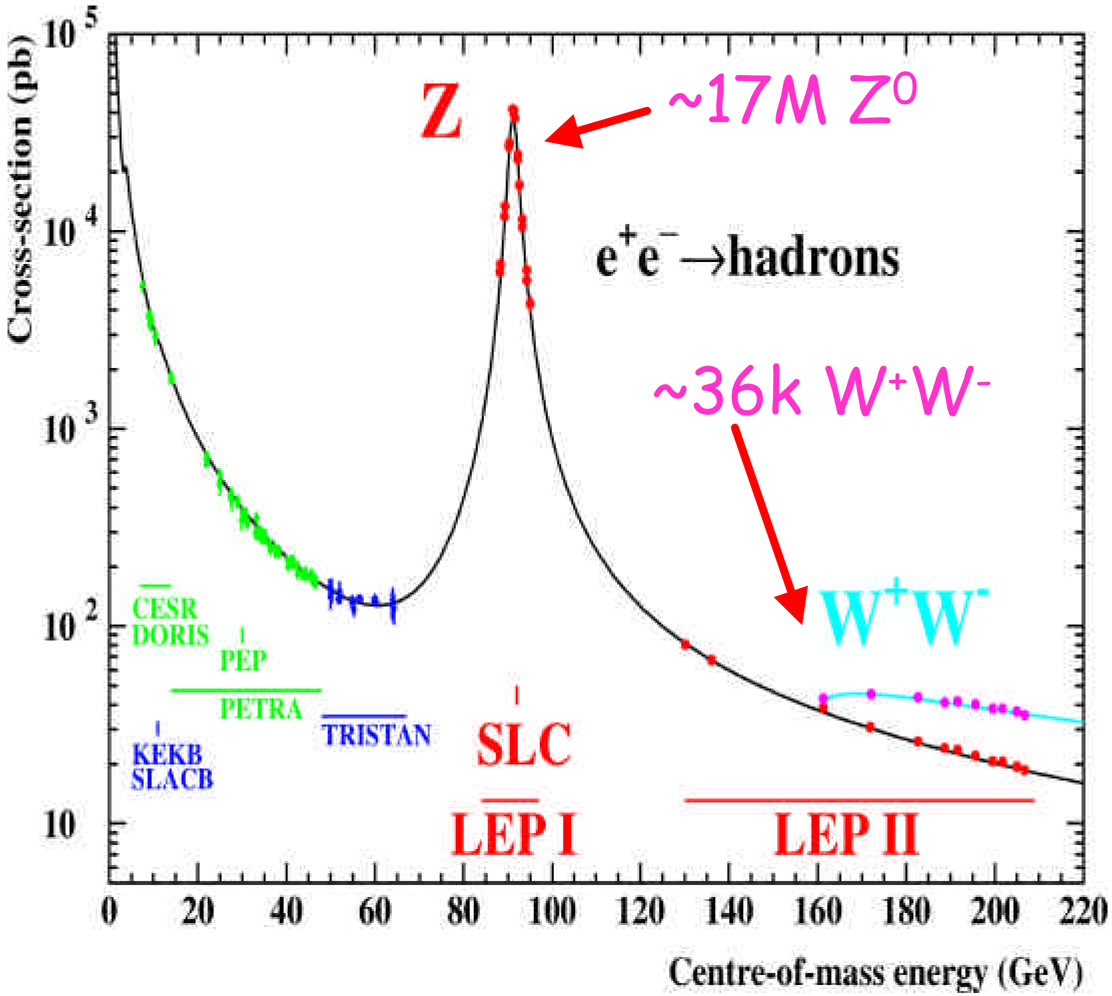
QCD and FSI at LEP



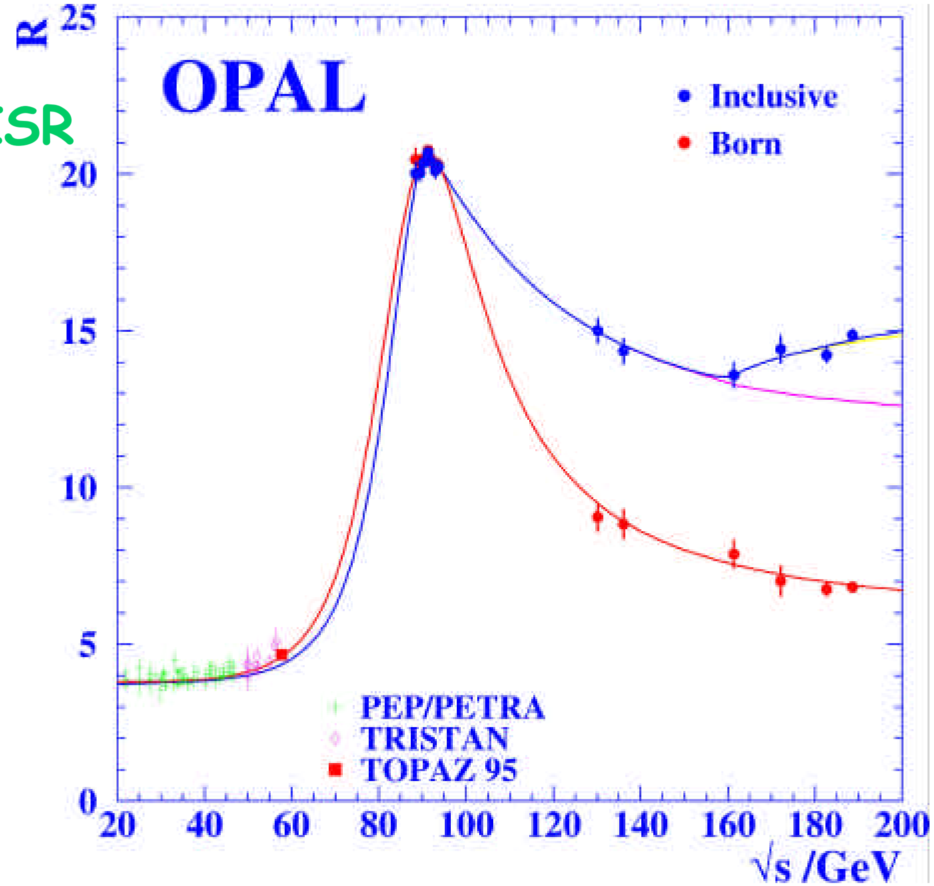
- α_s from event shapes
  - Data
  - Fits
  - LEP Combination
- Colour Reconnection
  - Multiplicity
  - Particle Flow
  - LEP Combination
- Summary

e^+e^- ® hadrons data

Illustrative numbers, per experiment

- LEP1
  - High statistics, » 0 background or ISR

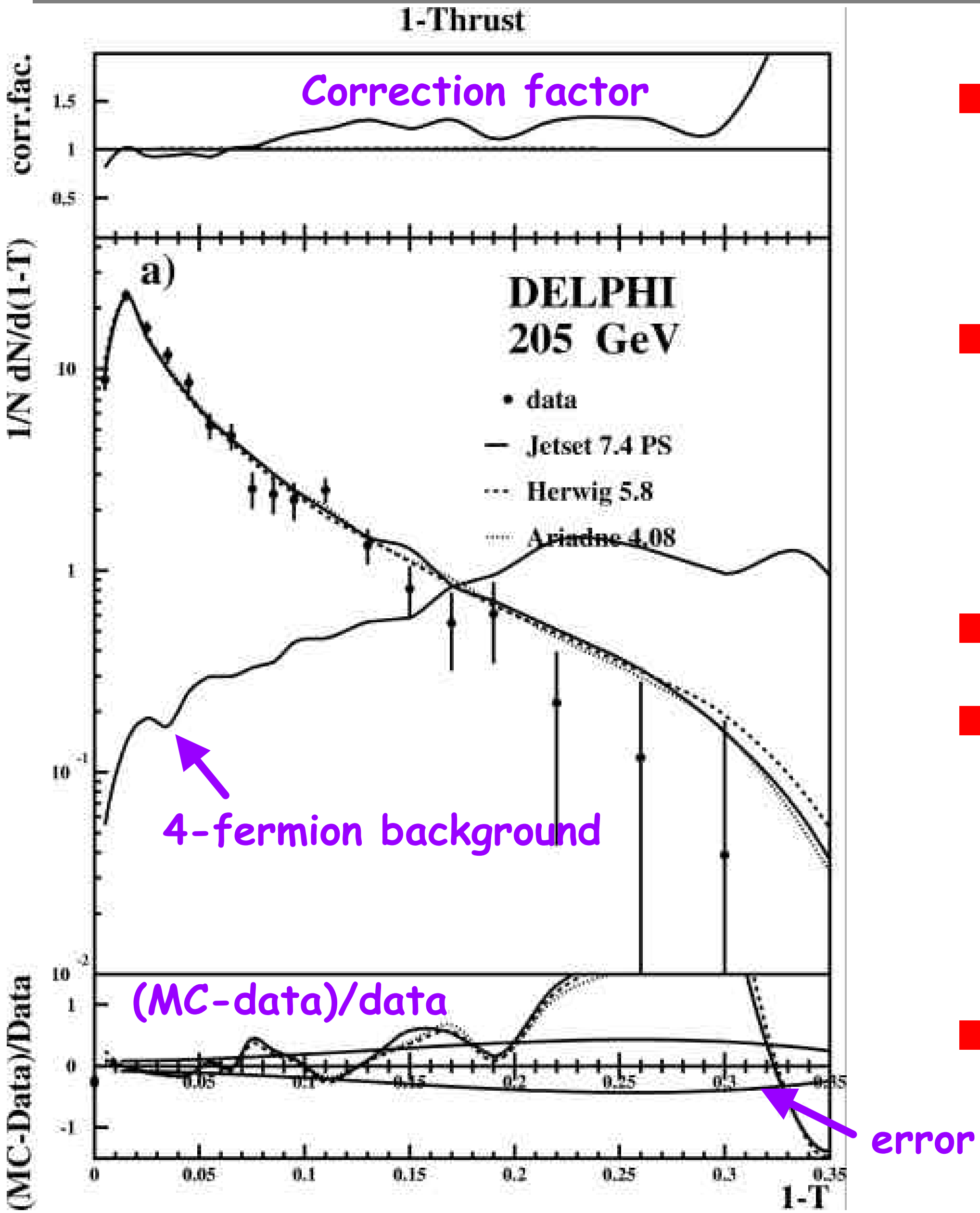
Ös [GeV]	?Ldt [pb^{-1}]	No. events	Impurity
91	100	> 10^6	< 0.5%
"133"	12	800	< 0.5%
161	11	300	5%
172	10	250	10%
183	60	1100	10%
"189"	185	3300	11%
"200"	200	3000	14%
"206"	210	3500	15%



