COLOUR RECONNECTION AT LEP2

RAJA NANDAKUMAR
Tata Institute of Fundamental Research, India
E-mail: Raja.Nandakumar@cern.ch

Colour reconnection is the final state interaction between quarks from different sources. It is not yet fully understood and is a source of systematic error for W-boson mass and width measurements in hadronic W^+W^- decays at LEP2. The methods of measuring this effect and the results of the 4 LEP experiments at $183\text{ GeV} \leq \sqrt{s} \leq 202\text{ GeV}$ will be presented.

1 Introduction

The W–boson is a carrier of charged weak interactions and it decays into lepton–neutrino ($l\nu$) or quark–antiquark ($q\bar{q}$) pairs. The LEP2 W–factory[1] at CERN, Geneva has produced thousands of W–pair events which have been collected by the 4 LEP experiments (Aleph, Delphi, L3 and Opal).

The typical distance between W decay vertices at LEP2 (0.1 fm) is much smaller than the typical hadronisation distance (1 fm). When both the W's decay in the $q\bar{q}$ mode, this leads to the possibility of gluon exchange between quarks from different W's, called Colour Reconnection (CR).

CR[2] can thus be defined as the strong interaction between independent colour singlets, before hadron formation. This causes a change in the string configuration (figure 1) leading to changes in the reconstructed 4–momentum of the W's. Thus, a study of CR tells us about the space–time evolution of hadronic systems and about the systematic uncertainty of the $\mathrm{M_W}$ and Γ_W measurements at LEP2.

2 Methods of measuring CR

Changes in the string configuration change the momentum distribution of the particles and hence, also the expected event multiplicity. Thus, these quantities carry information about CR. The typical analysis procedure to study CR is to compare the data with Monte Carlo events simulated using various models[3] (SKI, SKII, GH, etc). We note that the $q\bar{q}$ sector of $q\bar{q}l\bar{\nu}_l$ events is a source of W's without CR.

In $q\bar{q}q\bar{q}$ events, there is an additional problem of pairing the jets correctly, due to the existence of 3 different ways of pairing up 4 jets into two W–bosons. This problem does not arise in the $q\bar{q}l\bar{\nu}_l$ events.

3 Multiplicity based measurements

CR typically leads to a reduction in the string length. This implies that the average multiplicity is decreased. This is a small effect, as shown for charged particles in OPAL data (figure 2).

One can define the average charged multiplicities

$$\langle N_{\rm ch}^{4q}\rangle : \text{from } q\bar{q}q\bar{q} \text{ events,} \qquad \langle N_{\rm ch}^{2q}\rangle : \text{from } q\bar{q} \text{ system of } q\bar{q}l\bar{\nu}_l \text{ events}$$

$$\Delta\langle N_{\rm ch}\rangle = \langle N_{\rm ch}^{4q}\rangle - 2\langle N_{\rm ch}^{2q}\rangle \qquad (\neq 0 \text{ for CR})$$

Averaging over all LEP data [4], the author obtains for $\Delta\langle N_{\rm ch}\rangle$, a value of about $0.22 \pm 0.20 \pm 0.35$. This result is consistent with 0 and the error is dominated by systematics (mainly fragmentation modelling).

Another approach[4] is to study the fragmentation functions $x_p = 2p/\sqrt{s}$ and $\xi = -log x_p$, where p is the momentum of the particle under consideration and $\sqrt{s}$ is the center of mass energy.

The sensitivity of the fragmentation function to the presence of CR is shown in figure 3. Sensitivity is maximum in the region $4.5 \le \xi \le 6.1 \quad \Rightarrow \quad 0.001 \le x_p \le 0.005$. Similar studies can also be performed with heavy hadrons (eg. protons, kaons) which will be more sensitive to CR effects. However, the net result is that the systematic error of the method is greater than the expected effect and no significant non-zero result is seen in the data.

4 Particle flow based measurements

The particle flow method[5] studies the event's string topology by looking at the particle momentum distribution across the jets. The event (satisfying the topology in figure 1) is forced into 4 jets to reconstruct the 4 parent quarks. Two adjacent jets – the most energetic jet (jet 1) and the jet associated to it (jet 2) – are used to form a plane and the particles in the event are projected onto this plane. The angle of the projection (ϕ) from jet 1 is called the particle flow of the event (figure 4). The distribution for ϕ is shown in the figure 5(a).

The angle ϕ is rescaled to the jet–jet angle to obtain $\phi_{\rm resc} = \frac{\phi}{\phi_{jj}}$. The distributions are symmetrised between the 3 adjacent pairs of jets, as shown in figure 5(b). The energy flow distributions correspond to the same distributions, with each particle in the distribution being weighted with its energy, normalised to the visible energy in the event. The background is subtracted from the data distribution before comparison with Monte Carlo.

The regions A and B in figure 5(b) arise when the two jets come from the same W and the regions C and D arise when the two jets are wrongly paired. Hence, one expects CR to cause a depletion in A and B, and an enhancement in C and D. This can be clearly seen by taking the ratio $\frac{\mathrm{A+B}}{\mathrm{C+D}}$ as shown in figure 6. This ratio also has the advantage of cancellation of some systematics.

