Tests of the Standard Model

Joachim Mnich

CERN EP

International Europhysics Conference
on High Energy Physics 1999

Tampere, 15 – 21 July 1999

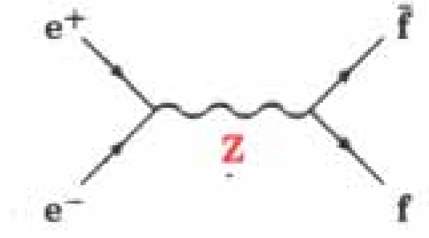
Outline

- Precision measurements at the Z resonance
- Fermion-pair production above the Z
- Production of neutral bosons pairs $e^+e^- \rightarrow \gamma\gamma$, $e^+e^- \rightarrow$ ZZ and the couplings of the neutral gauge bosons
- The properties of the $W^\pm$ boson
- Interpretation in the Standard Model and limits on the Higgs boson

New results from

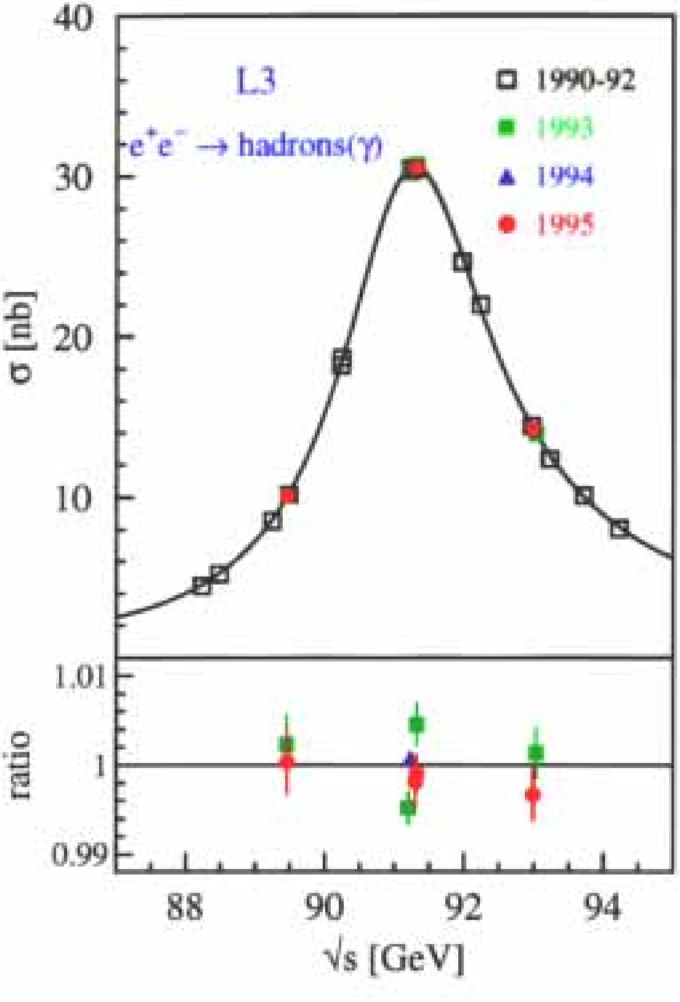
- LEP up to $\sqrt{s} = 196$ GeV
- SLD
- CDF and DØ
- HERA

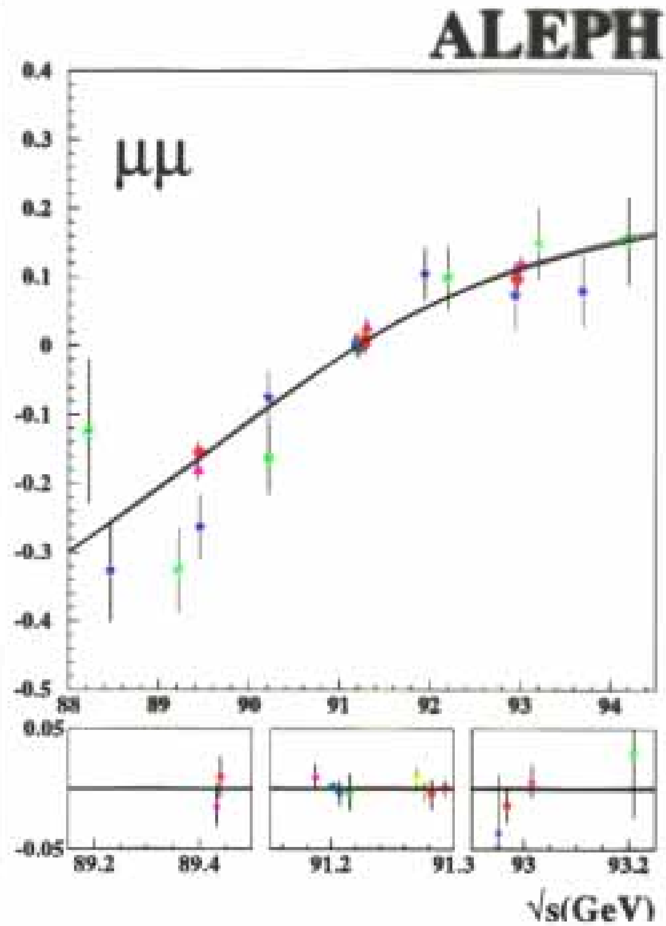
Most of the results are preliminary



$e^+e^- \rightarrow \text{hadrons}$ $e^+e^- \rightarrow e^+e^-$
$e^+e^- \rightarrow \mu^+\mu^-$ $e^+e^- \rightarrow \tau^+\tau^-$

- Precision measurements of total cross sections and leptonic forward-backward asymmetries at LEP:





- 17 million Z decays observed at LEP (1989 – 1995)
- Finalizing the analyses of the experiments
- Determination of Z parameters

- Improvements on theoretical calculations

ZFITTER 6.10 (D. Bardin et al.)
TOPAZ0 4.4 (G. Passarino et al.)
ALIBABA (W. Beenaker et al.) for $e^+e^- \rightarrow e^+e^-(\gamma)$

ZFITTER & TOPAZ0 calculate

- QED and QCD corrections

ISR: $\mathcal{O}(\alpha^2), \mathcal{O}(\alpha^3 L^3)$ $L = \ln(s/m_e^2)$ FSR: $\mathcal{O}(\alpha), \mathcal{O}(\alpha\alpha_s), \mathcal{O}(\alpha_s^3)$
+ interference

- Electroweak

leading two-loop $\mathcal{O}(G_F^2 m_t^4)$, sub-leading two-loop $\mathcal{O}(G_F^2 m_t^2 m_Z^2)$

- Mixed QCD × EW

$\mathcal{O}(\alpha\alpha_s)$, leading $\mathcal{O}(\alpha\alpha_s^2)$

Contributions from G. Degrassi et al., S. Jadach et al., B. Kniehl, J. Kühn et al., G. Montagna et al.

$\Longrightarrow$ Small theoretical uncertainties:

- Uncertainties on QED corrections of Z lineshape:

$$\Delta m_Z = \pm 0.3 \text{ MeV}$$
$$\Delta \Gamma_Z = \pm 0.5 \text{ MeV}$$
$$\Delta \sigma^0_{\text{had}} / \sigma^0_{\text{had}} = \pm 2 \cdot 10^{-4}$$

- Very good agreement between ZFITTER and TOPAZ0:

$$\leq 10^{-4} \text{ (peak)} \qquad \leq 3 \cdot 10^{-4} \text{ (off − peak)}$$

- SM parameter uncertainty

$$\Delta m_Z = \pm 0.3 \text{ MeV}$$

- $0.54 - 0.61 \cdot 10^{-3}$ on the luminosity measurement (B. Ward et al.)

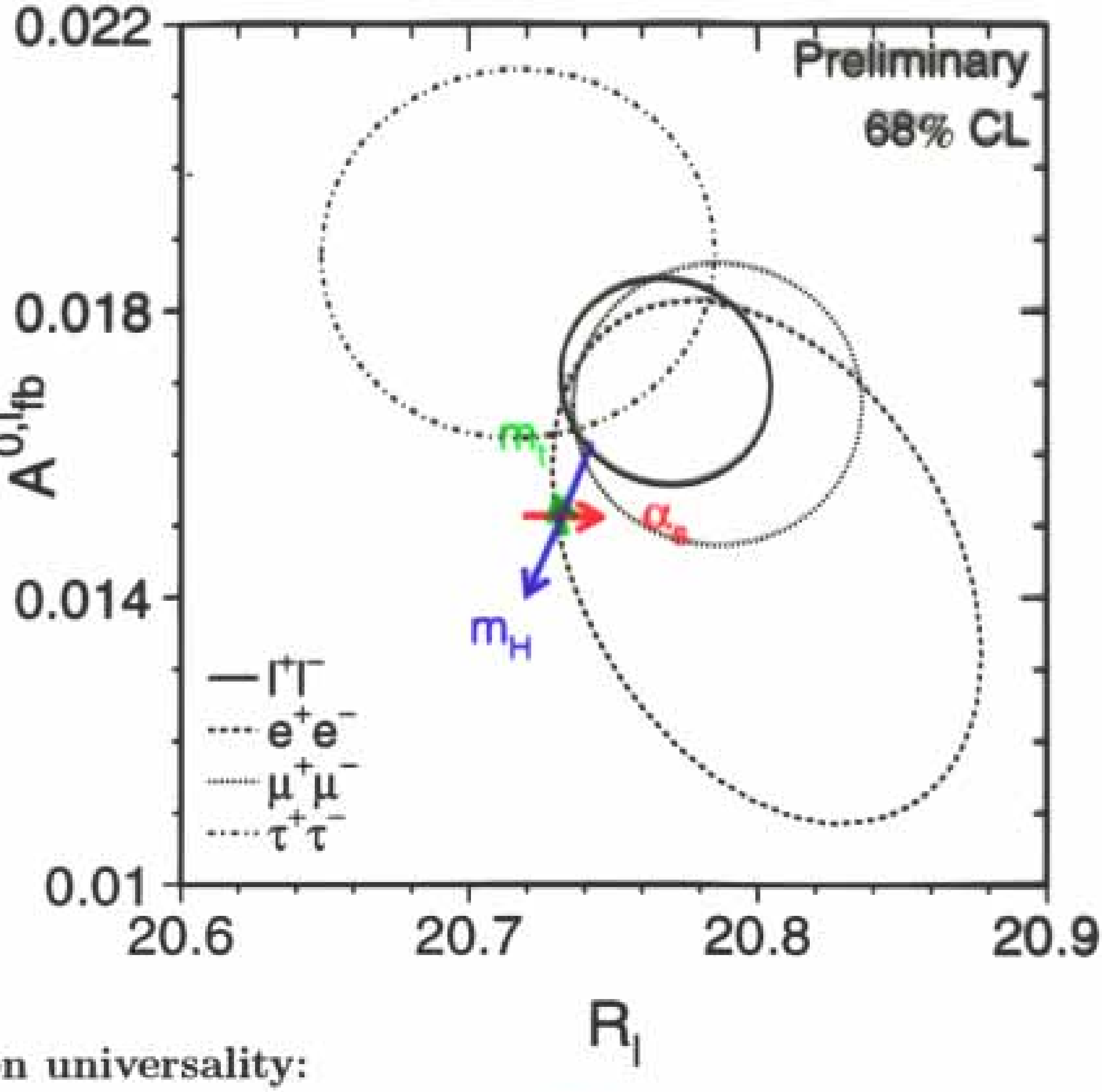
- Experiments determine 9 parameter from total cross sections and forward-backward asymmetries
- Combination of the four LEP experiments:

m_Z	$91\,187.2 \pm 2.1$ MeV
Γ_Z	$2\,499.4 \pm 2.4$ MeV
σ^0_{had}	41.544 ± 0.037 nb
R_e	20.803 ± 0.049
R_μ	20.786 ± 0.033
R_τ	20.764 ± 0.045
$A_{\text{FB}}^{0,e}$	0.0145 ± 0.0024
$A_{\text{FB}}^{0,\mu}$	0.0167 ± 0.0013
$A_{\text{FB}}^{0,\tau}$	0.0188 ± 0.0017

(+ small correlations)

$$\sigma^0_{\text{had}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_{\text{had}}}{\Gamma_Z^2}, \quad R_\ell = \frac{\Gamma_{\text{had}}}{\Gamma_\ell},$$

$$A_{\text{FB}}^{0,\ell} = \frac{3}{4}A_e A_\ell, \quad A_\ell = \frac{2\bar{g}_V^\ell \bar{g}_A^\ell}{(\bar{g}_V^\ell)^2 + (\bar{g}_A^\ell)^2}$$



Lepton universality:

$R_\ell = 20.768 \pm 0.024$ $\qquad$ $A_{FB}^{0,\ell} = 0.01701 \pm 0.00095$

$(\alpha_s = 0.1229 \pm 0.0036\,^{+0.0033}_{-0}(m_H))$

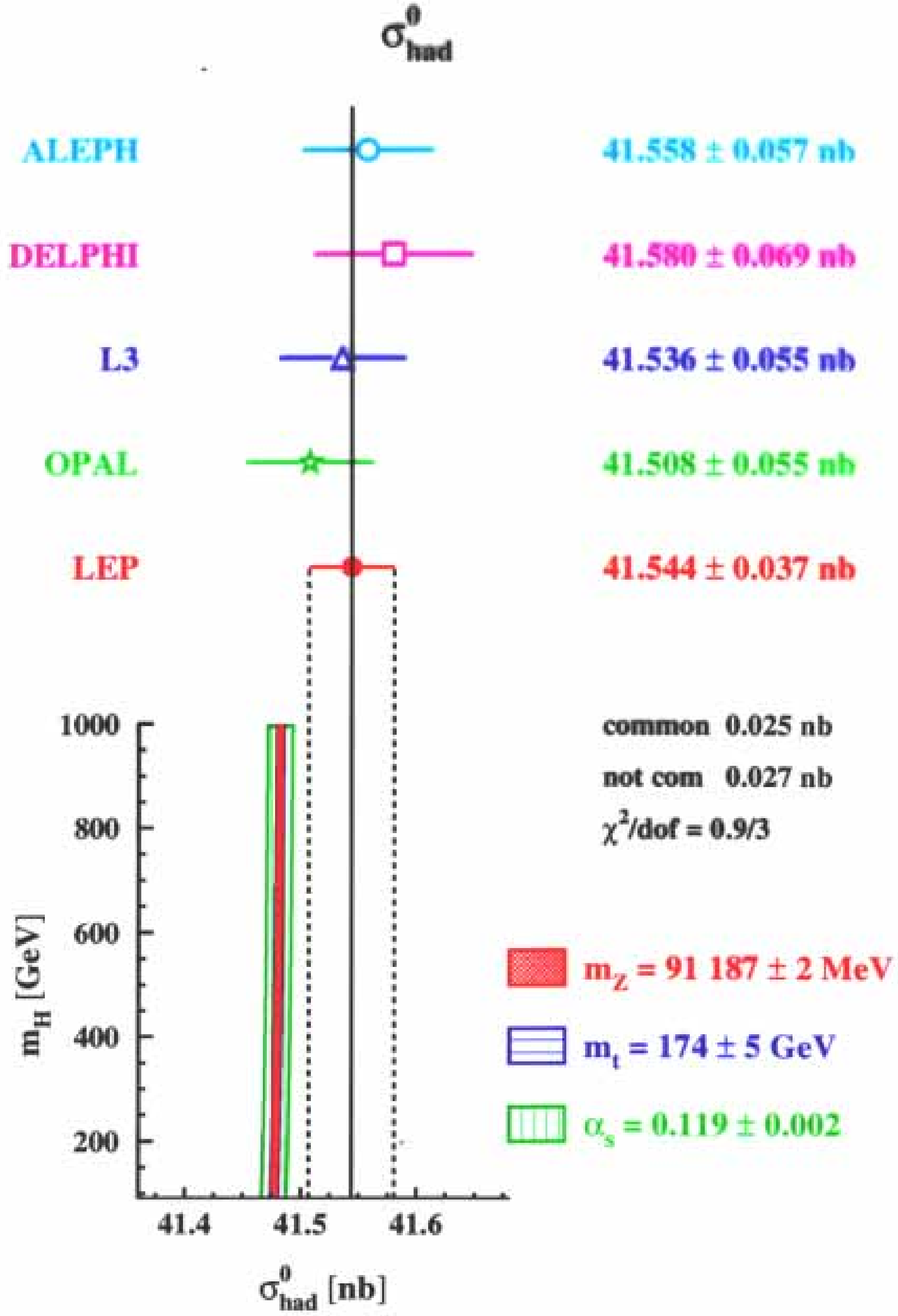
Partial decay widths:

$$\Gamma_{had} = 1743.9 \pm 2.0 \text{ MeV}$$
$$\Gamma_\ell = 83.958 \pm 0.089 \text{ MeV}$$
$$\Gamma_{inv} = 498.80 \pm 1.5 \text{ MeV}$$
$$\Delta\Gamma_{inv} < 2.0 \text{ MeV} \qquad 95\% \text{ CL}$$

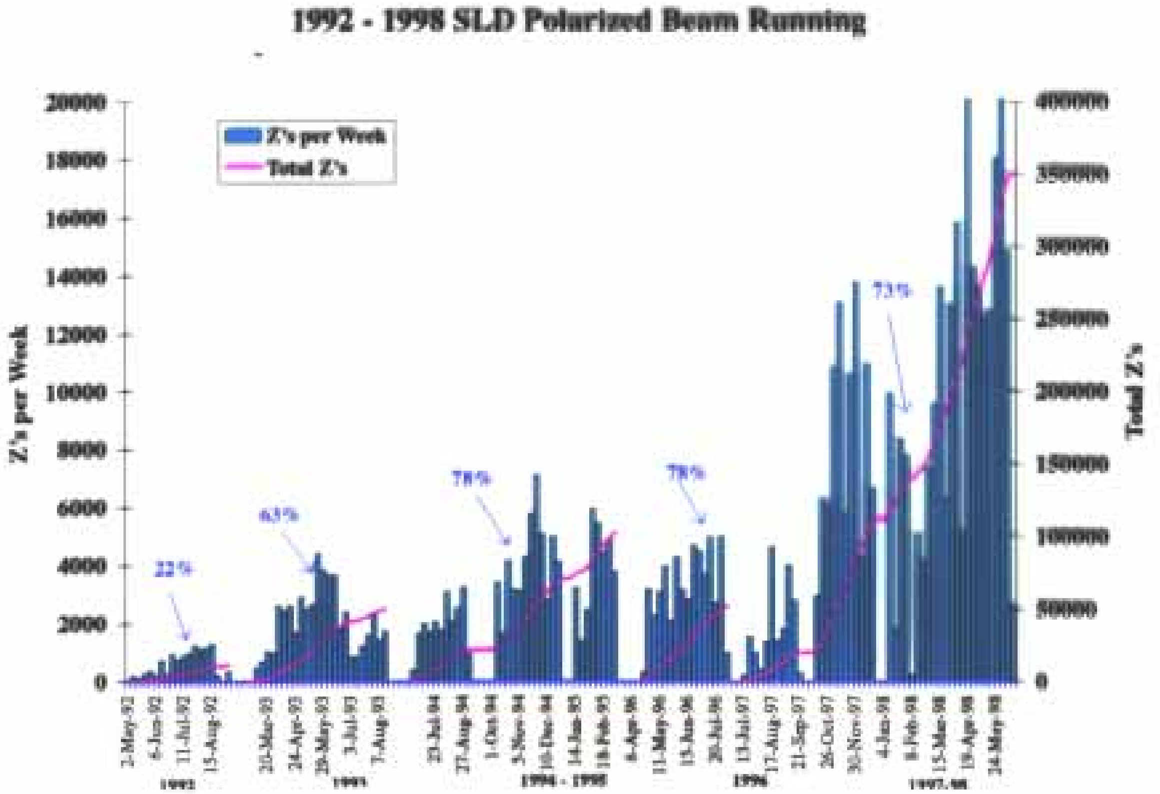
Number neutrino families:

$$N_\nu = 2.9835 \pm 0.0083$$

Measurements of the hadronic pole cross section



- SLD: 550k $e^+e^- \rightarrow$ hadrons(γ) events collected in total
  Polarized e^- beam



Left-right asymmetry A_{LR} in $e^+e^- \rightarrow$ hadrons

$$A_e = 0.1510 \pm 0.0025$$

Left-right forward-backward asymmetries $e^+e^- \rightarrow \ell^+\ell^-$:

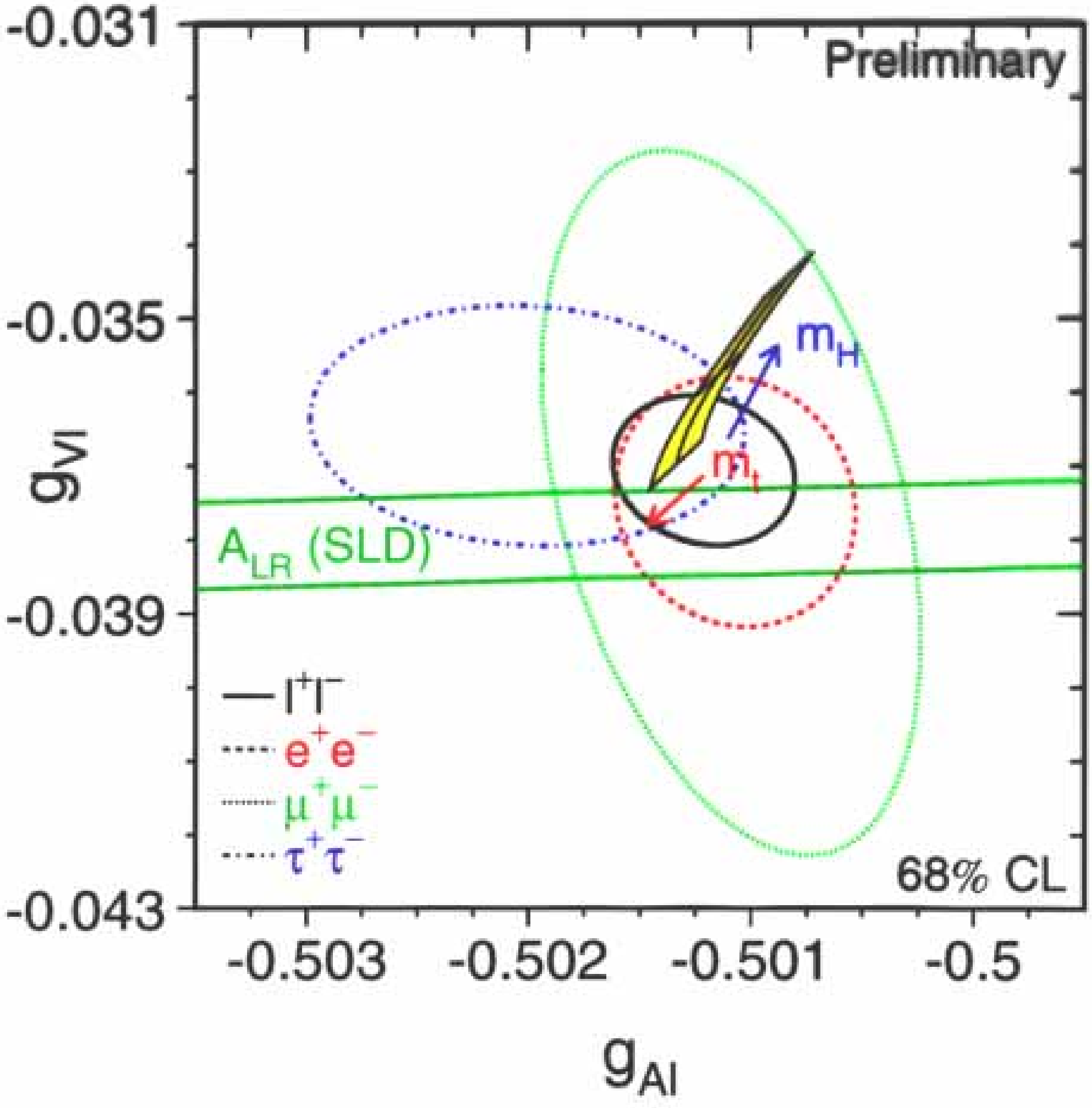
$$\begin{aligned} A_e &= 0.1504 \pm 0.0072 \\ A_\mu &= \;\; 0.120 \pm 0.019 \\ A_\tau &= \;\; 0.142 \pm 0.019 \\ \hline A_\ell &= 0.1459 \pm 0.0063 \end{aligned}$$

Measurement of the effective weak mixing angle:

$$\sin^2\overline{\theta}_{\mathrm{W}} = 1 - 4\,\frac{\bar{g}_{\mathrm{V}}^{\ell}}{\bar{g}_{\mathrm{A}}^{\ell}} = 0.23109 \pm 0.00029$$

Include LEP tau polariziation measurements:

$$A_e = 0.1483 \pm 0.0051$$
$$A_\tau = 0.1425 \pm 0.0044$$



Ratios of neutral current coupling constants (LEP & SLD):

$\bar{g}_A^\mu/\bar{g}_A^e = 1.0001 \pm 0.0014$ $\quad$ $\bar{g}_V^\mu/\bar{g}_V^e = 0.981 \pm 0.082$

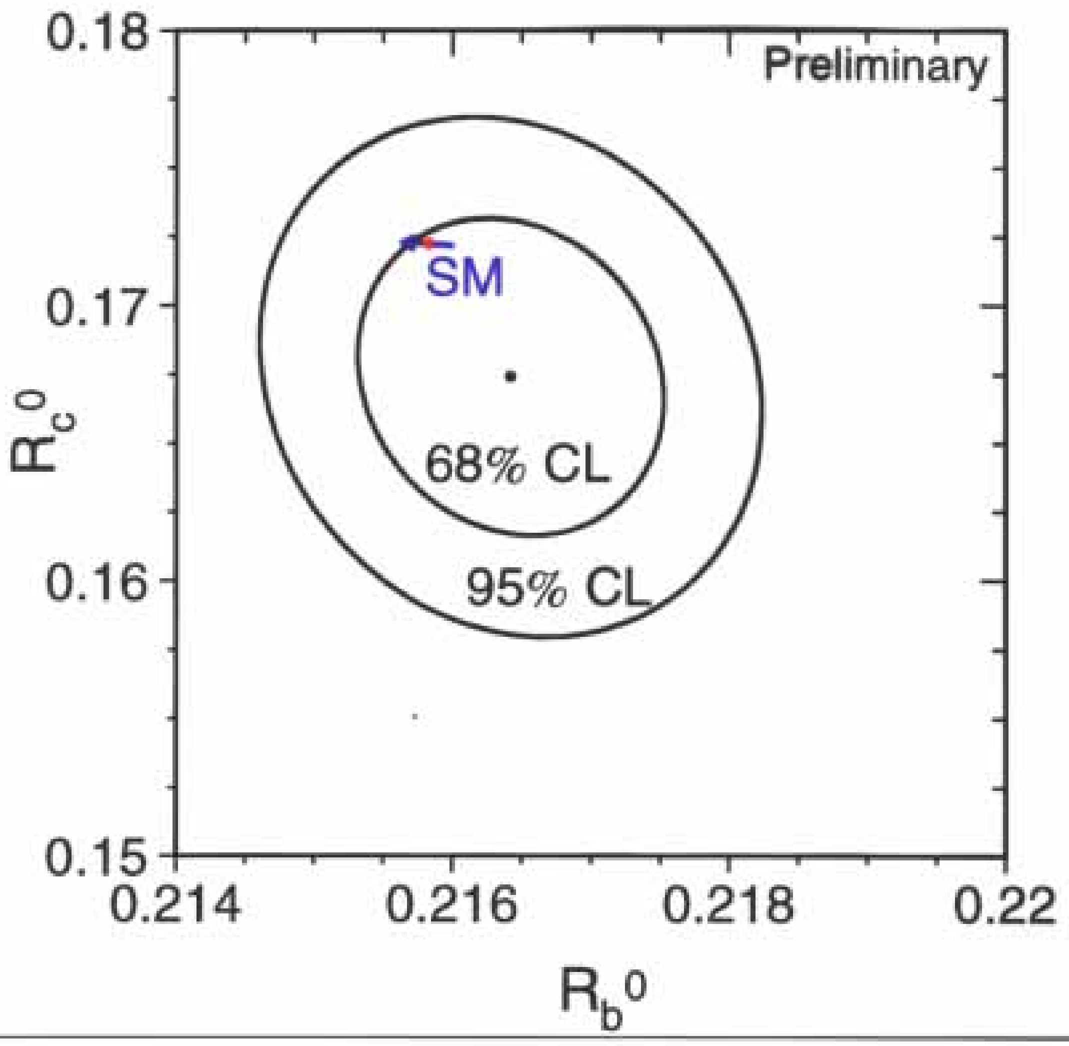
$\bar{g}_A^\tau/\bar{g}_A^e = 1.0019 \pm 0.0015$ $\quad$ $\bar{g}_V^\tau/\bar{g}_V^e = 0.964 \pm 0.032$

