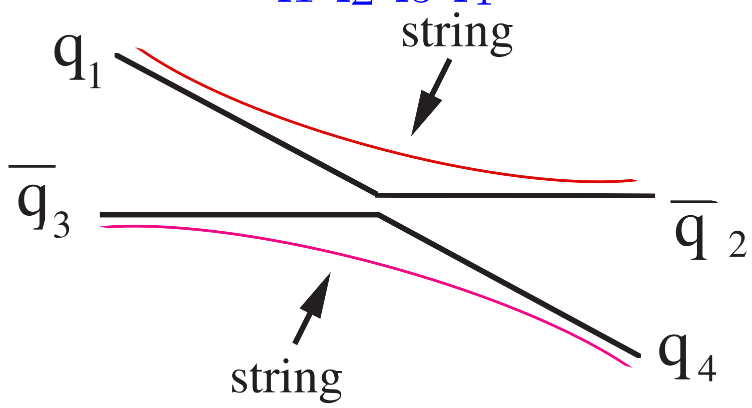
Studies of Colour Reconnection effects in hadronic W pair decays at LEP

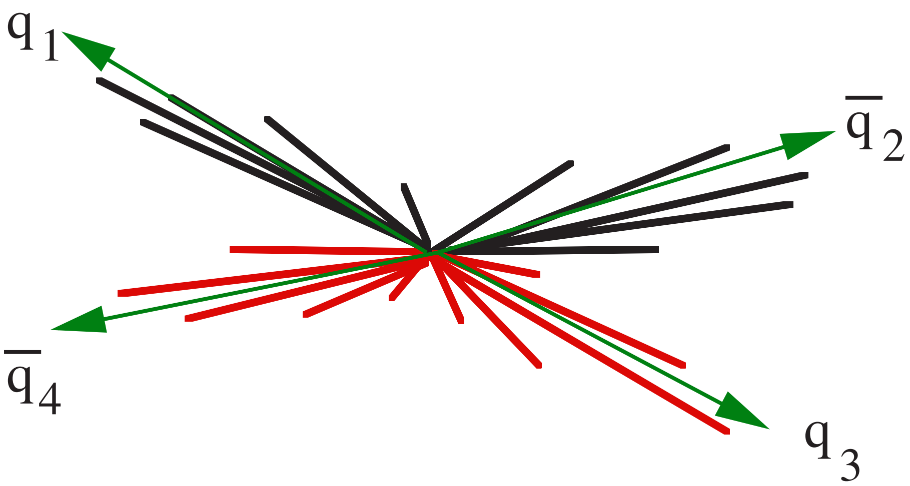
D. Duchesneau
LAPP, Annecy

- Introduction
- Phenomenological models
- Particle multiplicities
  - Inclusive distributions
  - Identified heavy particles
- Energy and particle flow
- Conclusions

QCD00, 6-13 july 2000
Montpellier

$e^+e^- \rightarrow W^+W^- \rightarrow q_1\overline{q}_2q_3\overline{q}_4$ events





- In the case of no "cross-talk" or interference effects between W^+ and W^-:

$\Rightarrow$ each pair decays independently and Hadrons can be uniquely assigned to a W boson along a string.

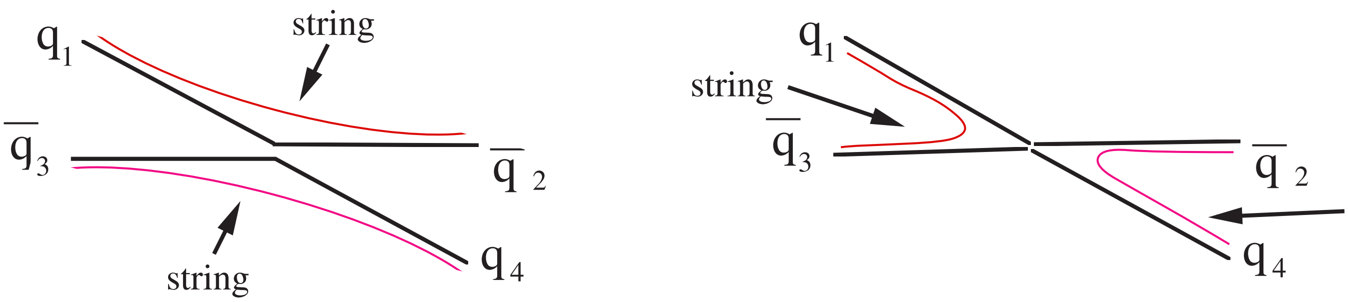
W bosons decay at short distances ($1/\Gamma_W$=0.1fm)

$\Rightarrow$Possibility of cross-talk or interference effects due to:

$\rightarrow$ Coherent gluon emission from both $q\overline{q}$ systems for $E_g < \Gamma_W$

$\rightarrow$ Large space-time overlap during hadronisation process (typical scale about 1fm)

Non perturbative phase: reconnection



$\Rightarrow$ Colour flow pattern is modified

Effects:

- Particle distributions are modified due to change in the initial colour pattern $\Rightarrow$ depletion, enhancement etc...of:
  - soft particles
  - Heavy particles ($K^{\pm}$,p)
- multiplicity may be affected

$\Rightarrow$ investigate "soft" particle distributions

Observables:

- Charged particle multiplicity distributions
- Charged particle momentum and rapidity distributions
- Energy and Particle Flow distributions to study the interjet activity within same W and different W's

Phenomenological models

PYTHIA: Rearrangement of string topology

- SK: Sjöstrand-Khoze models (Z.Phys.C 62 (1994) 281.)
  Reconnections allowed if strings cross or overlap (space-time picture):
  - $\Rightarrow$ SKI: extended flux tubes
    1 reconnection: most overlapping
  - $\Rightarrow$ SKII: Vortex lines (No lateral extent)
    1 reconnection: earliest crossing
  - $\Rightarrow$ SKII': as SKII but only if string length (λ) reduces.
- GH: Model of Gustafson-Häkkinen (Z.Phys.C 64 (1994) 659.)
  Reconnection choosen if total string length decreases.

ARIADNE: Model of Gustafson-Häkkinen

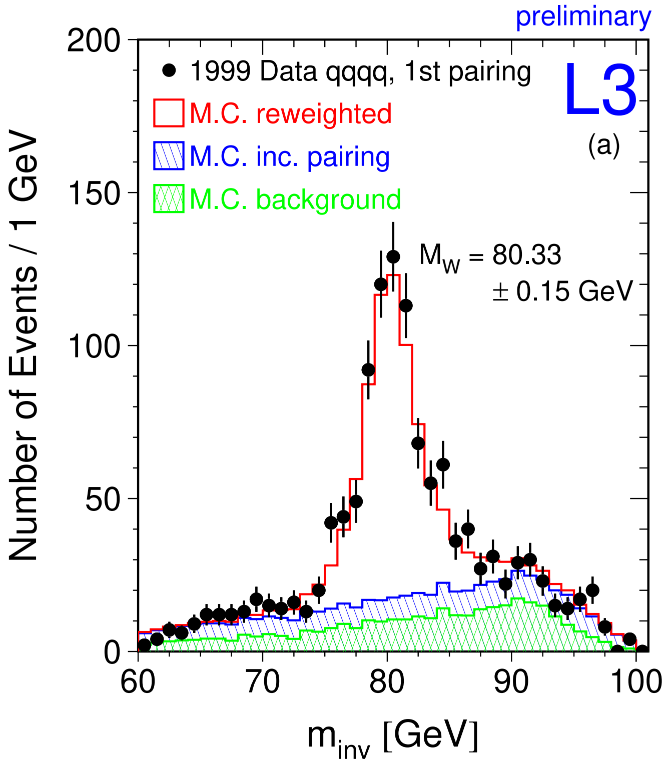
- Reconnections of colour dipoles if total string length reduced
  - $\Rightarrow$ AR2: only after radiation of gluons with $E_g > \Gamma_W$
  - $\Rightarrow$ AR3: All reconnections allowed

HERWIG: Local cluster reconnection (J.Phys.G24 (1998) 2.)

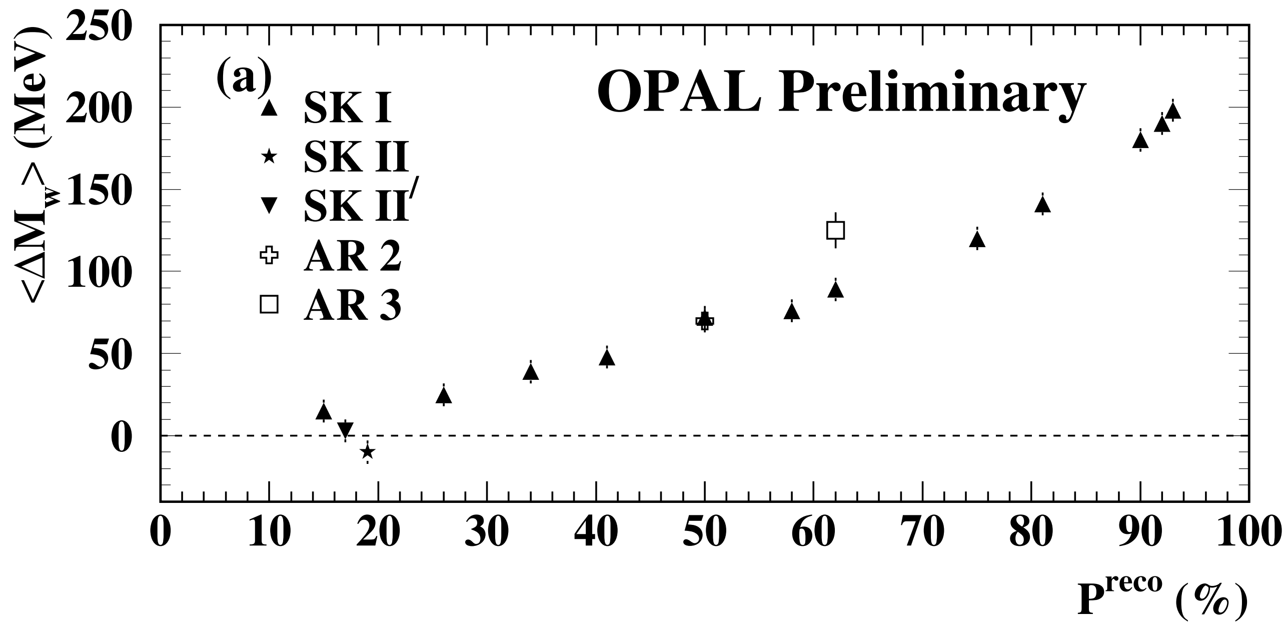
- In fragmentation phase, clusters are rearranged if reduction of the space-time extension of the clusters

Colour reconnection and W mass

Goal: at the end of LEP2: reach $\Delta M_W \approx 20 - 30 MeV$
But: CR effect on W mass reconstruction?



