Colo(u)r Reconnection in W Decays

results from ALEPH, DELPHI, L3, OPAL

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- Motivation
- Multiplicities
- Energy- and Particle Flow
- Effect on M_W^{qqqq} Measurement

Motivation

WW Production at LEP 2:

Year	$\sqrt{s}$ [GeV]	$\int \mathcal{L}dt$/expt. [pb^{-1}]	σ_{WW} [pb]
1997	183	55	15.3
1998	189	175	16.2
1999	192 − 202	220	16.5 − 17.1
2000	> 205	> 100	

This talk: 183-202 GeV, most results preliminary.

WW decays can be classified in 3 topologies:

WW → qqqq	46%	∼ 3200 evts/expt.
WW → qq$\ell\nu$	44%	∼ 2500 evts/expt.
WW → $\ell\nu\ell\nu$	11%	

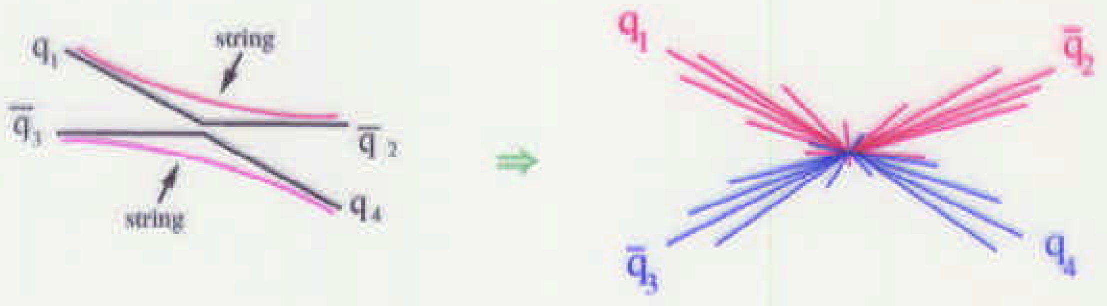
Major goal: measure M_W, from W decay kinematics; a statistical error of ∼ 20 MeV appears reachable.

Energy-momentum exchange between W decay products not simulated in Monte Carlo affects W mass measurement:

- QED: all decay modes, calculable, small
- QCD: colour reconnection, WW → qqqq only

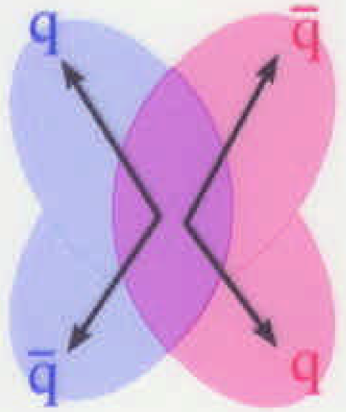
Colour Reconnection

Standard MC programs treat the two $q\bar{q}$ systems in WW → qqqq as two colour singlets without interactions.



⇒ all hadrons can be uniquely assigned to a W boson

However, interconnections in WW → qqqq are in fact to be expected in QCD:



WW decay vertices ~ 0.1 fm
hadronisation scale ~ 1 fm
⇒ large spacetime overlap

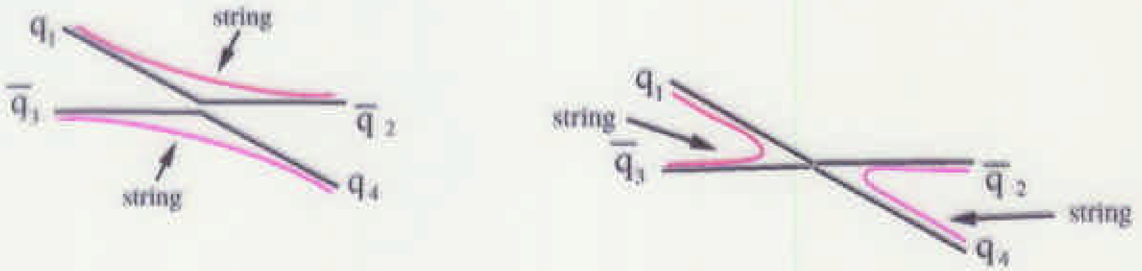
Coherent gluon emission from both $q\bar{q}$ systems for $E_g < \Gamma_W$ ⇒ interference

Perturbative effects of CR (hard gluon exchange between quarks from W decay) suppressed $(\sim (\alpha_s/\pi)^2\Gamma_W/N_c^2)$: few MeV

Colour reconnection is a non-perturbative hadronization uncertainty. ⇒ Study CR as implemented in hadronization models.

Colour Reconnection Effects

Colour reconnection: change of colour flow pattern, connection between different W's:



Effects:

- Change (decrease) of multiplicities
  - Soft particles $p < 1$ GeV
  - Heavy particles ($K^{\pm}$, p)
- Change of particle- and energy flow between jets

Goal in these analyses: regard CR as a signal, measure its strength, calibrate W mass shift in qqqq channel against measurements. $\Rightarrow$ Get CR M_W^{qqqq} systematic error from data, reduce model dependence.

Also interesting for better understanding of hadronization!

Compare $qqqq$ data to:

- MC models with and without CR
- data without CR: $qq\ell\nu$, mixed events

$e^+e^- \to$ ZZ events cannot help us: difficult separation from WW, low statistics.

Colour Reconnection Models

→ PYTHIA: based on reconfiguration of strings

- Models from Sjöstrand-Khoze

CR can occur for overlapping/crossing strings

- SK I: String is flux tube with lateral dimension. Reconnection based on string-string overlap O: $P_{\rm reco} = 1 - e^{(-k_i O)}$, k_i is free parameter. 1 reconnection allowed: most overlapping.
- SK II: String is vortex line, no lateral dimension, 1 reconnection allowed: earliest crossing.
- SK II': as SK II, but only if string length (λ) reduced.

GH: for demonstration purposes only

→ ARIADNE: rearrangement of colour dipoles if total string length reduced

- Based on model of Gustafson-Häkkinen
  - AR2: CR after radiation of energetic gluons $E_g > \Gamma_{\rm W}$
  - AR3: All CR allowed

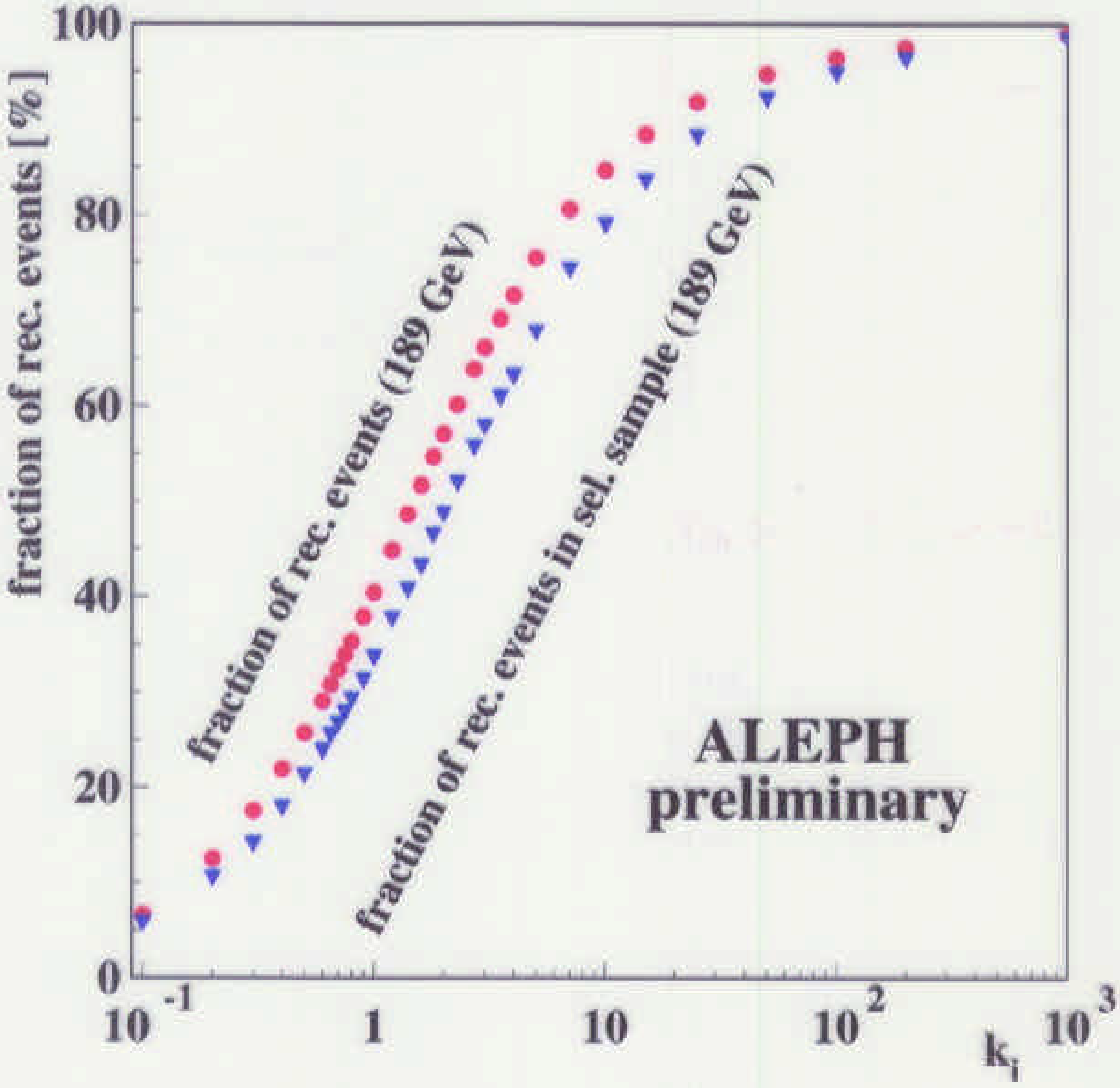
Note: affects LEP 1 data: OPAL analysis of Z data (properties of quark- and gluon jets) disfavours current ARIADNE reconnection models.

