Colour Reconnection Effects in WW Production at LEP

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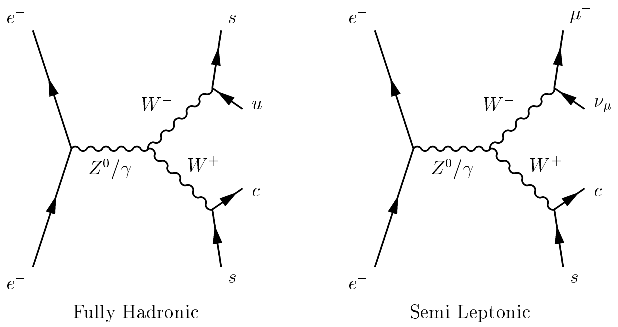
WW at LEPII

Produced in e$^+$e$^-$ collisions $\sqrt{s} > 161$ GeV

ALEPH, DELPHI, L3 and OPAL (ADLO) each collected ∼10,000 WW pairs

from 161 GeV to 209 GeV



$\Gamma(WW \to q\bar{q}q\bar{q}) \sim 46\%$

$\Gamma(WW \to q\bar{\ell}\nu q) \sim 44\%$

$\Gamma(WW \to \ell\nu\ell\nu) \sim 10\%$

W lifetime ~ 0.1 fm$/c$
QCD hadronisation scale ~ 1 fm

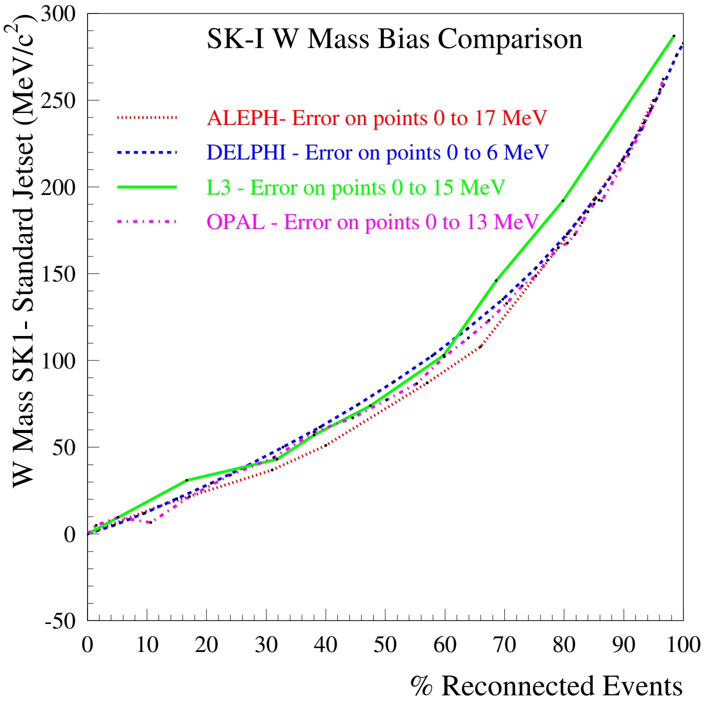
⇒ may not hadronise independently

⇒ colour reconnection (rearrangement)

Colour Reconnection

→ Might affect multiplicity and particle kinematics.

→ Might affect the W mass reconstruction.



Can occur in the:

- Perturbative phase: small effects

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- Non-perturbative phase:
  - Various models exist...

Models for Colour Reconnection

- JETSET CR SK I, II and II′

  Cannot be tuned at the Z^0

  - SKI $\rightarrow$ flux tubes, $P_{reco} = 1 - e^{-\kappa_I V_{overlap}}$
  - SKII and SKII′ $\rightarrow$ vortex lines

    reconnection if strings cross
  - CR minimises string length (reduces multiplicity)

- JETSET CR GAL
  - $P_{reco} = R_0(1 - e^{-b\Delta A})$

    ΔA - area difference between the two configurations (in energy-momentum coordinates), $R_0 \sim 1/N_C^2 \sim 0.1$
  - Reduction in multiplicity

- ARIADNE CR
  - Gluons $E < 2$ GeV reconnect the W's (AR2)
  - Reduction in multiplicity

- HERWIG CR
  - CR occurs if cluster *size* can be reduced
  - Cluster *mass* determines multiplicity - increase