Measurements of

- Cross sections (R_b, R_c) at LEP & SLD
  $R_q = \Gamma_q/\Gamma_{had}$ $\qquad \Gamma_q \propto (\bar{g}_A^q)^2 + (\bar{g}_V^q)^2$
- Forward-backward asymmetries at LEP
  $A_{FB}^{0,b}$, $A_{FB}^{0,c}$
- Left-right forward-backward asymmetries
  A_b, A_c $\qquad A_q = \frac{2\bar{g}_A^q \bar{g}_V^q}{(\bar{g}_A^q)^2 + (\bar{g}_V^q)^2}$

Combined fit to LEP & SLD data:

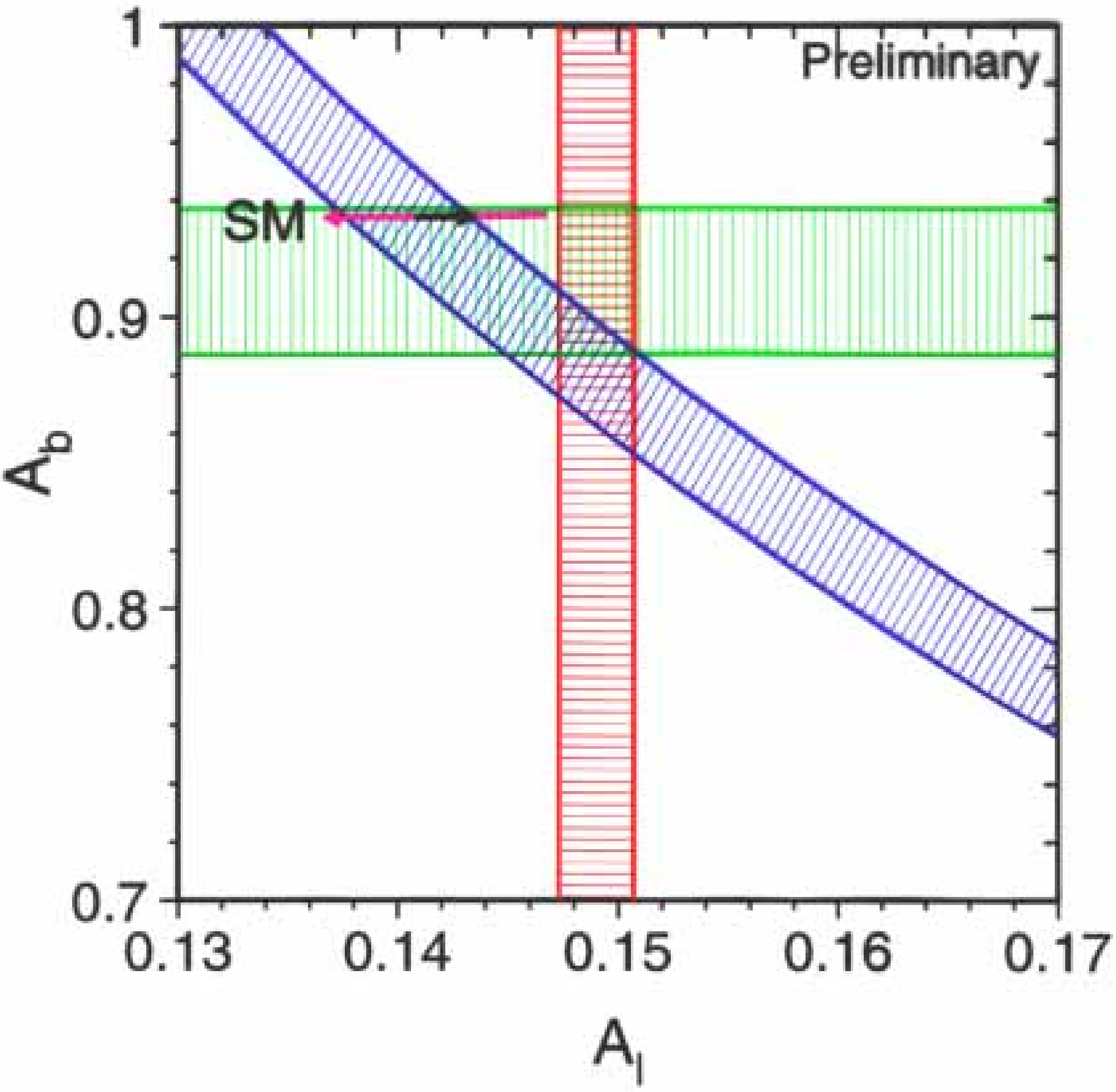
$$R_b = 0.21642 \pm 0.00073 \qquad R_c = 0.1674 \pm 0.0038$$
$$A_{FB}^{0,b} = 0.0984 \pm 0.0020 \qquad A_{FB}^{0,c} = 0.0691 \pm 0.0037$$
$$A_b = 0.912 \pm 0.025 \qquad A_c = 0.630 \pm 0.026$$



Z couplings to quarks

Comparison of

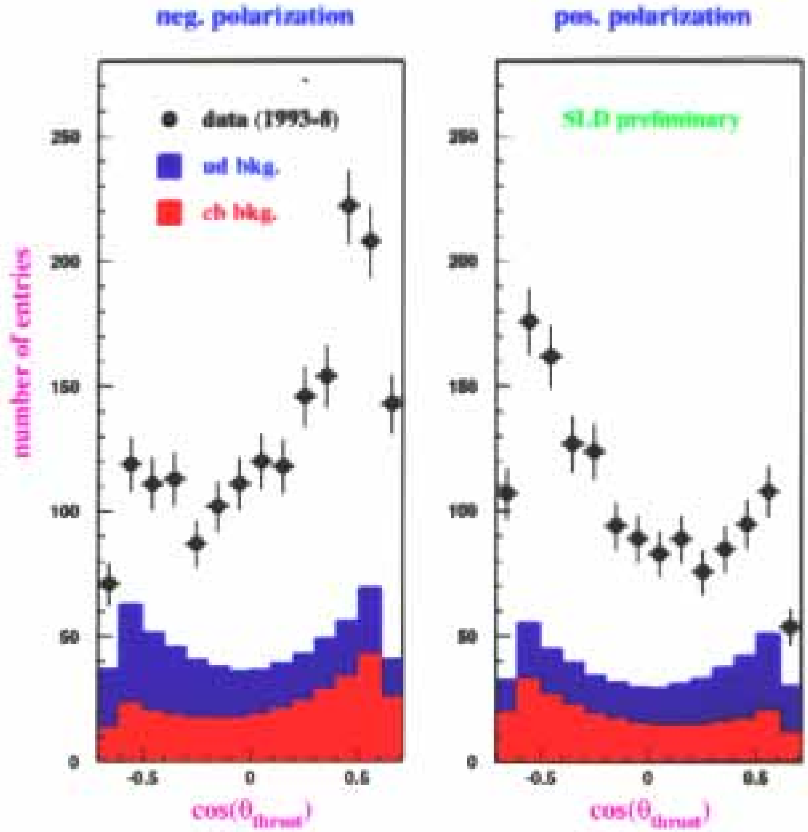
- A_b (left-right forward-backward asymmetry)
- A_ℓ (A_{LR}, $A_{FB}^{0,\ell}$, tau-polarization)
- $A_{FB}^{0,b} = \frac{3}{4} A_\ell A_b$
- SM (m_H, m_t)



	LEP	SLD	LEP & SLD	SM
A_ℓ	0.1471 ± 0.0026		0.1490 ± 0.0017	
A_b	0.892 ± 0.024	0.912 ± 0.025	0.893 ± 0.016	0.935
A_c	0.624 ± 0.035	0.630 ± 0.026	0.625 ± 0.021	0.668

Z couplings to s-quarks

Identify $e^+e^- \rightarrow s\bar{s}$ by high momentum K^+, K_s, Λ^0 in hadronic events

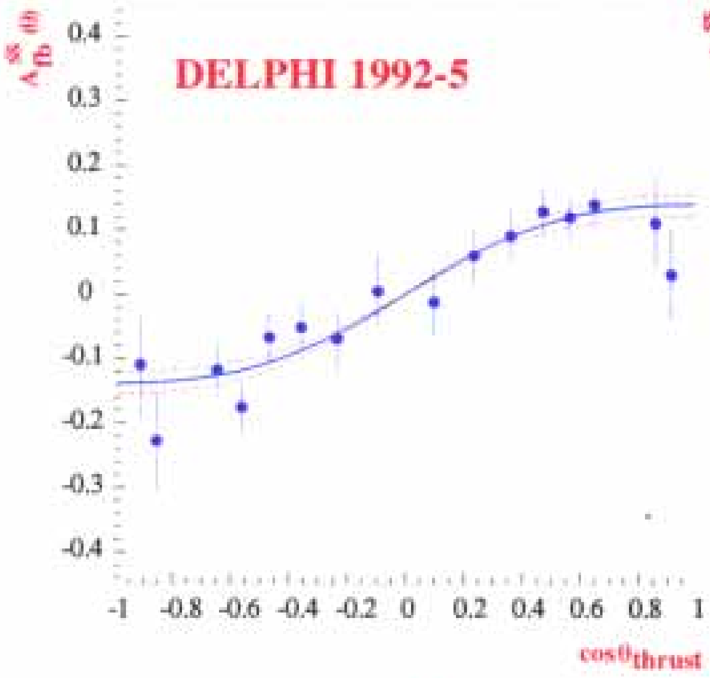


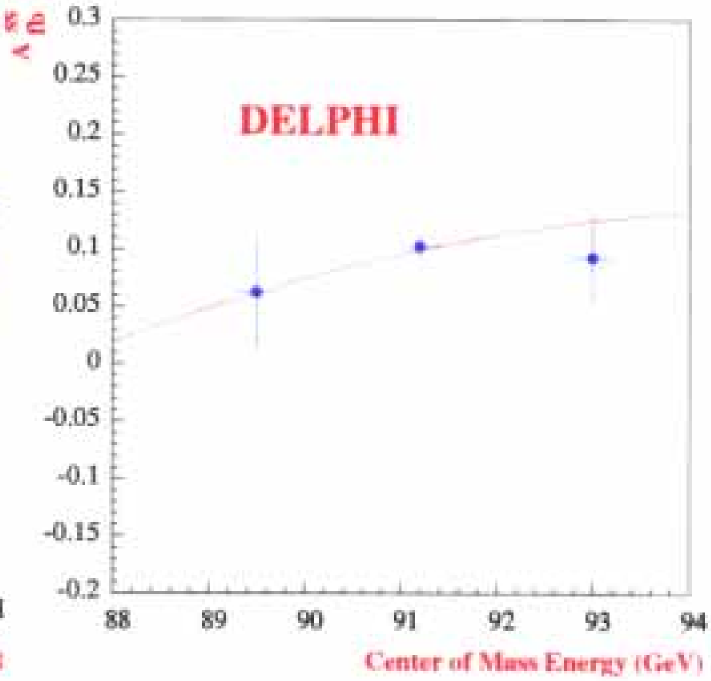
SLD:

0.07

$A_s = 0.85 \pm 0.06 \pm$ [redacted]

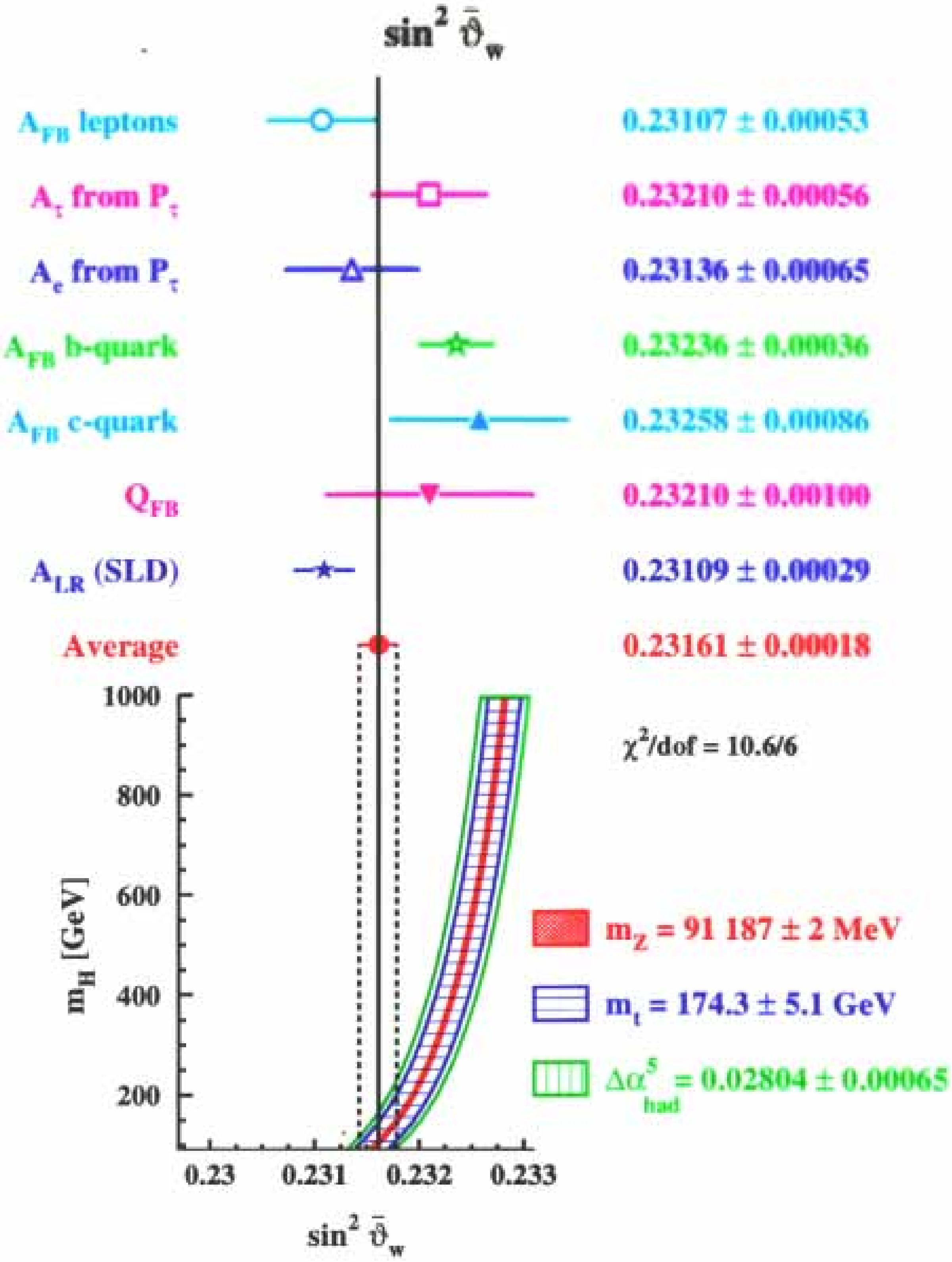
DELPHI: Forward-backward asymmetry





$$A_{FB}^{0,s} = 0.1008 \pm 0.0113 \pm 0.0040$$

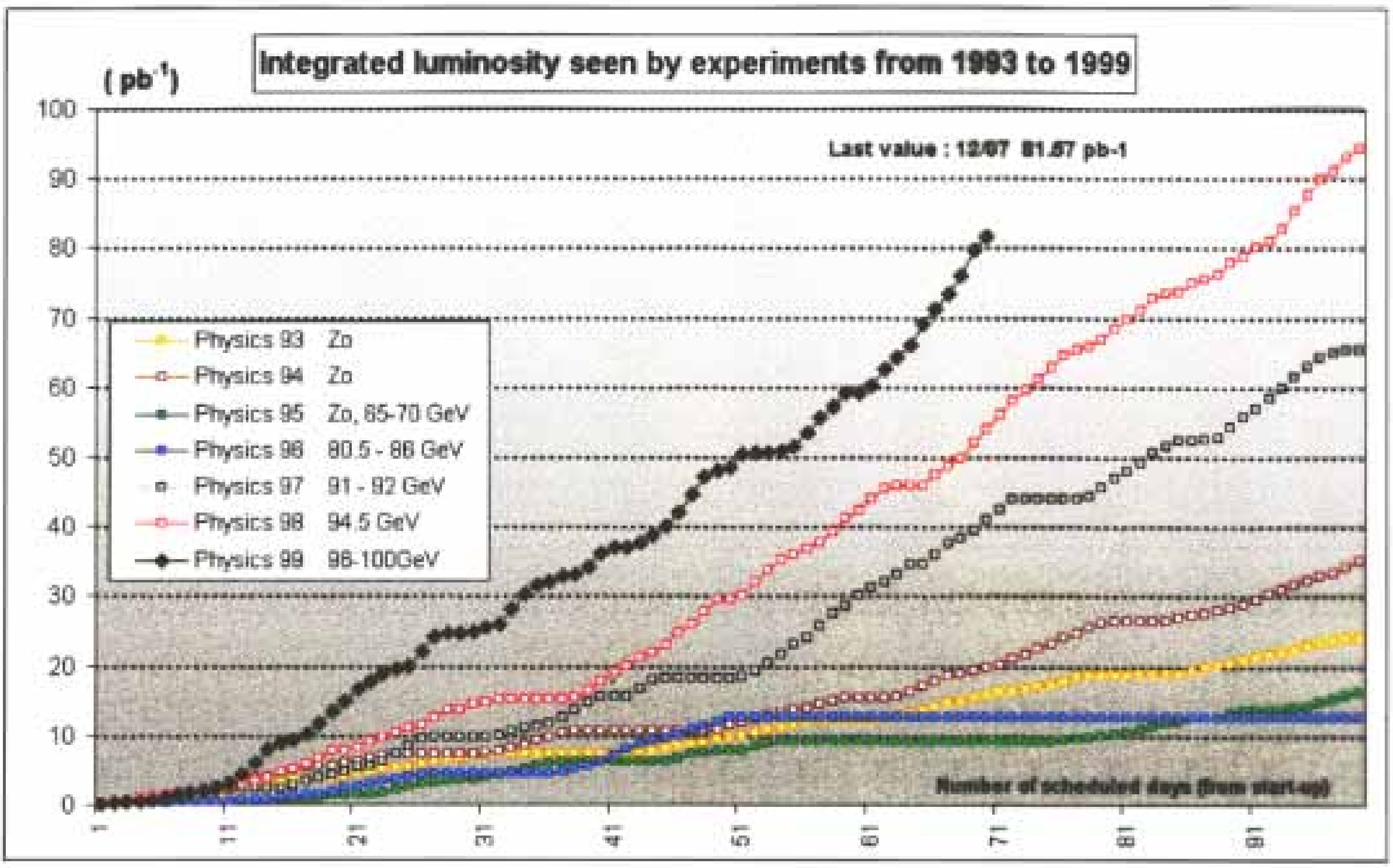
Measurements of the effective electroweak mixing angle



- **LEP II: Physics above the Z resonance**

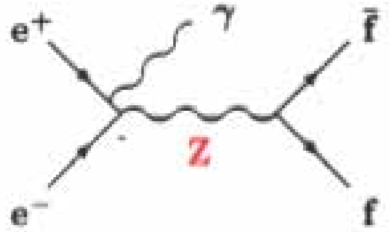
Centre-of-mass energies and approximate luminosities per experiment:

Year	$\sqrt{s}$	$\int \mathcal{L}\,dt$
1995	130 – 140 GeV	5 pb^{-1}
1996	161/172 GeV	21 pb^{-1}
1997	183 GeV	55 pb^{-1}
	130/136 GeV	7 pb^{-1}
1998	189 GeV	180 pb^{-1}
1999	192 GeV	27 pb^{-1}
	196 GeV	> 20 pb^{-1}



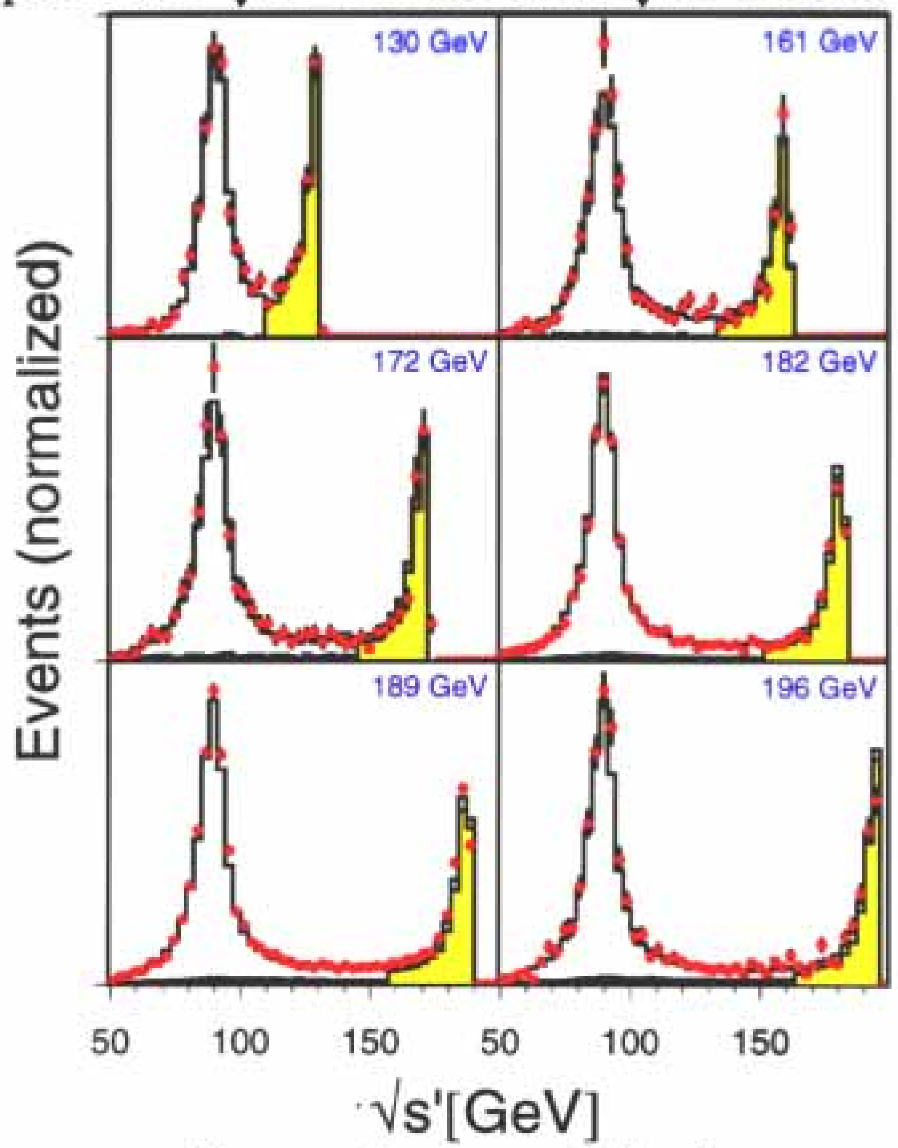
$e^+e^- \to f\bar{f}$ above the Z resonance

Important contribution from initial state radiation:



'Return-to-the-Z'

Effective cms energy $\sqrt{s'}$ in $e^+e^- \to \text{hadrons}(\gamma)$
Data samples from $\sqrt{s} = 130$ GeV to $\sqrt{s} = 196$ GeV:

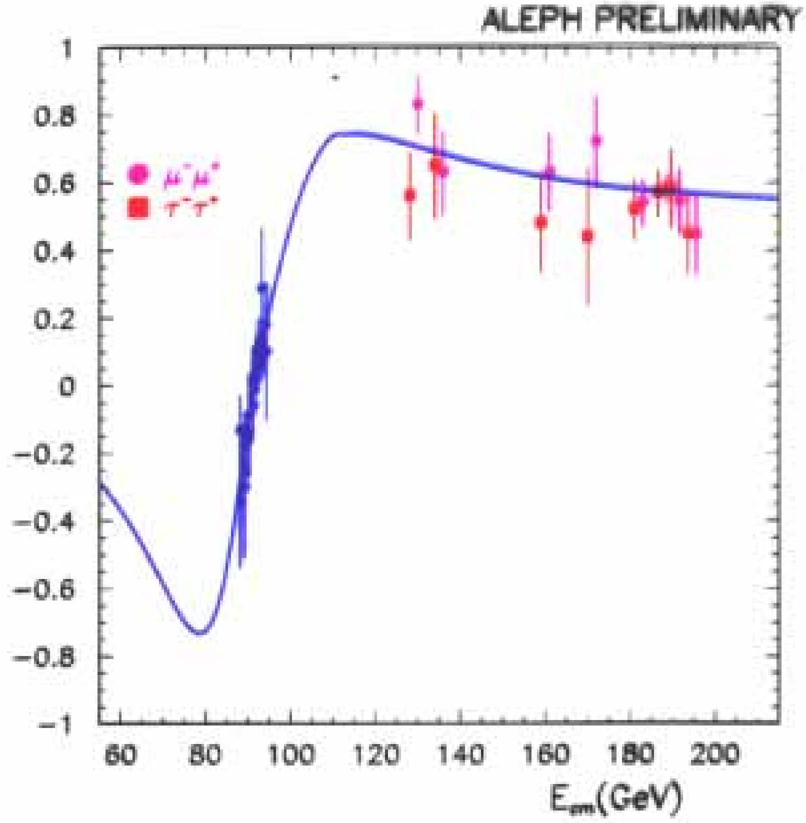


Measure cross sections and asymmetries for

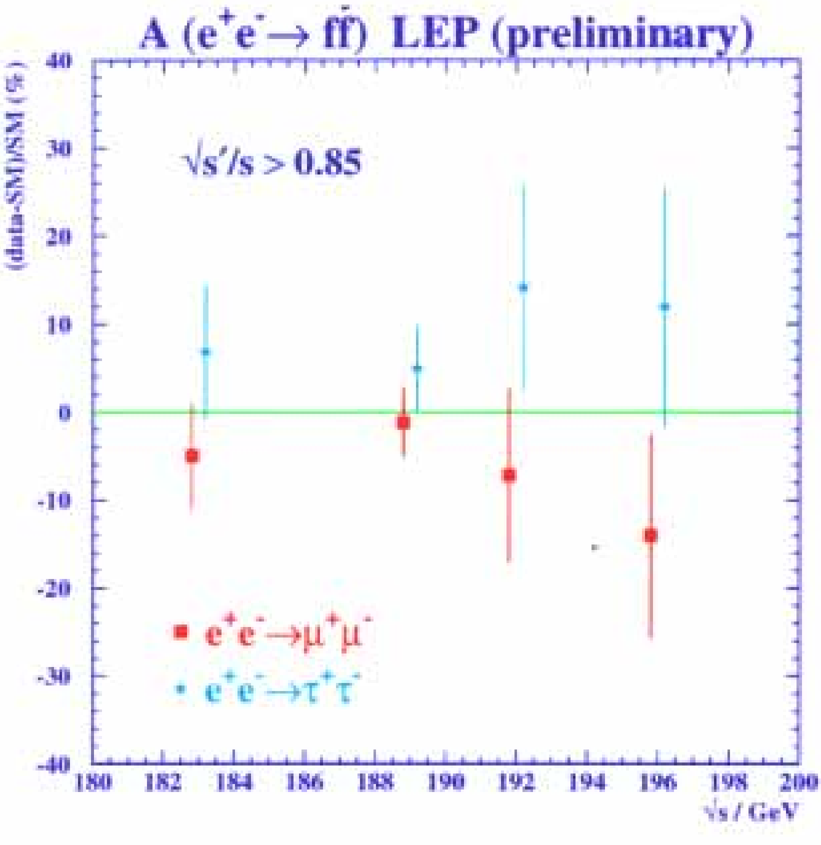
- Inclusive sample
- High energy sample $\sqrt{s'} > 0.85\sqrt{s}$

