COLOR RECONNECTION IN W PAIR EVENTS *

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Color Reconnection in $W^+W^- \to q\bar{q}q\bar{q}$ events is the main systematic effect on the W boson mass measurement. A review of the ongoing studies at LEP2 is reported.

1 Introduction

One of the primary goals of the LEP2 program was to measure the W boson mass to the best possible accuracy. At the LEP collider, W bosons are pair produced. When both W bosons decay hadronically, one usually refers to the fully hadronic (or four quarks) channel. The W boson mass extraction from the invariant mass spectra is based on the direct reconstruction of the decay products, assuming the W bosons to decay independently.

The hadronisation scale is larger than the distance between the W bosons at their primary vertex. Therefore, the decay products have a significant space-time overlap, allowing the exchange of color between the decay products of different W bosons. This effect is called the Color Reconnection (CR), which is the largest systematic uncertainty of the W boson mass, at the level of 100 MeV/c^2 (the statistical uncertainty being 35 MeV/c^2) [9].

2 Color Reconnection

In the realm of perturbative QCD, the color flow of the primary quark is re-arranged and possible CR effects can be quantified. The shift of the W boson mass is predicted to be small ($\Delta M_W \leq \mathcal{O}$ (5 MeV/c^2)) and can hence be neglected [1]. The effect of CR in later hadronization stages has to be estimated

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with non-pertubative QCD models. CR has been implemented in a number of fragmentation generators: SK1, SK2, SK2' [2] and GAL [3] for the Pythia (JETSET) [4] generator. In ARIADNE [5] and HERWIG [6], CR has also been inserted ([7] and [8] resp.). These simualtions predict about 30% reconnected events, except for the SK1 model, where this fraction is a free parameter. Its dependence is estimated through $P_{reco} = 1 - exp(-\kappa f)$ with the string overlap f and a free parameter κ.

3 Inclusive Mean Charged Multiplicity and Momentum Distribution

A large panel of observables can be tested for a possible manifestation of CR. One natural choice is the inclusive mean charged multiplicity, $< N_{ch}^{4q} >$.

To maximise the impact of CR, the difference $\Delta < N_{ch} > = < N_{ch}^{4q} >$ - 2. $< N_{ch}^{lqqq} >$ is chosen. It should vanish when CR is absent. As can be seen from Table 1, no CR is observed in any of the four LEP experiments.

experiment	$\sqrt{s}$ (in GeV)	$< N_{ch}^{qqqq} >$ - 2. $< N_{ch}^{qql\nu} >$
ALEPH	189 - 208	0.31 ± 0.23 ± 0.10
DELPHI	183 - 189	-0.26 ± 0.60 ± 0.38
OPAL	183 - 189	-0.29 ± 0.26 ± 0.30
L3	183 - 202	0.07 ± 0.39 ± 0.37

Table 1: Studies of the mean charged multiplicity of the four LEP experiments. They should not be combined, because different correction techniques have been applied. All numbers are preliminary [10].

CR should also occur in the low momentum region of fully hadronic WW events [1]. Figure 1b shows the ξ distribution of ALEPH [10]. However, the fragmentation modelling effect is larger than the CR, meaning that also this observable is not sensitive enough to CR.

