W Physics with L3

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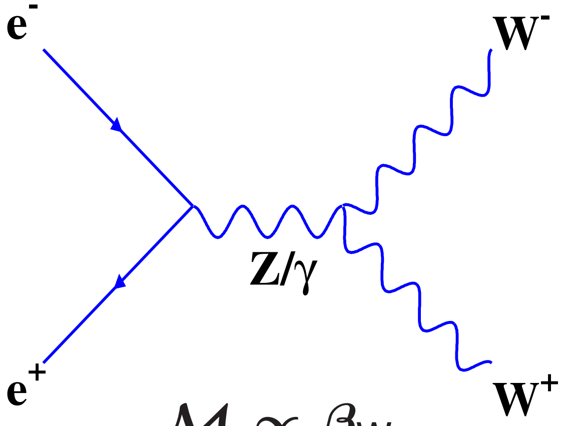
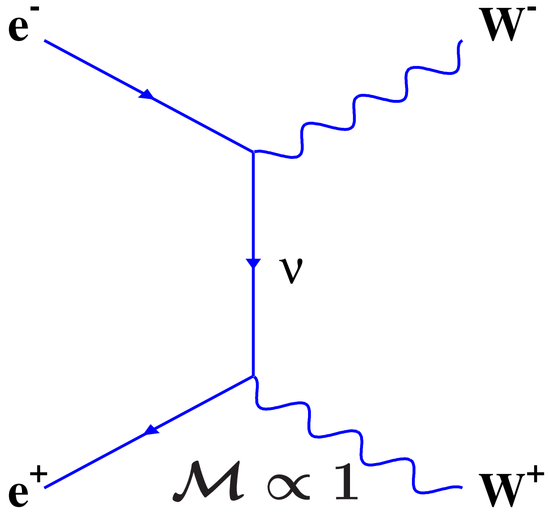
- WW Production and Selection
- W Boson Mass
- Triple Gauge Boson Couplings

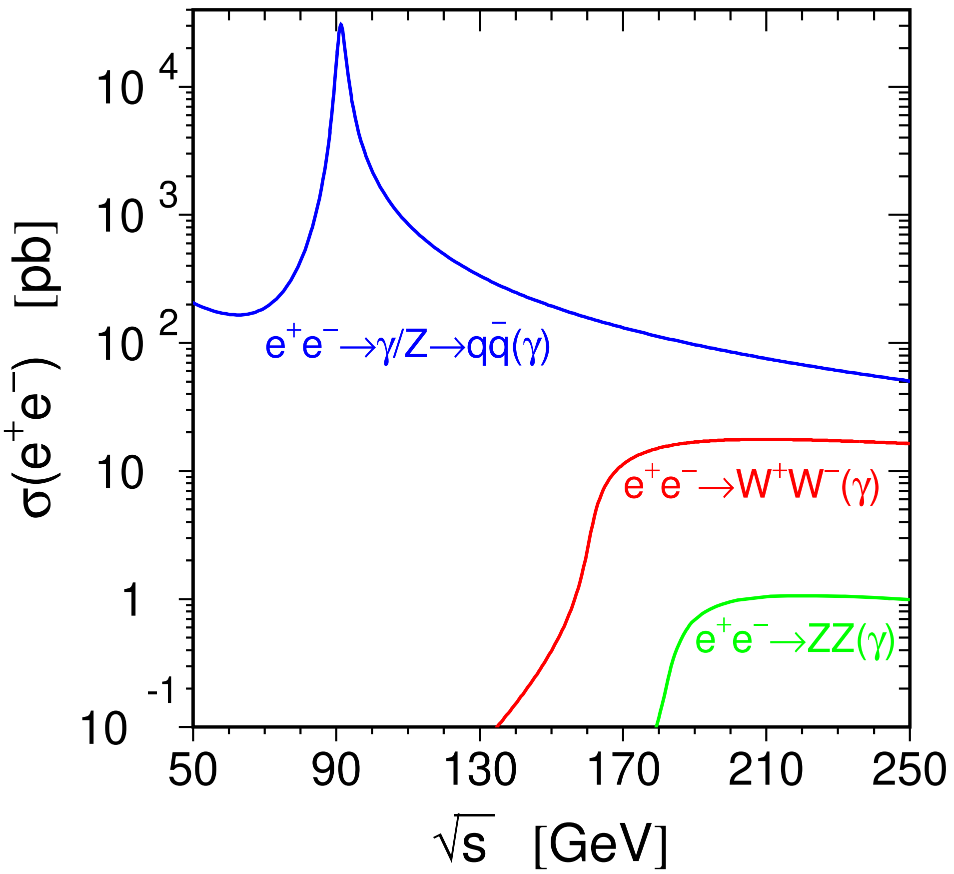
$e^+e^- \rightarrow W^+W^-$ at high energy:



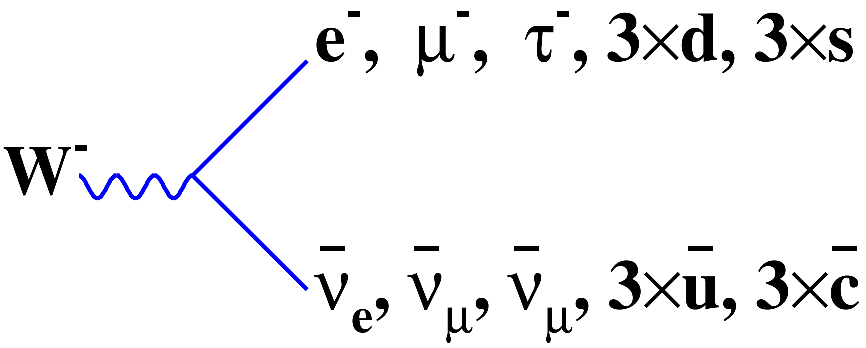
$\mathcal{M} \propto \beta_W$



$\mathcal{M} \propto 1$



$e^+e^- \rightarrow W^+W^- \rightarrow$ ffff



$\frac{1}{9}$ **each**

$e^+e^- \rightarrow W^+W^-$	**type**	**fraction, %**
$\rightarrow q\bar{q}q\bar{q} \rightarrow$ 4 jets	**hadronic**	**45.6**
$\rightarrow q\bar{q}\ell\nu \rightarrow$ 2 jets $\ell\nu$	**semileptonic**	**43.8**
$\rightarrow \ell^+\ell^-\nu\bar{\nu}$	**leptonic**	**10.6**

Studying Ws with e^+e^- easier than with $p\bar{p}$:

- **No beam remnants, hermetic detectors $\longrightarrow$ Full kinematics is known**
- **Study of $W \longrightarrow q\bar{q}$ also possible**

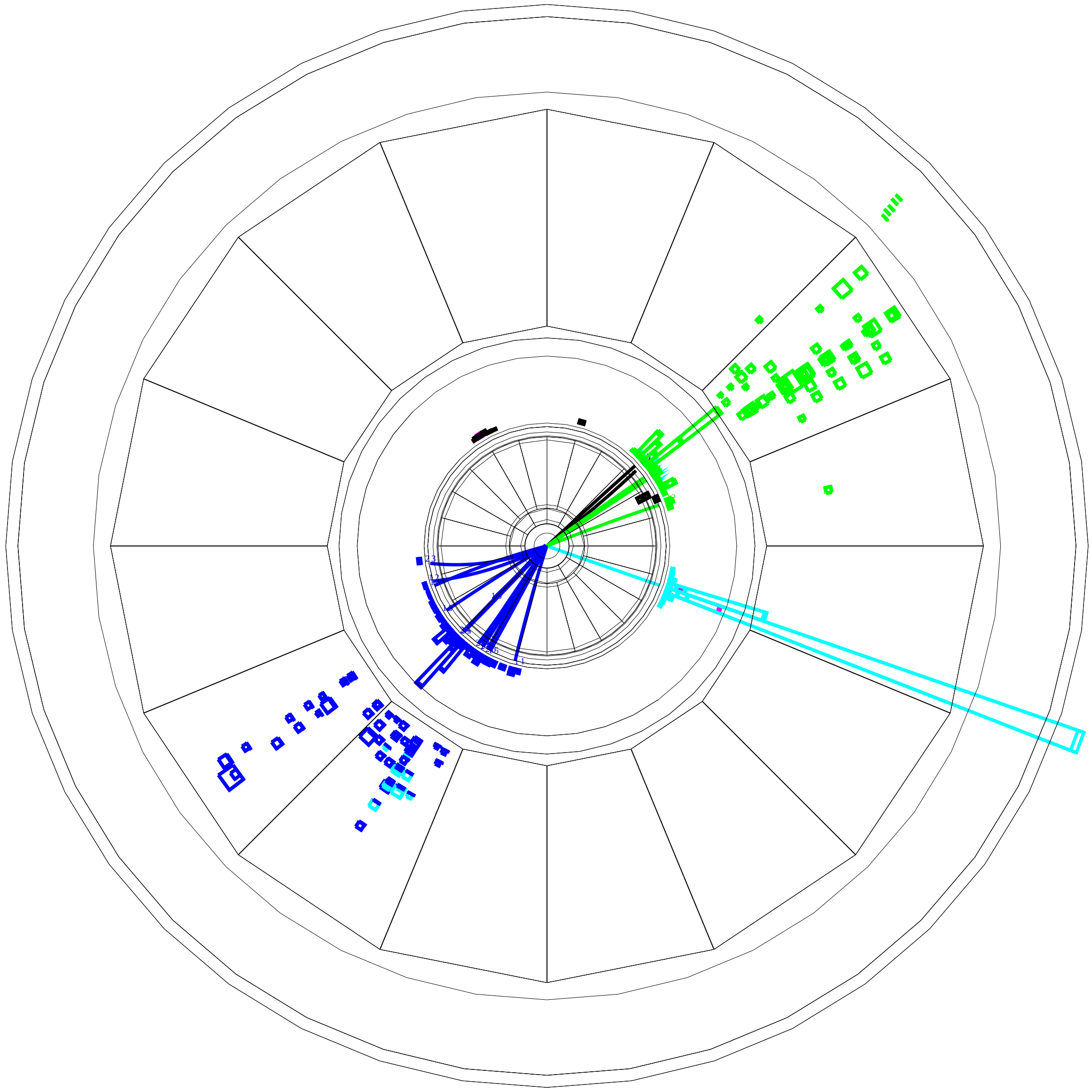
but needs integrated luminosity

LEP 2 program

	E_{CM} [GeV]	$\int \mathcal{L}dt$ [pb^{-1}]
1996	161	10
	172	10
1997	183	55
1998	189	175
1999-2000	192-200	150/year

3K WW events/experiment now, 6K in 2000

A WW $\longrightarrow$ $q\bar{q}e\nu_e$ event at 161 GeV:



E_e = 36 GeV M_{qq} = 90 GeV $M_{e\nu}$ = 80 GeV

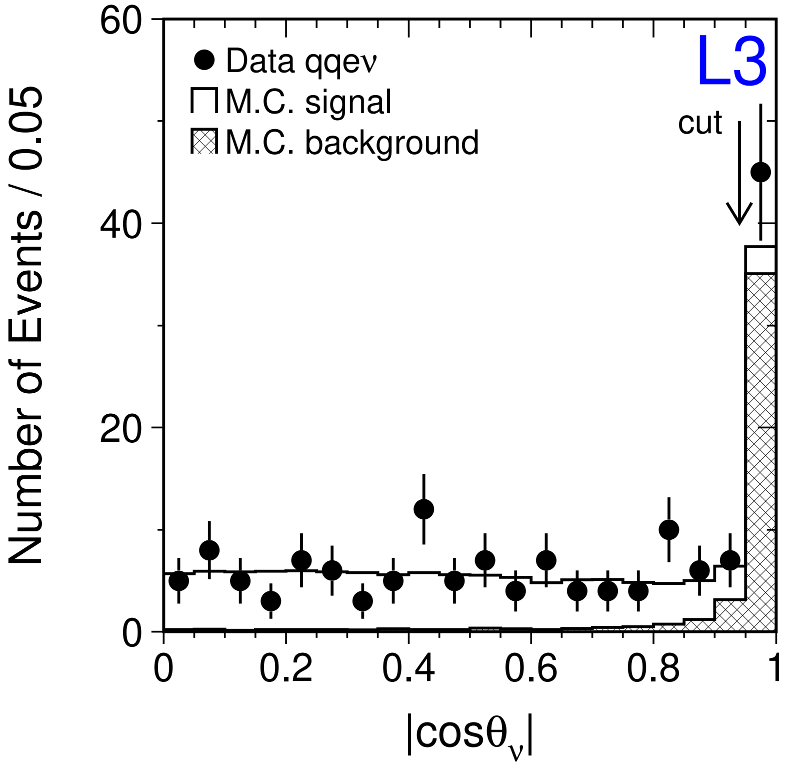
Selection Outline:

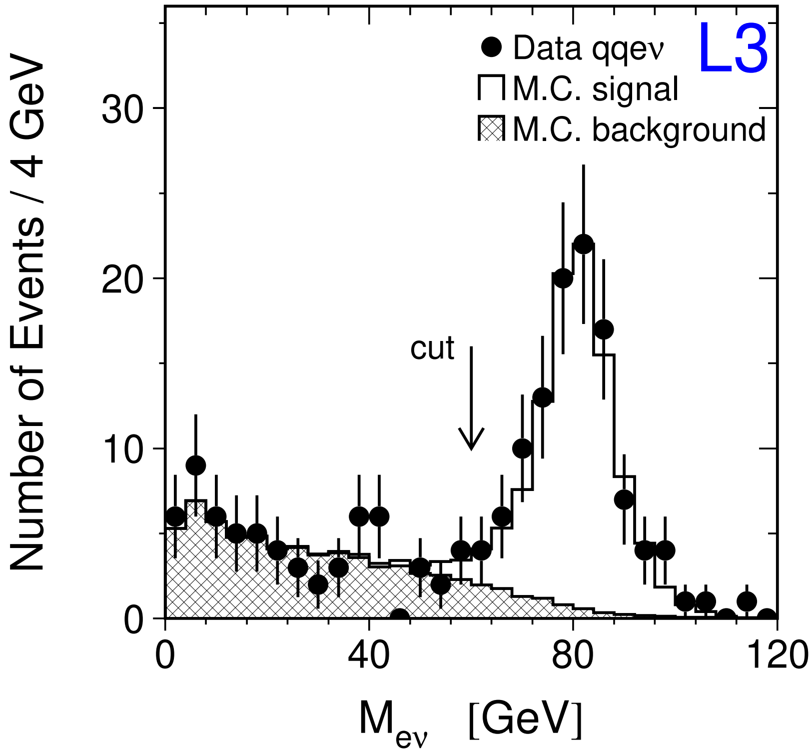
- High multiplicity events
- One energetic isolated lepton:
  - e: track + electromagnetic shower
  - μ: track in muon spectrometer or m.i.p. in central tracker, calorimeters
  - τ: lower energy e/μ or narrow, low multiplicity hadronic jet
- Hadrons $\longrightarrow$ two jets
- $\vec{p}_\nu \equiv$ missing momentum vector
- Cuts on 4f kinematics

Background: $q\bar{q}\gamma$

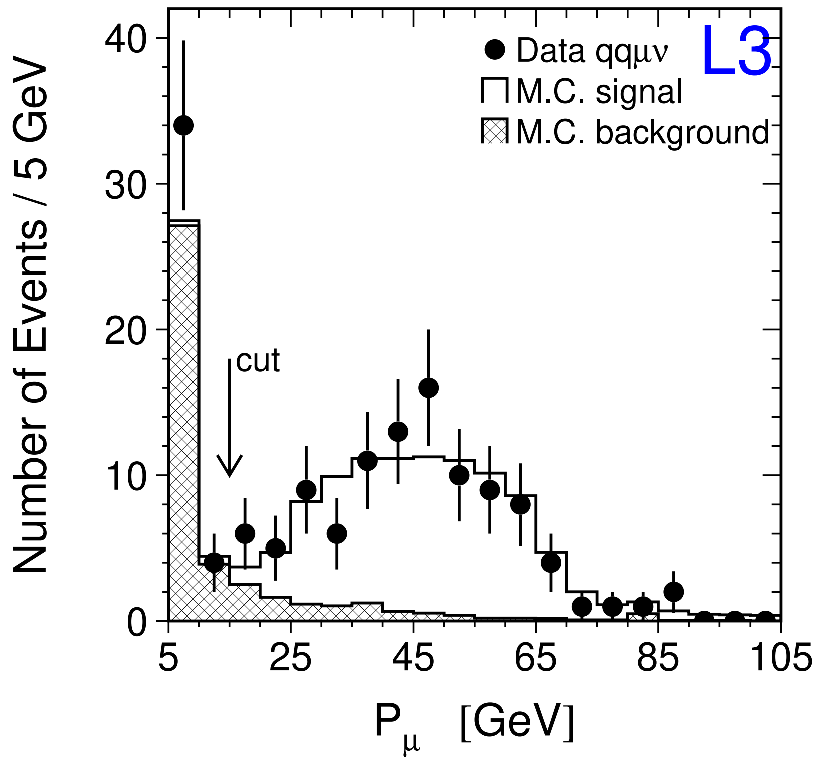
	$q\bar{q}e\nu_e$	$q\bar{q}\mu\nu_\mu$	$q\bar{q}\tau\nu_\tau$
ε,%	85.4	77.0	50.1
Purity, %	94	95	86

