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Colour Reconnection Studies in W Pair Events at LEP

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ABSTRACT: Recent results obtained from studies of colour reconnection effects in hadronic decays of W pairs produced in e^+e^- annihilations are reviewed. The investigations have been performed using a method based on the study of the particle-flow distributions in hadronic 4-jet events.

1. Introduction

In the process $e^+e^- \to W^+W^- \to hadrons$ it has been suggested that interactions may occur between the decay products of the two W bosons [1, 2, 3, 4]. The main justification is the relatively short distance separating the decay vertices of the W bosons produced in e^+e^- annihilation (≈ 0.1 fm) compared to the typical hadronisation scale (1fm) which implies a large space-time overlap of the two hadronising systems. The main consequence of these interactions, called Colour Reconnection (CR) effects, is a modification of the simple colour flow topology that would be obtained if the two W systems evolve independently. It results in some depletion and/or enhancement of soft particles in specific phase space regions, especially between the jets. The study of CR is interesting not only for probing some QCD dynamics but also for determining a possible bias in the W mass reconstructed from jets in the 4-jet channel since CR affects the hadron to W-jet assignments. Previous studies [5, 6, 7, 8] based on charged particle multiplicity and momentum distributions were limited by statistics and systematics. The experiments have then turned to the study of the particle flow distributions in $q\overline{q}q\overline{q}$ events using the method proposed in [9] showing more sensitivity to CR effects.

2. Phenomenological models

Most of the very successful models describing the $e^+e^- \to$ hadrons process (PYTHIA, ARIADNE and HERWIG) have implemented some CR schemes within their framework.
The various implementations existing in the PYTHIA model are all based on rearrangement of the string configuration during the fragmentation process. The models from Sjöstrand

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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, P_{reco}, equals $(1 - e^{-f.k_I})$ where k_I is a parameter which can be varied in the model and f is a function of the overlap volume of the two strings. The analyses presented here have used extensively this model which has the advantage of having a free parameter.

3. The particle flow method

The idea initiated by L3 is to investigate the particle and energy flow between jets in $q\overline{q}q\overline{q}$ events in order to probe the colour topology of the events. The main ingredient is the construction of the particle flow distributions between pair of jets for well defined jet configuration. The details are given in Ref. [9].

By convention the first two jets are associated to the same W and the last two to the second W boson. Figure 1 shows the particle flow obtained by ALEPH at $\sqrt{s}$=189 GeV [10]. The 4-jet structure is clearly visible with the decay products of one W covering the region

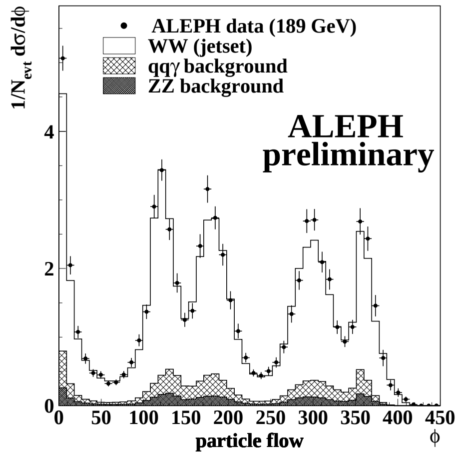

Figure 1: Particle flow distribution measured by ALEPH with a strict selection

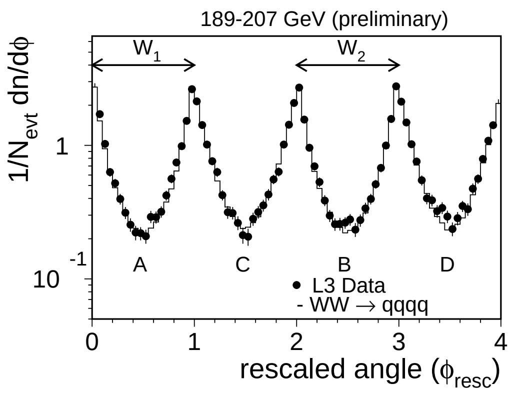

Figure 2: Particle flow distribution measured by L3 as a function of the rescaled angle after background subtraction

starting from 0 to ≈ 120 degrees while the second W covers the angular region from 140 to 340 degrees. In order to compare the interjet regions the distributions are transformed by redefining the angles with respect to the interjet angle of the region where the particle is associated. With this angle rescaling procedure the four jets have fixed rescaled angle values equal to 0, 1, 2 and 3. The background after selection comes essentially from $e^+e^- \rightarrow q\overline{q}$ and $e^+e^- \rightarrow ZZ$ and is subtracted bin-by-bin. It amounts to about 15-22% depending on the experiment. Figure 2 shows the rescaled normalised particle flow distribution obtained by L3 at $\sqrt{s}$=189-207 GeV [12]. The line corresponds to the standard KORALW prediction for $q\overline{q}q\overline{q}$ events without CR. The regions spanned by the two W bosons are indicated as

W_1 and W_2 on the figure. Since the interjet 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 2) with the particle activity between two different W systems (regions C+D).