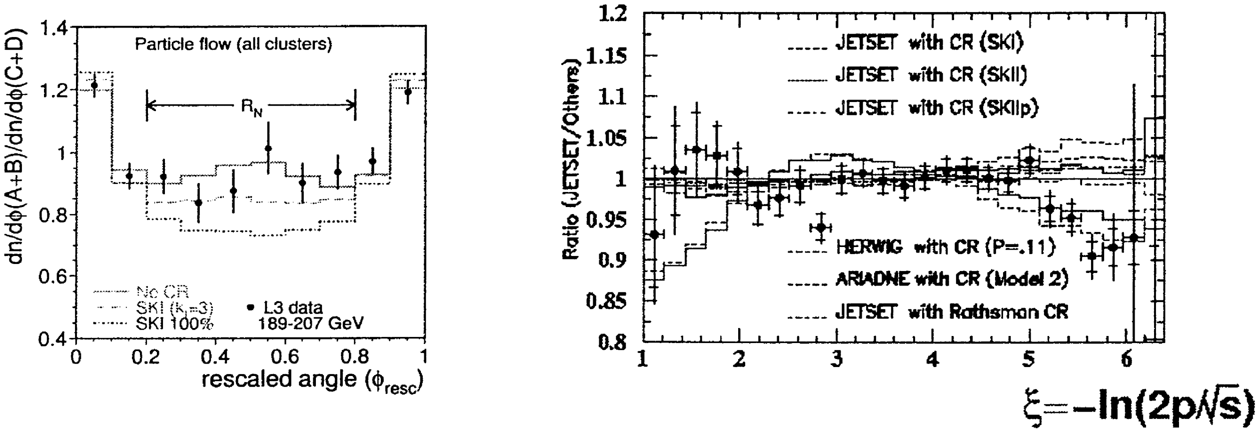

Figure 1: Left (a): Preliminary particle flow ratio using the L3 data. Right (b): Inclusive charged particle momentum distributions and comparison with MC including CR or not.

4 Particle Flow Analysis

The string fragmentation model tends to predict that more particles are produced in the region between jets from the same W boson (intra jet region) than between jets from different W bosons (inter jet region). This can be expressed in terms of a particle flow that describes the number of particles produced per angular unit between two adjacent jets. CR will modify the occupancy in these regions and alter the particle flow.

The analyses use the integrated particle flow of the intra and inter jet regions. The ratio R_N of these two quantities is estimated for several models with and without CR as shown in Figure 1a. To ease the comparison, this ratio is normalized to the expectation without CR, $r = R_N^{data}/R_N^{no-CR}$. Table 2 lists the LEP combined r values, accounting for the different purities [9].

no CR		*with CR*	
r_{AR}^{lep}	$0.959 \pm 0.010(stat.) \pm 0.010(syst.)$	r_{AR}^{MC}	0.989
r_{HW}^{lep}	$0.950 \pm 0.011(stat.) \pm 0.010(syst.)$	r_{HW}^{MC}	0.987
r_{SK1}^{lep}	$0.969 \pm 0.011(stat.) \pm 0.010(syst.)$	r_{SK1100}^{MC}	0.891

Table 2: Preliminary LEP combined r value.

The main uncertainty in r is due to the hadronisation ($\pm$ 0.008). The extreme SK1 100% scenario can be excluded at 5.2 σ. However, the data agree with the standard Monte Carlo (i.e. without CR) only up to 2 σ. For the particular SK1 model, the preferred value of the free parameter κ leads to a reconnection probability of 49 %. This value is currently used to extract the CR contribution to the systematic uncertainty of the W boson mass, which is in itself the most sensitive observable to CR. To illustrate the impact of CR on the W boson mass, the next section will be devoted to a new W boson mass analysis less sensitive to CR.

5 W Mass Analysis

Currently, the best estimate of the W boson mass is

$M_W = 80.412 \pm 0.029(stat.) \pm 0.031(syst.)\mathrm{GeV/c}^2$,

where CR yields the largest uncertainty. Therefore, alternative M_W estimators, originally proposed by the DELPHI collaboration [11], were studied to reduce the sensitivity to CR.

The first estimator uses only tracks with a momentum exceeding a given cutoff value (so called P_{cut}) for the reconstruction of the invariant mass. The second estimator is the so called hybrid cone: It starts with the jet direction obtained by the standard analysis. Only particles within a given cone radius (R_{cone}) are kept and new jet directions are reconstructed iteratively, until a stable jet is found.

These new methods lead to a significant reduction of the CR bias (as shown in Figure 2a), and considerably decrease the statistical uncertainty of the κ parameter: $\kappa = 2.4^{+14.6}_{-2.2}$ (particle flow) to $\kappa = 1.96^{+2.60}_{-1.30}$.

6 Rapidity Gap Analysis

CR is suspected to be one of the source of rapidity gap events, where two distinct rapidity regions can be discerned. These are not restricted to the W boson pair production. Therefore, the particulary large Z^0 resonance data set of LEP can be exploited to put more stringent requirements on CR models.