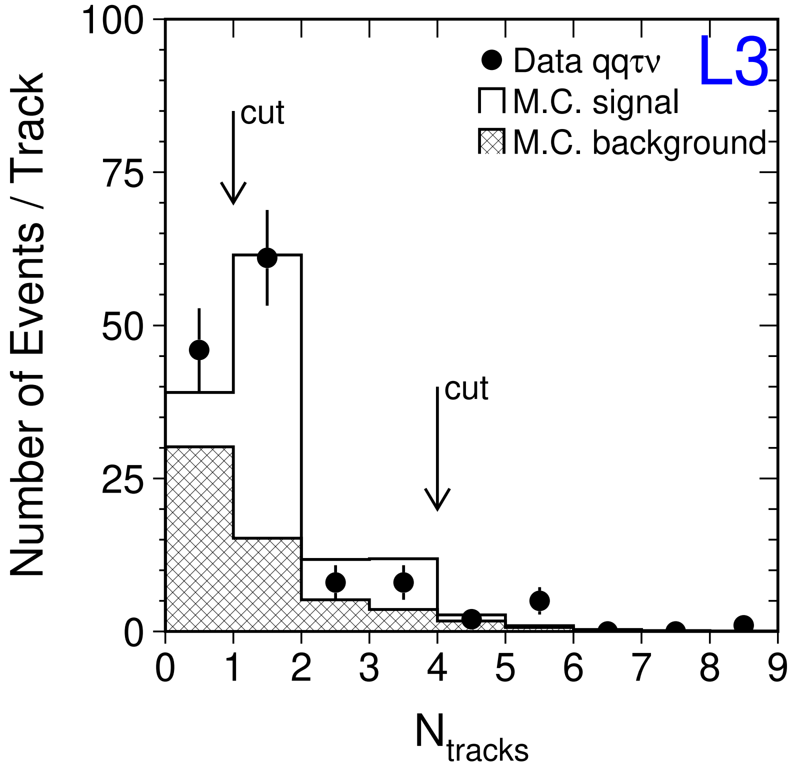
L3 data at 183 GeV:



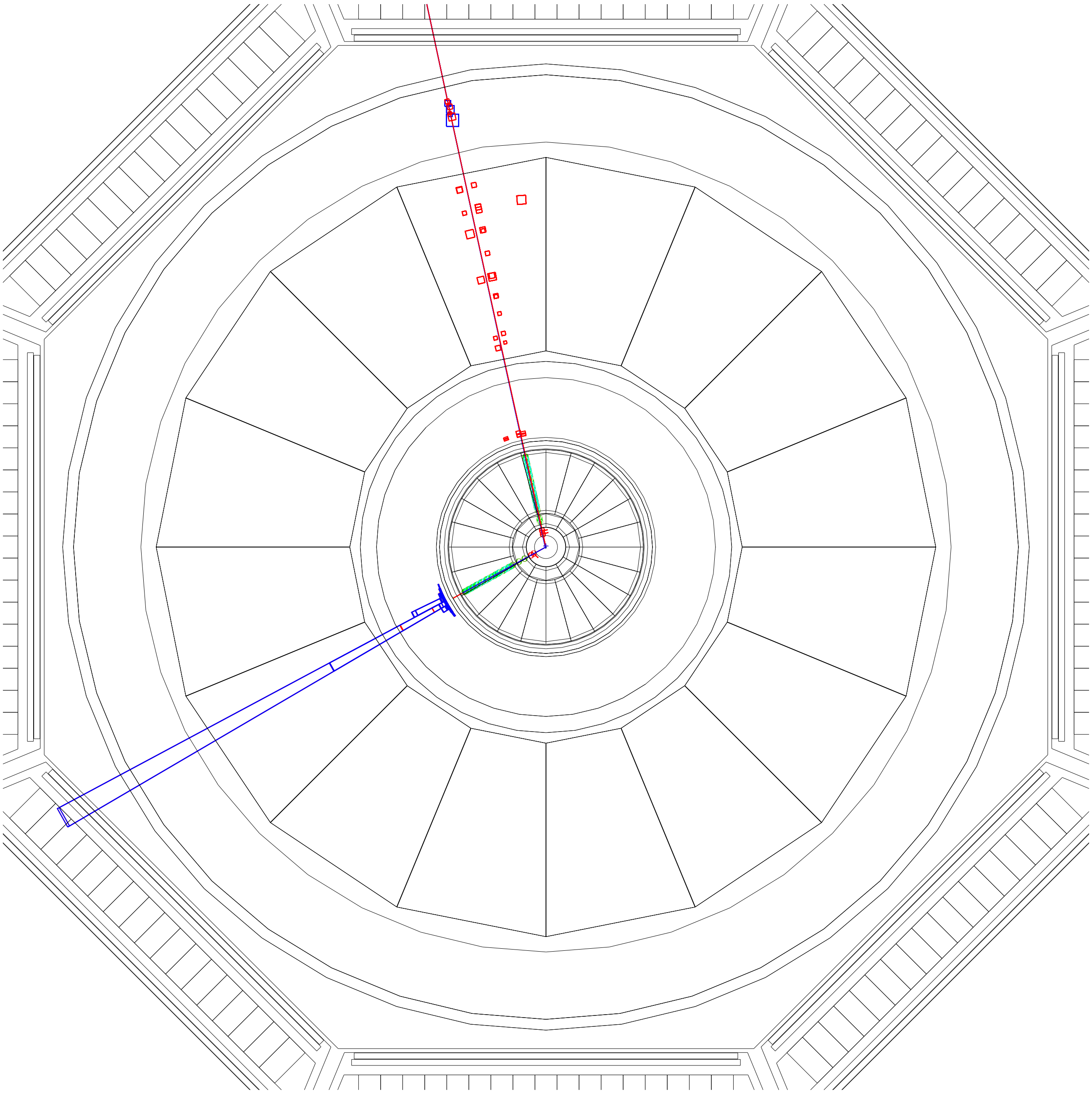


WW $\rightarrow q\bar{q}\ell\nu$ Selection





A WW $\rightarrow e\nu\mu\nu$ event at 161 GeV:



$P_\mu = 55$ GeV $E_e = 43$ GeV

Signatures:

- e/μ + e/μ, e/μ + τ $\longrightarrow$ hadrons jet **clean**
- two τ $\longrightarrow$ hadrons jets **high background**

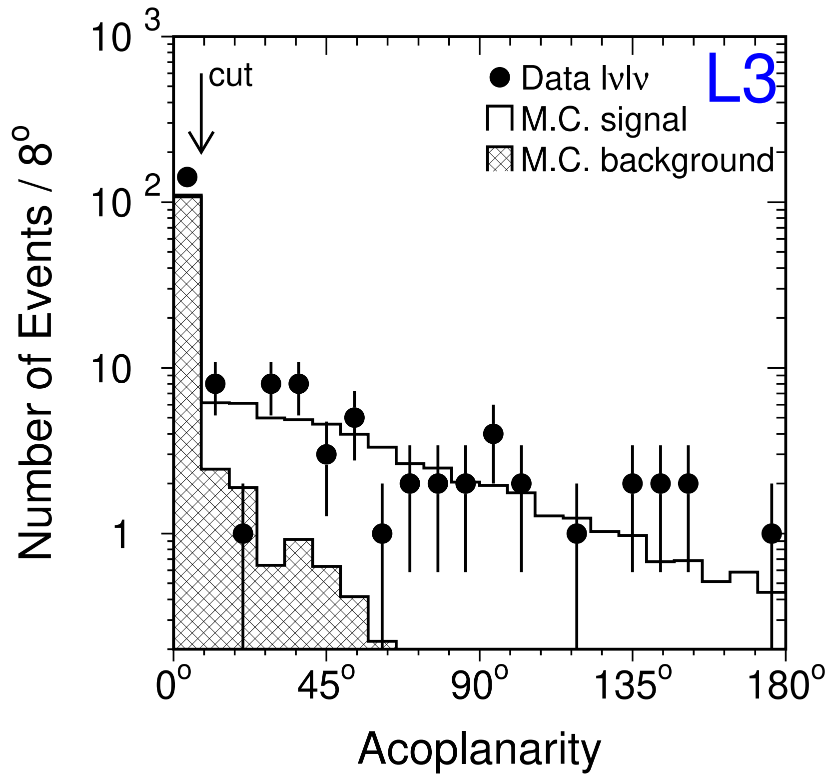
Background: $\ell^+\ell^-$, $\gamma\gamma$ interactions, cosmics

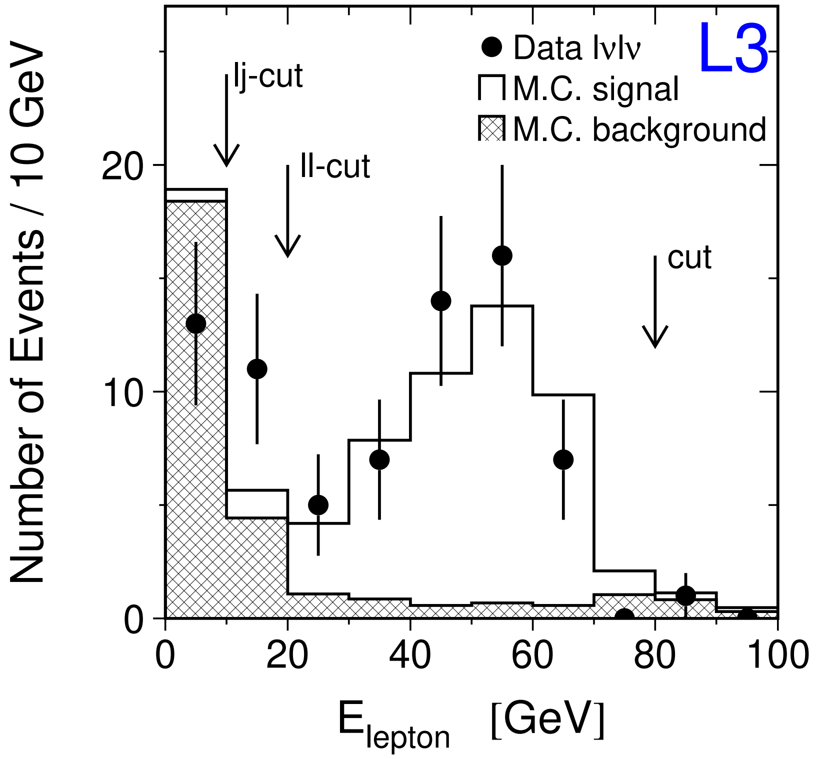
Selection Strategy:

- Low multiplicity events
- Two leptons/τ-jets
- Nothing (not much) else in the detector
- Reject background by cutting on:
  - lepton energies
  - missing energy size, momentum direction
  - acoplanarity of the leptons

ε = 48 % Purity = 82%

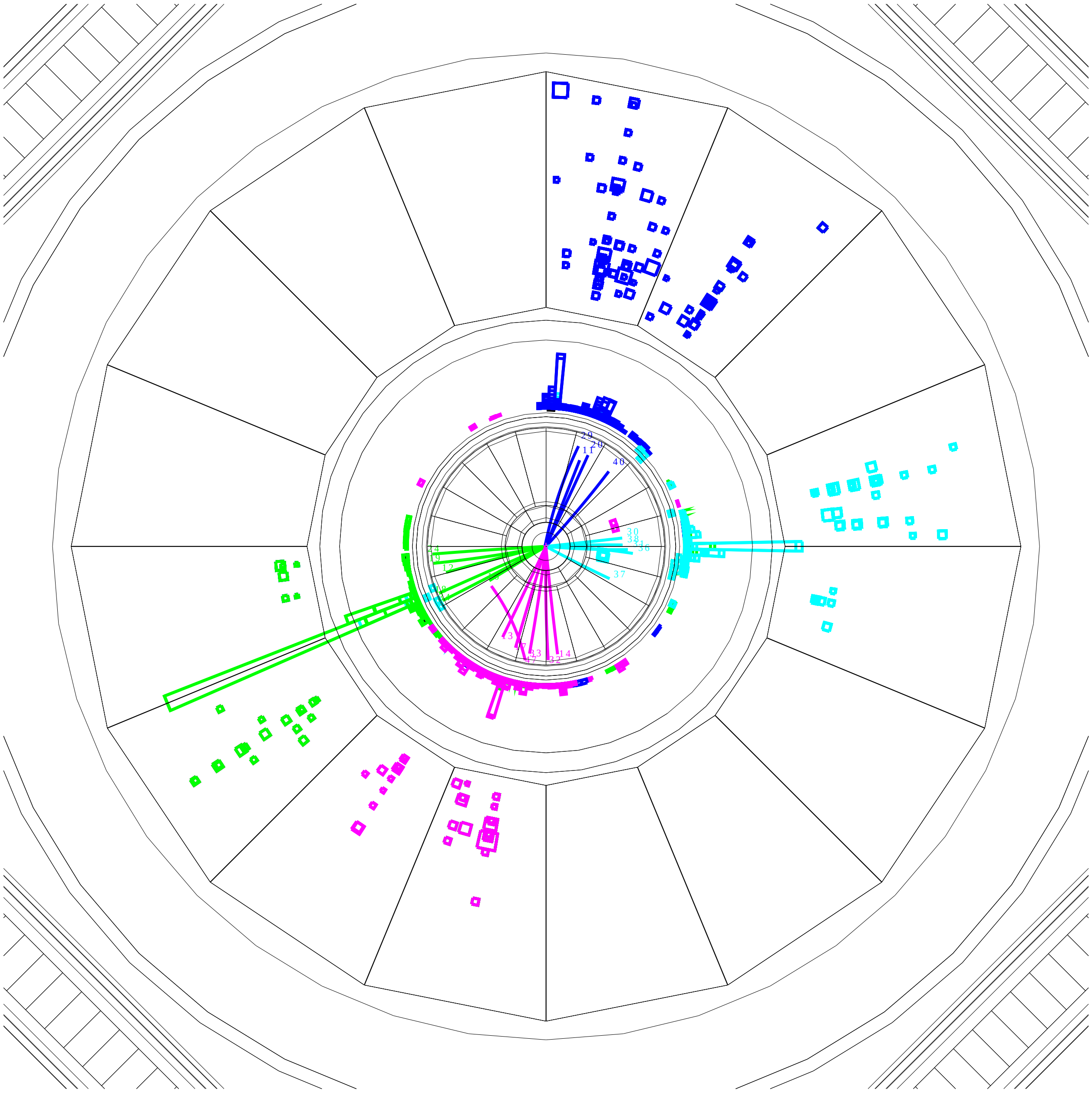
L3 data at 183 GeV:





WW $\longrightarrow$ q$\bar{q}$q$\bar{q}$ Selection

Run # 663205 Event # 3974 Total Energy : 173.13 GeV



Transverse Imbalance : .0515 **Longitudinal Imbalance :** -.0144

$M_1 = 77$ GeV $M_2 = 83$ GeV

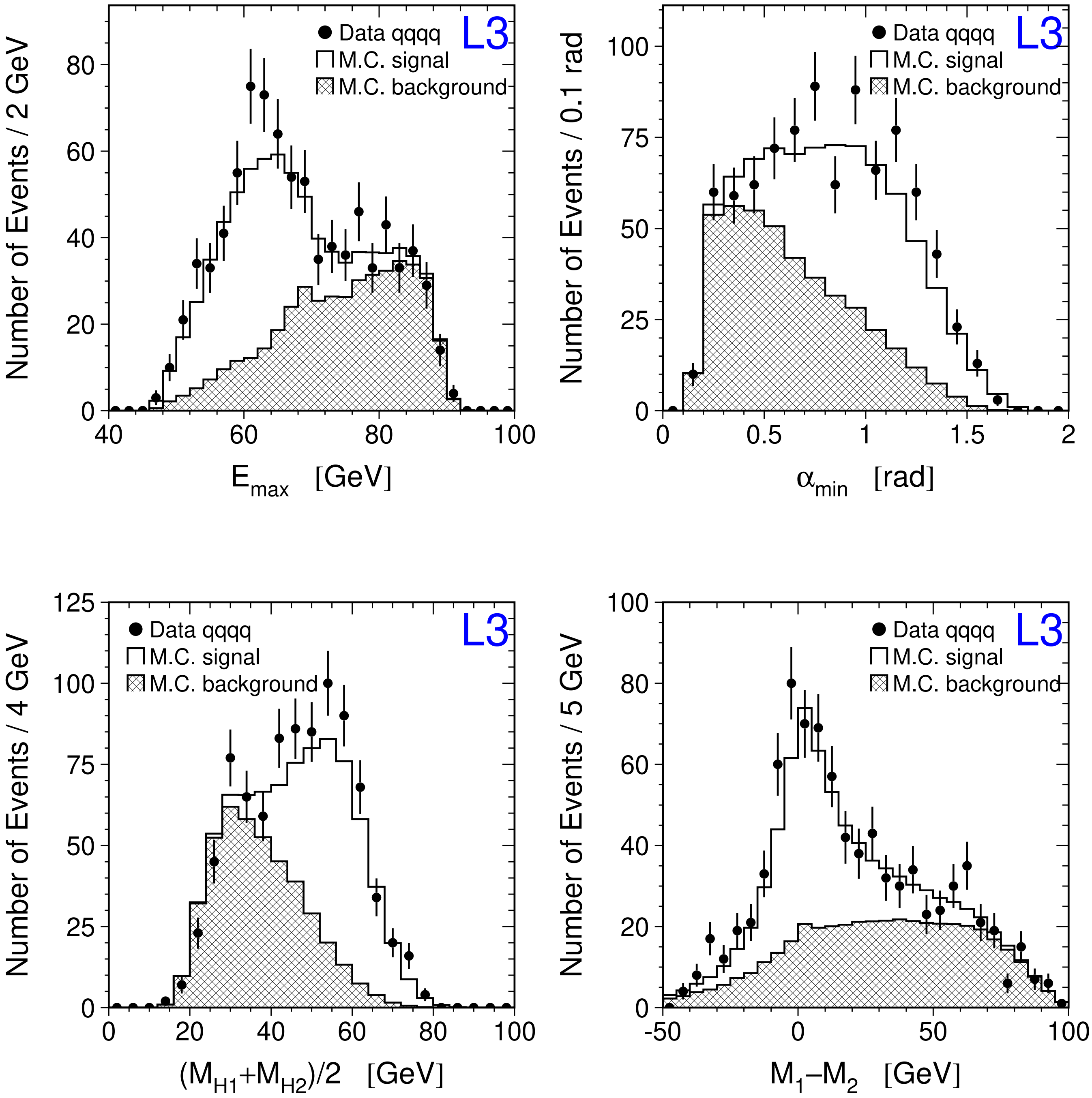
QCD ($q\bar{q}gg$) background is high. At threshold:

- **Signal:**
  $\sigma(e^+e^- \longrightarrow W^+W^- \longrightarrow q\bar{q}q\bar{q}) \simeq 1.5$ pb
- **Main background source:**
  $\sigma(e^+e^- \longrightarrow q\bar{q}) \simeq 150$ pb

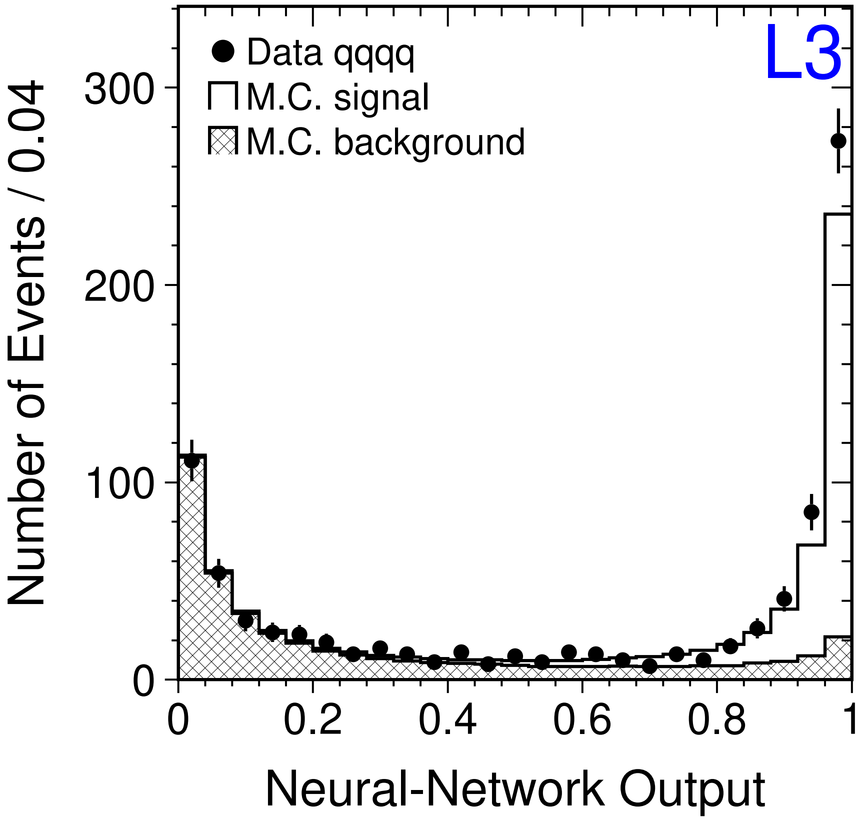
Selection is complicated:

- **Easy to reject much of background:**
  - low multiplicity, low visible energy, imbalanced events, events with leptons
  - "radiative returns to Z"
  - clear two-jet events
- **The remaining QCD background still high**

Some of the best variables at 183 GeV:



- **Neural Net** (8 best variables as inputs) $\longrightarrow$ best discrimination against $q\bar{q}gg$ events



- $\sigma(WW \longrightarrow q\bar{q}q\bar{q})$ **from a fit of NN output distribution**

$\sqrt{s}$ [GeV]	Efficiency [%]	Purity [%]
161	67	67
189	88	80

L3 efficiency matrix at 183 GeV:

Selected as	ε [%] $qqe\nu$	$qq\mu\nu$	$qq\tau\nu$	$l\nu l\nu$	$qqqq$	Purity [%]
$qqe\nu$	85.4	0.2	2.1			94
$qq\mu\nu$	0.1	77.0	4.3			95
$qq\tau\nu$	4.8	6.0	50.1	0.2		86
$l\nu l\nu$				48.0		82
$qqqq$	0.3		1.7		87.5	80

$\sqrt{s}$, GeV	Efficiency, %	Purity, %
161	62	74
189	76	85

Obtain

- **Total W-pair cross section** σ_{WW}
- **W-decay branching fractions** $\mathrm{B_{ff}}$

by maximizing

$$\mathcal{L} = \prod_i \mathcal{P}(N_i, \mu_i)$$

$$\mu_i = \left(\sum_j \epsilon_{ij} \boldsymbol{\sigma_j} + \sigma_i^{bg} \right) \cdot \mathcal{L}$$

where

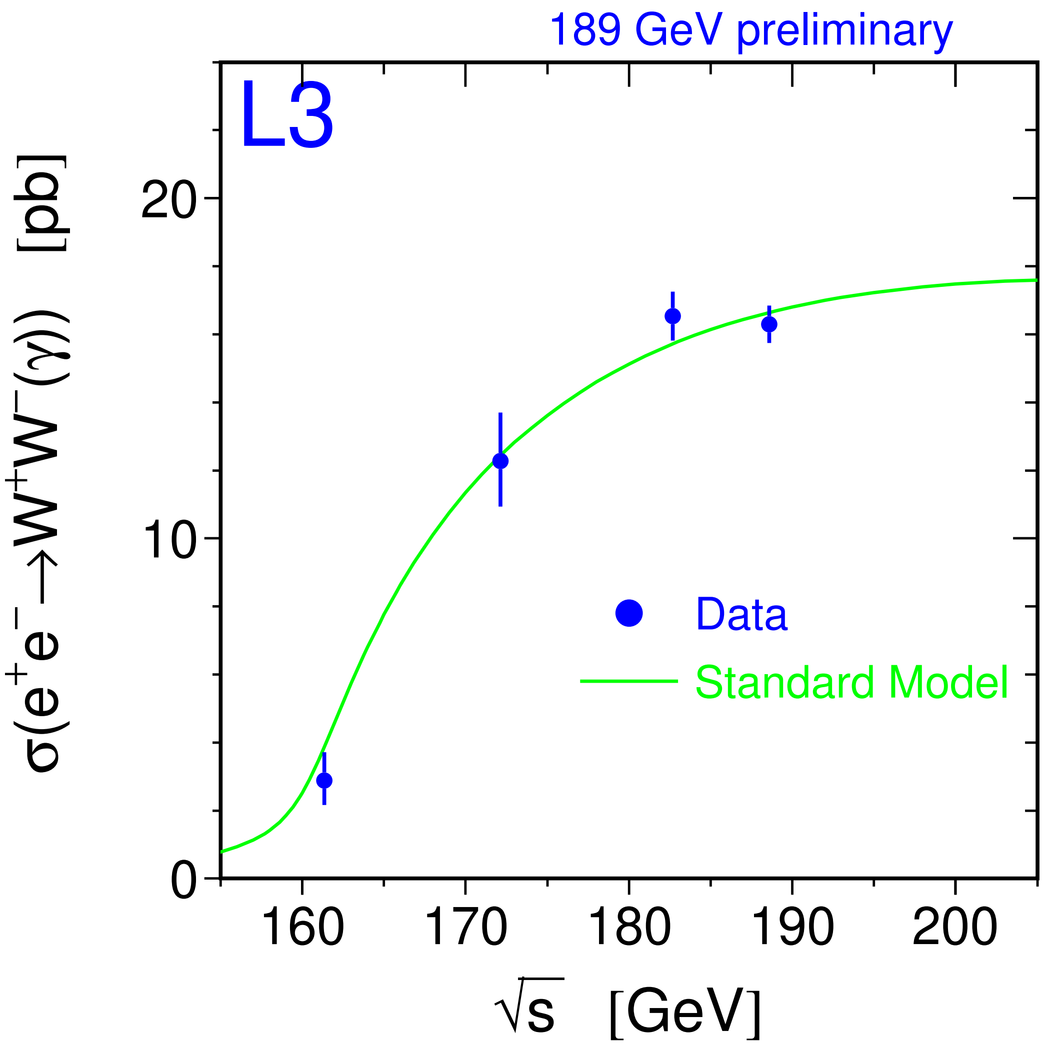
$\mathcal{P}(N_i, \mu_i)$ **- Poisson probability**

ϵ_{ij} **- the efficiency matrix,** σ_i^{bg} **- background**

$\boldsymbol{\sigma_j}$ **- channel cross-sections:**

$$\begin{aligned}
\sigma(\mathrm{qqqq}) &= \sigma_{\mathrm{WW}} \cdot \mathrm{B_{qq}B_{qq}} \\
\sigma(\mathrm{qq}\ell\nu) &= \sigma_{\mathrm{WW}} \cdot 2\mathrm{B}_{\ell\nu}\mathrm{B_{qq}} \\
\sigma(\ell\nu\ell\nu) &= \sigma_{\mathrm{WW}} \cdot (\mathrm{B}_{\mathrm{e}\nu} + \mathrm{B}_{\mu\nu} + \mathrm{B}_{\tau\nu})^2
\end{aligned}$$

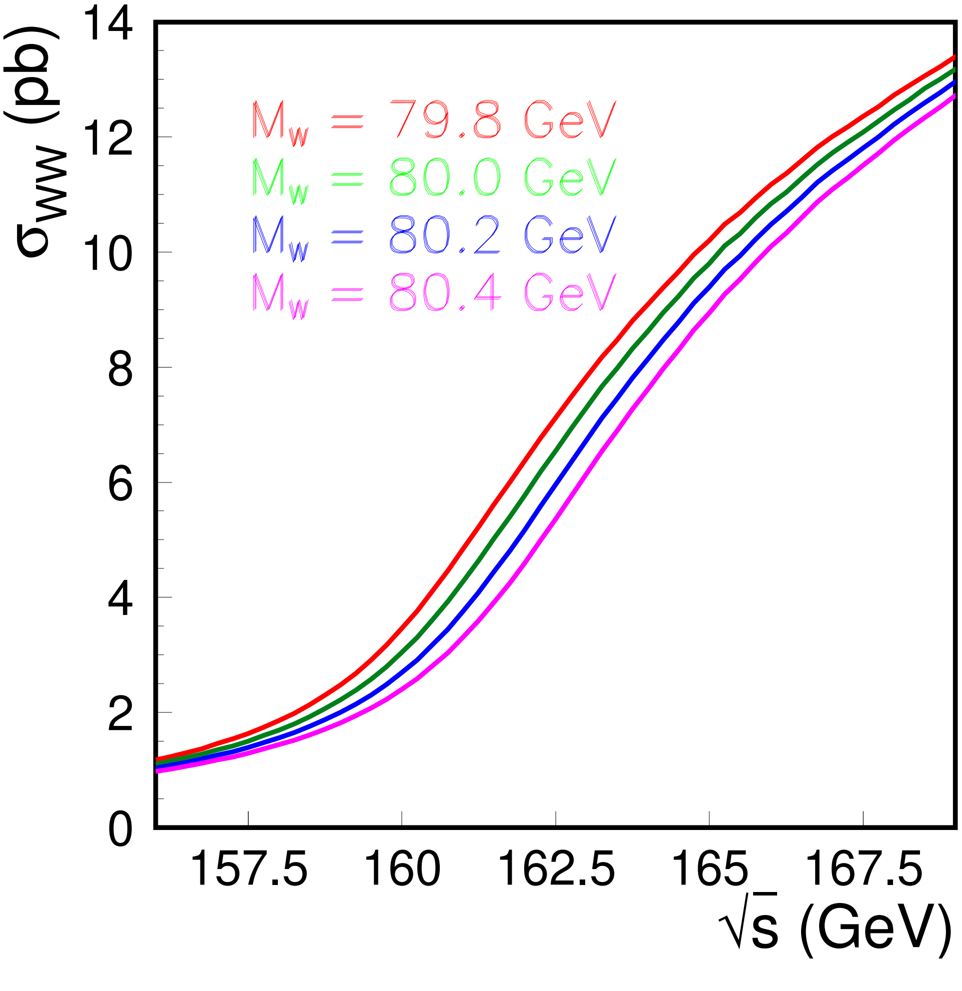
$\sqrt{s}$ [GeV]	σ(WW) [pb]	σ_{SM} [pb]
161	**2.89 ± 0.75 (stat) ± 0.14 (syst)**	
172	**12.27 ± 1.37 (stat) ± 0.23 (syst)**	**12.4**
183	**16.53 ± 0.67 (stat) ± 0.26 (syst)**	**15.7**
189	**16.29 ± 0.38 (stat) (prelim.)**	**16.65**



Including preliminary 189 GeV L3 data:

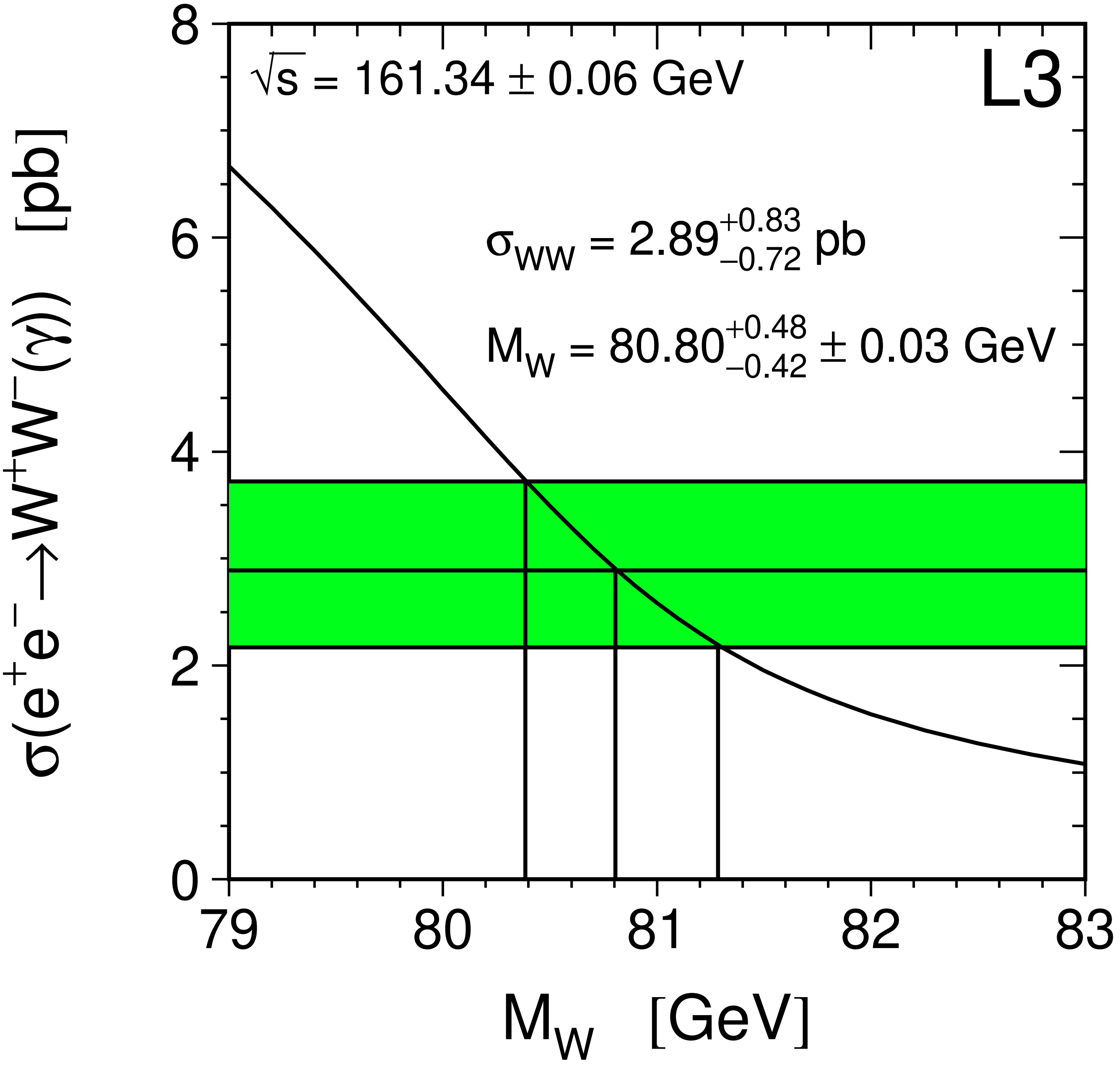
BR($W \longrightarrow f\bar{f}$) [%]	Lepton Non-Universality	Lepton Universality	Standard Model
$e\nu$	10.22 ± 0.45	—	
$\mu\nu$	10.18 ± 0.47	—	
$\tau\nu$	11.08 ± 0.63	—	
$\ell\nu$	—	10.45 ± 0.23	10.8
$q\bar{q}$	68.53 ± 0.71	68.66 ± 0.69	67.5

