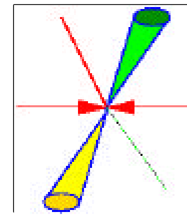
Measurement of the W mass at LEP

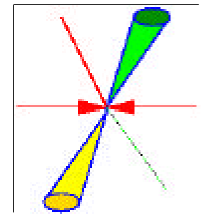


Richard Hawkings

EW & Higgs mass mini-workshop, Zeuthen 28/2/03

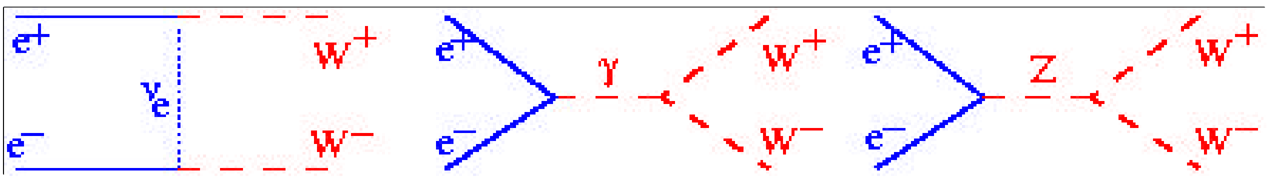
- W mass measurement at LEP:
  - Introduction: WW-ology
  - Extraction of the W mass
    - Statistics and systematics - where do we stand ?
    - Detector systematics
    - Hadronisation
  - Colour reconnection
  - Bose-Einstein correlations
  - Theoretical uncertainties
  - LEP energy
- Current W mass results (LEP+world)
  - Outlook for the future

    - See LEPEWWG: http://www.cern.ch/LEPEWWG

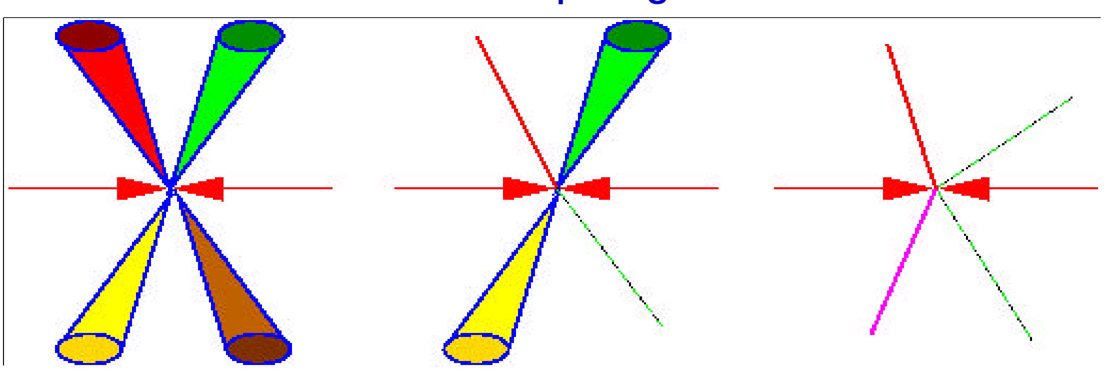


WW-ology at LEP

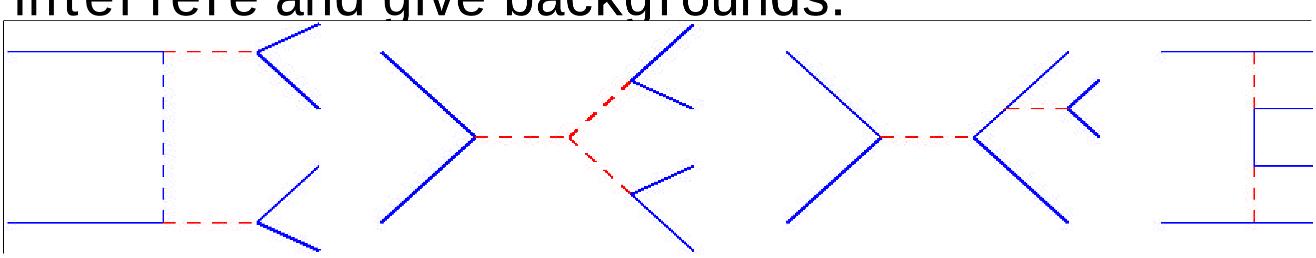
- At LEP, W bosons mainly produced in pairs:
  - t-channel n_e **exchange**
  - S-channel **Z/**g **exchange**



- W bosons decay to fermion pairs …
  - W→eυ, μυ, τυ (3 x 11%), or W→qq (68%)
- … producing four-fermion final states.
  - Three distinct event topologies:

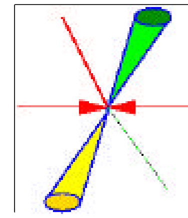


- Other four-fermion final states (mainly via ZZ) interfere and give backgrounds:

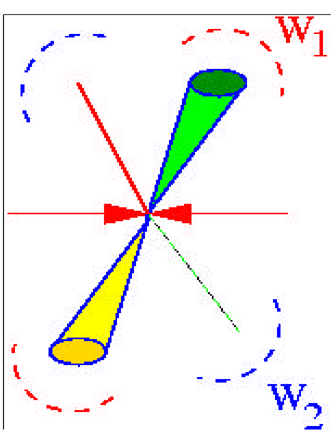


- Other significant background: $e^+e^- \to Z/\gamma \to qq(g)$

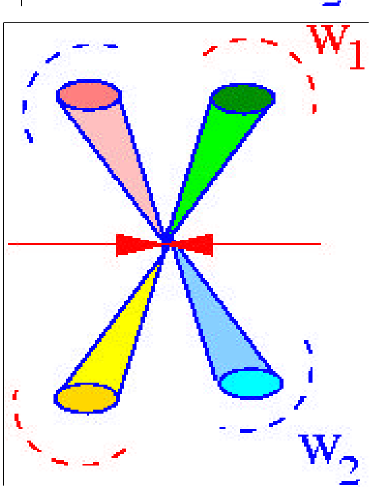
Measuring the W mass



- Above threshold, most precise measurement comes from **direct reconstruction**
  - Derive event-by-event estimator of W mass from kinematics of measured particles.
  - Find most likely W mass for whole sample
- Resolution improved using **kinematic fit**:
  - Constraint from 4-momentum conservation: $E_{tot}=2E_{beam}$; $\mathbf{p}_{tot}=0$; $\Rightarrow$ need LEP beam energy
  - Usually constrain both W masses in event to be equal (W width ~ 2 GeV, smaller than expt. resolution).



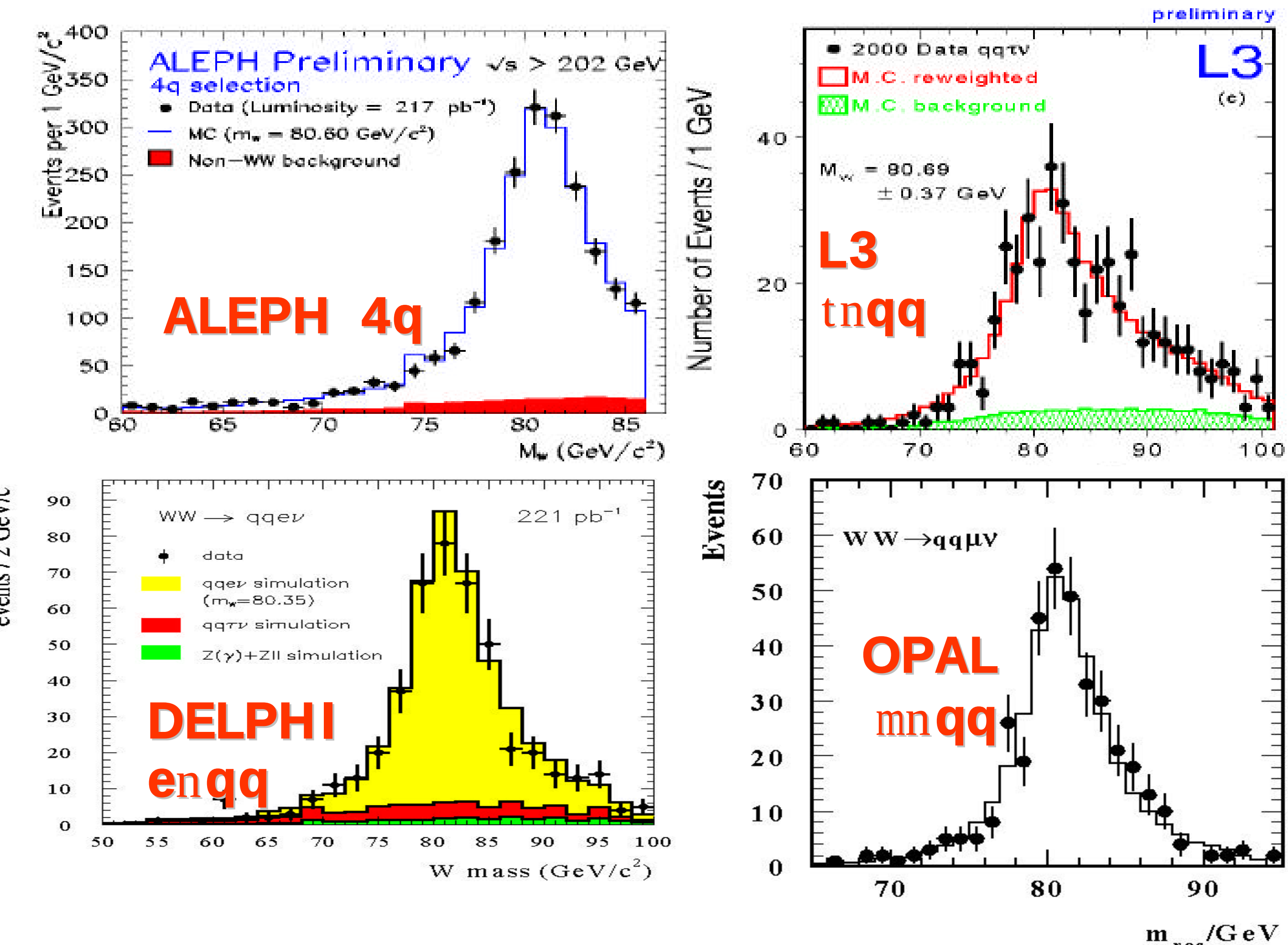
- WW$\rightarrow$qqlν events
  - 4 mom conservation + equal W mass$\Rightarrow$2 constraint fit (missing ν)
  - No constraints for qq$\tau\nu$ due to badly measured τ decay – use information from W$\rightarrow$qq only
  - Low background, resln ~3.5 GeV



