LEP Physics - An Overview

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Outline:

- Z physics
- W physics
- Higgs boson searches
- SUSY particle searches

Topics not included in this talk:

- other searches for new particles and physics effects
- QCD
- b physics
- τ physics
- Two-photon physics
- ...

Most of the results, in particular at $\sqrt{s} = 183$ GeV, are preliminary

LEP: Large Electron Positron collider at CERN
4 experiments: ALEPH, DELPHI, L3, OPAL

Phase I: 1989–1995 $\sqrt{s} \approx m_Z$

- about 4 million Z decays per experiment
- precise determination of Z parameters
- tests of QCD, b-quark and tau physics, searches for new particles

Phase II: 1995–2000

Increase of $\sqrt{s}$, ($\int \mathcal{L}\, dt$ per experiment)

1995	130/136 GeV	$\approx 5\ \mathrm{pb}^{-1}$
1996	161/172 GeV	$\approx 21\ \mathrm{pb}^{-1}$
1997	183 GeV	$\approx 55\ \mathrm{pb}^{-1}$ (prelim. results)
	130/136 GeV	$\approx 7\ \mathrm{pb}^{-1}$

1998	190 GeV	150 pb^{-1}
1999	200 GeV	
2000	$\geq$ 200 GeV	(not yet approved)

Precision Tests of the Standard Model at the Z

- Measurement of total cross section $e^+e^- \to \text{hadrons}(\gamma)$ and $e^+e^- \to \ell^+\ell^-(\gamma)$
  $\Rightarrow$ precise determination of Z parameters, e.g.

$$\begin{aligned} m_Z &= 91\,186.7 \pm 2.0 \text{ MeV} \\ \Gamma_Z &= 2\,494.8 \pm 2.5 \text{ MeV} \\ \Gamma_{had} &= 1\,743.2 \pm 2.3 \text{ MeV} \\ \Gamma_\ell &= 83.91 \pm 0.10 \text{ MeV} \end{aligned}$$

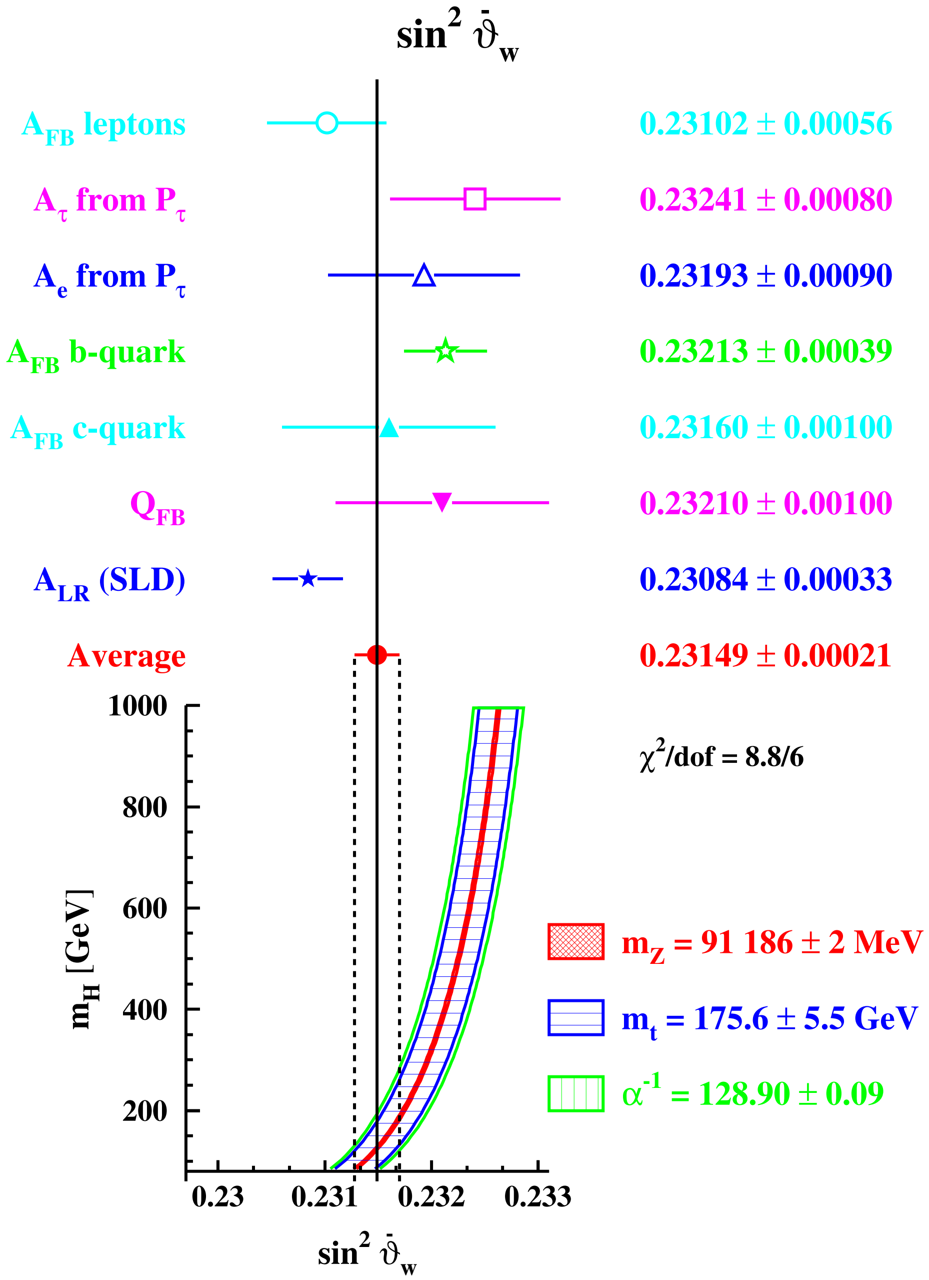
- Number of light neutrino generations

$$N_\nu = 2.993 \pm 0.011$$

  Independently from measurement of $e^+e^- \to \nu\bar{\nu}\gamma$ cross section

- Partial widths of the Z into quarks, e.g. R_b
- Forward-backward asymmetries, tau polarisation
  couplings of leptons to the Z
  effective weak mixing angle $\sin^2\bar{\vartheta}_W$

Measurements of the effective weak mixing angle $\sin^2\bar{\vartheta}_{\mathrm{W}}$ at LEP and SLD:

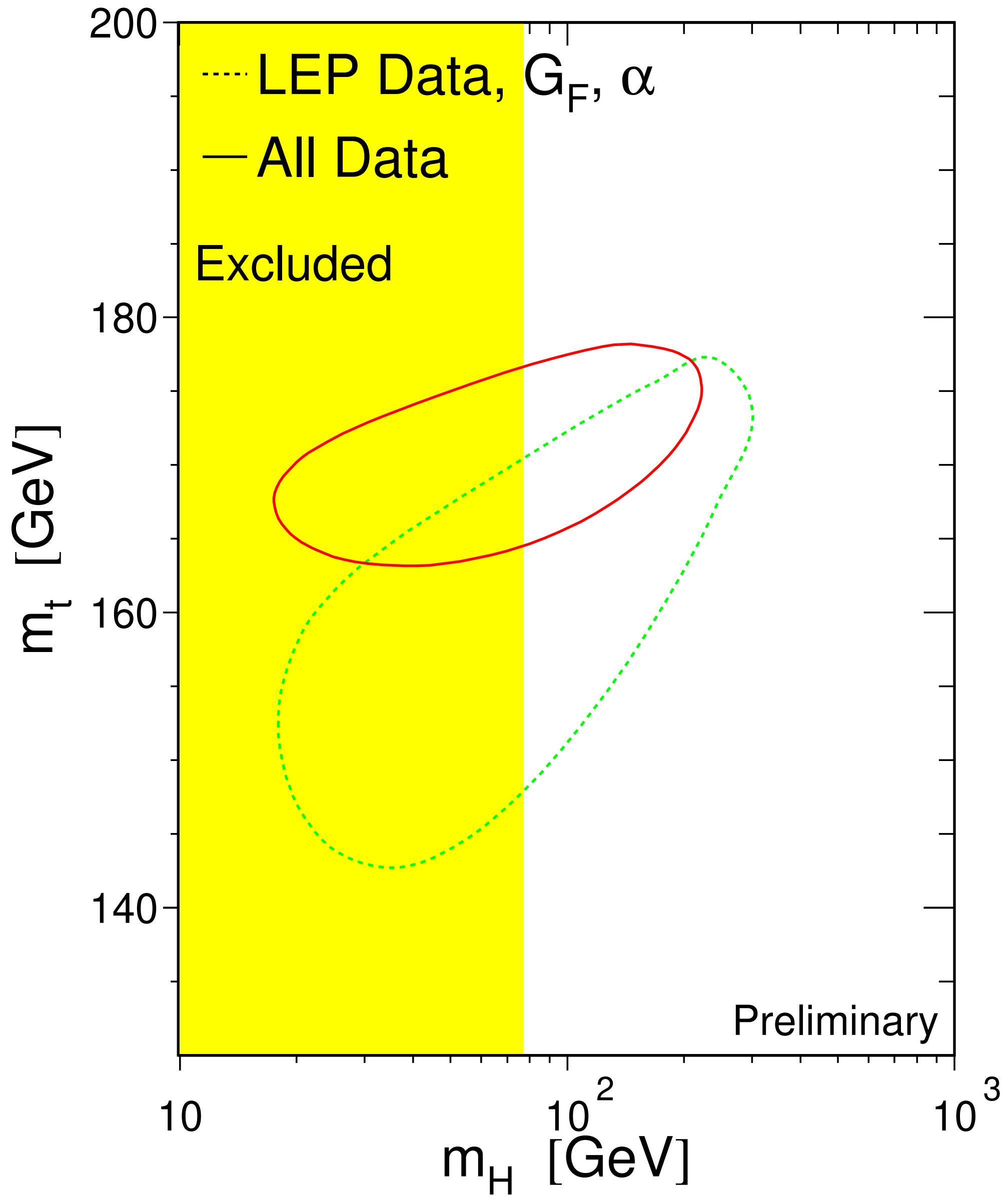


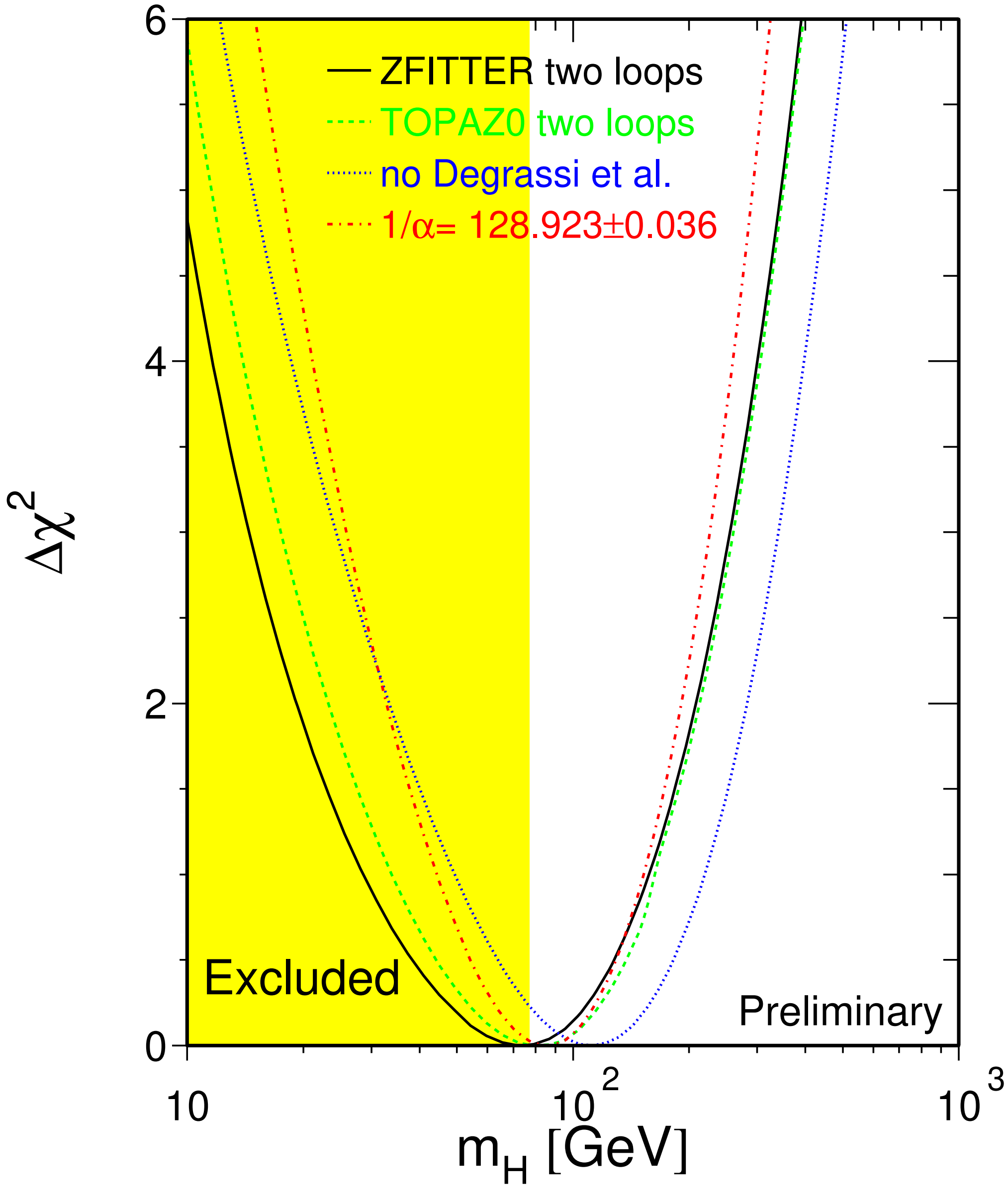
$\Rightarrow$ good agreement between all observables

$\Rightarrow$ preference for small m_{H}

Weak radiative corrections:
depend on m_t and on $\log m_H$

- SM fit to LEP measurements (Z parameter, $\sin^2\bar{\vartheta}_W$, m_W, ...)
- include direct m_t measurement and SLD (+ others)





Result of SM fit:

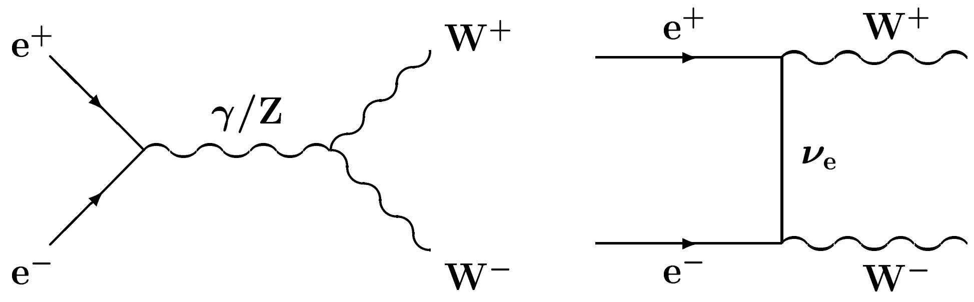
$$\log m_{\mathrm{H}}/\mathrm{GeV} = 1.87^{+0.33}_{-0.41}$$

$$m_{\mathrm{H}} = 74^{+84}_{-45}\ \mathrm{GeV}$$

$$m_{\mathrm{H}} < 250\ \mathrm{GeV} \qquad (95\%\ \mathrm{CL})$$

(+ small theory uncertainty)

