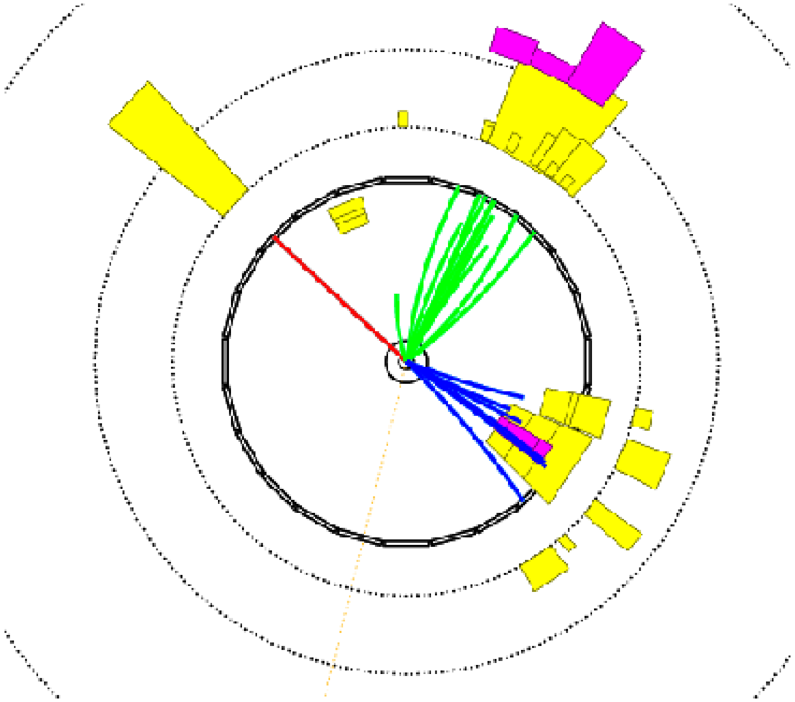
Measurement of m_{W} at LEP

Mark Thomson

University of Cambridge



- ★ Experimental Method
- ★ Recent Results
- ★ Systematic Uncertainties
- ★ Prospects for Final Results

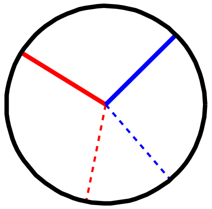
Introduction

- ★ 1997-2000: LEP operated above W pair production threshold ($\sqrt{s}$ = 183-209 GeV)
- ★ Total (summed over ADLO) LEP2 integrated lumi: ~ 2.5 fb^{-1}
- ★ Each experiment accumulated ~ 10000 $\mathrm{W^+W^-}$ events
- ★ relatively large cross-section ($\sim$16 pb) and clear decay topologies allow efficient and clean identification of $\mathrm{W^+W^-}$ events

Typical performance:

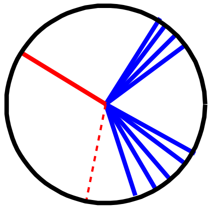
	Efficiency	Purity
$\ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$	70%	90%
$\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$	80%	85%
$\mathrm{q\overline{q}q\overline{q}}$	80%	80%

WW→lνlν



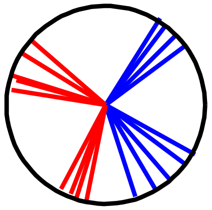
10.5 %

WW→qqlν



43.9 %

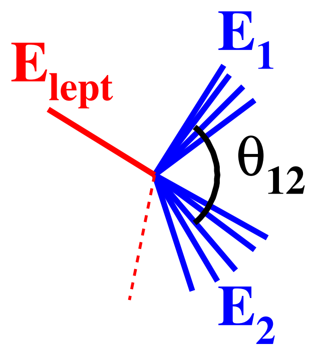
WW→qqqq



45.6 %

W-Mass from Direct Reconstruction

★ Above $\mathrm{W^+W^-}$ threshold : m_{W} determined from reconstruction of the invariant mass distribution of the $\mathrm{W^+W^-}$ decay products, *i.e.* $M_{\mathrm{q\bar{q}}}$, $M_{\ell\nu}$

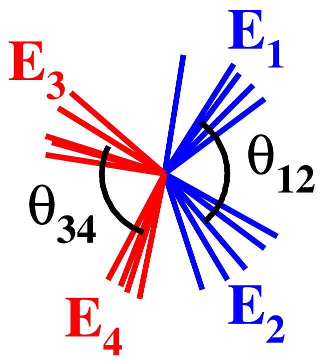


Two Distinct Stages:

❶ Reconstruct event-by-event mass

❷ Fit mass distribution $\Rightarrow m_{\mathrm{W}}$

★ require good measurements of the fermion four-momenta.



However:

- jet energies relatively poorly measured $\sigma_E/E > 60\%/\sqrt{E(\mathrm{GeV})}$
- neutrinos unobserved.

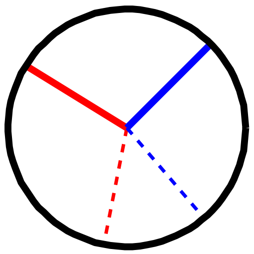
★ Kinematic fitting plays vital rôle.

Kinematic Fitting

5 Constraints:

★ Energy/momentum conservation : $(E, \vec{p}\,) = (\sqrt{s}, 0)$

★ Neglect Γ_{W} : and take $m_1 = m_2$

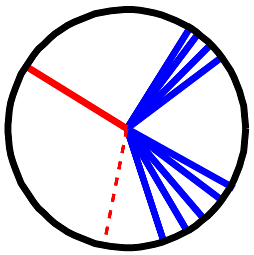


$\ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$: 6 unknowns ($\vec{p}_{\nu_1}$ $\vec{p}_{\nu_2}$)

Under-constrained

Limitted m_{W} sensitivity

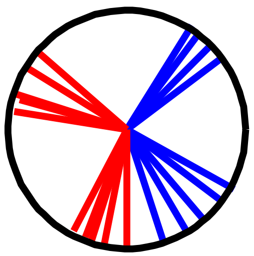
Results from ALEPH, OPAL



$\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$: 3 unknowns ($\vec{p}_\nu$)

Over-constrained : use kinematic fit

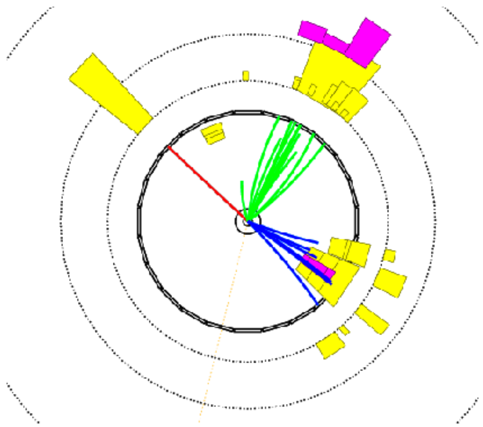
Most m_{W} sensitivity from $\mathrm{q\overline{q}}$

