Colour Reconnection in W Decays

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Contribution to the Proceedings of the XXX International Conference on High Energy Physics ICHEP2000, Osaka, Japan

Abstract

The studies of colour reconnection in $e^+e^- \to \mathrm{W}^+\mathrm{W}^- \to q\bar{q}'q\bar{q}'$ events at LEP are reviewed. It is shown that the analysis of the particle- and energy flow between jets is sensitive to realistic model predictions. The effects on the W mass measurement are discussed. Most results are preliminary.

1 Colour Reconnection

With some 450 pb^{-1} per experiment already recorded at $\sqrt{s} = 183 - 202$ GeV, and more to come at higher energies, each of the four LEP experiments have selected up to now some 3200 WW $\to qqqq$ and some 2500 WW $\to qq\ell\nu$ candidate events. The mass and width of the W boson are measured from the kinematics of W decay products. Any energy-momentum exchange between W decay products not well simulated in Monte Carlo will affect the W mass and width measurement. Conventional MC's treat the two $q\bar{q}'$ systems in a WW $\to q\bar{q}'q\bar{q}'$ event as independent. However, QCD interconnections, or colour reconnection (CR) can be expected [1]. Perturbative CR effects are estimated to be small [2]; CR is a non-perturbative hadronization uncertainty that can only be studied in the context of various models.

CR models being used in these studies are those implemented in PYTHIA, ARIADNE and HERWIG. The models in PYTHIA, SK I, SK II and SK II', are based on reconfiguration of overlapping or crossing strings [2]. In the SK I model, the probability of reconnection is calculated as $P_{\mathrm{reco}} = 1 - e^{(-k_i O)}$, where O is the overlap of two finite strings, and k_i is a free parameter. In the SK II and II' models, the string has no lateral dimension, and strings are reconnected when they cross. The ARIADNE models are based on rearrangement of colour dipoles if this reduces the string length [3]. It should be noted that these models also affect LEP 1 data and are disfavoured from an OPAL study of the properties of quark- and gluon jets [4].

A reconfiguration of the colour flow is expected to change the (charged) particle multiplicity (typically decreasing it by 0.2 to 0.9 units), especially at low momentum, and more specifically between jets associated to the same W.

	$< N_{ch}^{4q} >$	$< N_{ch}^{2q} >$	$\Delta < N_{ch} >$
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	$35.75 \pm 0.13 \pm 0.52$	$17.41 \pm 0.12 \pm 0.15$	$+0.93 \pm 0.27 \pm 0.29$

Table 1: Average charged multiplicity in $qqqq$ events, $< N_{ch}^{4q} >$, in $qq\ell\nu$ events, $< N_{ch}^{2q} >$, and the difference $\Delta < N_{ch} >=< N_{ch}^{4q} > -2 < N_{ch}^{2q} >$, as measured by the four LEP experiments. The ALEPH results are quoted within detector acceptance and not corrected to full phase space; DELPHI prefers to quote the ratio $R =< N_{ch}^{4q} > /2 < N_{ch}^{2q} >$, see text.

2 Multiplicities

2.1 Inclusive Charged Multiplicity

The charged multiplicity in WW events is measured by all four LEP experiments from charged tracks in the tracking system [5, 6, 7, 8]. The track multiplicity distribution is corrected to a charged particle multiplicity distribution by a matrix unfolding procedure. Alternatively, the multiplicity as a function of momentum (fragmentation function) or p_T is determined and corrected bin-by-bin. The results are shown in Table 1.

The difference $\Delta < N_{ch} >=< N_{ch}^{4q} > -2 < N_{ch}^{2q} >$ is also given in Table 1. DELPHI prefers to quote the ratio $R =< N_{ch}^{4q} > /2 < N_{ch}^{2q} >= 0.990 \pm 0.015 \pm 0.011$. Combining the results, it can be concluded that $\Delta < N_{ch} >$ is consistent with 0 within an error of 0.3-0.4. A proper average is difficult due to differences in the definition, and the correlated systematics; the size of these correlated systematics (0.2-0.3), which is of the same size as the CR effects, limits the sensitivity of this method.

