COLOR RECONNECTION AND BOSE-EINSTEIN CORRELATIONS AT LEP2

Th. Ziegler
Institut für Physik, Johannes Gutenberg Universität, Staudingerweg 7, 55099 Mainz, Germany

Abstract. Recent investigations of final state interactions of $W^+W^-$ events in $e^+e^-$ collisions up to center of mass energies $\sqrt{s} = 189$ GeV at LEP2 are reviewed. The data were used to look for color reconnection and Bose-Einstein correlations between the two color singlets of fully hadronic W events.

1 Motivation

In high energy $e^+e^-$ collisions at LEP the W bosons are produced in pairs. As the hadronisation scale is much larger than the distance of the W bosons at their primary decay vertices, the decay products have a significant space-time overlap and the two systems may interfere during the hadronisation phase. One important consequence is a possible shift in the invariant mass of the reconstructed W bosons in the fully hadronic channel. Two types of final state interactions are investigated and will be reviewed separately: color reconnection and Bose-Einstein correlations.

The results are based on $\approx 55$ pb$^{-1}$ at $\sqrt{s} = 183$ GeV and $\approx 173$ pb$^{-1}$ at $\sqrt{s} = 189$ GeV per LEP collaboration.

2 Color Reconnection (CRC)

Color reconnection (CRC) leads to a rearrangement of the color flow between the hadronic decay products of the W bosons. That this may cause a possibly significant shift in the W mass measurement was first suggested by Sjöstrand and Khoze [1]. In the perturbative case the color flow of the primary quarks is rearranged and possible effects can be estimated by perturbative QCD. The shift of the W mass is predicted to $\Delta M_W \leq O(5 MeV)$ and thus negligible. The effect due to the rearrangement of the color flow of the secondary decay products has to be investigated by MC studies and non-perturbative QCD models have to be used. The consequence for the W mass shift is estimated to be of the order of $\Delta M_W \leq O(50 MeV)$. The following review concentrates on the latter case.

[e-mail: Thomas.Ziegler@cern.ch]
\[ \Delta(N_{ch}) = \langle N_{4q}^{\text{ch}} \rangle - 2 \langle N_{qq\ell\nu}^{\text{ch}} \rangle \]

| Collaboration | Value |
|--------------|-------|
| ALEPH        | 0.47 ± 0.44 ± 0.26 |
| OPAL         | 0.7 ± 0.8 ± 0.6c |
| DELPHI       | -0.92 ± 0.66c |
| DELPHI       | \( \langle N_{4q}^{\text{ch}} \rangle / 2 \cdot \langle N_{qq\ell\nu}^{\text{ch}} \rangle \) |

![Figure 1](image)

a) Studies of the mean charged particle multiplicity of the LEP collaborations at \( \sqrt{s} = 189 \) GeV (table above).
b) Inclusive charged particle momentum distributions and comparison with MC predictions with and without CRC models (figure on the right).

2.1 Inclusive Mean Charged Particle Multiplicity

To investigate effects of CRC simple observables like the inclusive charged multiplicity \( N_{ch} \) are obvious candidates. There have been models [13] which predict a \( \approx 10\% \) effect of CRC on the mean charged multiplicity \( \langle N_{4q}^{\text{ch}} \rangle \) in the \( W^+W^- \rightarrow q\bar{q}q\bar{q} \) channel which were excluded in earlier analysis [4, a.o.] but encouraged the interest in these kind of studies.

As a reference for \( \langle N_{4q}^{\text{ch}} \rangle \) the mean charged multiplicity \( \langle N_{qq\ell\nu}^{\text{ch}} \rangle \) of the hadronic part of the semileptonic channel is used. Typically the difference \( \Delta(N_{ch}) = \langle N_{4q}^{\text{ch}} \rangle - 2 \cdot \langle N_{qq\ell\nu}^{\text{ch}} \rangle \) is chosen as an observable and should be 0 for no observed effect. The results of the four collaborations [6 - 9] in figure [1h] should not be compared directly with each other due to different unfolding and correction procedures.

MC studies with physically reasonable CRC models predict a shift in the mean charged multiplicity of the fully hadronic channel of \( |\Delta(N_{ch})^{MC}| \leq 0.3 \). Therefore all the results are still compatible with standard model predictions.