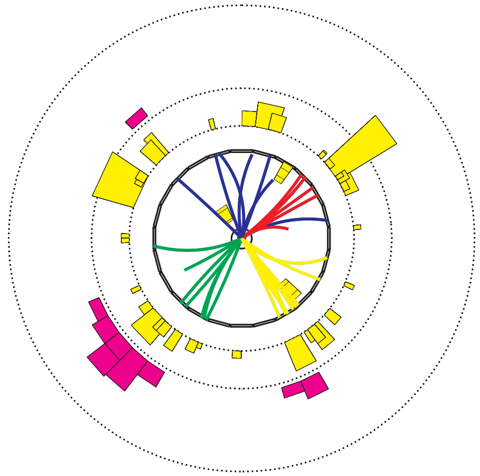


$\mathrm{q\overline{q}q\overline{q}}$: 0 unmeasured quantities

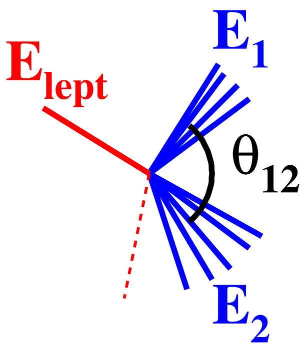
Over-constrained : use kinematic fit

Measure both W-decays





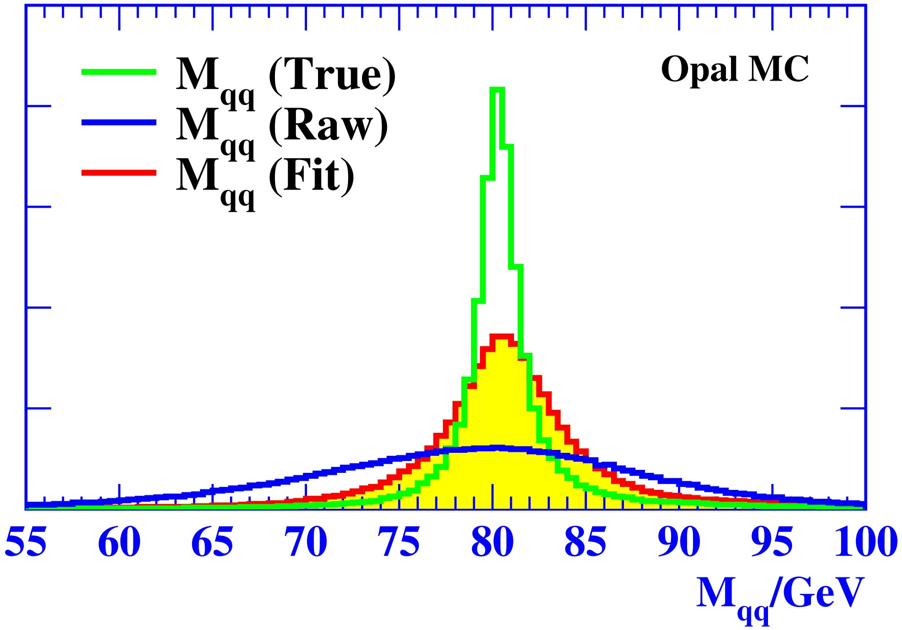
Mass Reconstruction : $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$



- ★ Identify energy deposits associated with lepton
- ★ Force remainder of event into 2 jets (DURHAM/LUCLUS)
- ★ Sum over tracks/clusters $\Rightarrow (E_{jet}, \vec{p}) \Rightarrow M_{jet}, \beta = |p|/E_{jet}$
- ★ Most sensitivity to m_W from jet-jet system

$$M^2_{q\overline{q}} = M_1^2 + M_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$

- ★ <u>Jets:</u> angles better measured than energies
- ★ Kinematic fit - scales sum of jet energies
- • $E_1 + E_2 = E_{beam}$
- ★ Significantly improves resolution
- + gives reduced sensitivity to jet energy scale
- ★ Reconstructed jet masses are important
- ★ In fits all experiments keep β fixed.

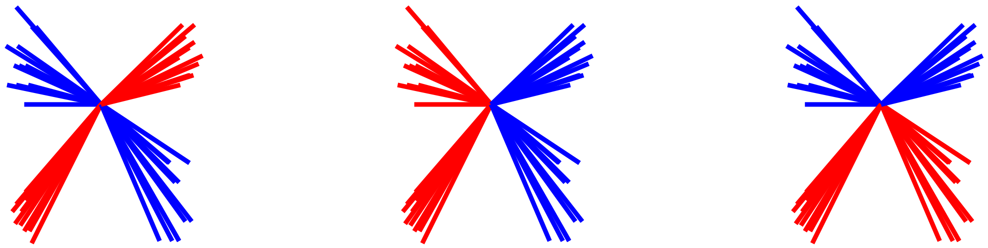


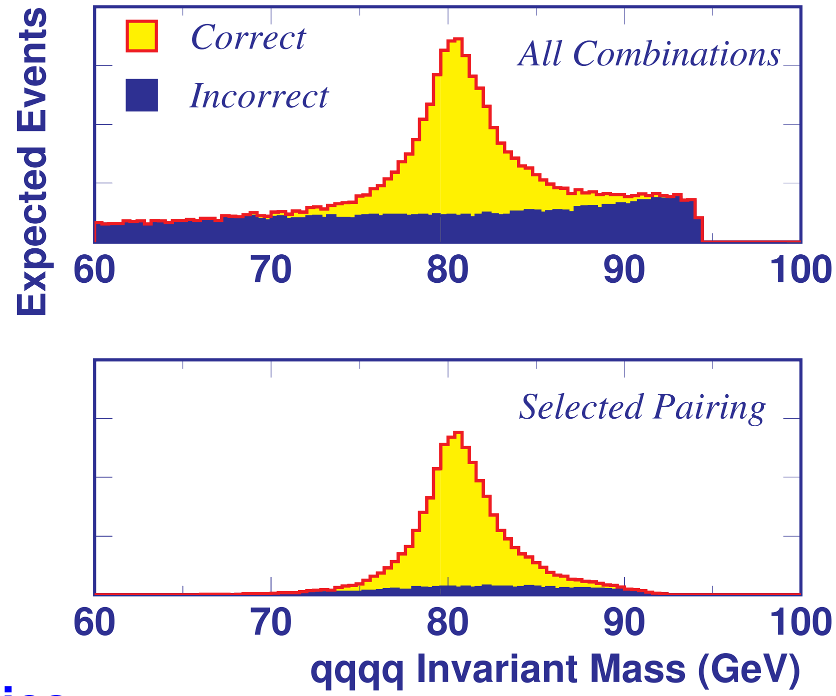
Mass Reconstruction : $W^+W^- \to q\bar{q}q\bar{q}$

★ **Force event into 4 jets (DURHAM)**

DELPHI/OPAL allow for additional gluon jet

3 Three possible pairings of jets to $W^\pm W^\mp$





★ **Incorrect pairings**

$\Rightarrow$ **Combinatoric background.**

★ **Apply Kinematic Fit to all 3 pairings**

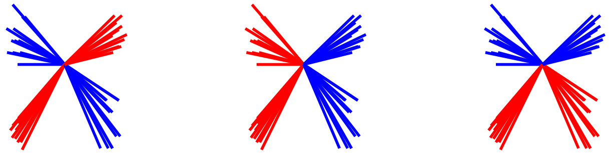
Best pairing selected using:

- **ALEPH : Consistency with W-decay kinematics**
- **L3 : Kinematic fit probability.**
- **OPAL : Multivariate selection / Kinematic Fit prob.**
- **DELPHI : use all pairings !**

Many tricks to improve m_W sensitivity, e.g.

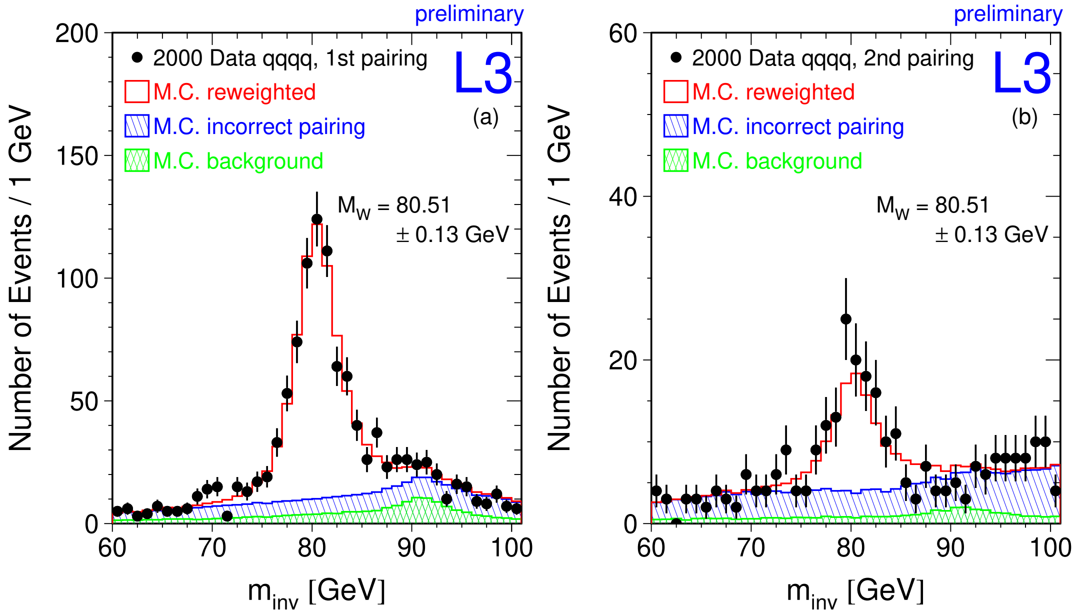
L3

★ Rank 3 jet pairings by 5C fit prob.



★ Use combination with highest fit prob.

