W **Properties at LEP**

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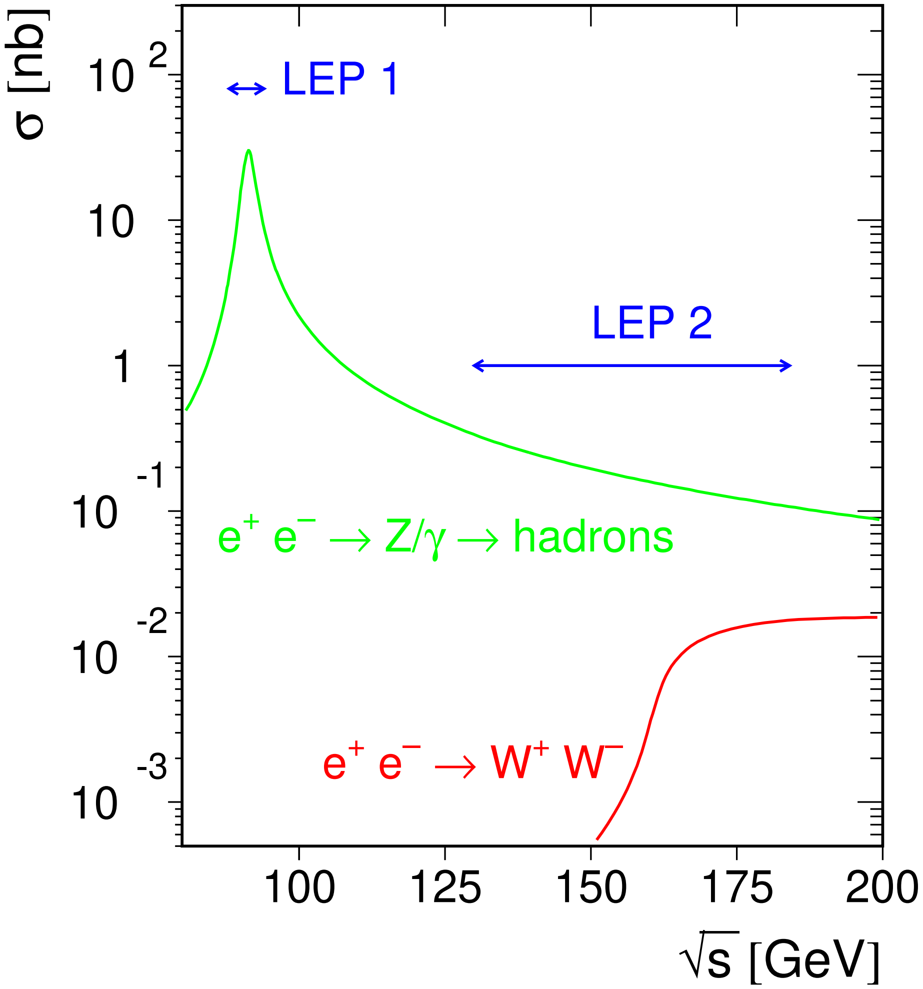
On behalf of the LEP collaborations

- Introduction
- W W selections and cross sections
- W branching ratios and $|V_{cs}|$
- Couplings of the W Boson
- Mass and Width of the W Boson
- Summary and Outlook

9^{th} Lomonosov conference
Moscow, Sept 20 - Sept 26, 1999

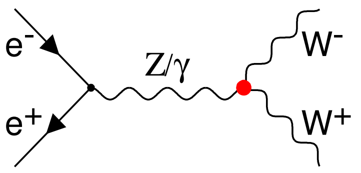
Introduction

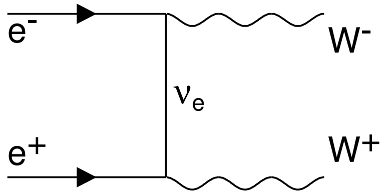


- LEP allows the production of W s in a clean environment
- Unique opportunity to study W s in all their decay modes

	$\sqrt{s}$ (GeV)	$\mathcal{L}(pb^{-1}$/exp)	W pair/exp
1996	161	~ 11	~ 20
1996	172	~ 10	~ 110
1997	183	~ 55	~ 840
1998	189	~ 176	~ 2800
1999	192	~ 29	~ 450
1999	196	~ 81	~ 1400
1999	200	> 54	> 800
total		> 400	> 6000

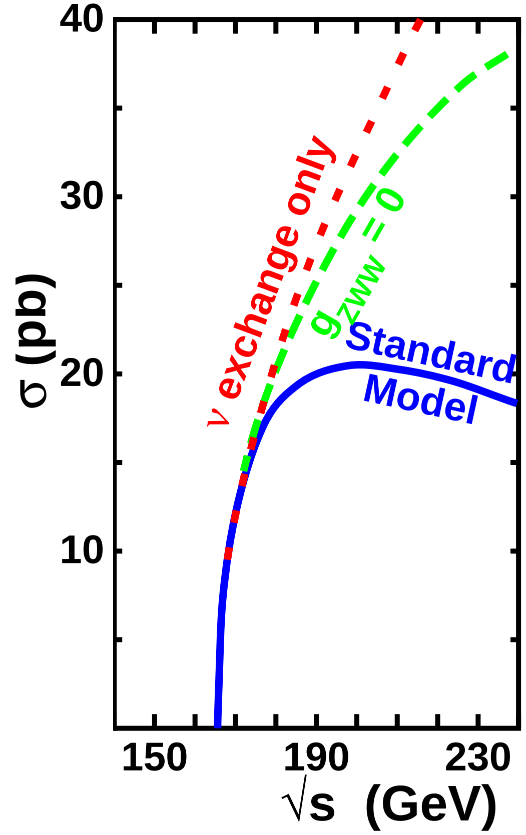
Motivation



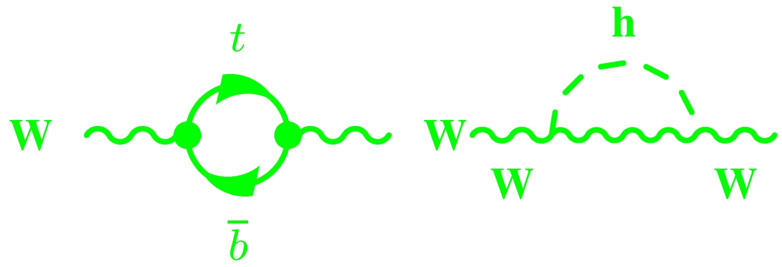


W mass is one of the key parameters in the SM, predicted from the muon decay :

sensitive to the Triple Gauge-Boson couplings



$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu(1-m_W^2/m_Z^2)} \; \frac{1}{1-\Delta r(m_t, m_H)}$$



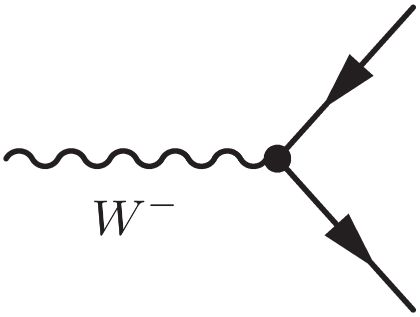
Precise measurement of M_W $\Longrightarrow$

- Tests Standard Model
- Constrains Higgs Mass
- Constrains a possible extention of SM

W decay

Branching fraction:

$\bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau,\ \bar{u}\ ,\bar{c},\ \bar{u}\ ,\bar{c},\ \bar{u}\ ,\bar{c}$



$e^+,\ \mu^-,\ \tau^-,\ d,\ s,\ d,\ s,\ d,\ s$

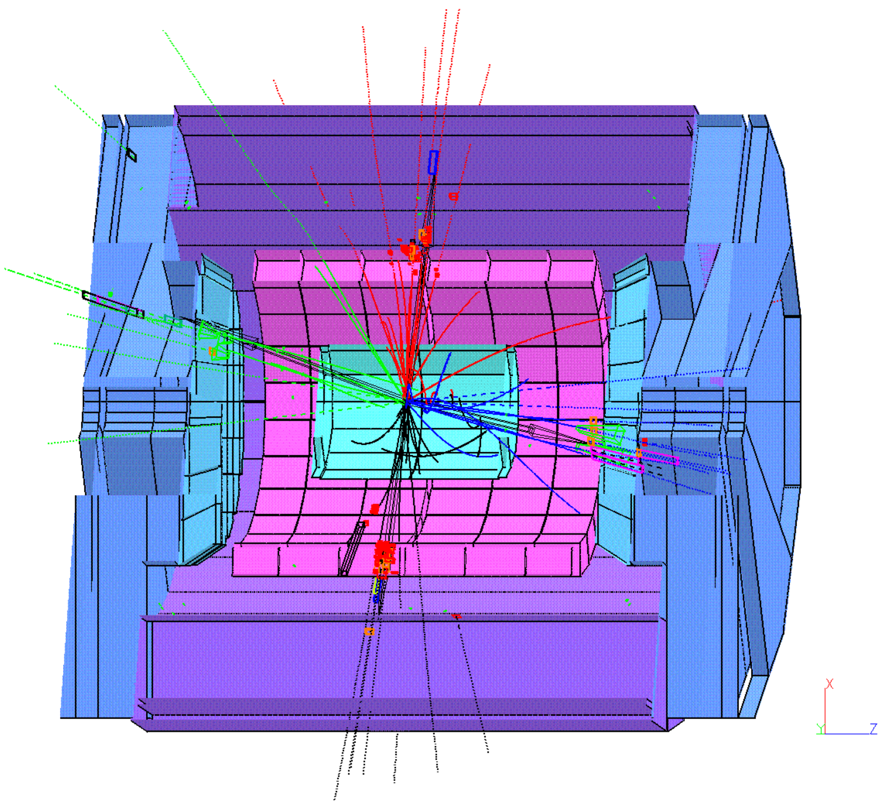
$$
\begin{aligned}
BR(\mathrm{W} \rightarrow l\nu) &= \tfrac{1}{9} \quad \text{(per lepton)} \\
BR(\mathrm{W} \rightarrow qq) &= \tfrac{6}{9}
\end{aligned}
$$

+ QCD corrections

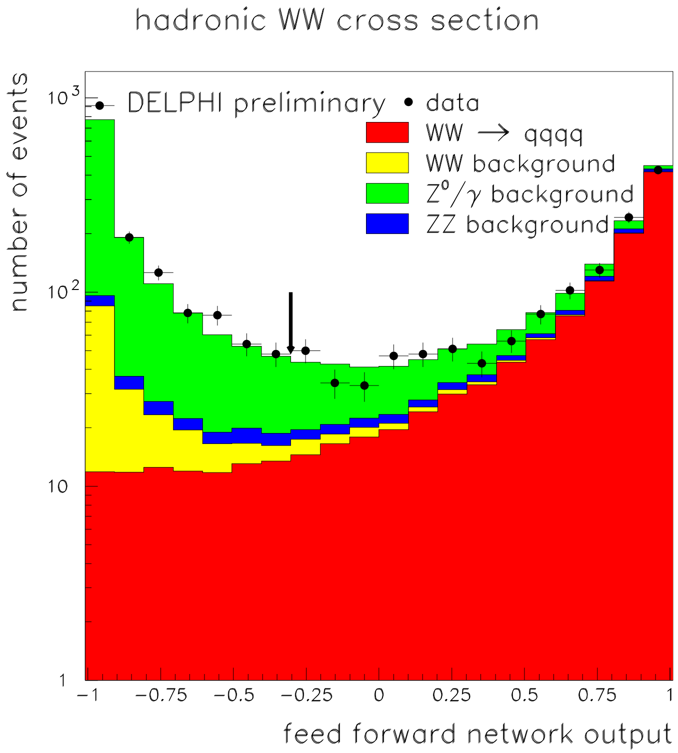
$e^+e^- \rightarrow \mathrm{W}^+\mathrm{W}^-$:

- qq qq : 45.6%
- $l\nu$ qq : 43.8%
- $l\nu l\nu$: 10.6%

$W^+W^- \rightarrow q\bar{q}q\bar{q}$



Using variables related to event shapes, jet properties and WW kinematics $\Longrightarrow$