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b) result for \( \sqrt{s} = 183 \) GeV
c) extracted from the numbers given in the DELPHI paper
2.2 Inclusive Charged Particle Momentum Distributions

From MC studies an effect of CRC [12], especially in the low momentum region of the hadronic WW events, is expected. ALEPH [1], DELPHI [2] and OPAL [4] performed similar analysis on momentum distributions. However no evidence for CRC within the statistical significance could be found. As an example the $\xi$ distribution of ALEPH is shown in figure 1b where $\xi$ is the transformed normalized momentum of the charged particles: $\xi = -\ln(x_p) = -\ln(\sqrt{s}/2p)$. A comparison of the hadronic and the semileptonic channel shows no evidence for color reconnection. Even more low momentum particles are observed whereas less are expected by the 3 shown CRC models of Sjöstrand and Khoze. Further MC studies claimed [12], that the effect should be enlarged for low momentum heavy particles in the context of Sjöstrands CRC models. DELPHI [2] and OPAL [5] performed analyses on the low momentum distributions of charged Kaons and Protons. The result of OPAL is shown in figure 2. In both channels some discrepancies between the data and the KORALW standard MC are found. Nevertheless the ratio $R = N_{K,p}^{q\bar{q}}/(2 \cdot N_{K,p}^{q\ell\nu})$ prefers the MC without CRC. For comparison 2 ARIADNE CRC models are shown. The ratio of the production rates in the momentum region $0.002 \leq x_p \leq 0.012$ was found to be

\[
R(183 \text{ GeV}) = 0.91 \pm 0.13 \pm 0.08 \\
R(189 \text{ GeV}) = 1.11 \pm 0.08 \pm 0.06
\]

For both energies the result is consistent with the expectation of standard QCD models without CRC.
2.3 Particle and Energy Flow Distributions between Jets

In the context of the string fragmentation model CRC should change the particle production between different jets. This can be investigated via particle and energy flow distributions. The particle flow describes the number of particles produced per angular unit between 2 adjacent jets. In the energy flow histogram the entries are weighted with the energy of the particles. The analysis of the L3 collaboration \[3\] uses a topological event selection, afterwards the jets coming from one W boson are identified and sorted. The angle between the jets is rescaled to be one. Angles from 0 to 1 (A) and from 2 to 3 (B) in figure 3a describe the region between the jets from the same W boson, angles from 1 to 2 (C) and from 3 to 4 (D) describe the region between jets from different W bosons. The data show no significant deviation from the MC without CRC. The ratio between the particle production of jets coming from the same and from different W bosons

\[
\frac{\text{particle flow (region A + B)}}{\text{particle flow (region C + D)}}
\]

can be used as a more sensitive variable to CRC. In figure 3b this ratio is shown for the energy flow distribution of the low momentum particles ($p < 1 \text{ GeV}$) in comparison with one of the Sjöstrand/Khoze models (SK I) as well as the somewhat extreme Gustafson/Häkkinen model (GH) \[14\]. Although the errors are still quite large it seems that most of the data points are systematically slightly lower than the standard MC prediction without CRC. Nevertheless no evidence for CRC can be claimed within the statistical significance.
3 Bose-Einstein Correlations (BEC)

From quantum mechanics it is known that the wave function of a pair of identical bosons must be symmetric. As a consequence the number of identical bosons, produced close in phase space, is enhanced. The so called Bose-Einstein correlations (BEC) are well established for pions in $Z^0$ decays. However it is not clear to what extent BEC are induced from the space-time overlap of the decay products of the pair-produced $W$ bosons. From MC studies the shift in the $W$ mass in the hadronic channel is estimated to the order of $\Delta M_W \leq O(50 \text{ MeV})$.

3.1 BEC Studies at ALEPH

The ALEPH collaboration uses the following double ratio \[6\]:

$$R^*(Q) = \left( \frac{N_{++,-}(Q)}{N_{-+,-}(Q)} \right)_{\text{data}} \left/ \left( \frac{N_{++,-}(Q)}{N_{-+,-}(Q)} \right)_{\text{noBEC}} \right. \right.$$  

The ratio of the number of 'like-sign pion pairs' to 'unlike-sign pion pairs' of the data is compared with a MC sample without BEC. This ratio is parametrized with $R^*(Q) = \kappa(1 + \epsilon Q)(1 + \lambda e^{-\sigma^2 Q^2})$. $Q$ is the Lorentz-invariant momentum distance of 2 bosons, $\kappa$ defines the strength of the correlations and $\sigma$ the source size of the boson emitter. The double ratio and the fit to the data are shown in figure \[4a\]. The data points are compared to MC with and without BEC which is tuned and corrected at the $Z^0$ peak. BEC between pions from different $W$ bosons are disfavoured by the MC.