WW Multiplicity - ALEPH update

Measure the charged particle multiplicities in fully hadronic ($4q$) and semi-leptonic ($2q$) events in data and compare $4q - 2(2q)$

Experiment	$\sqrt{s}$ GeV	4q - 2(2q)
ALEPH*	189-207	$0.31 \pm 0.23 \pm 0.10$
DELPHI	183-189	$-0.26 \pm 0.60 \pm 0.38$
L3	183-189	$-0.29 \pm 0.26 \pm 0.30$
OPAL	183-202	$0.07 \pm 0.39 \pm 0.37$

*Not corrected for event selection and P_T cut of 200 MeV

Account for selection biases by taking the double difference

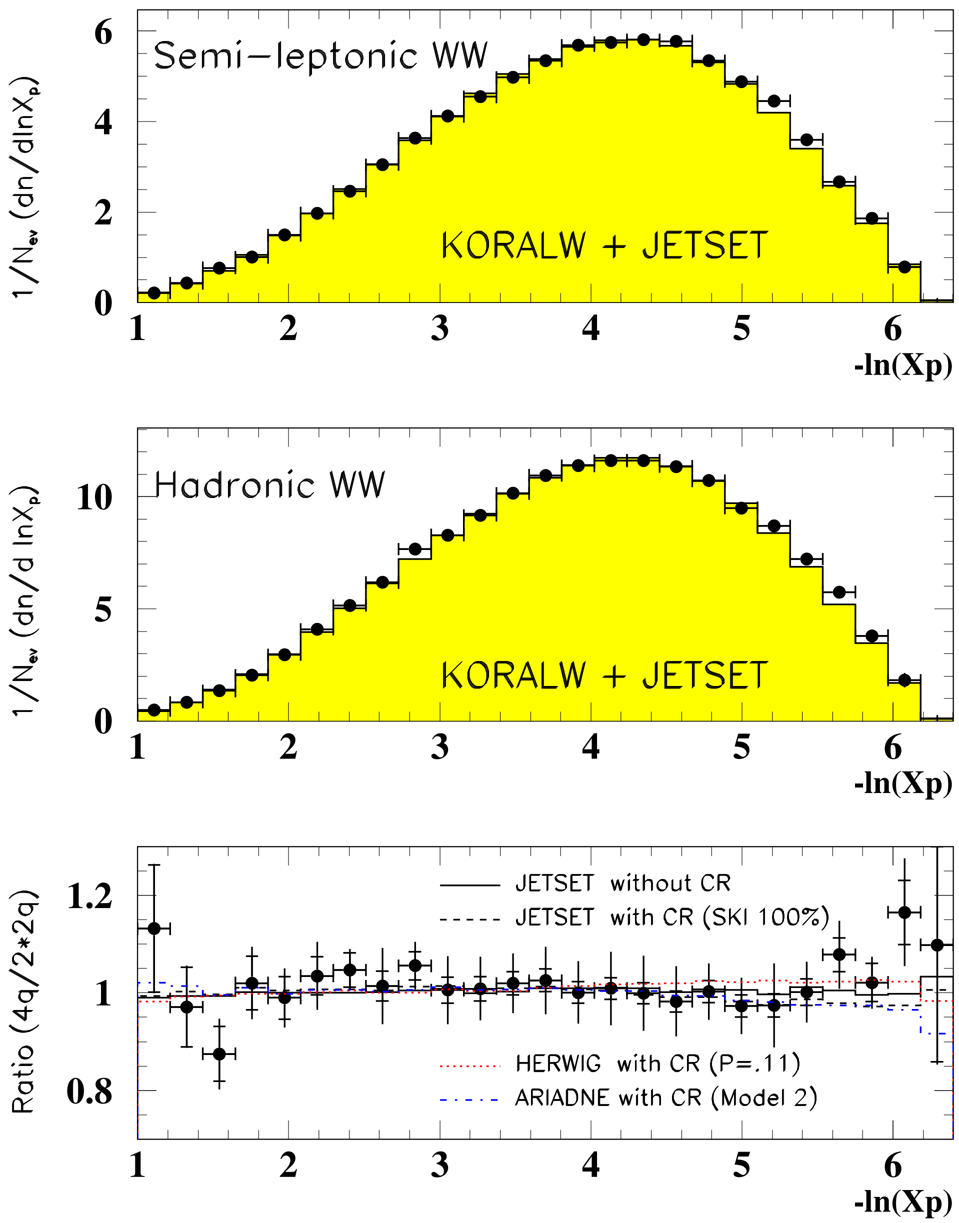
$$\Delta_{cr} = [4q - 2(2q)]_{data} - [4q - 2(2q)]_{mc}$$

