Overview of LEP Results

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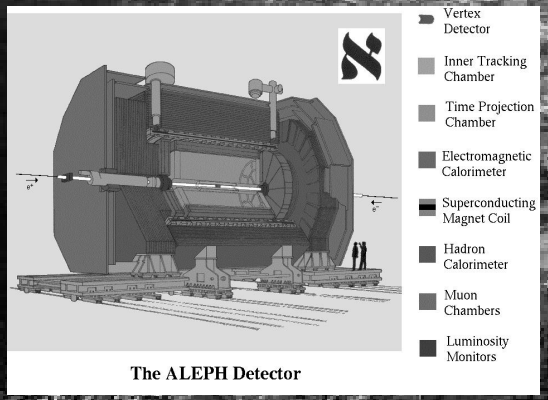
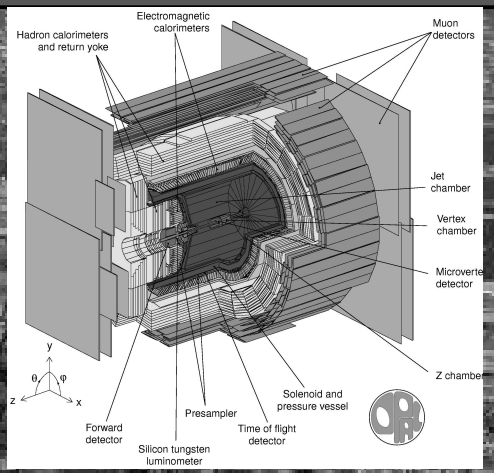
Outline:

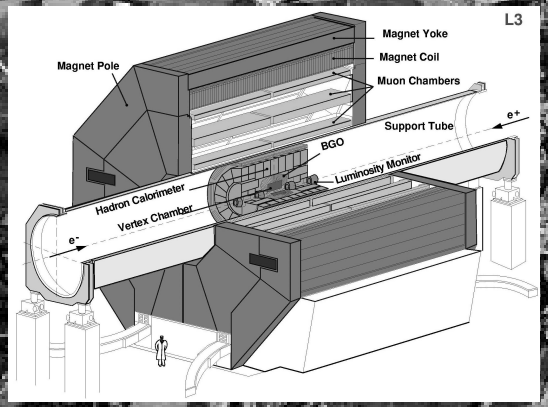
- **Z physics at LEP I**
- **W & other SM physics at LEP II**
- **Higgs searches**
- **New phenomena**

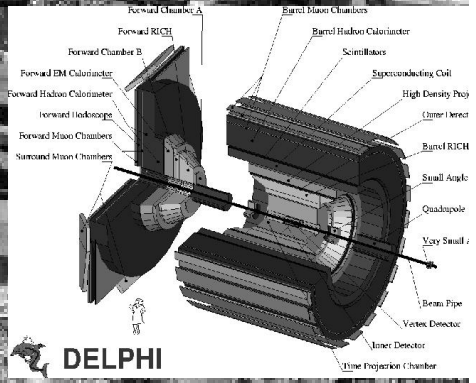
The Four LEP Detectors



The ALEPH Detector







2004 LHC days in Split

5 – 9 October 2004

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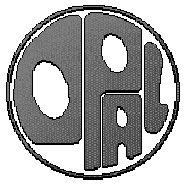
5.10.2004

LEP & the Experiments

- **ALEPH DELPHI L3 OPAL**

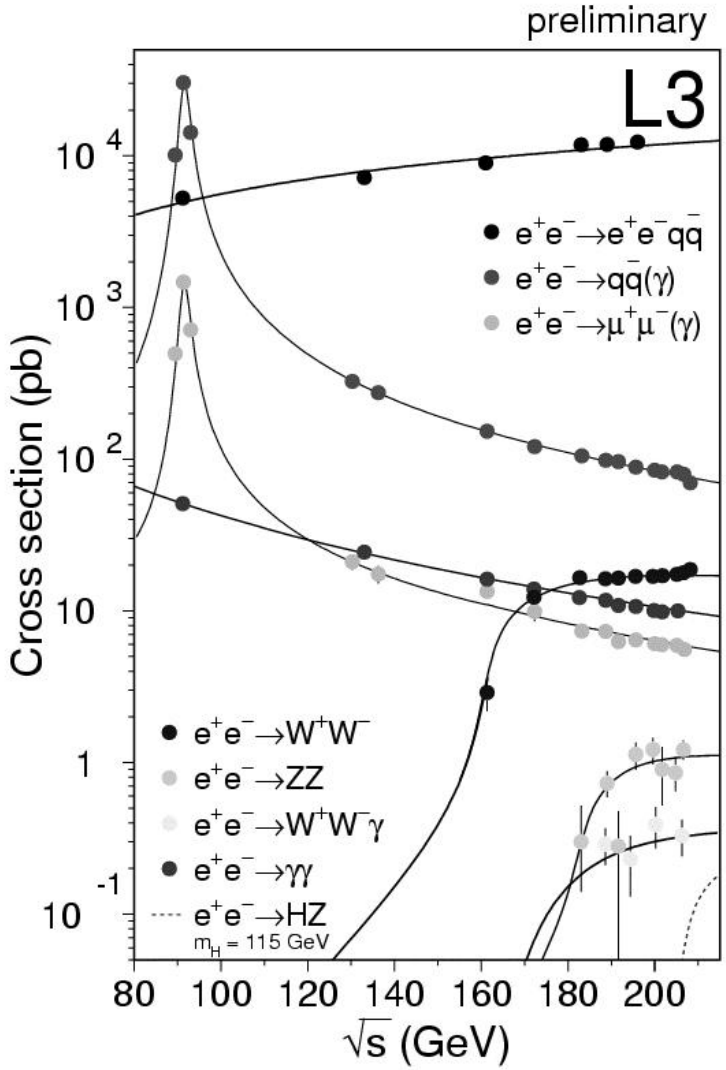




- **LEP I (1989 – 1995) $\sqrt{s} \approx m_Z$**
  - Z boson physics
- **LEP II (1995 – 2000) 130 GeV $\leq \sqrt{s} \leq$ 208 GeV**
  - W boson physics
  - searches
- **High luminosity**
  $\approx$ 1 fb^{-1}/experiment collected
  $\Rightarrow$ > 4·10^6 Z decays & $\approx$ 10 k WW events
- **Precise beam energy calibration:**
  < $\pm$ 1 MeV (LEP I) $\approx \pm$ 15 MeV (LEP II)
- **To date $\approx$ 1300 publications by the four experiments**

The Legacy of LEP

- **The SM is correct**
  - **up to 209 GeV**
  - **& beyond tree level**
- **Many high precision measurements**
  - **e.g. cross sections**
- **The only missing piece: The Higgs boson**
  - **$e^+e^- \rightarrow HZ$ not observed**
    $\Rightarrow m_H > 114.4$ GeV
- **No new phenomena observed**
  - **e.g. no SUSY particles found**

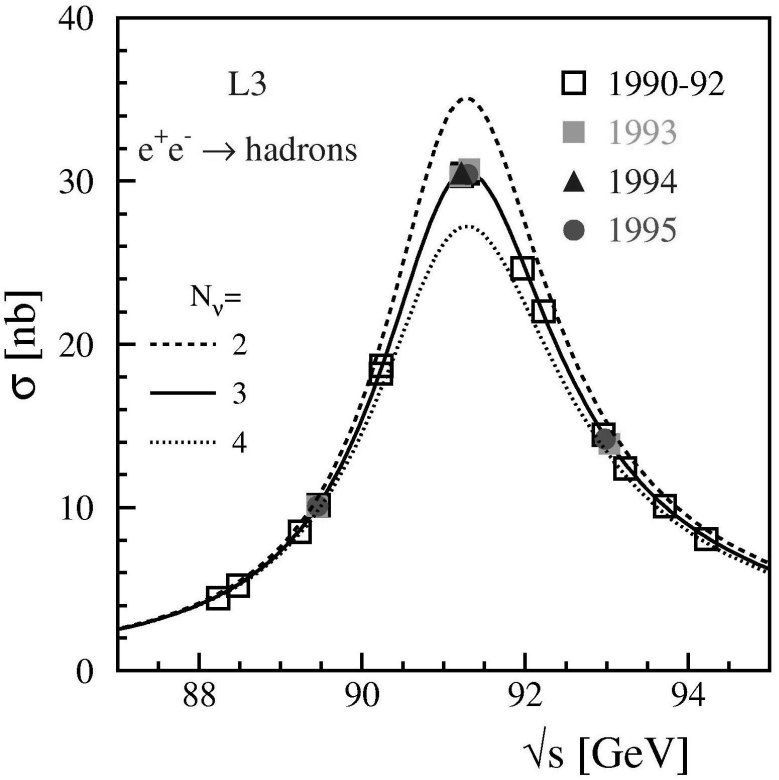


The Z Lineshape

- **LEP results from cross section and A_{FB} measurements around the Z pole**

m_Z	=	91.1875	± 0.0021	GeV
Γ_Z	=	2.4952	± 0.0023	GeV
σ^0_{had}	=	41.540	± 0.037	nb
R_l	=	20.767	± 0.025	
A^0_{FB}	=	0.0171	± 0.0010	

e.g. $\Delta m_Z / m_Z = \pm 2.3 \cdot 10^{-5}$



Number of neutrino families:

$N_\nu = 2.9841 \pm 0.0083$

Examples of Precison Measurements at the Z

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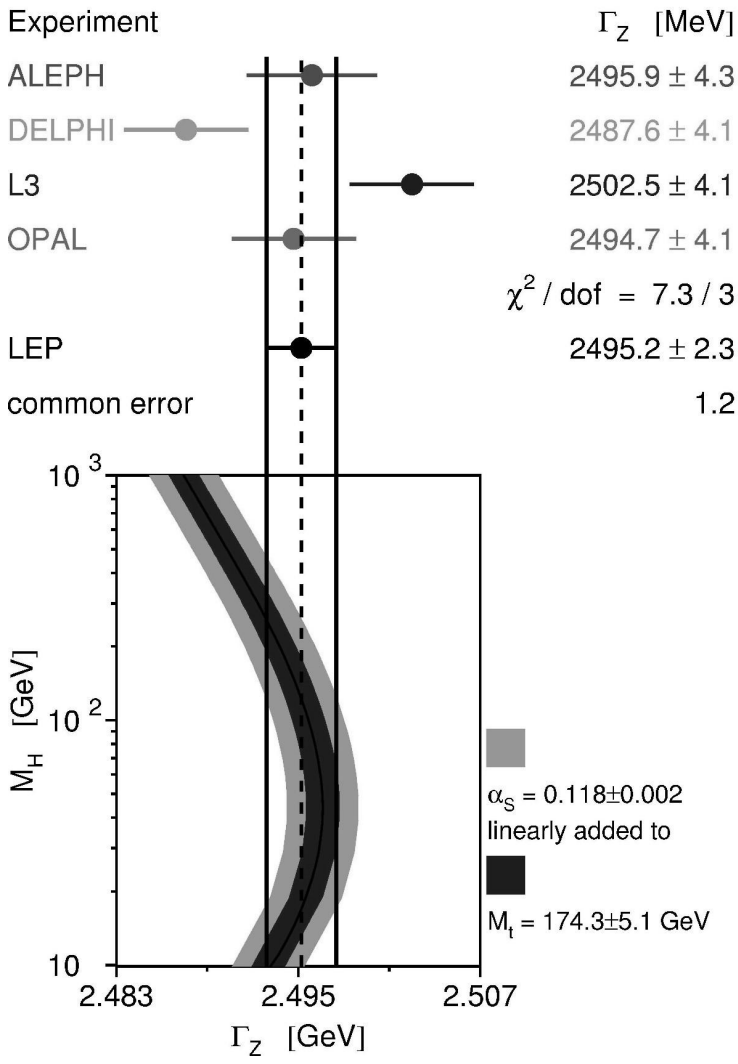
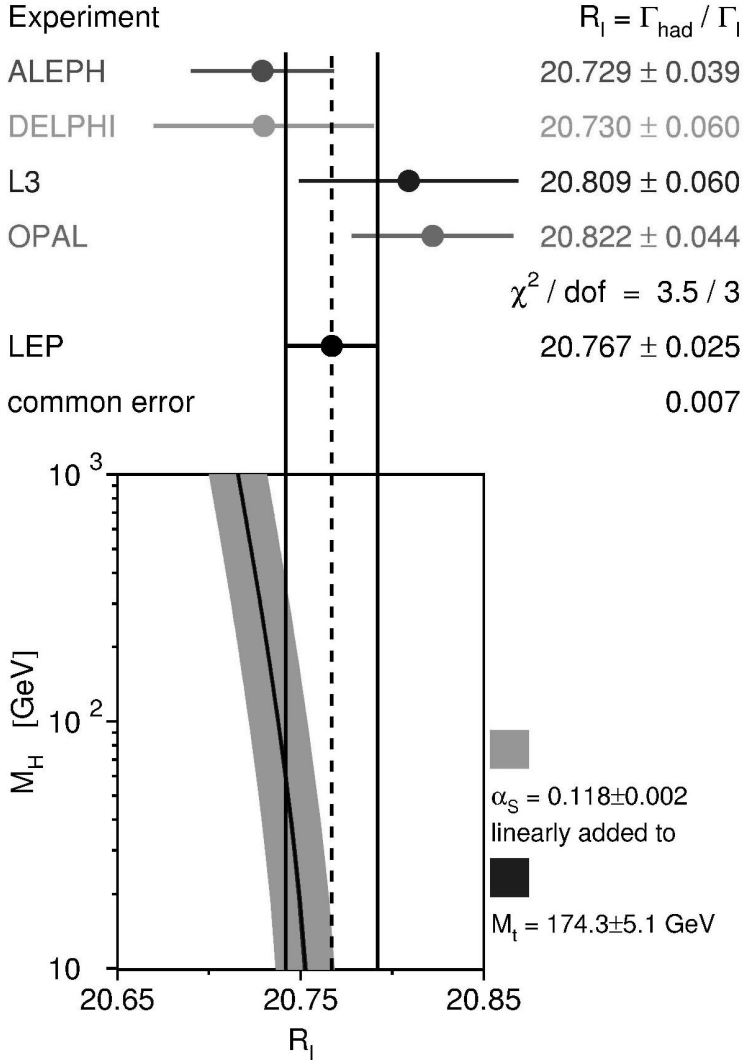
- **Comparison of LEP experiments to SM prediction**





