INTERCONNECTION EFFECTS AND W⁺W⁻ DECAYS
(a critical (p)(re)view) \(^a\)

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Color reconnection and Bose-Einstein correlations not only can have an influence on the measurement of the W-mass in the fully hadronic W⁺W⁻ decay channel at LEP2, but also can give essential information on the structure of the QCD vacuum and the space-time development of a q₁-bar q₂ system. Recent developments are critically analyzed, with particular emphasis on the models used in this field. More sensitive variables are needed to distinguish between color reconnection models, while more experimental knowledge has to be built into the Bose-Einstein models and, above all, these two closely related phenomena have to be treated in common. Both effects are determined by the space-time overlap of the W⁺ and W⁻ decay products. Vital experimental information on the space-time development of the decay of the q₁-bar q₂ system is becoming available from the high-statistics data on hadronic Z decay and models will have to be able to explain this evidence before being used to predict interference effects in hadronic W⁺W⁻ decay.

1 Introduction

When Bo Andersson reported on the incorporation of Bose-Einstein correlations into the Lund string during an earlier workshop, [1] he started: “this is the most difficult work I have ever participated in” and he did not even refer to the W⁺W⁻ overlap! The statement sets the scale, but should be squared when applied to the latter. That’s why it is easier to be critical on this topic than to review it and why I shall reduce my task at this Rencontre to giving a personal (though still critical) view, instead.

Interconnection effects, at first sight a nuisance when trying to measure the W mass, on the other hand may open new handles for the study of basic issues as the structure of the vacuum

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and the space-time development of a $q\bar{q}$ system at high energy.

Of course, the phenomenon of color reconnection is by no means restricted to $W^+W^-$ decay. Other examples are $J/\Psi$ production in B decay, event shapes in $Z$-decay or rapidity gaps at HERA.

# 2 Color reconnection

## 2.1 The models

If produced in the same space-time point, pairs of quarks and anti-quarks $(q_1\bar{q}_4)$ and $(q_3\bar{q}_2)$ originating from the decay of different W’s can form strings, if they happen to be in a color singlet. [2] From color counting, this is fulfilled in $1/9$ of the cases, but this recoupling probability can be enhanced by gluon exchange. However, the pairs $(q_1\bar{q}_2)$ and $(q_3\bar{q}_4)$ are produced at a distance $\propto 1/\Gamma_W \approx 0.1$ fm, small compared to the hadronic scale, but large enough to suppress exchange and/or interference of hard ($E_g \gtrsim \Gamma_W$) gluon. [3,4] Soft-gluon interference, is of course possible. It depends on the vacuum structure and a number of models exist. [3–8] According to the underlying software package used, they can be grouped into the following.

1. PYTHIA based models:
   a) SKI [3] uses Lund strings and allows at most one reconnection. The color field is treated as a Gaussian-profile flux tube (as in a type I superconductor) with a radius of $\sim 0.5$ fm and the recoupling probability $\rho$ depends on the overlap of the two flux tubes in space-time. The recoupling probability density is a free parameter quite arbitrarily chosen to be $0.9$ fm$^{-4}$ (but varied easily). At 183 GeV, recoupling is predicted to occur in 38% of the events. [9]
   b) SKII [3] also uses Lund strings with at most one reconnection, but the color field is treated as an exponential-profile vortex line (as in a type II superconductor). When two vortex lines cross, i.e. have a space-time point in common, for the first time, they recouple with unit probability ($\rho = 1$). At 183 GeV, this gives a recoupling in 22% of the events. [9]
   c) SKII’ [3]: like SKII' but with $\rho = 1$ upon first crossing reducing the total string length, giving a recoupling in 20% of the 183 GeV/c events. [9]
   d) ŠTN [5]: is an important extension of SKI and SKII to implement the space-time evolution of the shower, as well as multiple reconnection, including self-interaction of strings. This approach is more realistic than the SK versions, but still shares one problem: the color reconnection is performed after the generation of the complete parton shower and, therefore, cannot change its development.

