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Studies of colour reconnection effects in hadronic W pair decays at LEP

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abstract

The main results obtained from studies of colour reconnection effects in hadronic decays of W pairs produced in e^+e^- annihilation are reviewed. This includes results on charged particle multiplicity and momentum distributions as well as investigations using a new method based on particle-flow distributions.

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Studies of colour reconnection effects in hadronic W pair decays at LEP

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1. INTRODUCTION

In the process $e^+e^- \rightarrow W^+W^- \rightarrow hadrons$ it has been suggested that interactions may occur between the decay products of the two W bosons [1–4]. Colour rearrangement between two colour singlets are expected from simple QCD principles.

The W bosons produced in e^+e^- annihilation decay at short distances ($\approx$ 0.1 fm). Consequently, the hadronisation of the two quark pairs occurs with a large space-time overlap, since the typical hadronic scale is about 1 fm. Colour reconnection (CR) effects are thought to be suppressed in the hard perturbative phase, but may be larger in the non-perturbative stage of the hadronisation process [2]. While hard gluons ($E_g > \Gamma_W$) are emitted incoherently by the two original colour singlets only soft gluons could in principle feel the collective action of both systems and thus participate in cross-talk.

According to the string picture the particles produced in the process $e^+e^- \rightarrow W^+W^- \rightarrow hadrons$ in the absence of colour reconnection come from the fragmentation of two coloured strings which are stretched between the two quarks from the two W bosons. In this case the hadrons can be uniquely assigned to a particular W and there is a direct correspondence between the reconstructed jets and the primary quarks from the W boson decays. Energy momentum is conserved for each of the W systems.

In case of colour reconnection the modifications of this simple string topology picture would modify the colour pattern of the events and result in some depletion and/or enhancement of soft particles in specific phase space regions, especially between the jets.

It should affect mostly soft particle distributions like multiplicity and momentum distributions. Experimentally the main observables sensitive to colour reconnection effects which are studied at LEP are charged particle multplicities, momentum distributions and energy and particle flow.

2. PHENOMENOLOGICAL MODELS

Most of the very successful models describing the $e^+e^- \rightarrow$ hadrons process have implemented some CR schemes within their framework.

The implementations existing in the PYTHIA model are all based on rearrangement of the string configuration during the fragmentation process. The models from Sjöstrand and Khoze [2] follow the space time evolution of the strings and they allow local reconnections if the strings overlap or cross depending on the string definition. In the type I model (SKI) the strings are associated to colour flux tubes with a significant transverse extension. The reconnection occurs when these tubes overlap and only one reconnection is allowed, the one with the largest overlap volume. The reconnection probability depends on this volume of overlap and is controlled by one free parameter: k_I.

In type II models (SKII and SKII') the strings have no lateral extent. The reconnection occurs, with unit probability, when they cross. In SKII

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the first crossing is taken while in SKII' the reconnection is chosen if it reduces the total string length (λ).

The model of Gustafson-Häkkinen [3] (GH) is also implemented in the LUND string fragmentation framework. A reconnection is chosen if it reduces the total string length. This model corresponds to the scenario originally implemented in ARIADNE where reconnections occur between colour dipoles and are considered if the string length is reduced. Two options exist: AR2 and AR3. In AR2 only the reconnections occuring after the hard gluon emission ($E_g > \Gamma_W$) are allowed while in AR3 all reconnections are allowed.

A colour reconnection scheme is also implemented in HERWIG [5] which, like for the string fragmentation, is a local phenomenon since the cluster fragmentation process follows space-time development. In this model the clusters are rearranged if their space-time extension is reduced.

3. COLOUR RECONNECTION AND THE W MASS

One aim at the end of the LEP program is to achieve a precision on the W mass of the order of 20 to 30 MeV. Since the statistical error is already at the level of the systematics it is important to assess the possible effects of CR in the W mass determination. Especially because the hadronic channel corresponds to nearly 40% of the W pair decays. The W reconstruction determination relies mainly on reconstructed jets. Since CR affects the hadron to W-jet assignments it is important to quantify the possible bias introduced in the W mass determination.

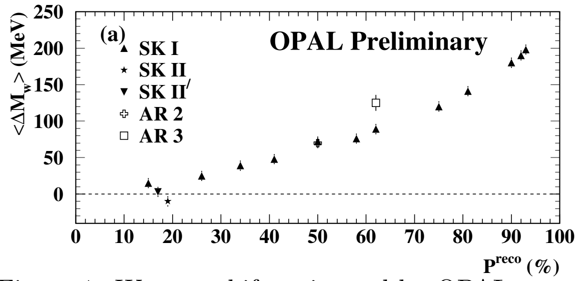

Figure 1. W mass shift estimated by OPAL as a function of the reconnection probability for various models.

