W Physics at LEP

Arno Straessner
CERN

Les Rencontres de Physique de la Valée d'Aoste
La Thuile
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Outline

- Introduction
- W Pair Production
- W Gauge Couplings
- W Mass Measurement
- Final State Interactions
- Conclusion

ECFA WORKSHOP ON LEP 200

Aachen, Federal Republic of Germany
29 September – 1 October 1986

LEP200 WORKSHOP SUMMARY

D.H. Perkins,

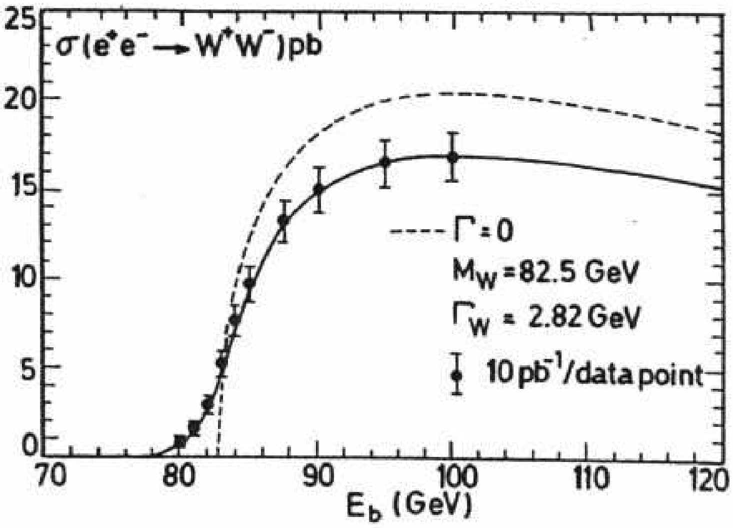
University of Oxford, Nuclear Physics Laboratory, Oxford.

4. W PAIR PRODUCTION AND THE W MASS

For an integrated luminosity of $500 pb^{-1}$ we expect, for $\sigma = \sigma_{max}$, 5–10,000 events for each of the 4 LEP experiments.

This constitutes the "final check" of the EWI theory via:

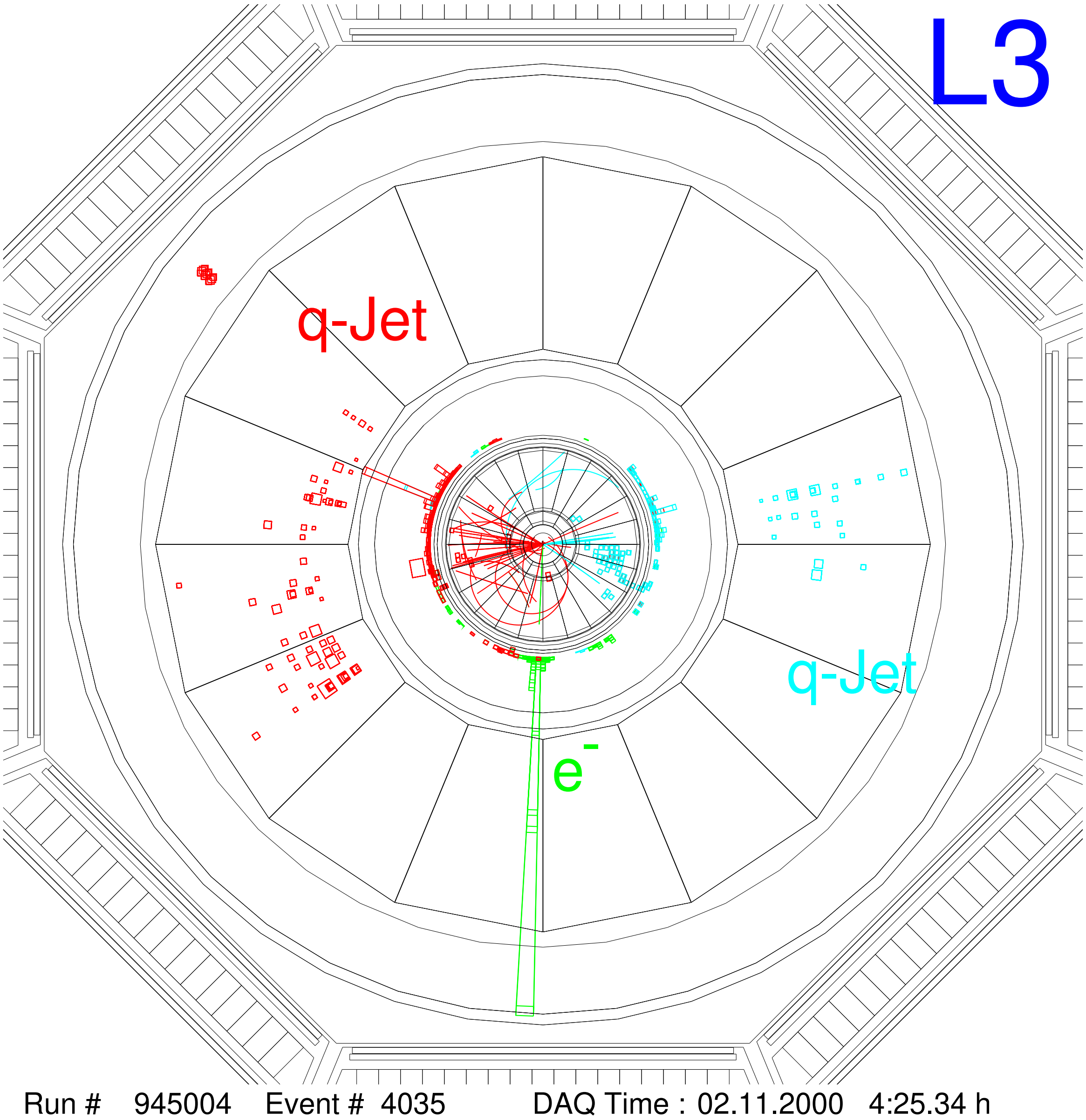
- $e^+e^- \to W^+W^-$; checking the gauge vertices.
- precise $M_{W^\pm}$; radiative corrections sensitive to M_H etc.
- measurement of σ_L and σ_T for the W from production angular distribution, detection of anomalies in electric and magnetic moments.
- study of $W \to \ell\nu$, $Q\bar{Q}$; precise measurements of KM matrix element, and of lepton universality.



ΔM_W=60MeV

- collected luminosity: $\mathcal{L} \approx 700\ \mathrm{pb}^{-1}$ per experiment

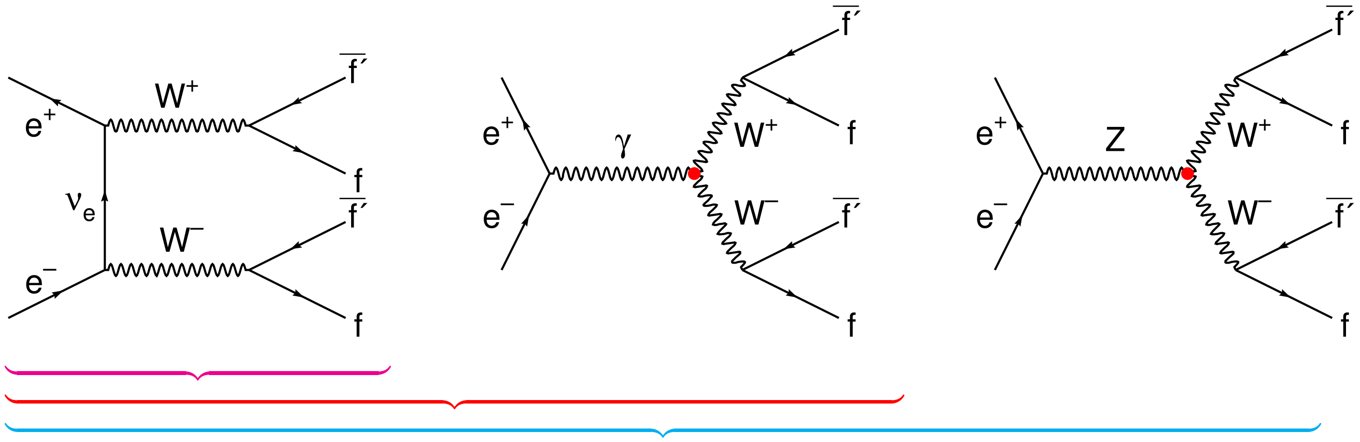
$$\rightarrow 4 \times 10000 \text{ WW events at LEP}$$

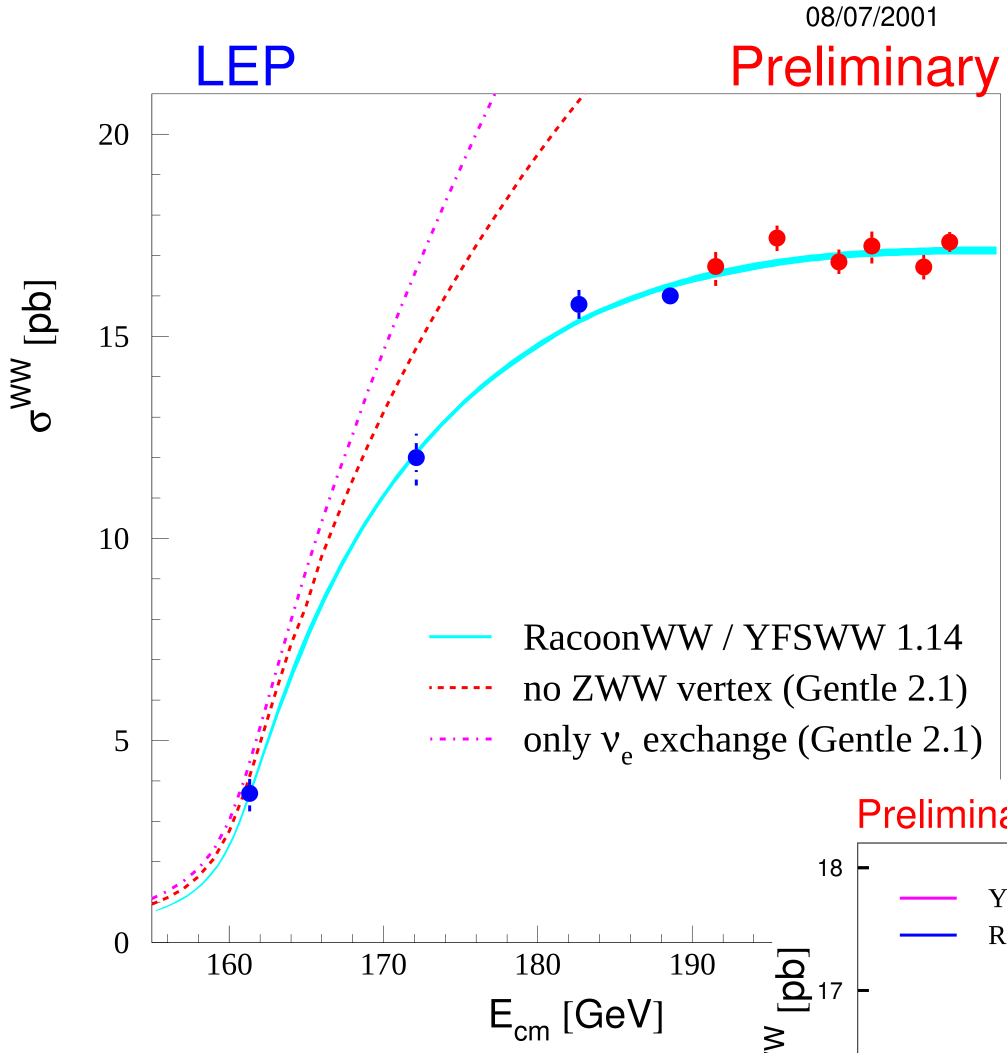


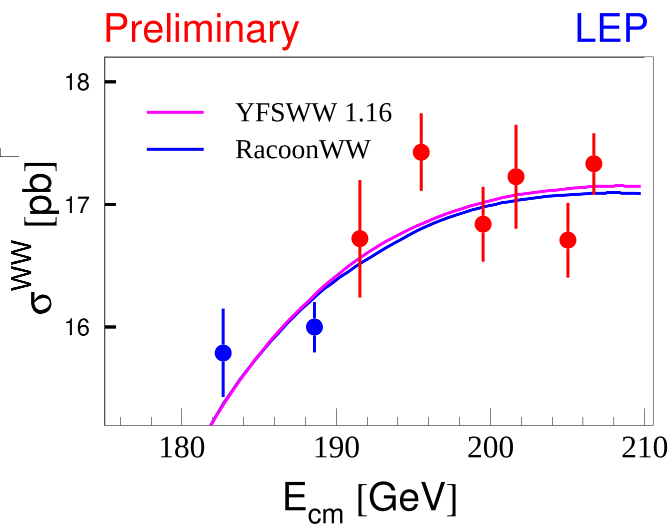
- 4-fermion final states:

$$\mathrm{WW} \rightarrow \begin{cases} \mathrm{qq}\ell\nu & 44\% \\ \mathrm{qqqq} & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$

