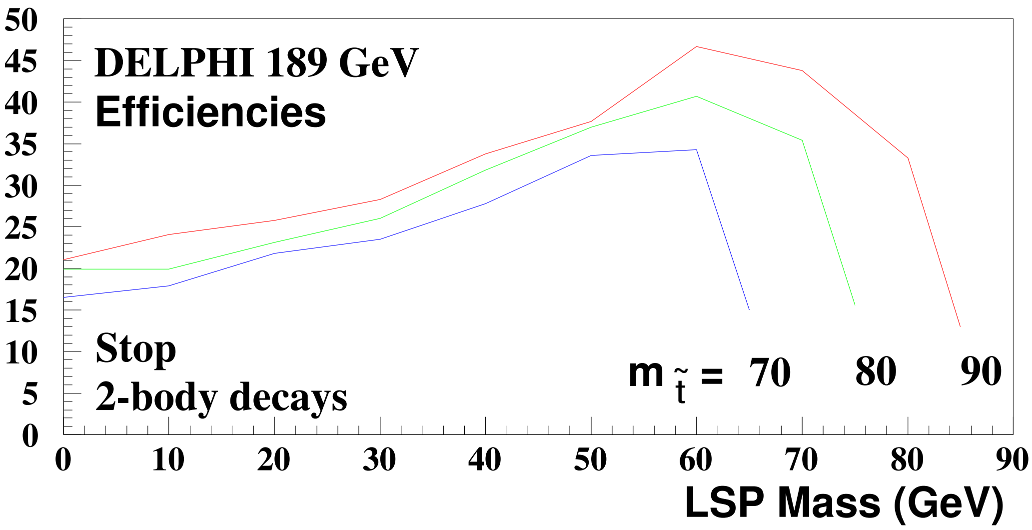


- Acoplanar Jets
- Missing E_T

If $m_{\tilde{\nu}} < m_{\tilde{t}_1} + m_{\text{bottom}}$, main decay is:

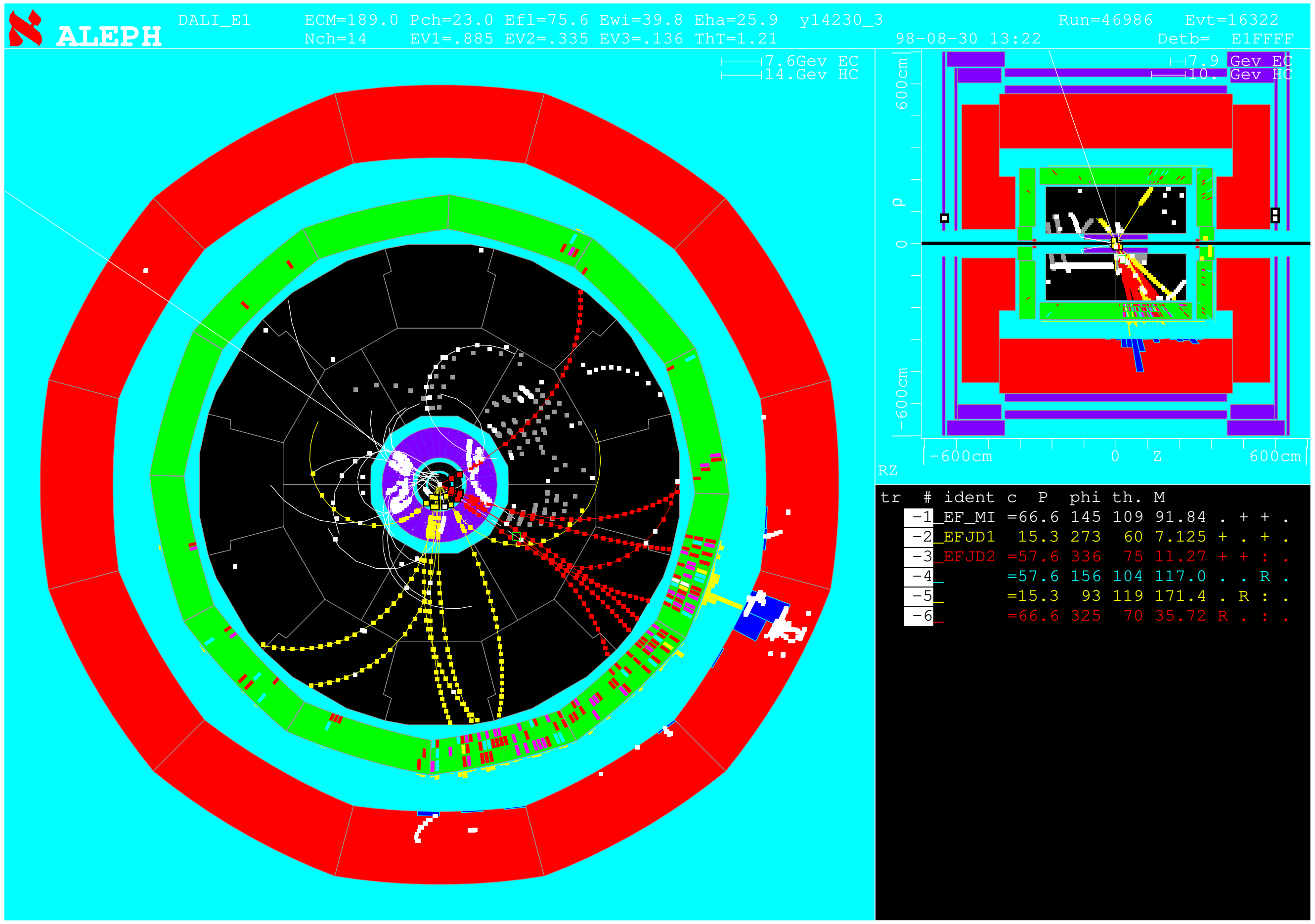


- Acoplanar b Jets
- 2 charged leptons
- Missing E_T



$\Rightarrow$ Candidates

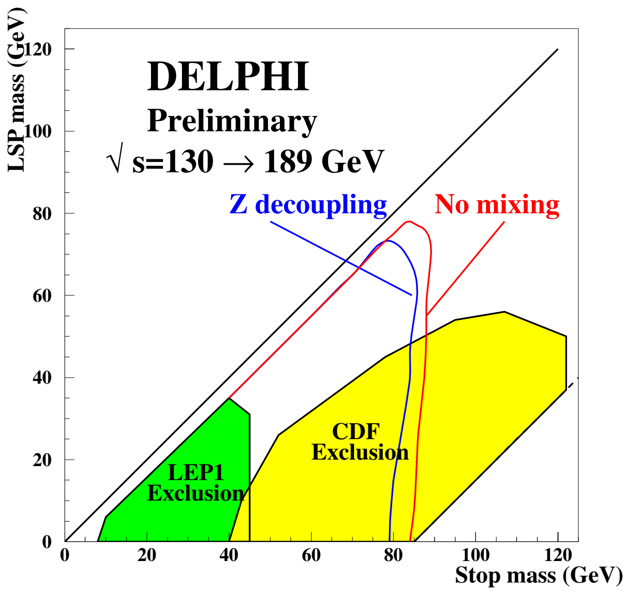
Stop Candidate, acoplanar di-jet

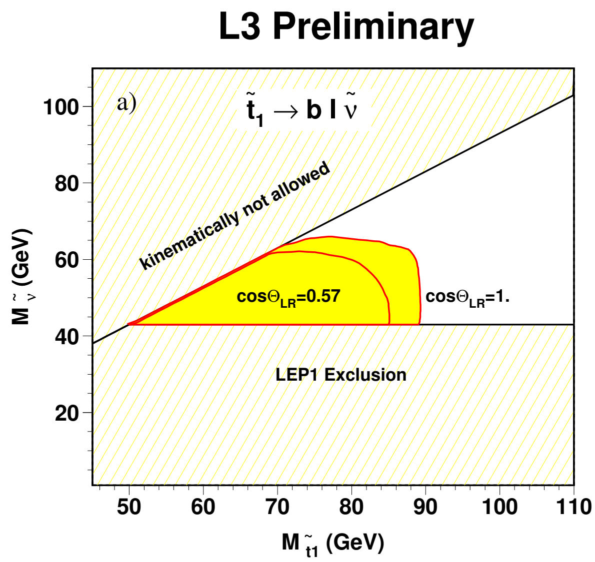


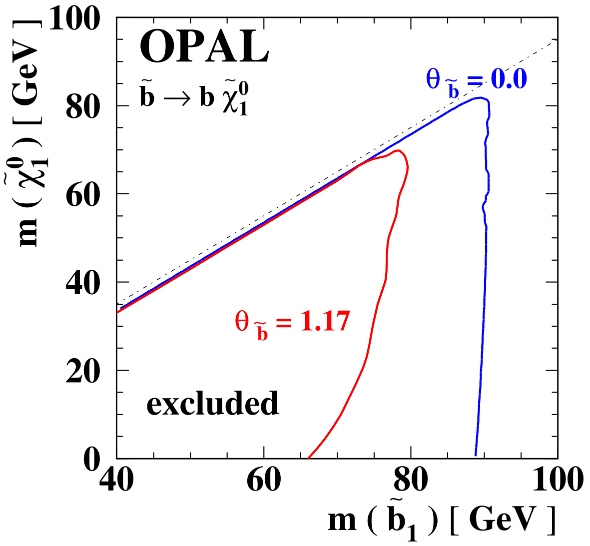
- $M_{\mathrm{jet-jet}} =$ 36 GeV
- $M_{\mathrm{recoil}} =$ 91.8 GeV

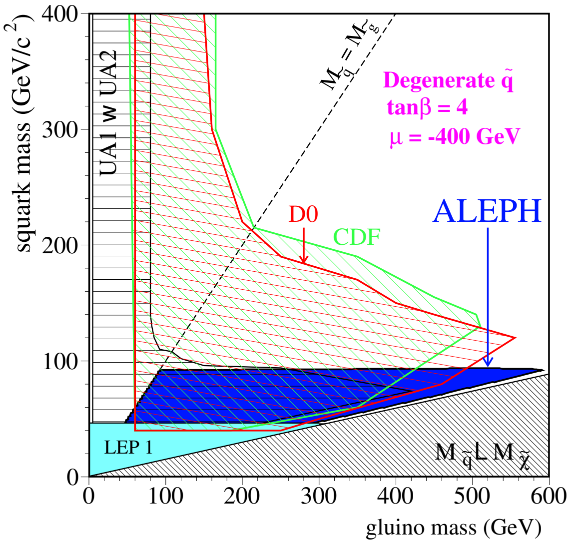
$\Big\}$ Consistent with $\mathrm{e^+e^-} \to \mathrm{Z^0}\gamma^* \to \nu\bar{\nu}\mathrm{q\bar{q}}$

Stop/Sbottom: Mass Limits