The difference between the mean reconstructed W mass and the mean generated W mass computed by OPAL [6] is shown in figure 1 as a function of the fraction of reconnected events for several CR models. According to these models the maximum expected effects on the W mass can be of the order of 200 MeV. It is clearly important to quantify at which rate CR occurs in W pair events.

4. LEP DATA SAMPLES

Table 1 summarises the main data samples which have been used for the colour reconnection studies described in this review.

Table 1
Center-of-mass energy, average luminosity and number of WW events per experiment in the LEP data samples used for CR studies.

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

They correspond to e^+e^- centre-of-mass energies ranging from 183 to 202 GeV. The average luminosity, number of qqqq and q$\overline{\text{q}}$ $l\nu$ events per experiment are given. The total amounts to about 450pb^{-1}/expt. This gives a sample of about 3800 fully hadronic events per experiment.

This year, LEP continues to deliver high energy data above 202 GeV with an accumulated luminosity larger than 100 pb^{-1}/exp.

5. CHARGED PARTICLE MULTIPLICITIES

The first observable which was investigated for CR studies is the mean charged particle multiplicity. It is expected to be sensitive to CR effects. The mean multiplicity from qqqq channel $< N_{ch}^{4q} >$ is usually compared to two times the mean multiplicity from semi-leptonic W decays without the lepton, $< N_{ch}^{q\overline{q}l\nu} >$, these events being unaffected by colour reconnection. The corresponding variable is given by:

$$\Delta < N > = < N_{ch}^{4q} > -2 < N_{ch}^{q\overline{q}l\nu} > \quad (1)$$

For the various CR models described in section 2, $\Delta < N >$ at 189 GeV varies between -0.2 and -0.9. The effects are less than a few percent of the average multiplicity, which is about 38 at 189 GeV.

The negative sign can be understood in the framework of the models where the string length, equivalent to its energy, is reduced. This leads to a reduction of the particle multiplicities.

Experimentally the mean charged particle multiplicities are obtained in two different ways. OPAL [6] and L3 [7] measure and correct the charged track multiplicity distributions while ALEPH [8] and DELPHI[9] integrate the fragmentation distributions after detector corrections.

The distributions and multiplicity numbers are not corrected at the same level by the different experiments. For example DELPHI, L3, and OPAL correct the distributions to full acceptance using Monte Carlo models while ALEPH corrects within their experimental acceptance and for particles having a momentum greater than 200 MeV. This explains their lower multiplicities compared to the other experiments. Table 2 summarises the charged particle multiplicities for $qqqq$ and $q\overline{q}l\nu$ events together with the difference $\Delta < N >$ measured by the four experiments. It should be noted that the four data samples are not the same. Within the statistical precisions the four numbers are compatible with the model predictions without CR as well as with the CR models. The systematic errors are partially correlated and the dominant correlated contribution is coming from fragmentation model uncertainties in the acceptance corrections. This contribution is typically 0.2-0.3 on $\Delta < N >$ which is at the same level as the expected effect. This means that even after combining the four LEP experiments (assuming they agree on a common definition) it will be difficult to reach any definite conclusion from $\Delta < N >$ since there is no large deviation from 0. A similar conclusion can be reached when comparing the scaled momentum distribution of charged particles obtained from $qqqq$ with the one obtained from semi-leptonic events. Figure 2 shows the corrected $\xi(= -ln(x_p))$ distributions measured by DELPHI at 189 GeV for $qqqq$ and $q\overline{q}l\nu$ events (a) and the difference between the $qqqq$ and twice the $q\overline{q}l\nu$ distributions (b). The expected effect in the low momentum (high ξ) region is about 2-4%.

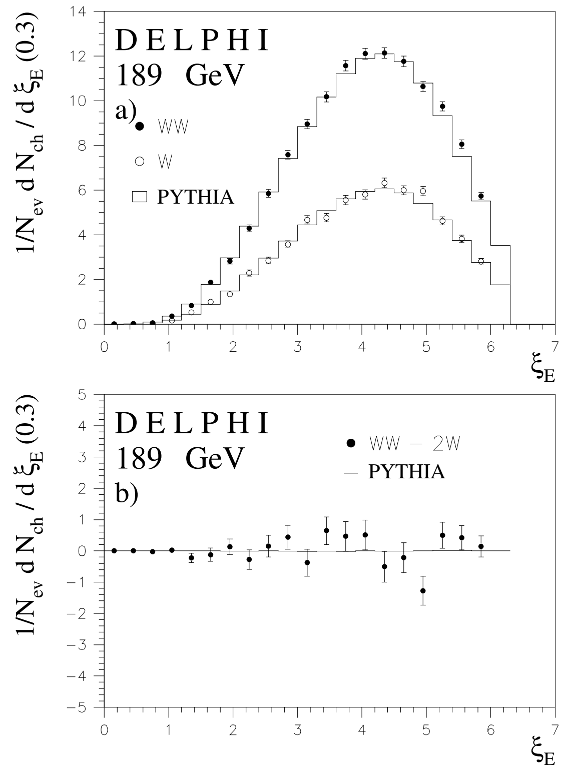

Figure 2. Corrected ξ distributions of charged particles for $qqqq$ and $q\overline{q}l\nu$ events (a) and the difference between $qqqq$ and twice $q\overline{q}l\nu$ (b).