W-pair production at LEP:



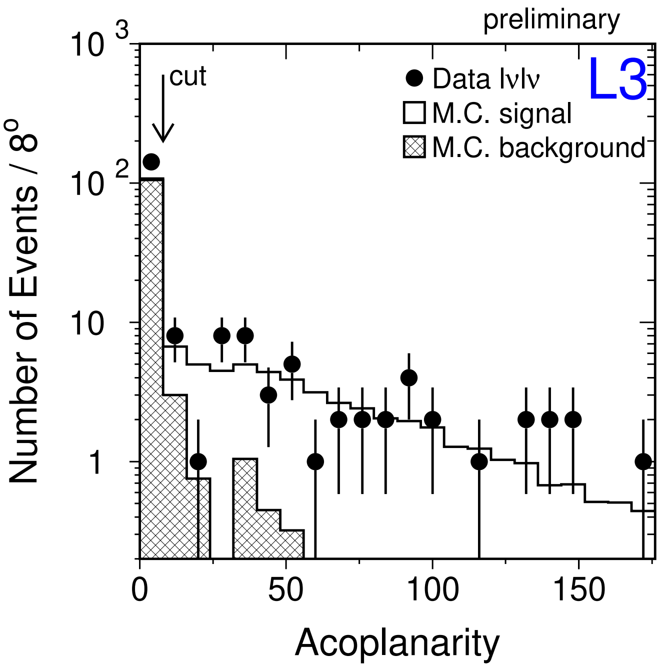
Measurement goals:

- Total cross section $e^+e^- \to W^+W^-(\gamma)$ as function of $\sqrt{s}$
- Differential cross sections
  $\Rightarrow$ Triple boson couplings
- Precise determination of m_W and Γ_W

Selection of $e^+e^- \to W^+W^-$ events

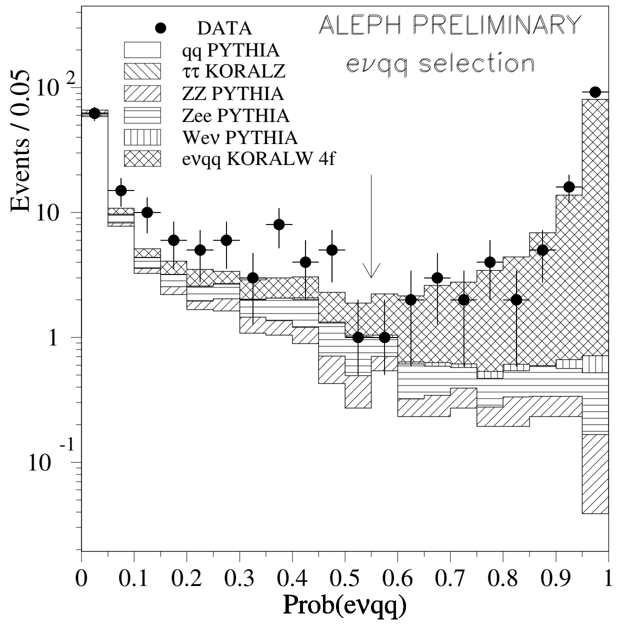
- $W^+W^- \to \ell\nu\ell\nu \quad (\approx 11\%)$

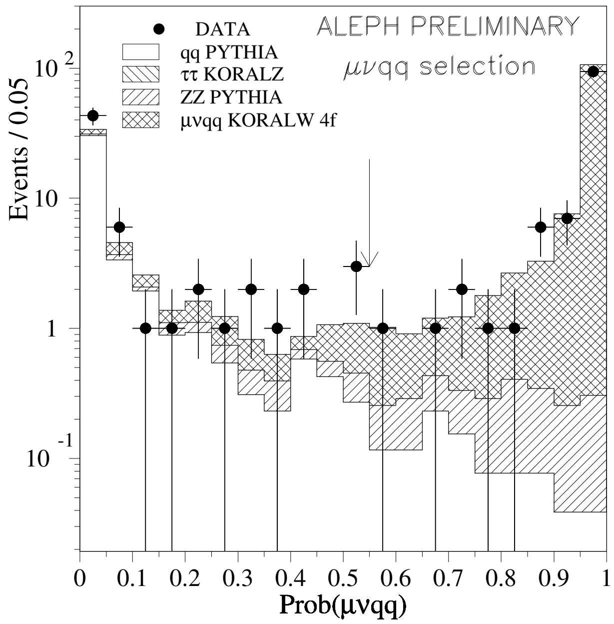
  two energetic, acoplanar leptons



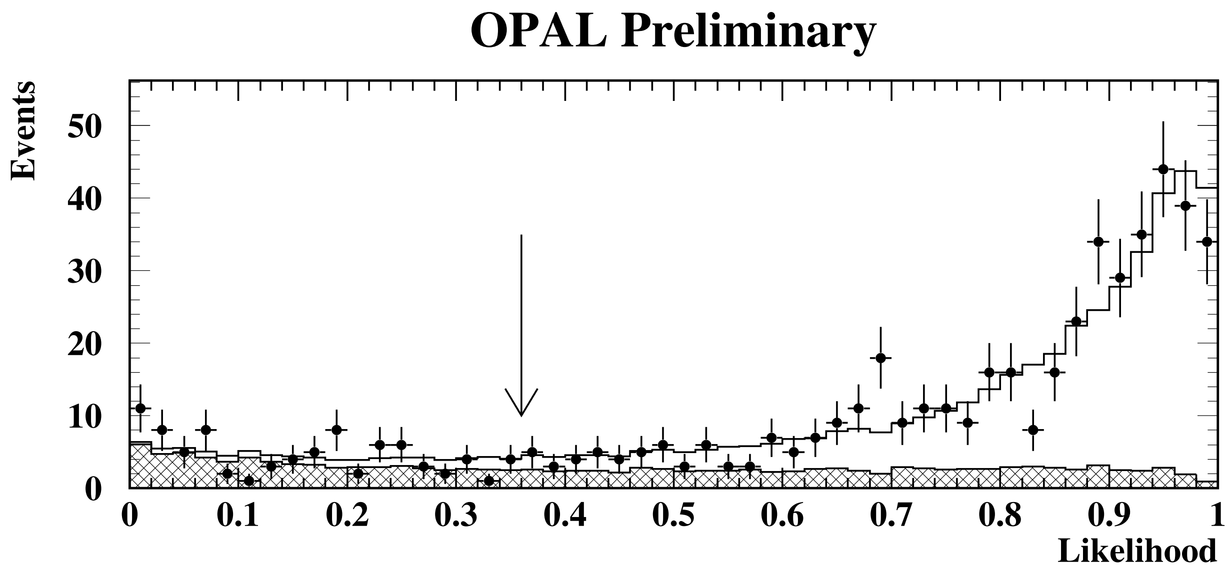
- $W^+W^- \to q\bar{q}\ell\nu \quad (\approx 44\%)$

  two jets plus isolated energetic lepton (or jet for $W^+W^- \to q\bar{q}\tau\nu$)





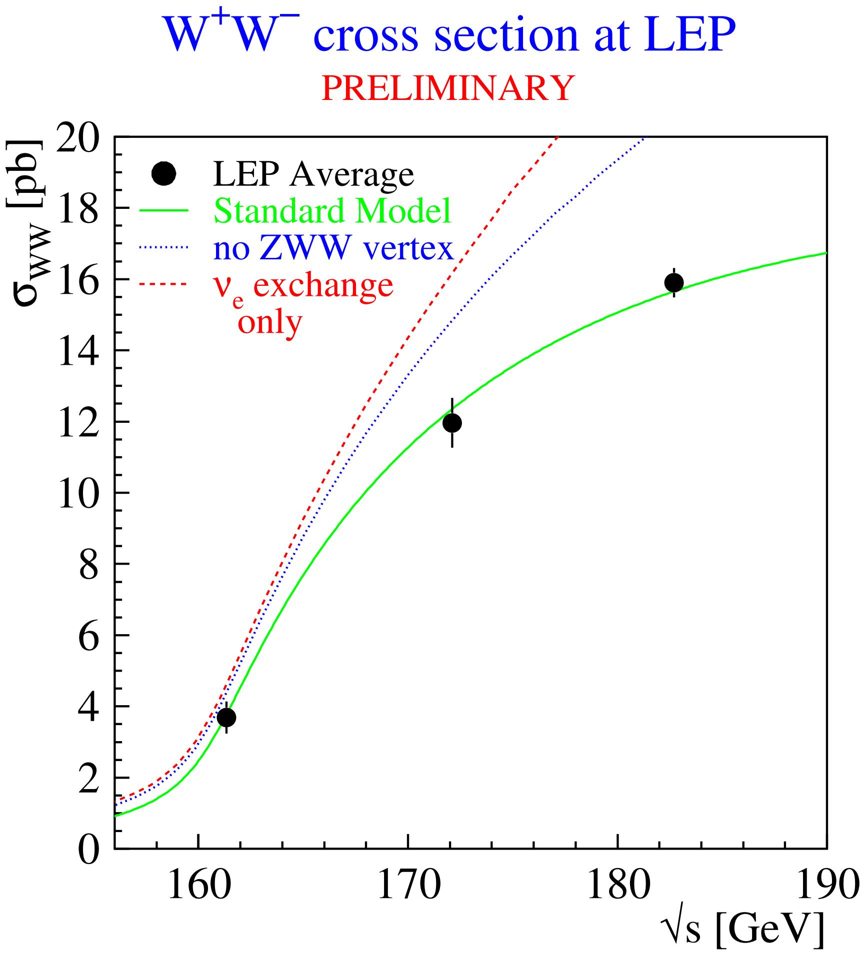
- $W^+W^- \to q\bar{q}q\bar{q}$ $(\approx 46\%)$
  four jets of similar energy
  severe background from QCD:
  $e^+e^- \to q\bar{q} + n$ gluons (≈ 100 pb)
  neural networks, likelihood analyses



≈ 900 $e^+e^- \to W^+W^-$ events per experiment
mostly at 183 GeV

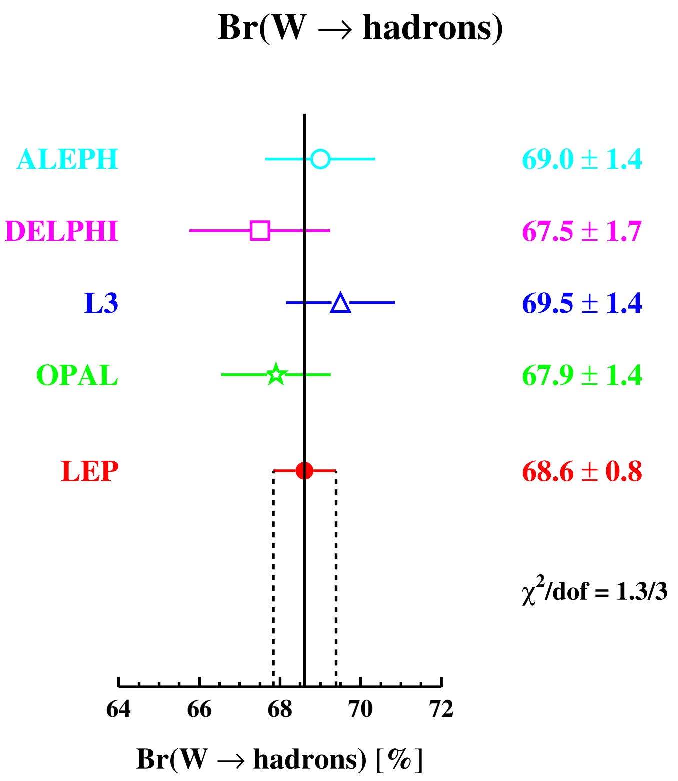
Cross section $e^+e^- \to W^+W^-$ at $\sqrt{s} = 183$ GeV:

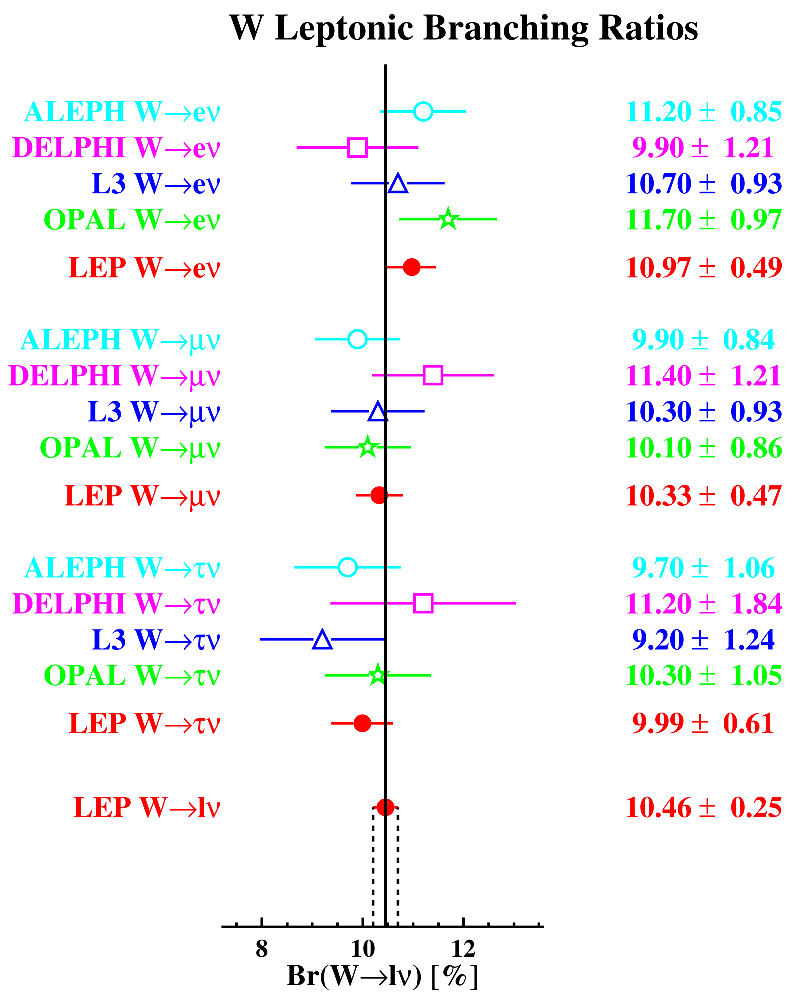
	σ_{WW}
ALEPH	15.51 ± 0.71 pb
DELPHI	16.01 ± 0.83 pb
L3	16.66 ± 0.73 pb
OPAL	15.52 ± 0.71 pb
combined	15.90 ± 0.41 pb