★ Also use second best
in a separate distribution

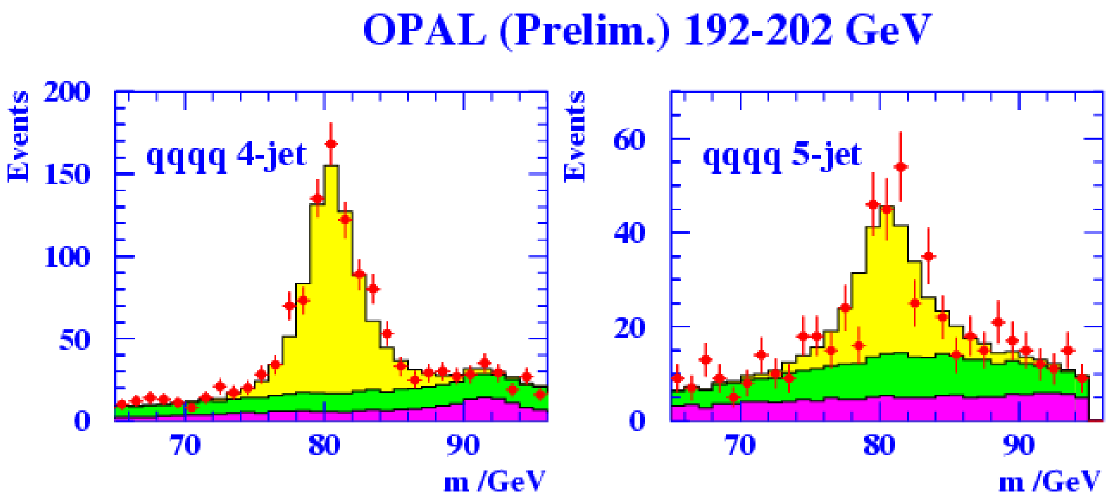


OPAL

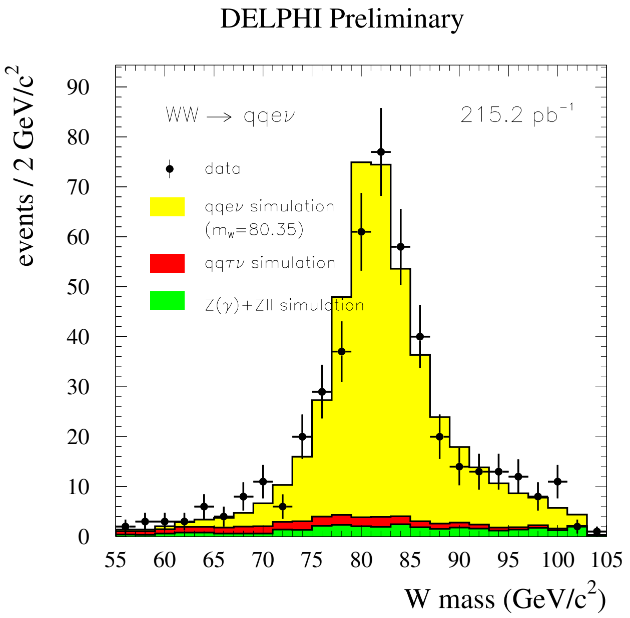
★ Reconstruct some events as 5 jets
i.e. allow for a gluon jet

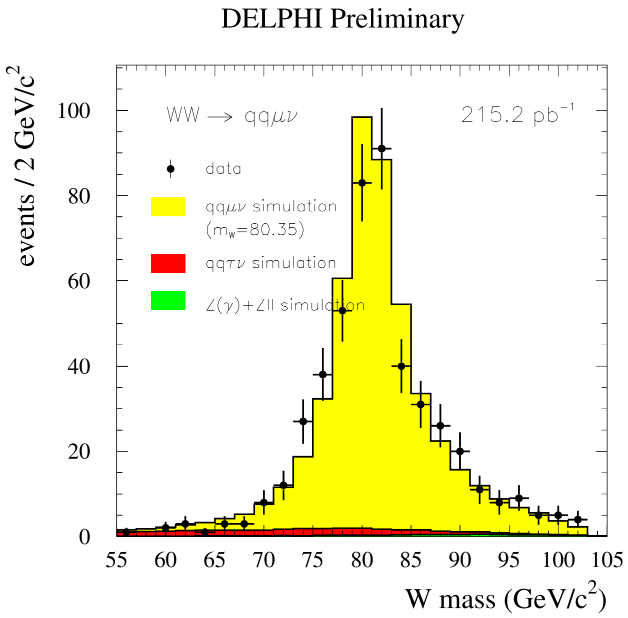
★ 10 ways of assigning 5 jets to 2 Ws
large combinatoric background

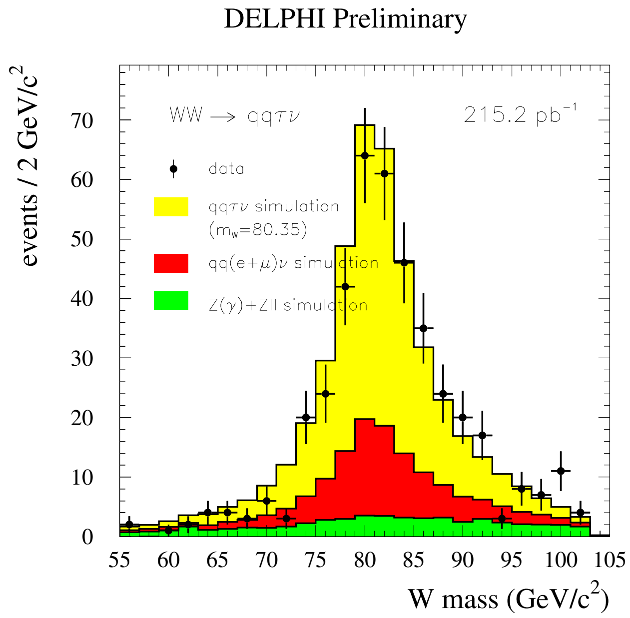
★ Select best using relative likelihood

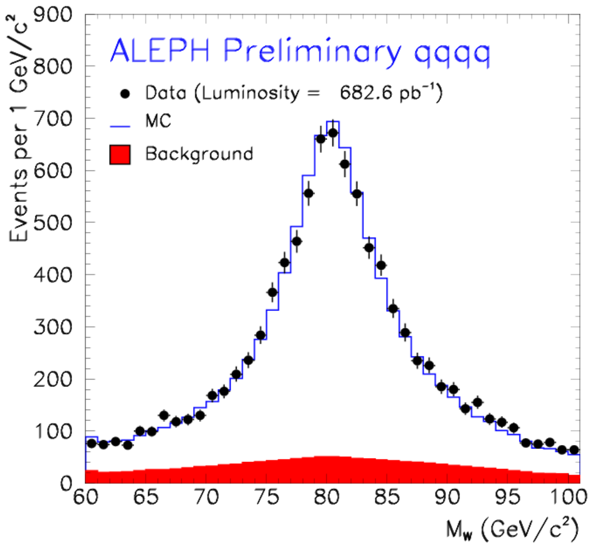


From Mass Distributions to m_W









★ **Determination of m_W from mass distributions**

THREE METHODS :

➊ **Breit-Wigner Fit (OPAL)**

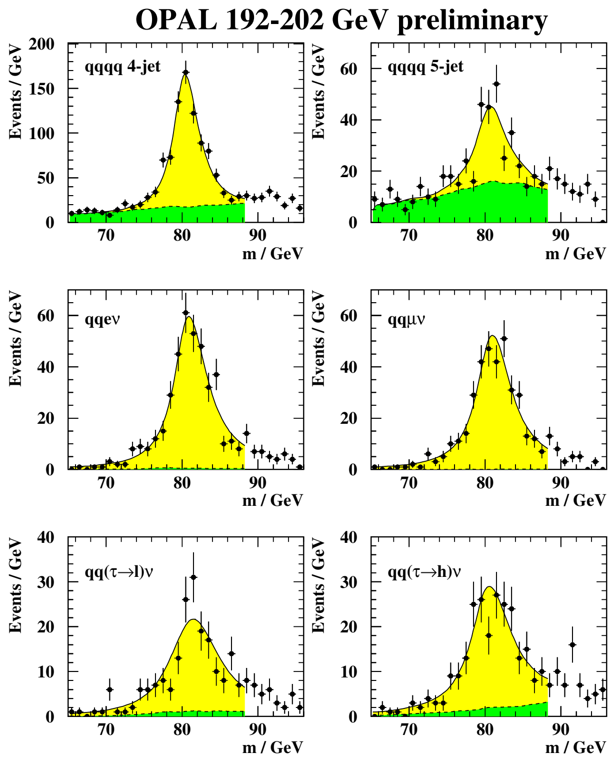
➋ **Monte Carlo Reweighting (ALEPH/L3/OPAL)**