Examples of Precison Measurements at the Z

- **Lepton universality in neutral currents (incl. SLD results)**

- **Lepton coupling to the Z**

  Ratios of coupling constants:

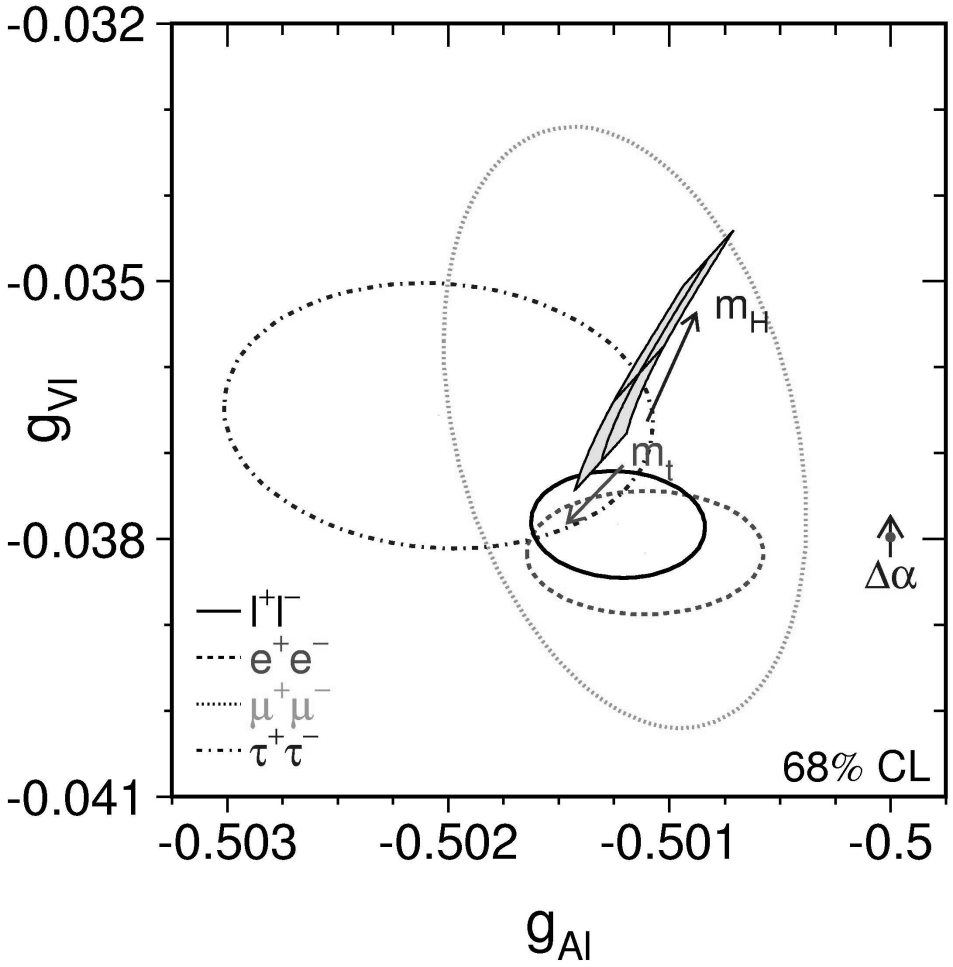
$g_A^{\mu}/g_A^{e} = 1.0002 \pm 0.0014$

$g_A^{\tau}/g_A^{e} = 1.0019 \pm 0.0015$

$g_V^{\mu}/g_V^{e} = 0.962 \pm 0.063$

$g_V^{\tau}/g_V^{e} = 0.958 \pm 0.029$

Lepton universality tested to 10^{-3} in g_A



- **Comparison to SM: preference for light Higgs**

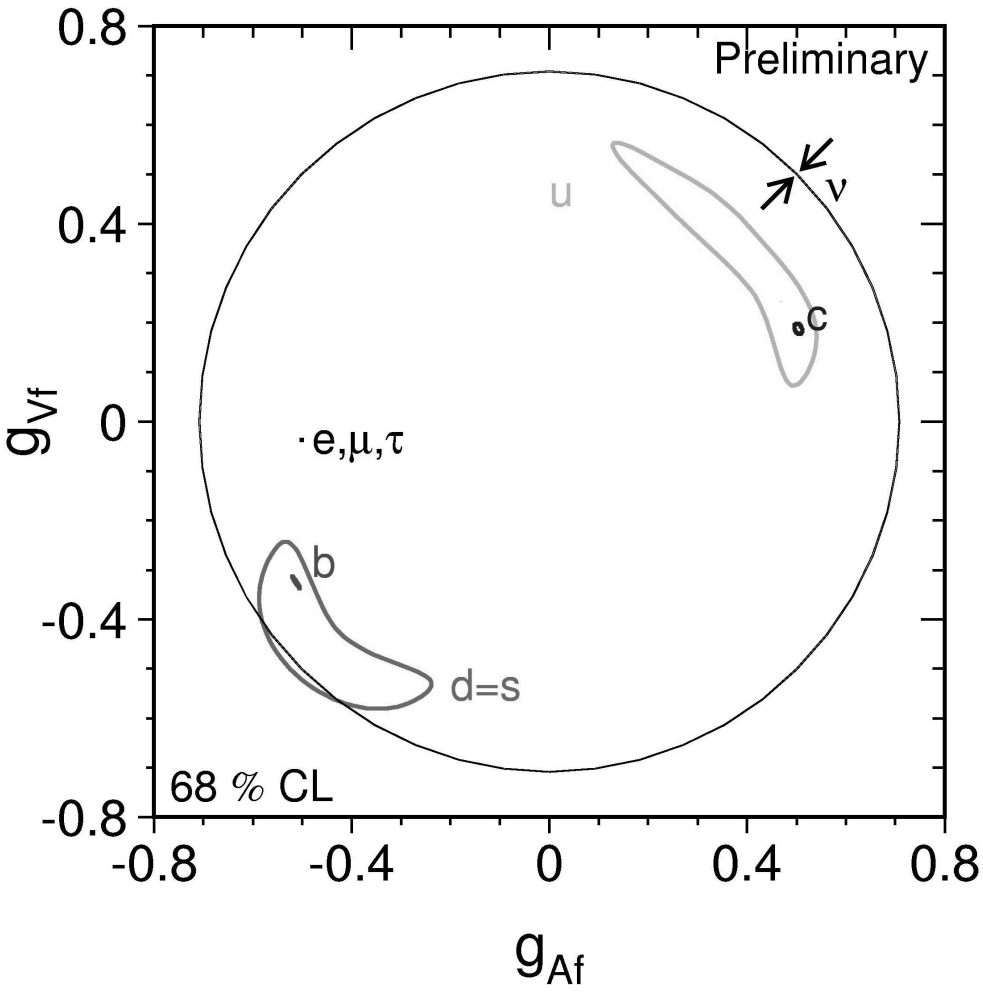
Fermion Couplings to the Z

- **All cross section and A_{FB} measurements expressed in terms of fermion couplings g_A^f and g_V^f**

  - high precision for charged leptons and c- & b-quarks

  - larger contours for light quarks

  - Γ_{inv} strongly constrains $(g_A^\nu)^2 + (g_V^\nu)^2$



The Effective Weak Mixing Angle

- **Asymmetries at the Z-pole**

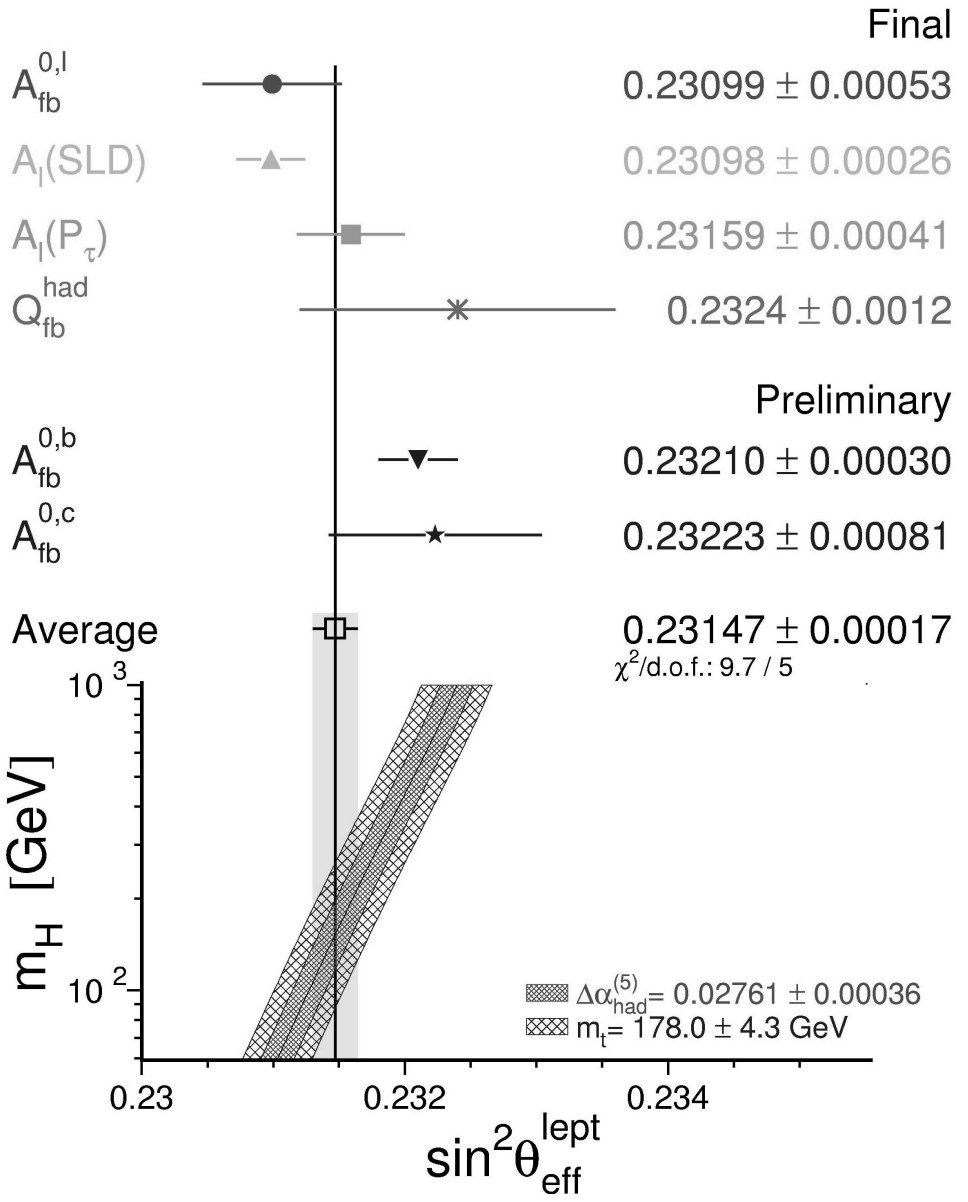
- forward-backward
- left-right (SLD)
- tau polarisation

$\sin^2\theta = 0.23147 \pm 0.00017$

$7 \cdot 10^{-4}$ precision!