Particles cannot be uniquely assigned to a particular W
$\Rightarrow$ potential bias when determining M_W from reconstructed jets.



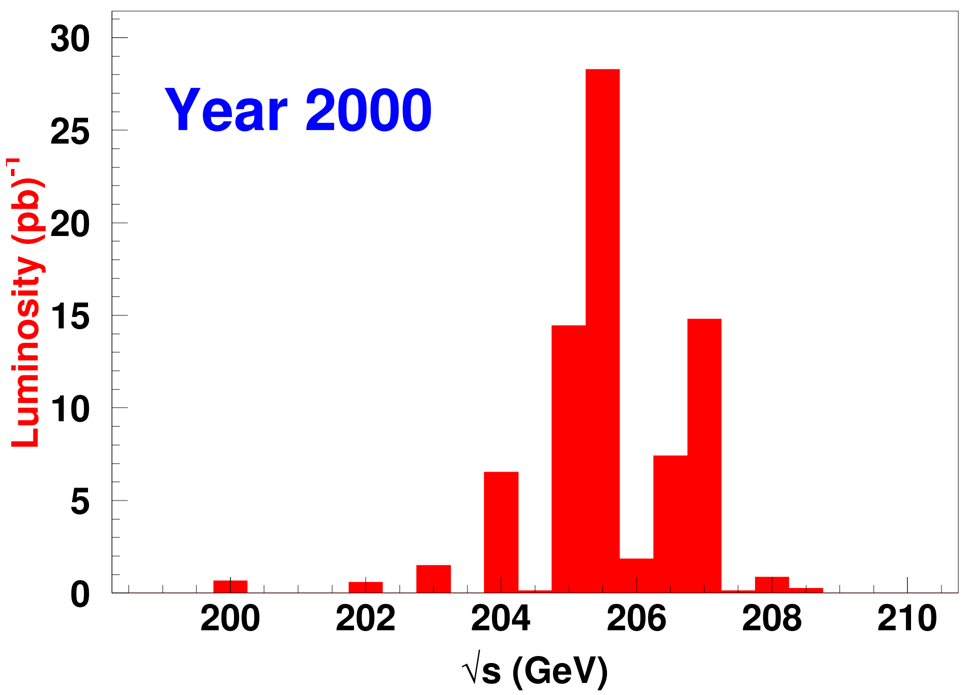
LEP2 Data samples

Average number of hadronic and semi-leptonic WW events per experiment at $\sqrt{s} > 183$GeV:

$\sqrt{s}$ (GeV)	$\int \mathcal{L}(\mathrm{pb}^{-1})$	$qqqq$	$q\bar{q}l\nu$
183	55	470	300
189	176	1500	1000
192-202	220	1800	1300
Total	451	3770	2600

More to come from this year: $\sqrt{s} = 200$ - 209 GeV

Up to last week already $\int \mathcal{L} = 75\mathrm{pb}^{-1}$ collected/expt.

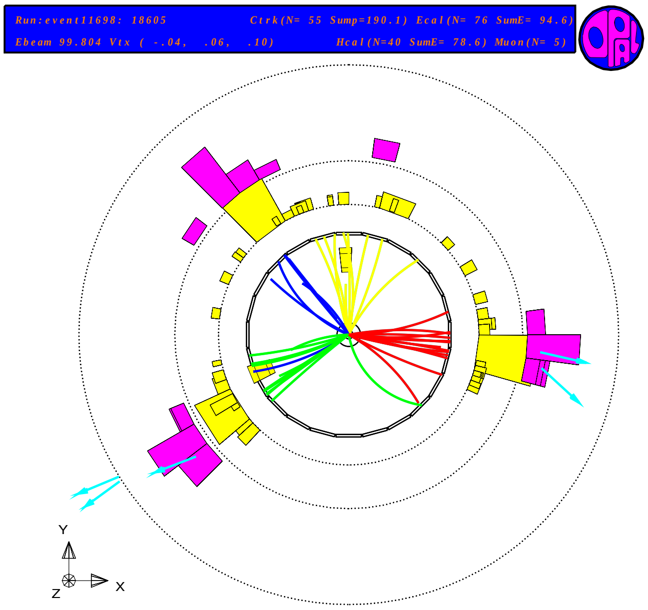


Inclusive distributions

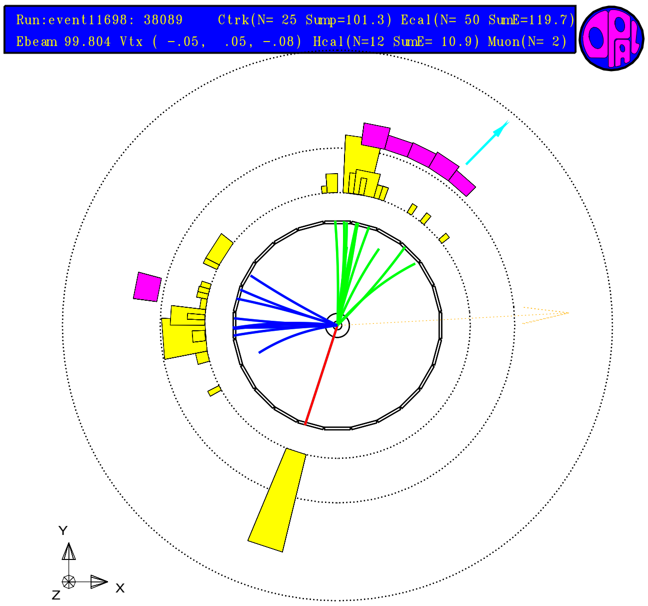
Charged particle multiplicity in qqqq channel should be affected by CR effects:

$\Rightarrow$ study $< N_{ch}^{4q} >$

But need a reference sample unaffected by CR effects:



$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$



$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}l\nu$

$$\Delta < N > = < N_{ch}^{4q} > - 2 < N_{ch}^{q\bar{q}l\nu} >$$

Model predictions:

$\sqrt{s} = 189$ GeV

$< N_{ch}^{4q} > \approx 38$

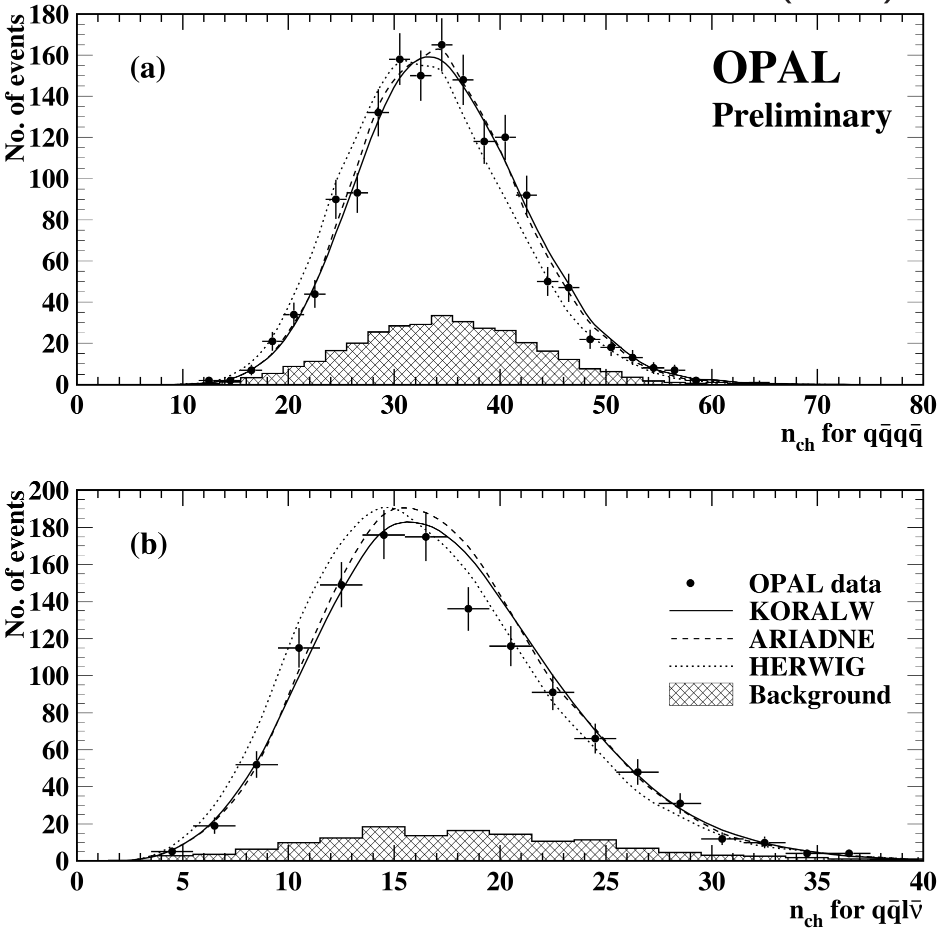
Model	$\Delta < N >$
SKI	-0.38
SkII	-0.19
SKII'	-0.24
GH	-0.35
AR2	-0.31
AR3	-0.90

$\Rightarrow$ Small effects (few %)!

