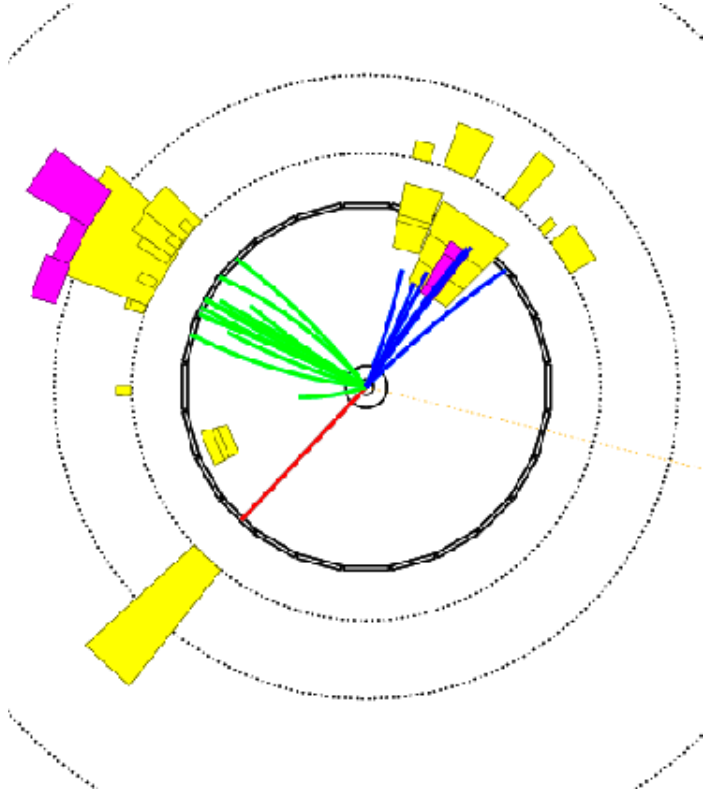


Measurement of m_W at LEP

Mark Thomson

University of Cambridge



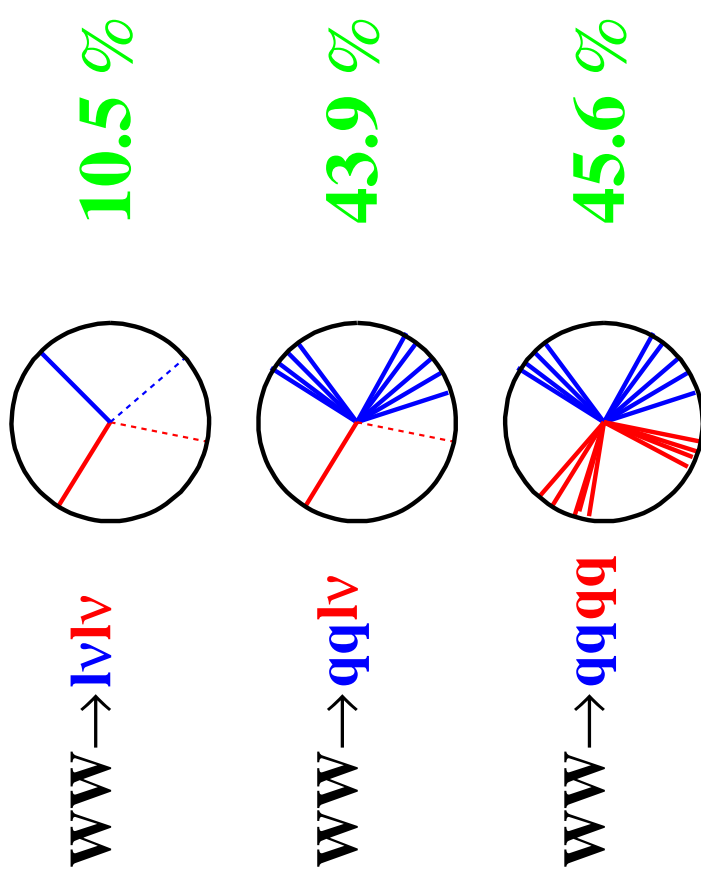
- ★ Experimental Method
- ★ Recent Results
- ★ Systematic Uncertainties
- ★ Prospects for Final Results

Introduction

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

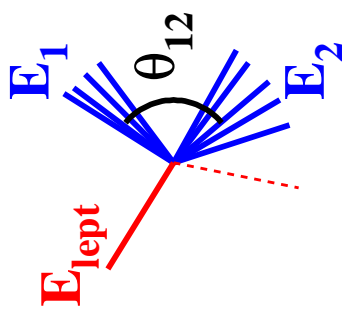
Typical performance:

	Efficiency	Purity
$\ell\bar{\nu}\ell\ell\bar{\nu}\ell$	70%	90%
$q\bar{q}\ell\bar{\nu}\ell$	80%	85%
$q\bar{q}q\bar{q}$	80%	80%



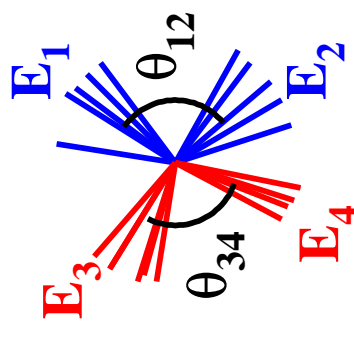
W-Mass from Direct Reconstruction

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



Two Distinct Stages:

- ① Reconstruct event-by-event mass
 - ② Fit mass distribution $\Rightarrow m_W$
- ★ require good measurements of the fermion **four-momenta**.



However:

- ✂ jet energies relatively poorly measured $\sigma_E/E > 60\% / \sqrt{E(\text{GeV})}$
- ✂ neutrinos unobserved.
- ★ Kinematic fitting plays vital rôle.

Kinematic Fitting

5 Constraints:

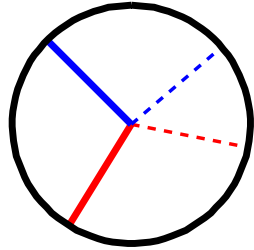
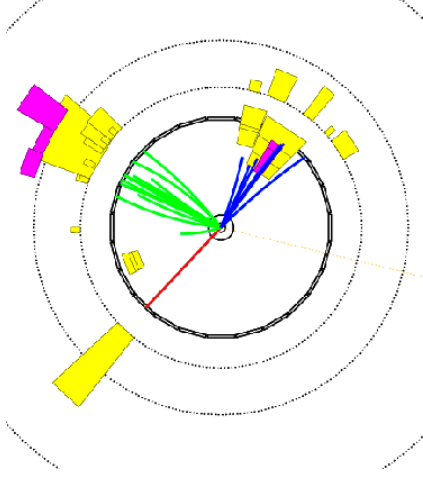
- ★ Energy/momentum conservation : $(E, \vec{p}) = (\sqrt{s}, 0)$
- ★ Neglect Γ_W : and take $m_1 = m_2$

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

Under-constrained

Limited m_W sensitivity

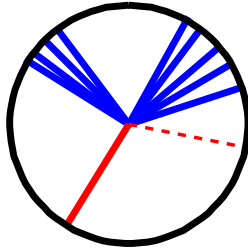
Results from ALEPH, OPAL



$q\bar{q}\ell\bar{\nu}_\ell$: 3 unknowns (\vec{p}_ν)

Over-constrained : use kinematic fit

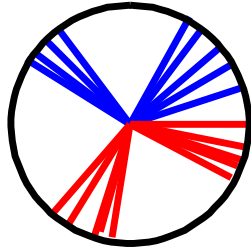
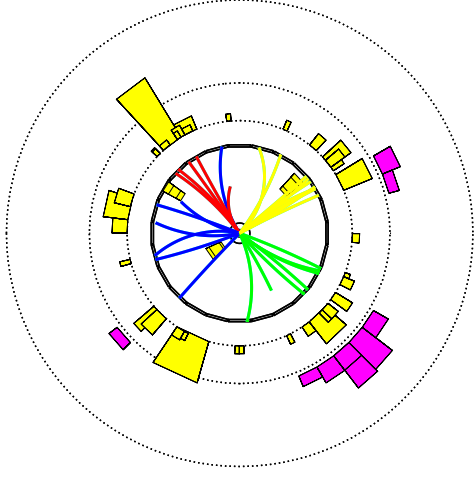
Most m_W sensitivity from $q\bar{q}$