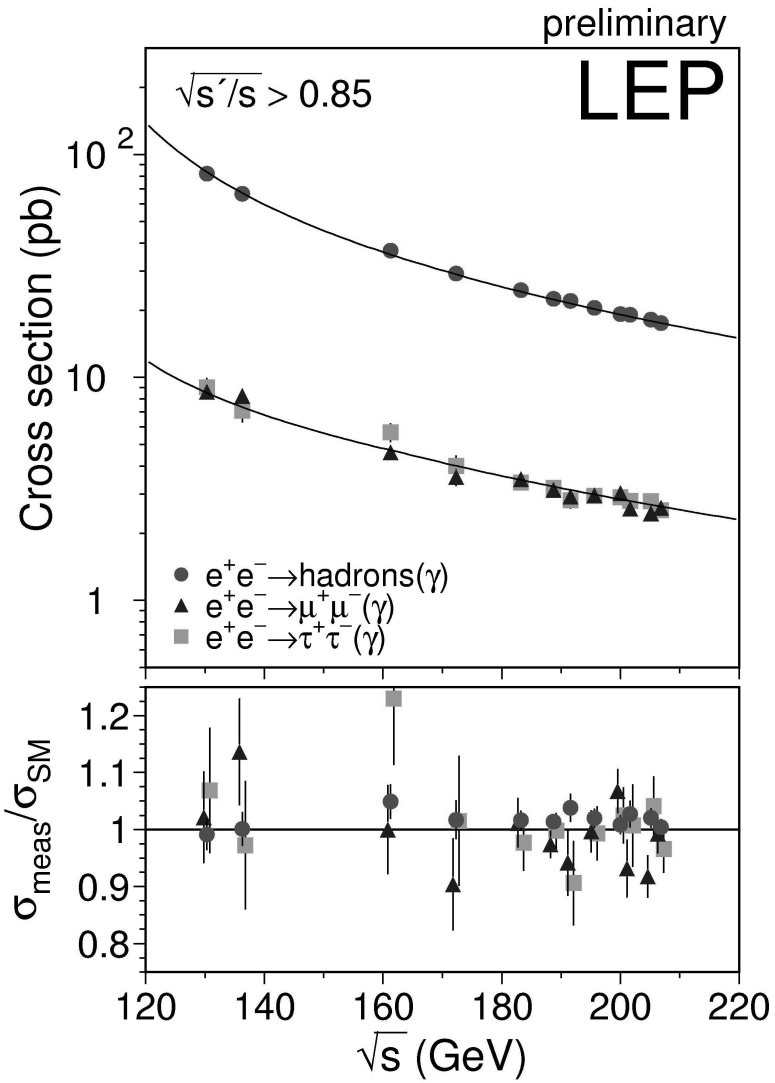
- **Preference for a light Higgs**

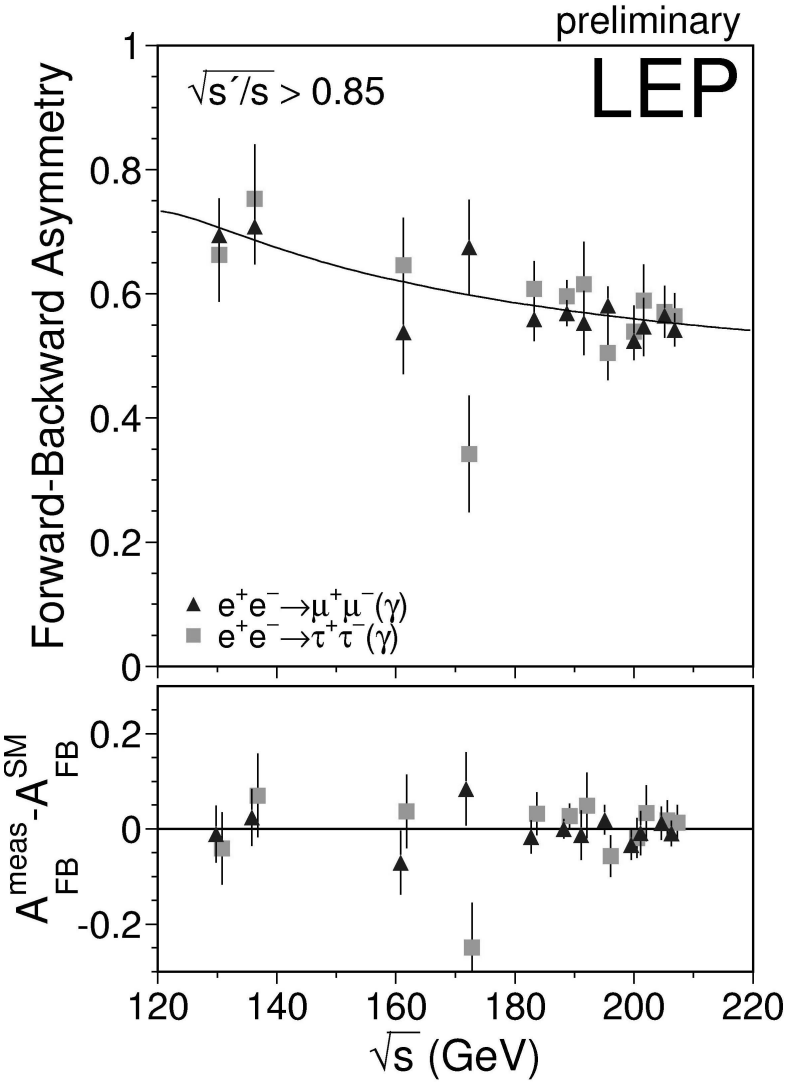
(consistent with Z widths)



LEP II: Fermion-Pair Production

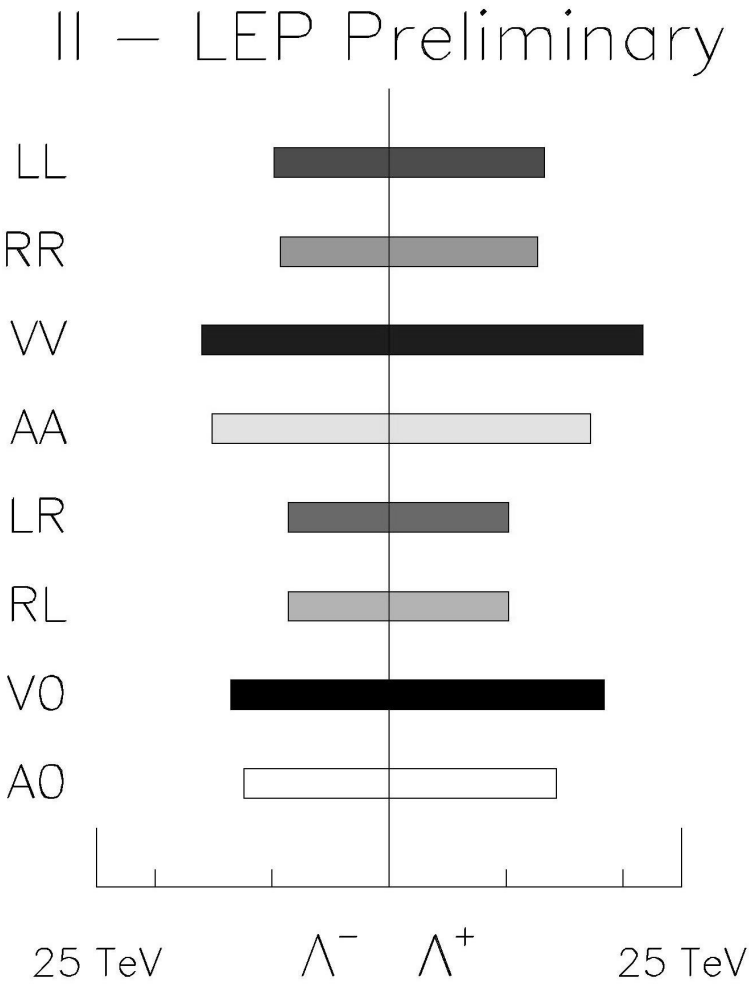
- **Cross sections and FB asymmetries at high energy**



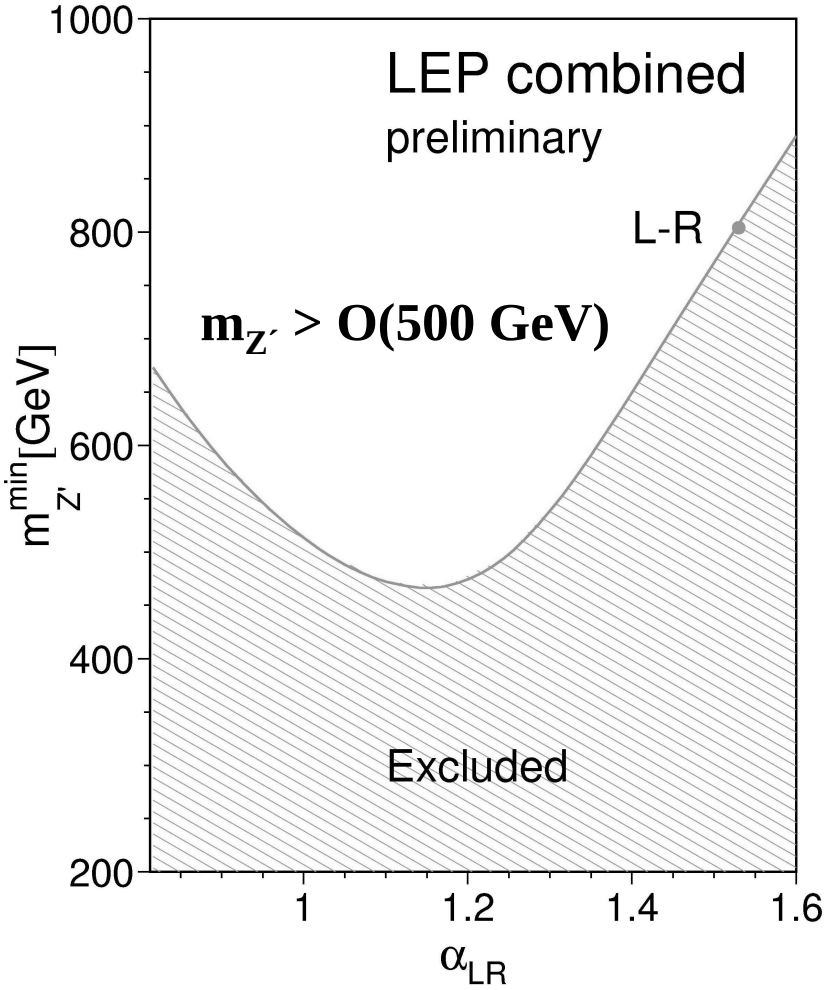


Limits from Fermion-Pair Production

- **Contact interactions:**
  Λ > O(10 TeV)
- **Example: $e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$**

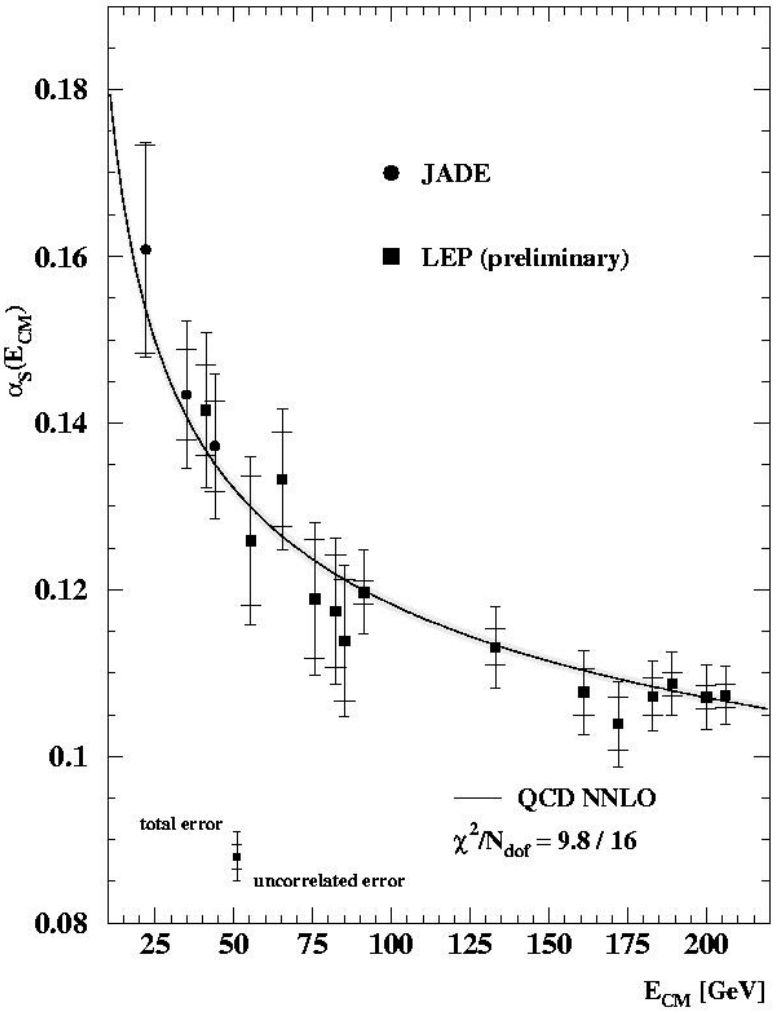


- **Z´ boson:**
  $m_{Z'}$ > 1.786 TeV (SSM)
- **Example: left-right model**



QCD at LEP

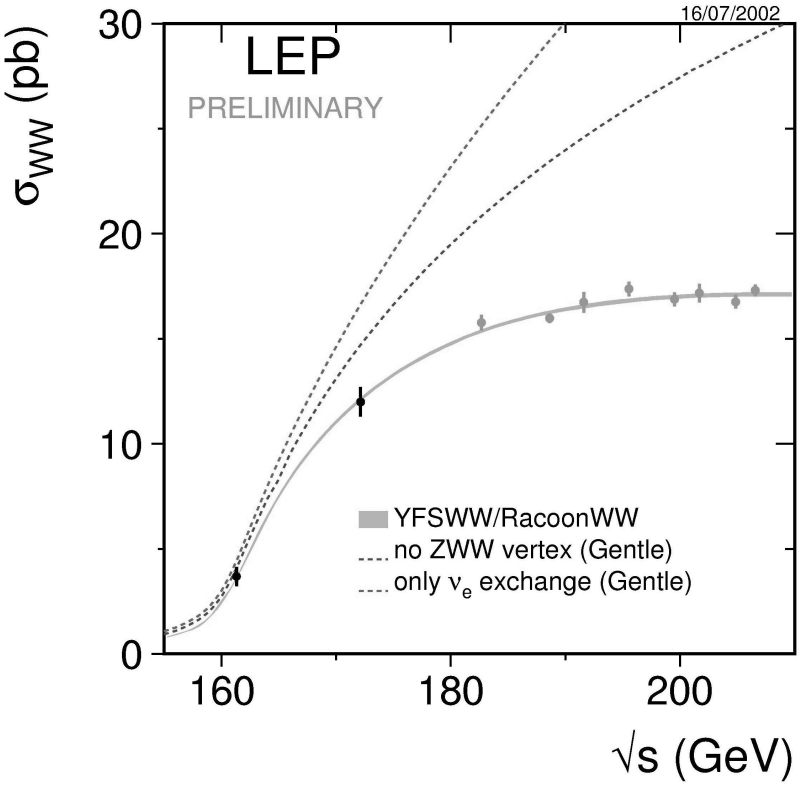
- **Important tests of QCD performed at LEP, e.g.**
  - **gluon self coupling $\rightarrow SU(3)_C$**
  - **Measurement of the strong coupling constant $\alpha_s(m_Z)$ from hadronic event shapes $\alpha_s(m_Z) = 0.1202 \pm 0.0050$**
  - **Running of α_s established between 40 – 208 GeV**