→ HERWIG: local cluster reconnection

- rearrangement of clusters if reduction of space-time extension.

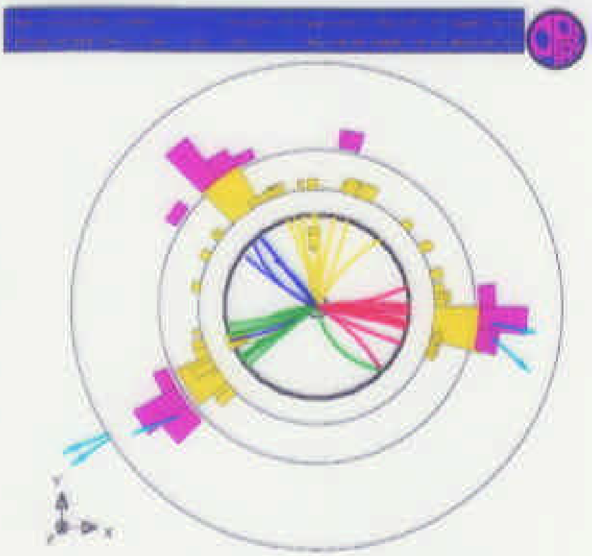
Role of k_i in SK I

SK I model at $\sqrt{s} = 189$ GeV:

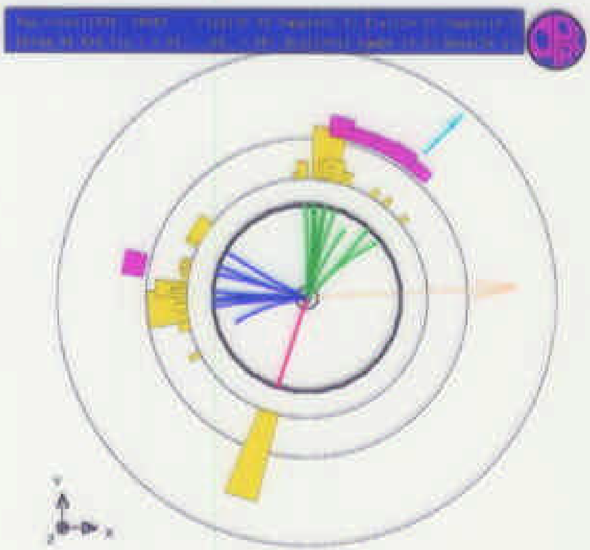


Charged particle multiplicity

Study charged particle multiplicity in WW → qqqq and WW → qq$\ell\nu$ events:



WW → qqqq (4q)



WW → qq$\ell\nu$ (2q)

Study $< N_{ch}^{4q} >$, $< N_{ch}^{2q} >$ and $\Delta < N_{ch} > = < N_{ch}^{4q} > -2 < N_{ch}^{2q} >$

Predictions for $\Delta < N_{ch} >$:

SK I:	-0.3
SK II:	-0.2
SK II':	-0.2
GH:	-0.4
AR 2:	-0.3
AR 3:	-0.9

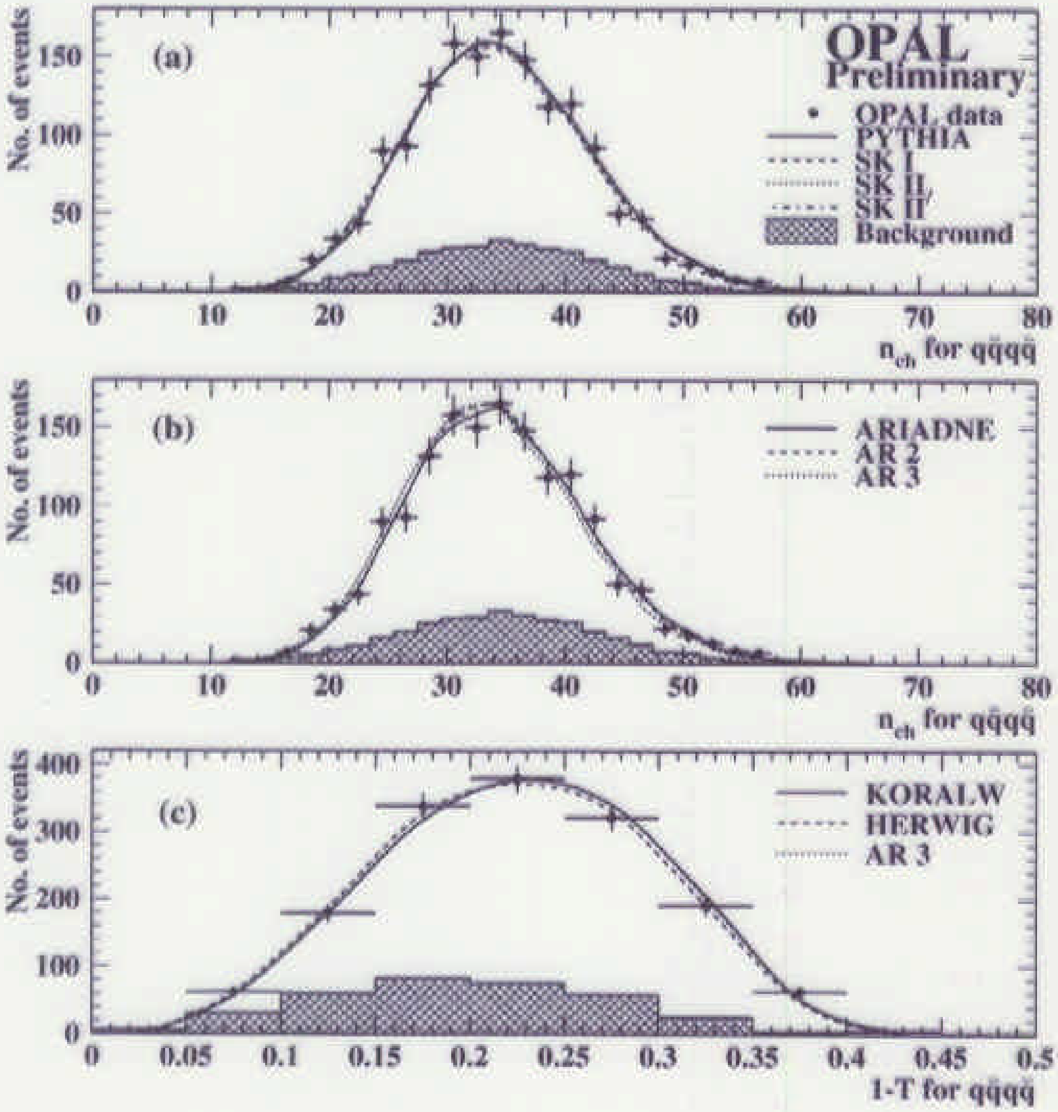
at $\sqrt{s} = 189$ GeV
$< N_{ch}^{4q} > \approx 38$
Effects $\sim 1 - 2\%$
(SK I: reconn. fraction $\sim 32\%$)

$< N_{ch} >$ obtained from charged tracks:

- Unfolded multiplicity distribution
- Corrected fragmentation function

Multiplicity Distributions

Example of multiplicity distribution at $\sqrt{s} = 189$ GeV:



Charged Multiplicities

Hadronic charged multiplicity measurements:

	$< N_{ch}^{4q} >$	$< N_{ch}^{2q} >$	$\Delta < N_{ch} >$
OPAL 183 GeV	$39.4 \pm 0.5 \pm 0.6$	$19.3 \pm 0.3 \pm 0.3$	$+0.7 \pm 0.8 \pm 0.6$
OPAL 189 GeV	$38.31 \pm 0.24 \pm 0.37$	$19.23 \pm 0.19 \pm 0.19$	$-0.15 \pm 0.44 \pm 0.38$
L3 183-202 GeV	$37.90 \pm 0.14 \pm 0.41$	$19.09 \pm 0.11 \pm 0.21$	$-0.29 \pm 0.26 \pm 0.30$
DELPHI 183 GeV	$38.11 \pm 0.57 \pm 0.44$	$19.78 \pm 0.49 \pm 0.43$	
DELPHI 189 GeV	$39.12 \pm 0.33 \pm 0.36$	$19.49 \pm 0.31 \pm 0.27$	
ALEPH 183-202 GeV	$35.75 \pm 0.13 \pm 0.52$	$17.41 \pm 0.12 \pm 0.15$	$+0.93 \pm 0.27 \pm 0.29$

ALEPH: not unfolded to full acceptance

DELPHI: $< N_{had}^{qqqq} > /2 < N_{had}^{qq\ell\nu} > = 0.990 \pm 0.015 \pm 0.011$

Averaging is difficult: definitions, correlated systematics

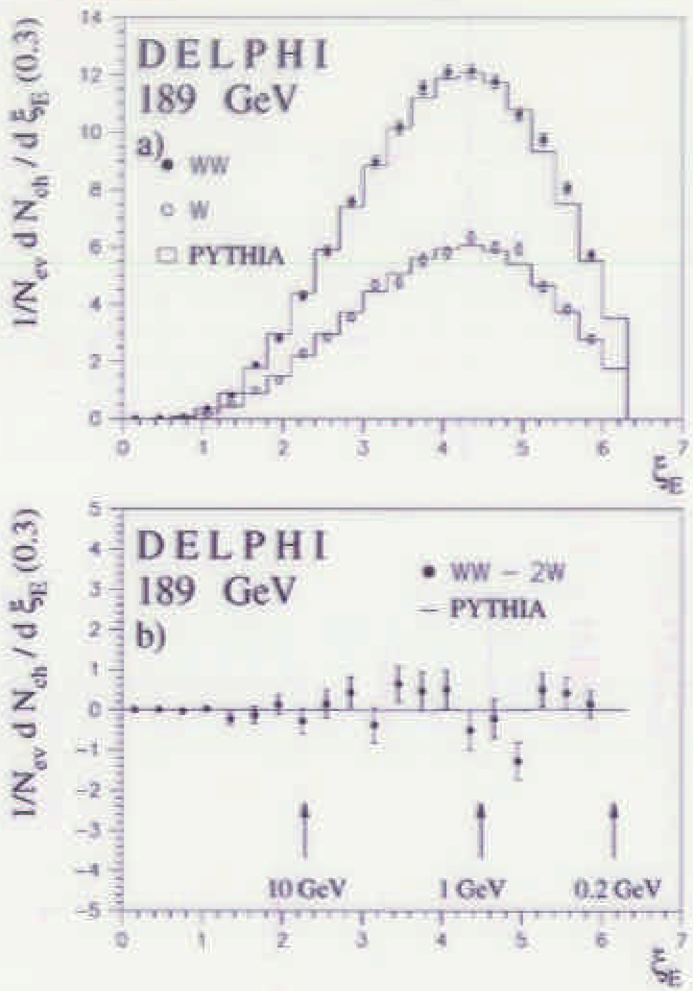
Unofficial: combined error 0.3-0.4, result consistent with 0.

$\Rightarrow$ Correlated systematics (0.2-0.3) of same size as effects $\rightarrow$ limited sensitivity

Same conclusions for dispersions D^{4q}, D^{2q}, $\Delta D = D^{4q} - \sqrt{2} D^{2q}$.

Fragmentation function

Fragmentation function: $x_p = 2p/\sqrt{s}$,
$\xi = -\log(x_p)$:



CR effects predominantly at $p < 1$ GeV ($\xi > 4.5$)

But measurements have 60% larger statistical error.

DELPHI 183+189 GeV, $0.1 < p < 1$ GeV:

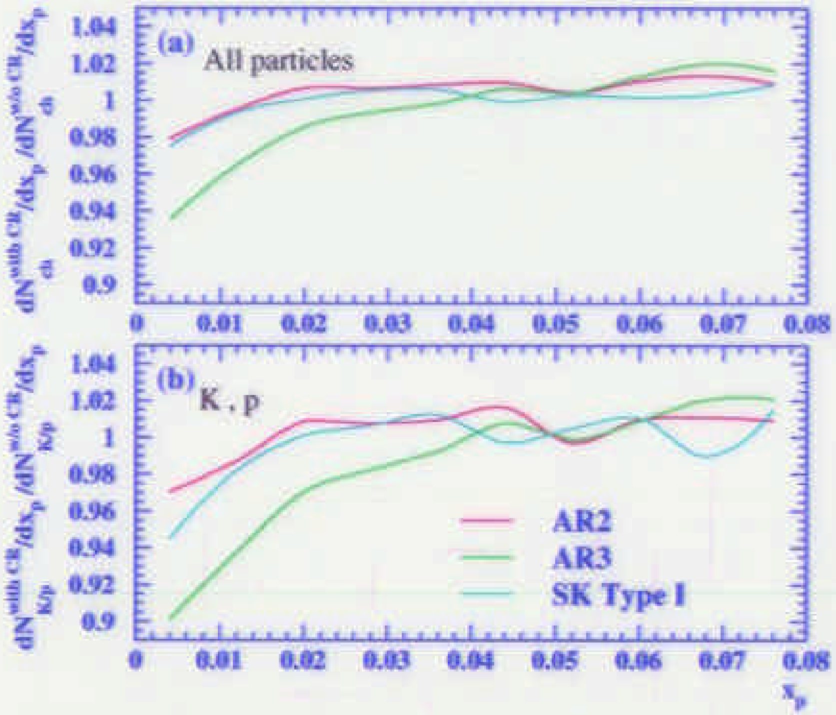
$$N^{4q}/2N^{2q} = 0.980 \pm 0.024 \pm 0.011$$

No significant effects observed by expts.
Sensitivity for realistic models still poor.

Further studies: multiplicity as function of p_T, rapidity. No gain in sensitivity seen.

Heavy Hadrons

Heavy particles, like $K^\pm$, p, are likely to be more sensitive to CR (factor ~ 2):



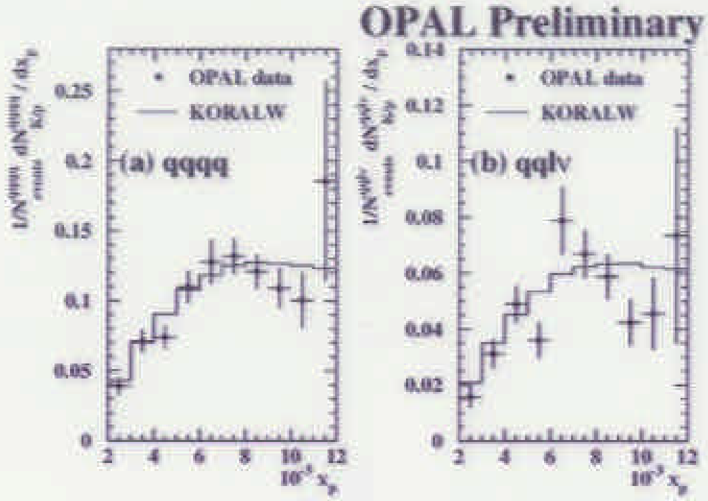
DELPHI: Use dE/dx in TPC, and Cerenkov information from RICH detectors, to tag $K^\pm$, p, $\bar{p}$ in WW events at $\sqrt{s} = 189$ GeV.

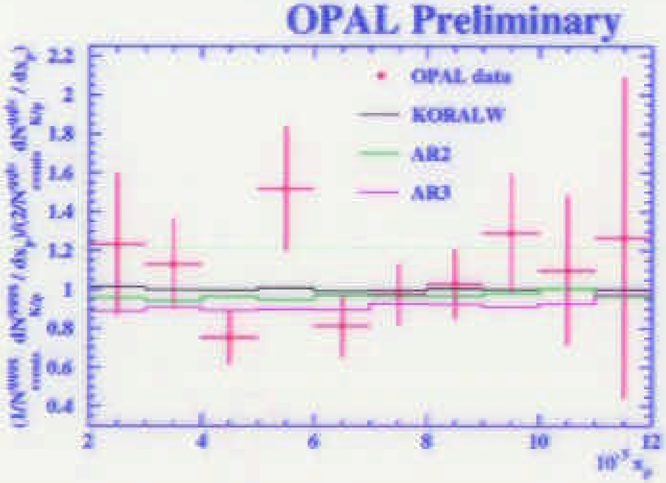
Efficiency depends strongly on p, average $\sim 60\%$. Purity $\sim 60\%$.