$e^+e^- \to f\bar{f}$ above the Z resonance

- Leptonic forward-backward asymmetries up to $\sqrt{s} = 196$ GeV

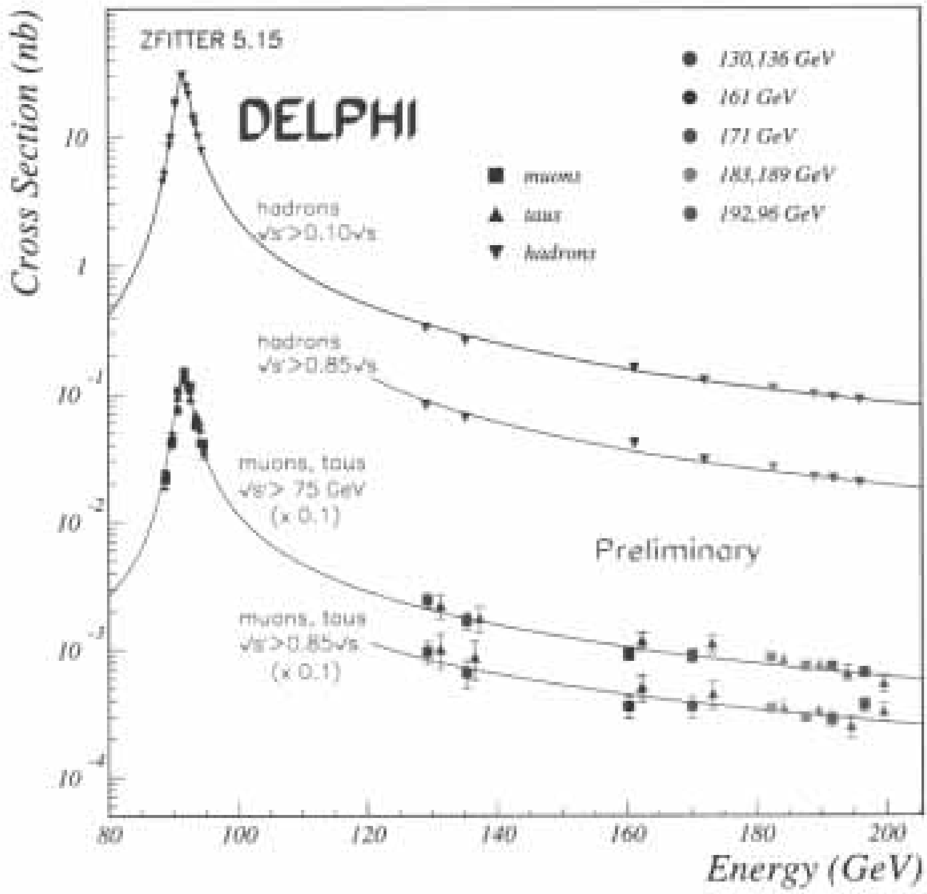


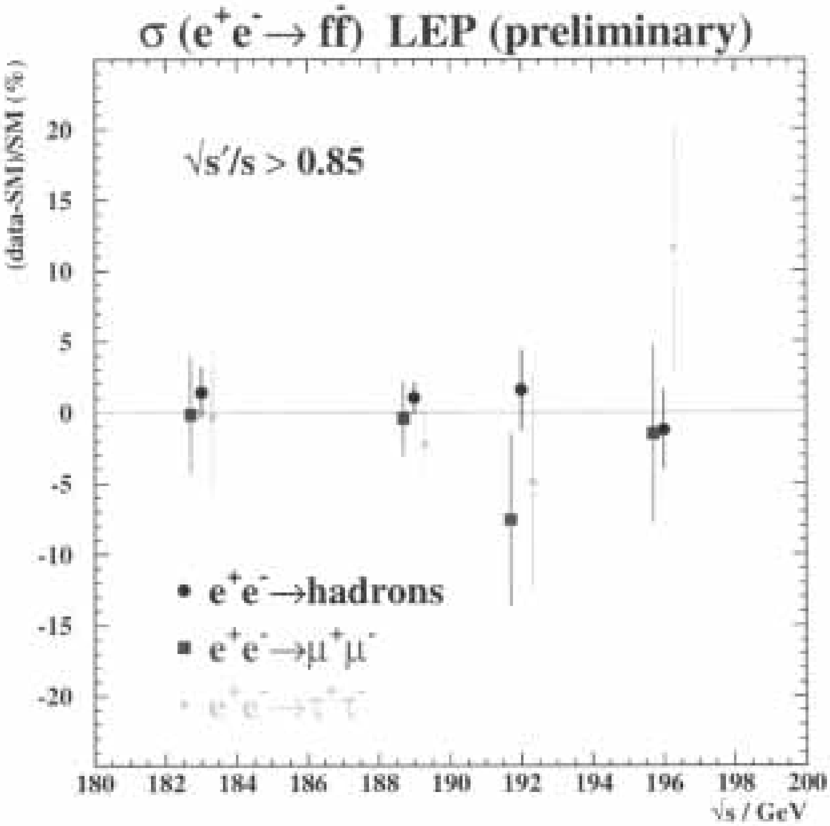
$\sqrt{s'}/\sqrt{s} > 0.9$



LEP combination
183 GeV $\leq \sqrt{s} \leq$ 196 GeV
(Difference to SM)

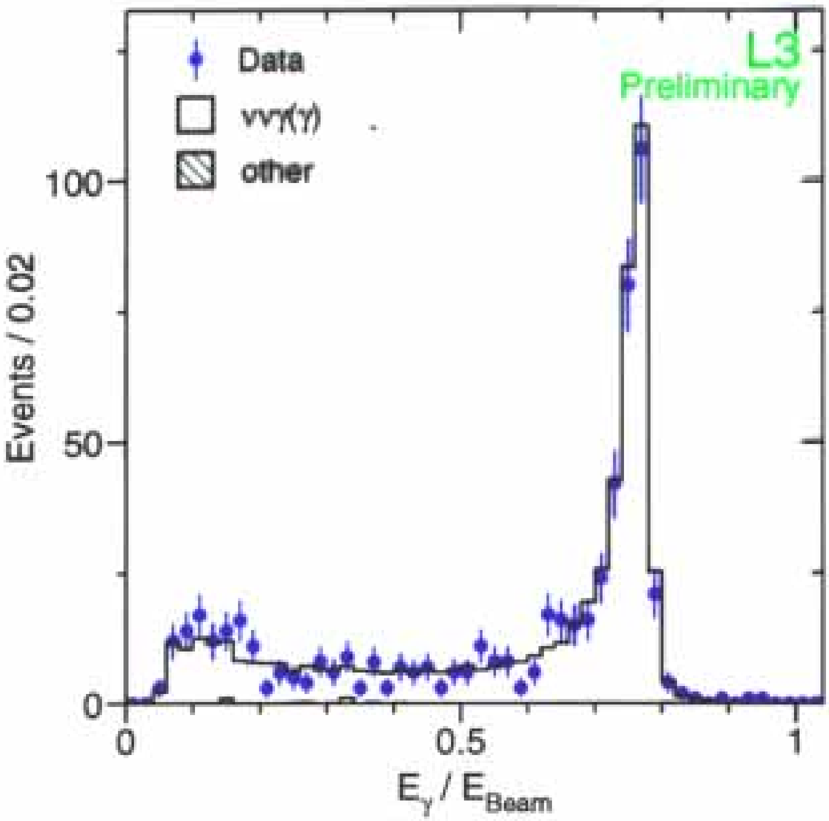
- **Quark- and lepton-pair cross sections up to $\sqrt{s} = 196$ GeV**





LEP combination
183 GeV $\leq \sqrt{s} \leq$ 196 GeV
(Difference to SM)

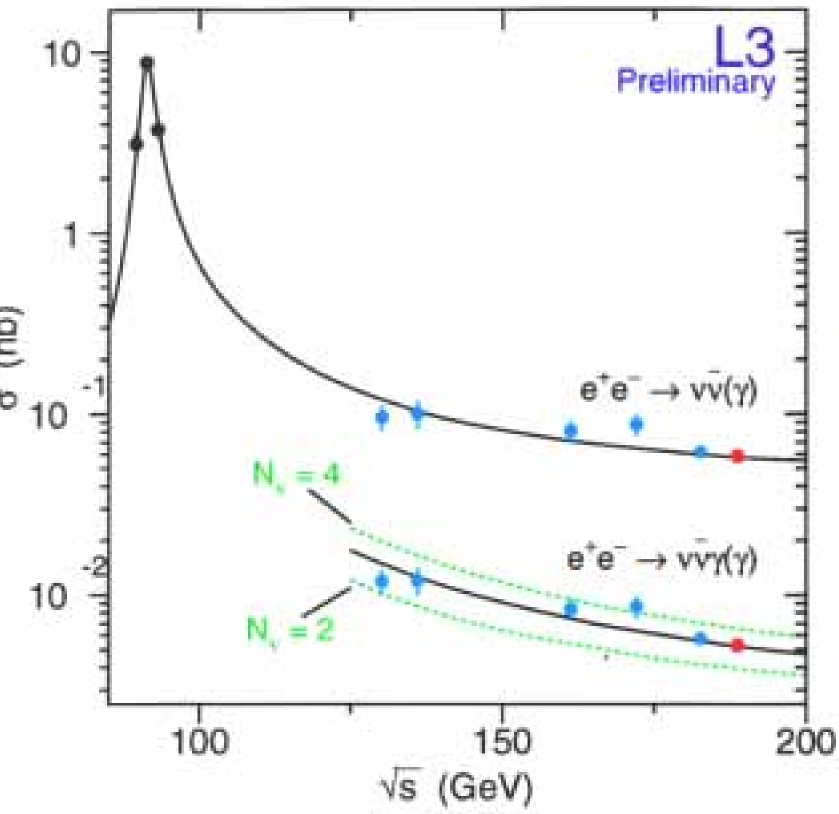
Cross section $e^+e^- \to \nu\bar{\nu}$ from single photon events



$\sqrt{s} = 189$ GeV

≈ 500 events per experiment

	$\sigma^{meas}/\sigma^{SM}$
ALEPH	1.017 ± 0.053
DELPHI	0.965 ± 0.088
L3	0.994 ± 0.044
OPAL	0.908 ± 0.053



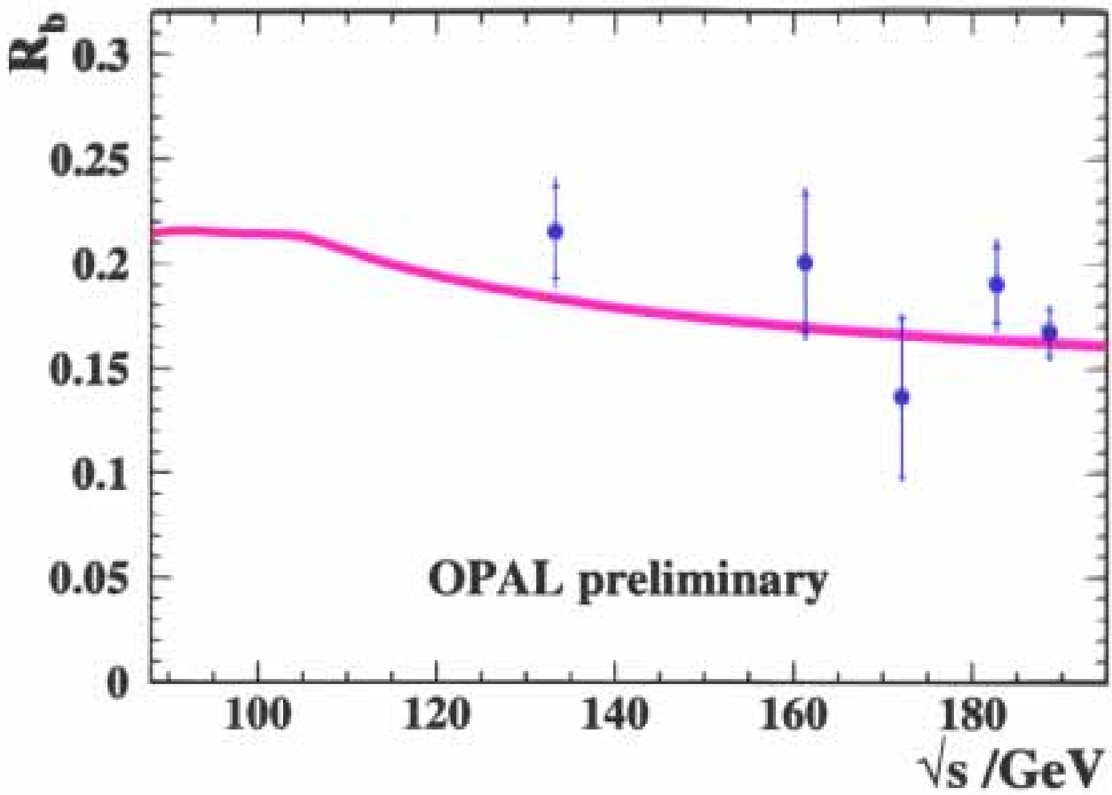
\# of neutrino species

L3	3.05 ± 0.12
DELPHI	2.83 ± 0.19
LEP II	2.99 ± 0.10

LEP I

single γ	3.00 ± 0.08
lineshape	2.9835 ± 0.0083

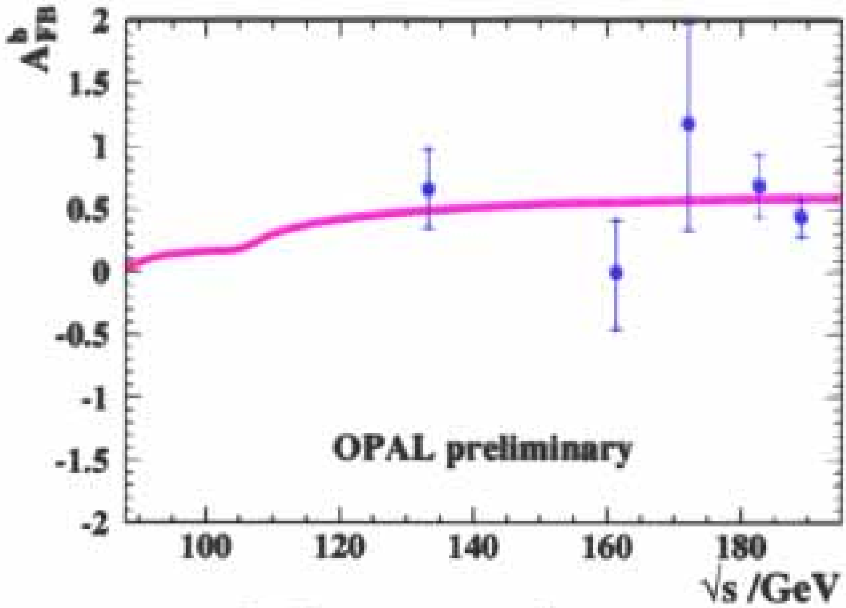
- Measurement of $R_b = \sigma(e^+e^- \to b\bar{b})/\sigma(e^+e^- \to q\bar{q})$



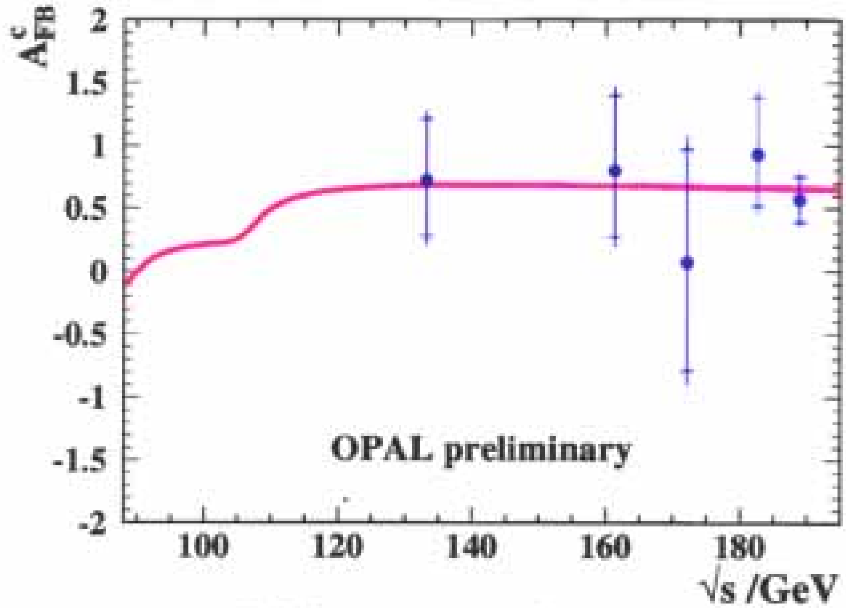
Compilation of measurements at $\sqrt{s} = 189$ GeV:

	R_b
ALEPH	$0.151 \pm 0.011\,^{+0.002}_{-0.004}$
DELPHI	0.167 ± 0.012
L3	$0.163 \pm 0.012 \pm 0.010$
OPAL	$0.167 \pm 0.011 \pm 0.008$
LEP	0.161 ± 0.007
SM	0.168

- Measurement of forward-backward asymmetries



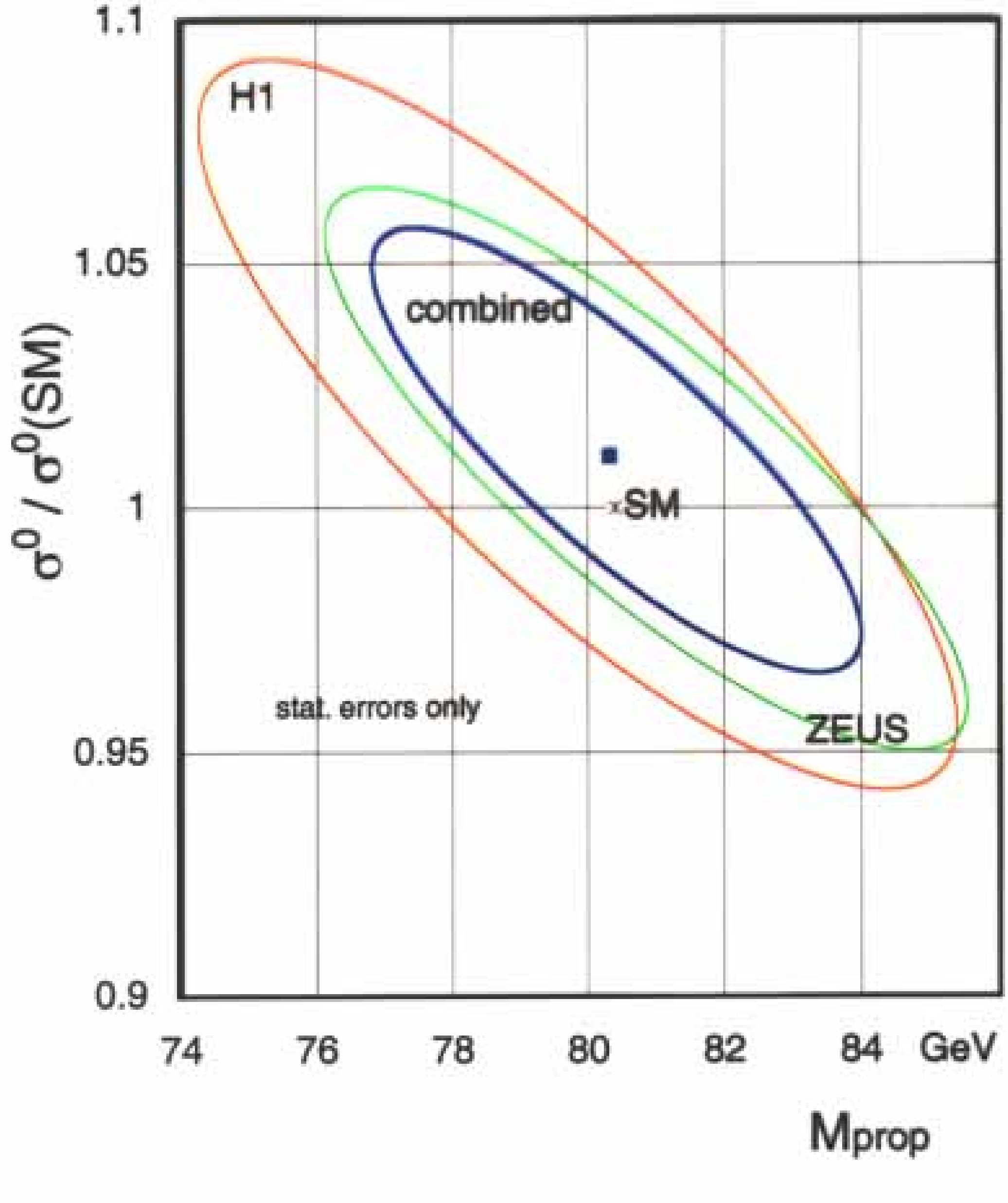
189 GeV	A^b_{FB}
ALEPH	$0.34 \pm 0.19 \pm 0.02$
L3	$0.66 \pm 0.23 \pm 0.08$
OPAL	$0.43 \pm 0.15 \pm 0.08$
LEP	0.44 ± 0.12
SM	0.58



189 GeV	A^c_{FB}
OPAL	$0.57 \pm 0.18 \pm 0.09$
SM	0.65

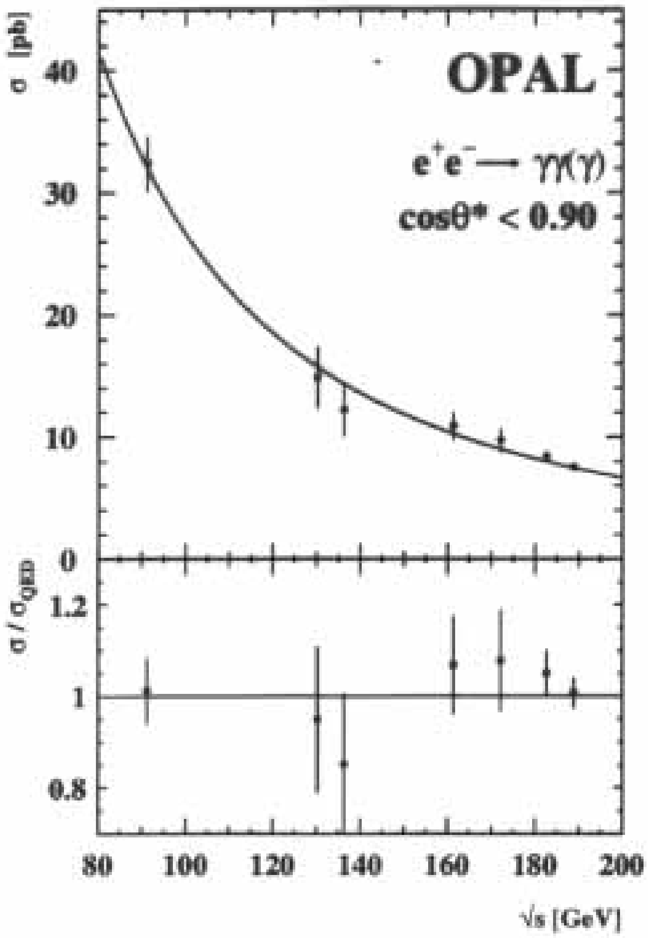
Space-like W exchange

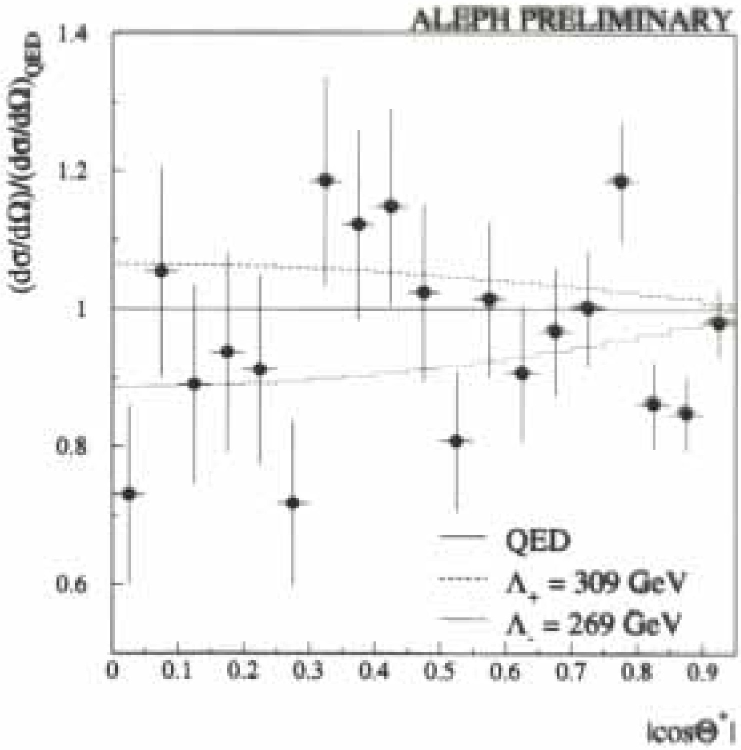
$$\frac{d\sigma}{dQ^2} = \sigma_0\left(\frac{M^2_{prop}}{M^2_{prop}+Q^2}\right)^2 \Phi W$$



$$\mathrm{H1}: \mathrm{M_{prop}} = 80.9 \pm 3.3 \pm 1.7 \pm 3.7\ \mathrm{GeV}$$
$$\mathrm{ZEUS}: \mathrm{M_{prop}} = 81.4^{+2.7}_{-2.6} \pm 2.0^{+3.3}_{-3.0}\ \mathrm{GeV}$$

- Test of QED in $e^+e^- \rightarrow \gamma\gamma(\gamma)$





Lower limits on QED cut-off parameter

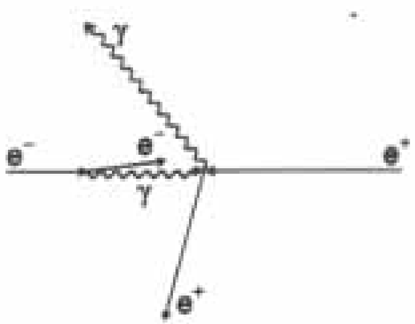
$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\rm Born} + \frac{\alpha^2 s}{2\Lambda_\pm^4}\left(1+\cos^2\theta\right)$$

and mass of excited electrons m_{e^*} for equal $e^*e\gamma$ and $ee\gamma$ couplings (189 GeV data)

	Λ_+	Λ_-	m_{e^*} [GeV]
ALEPH	309	269	335
DELPHI	284	278	262
L3	289	291	292
OPAL	304	295	306

Electron-boson scattering at LEP

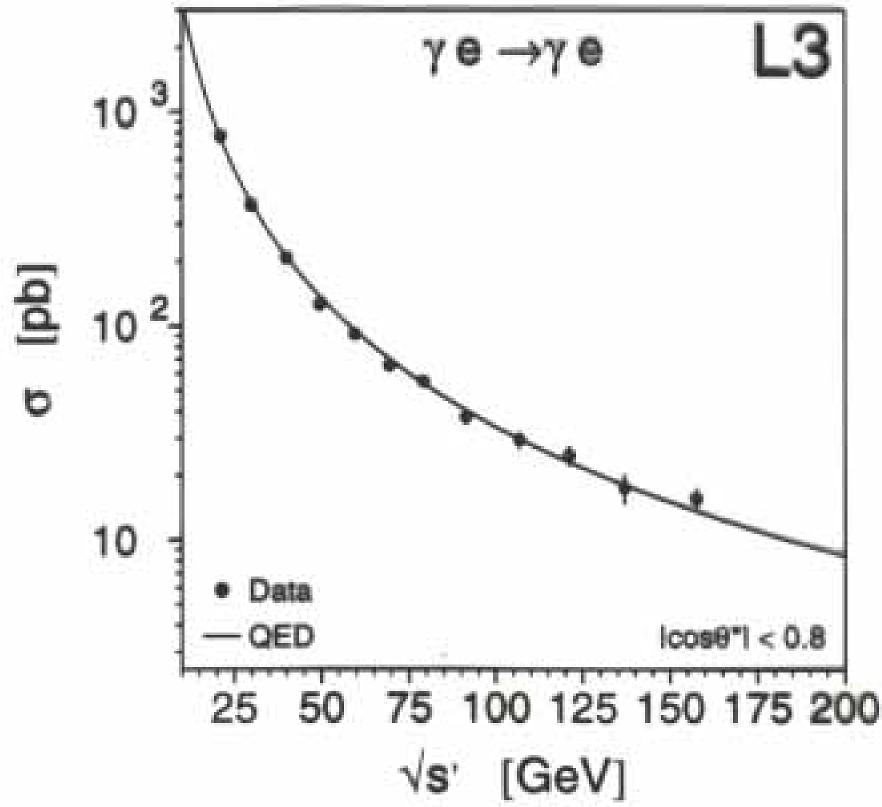
- Compton scattering $e^{\pm}\gamma \rightarrow e^{\pm}\gamma$



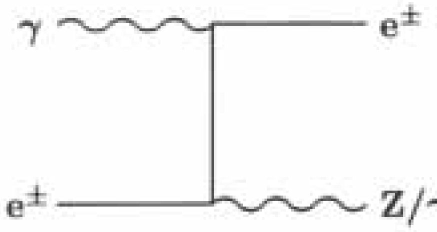
6000 events

$\sqrt{s'} \leq 160$ GeV

$91\text{GeV} \leq \sqrt{s} \leq 189$ GeV



- Electroweak Compton scattering $e^{\pm}\gamma \rightarrow e^{\pm}\, Z/\gamma^*$