- LEP 2
  - O(10^{-3}) LEP1 statistics, large 4-fermion contamination, ISR effects
  - Variable energy, averaged to "nominal" Ös

$$R = \frac{s\,(e^+e^- \ \circledR\ \text{hadrons})}{s\,(e^+e^- \ \circledR\ \mu^+\mu^-)}$$

Measurements



- Select hadronic final states, rejecting
  - 4-fermion-like
  - Hard ISR
- Observables formed from charged particles, neutrals, or energy flow objects
  - $1\text{-}T$, M_H, B_W, B_T, y_3, C-parameter
- 4-fermion background subtracted
- Bin-by-bin corrections
  - Acceptance
  - Resolution
  - ISR contamination
- OK description of data by MCs

α_s Fits

- NLO $\mathcal{O}(\alpha_s^2)$ pQCD prediction for event shape variables, y

$$\frac{1}{\sigma}\frac{d\sigma}{dy} = \alpha_s(\mu^2)A(y) + \alpha_s^2(\mu^2)B(y,\mu^2)$$

- NLLA (resummed) prediction

Leading, sub-leading logs to all orders in α_s

$$R(y) = \mathcal{F}(\alpha_s)\exp(Lg_1(\alpha_s L) + g_2(\alpha_s L))$$

$L = \ln\left(\frac{1}{y}\right)$ $\quad R(y) = \int_0 \frac{1}{\sigma}\frac{d\sigma}{dy}\,dy$

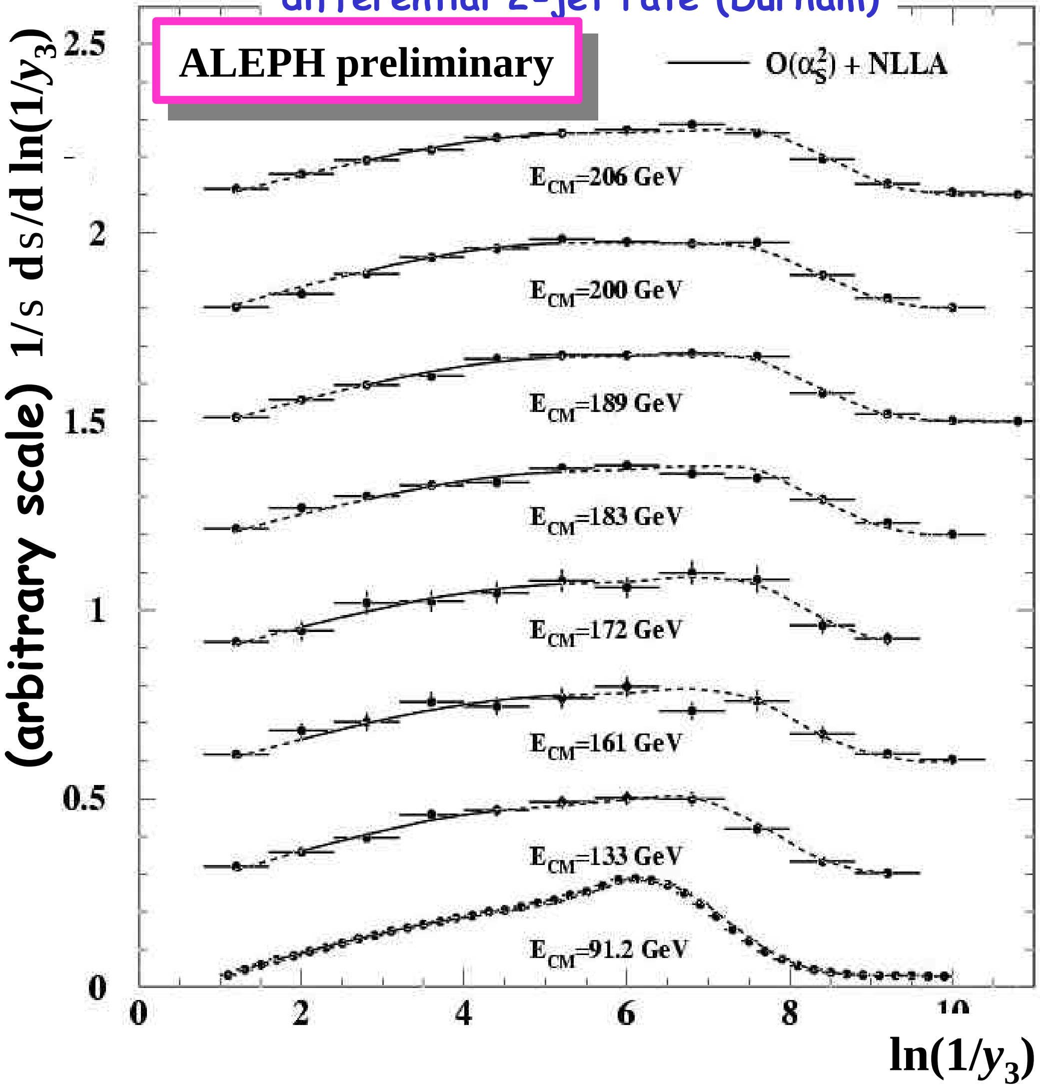
- Log$R$ and R matching avoids double counting of terms
- Use modified matching schemes, ensures L=0 for y=y_{max}

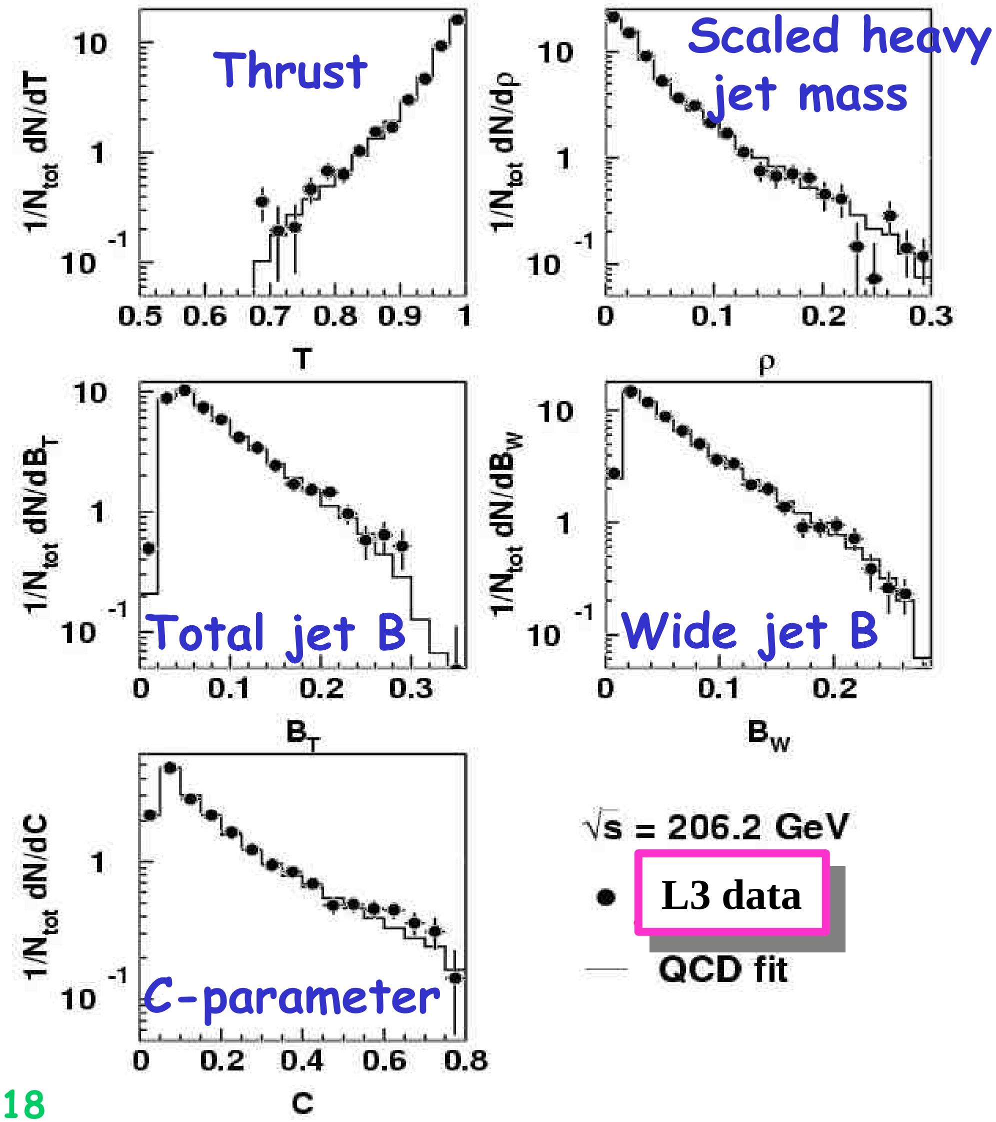
$$L = \ln\left(\frac{1}{y}\right) \rightarrow L' = \left(\left(\frac{1}{y}\right)^p - \left(\frac{1}{y_{\max}}\right)^p + 1\right)$$