Results for ratio $R = N^{4q}/2N^{2q}$:

Particle	All p	$0.2 - 1.25$ GeV/c
$\pi^\pm$	$1.02 \pm 0.03 \pm 0.04$	$1.03 \pm 0.03 \pm 0.01$
$K^\pm$	$0.98 \pm 0.17 \pm 0.08$	$0.96 \pm 0.38 \pm 0.08$
$p, \bar{p}$	$0.97 \pm 0.28 \pm 0.11$	$0.72 \pm 0.57 \pm 0.08$

OPAL: Use dE/dx in jet chamber.



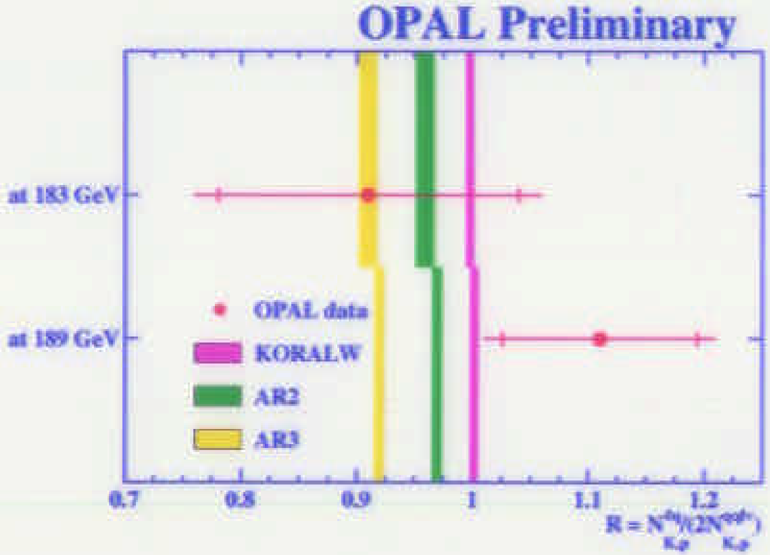


Mean efficiency ~ 60%, purity ~ 90%.

Results: (p between 0.2 and 1.1 GeV)

$$R(183\ \text{GeV}) = 0.91 \pm 0.13 \pm 0.08$$

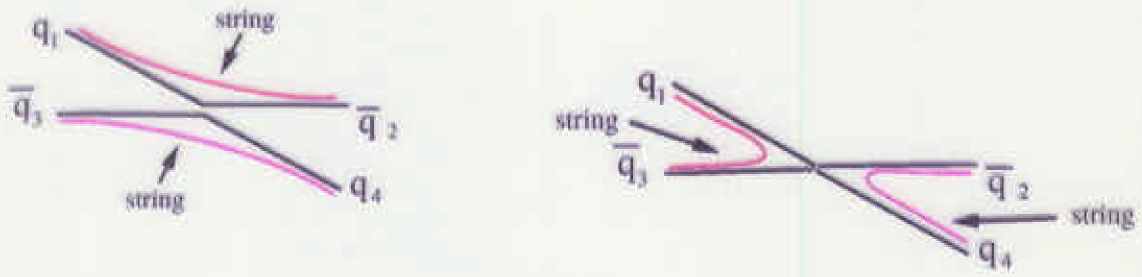
$$R(189\ \text{GeV}) = 1.11 \pm 0.08 \pm 0.06$$



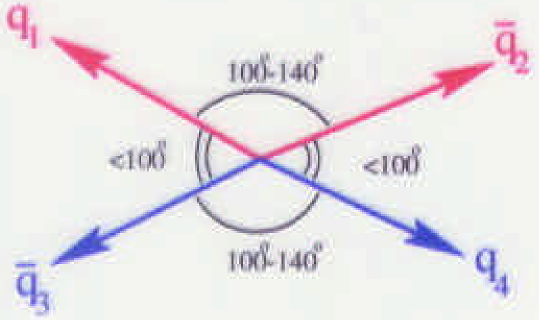
Outlook: combining experiments and all luminosity, statistical error can decrease by factor ~ 2.5 ⇒ test AR3

Particle Flow Between Jets

NEW: analysis of particle- and energy flow between jets in qqqq events: probe string topology (compare: "string effect")



Desired: clean topology: 4 jets with Durham algorithm, efficient jet-pairing, clear jet-ordering (prefer planar events):



Strong cuts on angles between jets
Selection efficiency ~ 15 %
Correct pairing: ~ 87 %

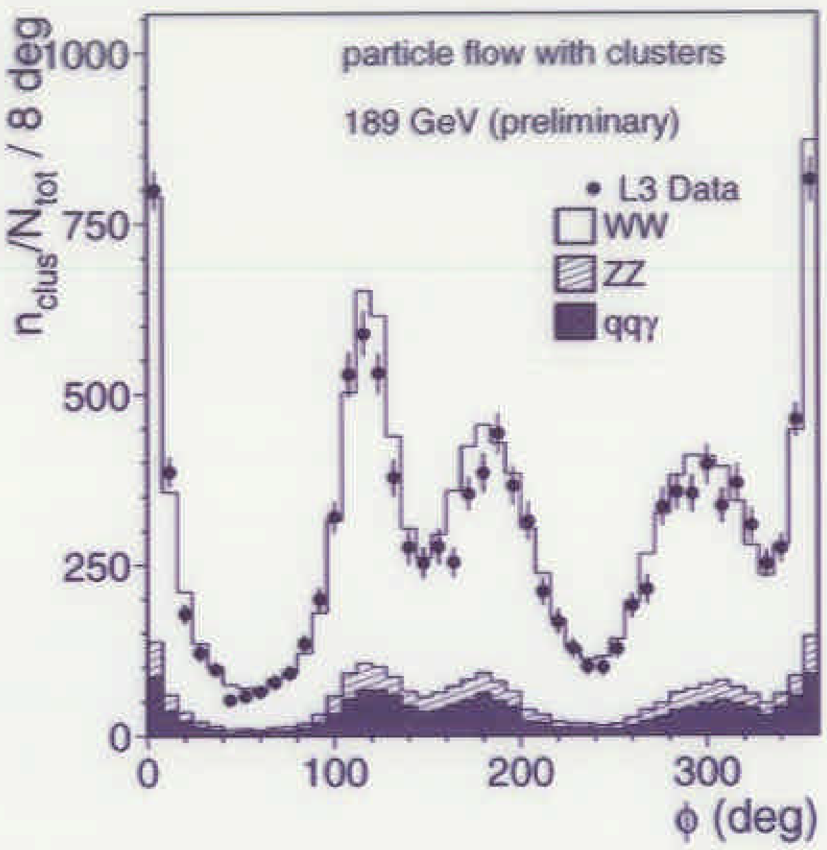
Build particle- and energy flow distributions:

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

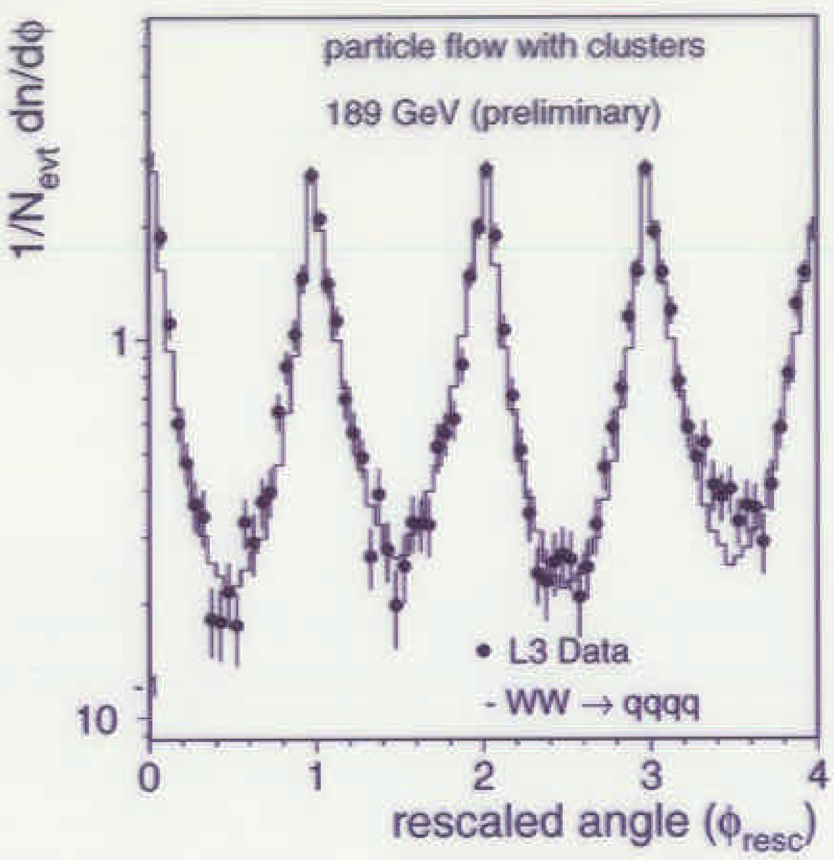
Particle flow: $\frac{1}{N_{evt}} \frac{\Delta n}{\Delta \phi}$

