W mass and WW couplings at LEP 2

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representing the LEP Experiments

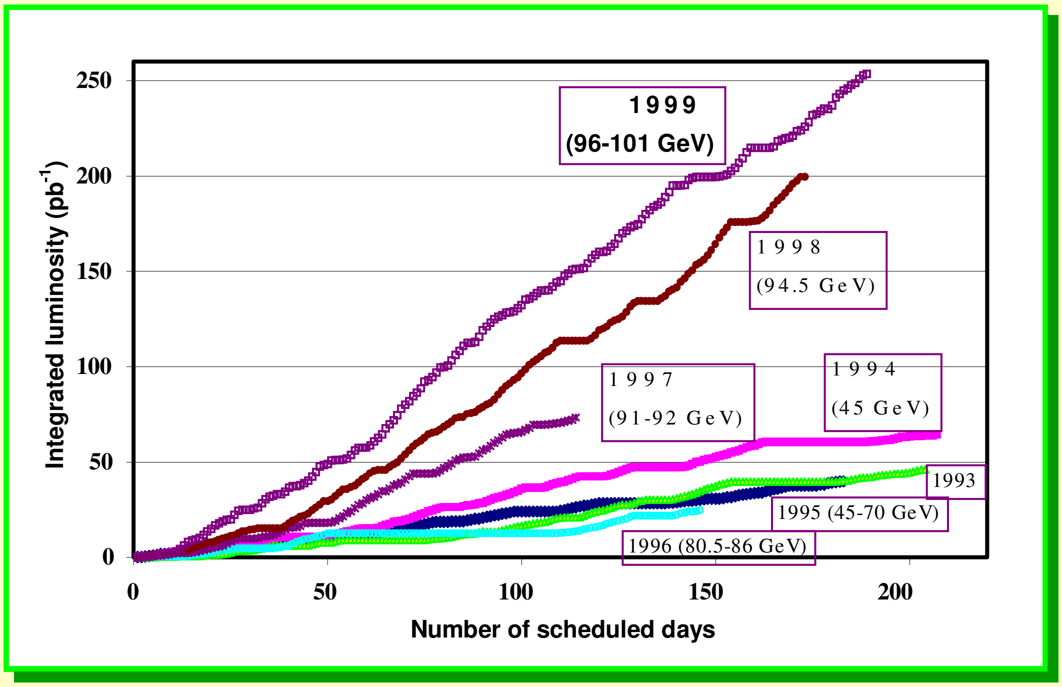
26 February – 4 March 2000
Les Rencontres de Physique de la Vallée d'Aoste

- W mass measurement
  - measurement methods
  - systematic errors
  - current results and prospects for LEP
- gauge boson couplings
  - methods
  - results on TGCs
  - longitudinal Ws
  - NO neutral TGCs or QGCs

Most results are preliminary

LEP–wide averages provided by the LEP Electroweak working group (W mass and TGC subgroups)

Recorded luminosity at LEP



$\approx$ **10** pb^{-1} at threshold

$\approx$ **500** pb^{-1} at $\sqrt{s}$ $\approx$**172–202** GeV $\Longleftrightarrow$ 6.5K W pairs/expt.

$\approx$ **100** pb^{-1} this year ?

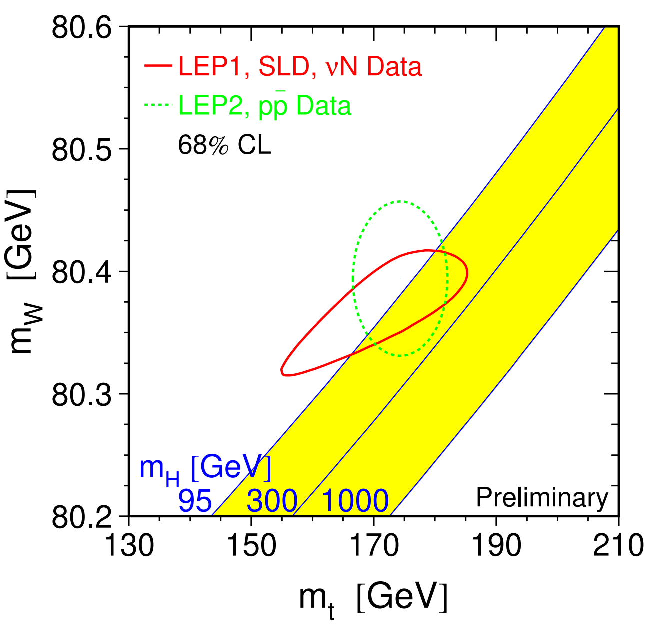
All results based on 1997/1998 data ($\approx$250 pb^{-1})

- Guess final precision of LEP 2
- Identify areas which need work

W mass measurement

Why measure M_{W}?

- Parameter of the $\mathcal{SM}$
- Test self–consistency of the $\mathcal{SM}$
- Sensitivity to M_{H} through radiative corrections



How ?

- Threshold cross–section with 10 pb^{-1}/experiment:

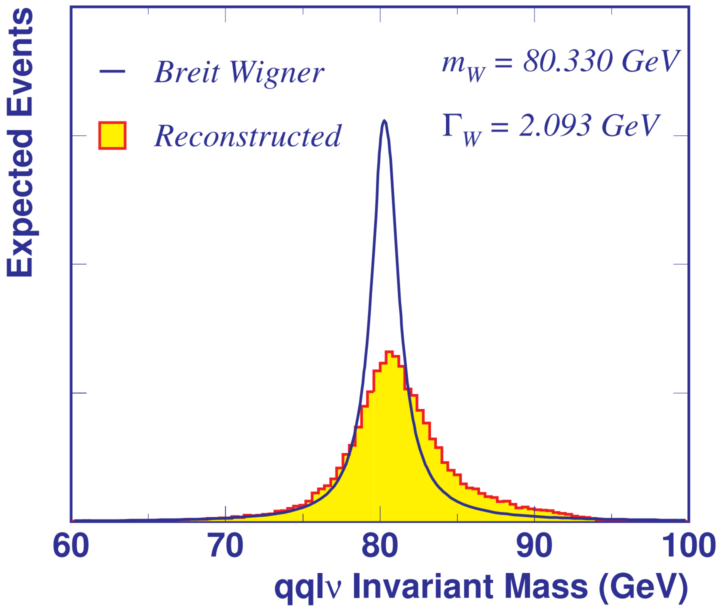
$$\boxed{(M_{\mathrm{W}} = 80.40 \pm 0.22)\ \mathrm{GeV}/c^2}$$

30 pb^{-1} more at $\sqrt{s} = 161$ GeV this year ?

- Direct reconstruction at $\sqrt{s} > 161$ GeV

Direct reconstruction

- Reconstruct mass distribution
- Fit $M_{\rm W}$

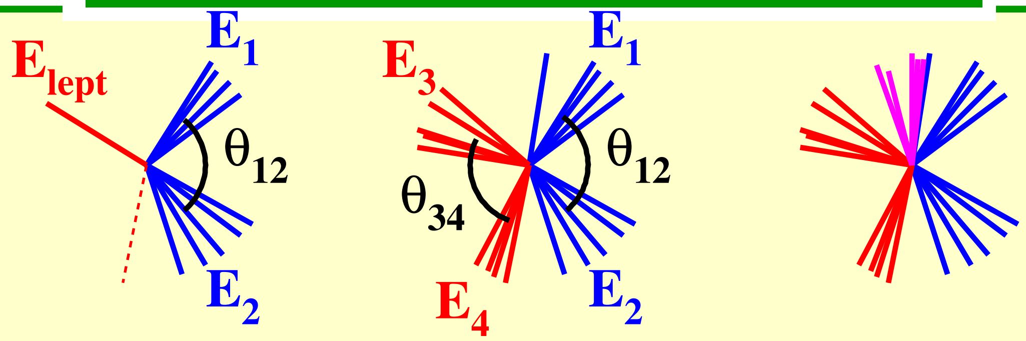


Mass distribution distorted by:

- Event selection
- Experimental resolution
- Initial state radiation
- 4–fermion effects (in $\mathrm{q\overline{q}'e\overline{\nu}_e}$ and $\mathrm{q\overline{q}'q\overline{q}'}$ final states)
- Hadronisation
- Final State Interactions (in $\mathrm{q\overline{q}'q\overline{q}'}$ final state)

➥Systematics

Invariant mass reconstruction – 1



Jet angles better measured than energies

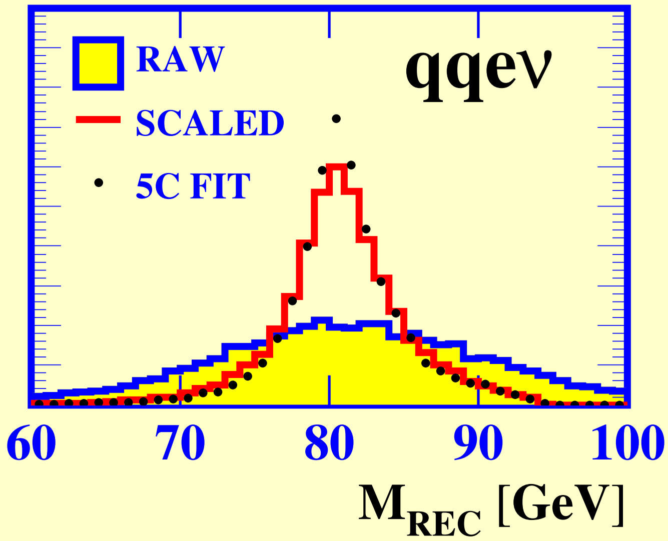
Mass reconstruction:

❶ **Raw:** $M_{q\overline{q}'} = 2E_1E_2(1-\cos\theta_{12})$

❷ **Scaled:** $M_{q\overline{q}'}{}' = M_{q\overline{q}'}\frac{E_{beam}}{E_1+E_2}$

❸ **Kinematic fit (4C) using** $E, \overrightarrow{p}$ **conservation**

❹ **Kinematic fit (5C)=(4C) and** $M_{12} = M_{34}$



Resolution per event

$$q\overline{q}'e\overline{\nu}_e,\ q\overline{q}'\mu\overline{\nu}_\mu : \approx 3\ \mathrm{GeV/event}$$