Inclusive distributions

Experimentally $< N_{ch} >$ is obtained from:

- Multiplicity distribution after matrix unfolding (L,O)
- Fragmentation function after correction (A,D)



But not treated at the same level:

- corrected to full acceptance (using MC) (DLO)
- within experimental acceptance and $p > 0.2$ GeV (A)

Exp.($\sqrt{s}$)	$< N_{ch}^{4q} >$	$< N_{ch}^{q\bar{q}l\nu} >$	$\Delta < N >$
A 189	35.52 $\pm$ 0.22 $\pm$ 0.43	17.53 $\pm$ 0.19 $\pm$ 0.24	0.47 $\pm$ 0.44 $\pm$ 0.26
D 183-189	38.80 $\pm$ 0.29 $\pm$ 0.38	19.57 $\pm$ 0.26 $\pm$ 0.32	-0.34 $\pm$ 0.60 $\pm$ 0.34
L 183-202	37.90 $\pm$ 0.14 $\pm$ 0.41	19.09 $\pm$ 0.11 $\pm$ 0.21	-0.29 $\pm$ 0.26 $\pm$ 0.30
O 189	38.31 $\pm$ 0.24 $\pm$ 0.37	19.23 $\pm$ 0.19 $\pm$ 0.19	-0.15 $\pm$ 0.44 $\pm$ 0.34

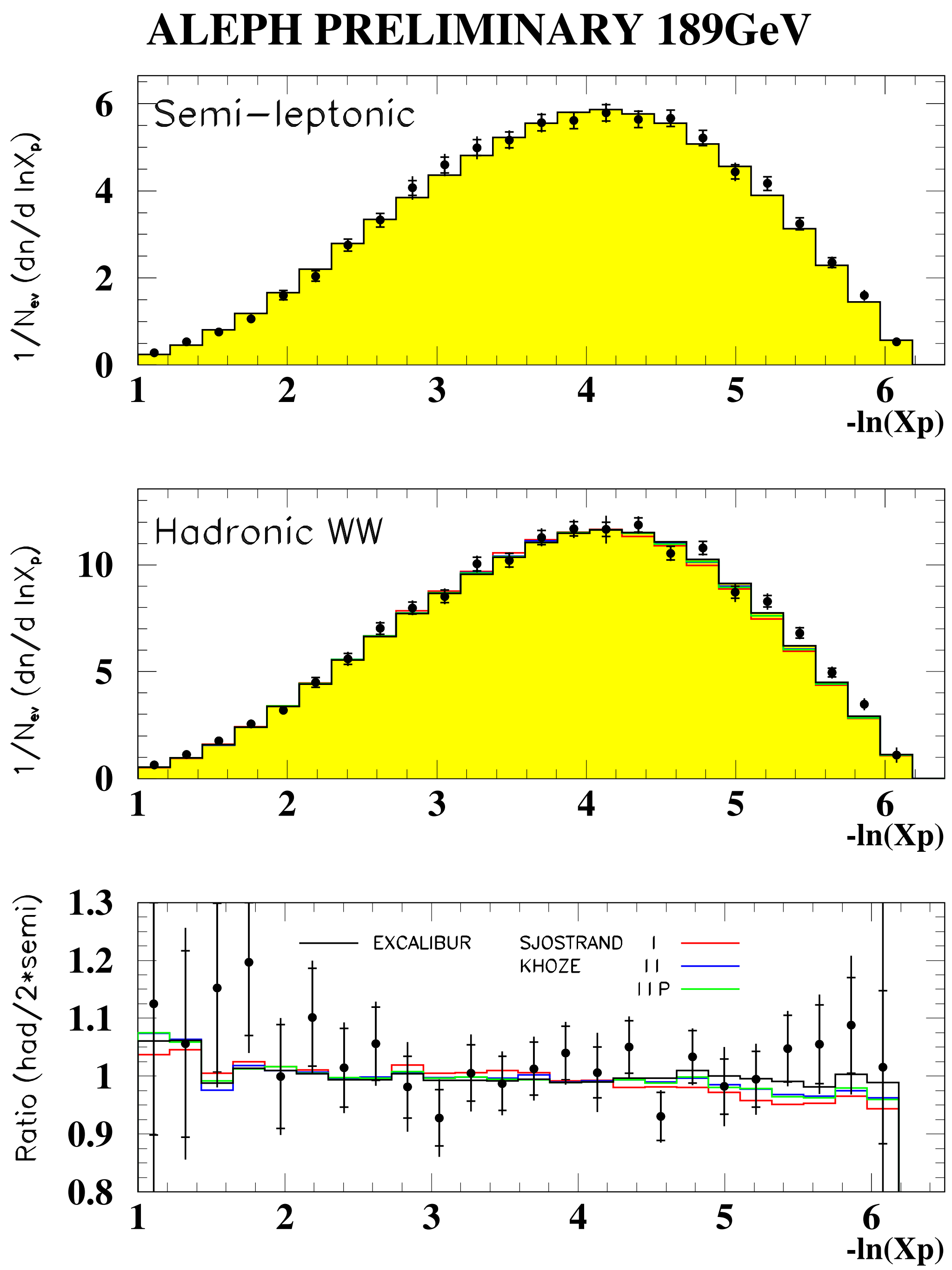
Size of effects $\approx$ correlated syst. uncertainties ($\approx$ 0.2-0.3)

No striking deviation $\Rightarrow$ It will be difficult to conclude

Inclusive distributions

More differences are expected for low momentum particles:

$\Rightarrow$ study N_{ch} as a function of particle momentum $x_p = 2p/\sqrt{s}$ or $\xi = -ln(x_p)$



Expected effects: 2-4% on particle rate.

$\Rightarrow$ Averaging experiments are really necessary!

Identified particles

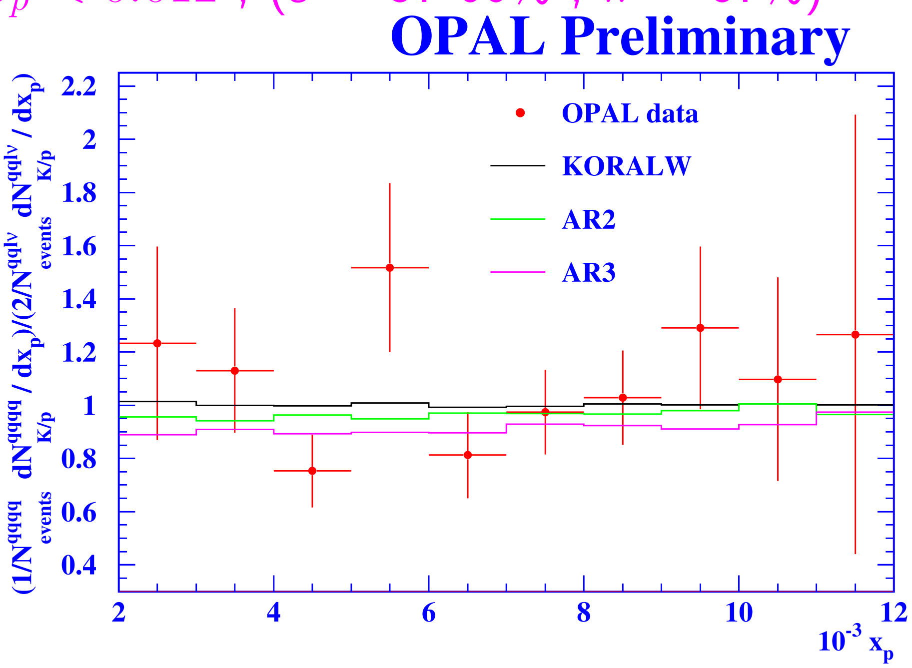
Heavy hadrons: CR effects on particle multiplicities are more pronounced (Khoze-Sjöstrand, Eur.Phys.J. C6 (1999)271.)

