Measurement of Mass and Couplings of the W Boson at LEP

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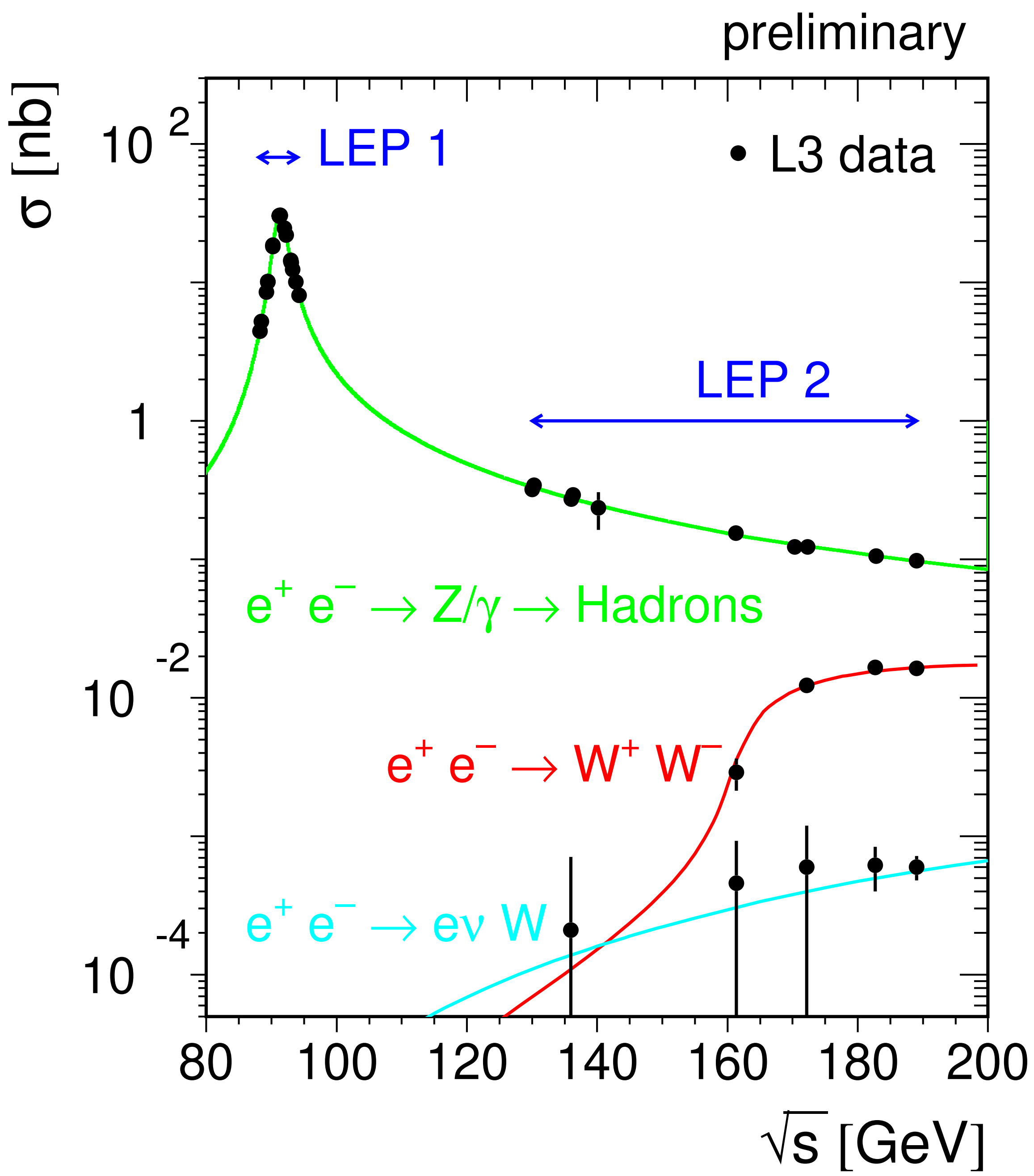
Outline

- Introduction
- W Mass Reconstruction
- Fitting Methods and Results
- Final State Interactions
- W Couplings Measurement
- Results from W-pairs, Single W's and Single γ's
- Conclusion

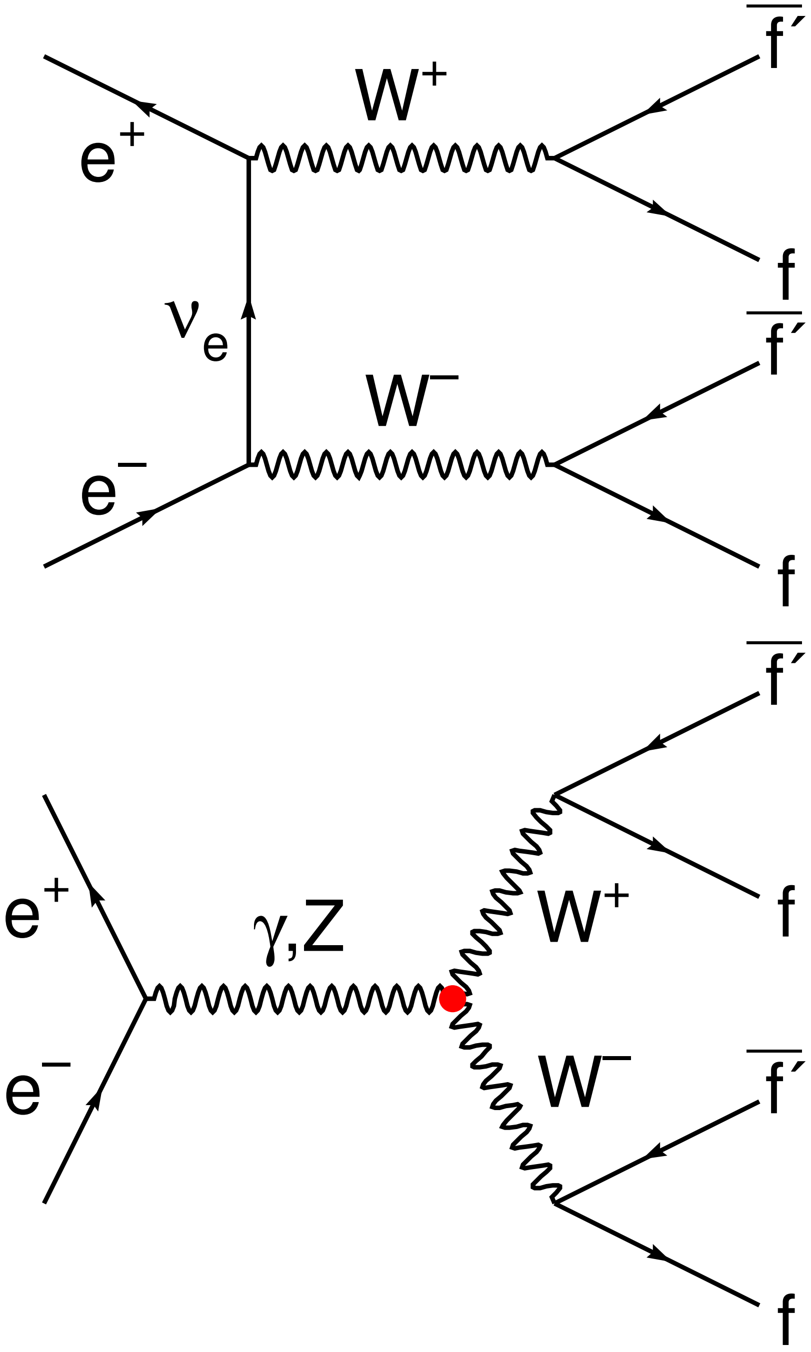
LEP Program



- ○ Luminosity 230 – 260 pb^{-1} per experiment
- ○ about 3500 W-pair events per experiment
- ○ about 100 single W events per experiment

▷ Most results include just 161 – 183 GeV data
+ some plots and expectations for 189 GeV

W Pair Production



- 4-fermion final states:

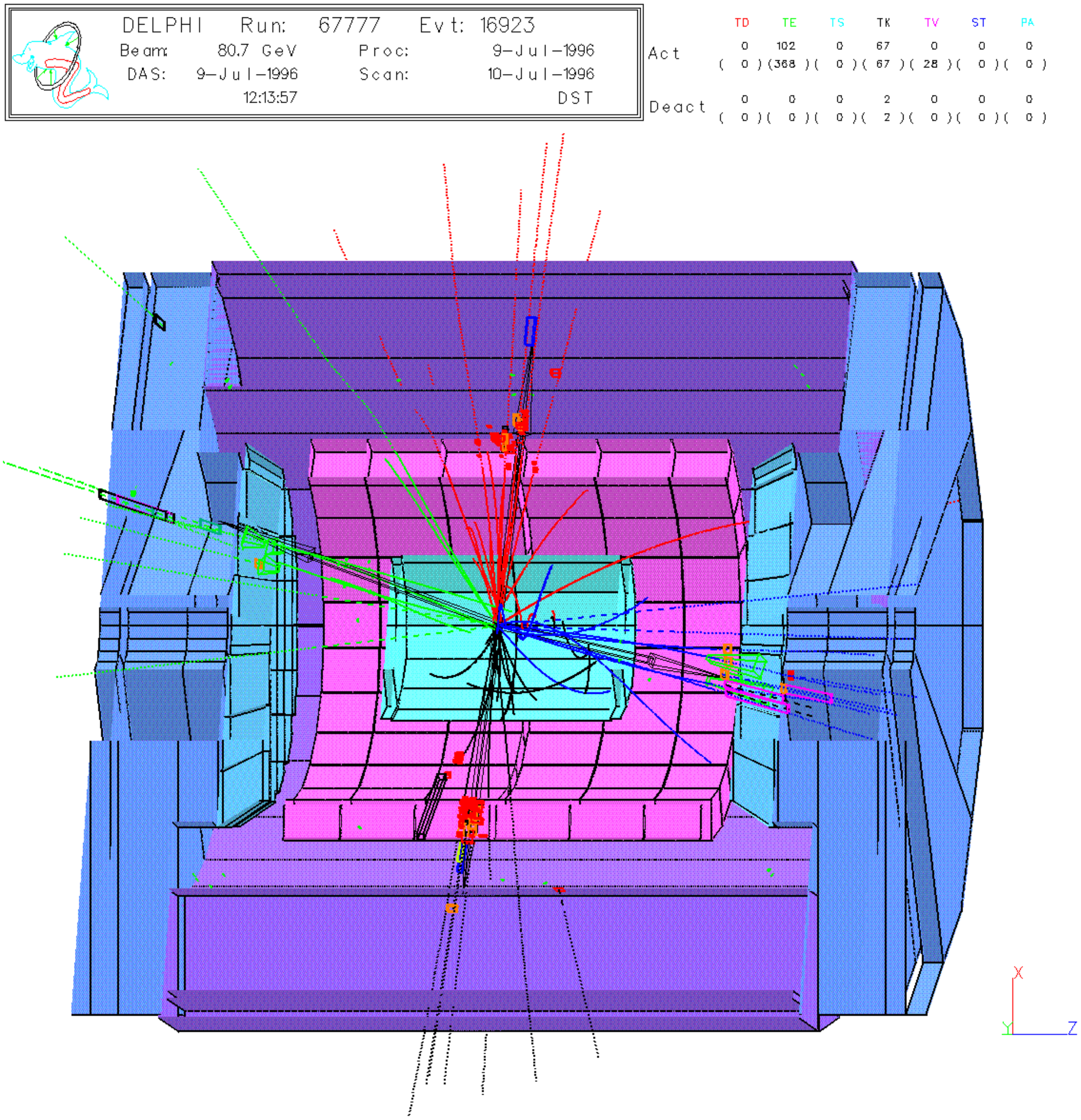
$$qqqq, qqe\nu, qq\mu\nu, qq\tau\nu, \ell\nu\ell\nu$$

- Cross-section
- Reconstructed W decay products

$\longrightarrow$ Measurement of the W mass

$\longrightarrow$ Determination of W couplings to γ and Z

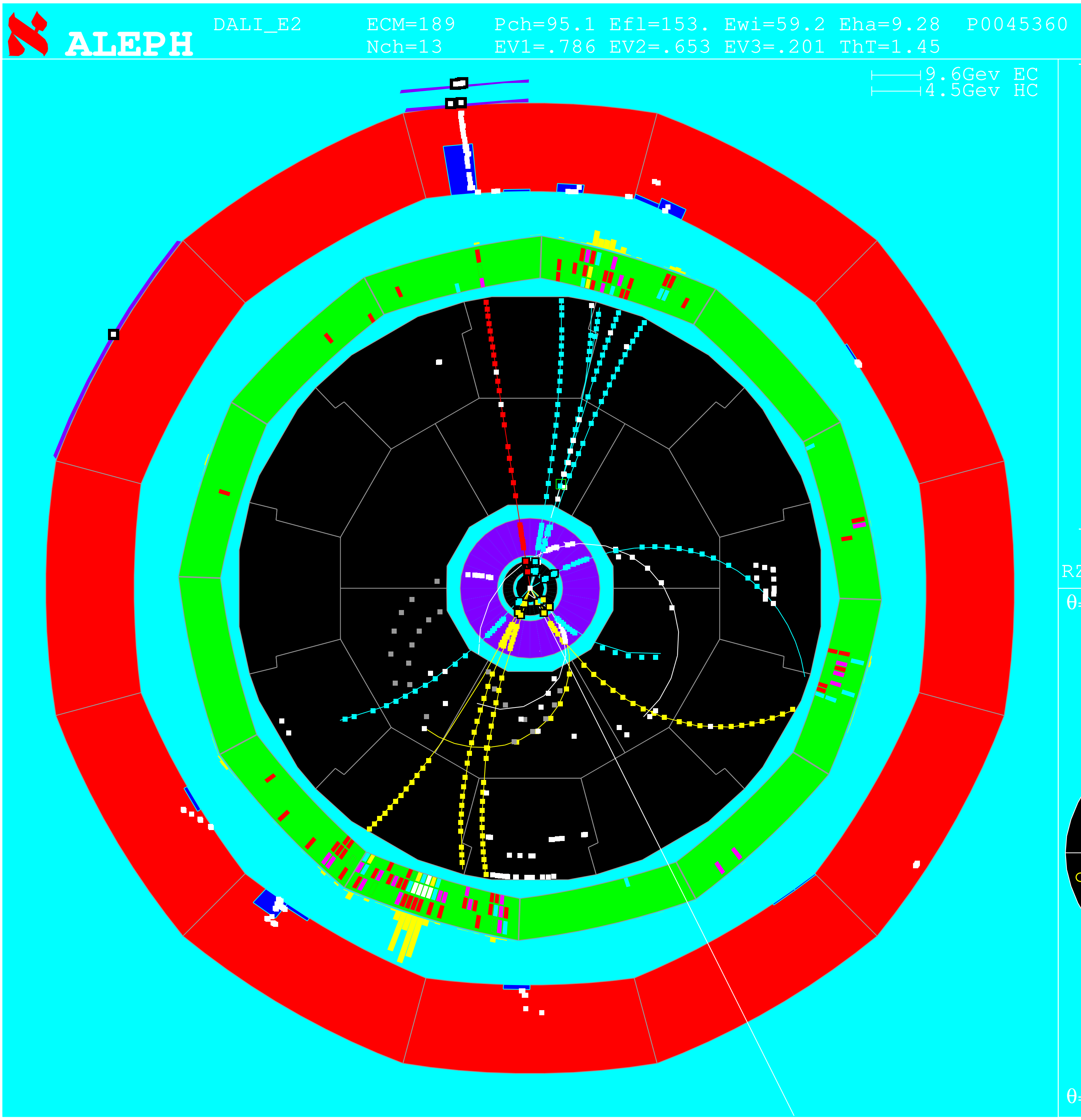
W-pairs: qqqq selection



- 45.6 % of all W-pairs
- Number of Events: now ≈ 1600 per experiment
- Efficiency: 80%
- Purity: 80%