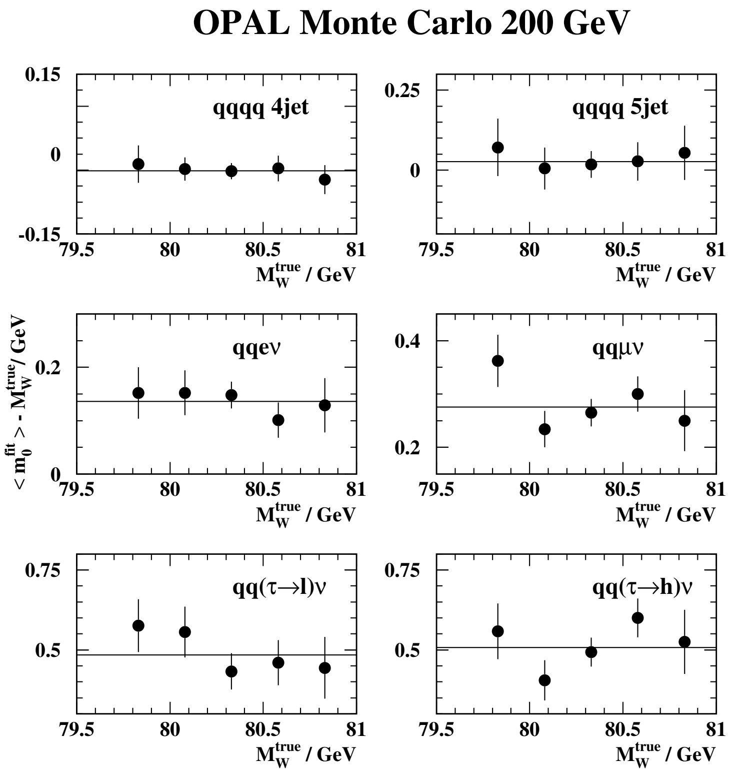
➌ **Convolution (DELPHI)**

❶ Breit-Wigner Fit (OPAL)

★ Parameterise using function based on BW - "find the peak"

★ Use Monte Carlo ('KandY') to correct for biases



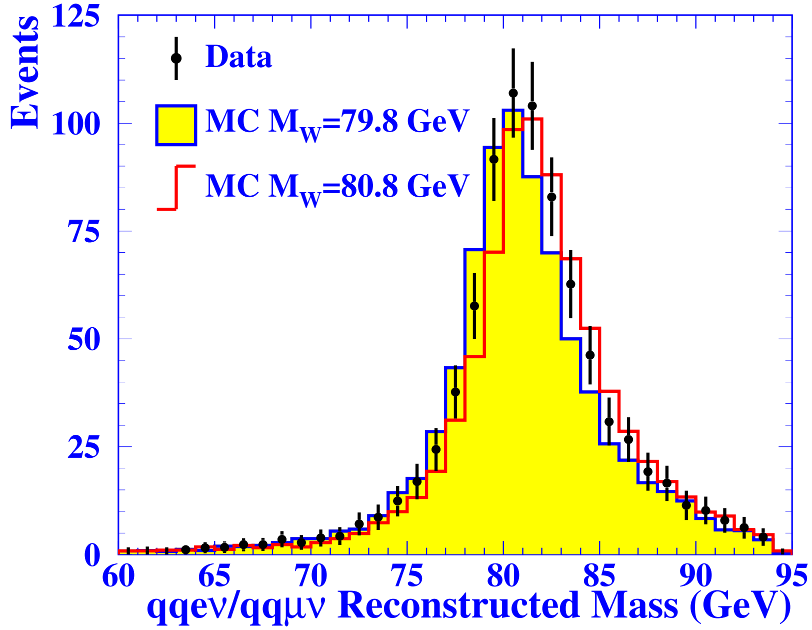


★ SIMPLE and ROBUST - used for preliminary results .

★ Not the most statistically powerful technique
plan to use Convolution for final results.

❷ Reweighting Fit (e.g. ALEPH,L3,OPAL)

- ★ Compare Data to MC ➡ $\chi^2(m_W)$
- ★ Could generate many MC samples with many values (m_W, Γ_W)
- ★ Instead generate one large sample (m_W, Γ_W) and REWEIGHT to $(m_W{}', \Gamma_W{}')$



For event i with generated masses (m_1, m_2)

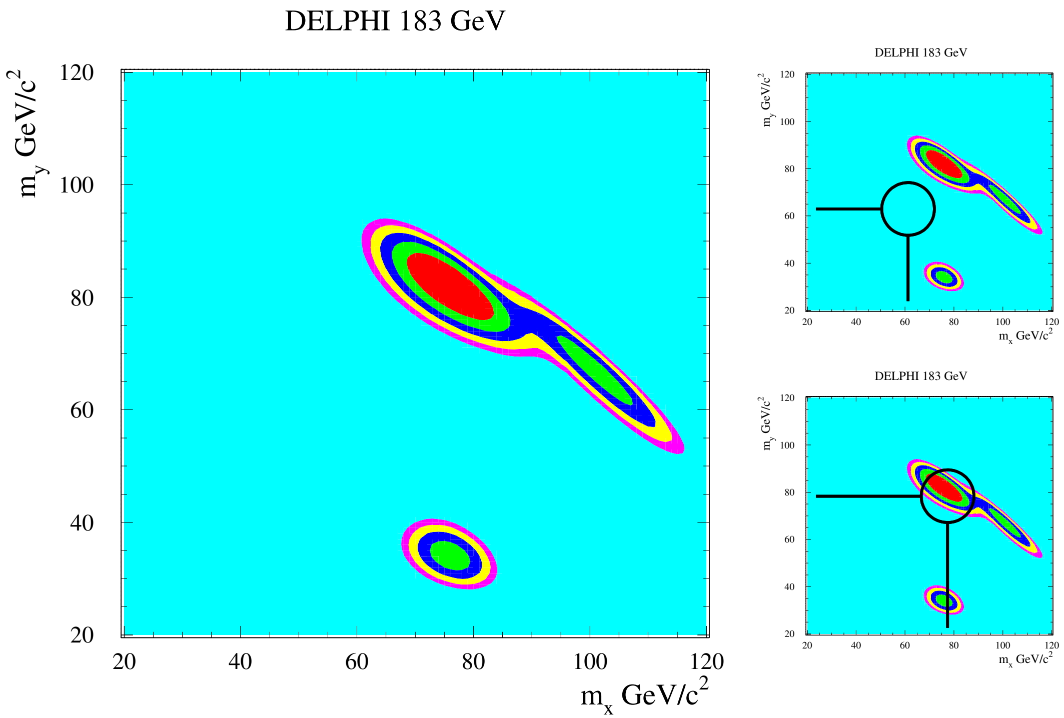
$$w^i = \frac{BW(m_1, m_2 : m_W{}', \Gamma_W{}')}{BW(m_1, m_2 : m_W, \Gamma_W)}$$

★ Monte Carlo bias correction implicit in fit

Convolution Method : DELPHI

Basic idea (e.g. $q\bar{q}q\bar{q}$):

- ★ Use 4C fit $\Rightarrow$ 2 masses + error matrix for each jet pairing
- ★ form event PDF using all 3 jet pairings used
- ★ calculate "overlap" of event PDF with a 2D Breit-Wigner, $\mathcal{BW}(m_{\mathrm{W}}) \Rightarrow$ event likelihood, $\mathcal{L}(m_{\mathrm{W}})$.

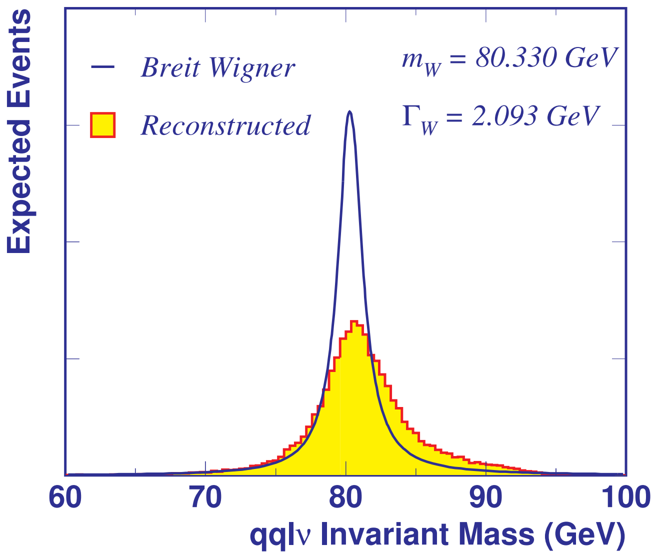


- ★ Statistically powerful
- ★ Still need to correct for biases as for BW method.