$\Rightarrow$ 2-3 X larger effects at low momentum for ARIADNE

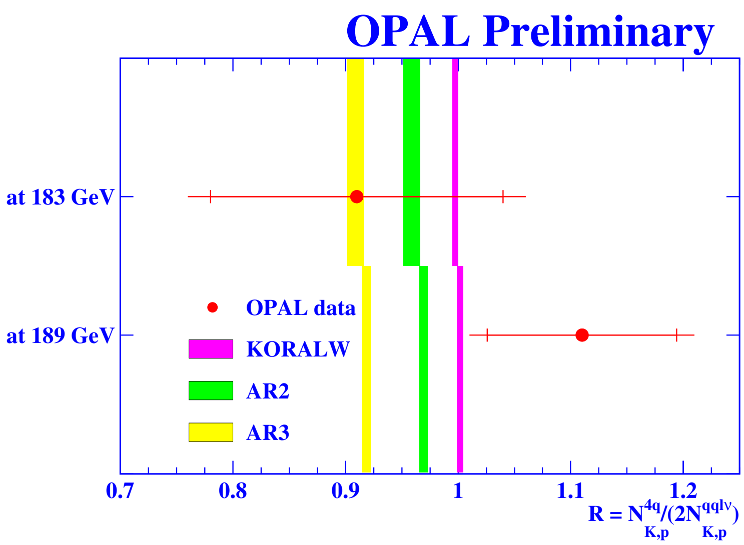
OPAL: Tag K and p using dE/dx measurements

$\Rightarrow 0.002 < x_p < 0.012$; ($\varepsilon \approx$ 57-60% ; $\pi \approx$ 87%)

$$R = \frac{N^{4q}_{K,p}}{2N^{q\bar{q}l\nu}_{K,p}}$$



$$R(183GeV) = 0.91 \pm 0.13(stat.) \pm 0.08(syst.)$$
$$R(189GeV) = 1.11 \pm 0.08(stat.) \pm 0.06(syst.)$$



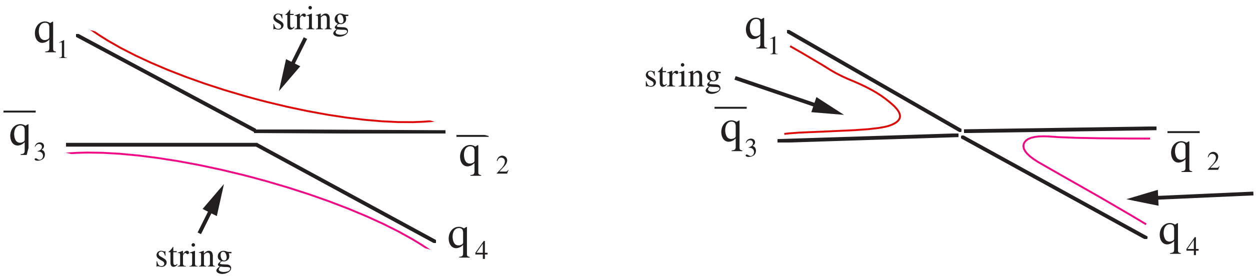
Full LEP2 stat:

R may be sensistive even to smaller effects

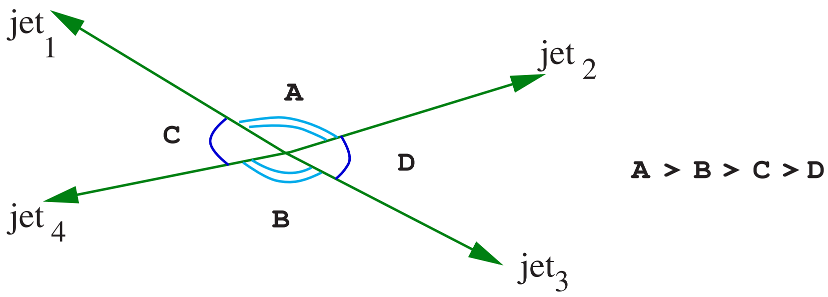
$\Rightarrow$ Keep an eye on it!

Particle flow

New method: investigate the particle- and energy flow between jets in qqqq events (D.Duchesneau, preprint LAPP-EXP 2000-02)
$\Rightarrow$ probe the colour topology of the events



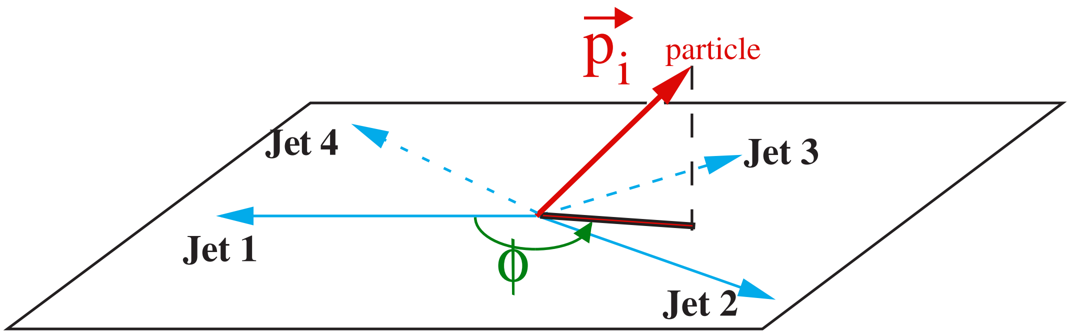
- Based on topological selection criteria on interjet angles
  - $N_{jet} = 4$ with Durham algorithm ($y_{cut} = 0.01$)



- 2 angles between 100^o and 140^o and other angles $< 100^o$

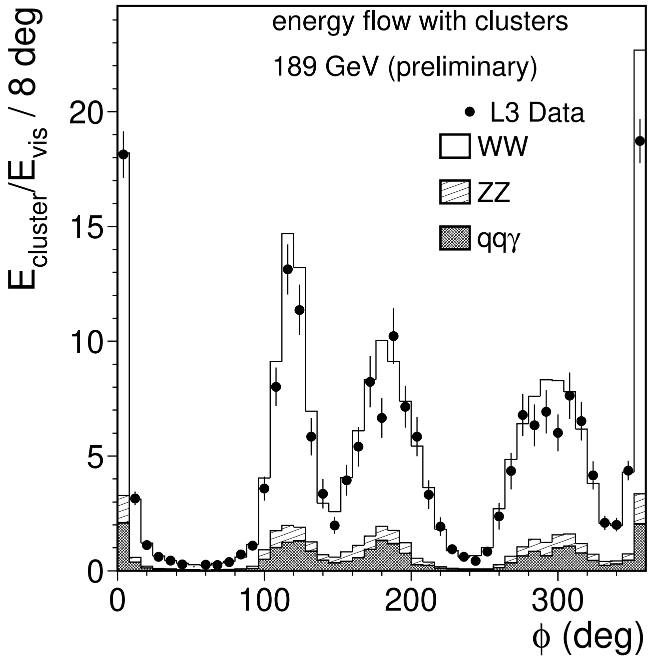
Probability to have perfect pairing $W^+W^- \to q\bar{q}q\bar{q}$: 87%