3.2 BEC Studies at DELPHI

The DELPHI collaboration uses an event mixing technique \[7\] where they compare the number of 'like-sign pion pairs' in the hadronic channel with the number of 'like-sign pion pairs' of a hadronic event, which is built of the hadronic part of 2 semileptonic events:

$$g'(Q) = \left( \frac{N_{++}(Q)}{N_{mix}(Q)} \right)_{\text{data}} \left/ \left( \frac{N_{++}(Q)}{N_{mix}(Q)} \right)_{\text{noBEC}} \right.$$  

By definition there are no correlations between the pions of different $W$ bosons. The double ratio is parametrized as $g'(Q) = 1 + \Delta e^{-\kappa^2 Q^2}$. The fit results in $\Delta = (7.3 \pm 2.5_{\text{stat}} \pm 1.8_{\text{syst}})\%$. If there are no BEC between pions from different $W$ bosons the expectation would be $\Delta = 0$. Therefore the BEC between the $W$ bosons are preferred by this analysis.
3.3 BEC Studies at L3

In the subtraction method of the L3 collaboration the 2 particle density function is defined as 
\[ \rho(p_1, p_2) = \frac{1}{N_{\text{evt}}} \frac{dN_{\text{pairs}}}{dQ}. \]
The overall 2 particle density can be written as:
\[ \rho_{WW} = 2 \rho_W + 2 \rho_{WW}^{\text{mix}} \rightarrow \Delta \rho = \rho_{WW} + 2 \rho_W + 2 \rho_{WW}^{\text{mix}} \]
with \( \Delta \rho = 0 \) for no BEC between pion pairs from different W bosons. The \( \Delta \rho \) distributions for the like-sign and unlike-sign charged pions are investigated as well as \( \delta \rho = \Delta \rho(\pm, \pm) - \Delta \rho(+, -) \) which should only depend on BEC. No excess is observed in the distributions and BEC between pions from different W bosons are disfavoured.

3.4 BEC Studies at OPAL

The OPAL collaboration uses the same double ratio as ALEPH but performs a simultaneous fit to the following event classes: hadronic WW, semileptonic WW and \( e^+e^- \rightarrow q\bar{q} \) events. In table the fit result of the source size R and the strength of the correlations \( \lambda \) are shown.

With \( \lambda = 0.05 \pm 0.67 \pm 0.35 \) BEC between pions coming from different W bosons cannot be established with the current level of precision.
### Table 1: The fit results of the OPAL collaboration

| Parameter   | $R_{(fm)}$ | $\lambda$ |
|-------------|------------|-----------|
| same $W$    | $1.07 \pm 0.07 \pm 0.12$ | $0.69 \pm 0.12 \pm 0.06$ |
| diff $W$    | $1.51 \pm 0.05 \pm 0.35$ | $0.05 \pm 0.67 \pm 0.35$ |
| $(Z^0/\gamma)^*$ | $1.01 \pm 0.08 \pm 0.14$ | $0.43 \pm 0.06 \pm 0.08$ |

4 Summary

Studies of final state interactions are an interesting field in itself and may help to obtain a deeper understanding of the space-time development of the fragmentation process.

The analyses on color reconnection show that all the investigated distributions are compatible with standard MC predictions. Nevertheless they are still limited by the statistics. The particle and energy flow analysis of the L3 collaboration looks promising as the statistics will be increased by at least a factor of 3. With similar analyses of the other LEP collaborations the statistical errors could be decreased by almost a factor of 4 with the final statistics.

The BEC analyses for the LEP collaborations use different methods and the results are not yet conclusive. More experimental effort is needed in this sector to understand BEC resulting from the interference of the hadronic decay products of different W bosons.

One should be aware that an interference between CRC and BEC may reduce or enhance the overall effect.

The present experimental status of the W mass \(^{10}\) is  
\[
M_W(q\bar{q}q\bar{q}) - M_W(q\bar{q}\ell\nu_\ell) = 152 \pm 74 \text{ MeV/}c^2
\]

As the actual systematic error on final state interaction is given with \(58 \text{ MeV/}c^2\) \(^{10}\) it is important to understand color reconnection and Bose-Einstein correlations because they are an important systematic uncertainty on the W mass measurement in the hadronic channel.

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particle flow with tracks ($p<1$ GeV)
189 GeV (preliminary)

- $\text{L3 Data}$
- $WW \rightarrow qqqq$
$\frac{1}{N_{\text{evt}}} \frac{dN}{d\phi (A+B)/(C+D)}$

189 GeV particle flow (particle level)

All particles

- No CR
- SK I
- GH
189 GeV particle flow (detector level)

All clusters

\[ \frac{1}{N_{\text{evt}}} \frac{dn}{d\phi}(A+B)/(C+D) \]

- No CR
- SK I
- GH
- L3 data
189 GeV energy flow (particle level) particles < 1 GeV

\[ \frac{1}{E} \frac{dE}{d\phi} \frac{(A+B)}{(C+D)} \]