$q\bar{q}q\bar{q}$: 0 unmeasured quantities

Over-constrained : use kinematic fit

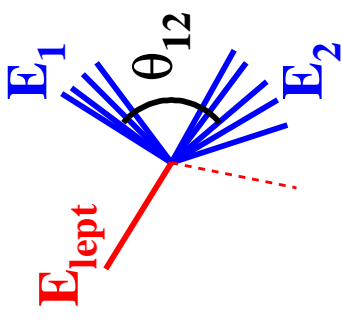
Measure both W-decays



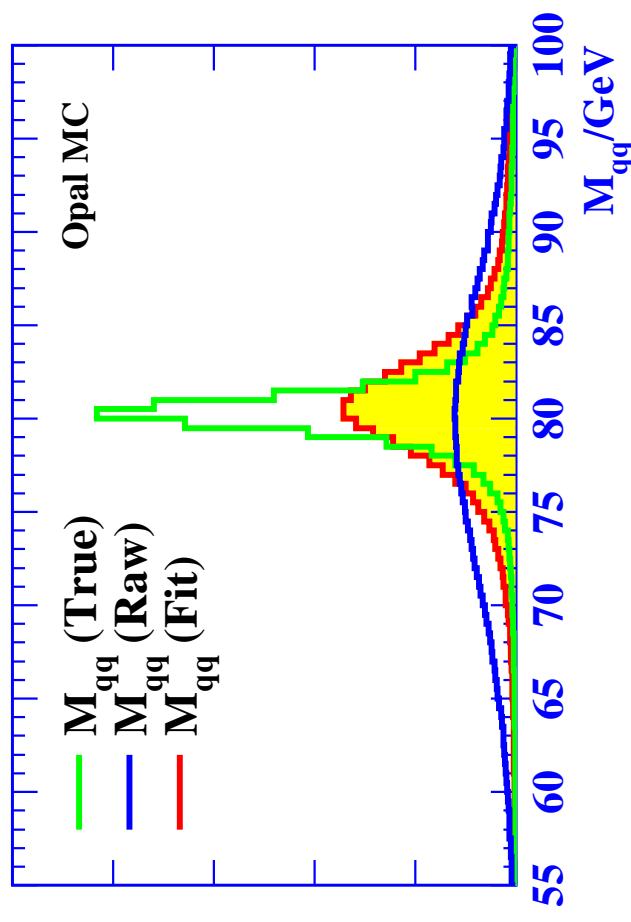
Mass Reconstruction : $W^+W^- \rightarrow q\bar{q}l\bar{\nu}_l$

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

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



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

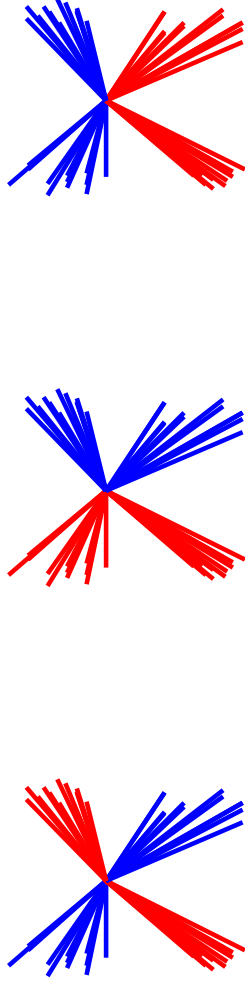


Mass Reconstruction : $W^+W^- \rightarrow q\bar{q}q\bar{q}$

- ★ Force event into 4 jets (DURHAM)

DELPHI/OPAL allow for additional gluon jet

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

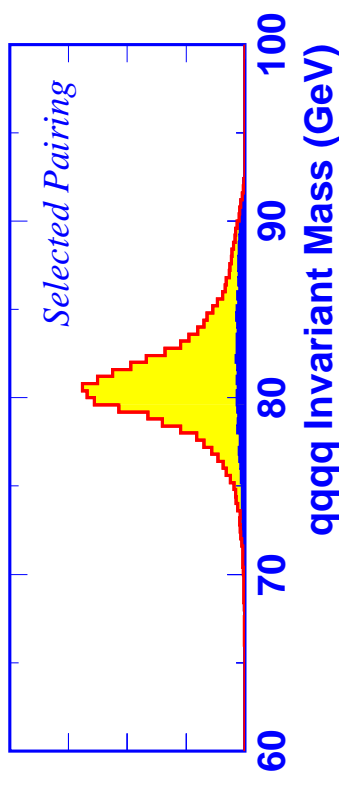
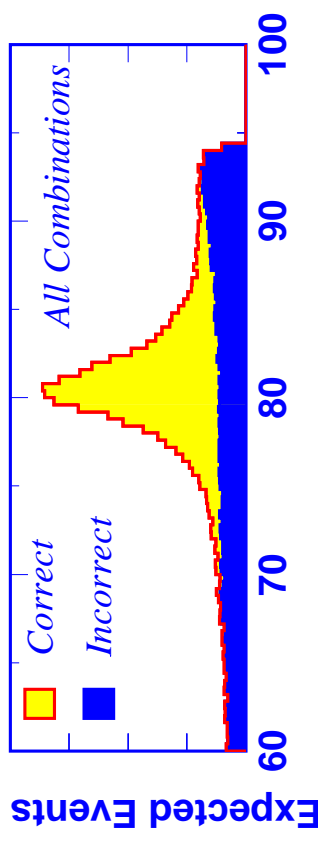


- ★ Incorrect pairings \Rightarrow Combinatoric background.

- ★ Apply Kinematic Fit to all 3 pairings

Best pairing selected using:

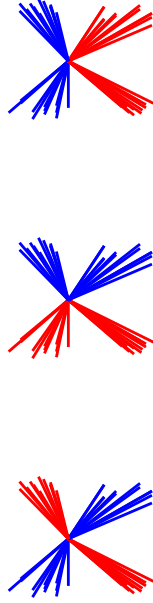
- ALEPH : Consistency with W-decay kinematics
- L3 : Kinematic fit probability.
- OPAL : Multivariate selection / Kinematic Fit prob.
- DELPHI : use all pairings !



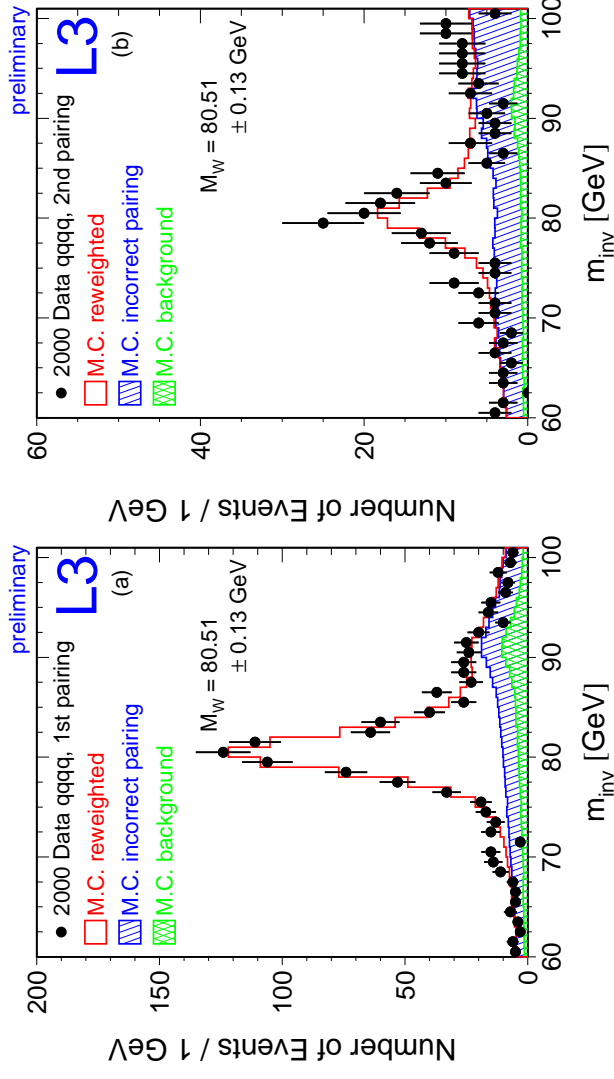
Many tricks to improve m_W sensitivity, e.g.