- perfect agreement with SM
- existence of triple gauge boson couplings

Direct measurements of W branching fractions:

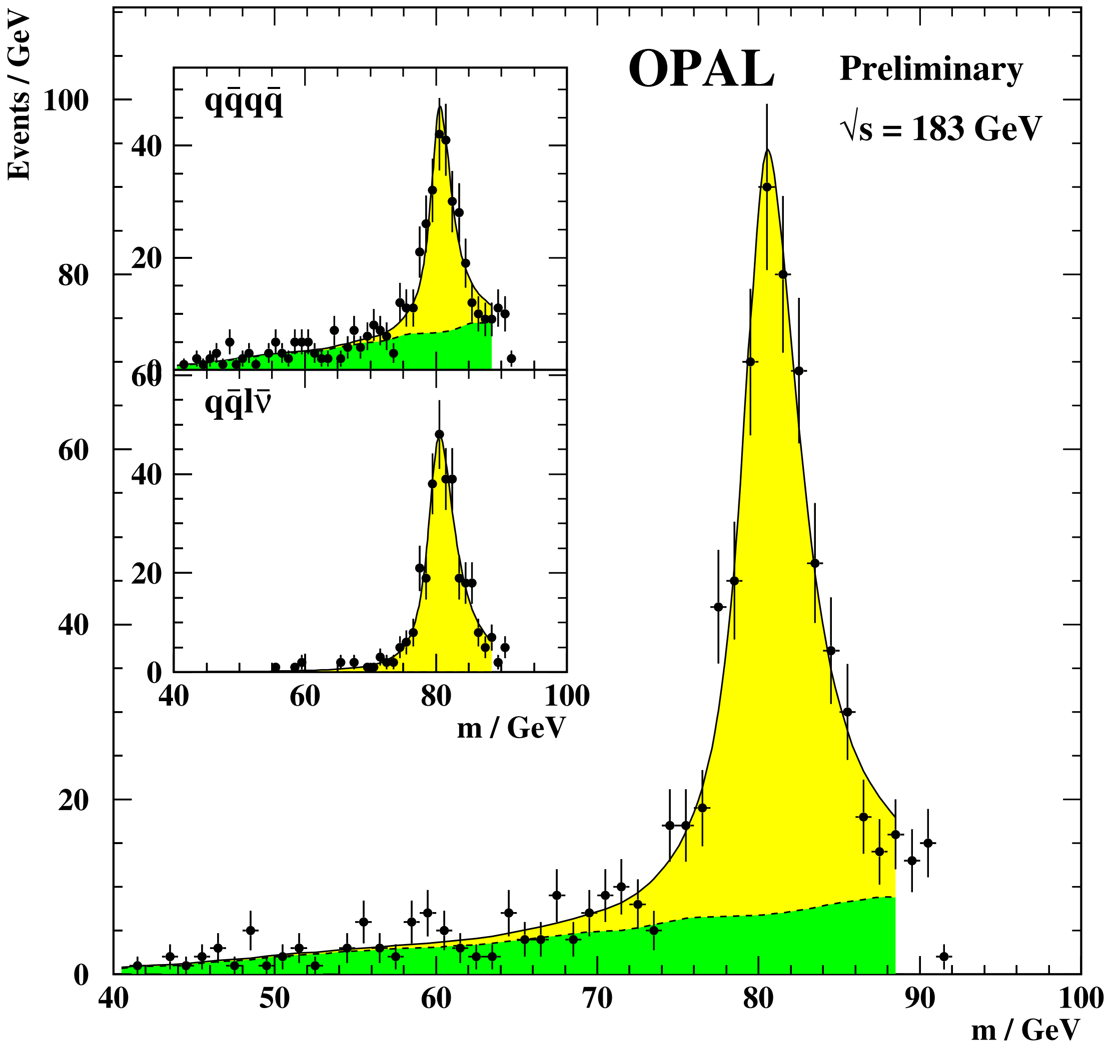




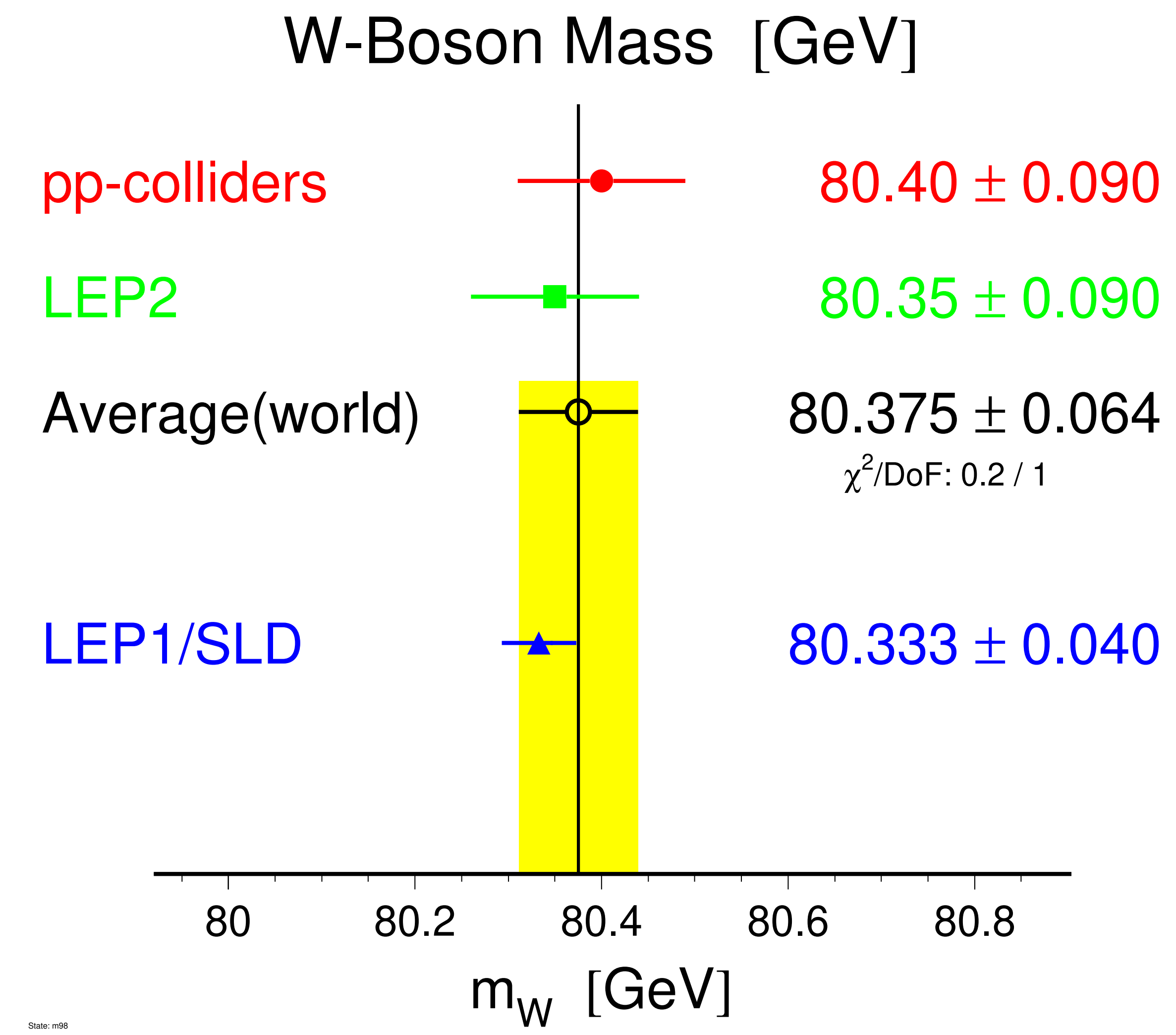
SM values: 67.5% 10.8%

Measurement of the W mass:

- at threshold $\sqrt{s} = 161$ GeV from σ_{WW}
  $m_{\mathrm{W}} = 80.40^{+0.22}_{-0.21}$ GeV
- at higher energies from direct reconstruction
  kinematic fit (WW $\rightarrow$ qqqq and WW $\rightarrow$ qq$\ell\nu$)
  constrain $m_{\mathrm{W}1} = m_{\mathrm{W}2}$ or $|m_{\mathrm{W}1} - m_{\mathrm{W}2}| \approx \Gamma_{\mathrm{W}}$



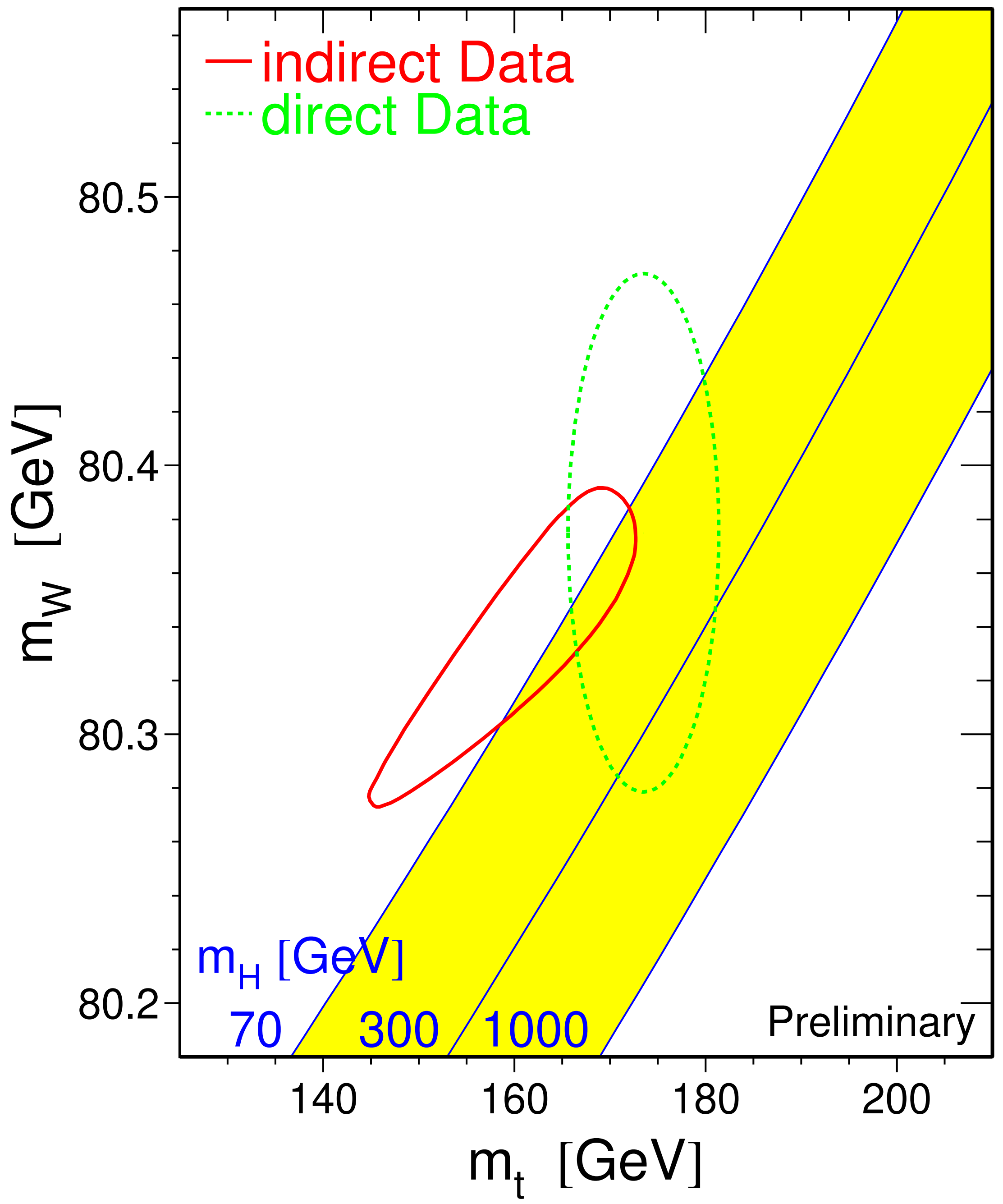
Comparison of m_{W} measurements:



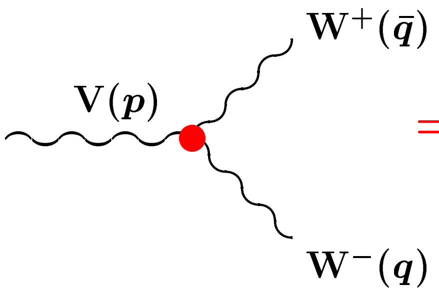
- good agreement between all determinations
- same precision for e^+e^- and $p\bar{p}$ experiments

Remark: LEP II m_{W} from WW $\rightarrow$ qqqq contains 100 MeV error from Bose-Einstein correleations and colour reconnection

Comparison of m_t and m_W determinations



Anomalous triple-gauge-boson couplings



$$= -ieg_{\rm VWW}\,\Gamma_{\rm V}^{\alpha\beta\gamma}(q,\bar{q},p)$$

2×7 complex couplings (V =, γ, Z)

Assume real couplings, C-, P- and CP invariance,
charge of W$^\pm$ ($=\pm e$)
$\Rightarrow$ 5 anomalous couplings

$$\delta_{\rm Z}, \kappa_\gamma, \kappa_{\rm Z}, \lambda_\gamma, \lambda_{\rm Z}$$

Standard Model:
$\delta_{\rm Z} = g_{\rm ZWW} - \cot\Theta_{\rm W} = 0$
$\kappa_\gamma = \kappa_{\rm Z} = 1 \qquad \lambda_\gamma = \lambda_{\rm Z} = 0$

Related to magnetic and electric quadrupole moment of W:
$\mu_{\rm W} = \dfrac{e}{2m_{\rm W}}(1+\kappa_\gamma+\lambda_\gamma), \quad Q_{\rm W} = -\dfrac{e}{m_{\rm W}}(\kappa_\gamma - \lambda_\gamma)$