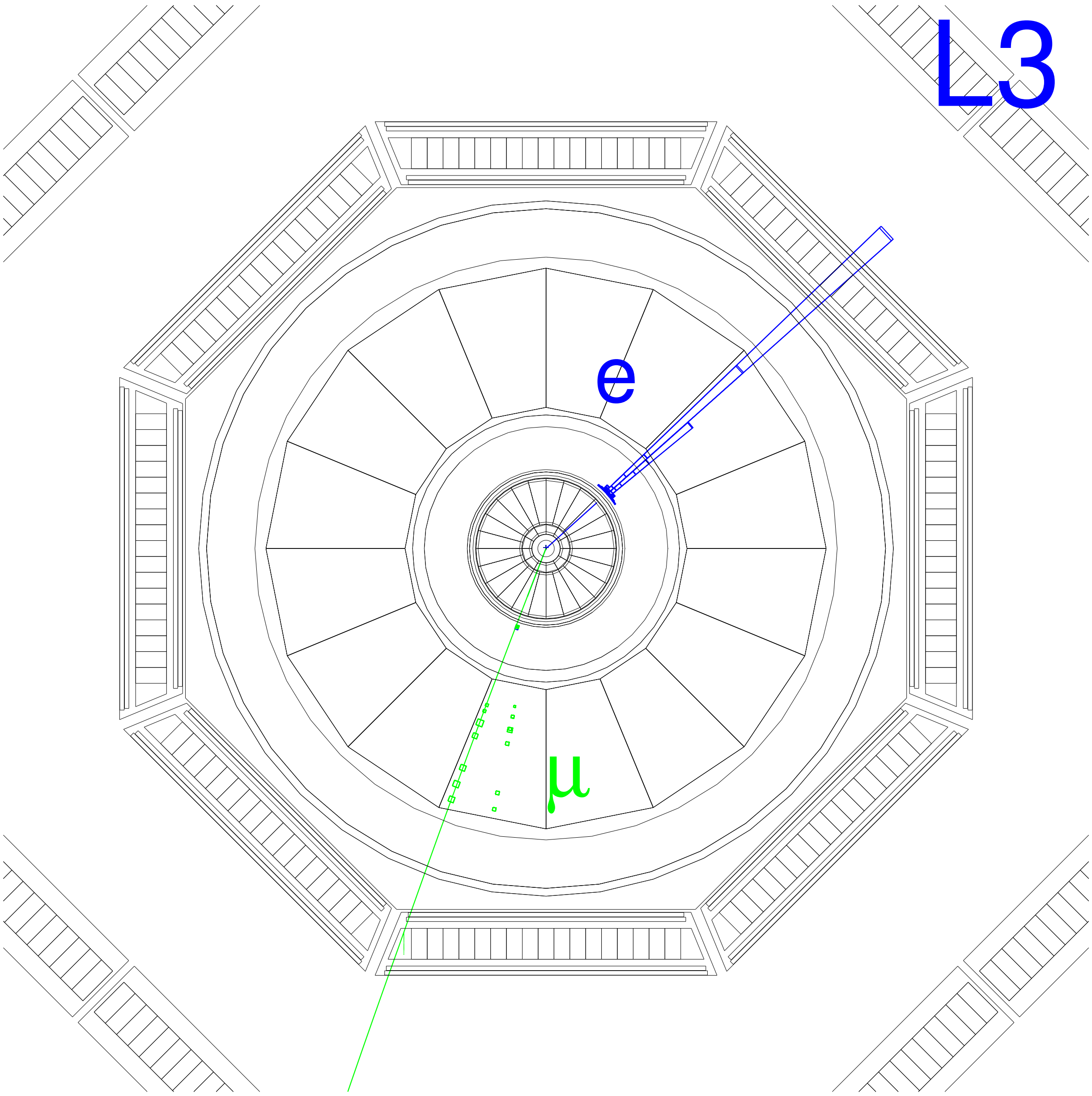
qq$\ell\nu$ Selection

Example: qq$\mu\nu$ Event



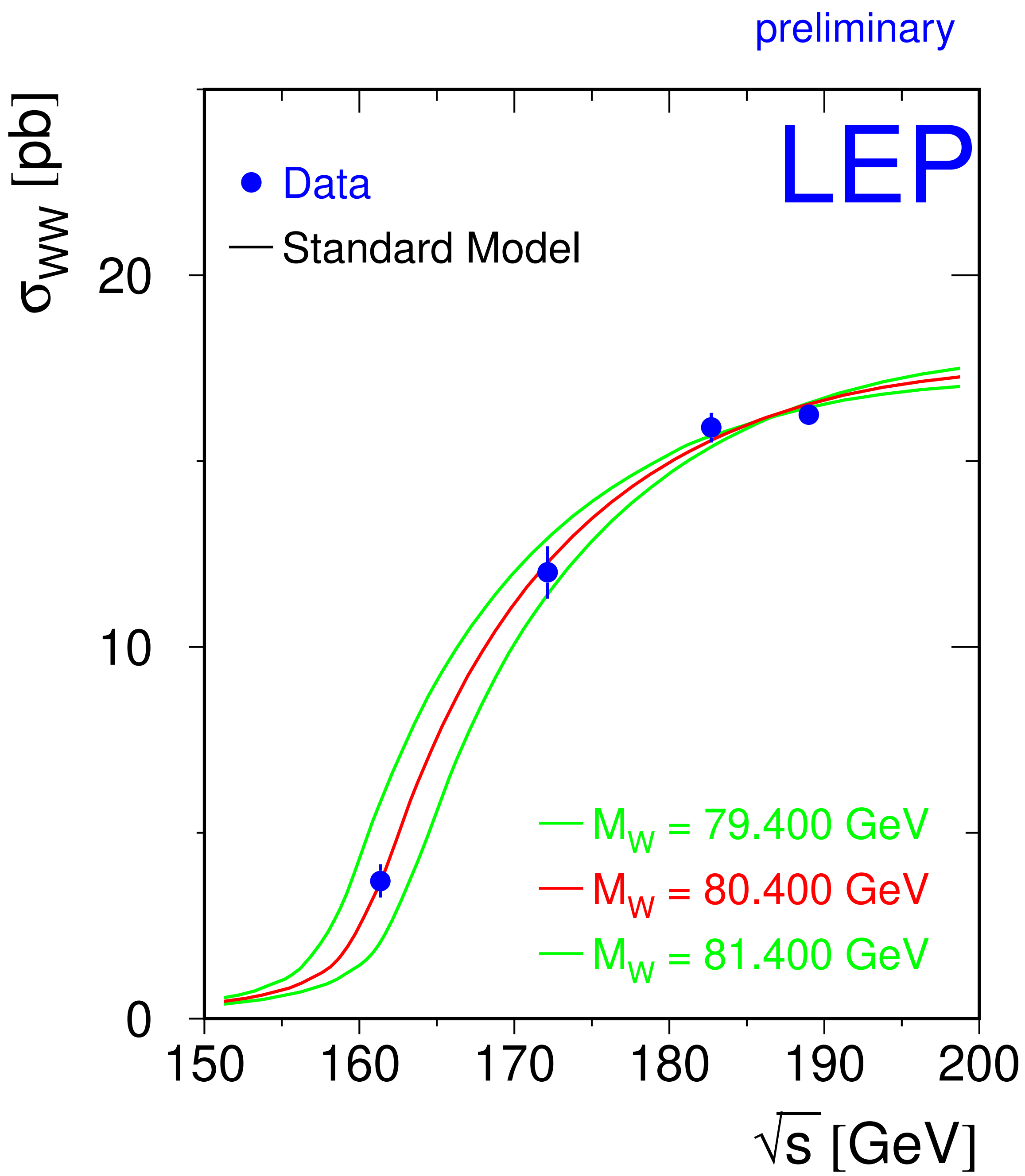
- 43.8 % of all W-pairs
- Number of Events: $\approx$ 1500 per experiment
- Efficiency: 50-80%
- Purity: 80-90%

$\ell\nu\ell\nu$ Selection



- 10.6 % of all W-pairs
- Number of Events: ≈ 400 per experiment
- Efficiency: 30-70%
- Purity: 80%

Cross-Section and W Mass



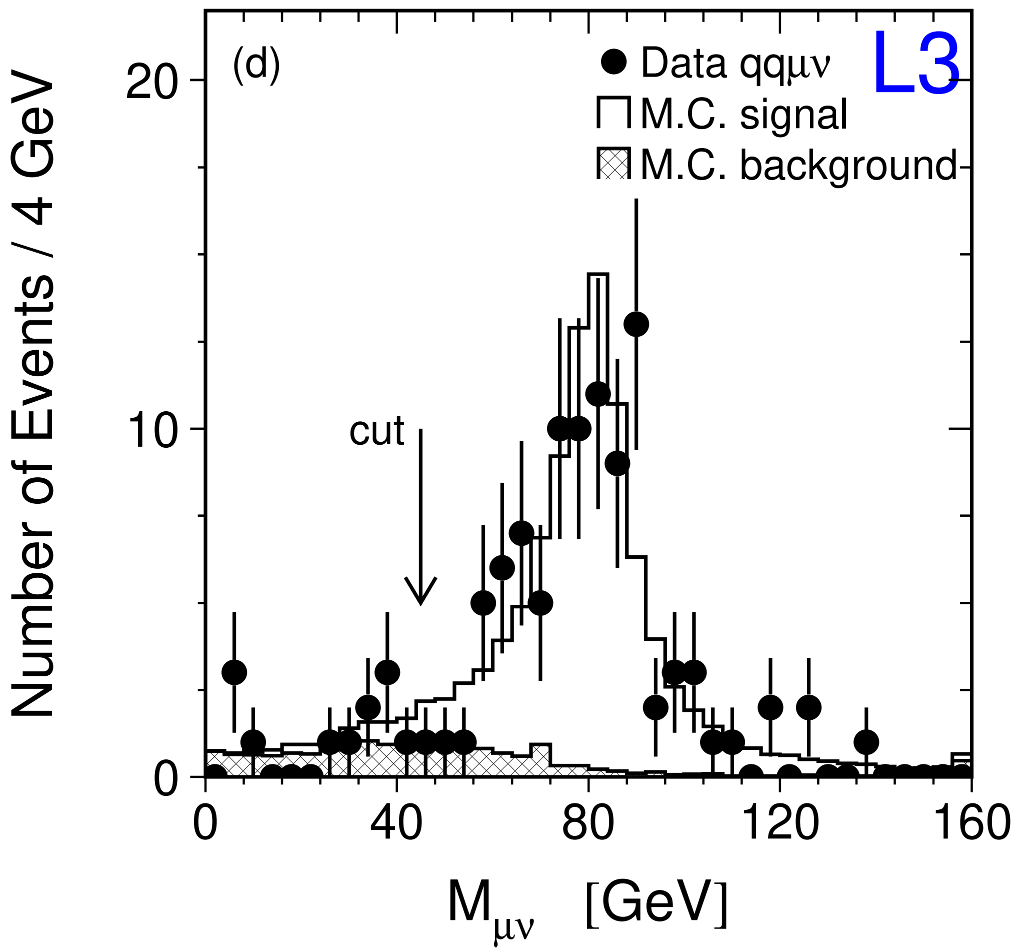
$\longrightarrow$ Largest sensitivity on M_W in the threshold region

∘ Just from cross-section information:

$$M_W = 80.40^{+0.22}_{-0.21}\ \mathrm{GeV}$$

Mass Spectrum

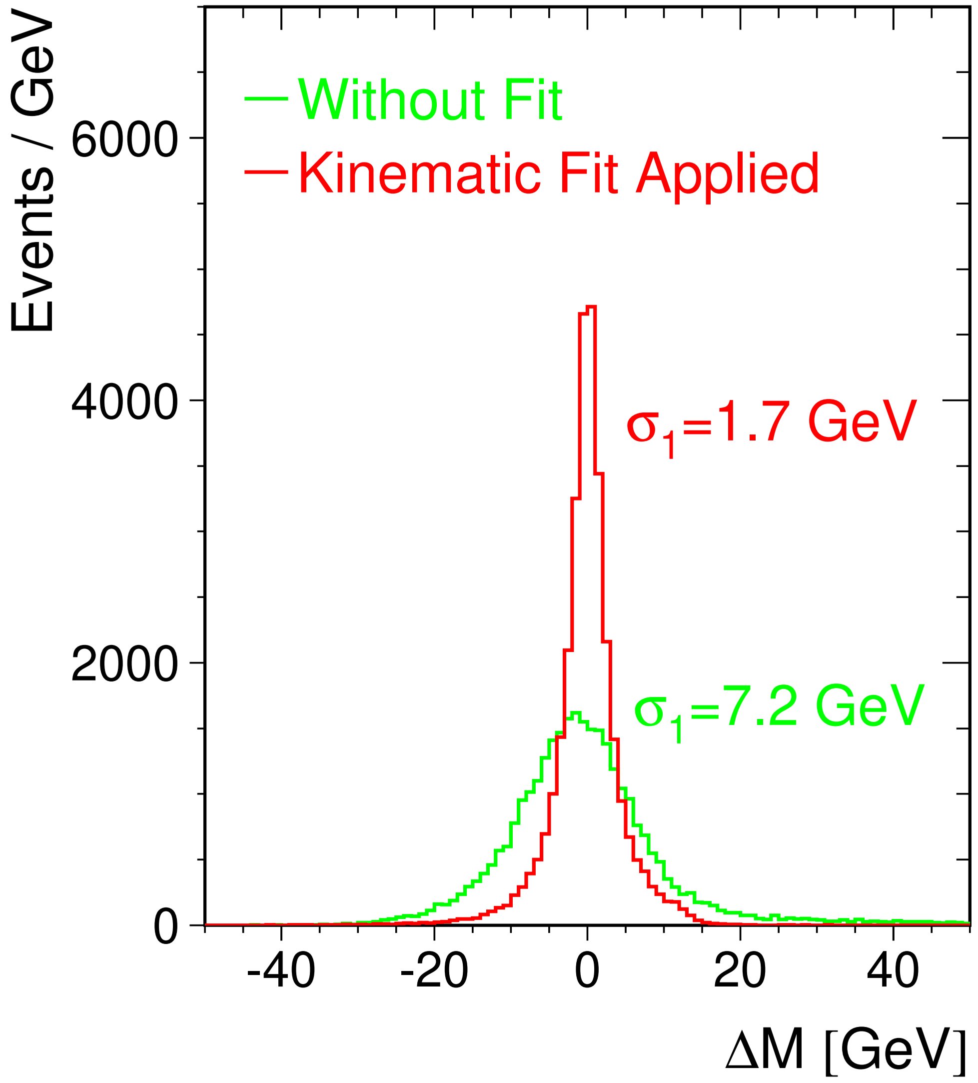
- Reconstruction of the W decay products: charged leptons and quark jets
- Invariant masses of jet-pairs or lepton-neutrino



▷ raw spectrum ⟶ kinematic fit

Improvements by Kinematic Fit

- Input: measured energies and angles of leptons and jets
- Constraints: 4-momentum, equal masses of the W's



▷ used to solve the problem of jet pairing in the qqqq channel (3 possibilities!)

Maximum Likelihood Method

- Unbinned maximum likelihood fit to the measured mass spectrum $d\sigma/dM$:

$$L = \Pi_i \left[\frac{d\sigma_{WW}}{dM}(M^i_{rec}, M_W) + \frac{d\sigma_{Bg}}{dM}(M^i_{rec}) \right] \cdot \frac{1}{\sigma_{WW}(M_W) + \sigma_{Bg}}$$

M^i_{rec} = reconstructed invariant mass

- Calculation of the differential cross-section with box method:

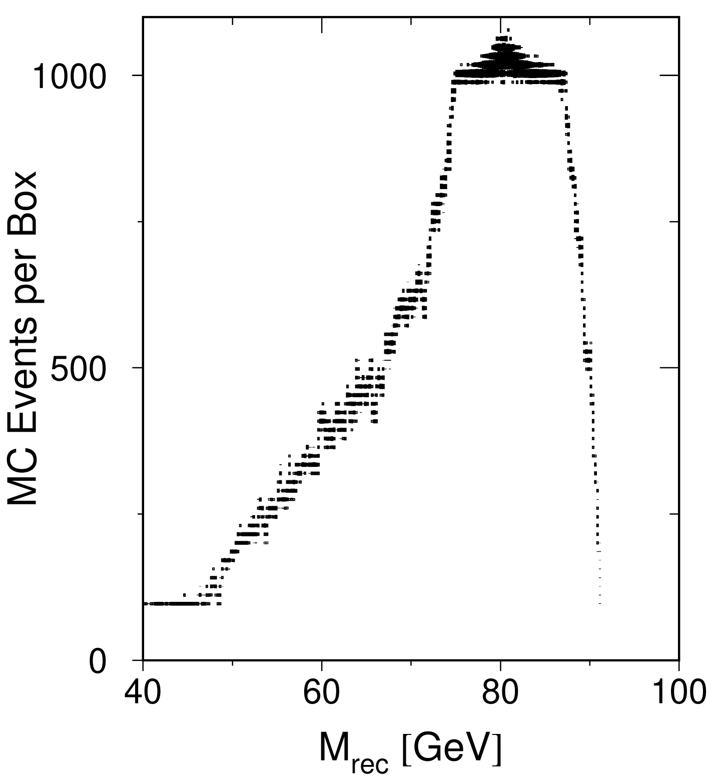
$$\frac{d\sigma_{WW}}{dM}(M_{rec}, M_W^{MC}) = N_{box} \cdot \frac{1}{\Delta_{box}} \cdot \frac{1}{\mathcal{L}_{MC}}$$

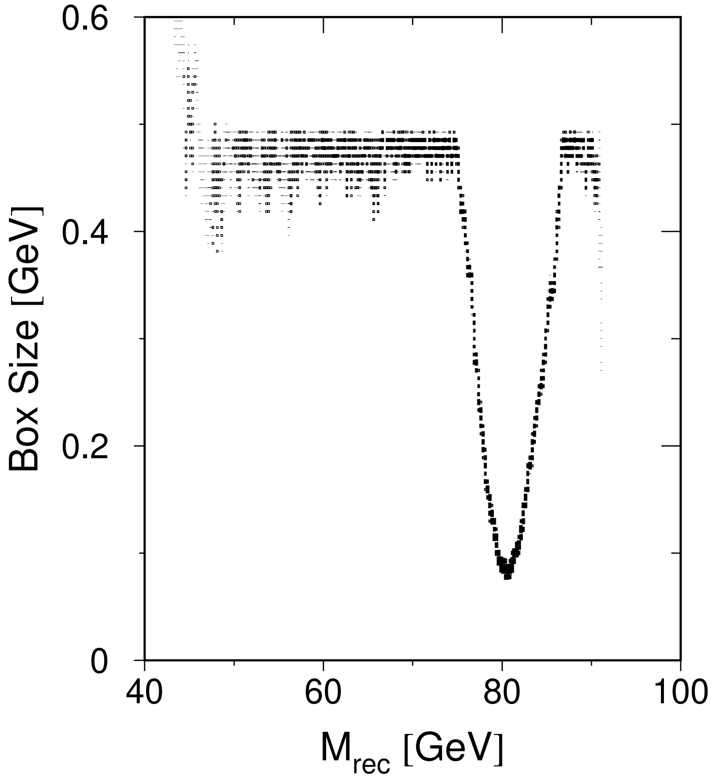
- Reweighting of MC events $\longrightarrow$ M_W dependence:

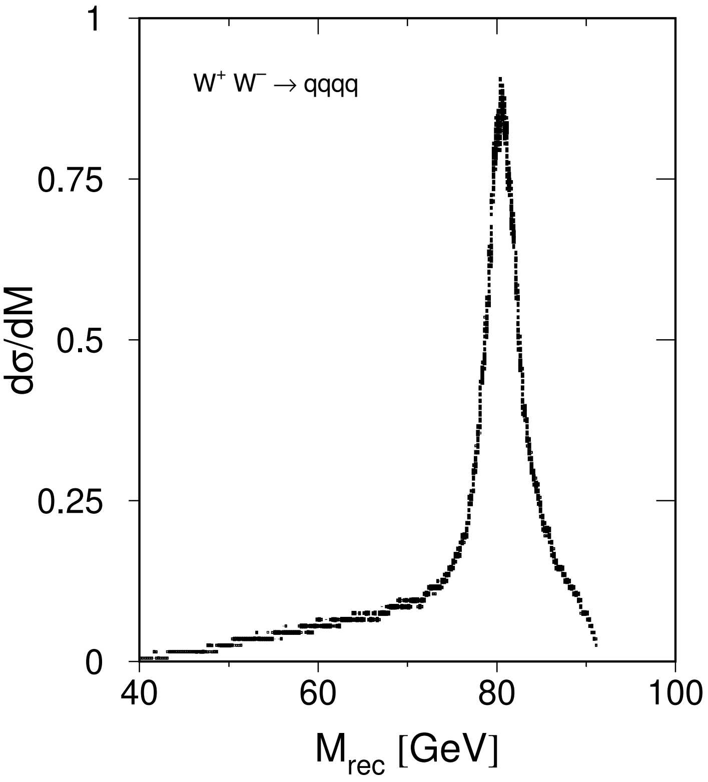
$$\omega = \frac{|\mathcal{M}(p_1, p_2, p_3, p_4, M_W)|^2}{\left|\mathcal{M}(p_1, p_2, p_3, p_4, M_W^{MC})\right|^2}$$

$$N_{box} \longrightarrow \Sigma_j\, \omega_j(M_W), \qquad M_j \in \text{box}$$

Example



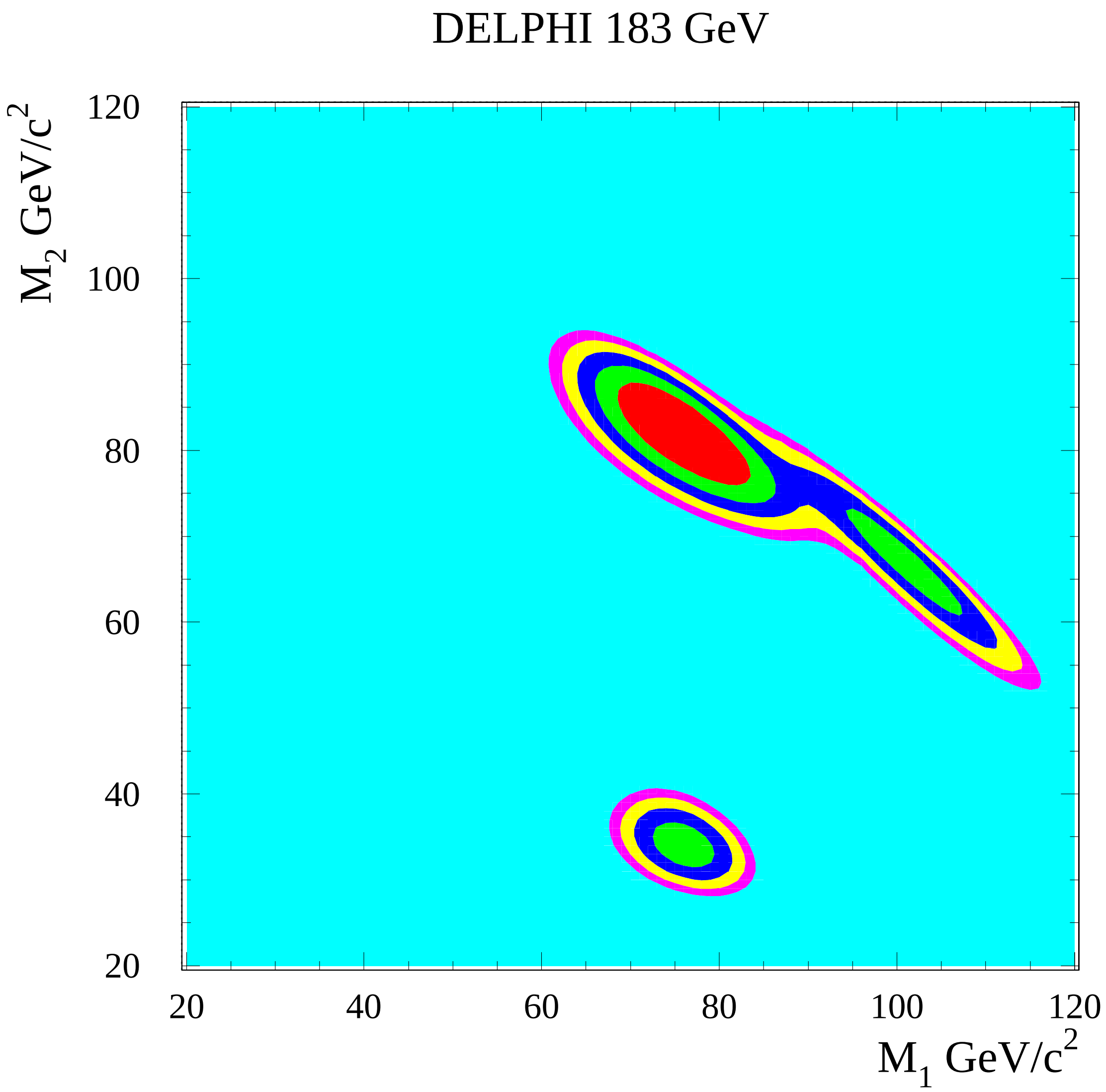




- ▷ also multi-dimensional (e.g. M_1, M_2)
- ▷ bins of different mass resolutions
- ▷ detector simulation included
- ▷ bias-free measurement

Kinematic Fit - 4 Jet Channel

- Delphi method:
  Use more information than just M_{rec}!
- Kinematic fit probability $p(M_1, M_2)$:



- Contains more kinematic information
  + all possible pairings
  + jet charges
  + gluon probablity (5-jets)

Construction of a Likelihood Function

- qqqq event likelihood $L_i(M_W)$:

  Covolution of $p(M_1, M_2)$ with

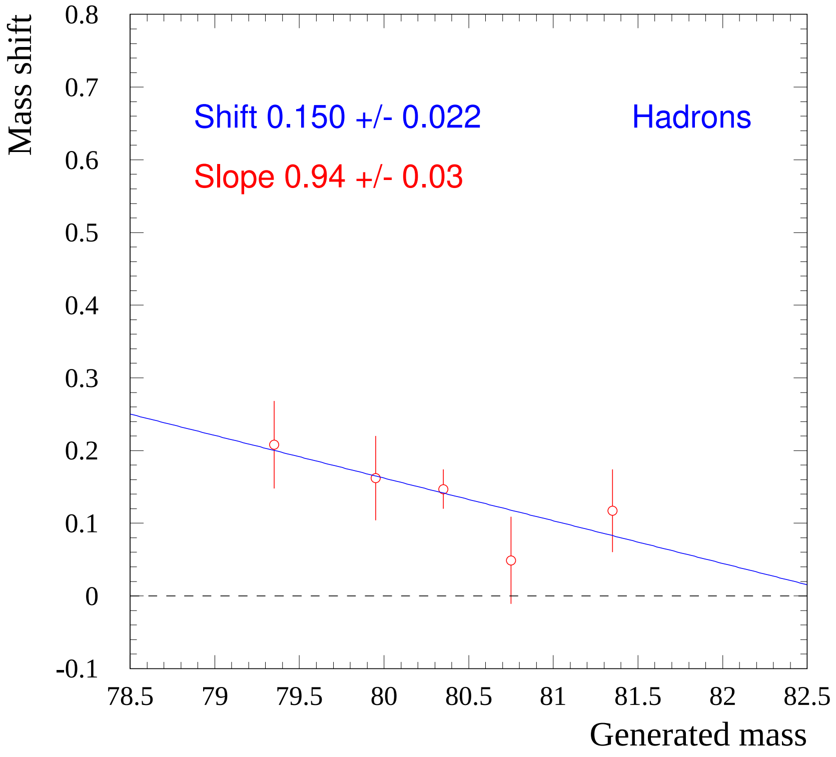
  $$S(M_W) = BW(M_1, M_W) \cdot BW(M_2, M_W) \cdot f_{ph.sp.}$$

  + background term

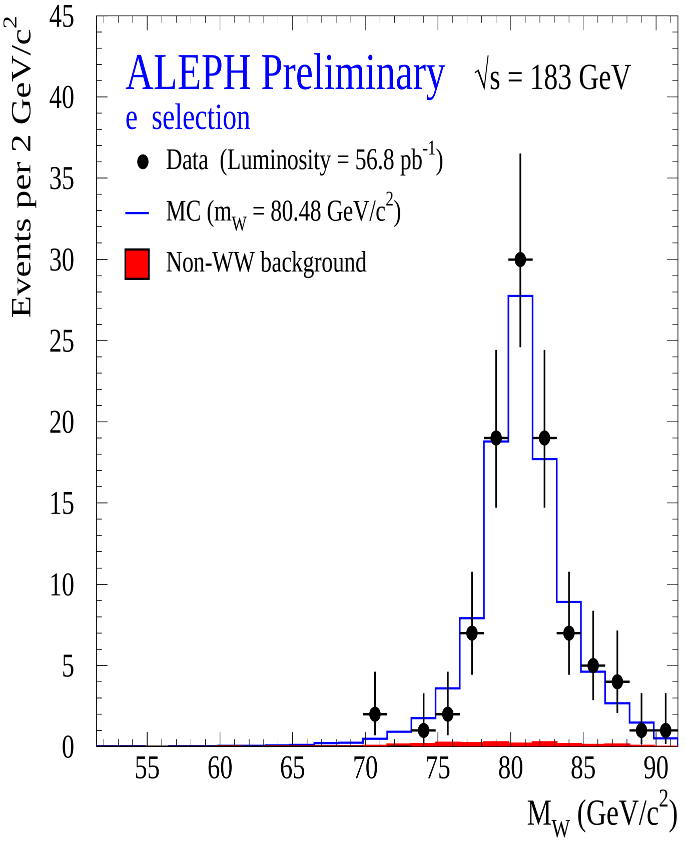
- Total likelihood:

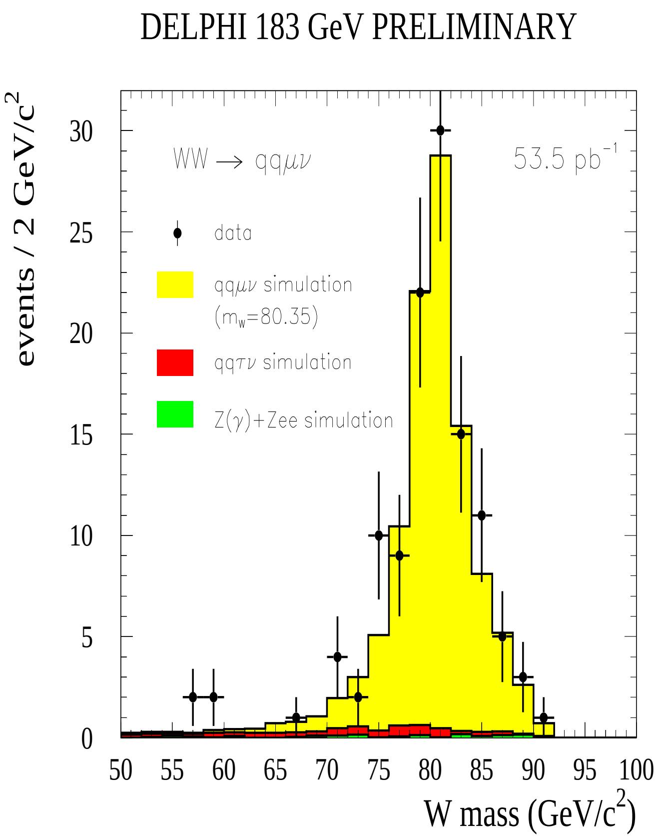
$$L(M_W) = \Pi_i \left\{ L_i(M_W) / L_i^{max} \right\}$$

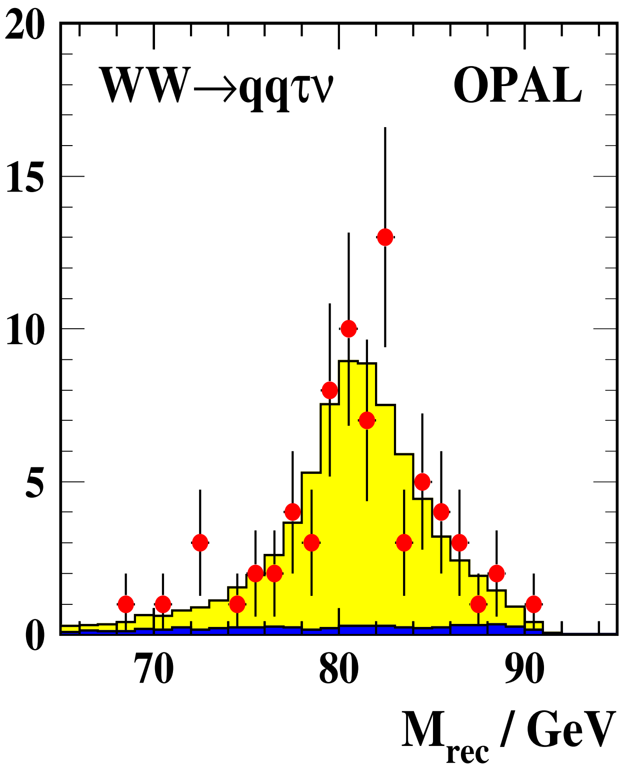
- Finally: bias correction

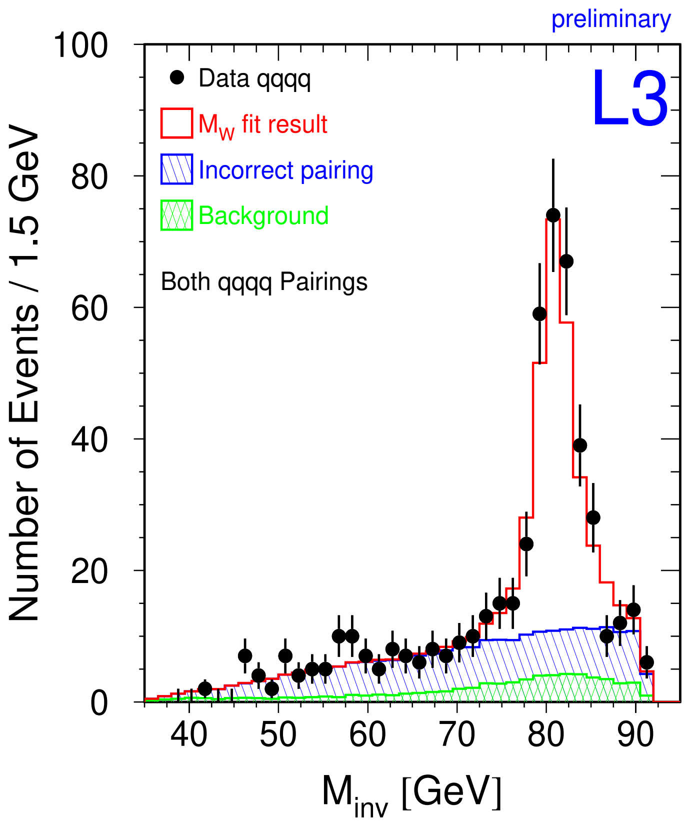


Mass Spectra



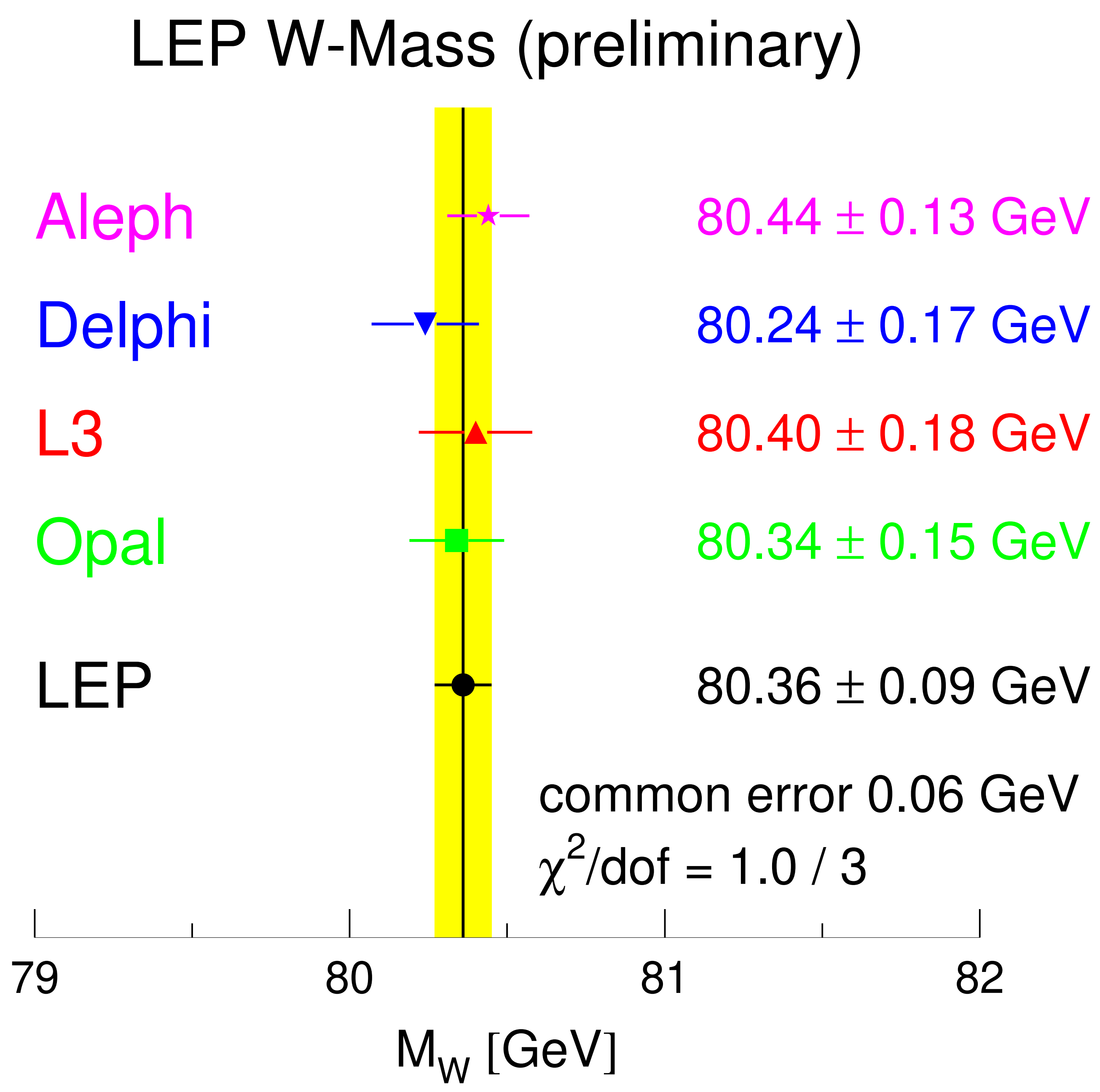






Mass Fit Results

- Results for 172 and 183 GeV:

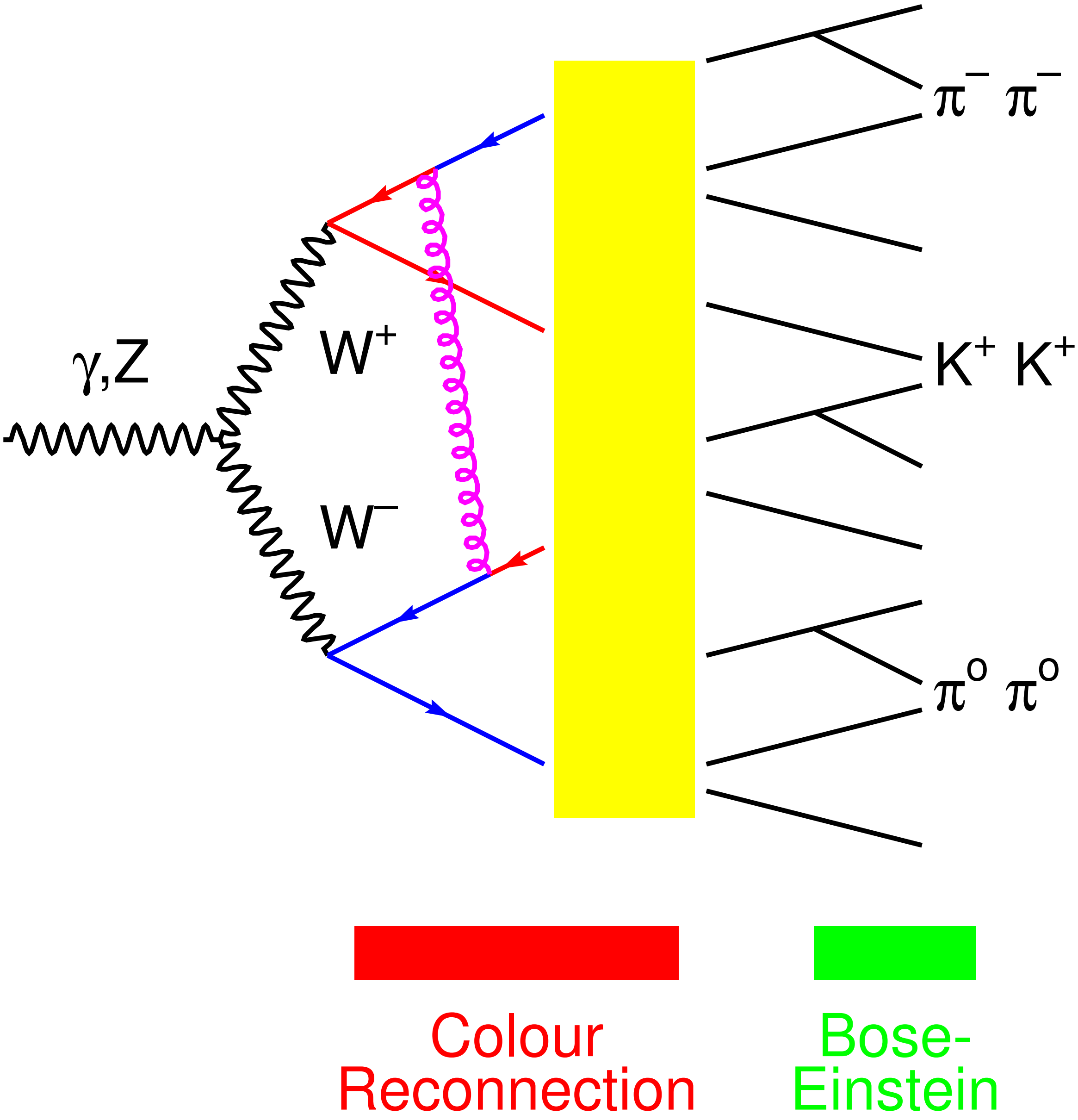


- Including cross-section information:

$$\boxed{M_W = 80.37 \pm 0.09 \ \text{GeV}}$$

Final State Interactions

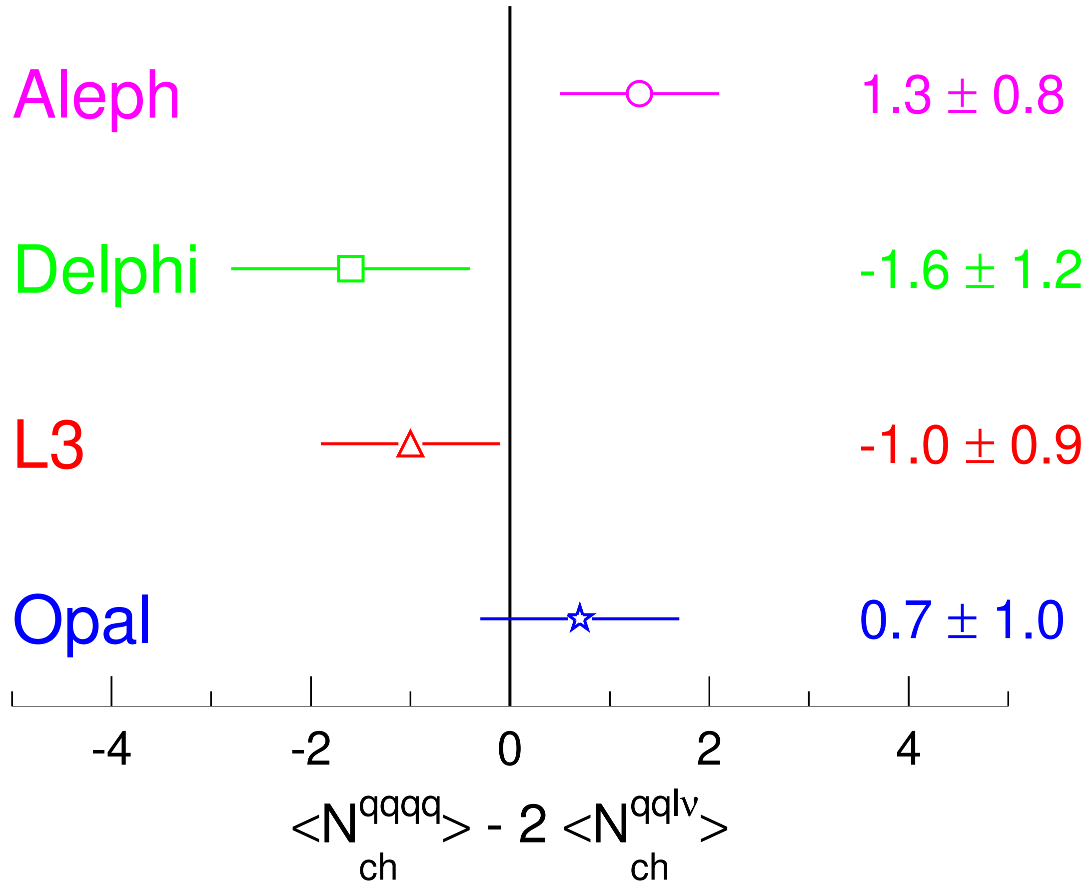
- W decay into quark pairs, $W^+W^- \to qqqq$:
  - Distance between W vertices ≈ 0.1 fm
  - Hadronisation scale ≈ 1 fm
- No independent fragmentation of the two W's



▷ FSI may affect invariant masses M_{jj}^1, M_{jj}^2 ◁

Colour Reconnection

- CR may change charged particle multiplicity in qqqq channel
- Compare $< N_{ch} >$ for qqqq and qq$\ell\nu$:

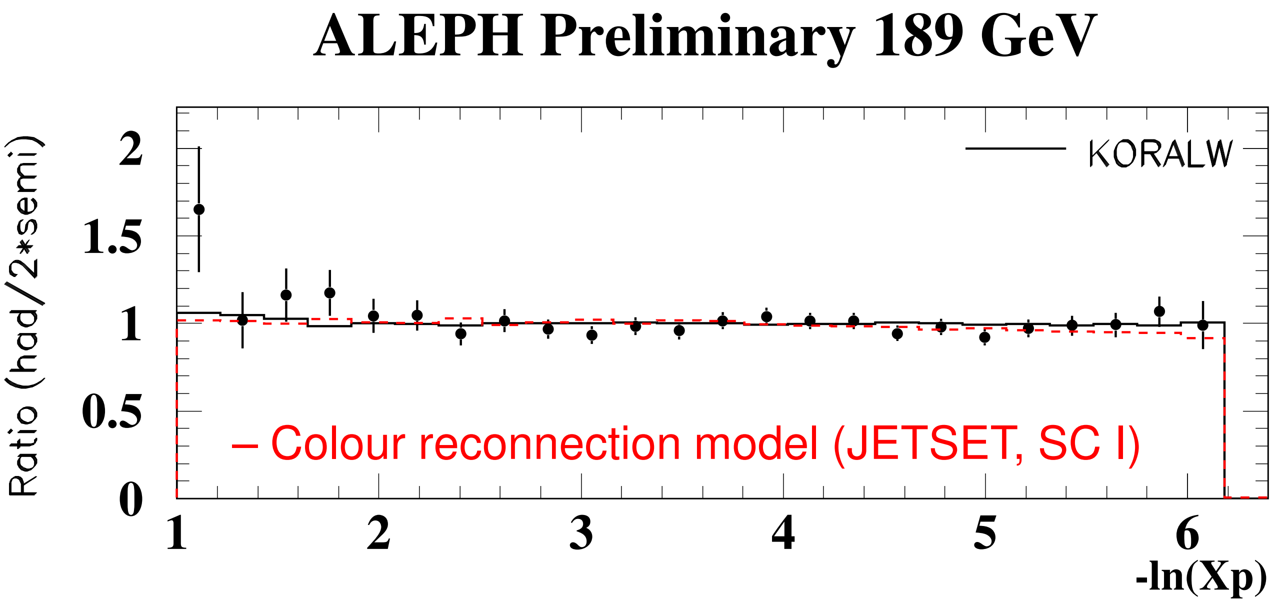


Colour Reconnection

- Charged particle momentum distribution of qqqq and qq$\ell\nu$:

$$-\ln(x_p) = -\ln(2p/\sqrt{s})$$

- Interesting region: low p $\longrightarrow$ high $\left[-\ln(x_p)\right]$



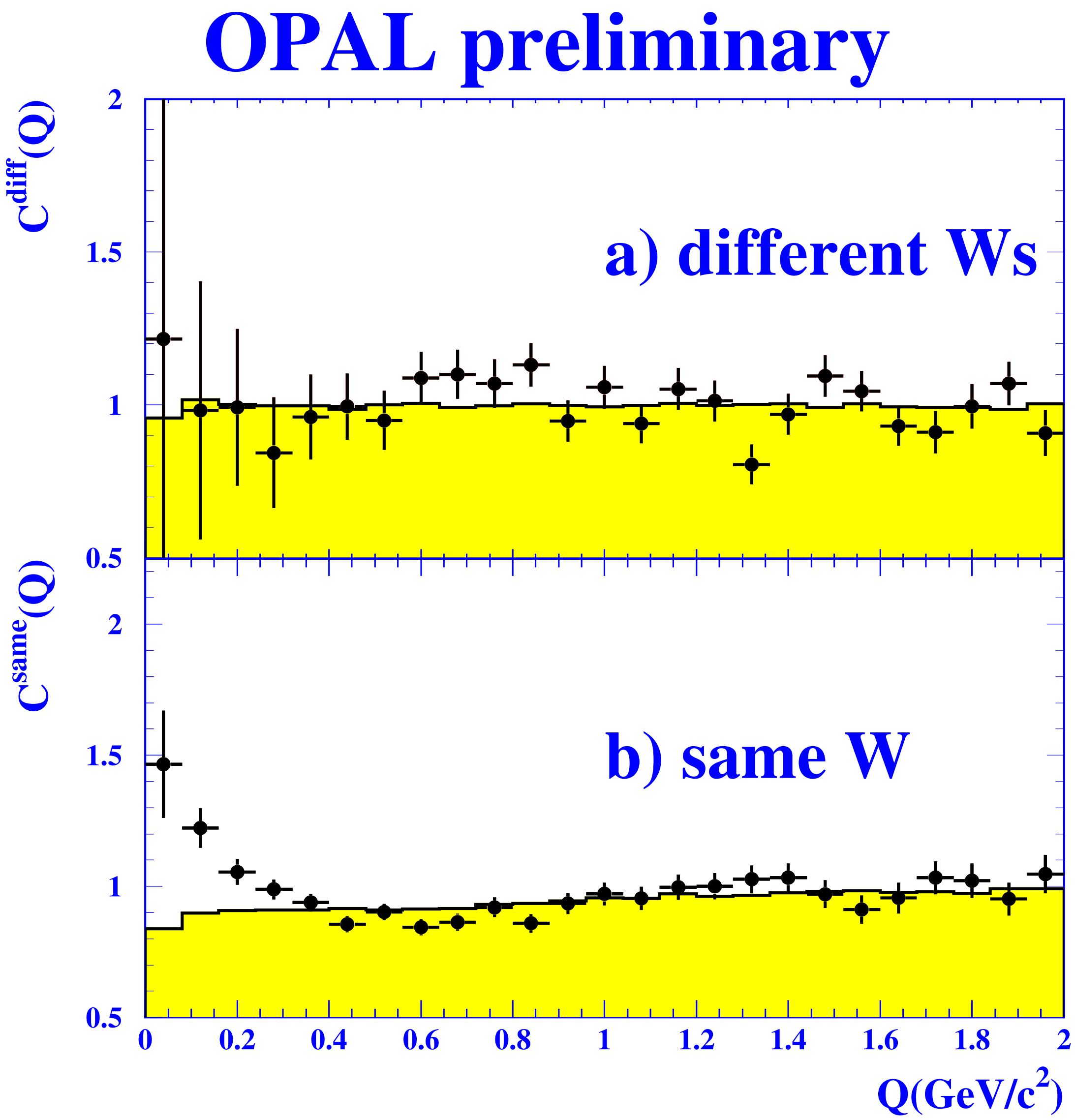
- No significant deviation from Monte Carlo without CR
- Systematic error on $M_W \approx 25 - 70$ MeV

Bose-Einstein Effects

- Symmetric decay amplitude for identical bosons
- Here: bosons = $\pi^{\pm}$, π^{o}, $K^{\pm}$, . . .
- Correlation between boson pairs:

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

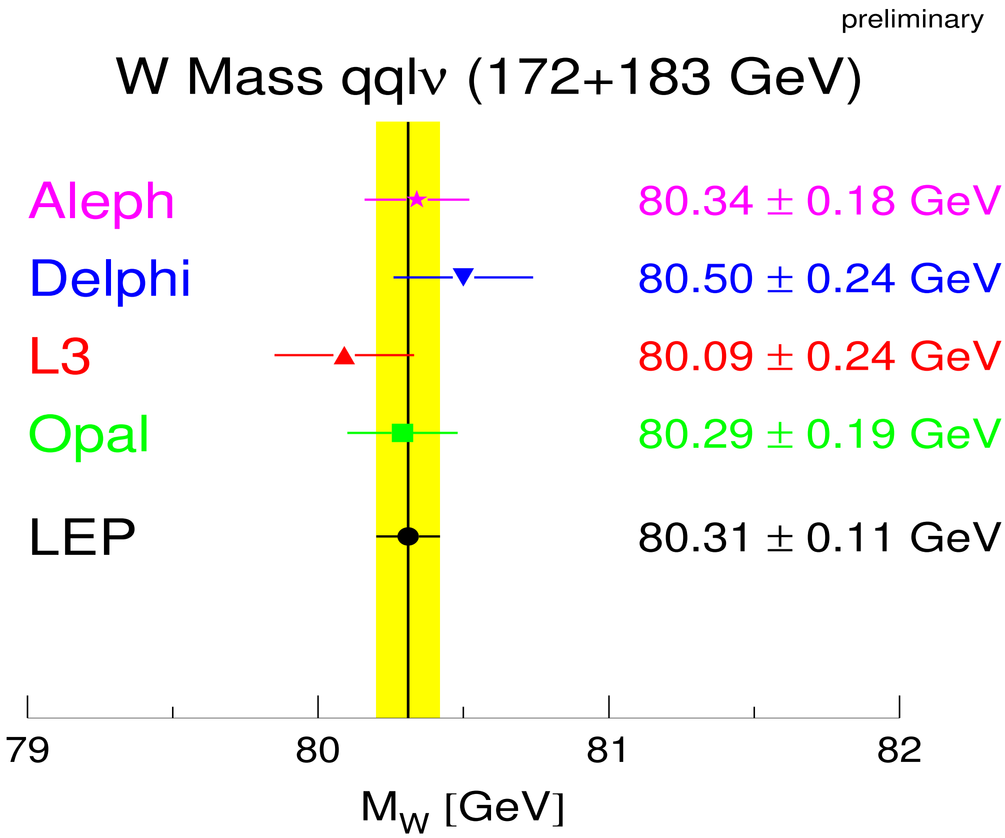
- Look at boson pairs from same/different W's:

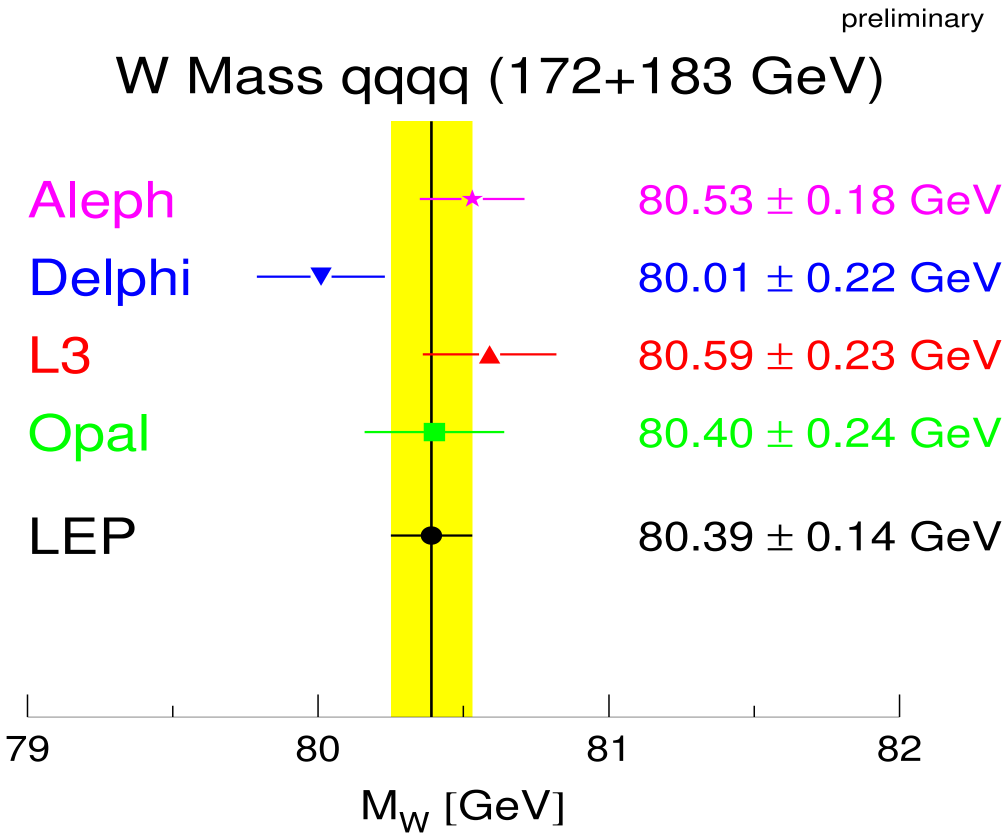


- Correlation just inside W's ?
- Systematic error on $M_W \approx 30 - 60$ MeV

LEP Results on qqqq and $qq\ell\nu$

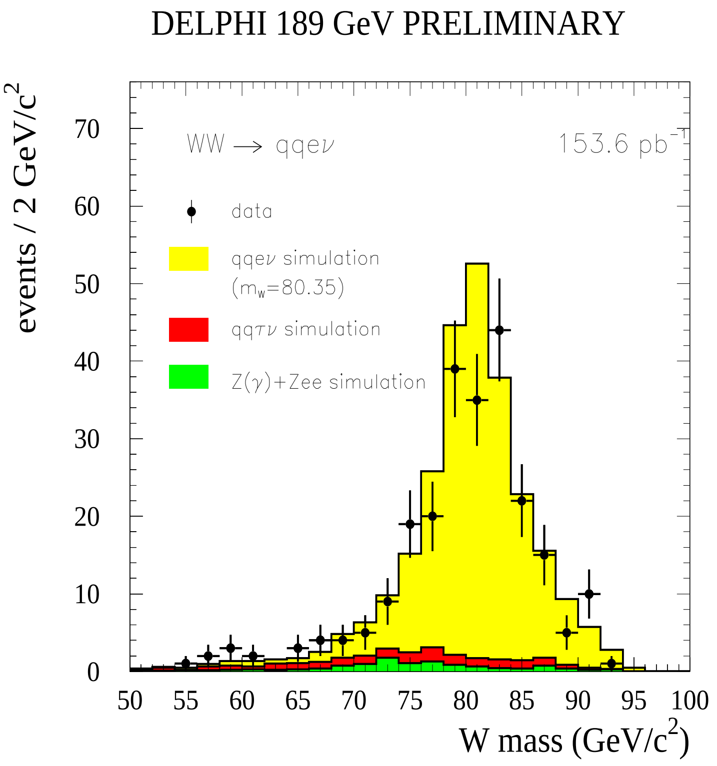
○ Are the masses from qqqq and $qq\ell\nu$ different?