- pQCD predictions corrected for hadronisation using MC

Fit Results

differential 2-jet rate (Durham)



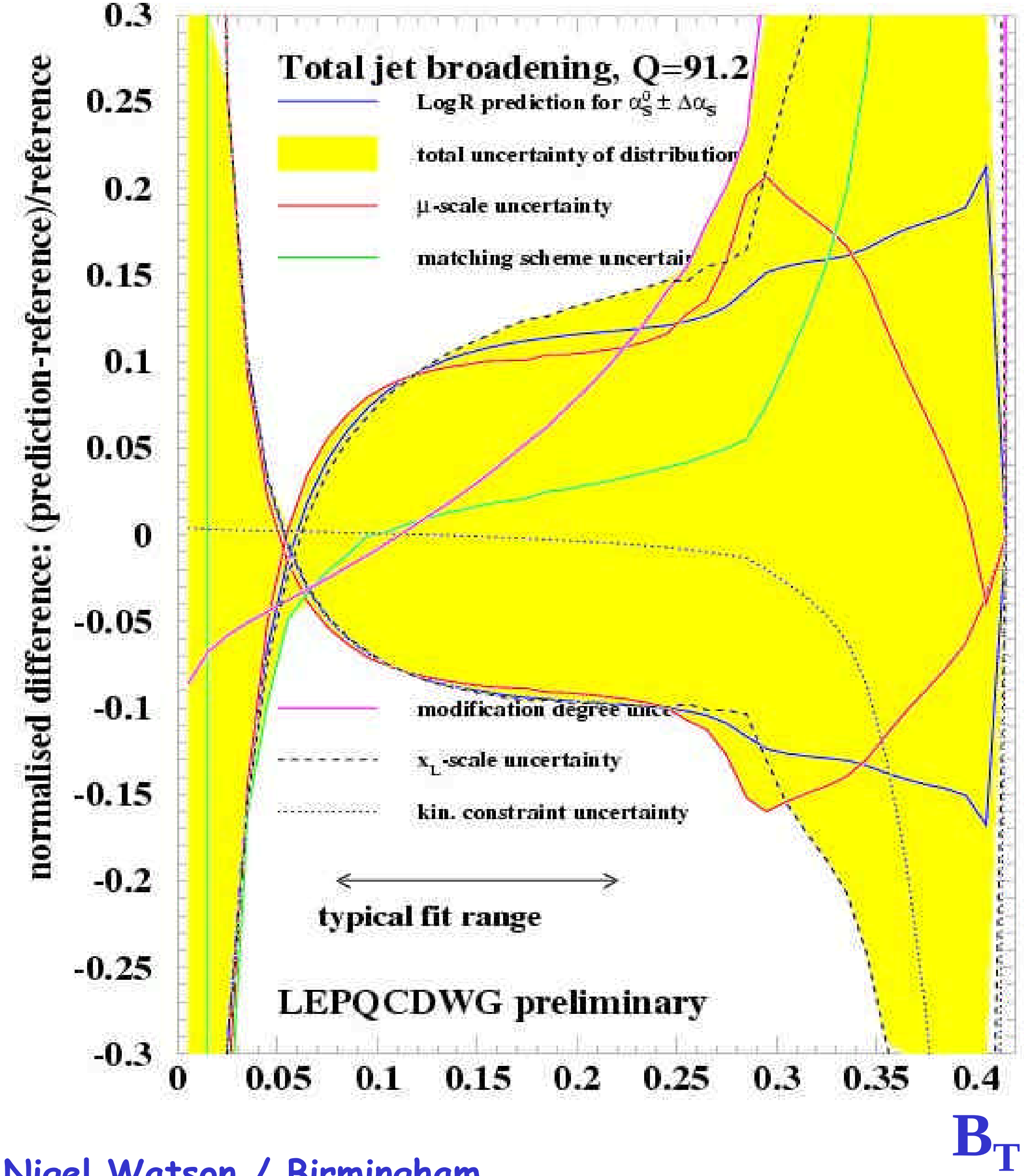


Uses Banfi, Salam and Zanderighi, JHEP 0201 (2002) 018

Systematic Uncertainties

- Experimental (little correlation, full covariance)
  - Event selection, particle reconstruction, detector corrections: vary cuts or models
  - Background subtraction (4-f criteria, s_{gg}, etc.)
  - ISR corrections (LEP2)
  - Typically around 1%
- Hadronisation (moderate correlation, on-diagonal covariance)
  - Model comparisons: string (Pythia), cluster (Herwig), colour dipole+string (Ariadne)
  - Model parameter variation (Pythia)
  - typically around 0.7-1.5 %
- Theoretical, pQCD (large correlation, on-diagonal only)
  - LEP QCD WG devised new prescription…

Theoretical Uncertainty

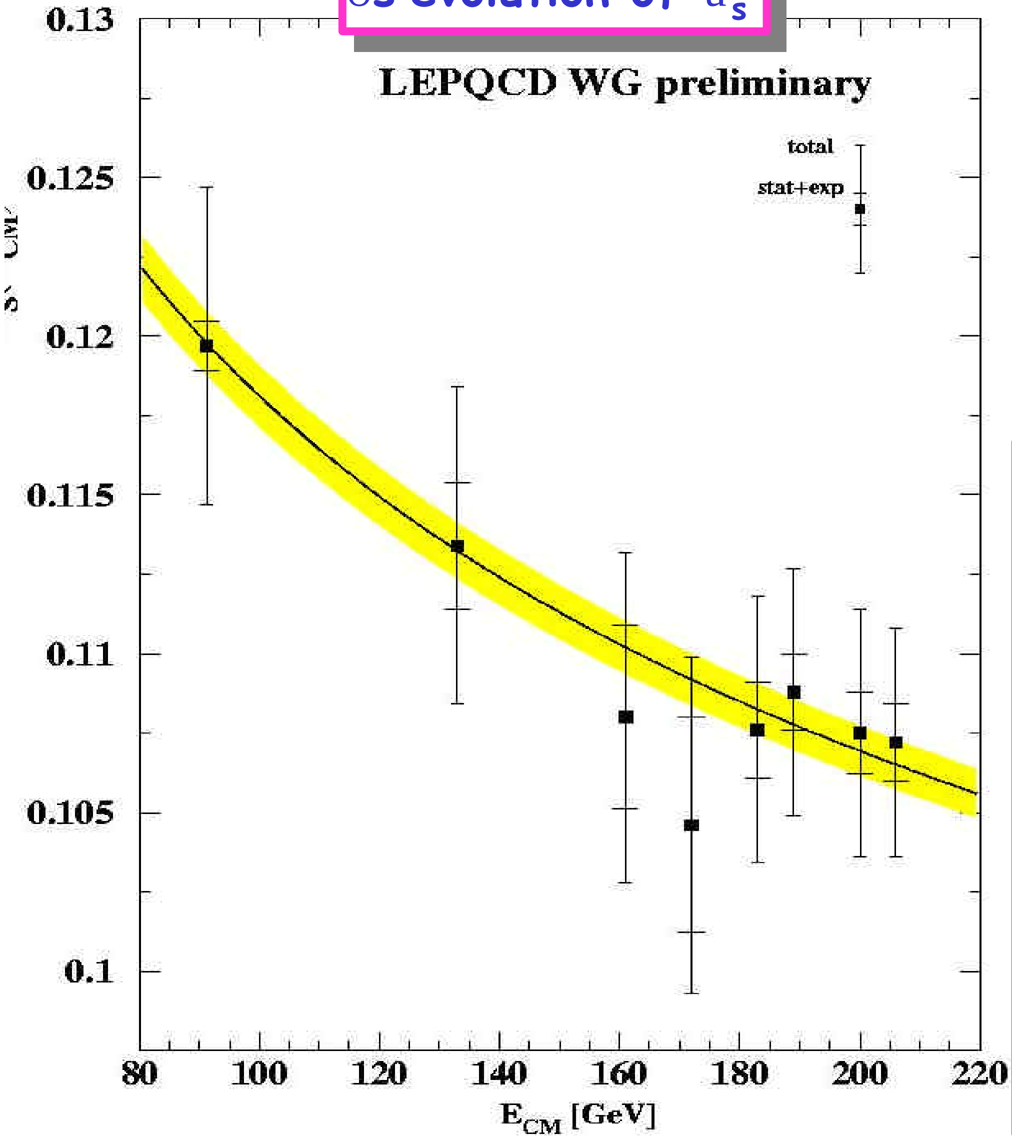


- Uncertainty band obtained (for fixed a_s), varying:
  - Renormalisation scale
  - Rescaling factor