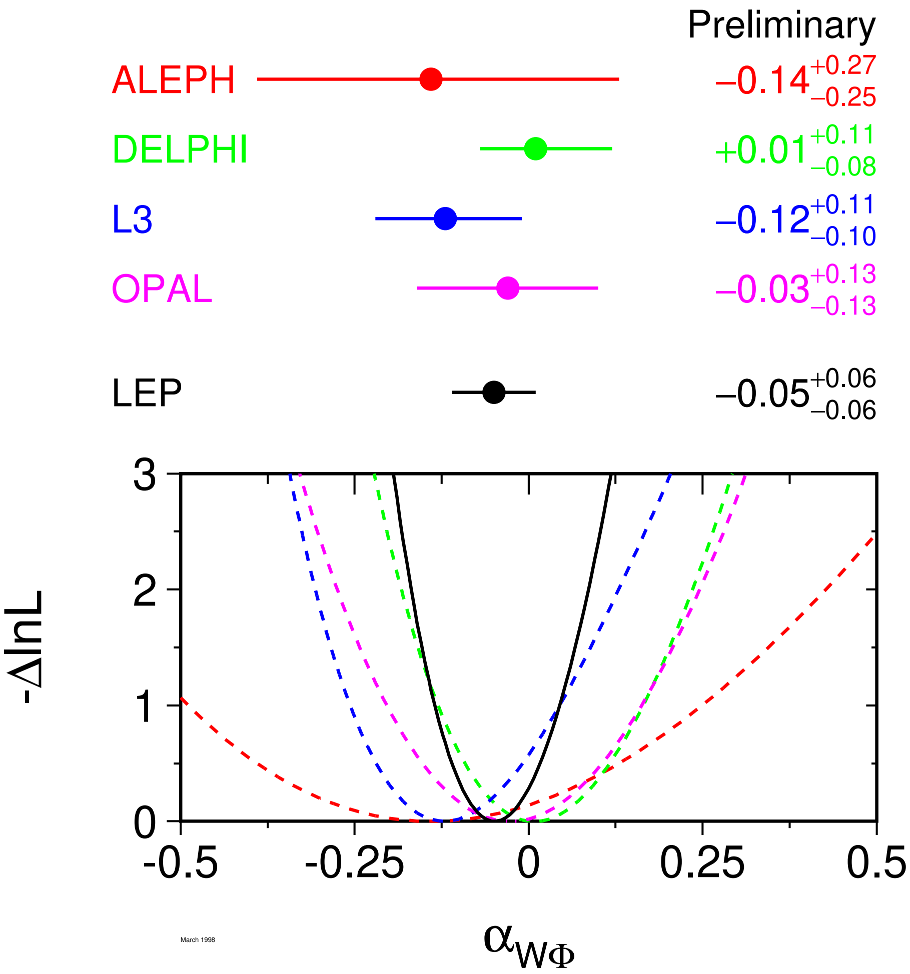
Linear combinations which do not alter gauge boson propagators at tree level:

$$\begin{aligned}
\alpha_{{\rm W}\phi} &= \Delta g_{\rm ZWW}\,\cos^2\Theta_{\rm W}\\
\alpha_{\rm W} &= \lambda_\gamma\\
\alpha_{{\rm B}\phi} &= \Delta\kappa_\gamma - g_{\rm ZWW}\,\cos^2\Theta_{\rm W}
\end{aligned}$$

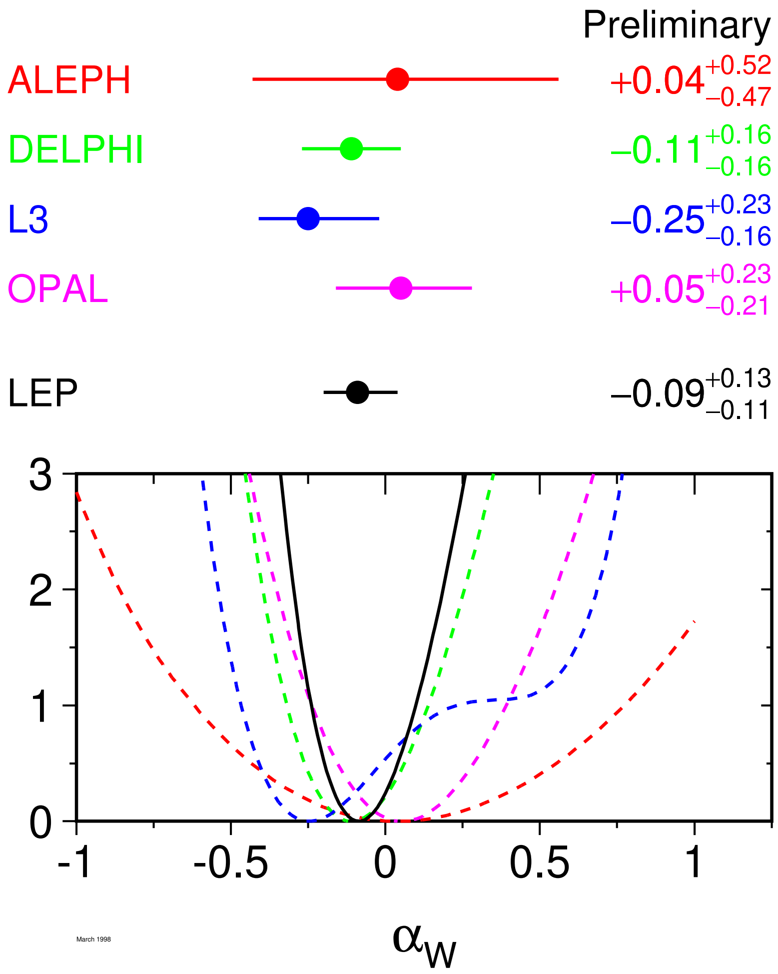
Δ denotes deviation from SM value

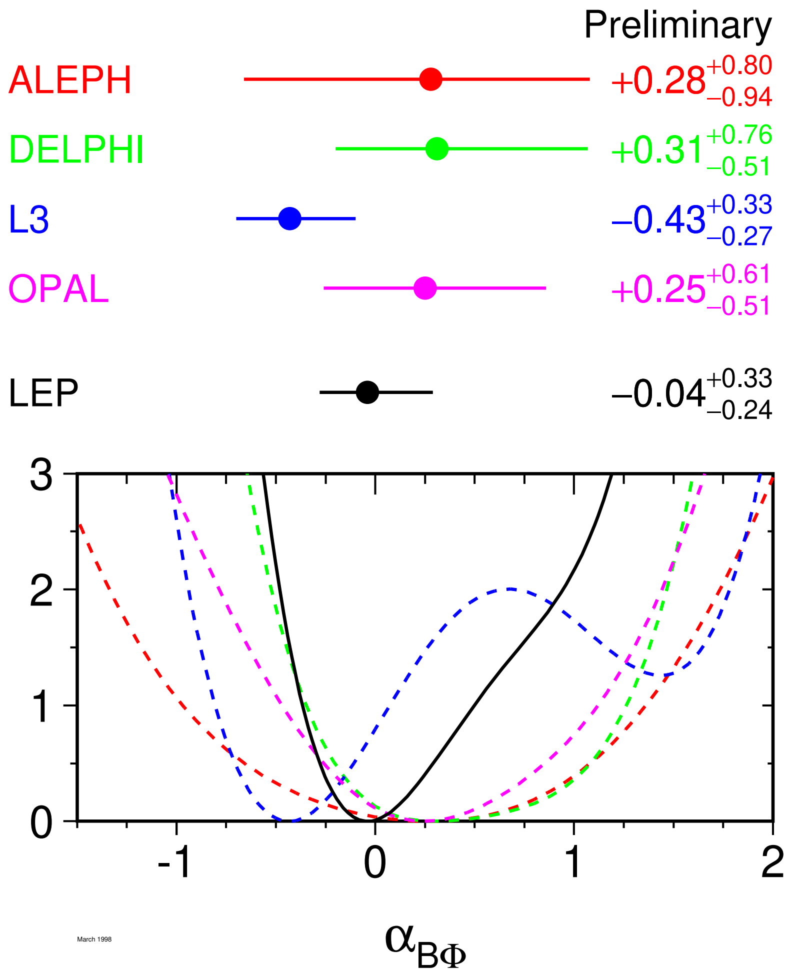
Anomalous couplings change

- Total cross section σ_{WW}
- Differential distributions
  W production angle, decay angles in the W system



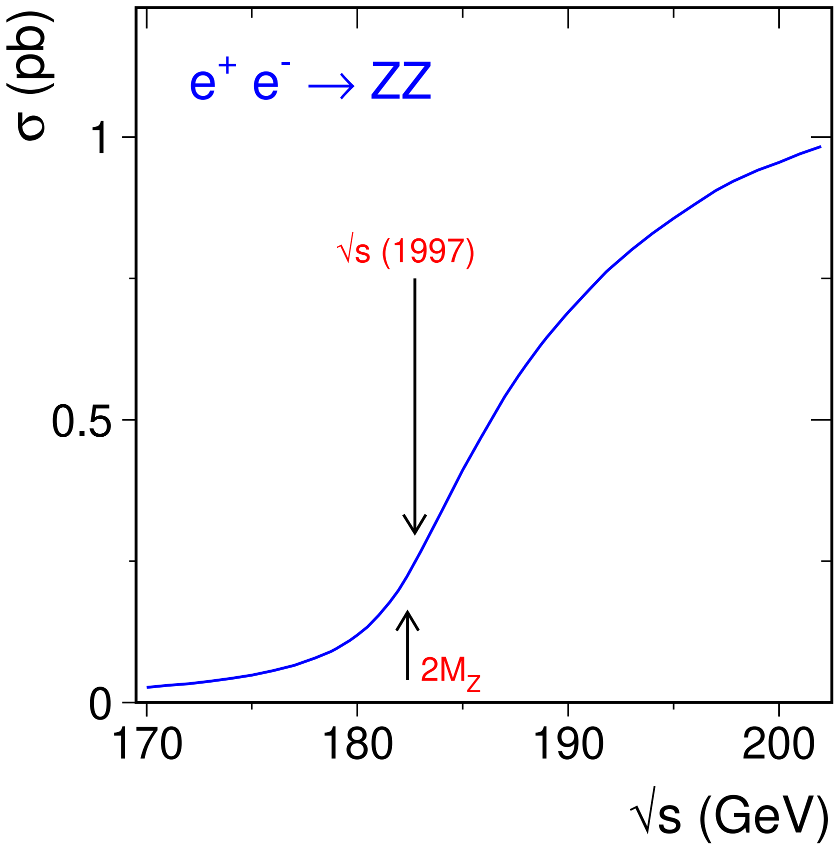
(ALEPH only 161 – 172 GeV data)


Preliminary
ALEPH +0.04 +0.52 −0.47
DELPHI −0.11 +0.16 −0.16
L3 −0.25 +0.23 −0.16
OPAL +0.05 +0.23 −0.21
LEP −0.09 +0.13 −0.11
-ΔlnL
α_W


Preliminary
ALEPH +0.28 +0.80 −0.94
DELPHI +0.31 +0.76 −0.51
L3 −0.43 +0.33 −0.27
OPAL +0.25 +0.61 −0.51
LEP −0.04 +0.33 −0.24
-ΔlnL
α_BΦ

Z pair production

New at $\sqrt{s} = 183$ GeV: $e^+e^- \to ZZ$



Few events observed in 1997
No physics results yet

Future:
cross section measurement
background for searches (Higgs)

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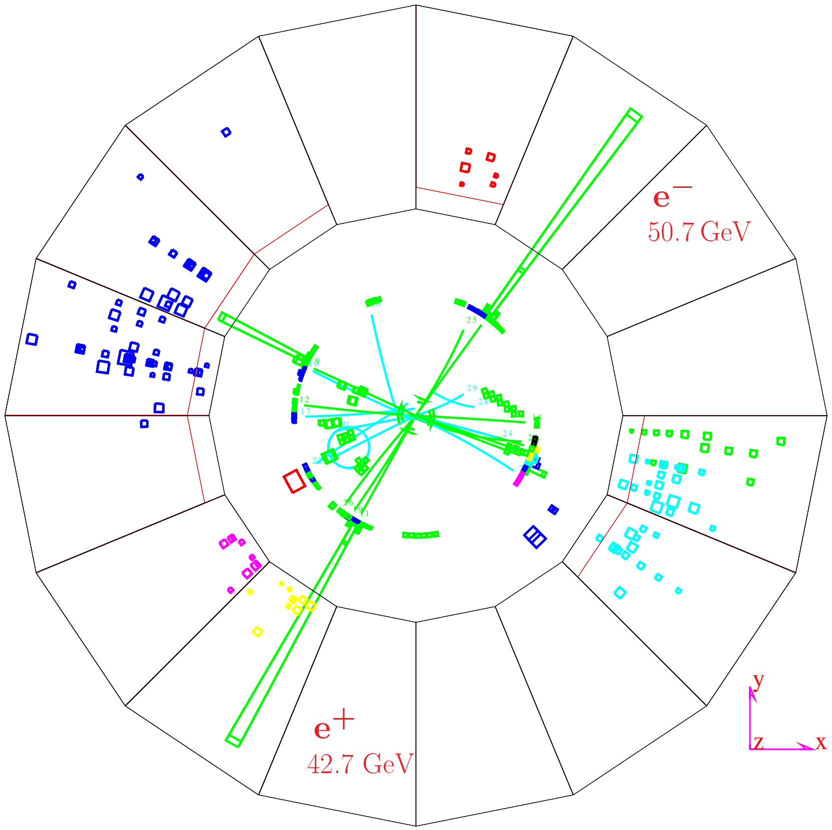
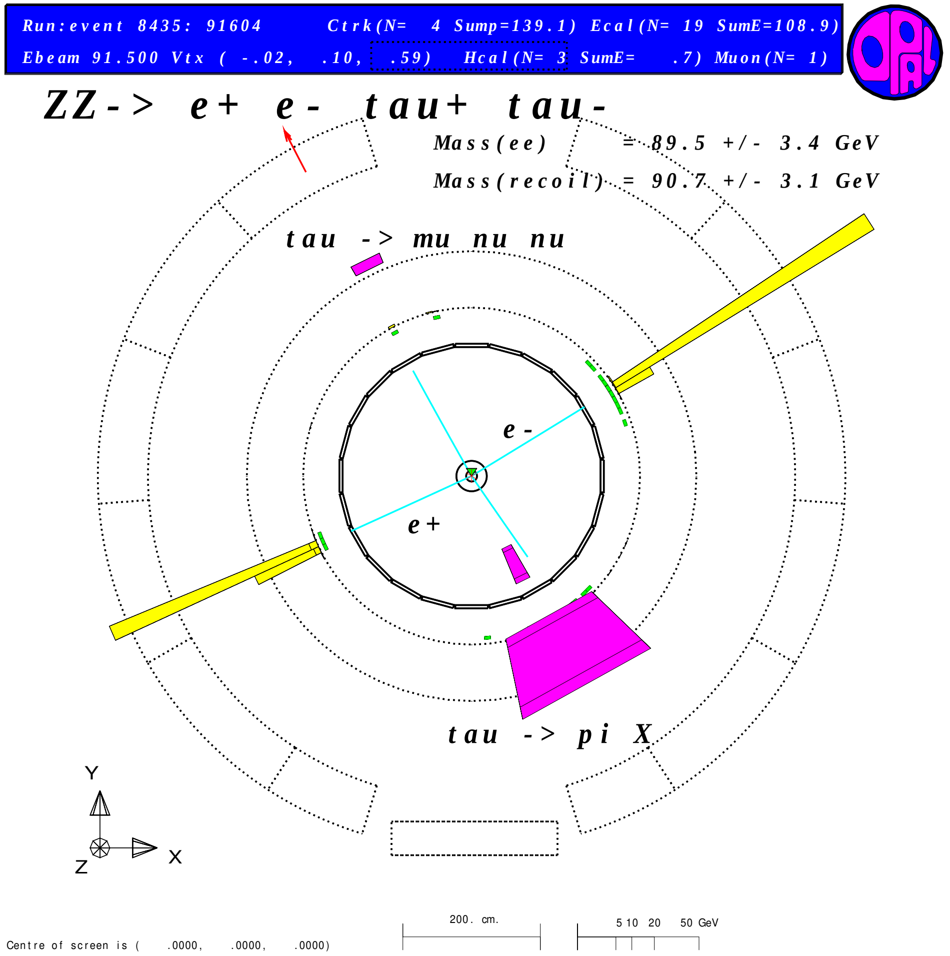
Z pair production