The ratio, R_N, of the particle activity between the quarks from the same W and the particle activity between quarks from a different W is defined as the sensitive observable to the cross-talk effects from colour reconnection [9]. The differences between the models with and without reconnection schemes are larger in the center of the interjet regions. Therefore, in order to quantify the colour reconnection effects, the ratio is computed for a restricted rescaled angle (ϕ_{resc}) interval ranging from 0.2 to 0.8. The corresponding expression is:

$$R_N = \frac{\int_{0.2}^{0.8} \frac{1}{N_{evt}} \cdot \frac{dn}{d\phi}(intra{-}Wregions)}{\int_{0.2}^{0.8} \frac{1}{N_{evt}} \cdot \frac{dn}{d\phi}(inter{-}Wregions)}$$

3.1 Event selection

Two types of selection are applied by the LEP experiments. The first one, used by DELPHI [11] and L3, corresponds to the original idea of selecting very well defined 4-jet topology based on criteria on the interjet angles [9]. This allows the selection of events with a very simple colour flow pattern with symmetric interjet regions and a probability of correct pairing between the W bosons and the associated jets greater than 85%.

	$\sqrt{s}$ (GeV)	$\int \mathcal{L}(pb^{-1})$	# evts	ϵ	π	right pair.
DELPHI	183-208	601.4	759	11%	82%	76%
L3	189-208	626.6	666	12%	85%	91%
ALEPH	189-208	626.8	5487	90%	78%	70%
OPAL	189	182.5	699	42%	83%	89%

Table 1: Summary of the 4 LEP experiment selection characteristics

However this tight selection has the disadvantage of having a low efficiency ($\approx$ 12%). The other selection, performed by ALEPH and OPAL [13], is based on the use of all the events selected with their standard W pair analysis. The association between the jet pairs and the W bosons is done using 4-jet matrix elements (ALEPH) or a multivariate likelihood discriminant variable (OPAL). This selection gives higher efficiency but corresponds to less trivial string configuration. In this case the interjet particle yields are not symmetric any more. Table 1 summarises the center-of-mass energies, integrated luminosities, event statistics, efficiencies, purities and fraction of correct pairing obtained by the different experiments. For consistency checks, both ALEPH and OPAL repeat their analysis with the tight topological selection.

3.2 Results

Each experiment has extracted the values of R_N at detector level for their various event samples. The systematic uncertainties on R_N which have been investigated are essentially effects from changing the quark fragmentation model (JETSET compared to HERWIG), from Bose-Einstein correlations, and from the $e^+e^- \to q\bar{q}$ background variation. In the case of L3 the change of particle definition is also considered. Figure 3 shows R_N measured by L3 as a function of the center-of-mass energy together with the PYTHIA No CR and SKI model predictions. The particle flow ratio distribution obtained by L3 by combining all the data taken at 189 GeV< $\sqrt{s}$ < 207 GeV is shown in figure 4 together with the PYTHIA model predictions. From these distributions it appears that the data seem to prefer no or little colour reconnection in the SKI framework.

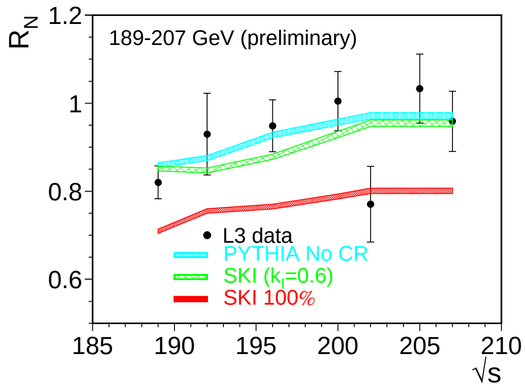

Figure 3: R_N as a function of $\sqrt{s}$ measured by L3 for data and Monte Carlo models

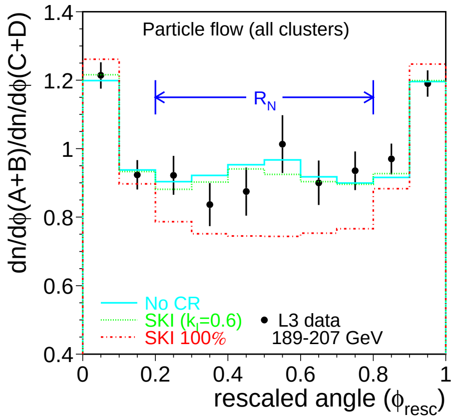

Figure 4: Ratio of particle flow distribution between quarks from same W and between quarks from different W for the complete L3 data sample