W Pair Cross Section

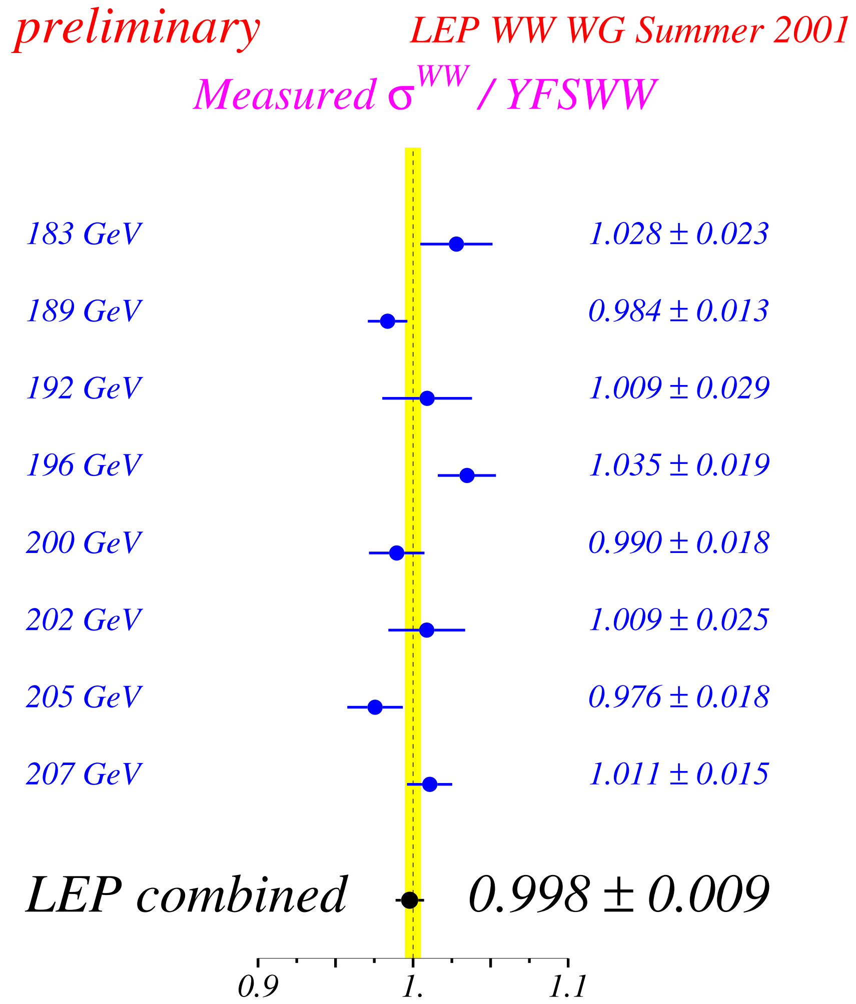






- clear evidence of $SU(2) \times U(1)$ gauge structure

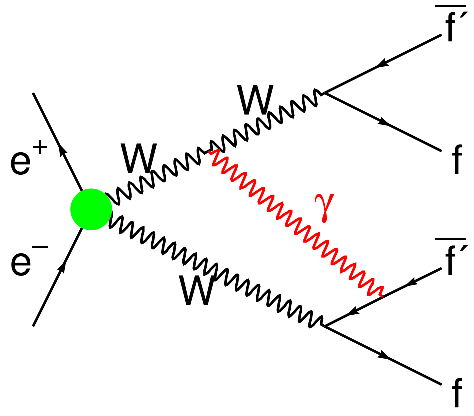
Measurement vs. Theory



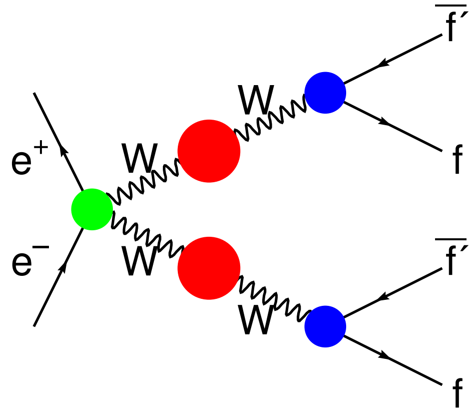
$\sigma_{\text{WW}}/\sigma_{\text{theo}} = 0.998 \pm 0.006$ (stat.) $\pm$ 0.007 (syst.)

- challenge for theorists $\longrightarrow$ radiative corrections

$\mathcal{O}(\alpha)$ corrections



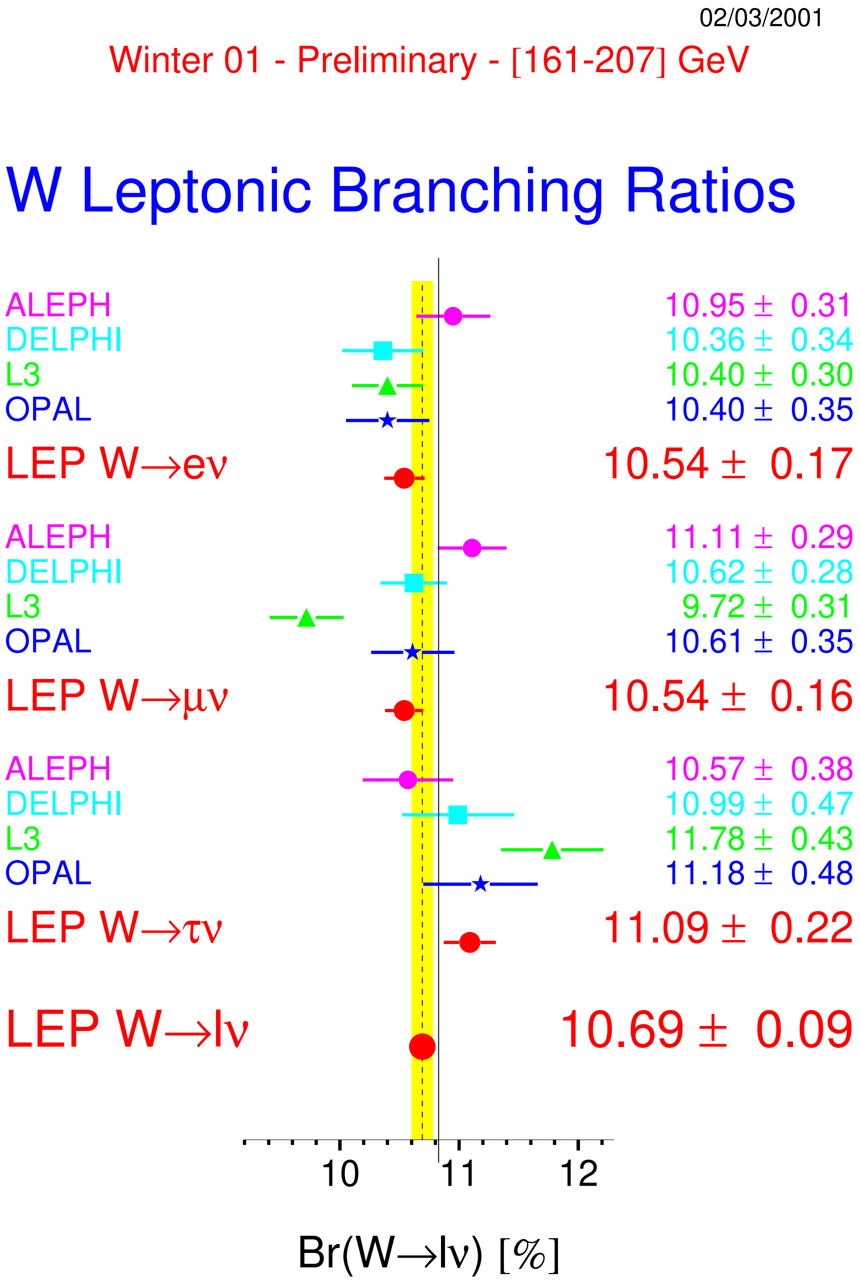
W pole approximation



$\longrightarrow$ RacoonWW (DPA and full $\mathcal{O}(\alpha)$)

$\longrightarrow$ KORALW+YFSWW (LPA and non-LL $\mathcal{O}(\alpha)$ + exponentation)

- theory uncertainty on σ_{WW} went down to 0.5%



- ratio of ratios:

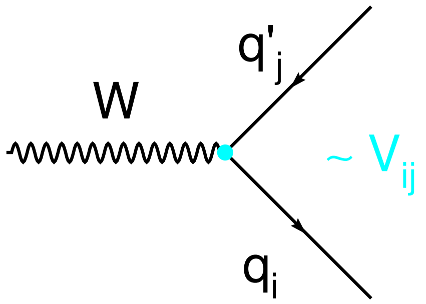
$$BR(W \to \mu\nu)/BR(W \to e\nu) = 1.000 \pm 0.021$$
$$BR(W \to \tau\nu)/BR(W \to e\nu) = 1.052 \pm 0.029$$
$$BR(W \to \tau\nu)/BR(W \to \mu\nu) = 1.052 \pm 0.028$$

- test of lepton universality at 3% accuracy
- W decay into hadrons:

$$BR(W \to q\overline{q'}) = 67.92 \pm 0.27\ \%$$

- Standard Model: $BR(W \to q\overline{q'}) = 67.51\%$

- branching ratio into hadrons

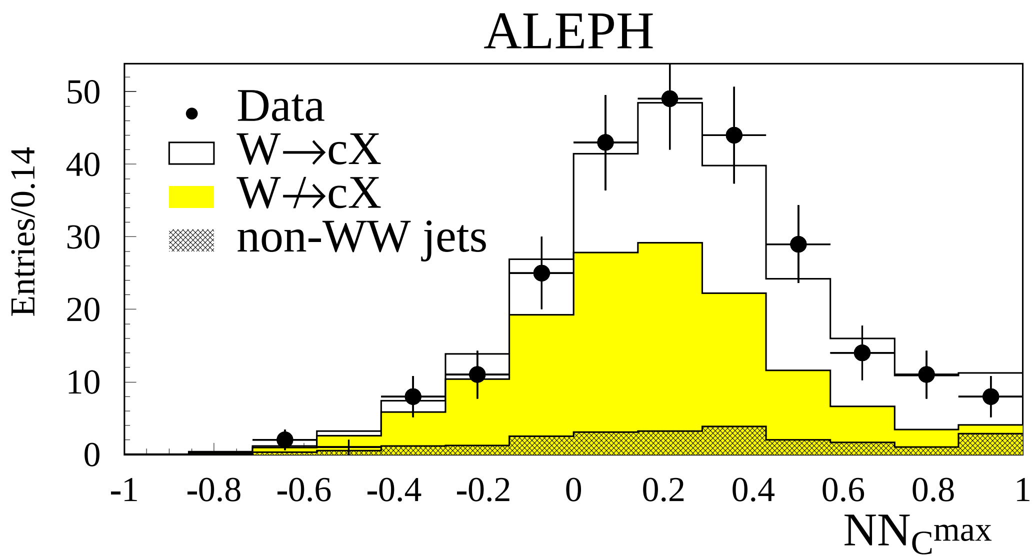


$$BR(W \longrightarrow q\overline{q'})/[1 - BR(W \longrightarrow q\overline{q'})] = (1 - \frac{\alpha_s}{\pi})\Sigma_{i,j}|V_{i,j}|^2$$

$\longrightarrow$ least know CKM matrix element

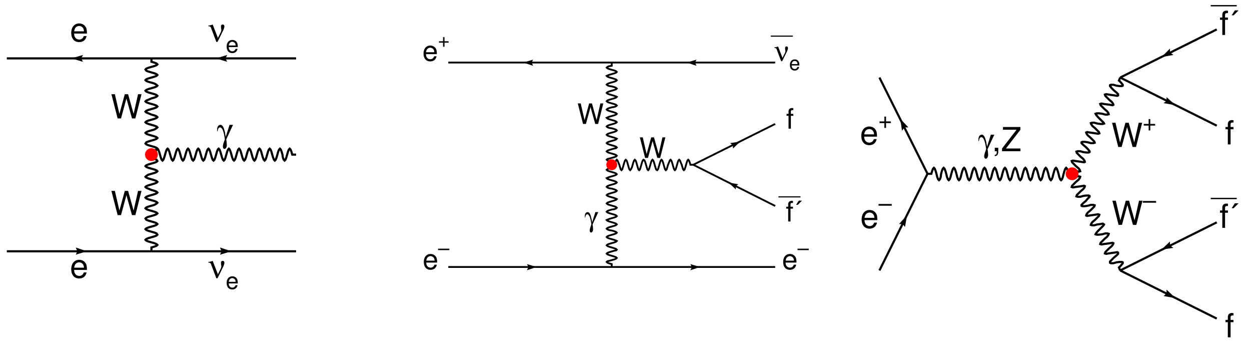
$$|V_{cs}| = 0.996 \pm 0.013$$

- compare direct measurement by tagging the c-quark in W decays



- e.g. Aleph: $|V_{cs}| = 1.00 \pm 0.11\ (\text{stat.}) \pm 0.07\ (\text{syst.})$