2.2 Fragmentation Function

By studying the particle multiplicity as a function of $x_p = 2p/\sqrt{s}$, or $\xi = -\log(x_p)$, one can study the low momentum region $p < 1$ GeV where CR effects predominantly reside, but at the cost of reduced statistics. No significant effects at low x_p are observed by any of the experiments.

2.3 Heavy Hadrons

Massive particles, like $K^{\pm}$ or (anti)protons, are more sensitive to CR effects than pions, by a factor 2 to 3. However, this is counterbalanced by the decreased statistics. DELPHI [6] and OPAL [9] have studied the production of heavy hadrons in $qqqq$ and $qq\ell\nu$ events and observe no significant differences.

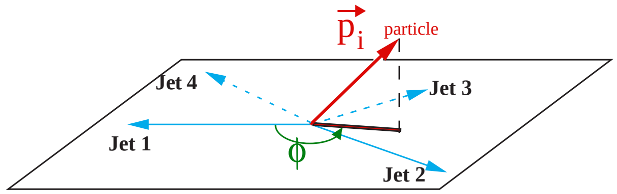

Figure 1: Construction of the particle flow.

3 Particle Flow

A more promising technique to study CR appears to be the study of the particle- or energy flow between jets from the same W and between different W's, in analogy to studies of the string effect [10].

The construction of the particle flow is explained in Figure 1. A jet-finder is used to construct four jets in $qqqq$ events. Each pair of jets defines a plane onto which all reconstructed particles in the event are projected; for the energy flow weighted with the particle energy. In the preliminary studies submitted to this conference, L3 [7] and ALEPH [11] use strong cuts on the angles between jets to select topologies with well separated jets and planar-like events, and obtain a selection efficiency of $\sim$ 15%; OPAL [12] uses less restrictive cuts and a jet-pairing likelihood that gives a higher efficiency of $\sim$ 42%, but selects also topologies with less clear separation between CR models. The flow is symmetrized with respect to the choice of jet-pairs, and particle angles between jets are rescaled between 0 and 1.

CR models indeed show a depletion of the particle flow between jets from the same W, and an increase between jets from different W's, as naively expected. It is convenient to average the flow in the two regions between jets from the same W (regions j1-j2 and j3-j4), and to do the same for the flow in the two regions between jets from different W's (regions j2-j3 and j4-j1). Subsequently, the ratio of these within-W/between-W flows is taken as a function of the rescaled particle angle.

L3 has studied 176 pb^{-1} of data taken at $\sqrt{s} = 189$ GeV. The ratio of the particle flow between jets from the same W and between jets from different W's is shown in Figure 2, for data, PYTHIA without CR, and PYTHIA with SK I and GH, as a function of the rescaled angle ϕ_{resc}. With this data sample only, a sensitivity of 3.5 σ to SK I ($k_i = 1000$) and 1.0 σ to SK I ($k_i = 0.6$) is reached. Varying the fraction of reconnected events, and calculating the χ^2 for the data-MC comparison, a fraction of $\sim$40% of reconnected events in the SK I model is favoured, and the No-CR scenario is disfavoured at 1.7 σ.

ALEPH has analyzed 347 pb^{-1} of data taken at $\sqrt{s} = 189 - 200$ GeV. Their particle flow ratio is shown in Figure 3, for data, KORALW without CR, and KORALW with the SK I model for various values of k_i. Varying k_i, ALEPH finds the best data-MC agreement for $k_i \approx 0.25$, and puts a 1 σ upper limit on k_i of 1.4 which corresponds to 45% of reconnected events at $\sqrt{s} = 189$ GeV.