6. HEAVY HADRONS

It has been suggested that CR effects may be more pronounced for heavy hadrons (Kaons, protons) [2]. The ARIADNE models predict effects for low momentum multiplicities two to three times larger than with inclusive particle distributions as shown in figure 3.

OPAL [10] and DELPHI [9] have investigated the production rates of kaons and protons in W pair events. They have compared the rate in $qqqq$ events to twice the rate measured in $q\overline{q}l\nu$ events (after removing the lepton). OPAL is tagging p and K using dE/dx measurements. The heavy

Table 2
$< N_{ch} >$ for $qqqq$ and $q\bar{q}l\nu$ events and $\Delta < N >$ measured by the 4 LEP experiments

Exp.($\sqrt{s}$)	$< N^{4q}_{ch} >$	$< N^{q\bar{q}l\nu}_{ch} >$	$\Delta < N >$
ALEPH 189	35.52 ± 0.22 ± 0.43	17.53 ± 0.19 ± 0.24	0.47 ± 0.44 ± 0.26
DELPHI 183-189	38.80 ± 0.29 ± 0.38	19.57 ± 0.26 ± 0.32	-0.34 ± 0.60 ± 0.34
L3 183-202	37.90 ± 0.14 ± 0.41	19.09 ± 0.11 ± 0.21	-0.29 ± 0.26 ± 0.30
OPAL 189	38.31 ± 0.24 ± 0.37	19.23 ± 0.19 ± 0.19	-0.15 ± 0.44 ± 0.34

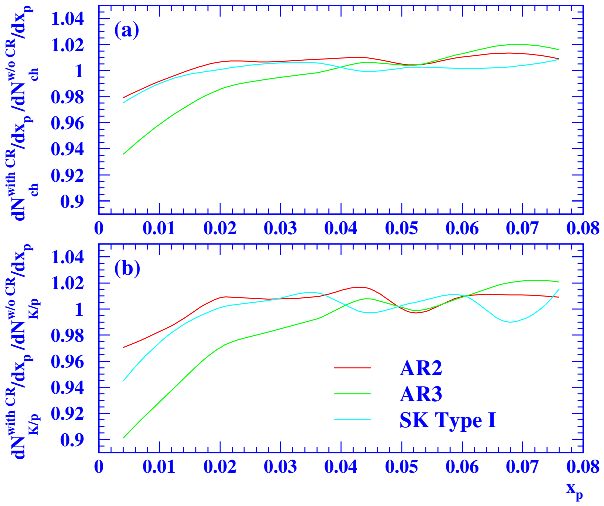

Figure 3. Ratio of reconnection to no reconnection x_p- spectra for all charged (a) and heavy hadrons (b) in $qqqq$ events at 189 GeV using SKI and ARIADNE models.

hadron purity and efficiency are about 87% and 57-60% respectively. The momentum range investigated corresponds to $0.002 < x_p < 0.012$ where x_p is the scaled momentum $= p/E_{beam}$. The rates are corrected for detector effects and the variable R= $N^{4q}_{K,p}/(2.N^{q\bar{q}l\nu}_{K,p})$ is determined. Figure 4 shows this ratio as a function of x_p for the data (dots) and KORALW prediction without CR and AR2 and AR3 predictions. AR3 model shows a reduction in the heavy hadron multiplicity of the order of 10% in the low momentum range. The values of R integrated over the whole momentum range for 183 and 189 GeV are:

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

and shown in figure 5 together with the ARIADNE model predictions and the No CR model. The results are compatible with both type of

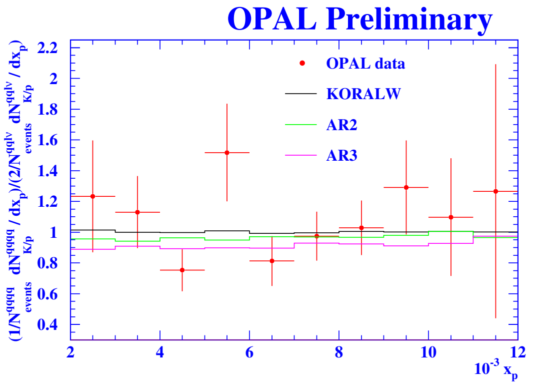

Figure 4. Ratio of the corrected x_p distributions between $qqqq$ and 2 times $q\bar{q}l\nu$ events for p and K measured by OPAL.