ALEPH Preliminary

Monte Carlo	$[\mathbf{4q\text{-}2(2q)}]_{mc}$	Δ_{cr}	significance
JETSET	0.17±0.03	0.14±0.23±0.1	0.6σ
HERWIG	0.17±0.03	0.14±0.23±0.1	0.6σ
ARIADNE	0.21±0.03	0.10±0.23±0.1	0.4σ
JETSET+SKI	-0.04±0.03	0.35±0.23±0.1	1.4σ
JETSET+SKII	0.11±0.03	0.20±0.23±0.1	0.8σ
JETSET+SKII′	0.07±0.03	0.24±0.23±0.1	1.0σ
HERWIG+CR	0.46±0.03	-0.15±0.23±0.1	-0.6σ
ARIADNE+AR2	-0.05±0.03	0.36±0.23±0.1	1.4σ
JETSET+GAL	0.19±0.03	0.12±0.23±0.1	0.5σ

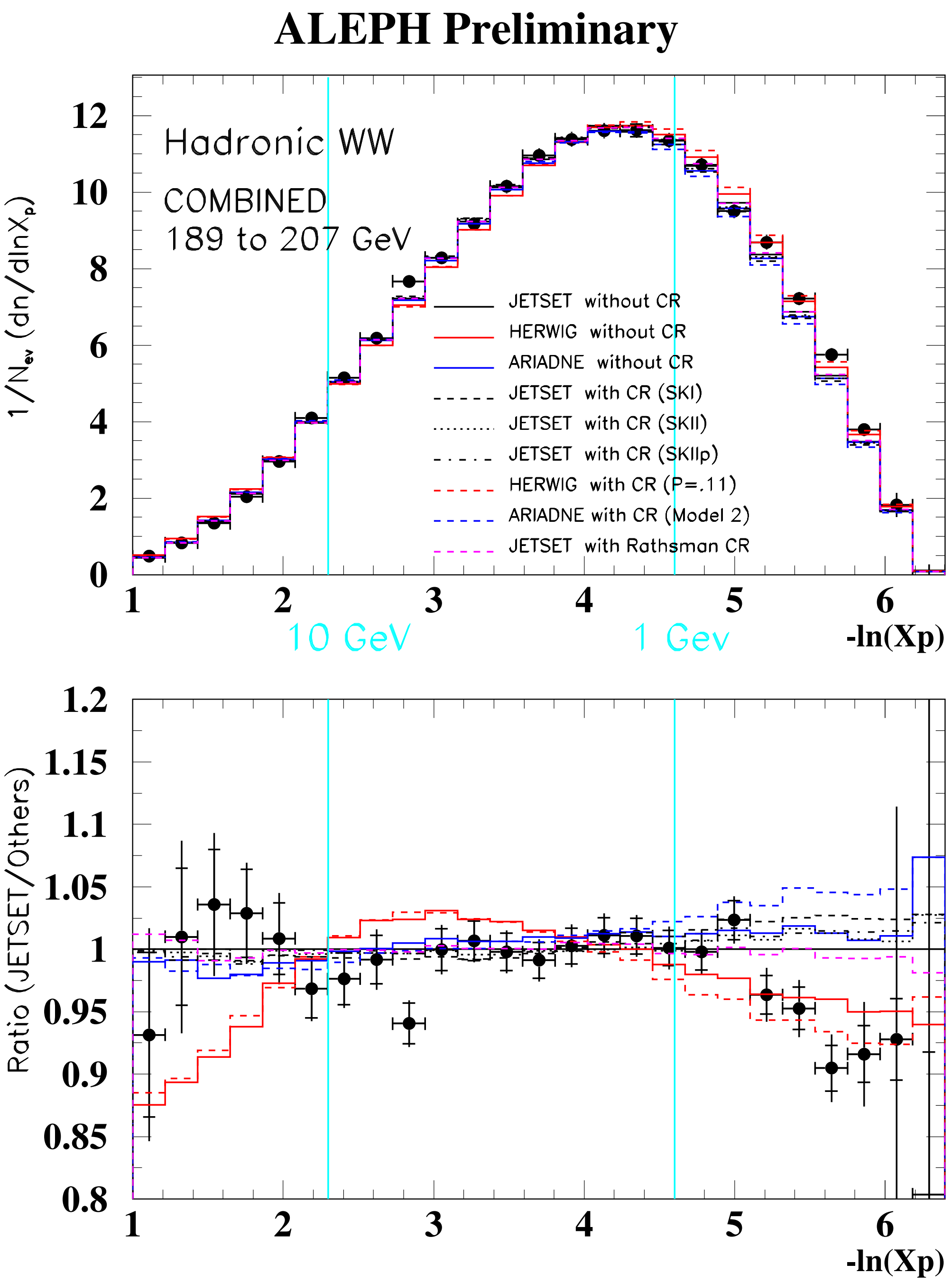
Fragmentation Functions

Combined 189-207 GeV



$$X_p = \frac{2p}{\sqrt{s}} = \frac{p}{E_{beam}}$$