- WW$\rightarrow$qqqq events:
  - 5 constraint fit (no neutrinos)
  - Best resolution, ~2.8 GeV
  - 3 choices of jet assignment to 2 W bosons – combinatorial background.
  - Higher background from ZZ, Z/γ
- WW$\rightarrow$lνlν events:
  - Poor resolution, special techniques

Fit techniques

- Examples of mass distributions:



- Variety of mass extraction methods:
  - Reweighting: generate MC ‘template’ distributions for various true W masses, find ‘best’ (A,L,O)
  - Convolution: decompose observed distribution into physics function ⊗ detector response (D,O)
  - Simple Breit-Wigner fit to reconstructed dist. (O)
    - Take into account resolution and ISR ⇒MC studies

Statistical and systematic errors

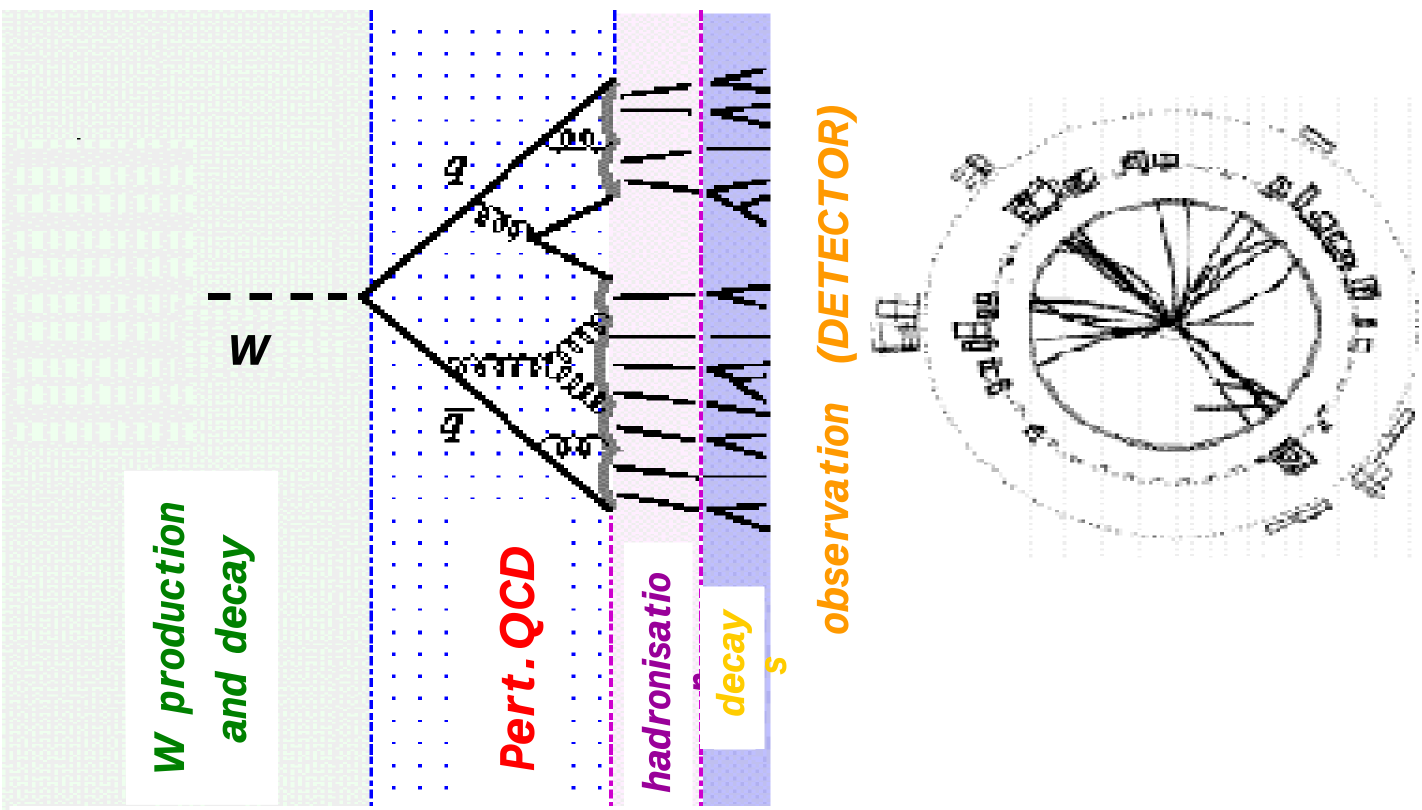
- Current LEP average, error breakdown in MeV
  - Preliminary analysis of entire LEP2 data sample, except OPAL year 2000 data.

Source	qqlv	qqqq	Combined
Hadronisation	**19**	**18**	18
Colour recon.	-	**90**	9
Bose-Einstein	-	**35**	3
Detector	12	8	11
ISR/FSR/rad	8	8	8
Beam energy	**17**	**17**	17
Other (uncorl)	4	5	4
Statistical	33	36	30
Total	**44**	**107**	**42**
Stat (no syst)	32	29	22

- Dominant systematics in **red:**
  - Hadronisation, and final state interactions (CR and BEC) in qqqq
    - This reduces weight of qqqq channel to 0.09.
    - LEP beam energy also significant.

From particles to measurements

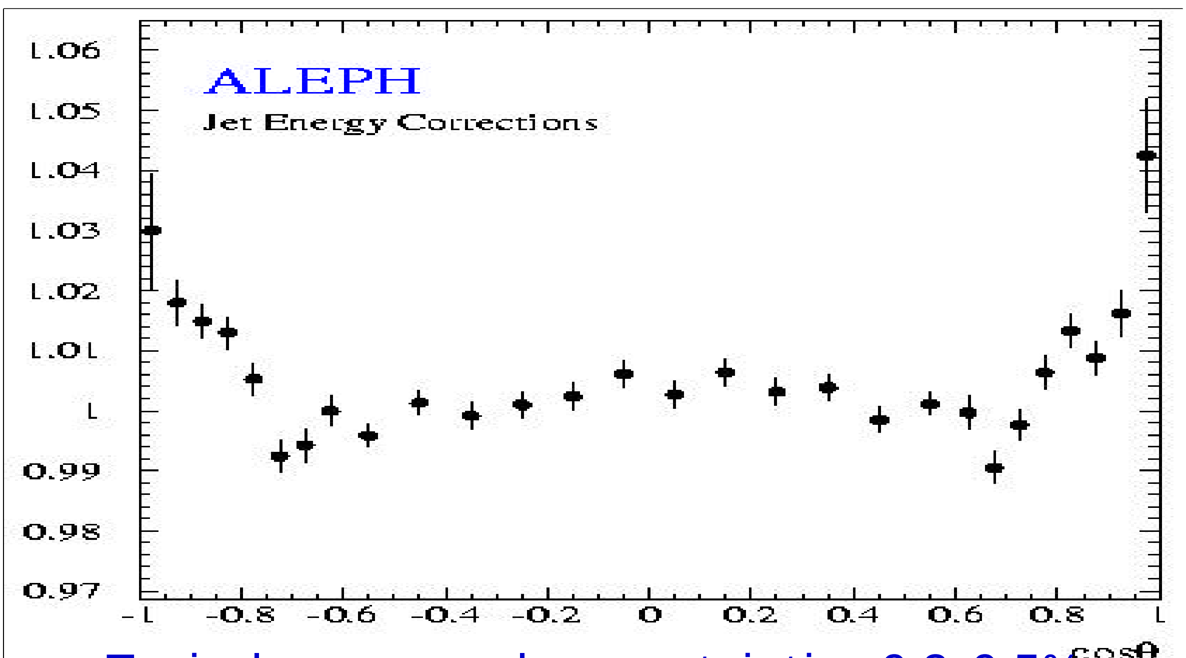
- Ideally, measure the 4-vectors of the four fermions produced in the WW event
  - In practice, not so easy…
    - For quarks, perturbative QCD, hadronisation, particle decays, detector effects, calibration, jet clustering…
    - Leptons simpler: detector response and radiation