Run # **688905** **Event #** **1652** Total Energy : 180.75 GeV



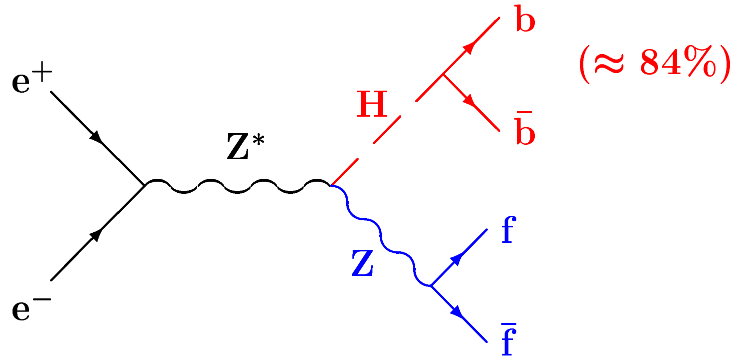


$m_{\mathrm{ee}} = 92.8$ GeV $\qquad m_{\mathrm{jj}} = 88.8$ GeV

March 26th 1998

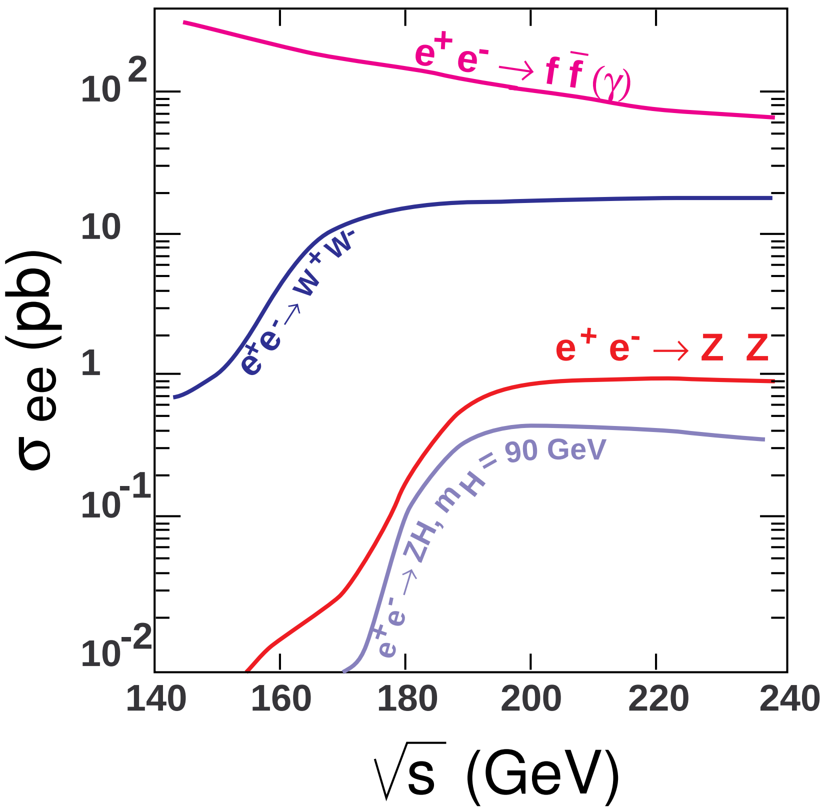
Search for the SM Higgs Boson

SM Higgs production at LEP II:



(+ small contribution from WW fusion diagram)

Requires $\sqrt{s} > m_Z + m_H$



- Sizeable Higgs production cross section
- Much better signal to background ratio as compared to LEP I

Four distinct final state topologies:

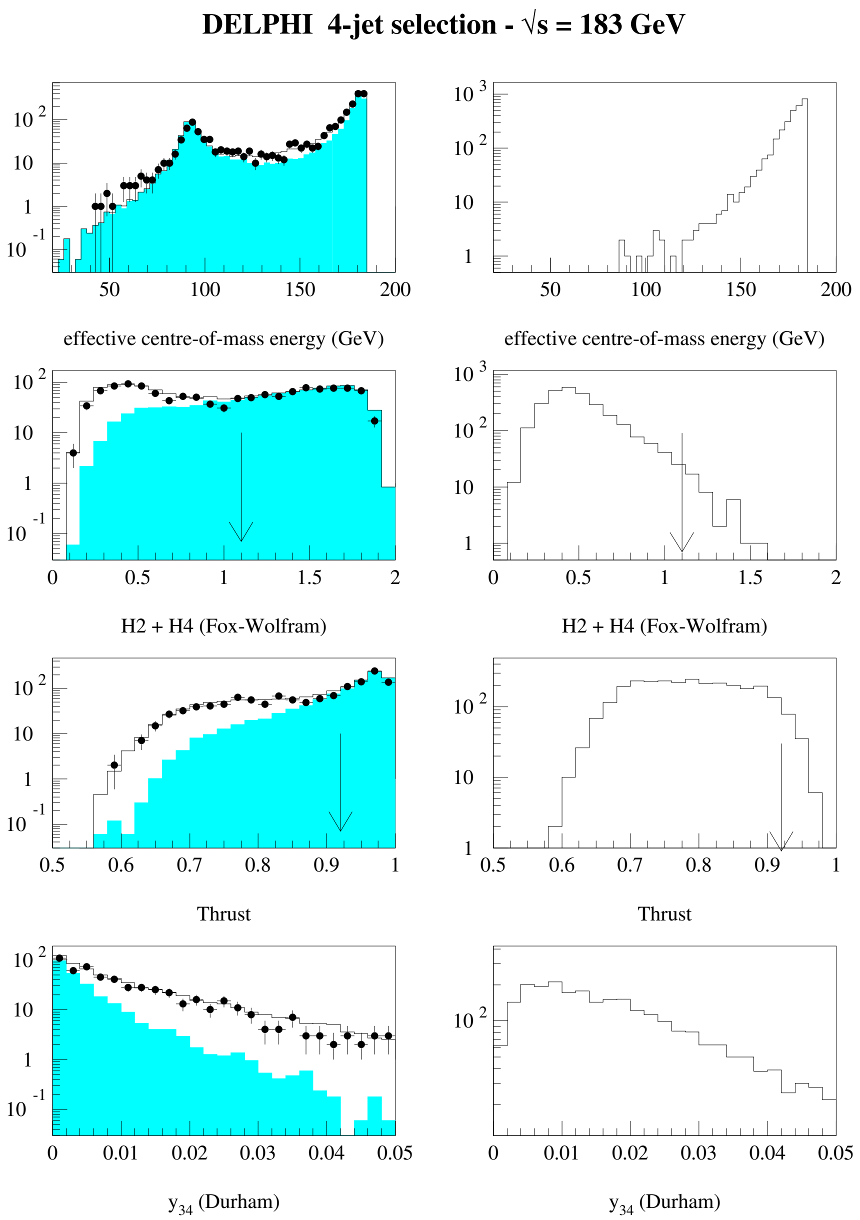
$\mathrm{H}q\bar{q}$	- four jets
$\mathrm{H}\nu\bar{\nu}$	- two acoplanar jets
$\mathrm{He^+e^-}$, $\mathrm{H}\mu^+\mu^-$	- two jets, two leptons
$\tau^+\tau^- q\bar{q}$	- two taus, two jets

Main backgrounds:

- **Fermion pairs, in particular** $\mathrm{e^+e^-} \rightarrow \mathrm{Z}/\gamma \rightarrow q\bar{q}(\gamma)$
- **Four fermion final states** $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$, ZZ
- **Single W production** $\mathrm{e^+e^-} \rightarrow \mathrm{W\,e}\nu$ **(for** $\mathrm{H}\nu\bar{\nu}$**)**

b-tagging is crucial

- preselection, e.g. 4-jet events for $Hq\bar{q}$ channel

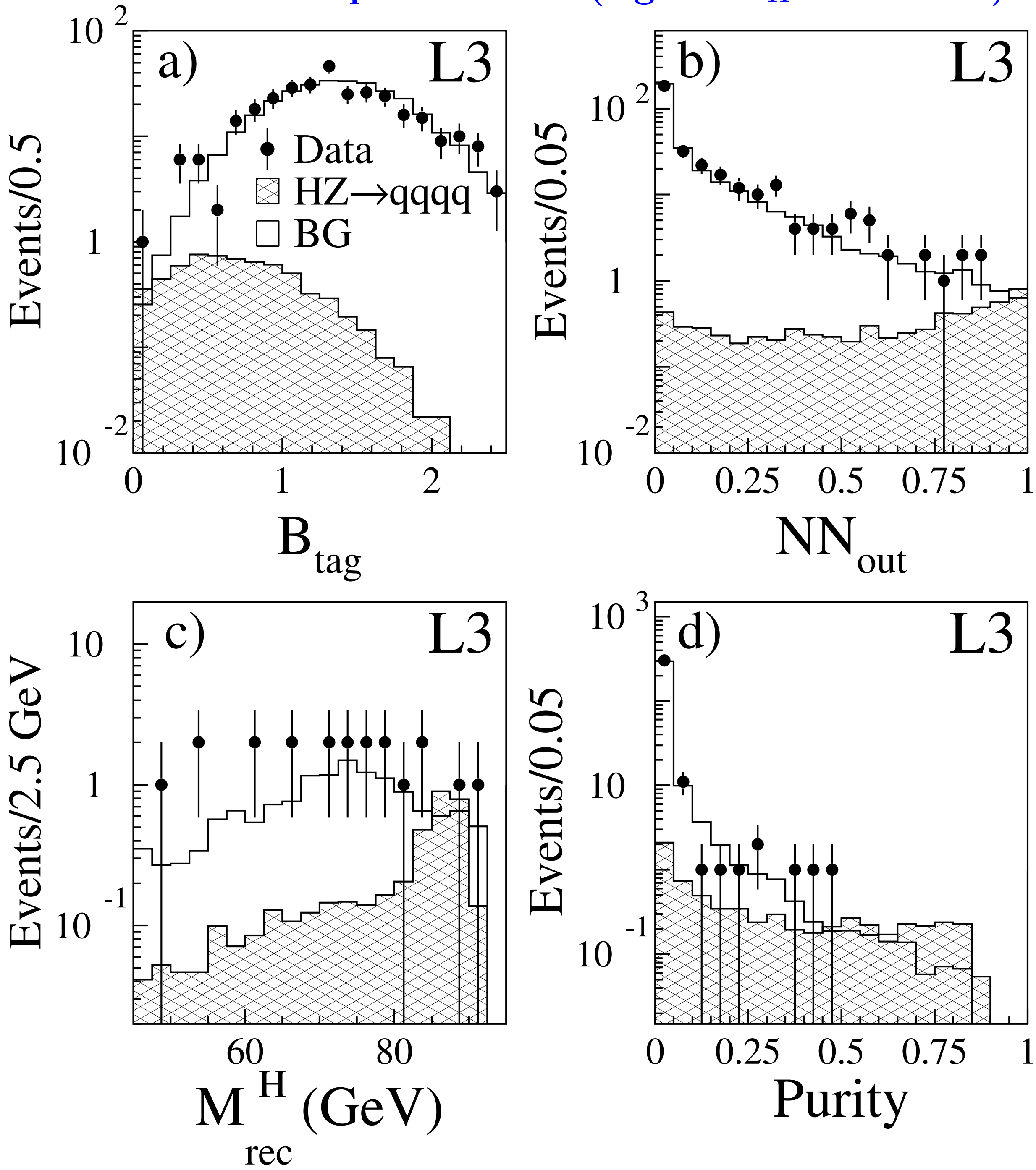


$e^+e^- \to f\bar{f}(\gamma)$ processes   signal $m_H = 85$ GeV

- mass-independent disriminant variable (b-tag, neural network)
- kinematic fit imposing m_Z constraint

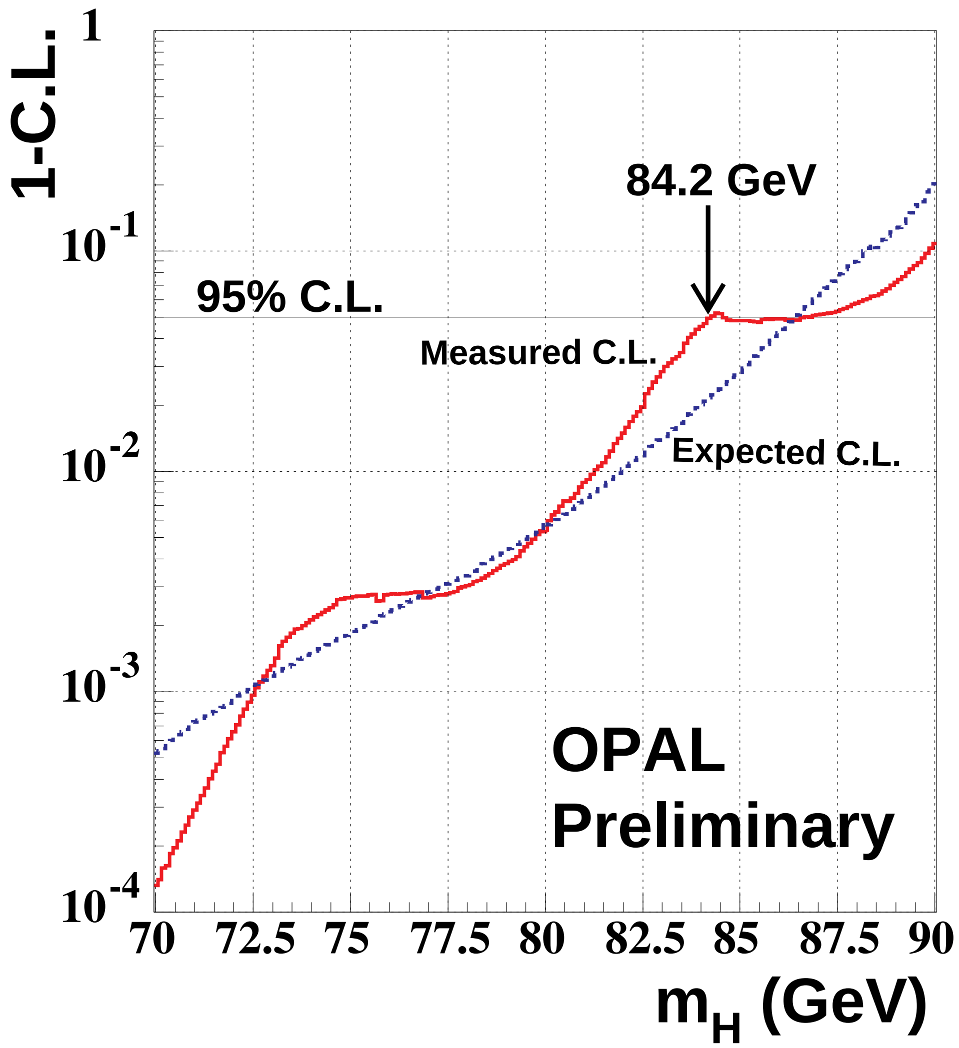
HZ $\rightarrow q\bar{q}q\bar{q}$

Distributions after preselection (signal $m_{\mathrm{H}} = 87$ GeV):