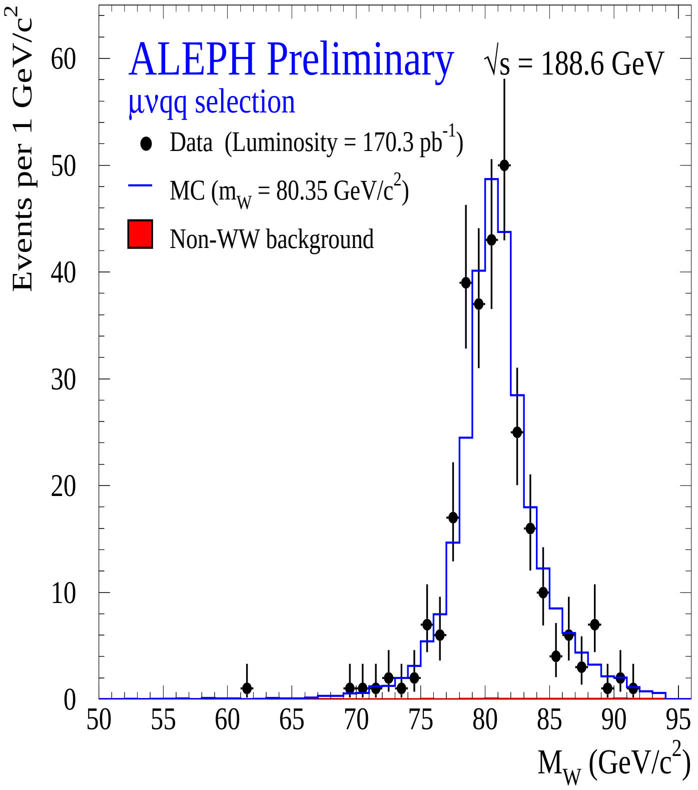


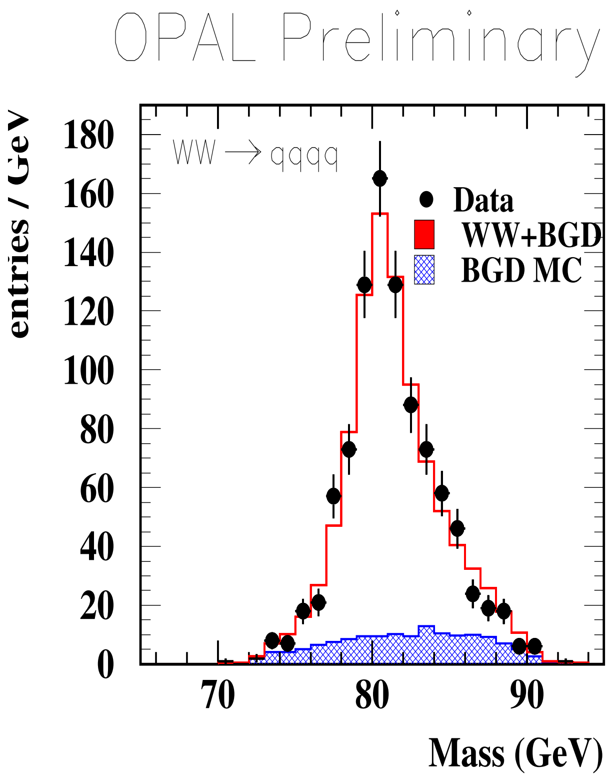


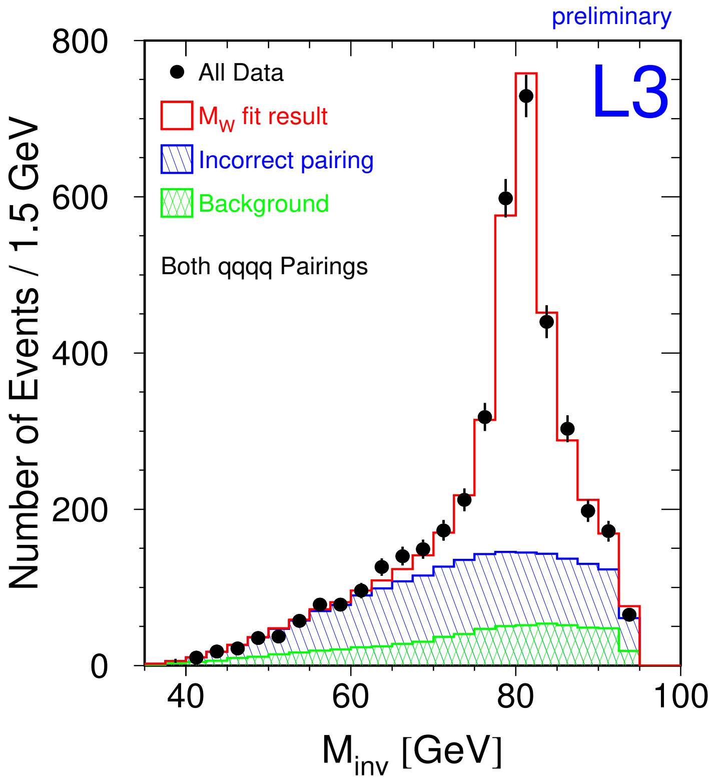
▷ Mass difference: 0.08 ± 0.18 GeV ◁

1998 Data









- Expected statistical error:

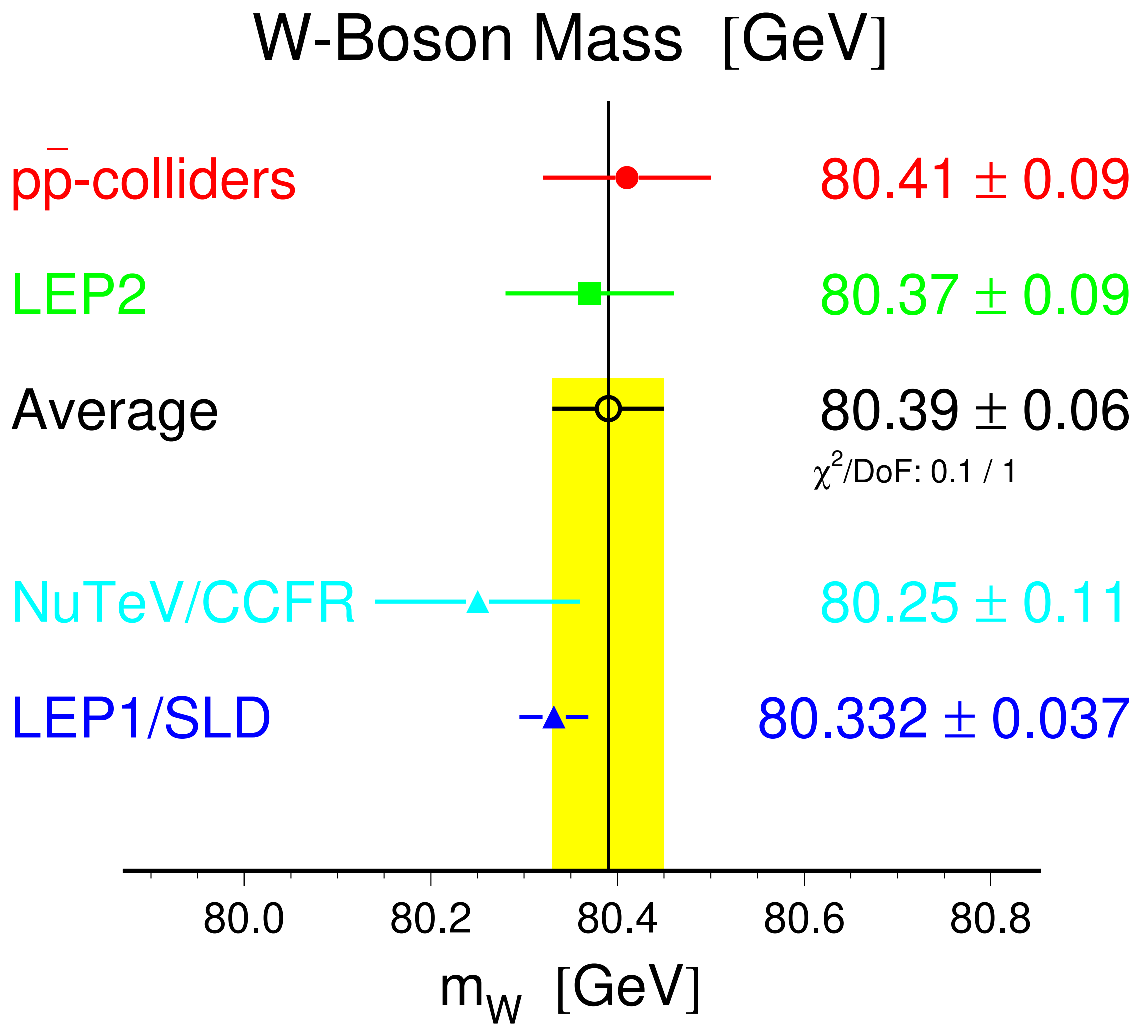
80 — 100 MeV per experiment →

40 — 45 MeV combined!

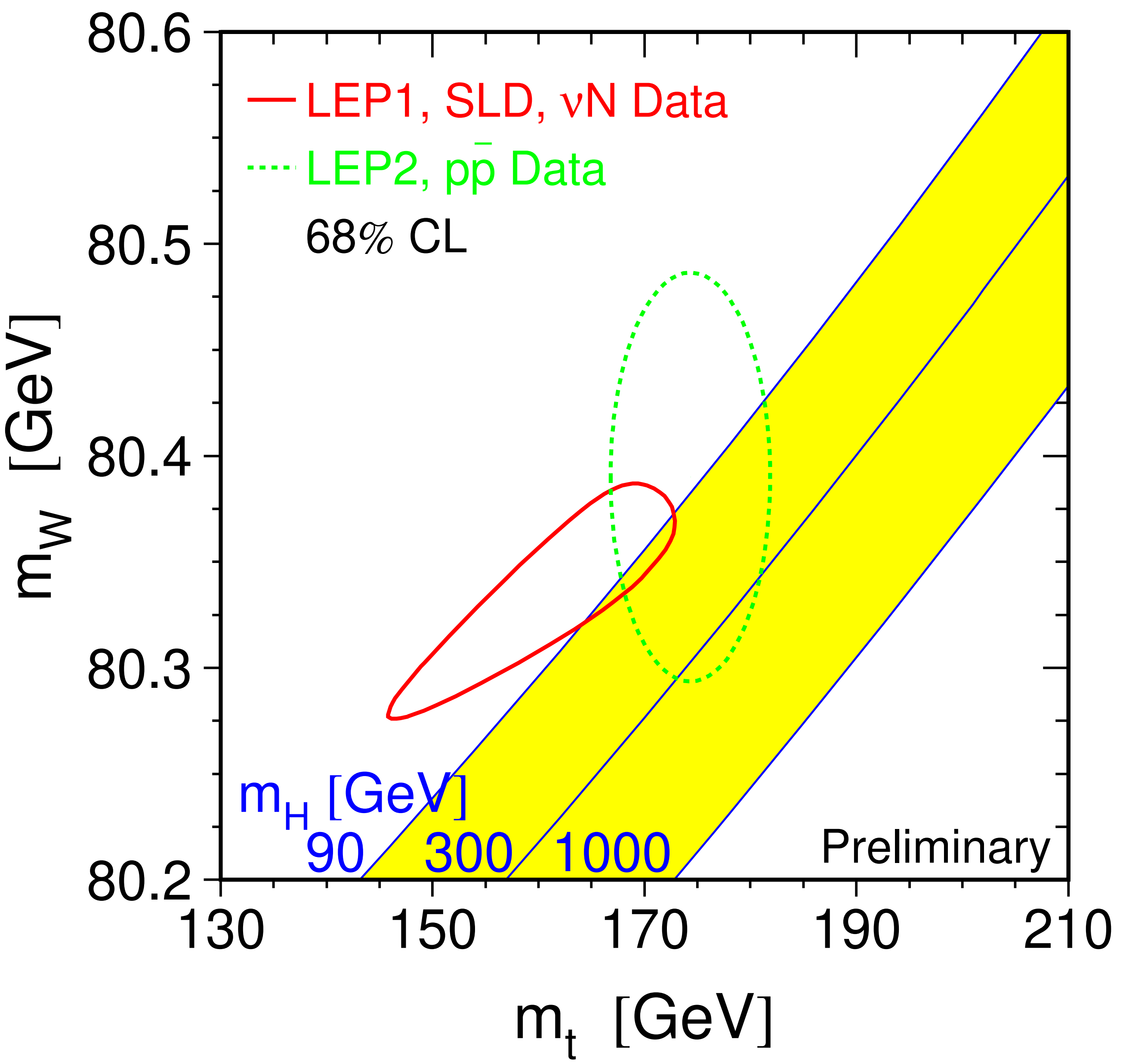
W Mass Measurements around the World

- Measurements by other experiments
- Determination within the Standard Model:

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$



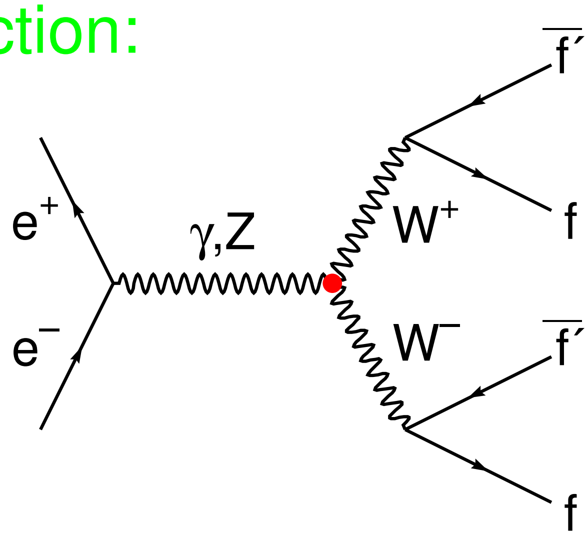
W Mass, Top Mass, and the Standard Model



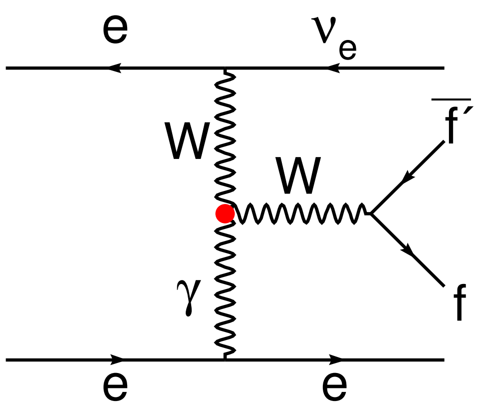
- ○ Standard Model band → G_μ relation

Another Test of the Standard Model: W Couplings Measurement

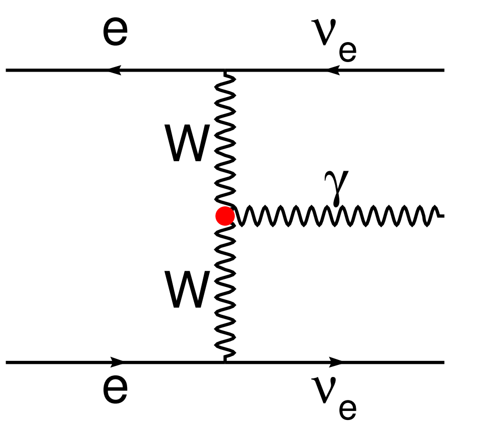
W pair production:



Single W production:



Single photon production:



Effective Lagrangian for VWW couplings

(C and P conserving; $V = \gamma, Z$)

$$\frac{i\mathcal{L}_{\text{eff}}}{g_{VWW}} = g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\,\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\,\rho}_\nu W^-_{\rho\mu}$$

Normalization: $g_{\gamma WW} = -e$, $g_{ZWW} = -e \cot\theta_W$

Static properties of the W

- Electric charge:

$$q_W = e g_1^\gamma$$

- Magnetic dipole moment:

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

- Electric quadrupole moment:

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

Standard Parameter Set

- Deviation from SM values:

$$\begin{aligned}\Delta\kappa_Z &= \kappa_Z - 1\\ \Delta\kappa_\gamma &= \kappa_\gamma - 1\\ \Delta g_1^Z &= g_1^Z - 1\\ \lambda_\gamma, \lambda_Z &\end{aligned}$$

- $U_{em}(1)$ and $SU(2) \times U(1)$ gauge invariance:

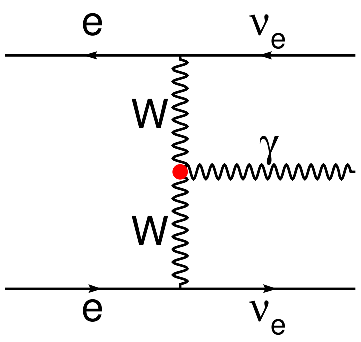
$$g_1^\gamma = 1 \qquad \begin{aligned}\Delta\kappa_Z &= \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W\\ \lambda_Z &= \lambda_\gamma\end{aligned}$$