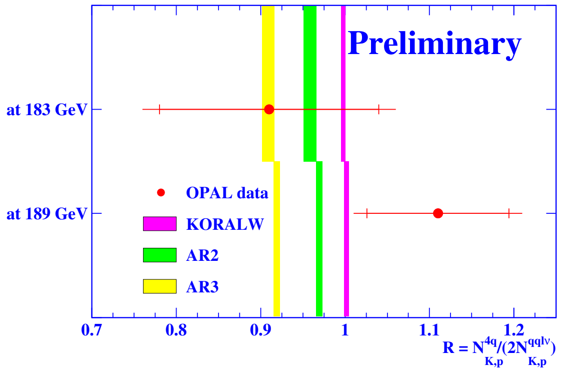

Figure 5. Ratio R= $N^{4q}_{K,p}/(2.N^{q\bar{q}l\nu}_{K,p})$ measured by OPAL for $0.002 < x_p < 0.012$ compared to model predictions.

models.

DELPHI is tagging the kaons and protons using the central tracker and the RICH detector. The following ratios for p and K are obtained by comparing the $qqqq$ and the $q\bar{q}l\nu$ events in the momentum range $0.2 < p < 1.25 GeV$:

$$R_K(\text{189 GeV}) = 0.96 \pm 0.38(stat.) \pm 0.08(syst.)$$
$$R_p(\text{189 GeV}) = 0.72 \pm 0.57(stat.) \pm 0.08(syst.)$$

These results are compatible with unity. The con-

clusion is similar when the momentum range is extended to all p.
The OPAL uncertainty at 189 GeV is of the order of the predicted effect by AR3. This means that at the end of LEP2 and if other competitive measurements exist this ratio may be sensitive to even smaller effects. We should certainly keep an eye on this identified particle study.

7. ENERGY- AND PARTICLE-FLOW

A new method has been proposed to study the particle flow in qqqq events in order to probe the colour topology of the events [11]. The method relies on the comparison of the particle activity between jets from one W and between jets from different W bosons. These characteristics should be sensitive to colour reconnection effects.

The method relies on a topological event selection criterion based on the interjet angles. This guarantees well defined 4 jet events with a probability of correct pairing between W bosons and the associated jets of about 87% at 189 GeV with an efficiency of about 15% for $e^+e^- \rightarrow W^+W^- \rightarrow$ qqqq.

7.1. Particle flow distributions

The particle flow distributions are built by projecting on a plane defined by two adjacent jets the momentum vector direction of all particles. The energy and particle flows are measured as a function of the angle ϕ in the plane between the most energetic jet (jet 1) and the projected momentum vector. This angle is defined as increasing from jet 1 toward jet 2 (from same W), then to the closest jet from the other W (jet 3) toward the remaining jet (jet 4) and back to jet 1. A particle i making an angle ϕ_i with respect to jet 1 adds an entry equal to 1 in the particle flow and adds an entry equal to its energy in the energy flow for the corresponding ϕ bin. The contribution of each event to the energy flow is normalised to the total event energy. The distributions are calculated for particles or detector objects like calorimetric clusters or tracks. Figure 6 shows the energy flow distribution as obtained by L3 at 189 GeV following this method [7]. The plane in which the angles are computed has been defined by the most energetic jet and the jet associated to the same W. The 4-jet structure is clearly vis-

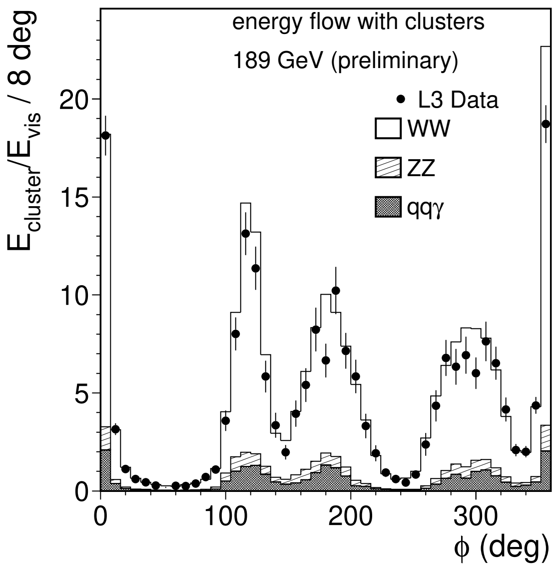

Figure 6. Energy flow distribution obtained at detector level for data and Monte Carlo predictions.

ible with the decay products of one W covering the region starting from 0 to ≈ 120 degrees while the second W covers the angular region from 140 to 340 degrees. A special transformation is performed in order to take into account the fact that the W events are not planar. This transformation consists of using four planes for projecting the particles instead of only one. The four planes correspond to the planes spanned by each pair of adjacent jets. The particles located between two jets are then projected only on the plane spanned by these two jets. Thus the colour pattern existing between the two partons can be studied.
In order to compare the interjet regions the distributions are transformed by redefining the angles with respect to the interjet angle with which the particle is associated. The procedure is called angle rescaling. For a particle i located between jets j and k, the rescaled angle is: $\phi_i^{resc} = \phi_i / \phi_{jk}$ where ϕ_{jk} is the angle between jets j and k. With this definition the four jets have fixed rescaled angle values equal to 0, 1, 2 and 3. The remaining background, coming essentially from $e^+e^- \rightarrow$ qq

and $e^+e^- \to ZZ$, is subtracted bin-by-bin. Figure 7 shows the rescaled normalised particle flow distribution obtained by L3 [7] using a combination of calorimetric clusters and tracks to define the particles. The line corresponds to the standard KORALW prediction for $qqqq$ events without CR. The regions spanned by the two W bosons are indicated as W_1 and W_2 on the figure.