L3

- ★ Rank 3 jet pairings by 5C fit prob.



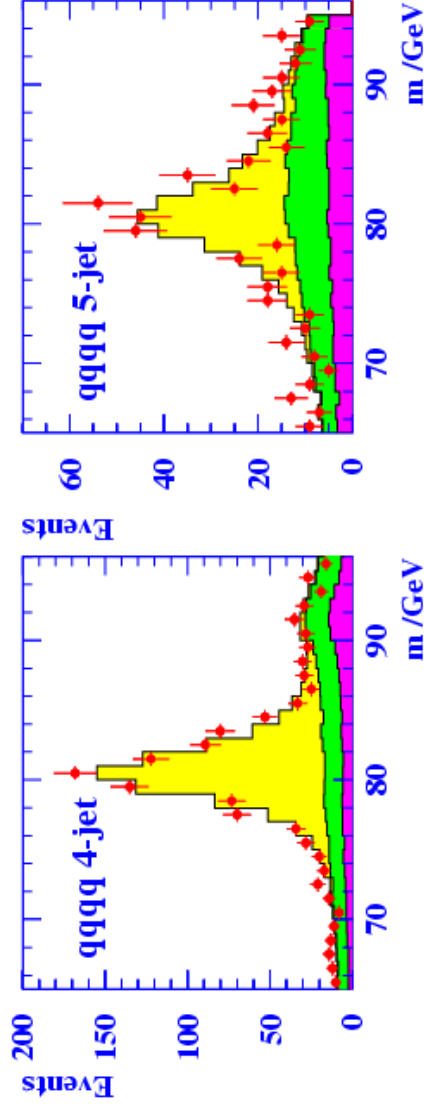
- ★ Use combination with highest fit prob.
- ★ Also use second best in a separate distribution



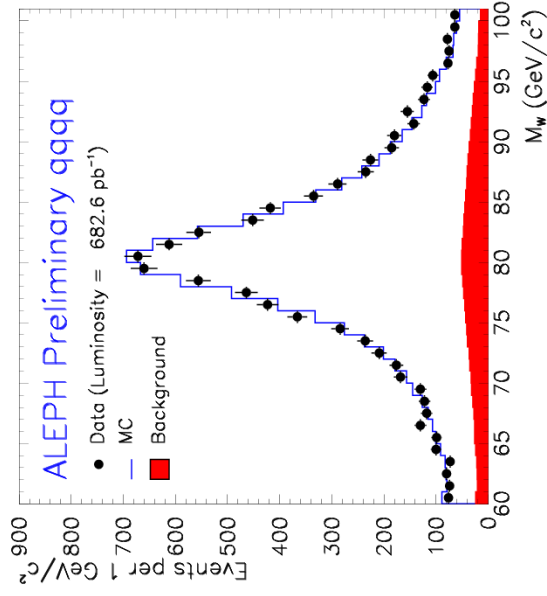
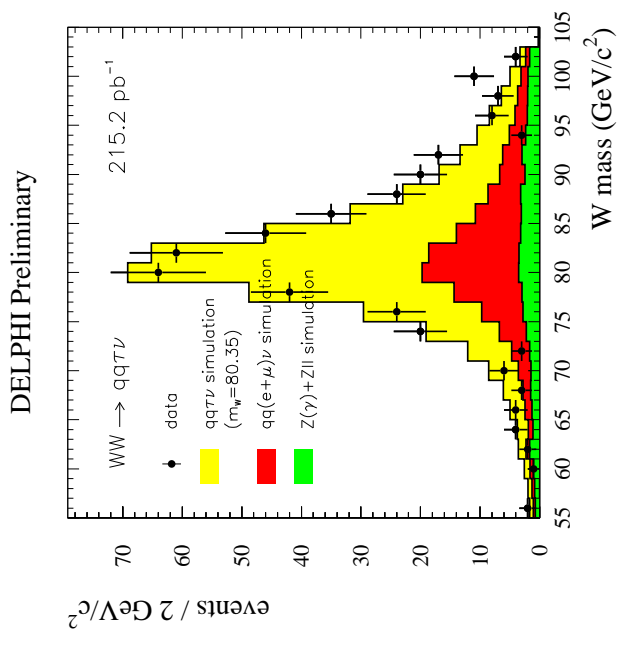
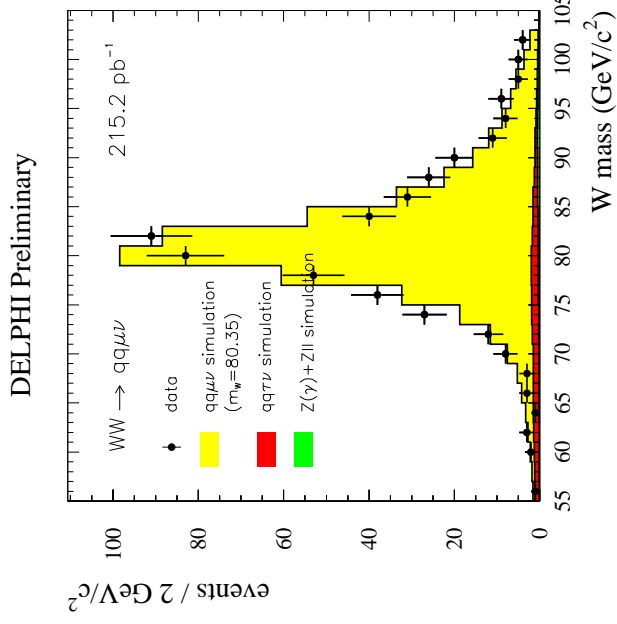
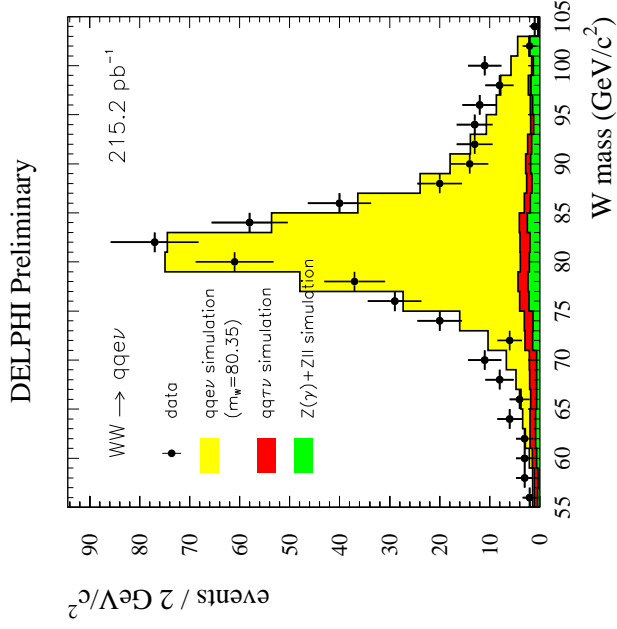
OPAL (Prelim.) 192-202 GeV

