Precision Electroweak tests

at LEP

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on Elementary Particle Physics

Moscow State University,
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Many many thanks to my colleagues of

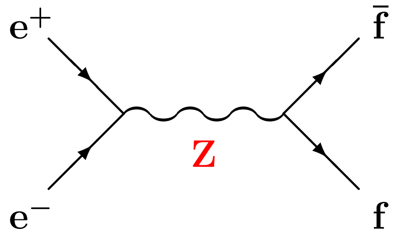
- **the four LEP experiments who provide nice results**
- **the LEP electroweak working group who combine them.**

Outline

- **LEP I : Z resonance**
- **LEP II:**
  - **Fermion pairs production**
  - **W^+W^- production and decays**
  - **W mass**
  - **Gauge Boson self interaction**
  - **Z Z production**
- **Impact on the Standard Model**

New LEP results up to $\sqrt{s} = 200$ GeV

Most of LEP II results are preliminary



$$e^+e^- \;\longrightarrow\; \mathrm{Z} \;\begin{array}{l}\longrightarrow \text{hadrons}\\ \longrightarrow e^+e^- \\ \longrightarrow \mu^+\mu^- \\ \longrightarrow \tau^+\tau^-\end{array}$$

Each LEP experiment provides data corrected of

- detector effects (acceptance, efficiency...),
- some first order QED radiations (ISR, FSR, ..)
- beam energy calibration ...

Higher order corrections and EW effects are absorbed in effective observables.

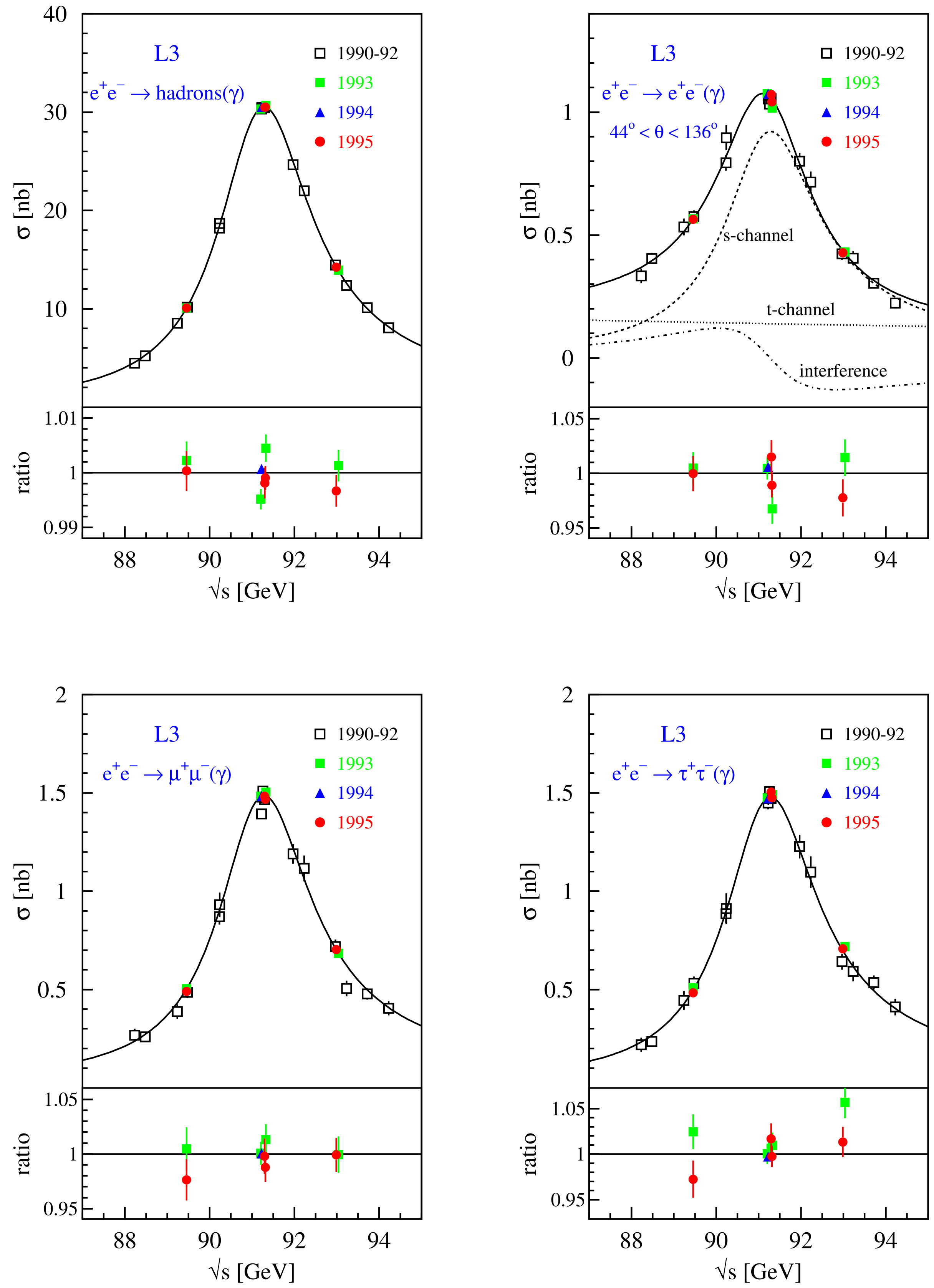
$$\sigma_{\mathrm{Z}}^{f}(s) \;=\; \frac{12\pi}{m_{\mathrm{Z}}^2}\,\frac{s\Gamma_{\mathrm{e}}\Gamma_{\mathrm{f}}}{(s-m_{\mathrm{Z}}^2)^2+s^2\Gamma_{\mathrm{Z}}^2/m_{\mathrm{Z}}^2};$$

$$\Gamma_{\mathrm{f}} \propto [(\bar{g}_{\mathrm{V}}^{\mathrm{f}})^2+(\bar{g}_{\mathrm{A}}^{\mathrm{f}})^2]$$

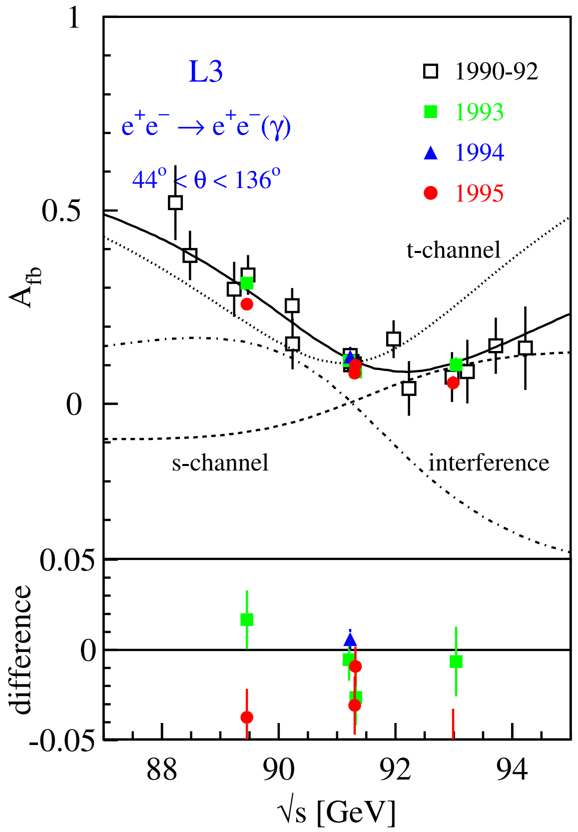
LEP I : (1989 – 1995)

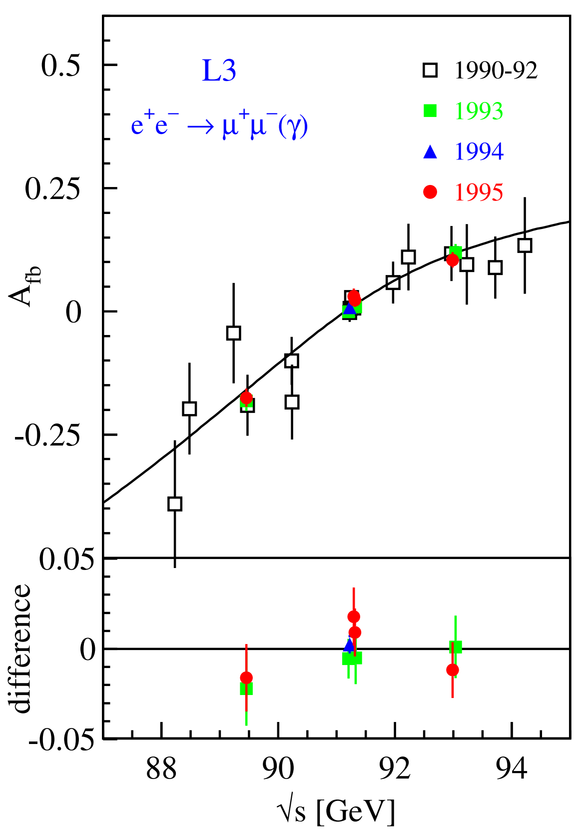
The four LEP experiments analysed 17 millions of Z decays

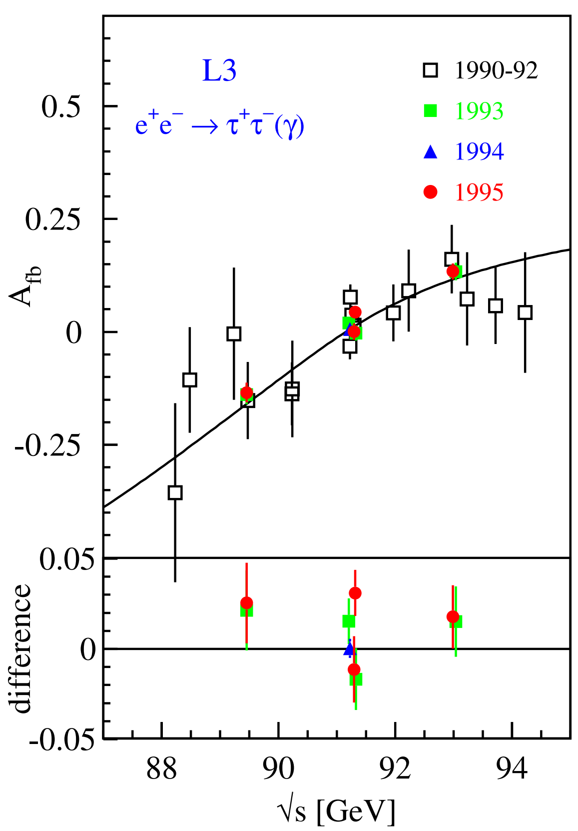
High precision measurements of the total cross sections



and of leptonic forward-backward asymmetries.







Improvements on theoretical calculations

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

ZFITTER & TOPAZ0 include

- **QED and QCD radiation 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.

$\Longrightarrow$ **THEORETICAL UNCERTAINTIES are NOW SMALL:**

- **Uncertainties on QED corrections of Z lineshape:**

$$\Delta m_Z = \pm 0.5 \text{ MeV} \qquad \Delta\Gamma_Z = \pm 0.8 \text{ MeV}$$

$$\Delta\sigma^0_{\text{had}}/\sigma^0_{\text{had}} = \pm 2 \cdot 10^{-4}$$

- **Very good agreement between ZFITTER and TOPAZ0:**

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

- **SM parameter uncertainty**

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

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

- A 9-parameter global fit on total cross sections and leptonic forward-backward asymmetries provides results compatible between the 4 experiments.
- Combination of the four LEP experiments:

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

(+ small correlations)

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

$$A^{0,\ell}_{\rm FB} = \frac{3}{4}A_{\rm e}A_\ell, \quad A_\ell = \frac{2\bar{g}^\ell_{\rm V}\bar{g}^\ell_{\rm A}}{(\bar{g}^\ell_{\rm V})^2 + (\bar{g}^\ell_{\rm A})^2}$$

S.M. contributions validated by S-matrix fit

Assuming lepton universality (5 parameter-fit):

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

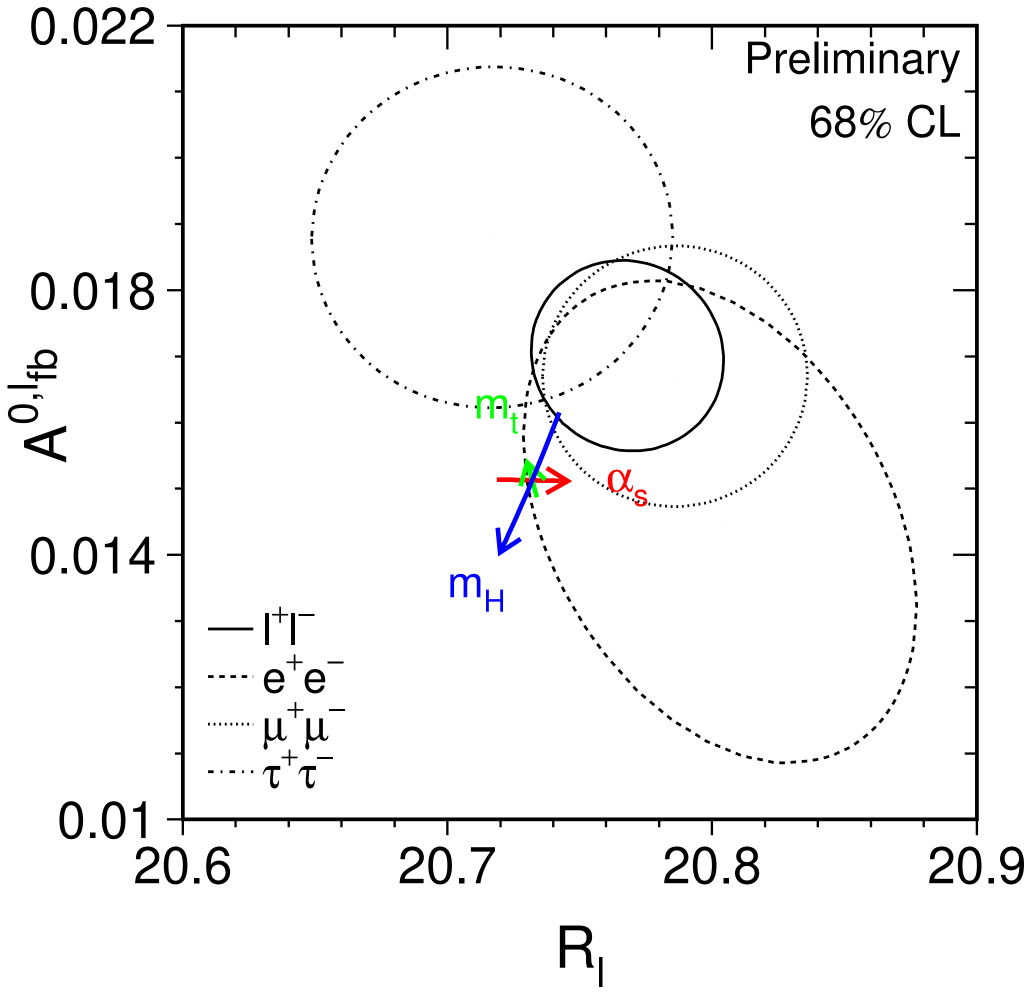
$(\alpha_s = 0.1229 \pm 0.0036\,^{+0.0033}_{-0}(m_H))$

Partial decay widths:

$$\begin{aligned}
\Gamma_{\mathrm{had}} &= 1743.9 \pm 2.0\ \mathrm{MeV} \\
\Gamma_\ell &= 83.958 \pm 0.089\ \mathrm{MeV} \\
\Gamma_{\mathrm{inv}} &= 498.80 \pm 1.5\ \mathrm{MeV} \\
\Delta\Gamma_{\mathrm{inv}} &< 2.0\ \mathrm{MeV} \qquad 95\%\ \mathrm{CL}
\end{aligned}$$