    $L¢ = 1/\ln(y.x_L)$
  - Kinematic limit y_{max}
  - Modification degree
- For fixed reference prediction (ln$R$) find a_s variation which covers this band (within the fit range)
- Typically 3.5 - 5%

Combined Result

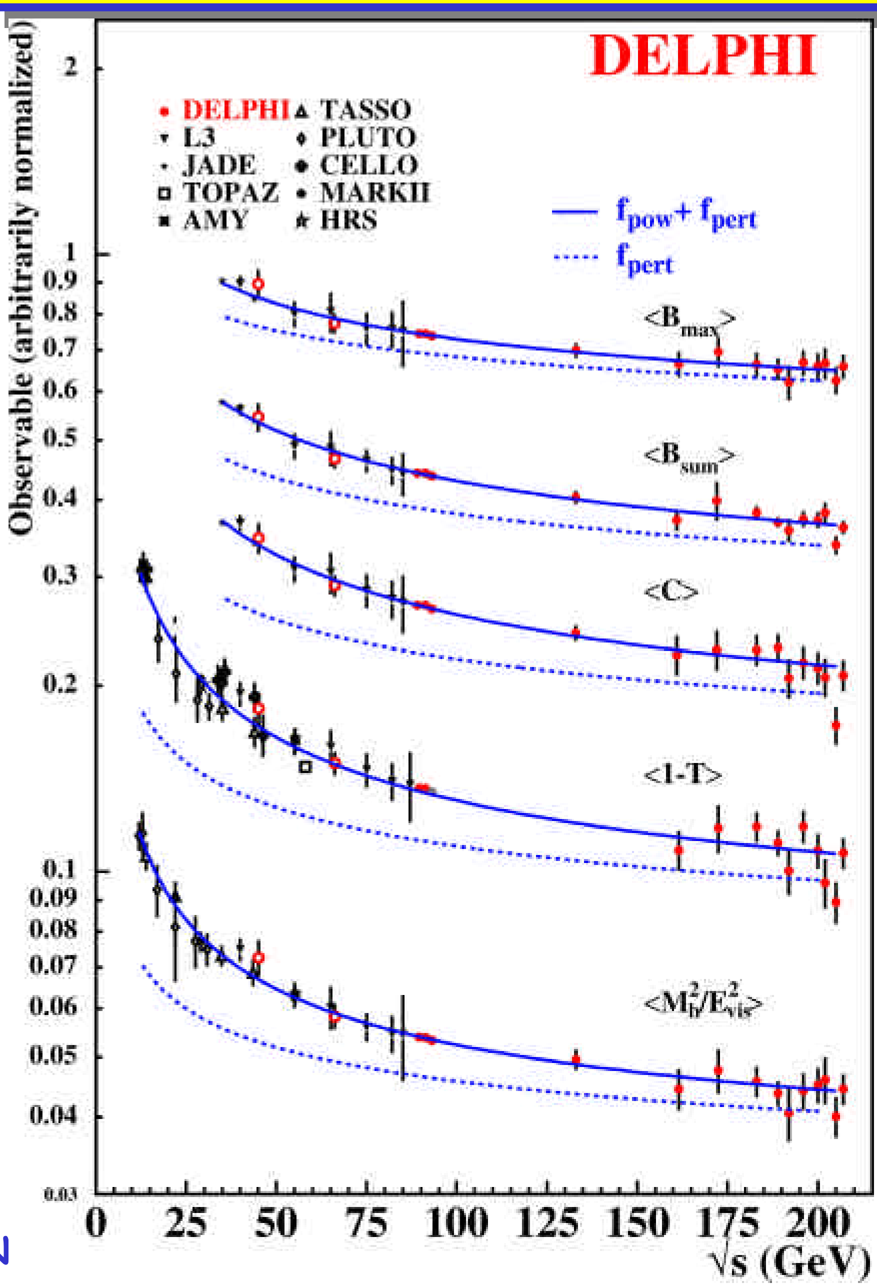
Ös evolution of a_s



- LEP QCD WG combination
  - 6 observables
  - ~8 nominal Ös (+L3 "ISR")
  - 4 experiments
  - Results evolved to M_Z

Prelim.	LEP I	LEP II	all LEP
$a_s(M_Z)$	0.1197	0.1196	0.1198
D stat.	0.0002	0.0005	0.0003
D expt.	0.0008	0.0010	0.0009
D had.	0.0010	0.0007	0.0008
D theo.	+0.0048 -0.0047	+0.0043 -0.0044	±0.0046
D Total	0.0049	0.0046	0.0048

Power Law Corrections

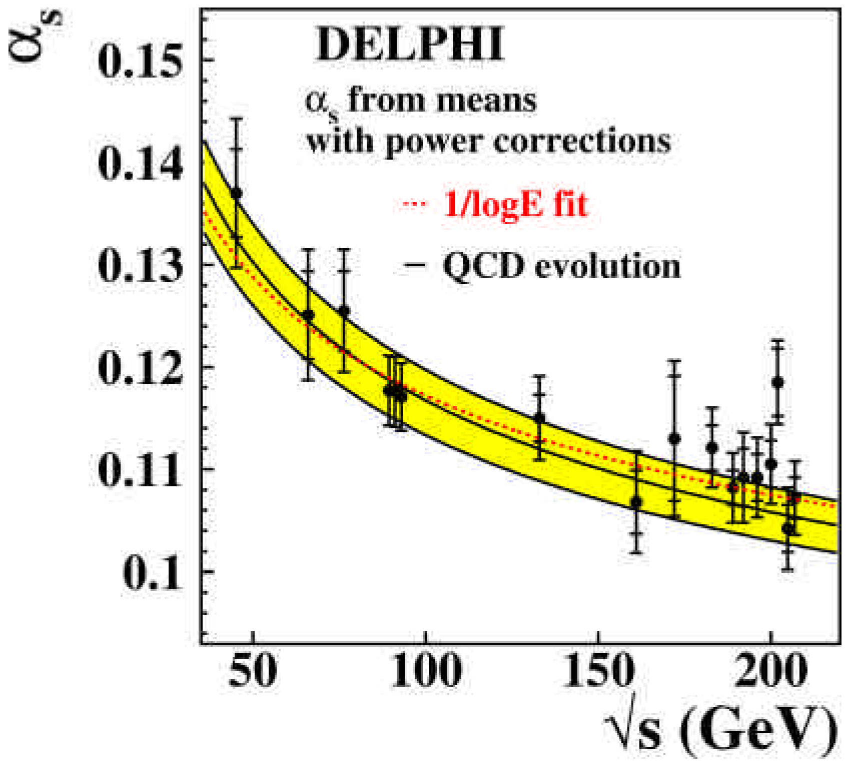


- Updated study (DELPHI):

$$\langle y\rangle = a_s(m^2)A + a_s^2(m^2)B + C\,\frac{a_0(m_{IR}^2)}{Q}$$

$\boxed{a_s(M_z)=0.1184 \pm 0.0033}$

(inc. $\pm$ 0.0031 (scale))



N

2002

4-jet rate

- Predictions (Durham) to NLO +resum

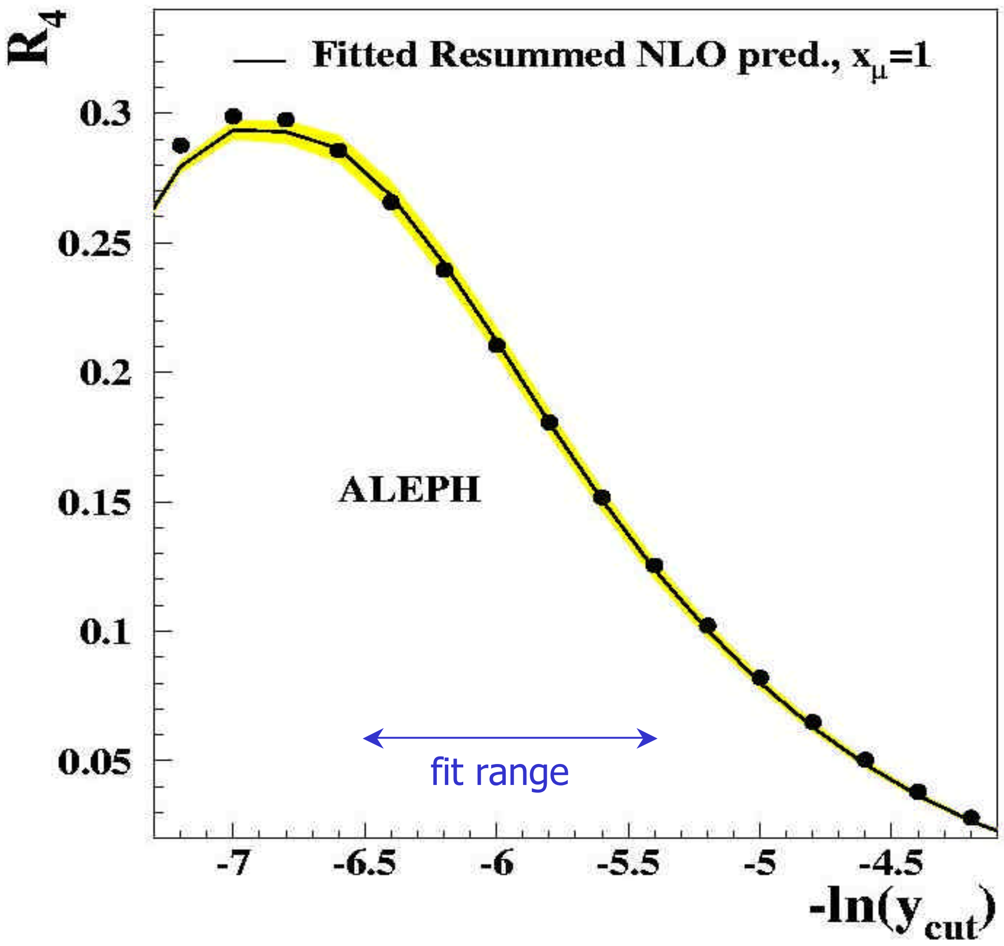
$$R_4(y) = a_s^2(m^2)B(y) + a_s^3(m^2)C(y)$$
$$+ f(a_s^n \ln^m y)$$
$$\frac{D a_s}{a_s} = \frac{1}{2}\frac{D s}{s}$$