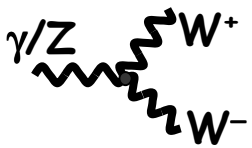
LEP II: Boson-Pair Production

- **Total cross section**

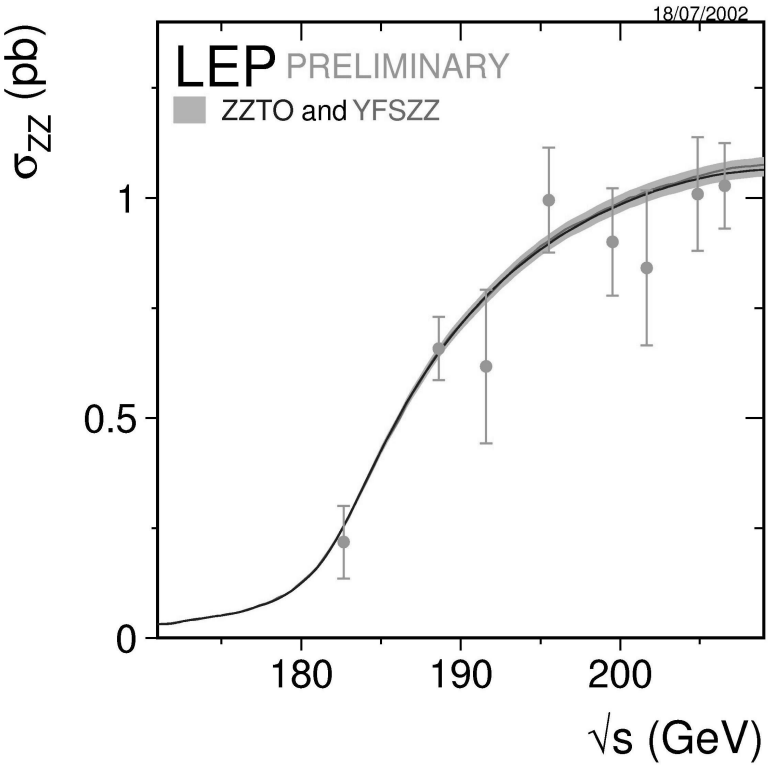
$e^+e^- \rightarrow W^+W^-$



→ **ZWW & γWW vertices exist**



$e^+e^- \rightarrow Z\,Z$



→ **no ZZZ or γZZ vertex**

LEP II: The Mass of the W Boson

- From $e^+e^- \rightarrow W^+W^-$ events:
  - use invariant mass spectra
  - and kinematic constraints

$$\sum \vec{p} = 0 \qquad \sum E = \sqrt{s}$$

- fully hadronic & semi-leptonic
- channels useable

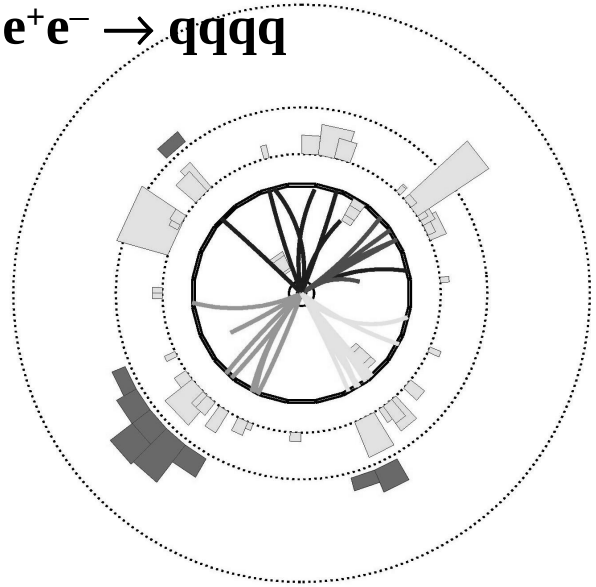
  $e^+e^- \rightarrow W^+W^- \rightarrow qqqq$

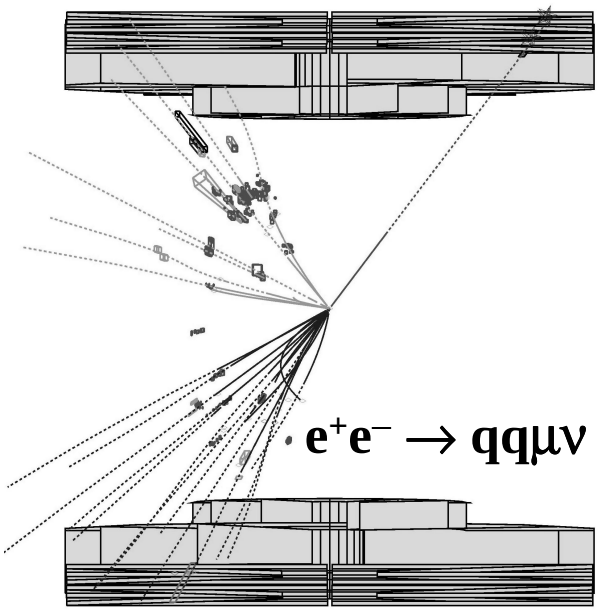
  $\rightarrow qql\nu$ (l=e,μ,τ)

- ≈ 10 k events/expt.
- Absolute energy scale given by LEP beam energy

  $\Delta E_b \approx \pm 17$ MeV

$e^+e^- \rightarrow qqqq$





$e^+e^- \rightarrow qq\mu\nu$

LEP W Mass

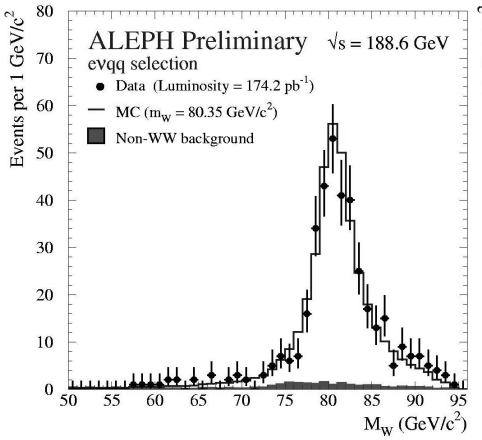
- **Sample spectra:**

- **LEP Result:**

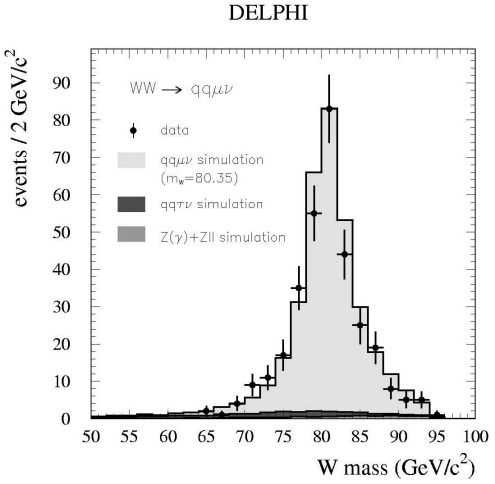
  $m_W = 80.412 \pm 0.042$ GeV

- **in agreement with Tevatron Run I**
  $m_W = 80.452 \pm 0.059$ GeV

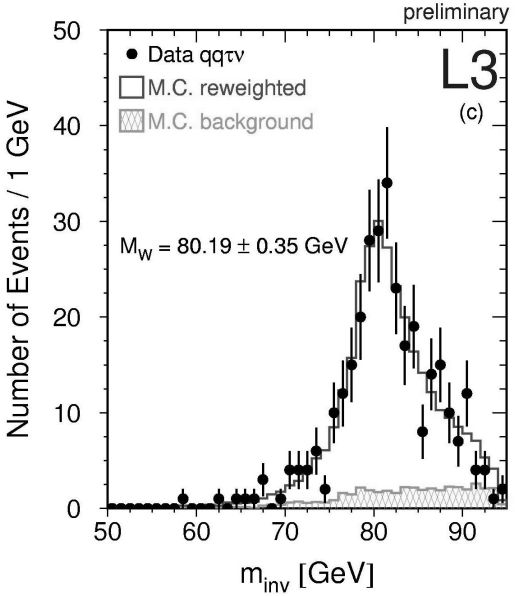
$WW \to q\bar{q}\,e\nu$



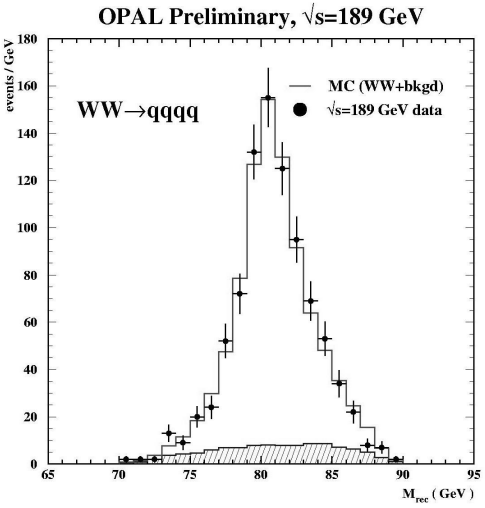
$WW \to q\bar{q}\,\mu\nu$



$WW \to q\bar{q}\,\tau\nu$



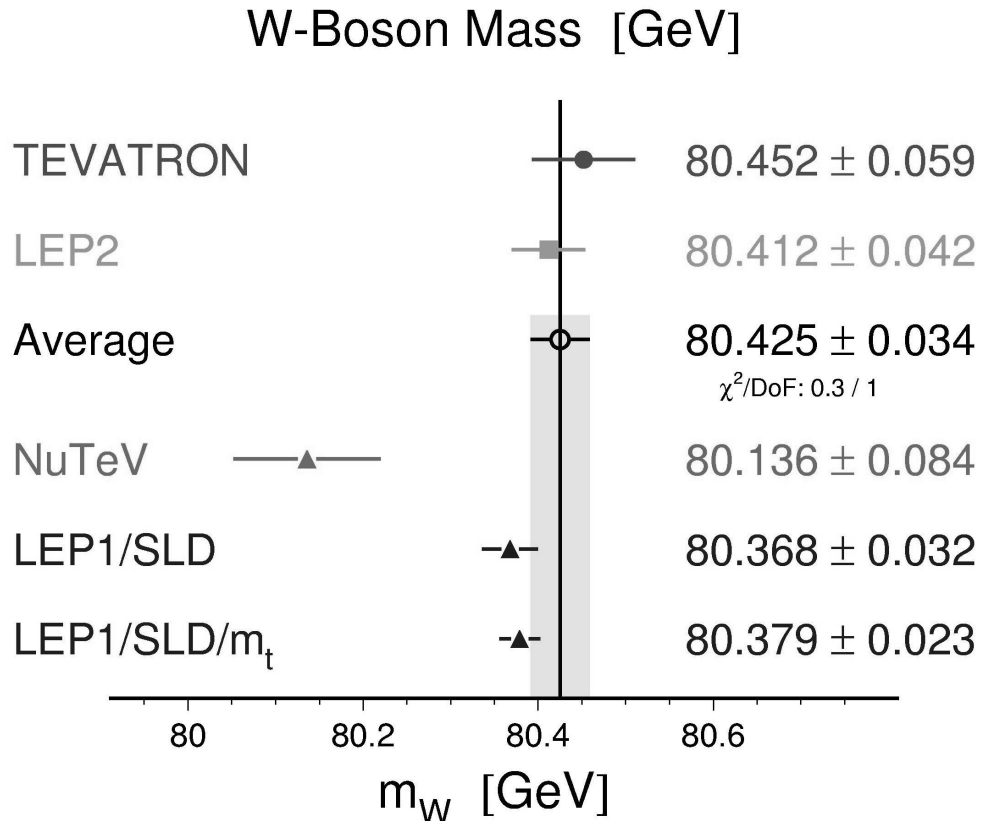
$WW \to q\bar{q}\,q\bar{q}$



Results on the W Mass

- **Comparison of direct & indirect W mass measurements**

$$\cos\theta = m_W/m_Z \rightarrow$$



$\Rightarrow$ **SM is correct at tree-level**

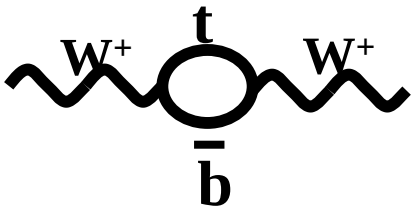
or: ρ = 1 + rad. corr.

Results on the Top Mass

- **Comparison of top masses from LEP & Tevatron**

  - Indirect measurement of m_t at LEP & SLD

  leading contribution to weak radiative corrections



$$\Delta r_W \propto (m_t^2 - m_b^2)$$

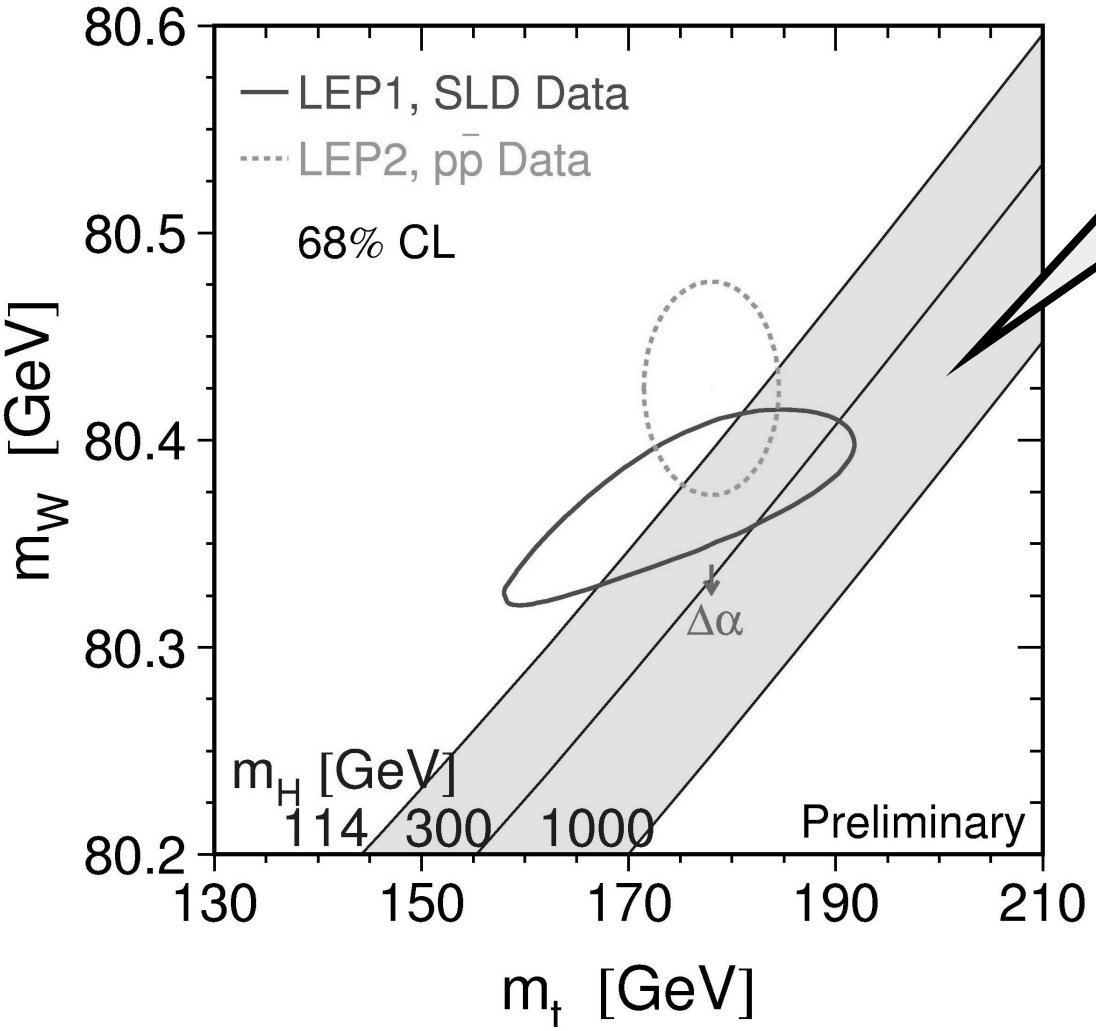
  - From precision Z observables: $m_t = 17^{+12}_{-9}$ GeV