Neural network output and mass information combined to final discriminating variable (purity)

Preliminary lower limits on $m_{\rm H}$ from LEP, e.g. Opal



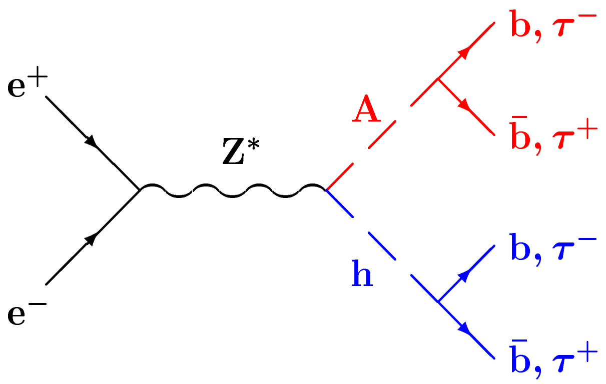
ALEPH	$m_{\rm H} > 88$ GeV
DELPHI	$m_{\rm H} > 84.4$ GeV
L3	$m_{\rm H} > 87.6$ GeV
OPAL	$m_{\rm H} > 84.2$ GeV

ALl we know about the SM Higgs boson mass today

$$88 \text{ GeV} < m_{\rm H} < 250 \text{ GeV}$$

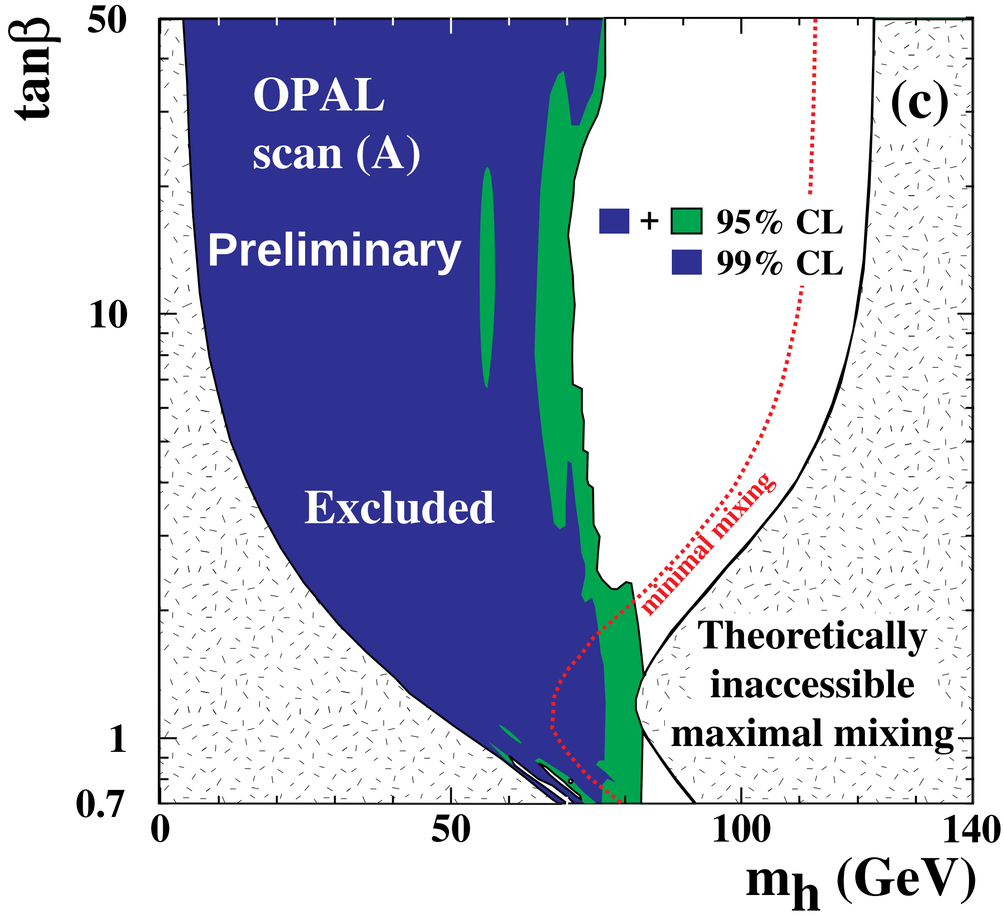
Supersymmetry:
Five fundamental scalar particle: H^+, H^-, H, h, A

- **Searches for hA**



- $\tan\beta$ large $\Rightarrow e^+e^- \rightarrow hA$
- $\tan\beta$ small $\Rightarrow e^+e^- \rightarrow hZ$

Combination of hZ and hA searches:
e.g. result from OPAL ($m_0 = M_2 = 1$ TeV)



ALEPH	$m_h > 73$ GeV
DELPHI	$m_h > 74.4$ GeV
OPAL	$m_h > 70.0$ GeV

parameter dependent

Possible SUSY scenarios

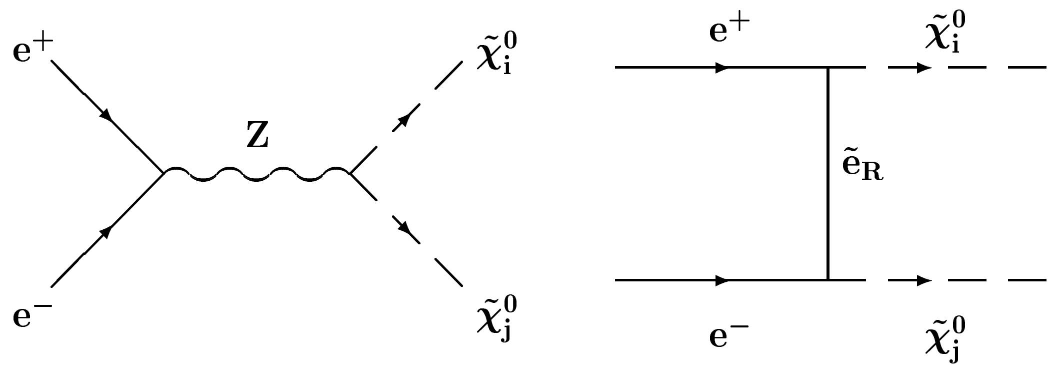
Candidates for LSP:

- $\tilde{\chi}_1^0$ gravity mediated SUSY breaking (heavy $\tilde{\mathrm{G}}$)
- $\tilde{\mathrm{G}}$ gauge mediated SUSY breaking
- R-parity violating SUSY; unstable LSP

Production of SUSY particles at LEP:

- $\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0 \qquad i,j = 1,\ldots,4$
- $\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$
- $\mathrm{e}^+\mathrm{e}^- \to \tilde{\ell}^+\tilde{\ell}^-$
- $\mathrm{e}^+\mathrm{e}^- \to \tilde{\mathrm{q}}\tilde{\mathrm{q}}$

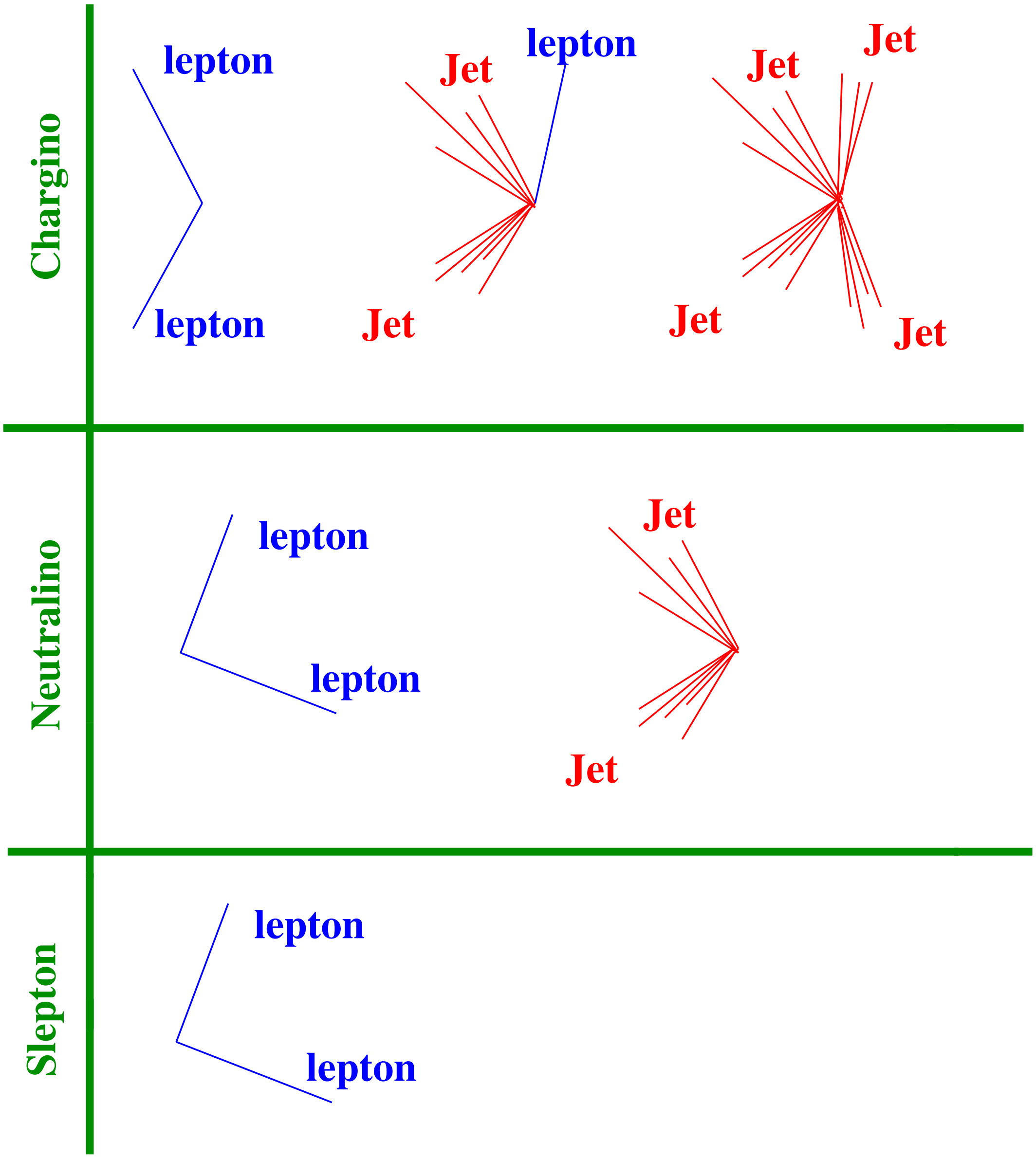
Example:



Decay of SUSY particles:

- $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q},\ \tilde{\chi}_1^0\ell\nu,\ \tilde{\nu}\ell$
- $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 f\bar{f},\ \tilde{\chi}_1^0\gamma$
- $\tilde{\ell}^\pm \to \ell^\pm\tilde{\chi}_1^0$

Typical signal topologies at $\sqrt{s} = 183$ GeV



Missing energy

Signatures depends on $\Delta M = m_{\mathrm{sparticle}} - m_{\mathrm{LSP}}$

$\approx$ visible energy

Results from the data at $\sqrt{s} = 183$ GeV:

No sign for Supersymmetry

e.g. summary L3 search results at 183 GeV

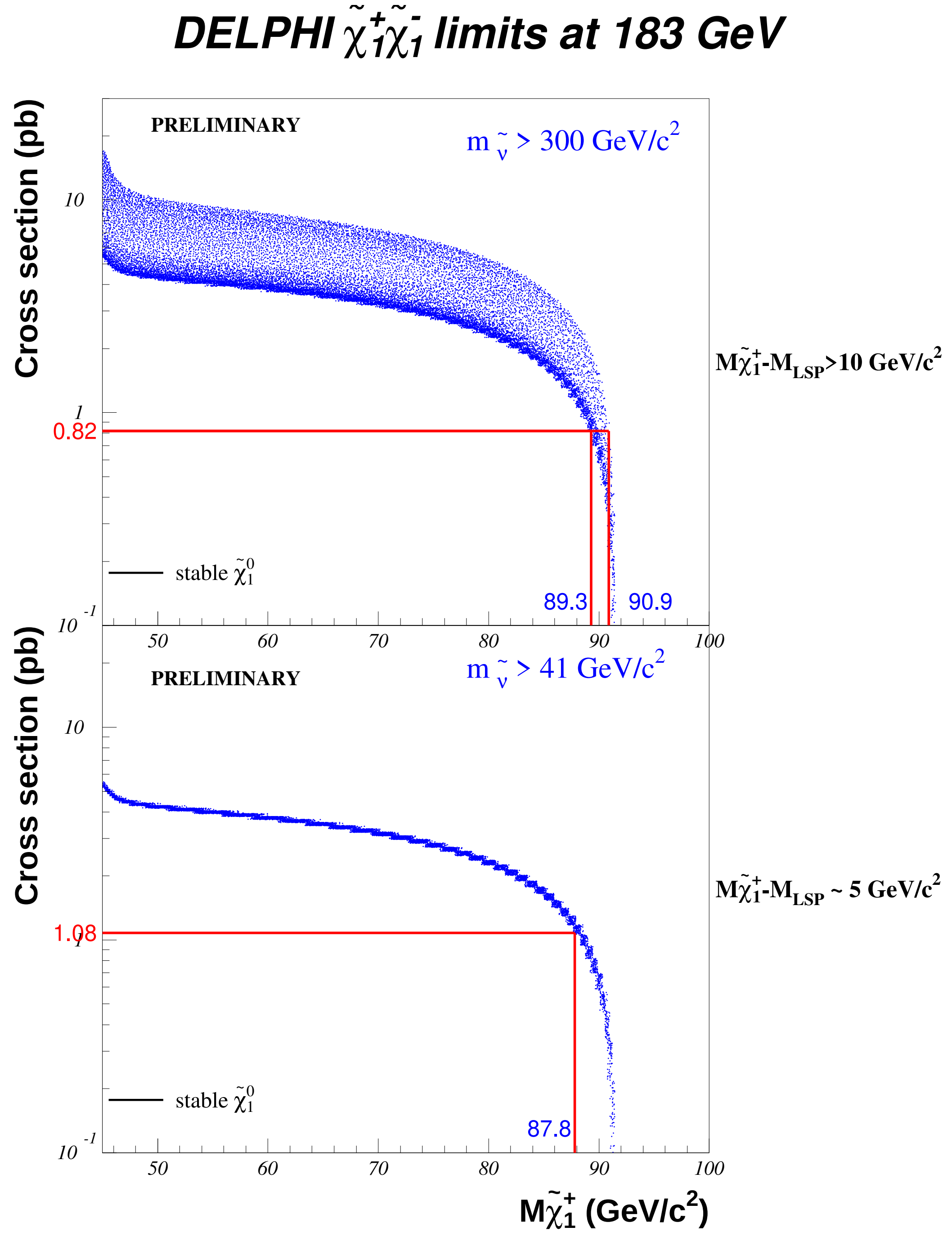
	$N_{\rm data}$	$N_{\rm bkgd}$
$\tilde{\rm e}$	3	7.1 ± 1.5
$\tilde{\mu}$	4	6.4 ± 1.8
$\tilde{\tau}$	8	7.9 ± 2.8
$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$	15	20.2 ± 7
Overall	27	32.4 ± 9

$\Rightarrow$ improved limits on production cross sections and SUSY parameters

A few examples given below ...