- Systematics arise in all stages
  - Need to be understood with detailed studies, based on data where possible.

Detector systematics

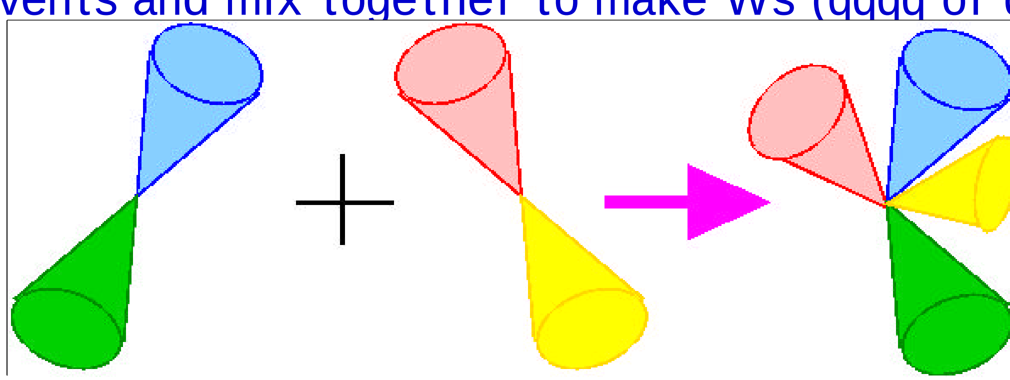
- Need to calibrate/understand detector response to jets and leptons.
- Jet energy scales and resolution:
  - Use $Z \rightarrow qq$ calibration data taken in each year of LEP2.
  - Correct Monte Carlo simulation so it correctly describes data biases and resolution.



  - Typical energy scale uncertainties 0.3-0.5%.
  - Also look at 3-jet Z events and high energy qq events to study linearity of jet energy scale.
  - Angular biases important – study tracking vs calo.
- Lepton energy scales and resolutions:
  - Similar procedures using $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events.
    - Final systematics limited by residual effects and Z data statistics.

Hadronisation

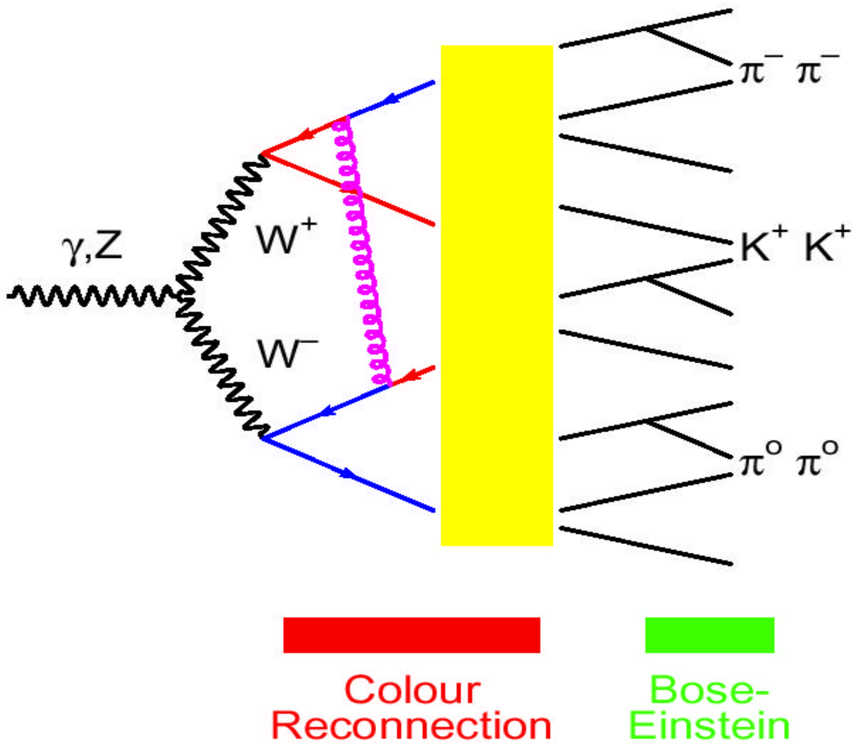
- Different hadronisation models are used:
  - Jetset, Herwig, Ariadne, with KoralW/WWFact
  - Hadronisation models tuned by each experiment to describe Z^0 data, but tunes are different.
    - Experiments put different emphasis on various event properties – event shapes, particle rates, fragmentation functions etc.
  - Within experiments, different models give W mass results differing by 10-50 MeV – significant.
    - But with same MC tune, expts get same results.
  - Some differences due to kaon and baryon rates
    - Often reconstructed with 'wrong' masses.
- DELPHI has ingenious Z^0 data-based approach:
  - Mixed-Lorentz-boosted Z (MLBZ) – take LEP1 Z^0 events and mix together to make Ws (qqqq or qqlv)



  - Boost Z^0 to get appropriate W-like kinematics.
  - Apply same procedure in MC and data – look for consistency.
  - Used for both hadronisation and detector effect studies.

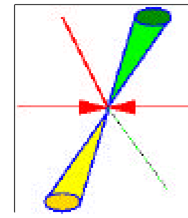
Final state interactions

- ‘Standard’ MC models assume decay products of two Ws do not interact.
  - But Ws decay within 1 fm of each other – typical strong interaction scale.



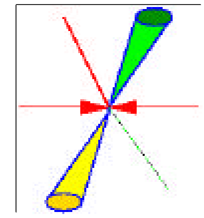
  - Colour reconnection: Colour flow between quarks from two W decays (perturbative or non-perturbative phase).
  - Bose-Einstein correlations: enhances production of identical particles nearby in phase space.
  - Both are known in other systems (B mesons, Z, W)
    - What happens in W-pair events ?
    - What does this do to the mass reconstruction ?

Colour reconnection models



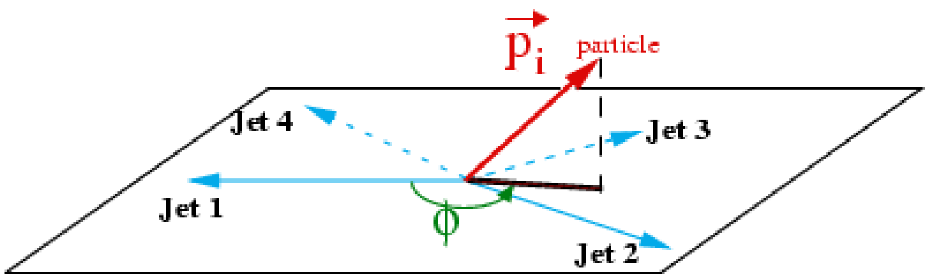
- Several viable models exist, usually implemented in terms of an existing hadronisation model
  - Sjöstrand-Khoze (**SK1**) – based on Lund fragmentation model, strings reconnecting between Ws; adjustable parameter for recon prob.
  - Ariadne dipole-cascade model: reconnection allowed if total string length reduced, and gluon energy smaller than Γ_w=2 GeV (**AR2**)
  - Herwig: cluster model: reconnection allowed for favourable parton-cluster assignments, prob 1/9.
  - ... etc.
- Models predict large effects on recon. m_W
  - SK1: up to ~300 MeV for full reconnection
  - Ariadne (AR2): ~100 MeV
  - Herwig: ~30 MeV

  $\Rightarrow$ Need to eliminate/constrain models from WW data.
- Initially, effects looked for by comparing W decay properties in qqqq and qqlν events:
  - Charged particle multiplicities, fragmentation functions, event shape variables.
  - No significant effects seen, but sensitivity to ‘realistic’ models is low.