  - Compare to direct messurement: $m_t = 178 \pm 4.3$ GeV

⇒ **The SM is correct at one-loop level**

This is the discovery of LEP & SLD

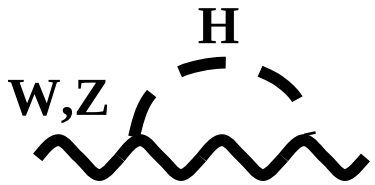
Comparison of Direct & Indirect Mass Measurements



$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2}\frac{1}{m_W^2 \sin^2\theta_W}\frac{1}{1-\Delta r}$$

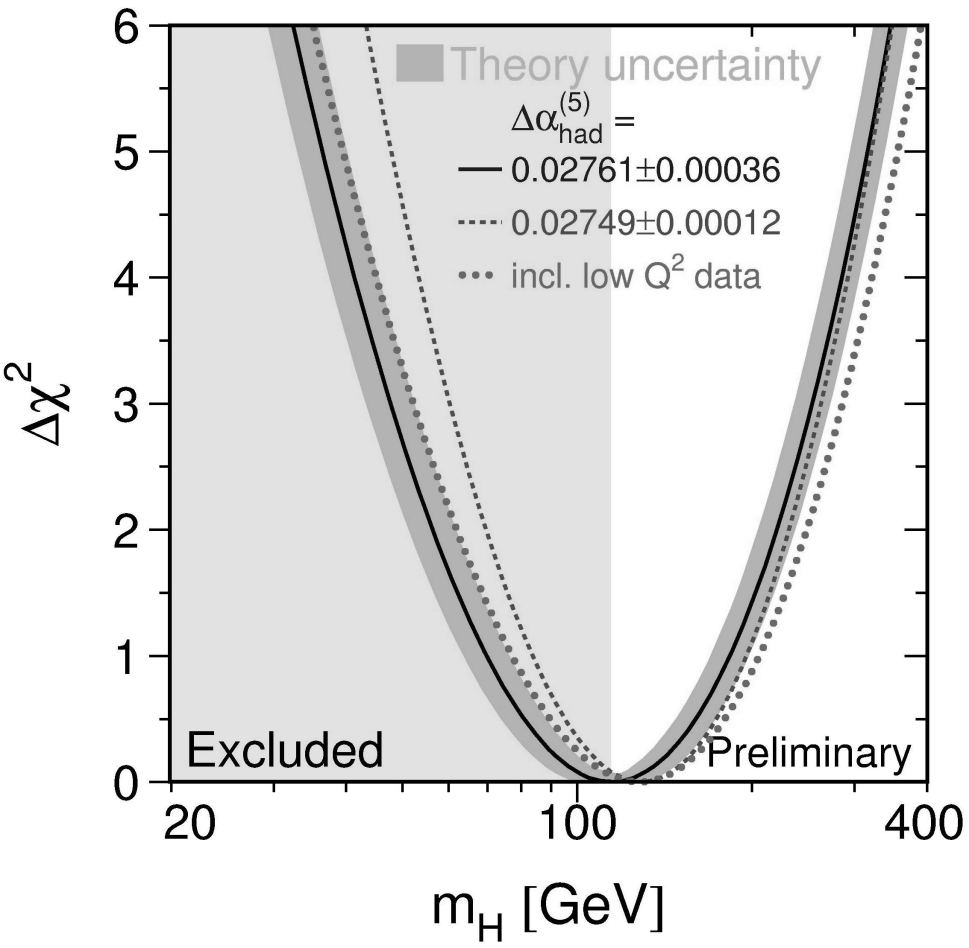
$1-\Delta r \approx (1-\Delta\alpha)(1-\Delta r_W)$

Sub-leading contribution to Δr_W:



$\propto \log m_H$

The Higgs Mass from Weak Radiative Corrections



$$\log m_H/\mathrm{GeV} = 2.0^{+0.20}_{-0.21}$$

$$m_H = 114^{+69}_{-45}\ \mathrm{GeV}$$

- **95% CL upper limit**

  $m_H < 260$ GeV

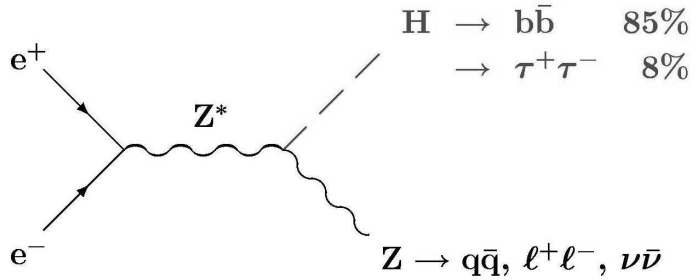
- **NB: higher m_H limit due to increased m_t**

Search for Higgs Bosons at LEP

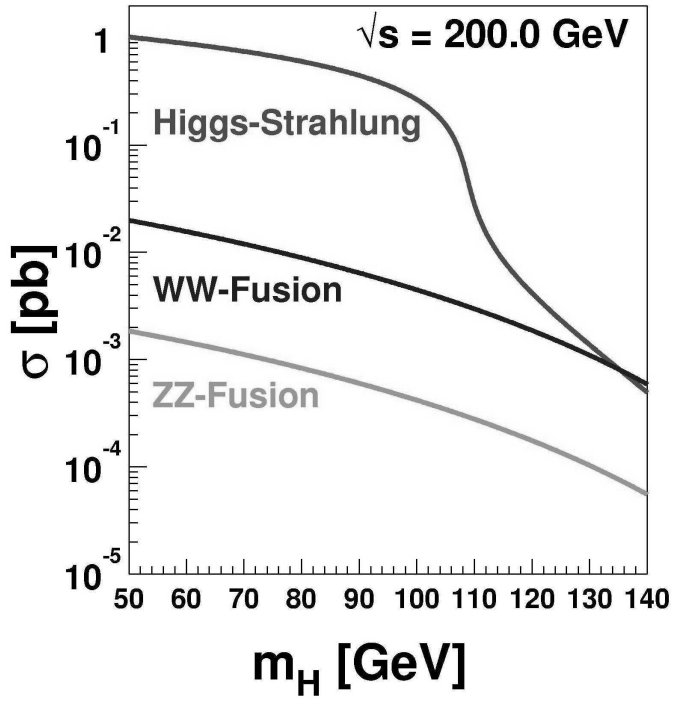
- **Search for the SM Higgs boson**
  - **before LEP: no solid mass limit**
  - **Higgs search needs copious source of heavy particles, e.g. Z bosons**

⇒ Higgs search started with LEP

- **Higgs-strahlung $e^+e^- \rightarrow HZ$ at LEP II**



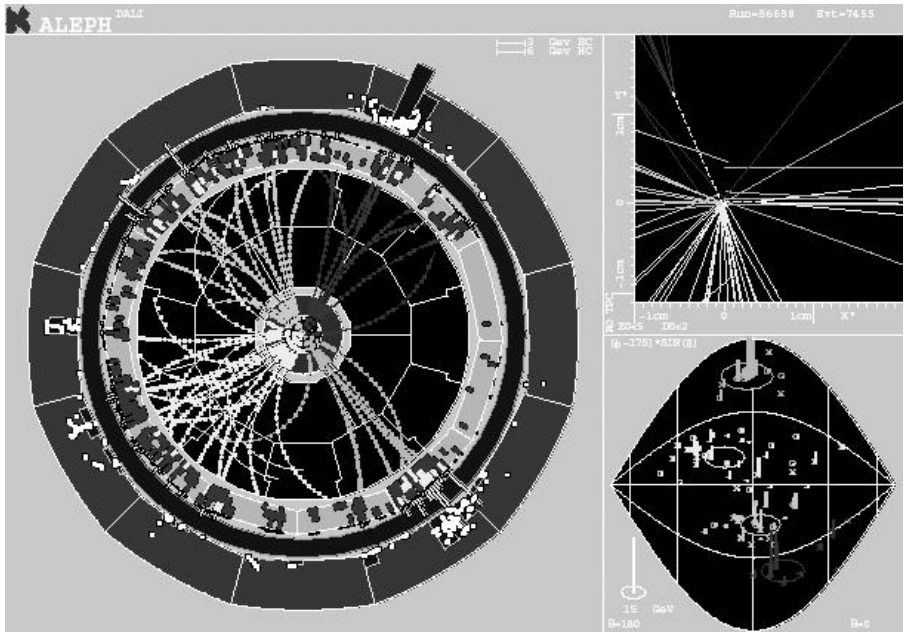
- **Production of a real Z boson**
  - ☺ **Mass information $m_{ff} \approx m_Z$**
  - ☹ **Max. sensitivity $m_H \approx \sqrt{s} - m_Z$**



Examples for Higgs candidates

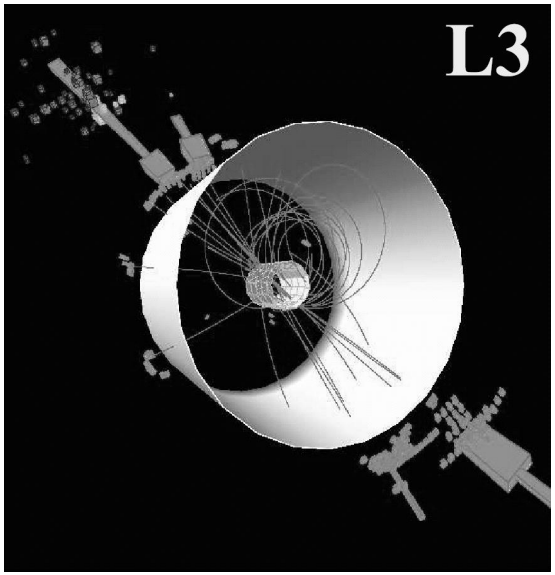
- **ALEPH**

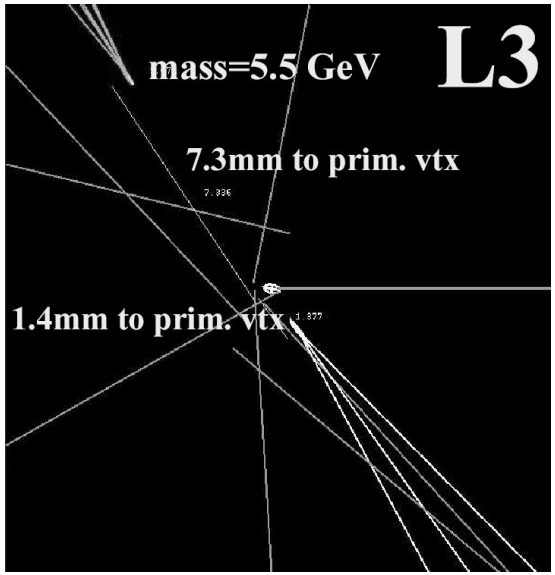
$$e^+e^- \to b\bar{b}\,q\bar{q}$$



- **L3**

$$e^+e^- \to b\bar{b}\,\upsilon\bar{\upsilon}$$





Final LEP Result on the SM Higgs

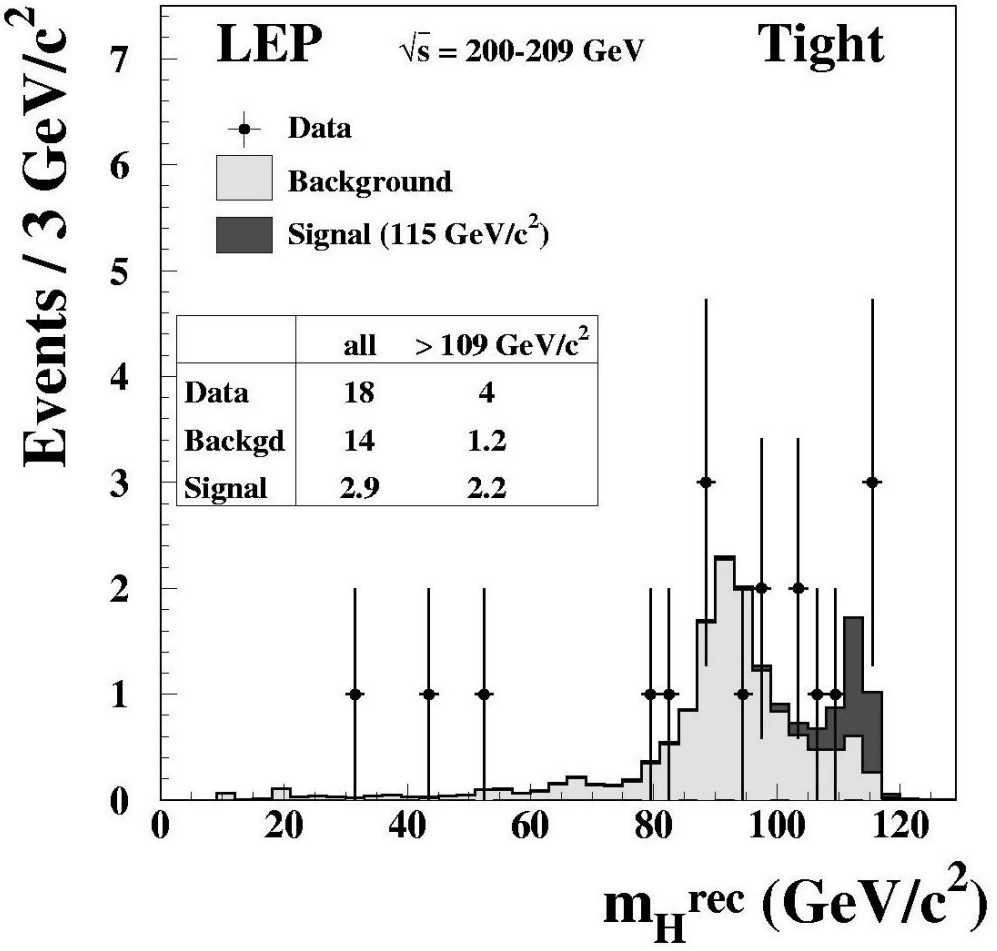
- **Example: mass distribution of best candidates**