OPAL has studied 183 pb^{-1} of data taken at $\sqrt{s} = 189$ GeV, and find sensitivities of 4.0 σ for SK I ($k_i = 100$), 1.1 σ for SK I ($k_i = 0.9$), 0.4 σ for SK II and II', and 0.5-1.8 σ for AR2 and AR3. As a cross-check, OPAL uses the strong cuts like L3 and ALEPH, and observes slightly smaller sensitivities. The actual data is ambiguous, and prefers some reconnection in the default analysis, but no CR in the cross-check analysis. This, and in particular the role of the background, will be

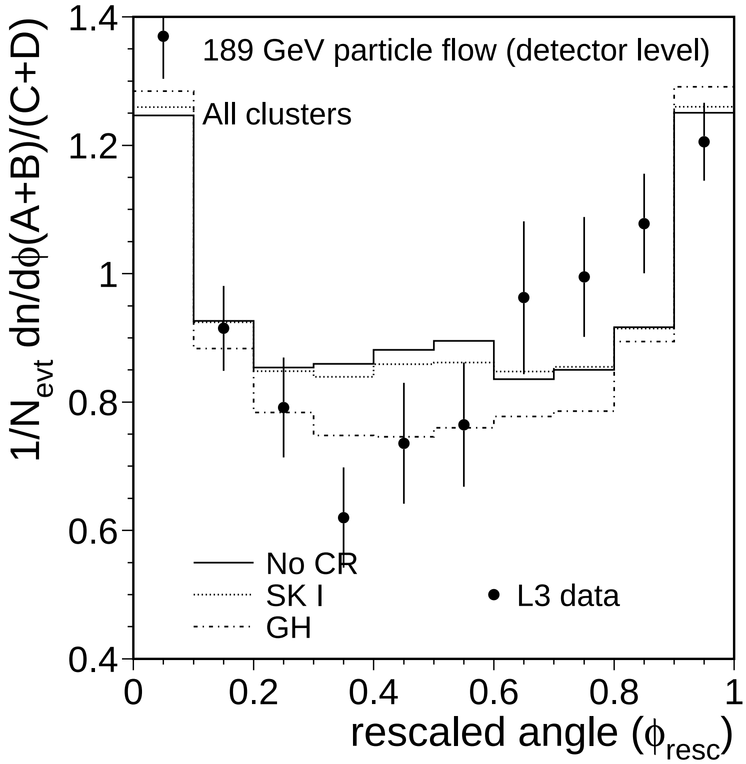

Figure 2: Ratio of the particle flows between jets from the same W and between jets from different W's, as a function of the rescaled angle, for L3 data at $\sqrt{s} = 189$ GeV and Monte Carlo.

further studied.

DELPHI is also working on a similar analysis, but was not yet able to submit results to this conference.

With the full LEP 2 data sample, and combining all experiments, a further gain in sensitivity by a factor ~ 3.5 can be expected.

4 Effect on M_{W}^{qqqq}

The estimates for $\Delta M_{\mathrm{W}}^{qqqq}$ from the individual experiments calculated with their own Monte Carlo samples are summarized in Table 2 [13]. A difference in reconnection probability in the SK II model can be expected from differences in the parton shower cutoff scale Q_0 [2], which ranges between 1.0 GeV (L3) and 1.9 GeV (OPAL).

Common samples of KORALW + JETSET Monte Carlo events, with (SK I) and without colour reconnection, have been generated for the four experiments; each experiment then passed these samples though detector simulation, event selection and analysis procedures. The resulting mass