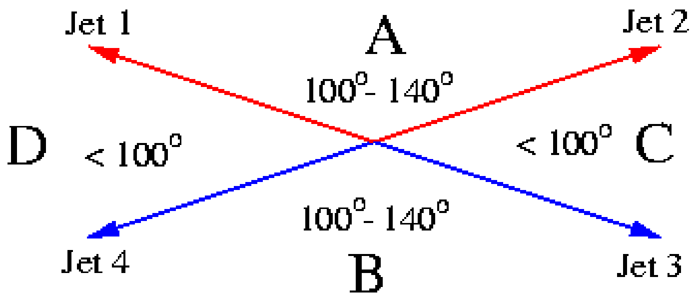
Fragmentation Functions



The particle flow method

Compare the particle flow in the regions between jets from the same W (A & B) and between jets from different W's (C & D)

- Topological selection



used by L3, DELPHI, ALEPH (as a cross-check)

event selection efficiency 14%

correct pairing 90%

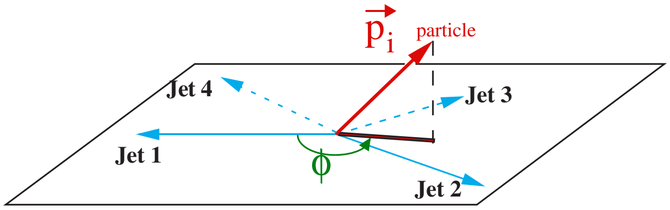
- W mass analysis selection:

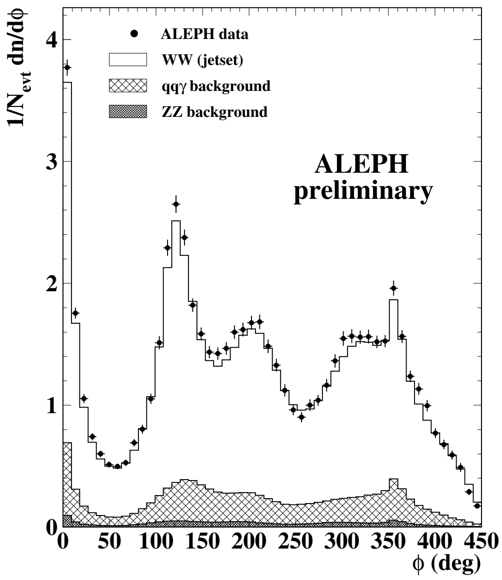
used by ALEPH, OPAL

event selection efficiency 85% (A) 40% (O);

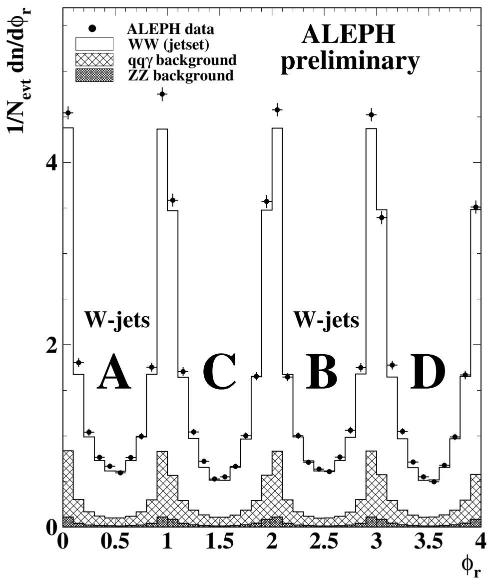
correct pairing 75% (A) 90% (O);