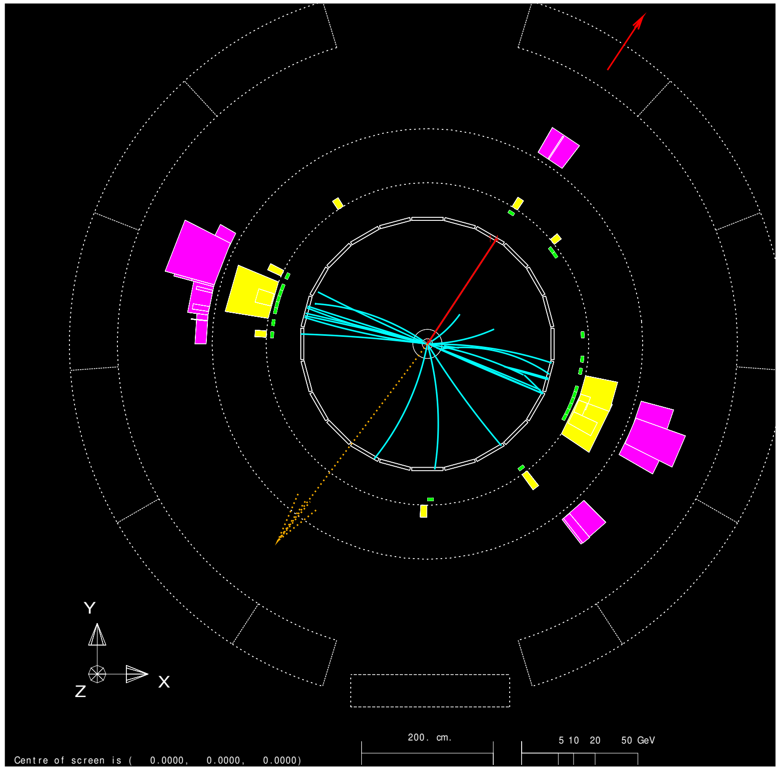
- high multiplicity
- no missing energy and momentum
- four well separated Jets

Main Background : QCD-Jets $q\bar{q}gg$

The cross section is determined by a fit to the Neural Network Output

Selection efficiency	:	~ 90 %
Selection purity	:	~ 80 %

$W^+W^- \to q\bar{q}l\nu$

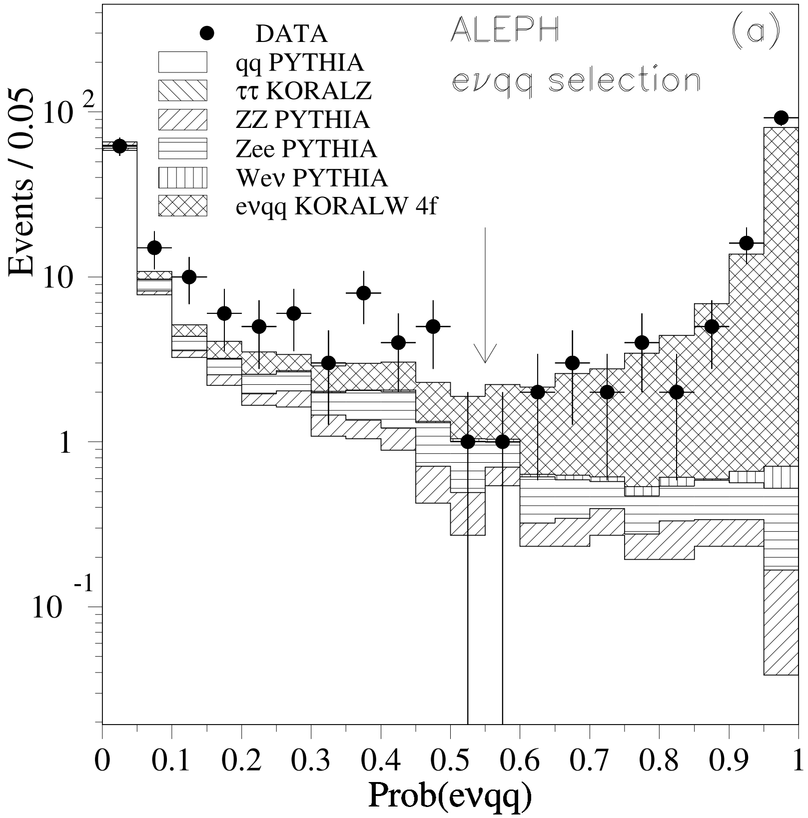


- 2 hadronic Jets
- isolated lepton
- missing transverse momentum (Neutrinos)

Main Background :

radiative quark pair $q\bar{q}\gamma$, $q\bar{q}g$

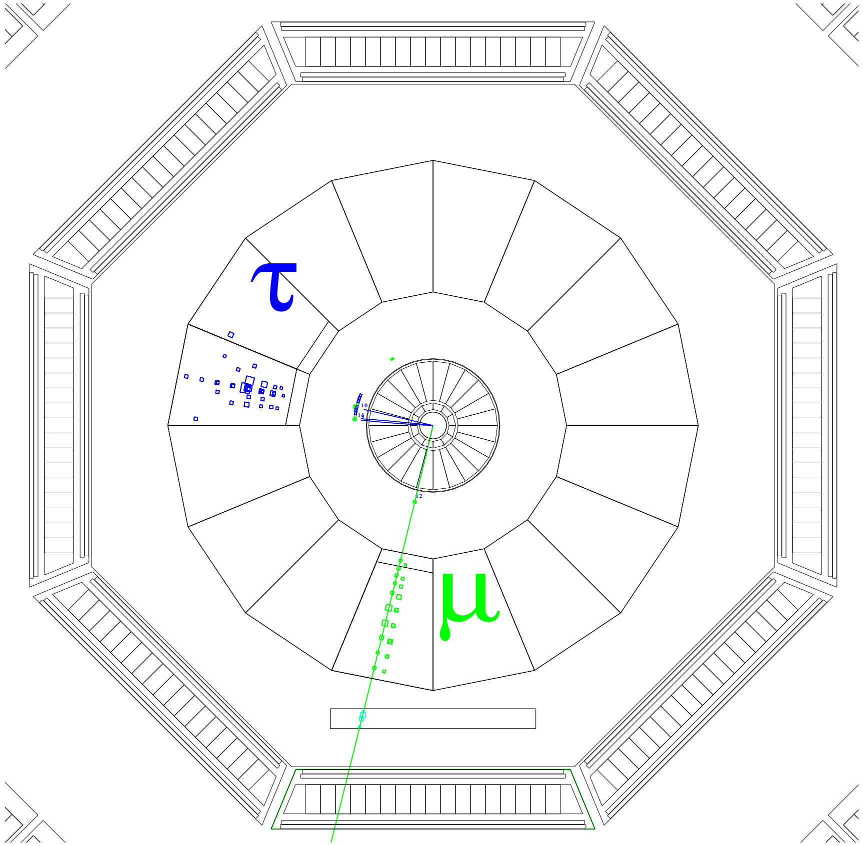
Using event shape variables $\Longrightarrow$



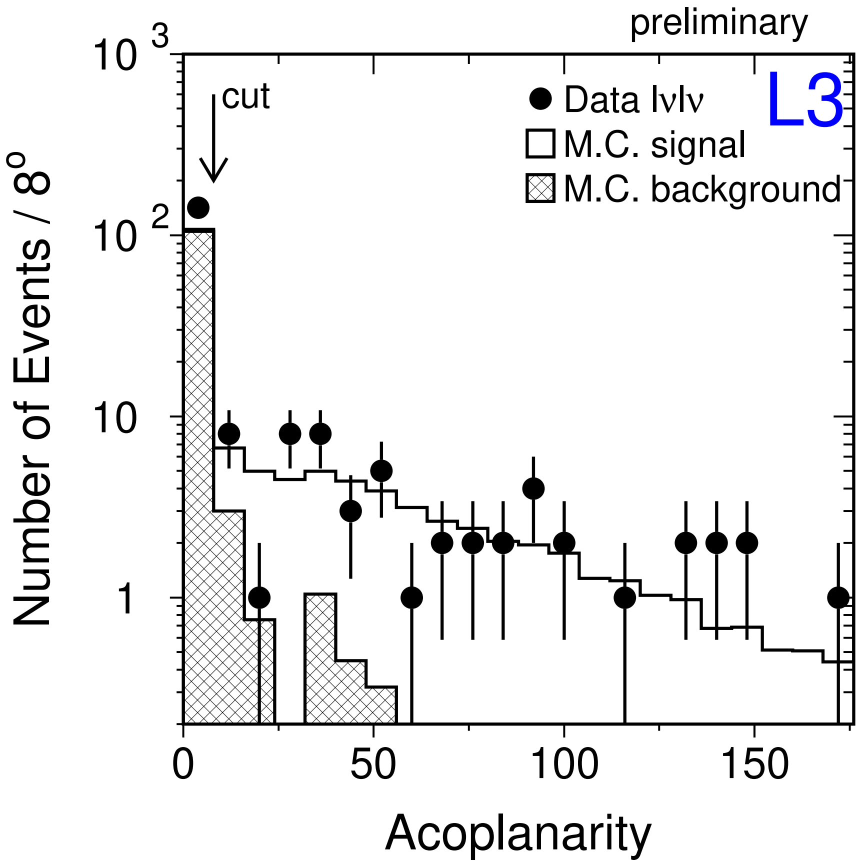
Selection efficiency : ~ 85 %

Selection purity : ~ 95 %

$W^+W^- \to l\nu l\nu$



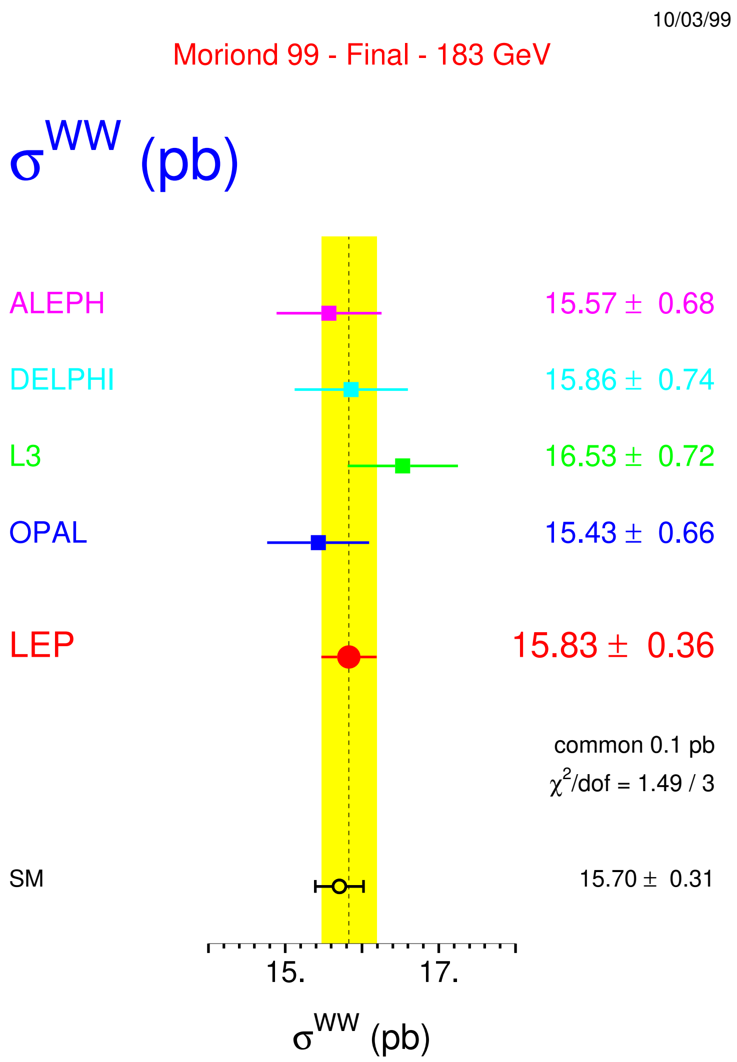
Background : $l^+l^-\gamma$

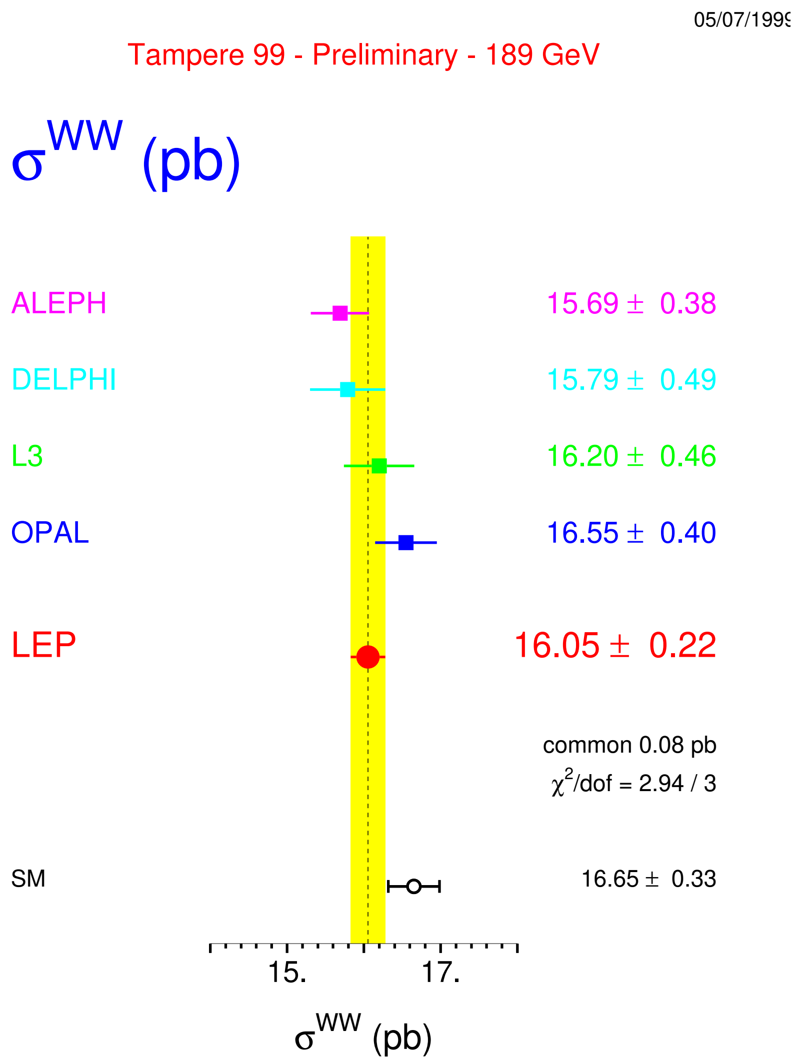


- large acoplanarity
- high energy of leptons
- identification of e, μ and τ
- missing transverse momentum (Neutrinos)