The corresponding ratio value is: $R_N = 0.911 \pm 0.023(stat.) \pm 0.021(syst.)$ The dependence of R_N on the reconnection probability has been investigated with the SKI model. A χ^2 between data and Monte Carlo is evaluated as a function of k_I. This gives a minimum at k_I=0.32, corresponding to about 18% reconnection probability if computed at $\sqrt{s}$=189 GeV, with a large uncertainty making the result also consistent with no CR effect. An upper limit $k_I < 1.55$ is obtained at 68% CL using the whole L3 data sample. This value should correspond to a reconnection probability of about 50% at $\sqrt{s} = 189$ GeV.
The particle flow ratio distribution obtained by DELPHI at $\sqrt{s}$=189 GeV is shown in figure 5 together with several MC predictions. The 100% reconnected SKI prediction shown on the figure is called CRCC while the No CR prediction is called CRJS. Figure 6 shows R_N measured by DELPHI as a function of the center-of-mass energy together with the EXCALIBUR prediction with no CR effect. The triangle symbol shows the SKI model prediction for fully reconnected events at $\sqrt{s}$=189 GeV. DELPHI has computed the quantity R_R=R_N^{data}/R_N^{KORALW} at each center-of-mass energy considered. Averaging over the different energies gives $< R_R >= 1.009 \pm 0.030(stat.) \pm 0.019(syst.)$ which is compatible with No CR effect. However one should pay attention that the sensitivity to a maximal effect amounts to about 3σ with their analysis.

Figure 7 shows the particle flow ratio distribution measured by ALEPH from 189 GeV to 208 GeV together with predictions from the SKI model. For each bin of the distributions shown the data points are between the No CR and the fully reconnected SKI predictions.

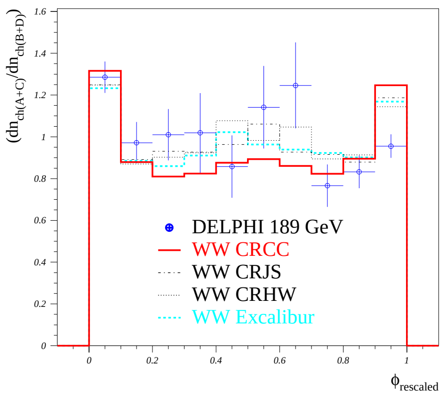

Figure 5: Ratio of particle flow distribution for DELPHI at 189 GeV

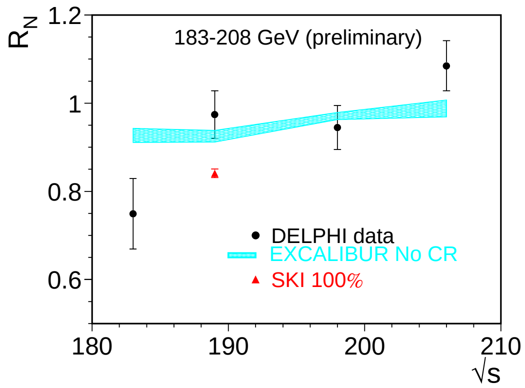

Figure 6: R_N as a function of $\sqrt{s}$ measured by DELPHI

This result is compatible with the presence of a certain fraction of reconnected events within the SKI framework. The k_I dependence of R_N measured from Monte-Carlo samples has been parameterised and a χ^2 between data and Monte Carlo has been evaluated as a function of k_I for each center-of-mass energy studied. These χ^2 values are summed over the different energy samples from 189 GeV to 208 GeV as a function of k_I. From the χ^2 distribution ALEPH obtains a preferred value of k_I=3.5 which corresponds to a reconnection probability P_{reco} =70% at $\sqrt{s}$=189 GeV in the SKI framework. It corresponds to a 1.6 σ effect. The analysis performed with the tight cut selection gives a consistent result with what ALEPH obtains with the default loose selection.

The OPAL analysis which has been performed only at $\sqrt{s}$=189 GeV favours also models with CR but an analysis based on the topological selection gives the opposite conclusion. The origin of this discrepancy is under investigation.

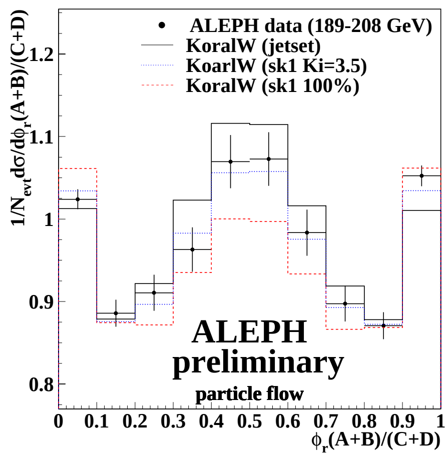

Figure 7: Ratio of particle flow distribution for ALEPH at 189-208 GeV

4. Conclusion

The particle flow distribution which is sensitive to CR effects in $W^+W^- \to q\bar{q}q\bar{q}$ has been studied by the four LEP collaborations. DELPHI and L3 analyses agree with no or very little CR effects in the framework of the SKI model but their sensitivities are quite different. ALEPH analysis shows a 1.6 σ effect towards CR. In the SKI scheme their data are well described when the parameter k_I=3.5. It is clear that more work is needed to conclude about the existence or not of colour reconnection phenomena in the data. In the future all experiments should test and control the particle flow analysis with semi-leptonic events. Following this prescription L3 has shown that the particle flow measured in the W semileptonic events is well simulated by their standard MC model. After having understood these effects the next step should be a LEP combination of the particle flow results in order to achieve a better sensitivity to CR effects.

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