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



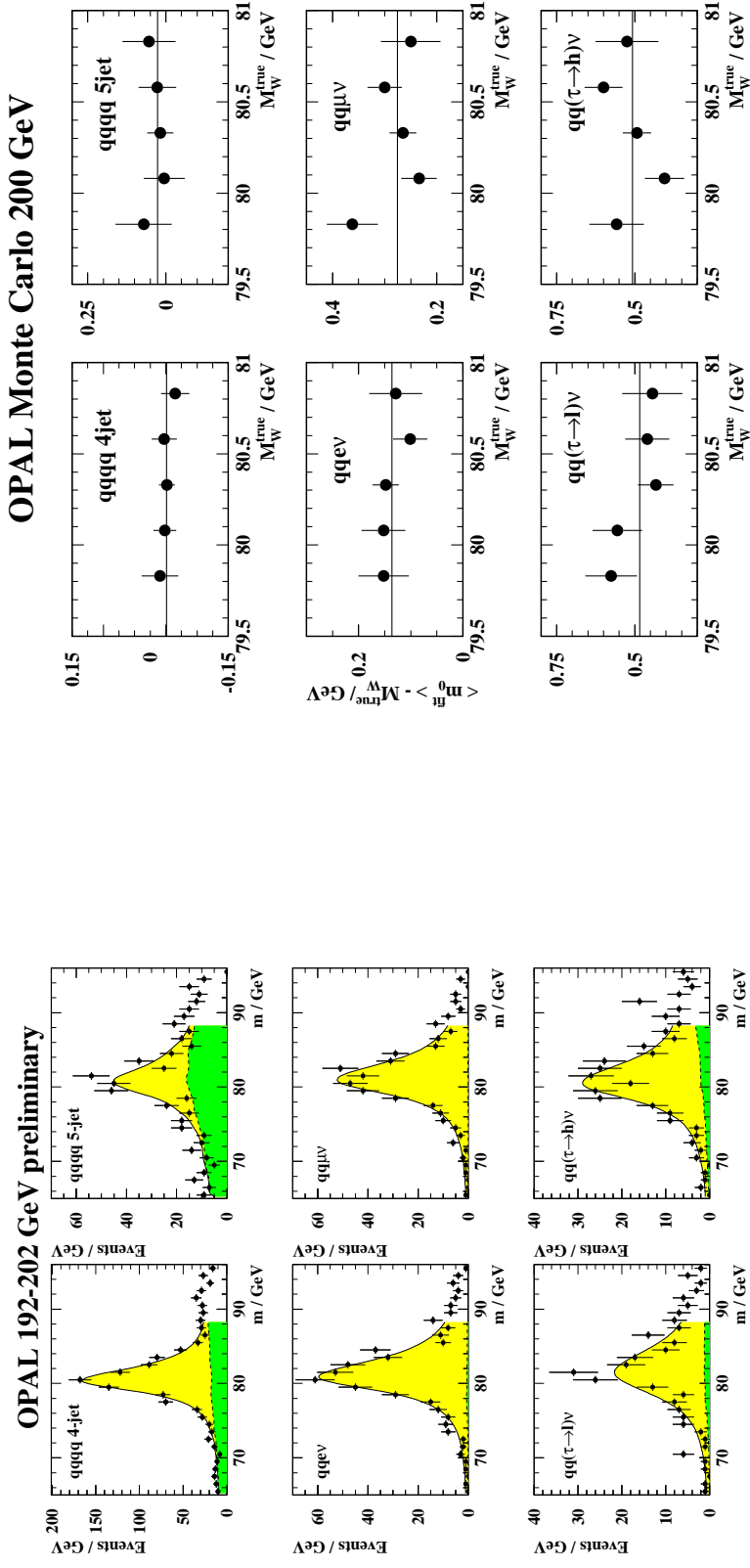
★ **Determination of m_W from mass distributions**

THREE METHODS :

- ① **Breit-Wigner Fit (OPAL)**
- ② **Monte Carlo Reweighting (ALEPH/L3/OPAL)**
- ③ **Convolution (DELPHI)**

1 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.

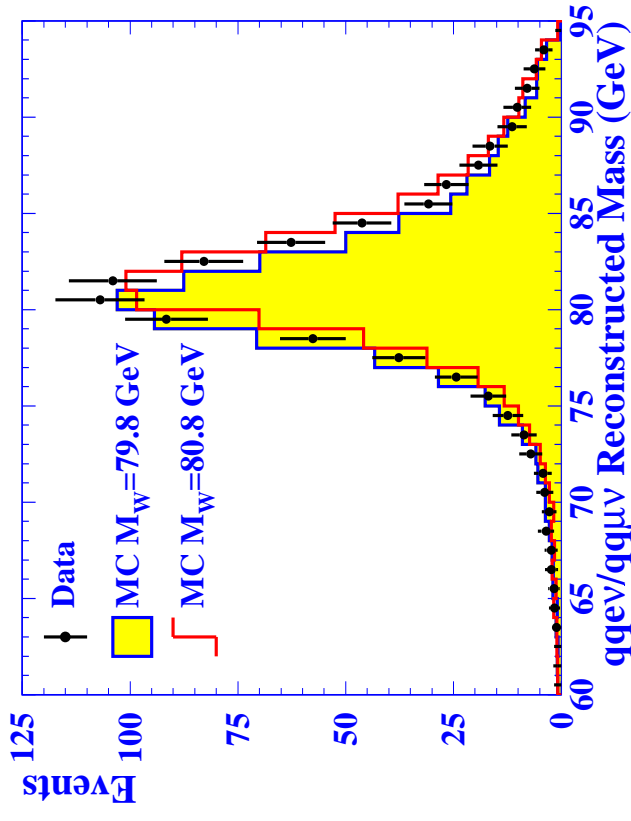
② Reweighting Fit (e.g. ALEPH,L3,OPAL)

- ★ Compare Data to MC $\rightarrow \chi^2(m_W)$
- ★ 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', Γ_W')

For event i with generated masses (m_1, m_2)

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

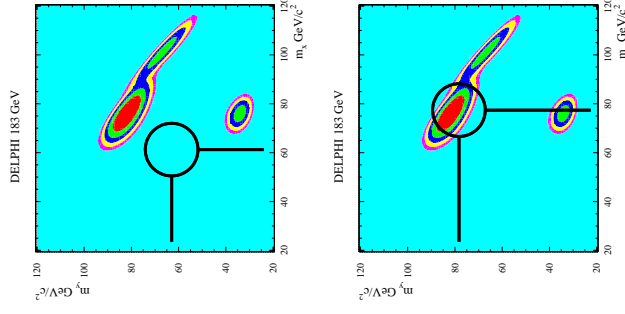
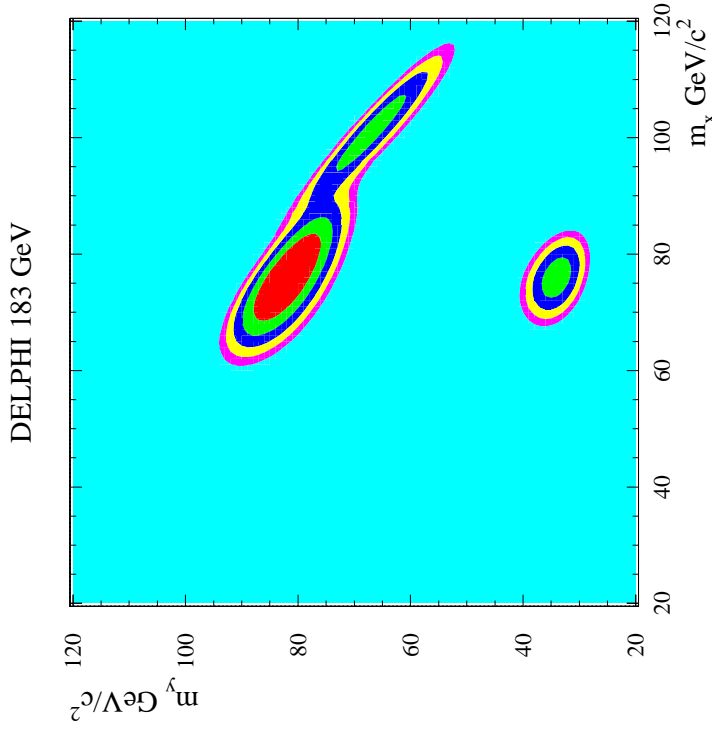
- ★ Monte Carlo bias correction implicit in fit