Particle Flow Between Jets

Particle flow distributions:

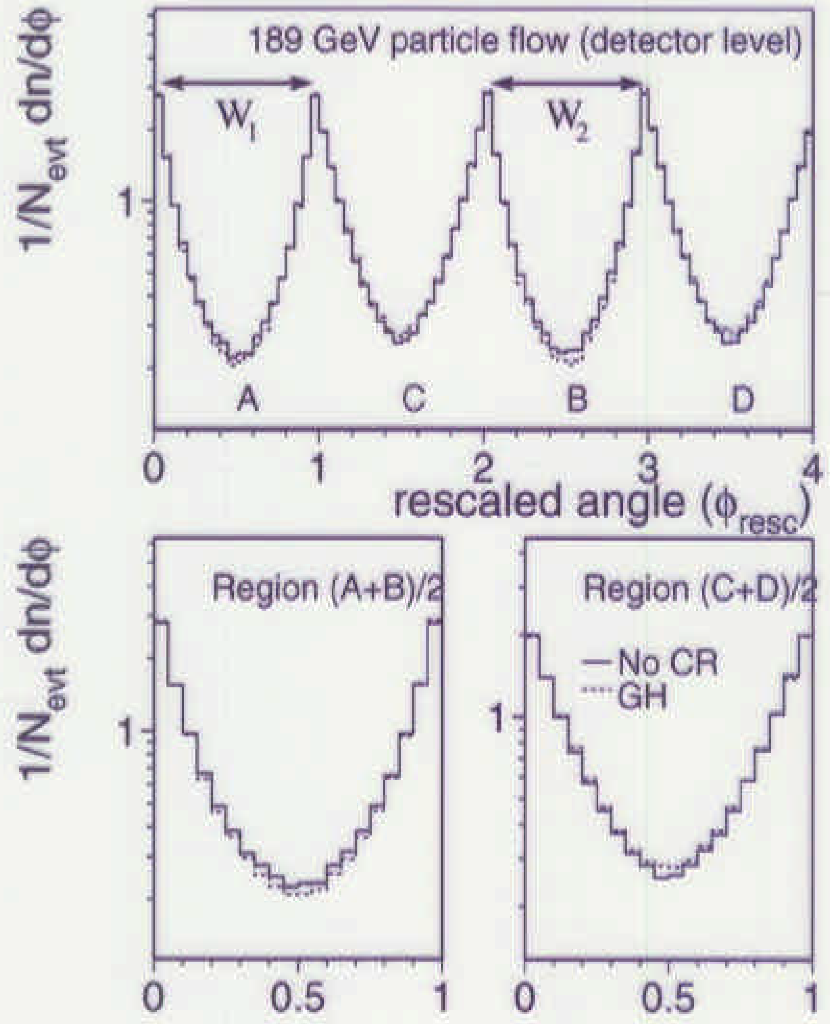


Subtract background, rescale angles between jets, symmetrize by using 4 planes.



Model Predictions

CR model predictions for flow between jets:



⇒ Depletion between same W, increase between diff. W

Sensitivity at detector level similar to particle level

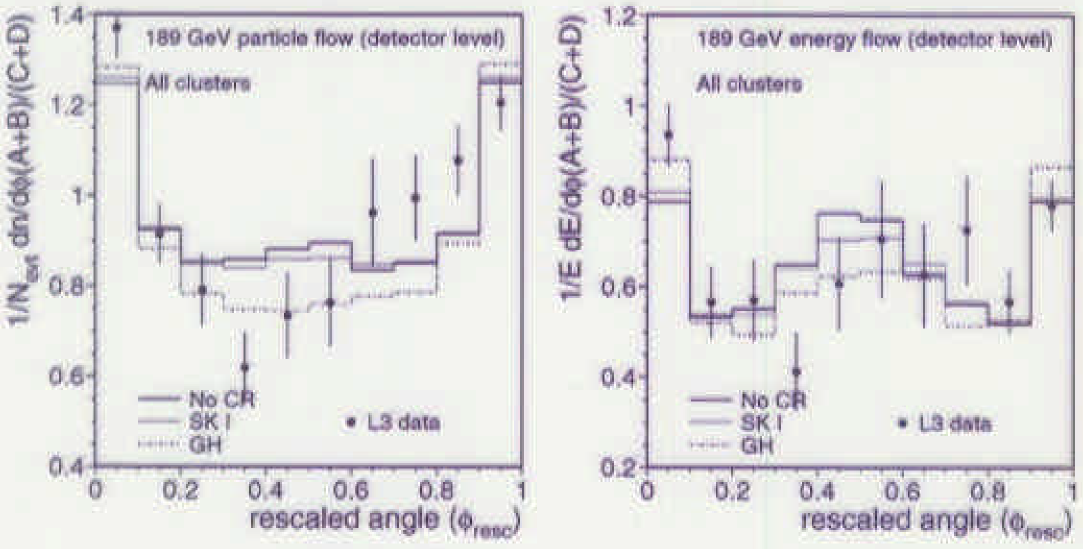
Combine regions between same W (A+B) and between different W's (C+D)

Take ratio $R = (A + B)/(C + D)$ = flow between same W normalized to flow between different W's.

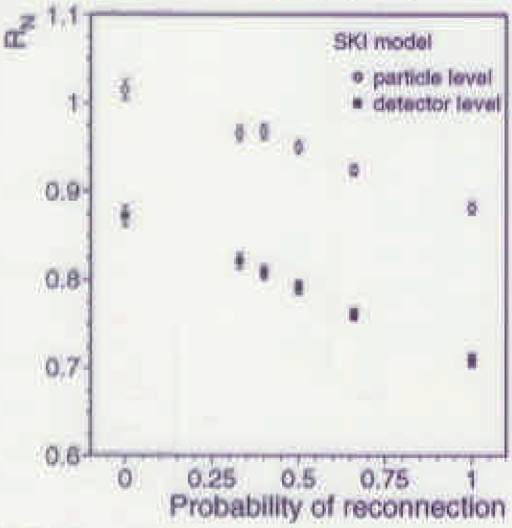
(⇒ ratio: some systematics cancel.)

L3 Results

L3, $\sqrt{s} = 189$ GeV, 176 pb^{-1}, 208 data events:



$R = \int(A+B)d\phi / \int(C+D)d\phi$, $0.3 < \phi_{\rm resc} < 0.7$:



Model	R_N	R_E
No CR	0.868	0.696
SK I (100%)	0.709	0.565
SK II	0.855	0.680
GH	0.758	0.615

Sensitivity for SK I (100%): 3.2 σ
Sensitivity for SK I (32%): $\sim 1\ \sigma$

L3 data:

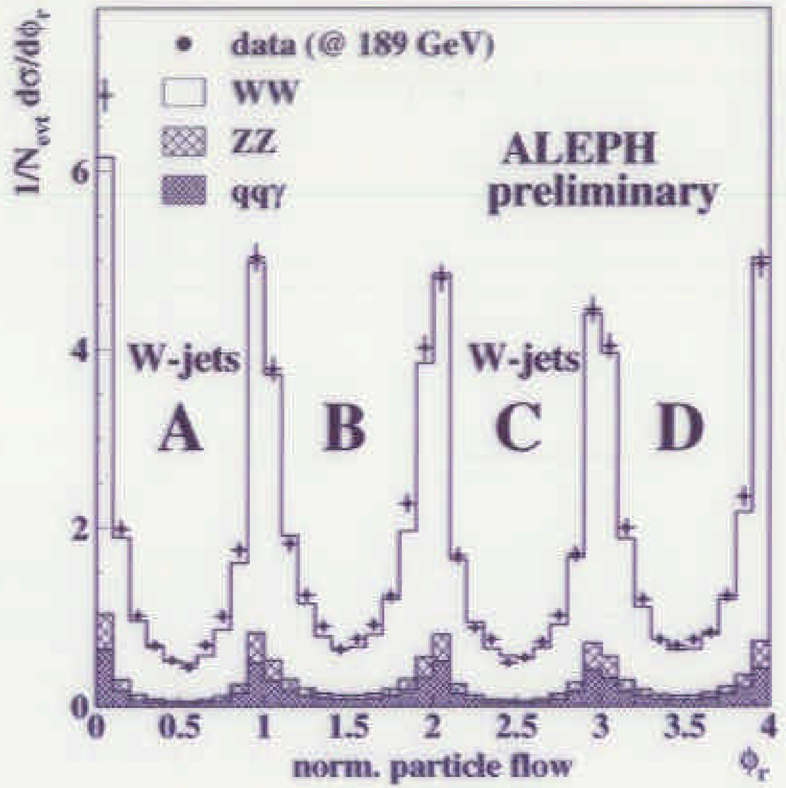
$$R_N = 0.771 \pm 0.049\,(\text{stat.}) \pm 0.029\,(\text{syst.})$$

$$R_E = 0.593 \pm 0.058\,(\text{stat.}) \pm 0.020\,(\text{syst.})$$

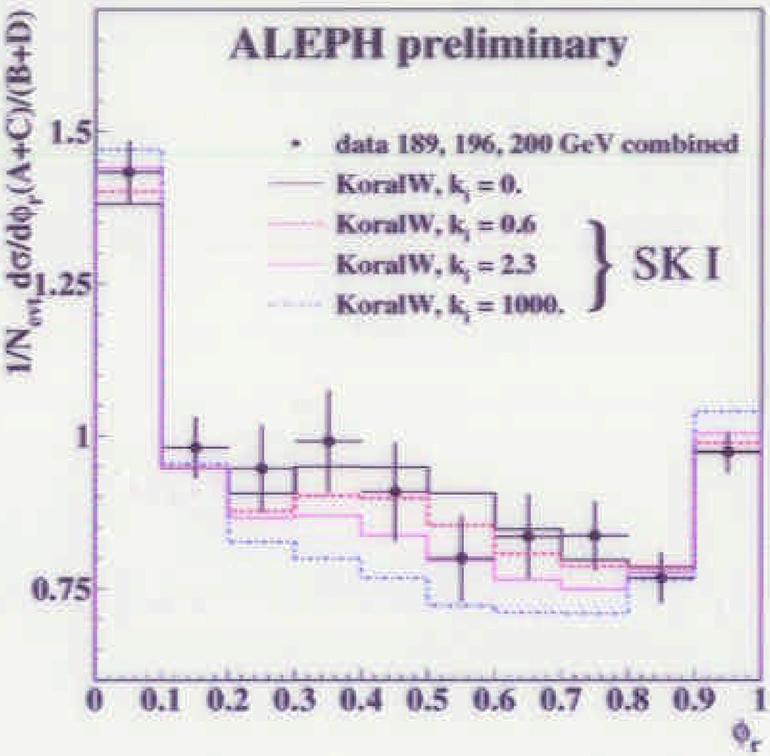
Systematics: fragmentation (JETSET-HERWIG), background, flow objects construction, Bose-Einstein cor.

ALEPH Results

ALEPH: very similar particle flow analysis, $\sqrt{s} = 189-200$ GeV, 347 pb^{-1}, 446 events:

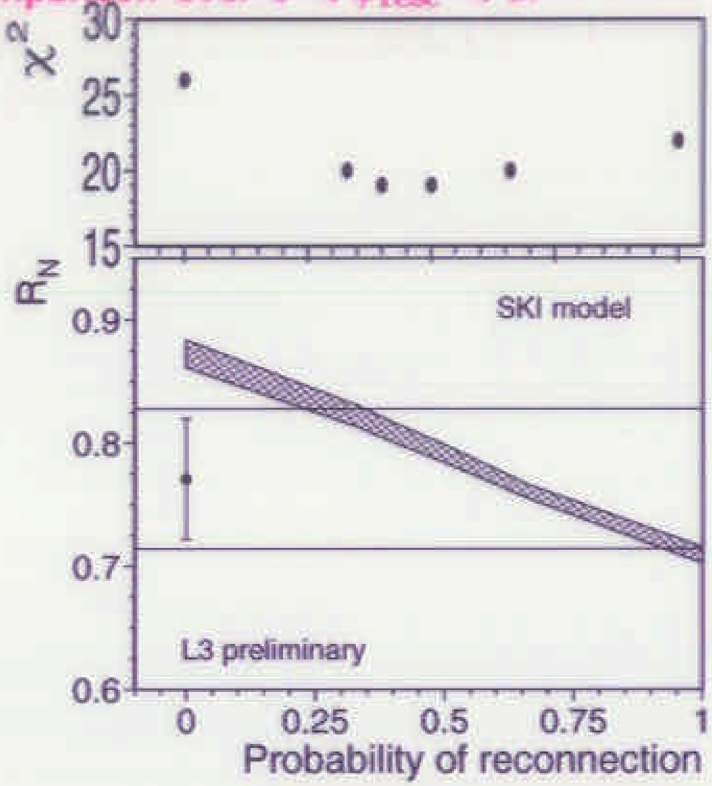


Compare flow (A+C)/(B+D) to SK I model with various values of free parameter k_i:

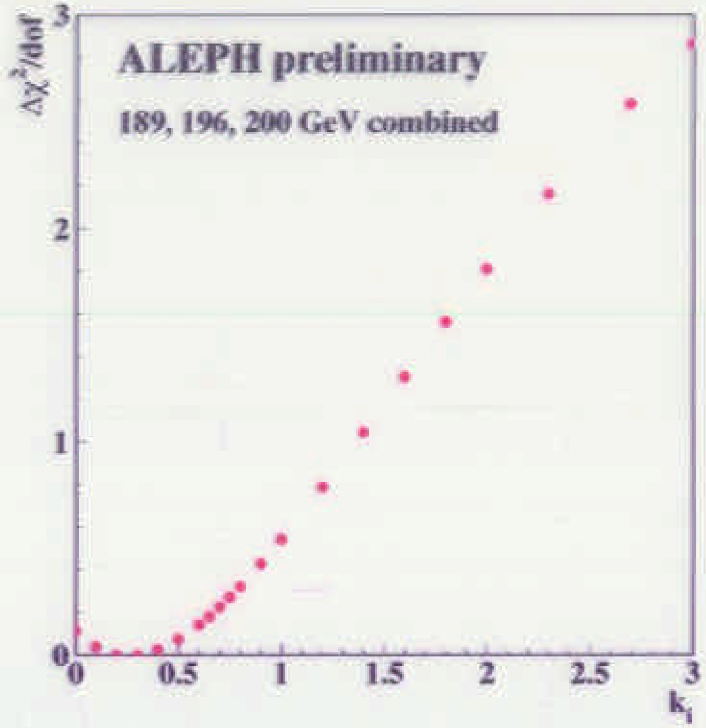


L3 and ALEPH Data - SK I comparison

L3: vary P_{reco} and calculate χ^2 for data-MC comparison over $0 < \phi_{resc} < 1$:



Minimize χ^2: data prefers $\sim 40\%$ of reconnected events, difference with No CR ~ 1.7 standard deviations.



ALEPH data prefers $k_i \approx 0.25$ ($\sim 15\%$ reconnection), $1\ \sigma$ upper limit for k_i: 1.4 ($\sim 45\%$ reconnection).