- ALEPH (x_m=1)

$a_s(M_z)$ = 0.1170 ± 0.0001 (stat)
± 0.0003 (had.)
± 0.0008 (scale)
=0.1170 ± 0.0013

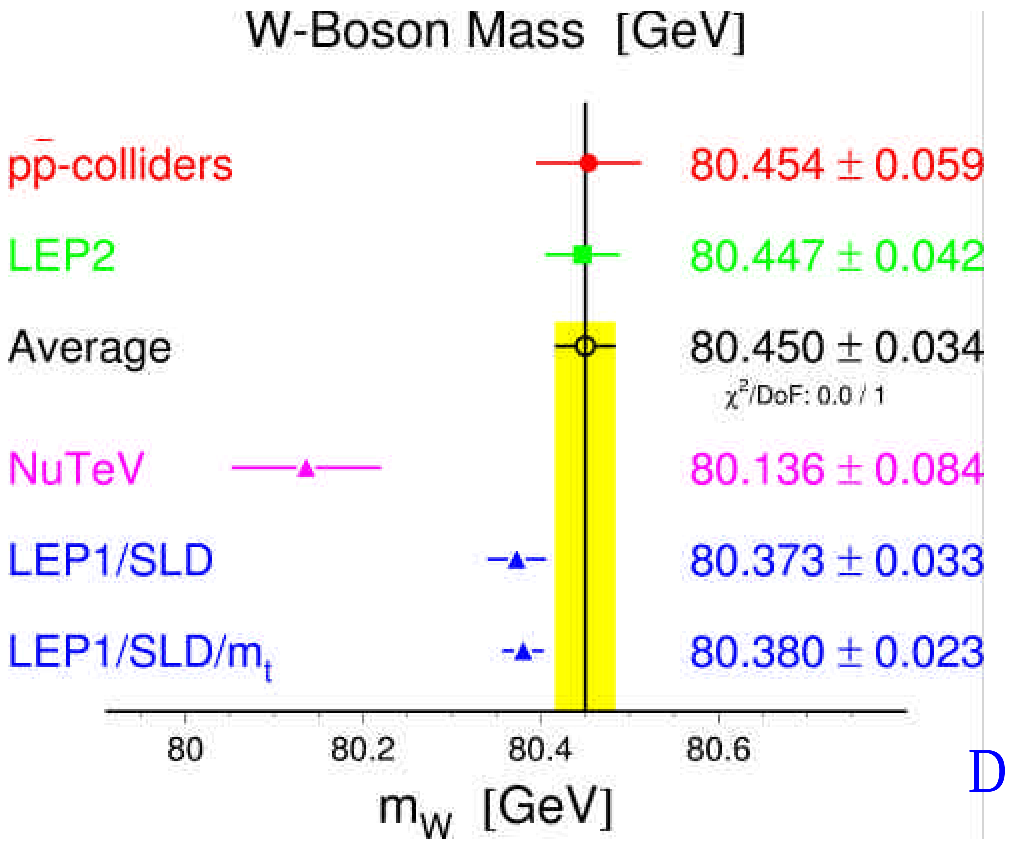
- x_m = 0.729 (fit for scale and a_s)

$a_s(M_z)$ = 0.1175 ± 0.0013



Similar to earlier DELPHI results

Motivation: W Boson Mass



- LEP gives best measurement
- Agreement, direct/indirect

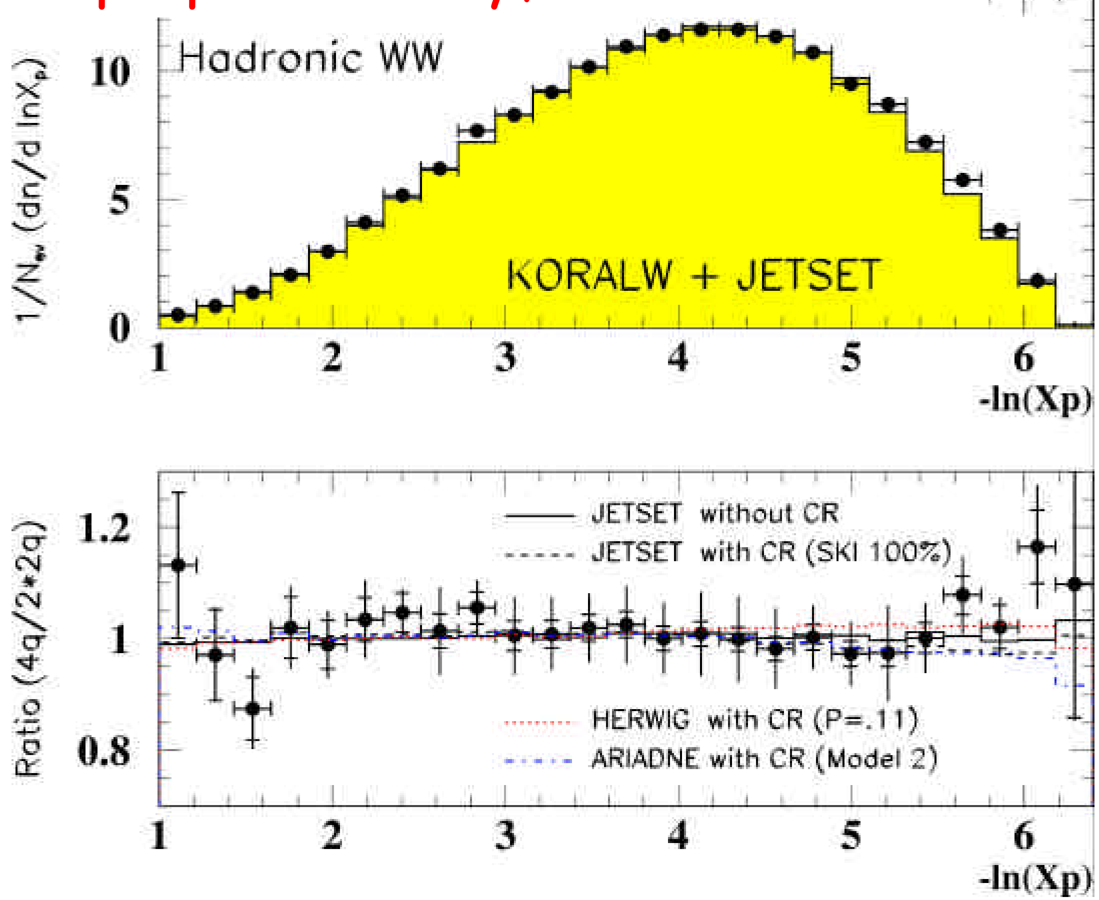
- Single dominant uncertainty:
  - "Final state interactions"
  - WW®qqqq only

D(W^+–W^-) decay vertices ~ 0.1 fm
hadronic scale ~ 1 fm

Þ Large spacetime overlap
Þ Colour exchange W^+ « W^-
Þ DM_W bias ~ 25-300 MeV

Charged Particle Multiplicity

Aleph preliminary, 189-207 GeV

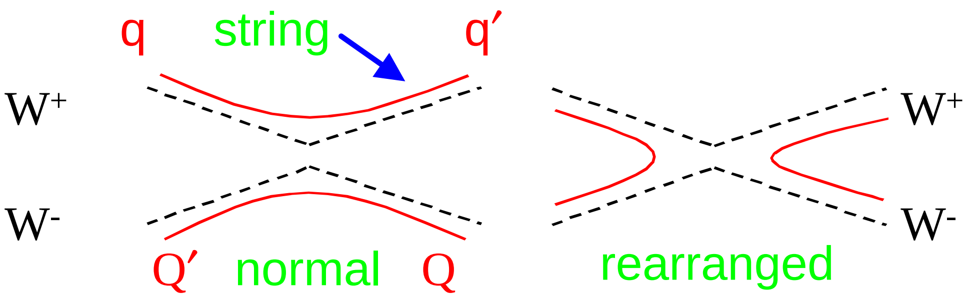


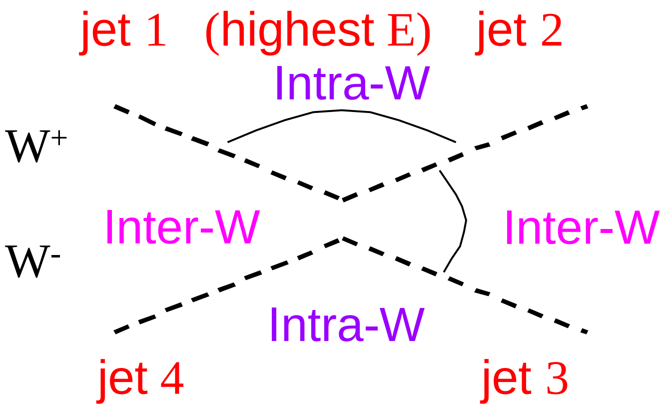
- CR may alter n_{ch} in qqqq
- W hadronisation modelling
  - Compare qqqq/qqlv
- More important for low p
- Studied by all LEP expts.
- ALEPH update, all data
  - Conclusion: only limited sensitivity to CR