- couplings accessible in single-γ, single-W and W-pair production:



- effective Lagrangian, the C and P conserving part (V=Z,γ):

$$\frac{i\mathcal{L}_{\mathrm{eff}}}{g_{\mathrm{VWW}}} = g_1^{\mathrm{V}} V^{\mu}(W^{-}_{\mu\nu}W^{+\,\nu}) + \kappa_{\mathrm{V}} W^{+}_{\mu}W^{-}_{\nu}V^{\mu\nu} + \frac{\lambda_{\mathrm{V}}}{M_{\mathrm{W}}^2} V^{\mu\nu}W^{+}_{\nu}W^{-}_{\mu}$$

- electric charge $q_{\mathrm{W}} = e g_1^{\gamma}$
- magnetic dipole moment $\mu_{\mathrm{W}} = \frac{e}{2M_{\mathrm{W}}}(g_1^{\gamma} + \kappa_{\gamma} + \lambda_{\gamma})$
- electric quadrupole moment $Q_{\mathrm{W}} = -\frac{e}{M_{\mathrm{W}}^2}(\kappa_{\gamma} - \lambda_{\gamma})$

- SU(2)$\times$U(1): $g_1^{\gamma} = 1$

$$\kappa_{\mathrm{Z}} = g_1^{\mathrm{Z}} - (\kappa_{\gamma} - 1)\tan^2\theta_{\mathrm{W}}$$

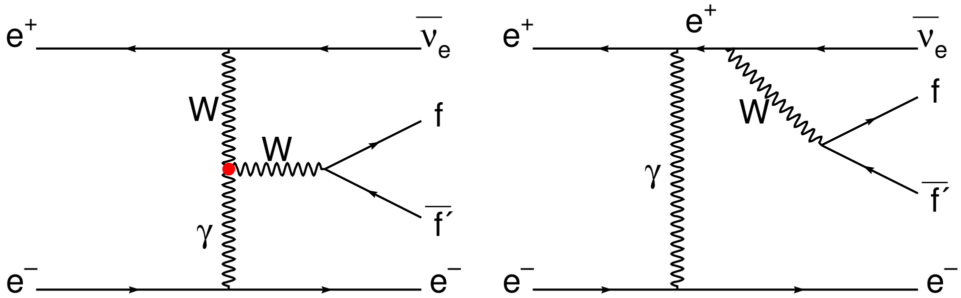
$$\lambda_{\gamma} = \lambda_{\mathrm{Z}}$$

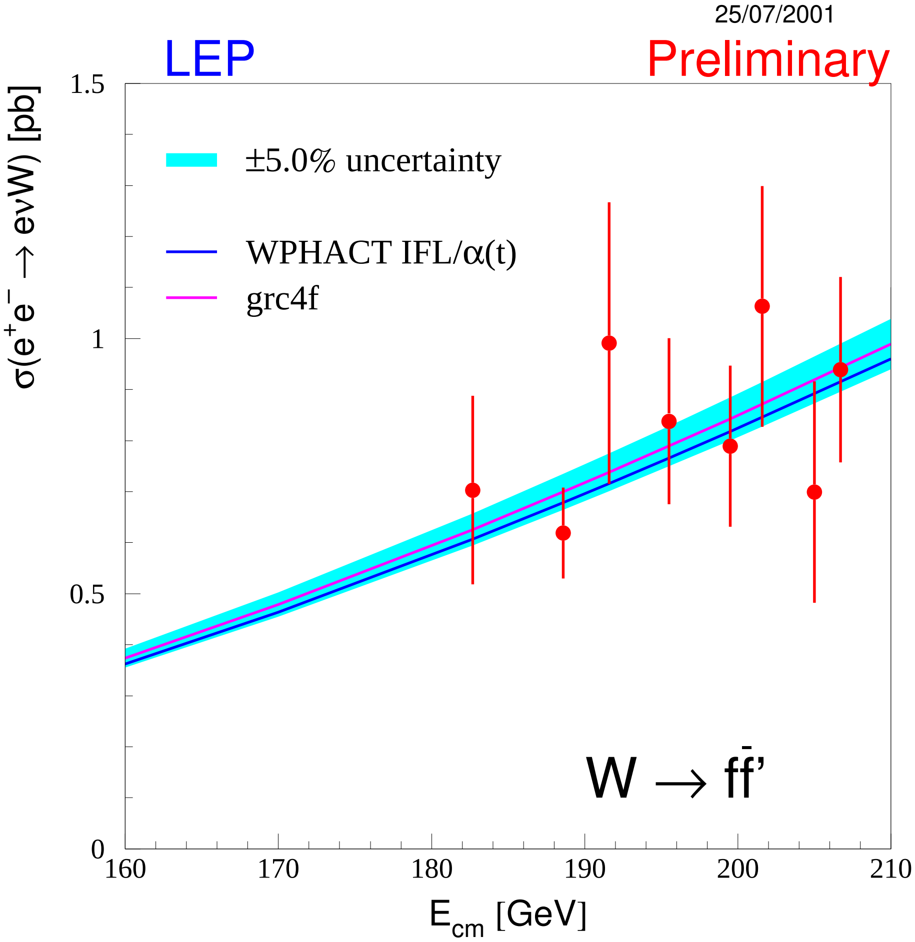
- SM values: $\kappa_{\gamma} = 1$

$$g_1^{\mathrm{Z}} = 1$$

$$\lambda_{\gamma} = 0$$

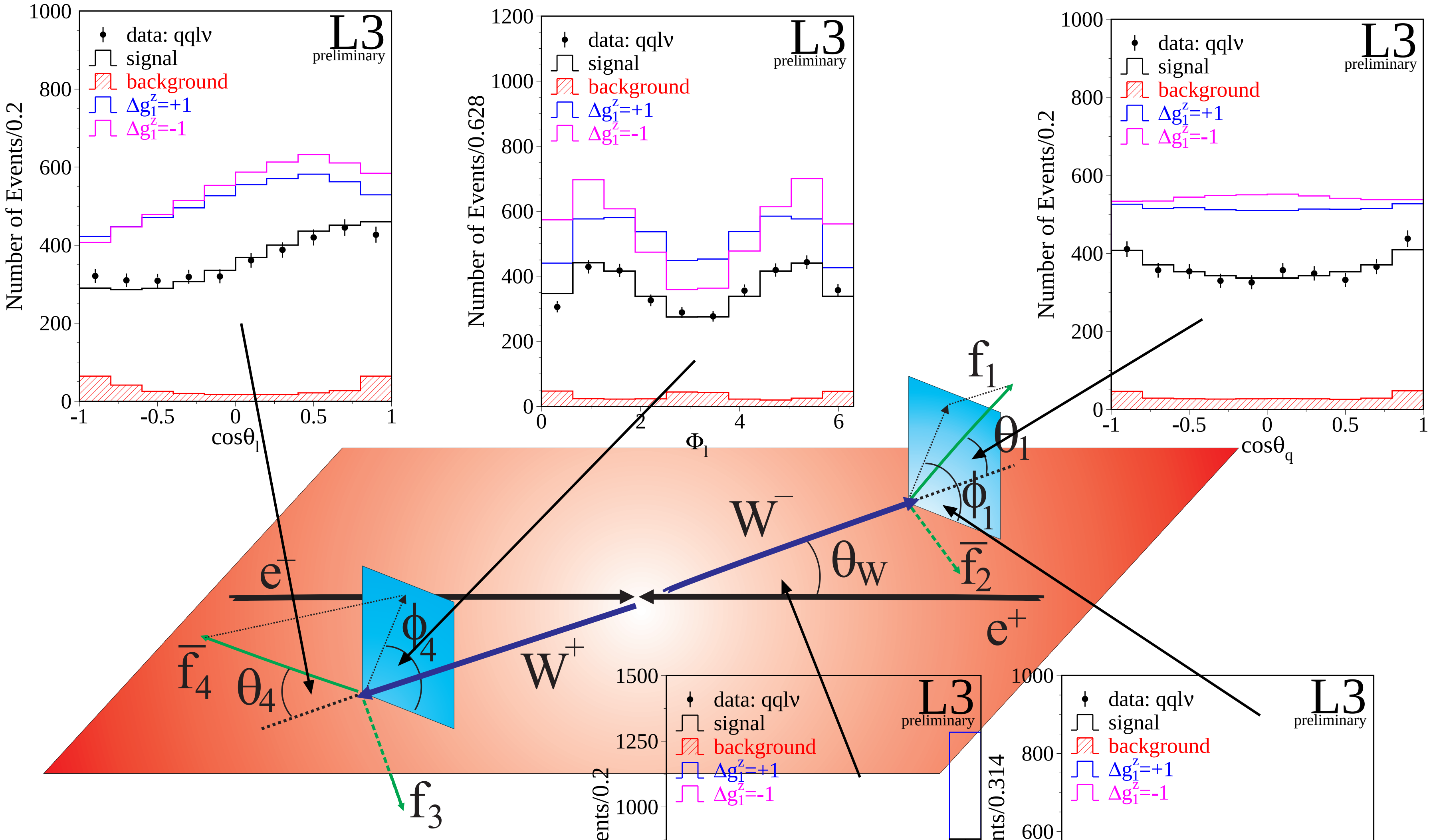
γW-Fusion and W-Bremsstrahlung

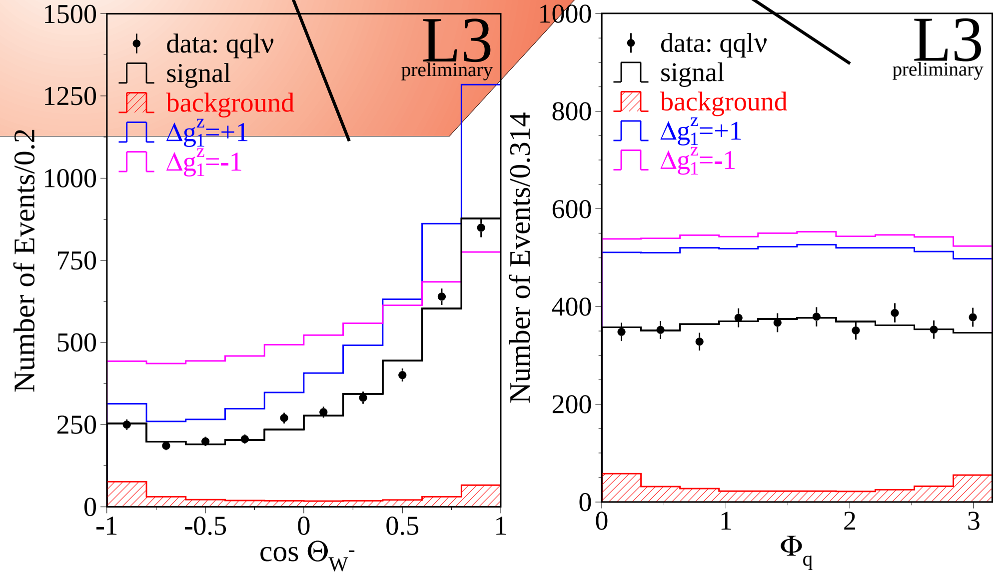




	κ_γ	λ_γ	
Aleph	[0.46,1.15]	[-0.57,0.44]	(490 pb^{-1}, 95% CL)
Delphi	$1.19^{+0.36}_{-0.58}$	$0.42^{+0.39}_{-1.21}$	(180 pb^{-1}, W$\rightarrow q\overline{q'}$)
L3	$1.10^{+0.13}_{-0.14}$	$-0.10^{+0.42}_{-0.25}$	(490 pb^{-1})
Opal	$1.06^{+0.17}_{-0.19}$	$-0.44^{+0.43}_{-0.24}$	(180 pb^{-1})