- 2 sigma excess at high masses

- from likelihood analysis final LEP result:

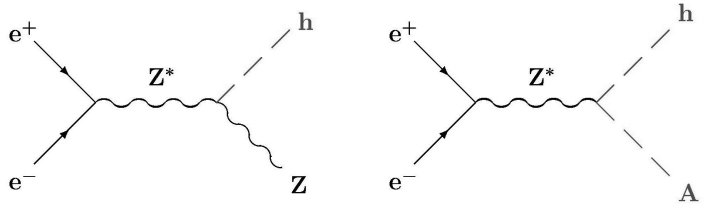
$m_H > 114.4$ GeV

(95% CL)



Search for non-SM Higgs Bosons

- **MSSM: five Higgs bosons**
  - **h, H CP even**
  - **A CP odd**
  - **$H^{\pm}$ charged**
- **Example: search for neutral Higgs bosons**
  main production mechanism:
  $e^+e^- \rightarrow hZ$ $(m_h < m_H)$
  $e^+e^- \rightarrow hA$

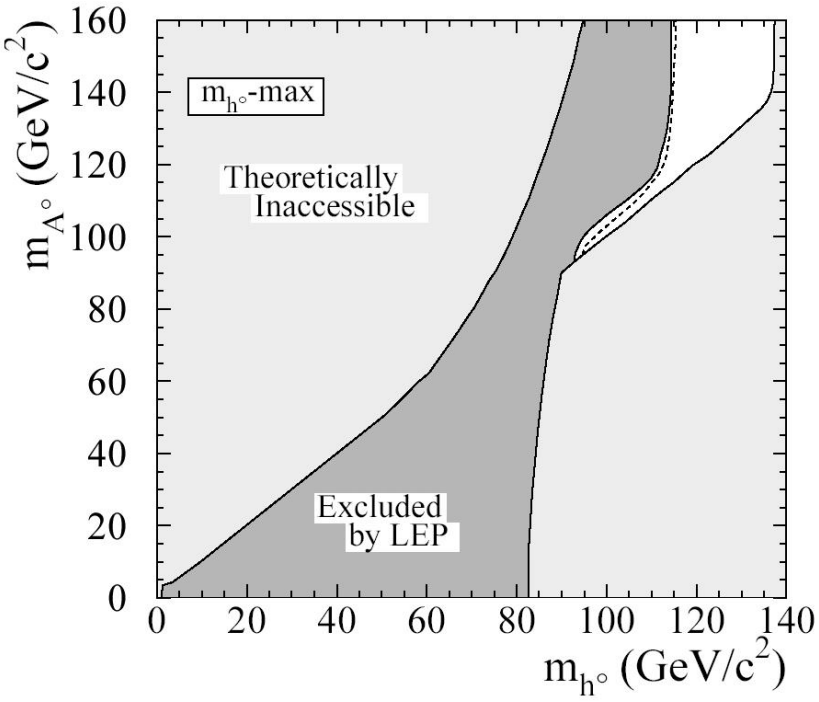


$\sigma \propto \sin^2(\beta-\alpha)$ **$\sigma \propto \cos^2(\beta-\alpha)$**

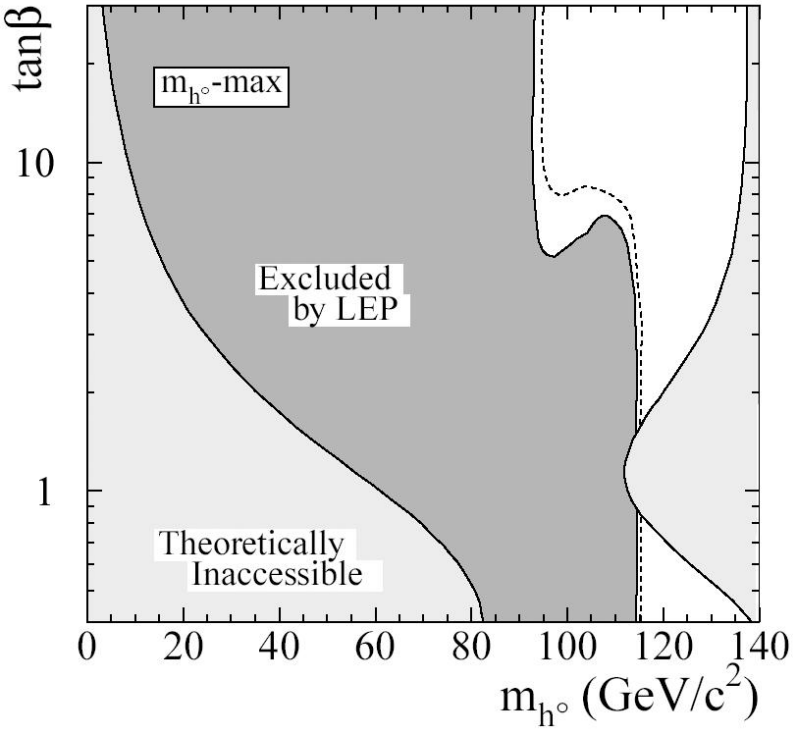
- **H and A decays depend on MSSM paramters**
  SM analysis h→ bb to be complemented by
  flavour independent searches
- **Consider here m_h max. mixing scenario**
  designed to maximise theoretical upper bound on m_h

Neutral MSSM Higgs Bosons

- **Exclusion in the m_h – m_A plane**

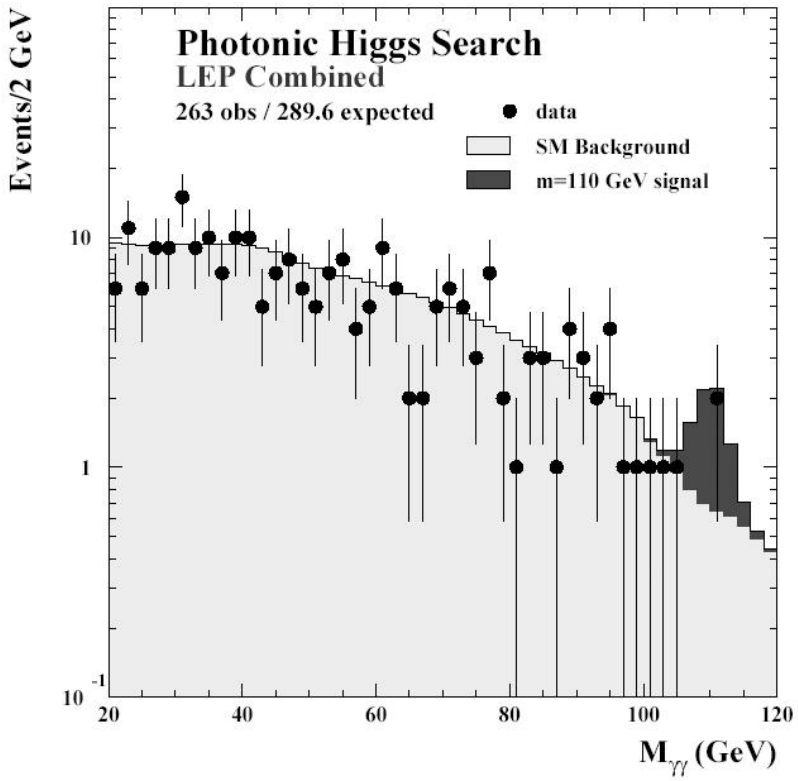


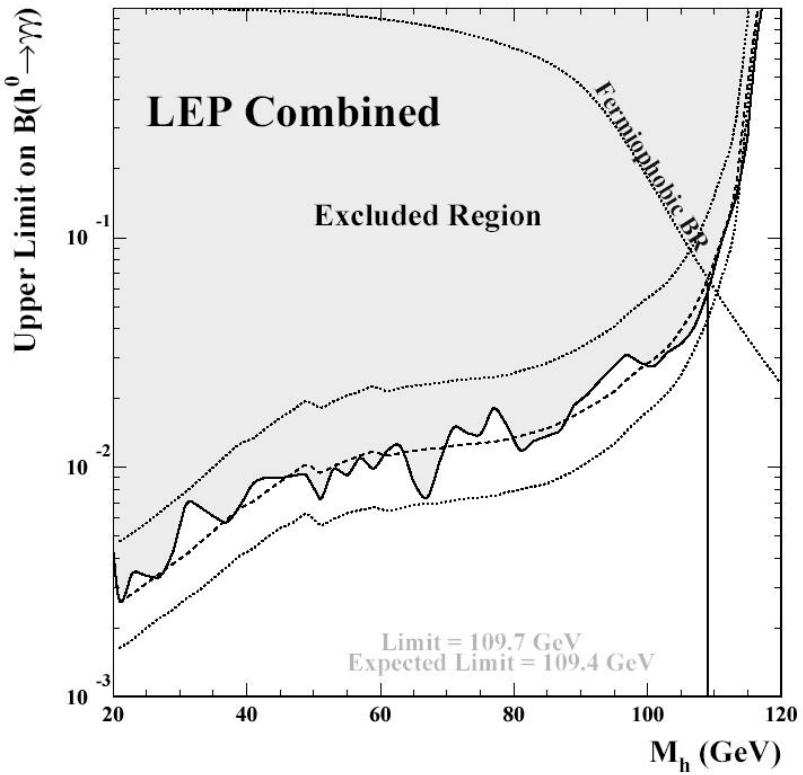
- **Projection in the m_h – tan β plane using MSSM relations**
  ⇒ Exclusion of tan β ≈ 1



Fermiophobic Higgs

- **2HDM: Higgs decays predominately into bosons**
- **Benchmark: all fermionic decays turned off**
- **LEP: Search for $H \rightarrow \gamma\gamma$ and $H \rightarrow W^+W^-$**



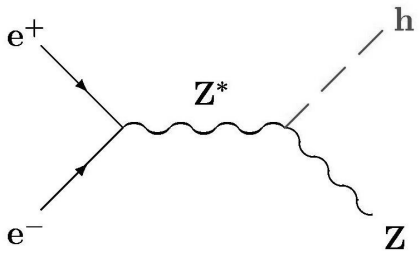


Result: $m_H < 108.2$ GeV

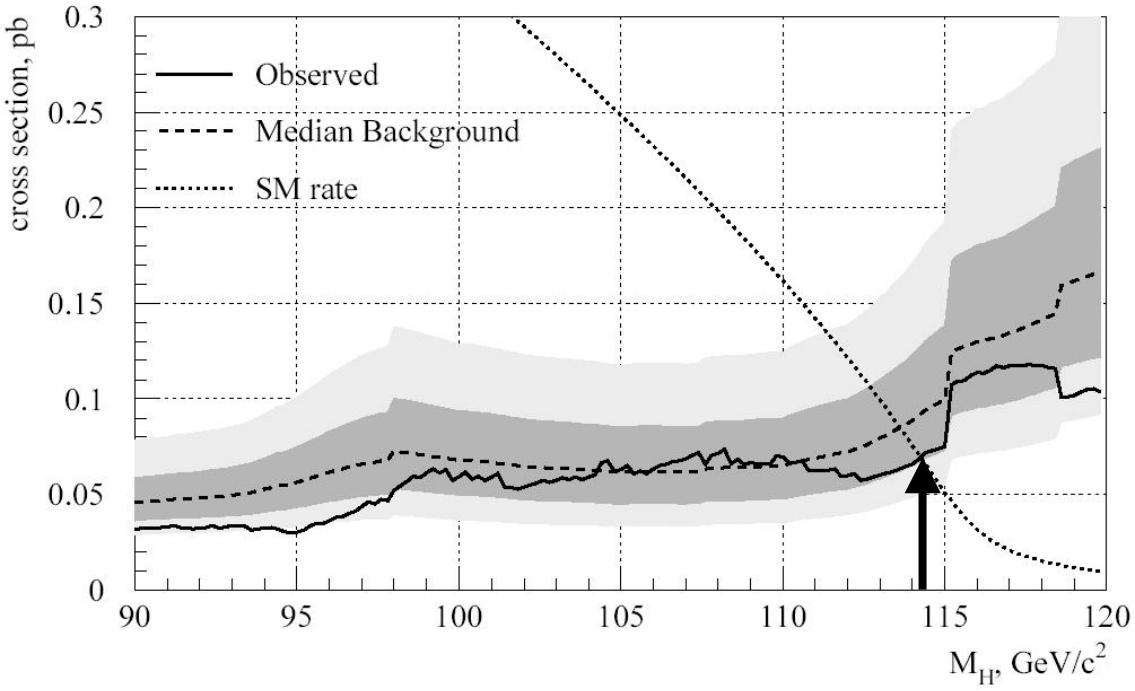
$BR(H \rightarrow \gamma\gamma) < 6\%$

Invisible Higgs

- **Search for Higgs bosons decaying into invisible particles e.g. neutralinos, majorons, ...**
- **Exploit Higgs-strahlung process**