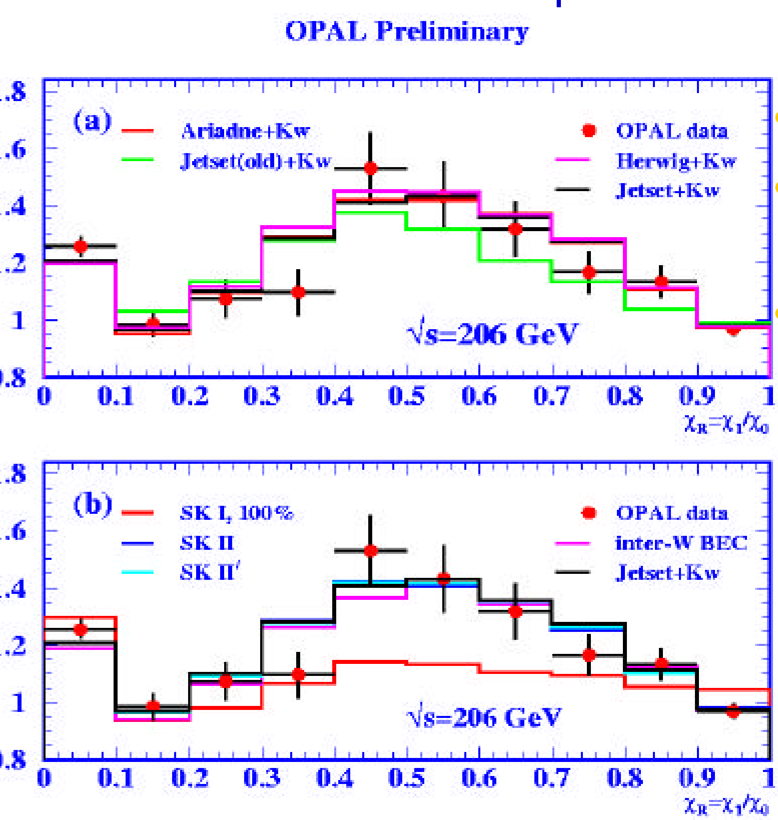


Particle flow analyses

- Look for CR effects more directly:
  - Particle flow in inter-jet regions, between jets from same and different Ws.



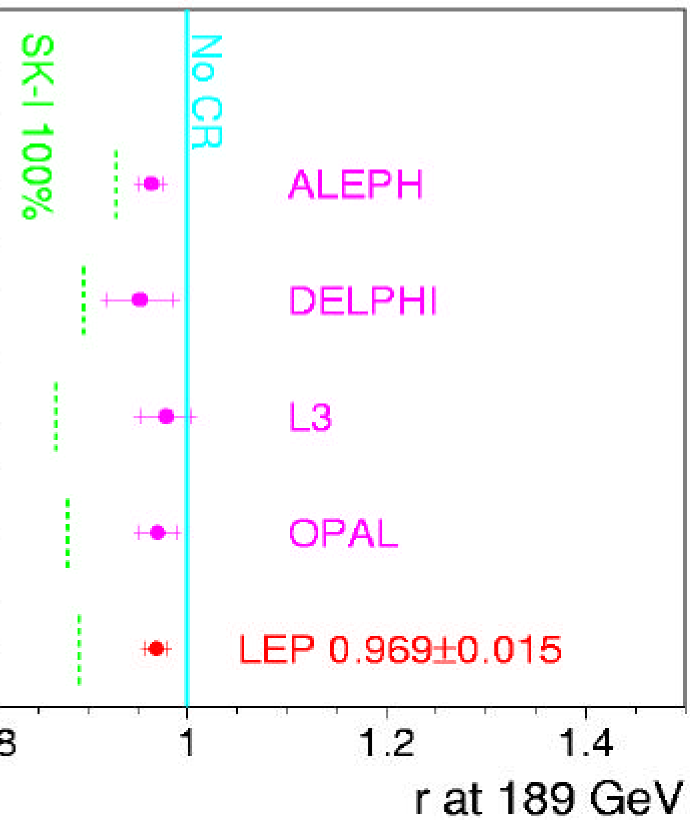
    - As in mass analysis, requires jet-W association.
    - Use W-mass like selection (A, O) or more restrictive selection of events with clear topology (D,L)
  - Look at ratio of particle flow:

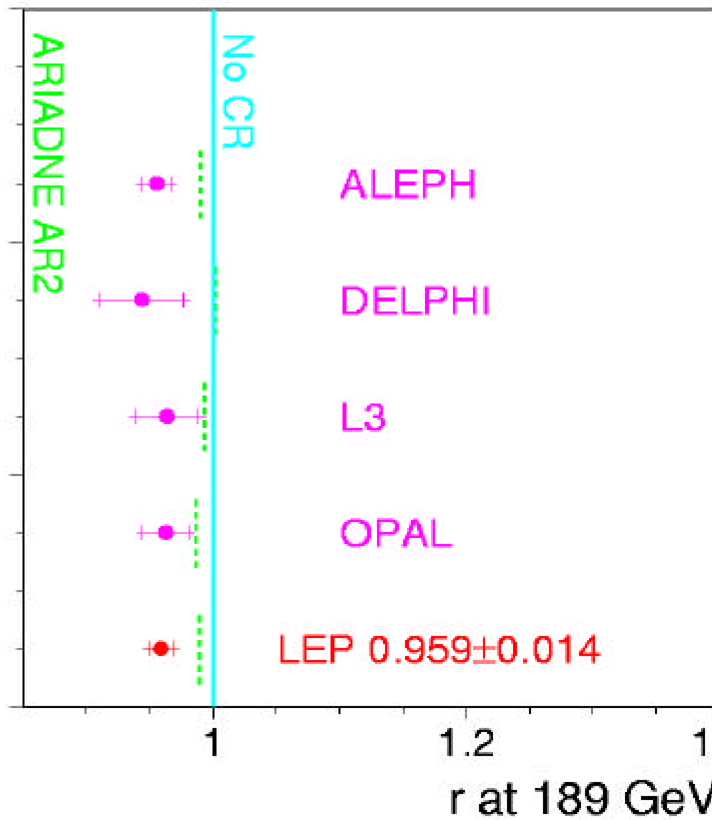


- R=N(intra W)/N(inter W)
- 'Fold over' angular distributions to $0<\chi<1$
- Compare data with models
  - Extreme SK1 scenario with full recon. excluded
  - Method not sensitive to AR2 CR model
  - Significant differences between non-CR hadronisation models.

LEP particle flow results

- Preliminary results available from all experiments
  - Combination done by 'calibrating' analyses using common MC samples of various models.
    - Integrate R over $0.2 < \chi < 0.8$
    - Define **r** as ratio of data/no-CR MC
    - Compare measured r with that expected in specific CR model, normalise LEP expts and combine:

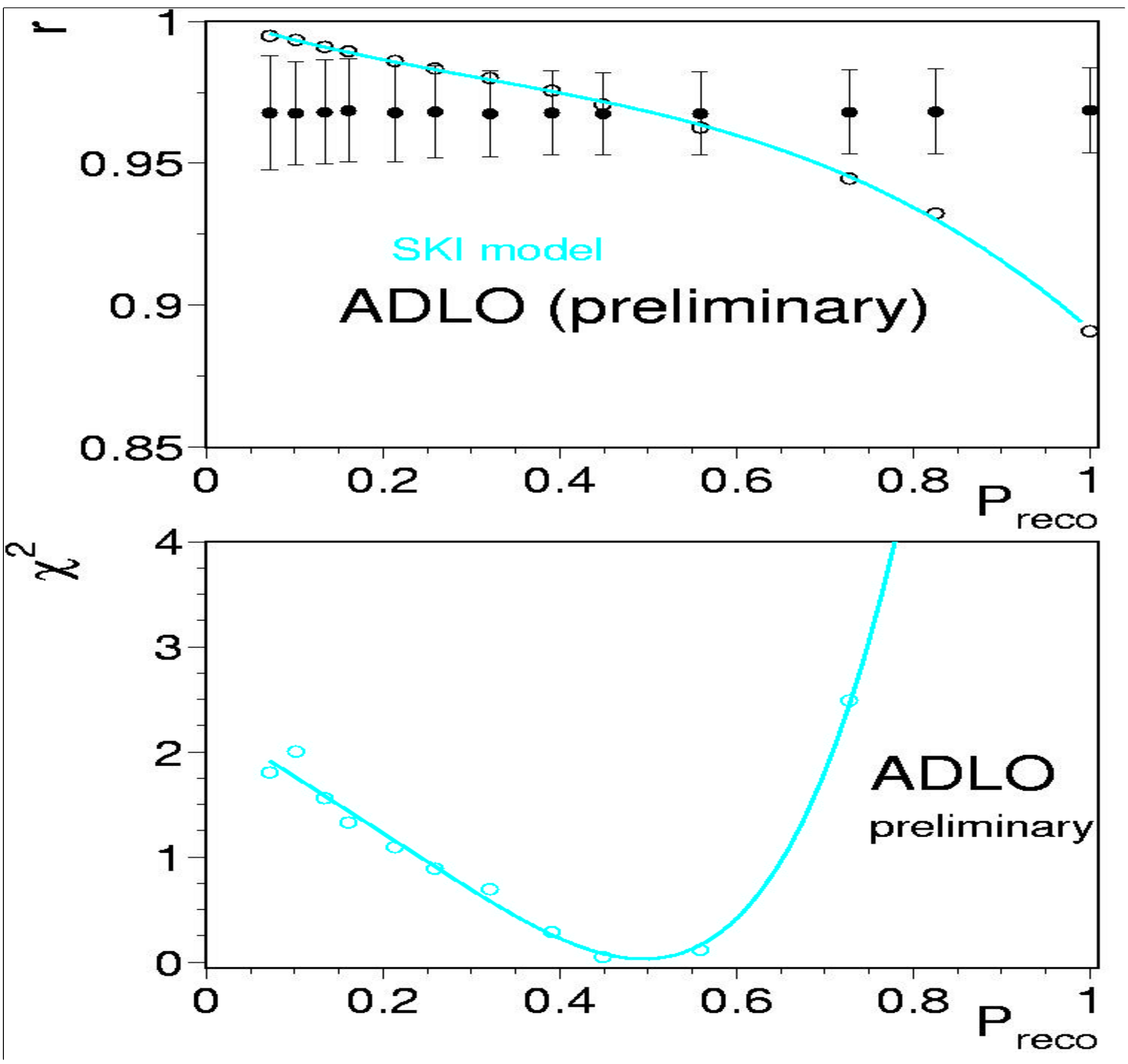




- Data disfavour no-CR scenario at $\sim 2\sigma$
- Extreme SK1 scenario excluded at 5.2σ
- AR2 (and Herwig CR) disfavoured at $2\text{-}2.5\sigma$
  - But little sensitivity to these models – systematics ?

CR-parameter in SK1 model

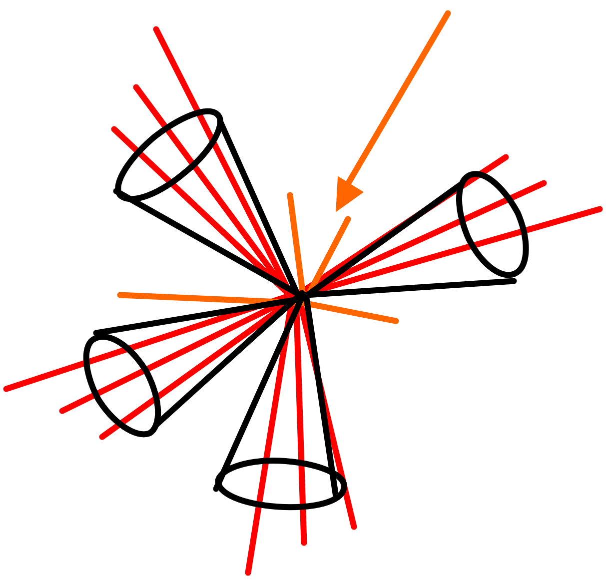
- SK1 model has parameter allowing fraction of reconnected events to be adjusted.
  - Tune to LEP data results from particle flow:

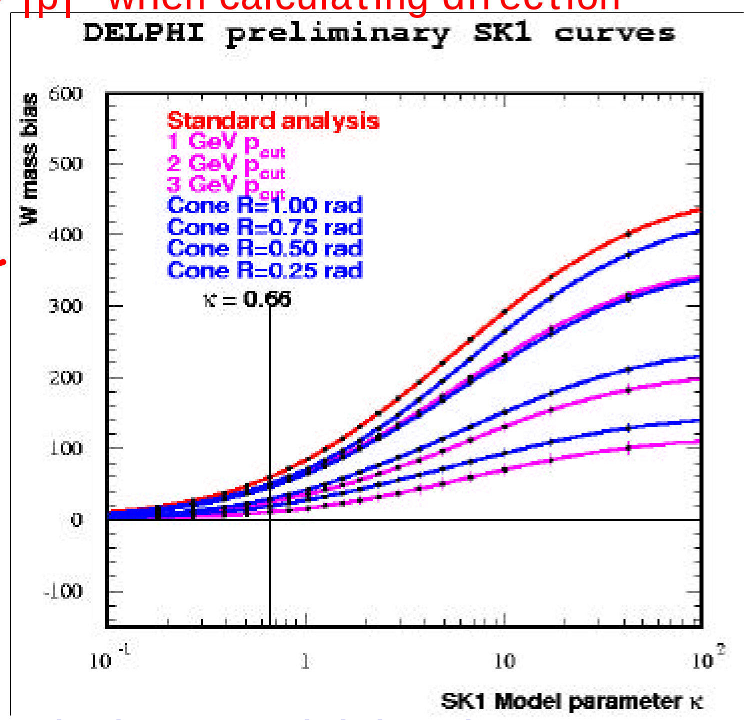


  - 68% C.L. limit: 25%<P_{reco}<65%; moderate CR.
    - Systematic error on qqqq W mass of **90 MeV** from 65% recon probability compared to no-CR
    - Result valid only in SK1, but full AR2 mass shift is also ~90 MeV.

Changing the analysis sensitivity

- Another recent idea:
  - Modify jet algorithm to reduce influence of soft particles between jets.
    - Cone of restricted radius (R~0.25-1.0)
    - Momentum cut to remove soft particles (1,2,3 GeV)
    - Weight particles by $|p|^{\kappa}$ when calculating direction

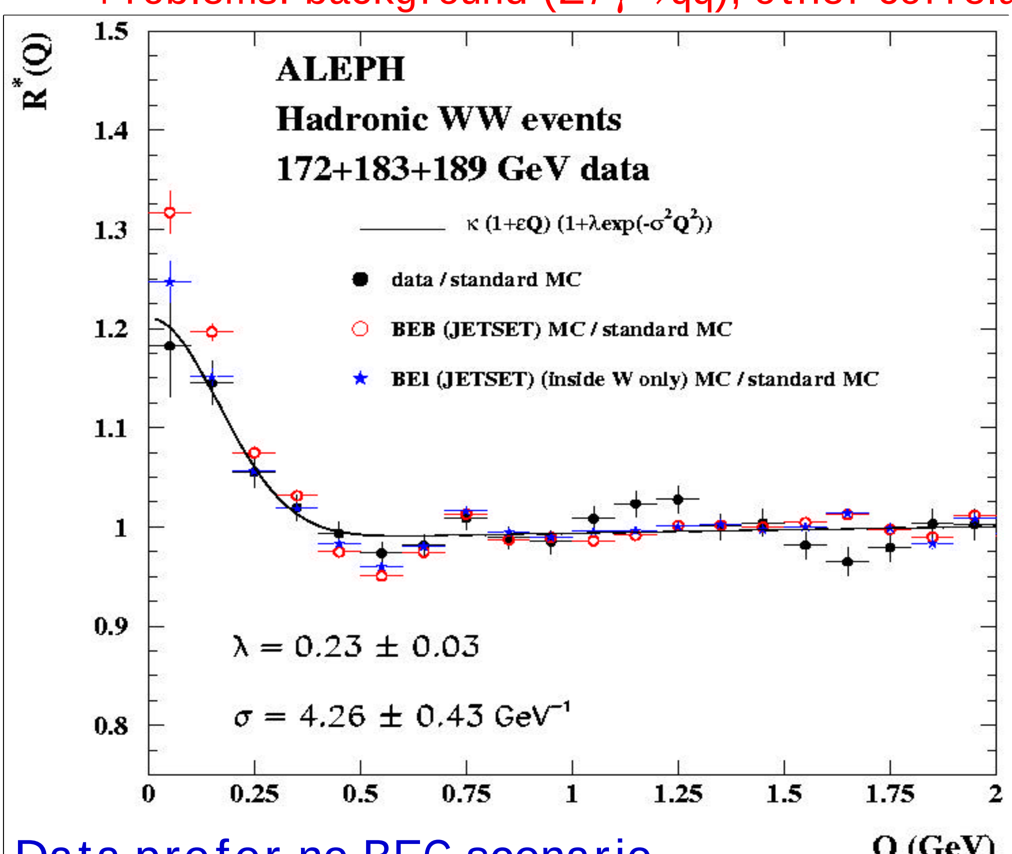




  - Techniques reduce statistical sensitivity, but also reduce systematics due to some CR models.
  - Can also use differences between jet algorithms to search for or constrain CR models.
    - Similar sensitivity to particle flow method, uncorrelated
    - Ongoing analysis by experiments, eventual LEP combination.
    - Not sensitive to Ariadne AR2 model – unless this can be eliminated another way, qqqq channel is sunk…