Convolution Method : DELPHI

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

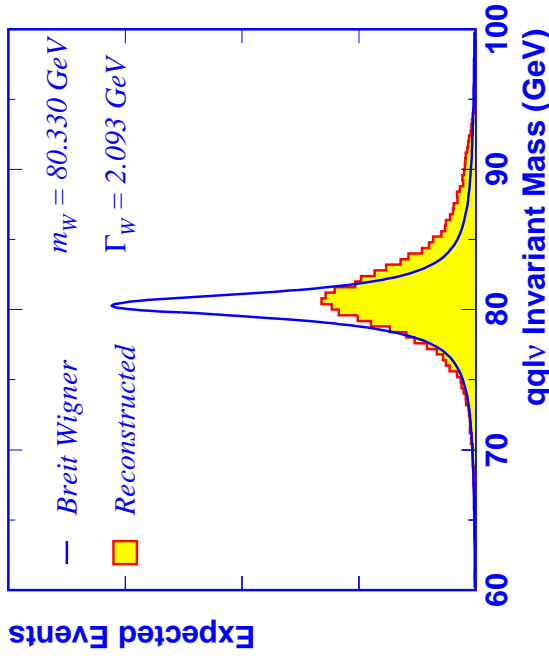
- ★ Use **4C fit** \Rightarrow 2 masses + error matrix for each jet pairing
- ★ form event **PDF** using all 3 jet pairings used
- ★ calculate “**overlap**” of event **PDF** with a 2D Breit-Wigner, $BW(m_W)$ \Rightarrow event likelihood, $\mathcal{L}(m_W)$.



- ★ 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

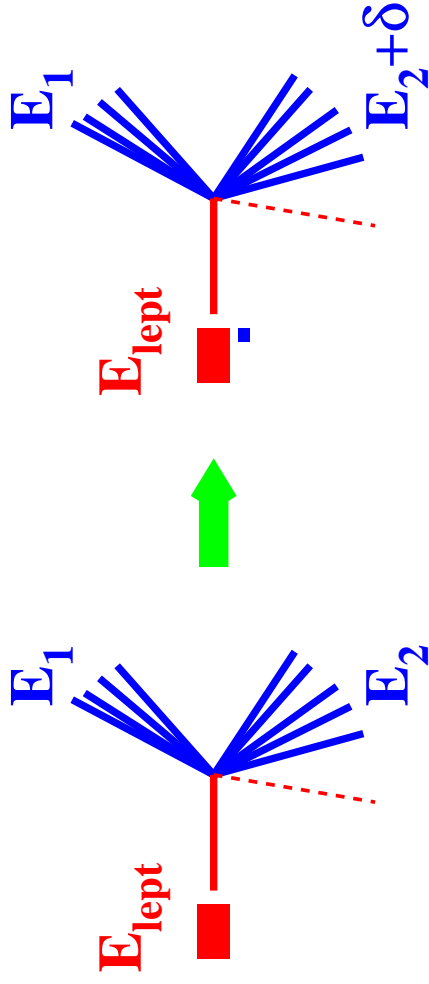
- ★ Trying to measure W -mass to $\sim 0.05\%$ - method of direct reconstruction sensitive to poorly modelled detector effects.

Detector Calibration:

- ★ Detector calibration determined from data mainly using $e^+e^- \rightarrow Z^0$ 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 $q\bar{q}e\bar{\nu}_e$: changed by -150 MeV.
- ★ Due to population of non-simulated low energy “satellite” clusters near to electromagnetic showers.

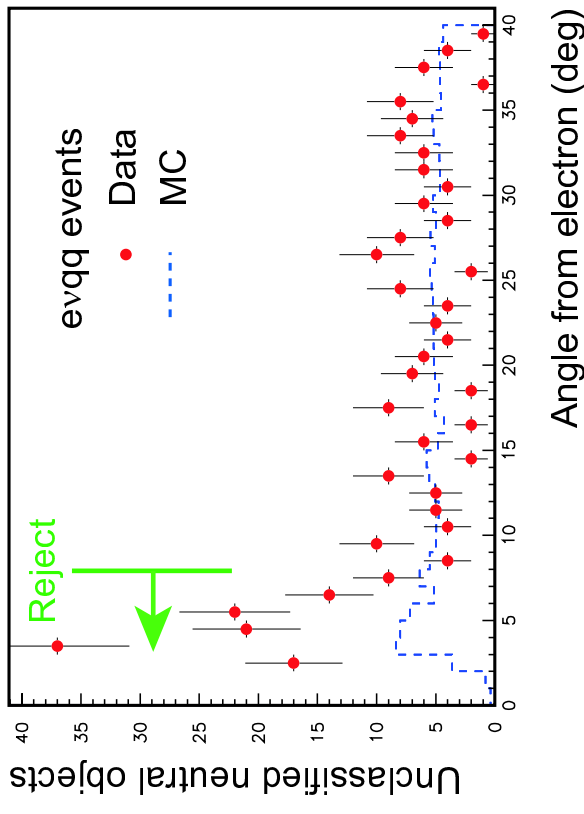


- ★ In the event reconstruction **Satellite clusters** are not associated with lepton
- ★ Therefore **associated with nearest jet**
- ★ Bias jet angle
- ★ Significant bias to jet mass

Recall: $M_{q\bar{q}}^2 = M_1^2 + M_2^2 + 2E_1E_2(1 - \beta_1\beta_2 \cos \theta_{12})$

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

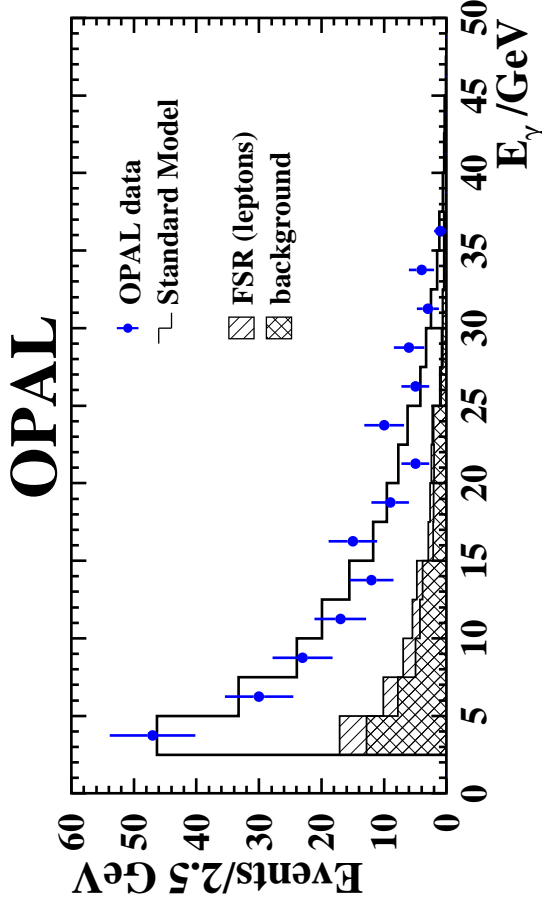


★ **DELPHI, L3, OPAL do not observe similar problems**

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 $W^+W^-\gamma$ cross-section ($E_\gamma > 2.5$ GeV) provides test of modelling of real photon production in m_W MCs

$$R(\text{data}/\text{KandY}) = 0.99 \pm 0.09 \pm 0.04$$



- ★ 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:

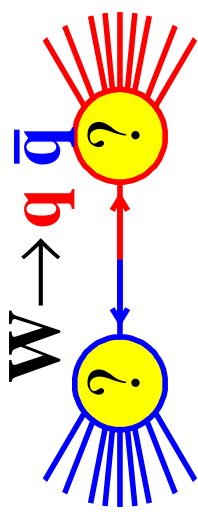
JETSET string model

HERWIG cluster model

ARIADNE colour dipole model

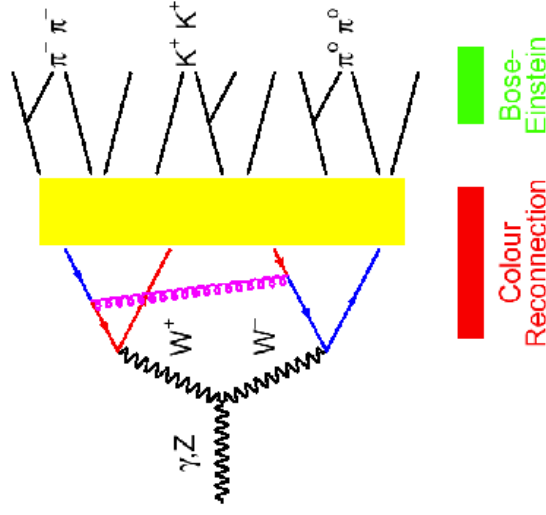
- ★ \Rightarrow 18 MeV systematic uncertainty

taken as correlated between experiments/channels



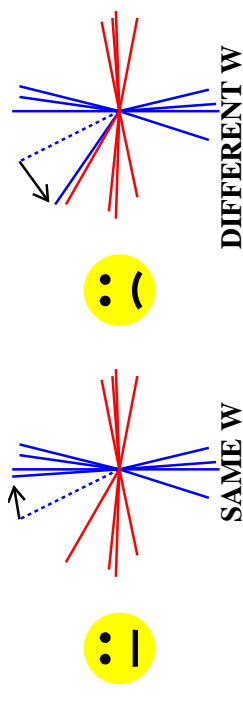
Final State Interactions

- ★ W decay vertices separated by ~ 0.1 fm
- ★ Hadronisation scale ~ 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 π s tend to be close in phase space
- BEC between pions from different **Ws** ?



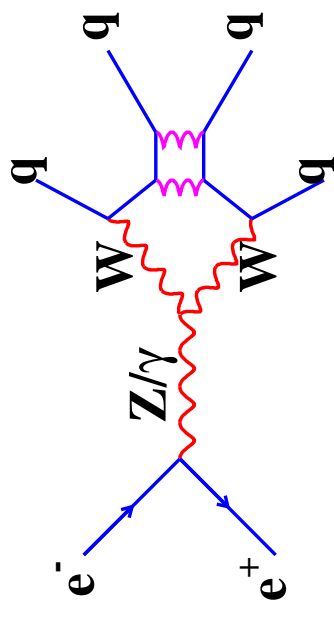
Colour Reconnection (Jorgen d'Hondt's talk)

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 $q\bar{q}q\bar{q}$ channel - but not $q\bar{q}l\bar{\nu}_l$

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

$$\Delta m_W (q\bar{q}q\bar{q} - q\bar{q}l\bar{\nu}_l) = +22 \pm 43 \text{ MeV}$$

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

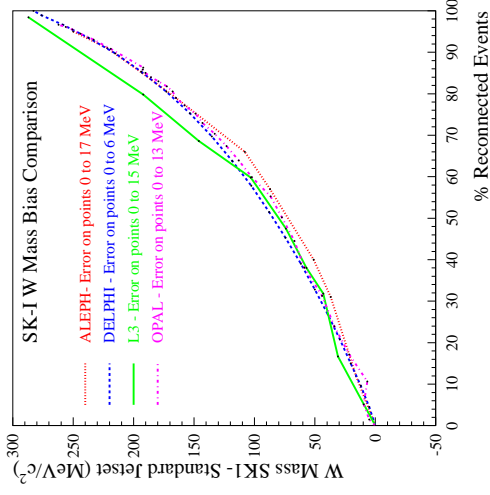
FSI Systematic Error Estimate

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

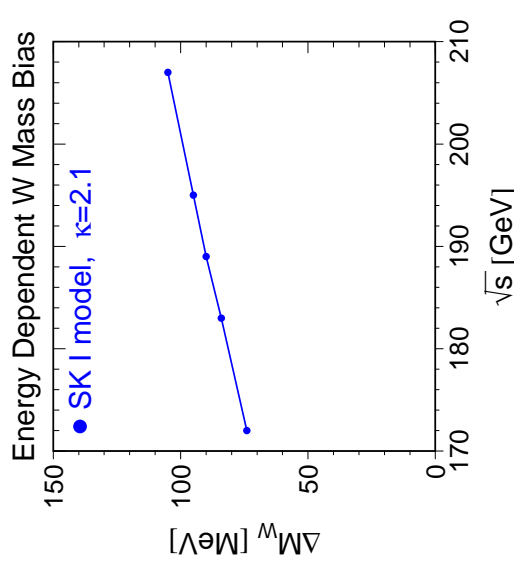
Model	Effect	Mass shift
Herwig	CR	~ 30 MeV
SK-I $\kappa=2.1$	CR	~ 90 MeV
SK-I 100%	CR	~ 300 MeV
Ariadne AR2	CR	~ 70 MeV
LUBOEI	BE	~ 35 MeV

★ Observe equal experimental sensitivity

FSI assumed 100% correlated between expts.



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



Systematic Uncertainties (LEP Combined)

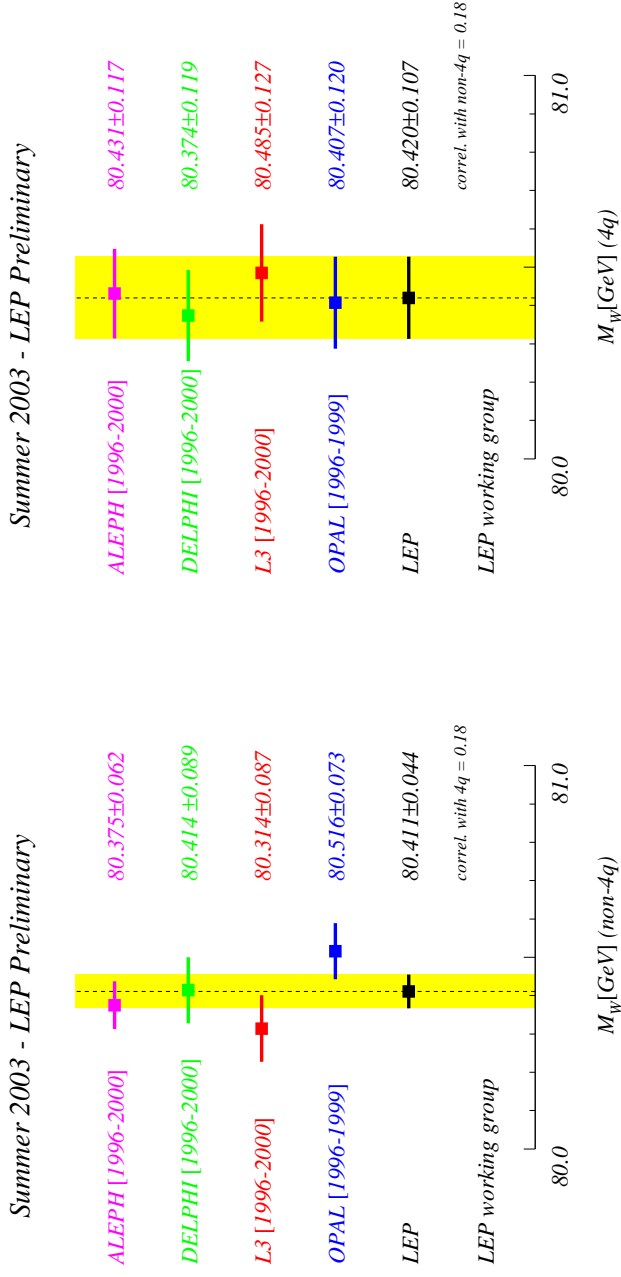
Source	Systematic Error on m_W (MeV)		
	$q\bar{q}l\bar{\nu}_l$	$q\bar{q}q\bar{q}$	Comb.
Hadronization	19	18	18
QED (ISR/FSR, etc)	8	8	8
Detector Systematics	14	10	14
LEP Beam Energy	17	17	17
Colour Reconnection	—	90	9
Bose-Einstein Correlations	—	35	3
Other	4	5	4
Total Systematic	31	101	31
Statistical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