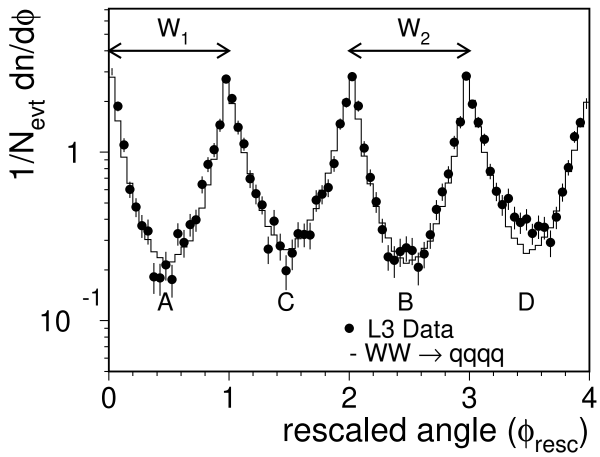

Figure 7. Particle flow distribution as a function of the rescaled angle after background subtraction for L3 data and KORALW prediction at $\sqrt{s} = 189$ GeV.

Since the events are symmetric and the inter-jet regions should be sensitive to CR effects the analyses are based on the comparison of the particle activity within W systems (regions A+B on figure 7) with the particle activity between two different W systems (regions C+D).

The ratio (R(ϕ)) of the particle activity between the quarks from the same W and the particle activity between quarks from a different W is found to be a sensitive observable to the cross-talk effects from colour reconnection [11]. In addition some systematic effects cancel when doing these ratios.

In order to quantify the colour reconnection effects the ratio R is computed in a restricted ϕ_{resc} interval, ranging from 0.3 to 0.7 in the case of L3, where the sensitivity is found to be larger.

The corresponding variables for particle (R_N) and energy flow (R_E) are defined as: [2]

$$R_N = \int_{0.3}^{0.7} \frac{\frac{1}{N} \cdot \frac{dn}{d\phi}(regionsA + B)}{\frac{1}{N} \cdot \frac{dn}{d\phi}(regionsC + D)} d\phi \qquad (2)$$

$$R_E = \int_{0.3}^{0.7} \frac{\frac{1}{E} \cdot \frac{dE}{d\phi}(regionsA + B)}{\frac{1}{E} \cdot \frac{dE}{d\phi}(regionsC + D)} d\phi \qquad (3)$$

7.2. Model predictions

Colour reconnection effects could appear as depletion or enhancement of particles between the quark jets. Figure 8 shows $R_N(\phi_{resc})$ for different Monte Carlo predictions obtained at particle level. The full line corresponds to No CR while the two dashed and dotted lines correspond to SKI and GH models. The reconnection probability in these two models were 34% and 92% respectively. The values obtained for R_N and R_E

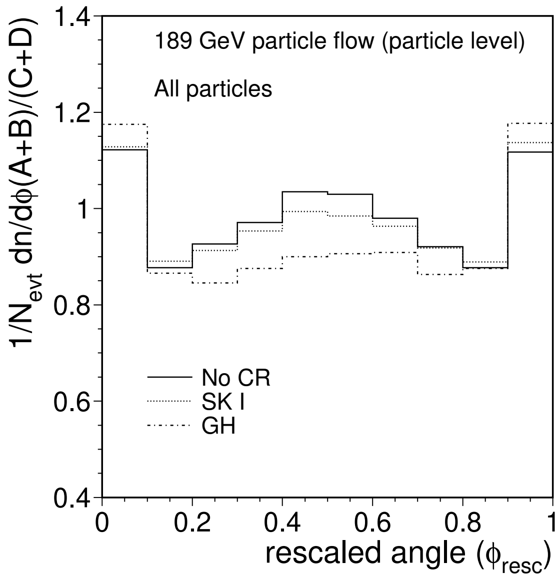

Figure 8. Ratio of particle flow distribution between quarks from same W and between quarks from different W from various Monte Carlo models at particle level.

using all particles are given in table 3 for the model without CR and for the SKII, SKI and GH models. The errors quoted are from Monte Carlo statistics only.

[2] The R formulas in the Ref. [7] and [11] were incorrectly written. They should be replaced by the above ones.

Table 3
Values of R_N and R_E at particle level for various Monte Carlo models.