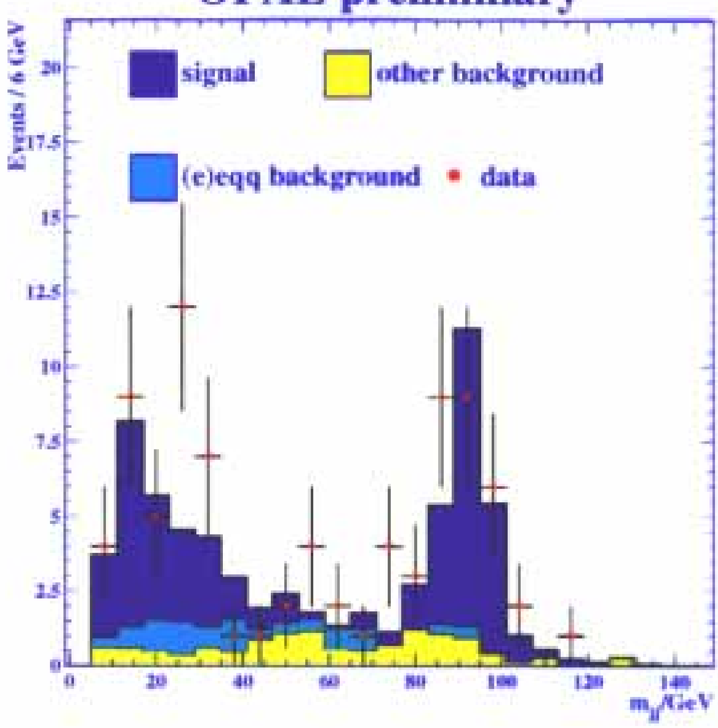


OPAL: $Z/\gamma^* \rightarrow$ hadrons

2 jets and isolated electron

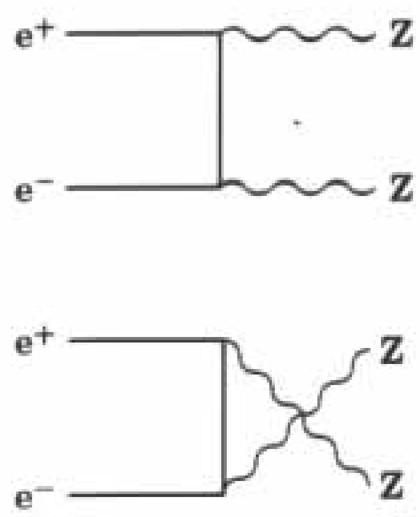
m_{jj} [GeV]	5 − 60	> 60
	γ^*e	Ze
data	52	38
σ [pb]	4.6 ± 0.9	1.5 ± 0.3
σ^{SM} [pb]	3.06	1.19

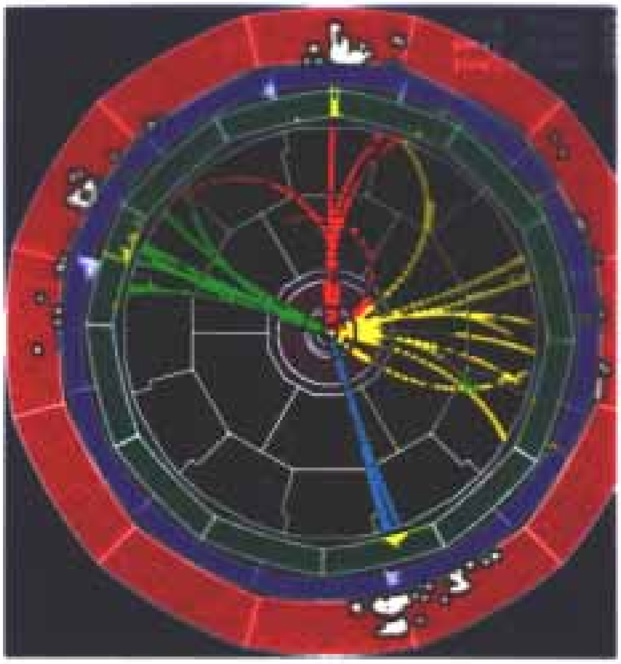
OPAL preliminary

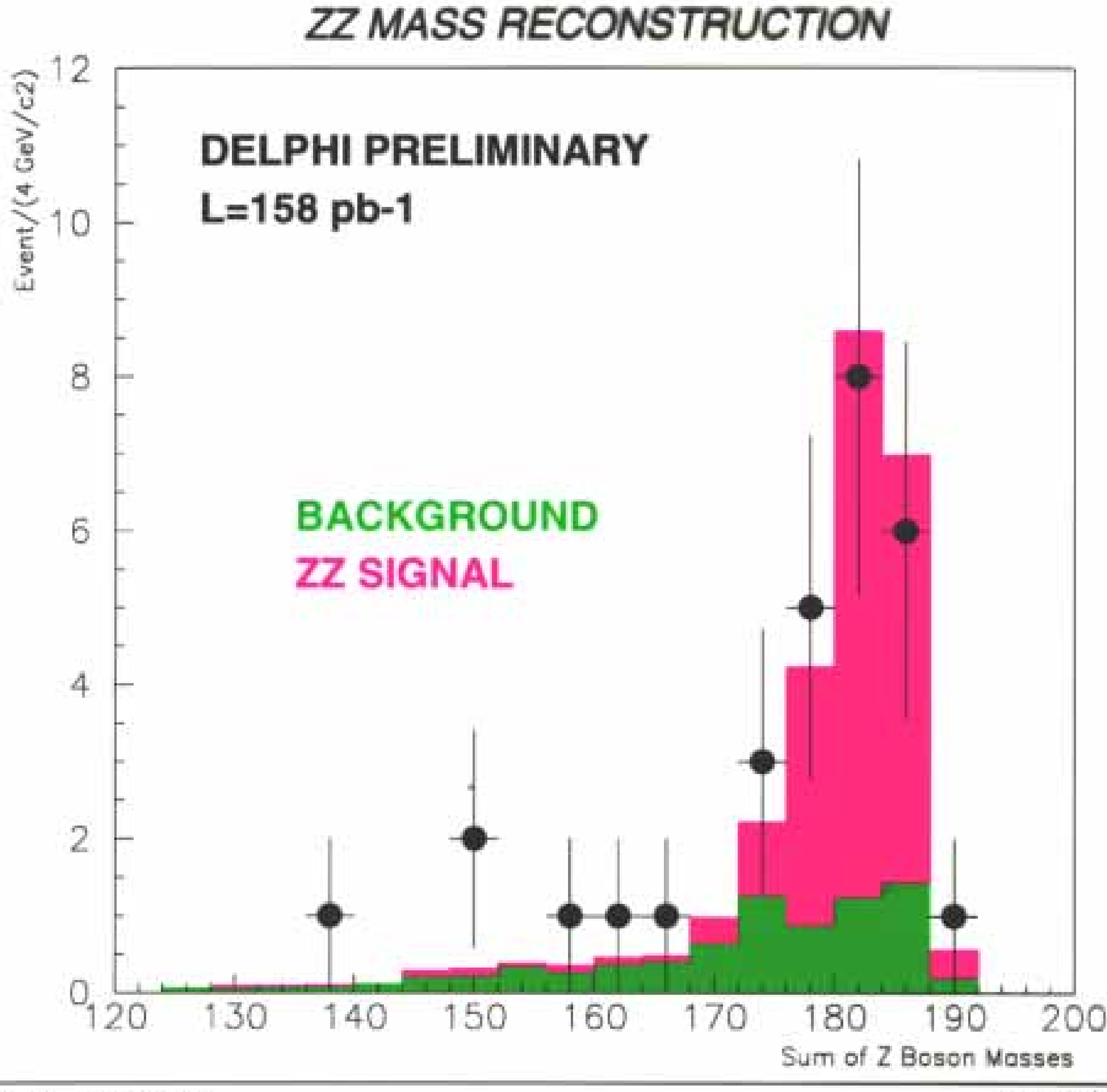


Production of Z-boson pairs

Signal definition

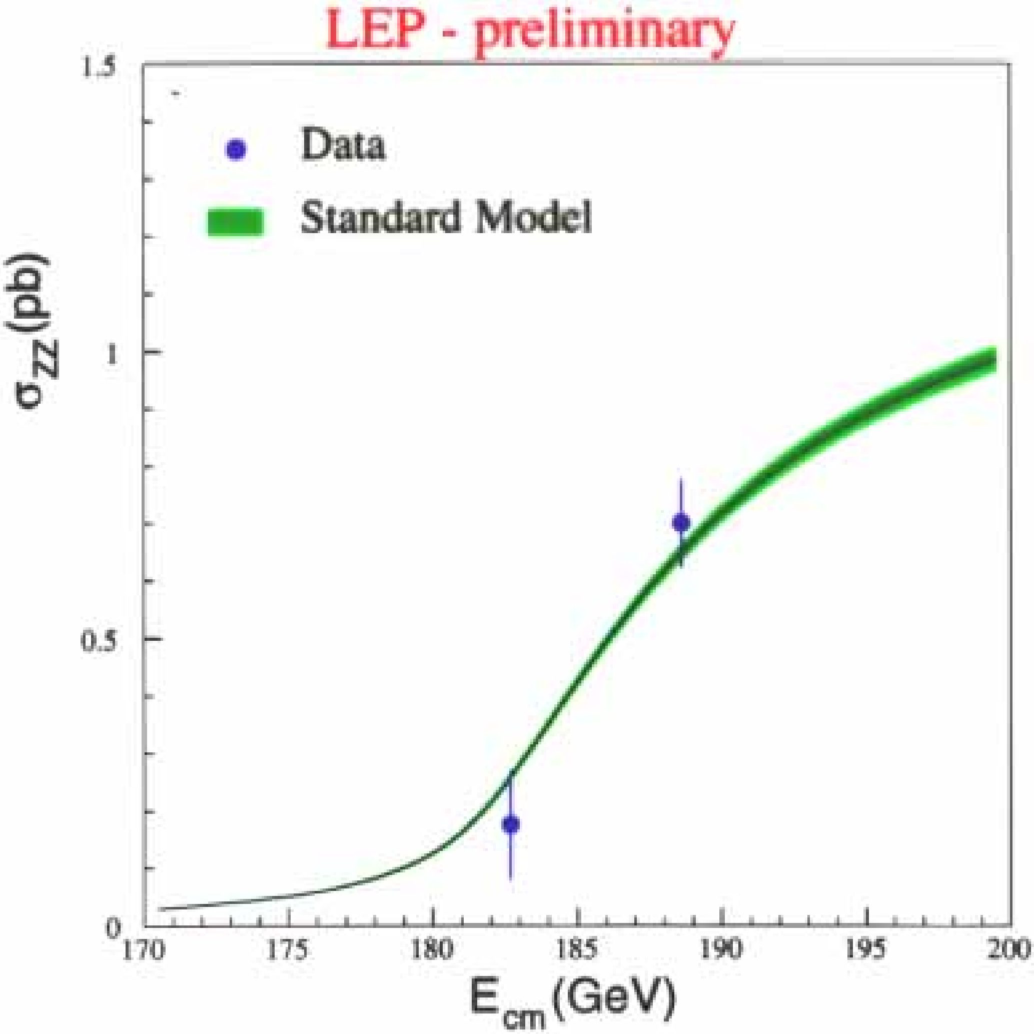






Cross section $e^+e^- \to ZZ$

- Combined LEP cross sections



- $e^+e^- \to ZZ$ probes ZZZ and $ZZ\gamma$ vertices

4 coupling parameter f_i^V; $V = \gamma, Z$
$i = 4$ CP violating
$i = 5$ C & P violating

Typical limits:

$|f_4^Z| < 2 \qquad |f_4^\gamma| < 1$
$|f_5^Z| < 5 \qquad |f_5^\gamma| < 3$

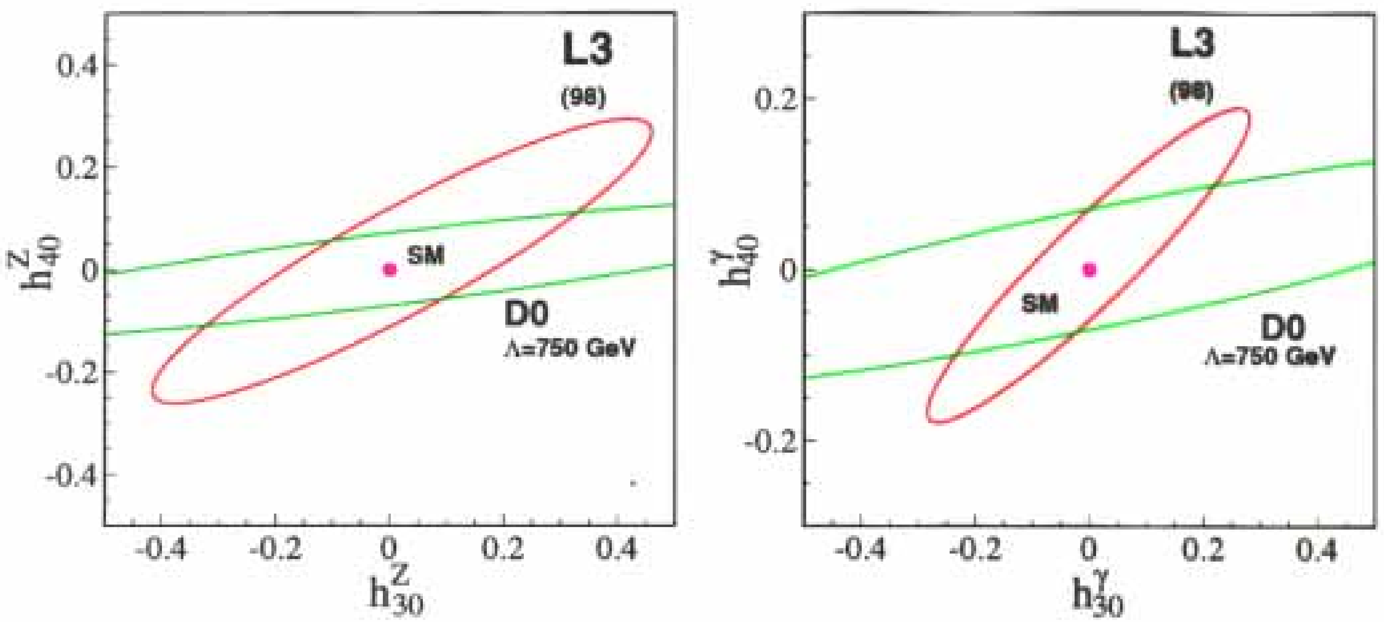
Testing the Z and γ couplings

- $e^+e^- \rightarrow Z/\gamma \rightarrow f\bar{f}\gamma$ probes $ZZ\gamma$ and $Z\gamma\gamma$ vertices

8 coupling parameter h_i^V; $V = \gamma, Z$
$i = 1,2$ CP violating
$i = 3,4$ CP conserving

Study of rate and differential distributions in $e^+e^- \rightarrow q\bar{q}\gamma$ and $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ events

- $Z\gamma$ production at the Tevatron:
study of $p\bar{p} \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$ events (DØ)



Summary on anomalous Z and γ couplings 95% CL

- $e^+e^- \to ZZ$

  DELPHI:

$$-2.67 < f_4^Z < +2.67 \qquad -1.59 < f_4^\gamma < +1.58$$
$$-7.09 < f_5^Z < +5.71 \qquad -3.90 < f_5^\gamma < +3.87$$

  L3:

$$-1.9 < f_4^Z < +1.9 \qquad -1.1 < f_4^\gamma < +1.1$$
$$-4.9 < f_5^Z < +4.7 \qquad -3.0 < f_5^\gamma < +2.9$$

  OPAL:

$$-2.0 < \Re\{f_4^Z\} < +2.0 \qquad -1.2 < \Re\{f_4^\gamma\} < +1.2$$
$$-5.1 < \Re\{f_5^Z\} < +5.1 \qquad -3.2 < \Re\{f_5^\gamma\} < +3.0$$
$$-2.0 < \Im\{f_4^Z\} < +1.9 \qquad -1.2 < \Im\{f_4^\gamma\} < +1.2$$
$$-5.2 < \Im\{f_5^Z\} < +5.4 \qquad -3.2 < \Im\{f_5^\gamma\} < +3.0$$

- $e^+e^- \to q\bar{q}\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma$

  DELPHI ($e^+e^- \to q\bar{q}\gamma$ only):

$$|h_{30}^Z| < 0.38 \qquad | < h_{30}^\gamma| < 0.23 \qquad (\Lambda = 1000\ \mathrm{GeV})$$

  L3:

$$-0.09 < h_1^Z < 0.20 \qquad -0.09 < h_1^\gamma < 0.08$$
$$-0.12 < h_2^Z < 0.06 \qquad -0.05 < h_2^\gamma < 0.07$$
$$-0.16 < h_3^Z < 0.15 \qquad -0.09 < h_3^\gamma < 0.07$$
$$-0.09 < h_4^Z < 0.10 \qquad -0.05 < h_4^\gamma < 0.06$$

- $Z\gamma$ production at the Tevatron

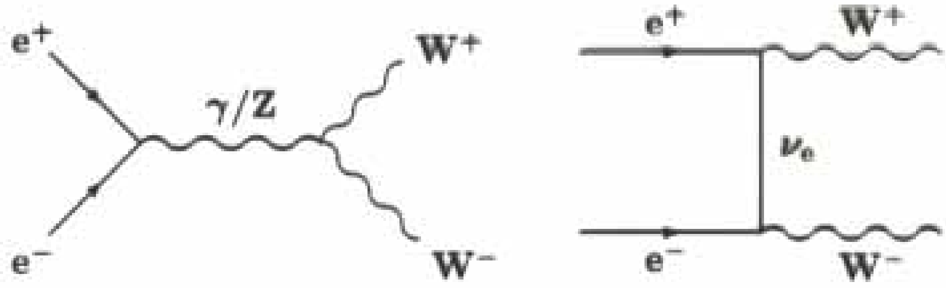
  DØ:

$$|h_{30}^Z| < 0.36 \qquad < |h_{30}^\gamma| < 0.37$$
$$|h_{40}^Z| < 0.05 \qquad < |h_{40}^\gamma| < 0.05 \qquad (\Lambda = 750\ \mathrm{GeV})$$

$$h_i^V = \frac{h_{i0}^V}{\left(1 + \frac{s}{\Lambda^2}\right)^3} \quad i = 1,3 \qquad\qquad h_i^V = \frac{h_{i0}^V}{\left(1 + \frac{s}{\Lambda^2}\right)^4} \quad i = 2,4$$

Production of W bosons at LEP

- W-pair production at LEP $e^+e^- \rightarrow W^+W^-(\gamma)$:



Event samples (per experiment):

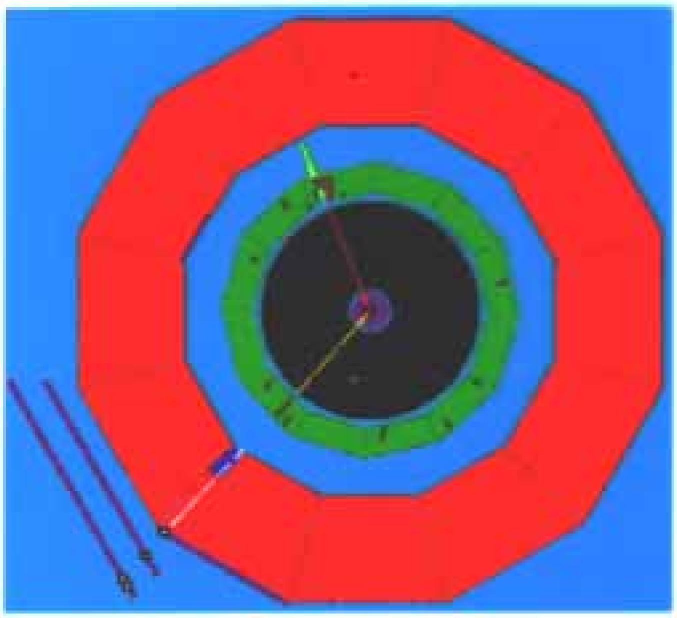
$161 \text{ GeV} \leq \sqrt{s} \leq 189 \text{ GeV} \approx 3500$
$192 \text{ GeV} \leq \sqrt{s} \leq 196 \text{ GeV} \approx 1000$

Three different event topologies:

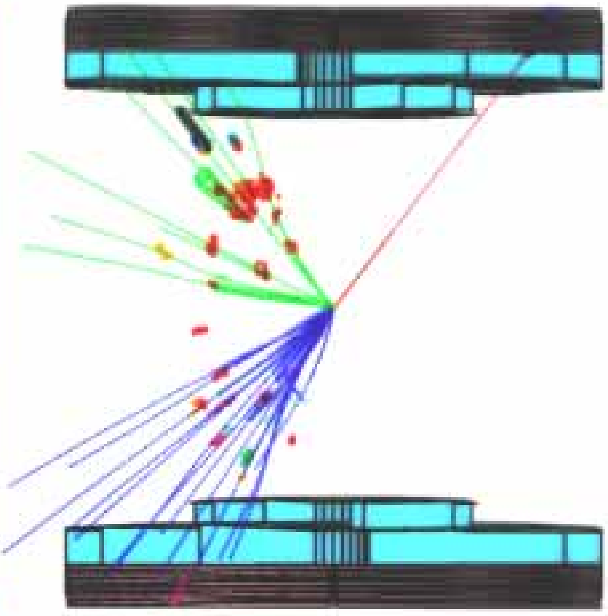
- $W^+W^- \rightarrow \ell\nu\ell\nu,\ \ell = e, \mu, \tau \quad (\approx 11\%)$
  two energetic, acoplanar leptons
- $W^+W^- \rightarrow q\bar{q}\ell\nu \quad (\approx 44\%)$
  two jets plus isolated energetic lepton
  or jet for $W^+W^- \rightarrow q\bar{q}\tau\nu$
- $W^+W^- \rightarrow q\bar{q}q\bar{q} \quad (\approx 46\%)$
  four jets of similar energy
  severe background from QCD:
  $e^+e^- \rightarrow q\bar{q} +$ gluons (≈ 100 pb)
  neural networks, likelihood analyses

$e^+e^- \to W^+W^-$ candidates at $\sqrt{s} = 189$ GeV

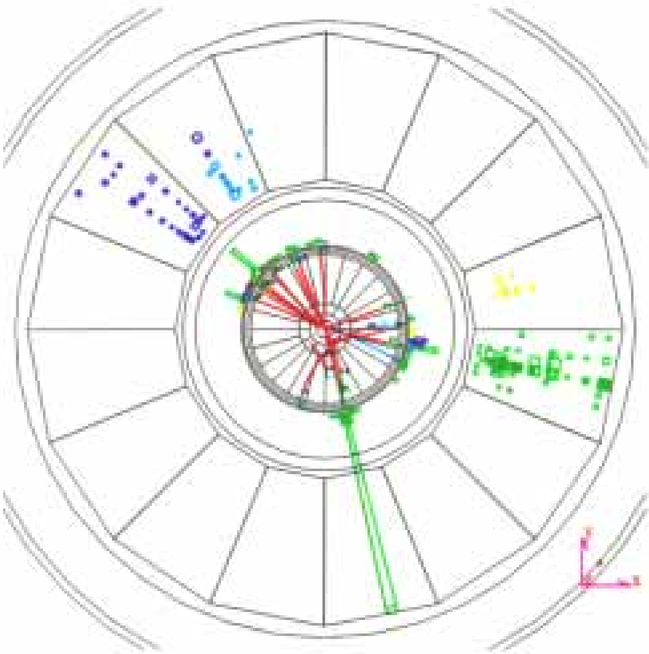
$e^+e^- \to \ell\nu\ell\nu$



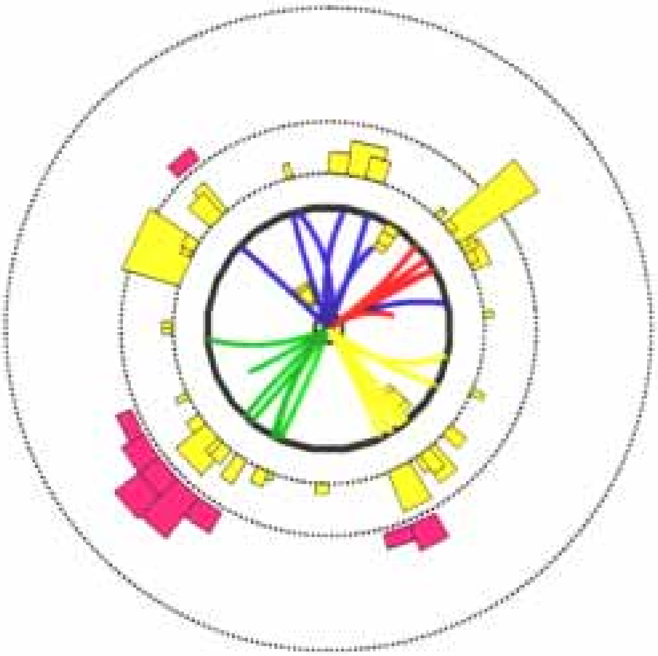
$e^+e^- \to q\bar{q}\mu\nu$



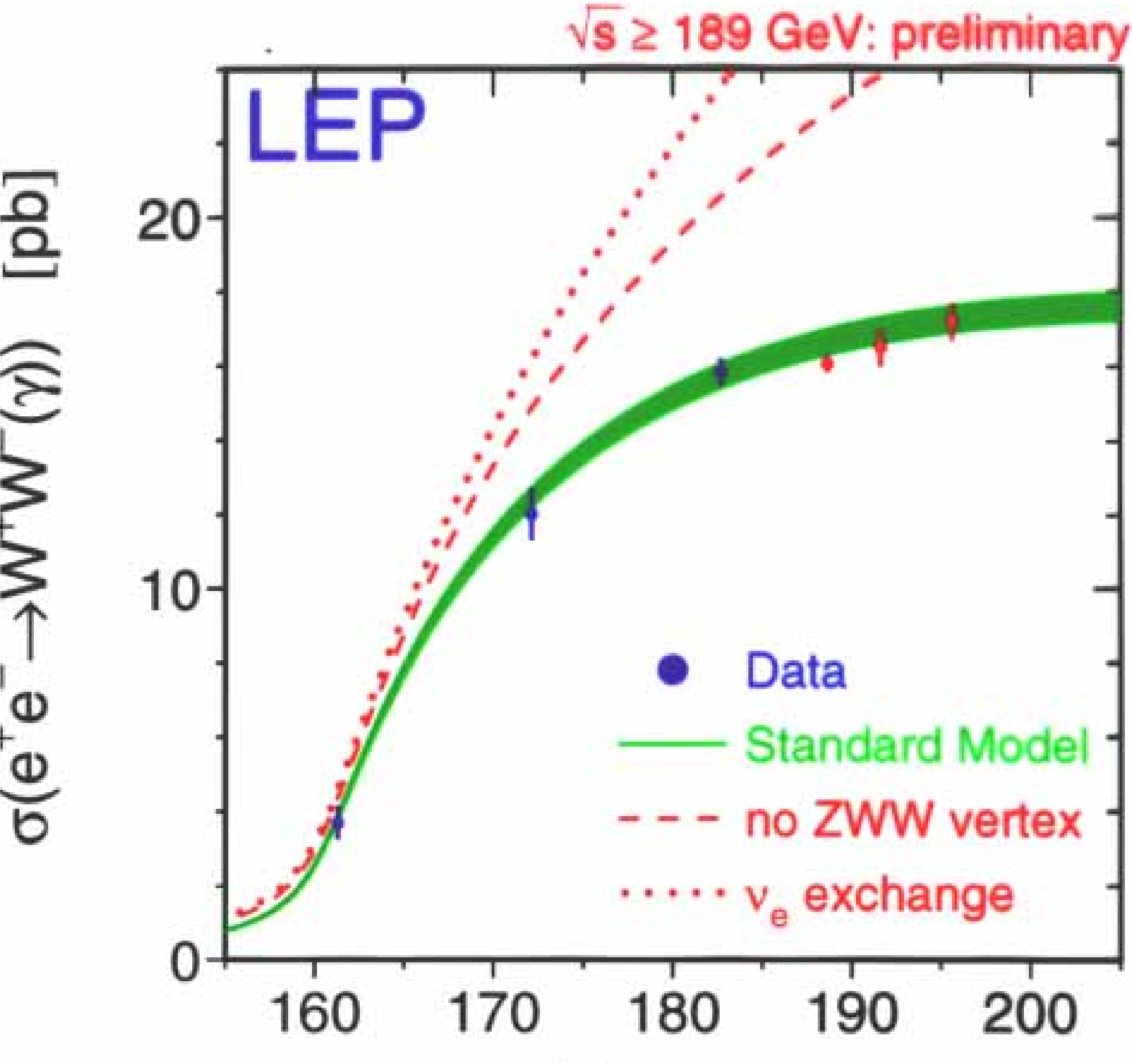
$e^+e^- \to q\bar{q}e\nu$



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

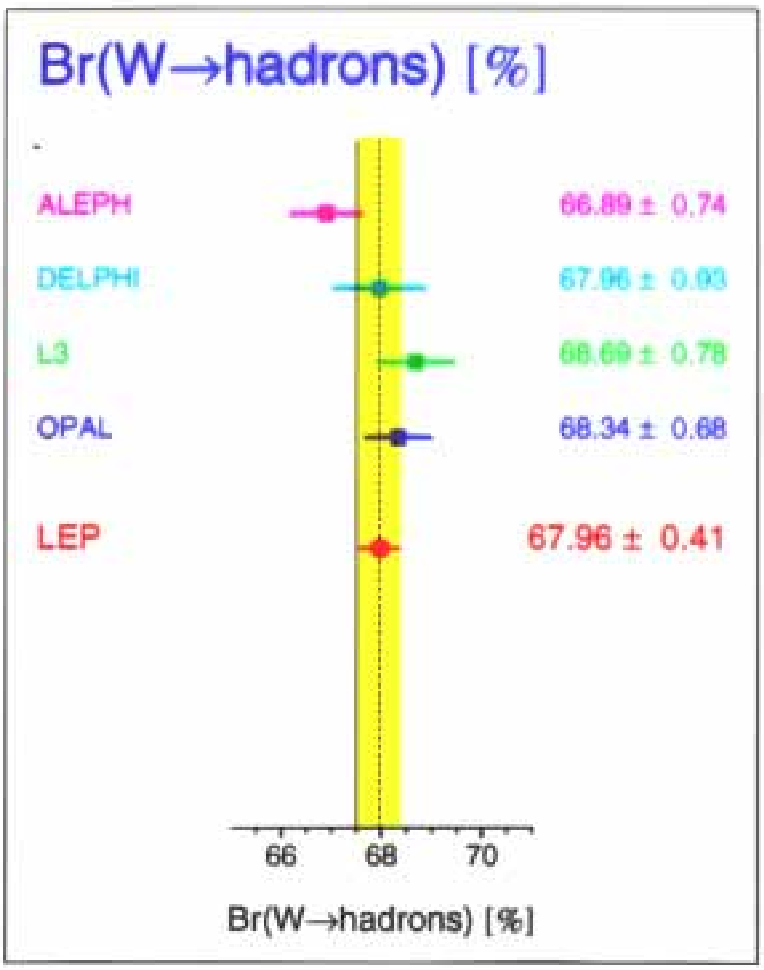


Combined LEP cross section measurement $e^+e^- \rightarrow WW$ for 161 GeV $\leq \sqrt{s} \leq$ 196 GeV



