Color Reconnection phenomena in $WW \to qqqq$ events

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Color reconnection, a QCD interaction between W decay products produced at LEP2. This phenomena represents the biggest systematic error on the measured W mass in the 4 quarks final state.

1. Introduction

At LEP2, 47% of the W pairs created in the e^+e^- annihilation events are 4 quarks final states. The typical distance between decaying W's is 0.5 fm which is within the QCD scale. During the fragmentation process, there is no theoretical reason to exclude a QCD interaction between the two systems corresponding to the decay products of the two W's. This cross talk which occurs at the parton level is called color reconnection (CR). It is studied for mainly two reasons.

First, it can give information on color fields. However, the present measurements did not reach enough sensitivity.

The second reason is related to the W mass measurement which relies on the direct reconstruction of the final states. When CR occurs, final hadronic singlets do not correspond to the initial W bosons. The amplitude of the effect is unknown, making it the most important systematic error on the W mass measurement.

No systematic difference was found between the W mass measured from the fully hadronic channel ($WW \to qqqq$) and from the semileptonic channels ($WW \to \ell\nu qq$) for which this interaction is not possible. The latest data (winter 2001) [1] give $MW(qqqq) - MW(\ell\nu qq) = 18 \pm 46 MeV/c^2$. This cross check excludes a large effect of CR.

2. Color reconnection in models

At the perturbative level, CR is strongly suppressed [2] while at the non-perturbative level no precise calculations are possible and only phenomenological models are available. Since CR interferes with the fragmentation process, at least one reconnection model is associated to each fragmentation model.

2.1. Studied Models

For the LEP2 studies, the Jetset program [3] (Lund model [4]) is the reference with the corresponding CR models from Sjöstrand-Khoze (SK) [5–7]. For the fragmentation process, the behavior of the color field is irrelevant. However, in these CR models the notion of string overlap is introduced. Its nature has an impact on the predictions.

The SK1 model has a free parameter. As this model was developed for two resonant decays it can not be tuned with Z events ($e^+e^- \to Z$). Its parameter governs the strength of the interaction and is related to the reconnection probability.

The model of Lönnblad [5,8] based on the dipole cascade model is implemented in the Ariadne [9] program. The model of Weber et al. [5,6] is implemented in the Herwig program [10] in the framework of cluster fragmentation. These two models are tunable with Z data.

2.2. Color reconnection effects

All CR models predicts an effect on event multiplicities and particle momenta distributions. The most affected particles are soft particles and particles outside W decay planes. CR is also expected to cause a change in the angular distribution of particles between W jets. This cross talk between W decay products affects the measured W mass which is the most sensitive observable.

3. Color reconnection measurement by Multiplicity and Momentum

CR can be measured using the distribution ξ, defined by

$$\xi = -lnX_p = -ln(\frac{2p}{\sqrt{s}})$$

where p is the particle momentum and $\sqrt{s}$ the centre-of-mass energy.

The ratio of this distribution computed for hadronic events and semileptonic events, $\frac{\xi(qqqq)}{2\times\xi(\ell\nu qq)}$, is sensitive to the reconnection effect. This ratio is compared between DATA and models as shown on figure 1 for ALEPH. The analysis was performed by all LEP experiments. No evidence for CR was found.

Particle multiplicity can be used also to detect the reconnection effect. This analysis is based on the comparison of the multiplicities in the fully hadronic and the semi-leptonic channels. An observable is defined by the difference in multiplicity of the hadronic and two times semileptonic channels:

$$\Delta < N > = < N >^{4q} - 2\times < N >^{\ell\nu qq}$$

The expected effect is tiny, smaller than systematics. No evidence for CR was found with this analysis.

4. Color reconnection measurement using the Particle Flow

CR is expected to cause a depletion of soft particles in inter W regions and an enhancement in intra W regions.

4.1. Method

In order to quantify this effect, a distribution called particle flow is defined. Fully hadronic events are preseleted with an algorithm based on angular criteria which can vary between experiments. These selections suffer from a low efficiency : about 15% of the events are used.

The particle Flow distribution is an angular distribution. Each particle has its momentum projected onto a plane defined by two jets as illustrated on figure 2. Since a hadronic event contains 4 jets, 4 di-jets systems, thus 4 planes, can be used for the projection. The plane which minimizes the transverse momentum of the particle is chosen. The angle of the projected momentum with respect to the nearest jet is normalized to the interjet angle. The resulting distribution is shown on figure 3. One distinguishes 4 regions corresponding to the inter W and the intra W regions. The use of energy ordering and angular criteria permits to assign each sector to an inter/intra W region. Sectors A and B of figure 3 correspond to the two W regions while sectors C and D correspond to the two non W regions. This distribution is finally compacted taking the ratio $\frac{A+B}{C+D}$. It is sensitive to CR effects and is computed for data and simulations in order to be compared.

4.2. Results

Data are compared with models. In figure 4, data are compared to the SK1 model with different values of its parameter ki. This parameter is then extracted with a χ^2 minimization.

The particle flow analysis has a limited sensitivity similar to the difference $\Delta MW(qqqq - qq\ell\nu)$. A combination of all LEP experiments is needed.

5. CR as systematic effect on MW

CR is the most important systematic error on MW.

5.1. Evaluation of the systematic error

This effect is evaluated considering the difference between CR Monte-Carlo sample and CR free sample. This estimation of the error is model dependent. All available models are tested (as shown on table 1) and the biggest shift is taken for the estimate of the systematic error. This effect is considered to be 100% correlated between the 4 LEP experiments.

The $SK1$ model predictions on MW depend on its parameter ki. The correspondence between ki (or the reconnection probability) and the predicted shift varies from 0 to $300 MeV/c^2$. However, high values of ki can be excluded by the particle flow measurement described before. The combined LEP measurement will give a limit on ki and the corresponding mass shift will be taken as systematic error.

