The preliminary results on the search of colour reconnection effects (CR) from the four experiments at LEP, Aleph, Delphi, L3 and Opal, are reviewed. Extreme models are excluded by studies of standard variables, and ongoing studies of a method first suggested by L3, the particle flow method, are yet inconclusive.

1 Introduction

Colour reconnection, better said colour rearrangement between partons or cross-talk (CR), corresponds to a colour interference between partons close-by in space-time, and is a good probe to understand the dynamics of hadronization. It is expected to be the cause for the \( \psi \) formation in the decays of the \( B \) meson, in which occurs a cross-talk between two original colour singlets, \( \bar{c}+s \) and \( c+\)spectator.\footnote{In the case of double production of heavy particles (WW, ZZ, ZH, \( t\bar{t} \)), if both decay hadronically almost simultaneously in space and time, there could be also cross-talk effects between the decay products. In this case particles cannot anymore be assigned unambiguously to one parent particle, and the parent particle’s properties such as invariant mass cannot be inferred from its alleged decay products. Finally it could also induce additional interference between beam and final state partons in hadron machines.}

LEP2, the second phase of the LEP machine at CERN, has been working since 1996 at centre of mass energies above the threshold for double W boson production, aiming at measuring the W boson mass with a precision of the order of 50 MeV.\footnote{Each of the four LEP experiments collected about 10000 WW events, for a total luminosity per experiment of about 700 pb\(^{-1} \).}

In the hadronic channel, in which both W bosons decay hadronically, the decay products from different W bosons can interfere, since the distance traveled by the W boson before decaying, \( c\tau_W \approx \hbar c/\Gamma_W \approx 0.1 \text{fm} \), is much smaller than the typical hadronization scales of 1 fm. At several stages these effects could be caused by colour rearrangement between the quarks coming from the W bosons, gluon exchange in the parton cascade, and by Bose Einstein interference between identical bosons (e.g., pions). The third item is the topic of other proceedings in this conference (see Jorn van Dalen’s contribution),
and the first two items are the main subject of the review presented below, with most of the results preliminary.

2 Theoretical aspects of colour rearrangements

The effects of colour rearrangement between the primary quarks or energetic hard gluons from different W bosons, are small at perturbative level, with the effect in the W mass of the order of

\[(\delta M_W)_{PT} \approx \left( \frac{C_F \alpha_s (\Gamma_W)}{\pi} \right)^2 \frac{1}{N_C^2 - 1} \Gamma_W \approx O(1 \text{ MeV}). \] (1)

Non-perturbative QCD effects between soft gluons \((E_g < \Gamma_W)\) coexisting in space and time could be large, of \(O(10 \text{ MeV})\) in the W mass, and affect average multiplicities and inclusive particle distributions, with enhancements for low-momentum and/or heavier particles. To estimate these effects phenomenological models are needed and were developed in the past by T. Sjöstrand and V. A. Khoze (skI, skII, skII'), G. Gustafson and J. Hakkinen (gh), L. Lönnblad (ar2, ar3), G. Marchesini et al. (herwig), J. Ellis and K. Geiger (eg), and more recently by J. Rathsman.

The models of Sjöstrand and Khoze, implemented in the Pythia Monte Carlo generator, type I and type II in analogy to the super-conducting vortices associated to the strings, allow for reconnection if the strings cross each other. In type I model (skI), the most commonly used as a basis for the studies reported here, the strings have a transverse dimension, similar to flux tubes, and they may cross with different overlapping volumes \(V_{\text{overlap}}\). Then the probability of reconnection in one event is given by \(P_{\text{reco}} = 1 - e^{-k_I V_{\text{overlap}}}\), with \(k_I\) a user parameter allowing to vary the percentage of reconnected events (probability of reconnection integrated for the accepted phase space).

3 Analysis of standard variables

The effects on the average charged multiplicities \(n(4q)\) in fully hadronic WW events (WW(4q)), were the first signatures probed by the four experiments, in particular by comparing with the average charged hadronic multiplicities \(n(2q)\) in semi-leptonic WW events (see 11, 12, and 13 for a review). In the absence of these effects, there should not be any statistically significant difference between \(n(4q)\) and twice \(n(2q)\). The latest results 14, 15, 16, 17 on the average multiplicities in WW events and on their differences and ratios are
Table 1. Average charged multiplicities in WW(4q) \( (n(4q)) \) and WW(2q) \( (n(2q)) \) events, their differences and ratios. The Aleph results are not corrected for momentum acceptance and selection biases.