★ $q\bar{q}q\bar{q}$ channel: systematics from **Final State Interactions** dominate

★ $q\bar{q}l\bar{\nu}_l$ and $q\bar{q}q\bar{q}$ yield similar statistical uncertainties

★ LEP combination: the $q\bar{q}q\bar{q}$ channel only has 10 % weight due to **FSI**

- ★ Combined LEP results from 172-209 GeV ($\sim 650 \text{ pb}^{-1}/\text{expt.}$)
- OPAL/ALEPH $\ell\bar{\nu}_\ell\ell\bar{\nu}_\ell$ results (factor ~ 10 less sensitive) combined with $q\bar{q}\ell\bar{\nu}_\ell$
- ALEPH and L3 results take account of inter-channel correlations
- OPAL does not yet include the 2000 data ($\approx 220 \text{ pb}^{-1}$)



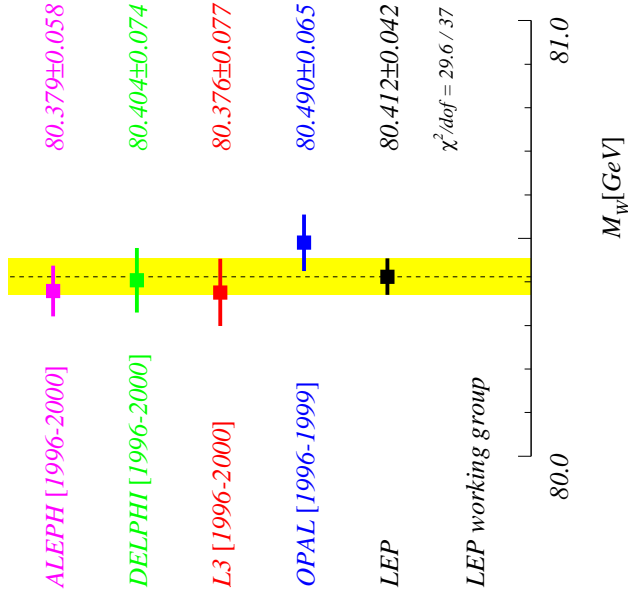
$$m_W(q\bar{q}\ell\bar{\nu}_\ell) = 80.411 \pm 0.032(\text{stat.}) \pm 0.030(\text{sys.}) \text{ GeV}$$

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

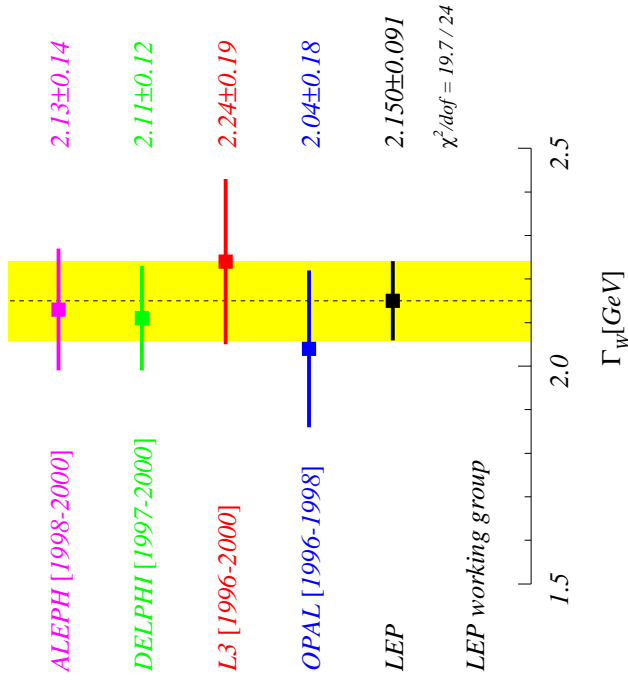
- ★ Systematics completely dominate in $W^+W^- \rightarrow q\bar{q}q\bar{q}$!
- ★ Systematics also important in $W^+W^- \rightarrow q\bar{q}\ell\bar{\nu}_\ell$ channel

LEP Combined m_W and Γ_W Results

Summer 2003 - LEP Preliminary



Summer 2003 - LEP Preliminary



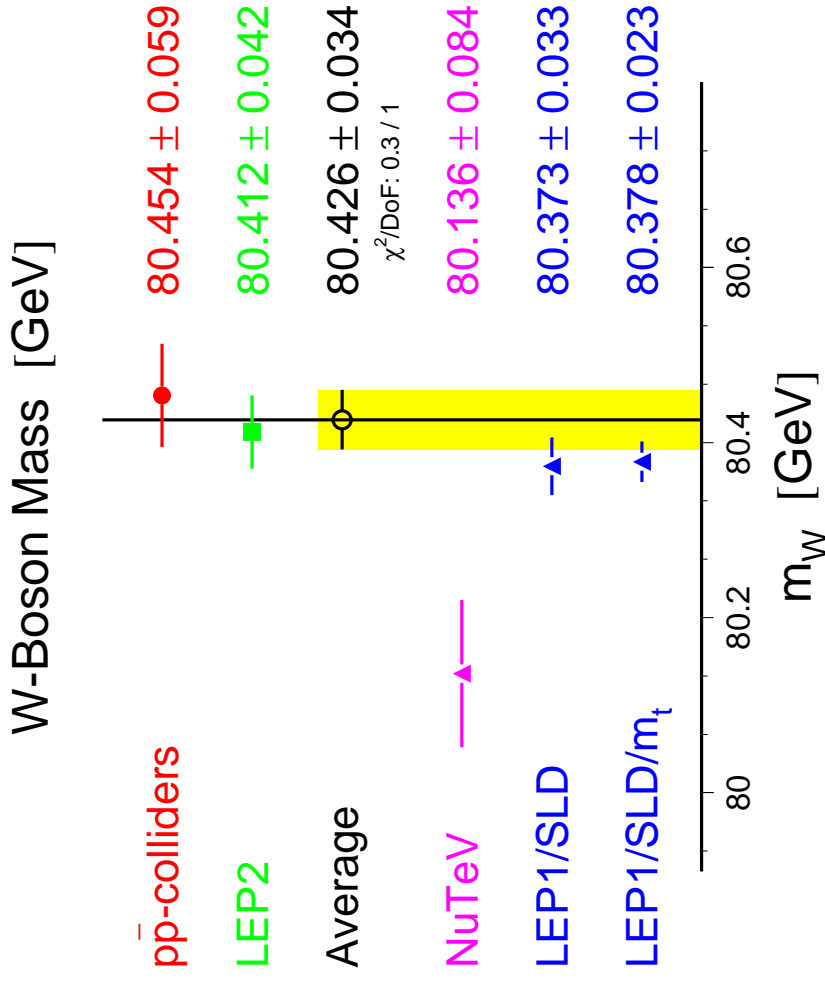
$$m_W(L\text{EP}) = 80.412 \pm 0.029(\text{stat.}) \pm 0.031(\text{sys.}) \text{ GeV}$$