Table 1
Shifts on the W mass predicted by different CR models in the ALEPH analysis [11]. For the SKI model, the ki parameter has been fixed to 0.6. This value was taken from the SKII model but has to be measured.

Models	SKI	SKII	HERWIG	AR2
$\Delta MW\ (MeV/c^2)$	37 ± 12	6 ± 8	20 ± 10	21 ± 19

5.2. Minimizing CR impact on the W mass

Since CR is known to affect soft particles and particle flow in inter jet regions, it is possible to modify the MW measurement in order to cut out affected particles. The developed techniques are based on dedicated jet algorithms or cuts on particle momenta. If the systematic error decreases, the exclusion of a part of the events leads to a statistical sensitivity loss. The minimization of the total error on MW has to be done at the level of the LEP combination. It is an ongoing work.

6. CR measurement with the W mass

The W mass is the most sensitive observable to CR. The analyses described before are able to reduce CR effect on MW. They may also be used to measure CR as a variation of the W mass in the data. The statistical precision we have on MW allows to perform such a measurement.

7. Conclusion

Color reconnection is still an important systematic error on the W mass. A final LEP combination of the Particle flow analysis is needed in order to extract a precise evaluation of the effect. The reduction of CR sensitivity in MW measurement is a promising strategy which opens also the perspective of measuring the reconnection effect in data using MW as observable.

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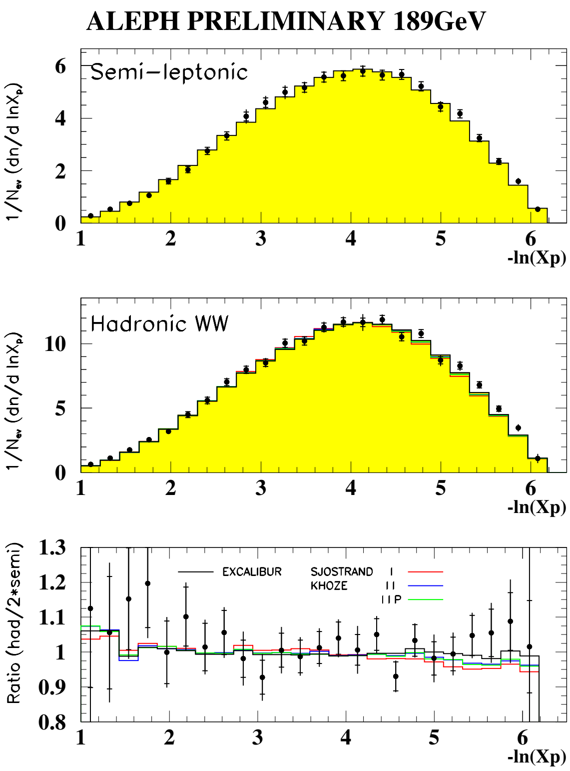

Figure 1. $\xi = -ln(X_P)$ distributions from ALEPH experiment, computed from DATA collected at centre of mass energy equal to $189GeV$. The first distribution corresponds to semileptonic events while the second to fully hadronic events. The ration defined by (hadronic/2 $\times$ semileptonic) is compared between data and different CR models.

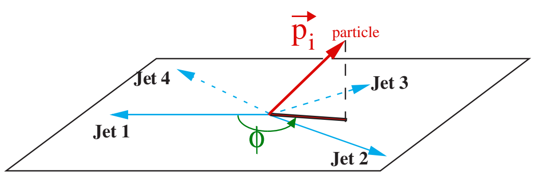

Figure 2. Particle momentum is projected on a plane defined by a di-jet system

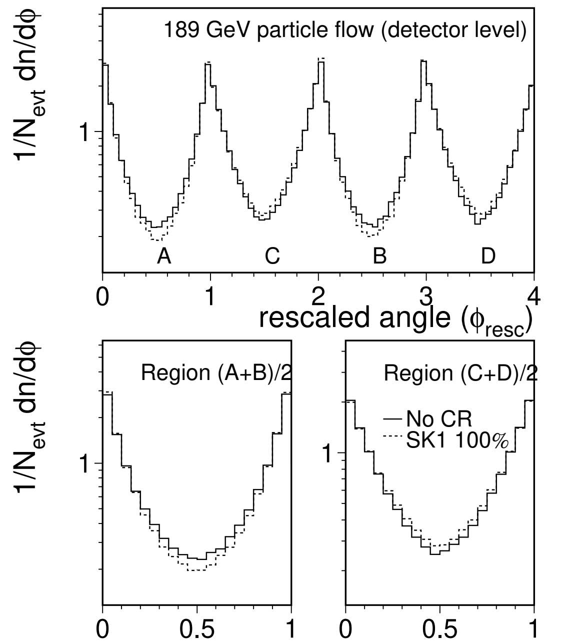

Figure 3. Particle Flow distribution defined in L3 computed for simulated signal events. In order to test the sensitivity of the distribution, two models are compared: the standard jetset (no CR) and the SK1 model ($ki = \infty$).

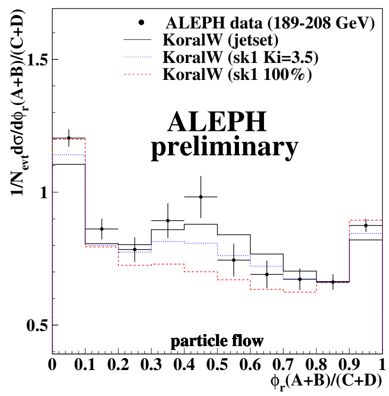

Figure 4. The ratio $\frac{A+B}{C+D}$, for all ALEPH LEP2 data, is compared to the SK1 model with different values of ki.