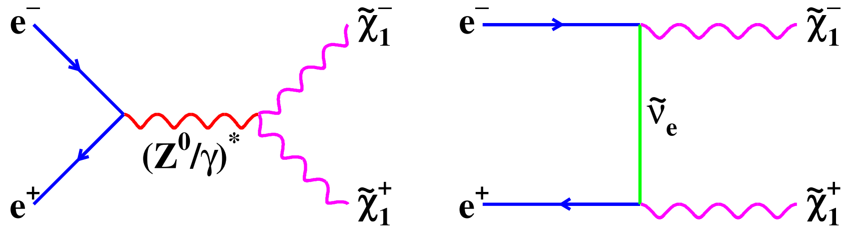




Assuming Minimum Cross-section

189 GeV	$\tilde{t} \to c\tilde{\chi}^0_1$	$\tilde{t} \to b\ell\tilde{\nu}$	$\tilde{b} \to b\tilde{\chi}^0_1$
ALEPH	>84 GeV $\Delta M > 10$ GeV	>86 GeV $\Delta M > 10$ GeV	>76 GeV $\Delta M > 10$ GeV
DELPHI	>79 GeV $\Delta M > 10$ GeV	>82 GeV $\Delta M > 15$ GeV	>62 GeV $\Delta M > 10$ GeV
L3	>78 GeV $\Delta M > 20$ GeV	>86 GeV $\Delta M > 10$ GeV	>57 GeV $\Delta M > 35$ GeV
OPAL	>87.2 GeV $\Delta M > 10$ GeV	88.0 GeV $\Delta M > 10$ GeV	65.8 GeV $\Delta M > 7$ GeV