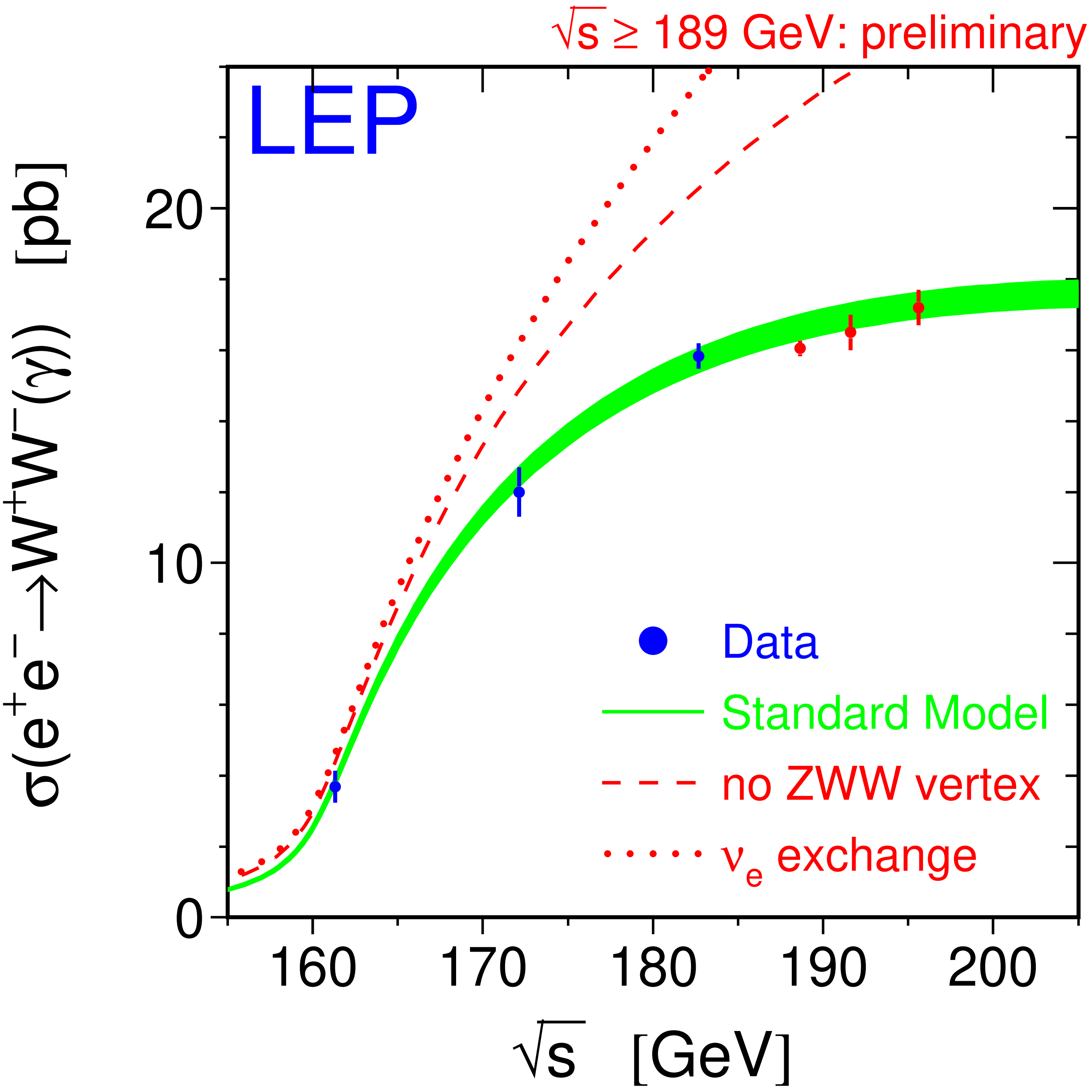
Selection efficiency : $\sim 60\ \%$

W-pair cross section





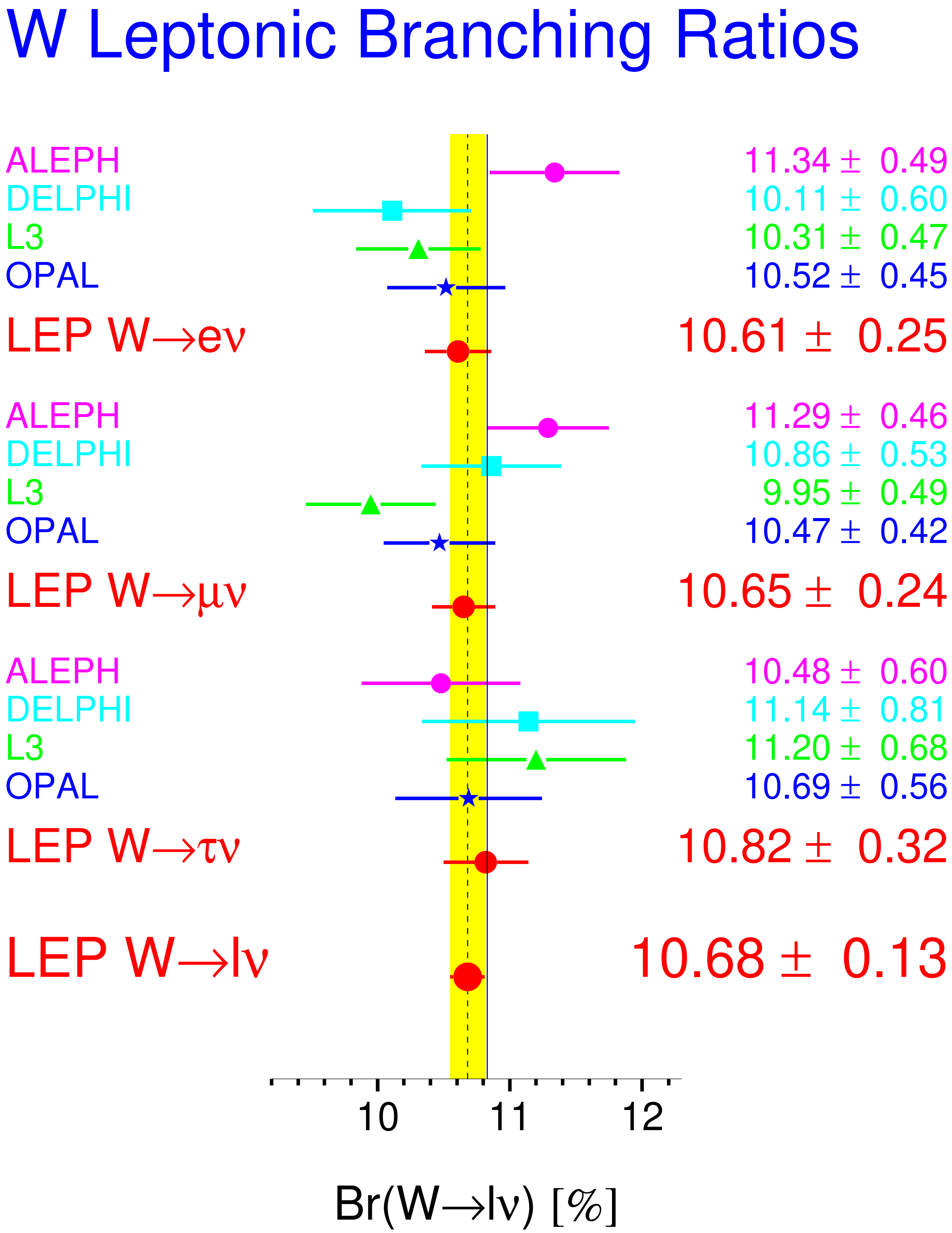
W-pair cross section



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

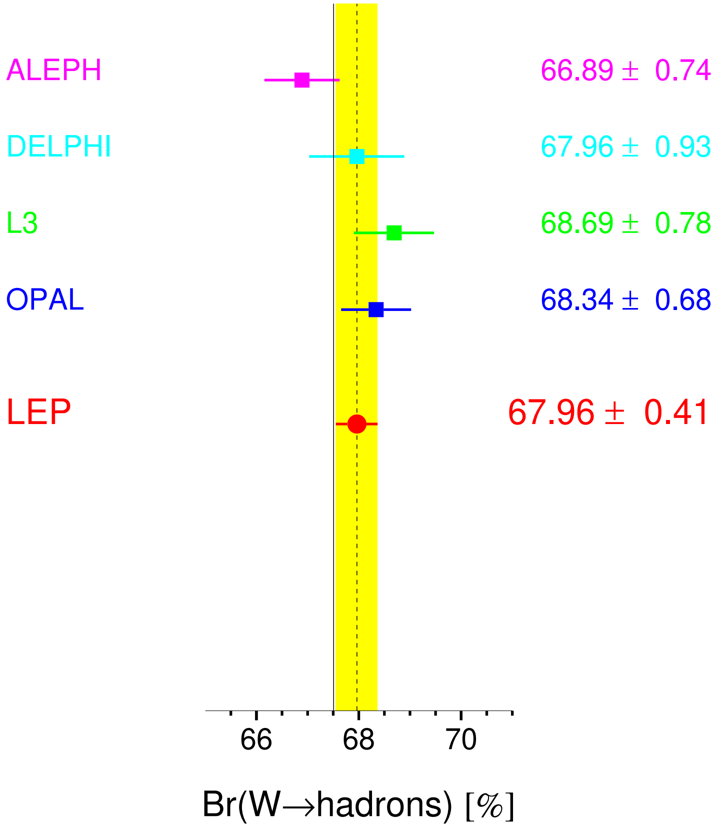
W Decay Branching Ratios

Test lepton universality in W decays SM: 10.8 %



Measurement of $|V_{cs}|$

Br(W→hadrons) [%]