- Build particle flow distributions



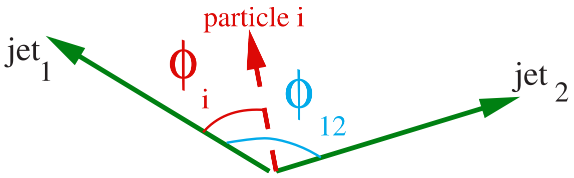
Energy and particle flows

- Flow distributions

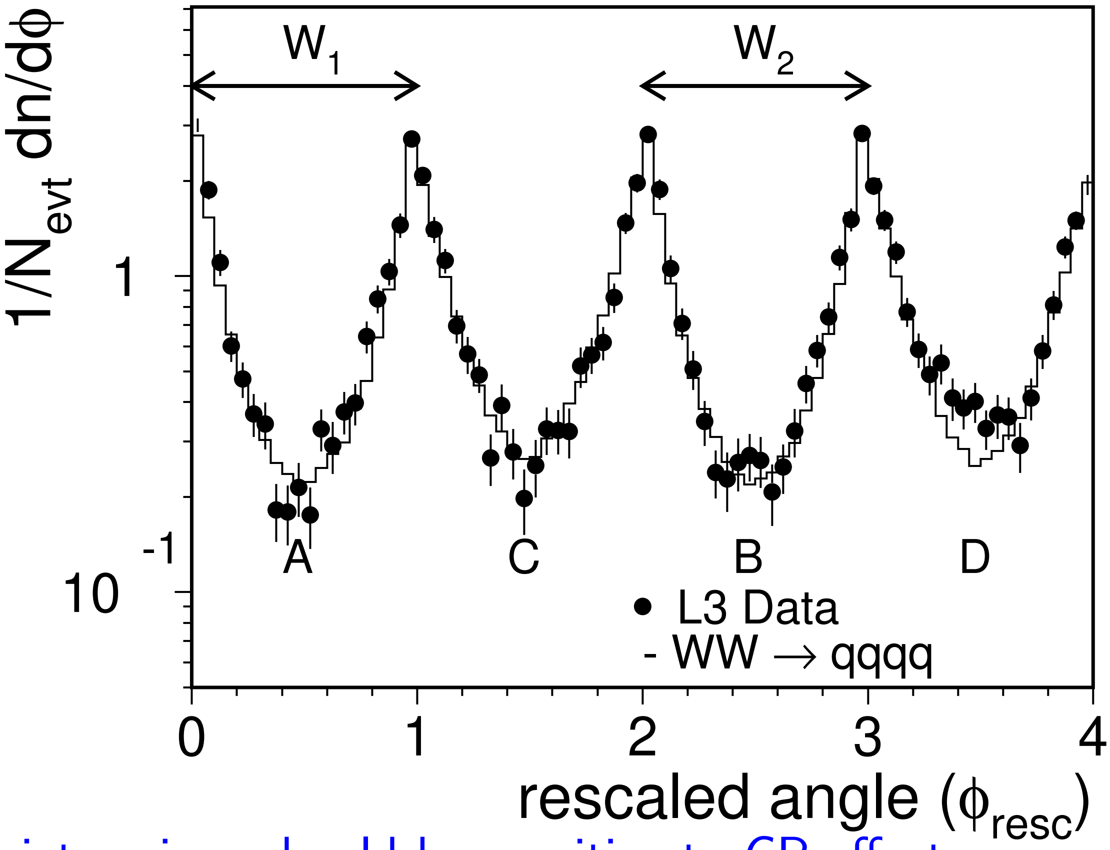


Energy flow: $\frac{1}{N_{evt}}\frac{1}{E_{tot}}\frac{\Delta E_i}{\Delta\phi}$

particle flow: $\frac{1}{N_{evt}}\frac{\Delta n}{\Delta\phi}$



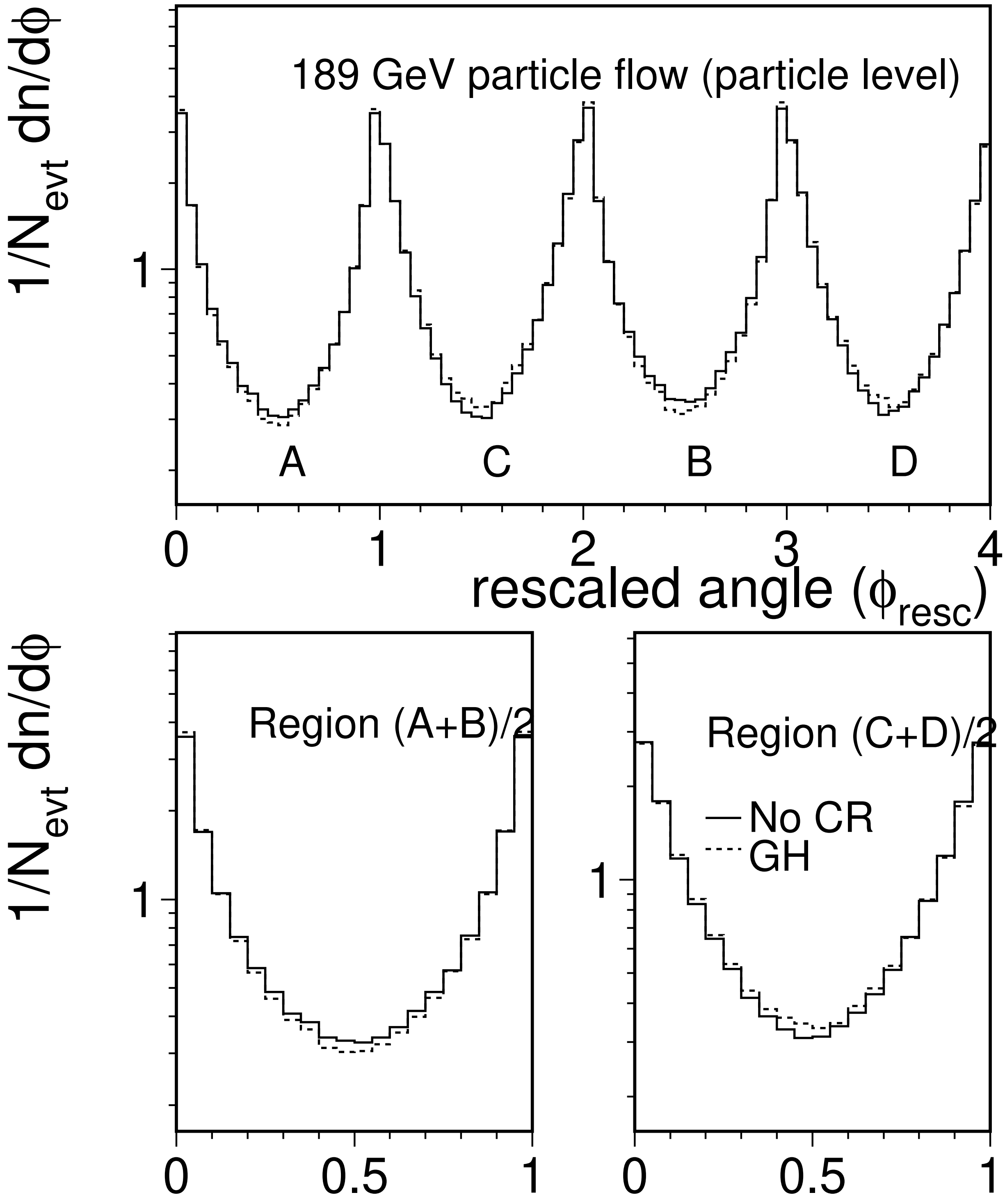
- Rescale angles and subtract background bin-by-bin



- Interjet regions should be sensitive to CR effects
- Compare regions (A+B) with (C+D)

Model predictions

Using PYTHIA 6.1 program: CR models implemented:

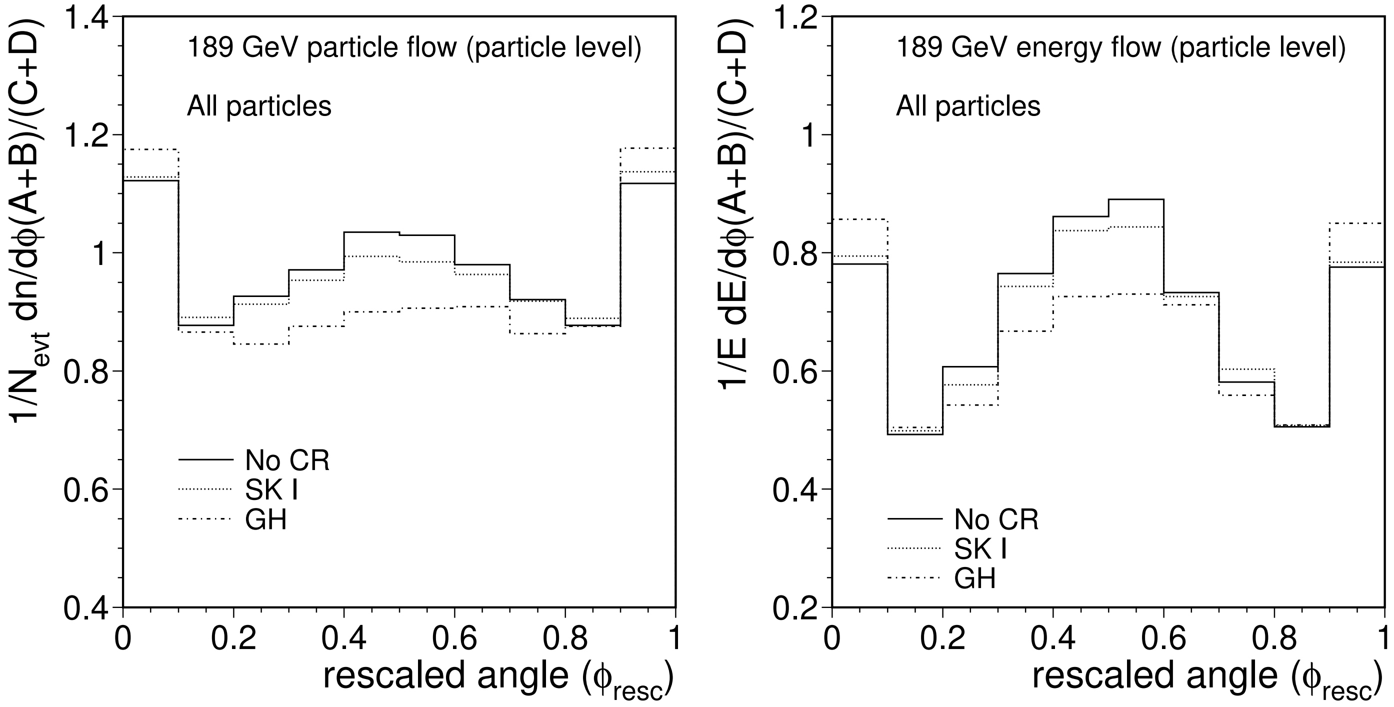


- Assuming symmetries ⇒ reduce statistical uncertainties by merging regions A and B (W) and C and D (between W's).

Monte Carlo ratios

Variable: particle density between q from same W compared to particle density between q from different W

$$R_N = \frac{\frac{1}{N}\cdot\frac{dn}{d\phi}(regions A+B)}{\frac{1}{N}\cdot\frac{dn}{d\phi}(regions C+D)} \qquad R_E = \frac{\frac{1}{E}\cdot\frac{dE}{d\phi}(regions A+B)}{\frac{1}{E}\cdot\frac{dE}{d\phi}(regions C+D)}$$



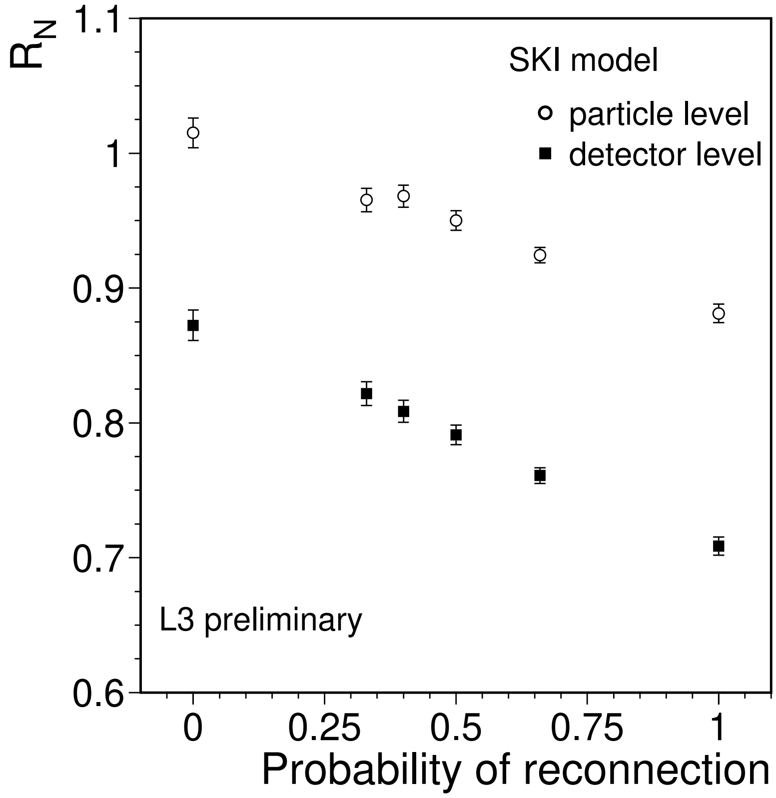
Integrating the ratio from 0.3 to 0.7 gives:

Model	R_N particle	R_E particle
No CR	1.004 ± 0.006	0.812 ± 0.009
SkII	0.977 ± 0.006	0.790 ± 0.009
SKI	0.974 ± 0.006	0.791 ± 0.009
GH	0.898 ± 0.006	0.710 ± 0.008

SKI and SKII do not show large effects with these variables.($\approx 4\%$)

GH shows much larger effects ($\approx 10\%$)

Monte Carlo ratios



The effect increases with the reconnection probability.
Sensitivity not degraded at detector level

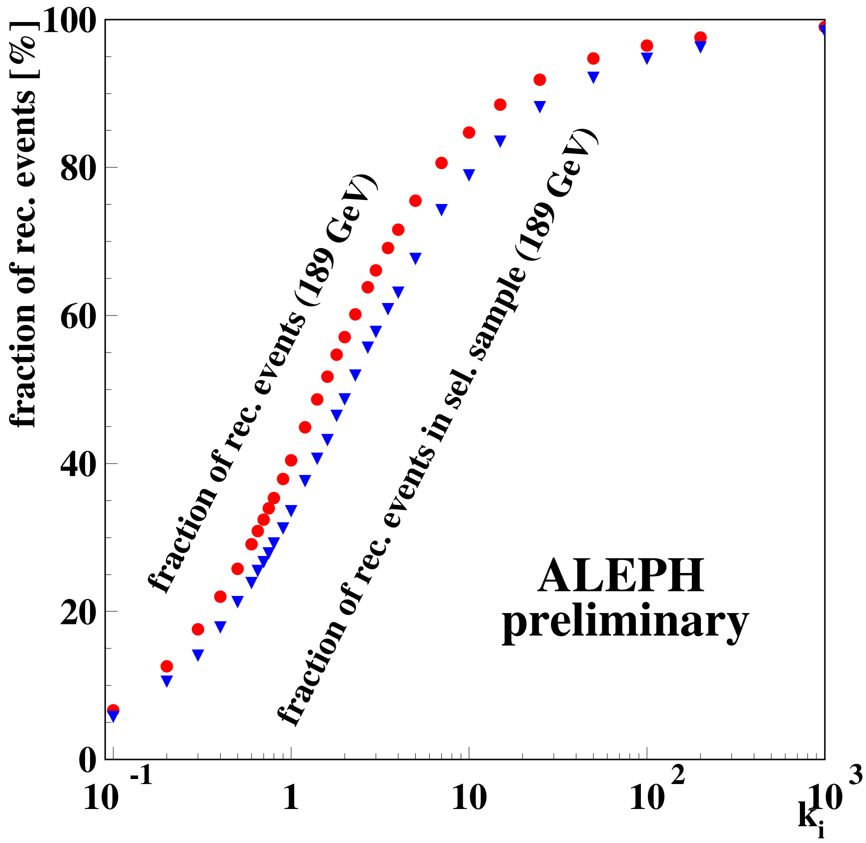
ΔR_N(stat)/expt $\approx$ 0.04 at $\sqrt{s}$ = 189 GeV

In SKI model: free strength parameter k_I

$$P_{reco} = (1\text{-}e^{f(\sqrt{s}).k_I})$$

$\Rightarrow$ $\sqrt{s}$ and topology dependence

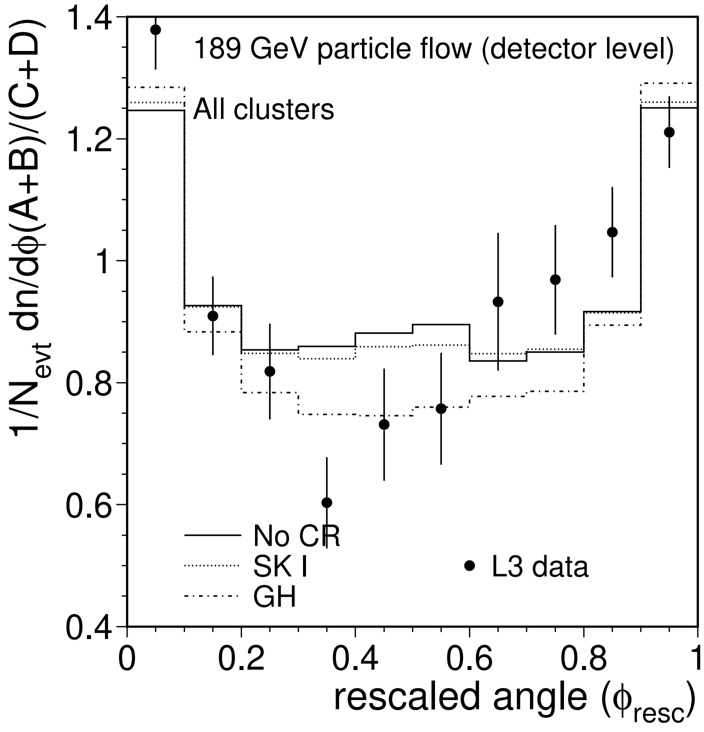
To consider when adding different energies

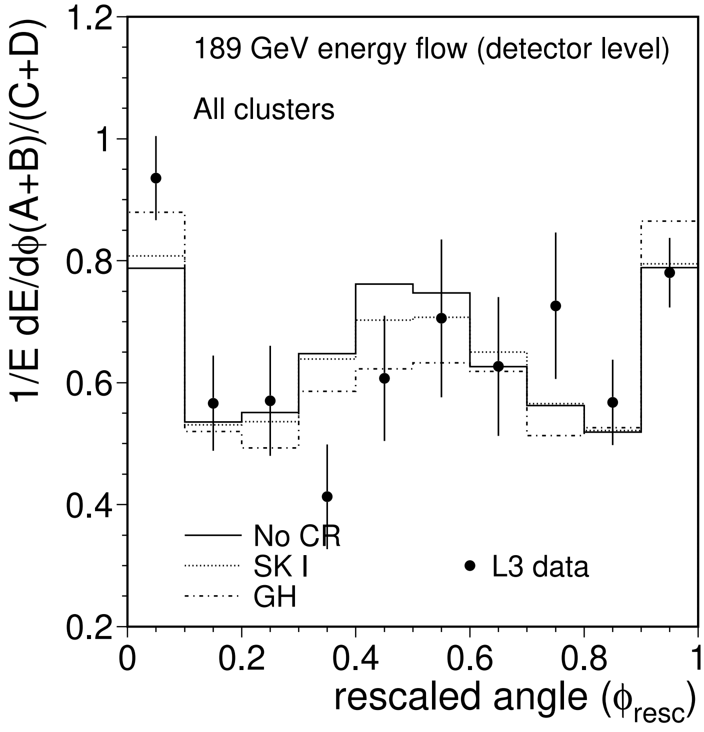


L3: $\sqrt{s} = 189$ GeV

$N_{data} = 208$ $\quad$ $Efficiency: 15\%$

$N_{MC} = 226$ $\quad$ $Purity: 85\%$ (back:$8\%q\bar{q}$; $6\%ZZ$)





Integrating the ratio from 0.3 to 0.7 gives:

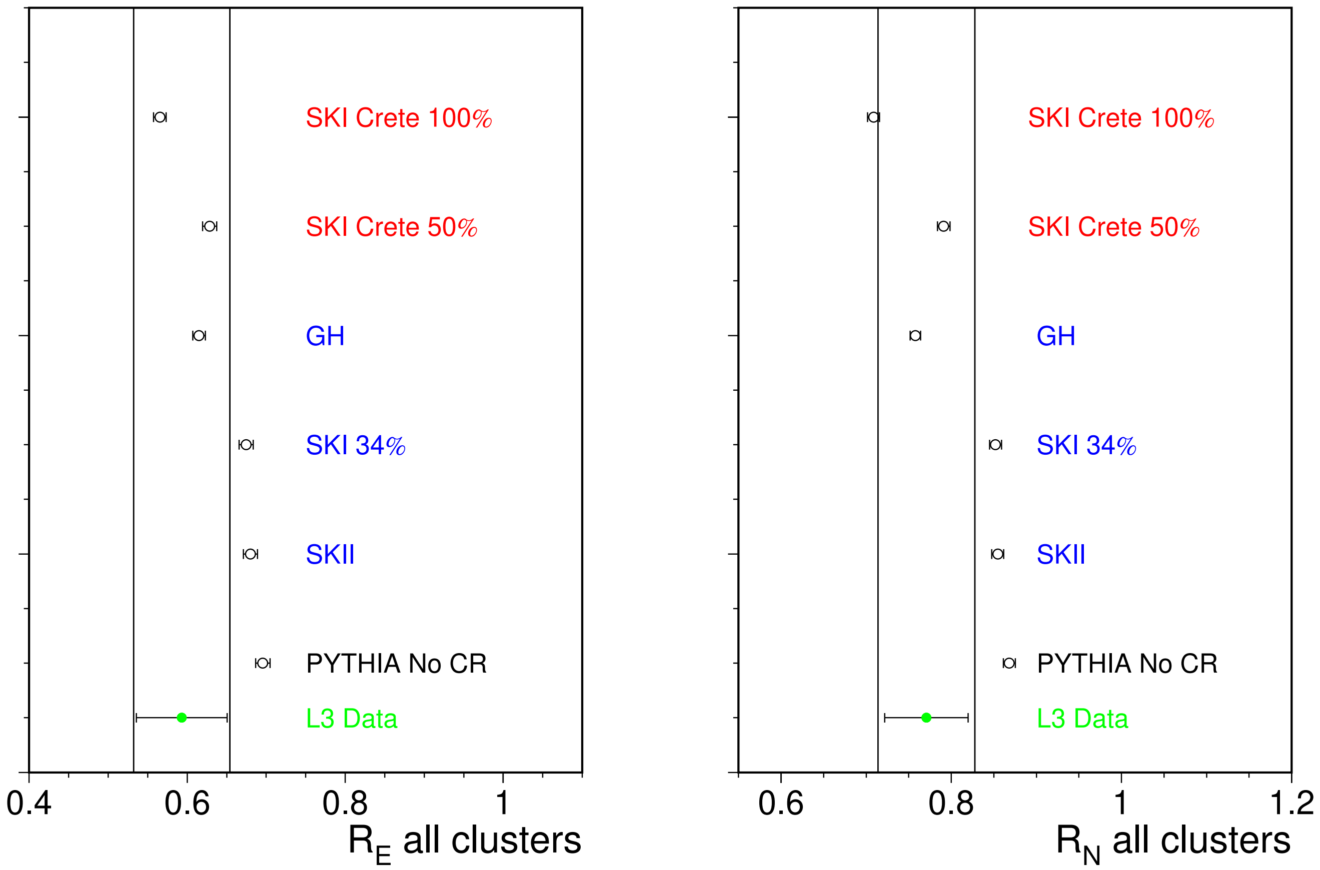
$$R_N = 0.771 \pm 0.049(stat.) \pm 0.029(syst.)$$
$$R_E = 0.593 \pm 0.058(stat.) \pm 0.020(syst.)$$