2. Color-dipole based models [4,6]:
Here, the Lund string and its gluon kinks are replaced by a chain of dipoles. Within, or between two dipole chains, reconnection is possible when the color indices (ranging from 1 to 9) of two (non-adjacent) dipoles are the same. Reconnection is indeed performed when the string length measure $\lambda = \sum_{i=1}^{n-1} \ln(m_{i,i+1}^2/m_0^2)$ is reduced ($m_{i,i+1}$ is the invariant mass of the string segment stretched by partners $i$ and $i+1$ and $m_0$ a hadronic mass scale around 1 GeV). Also these models exist in a number of versions. In [4], the number of reconnections per event was at most one, and there was no reconnection within a W. In version [6], two dipole systems $q_1\bar{q}_2$ and $q_3\bar{q}_4$ first evolve separately, radiating gluons with $E_g > \Gamma_W$ independently, but with color reconnections within each dipole system. Then, when $E_g < \Gamma_W$, reconnections between the two systems are switched on. In practice, because of the $k_T$-ordering of CDM, the cascade is run twice: first for $E_g > \Gamma_W$ without reconnections between the two systems, and a second time allowing only $E_g < \Gamma_W$ with interconnections. An an alternative, the second cascade can be omitted, but interconnections between the systems is allowed before fragmentation.

3. Cluster models: Quarks and gluons originating from the parton showers combine into clusters.
These are less extended and less massive than strings are and decay isotropically into a small number of hadrons.

a) HERWIG based [7]: After showering, the gluons are split non-perturbatively into quark-antiquark pairs and each may form a color-singlet cluster with a color-connected partner. At the start of the cluster-formation phase, color connections are established between clusters that reduce the space-time extension of the clusters, and reconnections are allowed in 1/9 of the cases. Reconnection among the products of a single shower are natural in this model.

b) VNI based [8]: Three scenarios are considered for cluster formation, one of which including non-singlet clustering, where the net color of the cluster is carried off by a secondary parton.

Two critical comments on all models: they should contain reconnection within a single W, and if they do, they should be very carefully retuned on the Z. Interesting in this connection is an OPAL study [10] of gluon production in Z decay, $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}g\bar{g}$, where reconnection effects are expected to contribute [4]. Two versions of the dipole model tested predict noticeably fewer particles at small rapidities and energies than are observed in the data (or the conventional QCD programs), as well as a downward shift of about one unit in the $g_{\text{incl}}$ charged-particle multiplicity.

2.2 The data

The recent data are beautifully summarized by the previous speaker, [11] so that I can restrict myself to a few comments.

Fig. 1 reproduces a comparison of OPAL data [9] and model predictions for the charged-particle multiplicity (a) and (b) and thrust distributions (c). The full lines correspond to model versions without reconnection, the other lines to models with reconnection. Two conclusions from this figure are:

1. The VNI based model [8] is way off, it does not fit the data at all, but the simulations are also in strong disagreement with results published in [8], which, in their turn, were equally far off (at least in thrust $T$), but in the opposite direction. Furthermore, the MC code is reported not to conserve energy. [9] I leave it to the reader to decide to do something about this or to forget the model.

2. All the other models (including reconnection or not) look so similar in $n_{\text{ch}}$ and $1 - T$, that these variables are obviously not discriminative.

So, the search for color reconnection boils down to the search for discriminative variables. As reconnections reduce the string length or the cluster size, and these determine the average...
multiplicity, $\langle n_{\text{ch}} \rangle$ was suspected to be a good candidate. Fig. 1 does, however, not give a lot of hope, but one can look at $\langle n_{\text{ch}} \rangle$ in the overlap regions, alone.

In Fig. 2 we reproduce a study of a recent working group. [12] The model predictions for the multiplicity shift

$$\Delta n_{\text{ch}} = n_{\text{ch}}^{\text{WW}} - 2 n_{\text{ch}}^{W}$$

are given for all momenta (leftmost points), as well as for a number of rapidity $y$ and momentum $P$ cuts reducing the sample to that of the overlap region. The present LEP average for the leftmost point (all $P$, all $y$) is $\Delta n_{\text{ch}} = 0.18 \pm 0.39$ [11] (or $0.54 \pm 1.08\%$ on Fig. 2). That means no effect outside errors, but also agreement with color reconnection as predicted by PYTHIA and HERWIG.

As the reduced available string length or cluster size will be felt first by heavy particles, it has been suggested to look at kaons + protons with momenta restricted to $0.2 - 1.2$ GeV/c. DELPHI [13] finds a shift of $(+3 \pm 15)\%$ while $(-8$ to $-3)\%$ is predicted.