$$\sigma(e^+e^- \to W^+W^-) = \sigma(\sqrt{s}, M_W, \ldots)$$



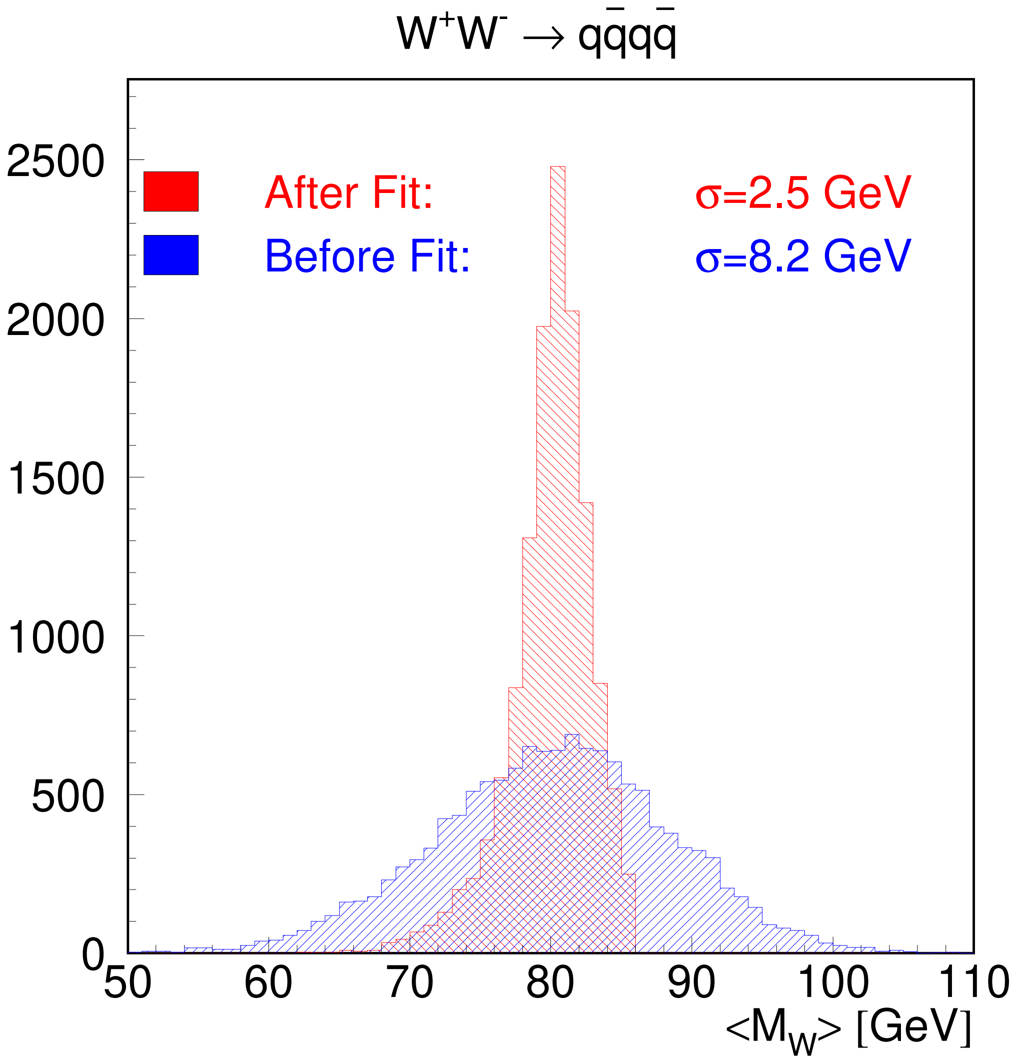
Sensitivity $\propto \frac{\sqrt{\sigma}}{d\sigma/dM_W}$

1996: $11.13\ \mathrm{pb}^{-1}$ at $\sqrt{s} = 161.34$ GeV
(22 WW events selected)



- **With** $e^+e^- \longrightarrow W^+W^- \longrightarrow q\bar{q}q\bar{q}, q\bar{q}\ell\nu$ **can reconstruct invariant masses of 2 Ws**
- **Kinematic fit:**
  - **adjust** $E, \vec{p}$ **of jets/leptons so that:**

$$\sum E = \sqrt{s} \qquad \sum \vec{p} = 0 \qquad (M_{W,1} = M_{W,2})$$



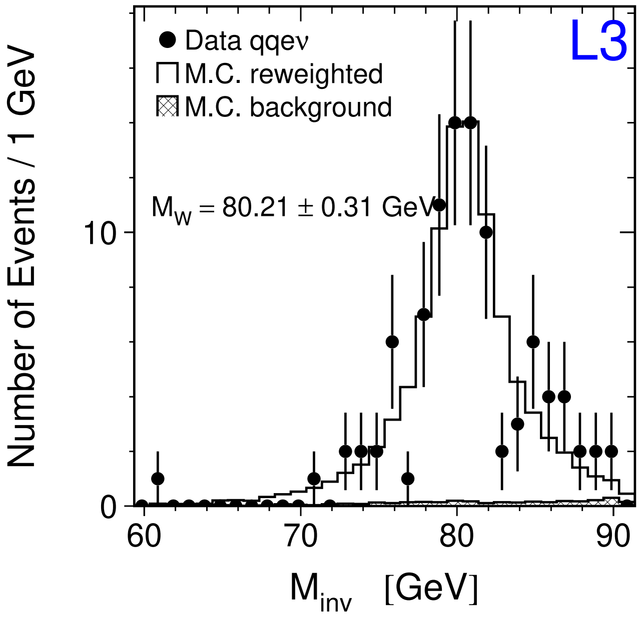
– great improvement in resolution

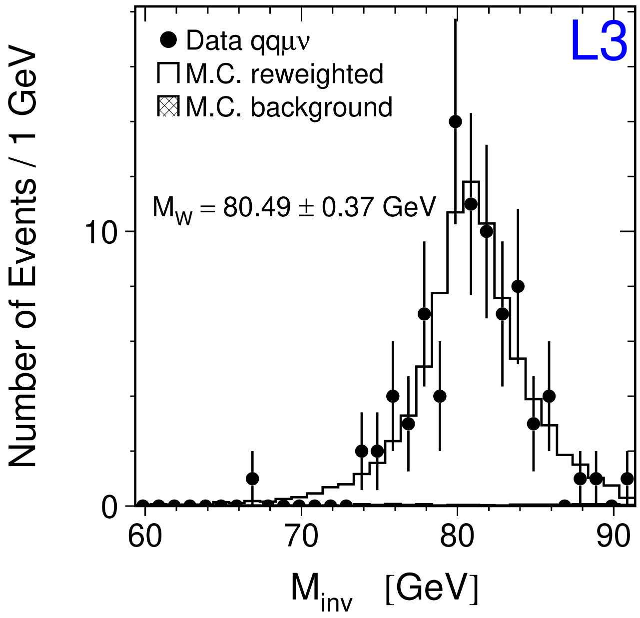
– 5 constraint fit ($\mathrm{M}_{5C} \equiv \mathrm{M}_{W,1} = \mathrm{M}_{W,2}$) $\longrightarrow$ one M_W/event

- M_W is obtained from the $\frac{d\sigma}{d\mathrm{M}_{5C}}$ distribution
- Statistical error as good as from threshold
- High $\sqrt{s}$ preferred. Applied to

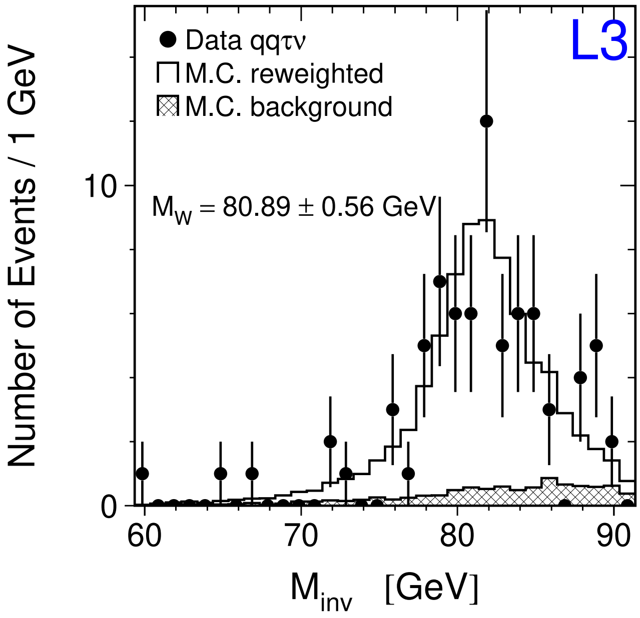
Year	$\sqrt{s}$ [GeV]	$\int \mathcal{L}dt$ [pb^{-1}]
1996	172.13 ± 0.05	10.25
1997	182.68 ± 0.05	55.47
1998	188.6 ± 0.2 (prelim.)	176.41

L3 183 GeV $q\bar{q}e\nu$, $q\bar{q}\mu\nu$,

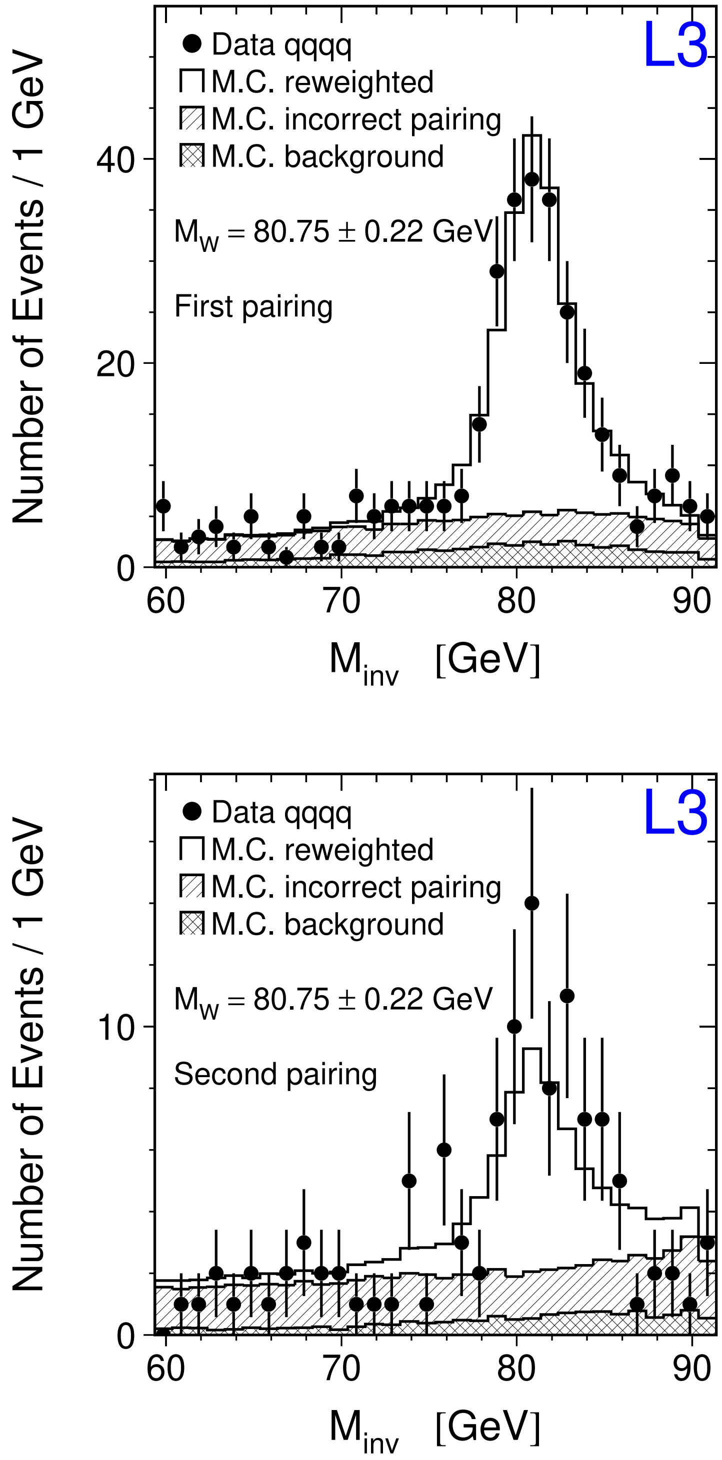




$q\bar{q}\tau\nu$ events:



L3 183 GeV $q\bar{q}q\bar{q}$ data: 2 best χ^2_{5C} jet combinations



Monte Carlo reweighting fit:

- Start with a WW MC sample at M_{W}^{MC}
- Obtain MC prediction for another M_{W} reweighting MC events with

$$\frac{|\mathcal{M}(M_{\mathrm{W}})|^2}{|\mathcal{M}(M_{\mathrm{W}}^{MC})|^2}$$

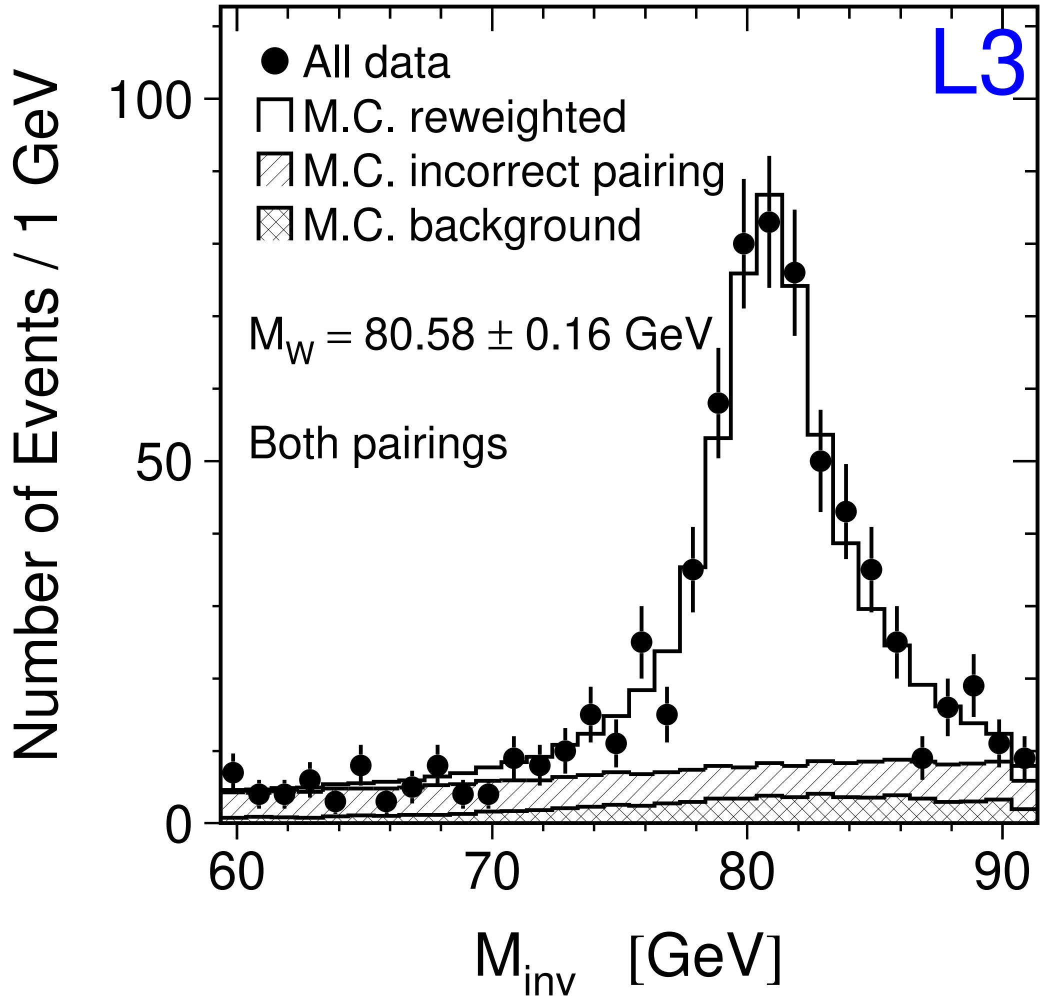
- Choose the M_{W} which best fits data $\frac{d\sigma}{dM_{5C}}$