All Methods basically:

★ locate the peak of the reconstructed invariant mass distribution

★ Use Monte Carlo to correct for biases



Mass Distribution Distorted by:

★ Experimental Resolution and response

★ Event Selection

★ ISR

★ Final state interactions ($q\bar{q}q\bar{q}$) ?

★ The degree to which the MC models these biases ultimately determines the systematic uncertainties

★ Need precise Monte Carlo Predictions !

Systematic Uncertainties I : Detector Effects

★ Trying to measure W-mass to $\sim 0.05\,\%$ - method of direct reconstruction sensitive to poorly modelled detector effects.

Detector Calibration:

★ Detector calibration determined from data
mainly using $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z}^0$ events at $\sqrt{s} = 91.2$ GeV

★ Typical resulting uncertainty on m_{W} is 20-30 MeV per experiment

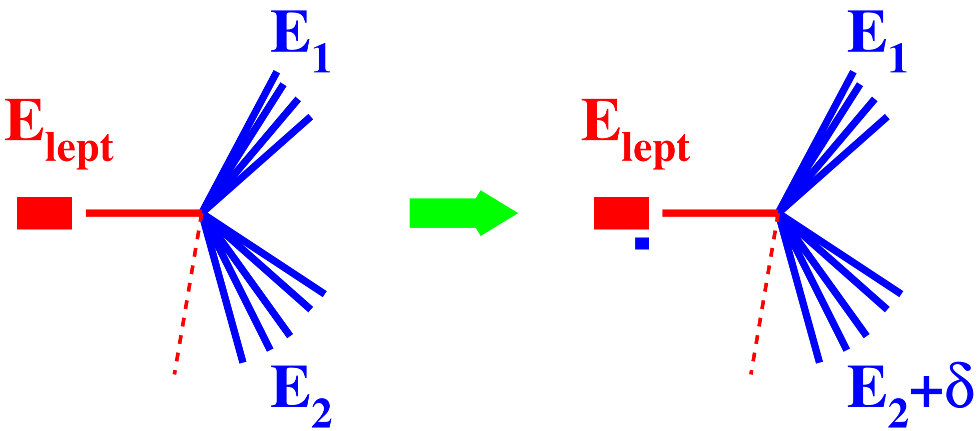
★ Uncorrelated between experiments - not the biggest concern

ALEPH Effect:

★ New ALEPH preliminary result shifted by -79 MeV compared to previous result from same data, 1.3 $\times$ ALEPH total uncertainty.

★ largest effect in $\mathrm{q\overline{q}e}\overline{\nu}_{\mathrm{e}}$: changed by -150 MeV.

★ Due to population of non-simulated low energy "satellite" clusters near to electromagnetic showers.

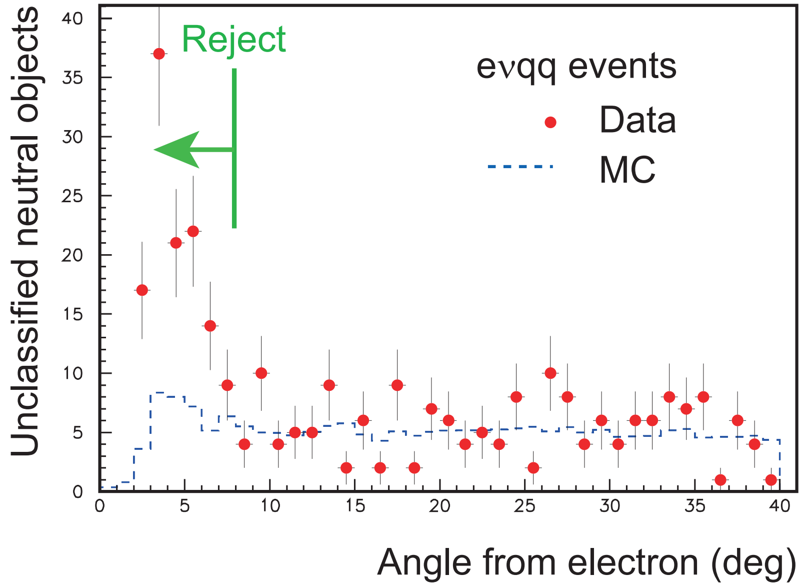


- ★ In the event reconstruction **Satellite clusters** are not associated with lepton
- ★ Therefore **associated with nearest jet**
- ★ Bias jet angle
- ★ Significant bias to jet mass

Recall: $\mathrm{M}^2_{\mathrm{q\bar{q}}} = \mathrm{M}_1^2 + \mathrm{M}_2^2 + 2\mathrm{E}_1\mathrm{E}_2(1 - \beta_1\beta_2\cos\theta_{12})$

Problem solved by "Cleaning":

- ★ Removing satellite clusters within 8° of leptons
- ★ Removing all unassociated neutral clusters which are observed within a single ECAL stack (such objects were never identified as photons)
- ★ SUBTLE EFFECT - negligible impact on other ALEPH analyses/results



★ **DELPHI, L3, OPAL do not observe similar problems**

QED Uncertainties: Experimental Constraints ?

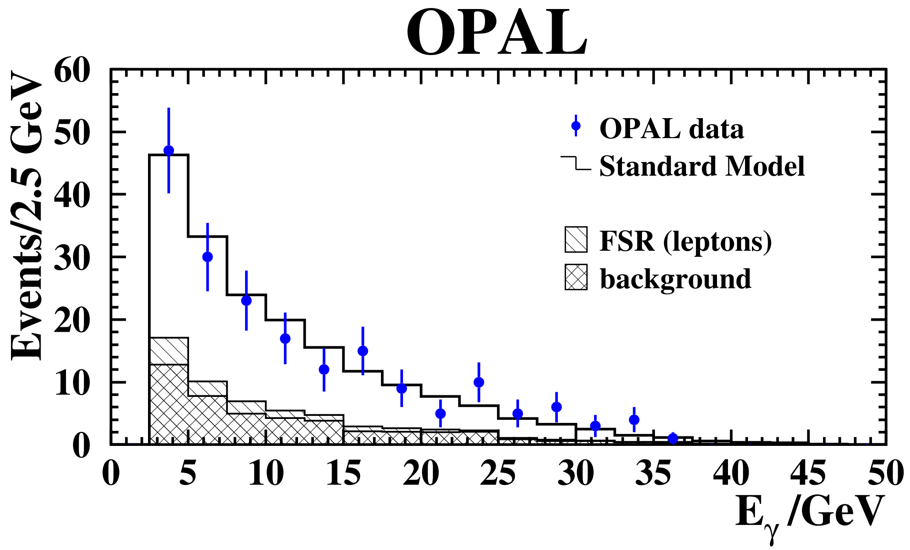
★ Due to kinematic fit - analysis very sensitive to ISR

★ However small systematic uncertainty from pure ISR:
$\mathcal{O}(\alpha^3)$ LL implementation in YFSWW

★ m_{W} analysis is also sensitive to radiation from W-bosons through negative interference with ISR

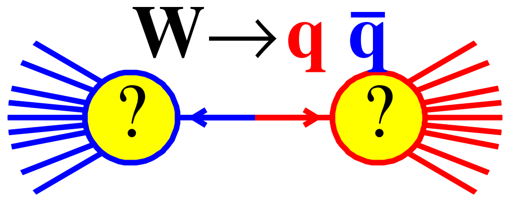
★ OPAL measure $\mathrm{W}^+\mathrm{W}^-\gamma$ cross-section ($\mathrm{E}_\gamma > 2.5\,\mathrm{GeV}$) provides test of modelling of real photon production in m_{W} MCs