| Exp. | \( n(4q) \) | \( n(2q) \) | \( n(4q) - 2n(2q) \) | \( n(4q)/(2n(2q)) \) |
|------|-------------|-------------|----------------------|----------------------|
| Aleph | 35.75±0.13±0.52 | 17.41±0.12±0.15 | 0.93±0.27±0.29 | 1.027±0.008±0.007 |
| Delphi | 38.87±0.29±0.29 | 19.57±0.26±0.23 | -0.32±0.60±0.54 | 0.990±0.015±0.011 |
| L3 | 37.90±0.14±0.41 | 19.09±0.11±0.21 | -0.29±0.26±0.30 | 0.993±0.007±0.015 |
| Opal | 38.51±0.22±0.33 | 19.25±0.16±0.16 | 0.06±0.39±0.32 | 1.003±0.010±0.012 |
| Average(DLO) | -0.18±0.21±0.21 | 0.996±0.006±0.008 |

shown in table 1. The Aleph result was not included in the averages because it is not corrected for momentum acceptance and selection biases.

It can be concluded that the measurements are compatible with equity between WW(4q) and twice WW(2q), and do not show any evidence for colour rearrangement effects.

These effects were also searched for in inclusive distributions of charged particles, as well as in the ratio of the average multiplicities of low momentum identified heavy hadrons (Kaons and protons) in WW(4q) to WW(2q) and no effects were found.

The conclusions of the studies on the standard variables are that the extreme models (e.g., ar3) can be excluded by these data, but these variables are insensitive to most of the other more realistic models.

4 The particle flow method

L3 has developed a new approach toward a more restrictive event selection criteria, and building new variables relating the particle and energy distributions with respect to jets. The tight event selection criteria enable the proper definition of inside W and outside W regions, but with the disadvantage of very low efficiency (less than \( \approx 15\% \)). This event selection has been followed also by the Delphi collaboration as the mainstream analysis, and by the other collaborations as a cross-check analysis (Aleph, Opal). Table 2 gives the luminosities, numbers of events analysed so far, the efficiency of the event selection(s), the purities of the selected data samples, and the efficiency for correct pairing of jets to their parent W bosons (all the results are preliminary).

For the events selected, which contain 4 jets, distributions of the particle and energy flows are built in a way to best reflect the inside W and outside W regions, depicted as regions A,B (inside W) and C,D (outside W) in figure 1.
Table 2. Luminosities, numbers of selected events used in the analysis, its efficiency, purity of the selected samples, and efficiency for correct pairing of jets to the parent W. AlephXC and OpalXC stand for the cross check analysis of Aleph and Opal.

| Exp.      | $\sqrt{s}$ (GeV) | $L$ (pb$^{-1}$) | Data | Expected | Eff.   | Pur.  | Pair |
|-----------|-------------------|-----------------|------|----------|--------|-------|------|
| Aleph     | 189-208           | 626.4           | 5487 | -        | 0.92-0.88 | 0.78 | 0.7  |
| AlephXC   | 189-208           | 626.4           | 684  | -        | 0.15-0.09 | 0.85-0.82 | 0.9-0.85 |
| Delphi    | 183-208           | 601.4           | 759  | 721.9    | 0.15-0.09 | 0.83-0.77 | 0.76   |
| L3        | 189-208           | 626.6           | 666  | 689.9    | 0.14-0.09 | 0.85 | 0.93-0.88 |
| Opal      | 189               | 182.5           | 699  | -        | 0.42    | 0.83  | 0.5  |
| OpalXC    | 189               | 182.5           | 260  | -        | 0.16    | -     | -    |

Figure 1. The definition of inside W and outside W regions.

Figure 2. The particle flow distribution of L3.

The method used to build these distributions, explained in detail in [21], uses the angles between particles and jets, and angles between jets, to define a rescaled angle and associate the particles to inside W and outside W regions. The rescaled angle distribution for the particle flow of L3 is shown in figure 2.

Adding the inside W regions and the outside W regions, the distributions
of the ratios of inside to outside are shown in figure 3 for the four experiments.

The ratios $R$ of the integrals, from 0.2 to 0.8 in the rescaled angle, of the particle flow distributions of inside W regions to outside W regions (sum of inside divided by sum of outside), are shown in table 3 for the four experiments, along with the values expected from simulation with and without CR effects. The experiment’s sensitivity to the model skI with 100% reconnection probability, computed as $S = |R_{MC_{noCR}} - R_{MC_{skI}}|/\text{Error}_{\text{data}}$, is also shown in the table. The $R$ value given for Delphi is the average of the $R$ values at each centre of mass energy, after rescaling using simulation to the luminosity weighted average centre of mass energy of 196 GeV. Please note that the $R$ values shown, uncorrected for detector effects, cannot be directly compared between different experiments. In the systematic errors, it were considered the effects of background subtraction and modeling (Aleph(A),
Table 3. R values for the data, simulation without and with CR effects (from model skI with 100% reconnection probability), and sensitivity to the CR effects. OpalXC stand for the cross check analysis of Opal; the Aleph cross-check analysis gives results compatible with the standard analysis’s results shown here. In the data values, the first error is statistical and the second error is systematic.