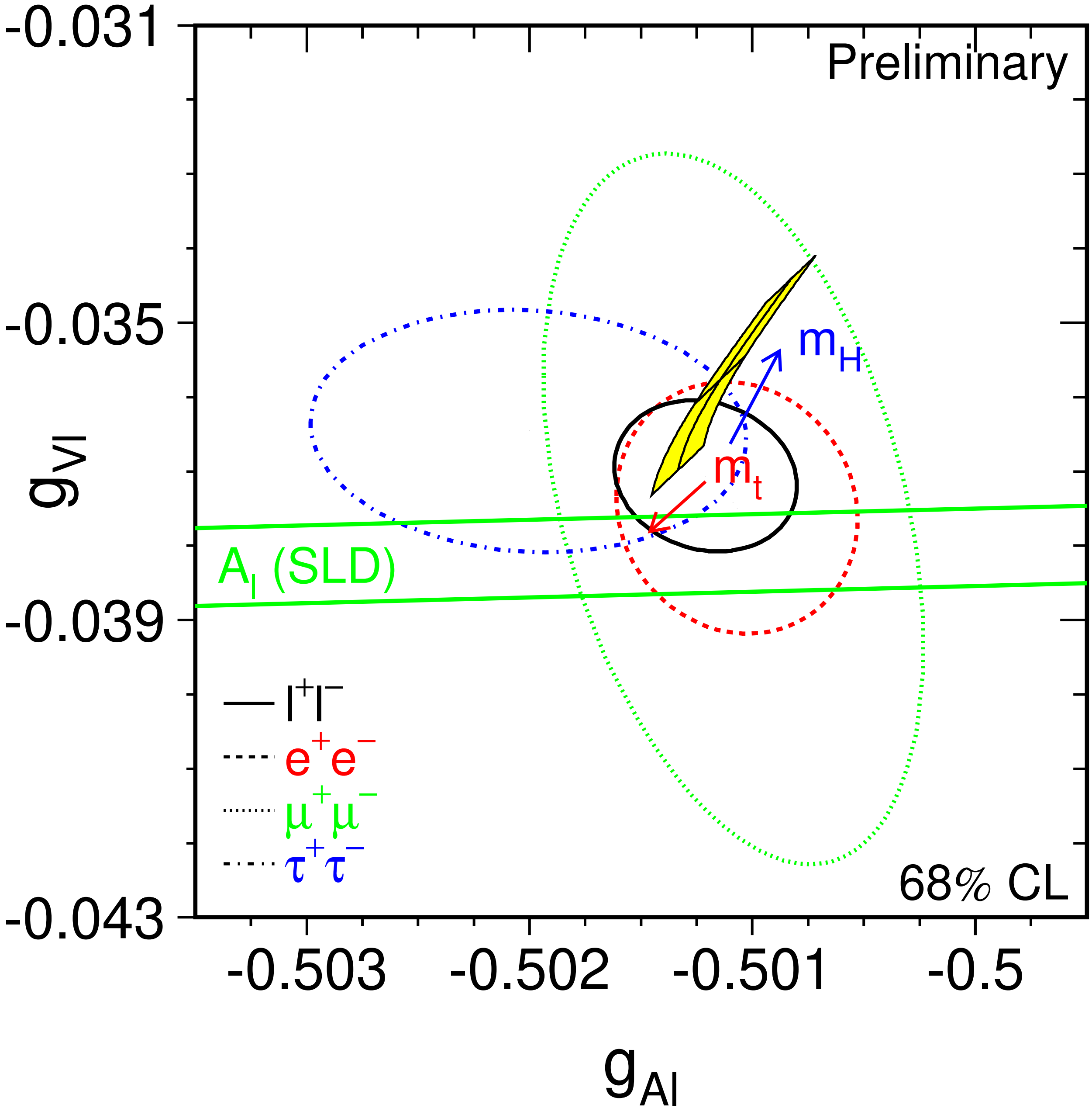
Number of neutrino families:

$N_\nu = 2.9835 \pm 0.0083$



The longitudinal tau polarization provides a ≈ independent measurement in agreement with lepton universality

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



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

$$\bar{g}_A^\mu/\bar{g}_A^e = 1.0002 \pm 0.0013 \qquad \bar{g}_V^\mu/\bar{g}_V^e = 0.946 \pm 0.065$$
$$\bar{g}_A^\tau/\bar{g}_A^e = 1.0019 \pm 0.0015 \qquad \bar{g}_V^\tau/\bar{g}_V^e = 0.955 \pm 0.030$$

Measurements of

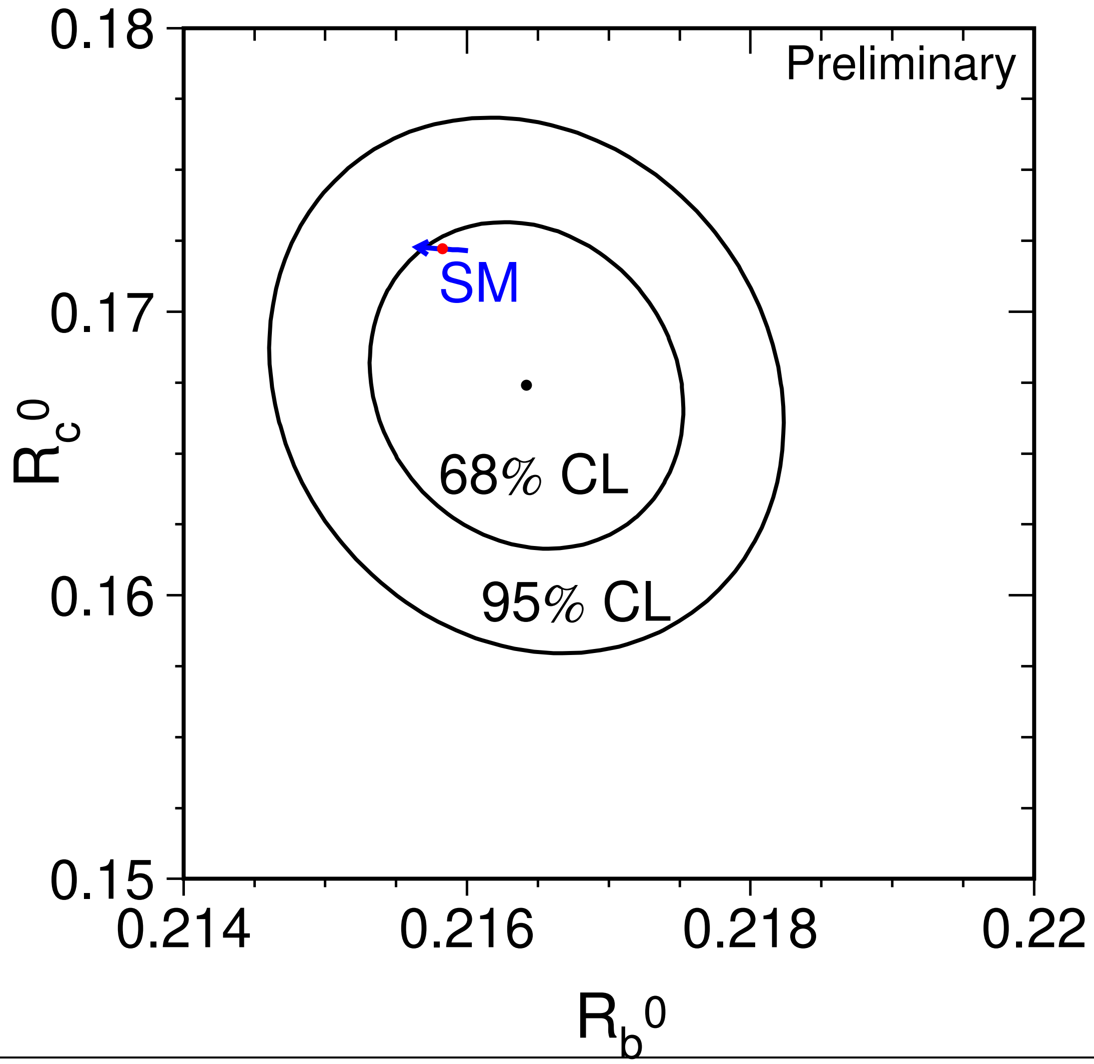
- Cross sections (R_b, R_c) at LEP & SLD
  $R_q = \Gamma_q/\Gamma_{had}$ $\Gamma_q \propto (\bar{g}_A^q)^2 + (\bar{g}_V^q)^2$
- Forward-backward asymmetries at LEP
  $A_{FB}^{0,b}$, $A_{FB}^{0,c}$
- Left-right forward-backward asymmetries
  A_b, A_c $A_q = \frac{2\,\bar{g}_A^q \bar{g}_V^q}{(\bar{g}_A^q)^2+(\bar{g}_V^q)^2}$

Combined fit to LEP & SLD data:

$R_b = 0.21642 \pm 0.00073$ $R_c = 0.1674 \pm 0.0038$

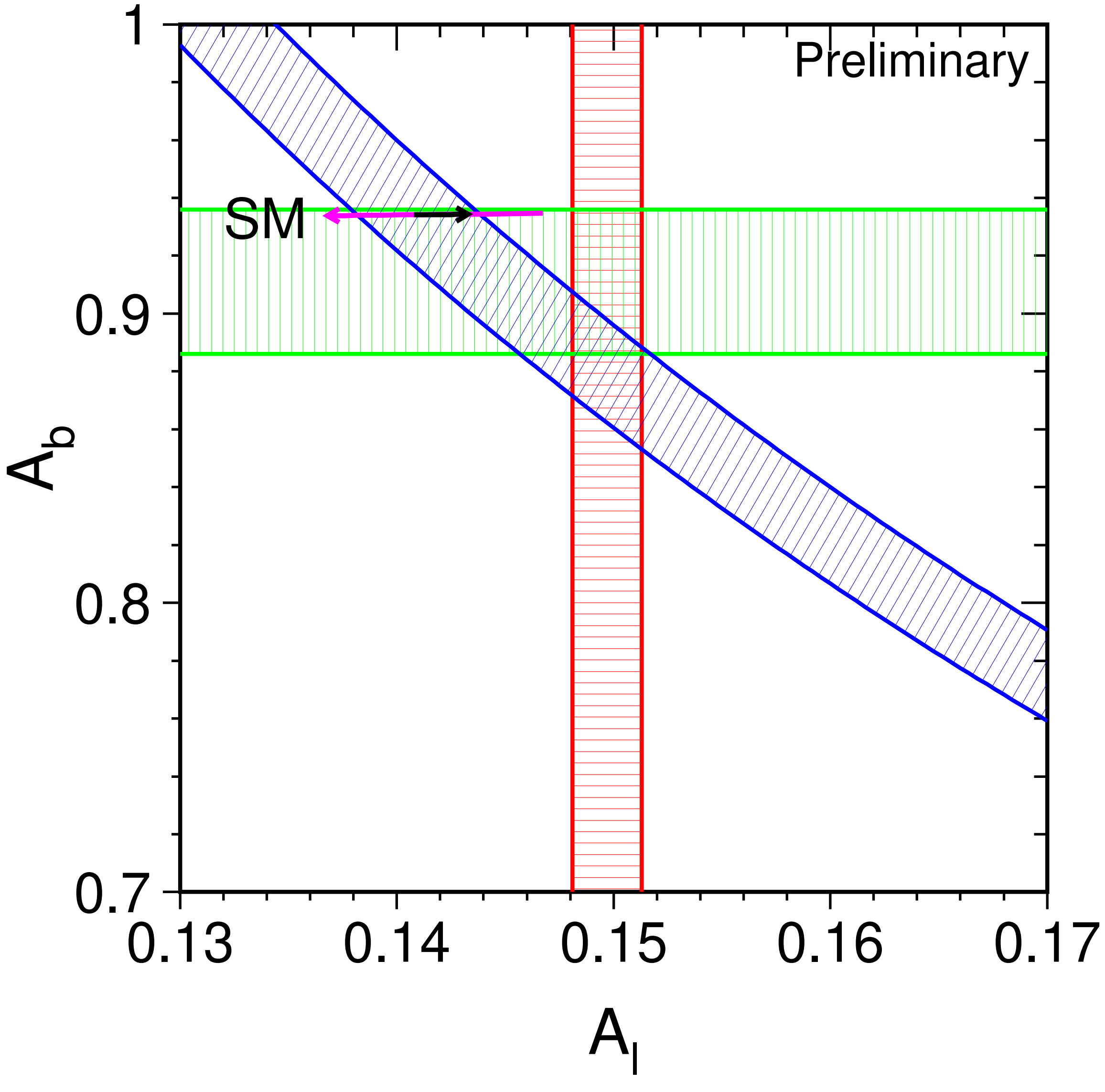
$A_{FB}^{0,b} = 0.0988 \pm 0.0020$ $A_{FB}^{0,c} = 0.0692 \pm 0.0037$