- single-W process mainly sensitive to κ_γ

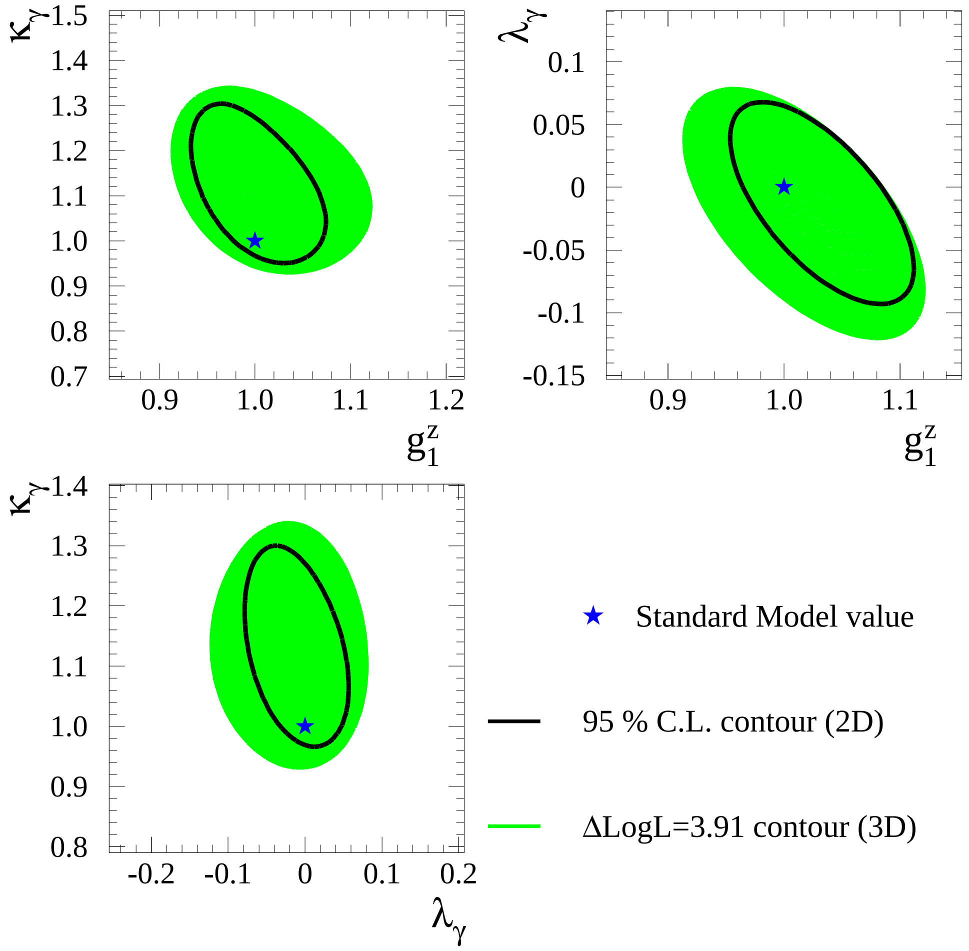




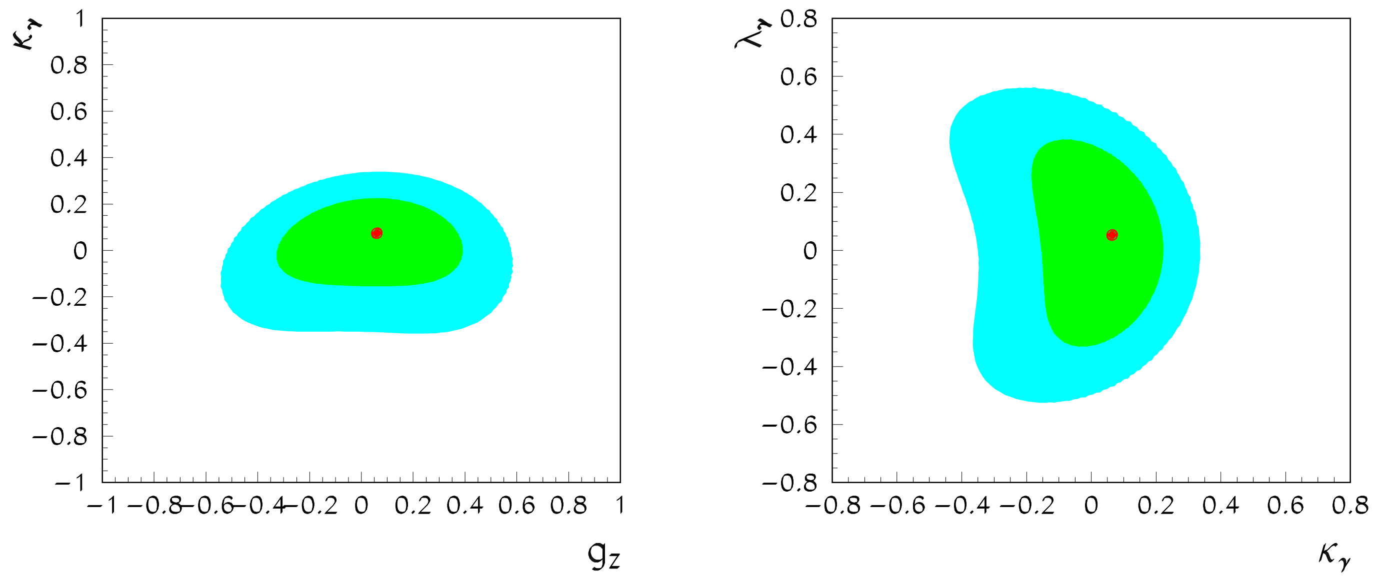
- $\mathcal{O}(\alpha)$ corrections need to be taken into account

- determine two or three couplings simultaneously

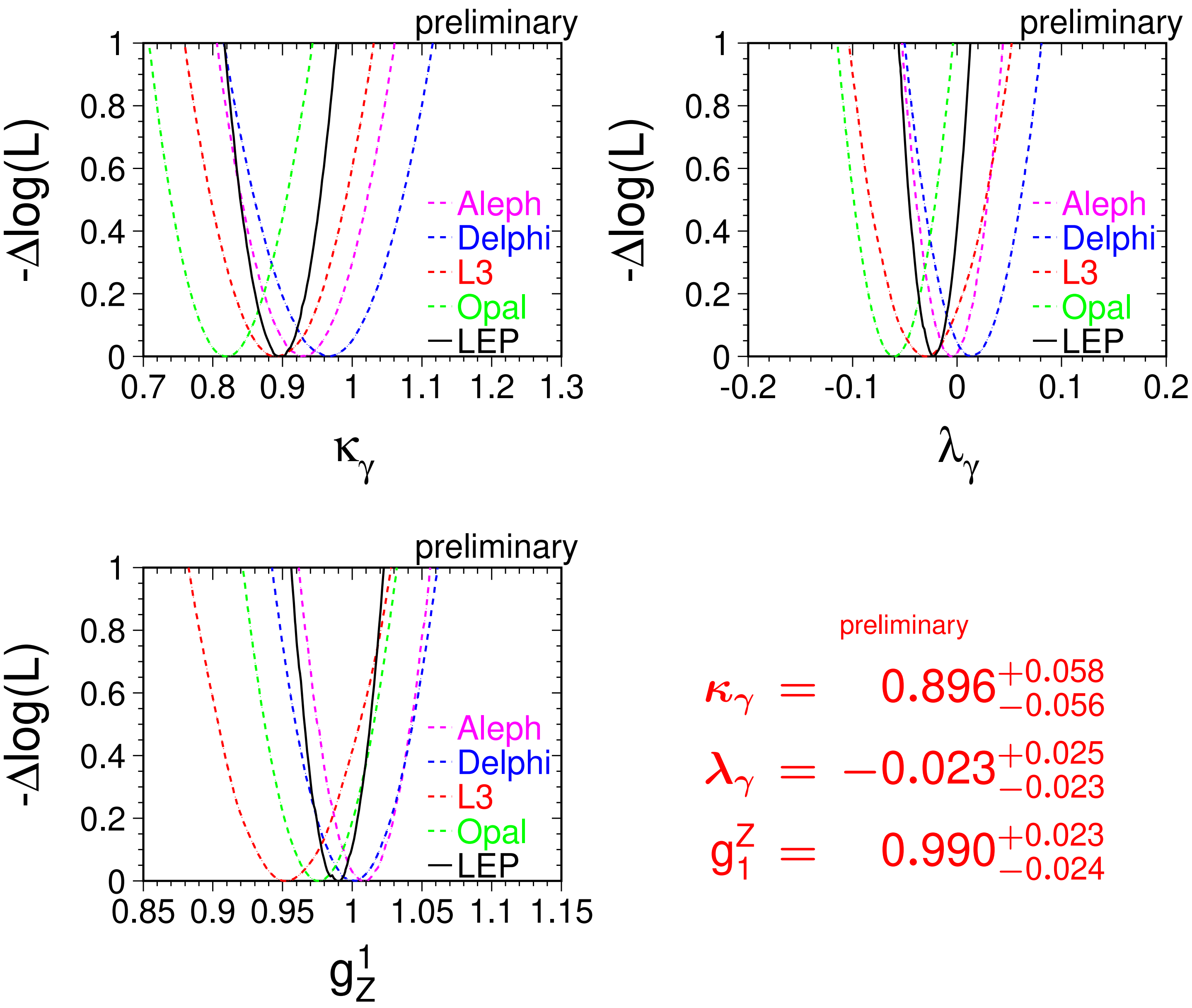
ALEPH Preliminary



- Delphi preliminary: (68% and 95% CL)



- single parameter fits to all channels
- LEP combined results



preliminary

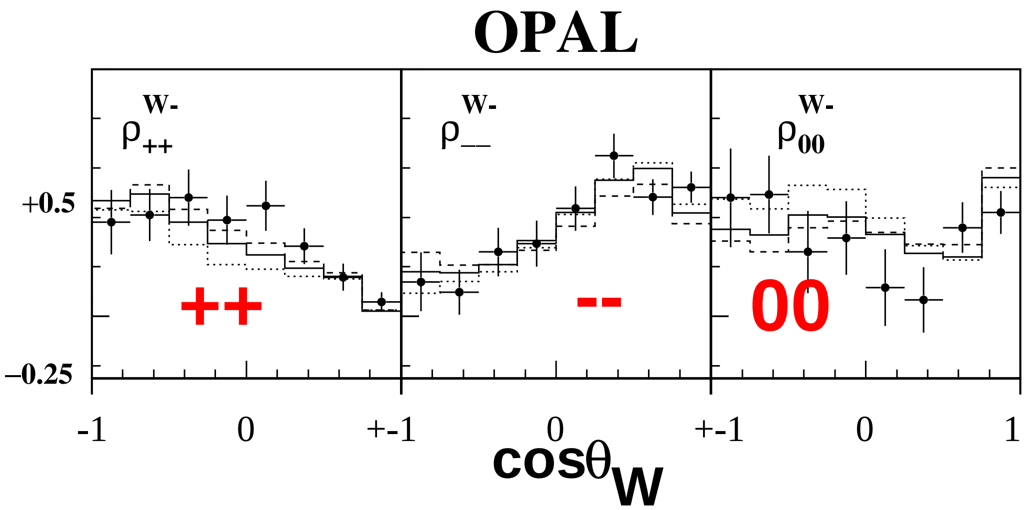
$$\kappa_\gamma = 0.896^{+0.058}_{-0.056}$$

$$\lambda_\gamma = -0.023^{+0.025}_{-0.023}$$

$$g_1^Z = 0.990^{+0.023}_{-0.024}$$

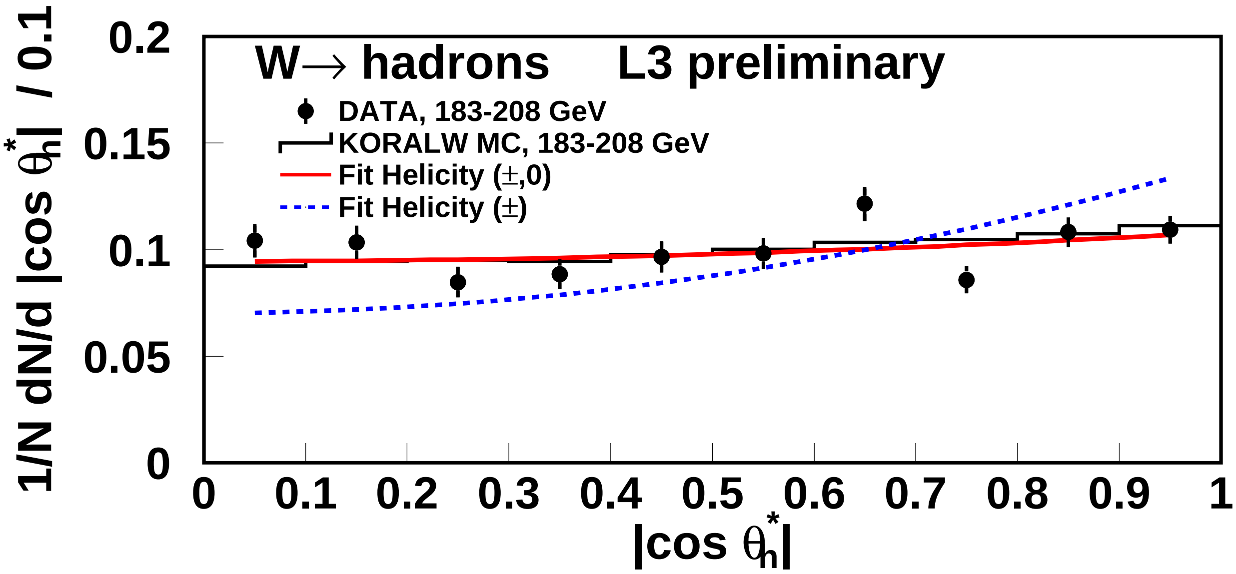
- $\mathcal{O}(\alpha)$ corrections largest correlated systematics
  $\longrightarrow$ ≈0.015 on g_1^Z and λ_γ, ≈0.04 on κ_γ
- not all LEP data analysed and included in combination
  $\longrightarrow$ reduction in statistical uncertainty
  $\longrightarrow$ need better estimates of theory error