Model	R_N detector	R_E detector
No CR	0.868 ± 0.007	0.696 ± 0.009
SkII	0.855 ± 0.007	0.680 ± 0.009
SKI	0.852 ± 0.007	0.675 ± 0.009
GH	0.758 ± 0.006	0.615 ± 0.008

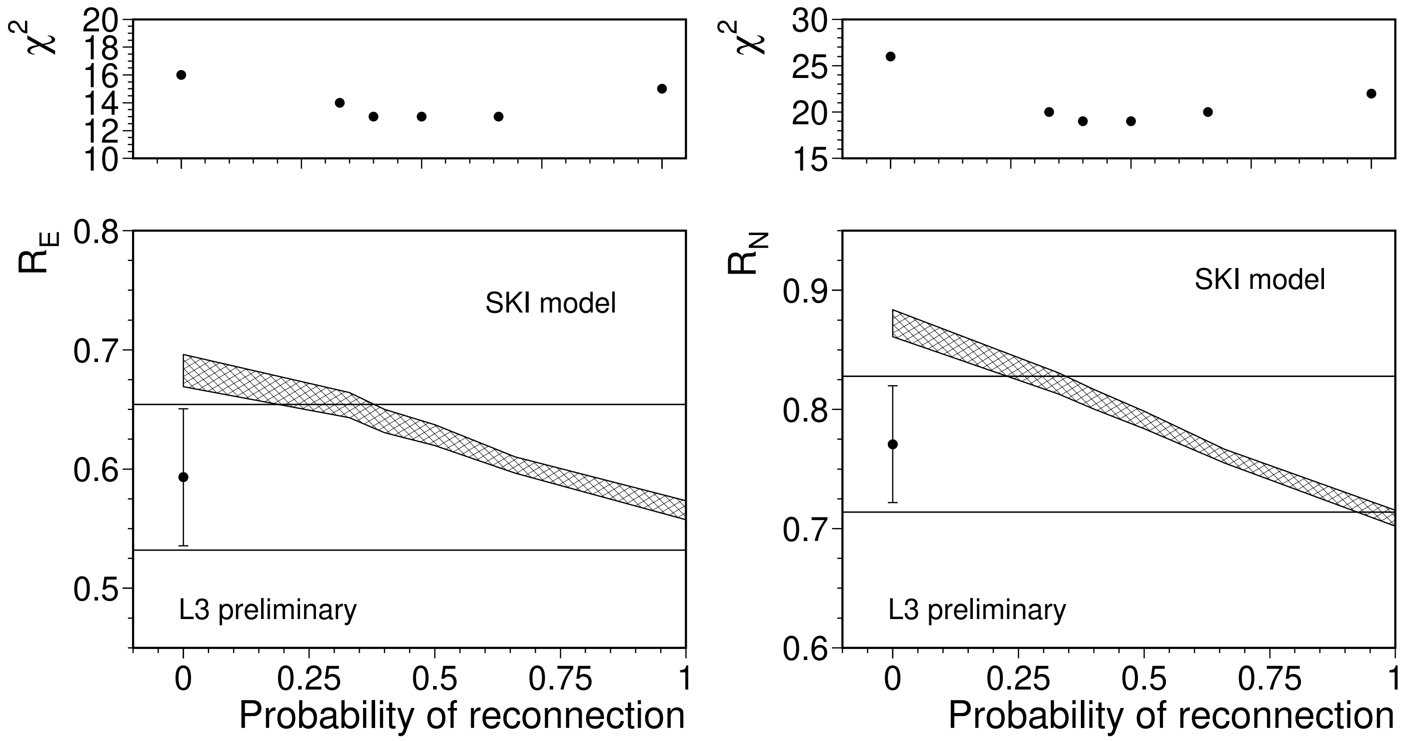
Data shows 1.7 σ deviation from No CR model prediction

Comparison with Models

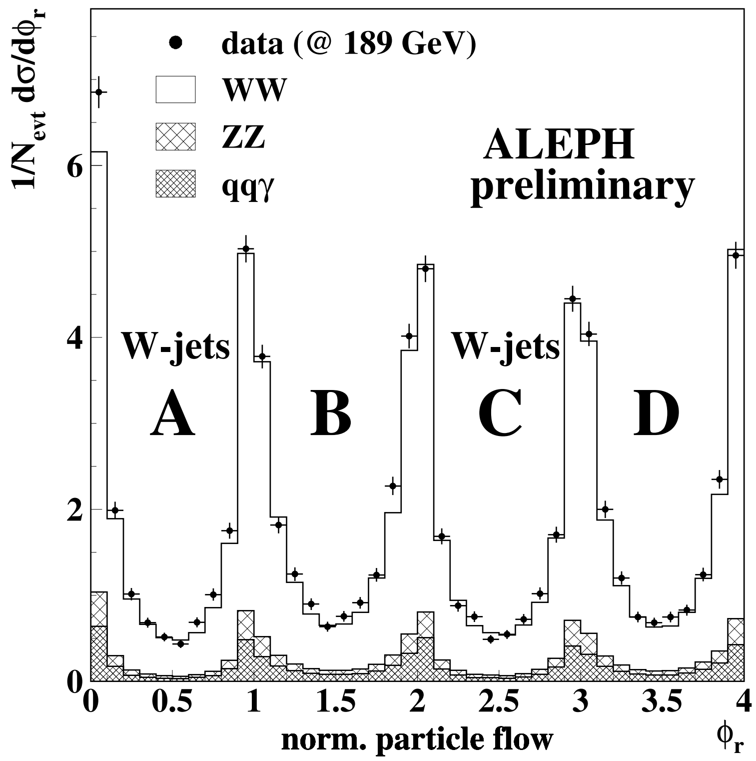
Colour reconnection models:

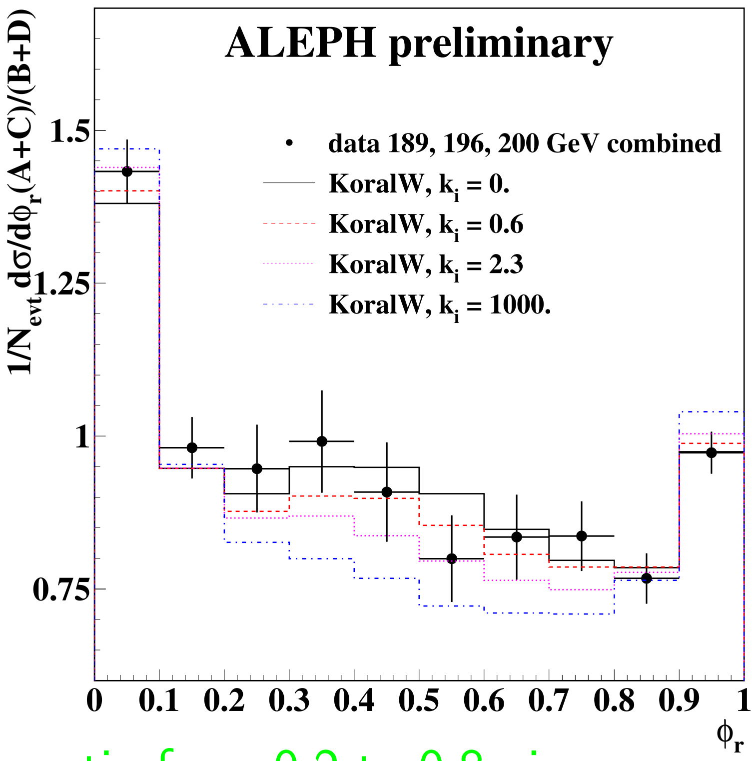


Compatibility with SK1 model: $\chi 2$ computed from ϕ_r=0 to 1



ALEPH: $\sqrt{s} = $ 189-200 GeV





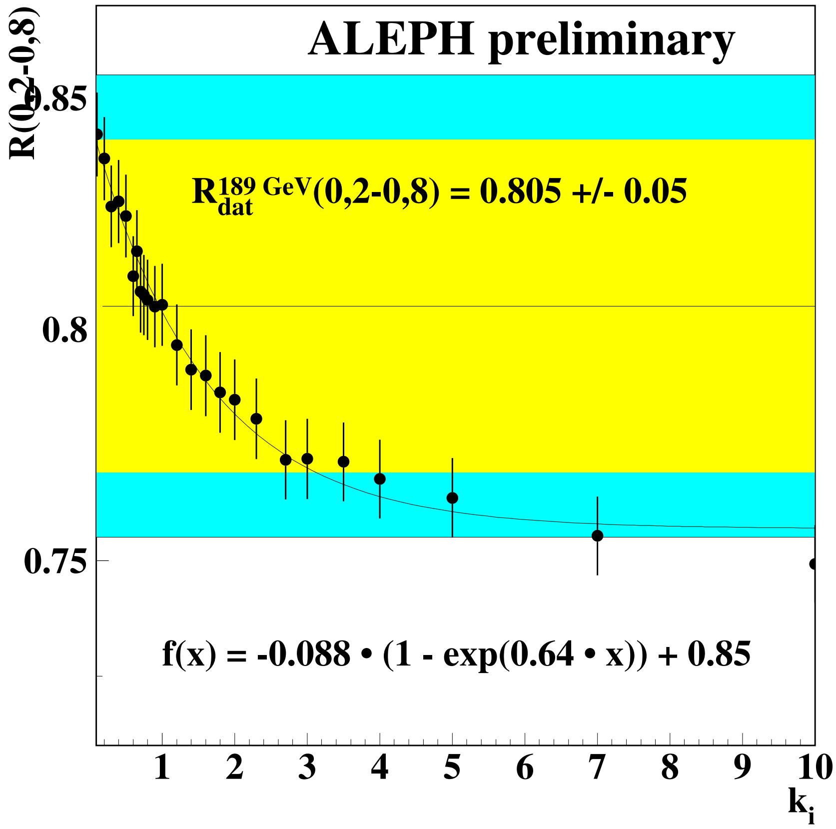
Integrating the ratio from 0.2 to 0.8 gives:

$$R_N(189GeV) = 0.805 \pm 0.039(stat.) \pm 0.032(syst.)$$

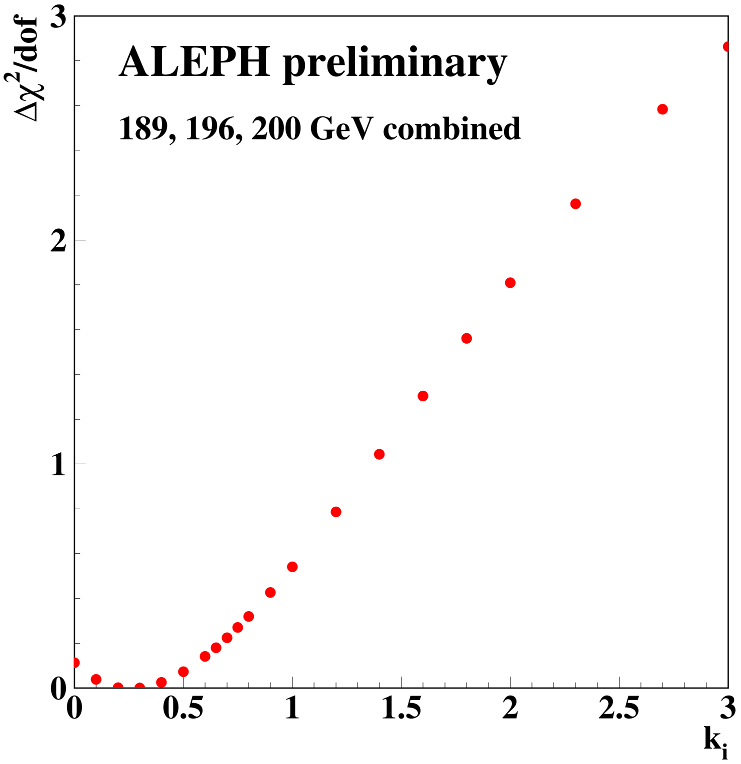
Comparison with SKI model

ALEPH: $\sqrt{s} = 189\text{-}200$ GeV

Parameterise the ratio as a function of k_I at each $\sqrt{s}$:



Compute a $\chi 2$ as a function of k_I summing all energies:



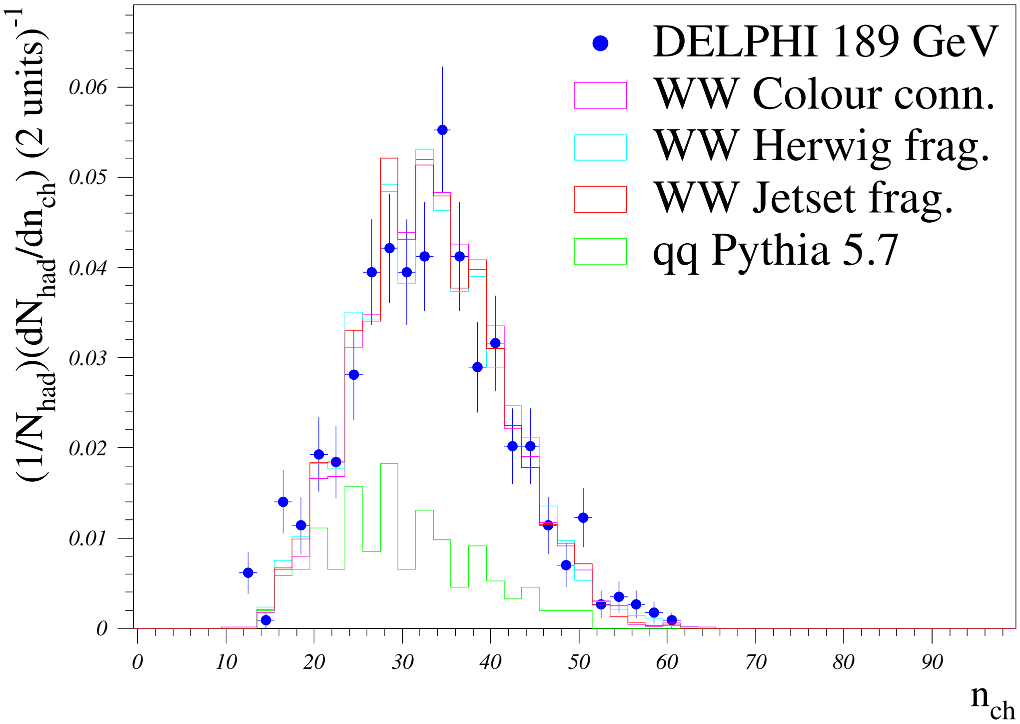
$k_I < 1.35$ at 68% C.L.

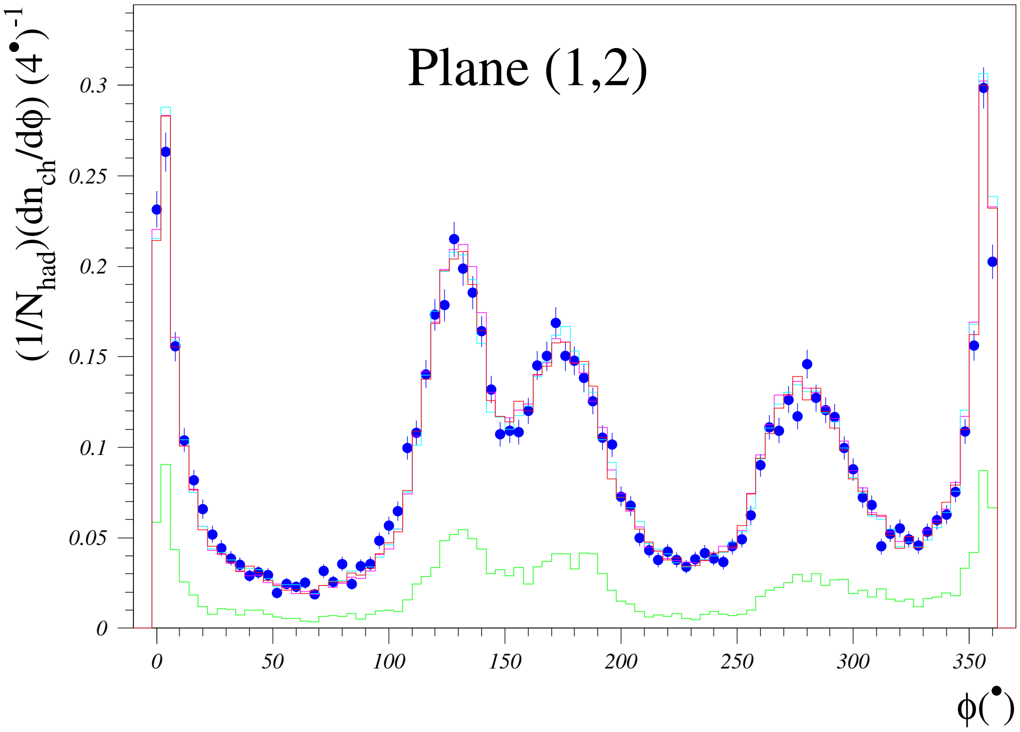
$\Rightarrow P_{reco} < 45\%$

Particle Flow

DELPHI: $\sqrt{s} = 189$ GeV

Analysis going on!





Conclusions

Charged particle multiplicities:

- Variables not very sensitive to correlation effects
- Some hope using identified Heavy particles

Energy and particle flow distributions:

- Very promising variables
- sensitive to Colour reconnection effects in $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}q\bar{q}}$

L3 Analysis of 189 GeV data shows a 1.7 sigma effect towards CR. $\Rightarrow$ In SKI scheme: preference for 40% CR probability.

ALEPH Analysis of 189-200 GeV data derives a limit on CR effect. $\Rightarrow$ In SKI scheme: limit on $k_I \approx$ 1.35 ($< 45\%$ CR probability).

- Studies following this approach should be continued and combined to make use of the full LEP2 data statistics

New Variables sensitive to correlation effect under study:
ex: Factorial moments, Lorentz invariant variables....