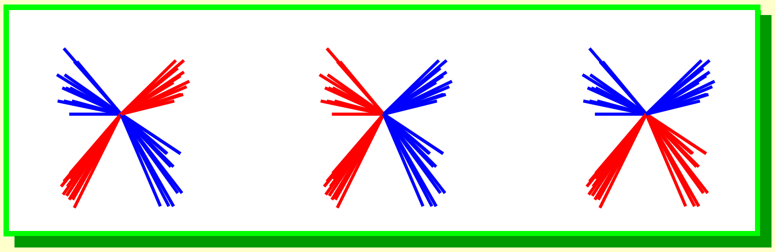
$$q\overline{q}'\tau\overline{\nu}_\tau : \approx 4\ \mathrm{GeV/event}$$

Invariant mass reconstruction – 2

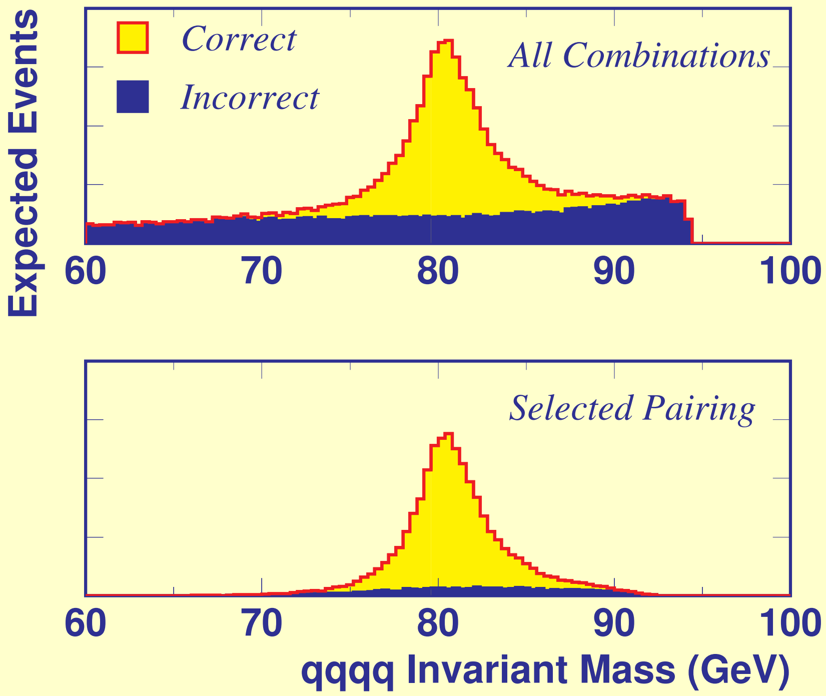
$$W^+W^- \rightarrow q\overline{q}'q\overline{q}':$$

all fermions detected ➠ better resolution ?

- hadrons assigned to wrong jet
- gluon radiation ➠ 5 jet events
- combinatorial background



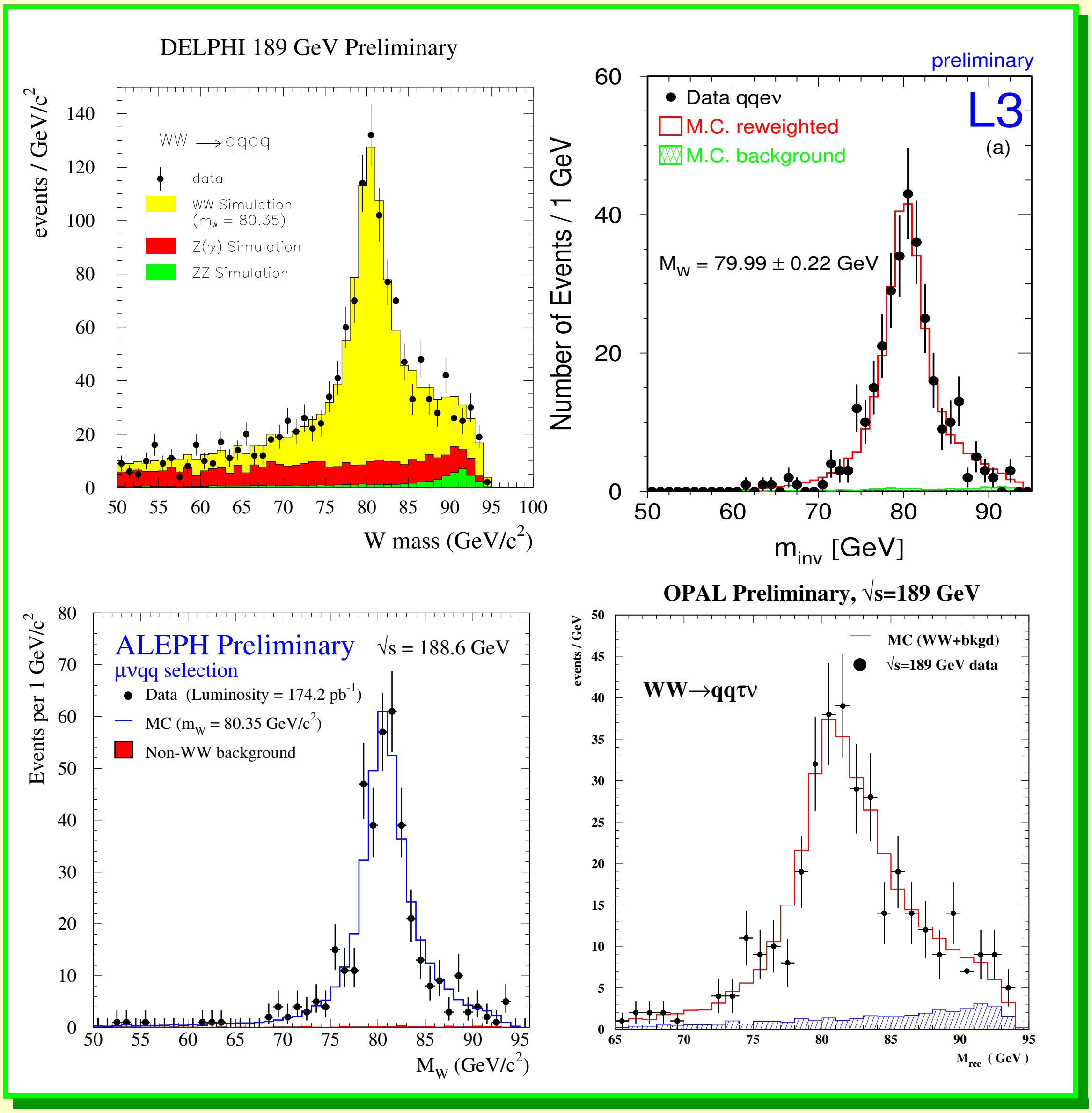
- combinatorial background
- select right combination or fit everything



Resolution per event

$$q\overline{q}'q\overline{q}' : \approx 3\ \mathrm{GeV/event}$$

Mass distributions



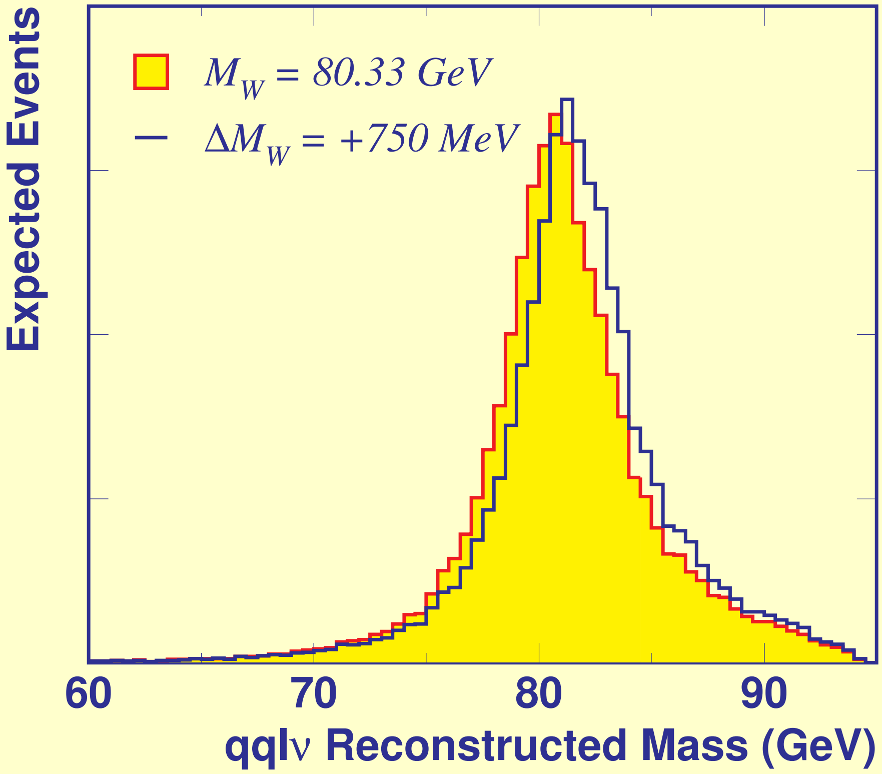
$M_{\rm W}$ extraction methods:

- ☞ Monte Carlo reweighting (ALO)
- ☞ Convolution/ideogram (D)
- ☞ Breit–Wigner fit (ADLO)

① Reweighting fit (ALO)

- Compare data / Monte Carlo templates (different M_W)
- Monte Carlo templates obtained with reweighting technique (from M_W,Γ_W to M_W',Γ_W'):