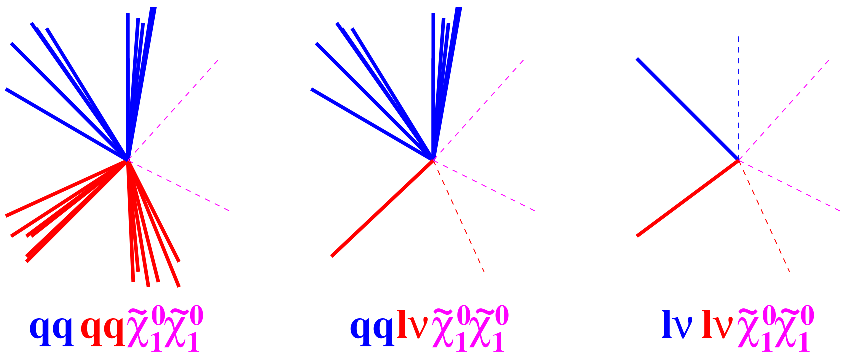
Very Standard SUSY: **Charginos**



- $\sigma > 4\ \mathrm{pb}$ unless $\tilde{\nu}_e$ is light.
- Chargino decay via W (in a large fraction of MSSM space)

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (\mathrm{W}^+ \tilde{\chi}_1^0)(\mathrm{W}^- \tilde{\chi}_1^0)$$