The distributions shown in figure 6 are integrated over their most sensitive region, to obtain $R = \int_{0.3}^{0.7} \frac{A+B}{C+D}\, \mathrm{d}\phi_{resc}$. This R is a good estimator of the presence of CR in the data. As seen from the L3 results in table 1 for 189 GeV, the systematics for this method are much smaller than the statistical error and the data are inconsistent with the result of no CR at the 2σ level.

For this method to work, one would obviously need jets that are clearly identified and with a high probability of correct pairing. This leads to a low efficiency ($\simeq 15\%$) in selection of the WW events.

Similar analyses have been performed by Aleph and Opal. One can define a χ^2 to estimate the best fit of data to Monte Carlo for different values of CR probability (figure 7). This is done using the SKI model, where the parameter k is proportional to the probability of CR. The data from Aleph, L3 and Opal, prefers in general, the existence of CR with probabilities ranging from 15% to 60% with an error from each collaboration, of about 30%. A combination of the results will result in an improvement of numbers.

5 Summary

CR can be measured in hadronic WW decays at LEP. The multiplicity and fragmentation function based methods do not yield significant results, and none are expected due to high systematic errors inherent to the method. However, first indications of CR have been seen using the particle flow method.

The W–boson mass and width measurements are major aims for LEP2. Current estimates of systematic uncertainties from CR for the mass is 50 MeV, fully correlated across experiments, while it varies from 40 to 70 MeV for the width. It is hoped that further studies on CR, especially through the particle flow method will help in improving these numbers.

Acknowledgement

The author would like to thank TIFR, CERN and KFKI for their support during ISMD 2000. Many thanks too to Som Ganguli, Martin, Paul, Luca, John, Dominique, Gagan and the LEP collaborations for their kind help during preparations.

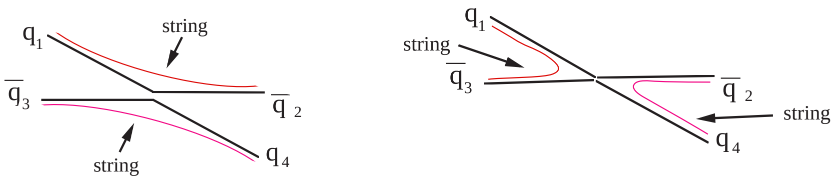
References

1. Physics at LEP-II, CERN 96–01, Vol.1

2. Š. Todorova-Nová, DELPHI 96–158 PHYS 651
3. T. Sjöstrand and V. Khoze, Z. Phys. C 62 (1994) 281
   T. Sjöstrand and V. Khoze, E. Phys. J. C 6 (1999) 271
   G. Gustafson and J. Häkkinen, Z. Phys. C 64 (1994) 659
4. ALEPH Collaboration, Contr. to ICHEP 2000, ALEPH 2000 – 058
   DELPHI Collaboration, CERN-EP/2000-023
   L3 Collaboration, Contr. to ICHEP 2000
   OPAL Collaboration, CERN EP / 98 – 196 ; Physics note, PN 412
5. ALEPH Collaboration, Contr. to ICHEP 2000
   L3 Collaboration, Contr. to ICHEP 2000
   OPAL Collaboration, Physics note, PN 412

R	Data	Monte Carlo : No CR
Particle flow	$0.771 \pm 0.049 \pm 0.029$	0.868 ± 0.007
Energy flow	$0.593 \pm 0.058 \pm 0.020$	0.696 ± 0.009

Table 1. 189 GeV results from L3 for particle flow



No Reconnection

Immediate Reconnection

Figure 1. Illustration of Colour Reconnection (CR) between two W's decaying into $q_1\bar{q}_2$ and $q_3\bar{q}_4$, respectively.

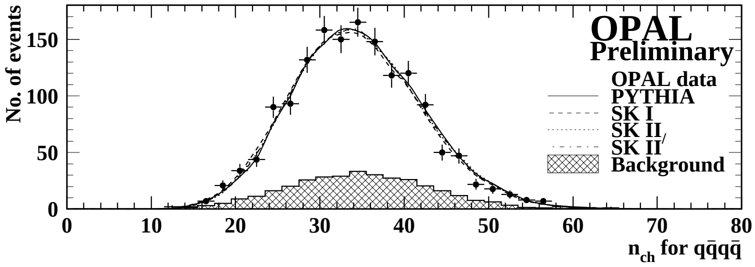


Figure 2. Charged particle multiplicity

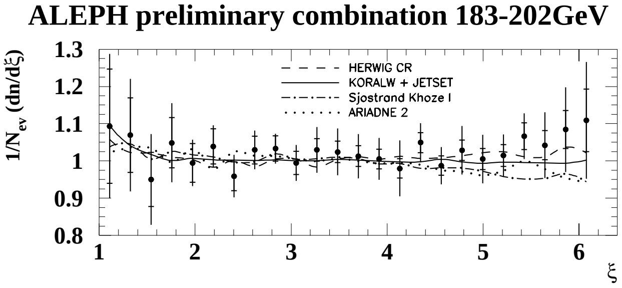


Figure 3. Sensitivity of the fragmentation function to CR (Aleph)