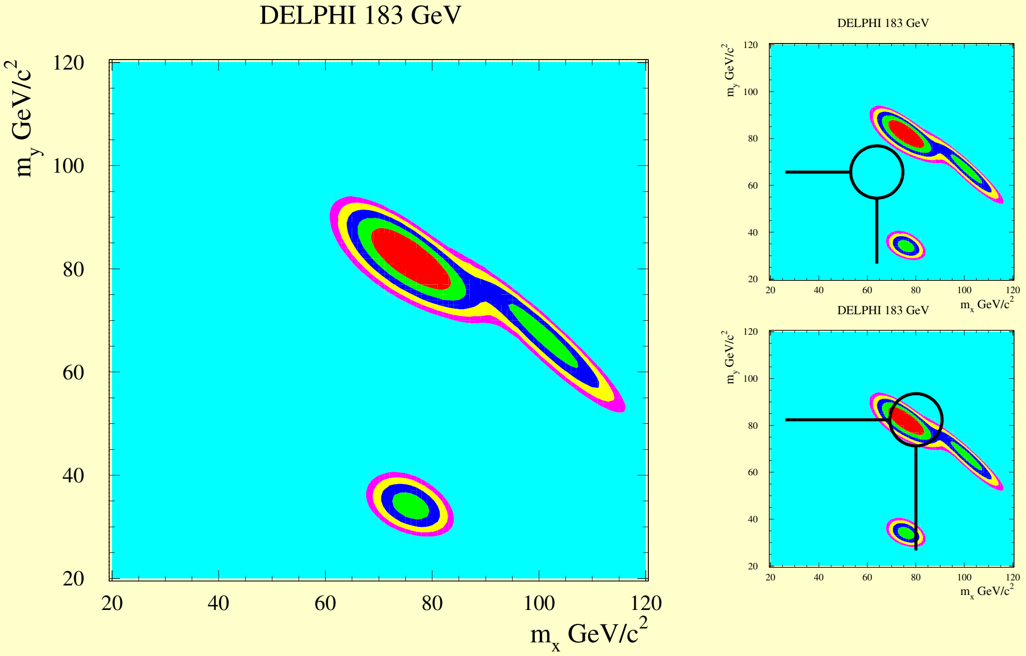
$$w = \frac{BW(m_1, m_2|M_\mathrm{W}', \Gamma_\mathrm{W}')}{BW(m_1, m_2|M_\mathrm{W}, \Gamma_\mathrm{W})}$$



- ✔ Simple/unbiased method
- ✔ No calibration (hidden in method)
- ✘ Requires that Monte Carlo describes data
- ✘ Lots of Monte Carlo

② Convolution fit (D)

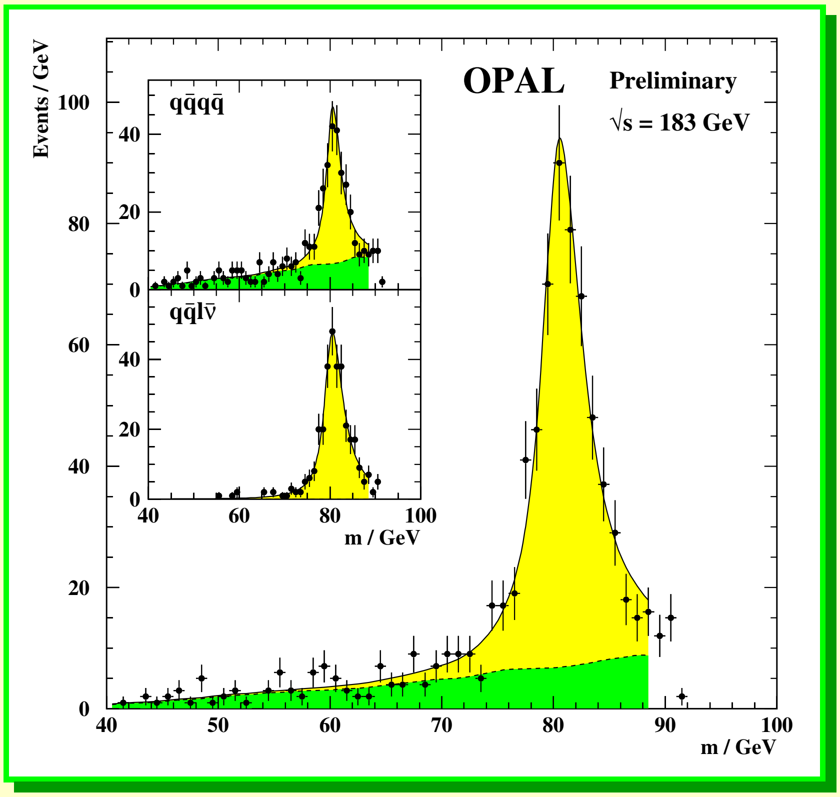
- ★ Use 4C fit ➠ 2 masses per jet pairing
- ★ Use ALL jet pairs ➠ event PDF
- ★ Event likelihood: convolution of PDF, Breit–Wigner, ISR, Phase Space



- ✔ Statistical power
- ✘ Requires Monte Carlo calibration: $\mathrm{M}_{fit} \rightarrow \mathrm{M}_{true}$
- ✘ Slow (needs CPU)

③ Breit–Wigner fit (ADLO – cross check)

- Parametrise mass spectrum with Breit–Wigner
- Use Monte Carlo to calibrate bias
- Used as cross-check method



- ✔ Simple
- ✘ Requires Monte Carlo calibration
- ✘ Arbitrary fit function
- ✘ Least statistical power

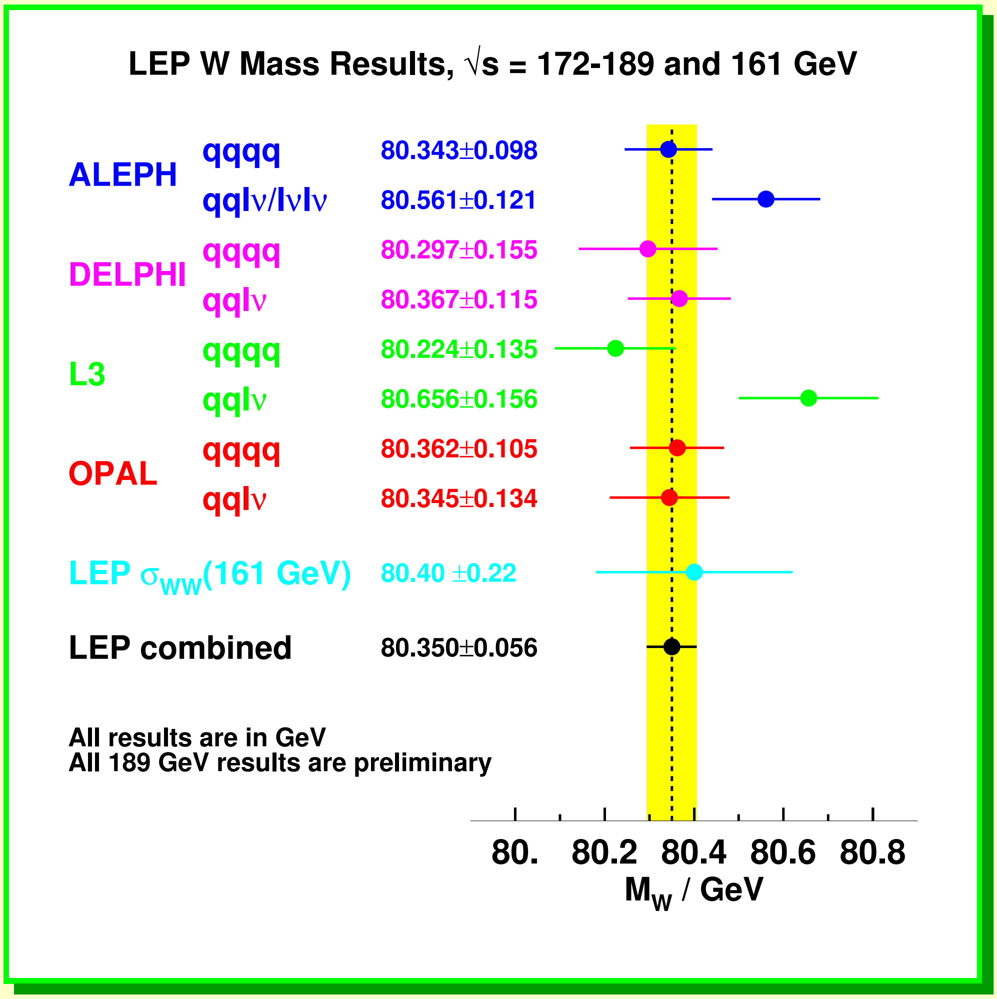
M_{W} results

Standard fits: use $\mathcal{SM}$ relation $M_{\mathrm{W}} \Longleftrightarrow \Gamma_{\mathrm{W}}$

LEP combined:

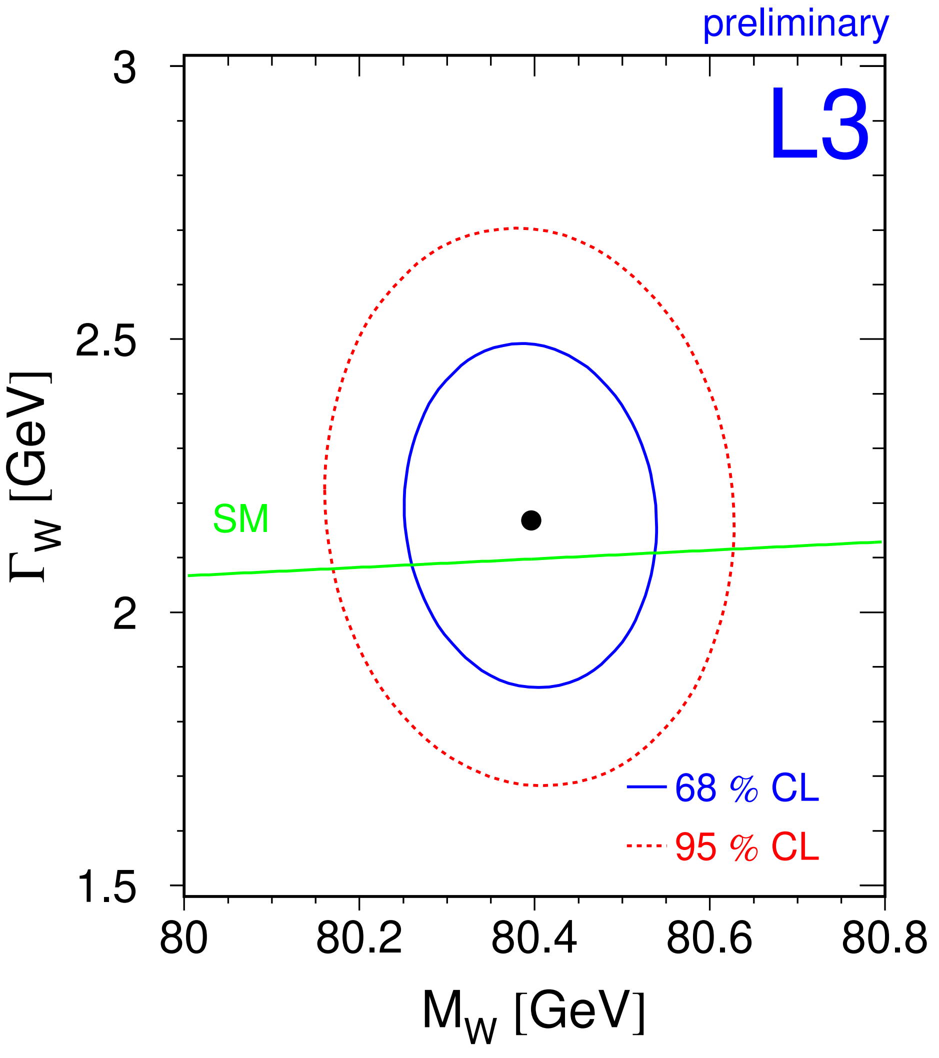
$$\mathrm{q\overline{q}'}\ell\overline{\nu}_\ell \quad : \quad (80.313 \pm 0.052 \pm 0.036)\ \mathrm{GeV}/c^2$$
$$\mathrm{q\overline{q}'q\overline{q}'} \quad : \quad (80.429 \pm 0.049 \pm 0.074)\ \mathrm{GeV}/c^2$$