- in the SM: Higgs mechanism $\longrightarrow$ longitudinal polarization of W bosons
- Spin-densitity matrix elements $\longrightarrow$ W polarization states (O):



$$\sigma_{\mathrm{L}} = \int \rho_{00}\, d\sigma/d\cos\theta_{\mathrm{W}}\, d\cos\theta_{\mathrm{W}}$$
$$\sigma_{\mathrm{T}} = \int (\rho_{++} + \rho_{--})\, d\sigma/d\cos\theta_{\mathrm{W}}\, d\cos\theta_{\mathrm{W}}$$

- unfolding the decay angle distribution (L):



$\sigma_{\mathrm{L}}/\sigma = 0.210 \pm 0.033 \pm 0.016$ (Opal, $\sqrt{s}$=189 GeV, SM=0.257)

$\sigma_{\mathrm{L}}/\sigma = 0.243 \pm 0.027 \pm 0.012$ (L3, $\langle\sqrt{s}\rangle$=197 GeV, SM=0.240)

- W bosons are indeed longitudinally polarized!

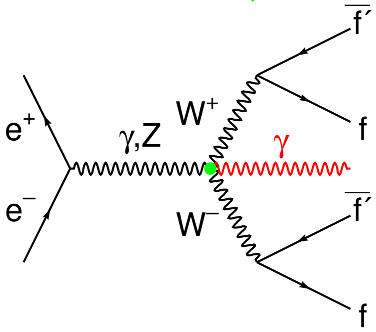
- anomalous contributions to 4-boson vertex:

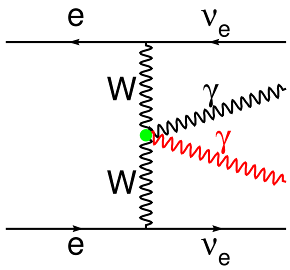
$$\mathcal{L}_0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2} F^{\mu\nu}F_{\mu\nu}\,\vec{W}^{\alpha}\cdot\vec{W}_{\alpha}$$

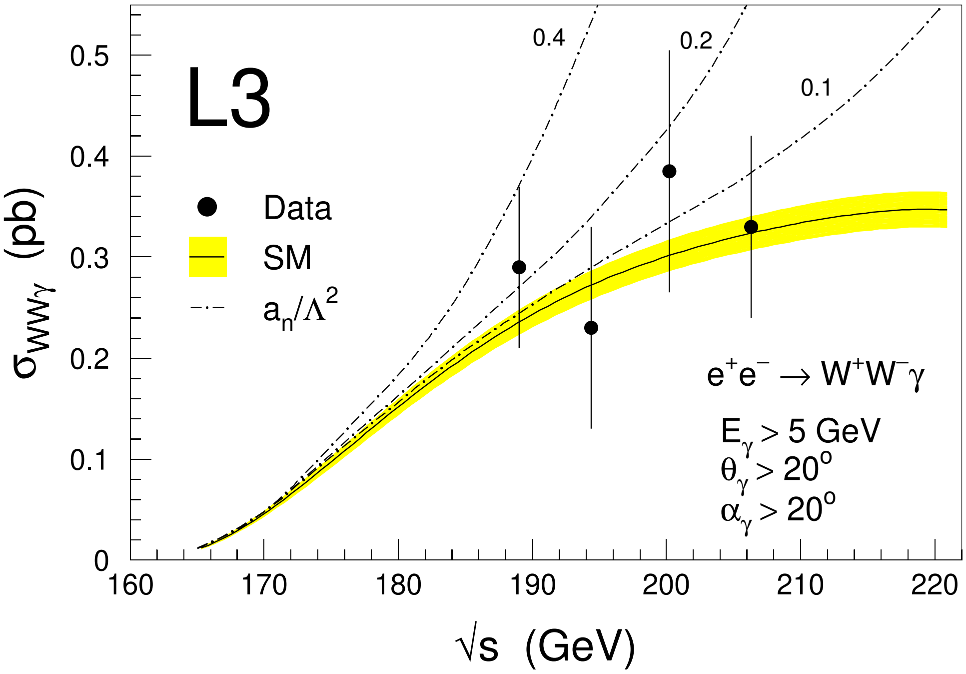
$$\mathcal{L}_c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2} F^{\mu\alpha}F_{\mu\beta}\,\vec{W}^{\beta}\cdot\vec{W}_{\alpha}$$

$$\mathcal{L}_n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2} \epsilon_{ijk}\, W^{(i)}_{\mu\alpha} W^{(j)}_{\nu} W^{(k)\alpha} F^{\mu\nu} \qquad \text{(CP viol.)}$$

- measured in $WW\gamma$ and $\nu\nu\gamma\gamma$ final states:







+ photon energy spectrum

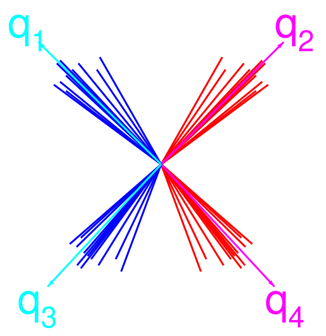
- LEP analysis of $WW\gamma$ and $\nu\nu\gamma\gamma$ channel:

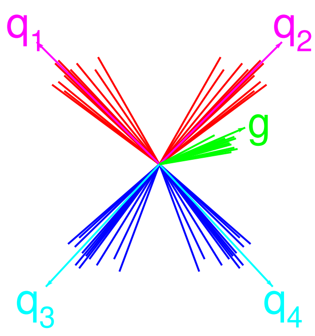
$$-0.02 \le a_0^W/\Lambda^2 \cdot \text{GeV}^2 \le 0.02 \qquad \text{(95\% CL)}$$

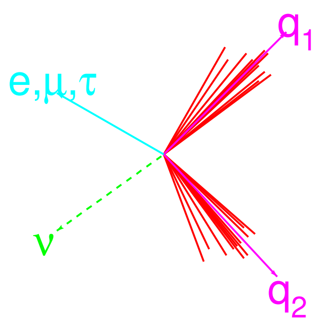
$$-0.03 \le a_c^W/\Lambda^2 \cdot \text{GeV}^2 \le 0.05 \qquad \text{(95\% CL)}$$

$$-0.17 \le a_n^W/\Lambda^2 \cdot \text{GeV}^2 \le 0.15 \qquad \text{(95\% CL, only WW}\gamma\text{)}$$

- reconstructed jets and leptons
- qqqq and $qq\ell\nu$ channel $\longrightarrow$ invariant masses $M_{qq(g)}$, $M_{\ell\nu}$







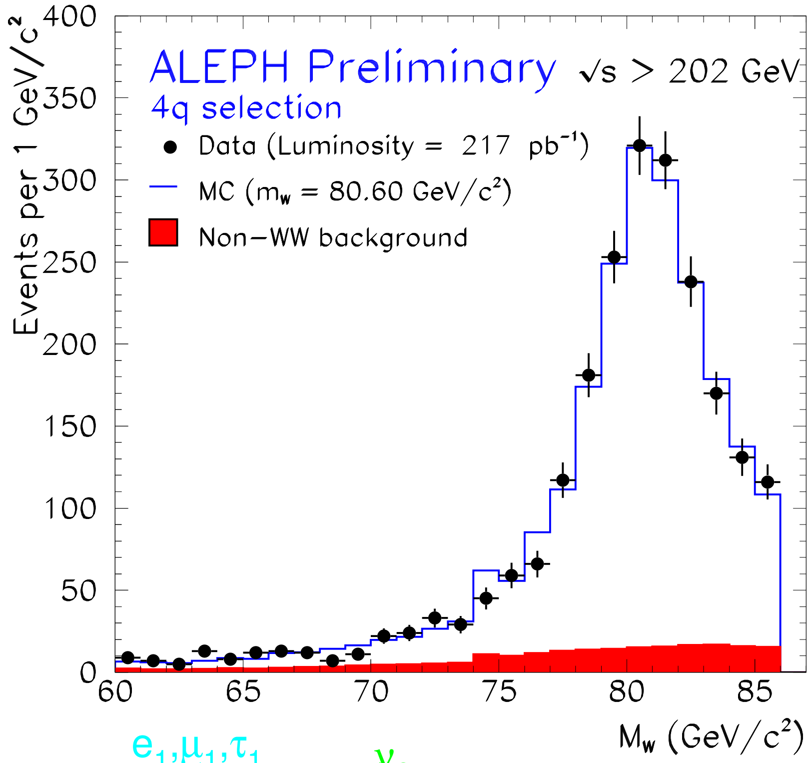
- constrained fit:

$\Sigma E_i = \sqrt{s}$

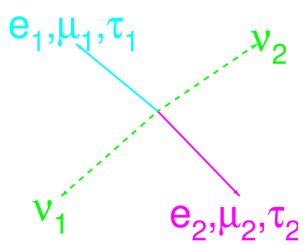
$\Sigma \vec{p}_i = 0$

$M_{W,1} = M_{W,2}$

$\longrightarrow$ improved resolution



- $\ell\nu\ell\nu$ channel $\longrightarrow E_\ell$, M_{pseudo}



- mass extraction methods:
  - ▷ MC reweighting with varied underlying M_W $\longrightarrow \geq 1$ observables ($\langle M_W \rangle$, M_{qq}, σ_{M_W}, ...)
  - ▷ Breit-Wigner fit to $\langle M_W \rangle$ + bias corr. with MC
  - ▷ convolution $\longrightarrow$ prob. density function $F(M_{W,1}, M_{W,2})$

- refined methods $\longrightarrow$ combined statistical precision
$$\sigma_{M_W}^{stat} = 26 \text{ MeV}$$

Source	Systematic Uncertainties on M_W in MeV		
	$qq\ell\nu$	qqqq	combined
ISR/FSR	8	9	8
Hadronisation	19	17	17
Detector Syst.	12	8	10
LEP Beam Energy	17	17	17
Colour Reconnection	–	40	11
BE Correlations	–	25	7
Other	4	4	3
Total Systematic	29	54	30
Statistical	33	30	26
Total	44	62	40

- reduced weight of qqqq channel: 0.27

$\longrightarrow$ possible effects of final-state-interactions

- enhancement of production of identical bosons close in phase space $\longrightarrow$ here: $\pi^{\pm}$, π^{0}, $K^{\pm}$, ...
- correlation function between pions:

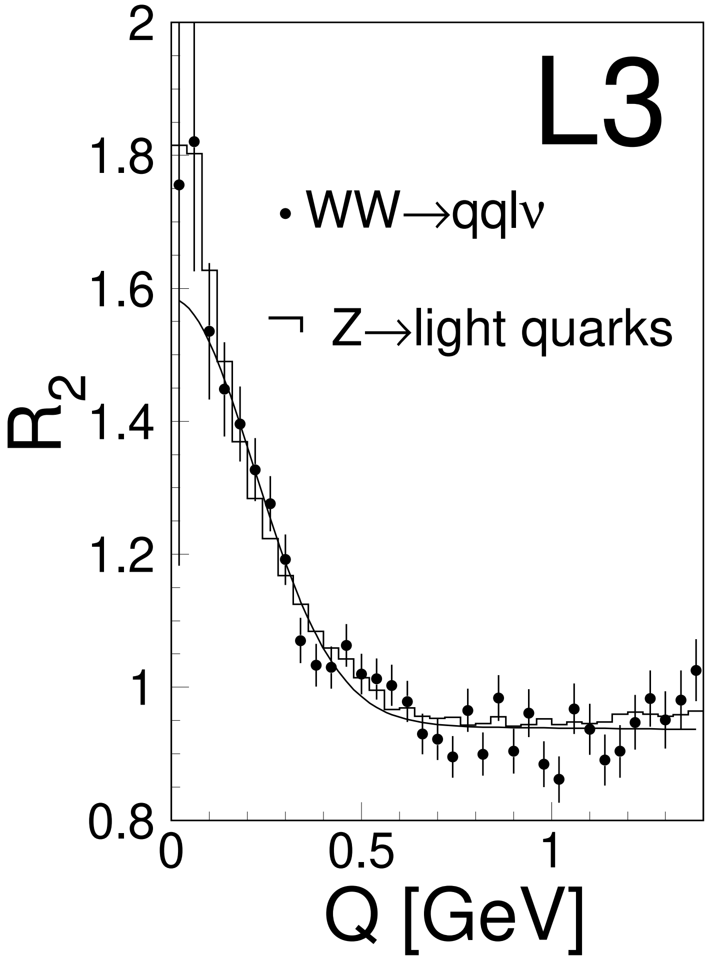
$$C(Q_{\pi\pi}) = 1 + \lambda \exp(-R^2 Q^2_{\pi\pi})$$

$$Q^2_{\pi\pi} = -(p_{\pi,1} - p_{\pi,2})^2$$

- ratio of two-particle densities:

$$R_2 = \rho_{\text{data}} / \rho^{\text{MC}}_{\text{noBE}}$$

$\longrightarrow$ correlations equal for light-quark Z decays and inside W's



- pions from different W's $\longrightarrow$ two-particle density:

$$\overbrace{\rho^{WW}(1,2)}^{\text{fully hadronic}} = \overbrace{\rho^{W^+}(1,2) + \rho^{W^-}(1,2)}^{\text{semi-hadronic}} + \underbrace{2\rho^{W^+}(1)\rho^{W^-}(2)}$$

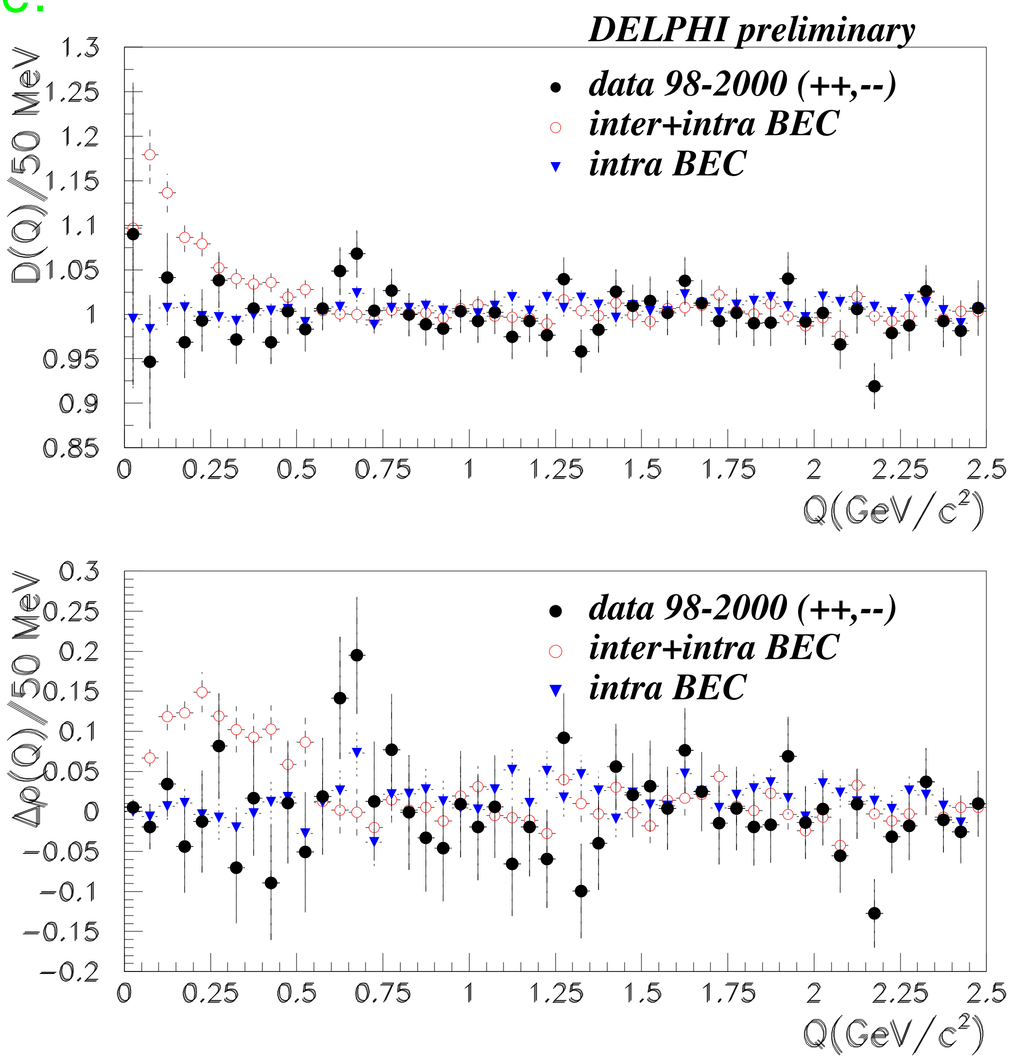
from mixed semi-hadronic events $\longrightarrow 2\rho^{W^+W^-}_{\text{mix}}$

- difference and ratio:

$$\Delta\rho = \rho^{WW} - 2\rho^{W} - 2\rho^{W^+W^-}_{\text{mix}} = 0\ ?$$

$$D = \frac{\rho^{WW}}{2\rho^{W} + 2\rho^{W^+W^-}_{\text{mix}}} = 1\ ?$$

- example:

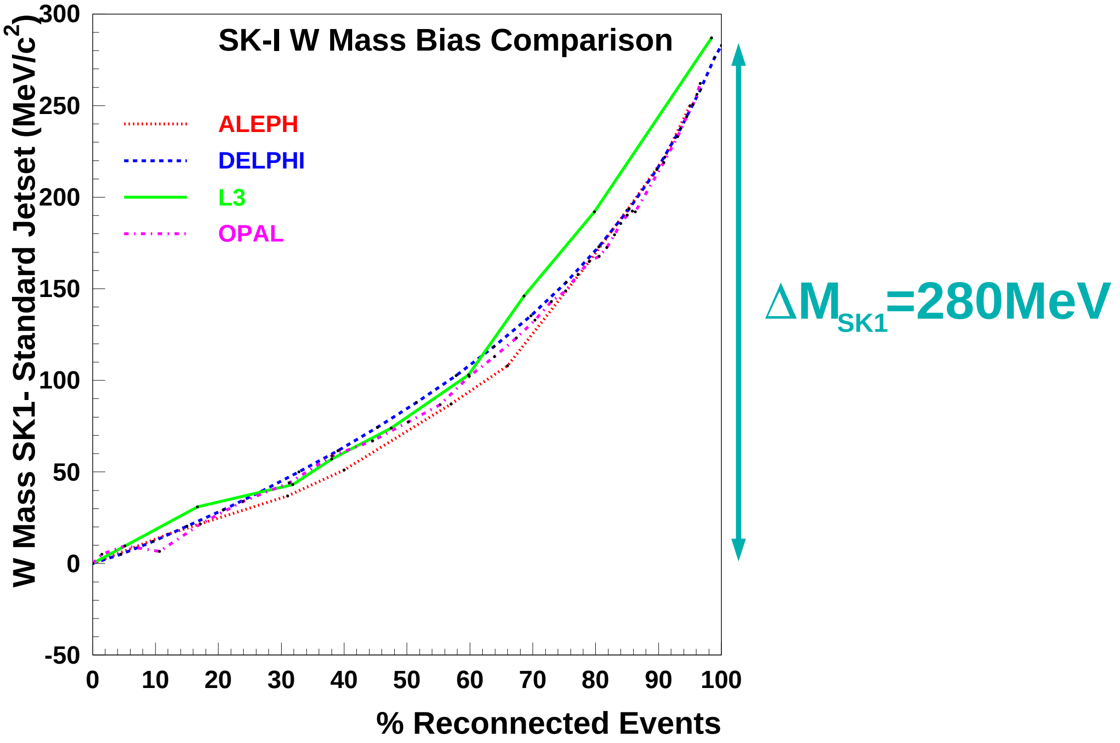


- no evidence for BE correlations between pions from different W's
- disfavoured also by Aleph, L3 and Opal
  $\longrightarrow$ each with significance $\approx$ 2-3σ
- currently working on LEP combination
- preliminary study shows linear relation between λ and ΔM_W

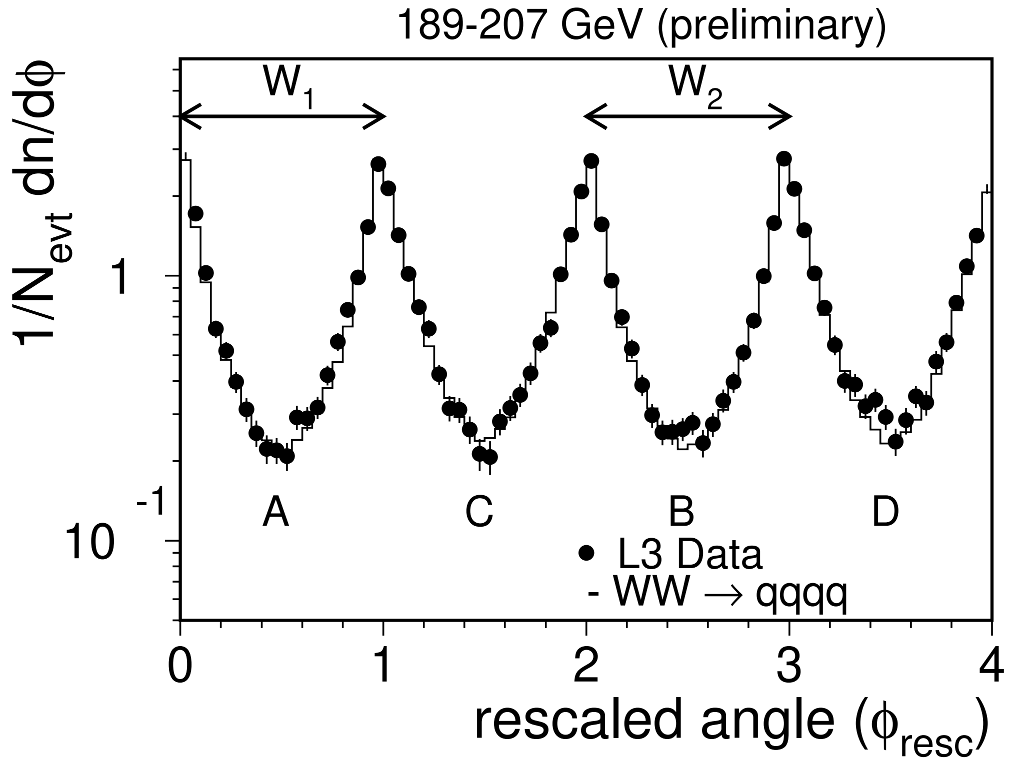
$\longrightarrow$ systematic uncertainty on M_W will be reduced

$$\sigma^{BE}_{M_W} = 25 \text{ MeV} \rightsquigarrow 10 \text{ MeV}$$

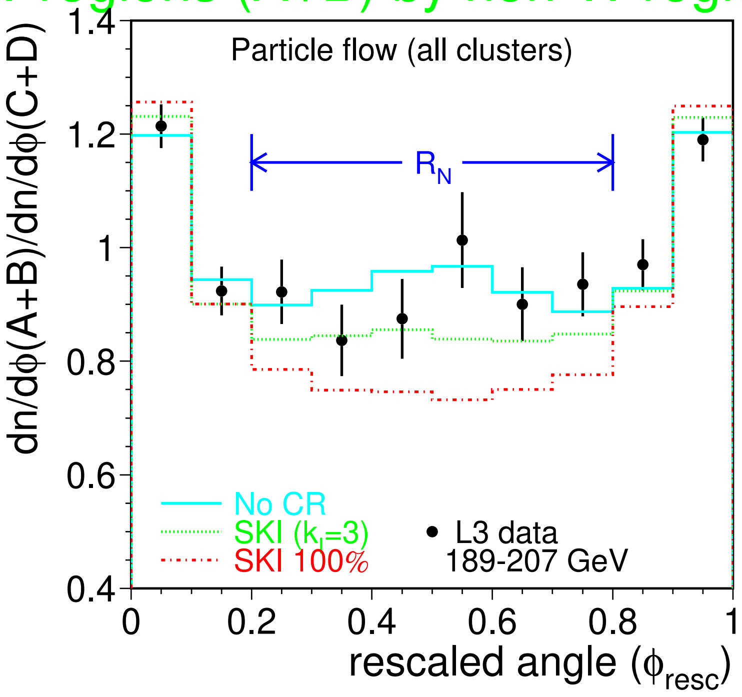
- rearrangement of colour flow $\longrightarrow$ cross-talk between W's
- several models: SKI, SKII, AR2, AR3, Rathsman, ...
- most sensitive observable is M_W