However, we have to do with a complex overlap of two complex systems, where correlations and not averages are at play! Besides that, where the multiplicity is reduced by reducing the string length, it is quite likely to be increased by Bose-Einstein correlations! The least I recommend, if one wants to restrict oneself to averages, is to study the shift in integrated two-particle density, i.e., the second-order factorial moment

$$\Delta F_2 = F_2^{\text{WW}} - 2 F_2^{W} - 2 \langle n^{W} \rangle^2$$

or, better, to look at the shift $\Delta \rho(1,2)$ in the two-particle density itself. [14]

3 Bose-Einstein correlations

The previous speaker [11] has given a beautiful summary on the contradictory results on inter-W BE effects. Obviously, before embarking on a study of inter-W BE correlation effect, we first have to understand intra-W BE correlations and the space-time shape of a single W. Since even that is impossible with present statistics, we have to go back and look at the $Z^0$ in more detail!

3.1 Experimental results on the $Z^0$

From BE analysis of the $Z^0$ [15] we know, first of all, that BE correlations indeed exist in its hadronic decay. So, they can, in principle, give problems in WW overlap. However, more importantly, these very BE correlations can be used as a pion-interferometry laboratory to measure the space-time development of hadronic $Z$-decay, and, ultimately in WW overlap. It is this, where actually much more is known already than generally used in WW studies:

1. **Elongation of the pion source** [16,17]: Applying a two- or three-dimensional (instead of the usual one-dimensional) parametrization of the correlation function [18]

$$R_2(Q_L, Q_{\text{out}}, Q_{\text{side}}) = 1 + \lambda \exp(-r_{L}^2 Q_{L}^2 - r_{\text{out}}^2 Q_{\text{out}}^2 - r_{\text{side}}^2 Q_{\text{side}}^2)$$

in the longitudinal, out and side components of the squared two-particle four-momentum difference $Q = (-(p_1 - p_2)^2)^{1/2}$ and the corresponding size parameters $r_L, r_{\text{out}}, r_{\text{side}}$, DELPHI [16] and L3 [17] find a clear elongation along the thrust axis of the pion source in the longitudinal cms. [19] The ratios of the transverse radii ($r_{\text{out}}, r_{\text{side}}$) and $r_T = (r_{\text{out}}^2 + r_{\text{side}}^2)^{1/2}$ are given in Table 1. The elongation is of course stronger in the 2-jet sample used by DELPHI, but even clear in the full data used by L3. This is in contradiction with the assumption of a spherically symmetric correlation function in most of the models (see below).

2. **Position-momentum correlation**: The correlation length of $0.7 < r_L < 0.8$ fm [16,17] (called the length of homogeneity) corresponds to the length in space from which pions are emitted that
have momenta similar enough to be able to interfere. The spatial extension of the Z emission function \( S(t, z) \), on the other hand, is expected to be of the order 100 times that of \( r_L \) (see Fig. 3a [20]). This invokes a strong momentum ordering in space. Experimentally, this emission has been measured only in hadron-hadron [21] and heavy-ion collisions, [22] so far (see Fig. 3b,c), but its measurement in Z decay will tell us the actual shape of such a decay in space-time, and therefore how the overlap of WW has to be visualized!

3. **Non-Gaussian correlation function**: For simplicity, parametrization Eq. (3), even if not spherically symmetric anymore, is still Gaussian. Strong deviation from such a behavior is known from hadron-hadron collisions, [23] but deviations also exist at the Z. [15] Generalizing the Gaussian to a so-called Edgeworth expansion [24]

\[
R_2 = 1 + \lambda \prod_i \exp(-r_i^2 Q_i^2) \left[ 1 + \frac{\kappa_3}{3!} H_3(r_i Q_i) + \ldots \right],
\]

(4)

where \( \kappa_3 \) is the third-order cumulant moment and \( H_3 \) is the third-order Hermite polynomial, shows [17] that the correlation is indeed stronger than Gaussian at small \( Q \) (see Fig. 4). While maintaining the elongation, the CL value of the 3-D fit is now increased from 3.1\% (see Table 1) to 30\%.

4. **The transverse mass dependence**: From heavy-ion collisions, [25] it is known that the radii in Eq. (3) decrease with increasing average transverse mass \( m_T \) of the particle pair. Preliminary results [16, 17] indicate that such a behavior is also present in Z decay. The \( m_T \) dependence is reproduced by JETSET/LUBOEI for \( r_{\text{out}} \), but not for the two other components (see Fig. 5).