- Statistical error similar in two channels
- Systematic much larger in $\mathrm{q\overline{q}'q\overline{q}'}$
- Weight of $\mathrm{q\overline{q}'q\overline{q}'}$ in combination: 1/3



W width

Simultaneous fit of Γ_W and M_W



Measurements by D@183, L@172–189 and D@172–183

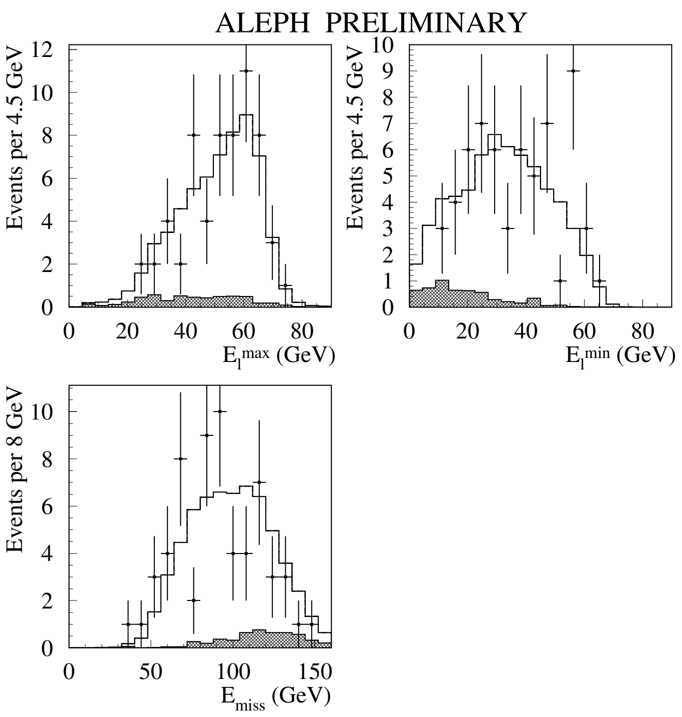
$$\Gamma_W = (2.12 \pm 0.20)\ \mathrm{GeV}/c^2$$

cfr. CDF direct: $(2.055 \pm 0.125)\ \mathrm{GeV}/c^2$

CDF+DØ indirect: $(2.167 \pm 0.040)\ \mathrm{GeV}/c^2$

Fully leptonic events (A)

- ★ Use $W^+W^- \to \ell^-\overline{\nu}_\ell \ell'^+\nu_{\ell'}$ decays and $W^+W^- \to q\overline{q}'\ell^-\overline{\nu}_\ell$ events failing kinematic fit
- ★ Use reweighting method
- ★ Fit to E_{max}, E_{min} and E_{miss}
- ★ Only on 183 GeV data

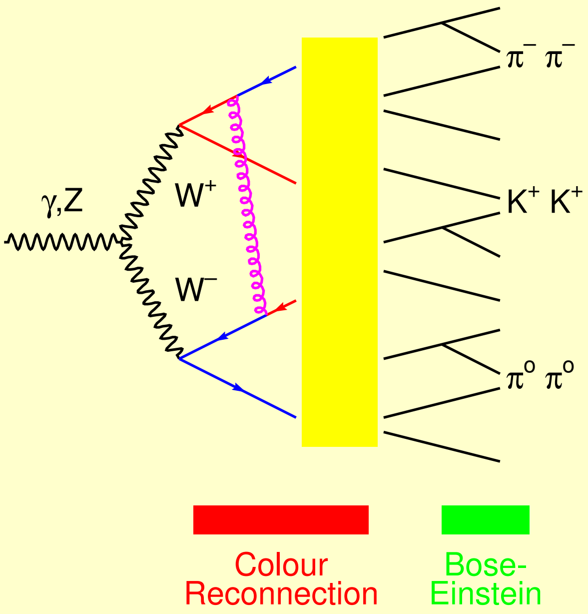


✔ ✘ Small improvement

Systematic uncertainties

Source	ΔM_W (MeV) $q\bar{q}'\ell\bar{\nu}_\ell$	$q\bar{q}'q\bar{q}'$
Detector calibration	15	5
non-WW background	5	5
MC statistics	10	10
Hadronization	20	20
Initial state radiation	5	5
Beam energy	17	17
Final State Interactions (FSI)	0	70
Total	35	80

FSI largest systematic ($q\bar{q}'q\bar{q}'$ only)

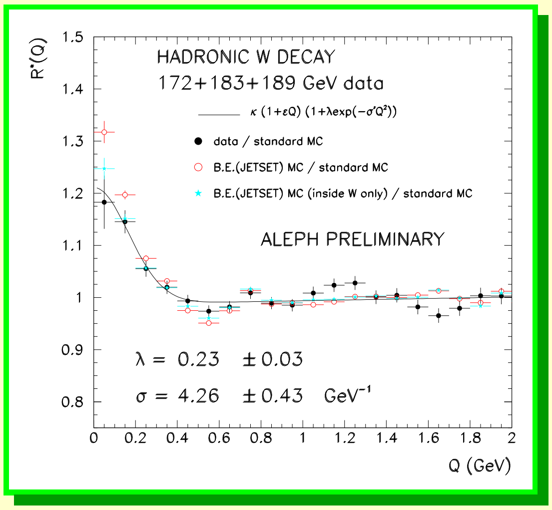


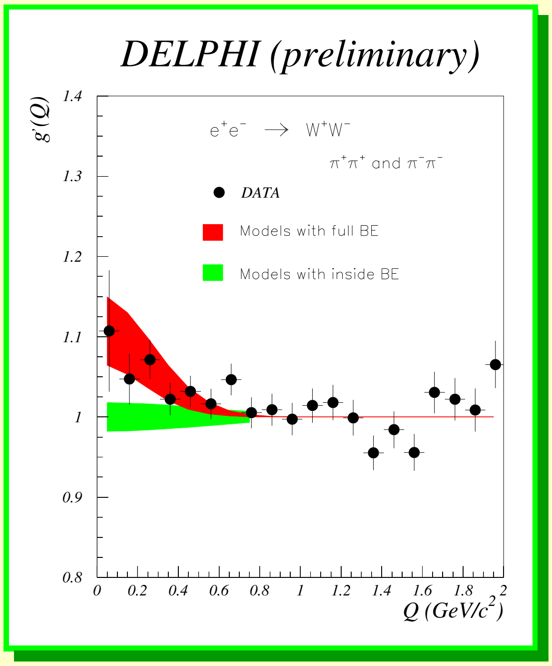
- W's decay on a scale $<$ hadronisation
- decay products from different W's may interact

➥ **Mass shift**

Bose–Einstein correlations

- ✔ Well established effect within same W
- ✔ Described by Monte Carlo tuned at the Z^0(udsc only)
- ✔ Like–sign pions closer in phase space
- ✘ Correlations between pions from different W's ?
- ✘ Different reference samples without B.E.C. are used
- ✘ Contradictory results
- ✘ Only 1 model to test (LUBOEI)



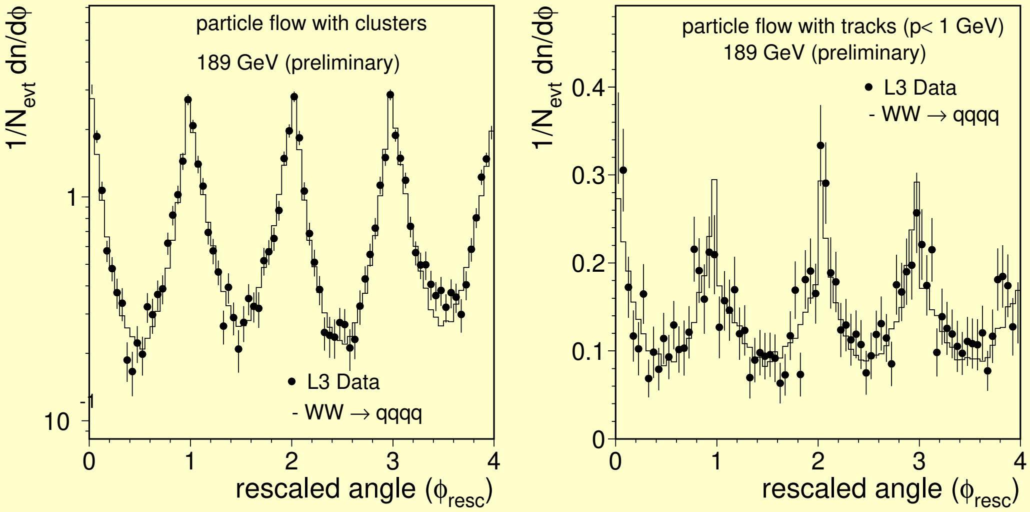


➥ Situation not clear

- ☞ Systematic uncertainty on M_{W} from LUBOEI
- ☞ $\Delta M_{\mathrm{W}} \approx 20$–$\mathbf{50}$ MeV/c^2

Colour Reconnection

- ✔ Perturbative effects $\mathcal{O}(\mathrm{MeV}/c^2)$
- ✘ Hadronisation phase: rely on models ➠ large M_W shifts
- ✔ No effects in multiplicity ($\langle n_{\mathrm{q\overline{q}'q\overline{q}'}}\rangle = 2\langle n_{\mathrm{q\overline{q}'}\ell\overline{\nu}_\ell}\rangle$)
  Predicted effect $\Longleftrightarrow$ LEP Measurement error
- ✔ CR effects larger for soft particles $p < \Gamma_\mathrm{W}$: investigate fragmentation functions, momentum spectrum
- ➥ Not enough sensitivity to exclude most models
- ✔ $\mathrm{Z}^0 \to b\bar{b}gg$ at LEP1 ➠ Exclude ARIADNE models (?)
- ✔ Investigate particle flow between jets



Different MC models predict mass biases:
0–100 MeV/c^2

Extreme models can be excluded with data

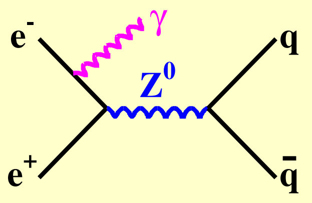
Is M_W the most sensitive variable to CR ?