$A_b = 0.911 \pm 0.025$ $A_c = 0.630 \pm 0.026$

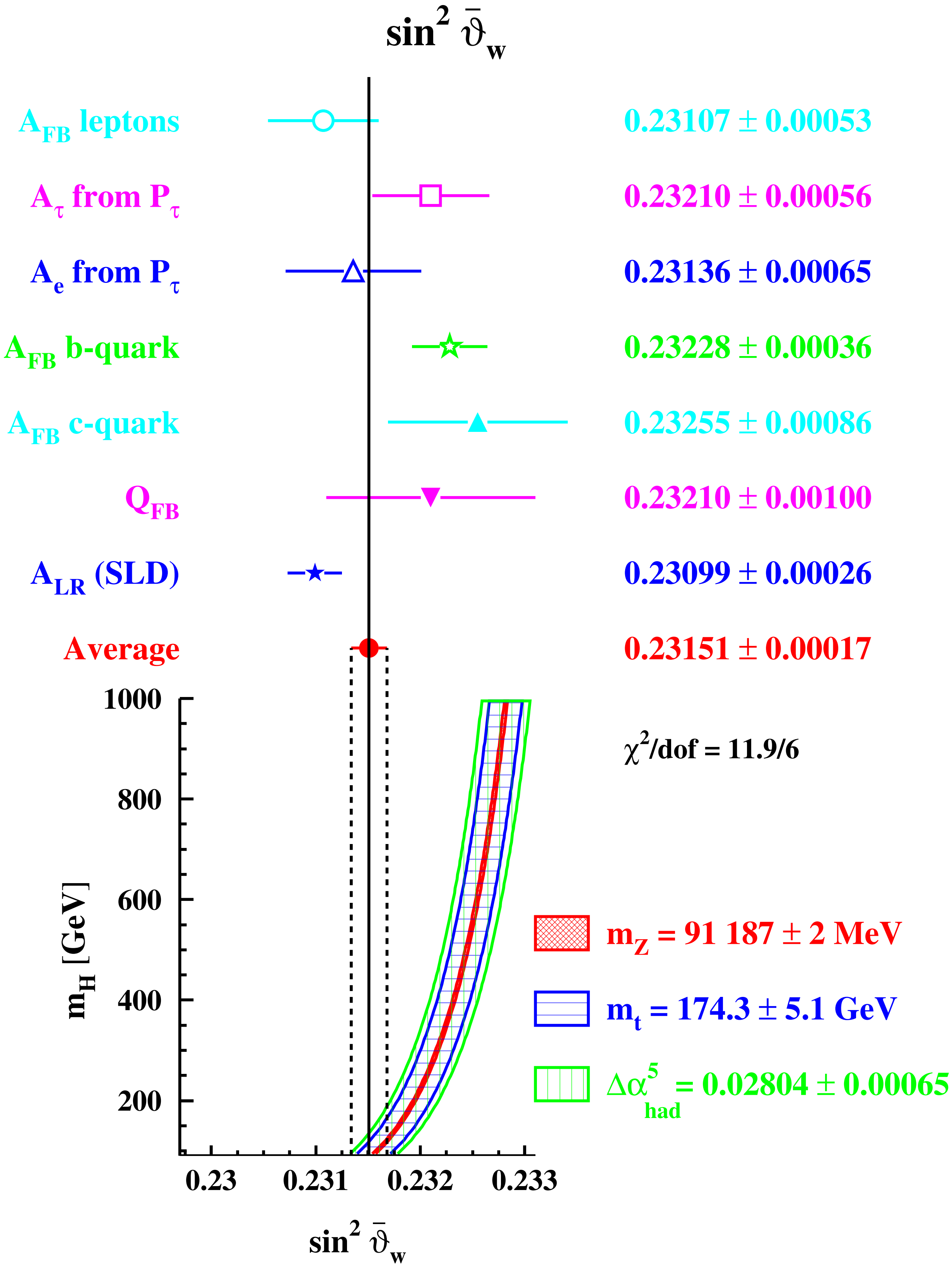


Comparison of

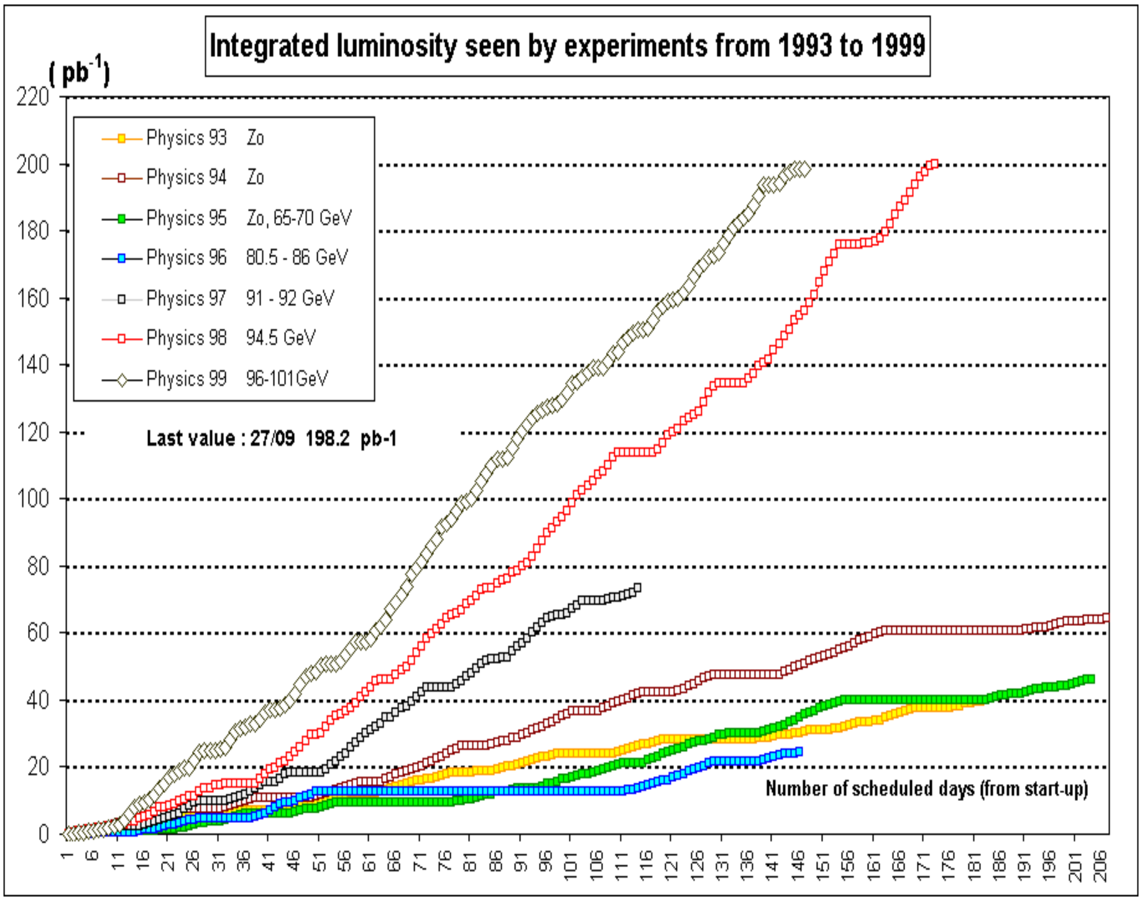
- A_{b} (left-right forward-backward asymmetry)
- A_{ℓ} (A_{LR}, $A_{\mathrm{FB}}^{0,\ell}$, tau-polarization)
- $A_{\mathrm{FB}}^{0,\mathrm{b}} = \frac{3}{4} A_{\ell} A_{\mathrm{b}}$
- SM (m_{H}, m_{t})



	LEP & SLD	SM
A_{l}	0.1492 ± 0.0015	0.1472
A_{b}	0.892 ± 0.016	0.935
A_{c}	0.625 ± 0.021	0.668

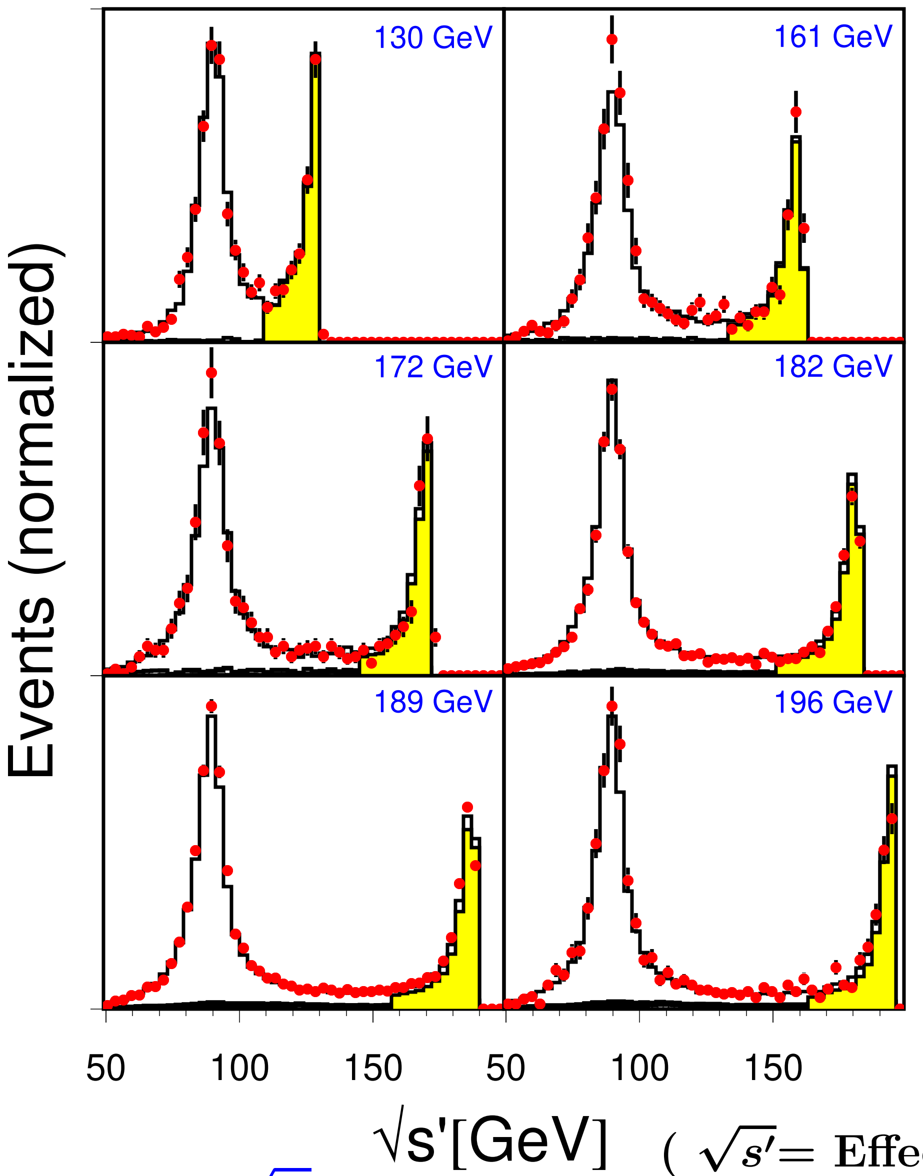

$\sin^2 \bar{\vartheta}_w$
A_{FB} leptons
A_τ from P_τ
A_e from P_τ
A_{FB} b-quark
A_{FB} c-quark
Q_{FB}
A_{LR} (SLD)
Average
0.23107 ± 0.00053
0.23210 ± 0.00056
0.23136 ± 0.00065
0.23228 ± 0.00036
0.23255 ± 0.00086
0.23210 ± 0.00100
0.23099 ± 0.00026
0.23151 ± 0.00017
χ^2/dof = 11.9/6
m_H [GeV]
1000
800
600
400
200
0.23
0.231
0.232
0.233
$\sin^2 \bar{\vartheta}_w$
m_Z = 91 187 ± 2 MeV
m_t = 174.3 ± 5.1 GeV
$\Delta\alpha^5_{had}$ = 0.02804 ± 0.00065

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



Approximate luminosity per experiment:

Year	$\sqrt{s}$	$\int \mathcal{L}\,dt$	
1995	130 – 140 GeV	5 pb^{-1}	
1996	161/172 GeV	21 pb^{-1}	W-pair threshold
1997	183 GeV	55 pb^{-1}	Z-pair threshold
	130/136 GeV	7 pb^{-1}	
1998	189 GeV	180 pb^{-1}	
1999	192 GeV	29 pb^{-1}	
	196 GeV	81 pb^{-1}	
	200 GeV	35 pb^{-1}	



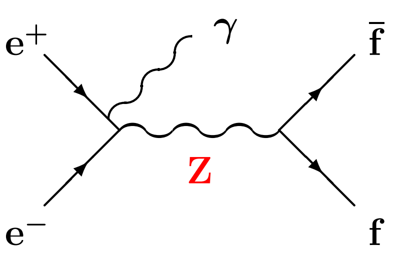
($\sqrt{s'}$= Effective c.m. energy)

peak at $\sqrt{s'} \approx m_Z$

named

'Return-to-the-Z'

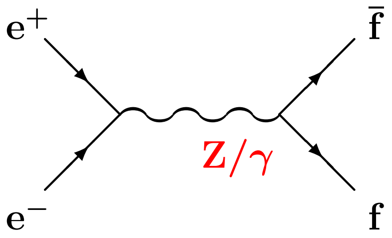
Initial State Radiation



at $\sqrt{s'} \equiv \sqrt{s}$

$(Z\ or\ \gamma)^*$

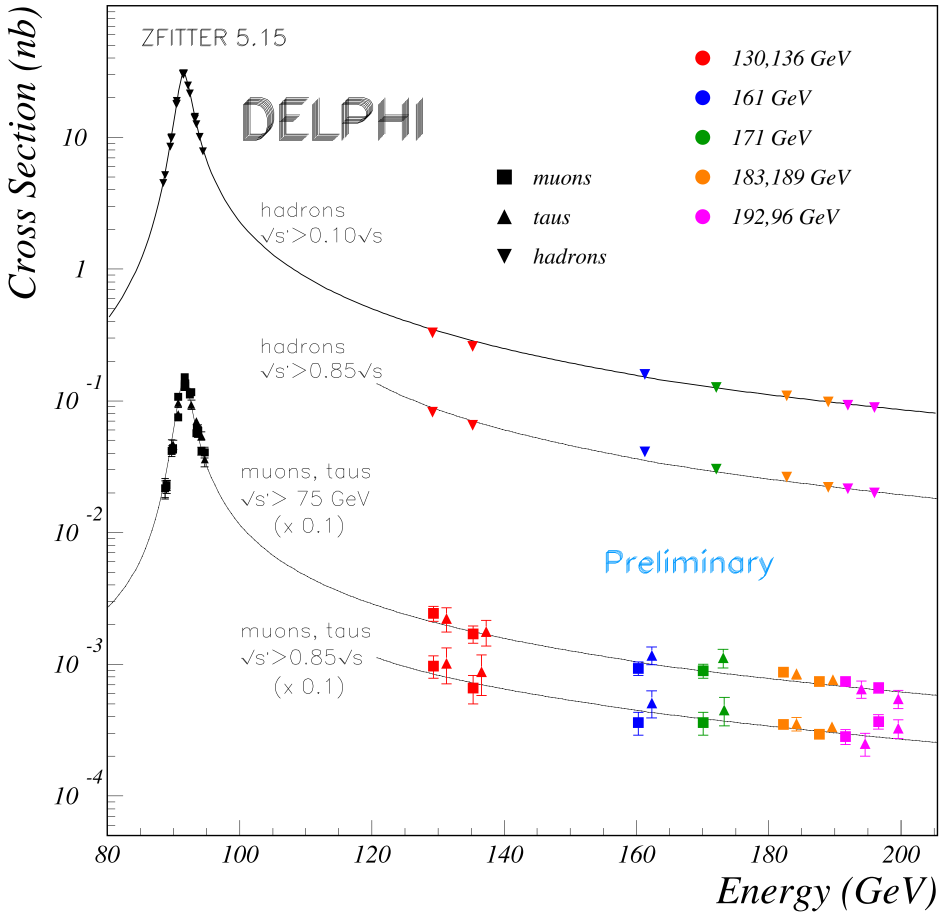
full Energy peak



Measure cross sections and asymmetries for

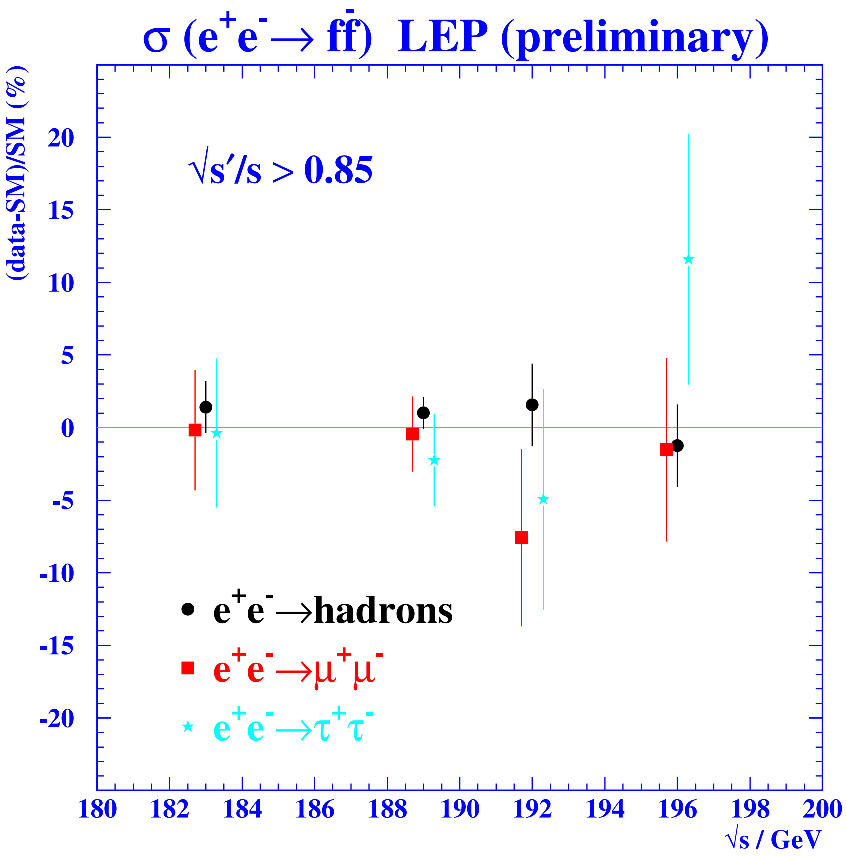
- Inclusive sample
- High energy sample $\sqrt{s'} > 0.85\sqrt{s}$

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



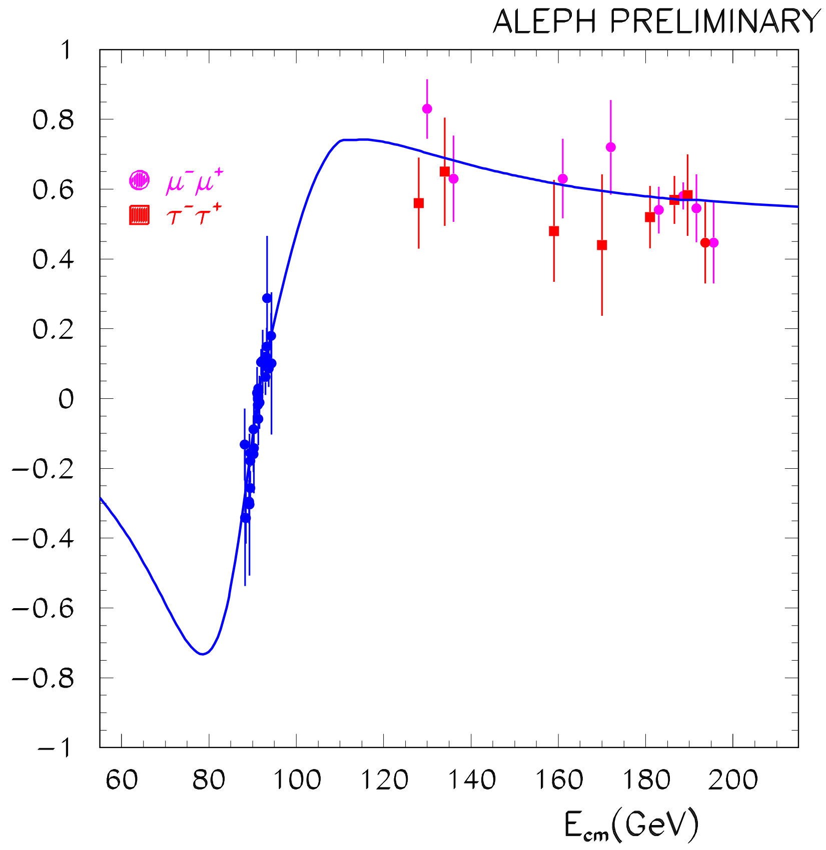
(Z/γ) + return to Z
(Z/γ)