$\Delta\langle n_{ch}\rangle$ = 4q - 2(qqlv) = 0.31 ± 0.23 ± 0.10

(within acceptance)

Particle Flow

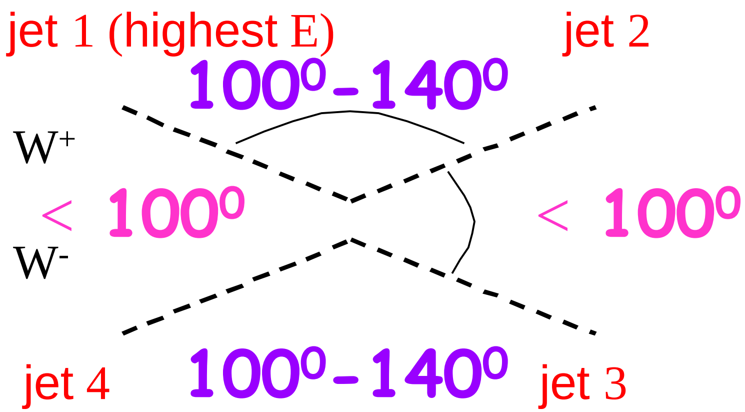




- Motivated by simple string picture of CR
- Regions of interest
  - Define 4 planes
  - Pair jet-jet Û W
  - Minimise Σ∠(j2-j3)+∠(j4-j1)
- Project particles ® planes
  - Compare intra-W / inter-W ~ "string effect"
  - Define R_N º $\dfrac{\text{ò intra-W}}{\text{ò inter-W}}$

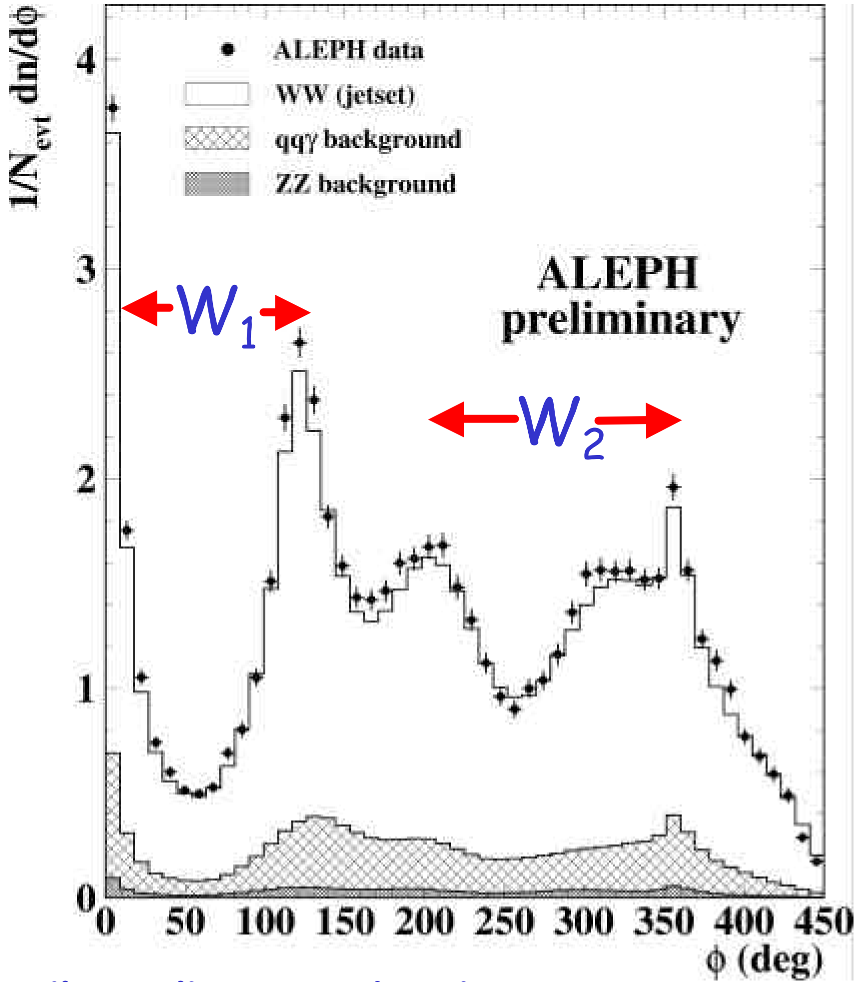
    (away from jet cores)

Event Selection



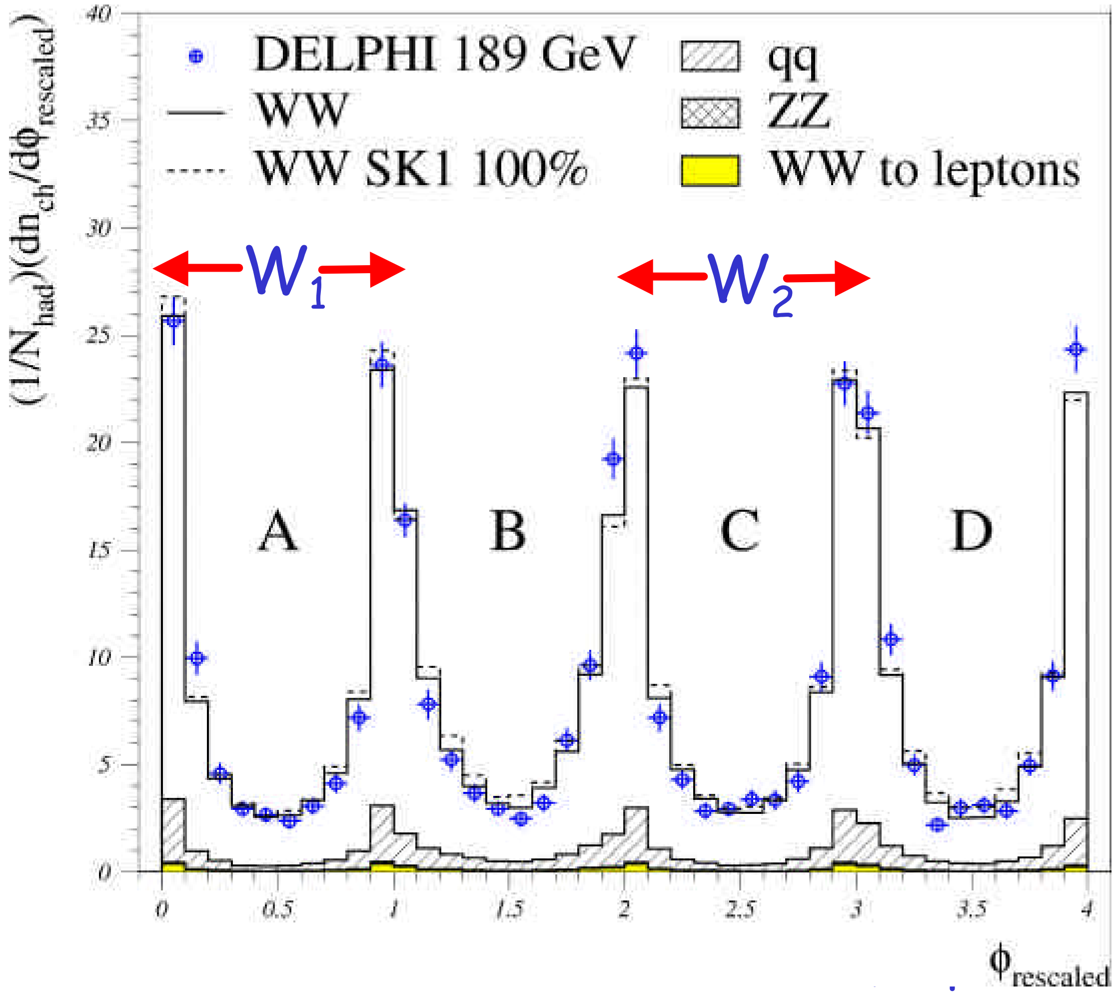
- **Topological**
  - 4 distinct jets, y_{34}>0.01
  - 2 angles < 100^0
  - 100^0 < angles < 140^0
  - Large/small not adjacent
  - Good jet-jet Û W
  - Efficiency ~ 15%
  - "Correct" pairing ~ 90%
- **W mass**
  - Minimise SĐ(j2-j3)+Đ(j4-j1)
  - Pairing integral to selection
  - Efficiency ~ 85% (A), 40% (O)
  - "Correct" pairing ~ 75% (A), 90% (O)