- Signature : $\mathrm{W}^+\mathrm{W}^-$ plus missing energy

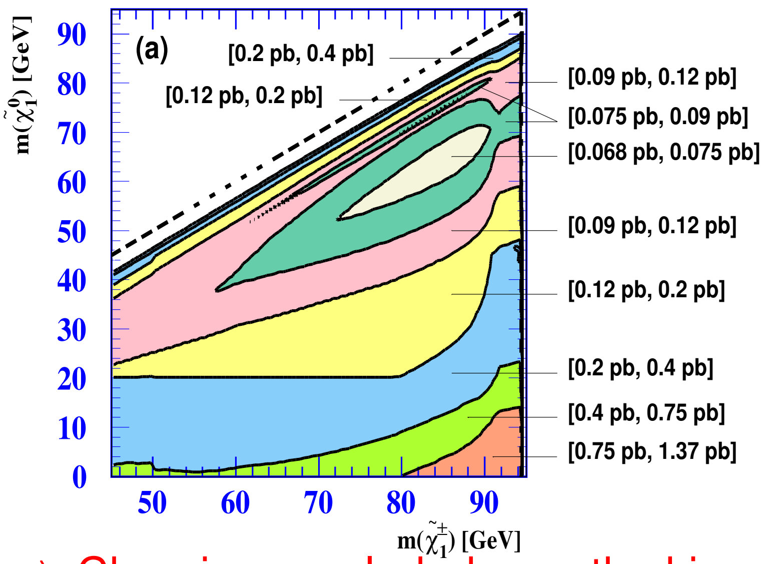


- Many selection $\Rightarrow$ Consistent with SM

LIMITS

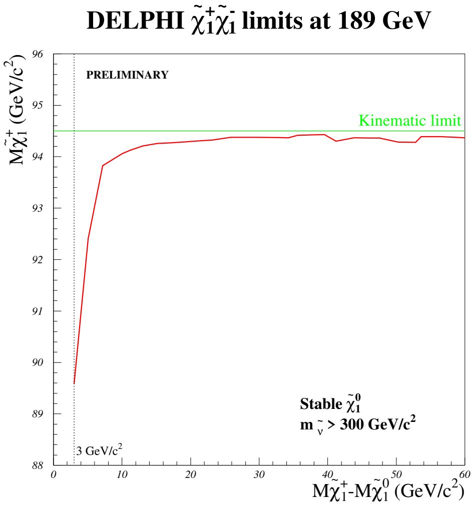
Cross-section | Mass

OPAL Preliminary



$M_{\tilde{\chi}^\pm} >$ 89.6 GeV

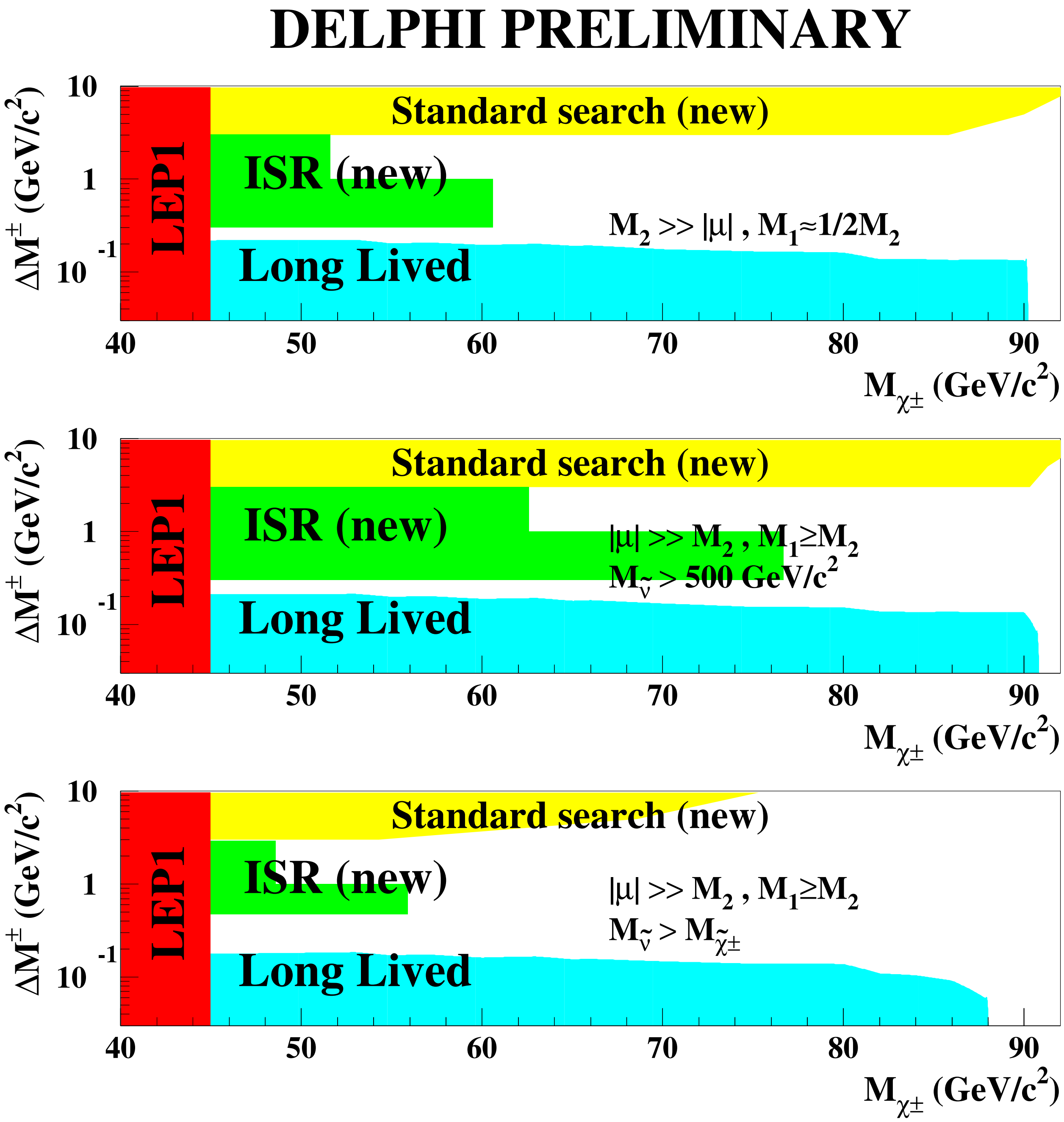
for $\Delta M =$ 3 GeV!