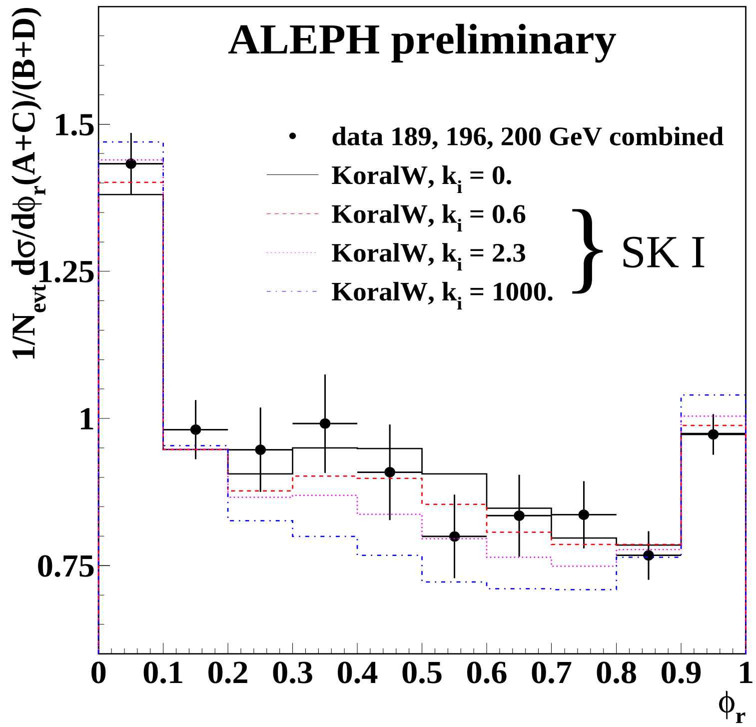

Figure 3: Ratio of the particle flows between jets from the same W and between jets from different W's, as a function of the rescaled angle, for ALEPH data at $\sqrt{s} = 189 - 200$ GeV and Monte Carlo.

shifts found by the experiments were equal within errors, and a correlation between experiments of close to 100% was found. In view of this, further LEP collaboration will be needed to fully understand the differences in Table 2, especially in the ARIADNE estimates. For the LEP M_{W} combination, a CR systematic error of 50 MeV was used, fully correlated between experiments.

Estimates of the CR effect on the W width in the $qqqq$ channel range between +40 and +70 MeV in the SK models [13].

The studies of the particle flow between jets have proven to be sensitive to realistic CR model predictions. These studies will thus directly measure the amount of CR in the data. In models with a free parameter, such as SK I, this parameter can be measured from data; a calibration curve of mass shift versus k_i can be used to estimate the CR systematic error. Already ALEPH, with a 1 σ upper limit on k_i of 1.4, puts a 1 σ upper limit on $\Delta M_{\mathrm{W}}^{qqqq}$ in the SK I model of 40 MeV [11]. With the full LEP 2 data sample and combining all experiments, the CR systematic error on M_{W} is likely to be below that, and, most important, actually measured from data.

	OPAL	L3	DELPHI	ALEPH
SK I	$+66 \pm 8$ (35.1%)	$+29 \pm 15$ (32.1%)	$+46 \pm 2$ (35.9%)	$+30 \pm 10$ (29.2%)
	($k_i = 0.9$)	($k_i = 0.6$)	($k_i = 0.65$)	($k_i = 0.65$)
SK II	$+3 \pm 8$ (19.8%)	-5 ± 15 (32.4%)	-2 ± 5	$+6 \pm 8$ (29.2%)
SK II'	$+10 \pm 8$ (17.6%)	-33 ± 15 (28.8%)		$+4 \pm 8$ (26.7%)
AR 2	$+85 \pm 8$ (50.3%)	$+106 \pm 26$	$+28 \pm 6$	$+21 \pm 19$
AR 3	$+140 \pm 10$ (62.3%)	$+170 \pm 26$	$+55 \pm 6$	$+34 \pm 34$
HERWIG				$+20 \pm 10$

Table 2: Experimental estimates of $\Delta M_{\mathrm{W}}^{qqqq}$, in MeV, from the four LEP experiments, as calculated with their own implementations of various CR models at $\sqrt{s} = 189$ GeV. The fraction of reconnected events in each sample is given between brackets.

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