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

The SK models show effects of the order of about 4% with these variables while the GH model implemented in PYTHIA (having a high reconnection probability) shows a larger effect of about 10%.

R_N is shown in figure 9 as a function of the reconnection probability, P_{reco}, in the SKI model at particle level (open circles) and at detector level (black squares). The effect increases with P_{reco} and the sensitivity is not degraded by detector effects. The sensitivity can be estimated by taking the slope of the variation and comparing it with the statistical error. This gives a 3.5 sigma sensitivity to 100% reconnection with only the statistics of one experiment at 189 GeV where the statistical uncertainty on R_N is about 0.04.

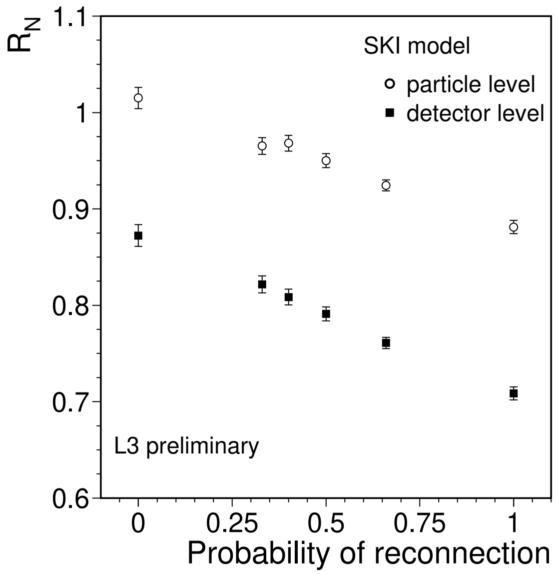

Figure 9. R_N at particle level and detector level as a function of reconnection probability for the SKI model.

Experimental values of R_N can be used to constrain allowed ranges of values for P_{reco} but one should be careful about the possible energy dependence and topology dependence of selection efficiency of reconnected events. The SKI model has one free parameter k_I which is related to P_{reco} by the following formula:

$$P_{reco} = (1 - e^{-f.k_I}) \tag{4}$$

where f is function of the overlap volume of the two strings which depends on W pair kinematics given by the e^+e^- center-of-mass energy. The fraction of reconnected events as a function of k_I is shown in figure 10 for all events and for the selected events by the ALEPH analysis [12]. The change of the k_I dependence due to selection and/or changes in e^+e^- center-of-mass energy has to be considered when adding the different energy samples and also when combining experimental results.

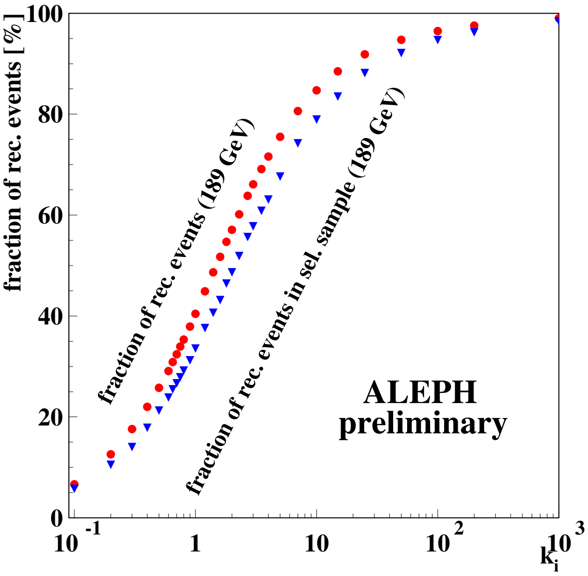

Figure 10. Fraction of reconnected events as a function of k_I in the SKI model before and after selection performed by ALEPH.

7.3. Experimental results

The particle flow ratio distribution obtained by L3 at 189 GeV is shown in figure 11. The ratio values for energy and particle flow are:

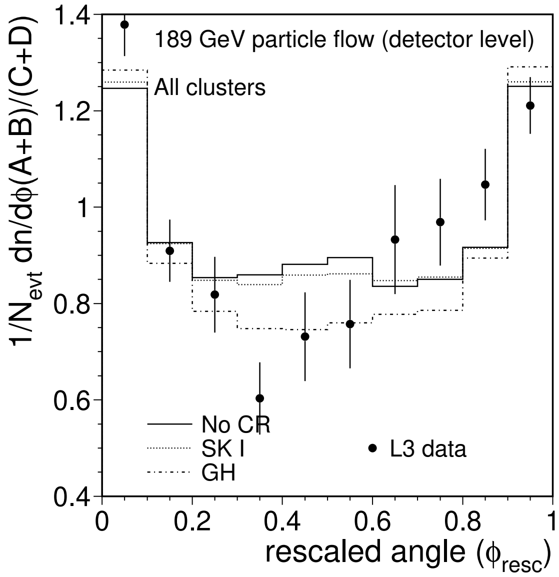

Figure 11. Ratio of particle flow distribution between quarks from same W and between quarks from different W for the L3 data at 189 GeV and for various models.