$\Rightarrow$ Charginos excluded near the kinematic limit for large m_0

Charginos Loophole: low ΔM

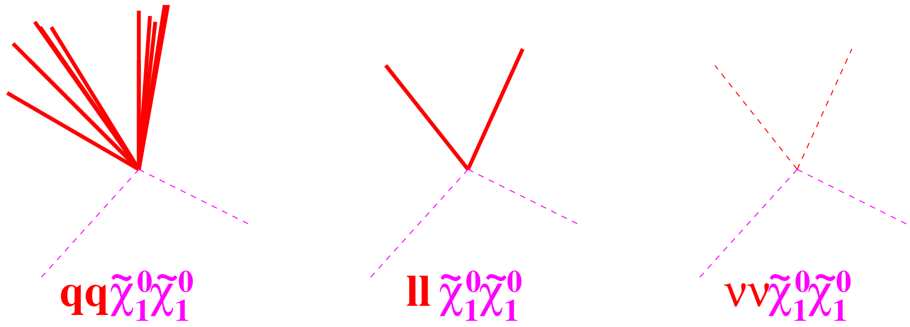
- $\Delta M < 200$ GeV: Stable heavy charged particles
- 200 GeV $\Delta M < 500$ GeV: Kinks, displaced vertices
- $\Delta M > 500$ GeV: Tag ISR photons



- Stable Chargino excluded to kinematic limit
- $m_{\tilde{\chi}^\pm} >\sim$ 51 GeV (higgsino, $\Delta M >$0.5 GeV)

Neutralino Search

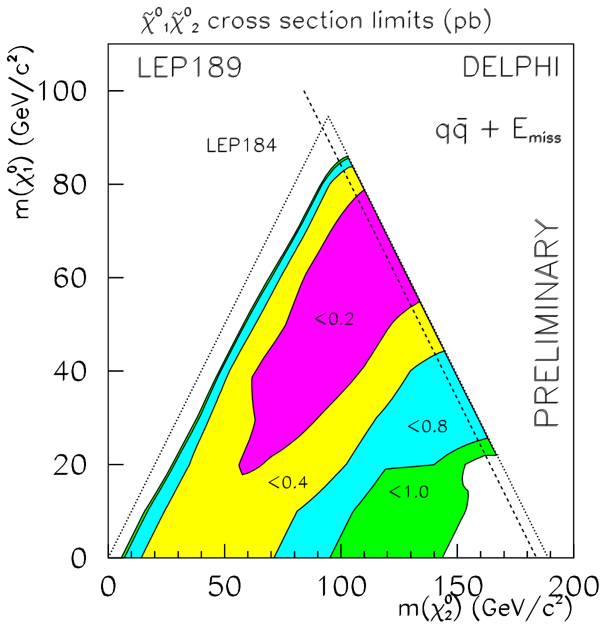
- Enough luminosity to search for neutralino production
- Observed as : $\tilde{\chi}^0_2\tilde{\chi}^0_1 \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 Z^* \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1 f\bar{f}$

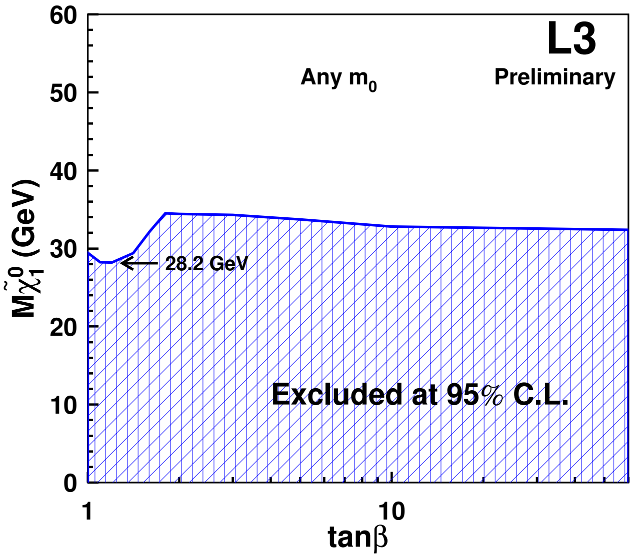


- Everything consistent with SM here too ...

LIMITS

Cross-section	Mass





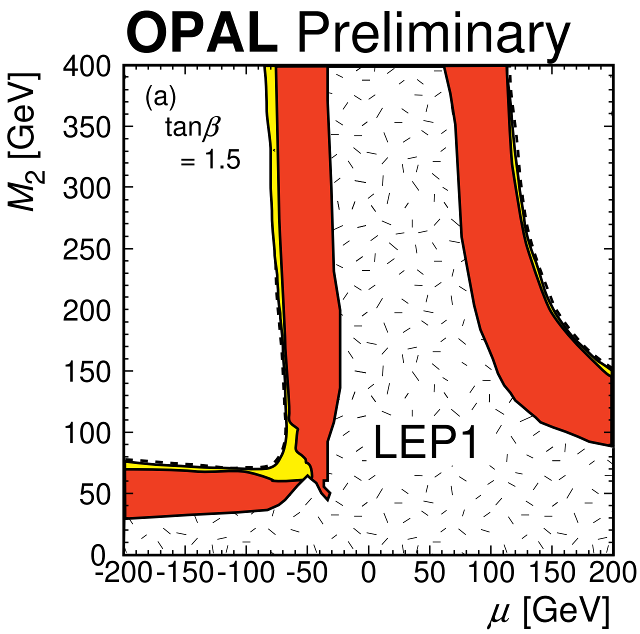
What do mass limits really mean? $\Rightarrow$