Bose-Einstein correlations

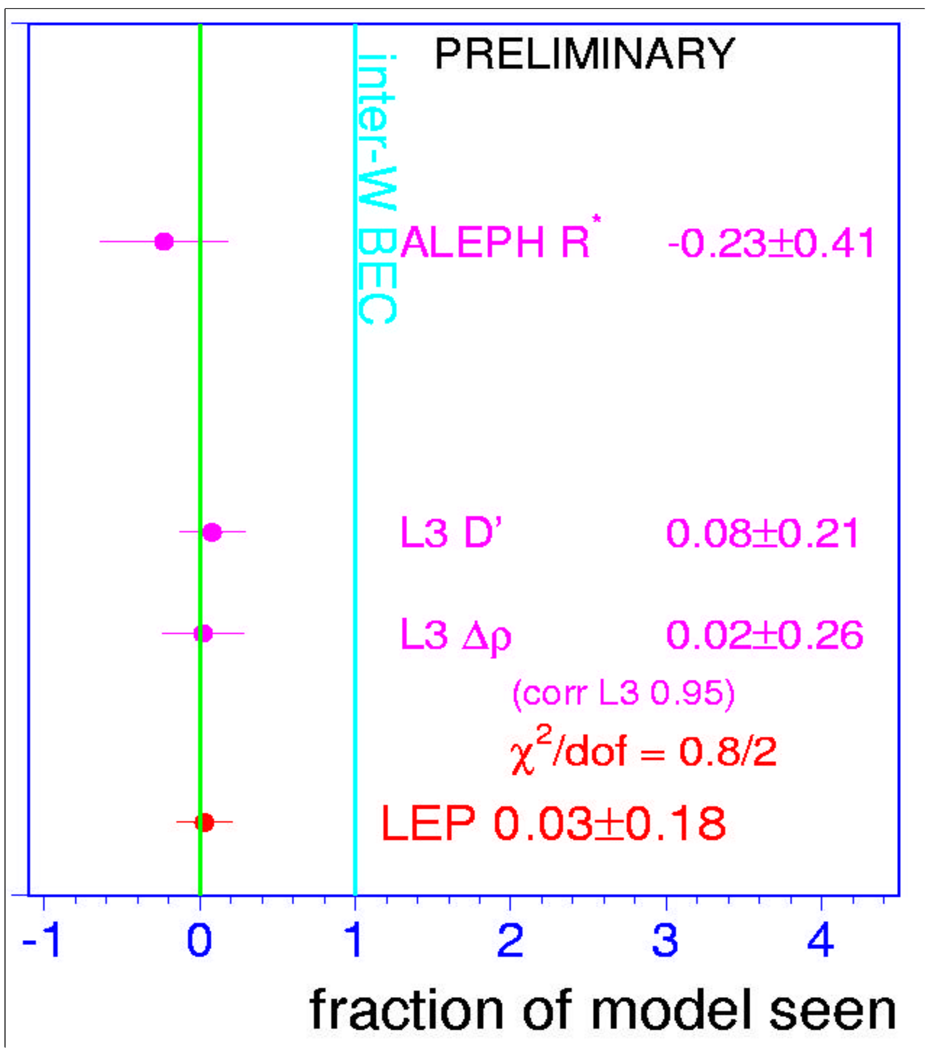
- Bose-Einstein correlations known in Z^0 decays:
  - $R(Q)=\rho(Q)^{data}/\rho^{ref}(Q)$; $Q^2=-(p_1-p_2)^2$
    - Enhancement at low Q for identical bosons (e.g π^+ pairs) compared to reference distrib. without BEC.
  - BEC exist between decay products of one W, what about between decay products of different Ws ?
  - Need ref. distribution with BEC in same W.
  - Construct by mixing hadronic parts of two qqlv events – data based reference distribution to compare with data WW→qqqq events
    - Problems: background ($Z/\gamma\to qq$), other correlations



- Data prefer no BEC scenario.
  - Delicate measurement with low sensitivity.

Bose-Einstein correlations: LEP combination

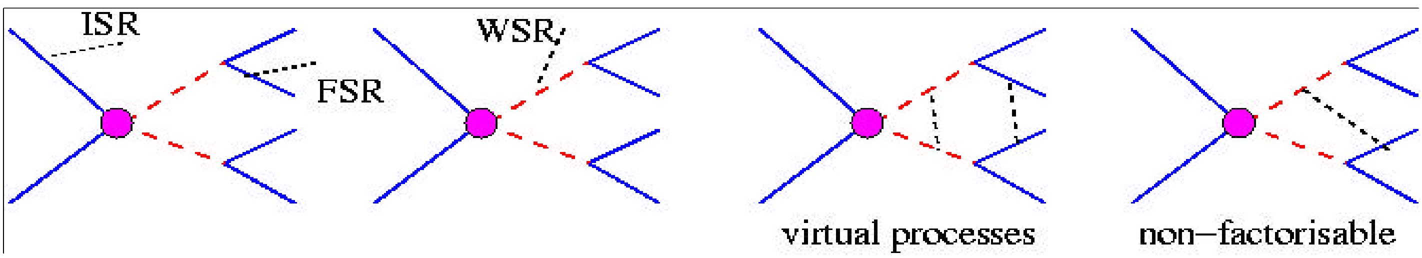
- Combine some existing LEP measurements (A,L)
  - Use common MC samples with/without inter-W BEC (LUBOEI) as for CR to calibrate analyses
    - Result in terms of 'fraction' of full inter-W BEC:



- Inter-W BEC disfavoured by this combination, but
  - ...need to include upcoming DELPHI and OPAL results
- W mass systematic for full inter-W vs no inter-W BEC is **35 MeV**, hopefully error can be reduced.
  - Need to generalise to other BEC models.

Theoretical uncertainties

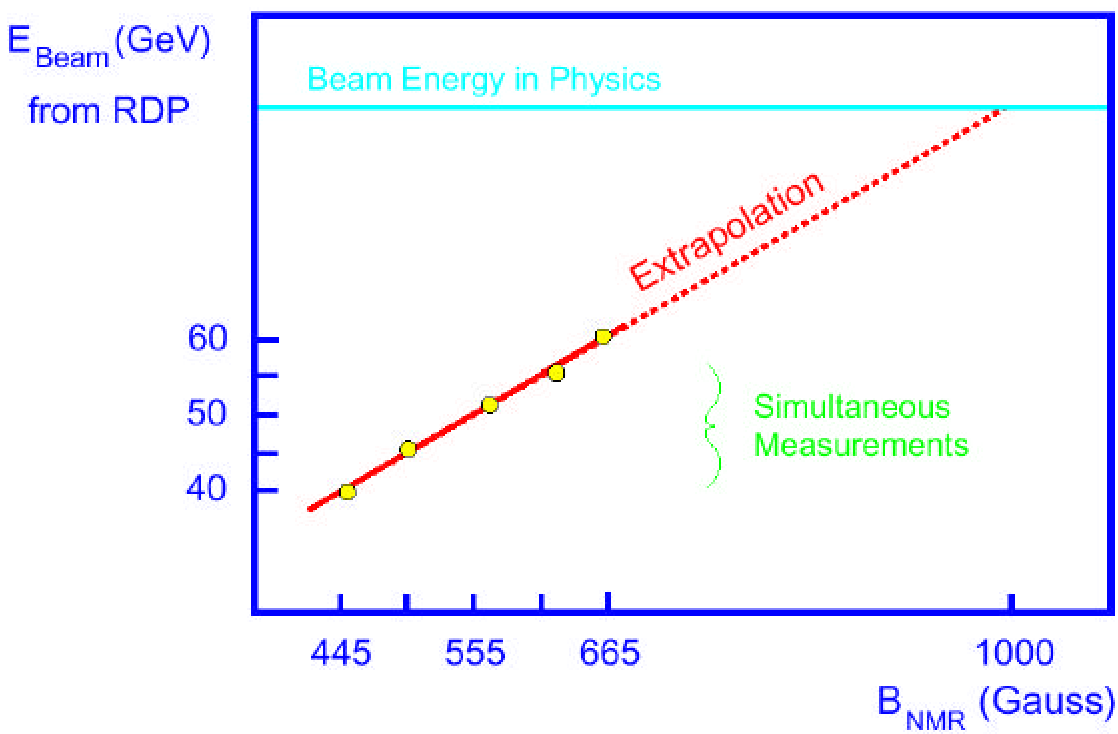
- O(α) QED corrections to W-pair production are not trivial:



- Published LEP analyses based on KoralW
  - Crudely, treats only ISR and FSR.
- New Monte Carlo programs available:
  - Leading or double-pole approximations …
  - **YFSWW** (Jadach et al) (YFS+KoralW=KandY): O(α) non-leading EW corrections, screened Coulomb correction.
  - **RacoonWW** (Denner et al): Full O(α) corrections to W-pair diagrams.
    - Interfacing generators to expt simulation is non-trivial.. e.g. problems of double counting FSR.
- Effects on analyses under study:
  - W mass: shifts of O(10 MeV) seen between KoralW and KandY, maybe larger.
    - Some evidence of cancellation between different effects
    - Comparisons of KandY and Racoon, different schemes (LPAa vs LPAb)

LEP energy calibration

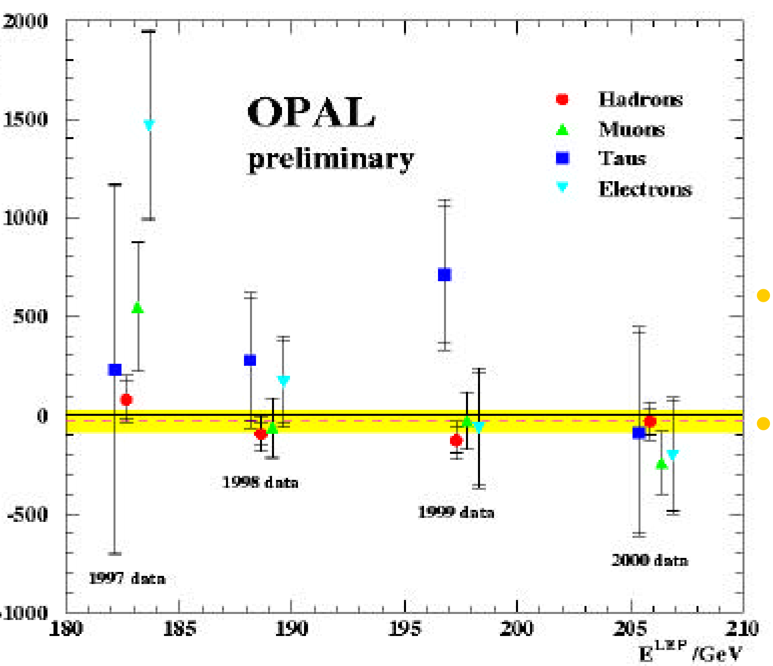
- Use of kinematic fit with energy constraint:
  - Drastically improves event-by-event mass resl^{n}.
  - ...but requires precise knowledge of beam energy.
    - For 20 MeV uncertainty on E_{beam}, (of 100 GeV) get 17 MeV uncertainty on m_W.
  - At LEP1, technique of **resonant depolarisaton** allowed ΔE_{beam} of 1-3 MeV for LEP1 Z^0 measurements.
  - Depolarisation does not work above 60 GeV, have to extrapolate using $E_{beam} \propto B$.
    - B measured with 8 dedicated NMR probes, plus flux loop as cross check.



  - Current ΔE_{beam} of 20 MeV $\Rightarrow$ 17 MeV on m_W
    - Error mainly from uncertainties in extrapolation.

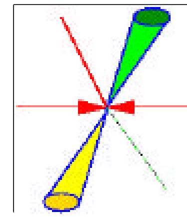
Alternative energy measurements

- A lot of ingenuity/effort cross-checking E_{beam}
- LEP spectrometer:
  - Measurement of beam bending in a carefully mapped dipole magnet.
    - Much harder than first thought, understanding of 'background' B-fields, BPM systematics.
- Synchrotron tune: Q_s vs RF voltage.
  - Dependence of synchrotron oscillation frequency on RF voltage allows beam energy to be deduced.
    - Detailed understanding of many machine effects, RF voltage distribution,…. dedicated machine expts.
- Radiative return measurements:
  - LEP experiments use radiative Z^0 production to 'measure' the Z mass ($e^+e^- \rightarrow Z\gamma \rightarrow ll\gamma$ or $qq\gamma$)

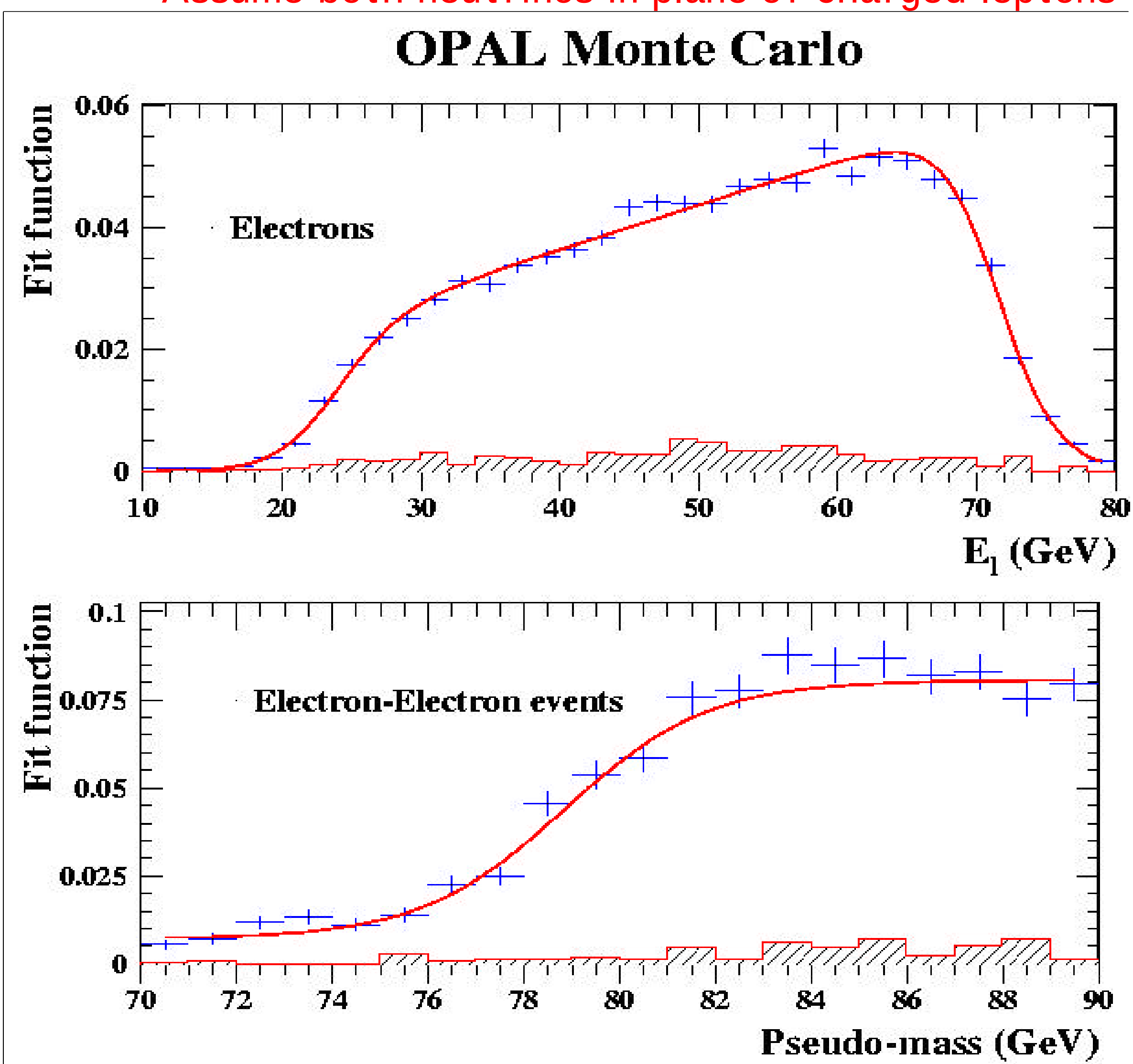


    - Uses similar kinematic fit techniques to W mass measurement.
    - Z-mass is known from LEP1, cross-check E_{beam}
- All methods now giving consistent results.
- Final error on LEP energy may be reduced
  - … include information on spectrometer and Q vs RF?