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

The systematic errors include uncertainties from Bose-Einstein correlations, quark fragmentation, estimated by comparing HERWIG to JETSET results, together with the experimental uncertainties. The ratio values obtained with different models are given in table 4. The data differs from No CR scheme by 1.7 standard deviation.

Table 4
Values of R_N and R_E at detector level for various Monte Carlo models as obtained by L3.

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

Figure 12 shows the comparison with SKI prediction (shaded band) as a function of P_{reco} for R_N. The point is the L3 measurement with the horizontal band showing the 1 sigma boundary. The top plot shows the χ^2 values computed over the whole angular range ($0 < \phi_{resc} < 1$) as a function of P_{reco}. The data shows some preference for non zero reconnection with a minimum χ^2 around 40% of reconnection probability.

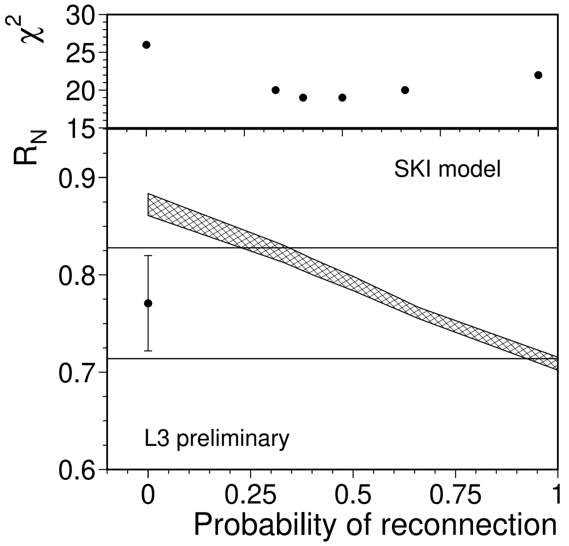

Figure 12. L3 results compared to SKI model as a function of the reconnection probability. The error bar is statistical only while the band width includes the systematic uncertainties.

ALEPH [12] has perfomed a similar study following closely the suggested particle flow method. Figure 13 shows their particle flow distribution as a function of the rescaled angle measured at 189 GeV using only one plane for the projection of the particle momenta. Figure 14 shows the particle flow ratio distribution defined similarly to L3 (activity within W/activity outside W). It includes all data distributions from 189 GeV to 200 GeV weighted with the corresponding statistics.

ALEPH chooses the sensitive region to be between 0.2 and 0.8 and R_N is defined like:

$$R_N = \int_{0.2}^{0.8} \frac{\frac{1}{N} \cdot \frac{dn}{d\phi}(regionsA + C)}{\frac{1}{N} \cdot \frac{dn}{d\phi}(regionsB + D)} dR' \qquad (5)$$

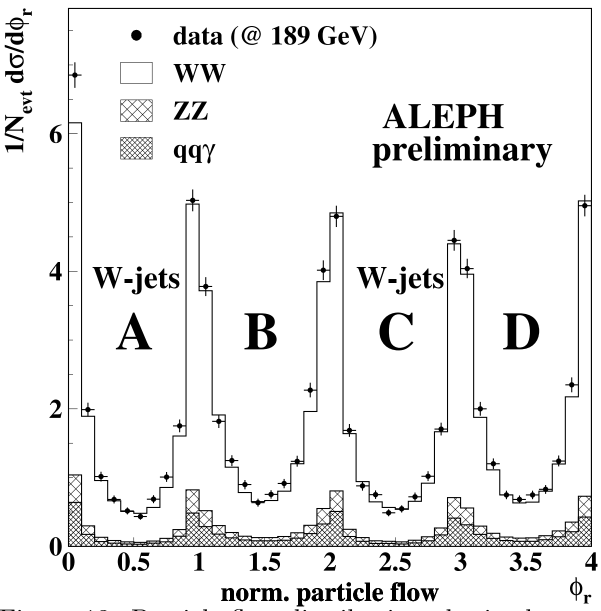

Figure 13. Particle flow distribution obtained at 189 GeV by ALEPH.