Applicable to M_W, Γ_W, Z/γWW couplings measurements

All effects modelled by MC (detector, selection, kinematic fit, ISR, background, ...) taken into account without parametrization

With 172 + 183 GeV data:

	M_W [GeV]
$q\bar{q}q\bar{q}$	$80.75 \pm 0.18\,(stat) \pm 0.12\,(syst)$
$q\bar{q}\ell\nu$	$80.41 \pm 0.21\,(stat) \pm 0.06\,(syst)$
ffff	$80.58 \pm 0.14\,(stat) \pm 0.08\,(syst)$

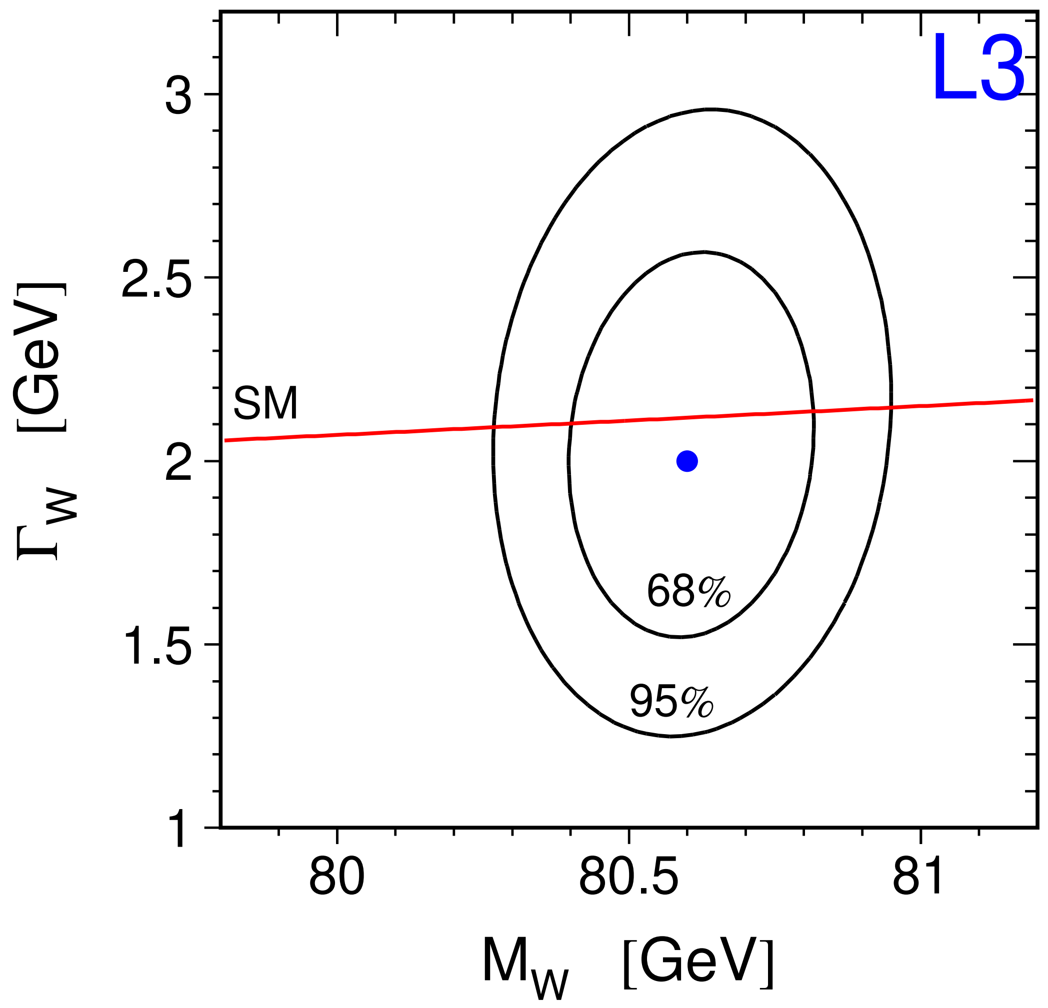


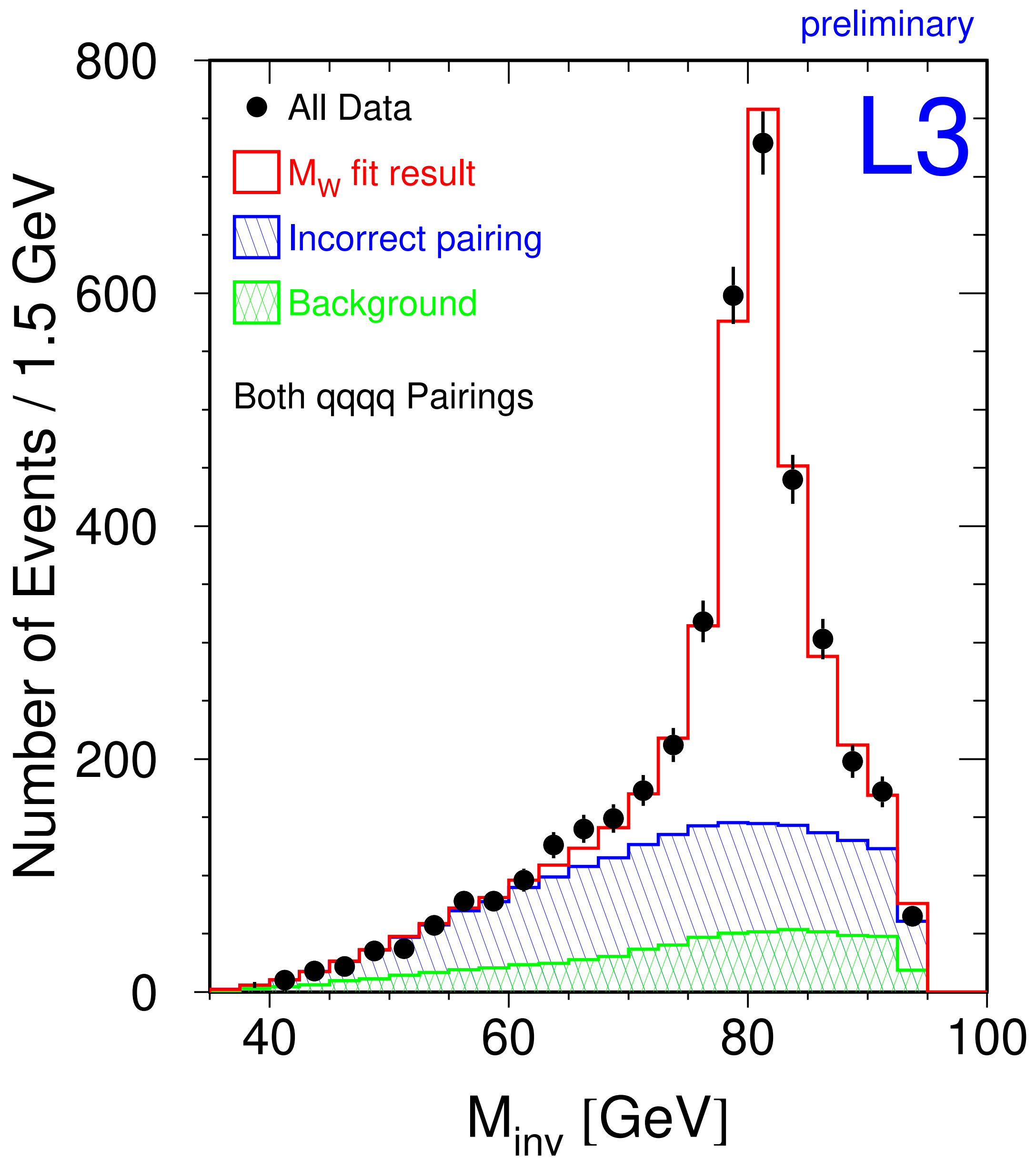
Combined with the threshold measurement

$$M_W = 80.61 \pm 0.15 \text{ GeV}$$

With 172 + 183 GeV data:

	Γ_W[GeV]
$q\bar{q}q\bar{q}$	$1.69 \pm 0.42\ (stat) \pm 0.22\ (syst)$
$q\bar{q}\ell\nu$	$2.44 \pm 0.59\ (stat) \pm 0.13\ (syst)$
ffff	$1.97 \pm 0.34\ (stat) \pm 0.17\ (syst)$





Statistical error of 75 MeV including 1998 data

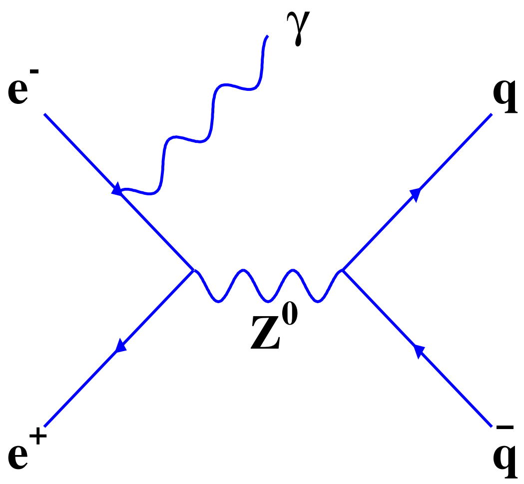
Systematic Errors on M_{W} [MeV]	Final State	
	$qq\ell\nu$	$qqqq$
LEP Energy	25	25
ISR	15	15
FSR	10	10
Jet Measurement	30	5
Fragmentation and Decay	30	60
Fitting Method	15	15
Total Correlated	55	69
MC Statistics	20 - 50	10
Colour Reconnection	—	70
Bose-Einstein Effects	—	60
Selection	20	20
Background	5 - 30	10
Lepton Measurement	0 - 15	—
Total Uncorrelated	32 - 62	95
Total Systematic	63 - 82	118

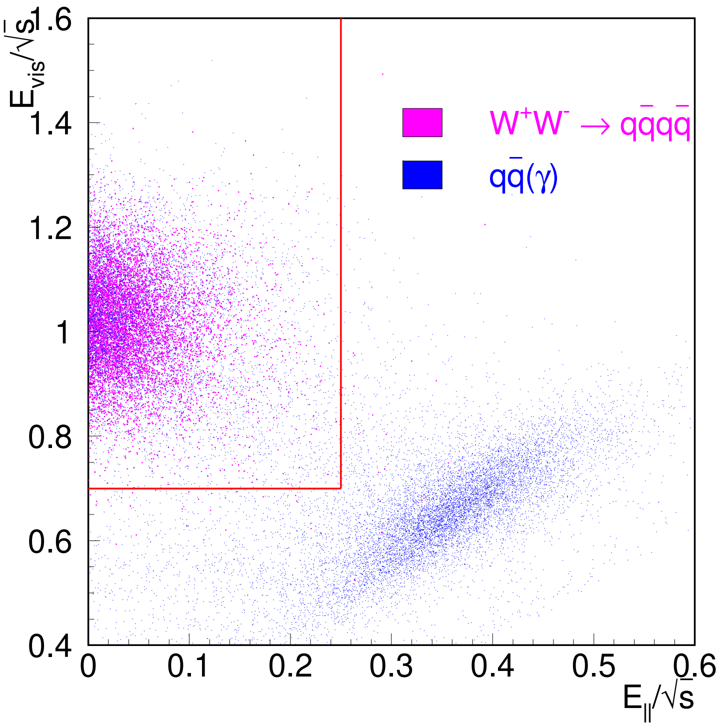
Many errors scale down as $\frac{1}{\sqrt{\mathcal{L}}}$ or $\frac{1}{\sqrt{\mathrm{N_{MC}}}}$

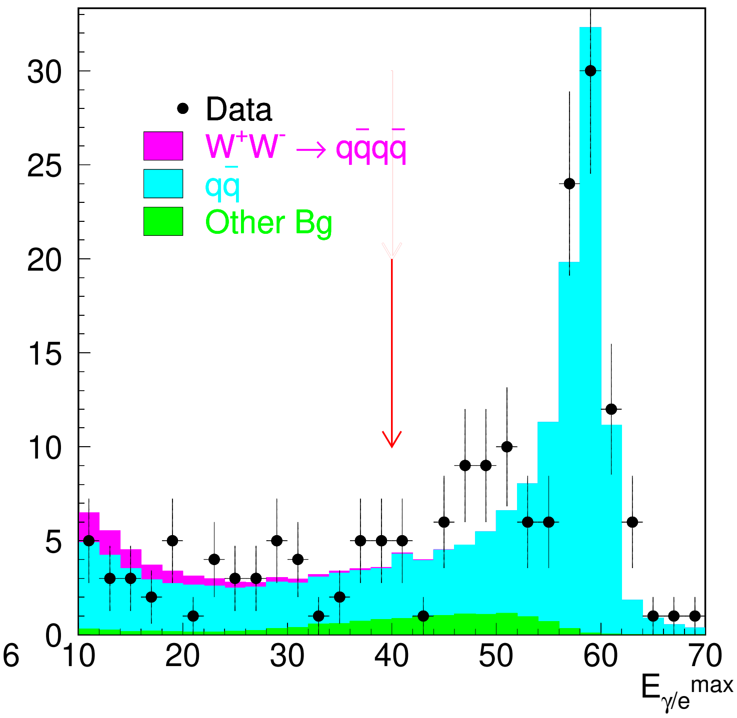
The largest are from modeling of final state interactions in $\mathrm{WW} \longrightarrow \mathrm{qqqq}$

W Mass at High Energy - Checks

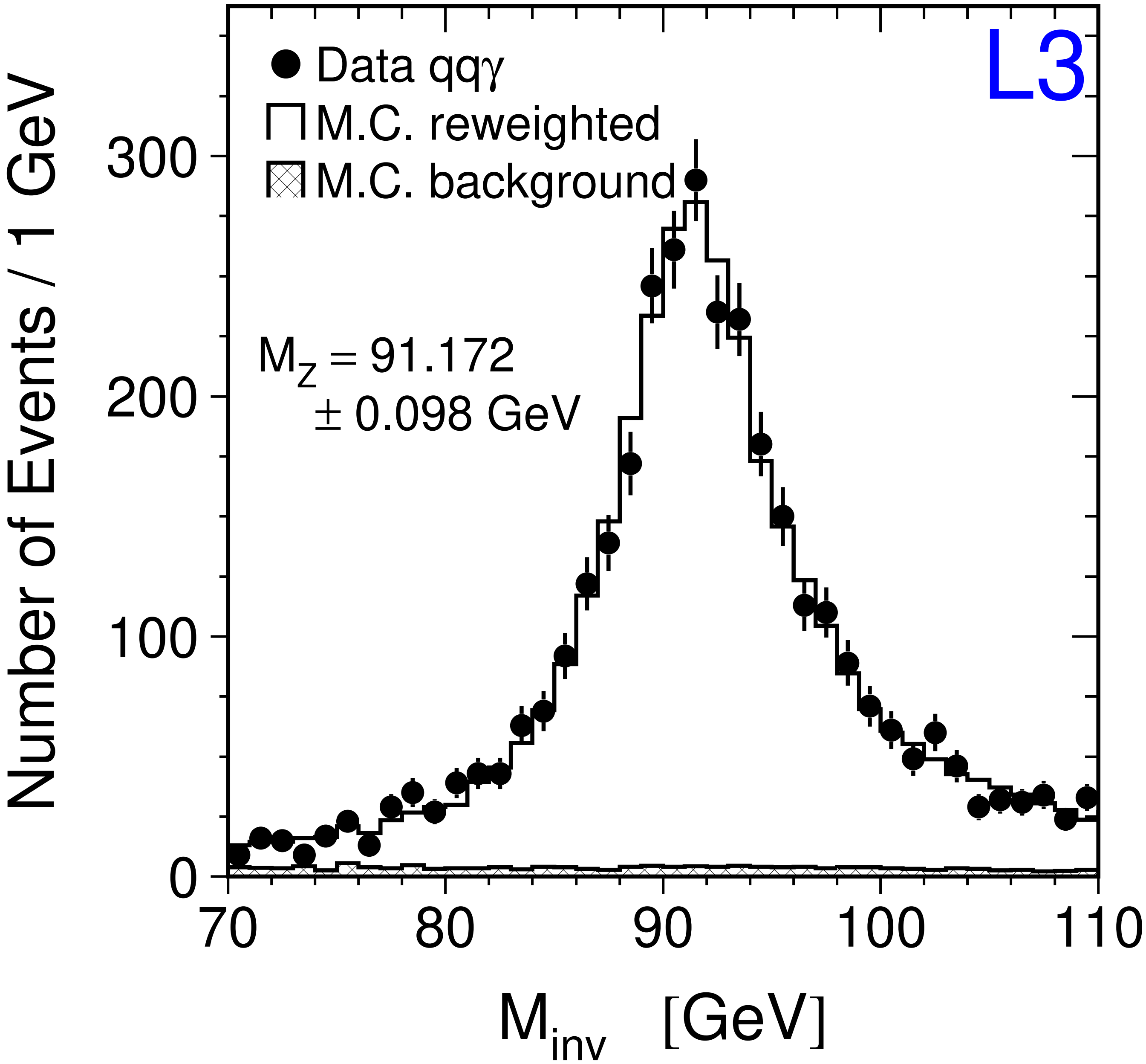
$e^+e^- \longrightarrow q\bar{q}$ **at** $\sqrt{s} > M_Z$**:**