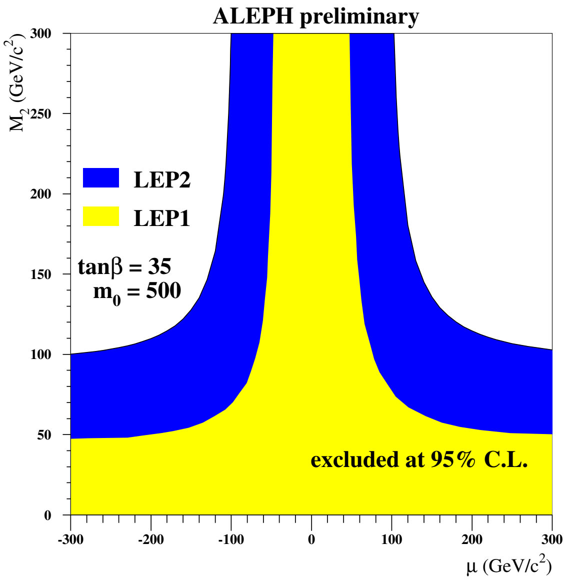
MSSM Parameter Limits

- Important parameters: $\tan\beta$, M_2, μ, m_0
- A_0 matters for mixing, especially if including MSSM higgs

$\Rightarrow$ Plot M_2 *vs.* μ for different $\tan\beta$

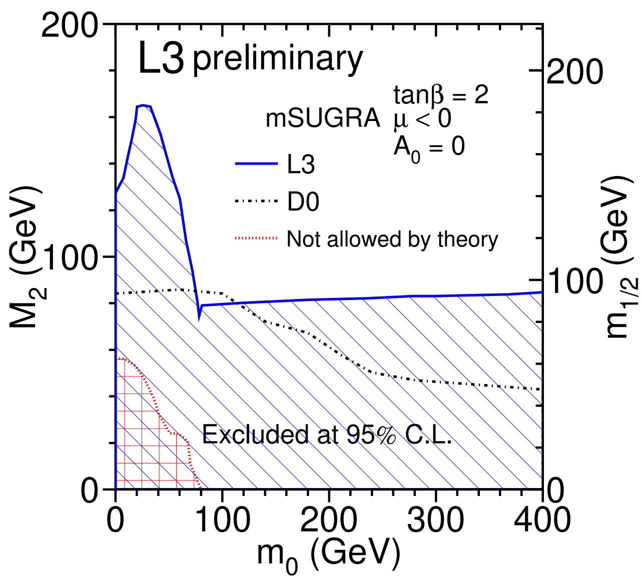
— Show Large and “any” m_0 separately (heavy/light $\tilde{\nu}$)
“any” $\Rightarrow$ parameter scan over allowed ranges



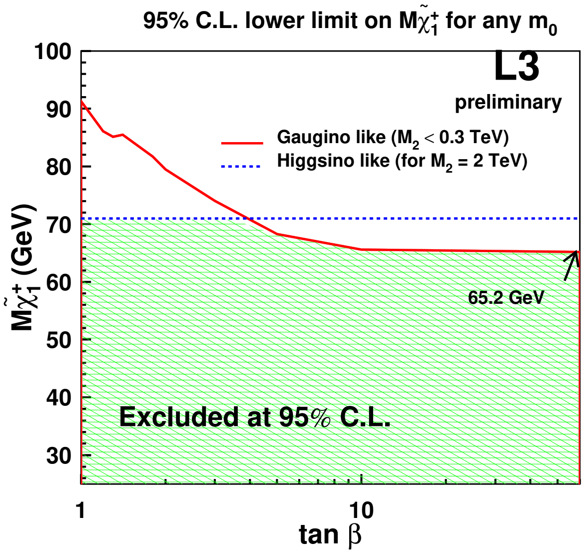


Other views:

M_2 *vs.* $m0$



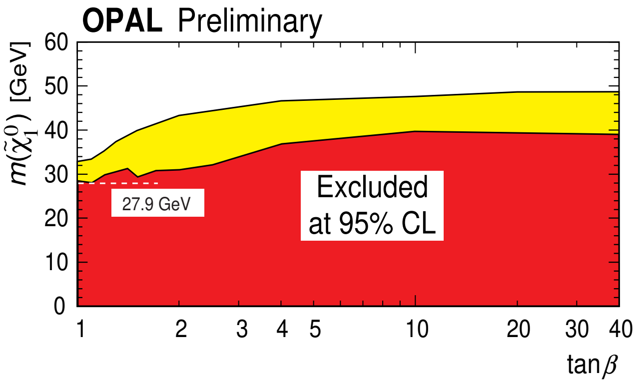
$M_{\tilde{\chi}^{\pm}}$ *vs.* $\tan\beta$

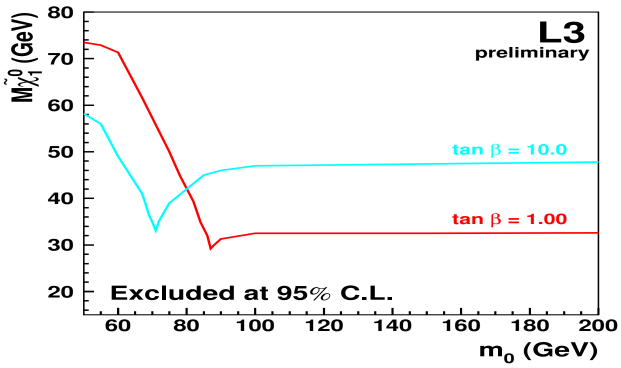


M_χ Excluded: All $\{\tan\beta, M_2, \mu, m_0, A_0\}$ $\Rightarrow$ M_χ excluded

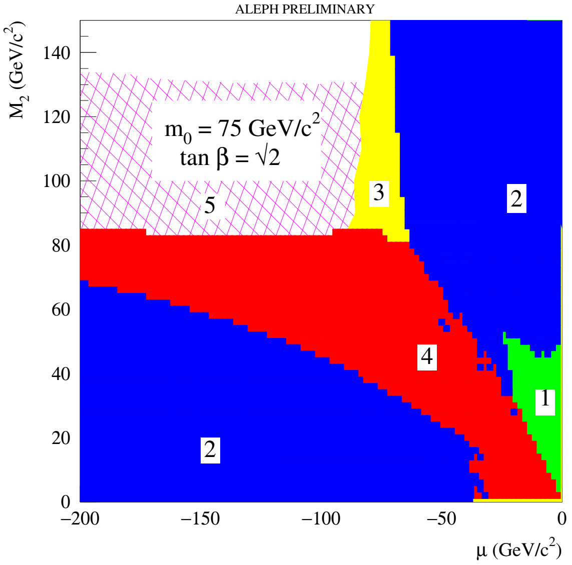
$\tilde{\chi}_1^0$ LSP Mass Limit

Use $\tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\ell}^+\tilde{\ell}^-$





MSSM higgs hA too? Blow up in M_2 *vs.* μ plane:



But still M_h =96 GeV at limiting point

$\Rightarrow$ Not quite yet ...

Mass Limits

$\sqrt{s} =$	LSP $\tilde{\chi}_1^0$ limit (GeV)	
189 GeV	Large m_0	Any m_0
ALEPH	32.3	32.3!
DELPHI	31.4	23.4
L3	32.7	28.2
OPAL	32.8	27.9

Conclusions

- LEP ran very well at $\sqrt{s} \sim$ 189 GeV
- No significant excesses in new particle search topologies
- Limits on SUSY particles in CMSSM extended

$$\boxed{m_{\tilde{\chi}^0_1} > 32.3 \text{ GeV, any } m_0}$$

- 1999: LEP2 finally becomes LEP200 GeV !!

$\Rightarrow$ This is the year ...