- Very good agreement with SM
  2% theoretical error
- ZWW vertex exist

Hadronic W branching ratio



Determination of $|V_{cs}|$

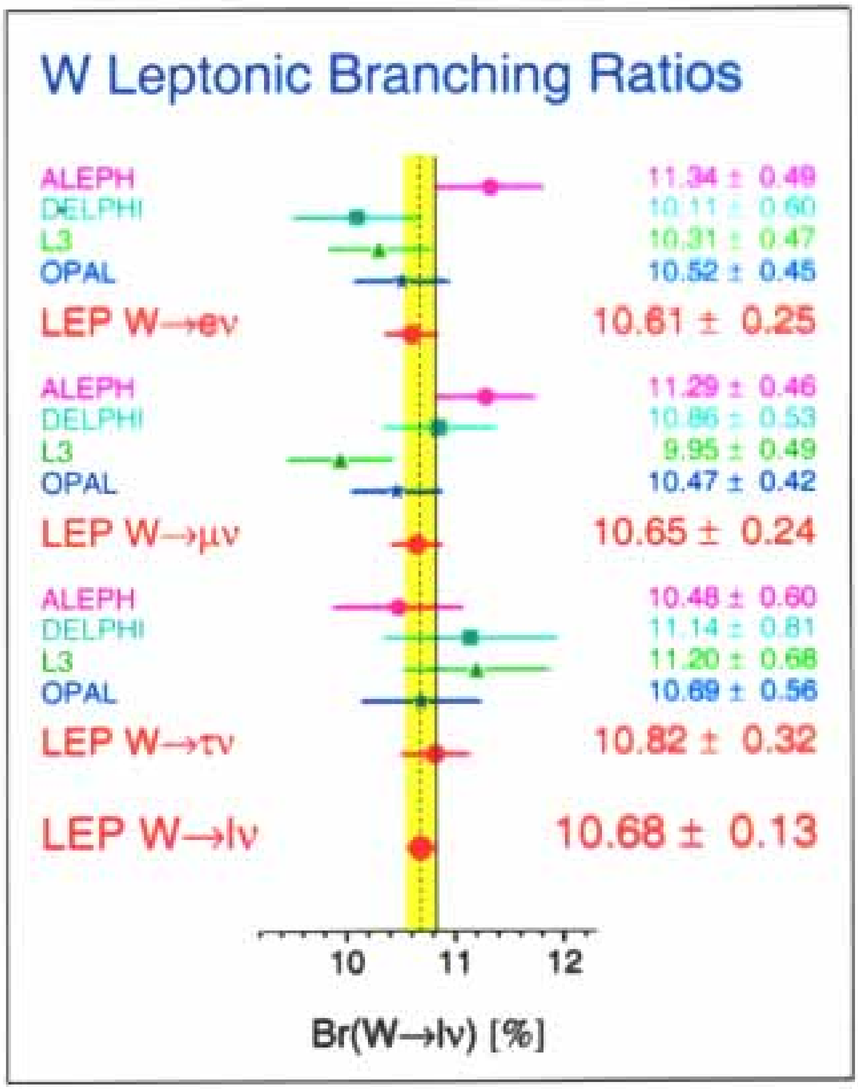
- indirectly from hadronic branching ratio

$$\frac{BR_{\mathrm{had}}}{1 - BR_{\mathrm{had}}} = \sum_{\substack{i=\mathrm{u,c}\\ j=\mathrm{d,s,b}}} |V_{ij}^2| \left(1 + \frac{\alpha_s}{\pi}\right)$$

LEP: $|V_{cs}| = 0.997 \pm 0.020$

- directly by charm tagging (189 GeV)

	$\Gamma(\mathrm{W} \to \mathrm{cX})/\Gamma(\mathrm{W} \to \mathrm{had})$	$\lvert V_{cs}\rvert$
ALEPH	$0.51 \pm 0.05 \pm 0.03$	$1.00 \pm 0.11 \pm 0.07$
OPAL	$0.47 \pm 0.04 \pm 0.06$	$0.91 \pm 0.07 \pm 0.11$



Charged current lepton universality ($Q^2 = m_W^2$):

$$g_\mu/g_e = 1.001 \pm 0.016$$
$$g_\tau/g_e = 1.010 \pm 0.022$$
$$g_\tau/g_\mu = 1.008 \pm 0.021$$

$$\text{CDF}: BR(W \to e\nu) = 0.1037 \pm 0.0022$$
$$\text{DØ}: BR(W \to e\nu) = 0.1080 \pm 0.0030$$

$$\text{DØ}: g_\tau/g_e = 0.98 \pm 0.03$$

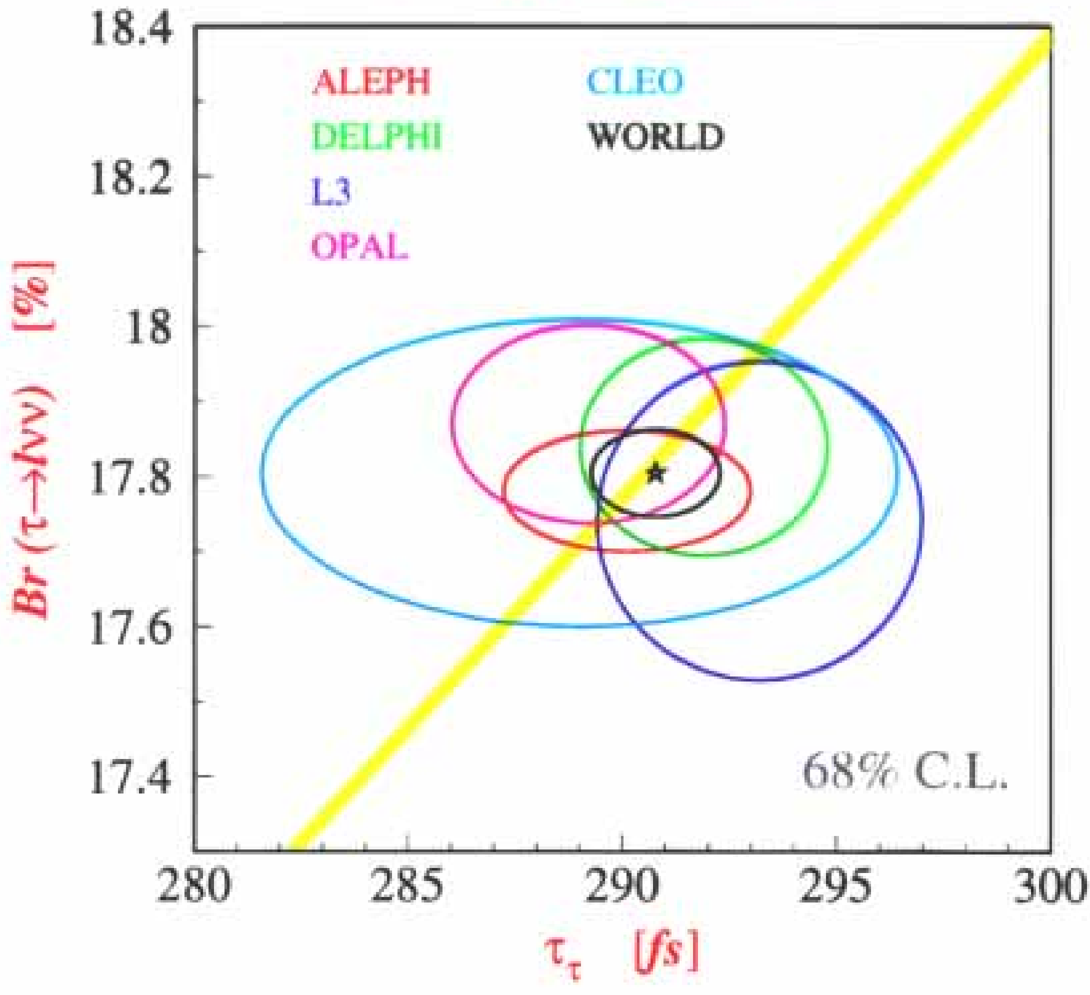
Charged current lepton universality in τ decays

- **Measurements of tau leptonic branching fractions:**

$$BR(\tau \rightarrow e\,\nu_e\,\nu_\tau) = (17.791 \pm 0.054)\%$$
$$BR(\tau \rightarrow \mu\,\nu_\mu\,\nu_\tau) = (17.333 \pm 0.054)\%$$
$$\Longrightarrow BR(\tau \rightarrow \ell\,\nu_\ell\,\nu_\tau) = (17.805 \pm 0.039)\% \quad \text{(massless } \ell\text{)}$$

- **Tau lifetime:**

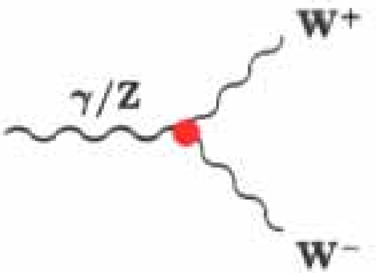
$$\tau_\tau = 290.77 \pm 0.99 \text{ fs}$$



Universality of couplings ($Q^2 = m_\tau^2$) :

$$g_\mu/g_e = 1.0006 \pm 0.0023 \qquad g_\tau/g_\mu = 0.9997 \pm 0.0024$$

Triple gauge boson vertices γWW and ZWW



Most general Lorentz invariant ansatz:
2 × 7 complex couplings

Assume real couplings,
C-, P- and CP invariance,
charge of $W^{\pm}$ ($= \pm e$)
no change of tree-level boson propagators

⇒ 3 coupling parameter to be studied:

$$g_1^Z,\ \kappa_\gamma,\ \lambda_\gamma$$

SM values:

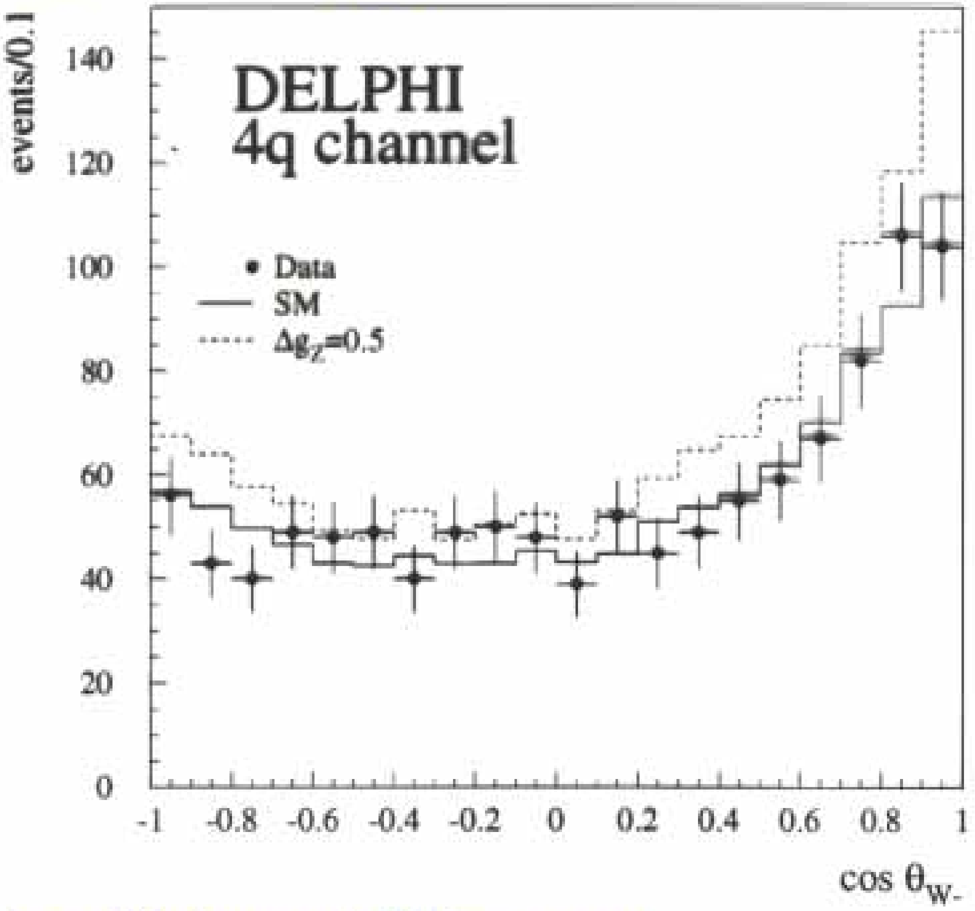
$$g_1^Z = 1, \quad \kappa_\gamma = 1, \quad \lambda_\gamma = 0$$

Deviations from Standard Model would

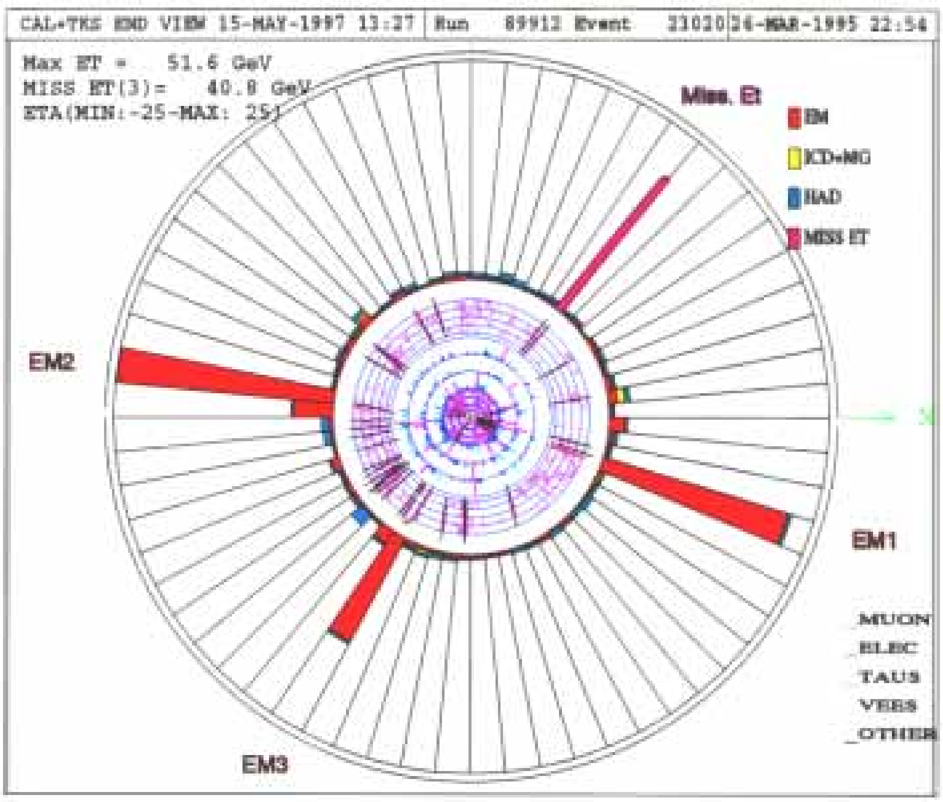
- at LEP
  - increase $e^+e^- \rightarrow$ WW cross section
  - modify W production angles
  - modify W polarization
- at Tevatron
  - enhanced boson pair production Wγ, WW, WZ

Signature of anomalous triple boson couplings

- $\cos\Theta_W$ in $WW \rightarrow q\bar{q}q\bar{q}$ events



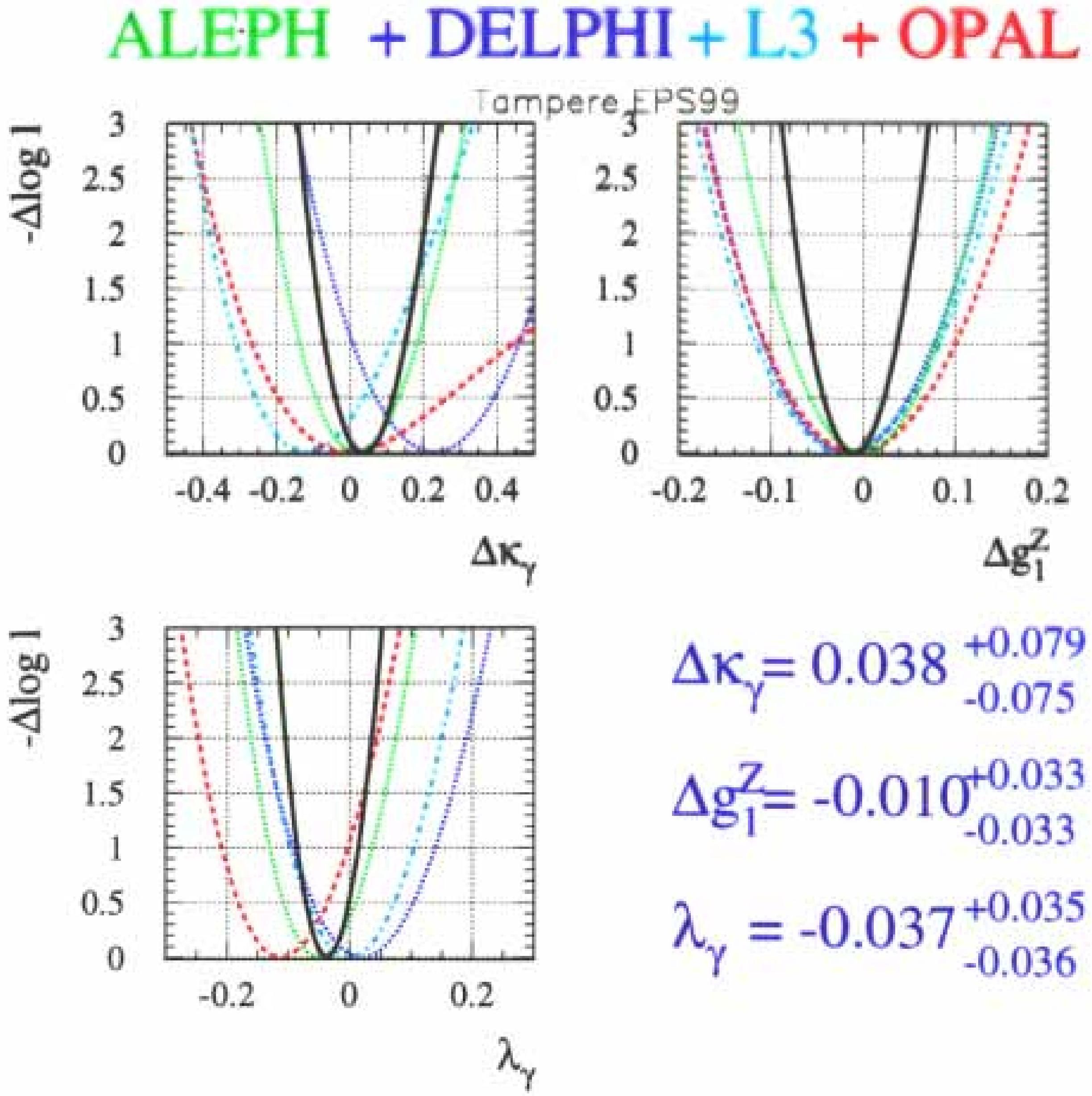
- DØ candidate event $ZW \rightarrow eee\nu$



$M_T(2)$=74.7 GeV M_{13}=93.6 GeV

Limits on anomalous triple boson couplings

- LEP combination ($e^+e^- \to WW$ up to 189 GeV)



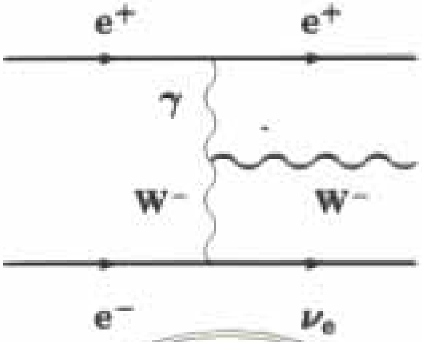
Result from DØ:

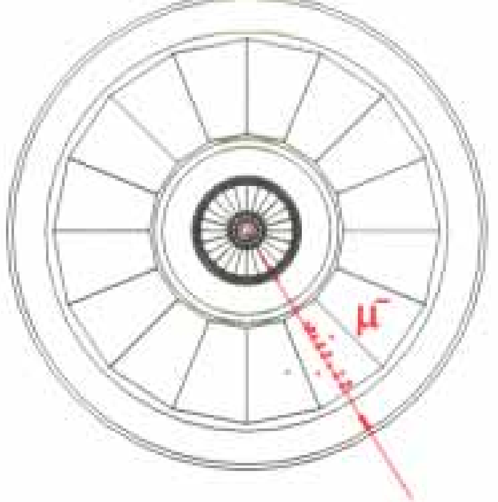
$$\Delta\kappa_\gamma = -0.08 \pm 0.34$$
$$\lambda_\gamma = 0.00^{+0.10}_{-0.09}$$

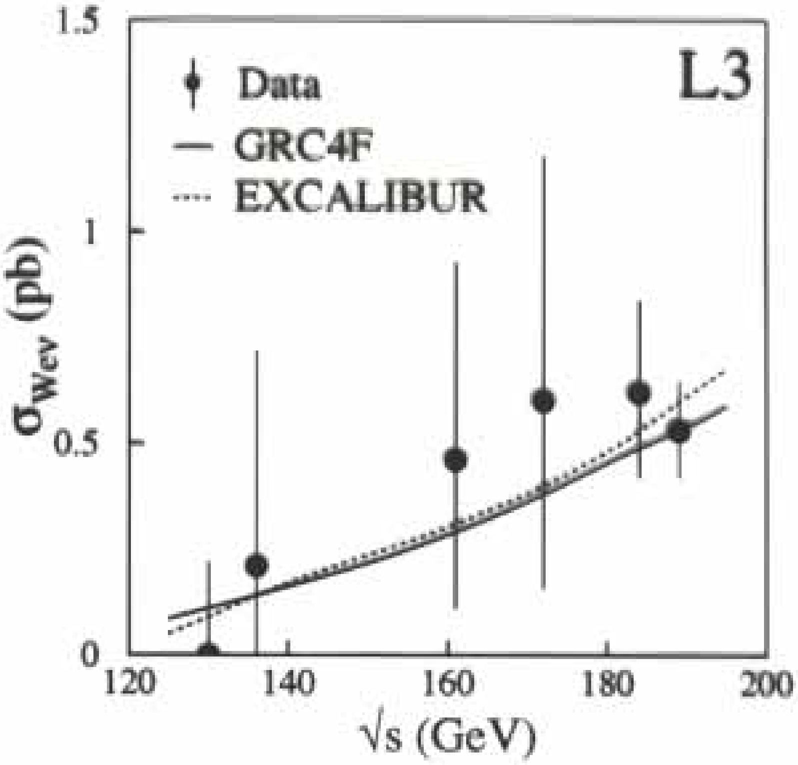
(Δ denotes deviation from SM value)

Single W production at LEP

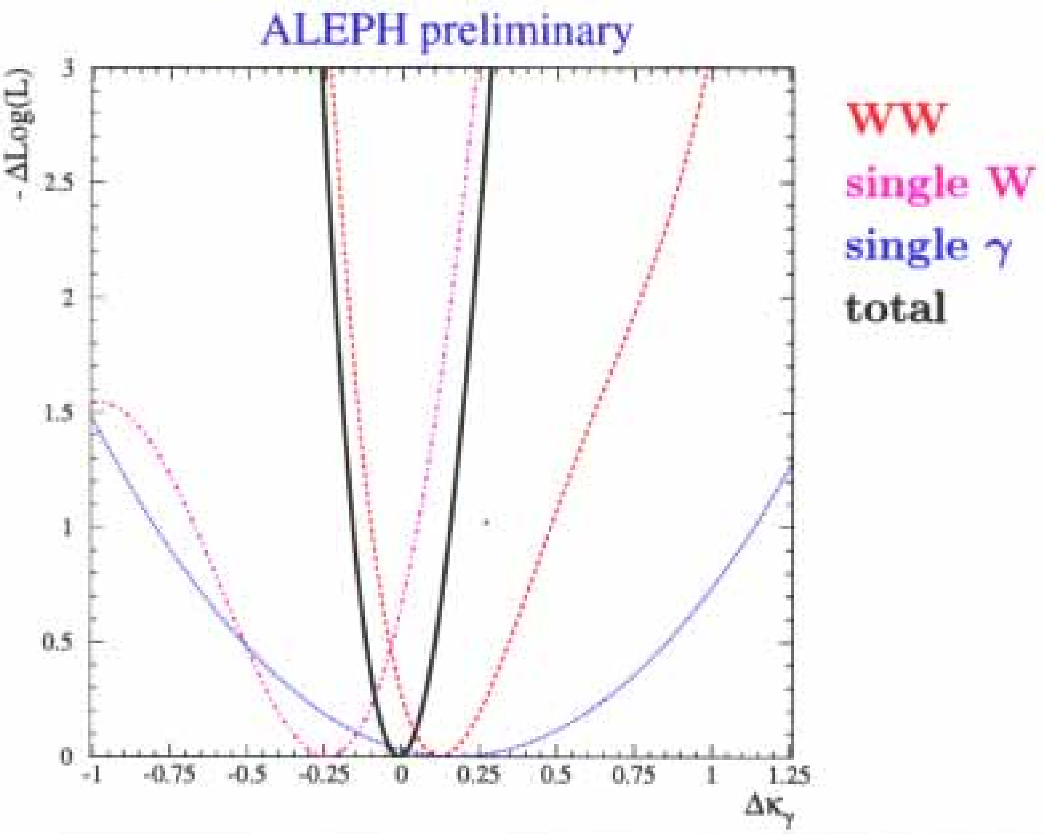
- More information on γWW vertex from single W events:



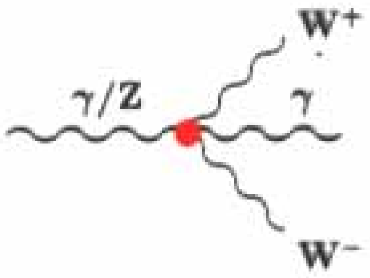




- and from single photon events



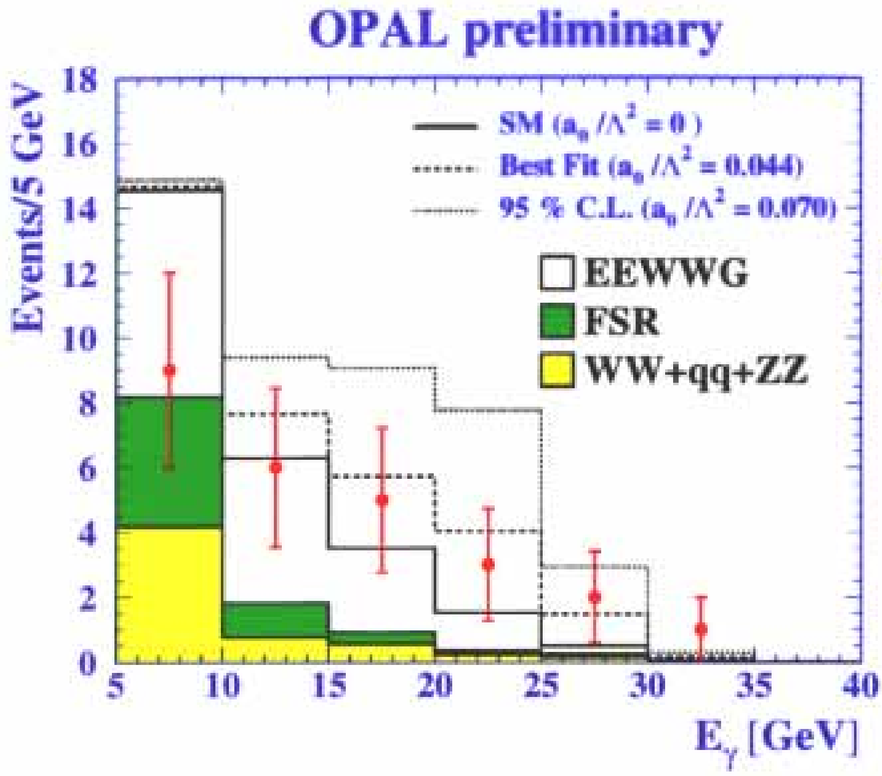
- $e^+e^- \rightarrow WW\gamma$ probes quartic boson vertices $WW\gamma\gamma$ and $WWZ\gamma$

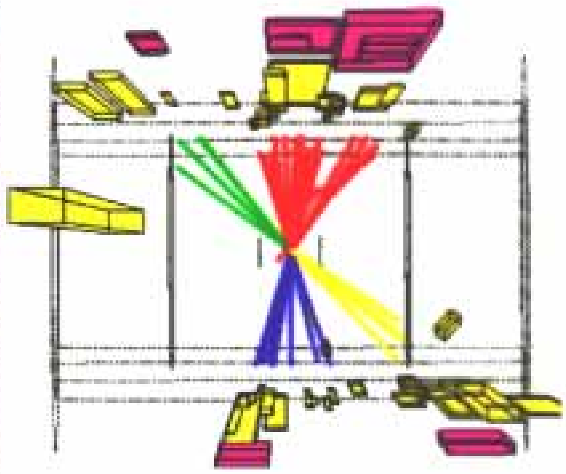


Genuine quartic gauge boson couplings:

6 dimensional operators
$a_0/\Lambda^2,\ a_c/\Lambda^2,\ a_n/\Lambda^2$

OPAL: 17 candidates with $E_\gamma \geq 10$ GeV
$\sigma_{WW\gamma} = 136 \pm 37 \pm 8$ fb $\qquad \sigma^{SM}_{WW\gamma} = 85 - 105$ fb





Combine with $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$:

$$-0.065\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < +0.065\ \mathrm{GeV}^{-2} \qquad WW\gamma\gamma$$
$$-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < +0.17\ \mathrm{GeV}^{-2} \qquad WW\gamma\gamma$$
$$-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < +0.57\ \mathrm{GeV}^{-2} \qquad WWZ\gamma$$

(More stringent indirect limits exist on a_0 and a_c)

Longitudinally polarized W bosons

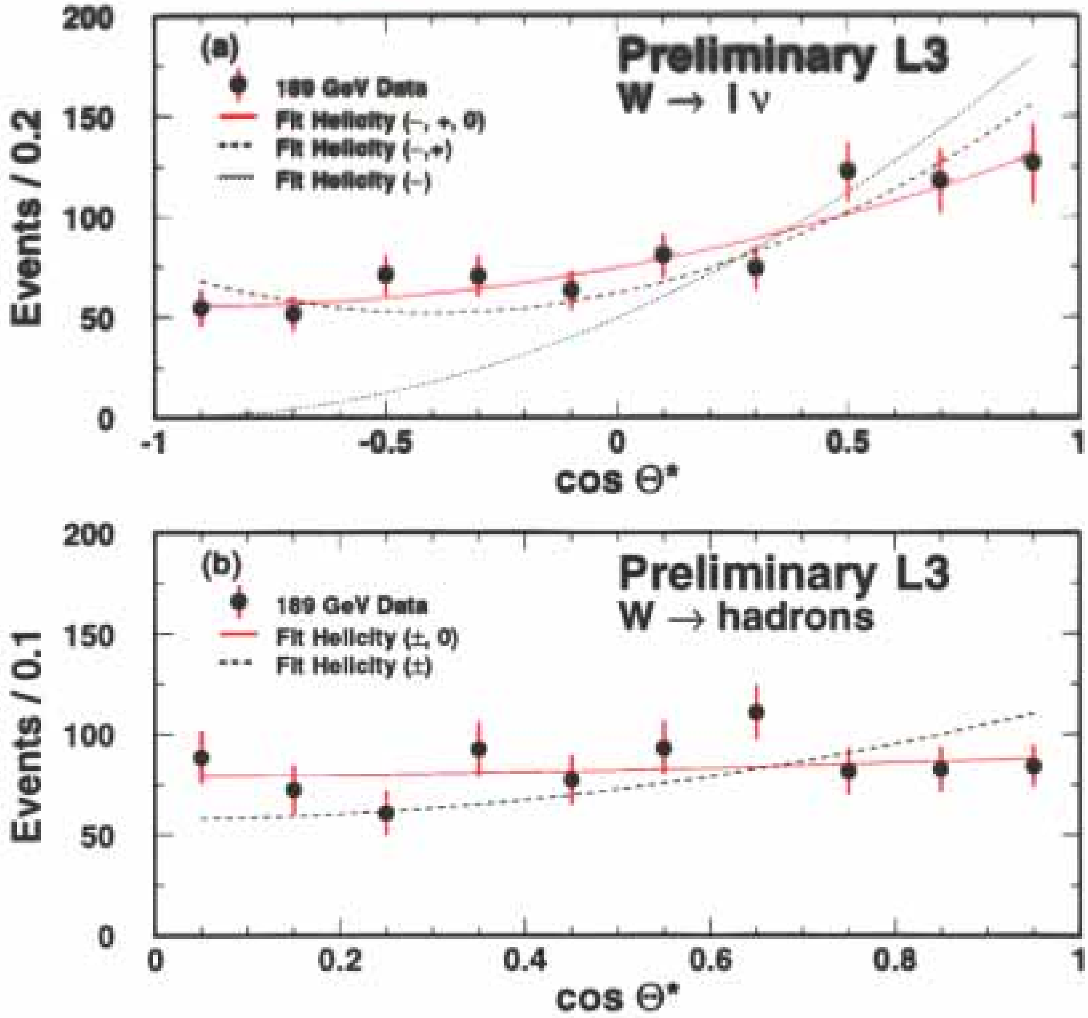
Massive gauge bosons have three polarization states

- transverse $(-\,+)$ • longitudinal (0)

Lepton (quark) angle in W rest frame θ^*:

$\propto (1 \pm \cos\theta^*)^2$ transverse W

$\propto \sin^2\theta^*$ longitudinal W

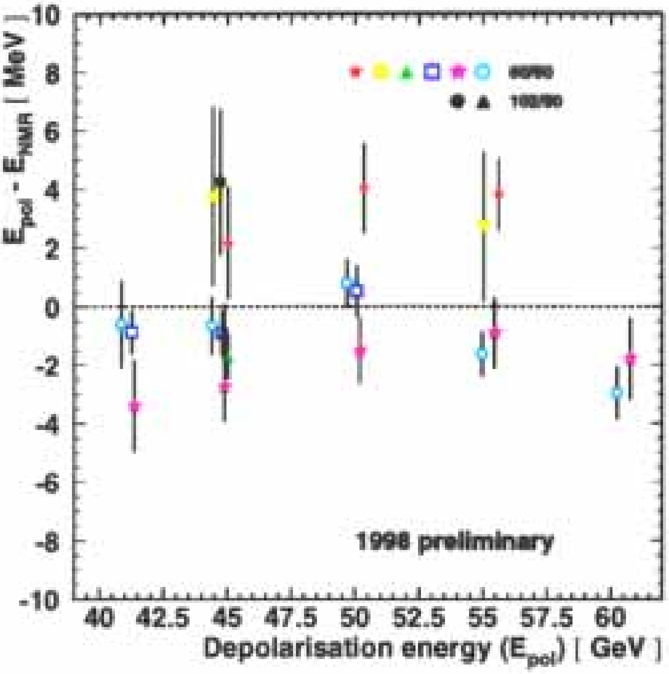


Fraction of longitudinally polarized W bosons:

183 GeV	$0.276 \pm 0.092 \pm 0.03$
189 GeV	$0.244 \pm 0.048 \pm 0.03$
SM	0.26

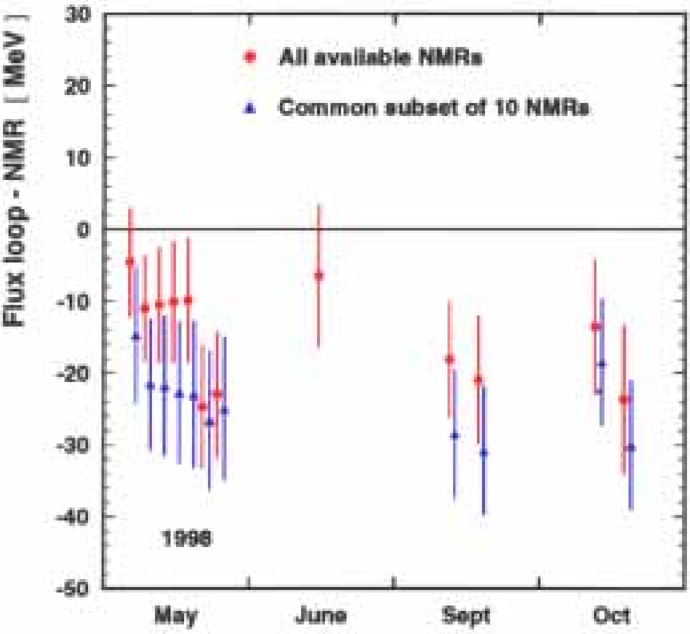
Top quark decays: CDF $0.91 \pm 0.37 \pm 0.12$ (SM: 0.70)

- m_W determined from invariant mass distribution in $e^+e^- \rightarrow WW$ events
  - Impose énergy and momentum conservation in kinematic fit to improve mass resolution
  - Absolute scale determined by LEP beam energy



Resonant depolarisation
$E_b \leq 61$ GeV

Precison $\mathcal{O}(1\ \text{MeV})$

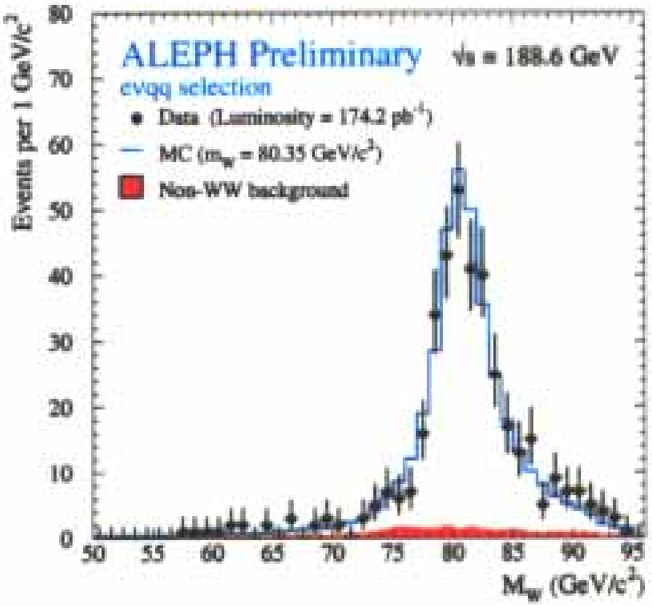


Extrapolate to $E_b = 94.5$ GeV using magnetic measurements NMR probes, flux loop

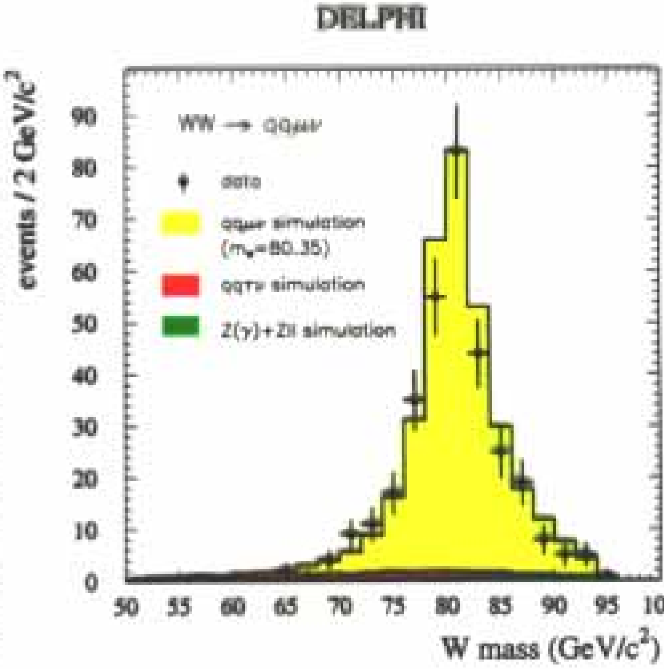
$\Longrightarrow \Delta E_b = \pm 20$ MeV

Data at $\sqrt{s} = 189$ GeV:

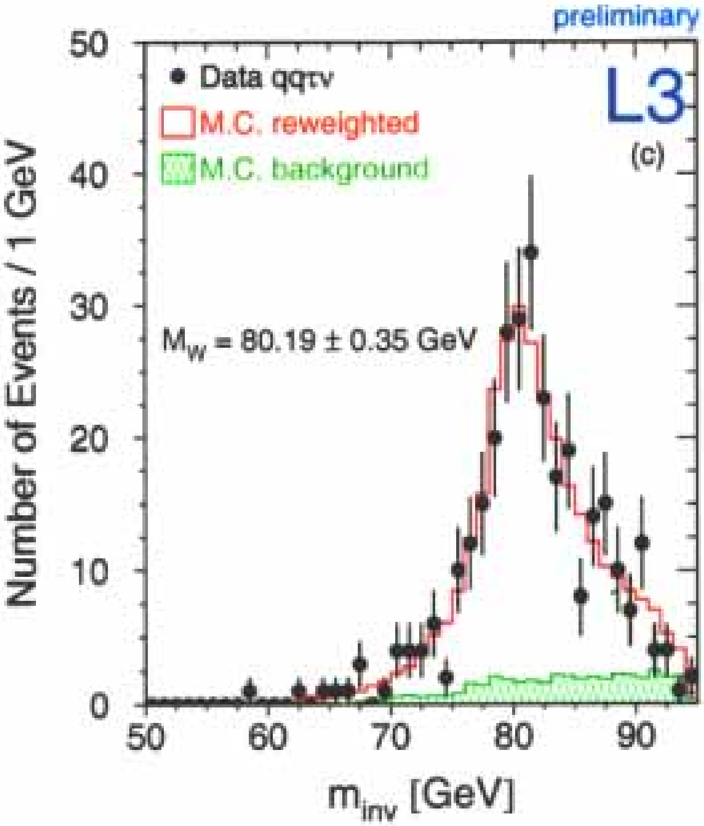
$WW \rightarrow q\bar{q}\, e\nu$



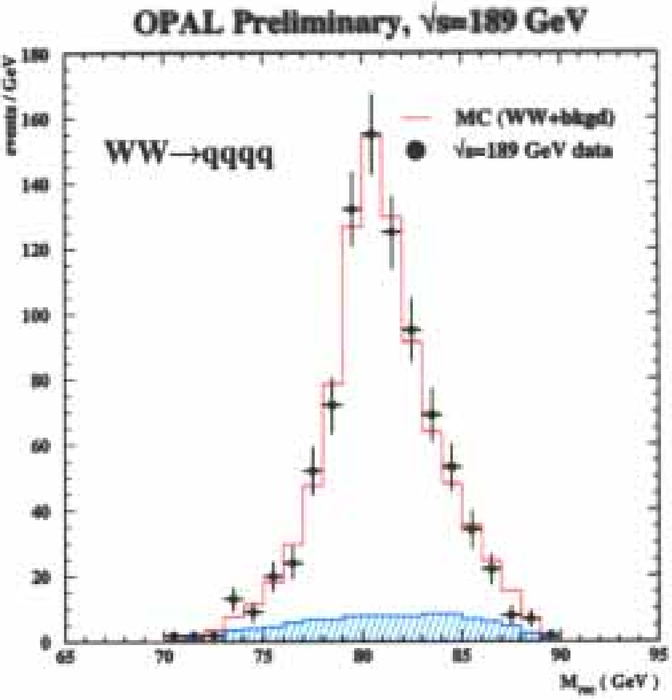
$WW \rightarrow q\bar{q}\, \mu\nu$

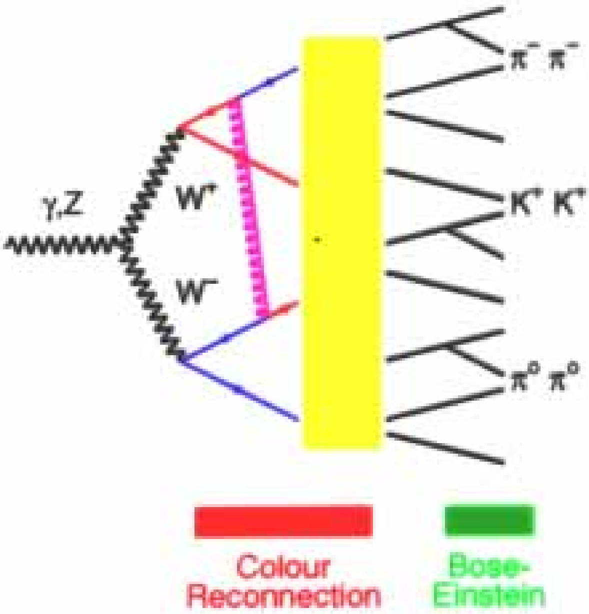


$WW \rightarrow q\bar{q}\, \tau\nu$



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





- Colour reconnection
  - Hadronisation scale $\mathcal{O}(1\ \text{fm})$ much larger than W decay length $\mathcal{O}(0.1\ \text{fm})$
  - Gluons carry momentum between quarks from different W bosons
  - Impact on reconstructed m_W

- Investigate charge multiplicity:

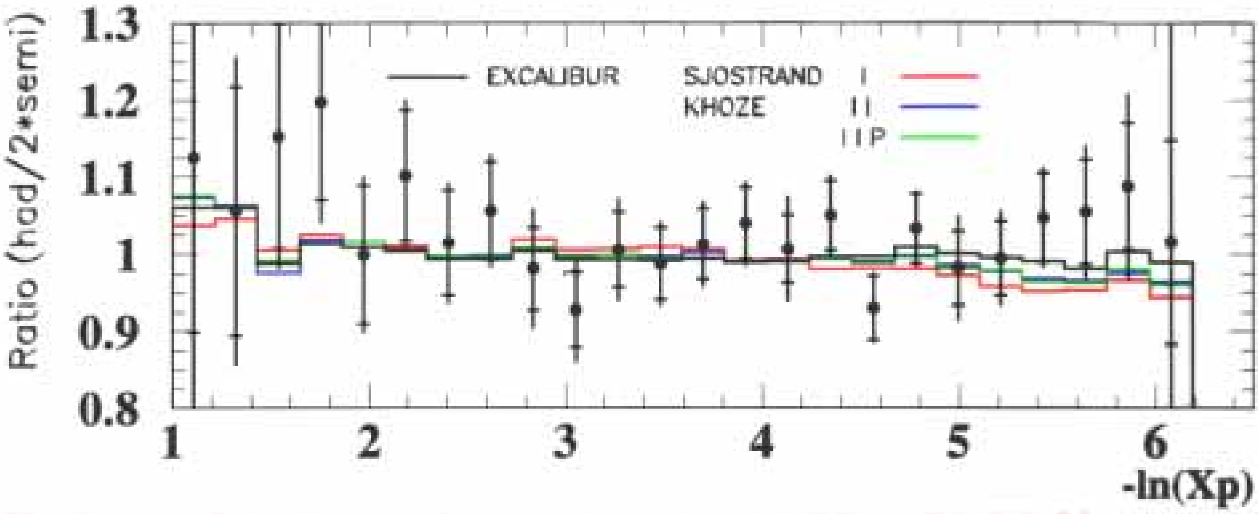
$$\Delta n_{ch} = <n_{ch}^{qqqq}> - 2 <n_{ch}^{qq\ell\nu}> \qquad r_{ch} = \frac{<n_{ch}^{qqqq}>}{2 <n_{ch}^{qq\ell\nu}>}$$

ALEPH	Δn_{ch}	$+0.52 \pm 0.52$
DELPHI	r_{ch}	$+0.977 \pm 0.017 \pm 0.027$
L3	Δn_{ch}	$-0.23 \pm 0.40 \pm 0.52$
OPAL*	Δn_{ch}	$+0.7 \pm 0.8 \pm 0.6$

* 183 GeV

- compatible with no or small effect

e.g. ALEPH result for scaled momentum x_p:



Estimated systematic error on m_W: 25 – 70 MeV

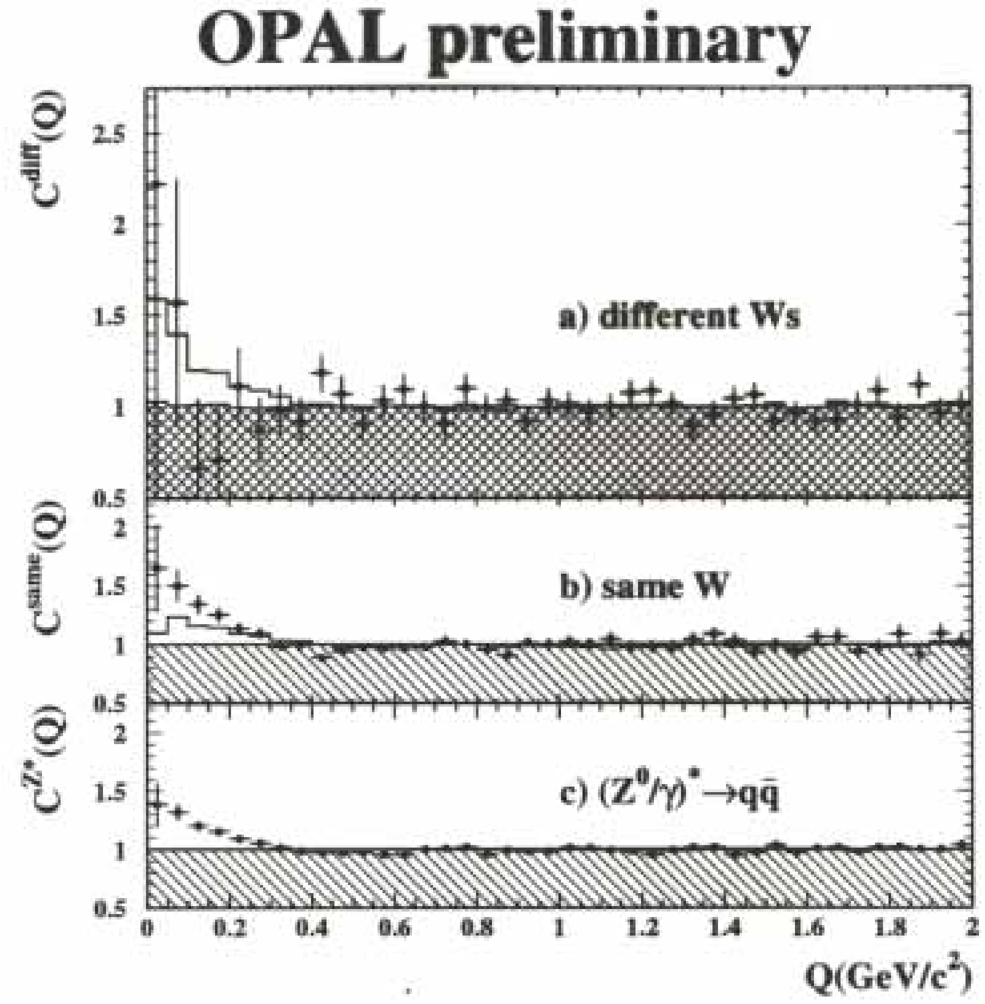
- Bose-Einstein correlation of decay hadrons

  may lead to momentum transfer between decay products of different W bosons

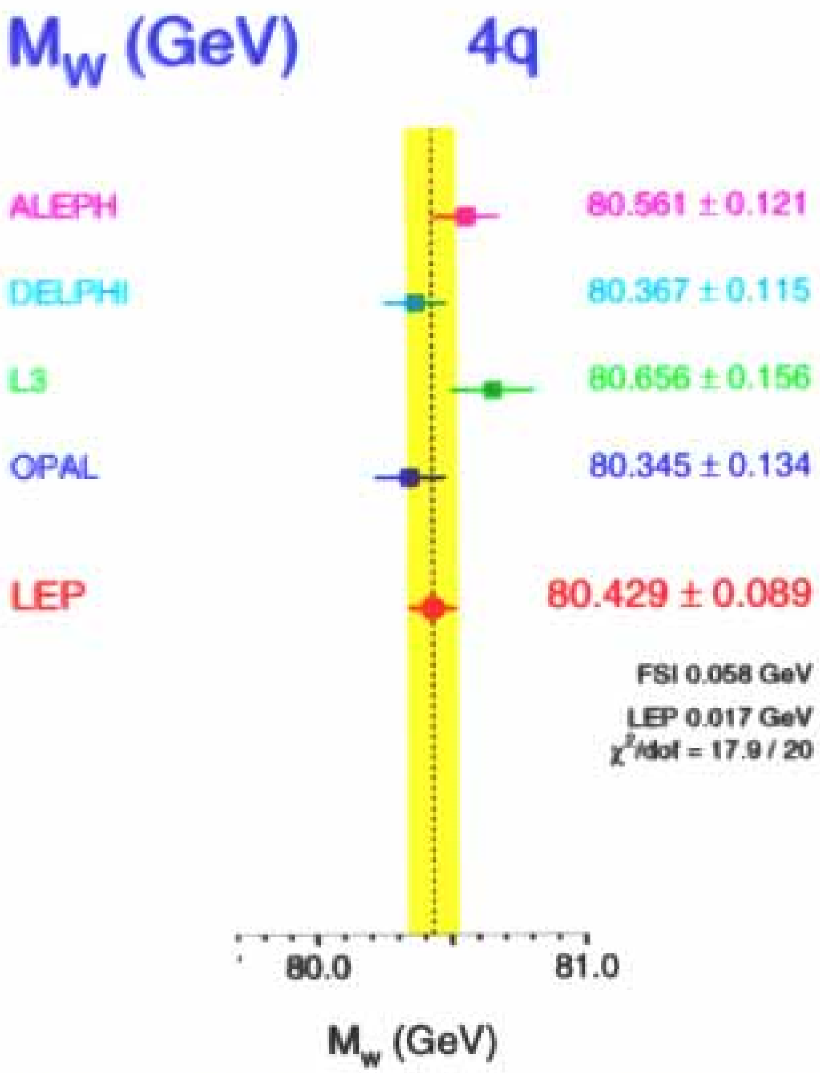
Study correlation function:

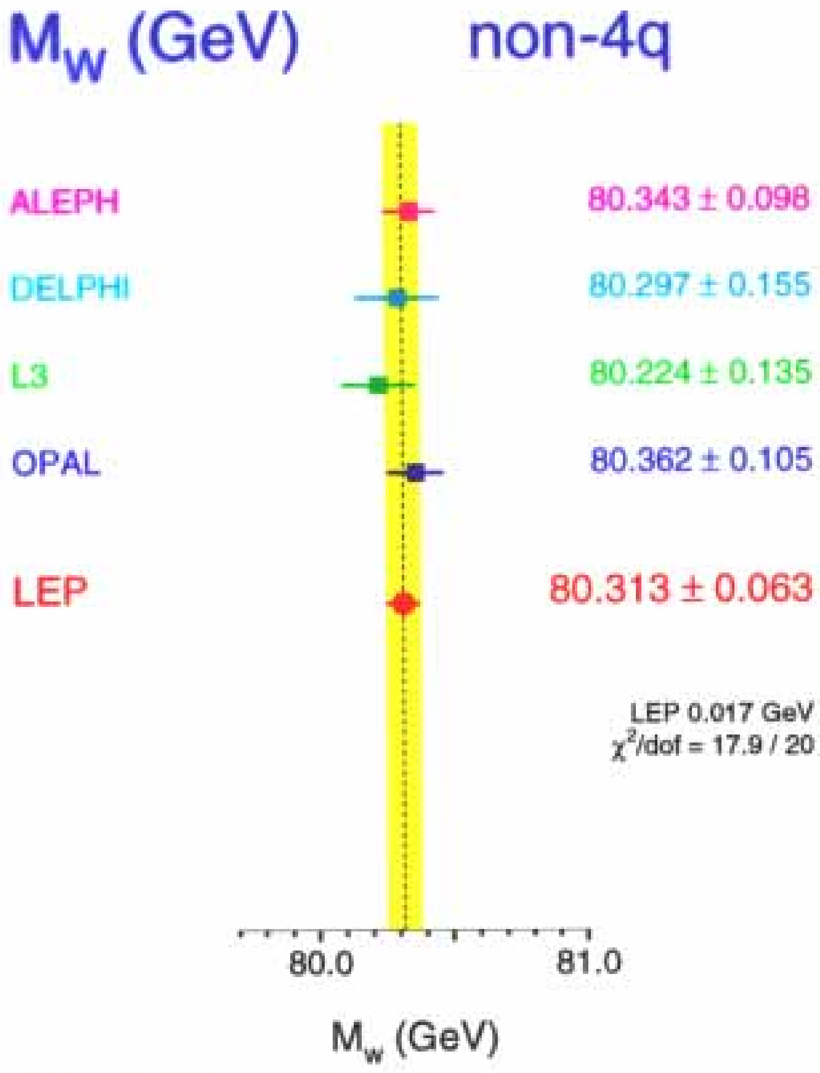
$$C(Q) = N\left[1 + \lambda \exp\left(-Q^2R^2\right)\right] \qquad Q^2 = -\left(p_1 - p_2\right)^2$$

Correlations established in hadronic Z decays and in decays of the same W



Estimated systematic error on m_W: 20 – 60 MeV





Combined LEP W mass measurement including 189 GeV data:

$$m_W = 80.350 \pm 0.056 \text{ GeV}$$

W mass from the Tevatron

- CDF & DØ results from complete Run I data set

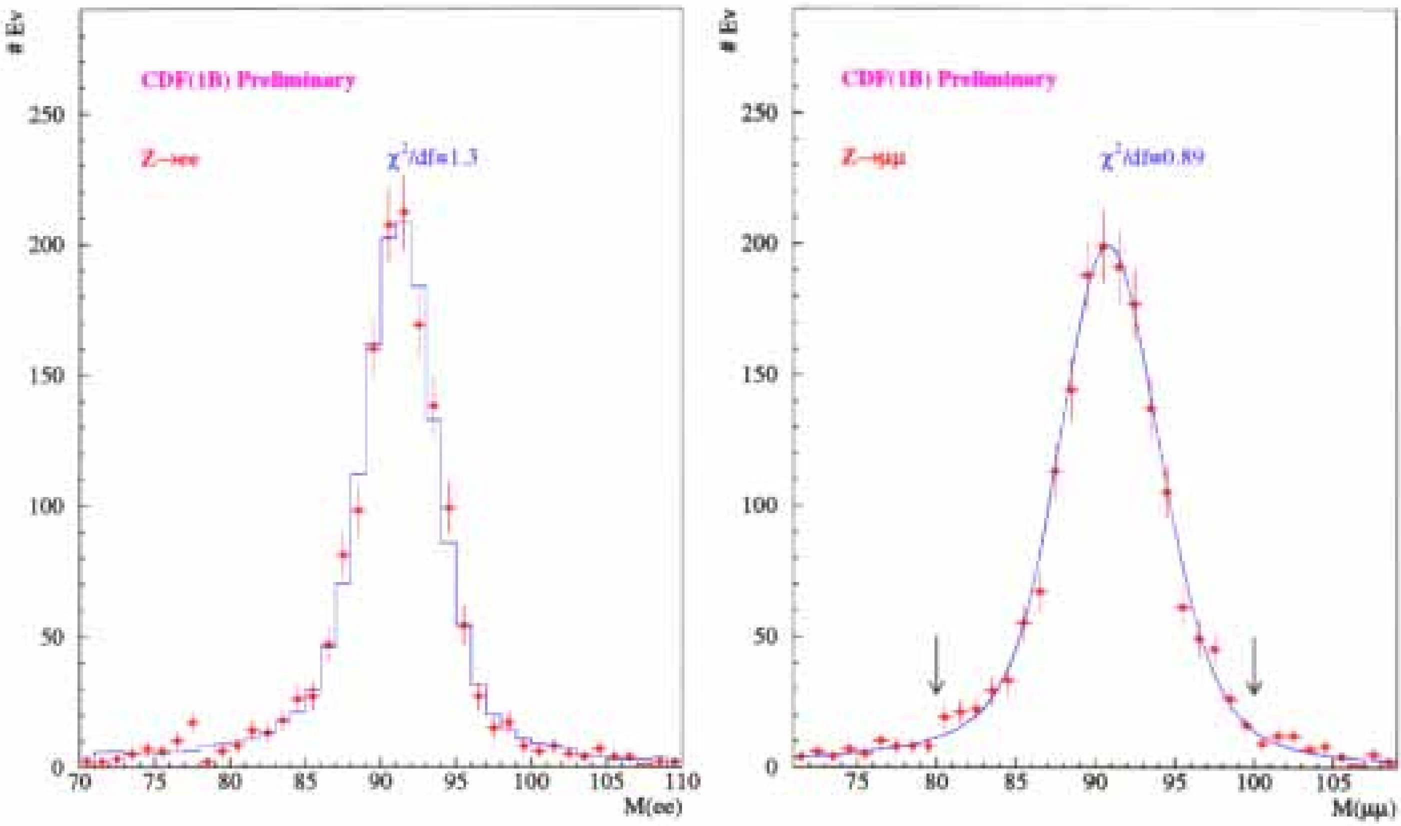
Events used for m_W measurement

30k $W \to e\nu$ and 15k $W \to \mu\nu$ (CDF)

45k $W \to e\nu$, incl. 11k in end calorimeter (DØ)

- Fit transverse mass or transverse momentum distributions of $W \to \ell\nu$ ($\ell = e, \mu$) events
- Fix energy scale with $Z \to \ell^+\ell^-$ events

Example CDF:



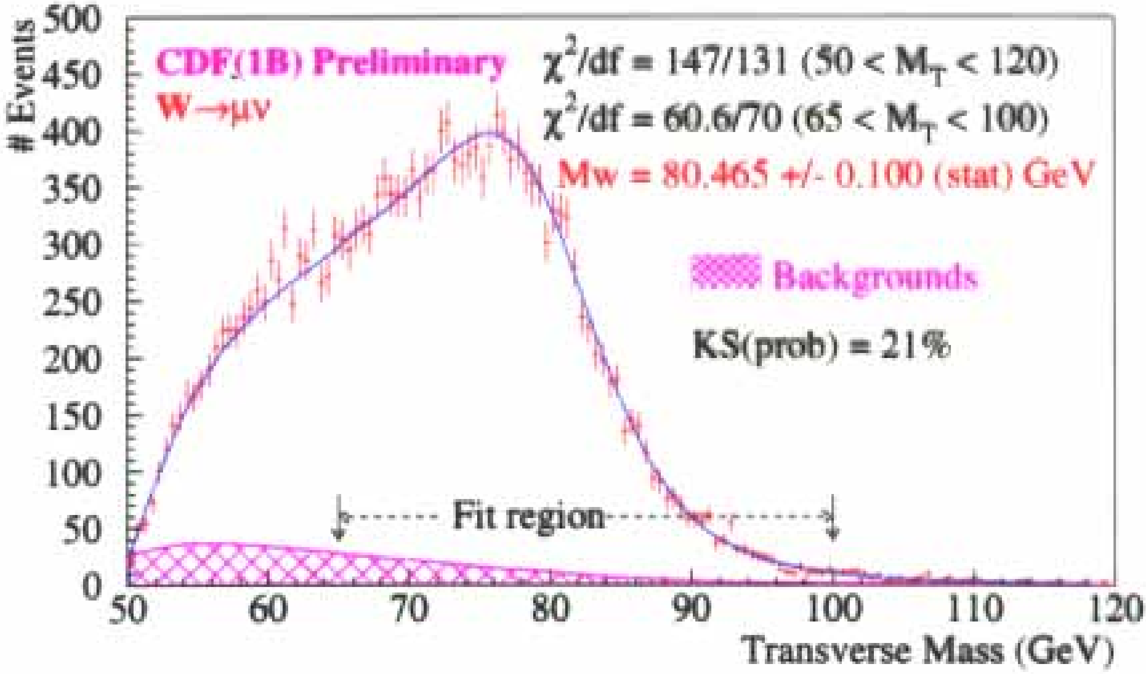
Z statistics is dominant systematic error on m_W:

CDF: $\pm$75 MeV ($W \to e\nu$) $\pm$85 MeV ($W \to \mu\nu$)

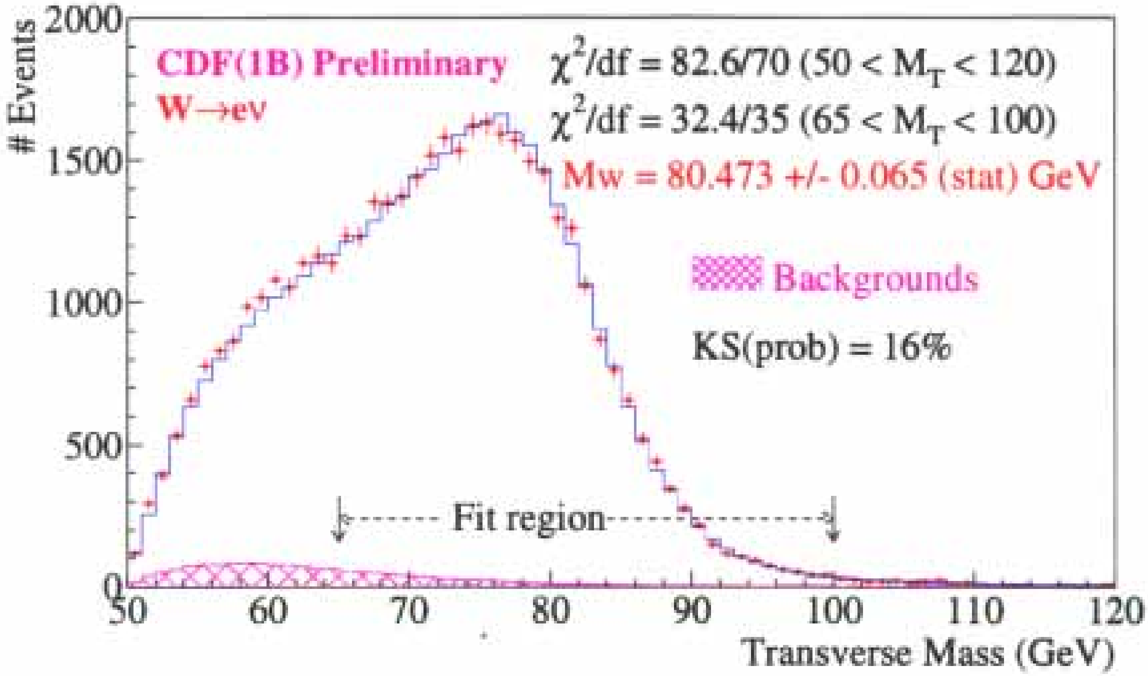
DØ: $\pm$59 MeV

W mass measured by CDF

- CDF transverse mass distributions:



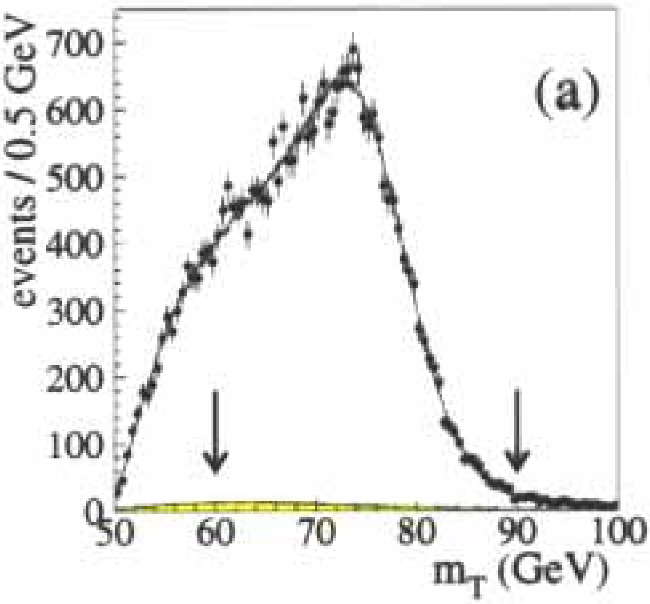
- New result from $W \rightarrow e\nu$:

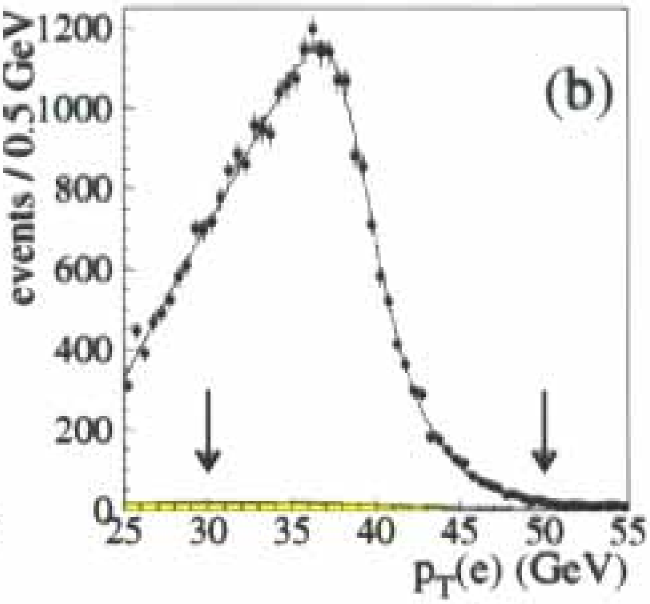


Combined CDF result:

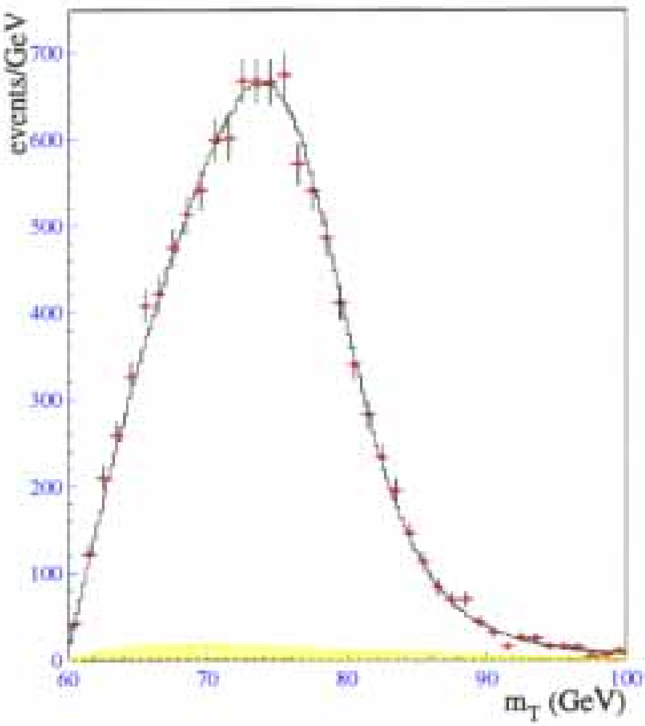
$$m_W = 80.433 \pm 0.079 \text{ GeV}$$

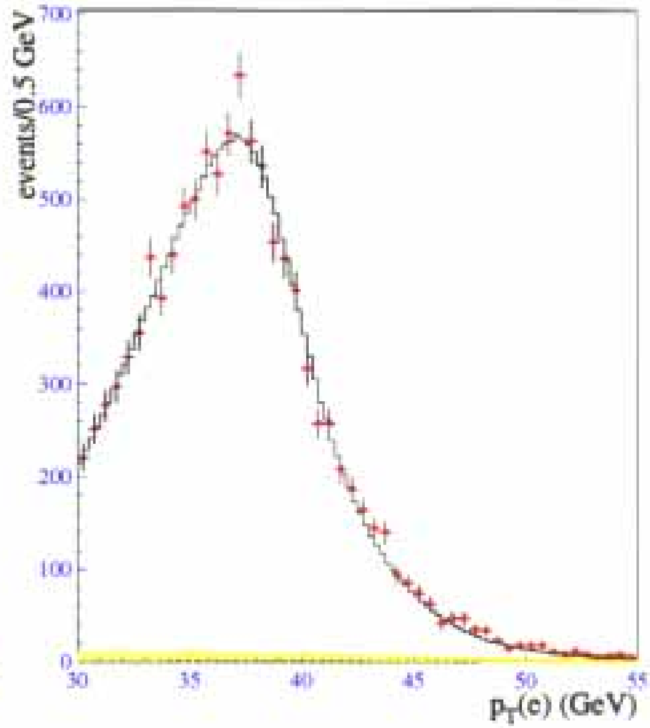
- DØ transverse mass and momentum distributions:





- New: including endcap electrons ($1.5 < |\eta| < 2.5$)





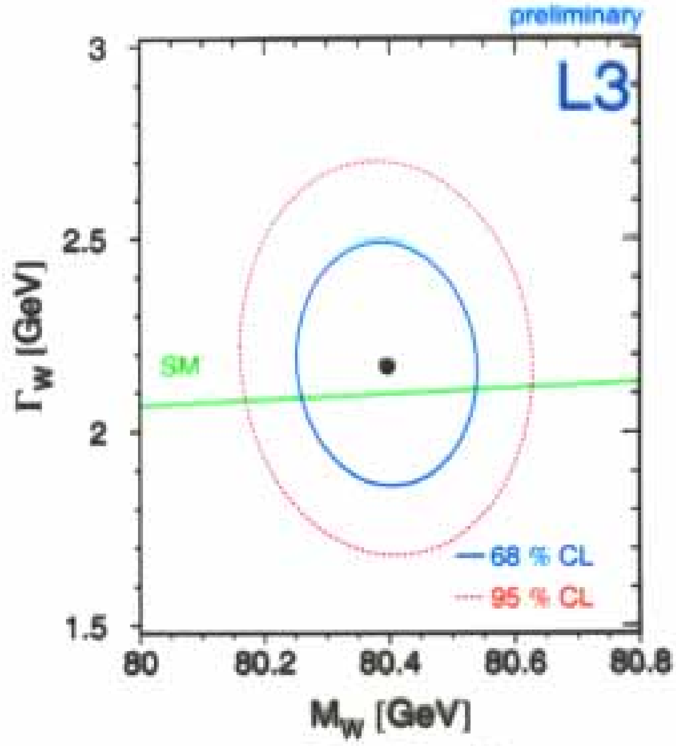
Combined DØ result:

$$m_W = 80.474 \pm 0.093 \text{ GeV}$$

- Direct determination
  - LEP: fit to invariant mass distributions:

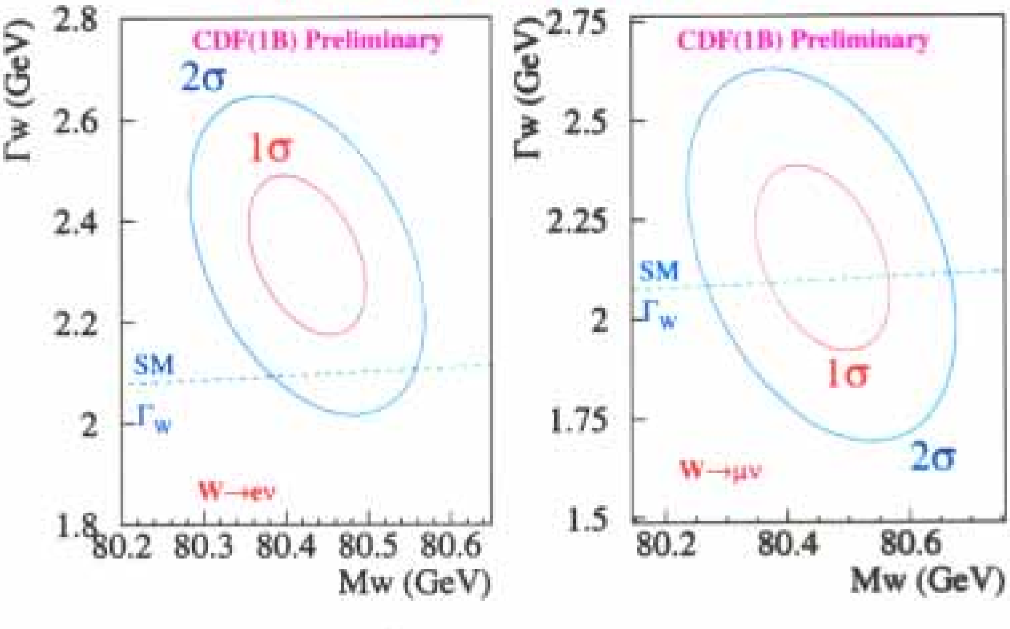
	Γ_W[GeV]
L3	2.12 ± 0.25
DELPHI*	2.48 ± 0.41
OPAL*	1.84 ± 0.38
SM	2.08

* 183 GeV data



  - CDF: high end of transverse mass distributions

$$\Gamma_W = 2.055 \pm 0.125\text{GeV}$$

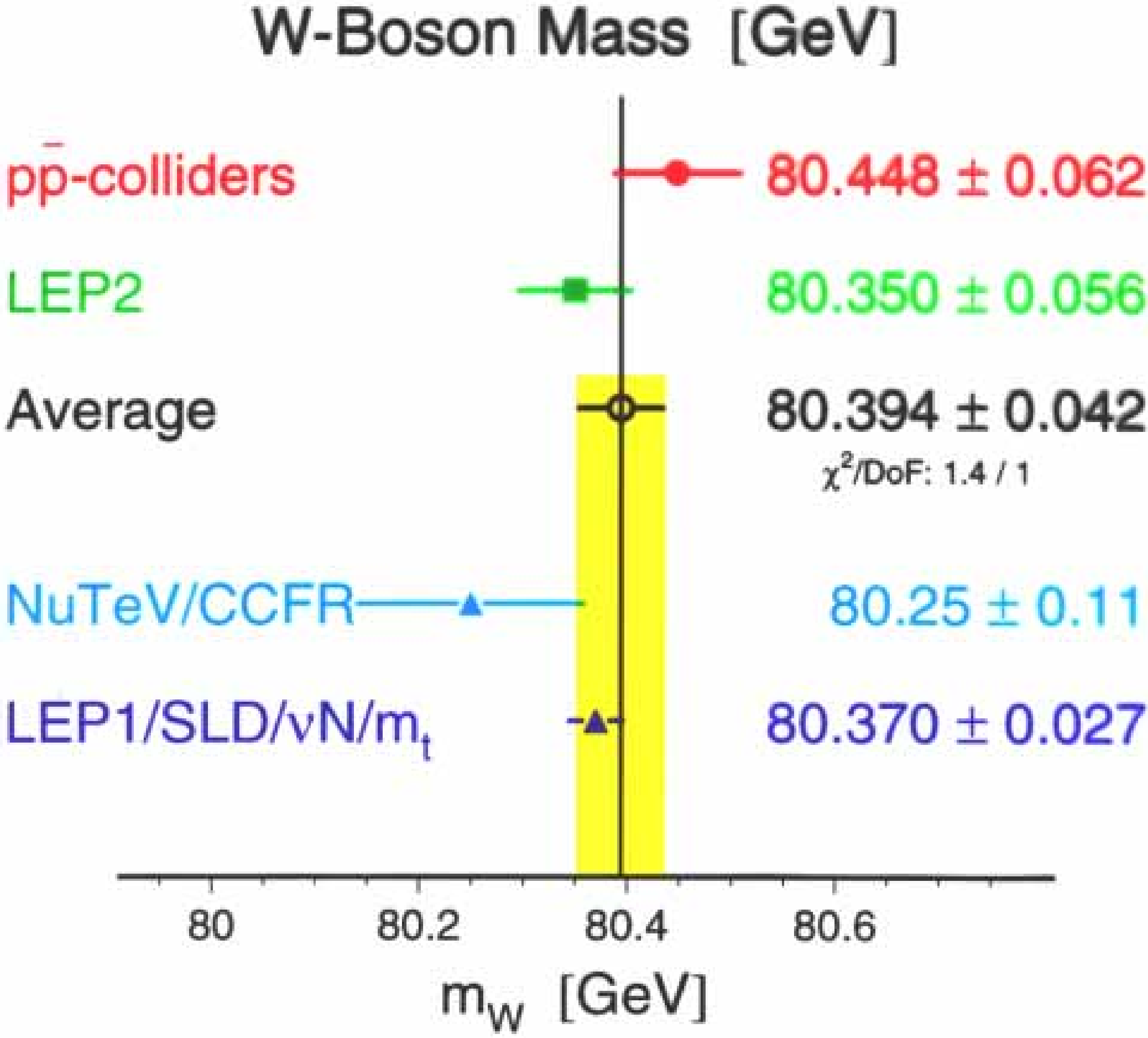


- Indirect measurement from

$$\frac{\sigma(p\bar{p} \to W + X)\, BR(W \to \ell\nu)}{\sigma(p\bar{p} \to Z + X)\, BR(W \to \ell\ell)} = \left(\frac{\sigma_W}{\sigma_Z}\right)^{SM} \left(\frac{\Gamma_Z}{\Gamma_{Z\to\ell\ell}}\right)^{LEP} \frac{\Gamma^{SM}_{W\to\ell\nu}}{\Gamma_W}$$

$$\text{CDF}: \Gamma_W = 2.179 \pm 0.046 \text{ GeV}$$

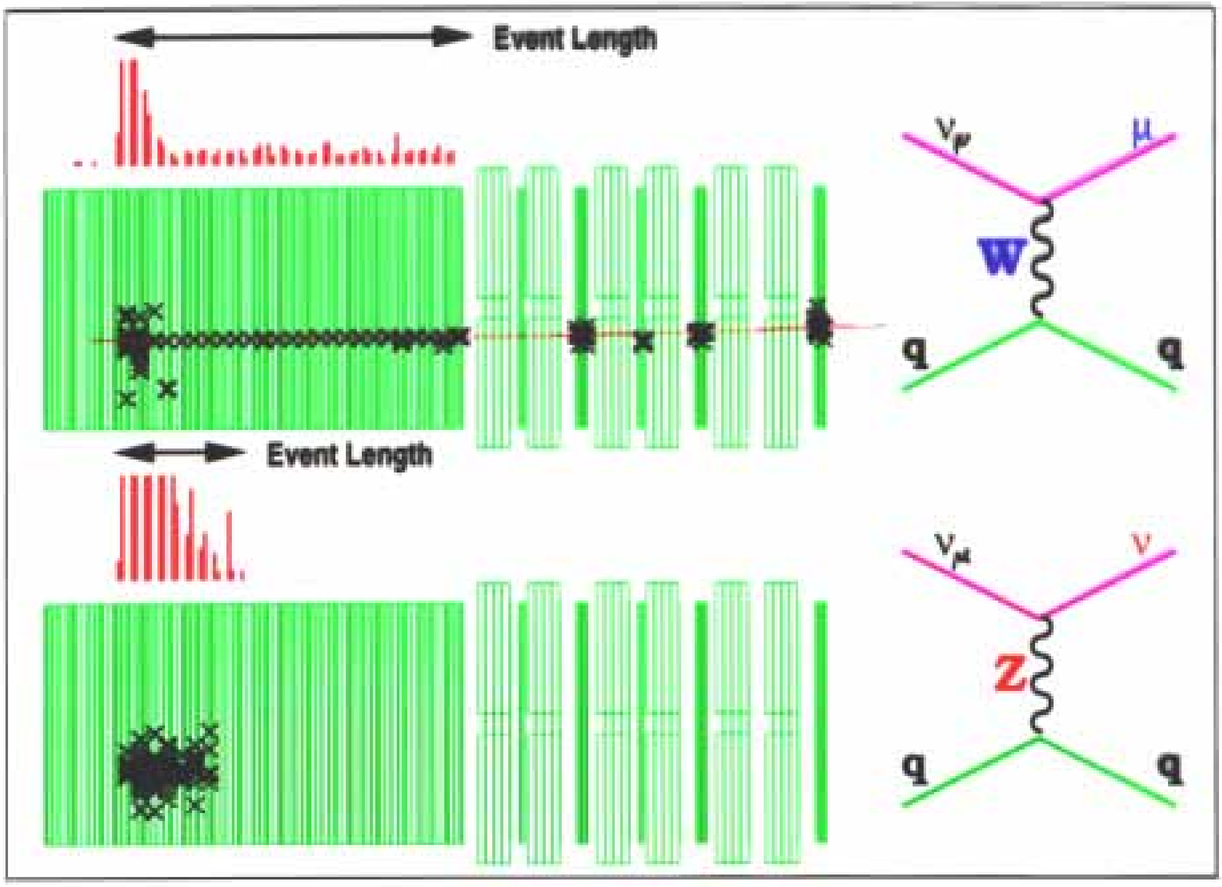
$$\text{DØ}: \Gamma_W = 2.107 \pm 0.054 \text{ GeV}$$