(Z/γ) + return to Z
(Z/γ)



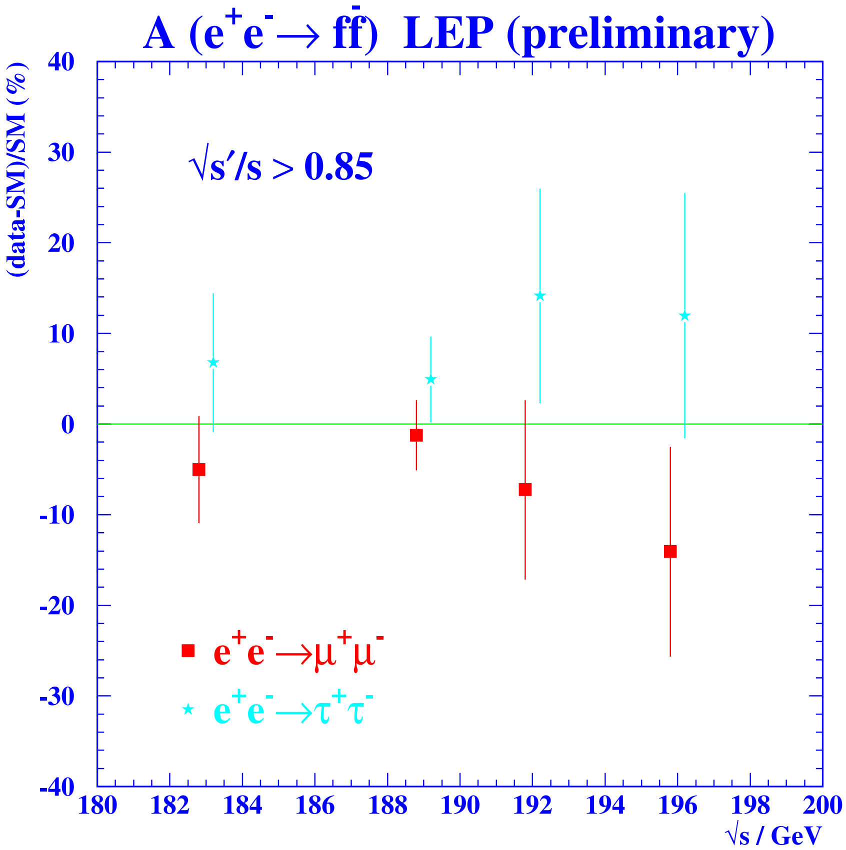
LEP combination
183 GeV $\leq \sqrt{s} \leq$ 196 GeV
(Comparison to SM)

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



$e^+e^- \longrightarrow \mu^+\mu^-$
$\tau^+\tau^-$

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



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

AT $\sqrt{s} = 189$ GeV

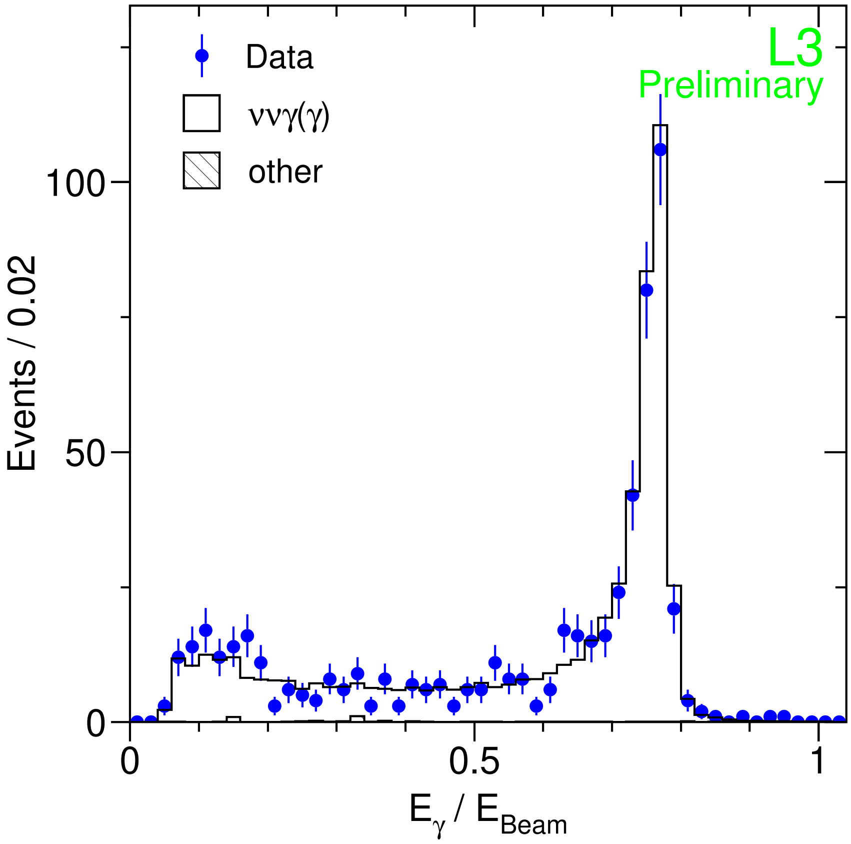
Measurement of $R_b = \sigma(e^+e^- \rightarrow b\bar{b})/\sigma(e^+e^- \rightarrow q\bar{q})$

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

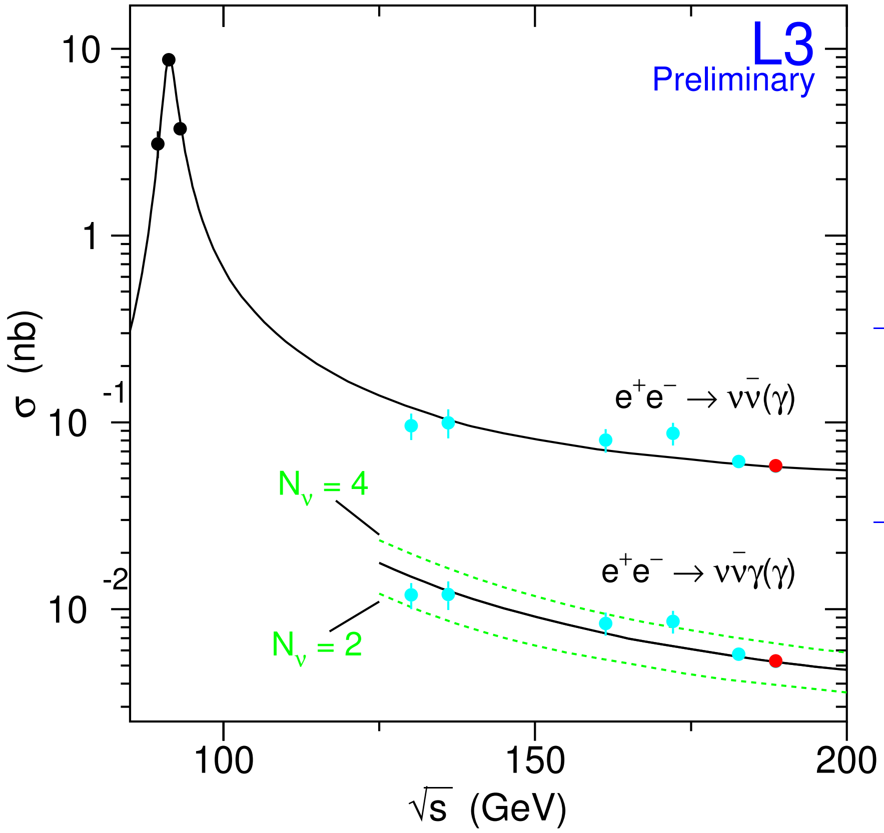
189 GeV	A^c_{FB}
OPAL	$0.57 \pm 0.18 \pm 0.09$
SM	0.65



$\sqrt{s} = 189$ GeV

$\approx$ 500 events per experiment

	$\sigma^{meas}/\sigma^{SM}$
ALEPH	0.984 ± 0.053
DELPHI	0.959 ± 0.069
L3	0.994 ± 0.045
OPAL	0.908 ± 0.054
LEP	0.965 ± 0.028



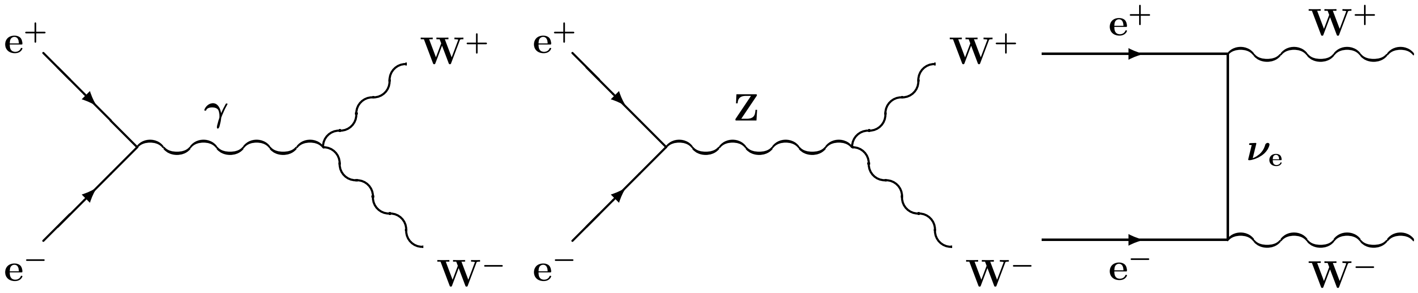
# of neutrino species

L3	3.05 ± 0.12
DELPHI	2.88 ± 0.19
LEP II	3.00 ± 0.10

LEP I

single γ	3.00 ± 0.08
lineshape	2.9835 ± 0.0083

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



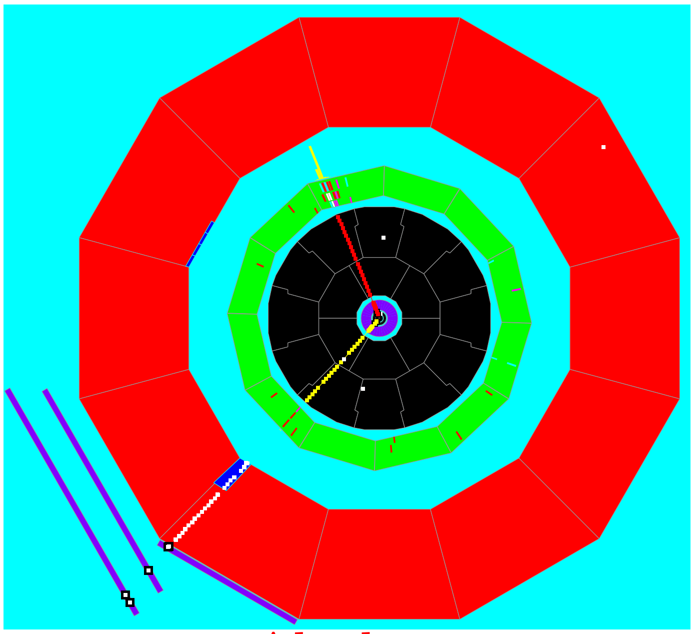
Nb of events / experiment: $161\ \text{GeV} \le \sqrt{s} \le 189\ \text{GeV} \approx 3500$
$192\ \text{GeV} \le \sqrt{s} \le 196\ \text{GeV} \approx 1000$

Three different event topologies:

- $W^+W^- \to \ell\nu\ell\nu,\ \ell = e, \mu, \tau \quad (\approx 10\%)$
  two energetic, acoplanar leptons
- $W^+W^- \to q\bar{q}\ell\nu \quad (\approx 44\%)$
  two jets plus isolated energetic lepton
  or jet for $W^+W^- \to q\bar{q}\tau\nu$
- $W^+W^- \to q\bar{q}q\bar{q} \quad (\approx 46\%)$
  four jets of similar energy
  severe background from QCD:
  $e^+e^- \to q\bar{q} +$ gluons (≈ 100 pb)
  neural networks, likelihood analyses

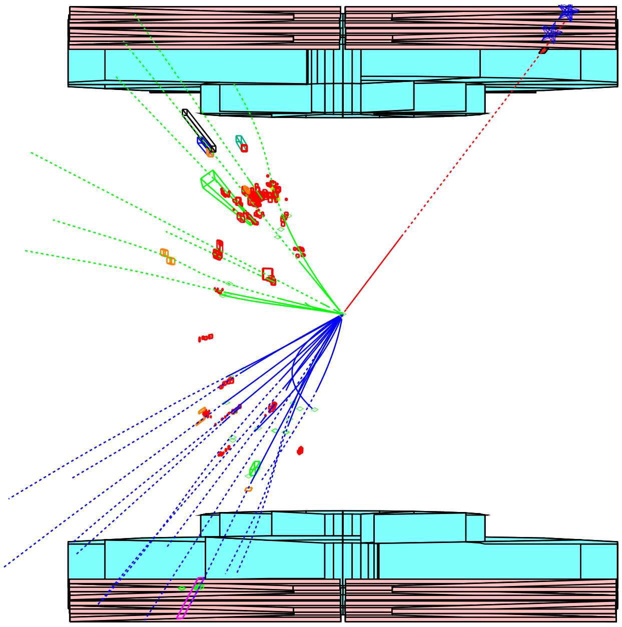
$e^+e^- \to W^+W^-$ candidates at $\sqrt{s} = 189$ GeV