Chargino:

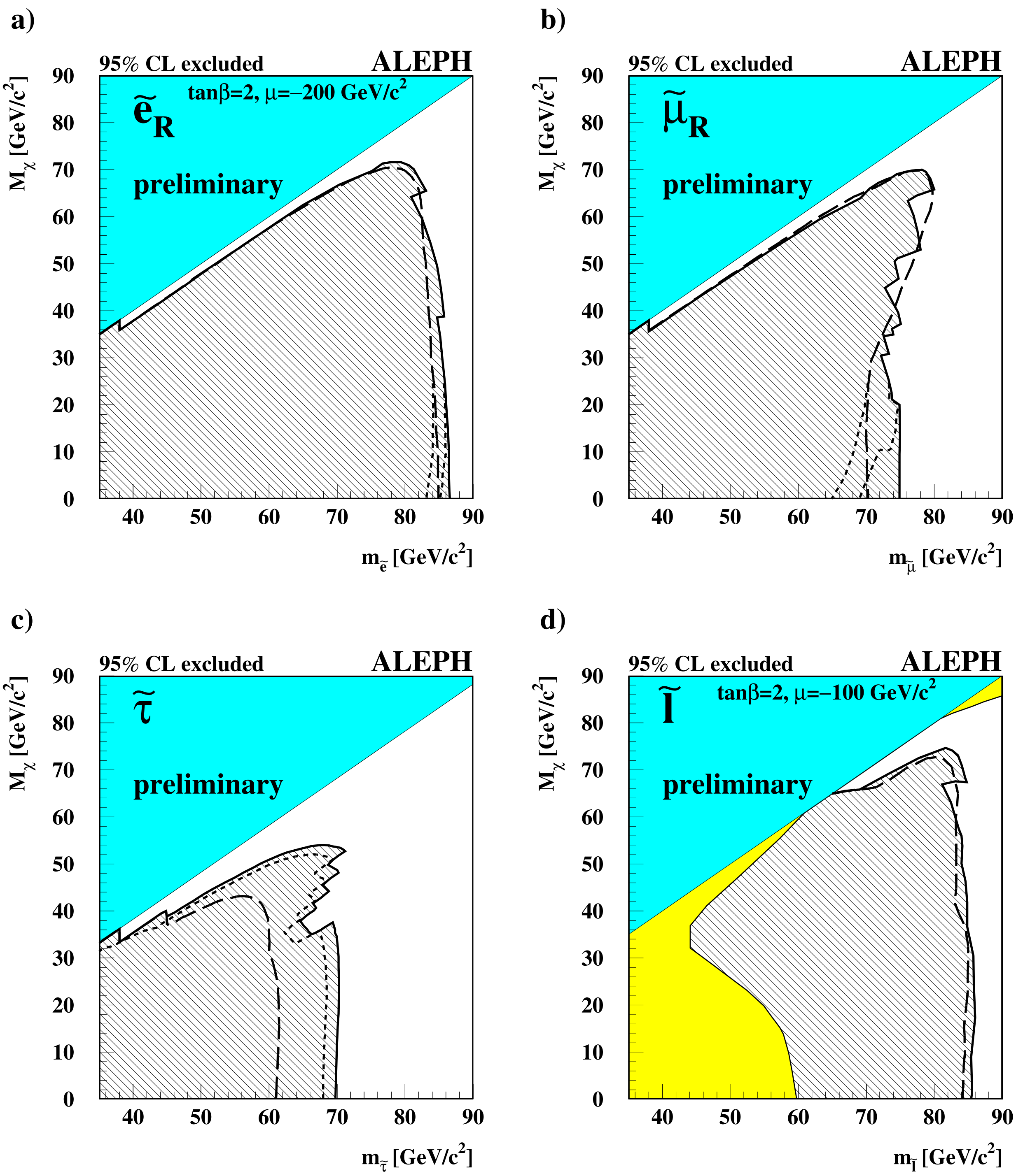
Large cross section



Masses close to kinematic limit are excluded

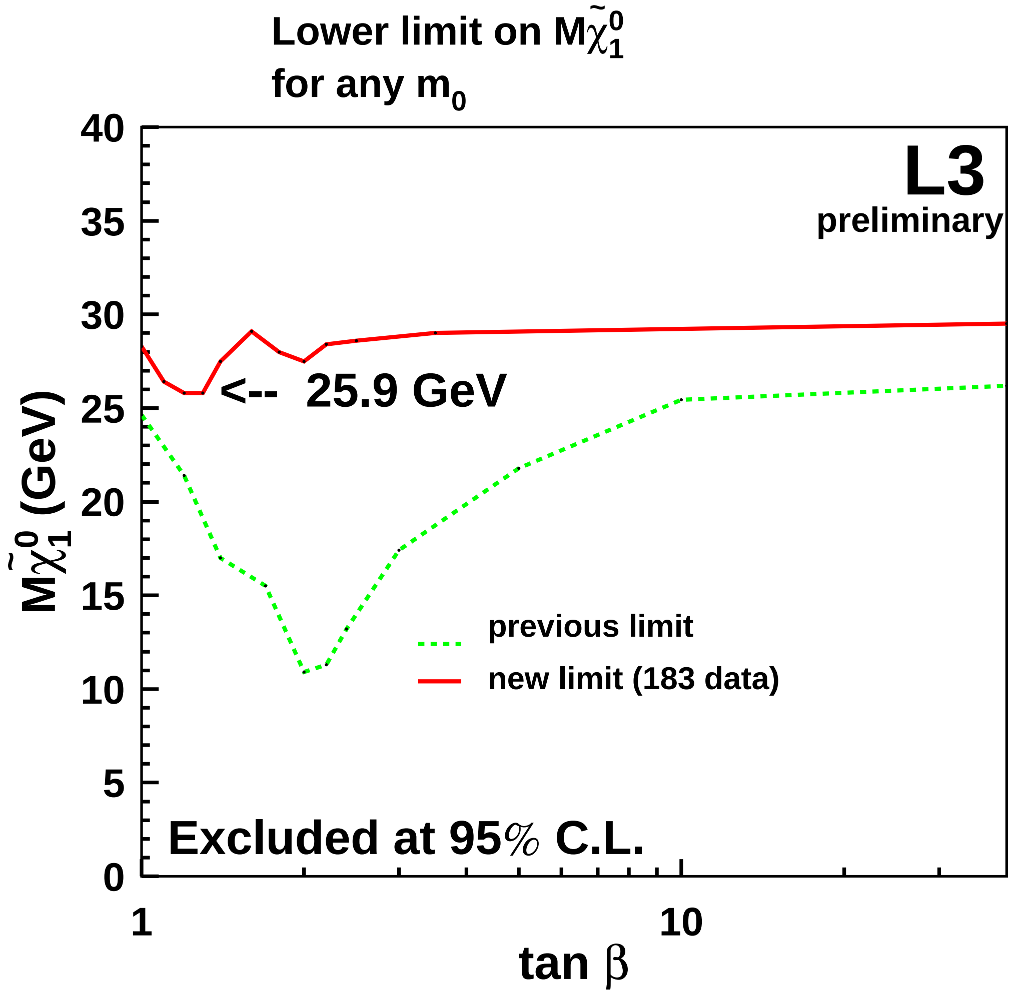
(for large m_0)

Search for scalar leptons
Mass limits in $\tilde{\chi}^0_1 - \tilde{\ell}$ plane (MSSM)



Result of chargino, neutralino and scalar lepton searches interpretation in MSSM

$\Rightarrow$ lower limit on $m_{\tilde{\chi}_1^0}$ valid for all m_0 and $\tan\beta > 1$