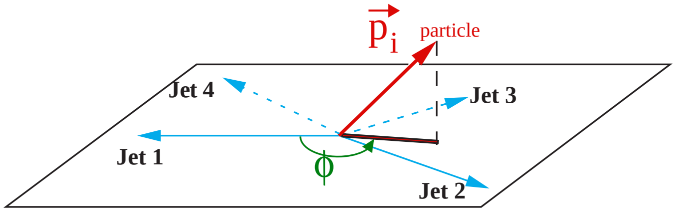
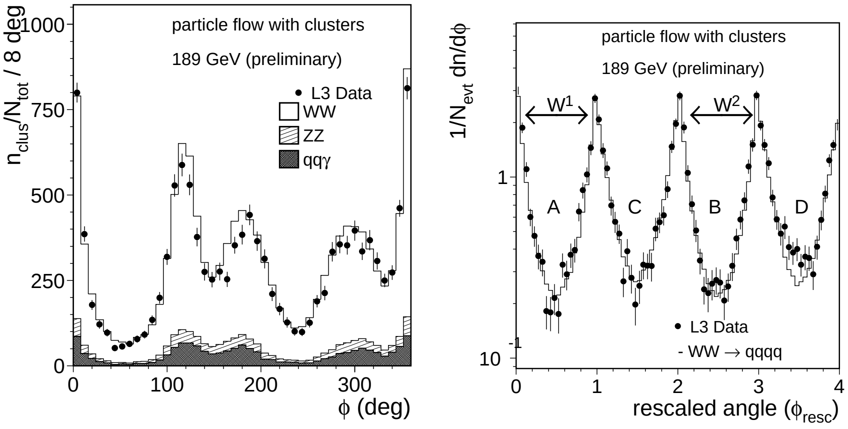


Figure 4. The particle flow method



(a) The raw distribution

(b) The symmetrised distribution

Figure 5. The particle flow distributions from L3

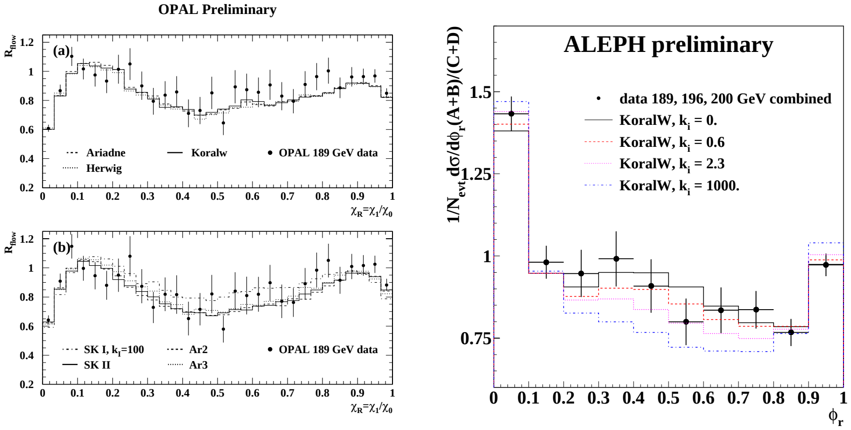


Figure 6. Distributions for $\frac{A+B}{C+D}$

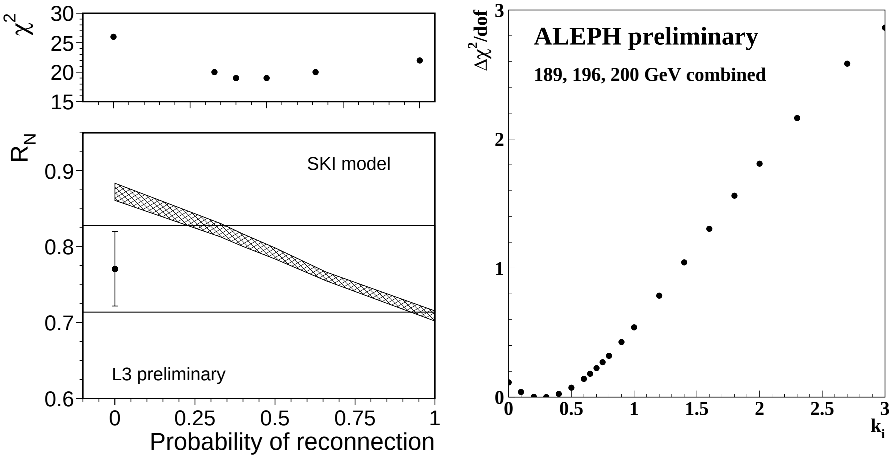


Figure 7. Chisquared vs SKI CR probability for L3 and Aleph data