Particle Density

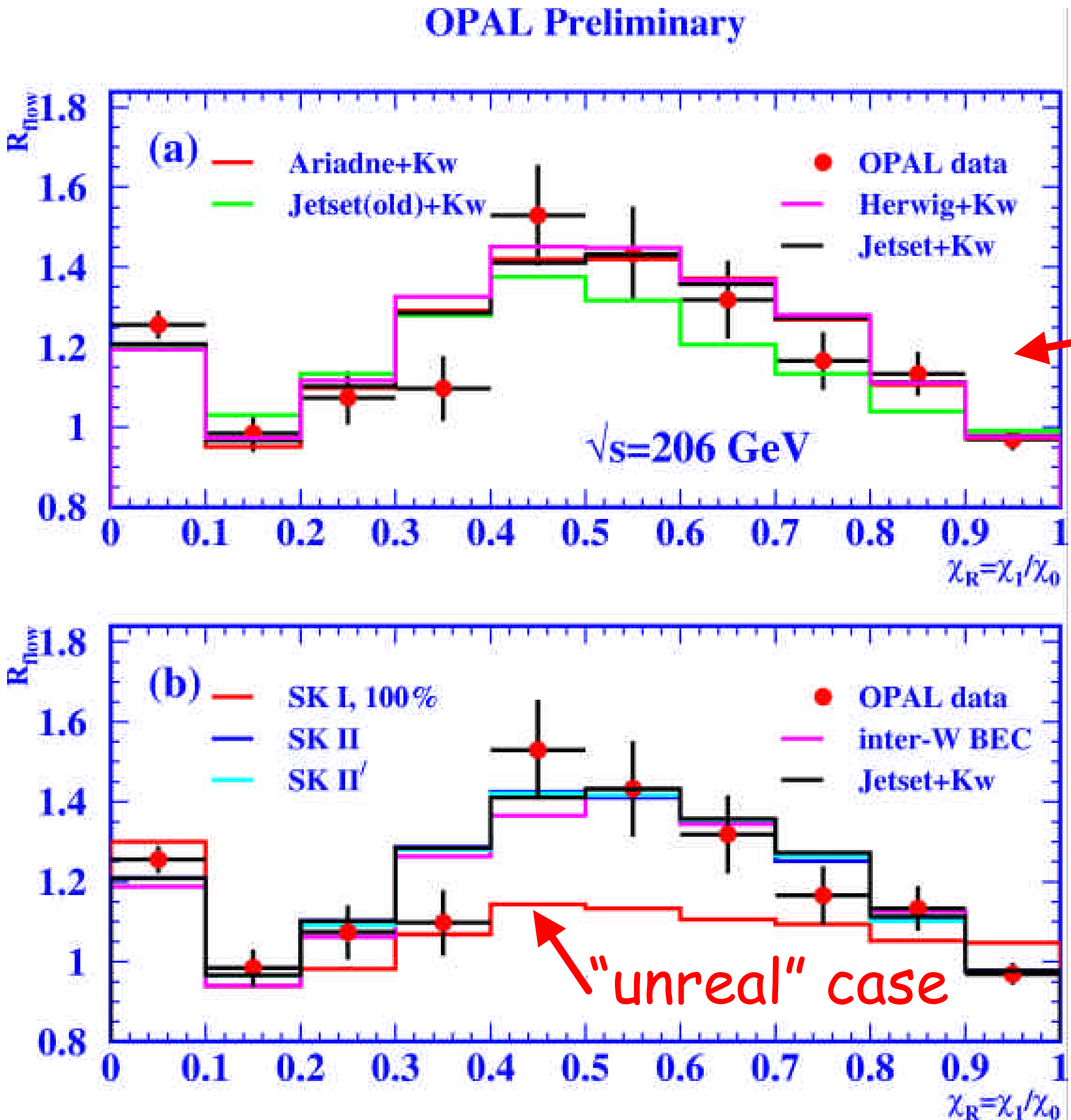


- "Raw" particle density
  - Non-planar
  - 4-jet structure evident

- Normalised particle density
  - Effect of CR shown



Particle Flow



- Ratio intra-W/inter-W particle density: R_{flow}
  - no-CR models
  - CR models
  - Most sensitivity outside jet cores
  - Statistically limited
    $\Rightarrow$ Combine LEP expts.

Quantitative Measure

- Quantify using ratio of sums, R_N

$$R_N = \frac{\int_{0.2}^{0.8} \frac{1}{N_{event}} \frac{\mathrm{d}n}{\mathrm{d}?_{\mathrm{R}}} \mathrm{d}?_{\mathrm{R}} \left(\text{intra - W regions}\right)}{\int_{0.2}^{0.8} \frac{1}{N_{event}} \frac{\mathrm{d}n}{\mathrm{d}?_{\mathrm{R}}} \mathrm{d}?_{\mathrm{R}} \left(\text{inter - W regions}\right)}$$

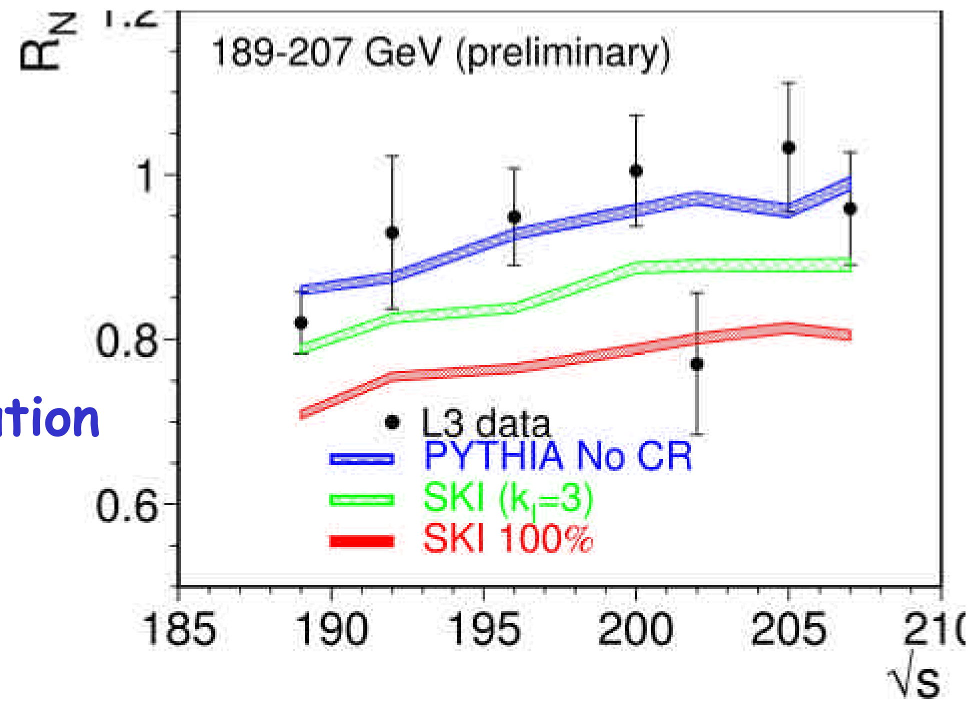
- Different experimental acceptances, normalise to shared no-CR MC sample before comparison

- Very different selections, weight by sensitivity for each CR model, i:

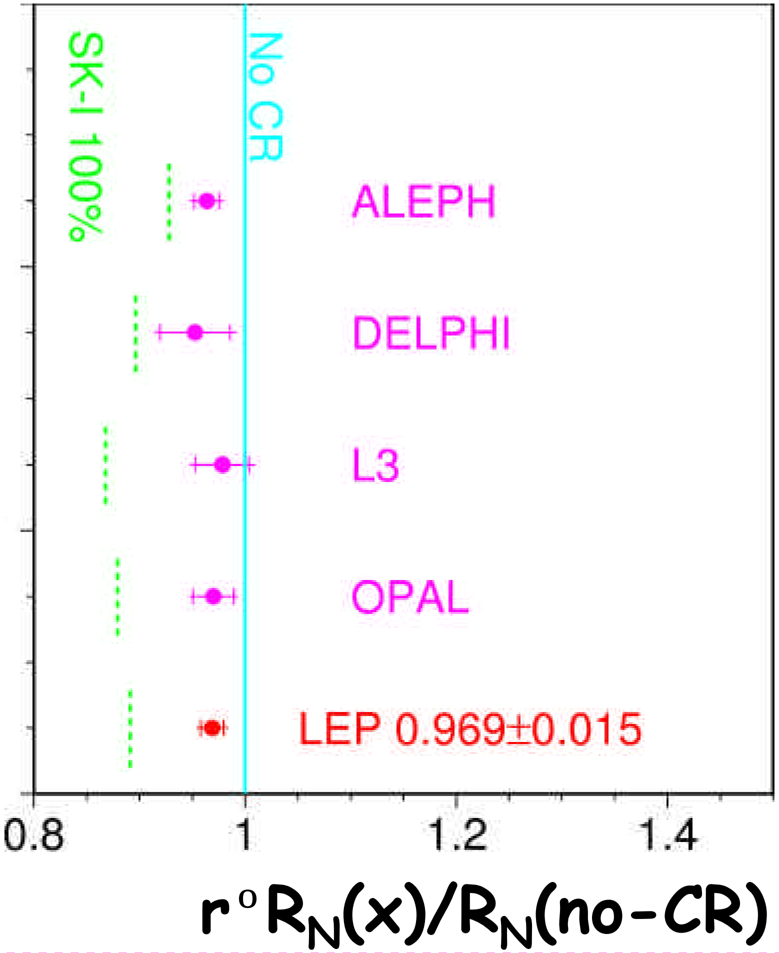
$$w_i = \frac{\left(R_N^i - R_N^{\text{no-CR}}\right)^2}{(\mathrm{d}R_N^{\text{stat.}})^2 + (\mathrm{d}R_N^{\text{syst.}})^2}$$