| R        | data                  | MC no CR              | MC (skI)               | S   |
|----------|-----------------------|-----------------------|------------------------|-----|
|         | Obs.                  | Obs.                  | Obs.                   | Obs.|
| Aleph   | 1.117±0.014±0.009     | 1.164±0.002           | 1.074±0.002            | 5.5σ|
| Delphi  | 0.951±0.028±0.022     | 0.950±0.030           | 0.864±0.010            | 2.8σ|
| L3      | 0.911±0.023±0.021     | 0.920±0.003           | 0.763±0.003            | 5.0σ|
| Opal    | 1.205±0.044±0.015     | 1.330±0.004           | 1.147±0.004            | 3.9σ|
| OpalXC  | 1.020±0.052±0.010     | 1.025±0.005           | 0.855±0.005            | 3.2σ|

Delphi(D), L3(L) and Opal(O)), the Bose-Einstein effects (ADL), fragmentation modeling (ADL), generators and tuning (DO) and definition of particles and cluster objects (L).

L3 has performed recently further studies, using a sample of WW semi-leptonic decay events, which by definition have no colour rearrangement effects between the decay products of different W bosons. L3 measures in this sample a ratio of values of R in data to R in simulation of $R_R = 1.011\pm0.035$, perfectly compatible with unity.

The ratio between the values of R for the data and for simulation with or without CR effects (as expected from skI model with 100% reconnection probability), averaged over the centre of mass energies for each experiment, using as weights the sum in quadrature of the statistical and systematic errors, is shown in table 4. The values for Aleph, L3 and Opal, were estimated from the respective values of R for data and simulation for the different centre of mass energies (the statistical error on the MC samples was considered as systematic error). Correlations in the systematic error were taken into account inside each experiment (correlations between experiments were not considered important at this level).

L3 and Delphi agree with no effect observed in their data, Aleph results are between the model without CR effects and the model of skI with 100% reconnection probability, and Opal has two analysis of similar sensitivity with incompatible preliminary results. Using simulation of skI model for different values of reconnection probability, as translated in the user set $k_I$ parameter, Aleph and L3 translate their results into limits for this parameter of $k_I < 25$ (68% Confidence Level), with the minimum of discrepancy ($\chi^2$) at $k_I = 3.5$, for Aleph, and $k_I < 1.55$ (68% Confidence Level), with the minimum of discrepancy at $k_I = 0.32$ for L3.
Table 4. Average over the centre of mass energies of the ratio of the values of R for the data to the values of R for simulation without CR effects, and with CR effects from sl(100%) (*† stands for the Opal/Cross check analysis, and the lines below Aleph, Delphi, and L3 values are the errors). The first error is statistical and the second error is systematic, and in the last line are given the distances from one in units of standard deviation.

| (R_R) | Aleph | Delphi | L3 | Opal |
|-------|-------|--------|----|------|
| D/noCR | 0.961 | 1.009  | 0.990 | 0.906 ±0.033±0.011 |
|       | ±0.012±0.007 | ±0.030±0.019 | ±0.025±0.023 | ±0.996±0.051±0.011 |
|       | -2.8σ | -0.3σ  | -0.3σ | -2.7σ / -0.1σ |
| D/CR  | 1.041 | 1.110  | 1.194 | 1.050±0.038±0.013 |
|       | ±0.013±0.008 | ±0.033±0.029 | ±0.039±0.028 | ±1.193±0.061±0.014 |
|       | +2.7σ | +2.5σ  | +4.7σ | +1.2σ / +3.1σ |

5 Conclusions

After five years of very successful LEP runs, 10,000 WW events have been collected by each of the four LEP experiments (Aleph, Delphi, L3, Opal).

The search for colour rearrangement effects in the WW fully hadronic events, using standard variables like average charged multiplicities and inclusive distributions, has excluded only the most extreme models of colour reconnection (Ellis and Geiger 'eg' and Ariadne 3 'ar3'). The sensitivity to other more realistic models has been shown to be negligible in these variables.

A preliminary search following a L3 idea, the particle flow, has proven sensitive for the different experiments, but inconclusive, as one experiment claims part of the effect, two experiments claim no observation, and one experiment has incompatible results in two nearly equal sensitive analysis. However, systematic studies are still in a very preliminary stage of study, and the exploration of the data to its full extent might improve the results in the near future.

In order to pin down models of colour rearrangement and estimate parameters, it is mandatory to combine the results from the four experiments in order to reduce sizeably the statistical errors.

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