W-Boson Mass [GeV]
pp̄-colliders
80.448 ± 0.062
LEP2
80.350 ± 0.056
Average
80.394 ± 0.042
χ²/DoF: 1.4 / 1
NuTeV/CCFR
80.25 ± 0.11
LEP1/SLD/νN/m_t
80.370 ± 0.027
80
80.2
80.4
80.6
m_W [GeV]

W mass from neutrino-nucleon scattering

- Ratio of neutral to charged current cross section measures

$$\sin^2\theta_W = 1 - \left(\frac{m_W}{m_Z}\right)^2$$



- Experimentally measure

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar\nu}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar\nu}_{CC}}$$

Sea quark contribution cancel: $\sigma_{\nu q} = \sigma_{\bar\nu\bar q}$ $\sigma_{\nu\bar q} = \sigma_{\bar\nu q}$

NUTEV $\sin^2\theta_W = 0.2253 \pm 0.0019 \pm 0.0010$

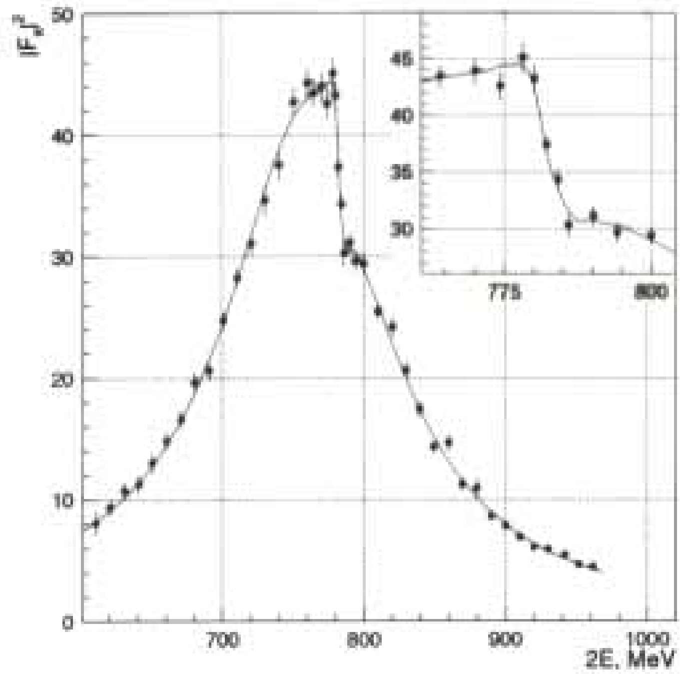
$$\Longrightarrow m_W = 80.25 \pm 0.11 \text{ GeV}$$

Cross section measurements $e^+e^- \to$ hadrons at low energy

- **CMD-2 at VEPP in Novosibirsk**

  $\sigma(e^+e^- \to \pi^+\pi^-)$ around the ρ

  630 MeV $\leq \sqrt{s} \leq$ 810 MeV

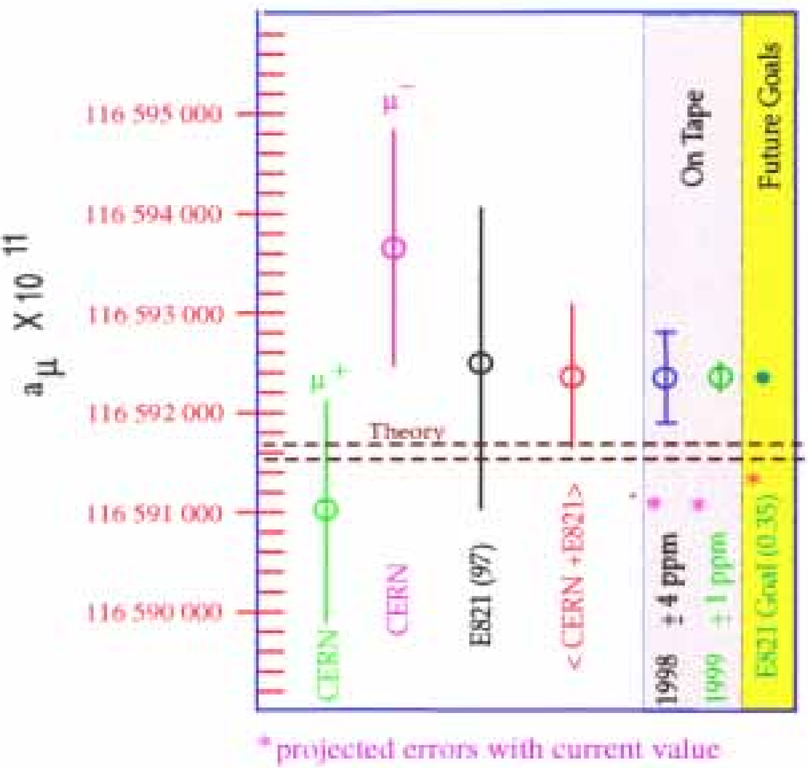


Improved determination of

$a_\mu^{had} = (29.03 \pm 0.41) \cdot 10^{-9}$

(combined with previous measurements)

- **BNL E821 measurement of $a_\mu = \frac{1}{2}(g_\mu - 2)$**



First result from 1997 pilot run:

$a_\mu = 1165925(15) \times 10^{-9}$

Expected precision:

$\pm 0.35 \cdot 10^{-9}$

Cross section measurements $e^+e^- \to$ hadrons at low energy

- Interpretation of electroweak measurements requires $\alpha(m_Z)$
- Contribution of 5 light quarks to vacuum polarization

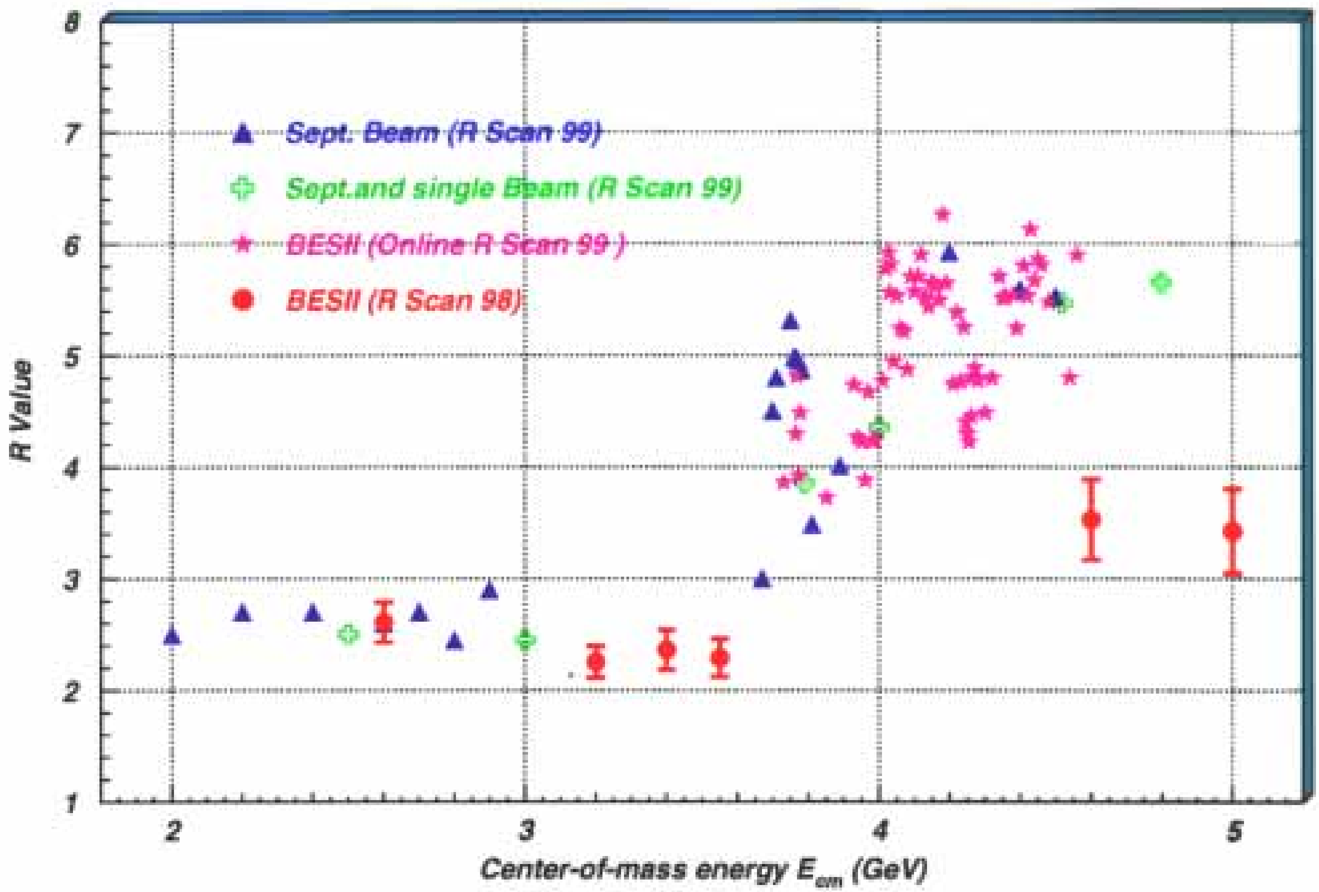
$$\Delta\alpha_{\mathrm{had}}^{(5)} = 0.02804 \pm 0.00065$$

Limited by knowledge of $R(s) = \dfrac{\sigma_{\mathrm{had}}}{\sigma_{\mu\mu}}$ at low energy

BES experiment:

- Energy range 2 GeV $\leq \sqrt{s} \leq$ 5 GeV
- Measure R to 6 − 10%
- Structures near charm threshold

R scan performed in 1999 (85 points)



Analysis is ongoing . . .

Interpretation of precision data in the SM

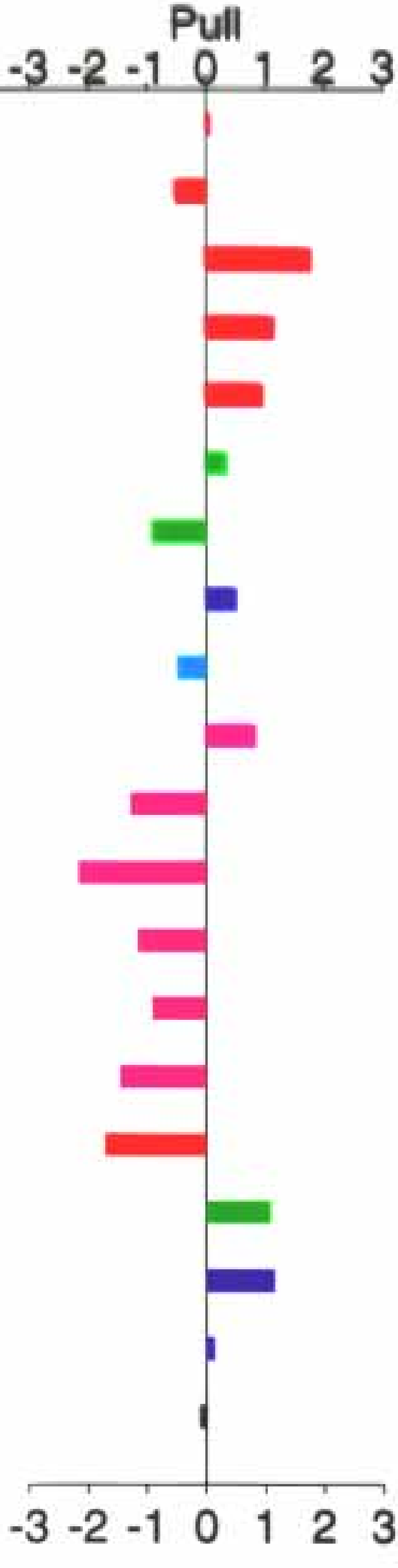
- Observables at the Z from LEP & SLC
- m_W from LEP II and CDF & DØ
- $\sin^2\theta_W$ from ν-nucleon scattering
- $m_t = 174.3 \pm 5.1$ GeV (CDF & DØ)
- Hadronic contribution to running of α: $\Delta\alpha^{(5)}_{\text{had}} = 0.02804 \pm 0.00065$

	LEP including LEP II m_W	all data except m_W and m_t	all data except m_W	all data
m_t [GeV]	172^{+14}_{-11}	167^{+12}_{-9}	173.2 ± 4.8	173.6 ± 4.6
m_H [GeV]	143^{+284}_{-87}	68^{+118}_{-36}	102^{+92}_{-52}	92^{+78}_{-45}
$\log(m_H/\text{GeV})$	$2.15^{+0.48}_{-0.41}$	$1.83^{+0.43}_{-0.32}$	$2.01^{+0.28}_{-0.31}$	$1.96^{+0.27}_{-0.30}$
α_s	0.120 ± 0.003	0.119 ± 0.003	0.119 ± 0.003	0.119 ± 0.003
χ^2/d.o.f.	11/9	20/12	20/13	22/15
$\sin^2\overline{\theta}_W$	0.23187 ± 0.00021	0.23161 ± 0.00018	0.23162 ± 0.00018	0.23159 ± 0.00016
$\sin^2\theta_W$	0.2238 ± 0.0006	0.2234 ± 0.0007	0.2232 ± 0.0005	0.2231 ± 0.0004
m_W [GeV]	80.340 ± 0.032	80.356 ± 0.035	80.370 ± 0.027	80.377 ± 0.022

Pulls from data to SM fit

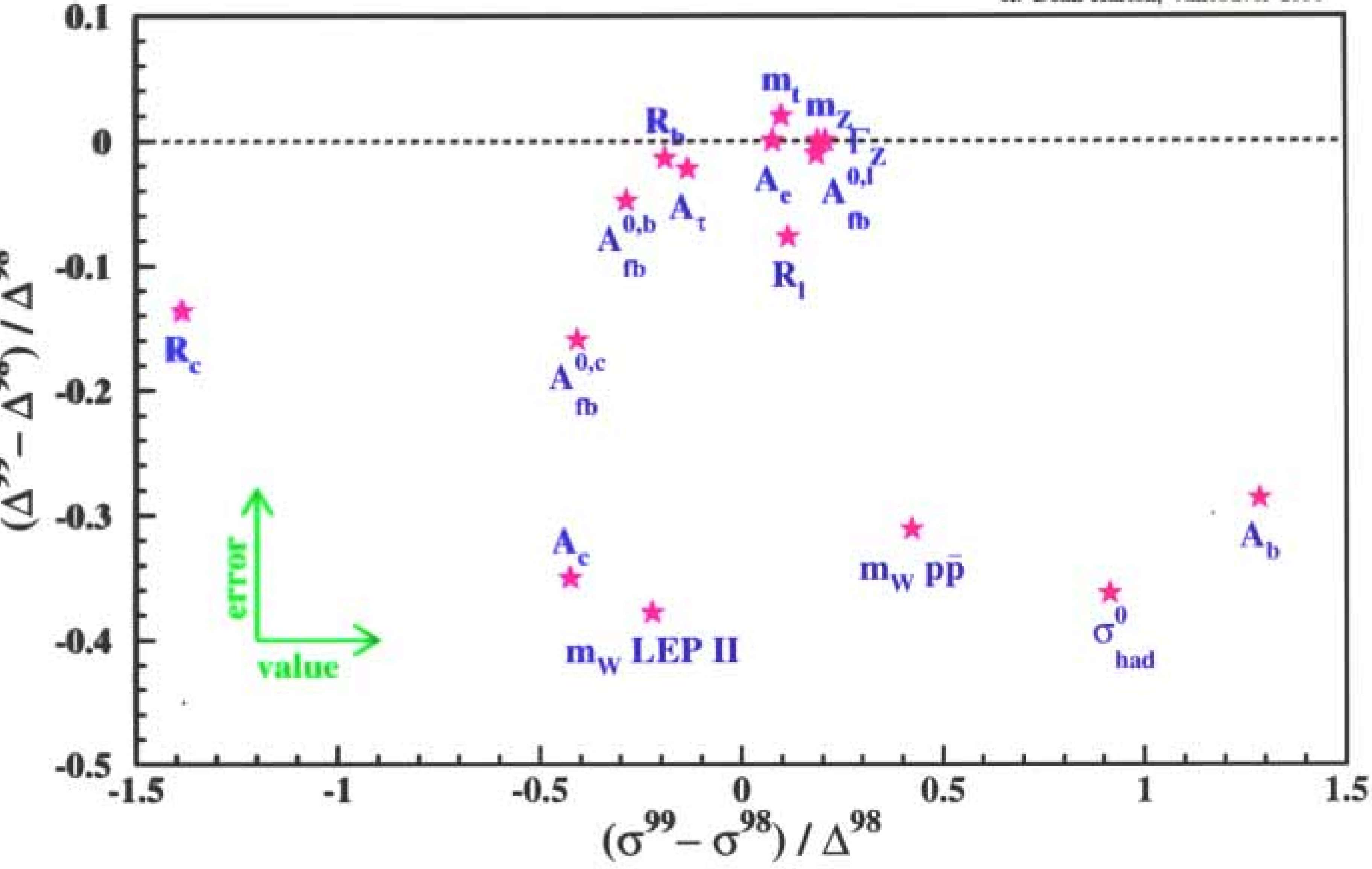
Tampere 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.07
Γ_Z [GeV]	2.4944 ± 0.0024	-.53
σ^0_{hadr} [nb]	41.544 ± 0.037	1.78
R_e	20.768 ± 0.024	1.15
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.96
A_e	0.1483 ± 0.0051	.35
A_τ	0.1425 ± 0.0044	-.91
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.51
m_W [GeV]	80.350 ± 0.056	-.48
R_b	0.21642 ± 0.00073	.83
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0984 ± 0.0020	-2.15
$A^{0,c}_{fb}$	0.0691 ± 0.0037	-1.15
A_b	0.912 ± 0.025	-.90
A_c	0.630 ± 0.026	-1.45
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.71
$\sin^2\theta_W$	0.2255 ± 0.0021	1.09
m_W [GeV]	80.448 ± 0.062	1.15
m_t [GeV]	174.3 ± 5.1	.13
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.10

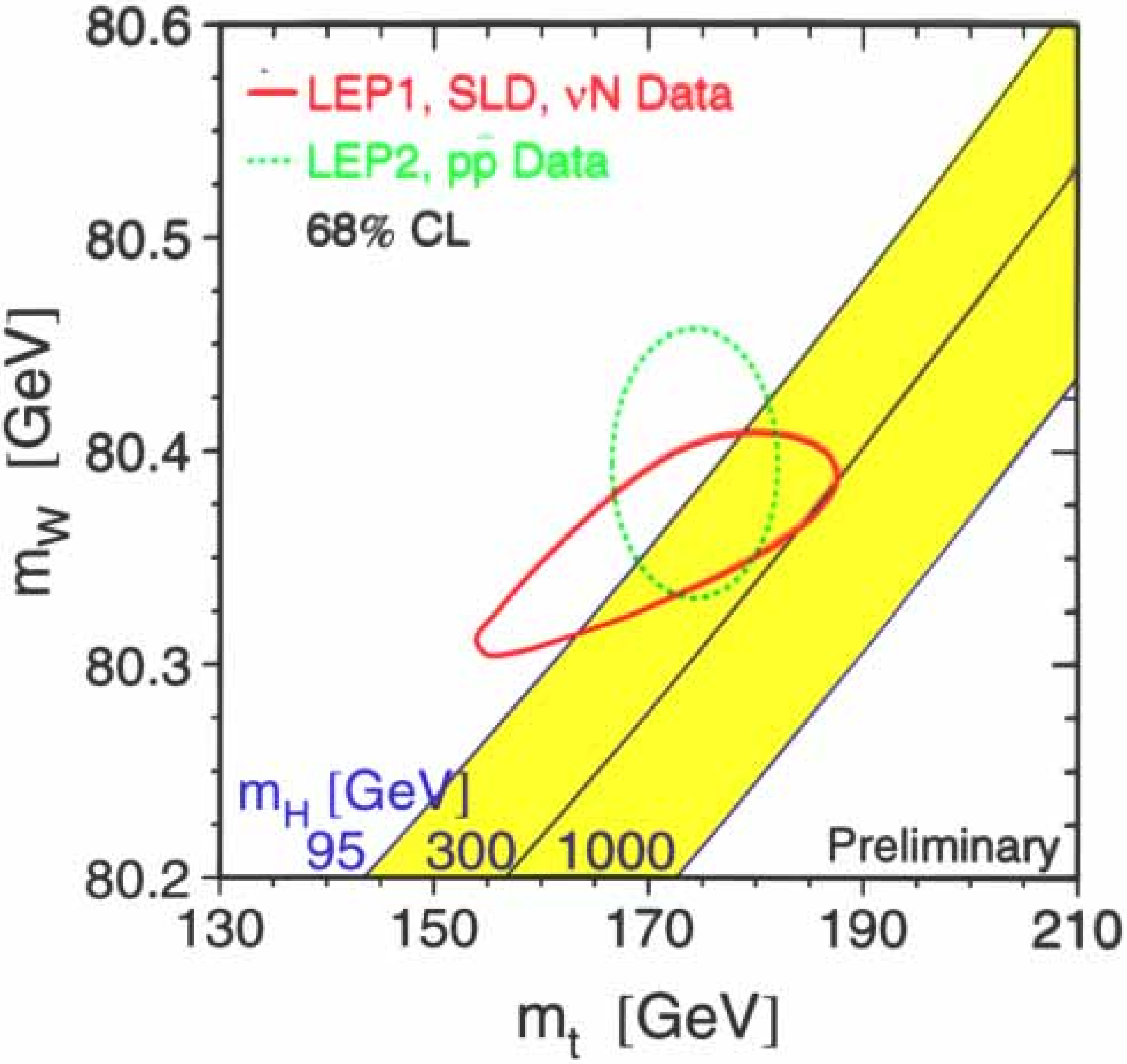


Changes of measurements since summer 1998

cf. Dean Karlen, Vancouver 1998



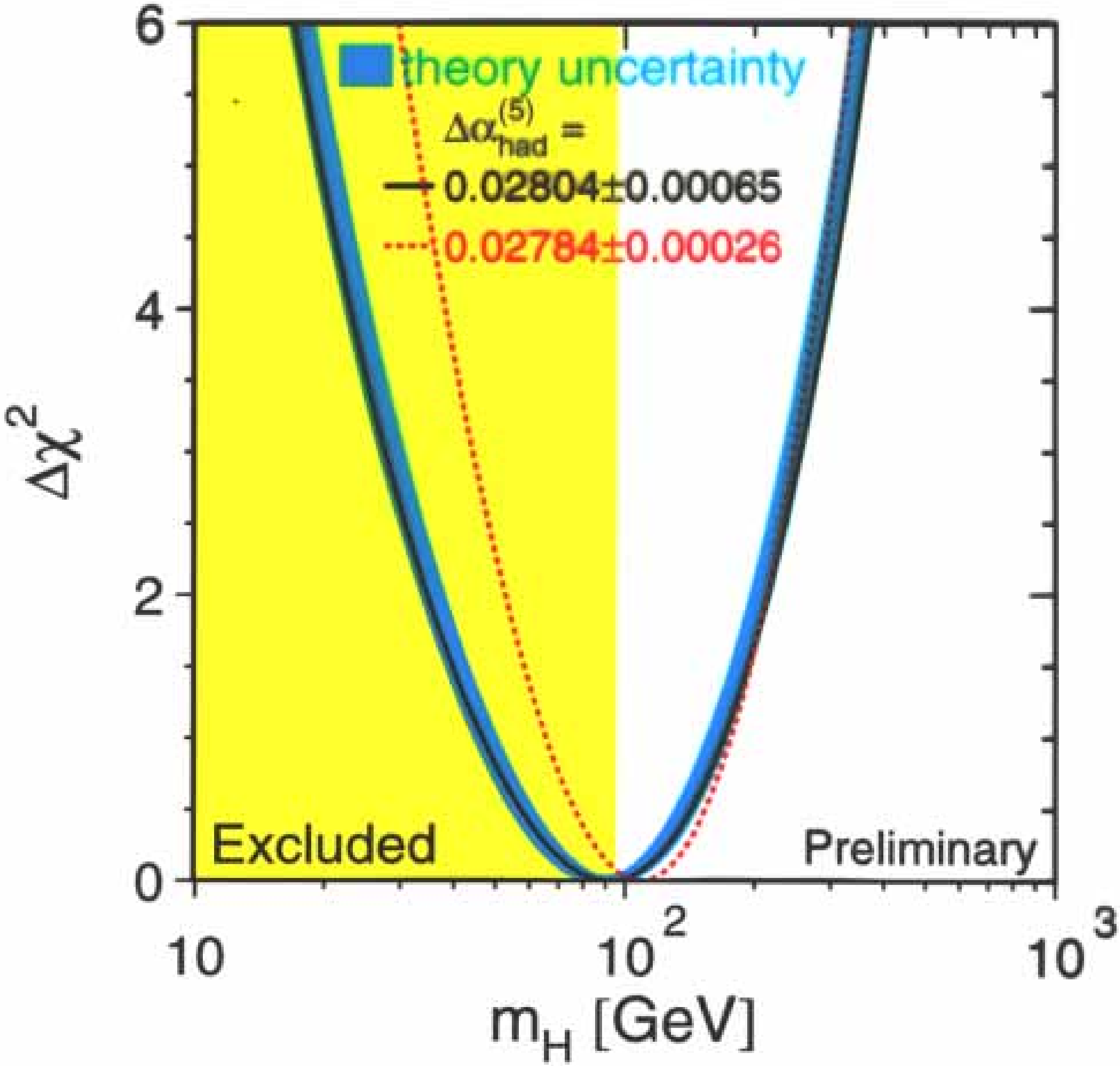
Comparison of direct and indirect measurements



- Good agreement between direct and indirect determinations of m_t and m_W

  The SM is correct at the one-loop level

- Data prefer a light Higgs boson



Electroweak precision data:

$$m_{\mathrm{H}} < 245 \text{ GeV} \qquad 95\% \text{ CL}$$

Search for Higgs production at LEP:

$$m_{\mathrm{H}} > 95.2 \text{ GeV} \qquad 95\% \text{ CL}$$

Conclusions and outlook

- 10 years of Z physics completed at LEP & SLD
- Rapid progress in W physics

$$m_{\mathrm{W}} = 80.394 \pm 0.042 \text{ GeV}$$

  from LEP & Tevatron

- Study of boson self couplings

Near future

- LEP: $\sqrt{s} = 200$ GeV
- Improvement on $\alpha(m_{\mathrm{Z}})$
- HERA
- Tevatron Run II

Far future

- LHC
- Linear collider
- ...

The Standard Model still works

The Higgs boson is light

Acknowledgements

Many thanks for results, plots and help to

- all colleagues from theory and experiments
- the LEP Electroweak Working Group
- and in particular to

Alessandro Ballestrero
Dimitry Bardin
Igor Boyko
Bob Clare
Pablo Garcia-Abia
Martin Grünewald
Atul Gurtu
John Holt
Paul de Jong
Ashutosh Kotwal
Mark Lancaster
Eric Lançon
Clara Matteuzzi
Kevin McFarland
Martin von der Mey
Klaus Mönig
Monica Pepe-Altarelli
Günter Quast
Eusebio Sanchez
Mark Thompson
Pat Ward
Stephane Willocq
Yongsheng Zhu
Eckhard Elsen