Combination Systematics

- Each expt. evolves their data to single Ös point and averages
- Systematics considered correlated or uncorrelated between expts.
- WW signal
  - ⇒ Hadronisation model, spread in predictions of Koralw + {Jt,Hw,Ar}
  - ⇒ BEC, D{intra-W — no-BE}   [no evidence for inter-W BEC]
- (4-jet) Background subtraction
  - ⇒ Z ® qq, vary s$_{qq}$ ±10%
  - ⇒ Z ® qqqq, vary s$_{ZZ}$ ±15%
  - ⇒ Z ® qq hadronisation models
- Energy dependence
  - ⇒ Model dependence of Ös evolution
- Detector effects



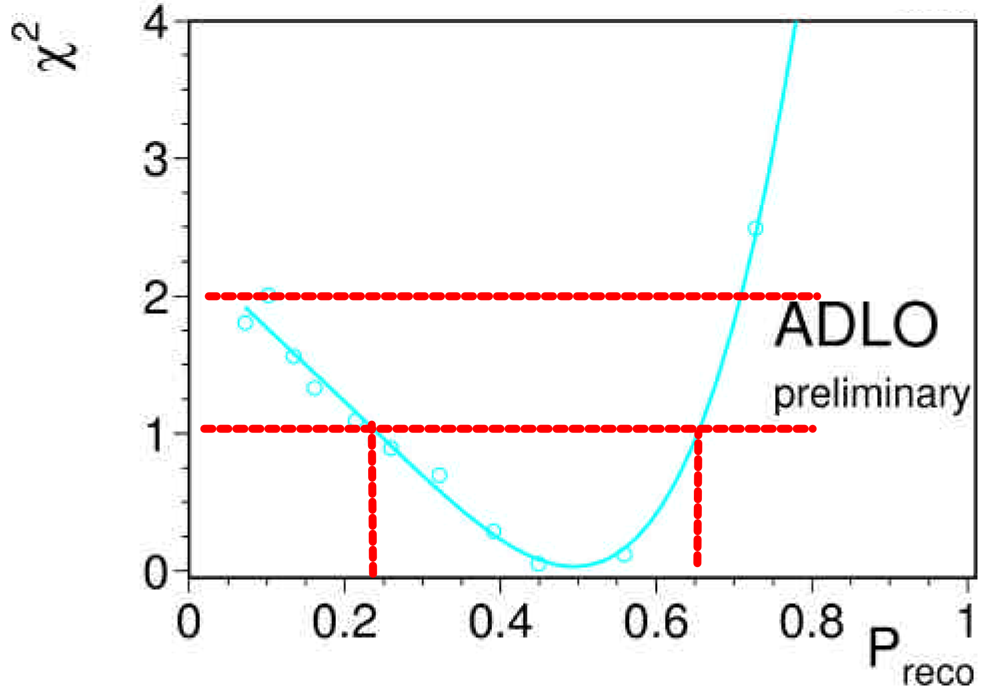
LEP CR Combination: SK-I model



r("SK1")=0.891

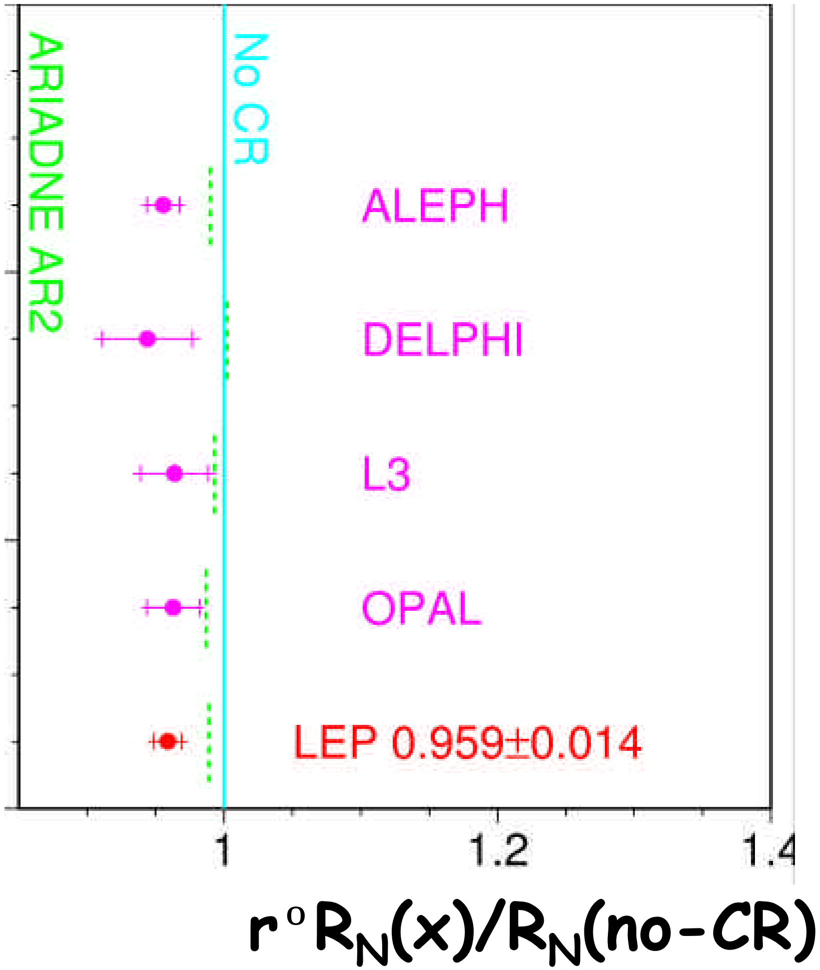
r(data)=0.969±0.015

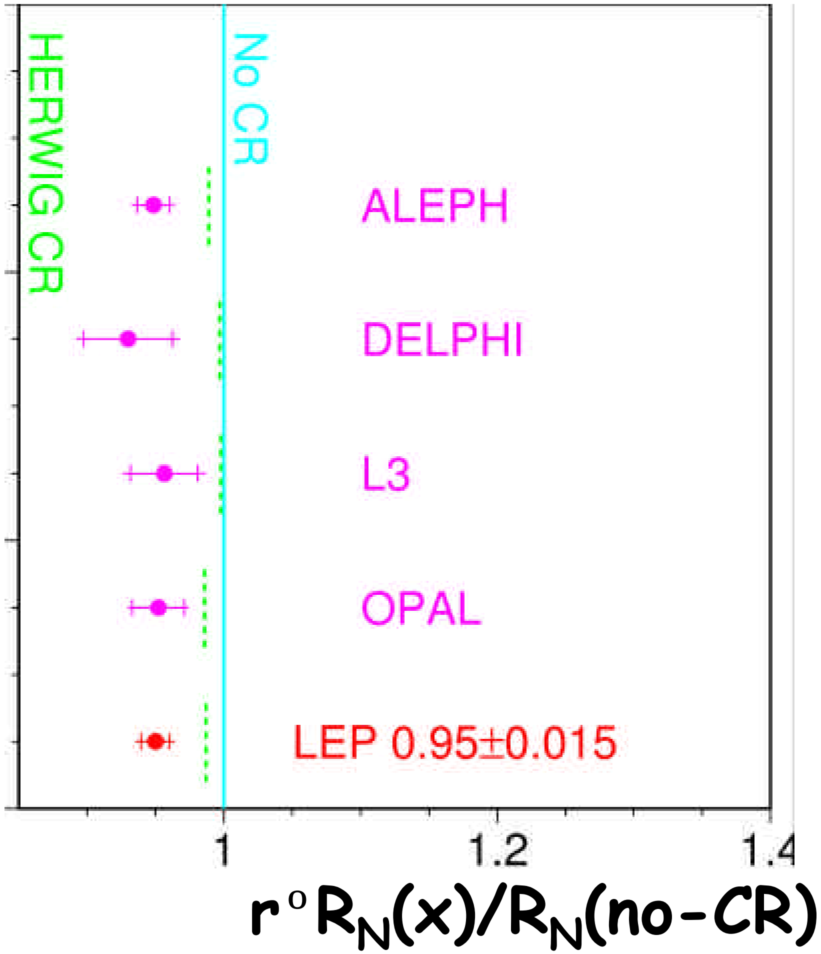
5.2σ



- NB: Extreme, 100% SK-I
- Vary reconnected fraction in combination
- Preferred P_{reco} ~ 49% in data
- Increases Dm_W from LEP

Ariadne and Herwig CR models





r("Ar-2")=0.989
r(data)=0.959±0.014
2.1σ

r("Herwig-CR")=0.987
r(data)=0.950±0.014
2.6σ

Summary

- α_s
  - New LEP average, LEP1+LEP2 event shapes
  - Improved prescription for theoretical uncertainties
  - V. precise α_s from 4-jet rate, mean values+power corrections

- Colour Reconnection
  - First combination, Summer 2002, all data
  - Extreme case "SKI 100%" excluded (favour P_{reco}= 49%)
  - Limited sensitivity to Ariadne, Herwig CR models
  - Data compatible models, with/without CR
  - Effect on W mass from Ariadne CR large, not understood!
  - Impact of qqqq channel on LEP m_W: 9%!