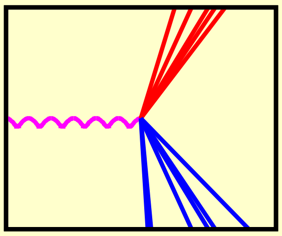
$$\boxed{{M_\mathrm{W}}^{\mathrm{q\overline{q}'q\overline{q}'}} - {M_\mathrm{W}}^{\mathrm{q\overline{q}'}\ell\overline{\nu}_\ell} = (152 \pm 74)\ \mathrm{MeV}/c^2}$$

Limiting factor for $\mathrm{q\overline{q}'q\overline{q}'}$ channel ?

Detector/Hadronization

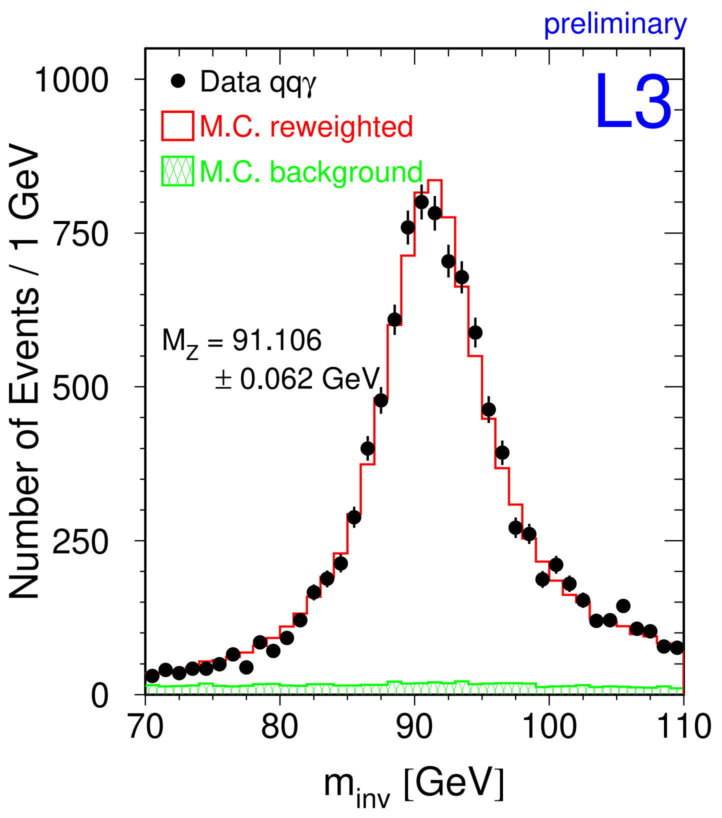
Many Cross-Checks e.g. Radiative Z^0





$$M_{q\bar{q}'} \quad = \quad M_{Z^0}$$

- ★ **Reconstruct $M_{q\bar{q}'}$ using kinematic fit.**
- ★ **Fit by reweighting MC**



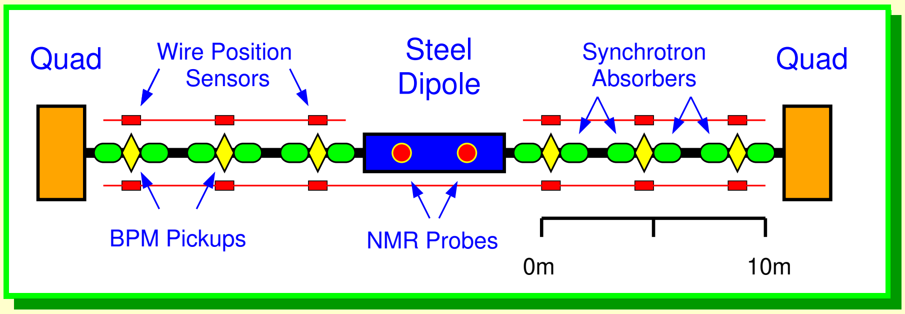
Beam energy

$$\frac{\Delta M_{\rm W}}{M_{\rm W}} = \frac{\Delta E_{beam}}{E_{beam}}$$

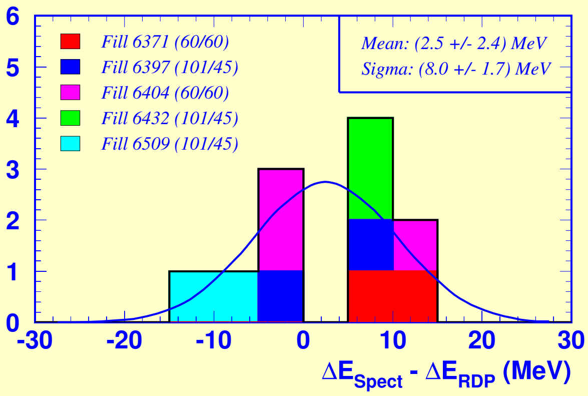
Current $M_{\rm W}$ error 17 MeV/c^2 ($\Delta E_{beam} = 20$ MeV)

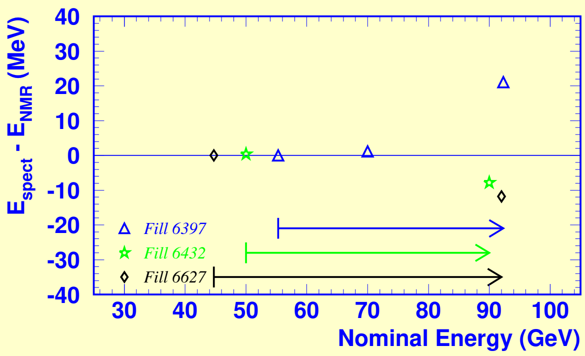
E_{beam} measurement

- **Resonant depolarisation at $\sqrt{s} = 40$–60 GeV**
- **Extrapolate at high energy/physics conditions with NMR probes**
- **Main systematic uncertainty: linearity of extrapolation**



- **Flux loop measurement: $\Delta E_{beam} = 20$ MeV**
- **LEP Spectrometer: calibrate at 45 GeV, measure at high energy $\Delta E_{beam} = 11$ MeV (3 fills)**
- **Synchrotrone Tune vs. V_{RF}: $\Delta E_{beam} = 25$ MeV**





Combined M_W result

LEP Combined M_W from

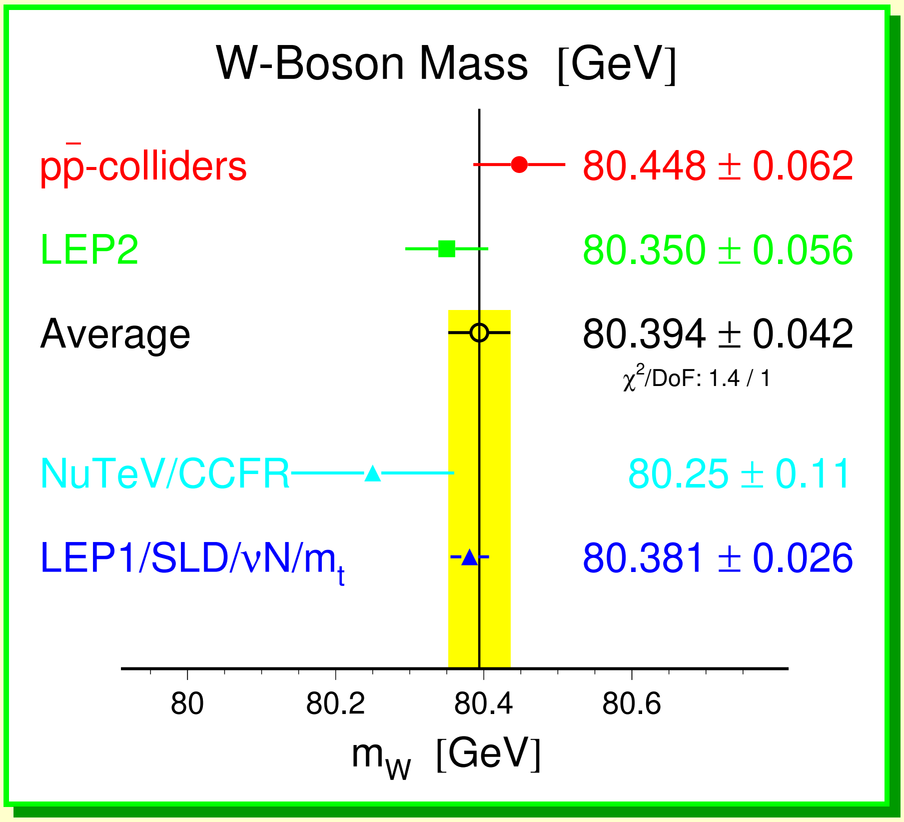
- **Threshold cross section**

$$M_W = (80.40 \pm 0.22)\ \mathrm{GeV}/c^2$$

- **Direct reconstruction:**

$$M_W = (80.347 \pm 0.036(\mathrm{stat}) \pm 0.036(\mathrm{syst}) \pm 0.020(\mathrm{FSI}) \pm 0.017(\mathrm{LEP}))\ \mathrm{GeV}/c^2$$

$$\boxed{M_W(LEP) = (80.350 \pm 0.056)\ \mathrm{GeV}/c^2}$$



Future prospects

- ★ Assume **600** pb^{-1}/ experiment
- ★ No improvement in the analyses
- ★ Scale some systematic errors with luminosity/ Monte Carlo statistics