R(data/KandY) = 0.99±0.09±0.04



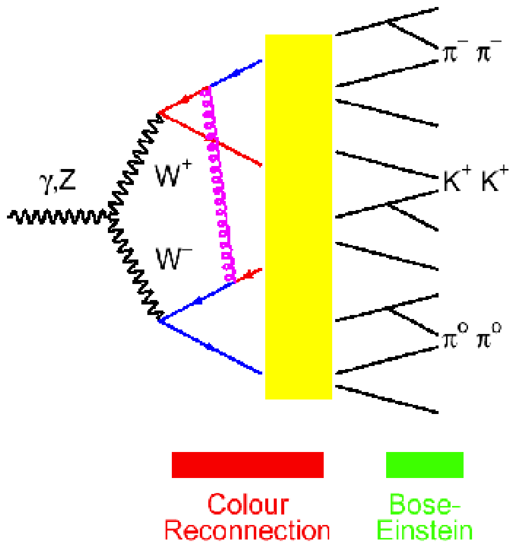
★ Interpreted as a new cross-check of related m_{W} systematics at level of 7 MeV

Fragmentation/Hadronization



- ★ Process of $q\bar{q} \rightarrow$ hadrons $\sim$ black magic
- ★ Rely on Monte Carlo models (all tuned at Z^0).
- ★ Compare:
  - JETSET string model
  - HERWIG cluster model
  - ARIADNE colour dipole model
- ★ $\Rightarrow$ 18 MeV systematic uncertainty
  taken as correlated between experiments/channels

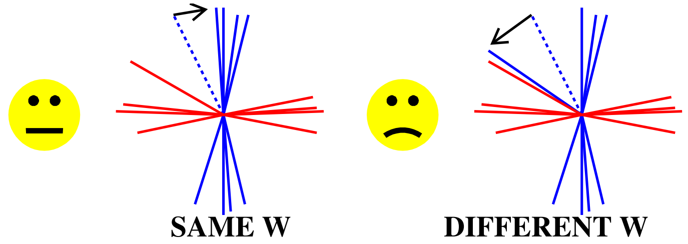
Final State Interactions



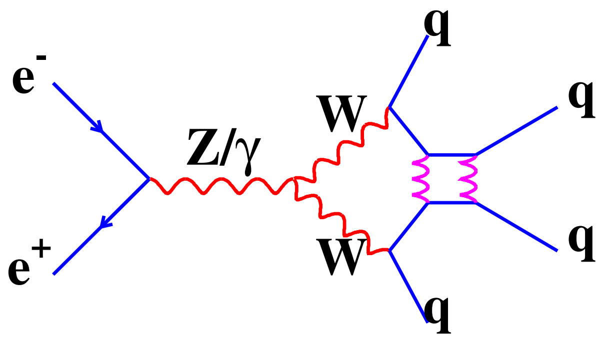
- ★ W decay vertices separated by $\sim$0.1 fm
- ★ Hadronisation scale $\sim$1.0 fm
- ★ Possibility of non-independent hadronisation for W bosons in $W^+W^- \rightarrow q\bar{q}q\bar{q}$ events.
- ★ Can distort reconstructed mass spectra
- ★ Possible sources: BEC and Colour reconnection

Bose-Einstein Correlations (Paul de Jong's talk)

- BEC - Quantum mechanical effect
- Like sign πs tend to be close in phase space
- BEC between pions from different Ws ?



Colour Reconnection (Jorgen d'Hondt's talk)



Perturbative phase (QCD)

- Suppressed by 2 gluon exchange + colour
- Negligible mass shifts < 10 MeV

Hadronization phase (non-perturbative)

- Rely on models (string, cluster...)
- Predictions of mass biases: 0-300 MeV

Effect: possible systematic bias in $\mathrm{q\bar{q}q\bar{q}}$ channel - but not $\mathrm{q\bar{q}}\ell\bar{\nu}_\ell$

★ LEP combined result (doesn't include FSI sys. errors):

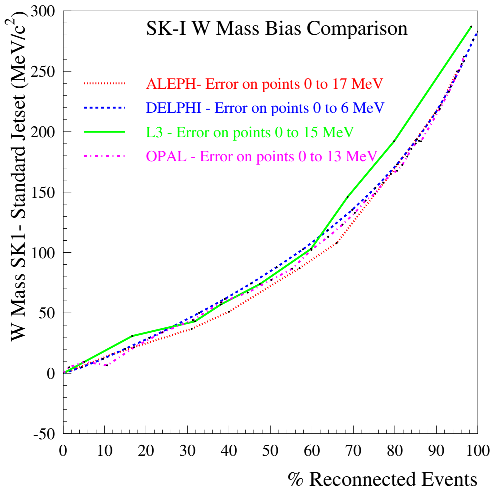
$$\boxed{\Delta m_{\mathrm{W}}(\mathrm{q\bar{q}q\bar{q}} - \mathrm{q\bar{q}}\ell\bar{\nu}_\ell) = +22 \pm 43\ \mathrm{MeV}}$$

★ Results consistent - but can't use this to set sys. error

FSI Systematic Error Estimate

★ Systematic error from models.
★ Current CR error from SK-I (κ=2.1)
★ κ determines amount of CR
★ Use largest value consistent with data (see Jorgen d'Hondt's talk)

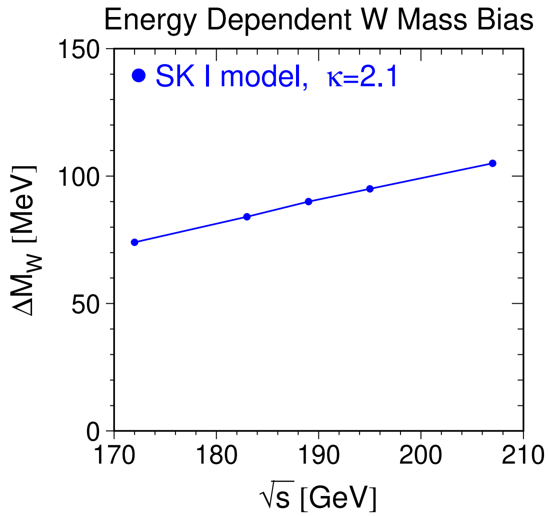
Model	Effect	Mass shift
Herwig	CR	∼ 30 MeV
SK-I κ=2.1	CR	∼ 90 MeV
SK-I 100%	CR	∼ 300 MeV
Ariadne AR2	CR	∼ 70 MeV
LUBOEI	BE	∼ 35 MeV



★ Observe equal experimental sensitivity

FSI assumed 100% correlated between expts.

★ common energy-dependent CR error is used in LEP combination



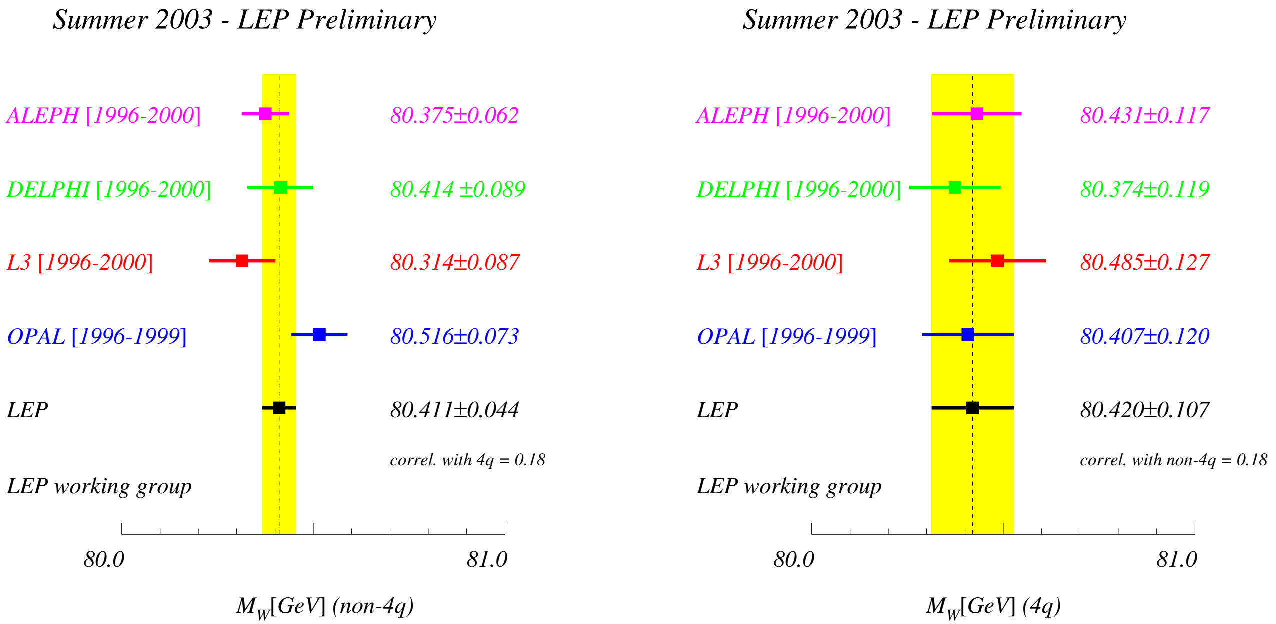
Systematic Uncertainties (LEP Combined)