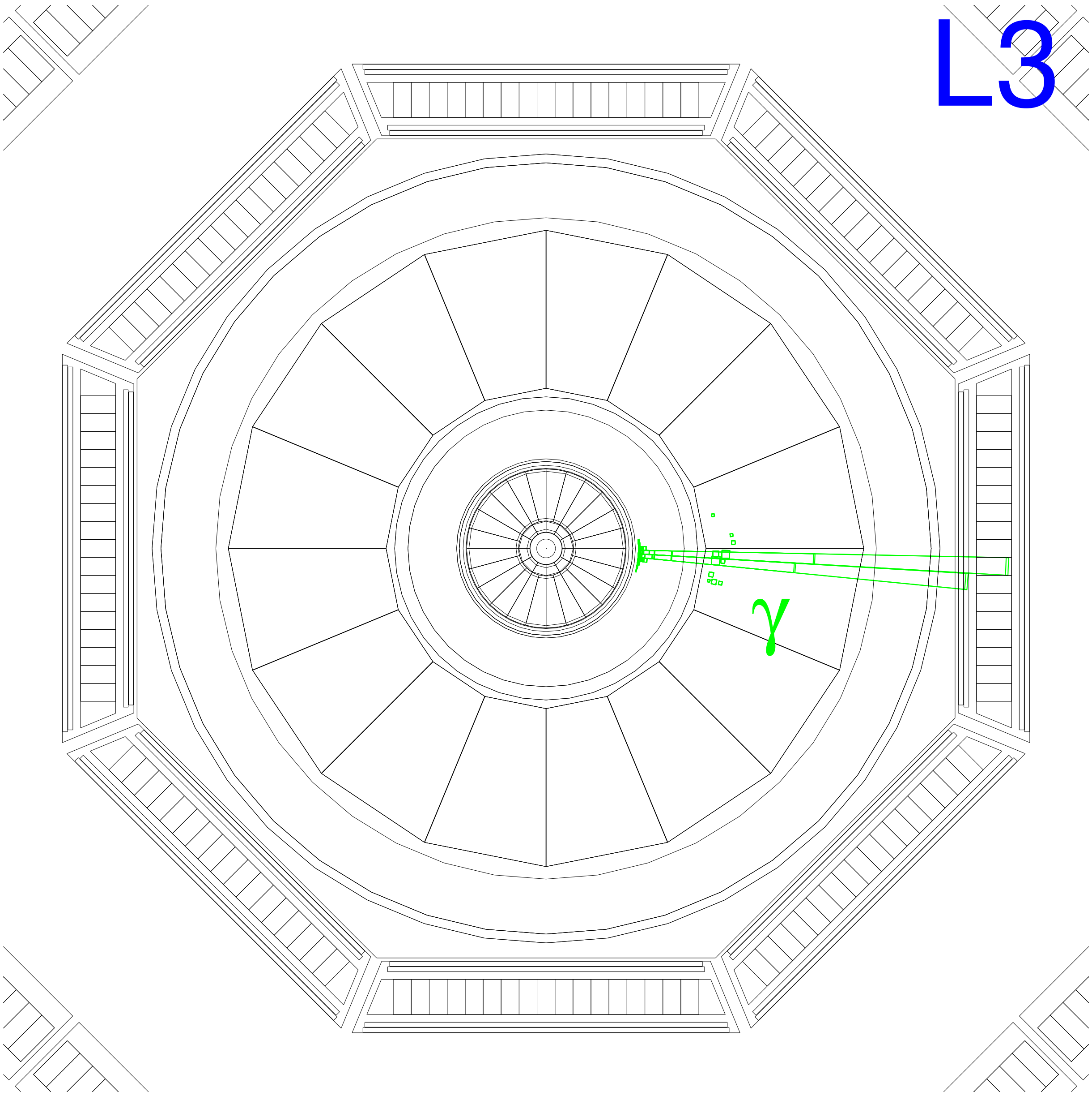
- Reduction to 3 parameters:

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

- Measurements:
  - ▷ Cross Sections (quadratic dependence)
- Single γ production
  - ▷ Energy spectrum
  - ▷ Polar angle
- Single W production
  - ▷ Lepton energy spectrum for $W \to \ell\nu$
- W-pair production
  - ▷ Polar angle distributions of the W's
  - ▷ Polar and azimuthal angle of the leptons in the W rest-frame (ϕ^*, θ^*)