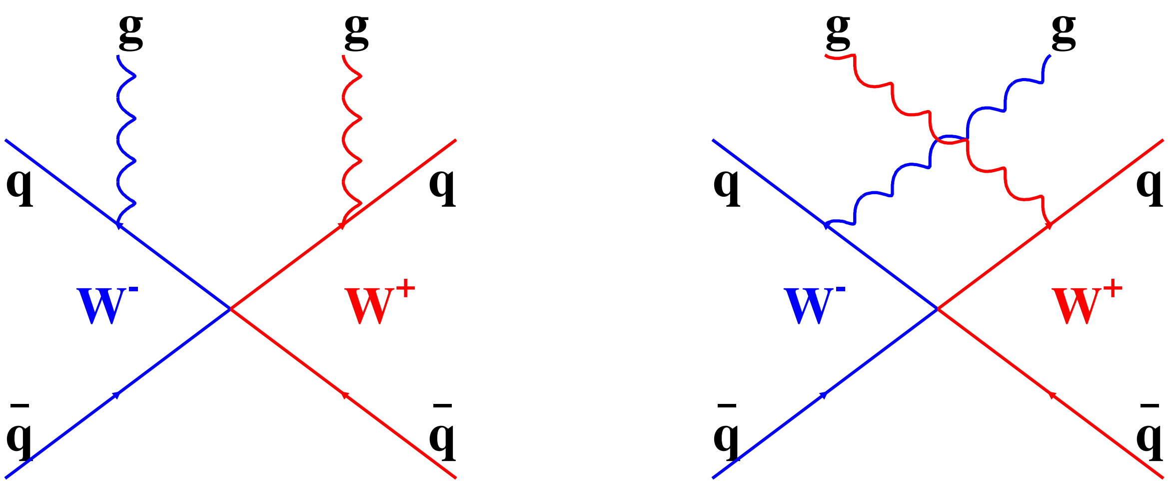
Direct reconstruction of M_Z with $q\bar{q}\gamma$ "radiative returns":



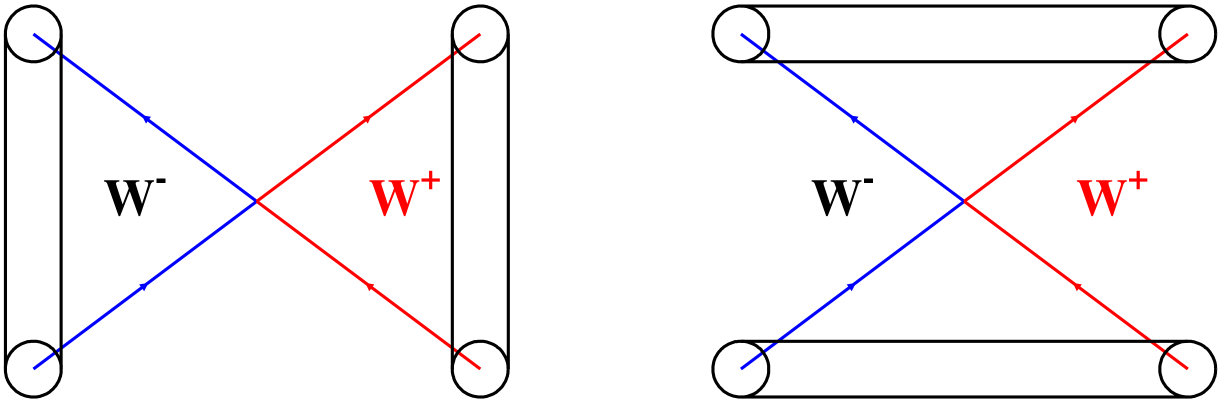
Test of the full measurement method (L3 at LEP 1: M_Z= 91.1883 $\pm$ 0.0029 GeV)

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

$1/\Gamma_W \ll 1$ fm - Ws hadronize together



Perturbative effects $\propto \frac{\alpha_s^2}{N_C^2-1}$ **small**

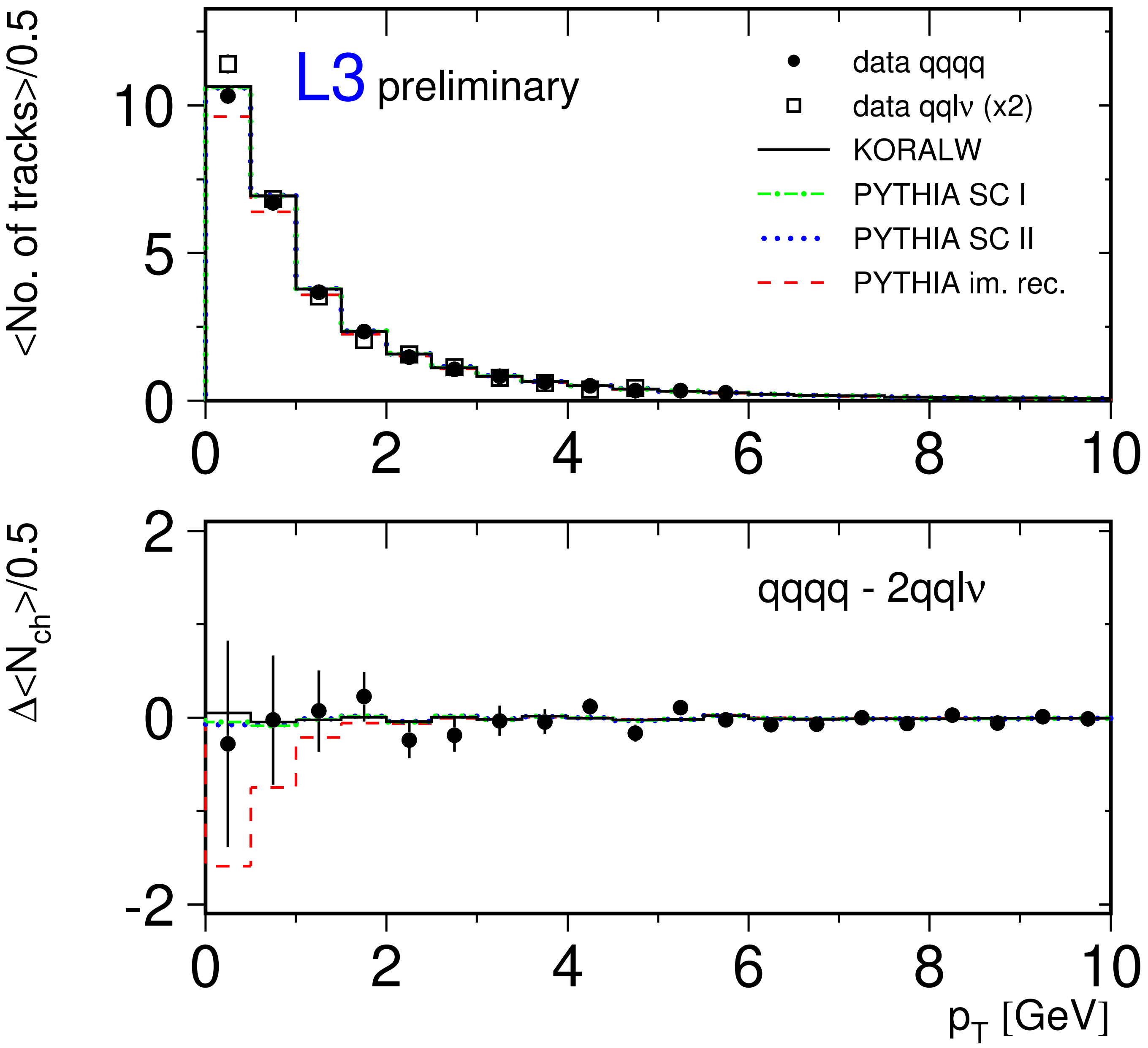


Non-perturbative effects – $\mathcal{O}(\frac{1}{9})$ **large**

Different models - $\mathcal{O}(50)$ MeV shifts of M_W

Extreme ones can be ruled out by data

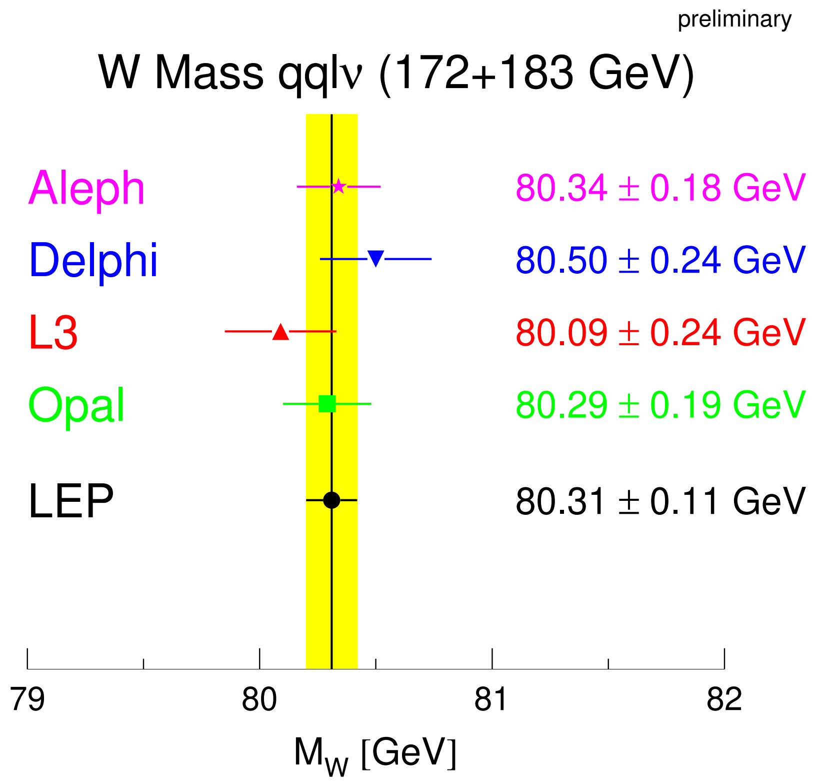
Look for cross-talk between different Ws

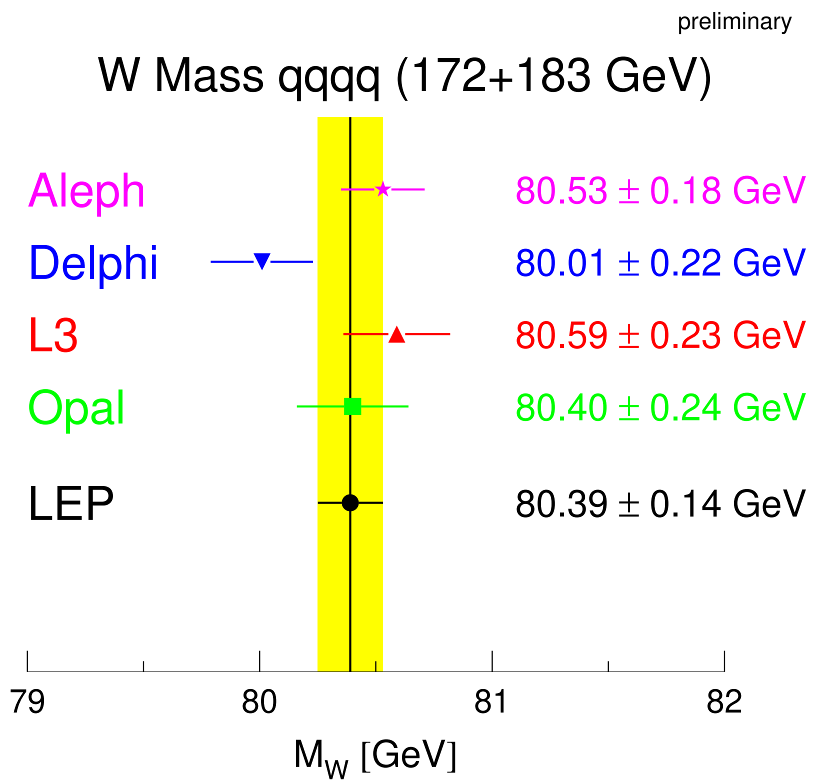


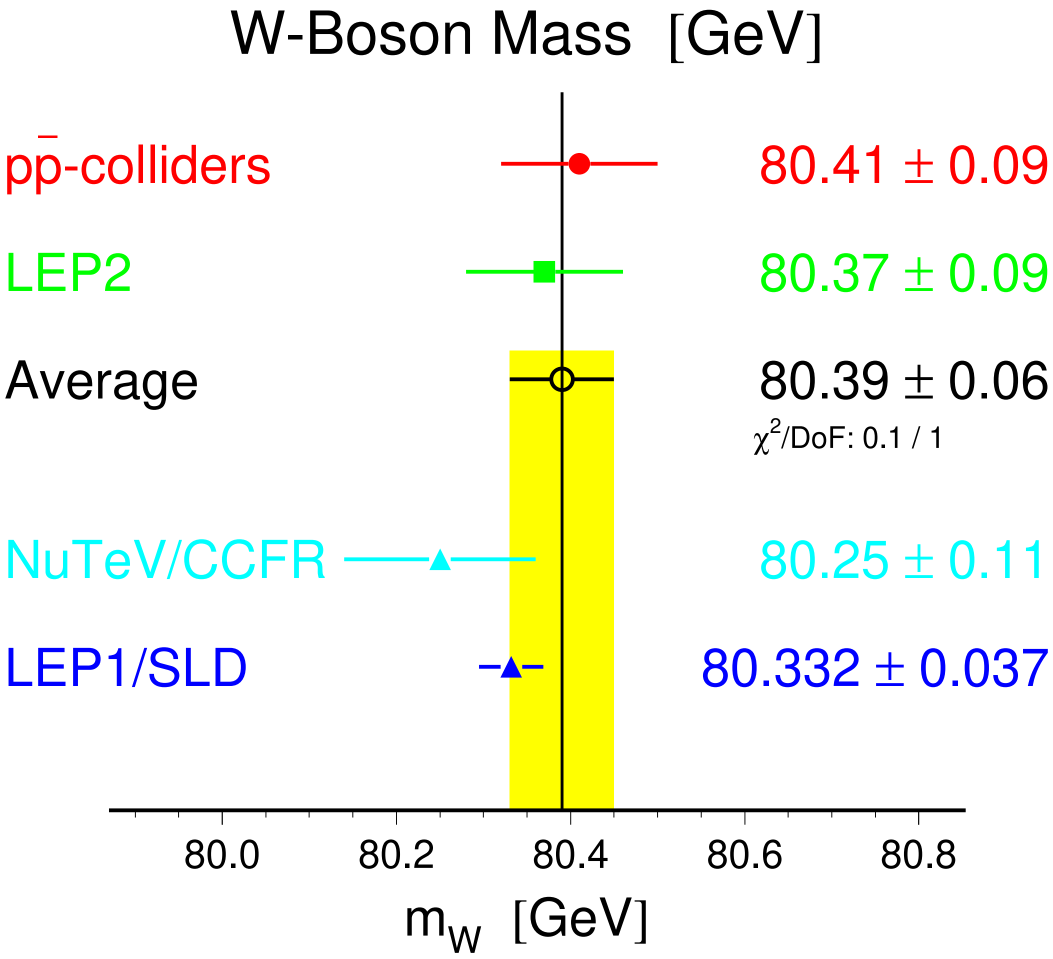
Comparing qqqq with $2qq\ell\nu$:

No significant difference seen

$M_W(q\bar{q}q\bar{q})$ vs $M_W(q\bar{q}\ell\nu)$ from LEP



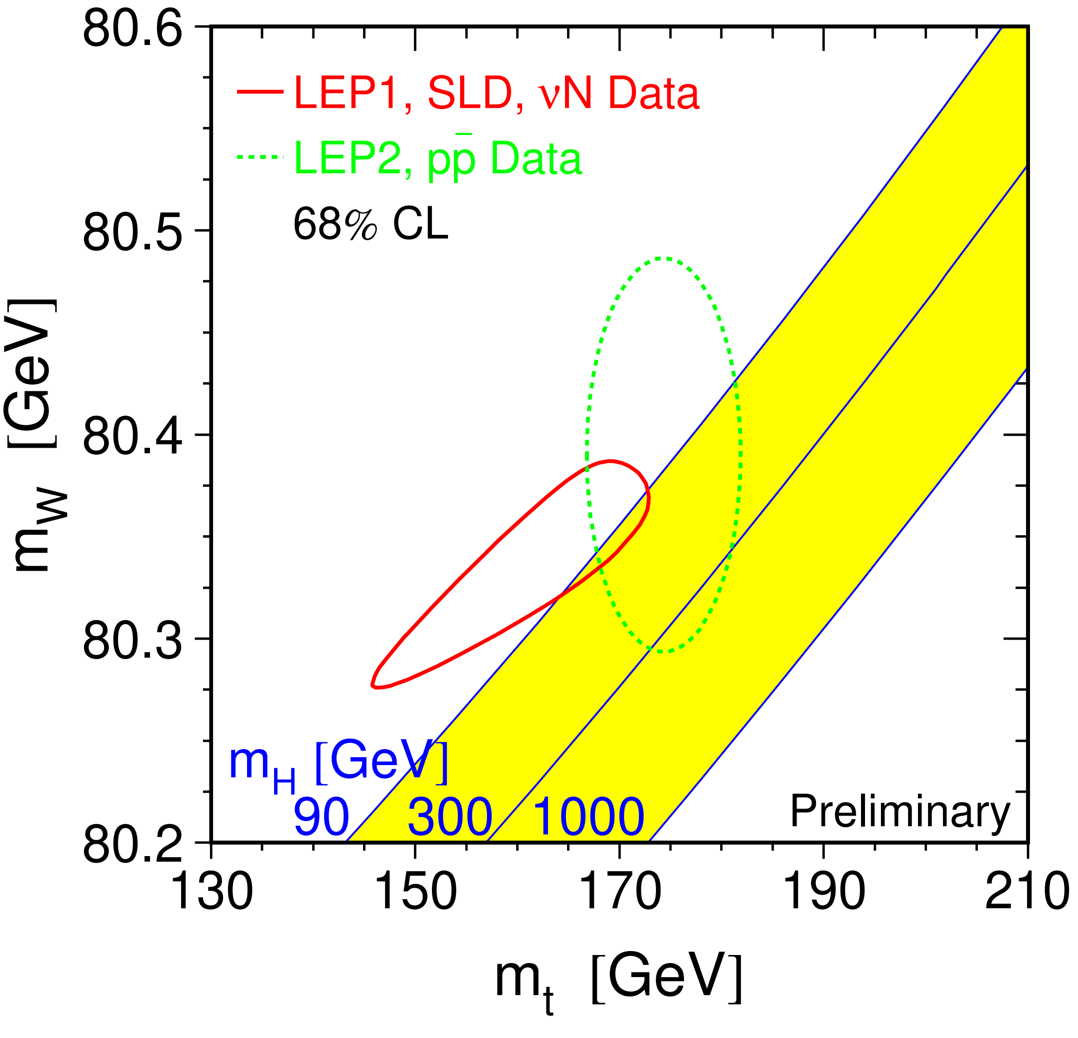




LEP2 error down by factor 2-3 by 2000

Compare measured M_{W} with

- $G_{\mathrm{F}} = \frac{\pi\alpha}{\sqrt{2}} \cdot \frac{m_{\mathrm{Z}}^2}{m_{\mathrm{W}}^2(m_{\mathrm{Z}}^2 - m_{\mathrm{W}}^2)} \cdot \frac{1}{1-\Delta r(M_{\mathrm{t}}, M_{\mathrm{H}})}$
- **Indirect measurements (SLD, LEP1, νN)**



No discrepancies so far

- 7 independent parameters in a general Lorentz-invariant Z/γWW vertex
- Symmetries reduce the number. C,P-even part:

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

$$g_{\gamma WW} = -e \qquad g_{ZWW} = -e \cot\theta_{Weak}$$

In SM: $g_1^{\gamma/Z} = 1, \lambda_{\gamma/Z} = 0, \kappa_{\gamma/Z} = 1$

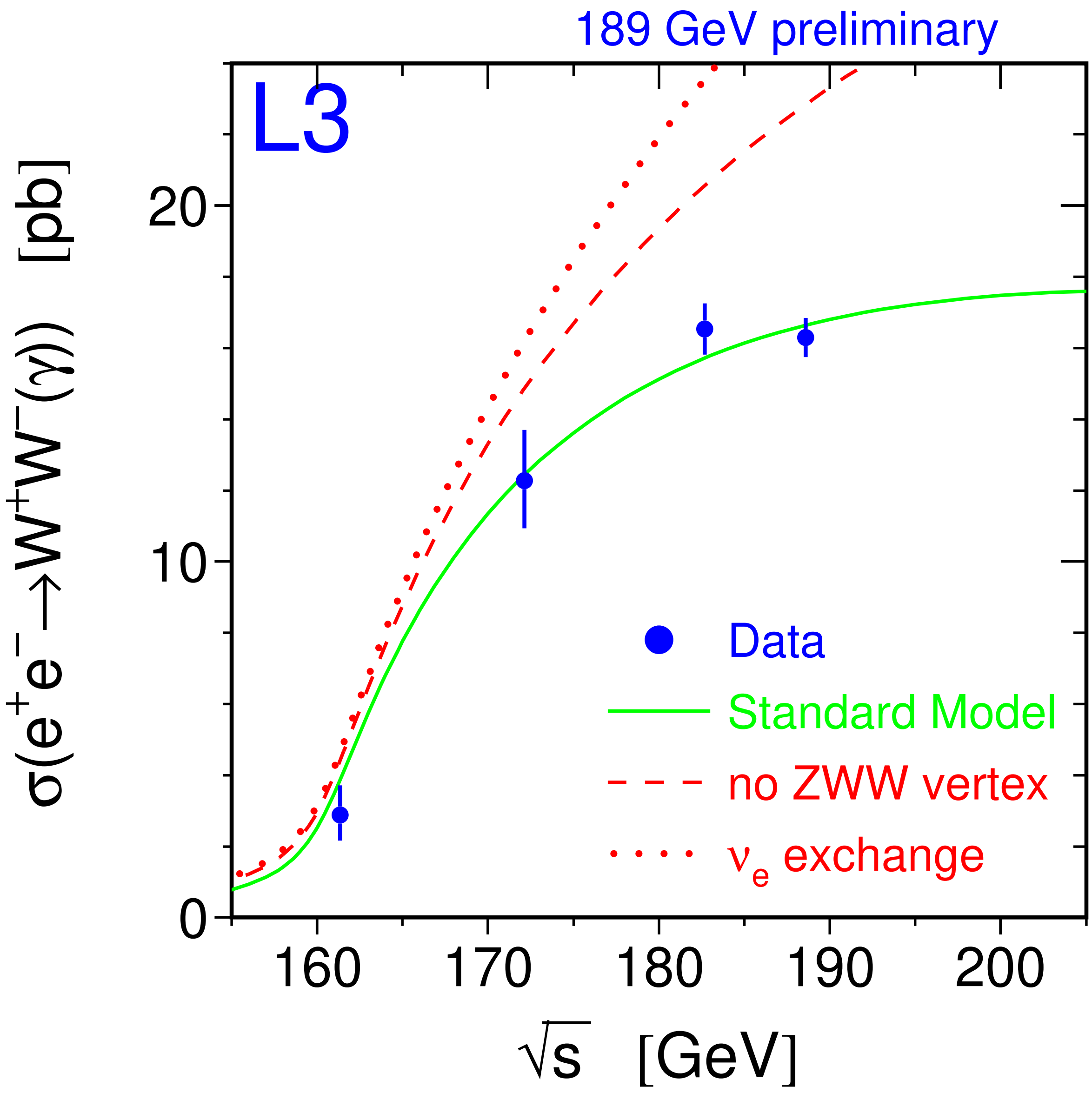
With $\mathrm{U}_{EM}(1)$ and SU(2)$\times$U(1) invariance:

$$g_1^\gamma = 1 \qquad \lambda_Z = \lambda_\gamma$$
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_{Weak}$$

- The 3 parameters left: $\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma$

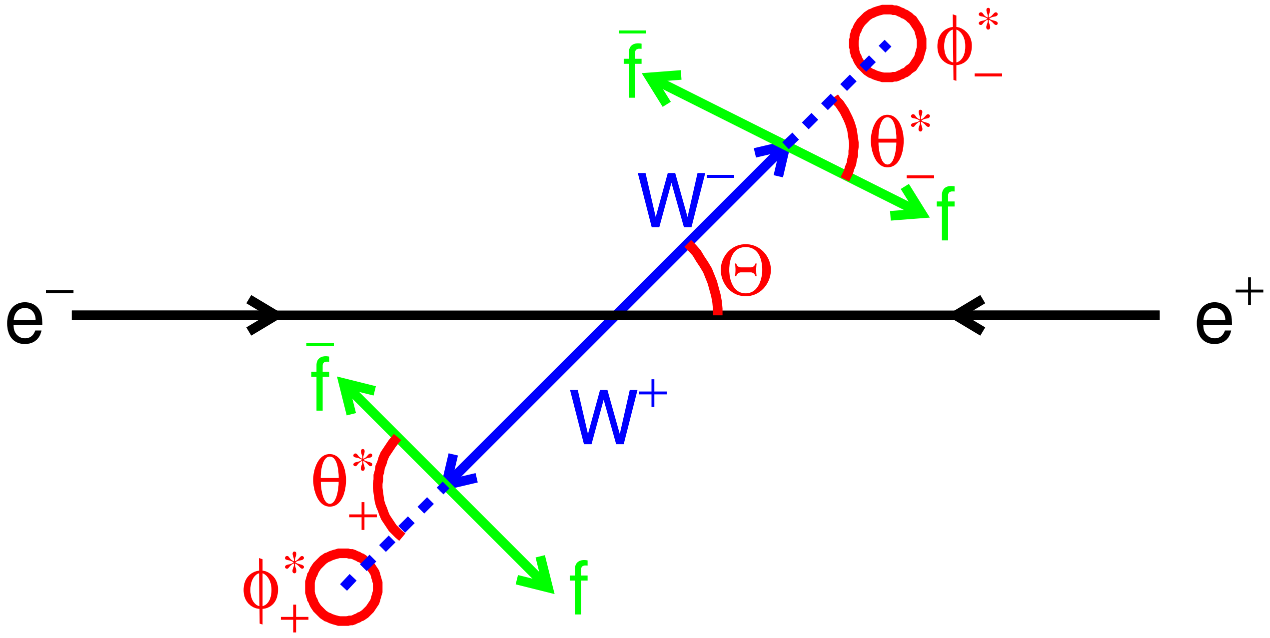
$$\mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$
$$Q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$

$Z/\gamma WW$ couplings necessary for good high-energy behaviour of σ_{WW}



Important already at LEP2 energies

Additional information in

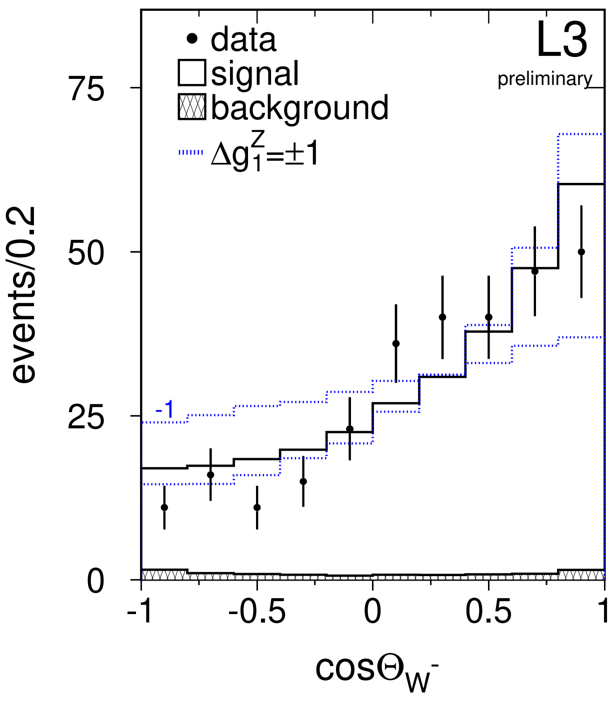


- **W scattering angle distribution (θ_W)**

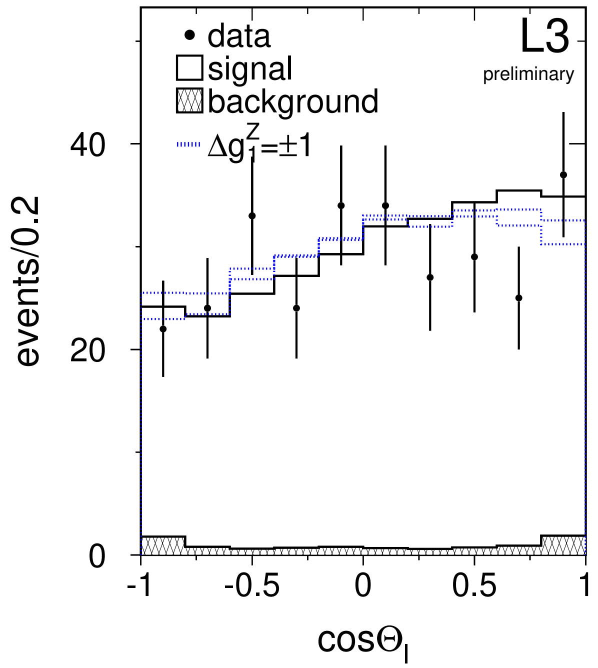
- **W polarization $\longrightarrow$ angular distributions of the decay in the W rest frame (θ^*_f, ϕ^*_f)**

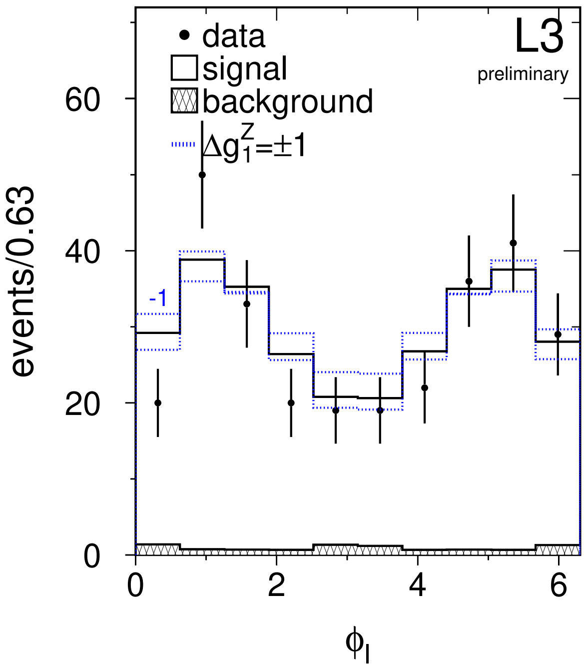
Ideally, we would study $\dfrac{d\sigma(e^+e^-\rightarrow W^+W^-)}{d\theta_W d\theta^*_1 d\phi^*_1 d\theta^*_2 d\phi^*_2}$

- **Know well which W was W^-**



- **Know all angles for the leptonic W**



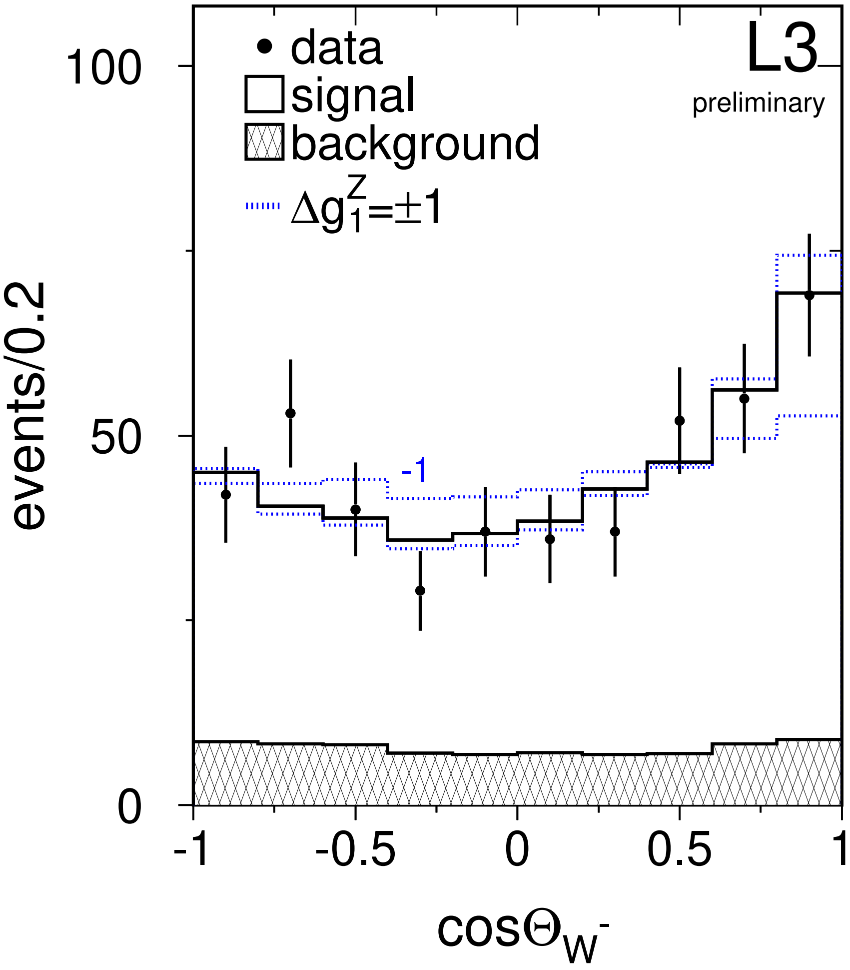


- W charge can be estimated using "jet charge"

$$C_{jet} \equiv \frac{\Sigma q_i p_i^\kappa}{\Sigma p_i^\kappa} \qquad (\kappa\text{=0.5})$$