Project each particle onto a plane: $\phi < \phi_{j\ j+1}$

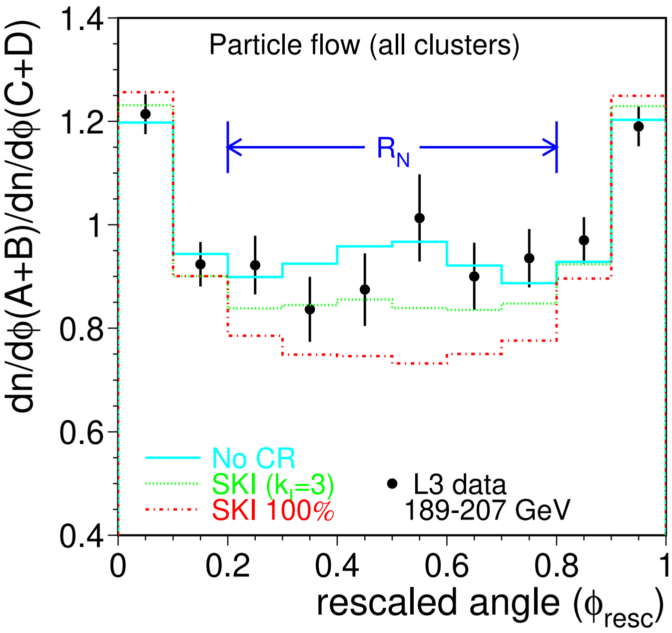




Rescale the distribution $\phi^r = \phi/\phi_{j\ j+1}$:

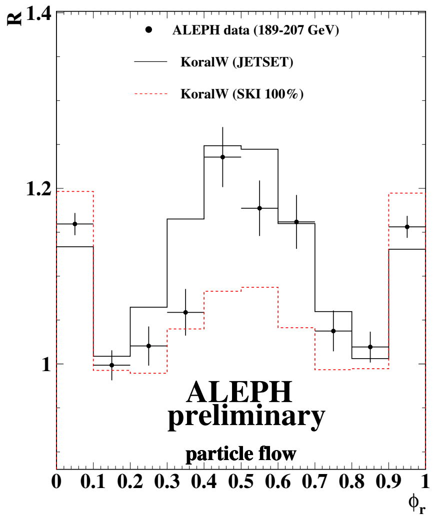


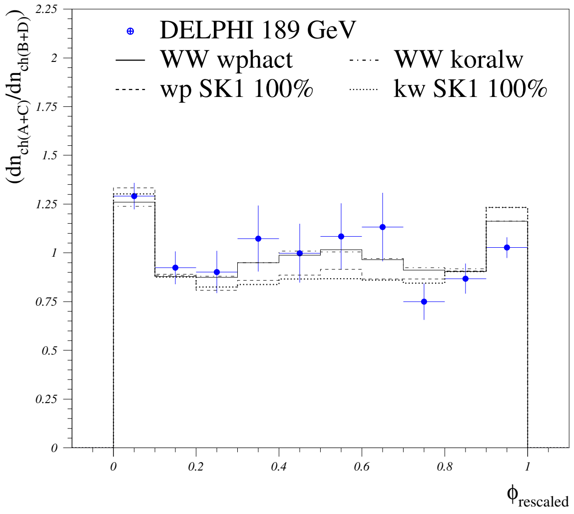
Take the ratio $R = \frac{A+B}{C+D}$



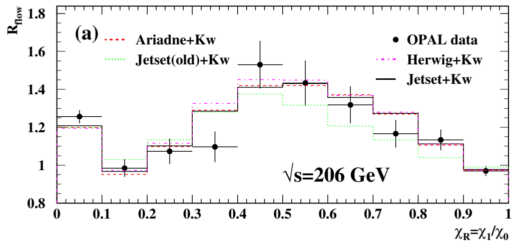
Integrate the most sensitive region, then take the ratio to form