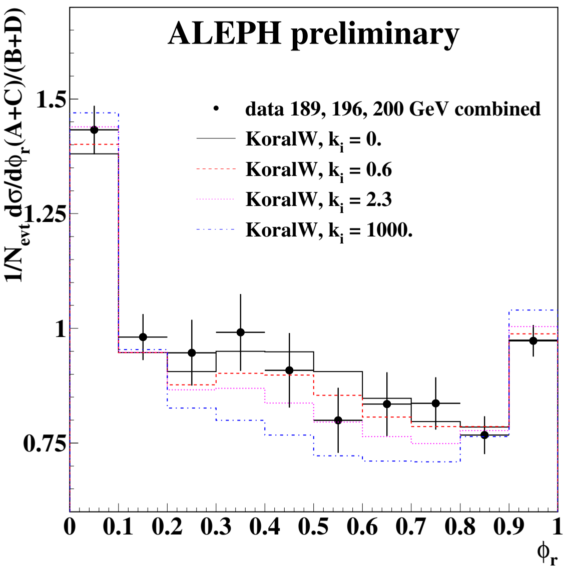

Figure 14. Ratio of the interjet particle flow for data from 189 to 200 GeV from ALEPH.

which gives at 189 GeV:

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

This value is compared to the SKI expectation for R_N as a function of k_I in figure 15. The k_I dependence of R_N measured from Monte-Carlo samples (black dots) is parameterised by the function given in the figure and a χ^2 between data and Monte Carlo is evaluated as a function of k_I for each center-of-mass energy studied. The χ^2 values are then summed over the different energy samples from 189 GeV to 200 GeV as a function of k_I. The resulting $\Delta\chi^2$ is shown in figure 16 as a function of k_I.

From this distribution they obtain an upper limit on k_I at 68% CL equal to 1.4. It corresponds to a reconnection probability P_{reco} <45%. In the SKI framework this limit corresponds to a shift of the W mass due to CR effect less than 40 MeV.

8. CONCLUSIONS

Various studies have been perfomed in order to investigate colour reconnection in hadronic W pair decays since a few years. These studies are motivated by a better understanding of the strong interaction mechanisms and by a desire to control the systematic uncertainties which may arise from these effects on the W mass measurements.

Several variables have been studied. The charged particle multiplicities are not very sensitive to correlation effects and systematic uncertainties should dominate the expected effects. But some hope exists by considering identified heavy particles for which the signal is enhanced.

The energy- and particle-flow distributions are very promising variables since they are sensitive to colour reconnection effects in $e^+e^- \to W^+W^- \to qqqq$ events as simulated in "realistic" CR models.

The L3 analysis of 189 GeV shows a 1.7 sigma effect towards CR. In the SKI scheme it gives a preference for a 40% reconnection probability.

ALEPH analysis of 189-200 GeV data derives a one sigma upper limit on k_I in SKI model equals to 1.4. This corresponds to a reconnection probability < 45%.

Studies following this approach should be continued. Combining the results from the four LEP experiments with the full LEP2 statistics should provide a good sensitivity to effects corresponding to reconnection probability of the order of 30% leading to a shift of the W mass smaller than 20 MeV.

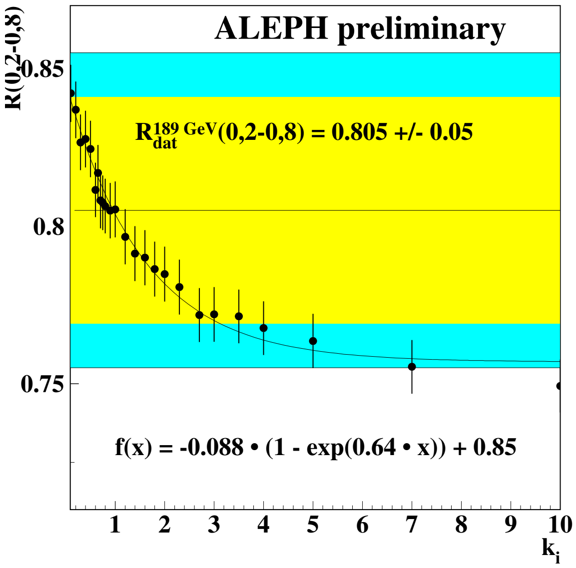

Figure 15. Comparison of the ALEPH result for R_N at 189 GeV with the SKI model prediction as a function of k_I parameter.

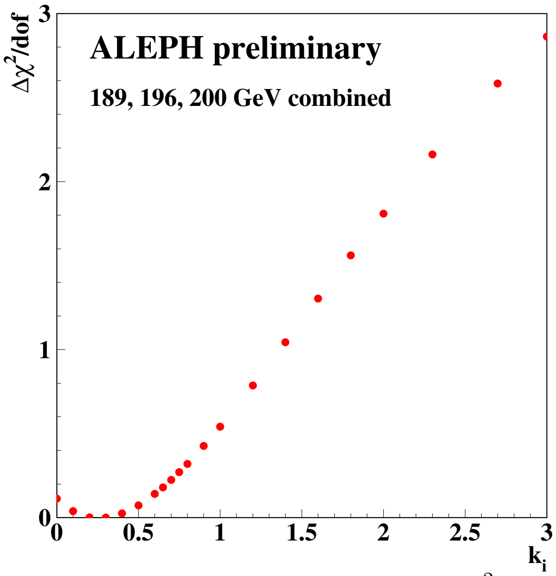

Figure 16. Result from the combined χ^2 as a function of k_I for e^+e^- center-of-mass energies of 189, 196 and 200 GeV.

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