Source	Systematic Error on m_W (MeV)		
	$q\overline{q}\ell\overline{\nu}_\ell$	$q\overline{q}q\overline{q}$	Comb.
Hadronization	19	18	18
QED (ISR/FSR, etc)	8	8	8
Detector Systematics	14	10	14
LEP Beam Energy	17	17	17
Colour Reconnection	—	90	9
Bose-Einstein Correlations	—	35	3
Other	4	5	4
Total Systematic	31	101	31
Statistical	32	35	29
Total	44	107	43

- ★ $q\overline{q}q\overline{q}$ channel: systematics from Final State Interactions dominate
- ★ $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ yield similar statistical uncertainties
- ★ LEP combination: the $q\overline{q}q\overline{q}$ channel only has 10 % weight due to FSI

★ **Combined LEP results from 172-209 GeV ($\sim$650 pb^{-1}/expt.)**

- OPAL/ALEPH $\ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$ results (factor $\sim$10 less sensitive) combined with $q\overline{q}\ell\overline{\nu}_\ell$
- ALEPH and L3 results take account of inter-channel correlations
- OPAL does not yet include the 2000 data ($\approx$ 220 pb^{-1})



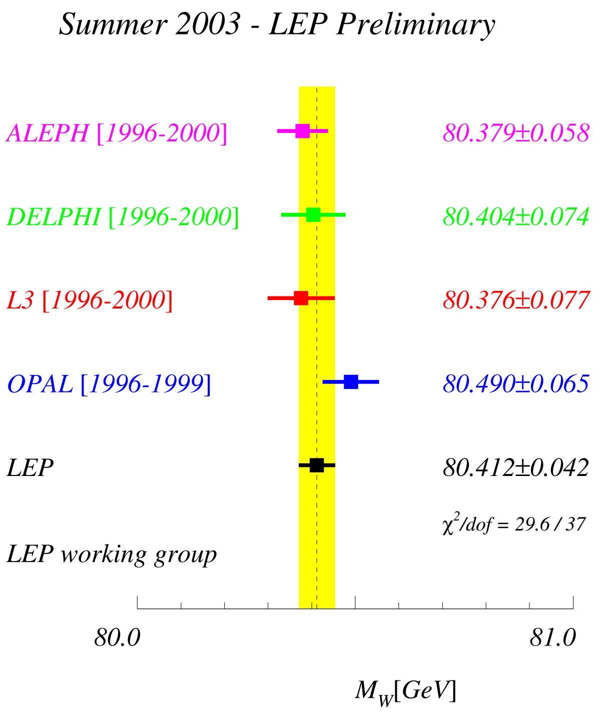
$$m_W(q\overline{q}\ell\overline{\nu}_\ell) = 80.411 \pm 0.032(stat.) \pm 0.030(sys.)\ \mathrm{GeV}$$

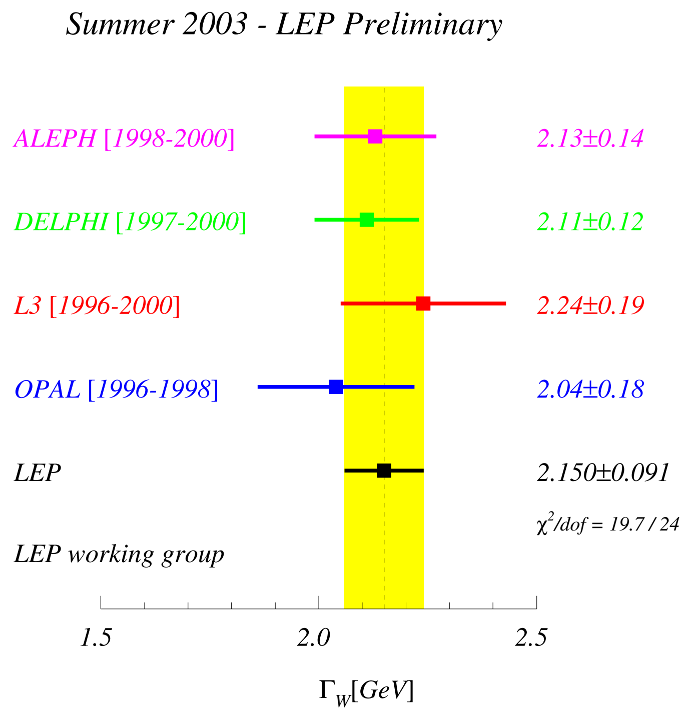
$$m_W(q\overline{q}q\overline{q}) = 80.420 \pm 0.035(stat.) \pm 0.101(sys.)\ \mathrm{GeV}$$

★ **Systematics completely dominate in $W^+W^- \rightarrow q\overline{q}q\overline{q}$!**

★ **Systematics also important in $W^+W^- \rightarrow q\overline{q}\ell\overline{\nu}_\ell$ channel**

LEP Combined m_W and Γ_W Results





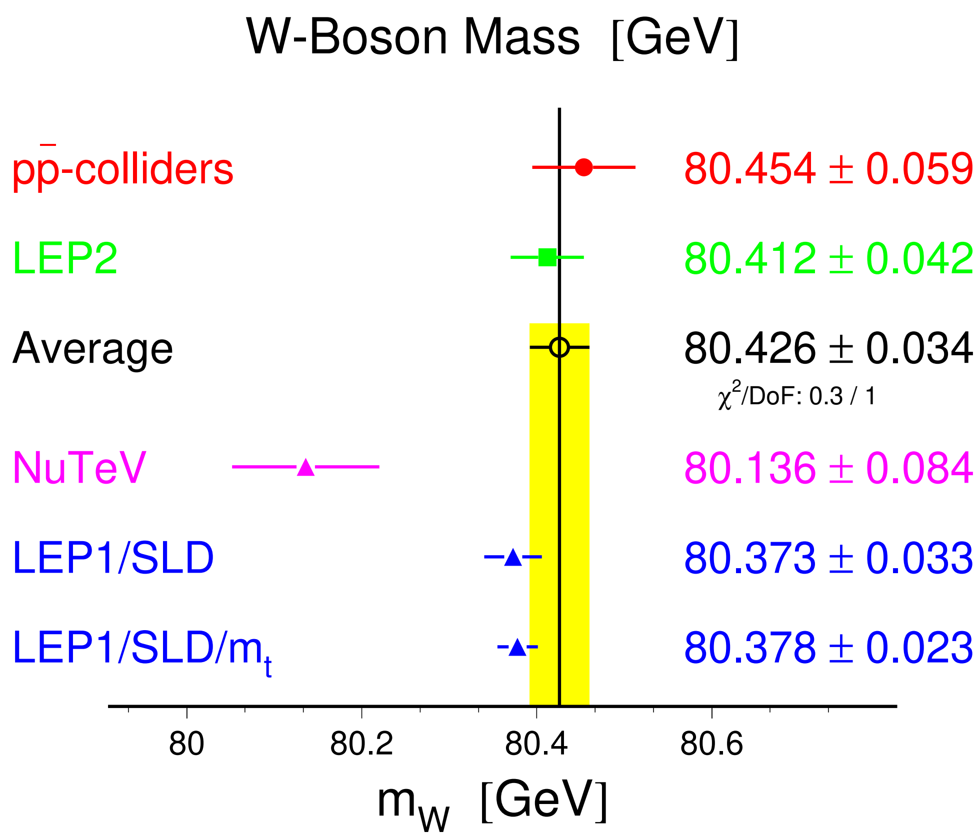
$$m_W(LEP) = 80.412 \pm 0.029(stat.) \pm 0.031(sys.)\ \mathrm{GeV}$$

(includes LEP result from threshold cross-section: $80.40 \pm 0.020(stat.) \pm 0.07(sys.)\ \mathrm{GeV}$)