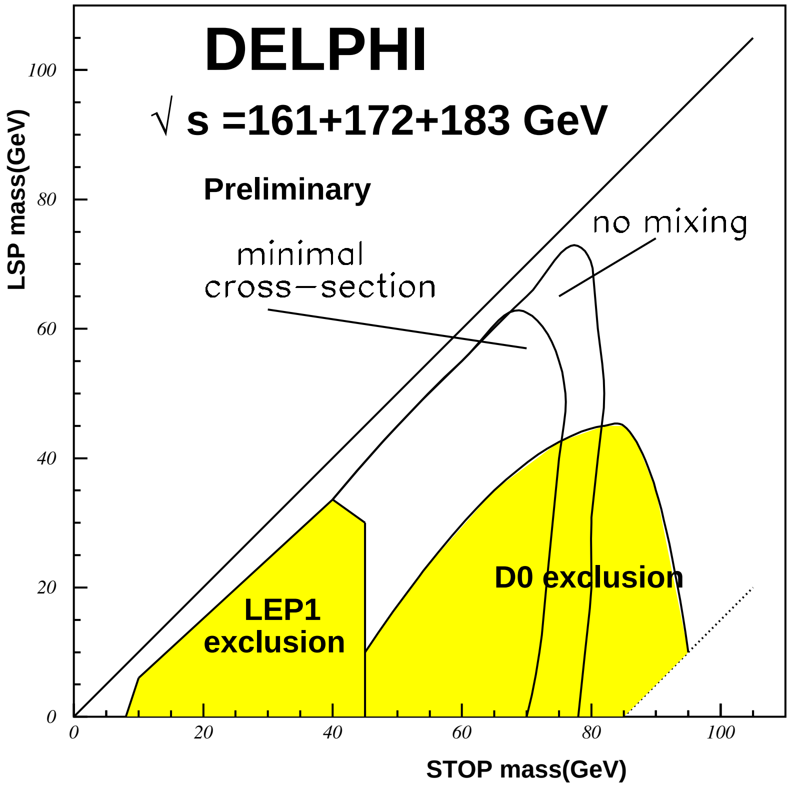


$$m_{\tilde{\chi}_1^0} > 25.9 \text{ GeV} \qquad 95\% \text{ CL}$$

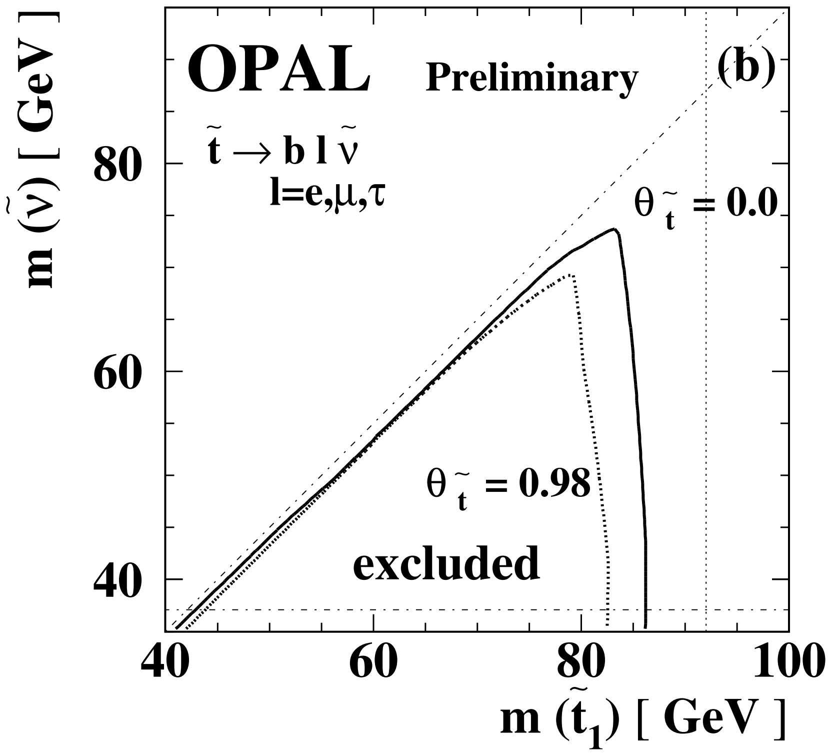
For large m_0 lower mass limit ≈ 30 GeV

Search for scalar top quarks

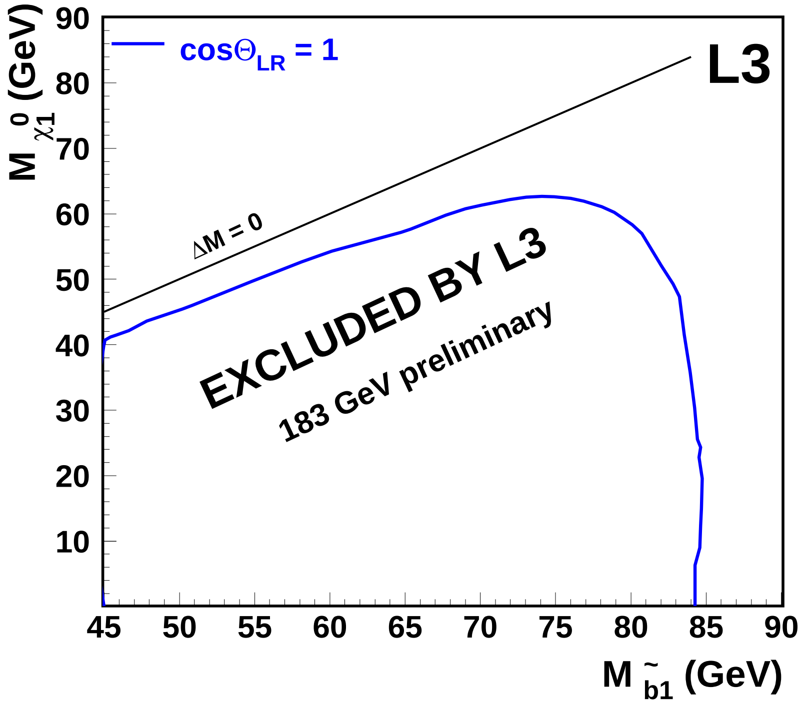
$\tilde{t} \to c\tilde{\chi}_1^0$

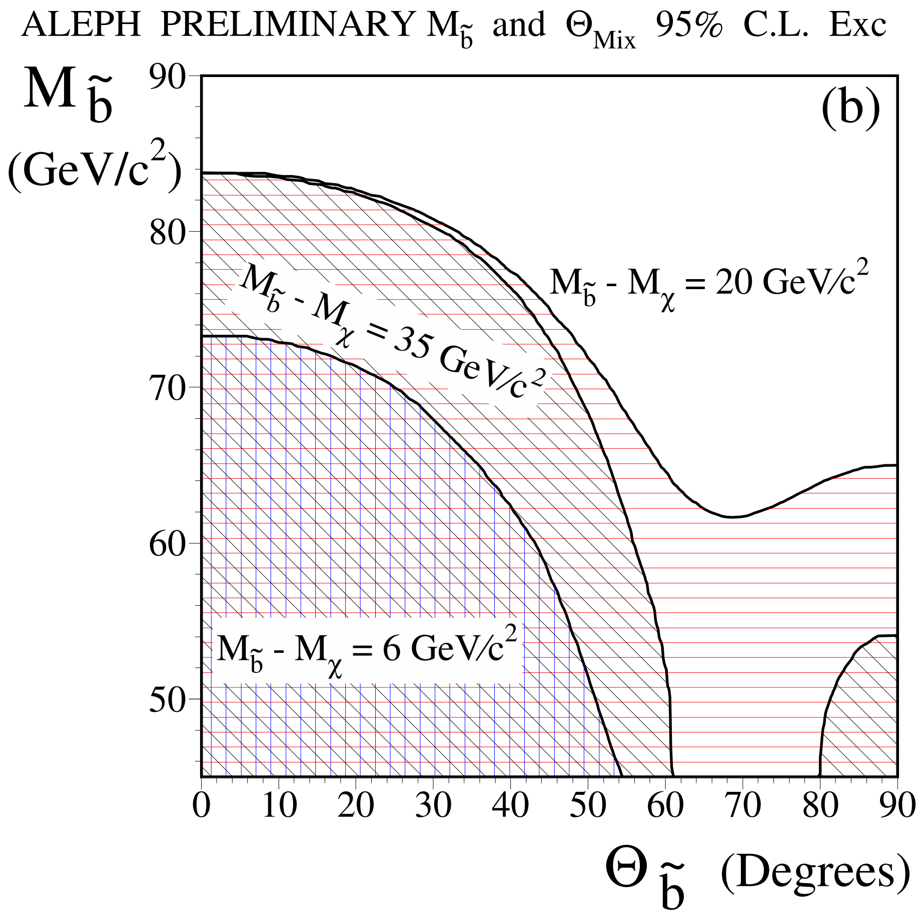


$\tilde{t} \to b\ell\tilde{\nu}$



Search for scalar bottom quarks





Single and multi-photons with missing energy at $\sqrt{s} = 183$ GeV

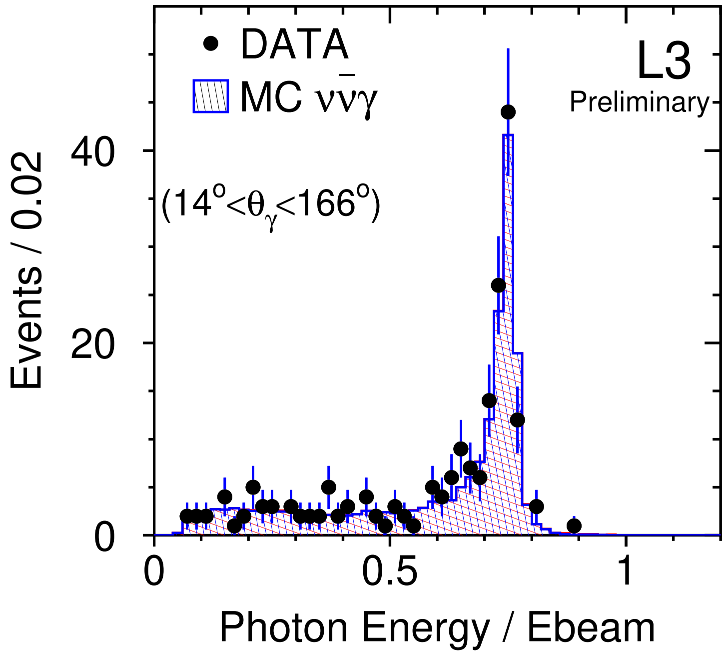
Standard Model:

- $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$
- $e^+e^- \to (e^+e^-)\,\gamma(\gamma)$

Supersymmetry

$$\begin{aligned} e^+e^- &\to \tilde{\chi}^0_2\tilde{\chi}^0_1 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma \\ &\to \tilde{G}\tilde{G}\gamma \\ &\to \tilde{\chi}^0_1\tilde{G} \to \tilde{G}\tilde{G}\gamma \\ &\to \tilde{\chi}^0_2\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma\gamma \\ &\to \tilde{G}\tilde{G} \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma\gamma \end{aligned}$$

Single photon energy spectrum at $\sqrt{s} = 183$ GeV

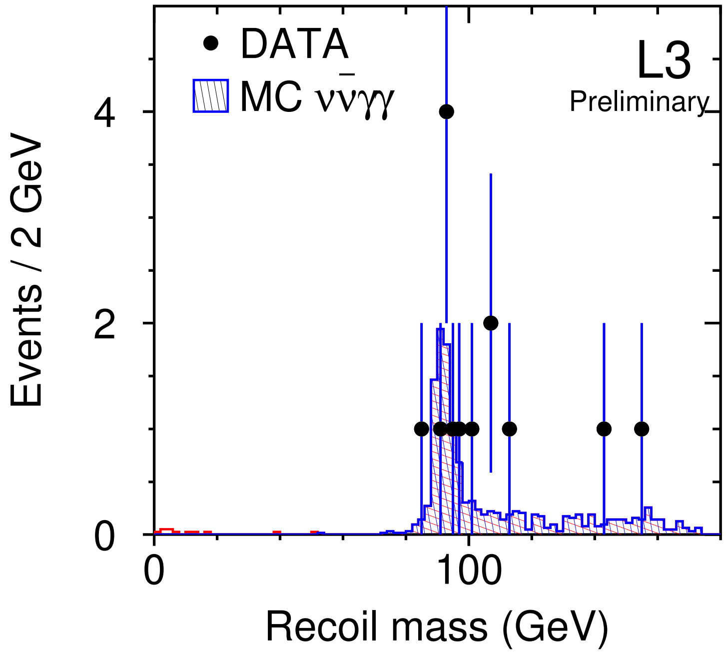


$E_\gamma > 5$ GeV:

$N_{\rm data} = 193$

$N_{\rm exp} = 193.4$

Di-photon recoil mass:



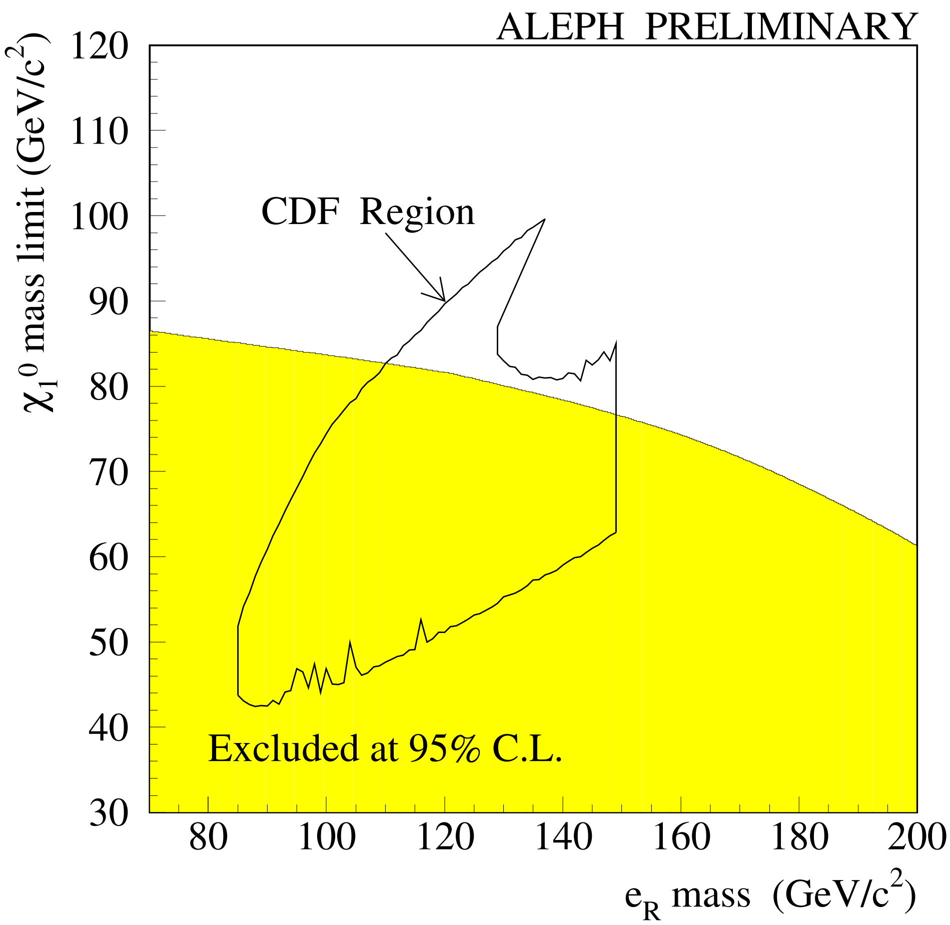
$E_\gamma > 5$ GeV,
$\Sigma\, p_\perp > 3$ GeV,
acopl. $> 2.4°$:

$N_{\rm data} = 14$

$N_{\rm exp} = 13.4$

$\tilde{e}^+\tilde{e}^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \to e^+e^-\tilde{G}\tilde{G}\gamma\gamma$ **interpretation of CDF event:**

LEP limits on $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{G}\tilde{G}\gamma\gamma$ cross section (GMSB)



(Bino configuration)

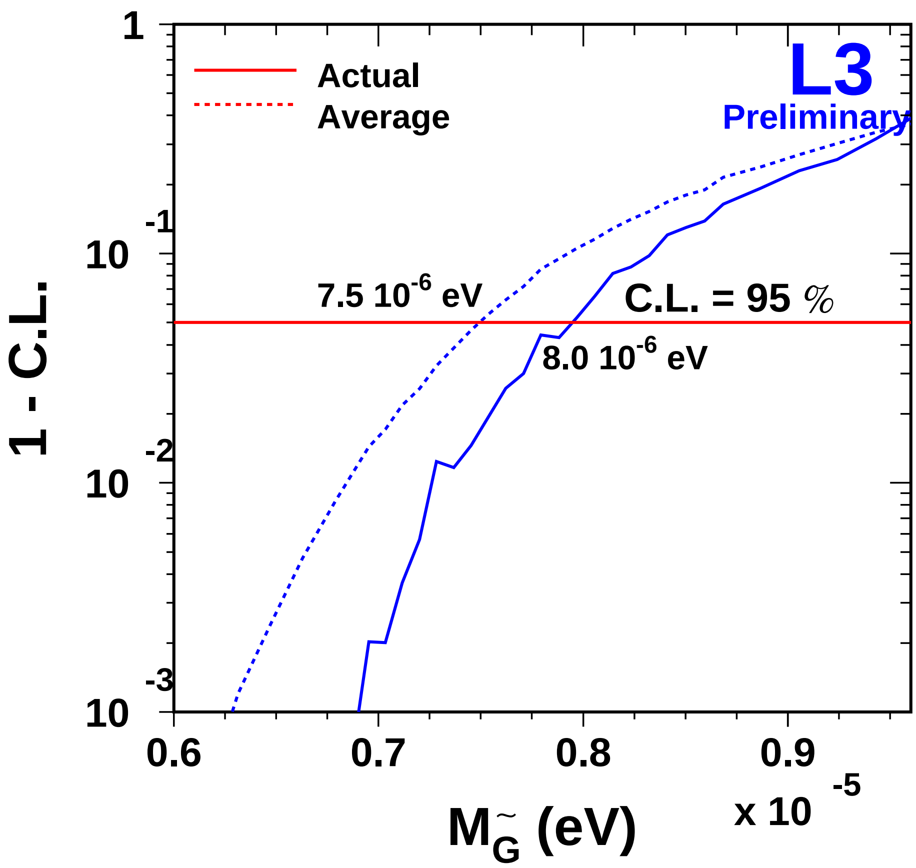
Similar result by DELPHI and L3

Mass limit on superlight gravitino:

$$e^+e^- \to \tilde{\mathrm{G}}\tilde{\mathrm{G}}\gamma$$

$$\sigma_{\tilde{\mathrm{G}}\tilde{\mathrm{G}}\gamma} = \frac{\alpha\, s^3}{320\pi^2|F|^4} I(E_\gamma, \cos\Theta_\gamma)$$

Assume other SUSY particles $m_{\mathrm{SUSY}} > \sqrt{s}$



ALEPH	$m_{\tilde{\mathrm{G}}} > 8\ \ 10^{-6}$ eV
DELPHI	$m_{\tilde{\mathrm{G}}} > 6.6\, 10^{-6}$ eV
L3	$m_{\tilde{\mathrm{G}}} > 8.0\, 10^{-6}$ eV

Lower limit on SUSY breaking scale:

$$\sqrt{F} > 181.9 \text{ GeV}$$

Many other searches for new particles and new physics carried out by LEP experiments up to $\sqrt{s} = 183$ GeV

e.g.
heavy leptons, excited leptons
leptoquarks
heavy gauge bosons (Z′)
contact interactions
R-parity violating SUSY

Result:

No discovery
improved limits on new physics

Conclusions

- Sucessful operation of LEP up to $\sqrt{s} = 183$ GeV
- W mass measurement at LEP II

$$m_{\mathrm{W}} = 80.35 \pm 0.09 \text{ GeV}$$

- Improved limits on anomalous W couplings
- From direct search and precision EW measurements

$$88 \text{ GeV} < m_{\mathrm{H}} < 250 \text{ GeV}$$

- Extended search for SUSY

$$m_{\tilde{\chi}_1^0} > 25.9 \text{ GeV} \qquad \text{for all } \mathrm{m}_0$$

All observed phenomena up to $\sqrt{s} = 183$ GeV described by the Standard Model

Many thanks to my colleagues
from all LEP experiments!