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



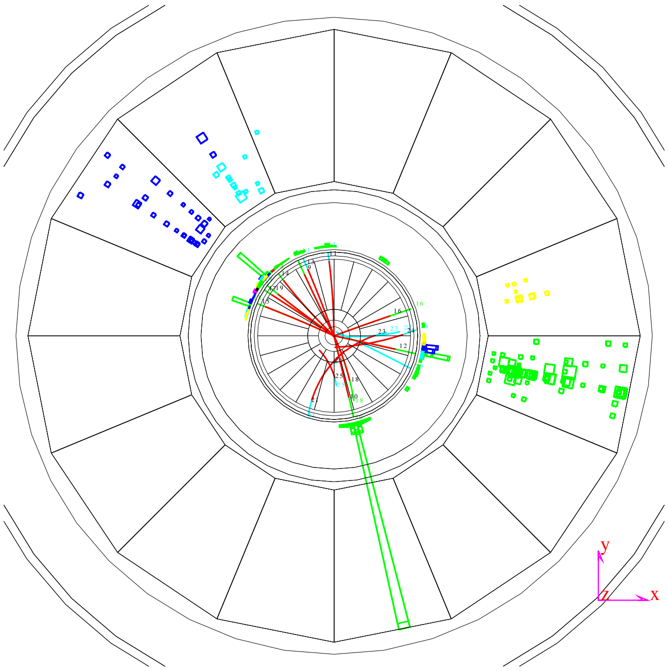
Aleph

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



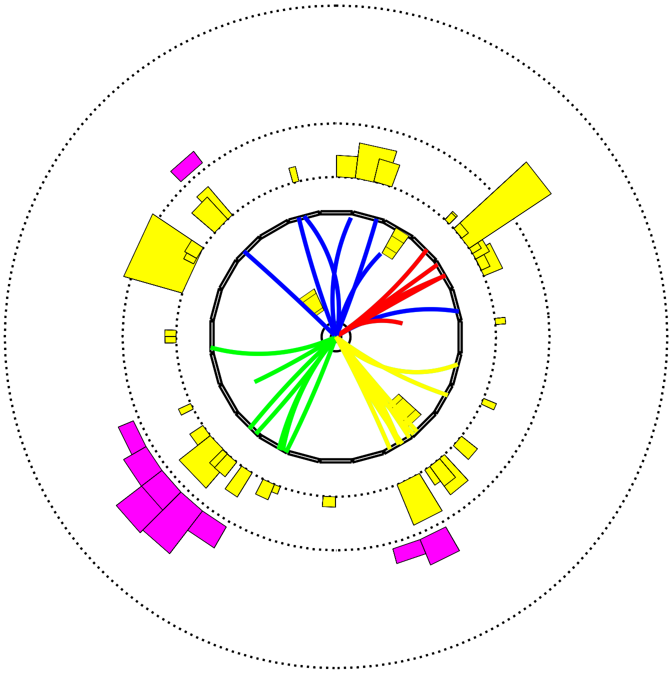
Delphi

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



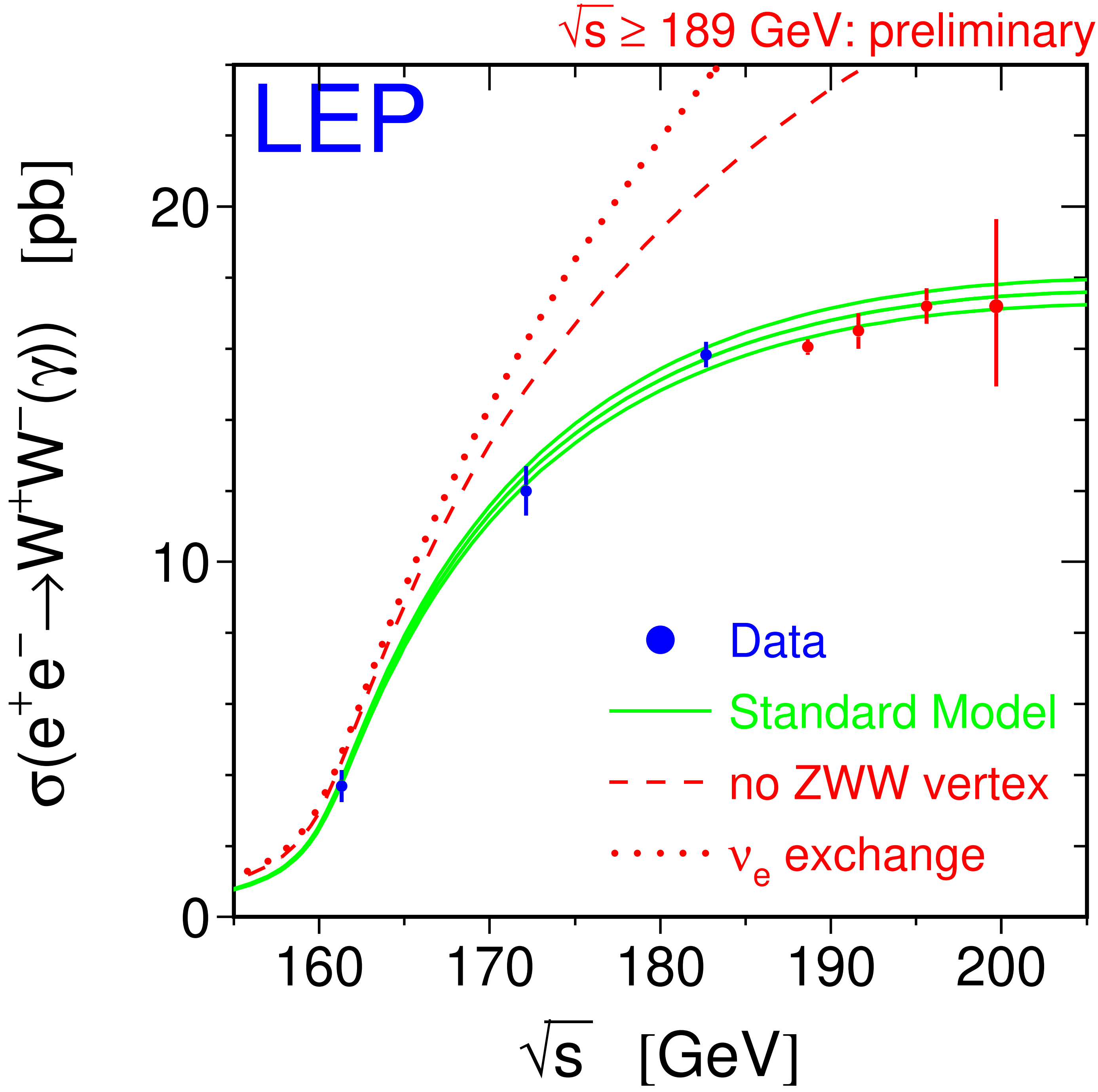
L3

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

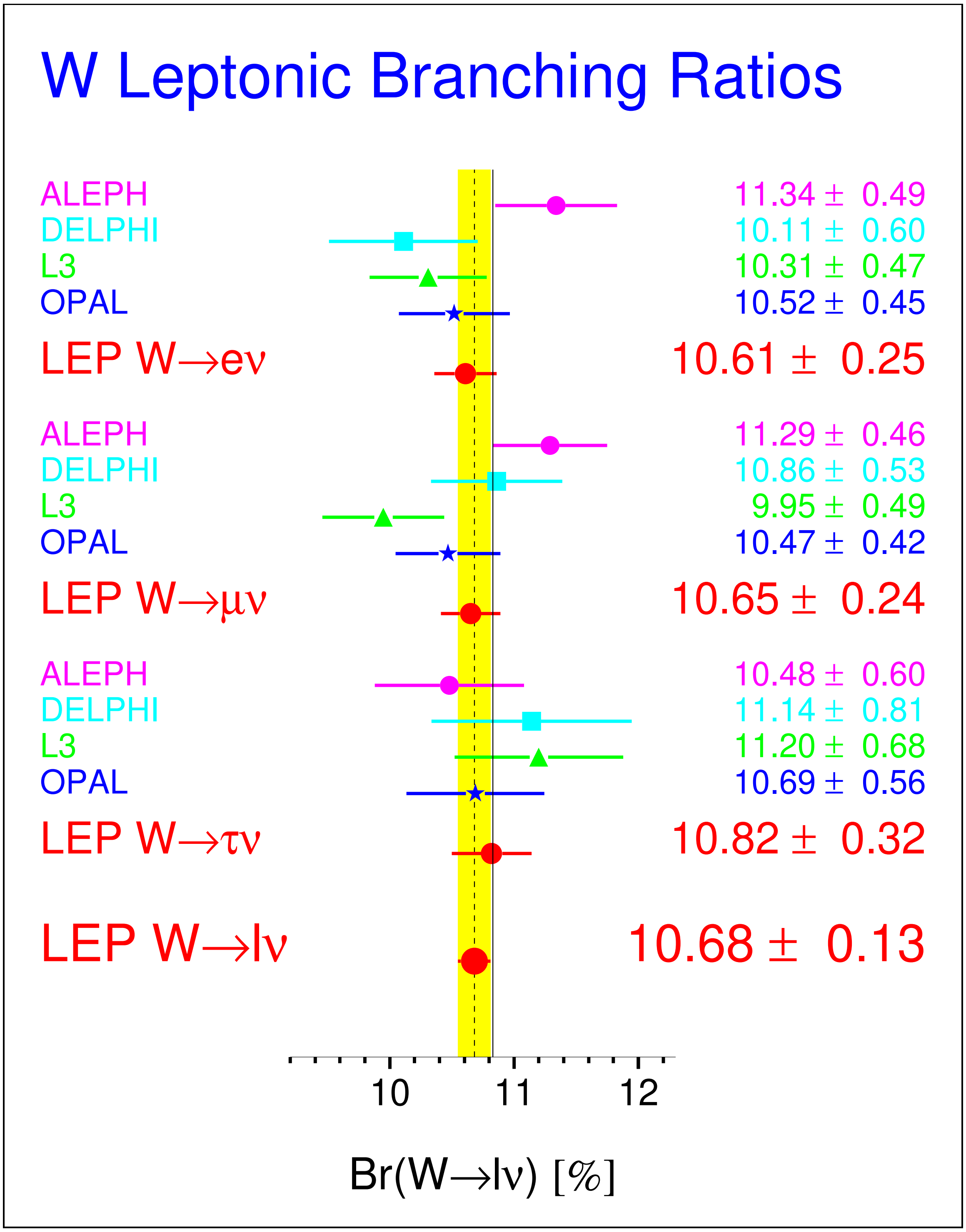


Opal

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



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



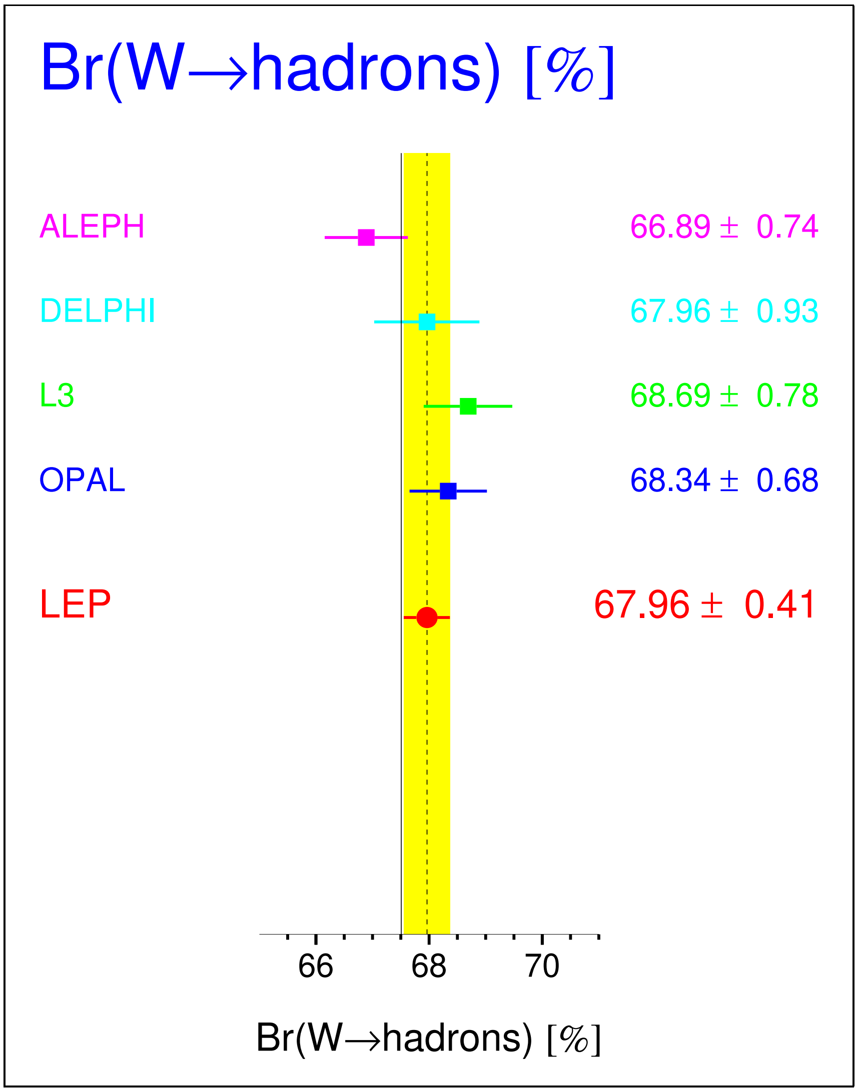
S.M. prediction for B.R. $W \to l\nu = 10.8$ %

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

$$g_\mu/g_e = 1.001 \pm 0.016$$

$$g_\tau/g_e = 1.010 \pm 0.022$$

$$g_\tau/g_\mu = 1.008 \pm 0.021$$



S.M prediction is 67.6 %

Provides the determination of $|V_{cs}|$

- **indirectly from hadronic branching ratio**

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

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

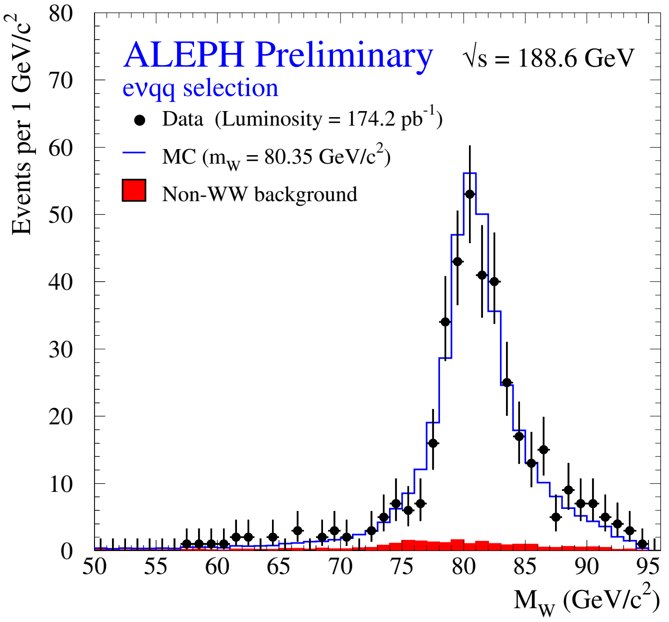
- **directly by charm tagging (189 GeV)**

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

Invariant W mass (after kinematic fit)

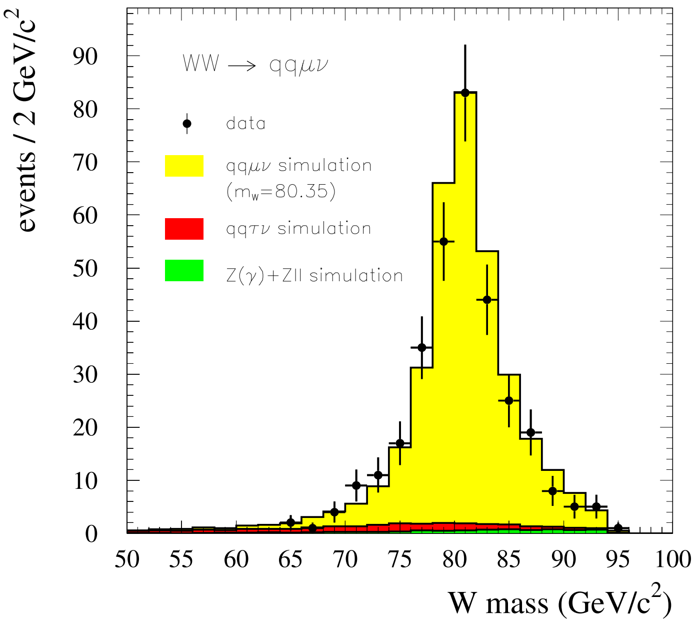
Data at $\sqrt{s} = 189$ GeV:

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

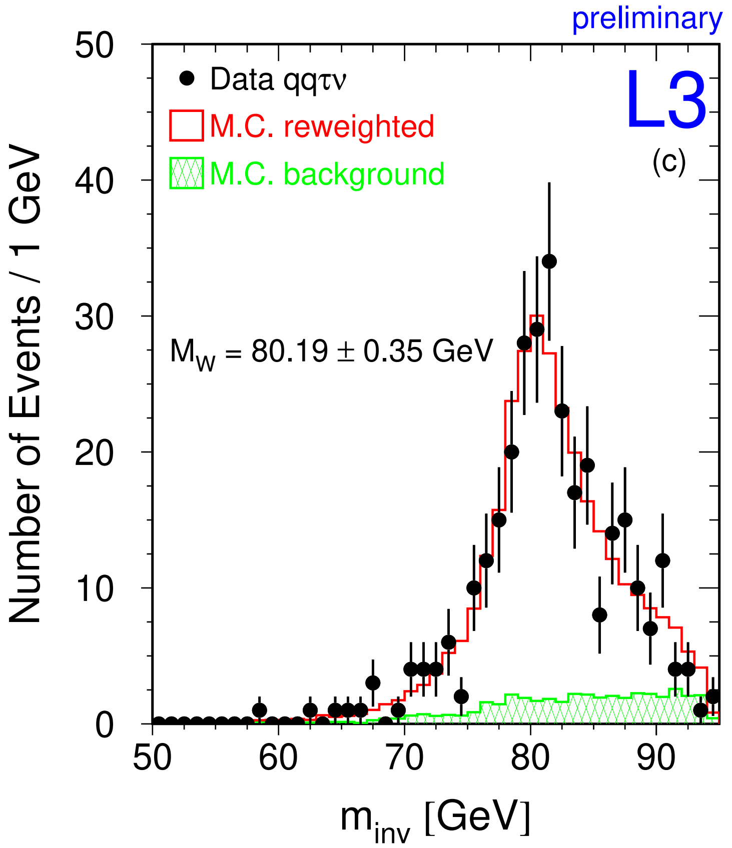


$\mathrm{WW} \to \mathrm{q\bar{q}}\, \mu\nu$

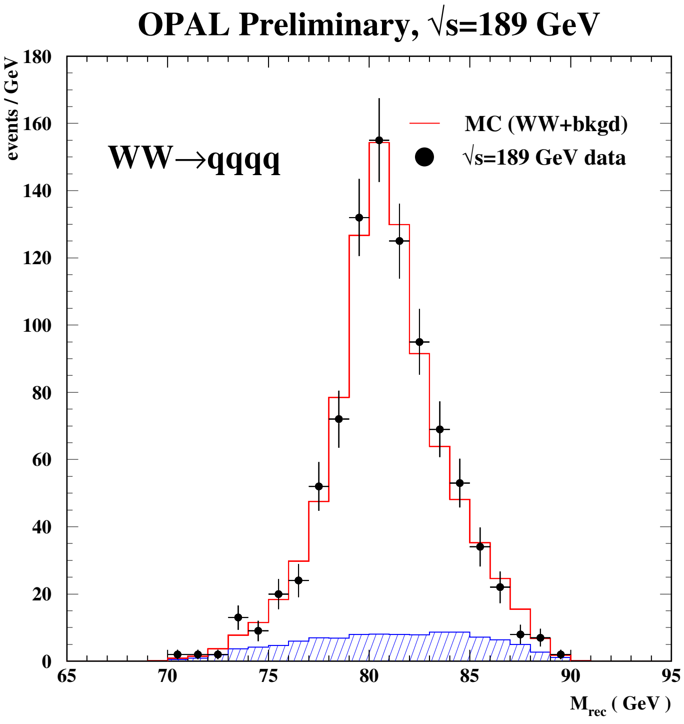
DELPHI

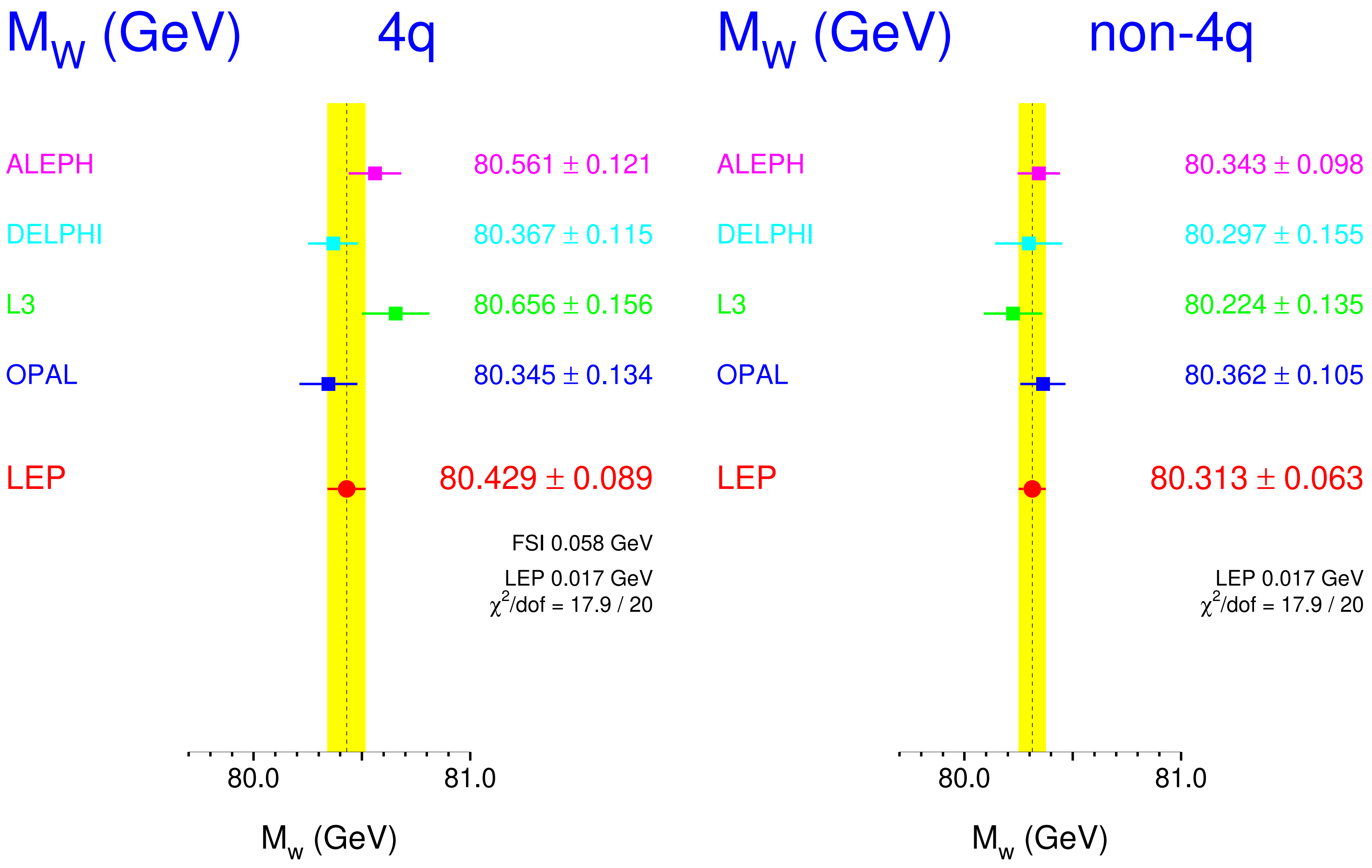


$\mathrm{WW} \to \mathrm{q\bar{q}}\, \tau\nu$



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





Combined LEP W mass measurement including 189 GeV data:

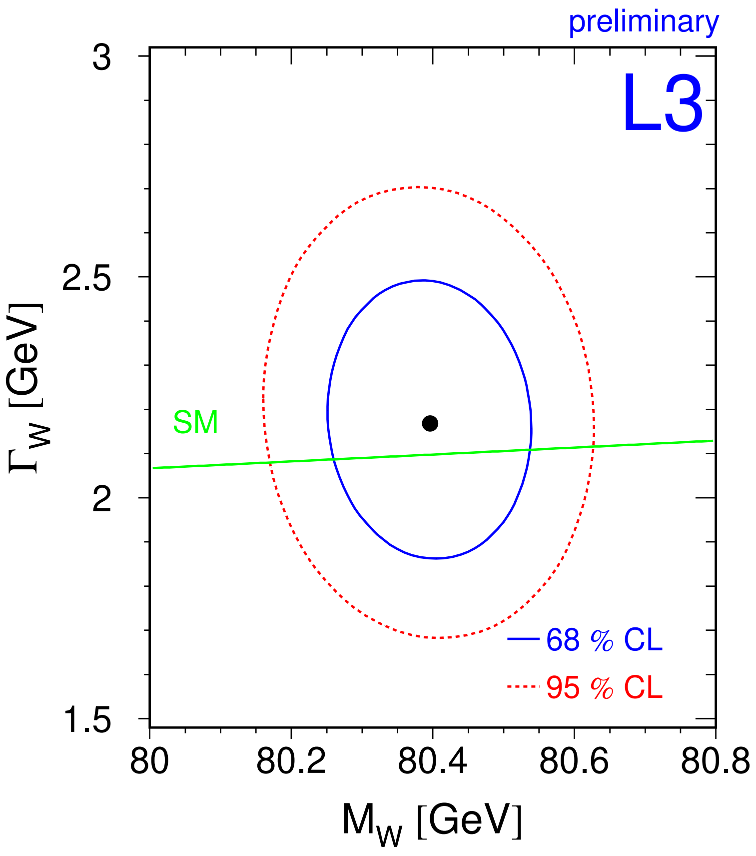
$$m_{\mathrm{W}} = 80.350 \pm 0.056 \ \mathrm{GeV}$$

- Direct determination

- LEP: fit to invariant mass distributions:

	Γ_W[GeV]
DELPHI*	2.48 ± 0.41
L3	2.12 ± 0.25
OPAL*	1.84 ± 0.38
LEP	2.12 ± 0.20
SM	2.08

* 183 GeV data

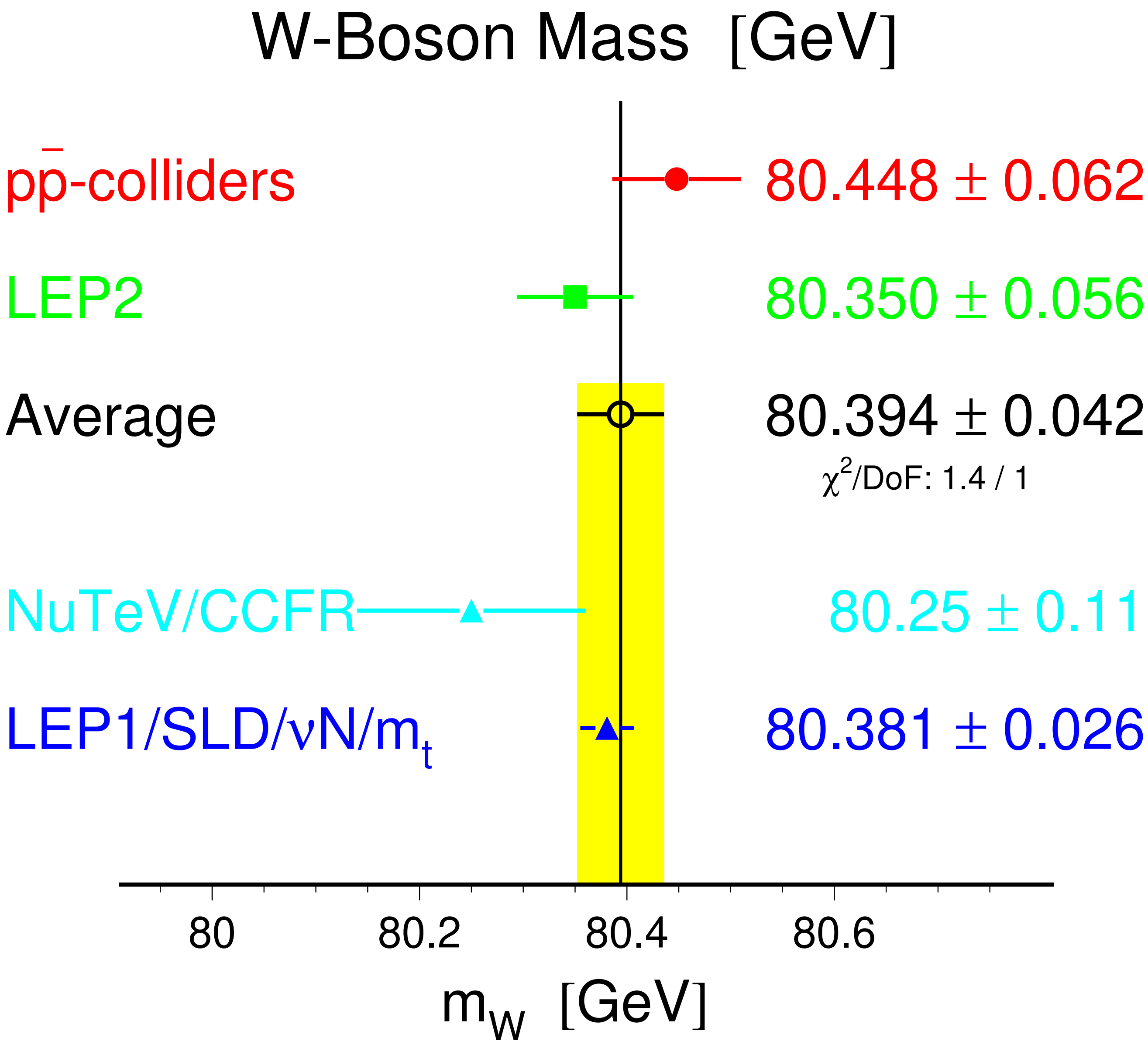


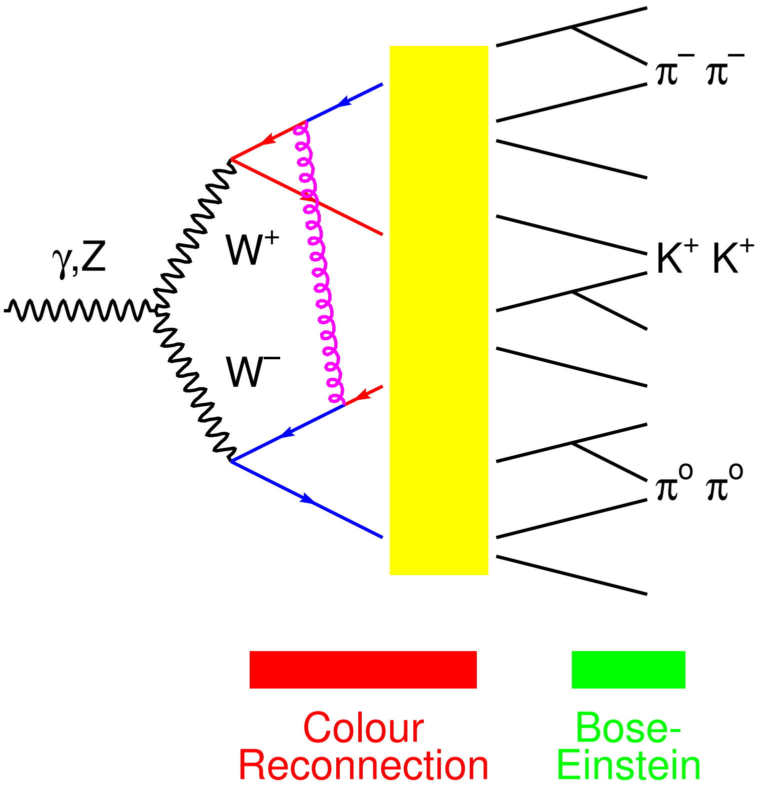
- Indirect measurement from

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

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

$$\mathrm{D0}: \Gamma_W = 2.107 \pm 0.054 \text{ GeV}$$


W-Boson Mass [GeV]
$p\bar{p}$-colliders
80.448 ± 0.062
LEP2
80.350 ± 0.056
Average
80.394 ± 0.042
χ^2/DoF: 1.4 / 1
NuTeV/CCFR
80.25 ± 0.11
LEP1/SLD/νN/m_t
80.381 ± 0.026
80
80.2
80.4
80.6
m_W [GeV]

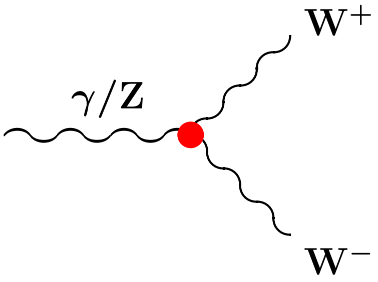


- Colour reconnection
  - Hadronisation scale $\mathcal{O}(1\ \mathrm{fm})$ much larger than W decay length $\mathcal{O}(0.1\ \mathrm{fm})$
  - Gluons carry momentum between quarks from different W bosons
  - Possible impact on reconstructed m_{W}
- Bose Einstein correlation of decay hadrons
  - possible momentum transfer between decays of different W bosons

Several studies underway

up to now - accounted for few 10 MeV by experiments

Triple gauge boson vertices γWW and ZWW



Description requires 14 parameters
By assuming: real couplings,
C-, P- and CP invariance,
charge of $W^\pm$ $(= \pm e)$
no change of tree-level boson propagators

$\Rightarrow$ 3 coupling parameters only:

$$g_1^Z,\ \kappa_\gamma,\ \lambda_\gamma \ \longrightarrow (1,1,0) \textit{ in S.M.}$$

static W properties:

$$\mu_W = \frac{e}{2m_W}(2 + \Delta\kappa_\gamma + \lambda_\gamma) \quad \text{magnetic dipole moment}$$

$$Q_W = -\frac{e}{m_W^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma) \quad \text{electric quadupole moment}$$

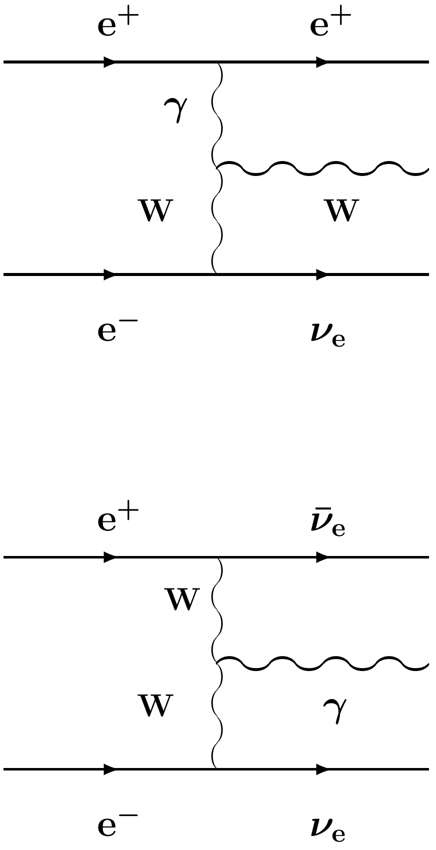
At LEP deviations from Standard Model would affect:

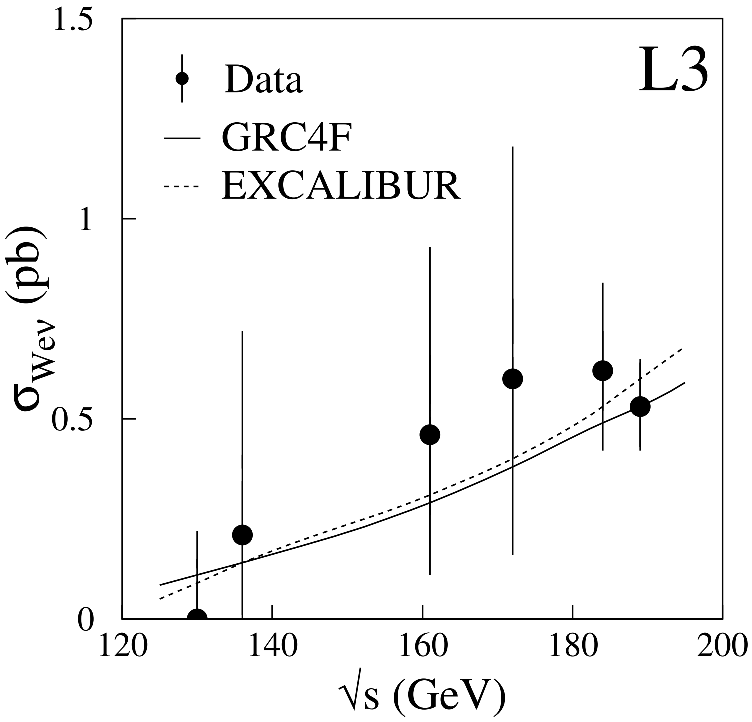
- $e^+e^- \rightarrow$ WW cross section
- angular distribution of W production
- W polarization (helicity mixture of W's)

Which are studied at LEP in:

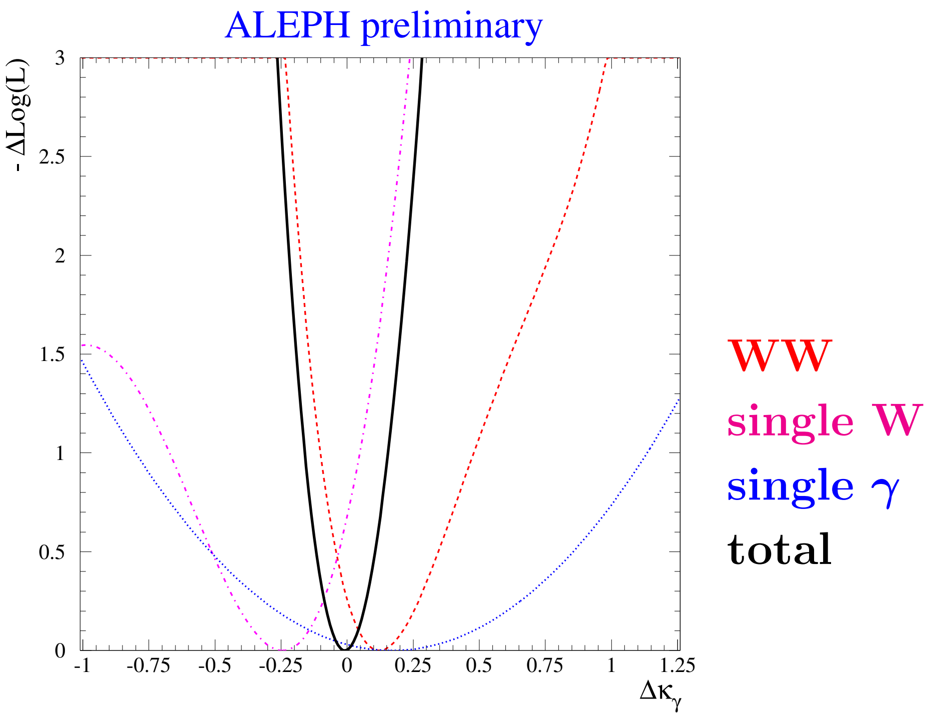
- WW production
- Single W production
- Single photon production

- **More information on γWW vertex from single W events:**

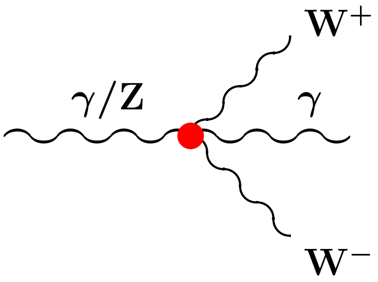




- **combination of WW, single W and single γ**



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



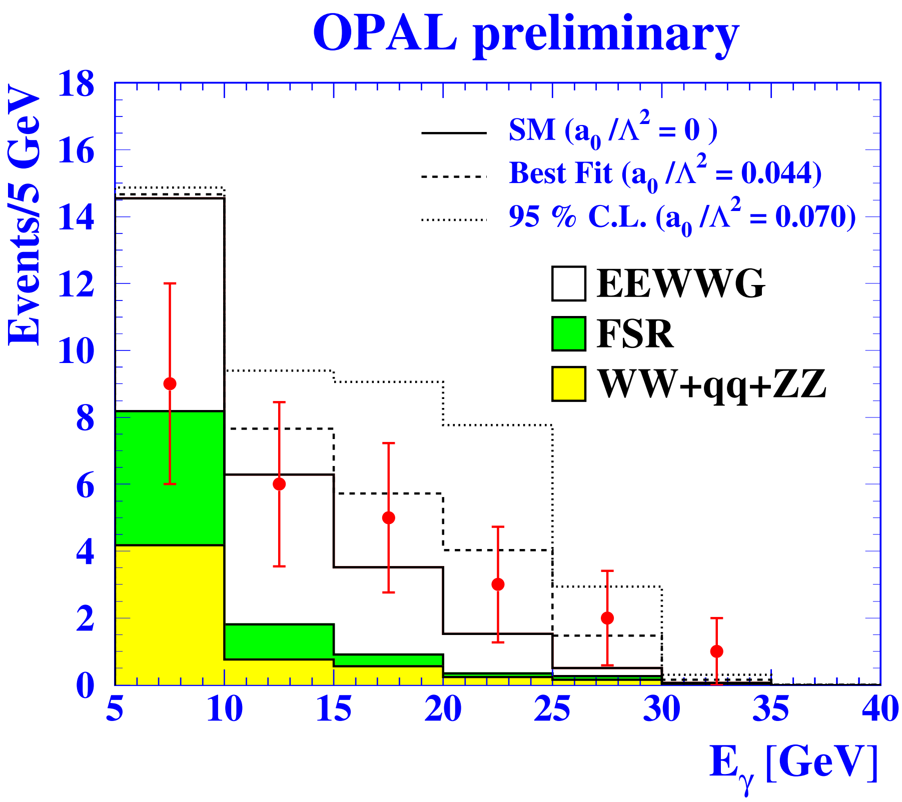
Genuine quartic gauge boson couplings:

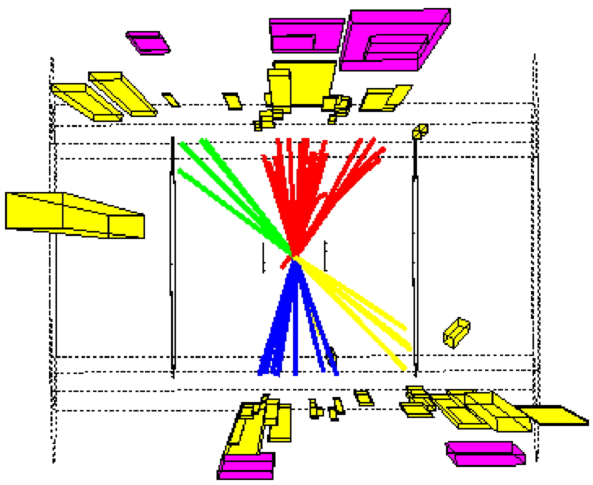
6 dimensional operators

$a_0/\Lambda^2,\ a_c/\Lambda^2,\ a_n/\Lambda^2$

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

$-0.065\ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < +0.065\ \mathrm{GeV}^{-2}$ $\quad WW\gamma\gamma$

$-0.13\ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < +0.17\ \mathrm{GeV}^{-2}$ $\quad WW\gamma\gamma$

$-0.61\ \mathrm{GeV}^{-2} < a_n/\Lambda^2 < +0.57\ \mathrm{GeV}^{-2}$ $\quad WWZ\gamma$

(More stringent indirect limits exist on a_0 and a_c)

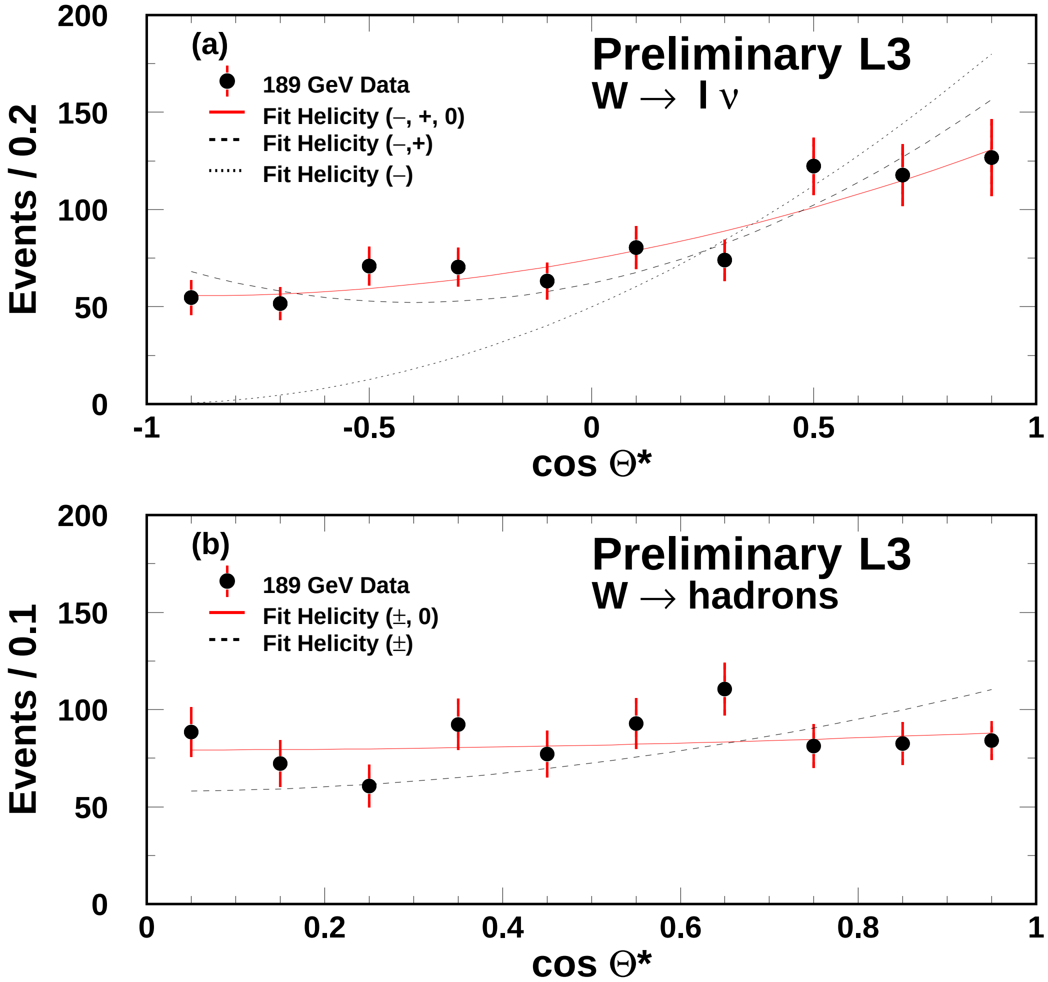
Massive gauge bosons have three polarization states

- 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

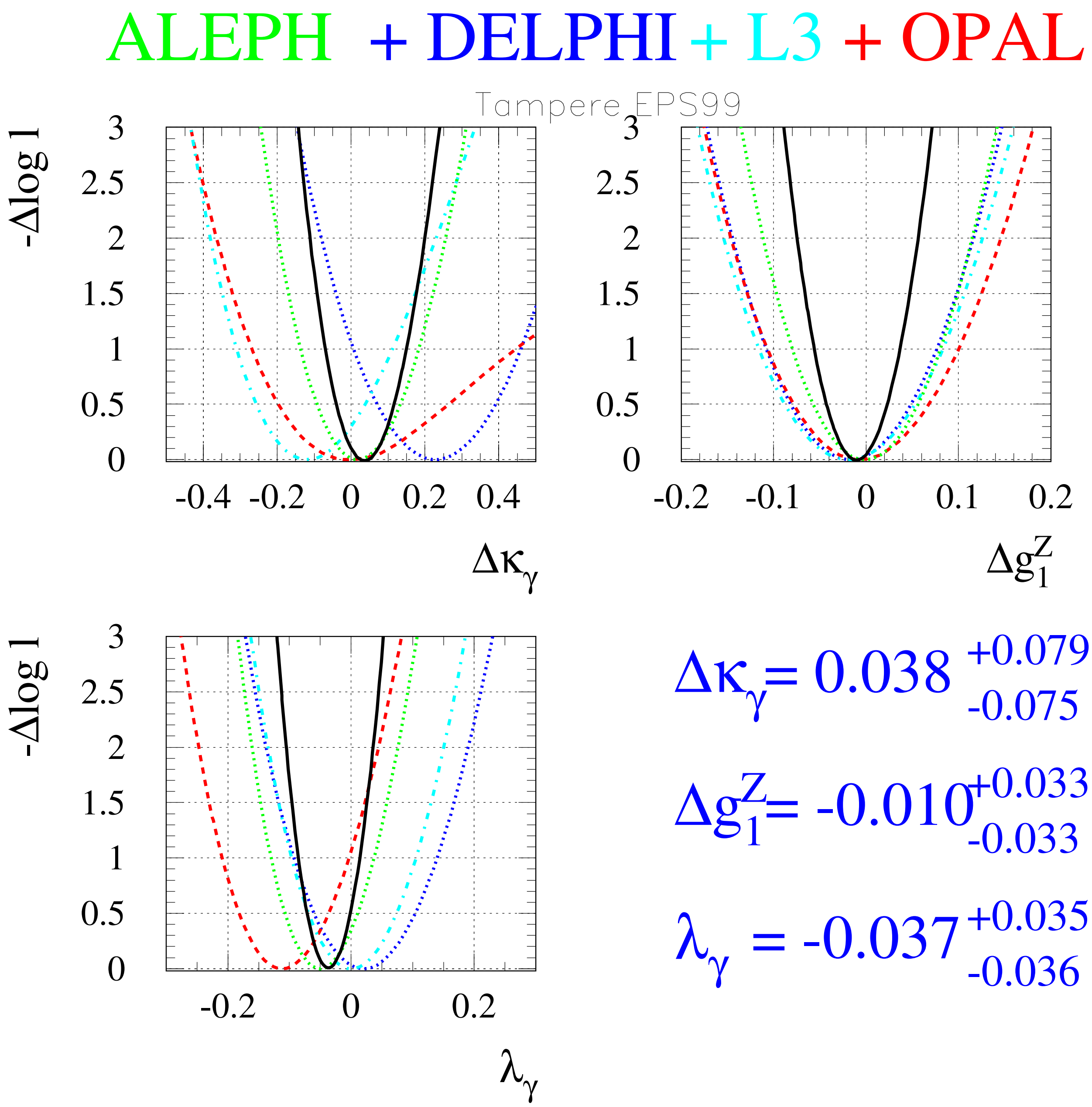


Fraction of longitudinally polarized W bosons:

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

First unambiguous observation of longitudinally polarized W's

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



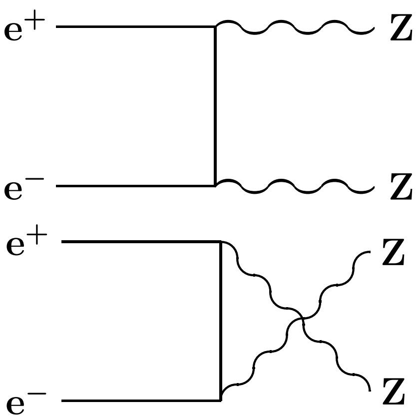
$$\Delta\kappa_\gamma = 0.038\,^{+0.079}_{-0.075}$$