OPAL Results

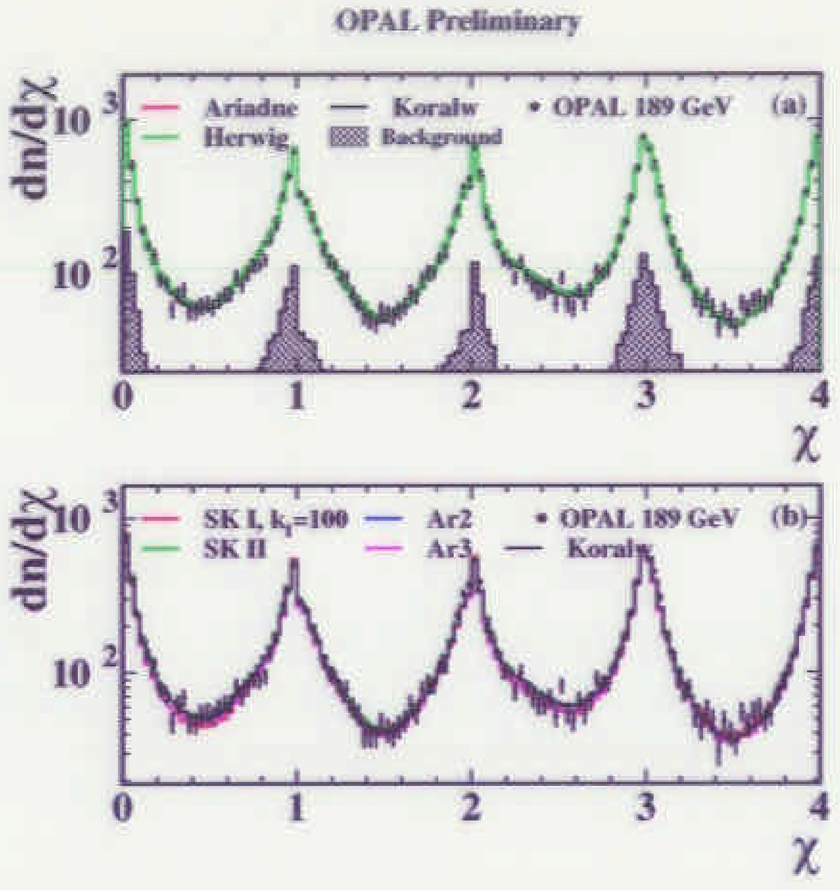
OPAL: particle flow analysis, $\sqrt{s} = 189$ GeV, 183 pb^{-1}.

Use less restrictive cuts, and jet-pairing likelihood variable to assign jets to W's: overall efficiency 42% (699 events), jet-pairing purity 89%.

But: less planar events, higher probability for cross-talk of particles to other inter-jet regions.
Overall: less separation between models, but more statistics, somewhat better sensitivity.

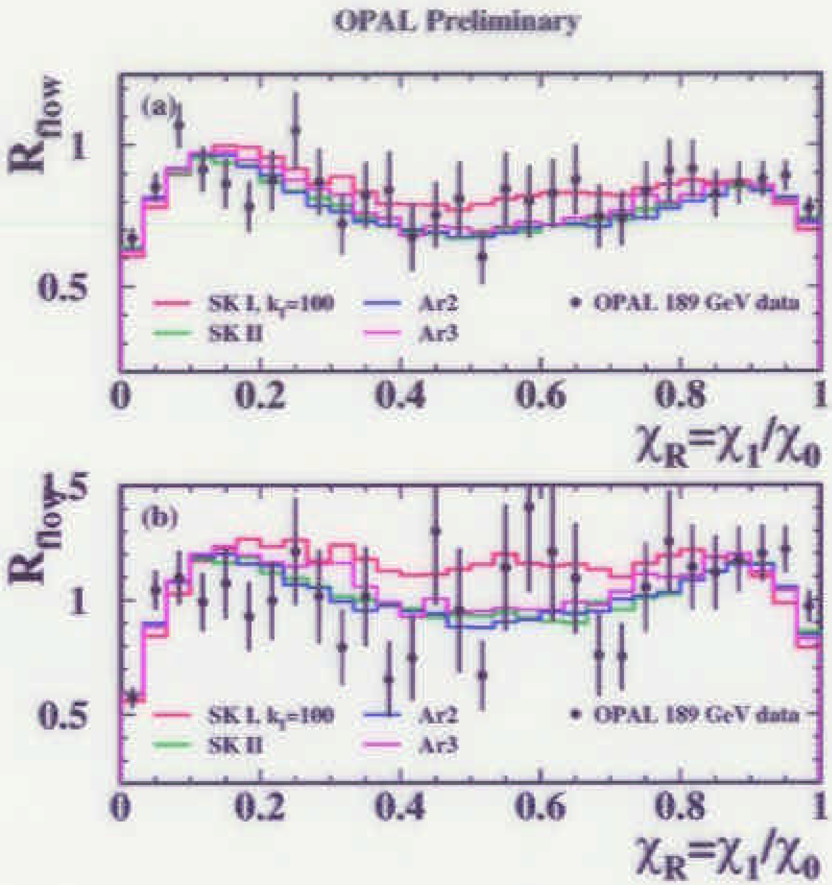
Cross-check: analysis with angular cuts

Particle flow:



OPAL Results

Ratio flow between W's/within W's:



Data: default analysis (a) prefers more CR than cross check (b):

(a): half-way between $k_i = 0.9$ and $k_i = 100$: $\sim 65\%$ reconnection in SK I model

(b): best agreement with No CR

Quality of QCD background MC in (a)?

Sensitivity (effect/$\sigma_{\rm stat}$) for OPAL at 189 GeV:

Sample	$P_{\rm reco}$	Sensitivity
SK I ($k_i = 100$)	95 %	3.2 − 4.0
SK I ($k_i = 0.9$)	35 %	0.8 − 1.1
SK II	20 %	0.2 − 0.4
SK II'	18 %	0.1 − 0.4
AR 2	50 %	0.2 − 0.5
AR 3	62 %	1.2 − 1.8

Outlook: All data, all expts: factor 3.5 in sensitivity to be gained!

Systematics small, not limiting combination.

W Mass Shifts

Back to electroweak physics: what are the effects on M_{W} in the qqqq channel?

Questions to be addressed:

- What are the estimates of the individual expts. for the shift in M_{W}^{qqqq} due to the various CR models?
- If these estimates differ, how much is due to CR model parameters, fragmentation model parameters, W mass analysis?
- What correlation should be used in average?
- What can particle flow tell us?

Common MC event samples generated (No CR and SK I), passed through detector-simulation, selection and analysis of the 4 expts.

Conclusions:

- Shifts in M_{W}^{qqqq} are identical for the 4 expts.
- Correlation in shift is ~100%

Model Estimates of ΔM_W^{qqqq}

Individual experimental estimates of shifts in M_W^{qqqq} (MeV):

	OPAL	L3	DELPHI	ALEPH
SK I	$+65 \pm 8$ (35.1%) ($k_i = 0.9$)	$+29 \pm 15$ (32.1%) ($k_i = 0.6$)	$+46 \pm 2$ (35.9%) ($k_i = 0.65$)	$+30 \pm 10$ (29.2%) ($k_i = 0.65$)
SK II	$+4 \pm 11$ (19.8%)	-5 ± 15 (32.4%)	-2 ± 5	$+6 \pm 8$ (29.2%)
SK II'	$+10 \pm 10$ (17.6%)	-33 ± 15 (28.8%)		$+4 \pm 8$ (26.7%)
AR 2	$+87 \pm 17$ (50.3%)	$+106 \pm 26$	$+28 \pm 6$	$+21 \pm 19$
AR 3	$+143 \pm 27$ (62.3%)	$+170 \pm 26$	$+55 \pm 6$	$+34 \pm 34$
HERWIG				$+20 \pm 10$

Between brackets: fraction of reconnected events.

There are certainly differences due to different CR and fragmentation model parameters.

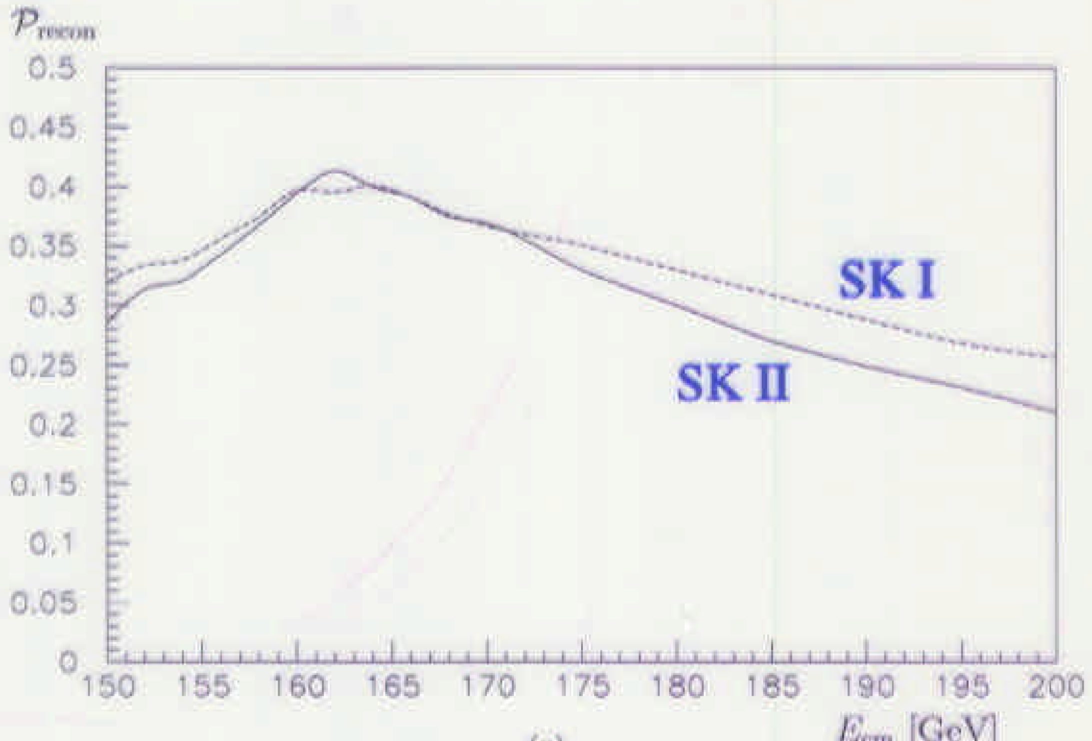
Example: Parton shower cutoff m_0 (O: 1.9 GeV, L: 1.0 GeV, D: 1.5 GeV, A: 1.5 GeV).