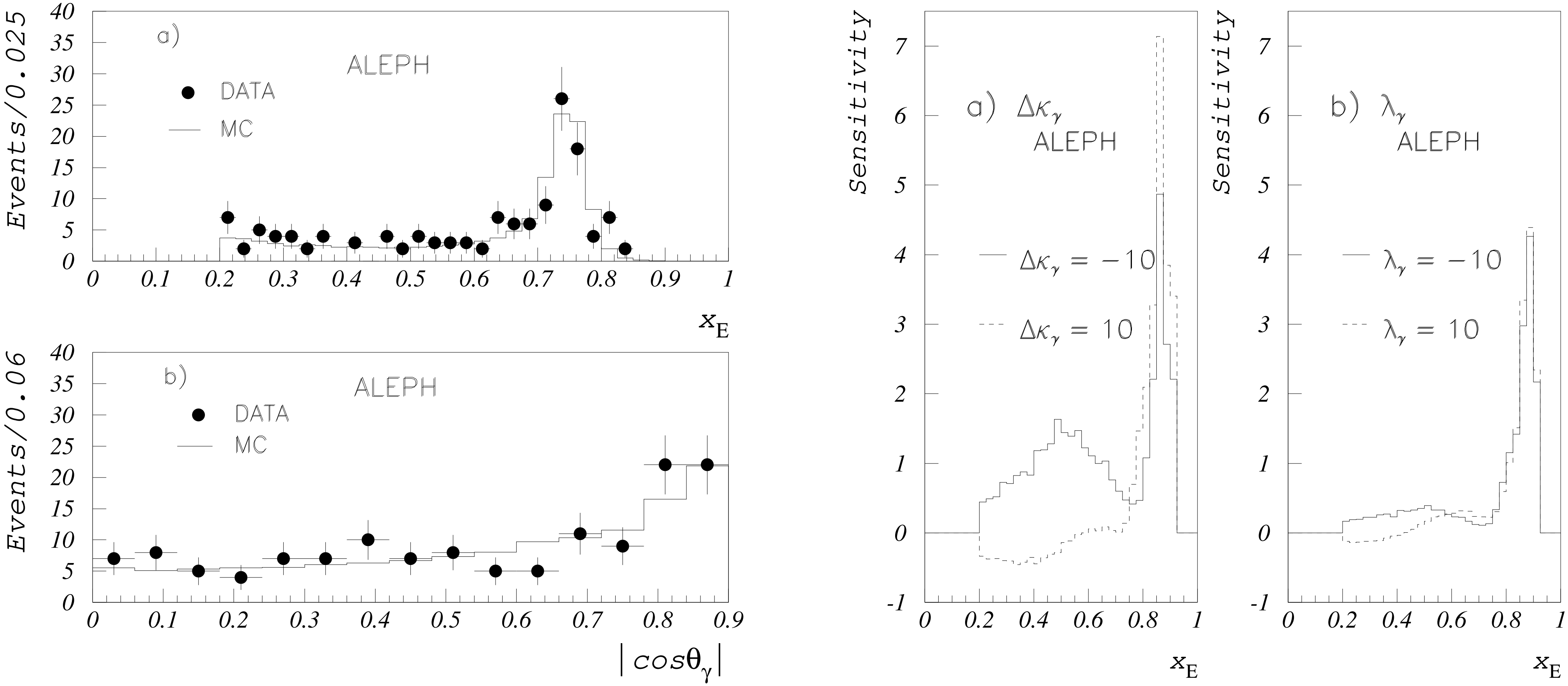
Single Photon Production





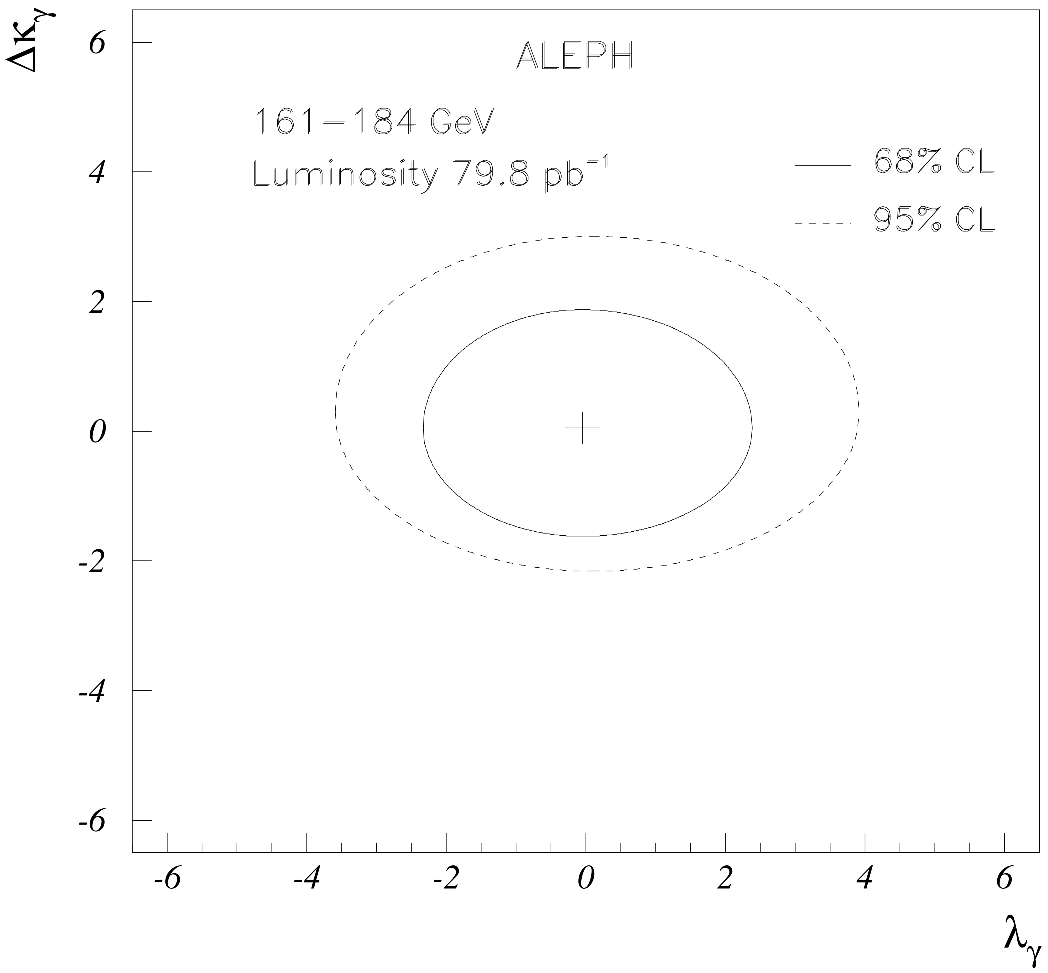
Single Photon Production

- Photon energy $x_E = \frac{E_\gamma}{E_{beam}}$ and polar angle



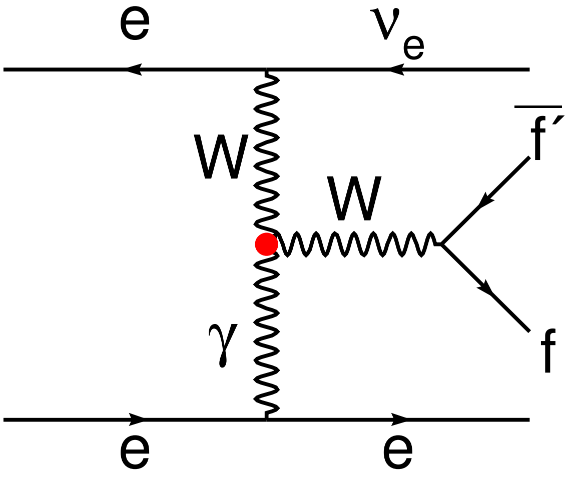
Single Photon Results

- Extended maximum likelihood fit to measured spectra and total number of events

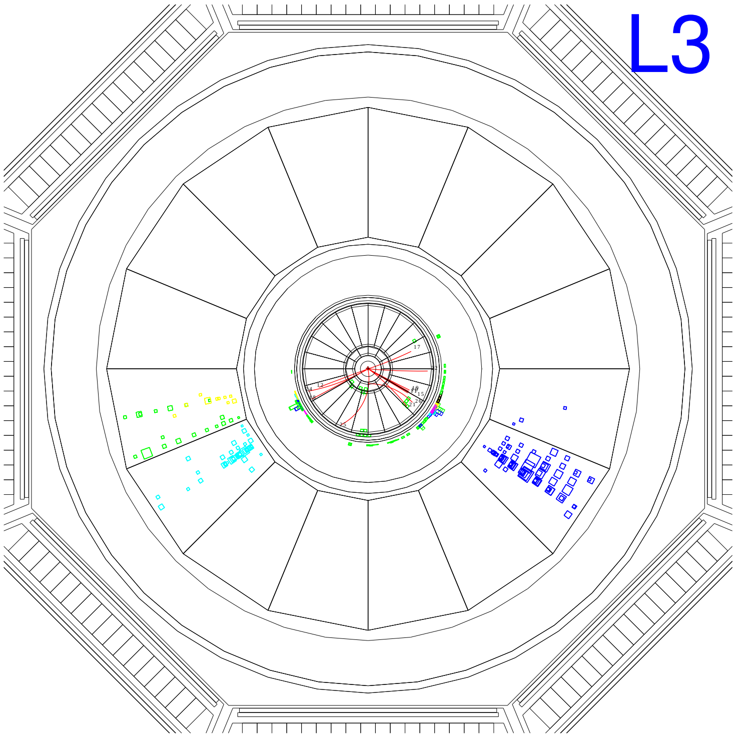


$$\Delta\kappa_\gamma = 0.1 \pm 1.2$$
$$\lambda_\gamma = -0.1 \pm 1.5$$

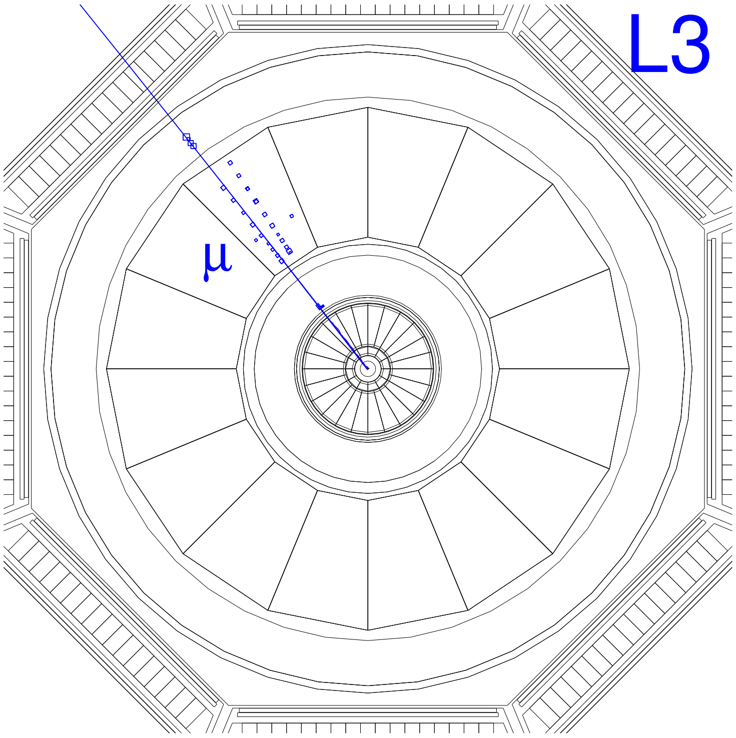
Single W Channel



- Electron is escaping along the beam pipe



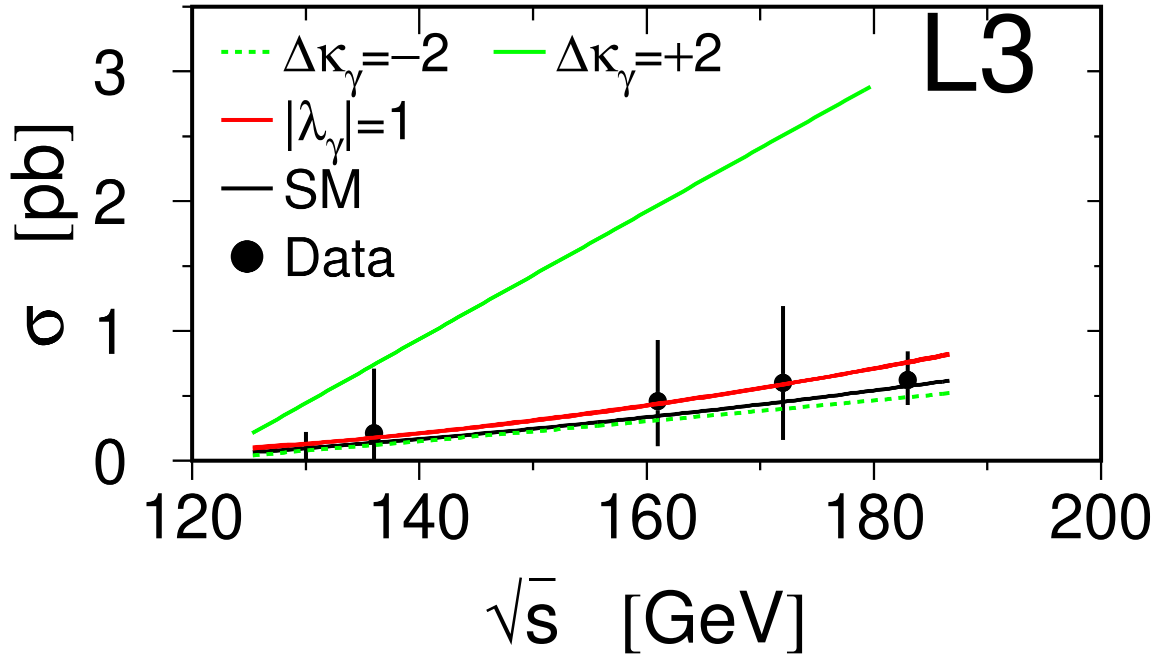
$W \rightarrow q\overline{q}'$



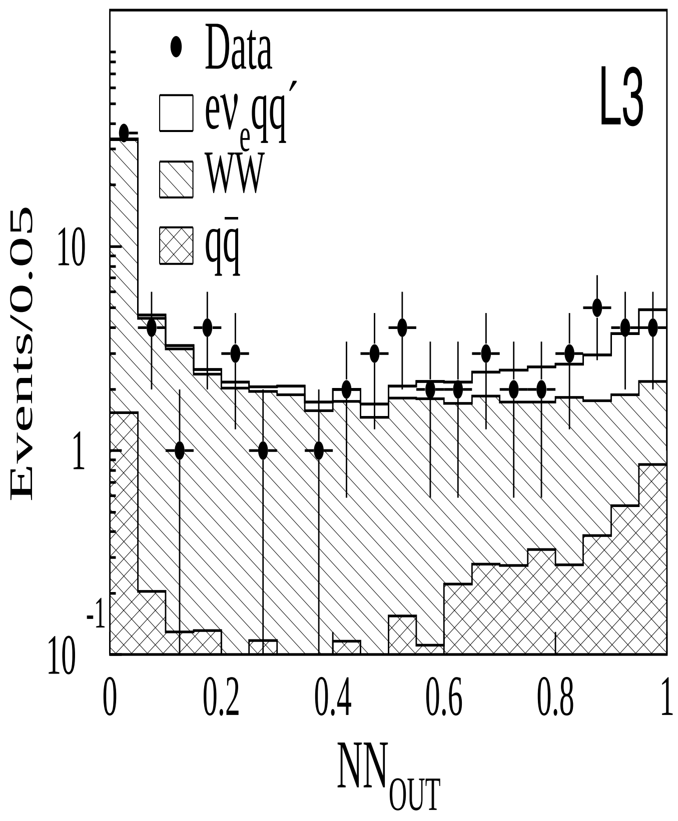
$W \rightarrow \ell\nu$

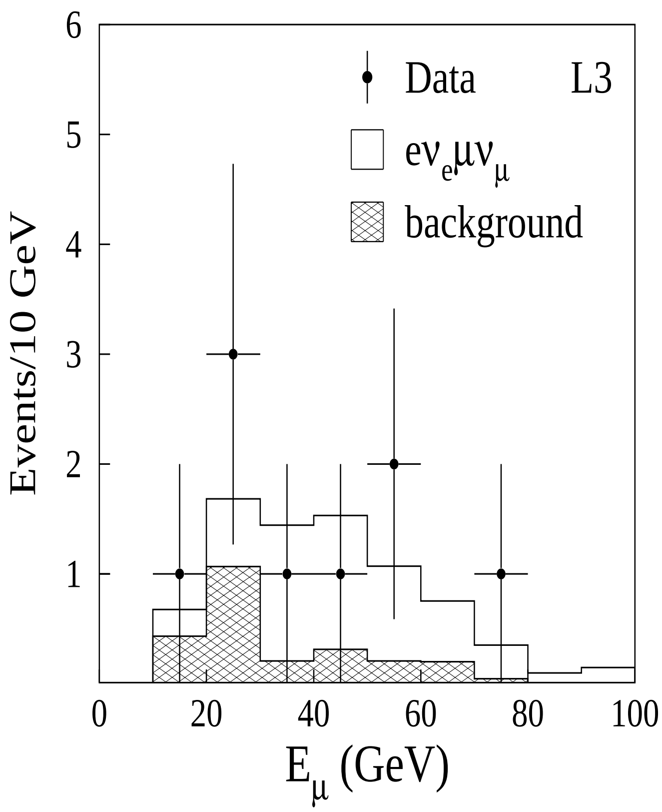
Single W Production

○ Cross-section



○ NN output and energy distribution

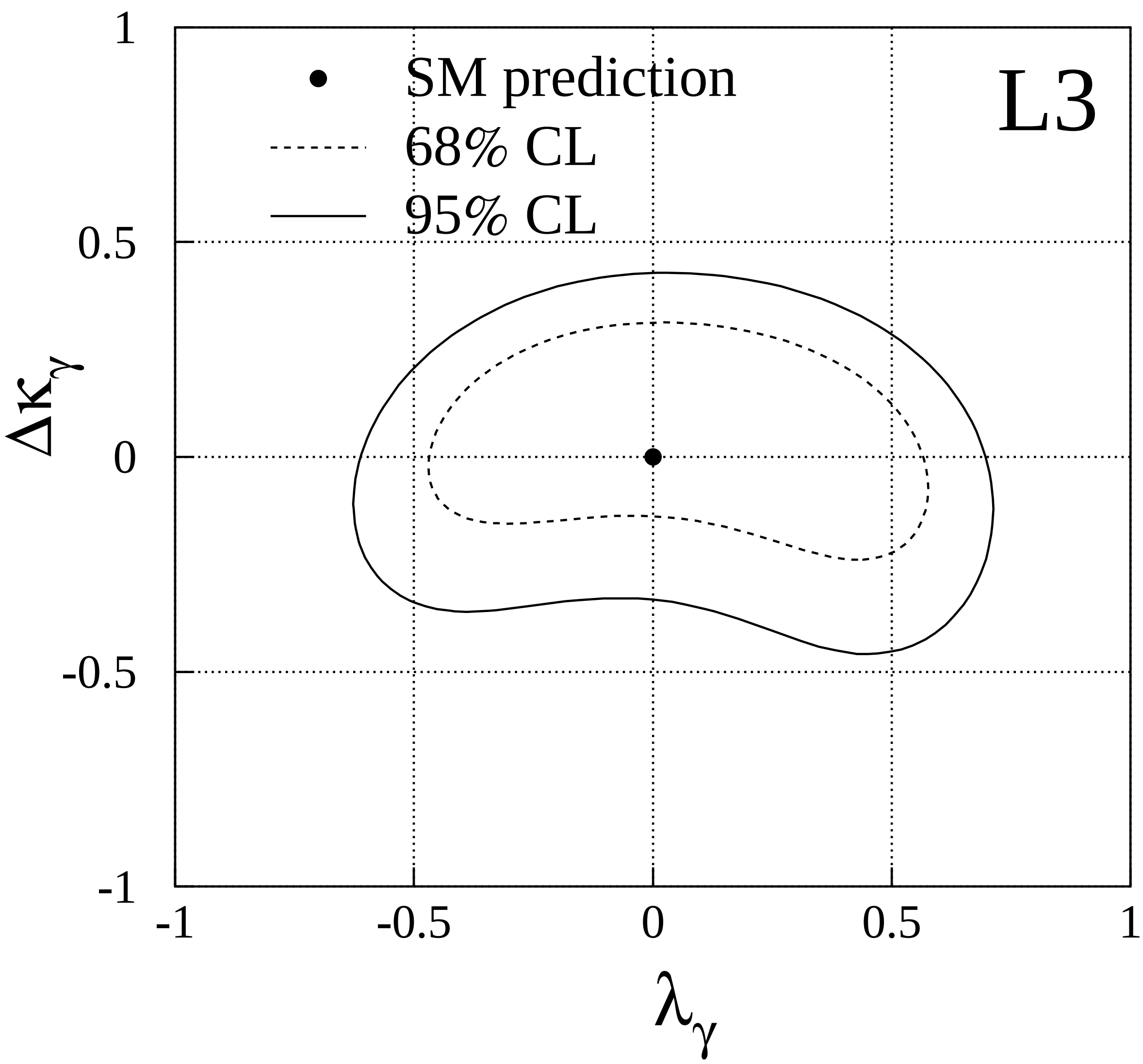




→ Input for couplings fit

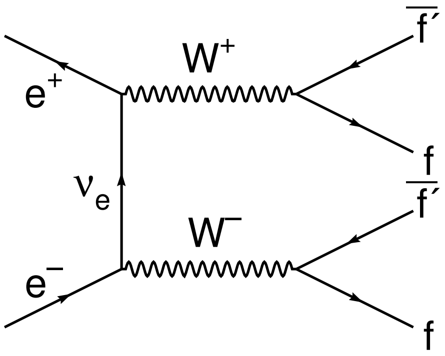
Single W Results

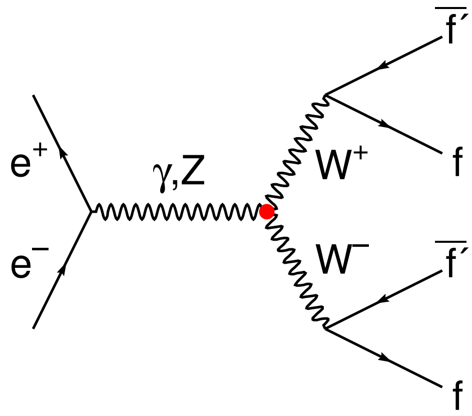
189 GeV preliminary

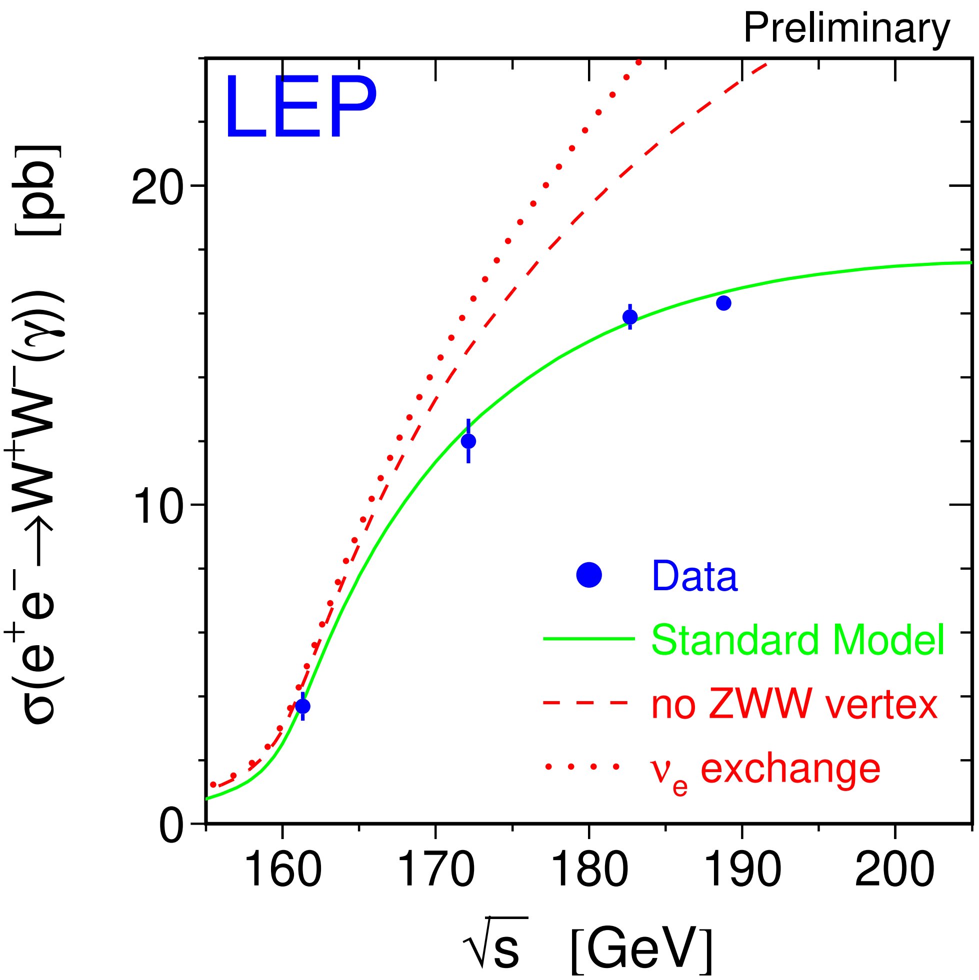


- Equal sensitivity to $\Delta\kappa_\gamma$ as W-pair events

W Pair Cross-Section and W couplings



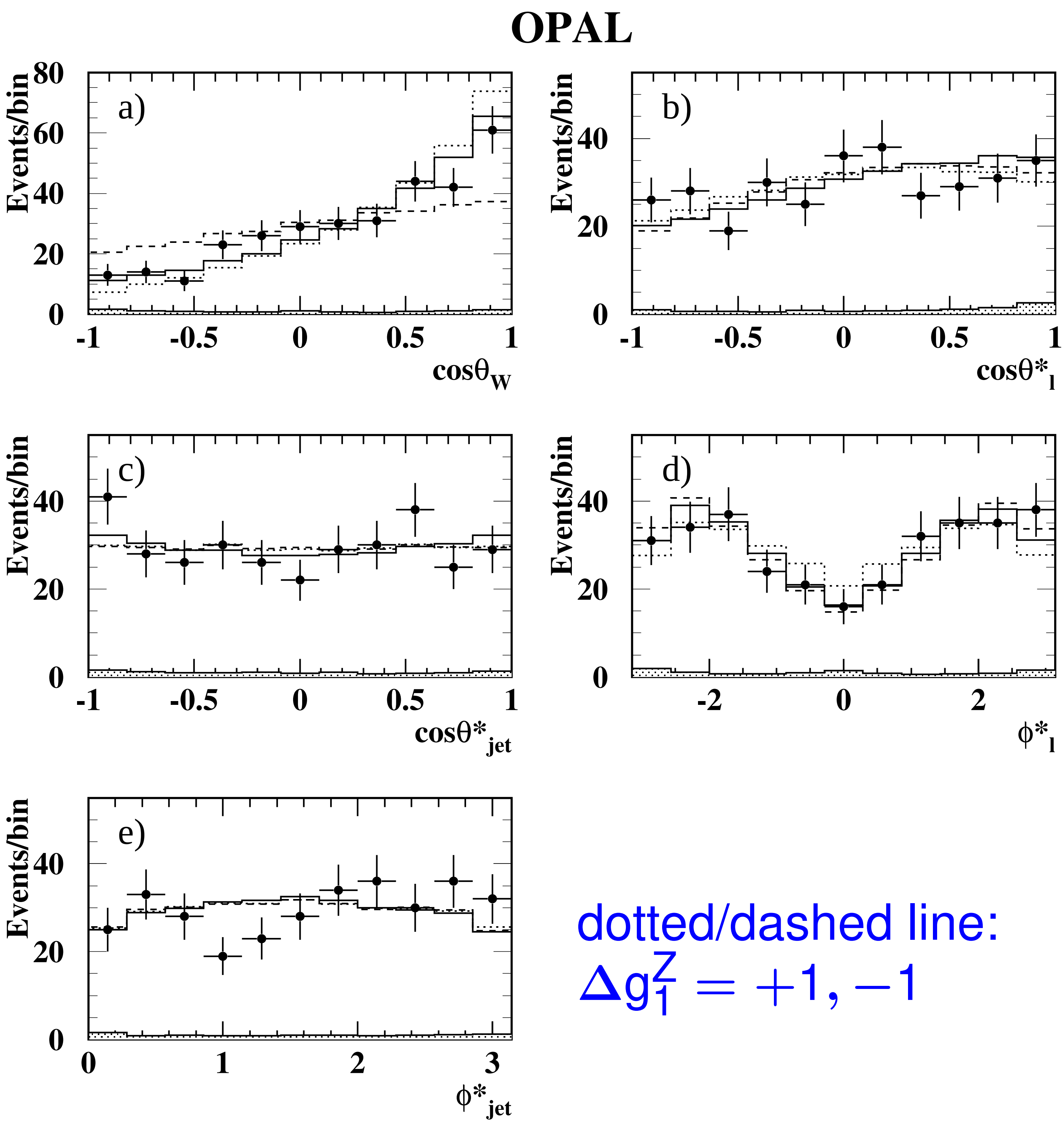




$\longrightarrow$ Three-boson vertex necessary!

- Quantitative measurement in terms of anomalous couplings $\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma$
- Cross section has large sensitivity

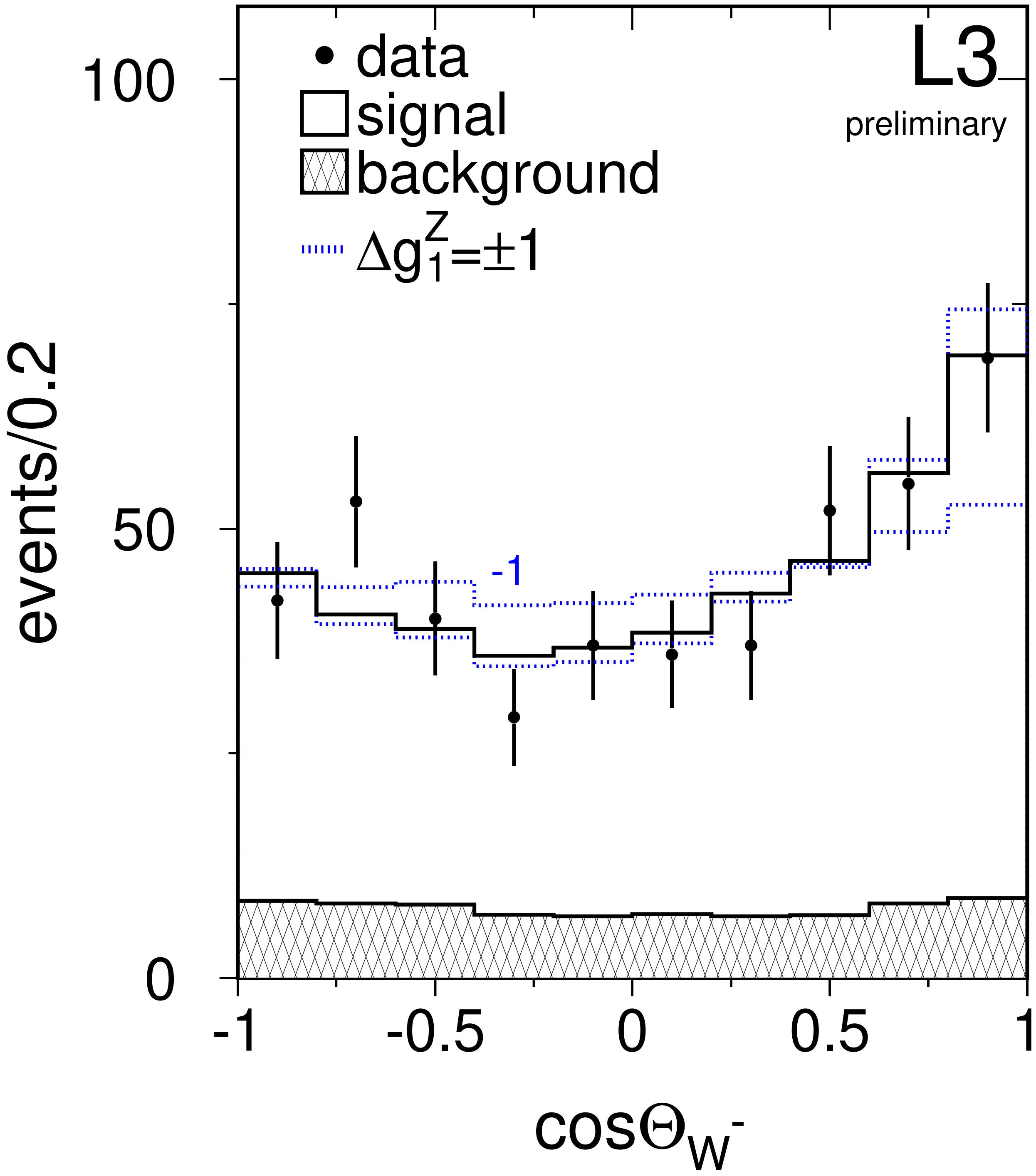
Input: Angular Distributions $qq\ell\nu$



dotted/dashed line:
$\Delta g_1^Z = +1, -1$

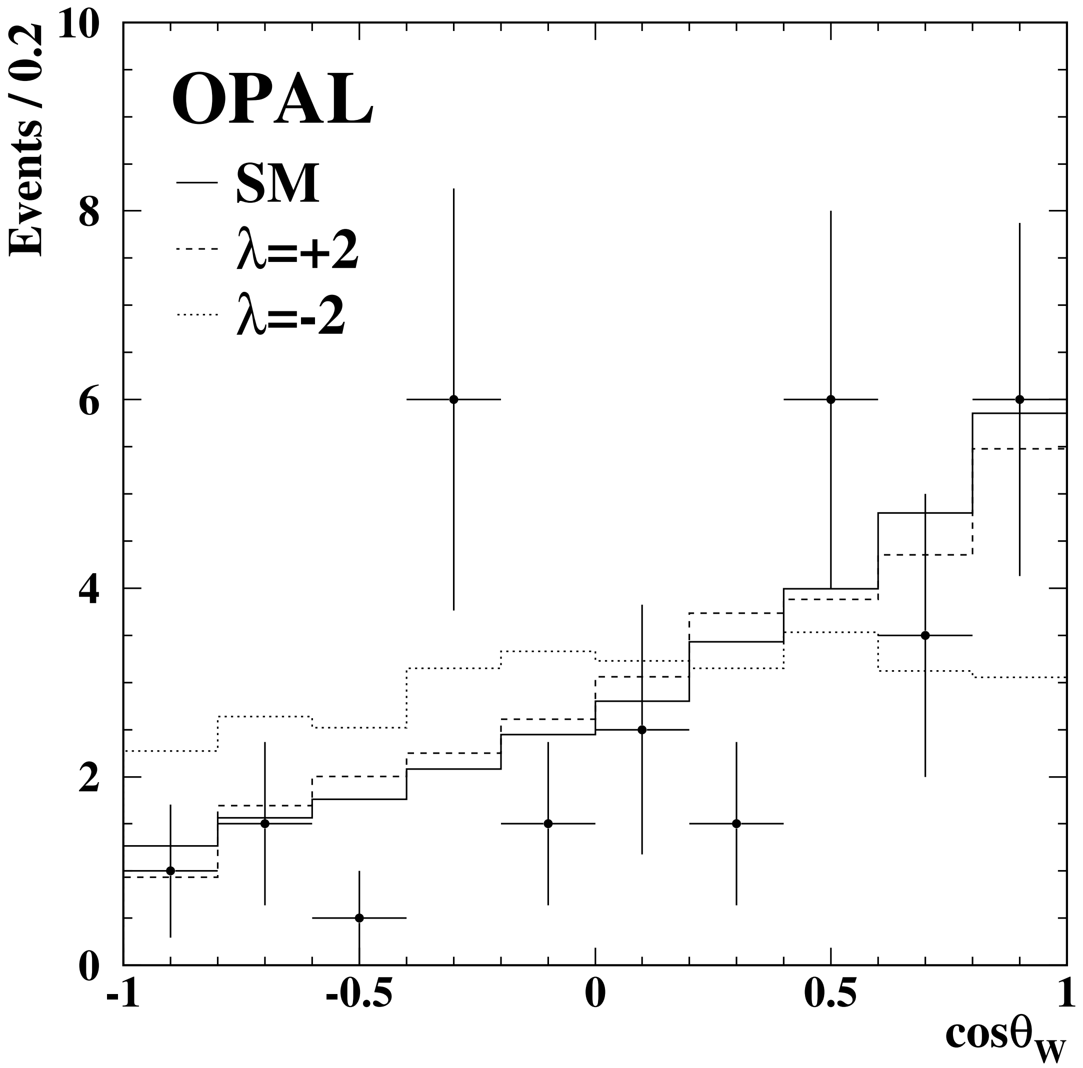
- Fit is performed using the complete multidimensional distributions