5. **Genuine higher-order correlations** exist in hadron-hadron collisions [23, 26] and also in Z decay. [27, 28] The DELPHI results are given in Fig. 6. For identical particles, they are not reproduced by JETSET/LUBOEI. [27]

6. **Density (or multiplicity) dependence**: A linear increase of the size of the pion-emission region with increasing particle density, combined with decrease of the correlation-strength parameter \( \lambda \) is well known from heavy-ion and higher-energy ISR and collider results (e.g. [29] and refs. therein). At least the decrease of \( \lambda \) can be understood from the overlap of an increasing number of independent mechanisms (e.g. strings or clusters). OPAL [30] has shown that a similar dependence is also present in Z decay (Fig. 7). It can at least in part be explained from the presence of two- and three-jet events.

3.2 **Three types of Monte-Carlo implementation**

1. **Reshuffling**: The MC code LUBOEI [31] in JETSET treats BE correlations as a final state interaction (!) and actually changes particle momenta according to a spherically symmetric Gaussian (or, alternatively, exponential) correlator. The advantages are that it is a fast and unit-weight (i.e. efficient) generator. The bad news are that it is imposed a-posteriori (without any physical basis), is even unphysical (since it changes the momenta), is not self-consistent

| Table 1: Transverse over longitudinal size parameters measured and predicted by JETSET |
| --- | --- | --- |
| \( r_T/r_L \) | L3 [17] | JETSET | DELPHI (2-jet) [16] |
| CL(\%) | 0.8 ± 0.02 | 0.92 ± 0.02 | 0.64 ± 0.02 ± 0.04 |
| \( r_{\text{out}}/r_L \) | 0.71 ± 0.02 | 0.82 ± 0.02 | 0.73 ± 0.01 ± 0.05 |
| \( r_{\text{side}}/r_L \) | 0.80 ± 0.02 | 1.06 ± 0.02 | 0.58 ± 0.01 ± 0.02 |
| CL(\%) | 3.1 | 0.016 | |
Figure 3. The emission function $S(t, z)$ as a function of time $t$ and longitudinal coordinate $z$ for a) MC for $Z^0$ [20], b) NA22: [21], c) NA44 [22].

Figure 4. The BE correlation function $R_2$ for hadronic $Z$ decay as a function of $Q_T = (Q_{side}^2 + Q_{out}^2)^{1/2}$ and $Q_L$ after the indicated cut in the other variable, compared to fits by a Gaussian (dashed), exponential (dotted) and Edgeworth expansion (full). [17]
Figure 5. Transverse mass $m_T$ dependence of the three-dimensional correlation function for hadronic Z decay compared to JETSET (full line). [16]

Figure 6. Genuine three-particle correlation in hadronic Z decay, compared to JETSET with and without LUBOEL. [27]
Figure 7. Dependence of $\lambda$ and $r$ on the charged-particle multiplicity $n$ for $e^+e^-$ collisions at the Z mass. [30]

Figure 8. LUBOEI output radius parameter $R_{\text{output}}$ value as a function of the input parameter $R_{\text{input}}$. [33]

(since it introduces an artificial length scale [32, 33]), see Fig. 8, is spherically symmetric, does not treat higher-order correlations properly, etc. The worse news is that it is used by everybody to correct for detector effects and that there is no perfectly tested alternative, at the moment.

2. **Global reweighting.** Another, theoretically better justified approach is to attach to each pre-generated event a BE weight depending on its momentum configuration, but leaving this momentum configuration untouched. Based on the use of Wigner functions [34] rather than amplitudes, a weight factor can be derived of the form [35]

$$W(p_1, \ldots, p_n) = \sum_{\{P_n\}} \prod_{i=1}^{n} K_2(Q_{iP_n(i)})$$

(5)

where $n$ is the number of identical particles, $K_2(= R_2 - 1)$ is the two-particle correlator and $P_n(i)$ is the particle which occupies the position $i$ in the permutation $P_n$ of the $n$ particles. Applications of the global weighting [36–40] are essentially all variations on this theme, with varying model assumptions on the exact form of $K_2$. In general, $K_2(Q)$ is still assumed to be spherical in $Q$, even though a generalisation would be simple to implement. Higher-order correlations are, in principle, included, but either assume [38] a quantum optical model, already shown to be wrong, [26,41] or factorization in terms of Eq. (5) not allowing for phases between the terms.

More seriously, as in [31] the weight is imposed a posteriori on a MC event pre-fabricated according to a given model, so not as a part of this model, itself.