In the standard Monte Carlo, only the simplest topology of the color flow is allowed, meaning that the quarks are directly connected without crossing. In

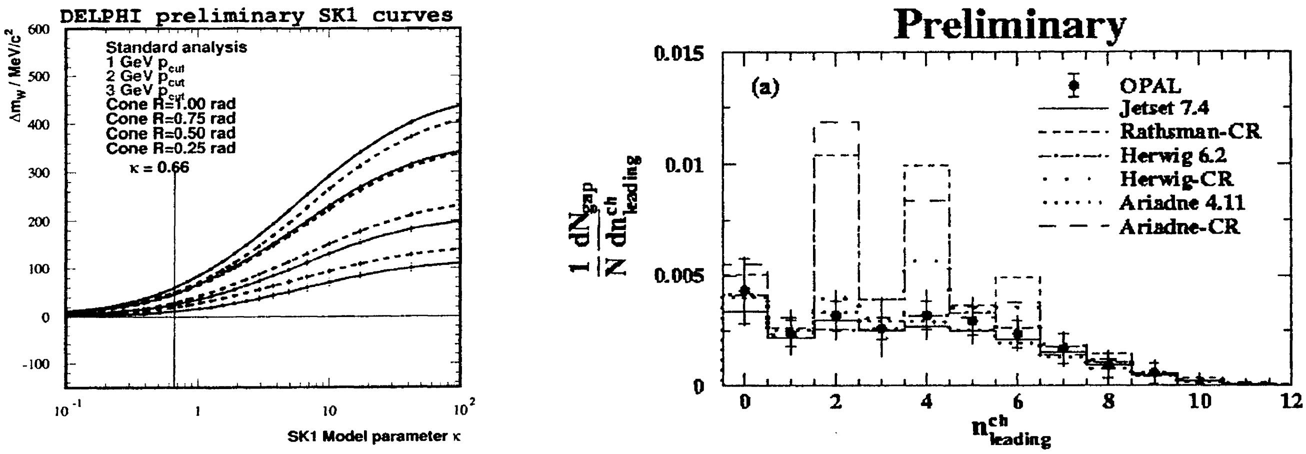

Figure 2: Left (a): Difference $m_w(\kappa)$ - $m_w(\kappa = 0)$ as a function of the SK1 free parameter. Right (b): Distribution of $n^{ch}_{leading}$ in the leading part of the gluon jet. N is the total number of gluon jets and N_{gap} is the number of jets with a rapidity gap.

CR models, the color flow can in addition either cross or appear as disconnected entities (gluons). Topologies with one additional reconstructed gluon jet are of special interest for CR studies. However, both Rathsmann and Ariadne-CR show a strong disagreement with the OPAL data [12] see Figure 2b, even when the MC parameters are retuned to account for this distribution. Only HERWIG CR can be brought into some agreements with the OPAL data. Similar analysis are currently being prepared by the other LEP collaborations.

7 Conclusion

Studies of CR may help to gain further understanding of the space-time evolution of the fragmentation. All studied distributions are compatible with standard Monte Carlo predictions. Recent developments, like the new m_W estimator or rapidity gap studies give hope to exclude some CR models.

No CR effects are observed on a level of 100 MeV/c^2 in the LEP data. However, the associated uncertainty of color reconnection in the W boson mass is 100 MeV/c^2, therefore it is still of importance to better understand this effect.

References

[1] V. Khoze and T. Sjöstrand, Eur. Phys. J. **C6** (1999) 271

[2] T. Sjöstrand and V. Khoze, Zeit. Phys. **C62** (1994) 281.

[3] J. Rathsman, Phys. Lett. **B452** (1999) 364.

[4] T. Sjöstrand, Comp. Phys. Comm **82** (1994) 74.

[5] L. Lönnblad, Comp. Phys. Comm. **71** (1992) 15.

[6] G. Marchesini *et al.*, Comp. Phys. Comm. **67** (1992) 465.

[7] L. Lönnblad, Zeit. Phys. **C70** (1996) 107.

[8] G. Corcella *et al.*, JHEP **0101** (2001) 010.

[9] The LEP collaborations and the LEP WW working group, Internal Note LEPEWWG/MASS/2003-01 (2003).

[10] E. Bouhova-Thacker, Colour Reconnection in WW pair production, talk given at the ICHEP02 (2002).

[11] The DELPHI Collaboration, Internal Notes DELPHI 2003-003 (2003).

[12] OPAL Collaboration, OPAL Note PN518.