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

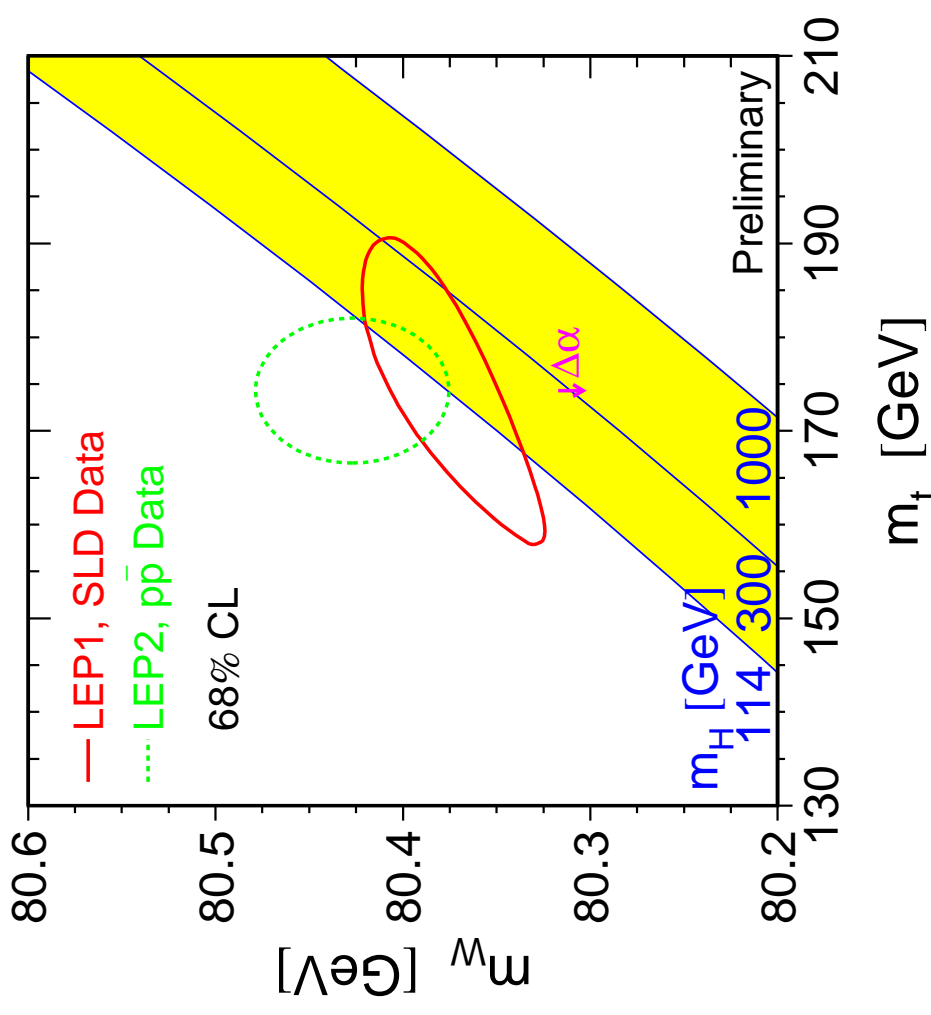
$$\Gamma_W(L\text{EP}) = 2.150 \pm 0.068(\text{stat.}) \pm 0.060(\text{sys.}) \text{ GeV}$$

Comparison with Other Results

Direct vs. Indirect:



SM Consistency:



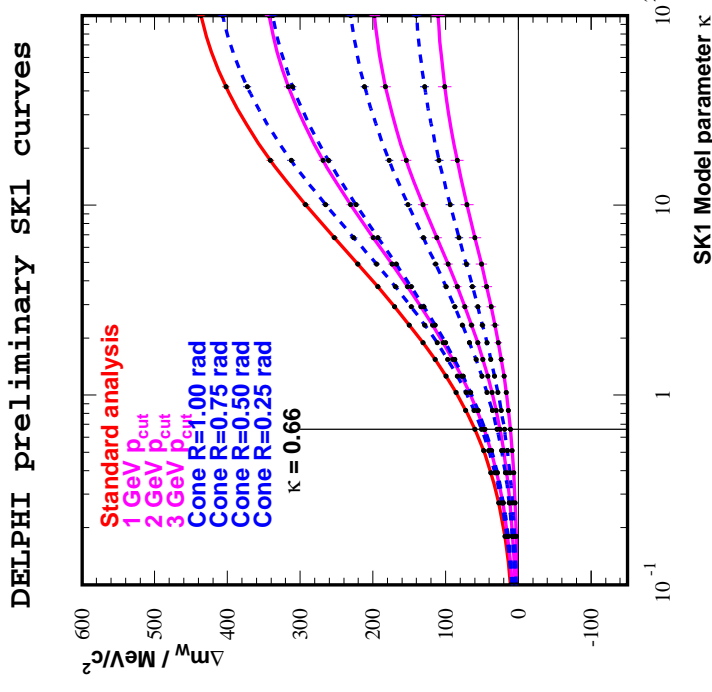
★ **Impressive consistency between direct and indirect measurements of m_W**
 (with possible exception of NuTeV result)

Outlook

- ★ In absence of systematics, LEP statistical precision on m_W : ± 21 MeV !
- ★ Due to current **FSI** uncertainties $q\bar{q}q\bar{q}$ -channel contributes very little
 - LEP Total Error : ± 43 MeV
 - LEP Total Error ($q\bar{q}\ell\bar{\nu}_\ell$ alone) : ± 44 MeV
- ★ Huge amount of ongoing work trying to address CR errors (J. D'Hondt's talk)

Trade-off sys. and stat. errors in $q\bar{q}q\bar{q}$ -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 uncertainties ?
- + Further constrain CR models using data



Outlook and Conclusions

- ★ Moving towards final LEP m_W results
- ★ Precision of $\pm 0.05\%$ requires careful analysis
- ★ Current result : $m_W = 80.412 \pm 0.029(stat.) \pm 0.031(sys.) GeV$
- ★ Expect improvements:
 - LEP beam energy uncertainty 21 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 !

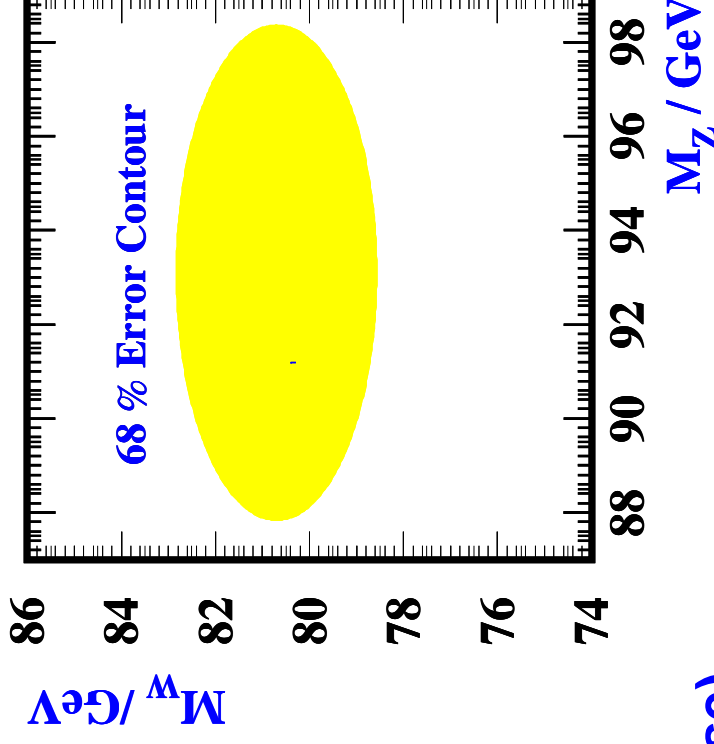
Conclusion: The joys of LEP

In the near future LEP physics will be summarised as:

“ precise measurements of the masses and couplings of the Z^0 and W^\pm ”

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

The situation in 1989 (yellow ellipse)....



.....and now (blue ellipse)