Angular Distribution qqqq



- ∘ Jet charge measurement → W charge:
  70 – 80% correct for correct jet pairing

Angular Distribution $\ell\nu\ell\nu$



Reconstruction of $\cos\theta_{\mathrm{W}}$:

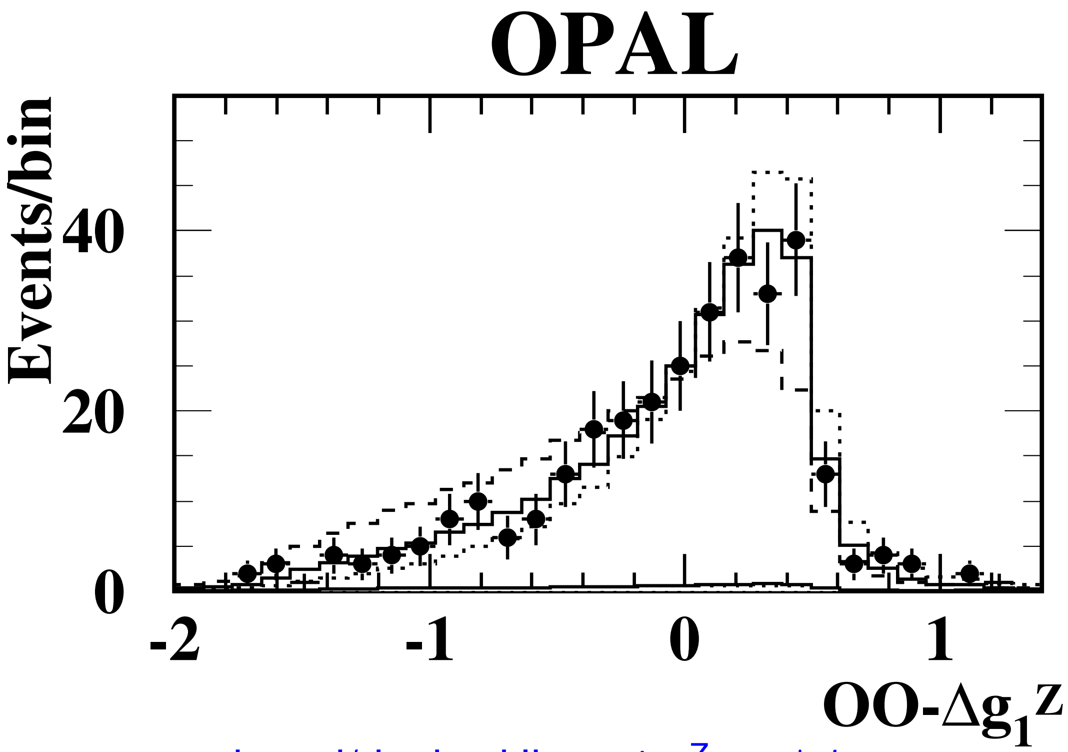
- two-fold ambiguity
- two entries per event with weight 0.5

Alternative: Optimal Observable

- Find optimal sensitivity on coupling α:

$$\frac{d\sigma}{d\Omega}(\Omega, \alpha) = c_0 + c_1 \cdot \alpha + c_2 \cdot \alpha^2$$

$$OO_\alpha = \frac{c_1}{c_0}(\Omega)$$

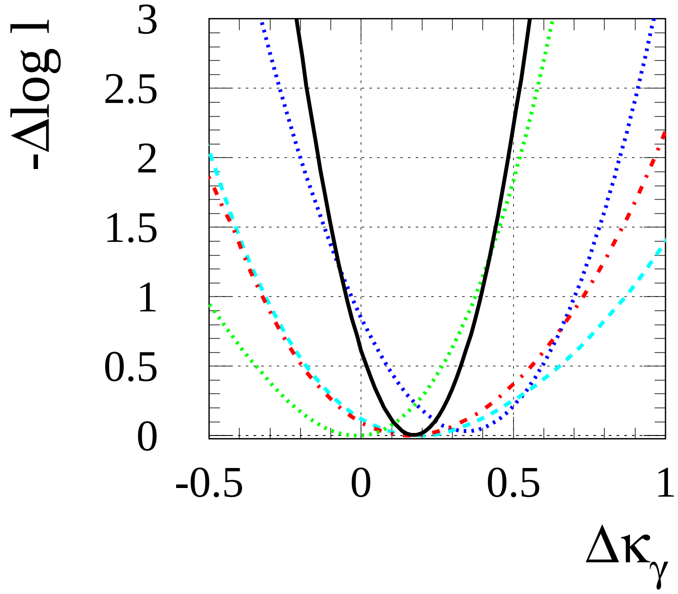


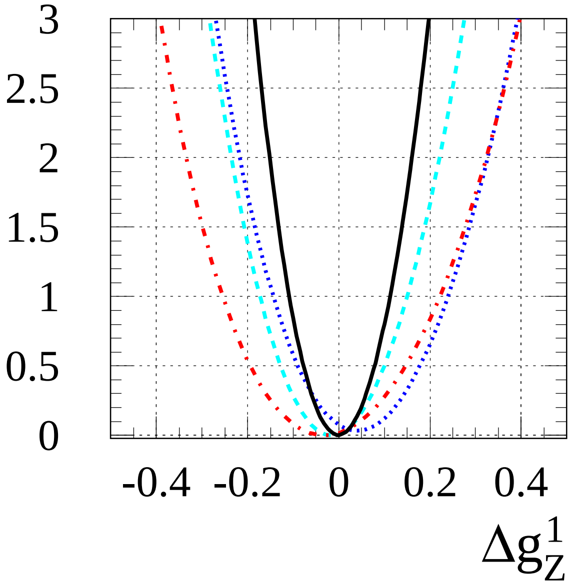
dotted/dashed line: $\Delta g_1^Z = \pm 1$

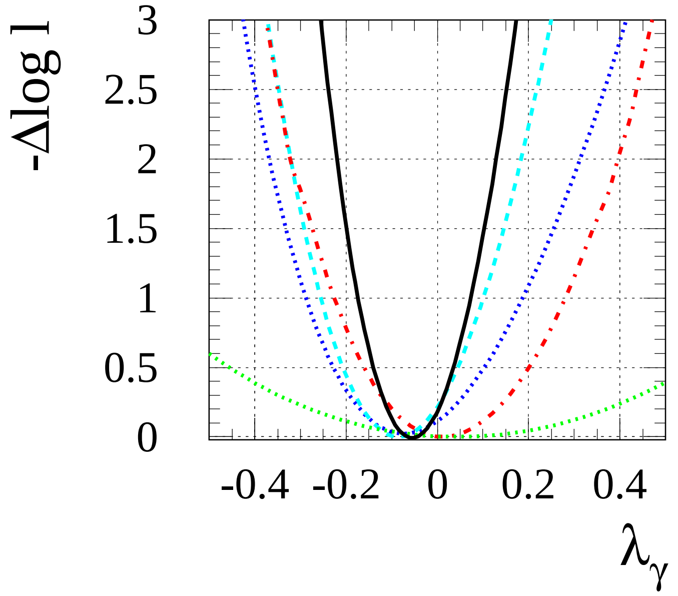
- Similar performance as fit to all measured angles
- Usually just used for 1-parameter fits

1 Dimensional Fits

ALEPH+ DELPHI+ L3 + OPAL





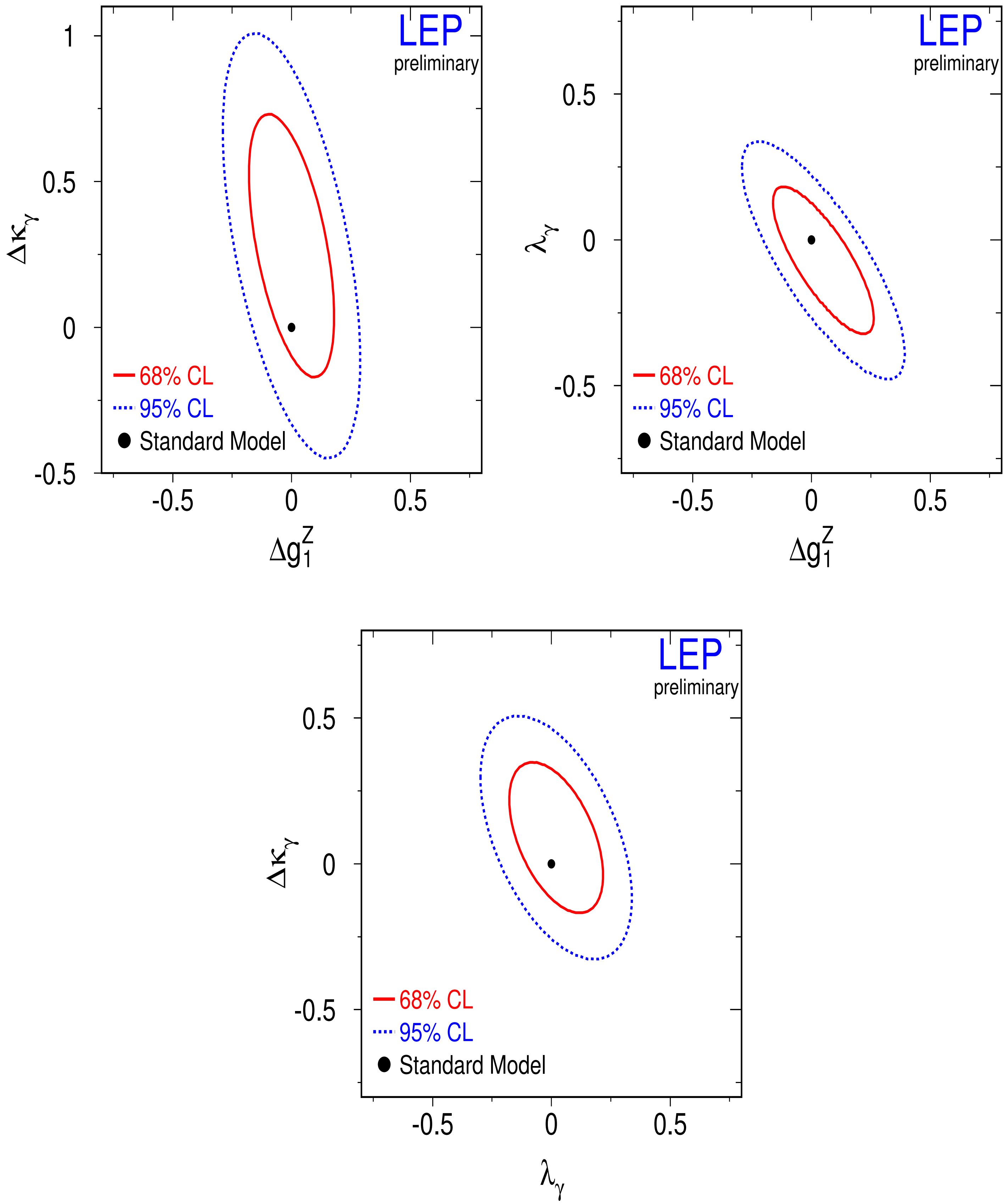


$\Delta\kappa_\gamma = 0.17 \,^{+0.16}_{-0.16}$

$\Delta g_1^Z = 0.00 \,^{+0.08}_{-0.08}$

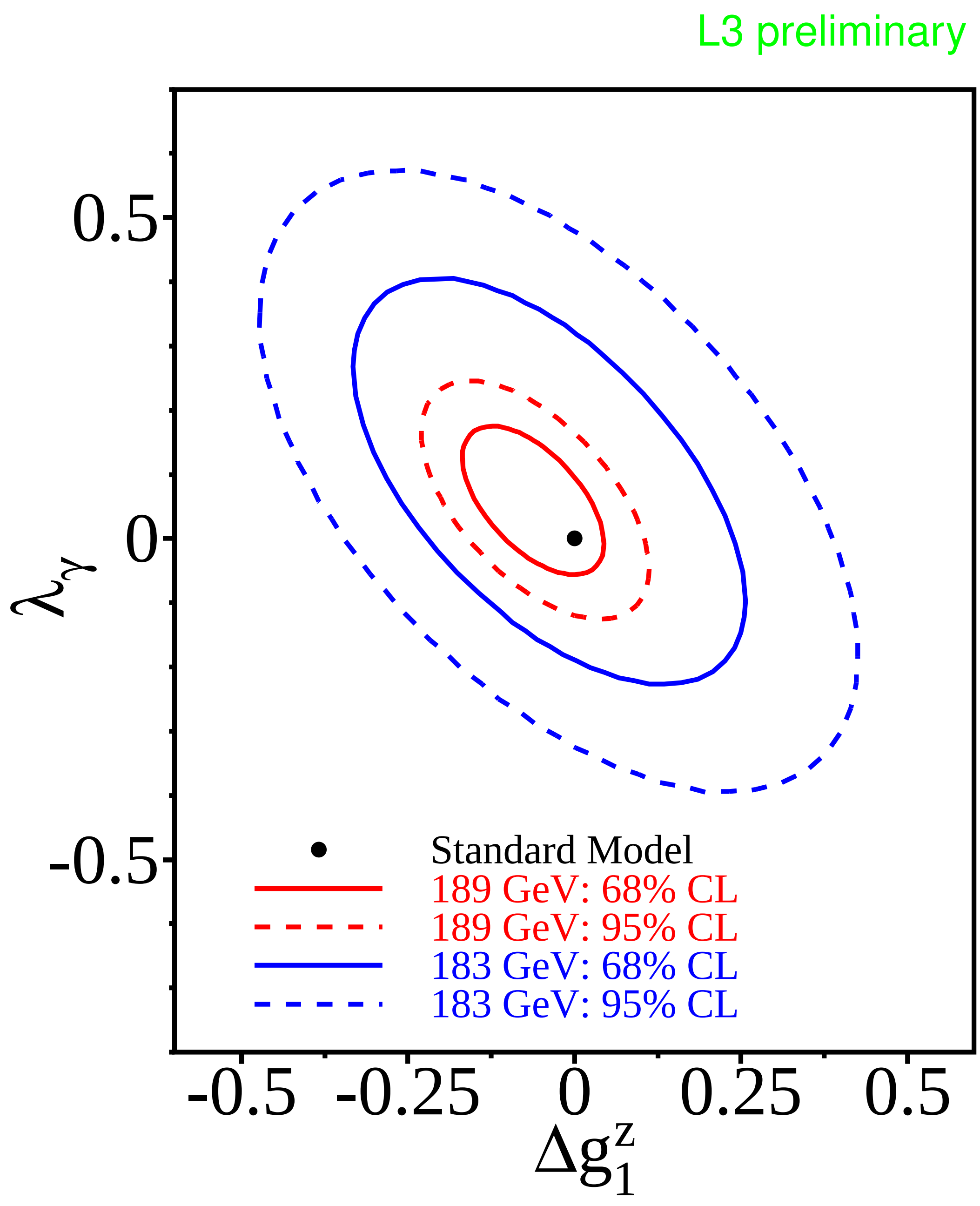
$\lambda_\gamma = -0.05 \,^{+0.08}_{-0.09}$

Fits in more Dimensions



▷All consistent with Standard Model◁

Improvements with 1998 Data



- One-parameter fit (W-pair events):

$$\Delta g_1^Z = -0.03 \pm 0.06$$
$$\Delta\kappa_\gamma = -0.12 \pm 0.13$$
$$\lambda_\gamma = -0.02 \pm 0.06$$

- Improvement with 1998 data: factor 3
- It is worth to combine results from W-pairs, single W's and single γ's

Conclusion and Outlook

- Current W mass value from LEP ($\sqrt{s} \leq 183$ GeV):

$$M_W = 80.37 \pm 0.09 \text{ GeV}$$

- Good agreement with other experiments and LEP 1 result.
- Improvement from 1998 data: $\Delta M_W \rightarrow 45$ MeV
- Systematic error sources will be important. More luminosity helps in limiting the effects.
- Couplings of the W to the other vector bosons agree with Standard Model values.
- Errors reduce a lot with 189 GeV data $\longrightarrow$ factor 3
- This year: a maximum of luminosity at highest possible center-of-mass energies

$$\sqrt{s} \rightarrow 200 \text{ GeV}$$