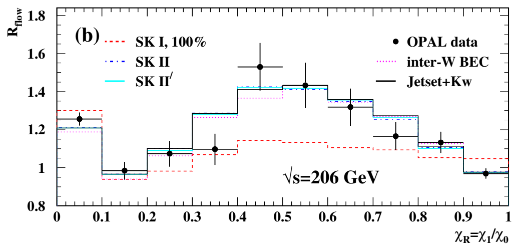
$$R_n(0.2 - 0.8) = \frac{\int_{0.2}^{0.8} (\frac{dn_A}{d\phi^r} + \frac{dn_B}{d\phi^r}) d\phi^r}{\int_{0.2}^{0.8} (\frac{dn_C}{d\phi^r} + \frac{dn_D}{d\phi^r}) d\phi^r}$$





OPAL Preliminary





$$\text{Statistical sensitivity} = \frac{|R_n(\text{model noCR}) - R_n(\text{model CR})|}{(\sigma_{R_n})_{stat}}$$

$(\sigma_{R_n})_{stat}$: statistical error on the full data sample (189 - 208 GeV)

Experiment	JETSET (SKI 100%)	HERWIG (11%)	ARIADNE (50%)
ALEPH	5.9	1.0	0.9
DELPHI	3.2	0.1	0.1
L3	5.0	0.0	0.2
OPAL	6.3	1.2	0.4

Systematic Uncertainties

- Inter-W Bose-Einstein correlations
- Background shape and cross-section

  $e^+e^- \rightarrow Z^0/\gamma \rightarrow q\bar{q}$

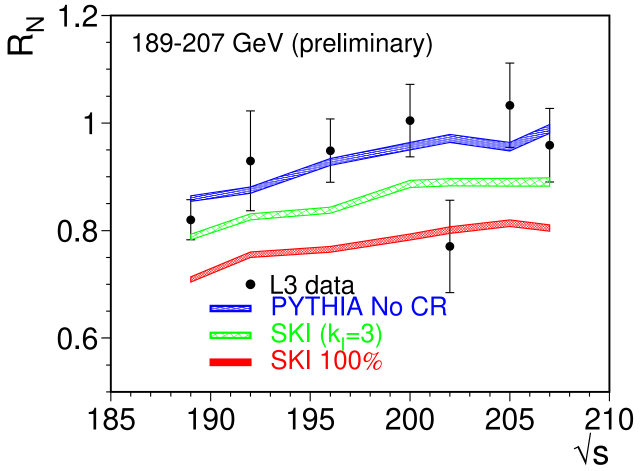
  $e^+e^- \rightarrow Z^0Z^0 \rightarrow q\bar{q}q\bar{q}$
- Detector effects (different for each experiment)
- Finite MC statistics
- Fragmentation

$\rightarrow$ assign an error assuming the two processes factorise

$\rightarrow$ compare data to overall "fragmentation + CR" in a model

For LEP combination: systematic uncertainties separated into correlated and uncorrelated between the experiments

Determine energy dependence from unreconnected JETSET MC samples and rescale to a single centre-of-mass energy



Statistically weighted average is formed

$$R_n(data) \pm \sigma(stat) \pm \sigma(syst) \pm \sigma(extrapol.)$$

at 189 GeV

Experiment	R_n (data)
ALEPH	$1.095 \pm 0.014 \pm 0.006 \pm 0.006$
DELPHI	$0.900 \pm 0.031 \pm 0.015 \pm 0.012$
L3	$0.844 \pm 0.022 \pm 0.021 \pm 0.002$
OPAL	$1.257 \pm 0.025 \pm 0.020 \pm 0.003$

Now compare Data with Monte Carlo:

Data - Model

Experiment	JETSET	SKI(100%)	HWG	HWG CR	ARIADNE	AR2
ALEPH	-2.44σ	2.87σ	-4.33σ	-3.17σ	-3.54σ	-2.26σ
DELPHI	-1.20σ	1.47σ	-1.83σ	-1.77σ	-1.44σ	-1.50σ
L3	-0.59σ	3.13σ	-1.24σ	-1.20σ	-1.01σ	-0.85σ
OPAL	-1.21σ	3.65σ	-1.95σ	-1.39σ	-1.52σ	-0.99σ

σ - total error, includes $\sigma(stat)$, $\sigma(syst)$, $\sigma(extrapol.)$ and error from limited MC statistics

Compare data with other models:

Experiment	Data - SKII	Data - SKII$'$	Data - GAL*
ALEPH (Mass)	-2.01σ	-2.32σ	-1.65σ
L3	-0.16σ	-	-
OPAL	-1.05σ	-1.18σ	-

* reconnection parameter $R_0 = 0.004$, from a global fit to the Z^0 data

LEP Combination procedure

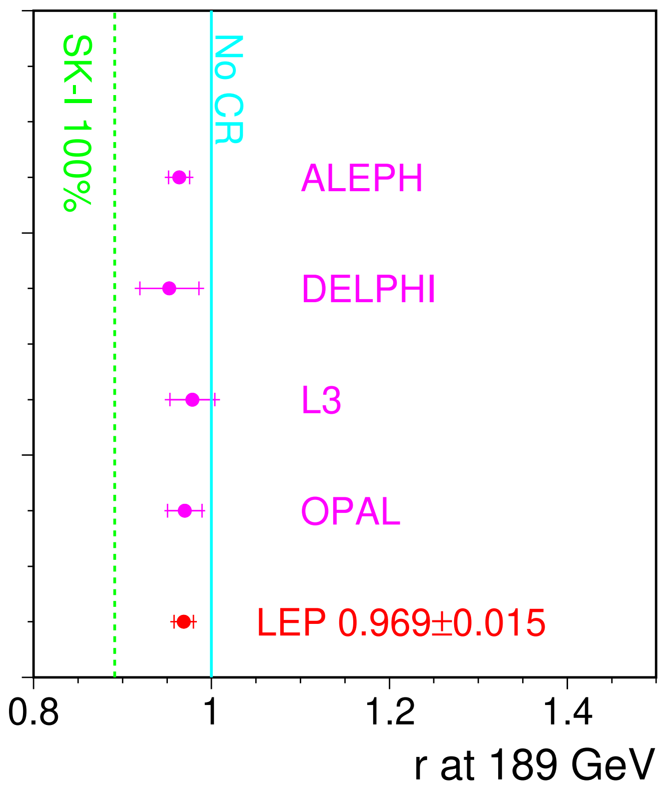
- Use common files, generated with KORALW at 188.6 GeV and hadronised with JETSET, HERWIG, ARIADNE
- Form the ratio $r = \frac{R_n^{data}}{R_n^{m,noCR}}$ for each experiment and for each model m
- For each model combine the r values of the four experiments for that model with weights

$$w^m = \frac{(R_n^{m,CR} - R_n^{m,noCR})^2}{\sigma^2(stat.) + \sigma^2(syst.)}$$

Combined results

- SKI 100% (JETSET)

r^{ADLO}=0.969±0.011(stat.)±0.009(syst.correl.)±0.006(syst.uncorrel.)
r^{ADLO}(SKI)=0.891



Model	Data - MC CR	Data - MC noCR
JETSET SKI	$+5.2\sigma$	-2.0σ

- AR2 (ARIADNE)

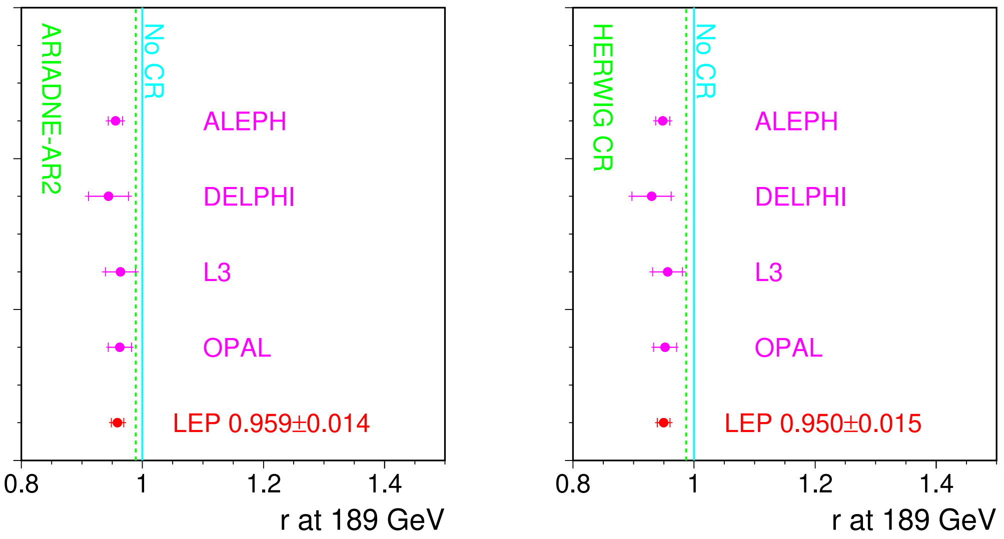
r^{ADLO}=0.959±0.010(stat.)±0.009(syst.correl.)±0.005(syst.uncorrel.)