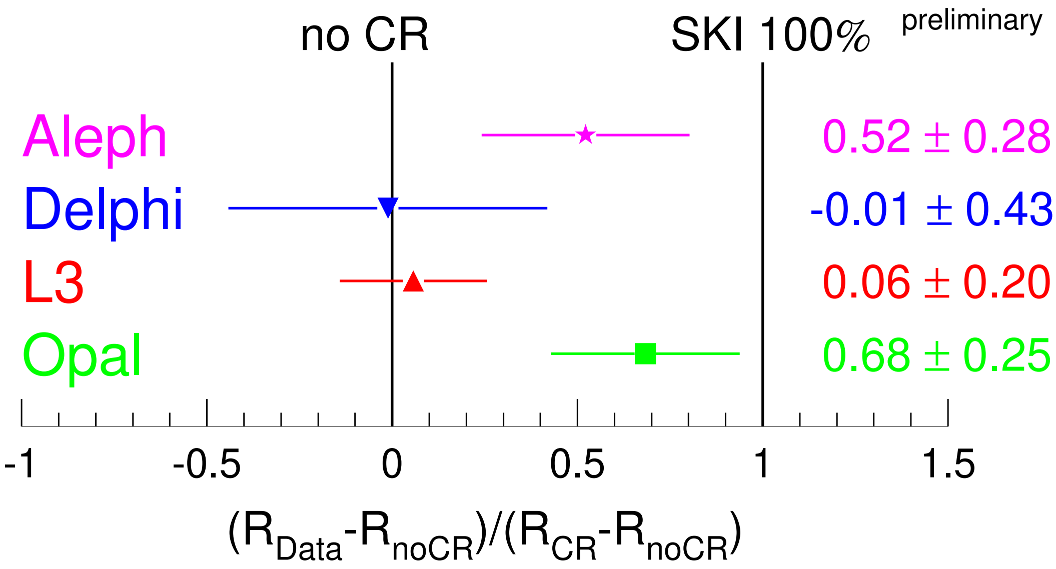
- mass difference $\Delta M_W(qqqq - qq\ell\nu) = +9 \pm 44$ MeV
- best other observable: $\rightarrow$ particle flow in inter-jet region



- divide inter-W regions (A+B) by non-W regions (C+D):

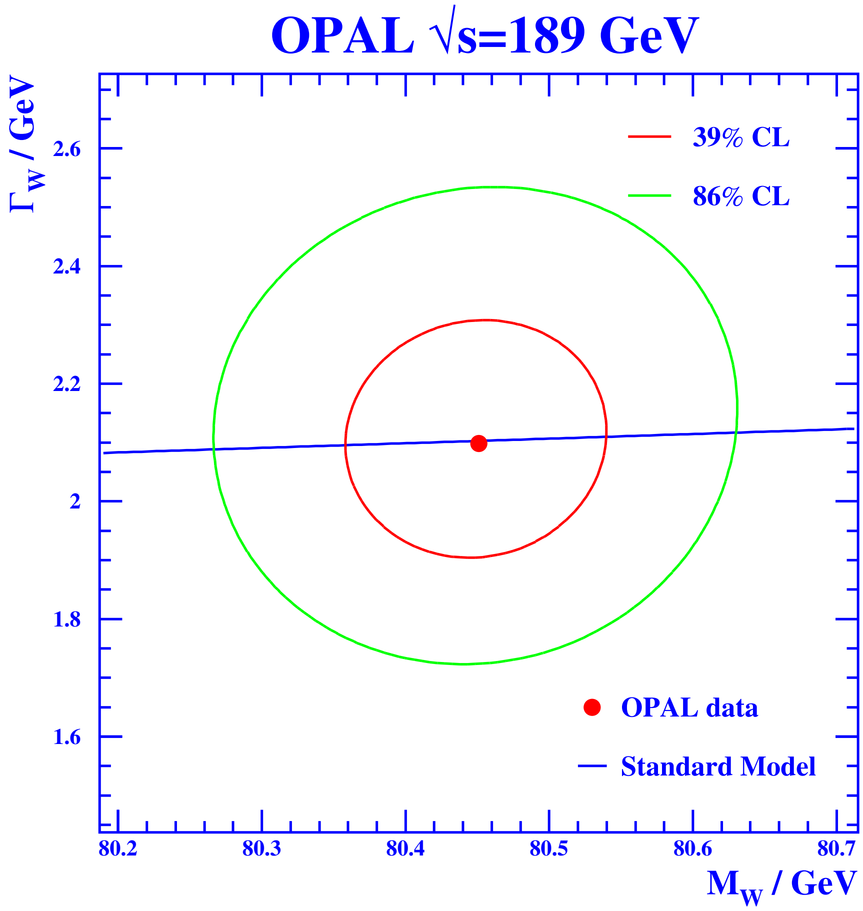


- ratio R of integral $[0.2, 0.8] \longrightarrow R_{data}$, R^{MC}_{noCR}, R^{MC}_{CR}
- normalized ratio:

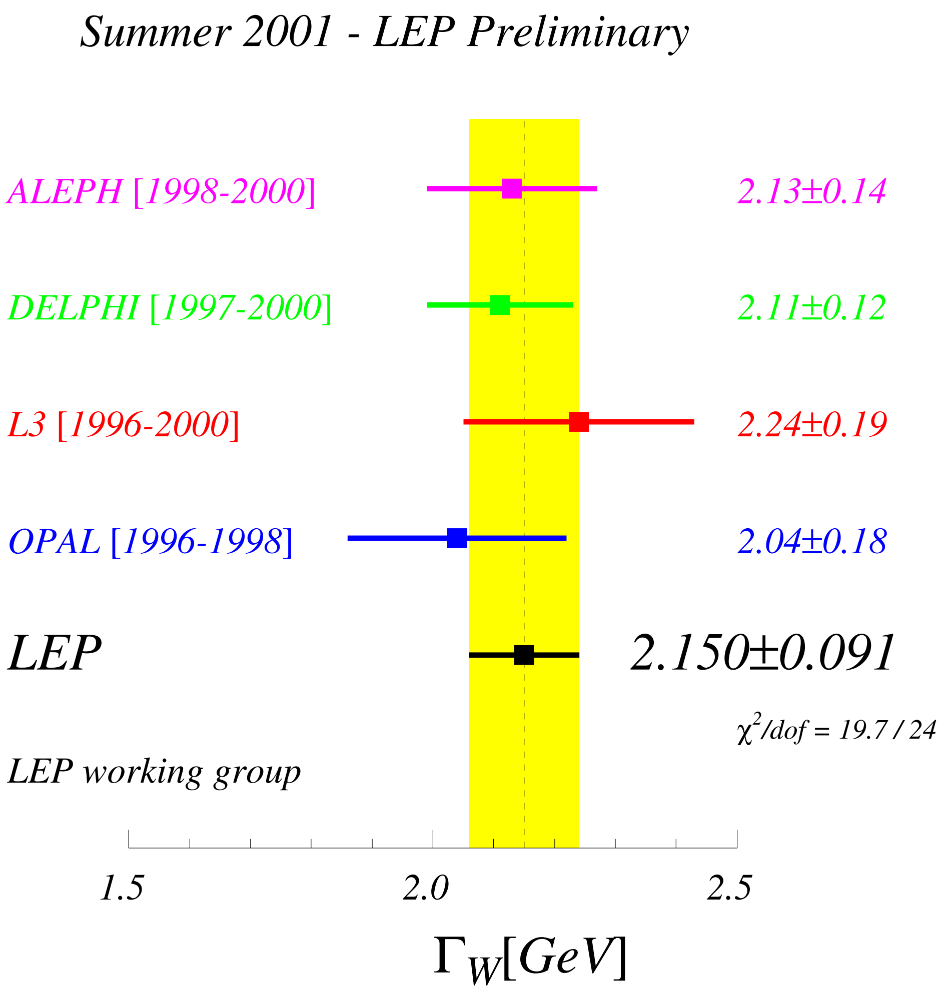


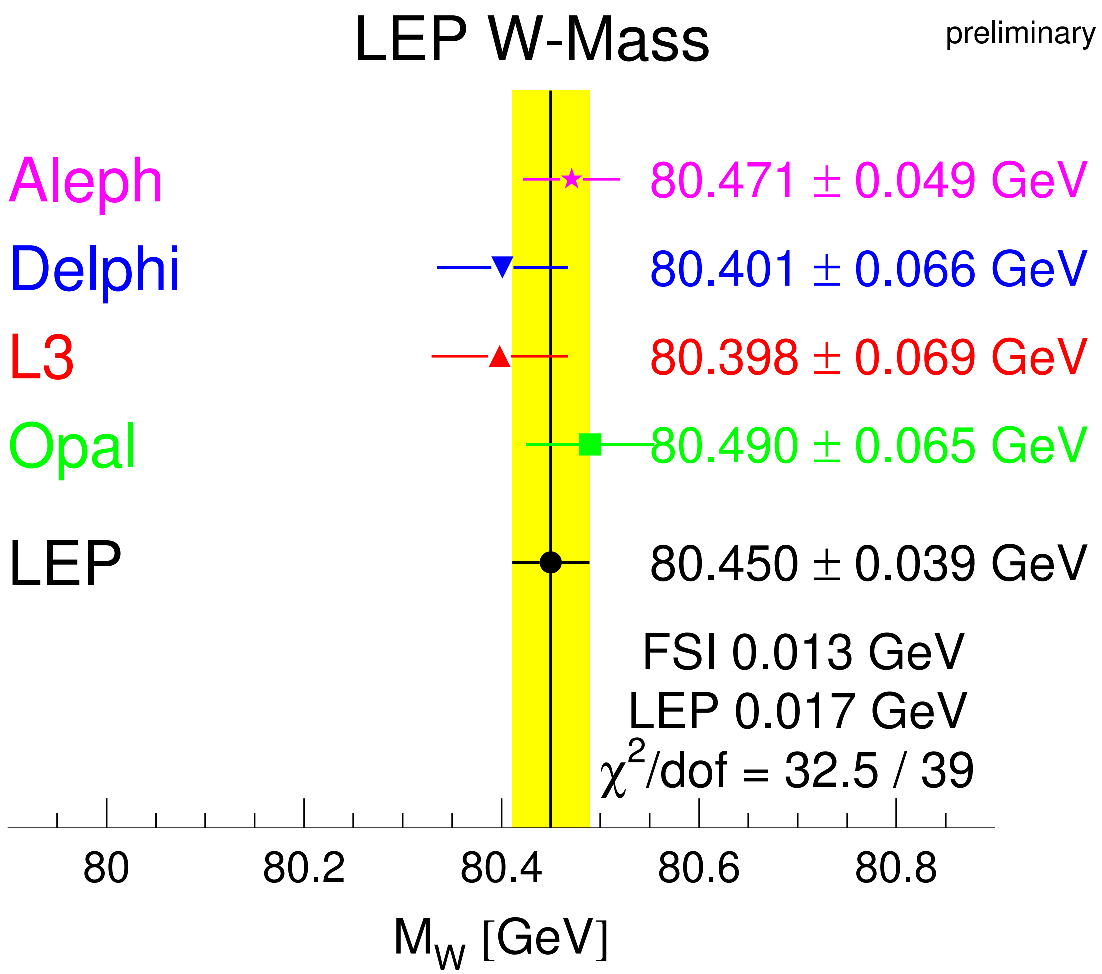
- 2 disfavour full CR (SKI), 2 are still undecided
- combination of LEP measurements ongoing
- aim: exclude models or limit parameters