Assuming lepton universality SM: 67.5 %

The W hadronic BR can be interpreted in terms of the CKM Matrix Element :

$$\frac{BR_{had}}{1-BR_{had}} = \sum |V_{qq}|^2 \ (1 + \frac{\alpha_s}{\pi})$$

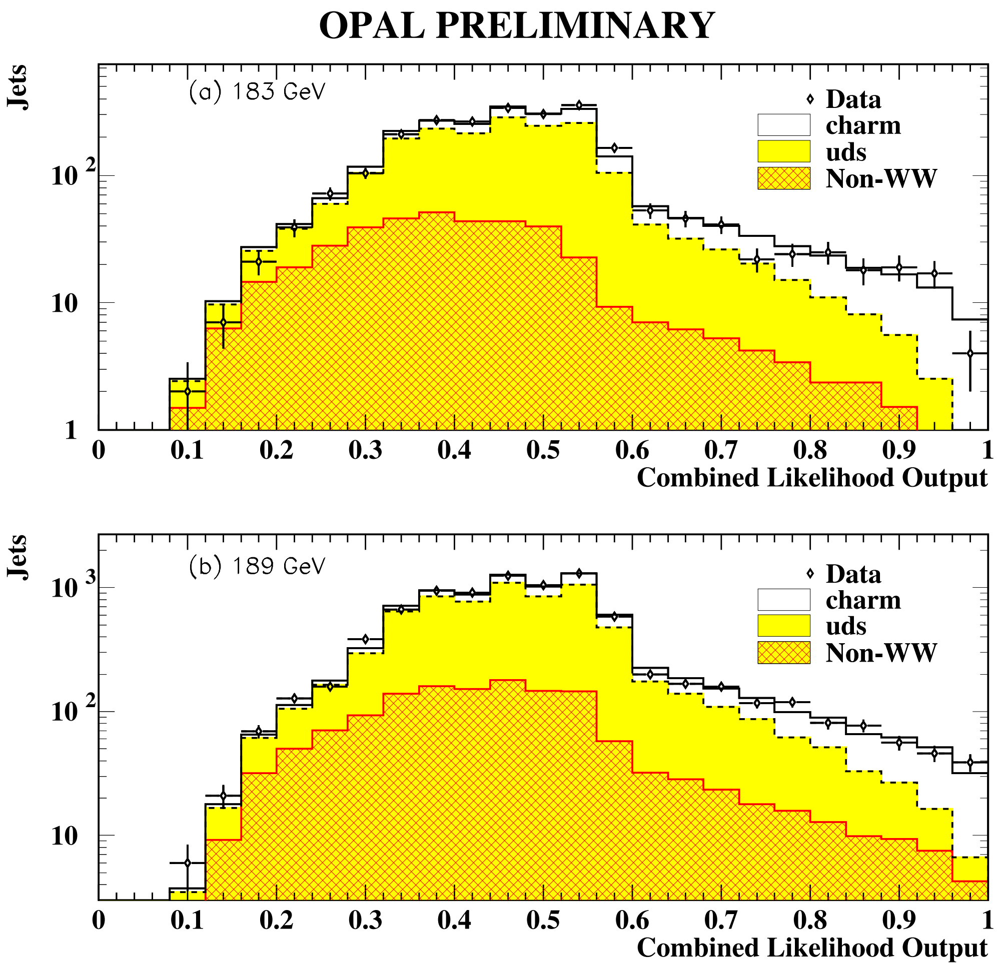
Challenging to derive the least well known element $|V_{cs}|$, using measured values of the other elements :

$$\Longrightarrow \qquad |V_{cs}| = 0.997 \pm 0.020$$

The most recent value of V_{cs} yields :

$$|V_{cs}| = 1.04 \pm 0.16$$

Direct Measurement of $|V_{cs}|$



direct determination of V_{cs} by charm tagging (183-189 GeV) :

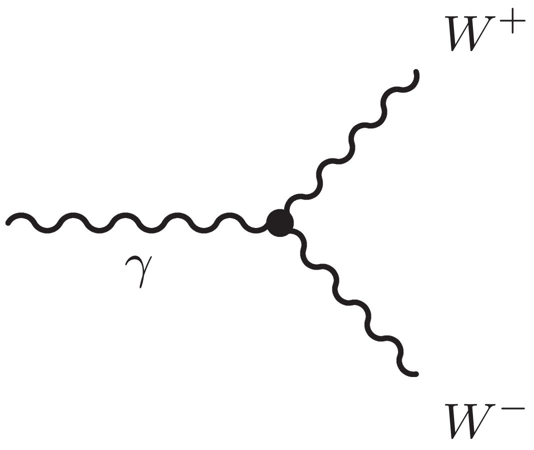
Measure :

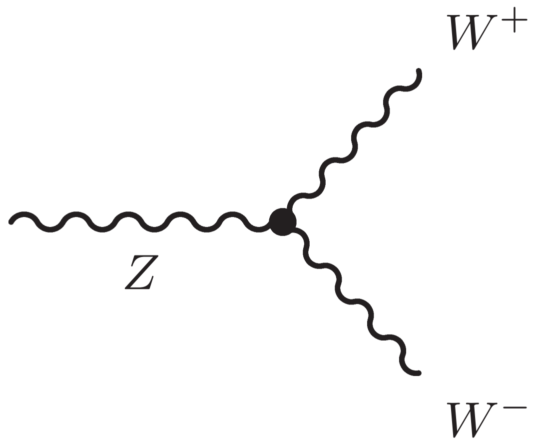
$$R_c = \frac{\Gamma(W \to cX)}{\Gamma(W \to hadrons)}$$

$$= \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{\sum |V_{qq}|^2}$$

	R_c	$\lvert V_{cs}\rvert$
ALEPH	$0.51 \pm 0.05 \pm 0.03$	$1.00 \pm 0.11 \pm 0.07$
OPAL	$0.47 \pm 0.04 \pm 0.06$	$0.91 \pm 0.07 \pm 0.11$

Couplings of the W Boson





E1 = $e g_1^\gamma$

M2 = $\frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$

E4 = $-\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$

SM values :

$$g_1^\gamma = g_1^Z = 1$$
$$\kappa_\gamma = \kappa_Z = 1$$
$$\lambda_\gamma = \lambda_Z = 0$$

Couplings of the W Boson

- 2 x 7 free parameters in a general Lorentz invariant ansatz
- Reduce the number by constraints
  - real couplings
  - C-,P- and CP invariance
  - QED gauge invariance (charge of $W^{\pm} = \pm e$)
- SU(2) gauge invariance
  - $\lambda_\gamma = \lambda_Z$
  - $\Delta\kappa_Z = \Delta\kappa_\gamma tan^2\theta_W + \Delta g_1^Z$

remaining parameter set :

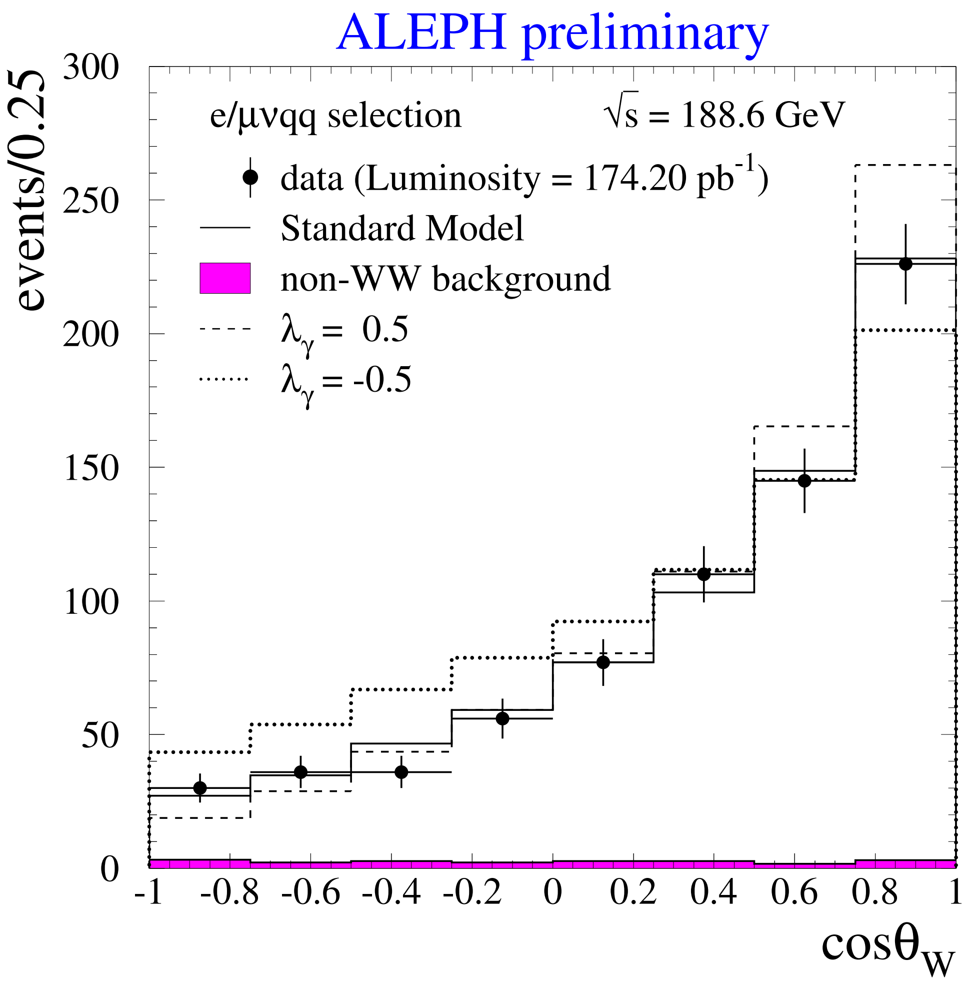
$$\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma$$

(Δ denotes deviation from SM value)

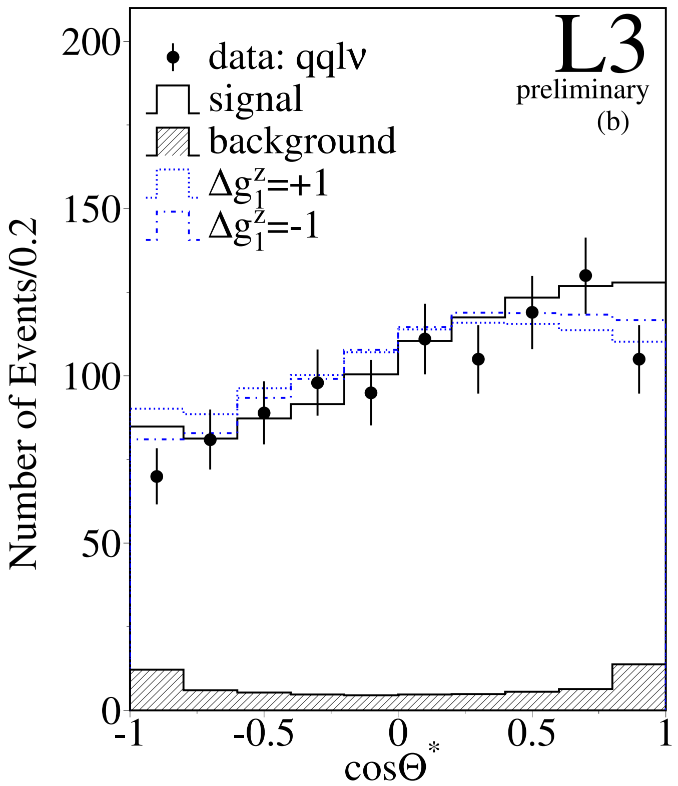
Deviations from the SM would :

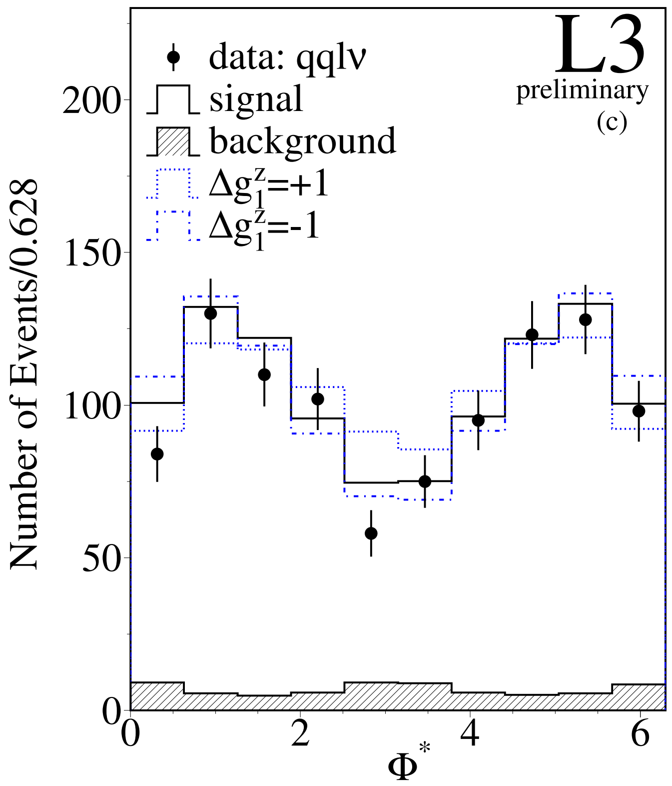
- increase $e^+e^- \rightarrow W^+W^-$
- modify W production angles
- modify W polarization