W^- has smaller ΣC_{jets} in 67% of events

- Jet pairing correct for ~70% of events



- Not possible to reconstruct θ^*, ϕ^*

$l\nu l\nu$ Events:

- Know both charges very well

but

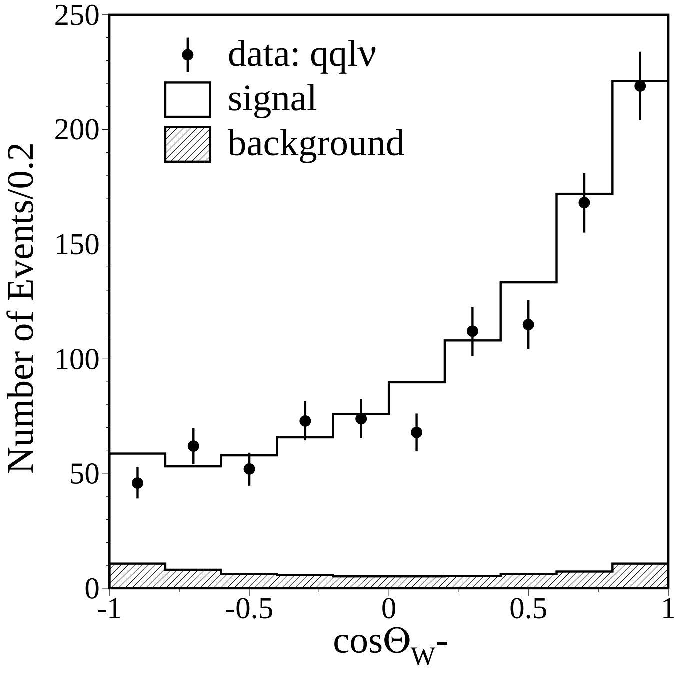
- 2-fold kinematic ambiguity in each event
- Less than 10% of selected events

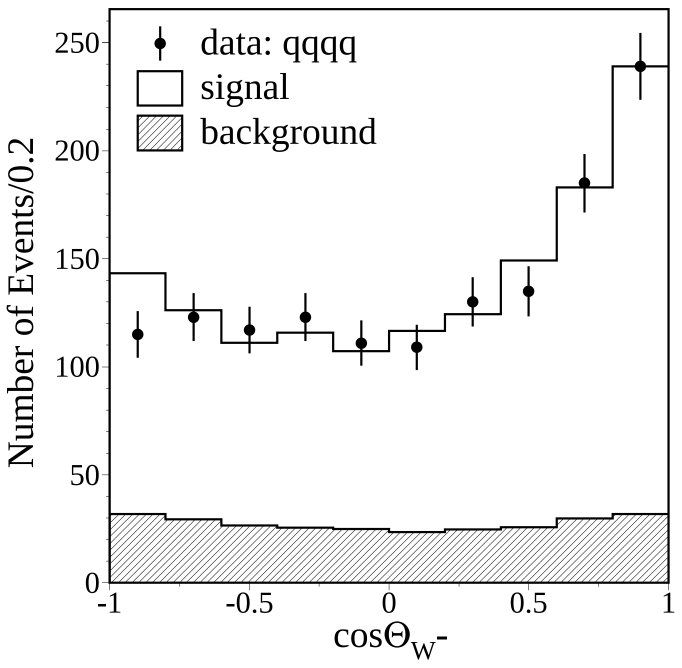
Used only as a part of the total cross-section

Information used in triple boson couplings fits:

- $\cos\theta_{\mathrm{W}}$ distribution for $\mathrm{q\bar{q}q\bar{q}}$ events
- $\cos\theta_{\mathrm{W}} \times \cos\theta^*_{\mathrm{l}} \times \phi^*_{\mathrm{l}}$ $\mathrm{q\bar{q}}\ell\nu$ events
- $\sigma(\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-})$

189 GeV (and all other) data



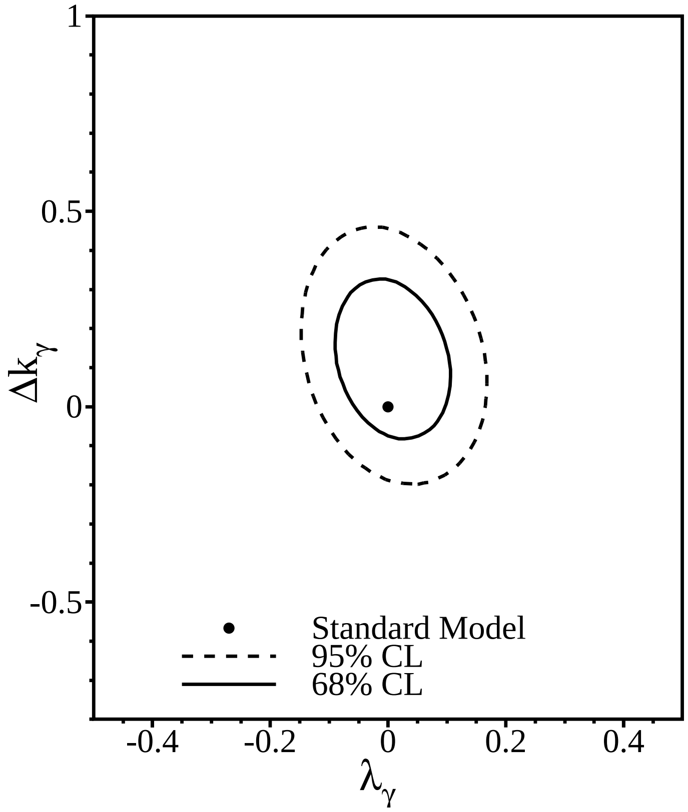


look like the SM prediction

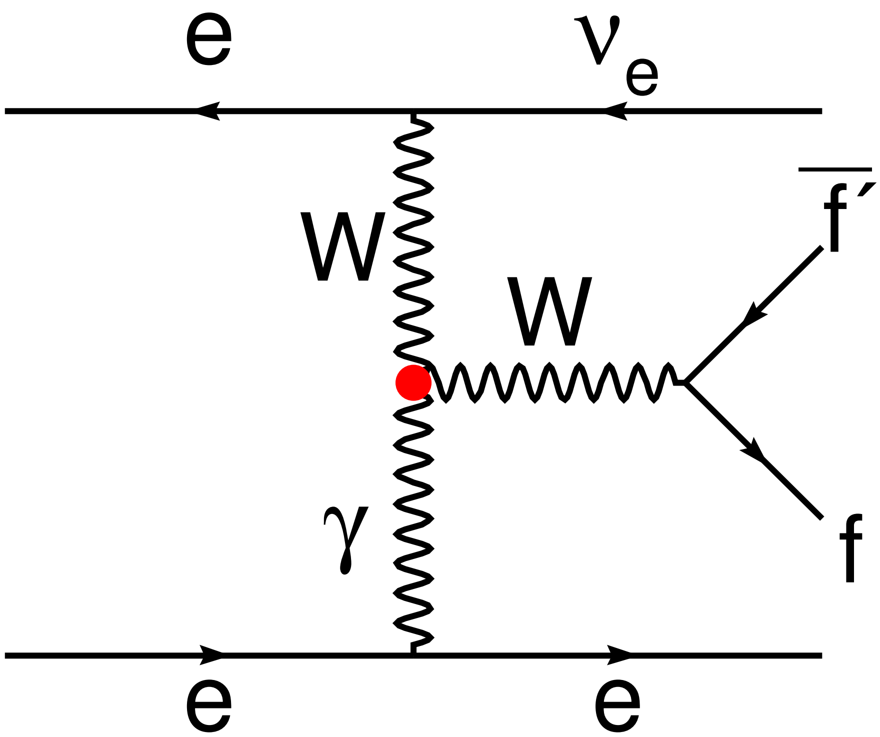
- **No significant deviation in either of the couplings (prelim. 189 GeV data included):**

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

- **Or in 2D fits:**



Separating γWW and ZWW: $e^+e^- \longrightarrow We\nu$

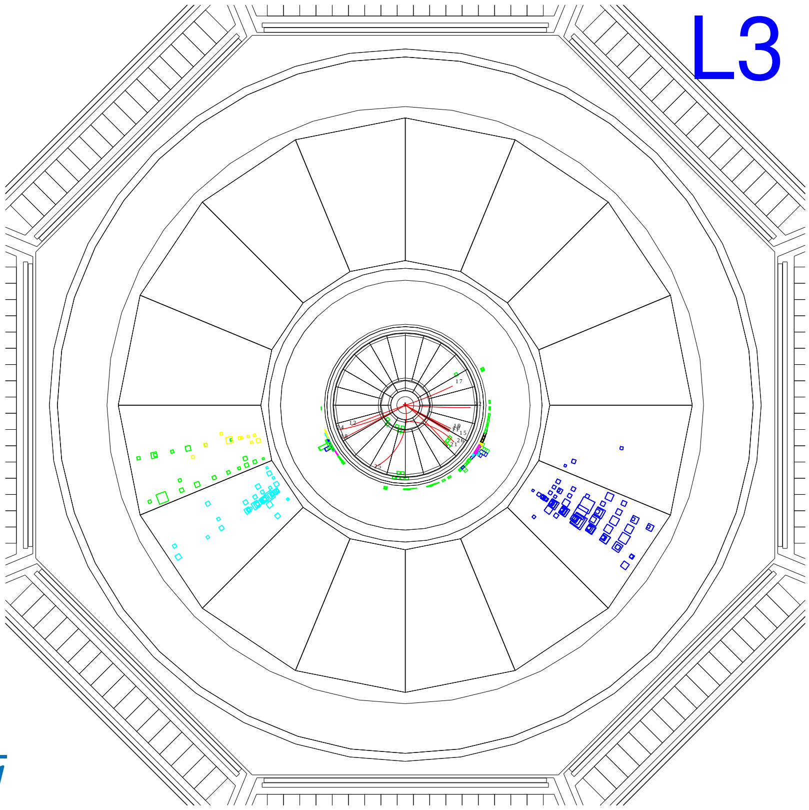


W decay products in the detector

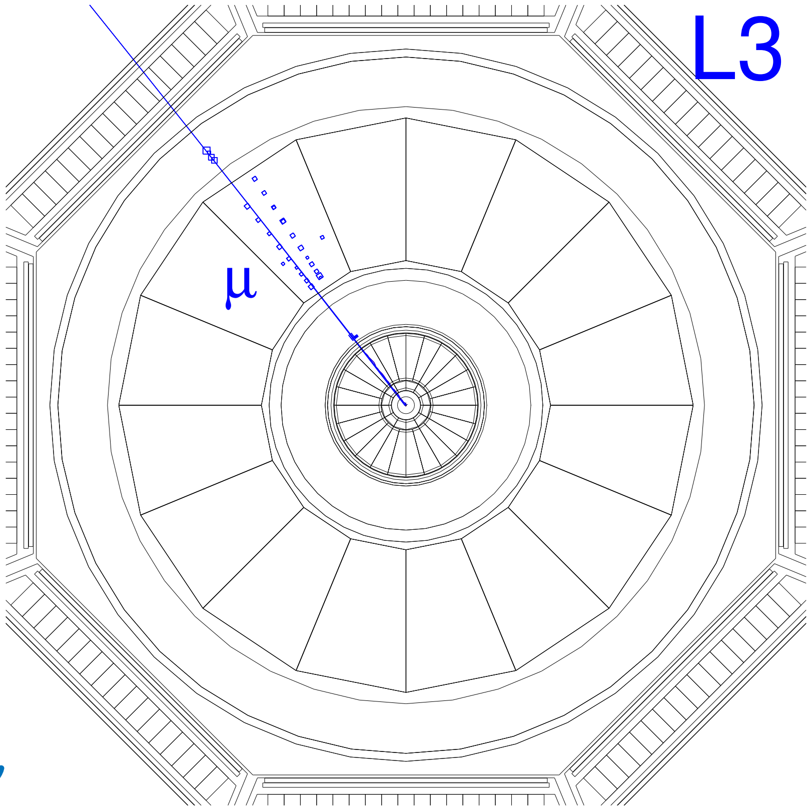
Electron lost in the beampipe $\longrightarrow$ "single W"

ZWW contribution suppressed

Triple Boson Couplings - Single Ws

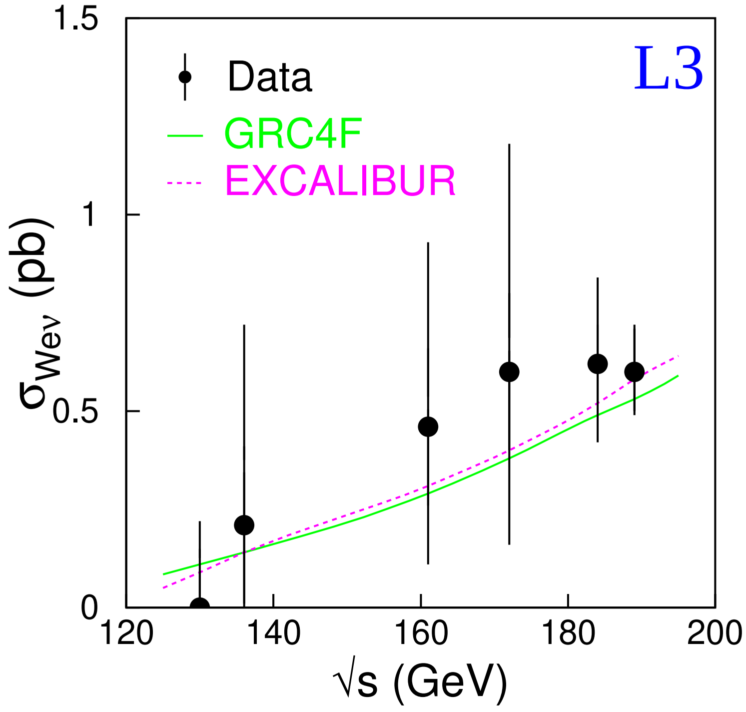


- **W** $\longrightarrow q\bar{q}$

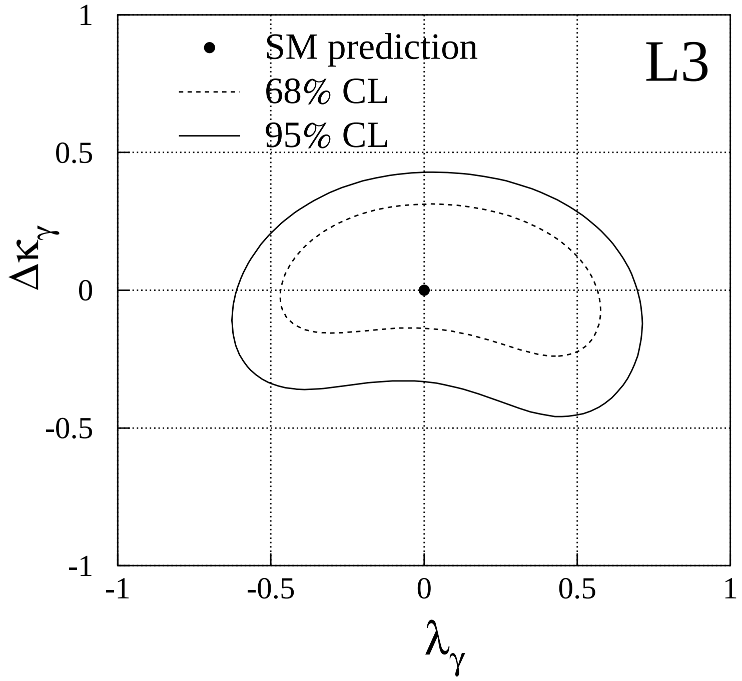


- **W** $\longrightarrow \ell\nu$

$\sigma(We\nu)$ agrees with the SM up to 189 GeV



Limits comparable to WW ones



- W mass and width with data up to 183 GeV

$$M_{\mathrm{W}} = 80.61 \pm 0.15\ \mathrm{GeV}$$
$$\Gamma_{\mathrm{W}} = 1.97 \pm 0.38\ \mathrm{GeV}$$

agree with indirect measurements and SM

With preliminary 189 GeV data

- $\sigma_{\mathrm{WW}}(\sqrt{s})$ at $\sqrt{s}$ = 161 - 189 GeV

$$\mathrm{BR}(\mathrm{W} \to \mathrm{q\bar{q}}) = (68.7 \pm 0.69)\%$$
$$\mathrm{BR}(\mathrm{W} \to \ell\nu) = (10.4 \pm 0.23)\%$$

compatible with the SM

- Anomalous VWW couplings

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

consistent with zero

- All the measurements to be improved by a factor 2-3 by the end of LEP2