- **Signature of invisible Higgs:**
  - acoplanar jet pair or
  - acoplanar lepton pair

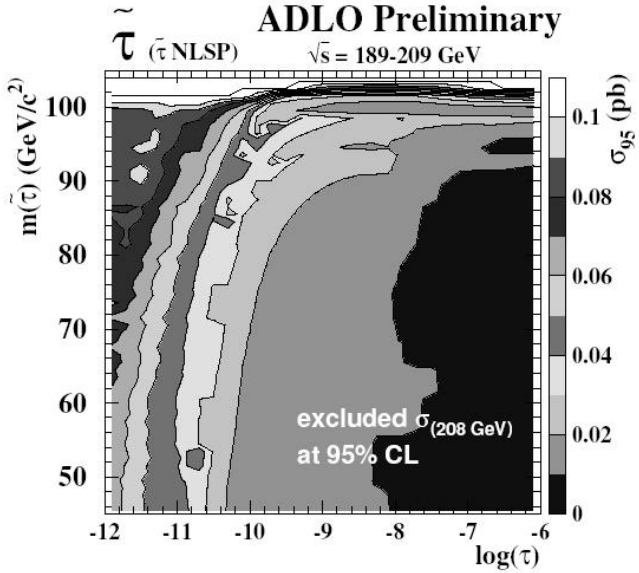


If SM cross section

$m_H > 114.4$ GeV

Search for Supersymmetry

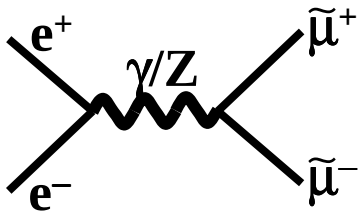
- **Search for supersymmetric particles was a key element of LEP physics**



- **Various models investigated:**
  - **Constrained MSSM**
  - **GMSB with gravitino as LSP**
  - **R-parity violation**
  - **...**
- **Searches for almost all SUSY partners sleptons, squarks, charginos, neutralinos**
- **Interpretation in terms of limits on cross sections, masses & SUSY paramters**
- **Here just a few examples**

Scalar Leptons

- **Easiest case:**
  - **scalar muons**
  - **pair produced in s-channel**



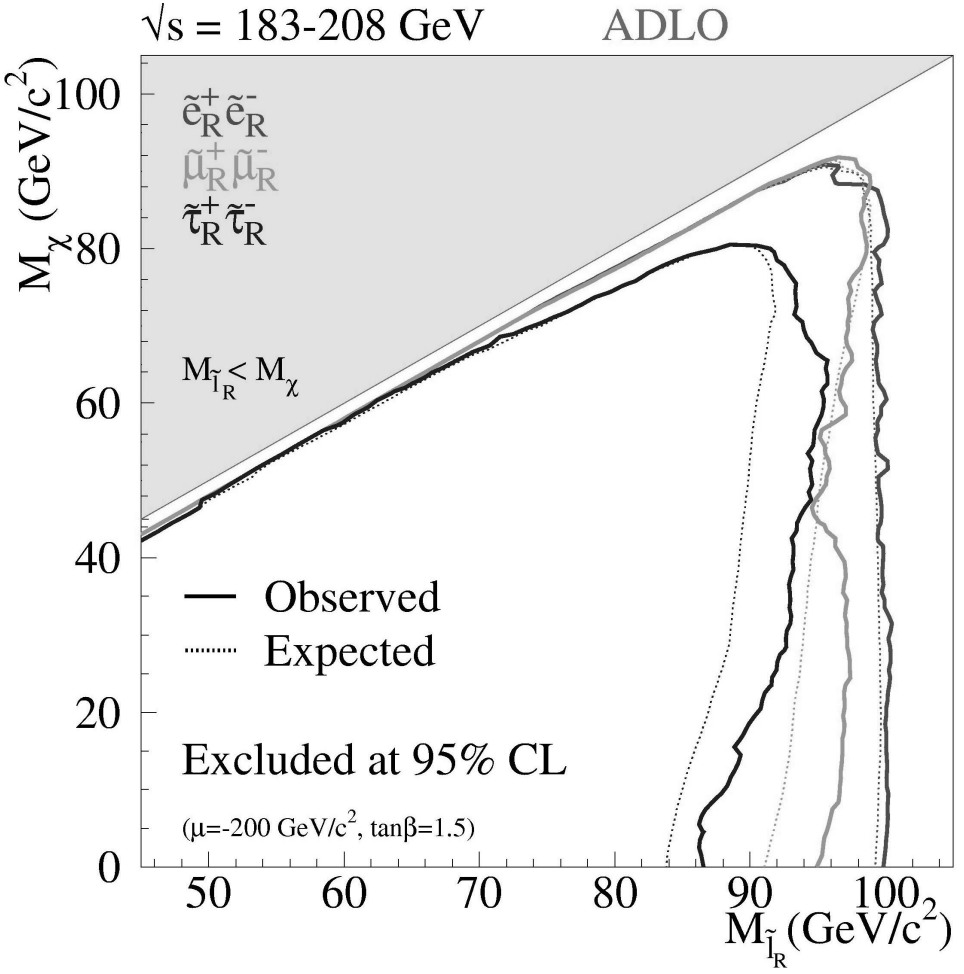
- **Scalar muon decay**

  $\tilde{\mu} \rightarrow \mu\chi^0$

  $\Rightarrow$ **acoplanar muon pair**
  bkgd from $WW \rightarrow \mu\nu\mu\nu$

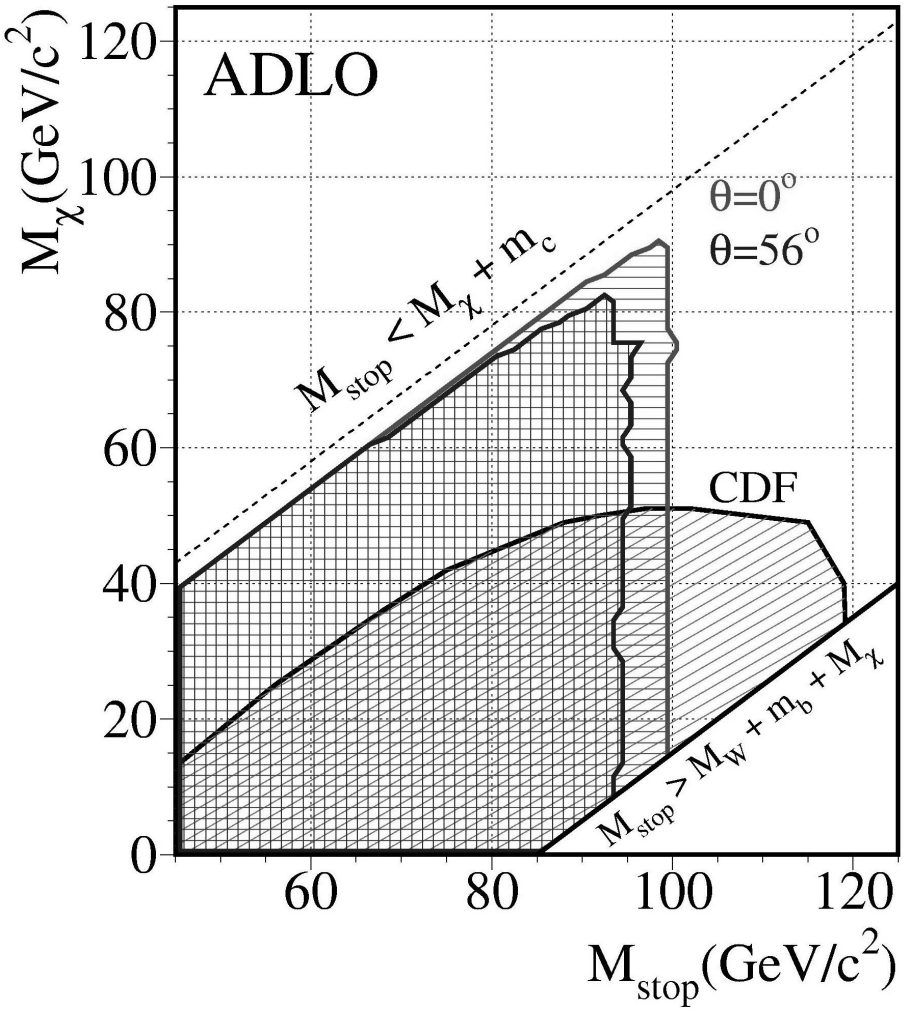
- **Other leptons more model dependent**
  - **L-R mixing for scalar taus**
  - **t-channel** χ^0 **exchange for scalar electrons**

- **Result:**
  Mass exclusion close to kinematic limit



Scalar Quarks

- **Complementary to TEVATRON**
- **Example:**
  scalar top in the decay channel
  $\tilde{t} \rightarrow c\chi^0$
- **Sentivity at LEP also for small**
  $\Delta m = m_t - m_{\chi 0}$



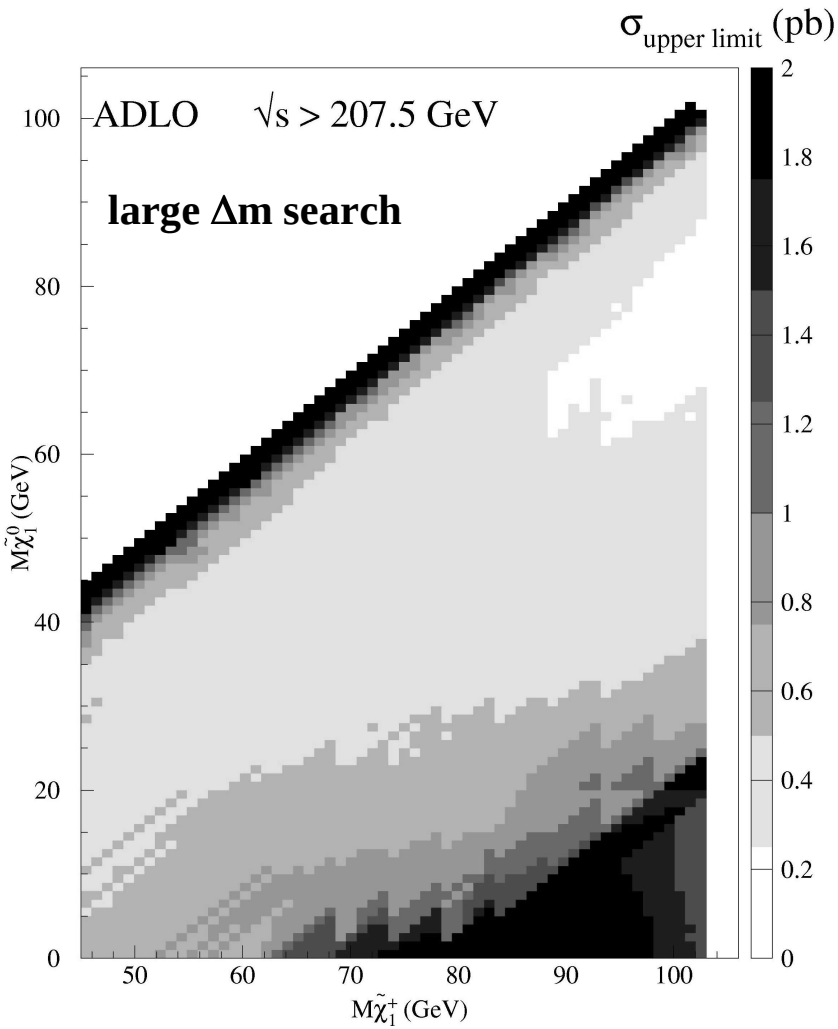
Charginos

- **Chargino pair production**
  - **t-channel γ/Z exchange or s-channel selectron (sneutrino) exchange**

- **Chargino decay through W* (Z*)**

$$\chi^{\pm} \rightarrow W^* \chi^0 \rightarrow qq \chi^0$$
$$\rightarrow l\upsilon \chi^0$$

- **Signatures:**
  - **large Δm (> 3 GeV) prompt lepton or jets**
  - **small Δm:**
    - **heavy stable charged particles**
    - **tracks with kinks**
    - **soft events with ISR**



- **Result for any Δm**
  $m_{\chi^{\pm}}$ > 91.9 GeV

Limit on the MSSM Neutralino

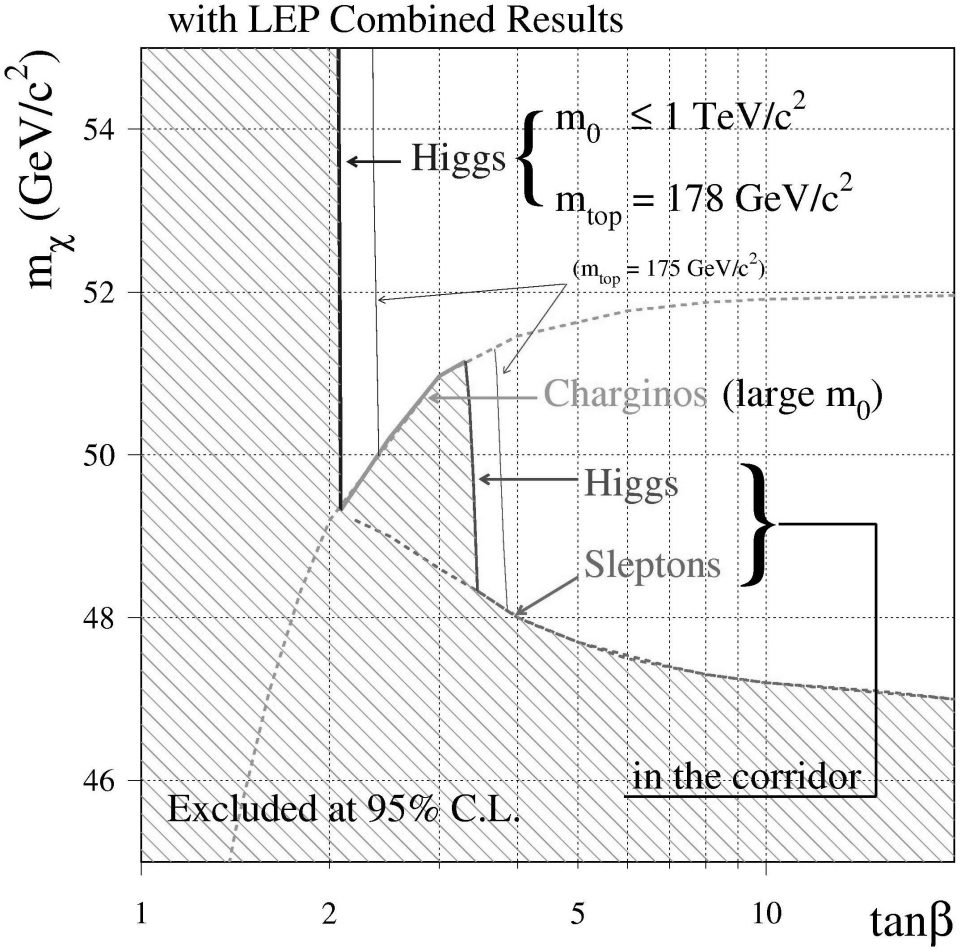
- **No direct absolute limit on neutralino (LSP)**