W production angle

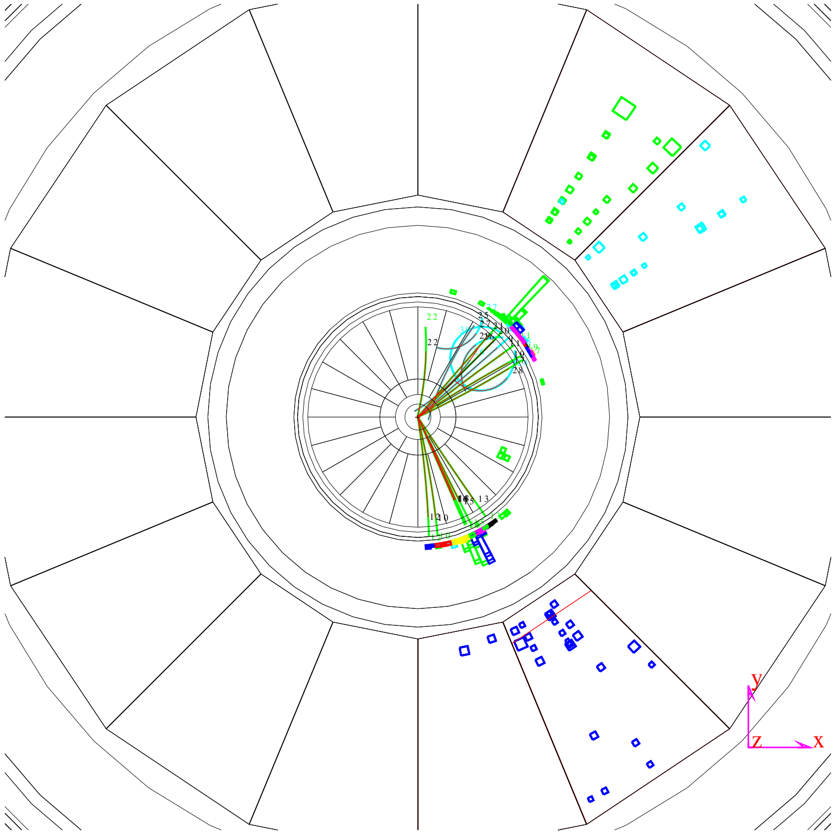


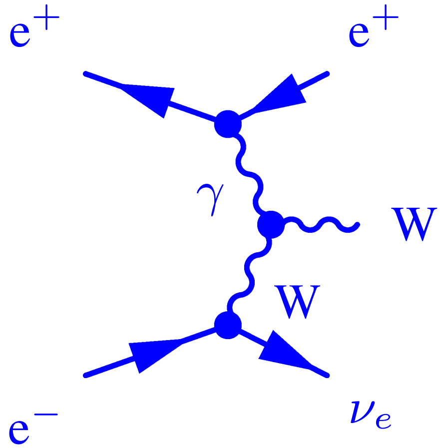
W decay angles





Single W production at LEP





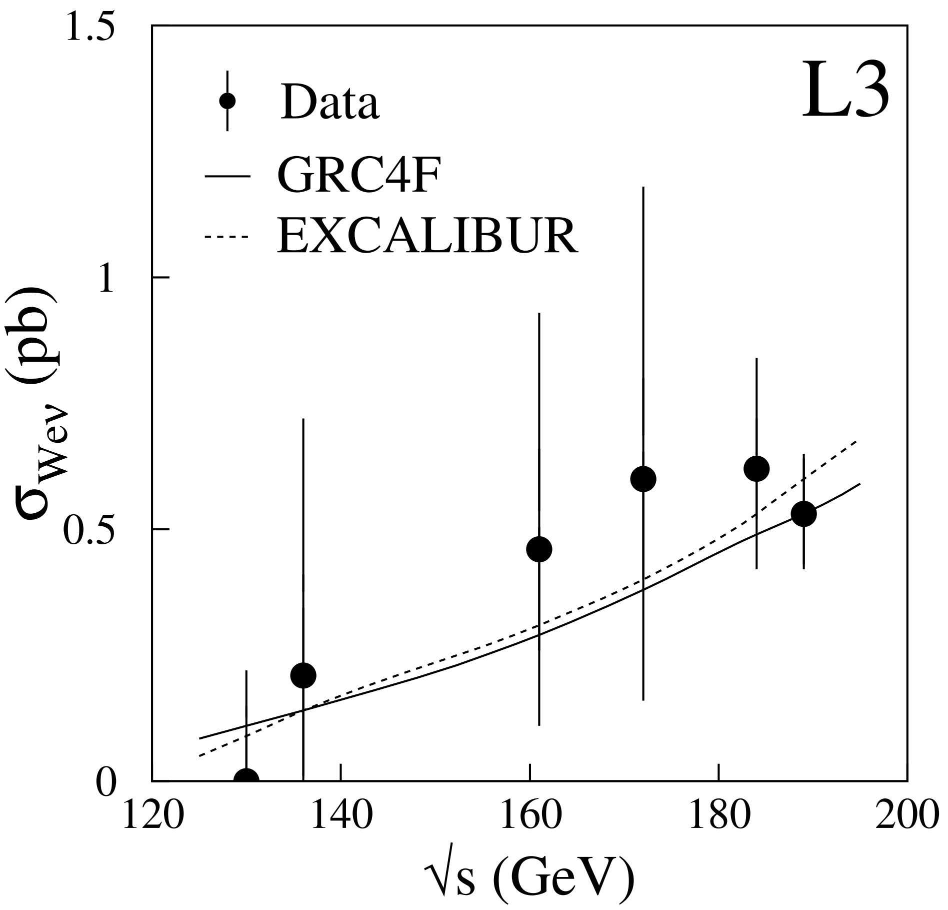
Signature :

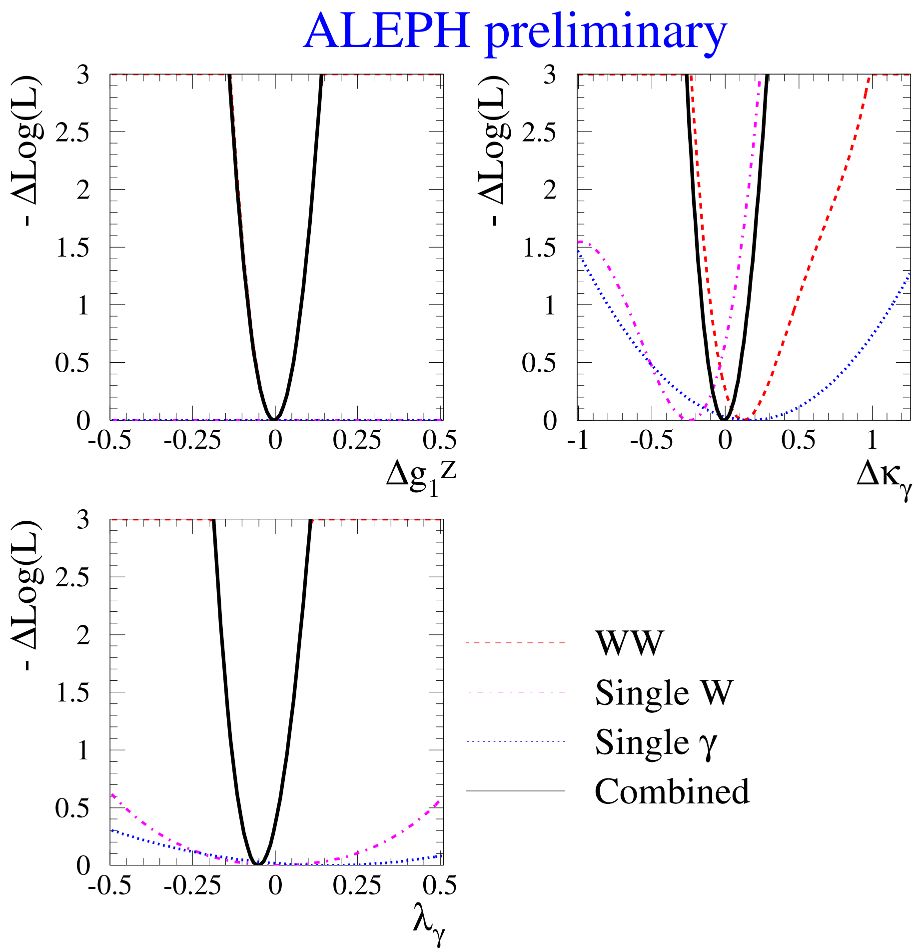
Wν + electron along the beam pipe

- 2 jets (large BR, large background)
- 1 Lepton (small BR, small background)

cross section as a pure test of the γWW vertex

take the information from single photon events

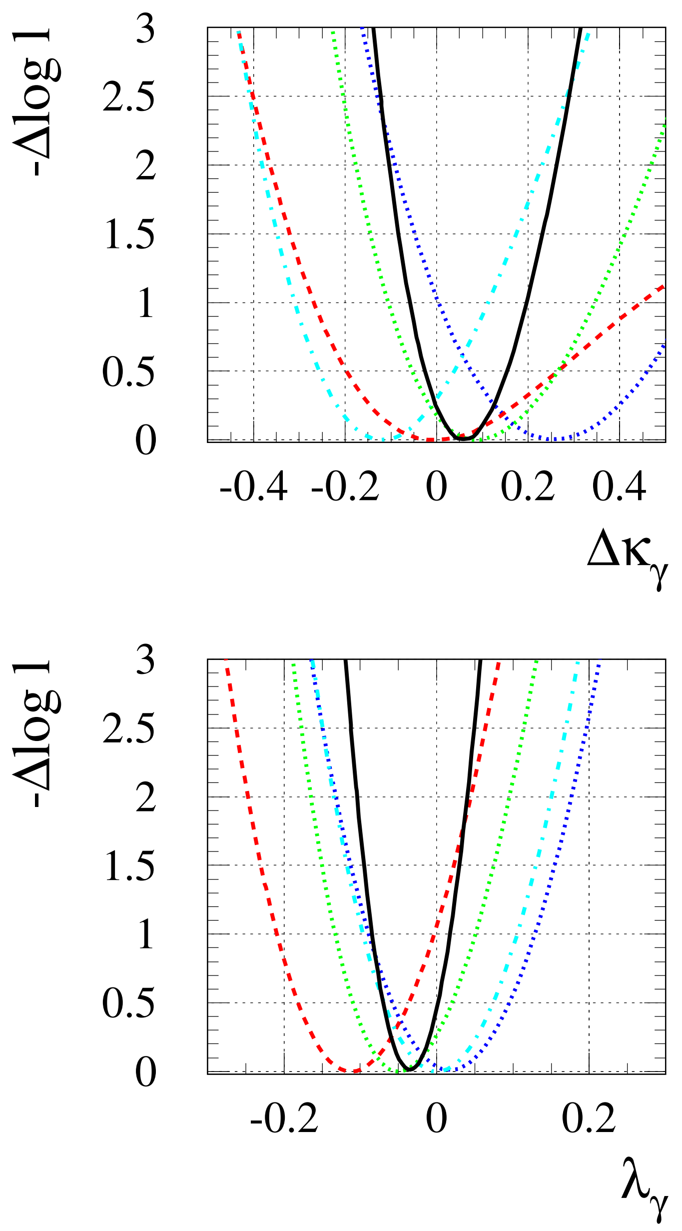




Limits on anomalous triple boson couplings

LEP combination up to 189 GeV :