W mass from fully leptonic events (ALEPH,OPAL)



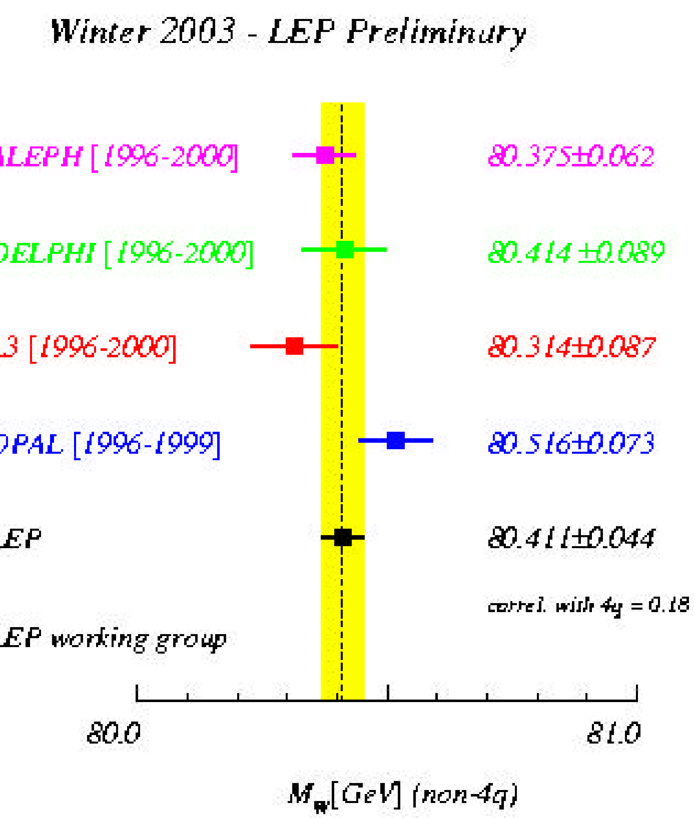
- lνlν events cannot be fully reconstructed
  - Lepton energy spectrum is sensitive to m_W
  - Additional assumption in kinematic fit allows a pseudo-m_W to be reconstructed
    - Assume both neutrinos in plane of charged leptons

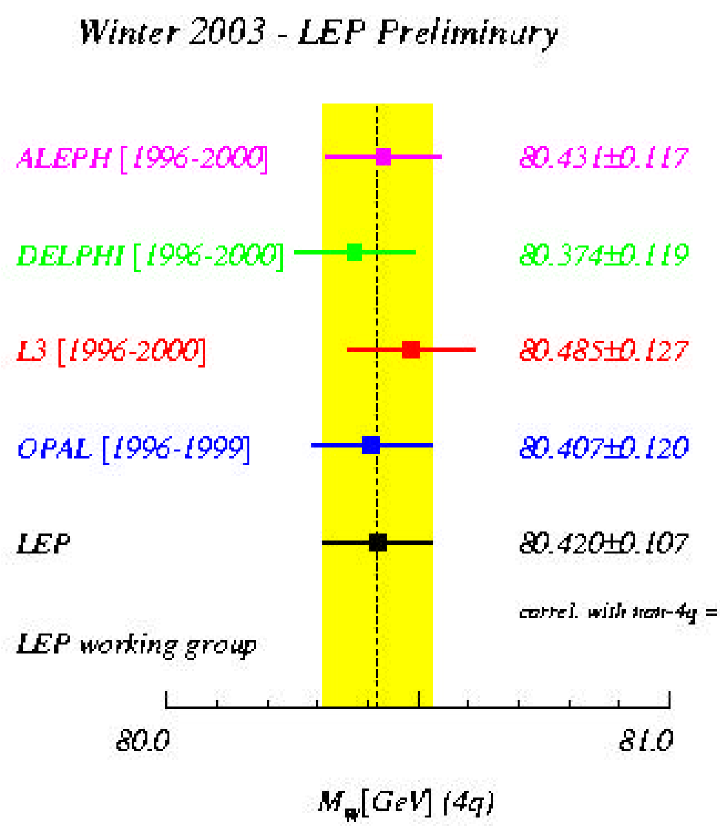


- OPAL result: m_W=80.41±0.41(stat)±0.13(syst) GeV
  - Not competitive with qqlν or qqqq results, but very different systematics ⇒useful at linear collider

LEP W mass results

- New LEP combined results for winter 03:
  - Change since summer: ALEPH shift by –79 MeV





- Including LEP threshold measurement …

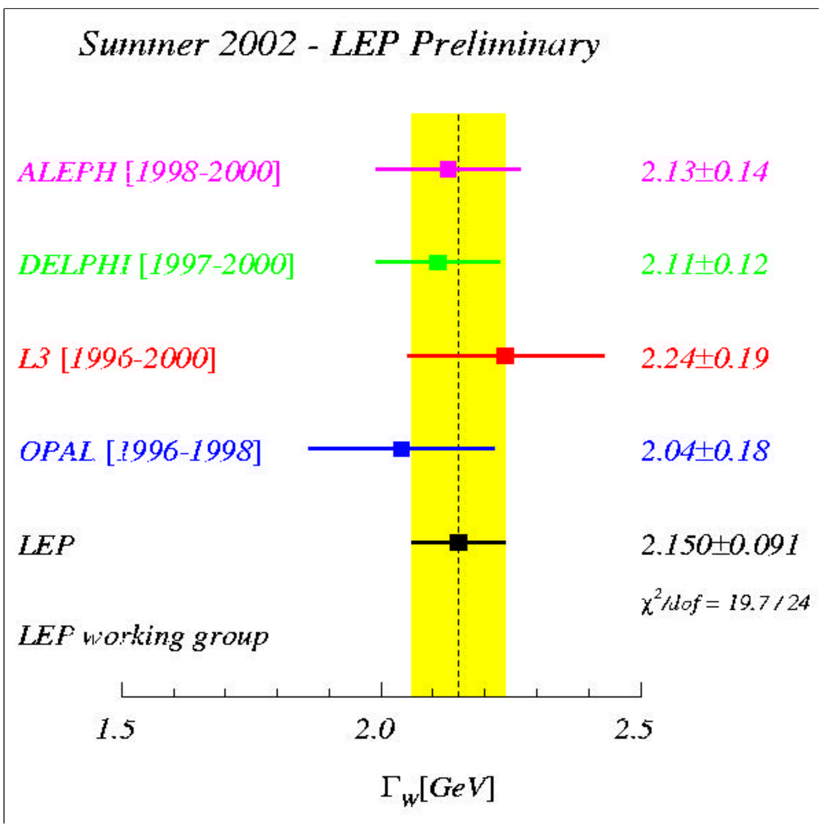
  m_W=80.412±0.030 (stat) ± 0.029 (syst) GeV
  - Change of –35 MeV since summer 02
- Difference between qqqq and qqlv channels currently 22±43 MeV – no evidence of qqqq shift due to FSI
  - (FSI systematic errors set to zero here)
- Combination with p-pbar m_W of 80.454 ± 0.059 GeV
- World average value:

m_W=80.427 ± 0.034 GeV

Change of –22 MeV since summer 02

Measuring the W width

- Very similar techniques used to measure Γ_W
  - Resolution > natural width, observed width dominated by detector/reconstruction effects.
    - qqqq and qqlv channels, similar systematic errors as for W mass.
    - Not all data and channels analysed yet:



  - LEP: Γ_W=2.150 ± 0.068 (stat) ± 0.060 (syst) GeV
  - Combine with Tevatron result to get world average

    G_W=2.136 ± 0.069 GeV
  - Standard Model predicts relation between W mass and width… expect around 2.09 GeV.

Outlook for the future

- LEP W mass results still all preliminary
  - Work on final systematics …
  - Current uncertainty on W mass from LEP: **42 MeV**
    - Improved understanding of FSI (esp. colour recon), incorporating results of dedicated analyses.
    - Improved understanding of O(α) radiative effects
    - Decreased LEP beam energy uncertainty
  - Hope for final LEP error around **35 MeV**.
- Beyond LEP:
  - Tevatron run I analyses: **59 MeV**
  - Run II now going on … good scope for improvement:
    - Larger data samples – more Z^0 for calibration
    - Eventually systematics limited
    - O(α) effects may become important
  - Hope to get to ~20 MeV error eventually.
- Beyond Tevatron:
  - LHC - ATLAS/CMS:
    - Hope for 15 MeV – some improvement over Tevatron, but completely systematics limited – very challenging.
    - 15 MeV is useful precision for 2 GeV error on m_{top}.
  - Linear Collider:
    - Threshold scan or direct reconstruction,
    - Both have potential to go below 10 MeV
  - Factor 4 reduction in next 10-15 years …