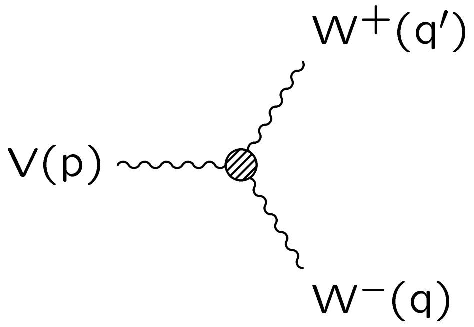
Source	ΔM_{W} (MeV/c^2)		
	$\mathrm{q\overline{q}}'\ell\overline{\nu}_\ell$	$\mathrm{q\overline{q}}'\mathrm{q\overline{q}}'$	Comb
Detector calibration	5	5	5
non-WW background	5	5	5
Hadronization	10	10	10
$O(\alpha_{em})$ + ISR	5	5	5
Beam energy	12	12	12
FSI	0	0–100	0–10
Statistical	35	35	25–35
Systematic	20	20–100	20
Total	40	40-110	30-40

- ➥ Final LEP M_{W} error $30 - 40\ \mathrm{MeV}/c^2$
- ➥ Depends on FSI error
- ➥ Lot of work on all systematic errors

Triple gauge boson vertices

- **SM**: non abelian gauge theory $(SU(2)_L \otimes U(1)_Y)$
  $\Longrightarrow$ vertices with 3 and 4 gauge bosons

➥ **predict form and strength of gauge couplings**



$$= -ie\, g_{VWW} \Gamma_V^{\alpha\beta\mu}(p, q, q')$$

- TGC or anomalous couplings of the triple gauge bosons:
  parameters of the triple–gauge boson part of the electroweak Lagrangian
- For each VWW vertex $(V = \gamma, Z)$ introduce general Lorentz invariant form
- Consider only operators with dimension ≤ 6
  $\Longrightarrow$ **7 independent terms for γ and Z**
- Require **C**,**P** and **CP** conservation
- Require $U(1)_{em}$ gauge invariance $(q_W = \pm 1)$

Only 5 parameters to describe the vertices:

$$g_1^Z, \kappa_\gamma, \lambda_\gamma, \kappa_Z, \lambda_Z$$

In the SM: $g_1^Z, \kappa_\gamma, \kappa_Z = 1$ and $\lambda_\gamma, \lambda_Z = 0$

Relation with physical quantities

$$
\begin{aligned}
q_W &= e \cdot g_1^\gamma && \overset{SM}{=} \quad e \\
\mu_W &= \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma) && \overset{SM}{=} \quad \frac{e}{2M_W} \\
Q_W &= -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma) && \overset{SM}{=} \quad -\frac{e}{M_W^2}
\end{aligned}
$$

- Still too many parameters (5) to measure
- Impose $SU(2)_L \otimes U(1)_Y$ gauge invariance
- Consider only operators not constrained from lower energy measurements
- ➥ Only 3 anomalous couplings remain

$$\boxed{\Delta g_Z^1,\ \Delta\kappa_\gamma \text{ and } \lambda = \lambda_\gamma}$$

Δ is the deviation from the SM value 1

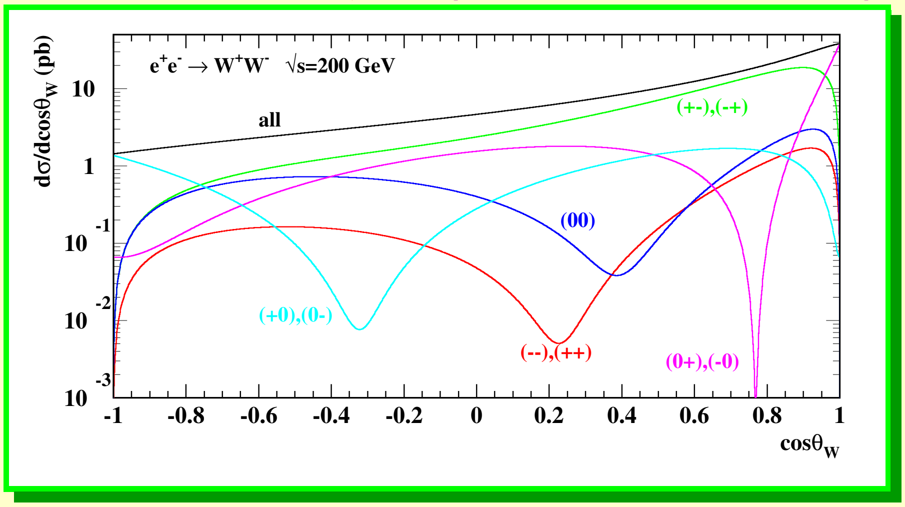
- All are zero in the SM
- The remaining parameters are obtained through gauge invariance:

$$
\boxed{
\begin{aligned}
\Delta\kappa_Z &= \Delta g_Z^1 - \Delta\kappa_\gamma \tan^2\theta_w \\
\lambda_Z &= \lambda_\gamma
\end{aligned}
}
$$

Sensitivity to anomalous couplings

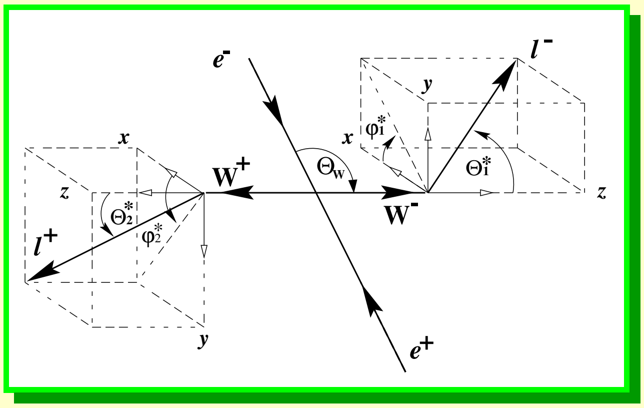
- Helicities of the two Ws
- Vary relative contribution of each W helicity
- Affect total cross section and $d\sigma/d\cos\theta_{W^-}$

$\mathcal{L}$ **linear in** TGCs ➠ $\sigma, d\sigma$ **quadratic in the couplings**



Measure the W^- scattering angle and the helicities of the two W bosons

- Use the W decay as a polarimeter



Accessibility of $\Omega = (\theta_W, \theta^*_f, \phi^*_f, \theta^*_{\bar{f}}, \phi^*_{\bar{f}})$ depends on W decay channels

In the real life

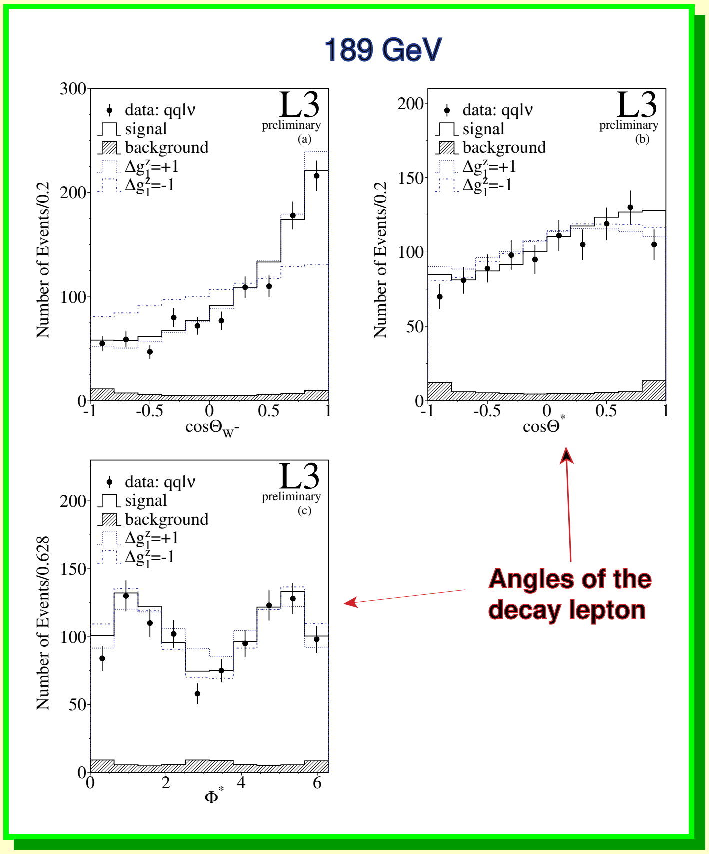
- Cannot neglect the W width, ISR photons
- Neutrinos are unmeasured (≥ 2 in τ events)
- Quark charges cannot be measured (efficiently ?)
- Detector resolution, Backgrounds

➥ Refine event selection (properly measured events)

➥ Improve resolution (kinematic fit)

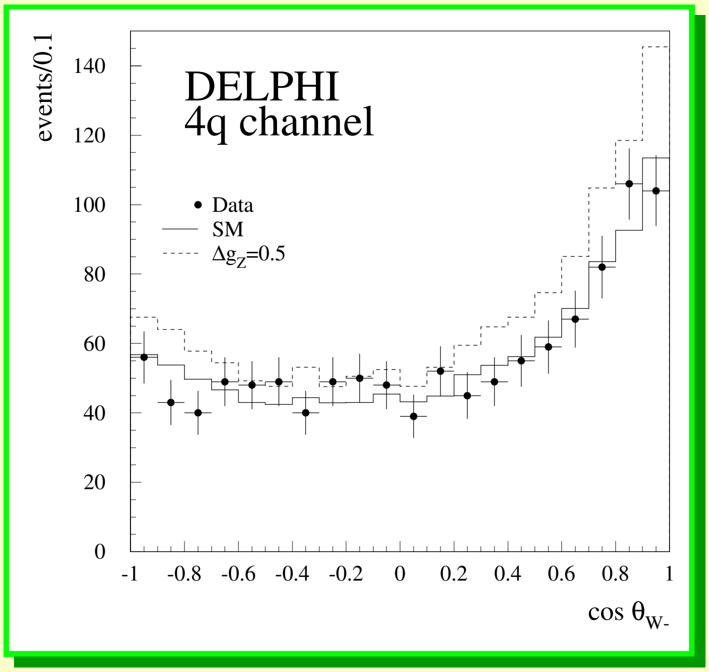
The $\mathrm{W^+W^-} \to \mathrm{q\overline{q}}'\ell^-\overline{\nu}_\ell$ channel