ALEPH + DELPHI + L3 + OPAL



$\Delta\kappa_\gamma = 0.06^{+0.09}_{-0.09}$

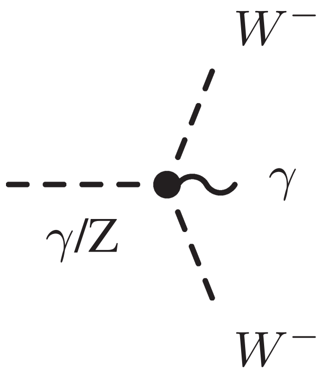
$\Delta g_1^Z = -0.01^{+0.03}_{-0.03}$

$\lambda_\gamma = -0.03^{+0.04}_{-0.04}$

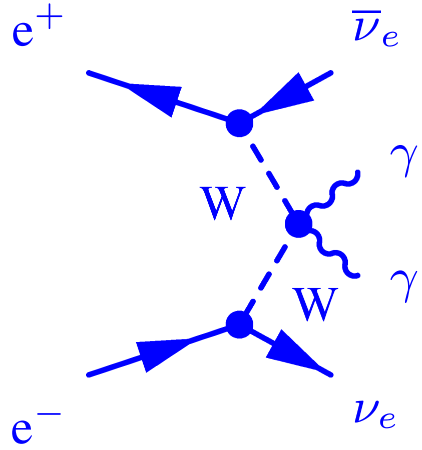
Quatic Gauge Couplings

First direct constraints on $WW\gamma\gamma$, $WWZ\gamma$

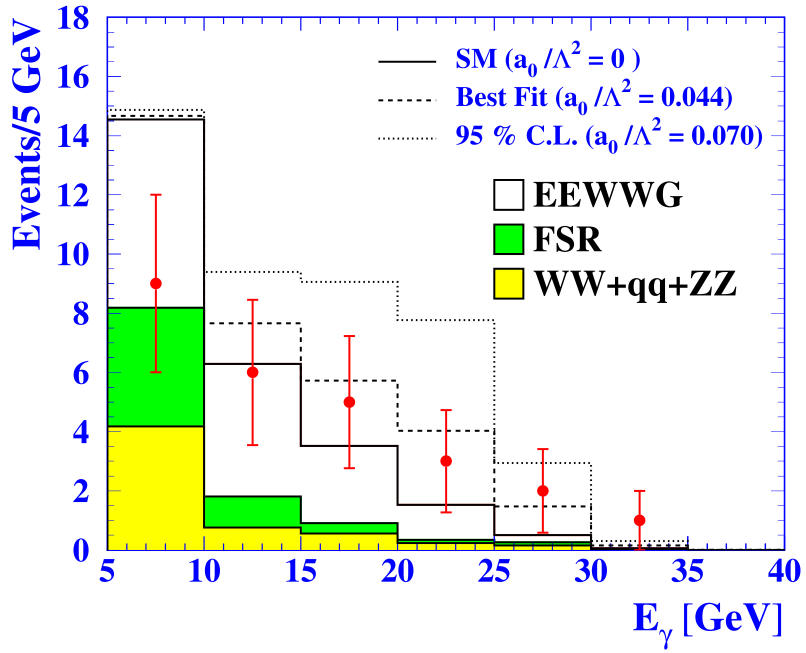
Anomalous QGCs a_0, a_c and a_n



Combine with analysis of $\nu_e\overline{\nu}_e\gamma\gamma$



OPAL preliminary



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

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

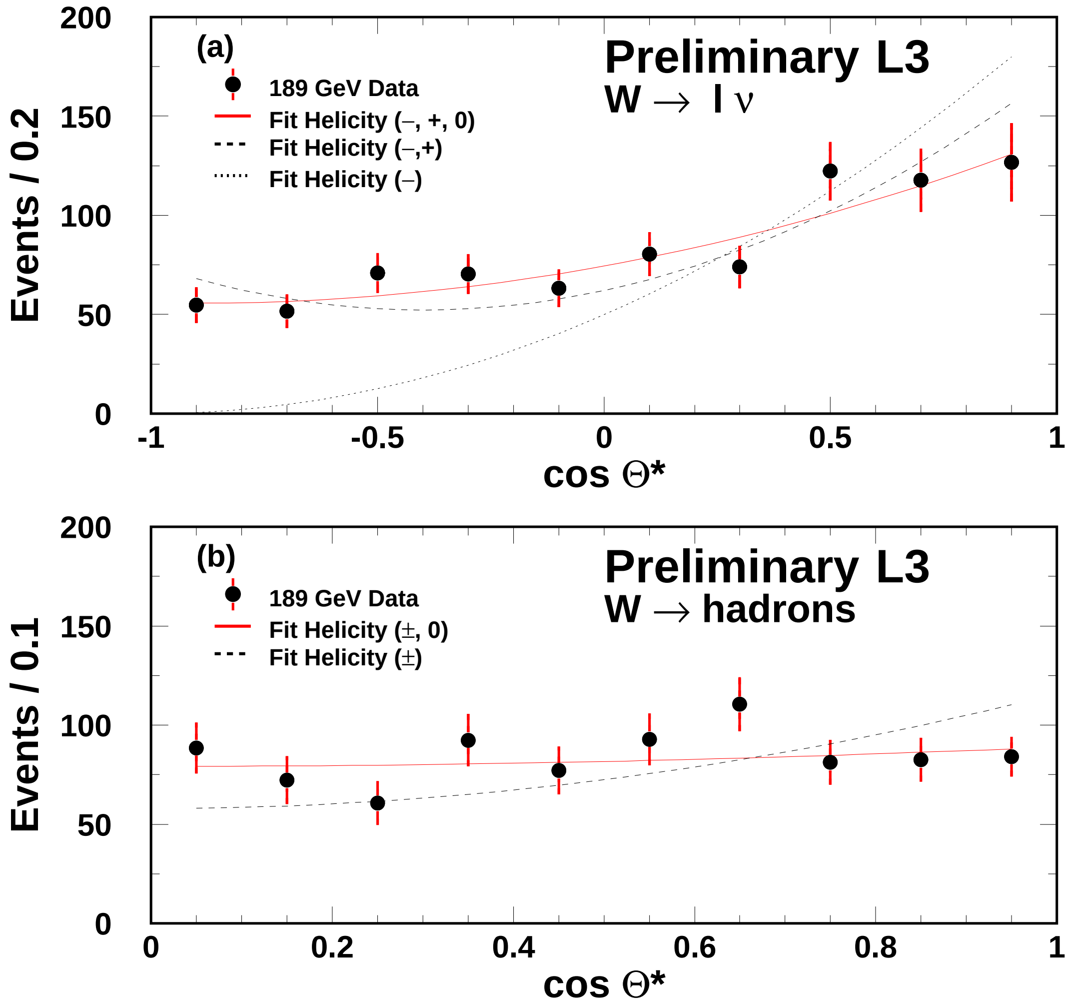
$$-0.61\ \mathrm{GeV}^{-2} < \quad a_n/\Lambda^2 \quad < +0.57\ \mathrm{GeV}^{-2}$$

Λ new physics scale

First unambiguous observation of longitudinally polarized W's

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

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

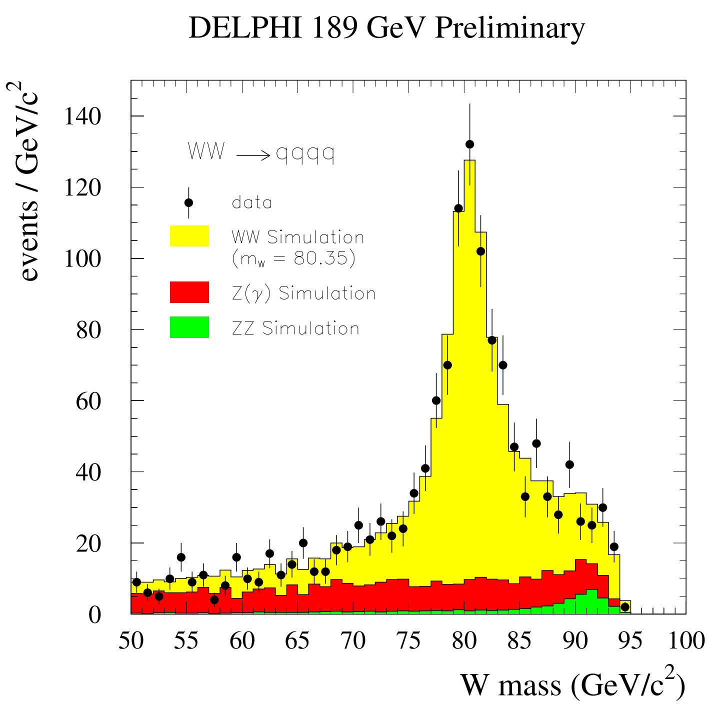


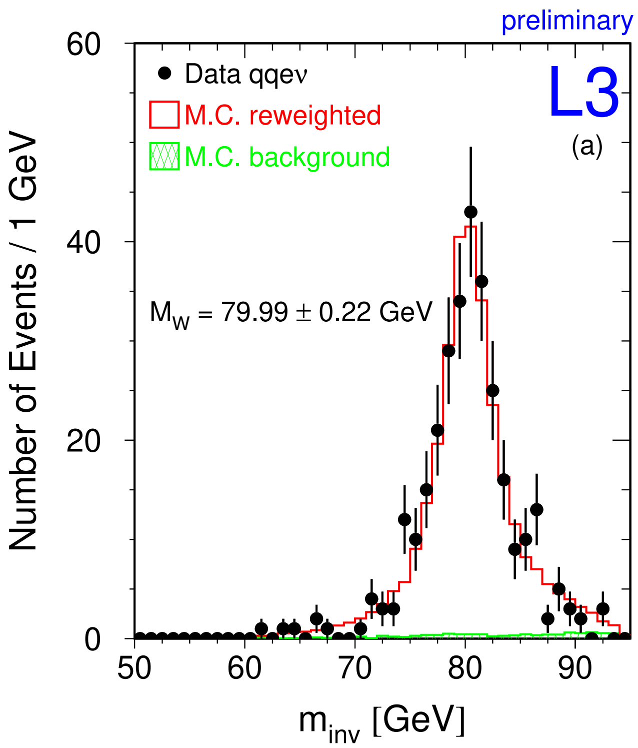
Fraction of longitudinally polarized W bosons:

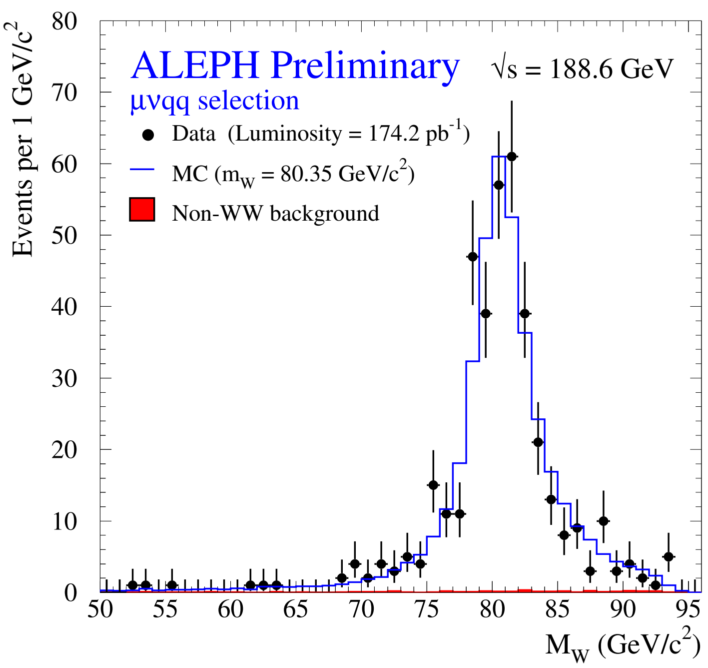
183 GeV	$0.276 \pm 0.092 \pm 0.03$
189 GeV	$0.244 \pm 0.048 \pm 0.03$
SM	0.26