  $e^+e^- \rightarrow \chi^0\chi^0$

  vanishes for pure photino & heavy selectrons

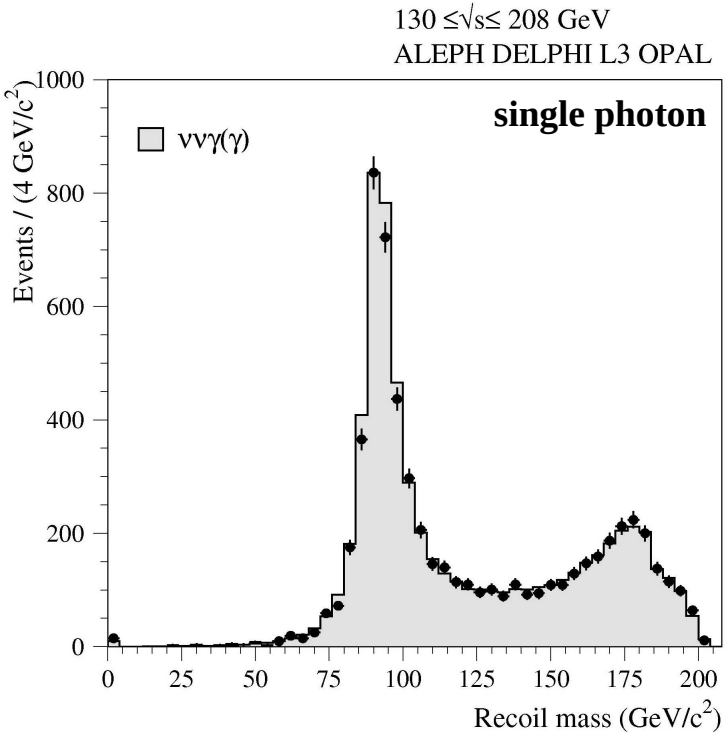
- **Limit obtained using**
  - **MSSM relations &**
  - **other SUSY searches**
    - **Higgs**
    - **chargino**
    - **sleptons**

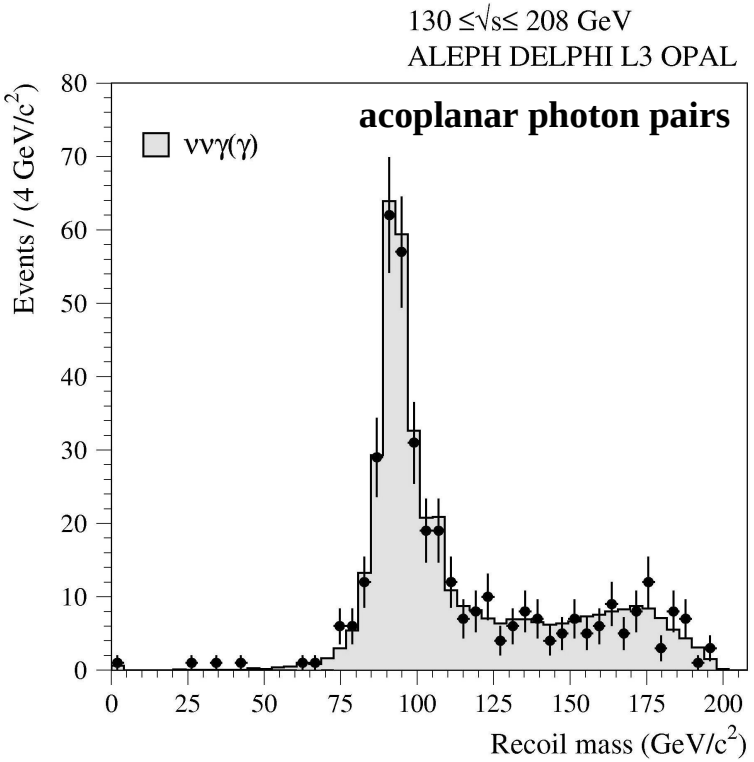
MSSM neutralino mass limit versus tan β



SUSY Photon Signatures

- **Signature of many SUSYprocesses:**
  single photon or acoplanar photons
  e.g. $e^+e^- \to \chi_2\,\chi_1 \to \chi_1\,\chi_1\gamma$, $e^+e^- \to \chi_2\,\chi_2 \to \chi_1\,\chi_1\,\gamma\gamma$ **MSSM**
  $e^+e^- \to \chi_1\,\chi_1 \to GG\,\gamma,\gamma$ **GSMB with χ1 NLSP**
- **LEP combined recoil mass distributions**
- **Perfect agreement with SM processes $e^+e^- \to \upsilon\upsilon\gamma$ and $e^+e^- \to \upsilon\upsilon\gamma\gamma$**

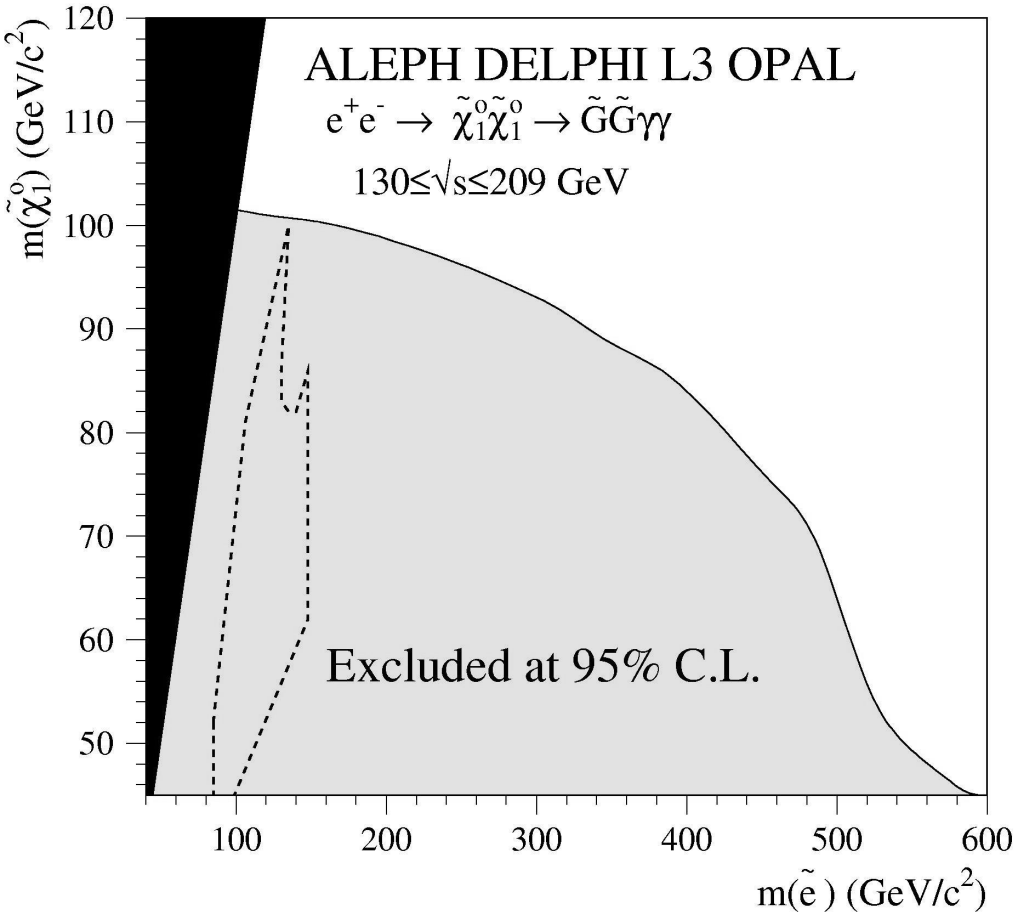




SUSY Photon Signatures

- **LEP exclusion of SUSY interpretation of the CDF event ($e^+e^-\gamma\gamma$ + miss. energy)**

$$qq \rightarrow \tilde{e}\,\tilde{e}$$
$$\rightarrow e^+e^-\,\chi_1\,\chi_1$$
$$\rightarrow e^+e^-\,\tilde{G}\gamma\,\tilde{G}\gamma$$



R-Parity Violating SUSY

- **SUSY in general does not require R-parity conservation**

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

Baryonic Number, Spin, Leptonic number

→ +1 for Standard Particles

→ -1 for Supersymmetric Partners

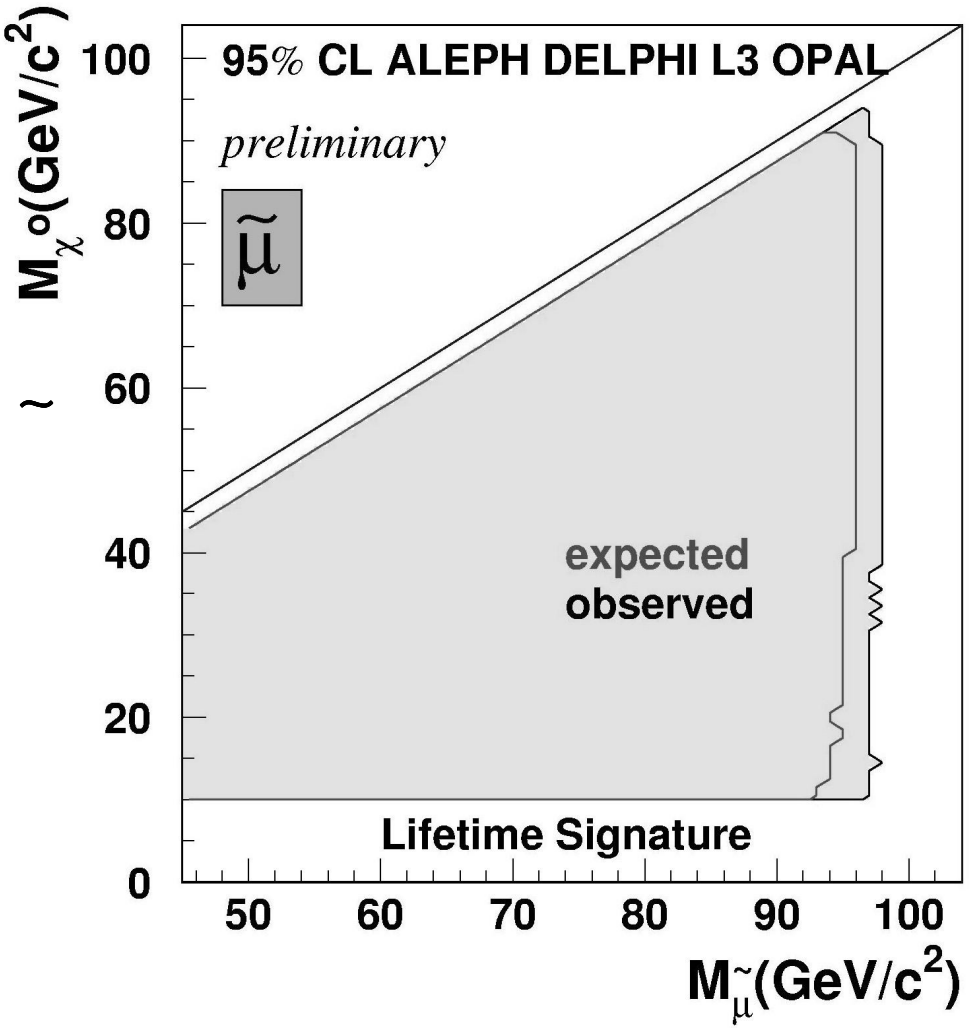
R_p conservation:	R_p violation:
Pair production of SUSY particles	Single production possible
All SUSY particle decay into LSP	LSP and other SUSY particles decay into standard particles
LSP is stable and interacts only weakly (good dark matter candidate)	LSP is no dark matter candidate
Main experimental signatures:	
Missing energy	Multi-jet and multi-lepton final states

Scalar Leptons in R-Parity Violating SUSY

- For high Δm:
  Limits reach values comparable R-parity conserving MSSM searches

$m_{\tilde{e}} > 96.6$ GeV
$m_{\tilde{\mu}} > 96.8$ GeV
$m_{\tilde{\tau}} > 95.9$ GeV

- Example: scalar muon exclusion



Summary I

- **LEP experiments established the validity of the SM with high precison**
  - **up to a cms energy of 208 GeV &**
  - **beyond the tree level**

- **The (SM) Higgs boson is light**
  - **$m_H > 114.4$ GeV from direct search**
  - **$m_H < 260$ GeV from rad. corrections**

- **No new physics observed**
  - **limits, e.g. on SUSY, often close to kinematic limit**

- **Legacy for the LHC**
  - **complete the triumph of the SM with the Higgs**
  - **replace it by a New SM**

Summary II

- **More information on LEP results from LEP Working Groups:**
  - **Electroweak**
  - **SUSY Searches**
  - **Energy Calibration**
  - **Exotica Searches**
  - **QCD/Two-Photon**
  - **Heavy Flavour**