r^{ADLO}(AR2)=0.989

- HERWIG CR (HERWIG)

r^{ADLO}=0.950±0.011(stat.)±0.009(syst.correl.)±0.005(syst.uncorrel.)

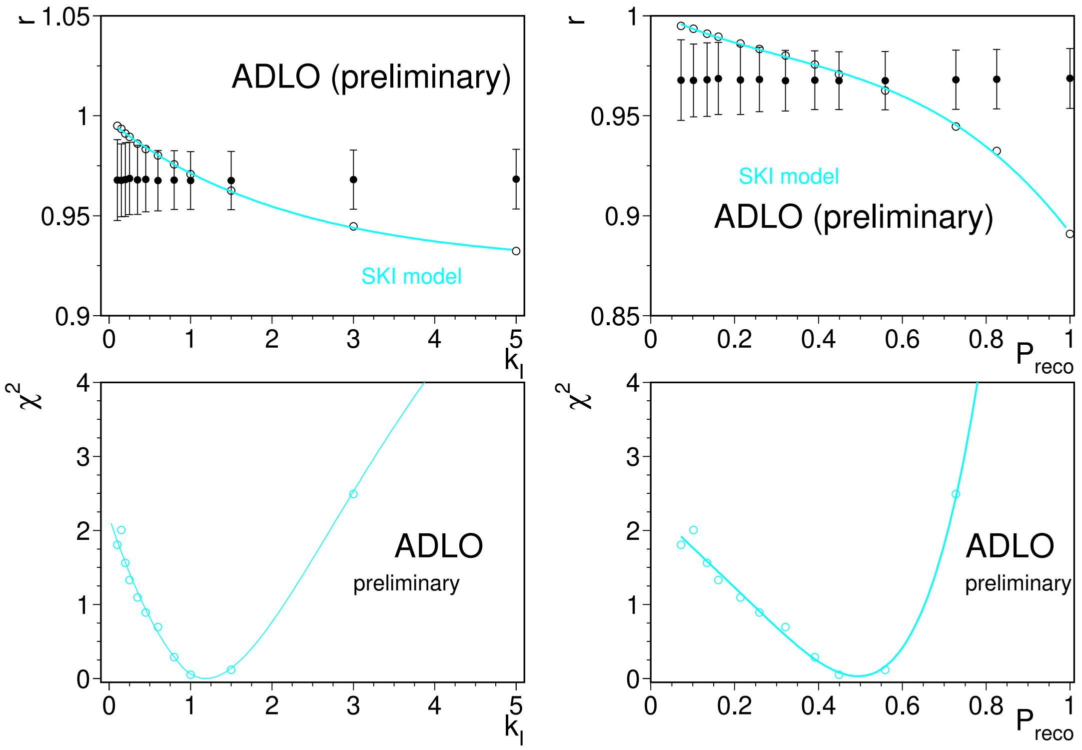
r^{ADLO}(HERWIG CR)=0.987



Model	Data - MC CR	Data - MC noCR
ARIADNE	-2.1σ	-2.9σ
HERWIG	-2.6σ	-3.3σ

Parameter space in SKI

Compare data with SKI model predictions evaluated at a variety of k_I values to determine the reconnection probability most consistent with data



Data preferred value: $k_I = 1.18 \to P_{reco} = 0.49$

68% confidence level range:

$k_I \subset [0.39, 2.13] \to P_{reco} \subset [0.25, 0.65]$

Conclusions

- Particle multiplicities and momentum distributions not sensitive to CR
- "Particle flow" observable R_n sensitive to CR in the SKI model
  - Combined LEP data disfavour by 5.2σ the extreme version of the model with maximal reconnection probability
  - no CR not ruled out
  - Data preferred value of k_I: 1.18 ($P_{reco} = 0.49$)
- Poor agreement for R_n between data and HERWIG and ARIADNE models with and without CR