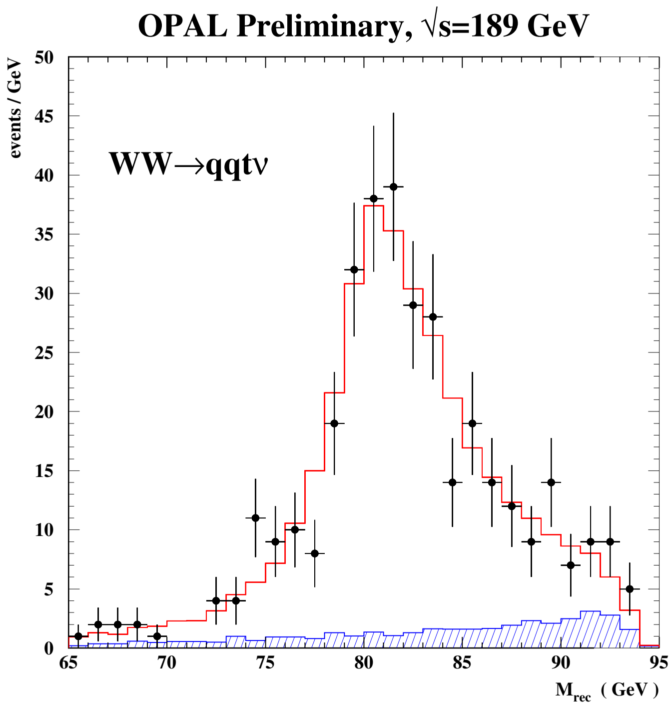
W Mass

Reconstructed mass distributions

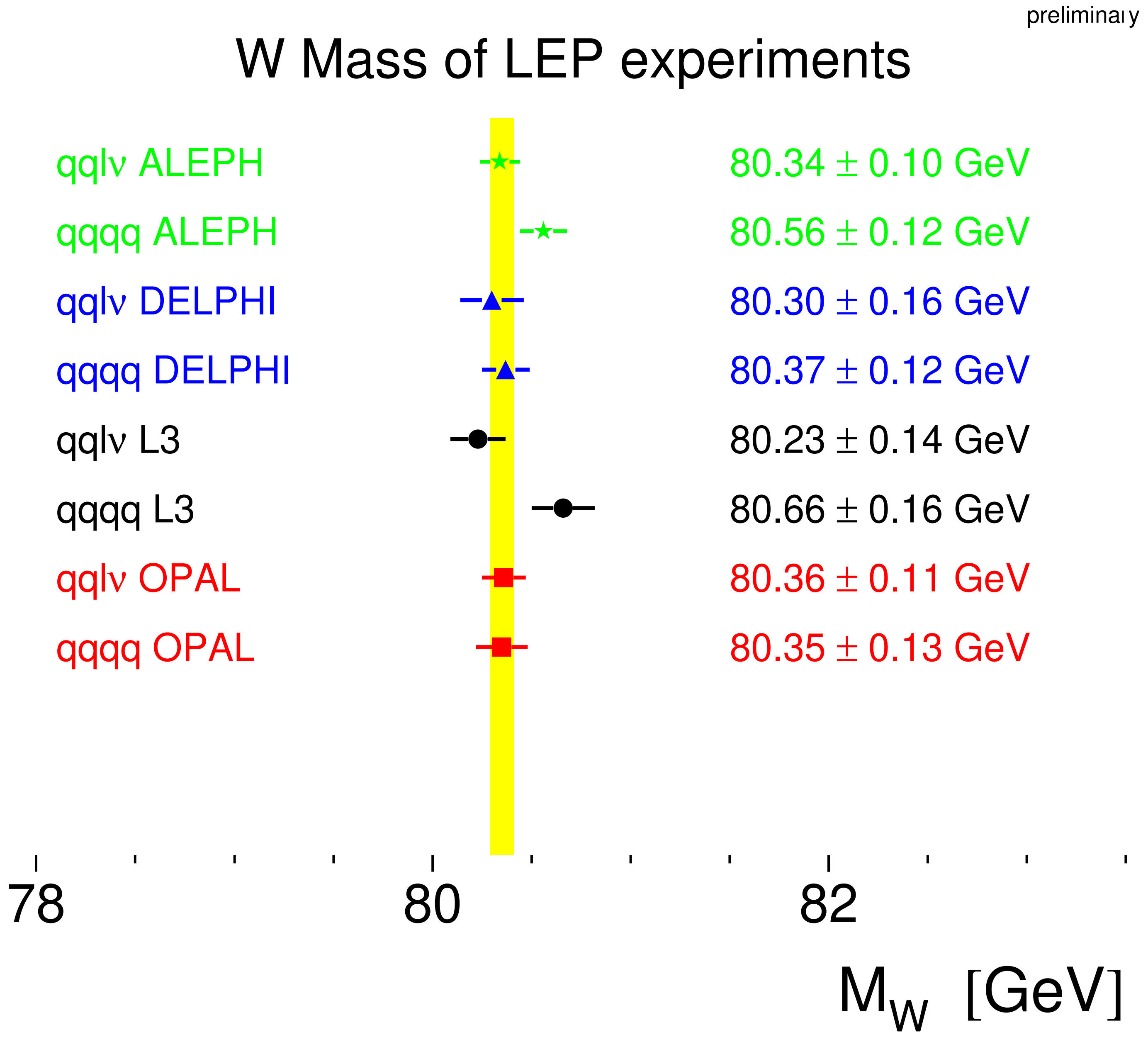








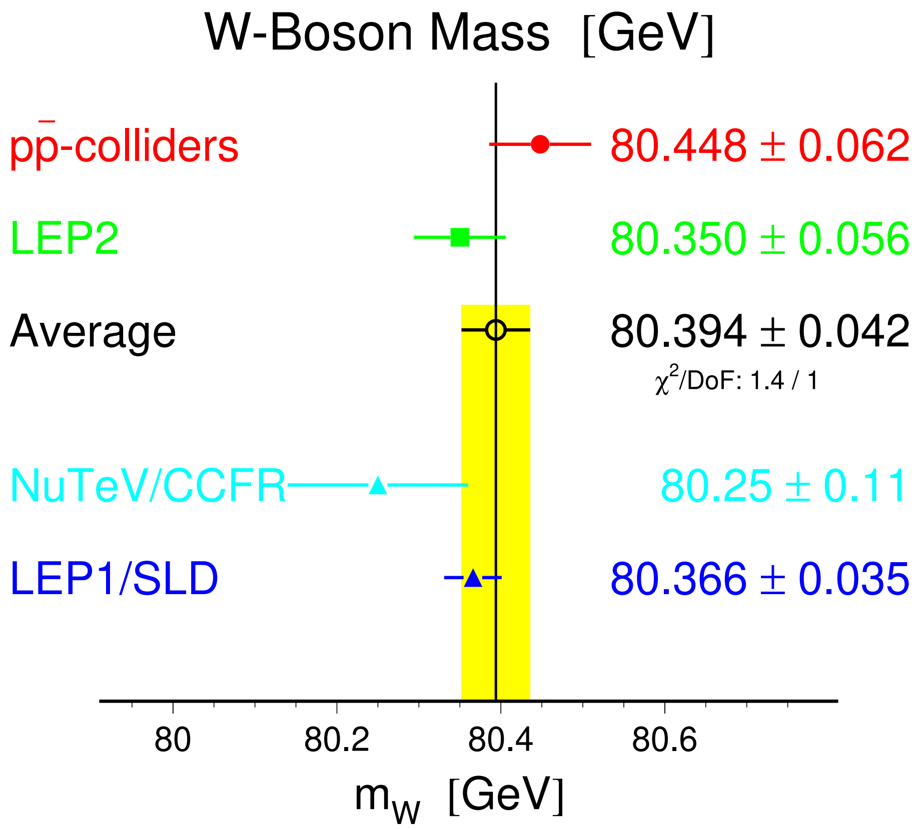
LEP W Mass, $\sqrt{s}$ = 172-189 GeV

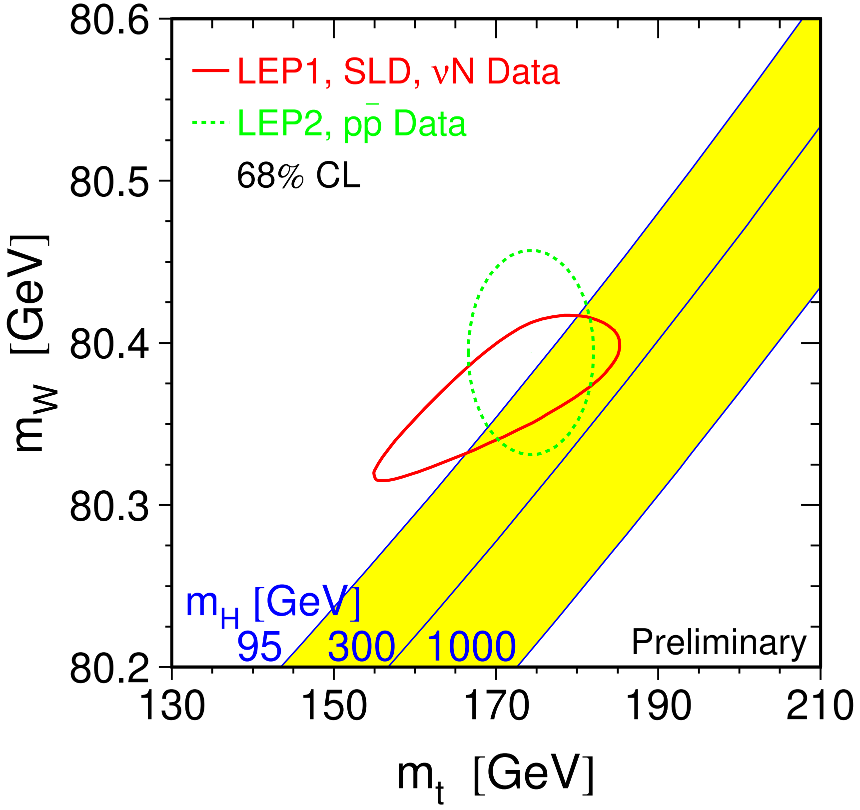


With LEP σ_{WW} (161 GeV) : $M_W = 80.40 \pm 0.22$ GeV

LEP combined : $M_W = 80.350 \pm 0.056$ GeV

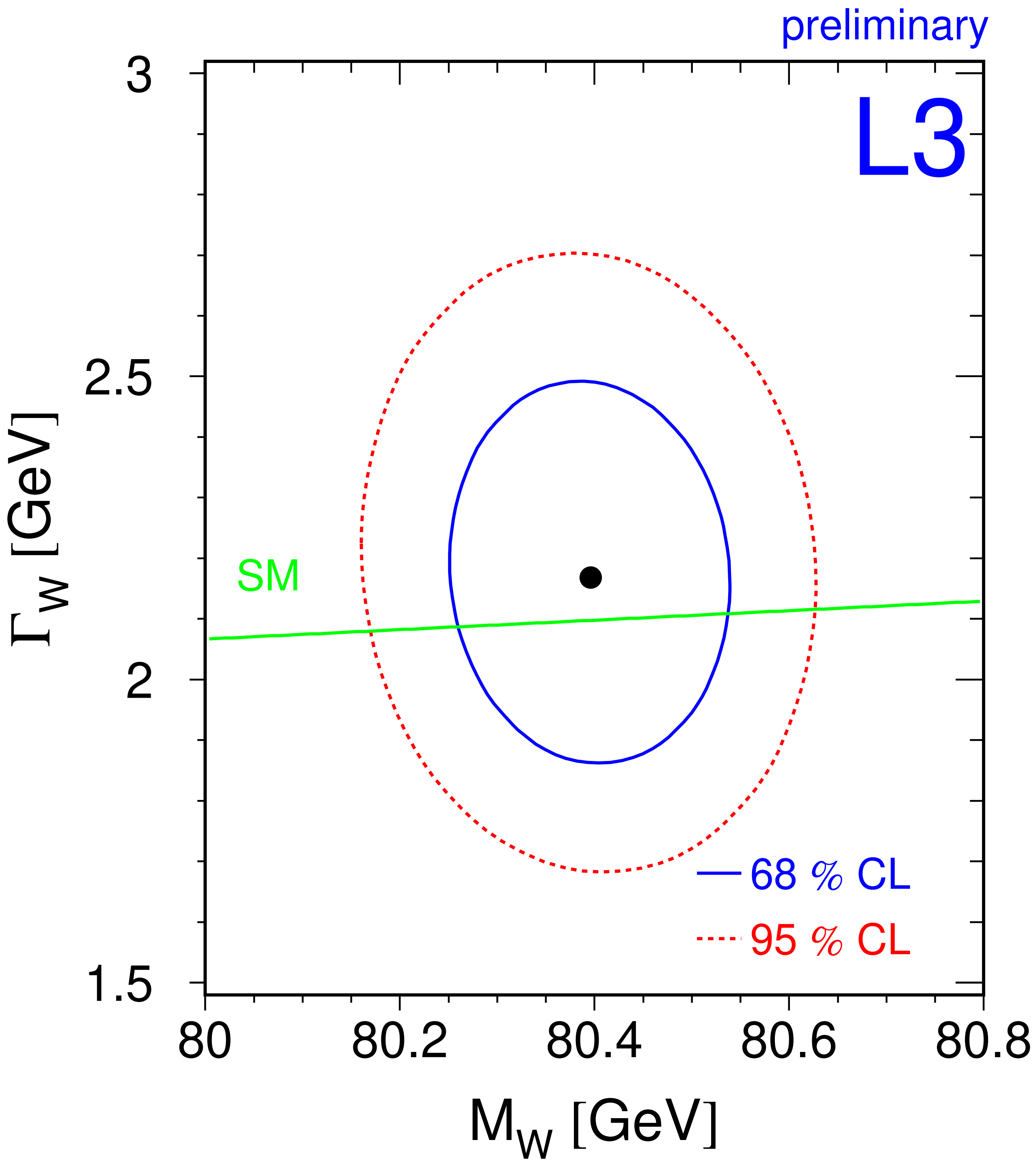
Impact of W Mass Measurement





W Width

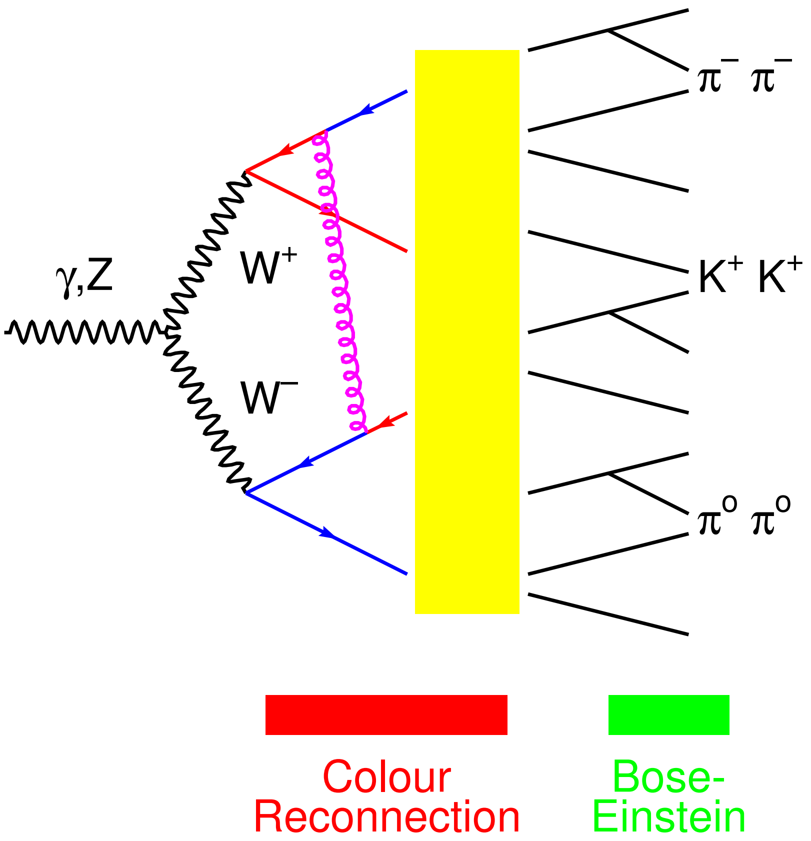
Fit simultaneously Γ_W and M_W



LEP combined : $\Gamma_W = 2.12 \pm 0.20$ GeV SM : 2.09

Tevatron : $\Gamma_W = 2.055 \pm 0.125$ GeV

Colour reconnection



- Investigate charge multiplicity:

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

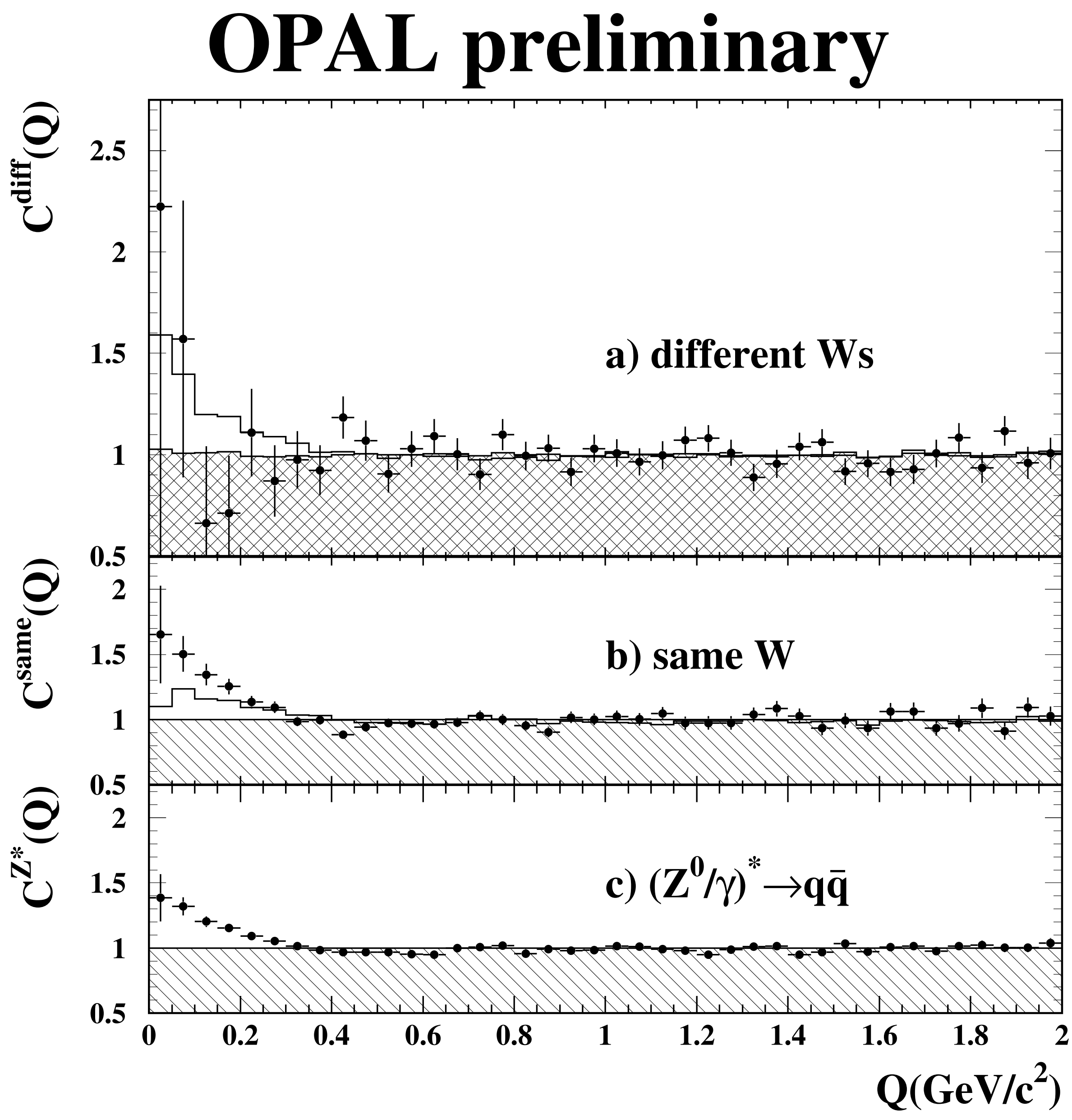
ALEPH	$\Delta n_{\rm ch}$	$+0.52 \pm 0.52$
DELPHI	$r_{\rm ch}$	$+0.977 \pm 0.017 \pm 0.027$
L3	$\Delta n_{\rm ch}$	$-0.23 \pm 0.40 \pm 0.52$
OPAL	$\Delta n_{\rm ch}$	$+0.7 \pm 0.8 \pm 0.6$

Estimated systematic error on M_W: 25 - 70 MeV

Bose-Einstein Correlation

Study correlation function:

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



Estimated systematic error on M_W: 20 - 60 MeV

Summary and Outlook

LEP is working very successful at high energy

The cross section measurements at 200 GeV on the way

W-Decay branching ratios are determined up to 189 GeV

Improved value of V_{cs}

WWZ and WWγ couplings measured at few percent level

$$g_1^Z = 0.99 \pm 0.03$$
$$\kappa_\gamma = 1.04 \pm 0.08$$
$$\lambda_\gamma = -1.04 \pm 0.04$$

First study of the Quartic Gauge Couplings

First observation of the longitudinally polarized W's

The W Mass up to 189 GeV

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

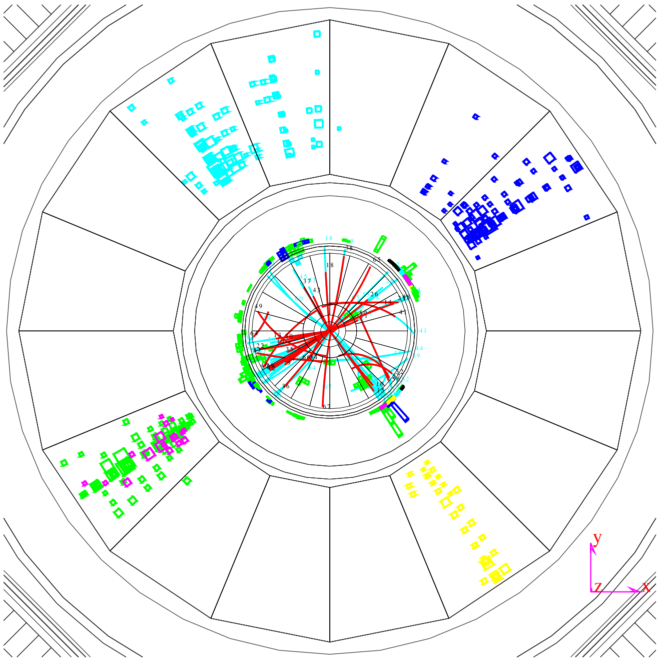
Final state interactions are studied

The W Width up to 189 GeV

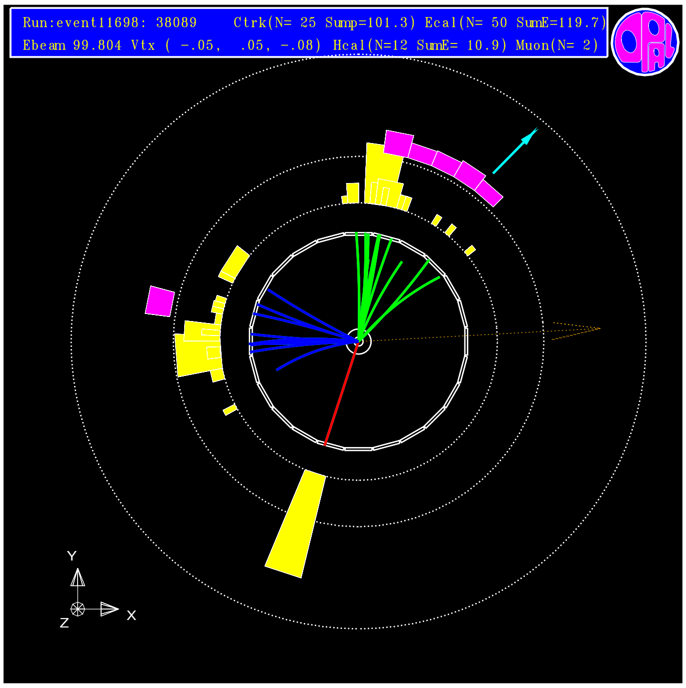
$$\Gamma_W = 2.12 \pm 0.20 \text{ GeV}$$

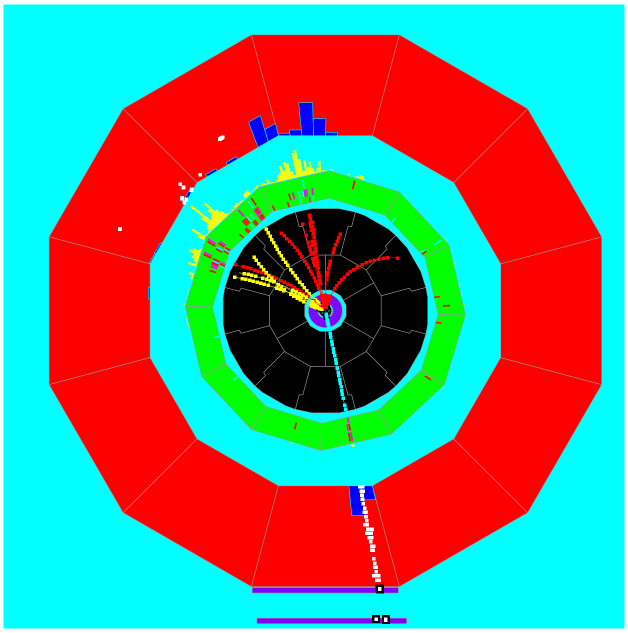
Events at $\sqrt{s} = 200$ GeV

L3 WW$\rightarrow q\bar{q}q\bar{q}$

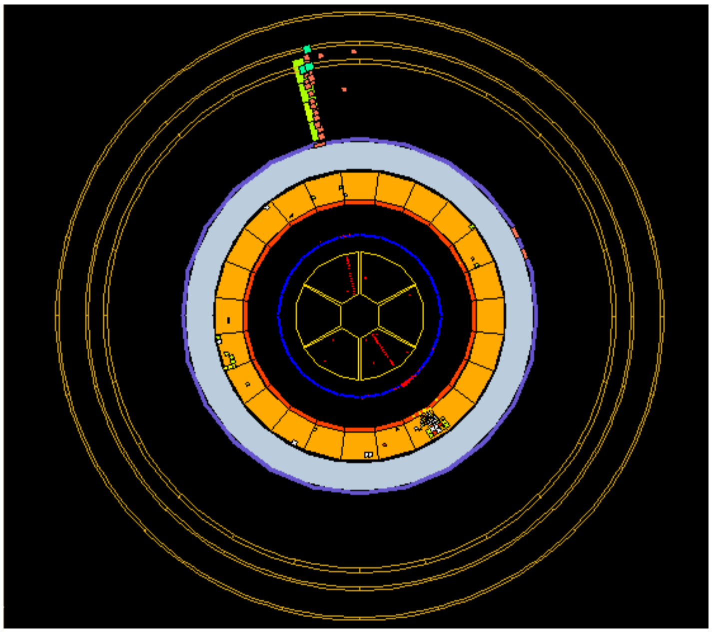


OPAL WW$\rightarrow q\bar{q}e\nu$





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



DELPHI WW$\rightarrow e\nu\mu\nu$