- Large branching ratio, W charge from the lepton
- Integrate over quark variables (twofold ambiguity)



The $W^+W^- \to q\bar{q}'q\bar{q}'$ channel

- Jet pairing $\Longleftrightarrow$ correct combination ($\epsilon = 74$%–84%)
- W charge assignment $\Longleftrightarrow$ jet charge ($\Delta Q = 2$ between $W^{\pm}$, $\epsilon = 71$%–79%)
- Complete folding over decay angles



$\oplus$

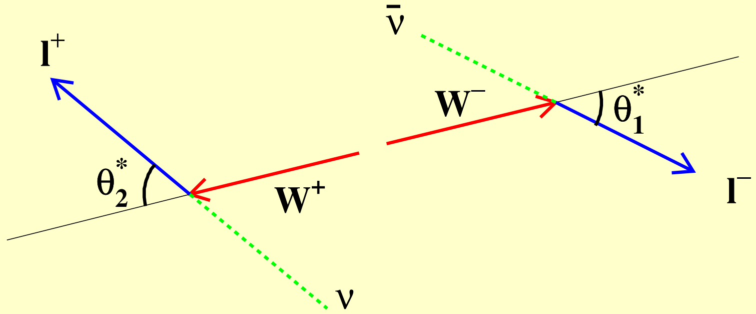
high statistics

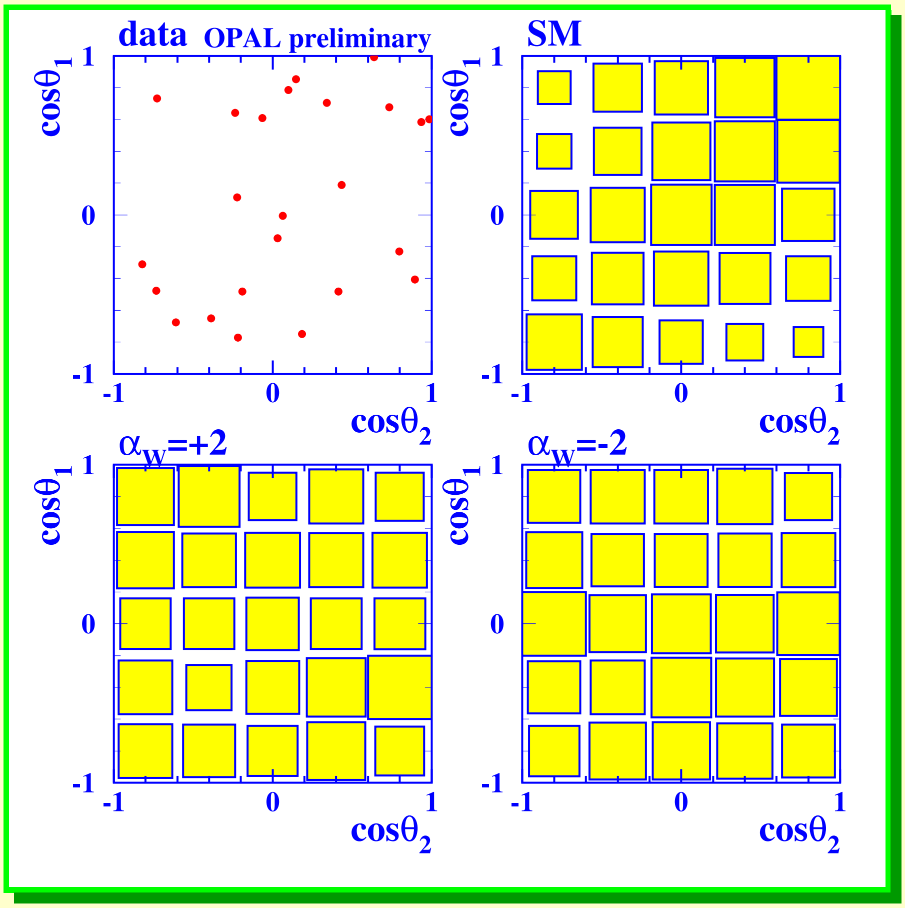
$\ominus$

only $\approx$ 60 % efficiency of correct reconstruction

The $W^+W^- \to \ell^-\overline{\nu}_\ell \ell'^+\nu_{\ell'}$ channel

- Small useful branching ratio ($\approx 5\%$)
- All 5 angles can be determined (up to a twofold ambiguity)
- Sensitivity to the correlation of the W helicities