⇒ LEP-wide collaboration.

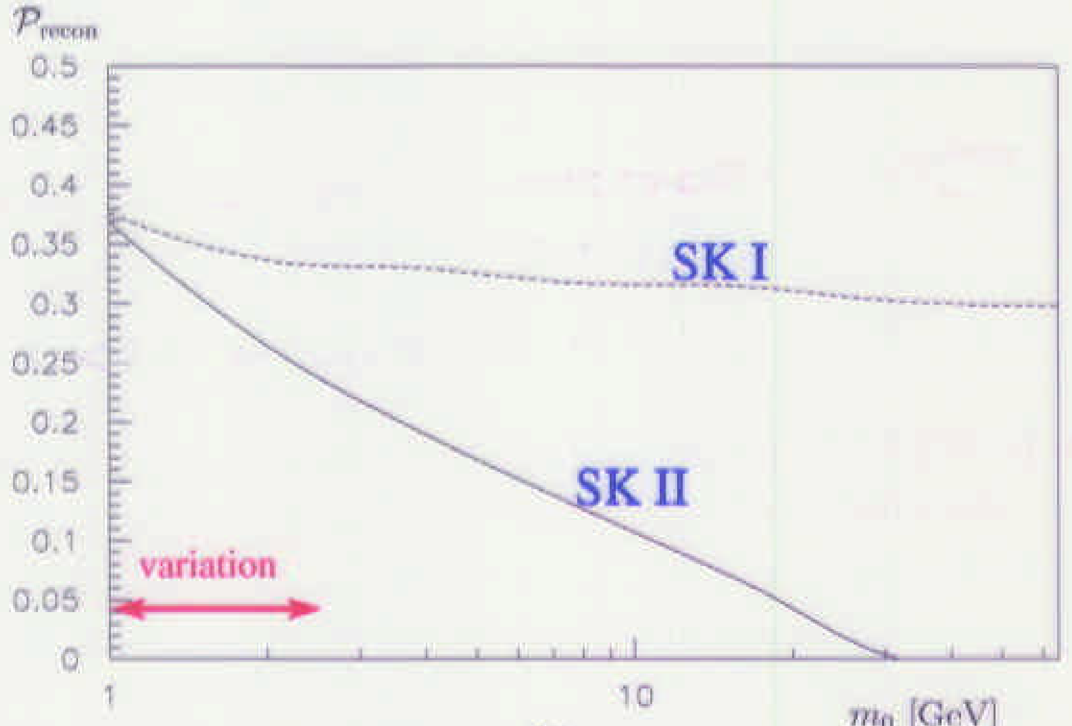
For ICHEP 2000: CR systematic error 50 MeV, fully correlated.

Indiv. papers: O: 65 MeV, L: 50 MeV, D: 50 MeV, A: 30 MeV

Reconnection Probabilities SK



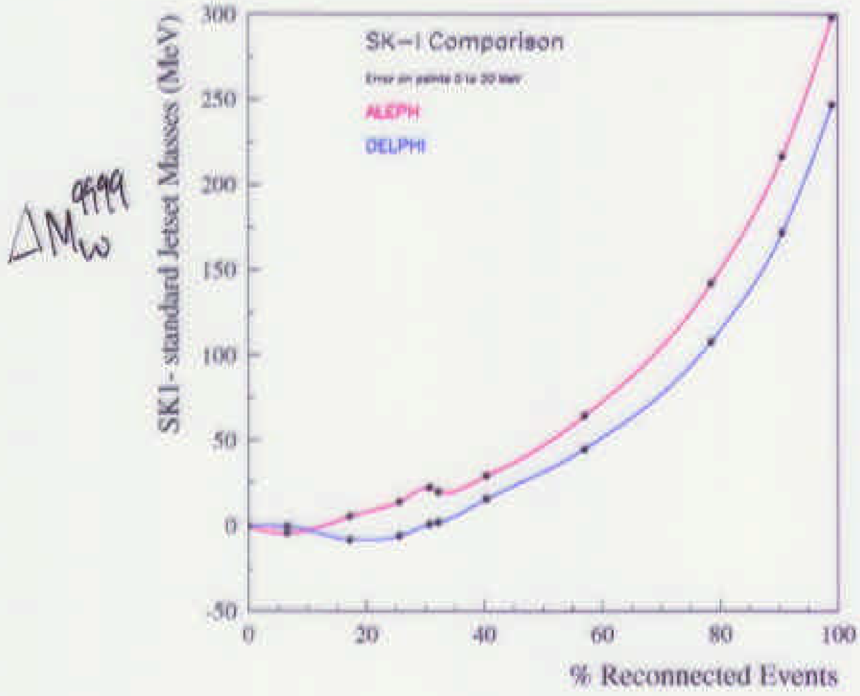
(a)



(b)

Particle Flow and $\Delta M_{\mathrm{W}}^{qqqq}$

Particle-flow analysis has been shown to be sensitive to realistic CR models $\Rightarrow$ Use to estimate $\Delta M_{\mathrm{W}}^{qqqq}$ from the data itself.



For models with free parameter, like SK I, make $\Delta M_{\mathrm{W}}^{qqqq}$ calibration curve.

($\leftarrow$ common LEP sample)

Then use particle flow measurement to calibrate $\Delta M_{\mathrm{W}}^{qqqq}$.

Already: ALEPH 189-200 GeV: 1 σ upper limit:

$$k_i < 1.4 \quad \Rightarrow P_{\mathrm{reco}} < 45\% \quad \Rightarrow \Delta M_{\mathrm{W}}^{qqqq} < 40\,\mathrm{MeV}$$

Outlook: 4 experiments, 600 pb^{-1}/expt., test SK I (35%) at 3.5 standard deviations, SK II at >1 standard deviation

$\Rightarrow$ CR uncertainty on M_{W}^{qqqq} likely to be significantly below 40 MeV, and actually measured from data!

Still many improvements under study: selections, sensitive variables quantifying particle flow.

W Width

Also measure W width Γ_W at LEP 2 from width of mass distributions.

CR also affects Γ_W measurements in qqqq channel.

Same models are used for estimates of $\Delta\Gamma_W$ in qqqq channel (preliminary):

OPAL:	+68 MeV	(SK I)
L3:	+41 MeV	(SK II)
DELPHI:	+54 MeV	(SK I)
ALEPH:	+70 MeV	(SK II')

⇒ Will also use particle flow analysis and calibration curve to estimate $\Delta\Gamma_W$ in qqqq channel from data.

Conclusions

- Charged multiplicity:
  - In agreement with expectations, no significant ΔN_{ch}
  - Difficult to improve sensitivity, only extreme models excluded
  - Heavy hadrons: more effect, less statistics
- Particle- and energy flow are shown to be more sensitive!
- Goal: to measure CR in data and use this as a calibration of M_W in the qqqq channel ⇒ significantly reduce model dependence.

Particle-flow measurements appear promising technique to fulfill that goal.

Already: L3 ($\sqrt{s} = 189$ GeV): preference for modest (40%) reconnection, 1.7 σ above No CR scenario

ALEPH 189-200 GeV: $P_{\rm reco} < 45\% \Rightarrow \Delta M_{\rm W}^{qqqq} < 40$ MeV

- All experiments and all data combined: can test realistic models significantly: SK I (35%) at > 3 standard deviations.

Reduce CR systematic error on $M_{\rm W}^{qqqq}$ significantly.

- Method is fresh and still being improved: selection, variables. All experiments have started such analyses.
- More studies are in progress: factorial moments, Lorentz-invariant variables from charged particles in W rest frames, ...
- LEP data: $M_{\rm W}^{qqqq} - M_{\rm W}^{qq\ell\nu} = +5 \pm 51$ MeV
- LEP 2 data indicates no large CR effects.