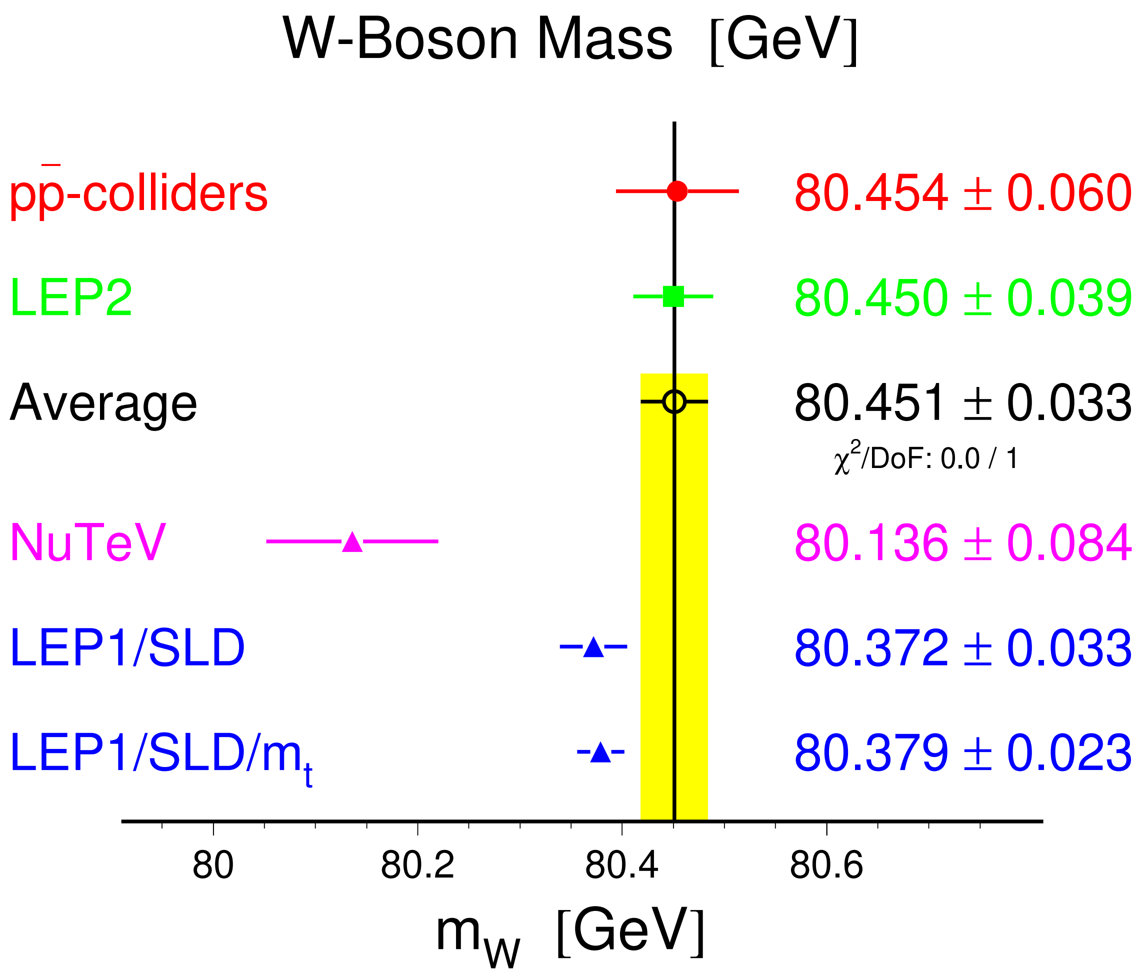
$\longrightarrow$ reduce M_W systematics, but . . . many different models

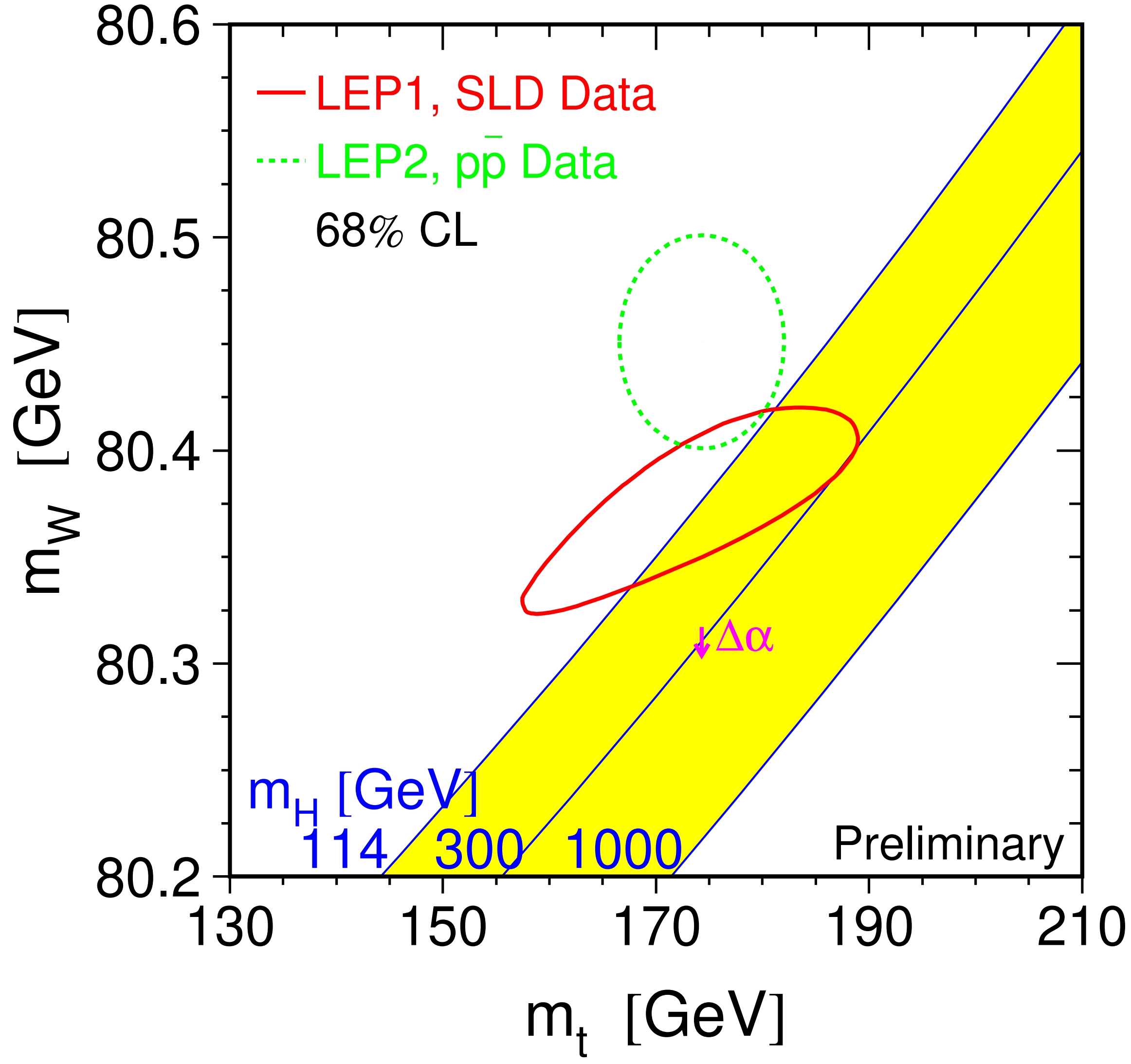


- M_W and Γ_W are uncorrelated

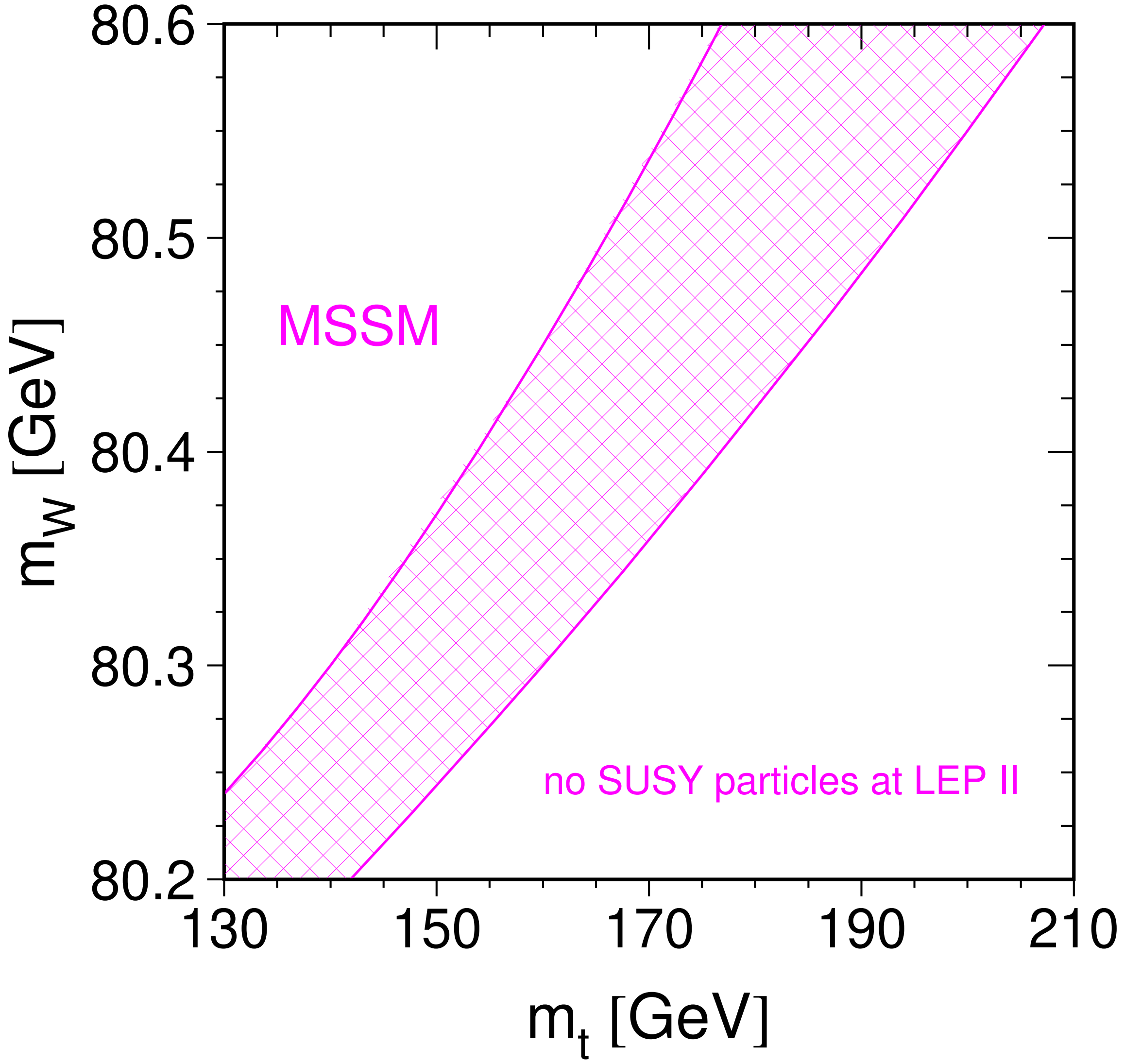



LEP W-Mass
preliminary
Aleph
80.471 ± 0.049 GeV
Delphi
80.401 ± 0.066 GeV
L3
80.398 ± 0.069 GeV
Opal
80.490 ± 0.065 GeV
LEP
80.450 ± 0.039 GeV
FSI 0.013 GeV
LEP 0.017 GeV
χ²/dof = 32.5 / 39
80
80.2
80.4
80.6
80.8
M_W [GeV]


W-Boson Mass [GeV]
pp̄-colliders
80.454 ± 0.060
LEP2
80.450 ± 0.039
Average
80.451 ± 0.033
χ²/DoF: 0.0 / 1
NuTeV
80.136 ± 0.084
LEP1/SLD
80.372 ± 0.033
LEP1/SLD/m_t
80.379 ± 0.023
80
80.2
80.4
80.6
m_W [GeV]



LEP1, SLD Data
LEP2, $p\bar{p}$ Data
68% CL
$\Delta\alpha$
m_H [GeV]
114 300 1000
Preliminary
80.6
80.5
80.4
80.3
80.2
130
150
170
190
210
m_W [GeV]
m_t [GeV]



- 1-loop calculation only (Dabelstein et al. ’95)
- more recent predictions include 2-loop $\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha^2)$ results (Heinemeyer et al. ’98 and ’01)

- LEP met the expectations and exceeded them
- many properties of the W boson measured
- gauge couplings well determined

$$\begin{aligned} \kappa_\gamma &= 0.896 \pm 0.057 \\ \lambda_\gamma &= 0.023 \pm 0.024 \\ g_1^Z &= 0.990 \pm 0.023 \end{aligned}$$

- precise measurement of W mass and width

$$\begin{aligned} M_W &= 80.450 \pm 0.039 \text{ GeV} \\ \Gamma_W &= 2.150 \pm 0.091 \text{ GeV} \end{aligned}$$

- good agreement with Standard Model predictions
- final analyses still going on . . .