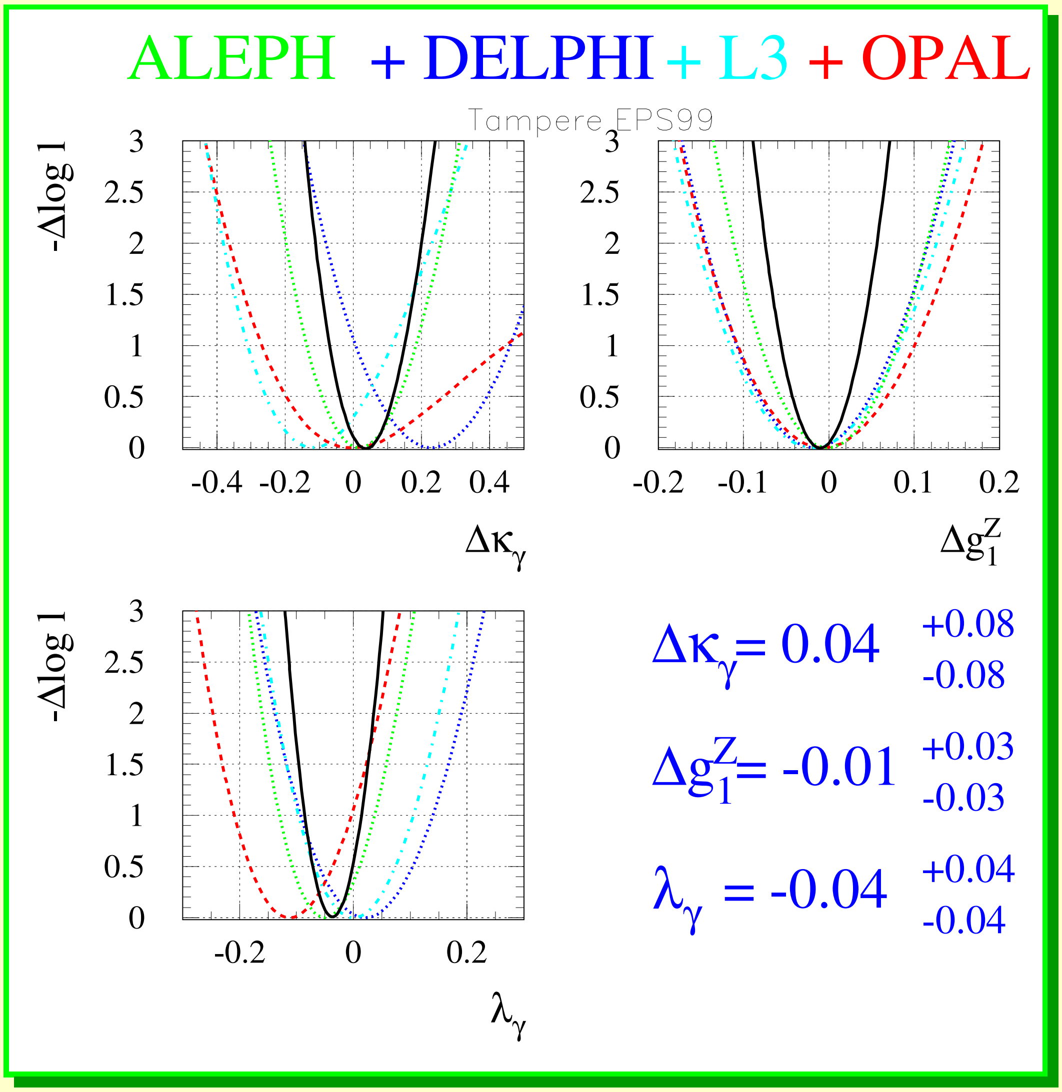
Only OPAL + ALEPH

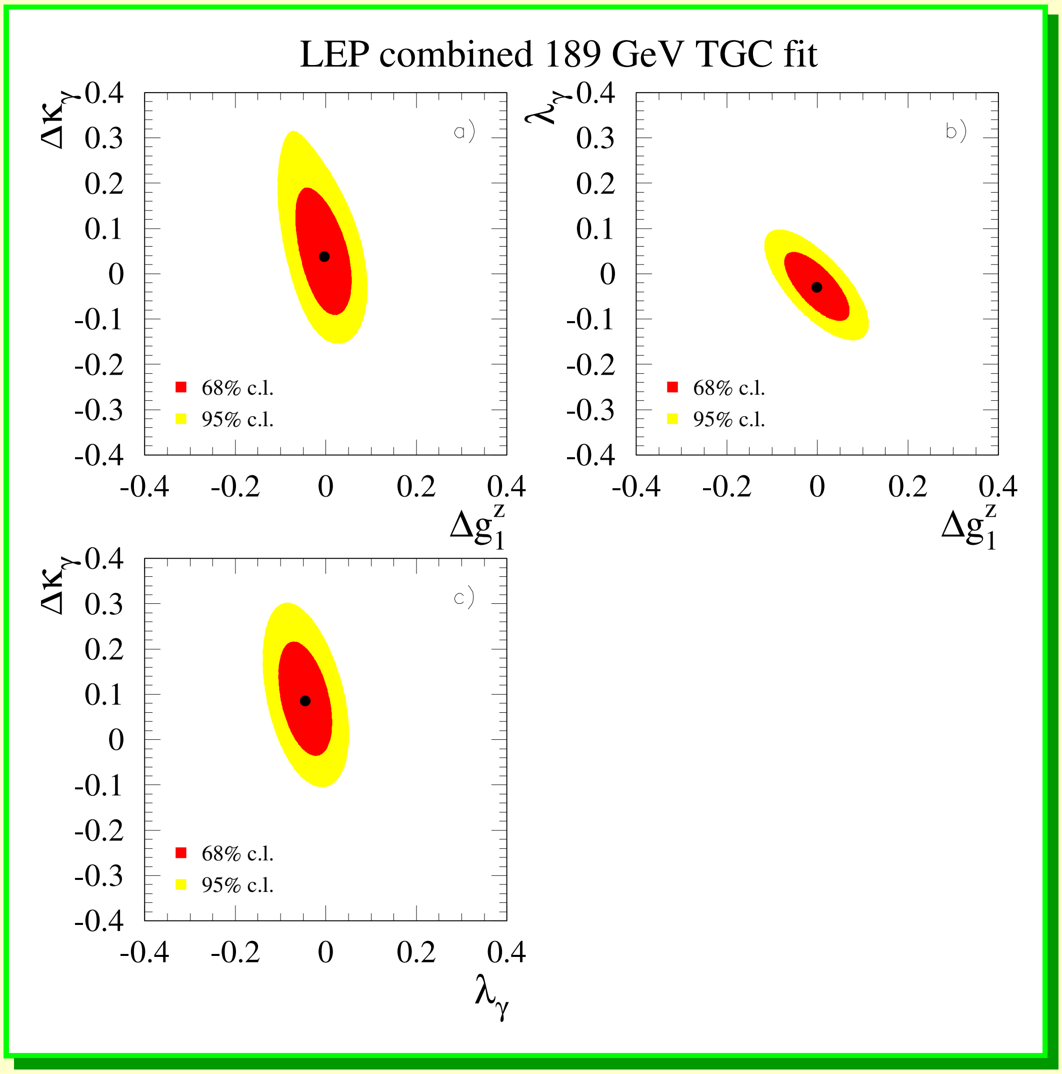
Methods to extract the couplings

- Event counting: fit to the total cross section
- Differential distributions:
  - ★ unbinned ML fit to theoretical distribution
    ISR, Γ_{W}, backgrounds not taken into account
    requires folding with detector resolution
  - ★ binned ML fit to MC
    take into account all physical and detector effects
    requires large MC samples
    some loss of statistical precision
  - ★ “optimal” observables method
    retain sensitivity of unbinned ML fit for small α
    all informations contained in a single variable
    value of α can be obtained from the mean value of the distribution or from a binned fit
- Checks for biases in the procedure using MC events generated with $\alpha \neq 0$
- Small event samples, non gaussian detector resolution
  $\Longrightarrow$ error calibration required
- Multidimensional fits also performed
- Results are presented as 1–dim or 2–dim likelihood curves which are then added when combining the different channels/experiments
- Include also single W and single γ results

LEP Combined results

- **LEP combined results obtained adding likelihood curves from different experiments**
- **Correlated systematic errors small relative to statistical and uncorrelated ones**





- **5% measurement of TGCs**
- **limited by statistics**
- **main systematic uncertainties:**
  - ★ $W^+W^- \to q\overline{q}'\ell^-\overline{\nu}_\ell$: **fragmentation, detection efficiency**
  - ★ $W^+W^- \to q\overline{q}'q\overline{q}'$: **fragmentation, FSI**

Spin Density Matrix elements

Summing over all possible helicities of the second W....

$$\rho_{\tau\tau'}(\cos\theta_W) = \frac{\sum_\lambda \mathcal{F}_\tau^{(\lambda)} (\mathcal{F}_{\tau'}^{(\lambda)})^*}{\sum_{\lambda\tau} |\mathcal{F}_\tau^{(\lambda)}|^2}$$

helicity of $W^\pm$

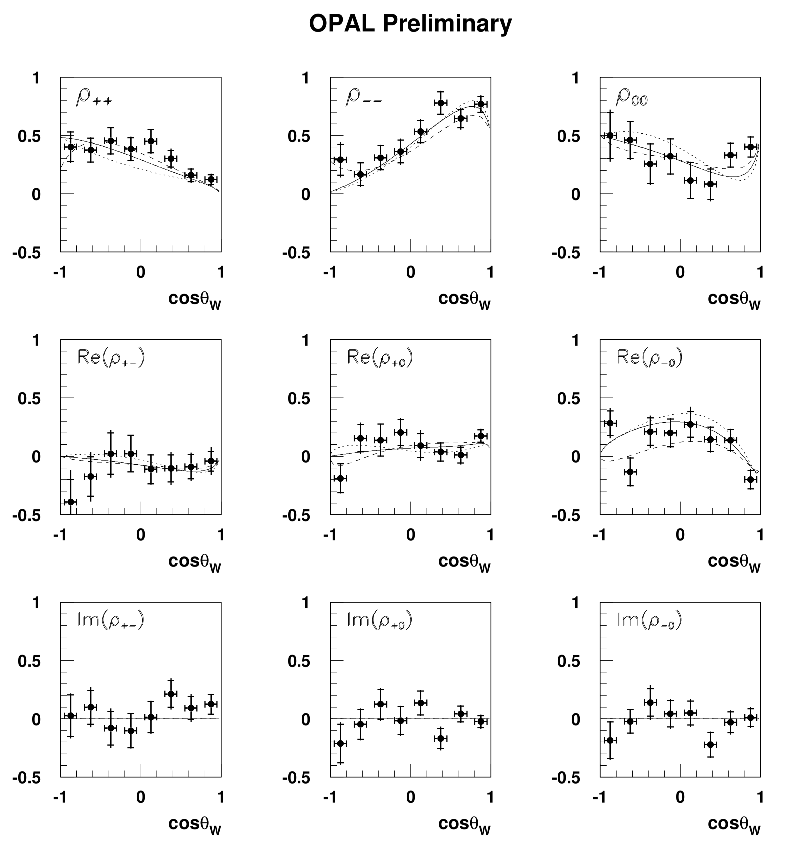
$\Rightarrow$ $\tau = 1$

$\Uparrow$ $\tau = 0$

$\Leftarrow$ $\tau = -1$

λ: e^- spin

- $\rho_{\tau\tau'}$ is a 3×3 hermitian matrix
- Practically the SDM elements are extracted in bins of $\cos\theta_W$ with projection operators that are functions of θ^* and ϕ^*
- $\rho_{\tau\tau}$ (diagonal elements)= probability to produce a boson with helicity τ
- imaginary part of off-diagonal elements: vanish in CP-conserving theories



Model independent measurement of W helicity structure

Helicity analysis: W decay angles only

$$\frac{1}{N}\frac{dN}{dx} = f_{-}\frac{3}{8}(1+x)^2 + f_{+}\frac{3}{8}(1-x)^2 + f_{L}\frac{3}{4}(1-x^2) \quad \text{with} \quad x = \cos\theta^*$$

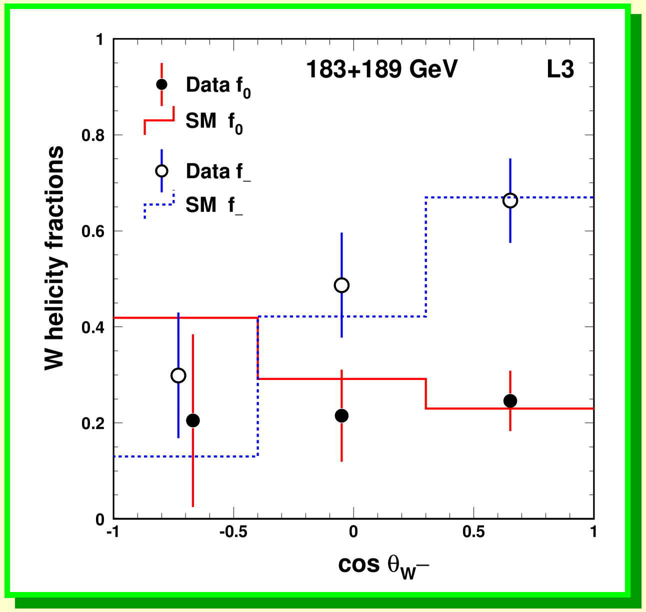
★ **L3: fit to $\cos\theta^*$ distribution**

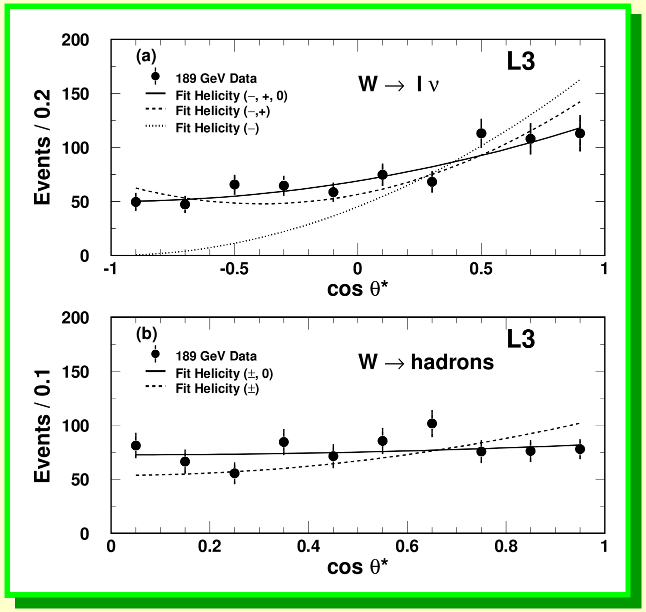
➥ $f(\mathrm{W}_L^{\pm}) = (0.261 \pm 0.051 \pm 0.016)$

★ $\mathcal{SM}$: $f(\mathrm{W}_L^{\pm}) = 0.26$

➥ **5 σ observation**

★ **CDF: longitudinal W from t decays**





★ **Measurement of W helicity vs $\cos\theta_W$ agrees with $\mathcal{SM}$**

Conclusions and future prospects

W Mass

- ➥ **Only half of the data analysed:** $\Delta M_{\mathrm{W}} = 56\ \mathrm{MeV}/c^2$
- ✘ **Lot of work on systematics (**E_{beam}**, Bose–Einstein, Colour Reconnection)**
- ✔ **Goal:** $\Delta M_{\mathrm{W}} \leq 40\ \mathrm{MeV}/c^2$

Triple gauge boson couplings

- ➥ **Measured with 5% precision, statistics dominated**
- ✘ **No hints of deviations from** $\mathcal{SM}$
- ✔ **Move toward more model independent analyses**