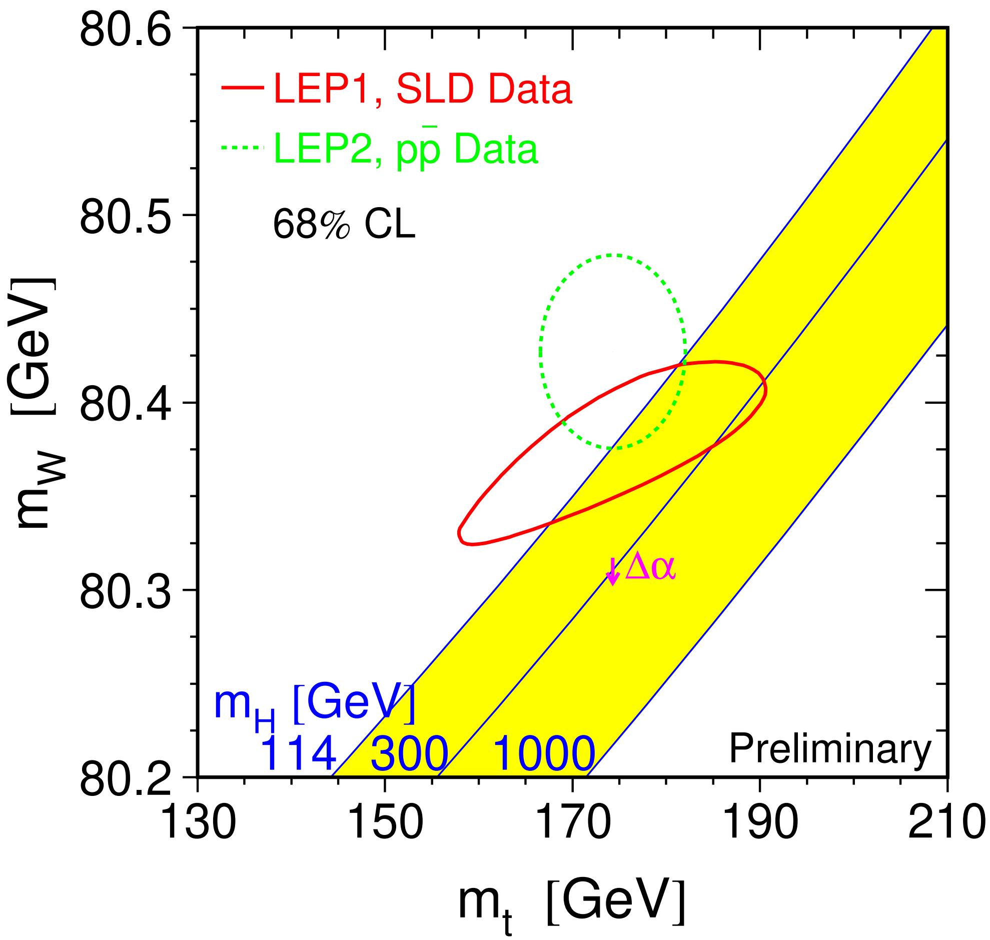
$$\Gamma_W(LEP) = 2.150 \pm 0.068(stat.) \pm 0.060(sys.)\ \mathrm{GeV}$$

Comparison with Other Results

Direct vs. Indirect:



SM Consistency:



★ **Impressive consistency between direct and indirect measurements of m_W**

(with possible exception of NuTeV result)

Outlook

★ In absence of systematics, LEP statistical precision on m_{W}: $\pm 21\,\mathrm{MeV}$!

★ Due to current FSI uncertainties $\mathrm{q\overline{q}q\overline{q}}$-channel contributes very little

LEP Total Error : $\pm 43\,\mathrm{MeV}$
LEP Total Error ($\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ alone) : $\pm 44\,\mathrm{MeV}$

★ Huge amount of ongoing work trying to address CR errors (J. D'Hondt's talk)

Trade-off sys. and stat. errors in $\mathrm{q\overline{q}q\overline{q}}$-channel ?

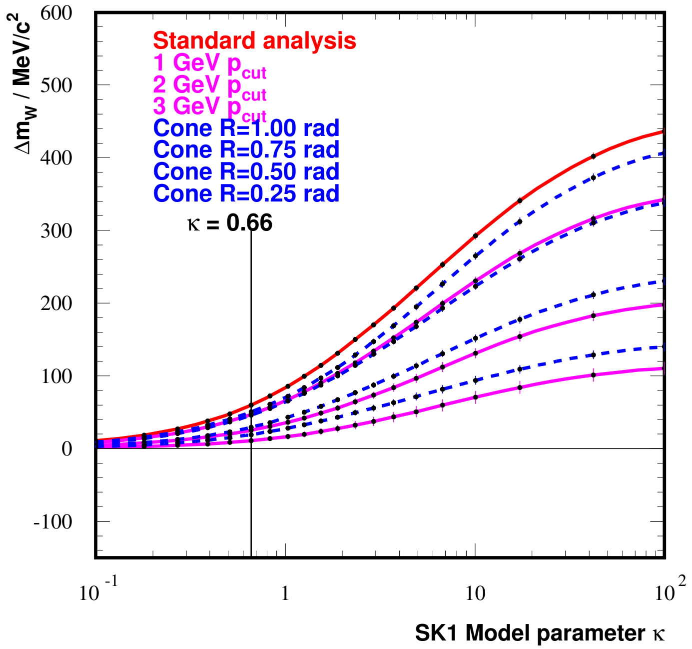
★ Remove particle most affected by FSI:
- ☆ Momentum cuts
- ☆ Jet cone cuts

★ Possible Gain:
- ☆ Reduce FSI errors by factor 3 ?
- ☆ cost: increase stat. errors by 20 %

★ Take care: hadronization uncertainities ?

\+ **Further constrain CR models using data**

DELPHI preliminary SK1 curves



Outlook and Conclusions

- ★ Moving towards final LEP m_W results
- ★ Precision of $\pm 0.05\,\%$ requires careful analysis
- ★ Current result : $m_W = 80.412 \pm 0.029(stat.) \pm 0.031(sys.)\ \mathrm{GeV}$
- ★ Expect improvements:
  - LEP beam energy uncertainty $21\ \mathrm{MeV}$ will come down
  - Reduced stat. error (improved analyses + OPAL 2000 data)
  - Better understanding of hadronisation/detector systematics

My guesstimates for final LEP error:

- ★ Without significant improvement in FSI:
  $37 - 40$ MeV
- ★ With significant improvement in FSI:
  $32 - 37$ MeV

Guesstimate Calibration:

- ★ I also predict England to win the next world cup at both Rugby and Football !

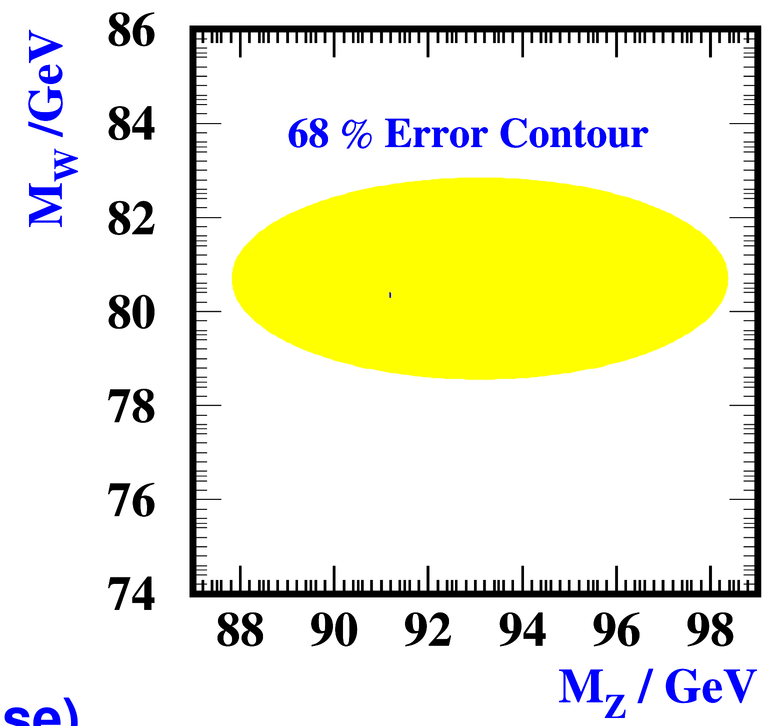
Conclusion: The joys of LEP

In the near future LEP physics will be summarised as:

"…. precise measurements of the masses and couplings of the Z^0 and $\mathrm{W}^{\pm}$ …"

PERKINS, High Energy Physics, V^{th} EDITION (2007)

The situation in 1989 (yellow ellipse)….



….and now (blue ellipse)