Problems arise from the fact that the number of permutations is $n!$ so that simplifications have to be introduced. [40] Wild fluctuations of event weights can occur, so that cuts on event weight are necessary. The weight may even change the parton distributions, while BE correlations only work on the pion level. Retuning is of course necessary, but this can, in practice be achieved by just retuning the multiplicity distribution. [40]
3. Symmetrizing: Bose-Einstein correlations have been introduced into string models, directly. [42,43] In these models, an ordering in space-time exists for the hadron momenta within a string. Bosons close in phase space are nearby in space-time and the length scale measured by Bose-Einstein correlations is not the full length of the string, but the distance in boson-production points for which the momentum distributions still overlap.

The (non-normalized) probability \( d\Gamma_n \) to produce an \( n \)-particle state \( \{p_j\}, j = 1, \ldots n \) of distinguishable particles is

\[
d\Gamma_n = [\prod_{j=1}^{n} N dp_j \delta(p_j^2 - m_j^2)] \delta(\Sigma p_j - P) \exp(-bA_n) ,
\]

where the exponential factor can be interpreted as the square of a matrix element \( M_n = \exp(i\xi A_n) \), \( \text{Re}(\xi) = \kappa \), \( \text{Im}(\xi) = b/2 \), and the remaining terms describe phase space, with \( P \) being the total energy-momentum of the state. \( N \) is related to the mean multiplicity and \( b \) is a decay constant related to the correlation length in rapidity. \( A_n \) corresponds to the total space-time area covered by the color field, or to an equivalent area in energy-momentum space divided by the square of the string tension \( \kappa = 1 \text{ GeV/fm} \). [43]

The production of two identical bosons (1,2) is governed by the symmetric matrix element

\[
M = \frac{1}{\sqrt{2}} (M_{12} + M_{21}) = \frac{1}{\sqrt{2}} [\exp(i\xi A_{12}) + \exp(i\xi A_{21})] .
\]

There is an area difference and, consequently, a phase difference between \( M_{12} \) and \( M_{21} \) of \( \Delta A = |A_{12} - A_{21}| \), where the indices 1, 2 particles 1, 2, respectively (see Fig. 9).

Using this matrix element, one obtains

\[
R_{BE} \approx 1 + \langle \cos(\kappa \Delta A)/ \cosh(b\Delta A/2) \rangle ,
\]

where the average runs over all intermediate systems I. In the limit \( Q^2 = 0 \) follows, \( \Delta A = 0 \) and \( R_{BE} = 2 \), in agreement with the results from the conventional interpretation for completely incoherent sources. However, for \( Q^2 \neq 0 \) follows an additional dependence on the momentum \( p_1 \) of the system I produced between the two bosons.

The model can account well for most features of the \( e^+e^- \) data, including the non-spherical shape of the BE effect. More recently, the symmetrization has been generalized to more than 2 identical particles. [44] This approach deserves strong support. A more detailed account will be given in the next talk. [20]

4 Conclusions

With respect to color reconnection, my view is that VNI is out, that no effect has been observed in WW decay with the variables used so far, but that more discriminative methods, as those applied in correlation and fluctuation analysis, have to be used.

With respect to BE correlations, I conclude, they may form a problem, but also can be used to study the very space-time development of the WW overlap. Since this first needs a detailed

Figure 9. Space-time diagram for two ways to produce two identical bosons in the color-string picture [42].
study of the space-time development of a single high-energy $q_1\bar{q}_2$ system, I suggest (in parallel to continued direct WW analysis) a four-step program for an analysis of the final data to come:

1. Look at the $Z$ in much more detail. In fact, a lot more information is available or becoming available than used by most of the model builders. E.g., the elongated, non-Gaussian shape of the correlation function excludes the present version of all models, except those of [20,42–44]. The shape of the emission function for a single $q_1\bar{q}_2$ system in space-time determines the actual WW overlap. This shape is known for hh and heavy-ion collisions and should be urgently measured at the Z. Higher-order correlations, a density dependence and a transverse-mass dependence are observed and can be expected to discriminate between models.

2. Tune the models passing these tests on the Z, with and without b-quark contribution.

3. Check them on a single W.

4. Only then apply them to WW decay.

One important last point: color reconnection and Bose-Einstein effects can (partially) cancel, as e.g. in multiplicity. So, in fully hadronic WW decay, their effects have definitely to be studied simultaneously, in the data, as well as in the models!

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