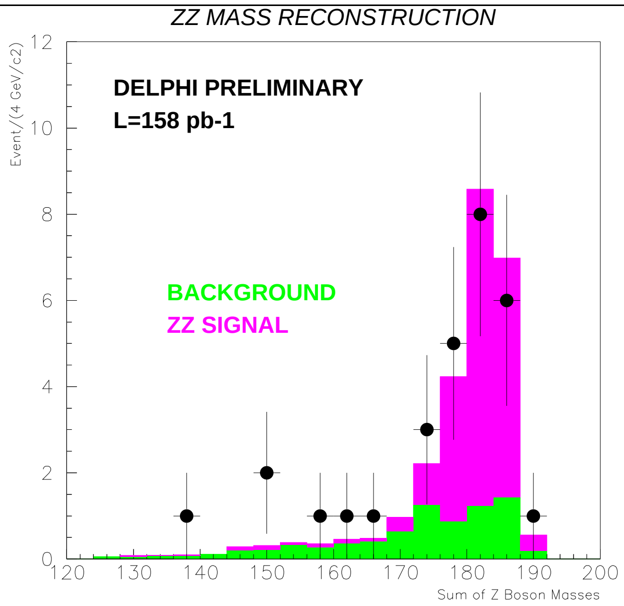
$$\Delta g_1^Z = -0.010\,^{+0.033}_{-0.033}$$

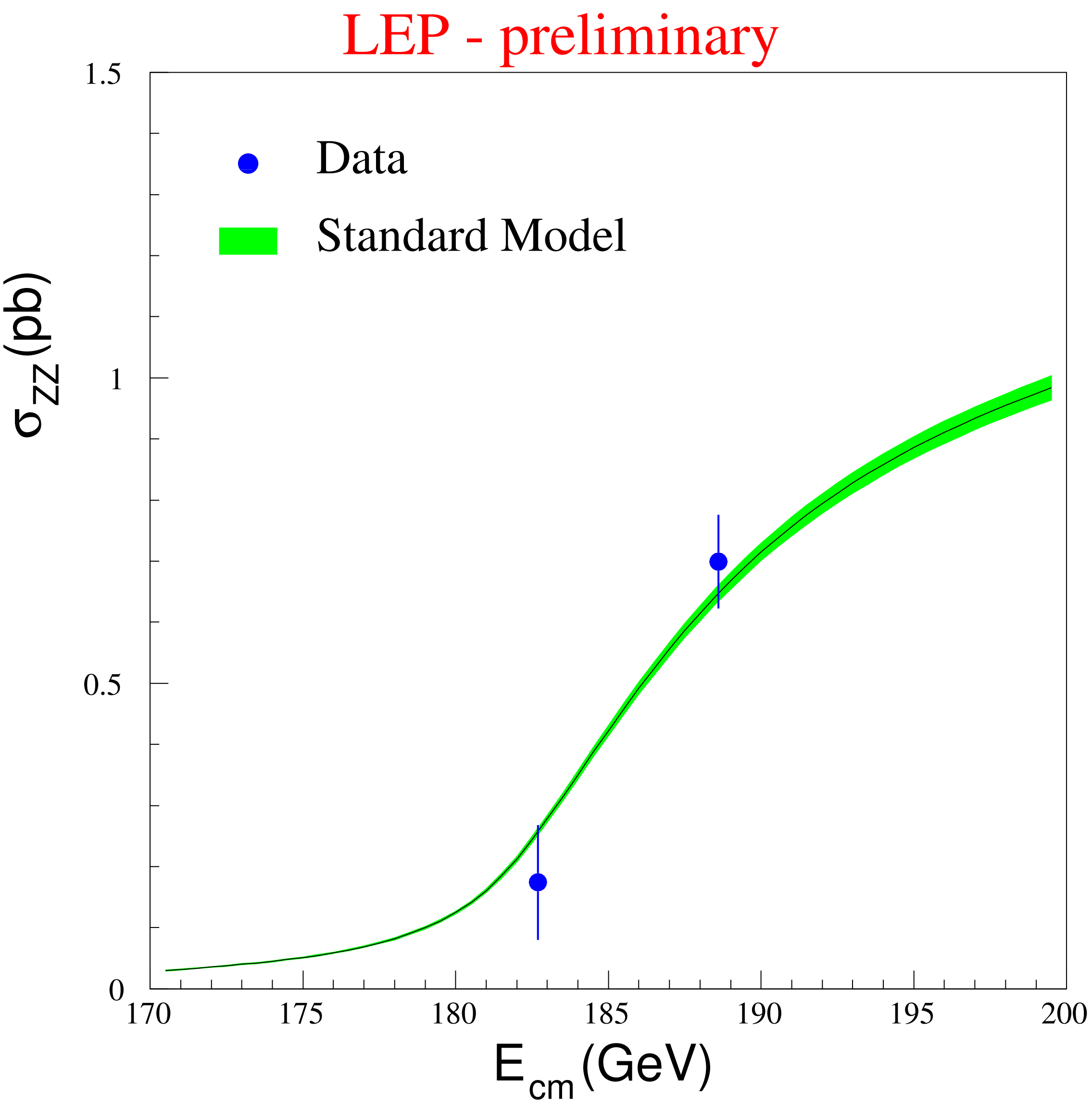
$$\lambda_\gamma = -0.037\,^{+0.035}_{-0.036}$$

No deviation from S.M

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



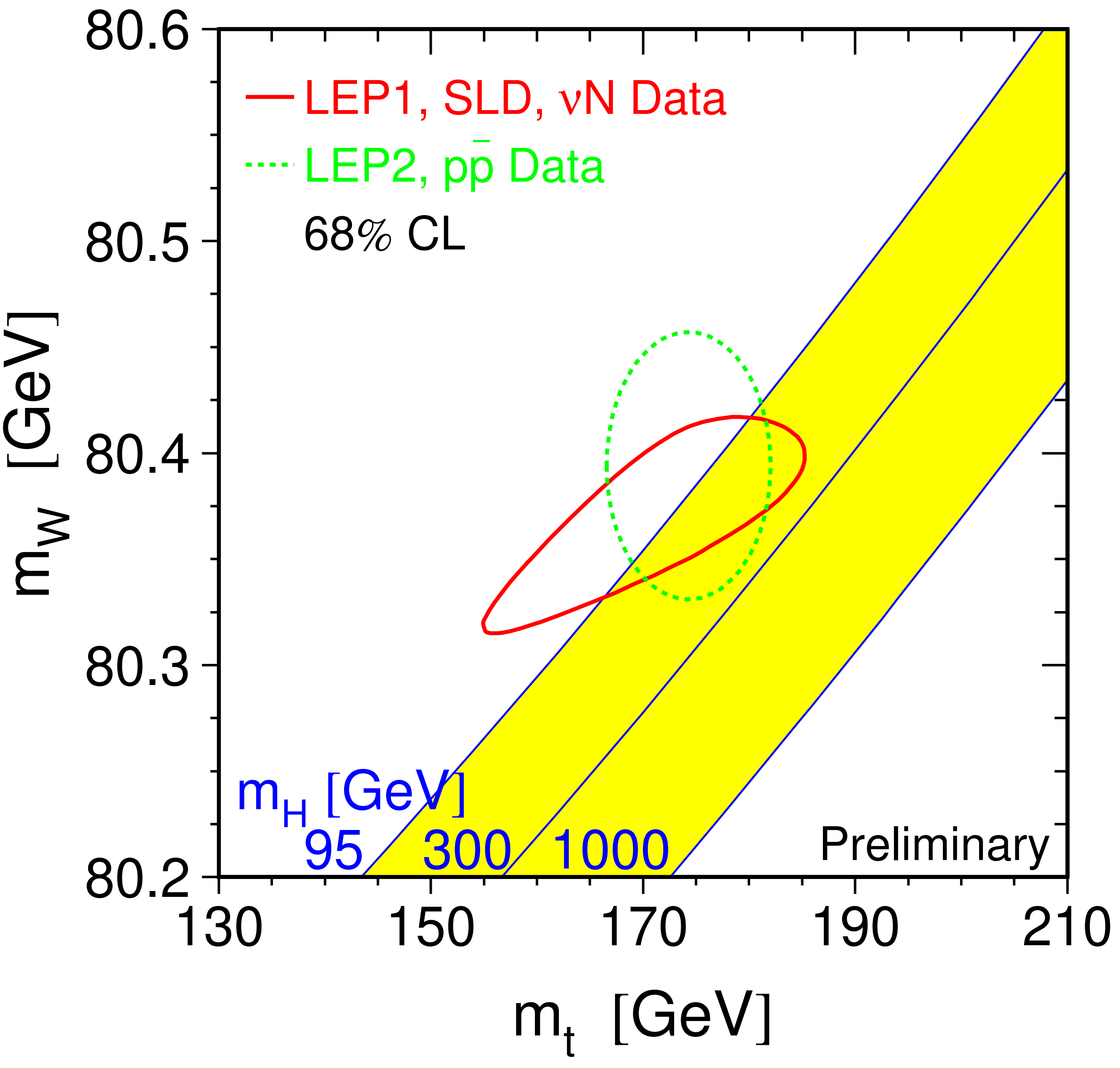




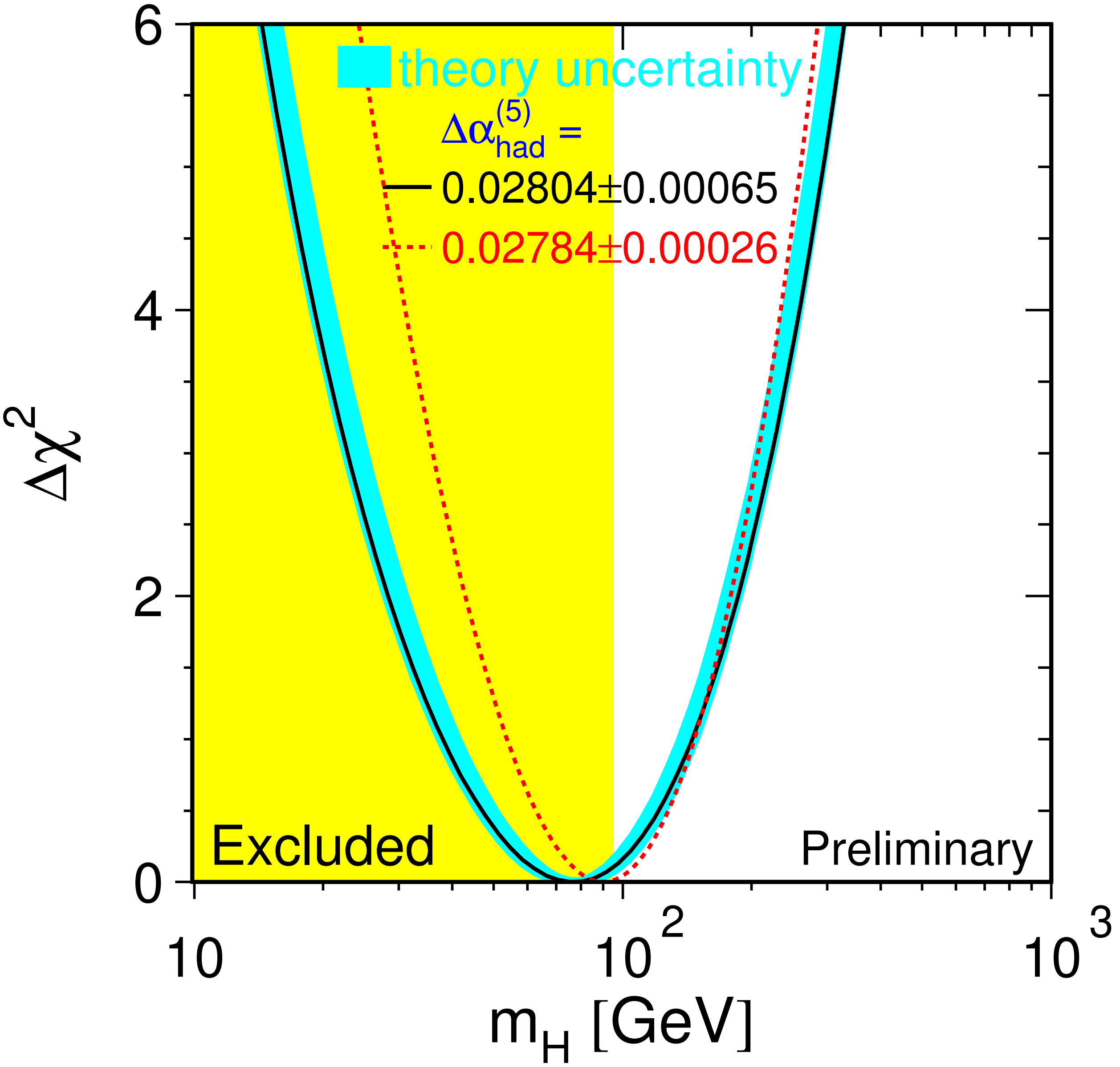
Combined LEP cross sections

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

	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}	$167.3^{+10.5}_{-10}$	172.9 ± 4.7	173.2 ± 4.6
m_{H} [GeV]	134^{+268}_{-81}	55^{+84}_{-27}	81^{+77}_{-42}	77^{+69}_{-39}
$\log(m_{\mathrm{H}}/\mathrm{GeV})$	$2.13^{+0.48}_{-0.40}$	$1.74^{+0.40}_{-0.30}$	$1.91^{+0.29}_{-0.32}$	$1.88^{+0.28}_{-0.30}$
α_{s}	0.120 ± 0.003	0.1183 ± 0.0026	0.1185 ± 0.0026	0.1184 ± 0.0026
χ^2/d.o.f.	10.5/9	21/12	21.5/13	22.9/15
$\sin^2\overline{\theta}_{\mathrm{W}}$	0.23184 ± 0.00021	0.23151 ± 0.00017	0.23152 ± 0.00017	0.23150 ± 0.00016
$\sin^2\theta_{\mathrm{W}}$	0.22372 ± 0.0006	0.22325 ± 0.00067	0.223 ± 0.0005	0.22289 ± 0.00042
m_{W} [GeV]	80.342 ± 0.032	80.366 ± 0.035	80.381 ± 0.026	80.385 ± 0.022



- **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:

$$m_{\mathrm{H}} < 215\ \mathrm{GeV} \qquad 95\%\ \mathrm{CL}$$

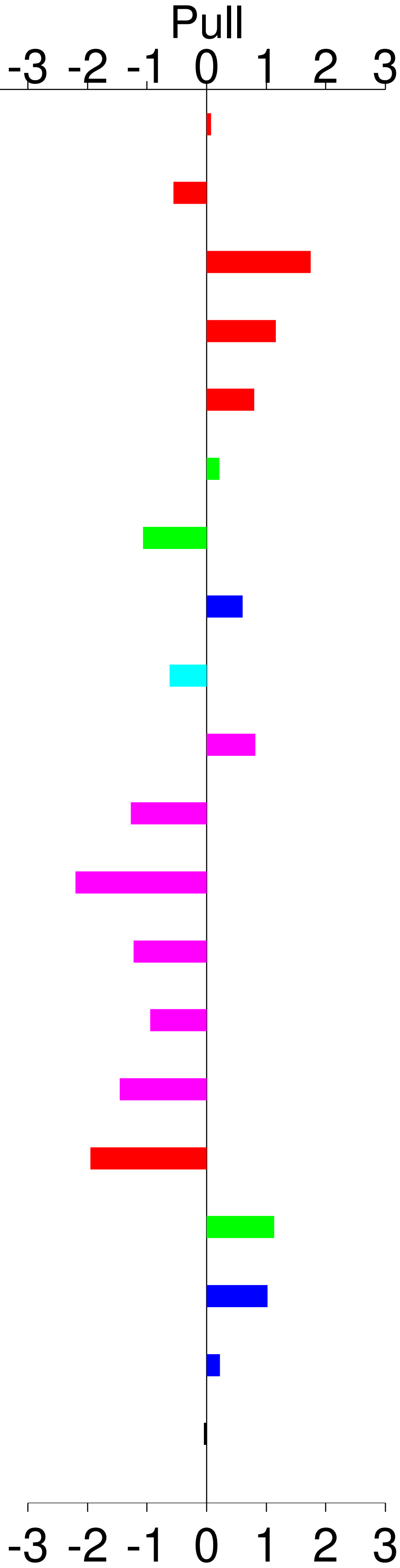
Search for Higgs production at LEP:

$$m_{\mathrm{H}} > 102.6\ \mathrm{GeV} \qquad 95\%\ \mathrm{CL}$$

(Peliminary combination LEPC september '99)

Lepton-Photon 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05



- LEP is working very well
- data taking at $\sqrt{s} = 200$ GeV ongoing
- hope take data at $\sqrt{s} = 202$ GeV next month
- Rapid progress in W physics

$$m_{\mathrm{W}} = 80.350 \pm 0.056 \text{ GeV } (\textit{LEP Preliminary})$$

will be improved next year (goal is 30 MeV precision)

- WWγ and WWZ couplings measured at few per cent

The Standard Model still works

The Higgs boson is light