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 $q_1\bar{q}_2$ 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 $q_1\bar{q}_2$ 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 and the space-time development of a $q\bar{q}$ system at high energy.

[a] see under http://www.hef.kun.nl/publ/publ-hens.html (HEN-420) for a more complete version, including figures

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 ($E_g \gtrsim \Gamma_W$) gluons. [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 ~0.5 fm.

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).

c) SKII' [3]: as SKII', but reconnection at first crossing reducing the total string length.

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.

These models share 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 is reduced. Also these models exist in a number of versions.

3. *Cluster models*: Quarks and gluons originating from the parton showers combine into clusters. These are less extended and less massive than strings are.

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.

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 (see [9] for a study on the Z).

2.2 The data

The recent data are beautifully summarized by the previous speaker, [10] so that I can restrict myself to a few comments. Two conclusions from a recent OPAL study [11] are:

1. The VNI based model [8] is way off, it does not fit the data at all, but the simulations are also in 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 does not conserve energy. [11] *It is 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_{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.*

In a study of a recent working group, [12] the model predictions for the multiplicity shift $\Delta n_{ch} = n_{ch}^{WW} - 2n_{ch}^{W}$ are given for all momenta, 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 all P and all y is $\Delta n_{ch} = 0.18 \pm 0.39$. [10] 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 <u>*reduced*</u> *by reducing the string length, it is quite likely to be* <u>*increased*</u> *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* $\Delta F_2 = F_2^{\rm WW} - 2F_2^{\rm W} - 2\langle n^{\rm W}\rangle^2$ *or, better, to look at the shift* $\Delta\rho(1,2)$ *in the two-particle density as a function of e.g.* $Q = (-(p_1 - p_2)^2)^{1/2}$*, itself.* [14]

3 Bose-Einstein correlations

The previous speaker [10] has given a summary on the (contradictory) results on inter-W BE effects. Obviously, before embarking on a study of inter-W BE effects, 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 that BE correlations indeed exist in its decay. So, they can, in principle, give problems in WW overlap. However, these very BE correlations can be used to measure the space-time development of hadronic Z-decay, and, ultimately in WW overlap. It is this, where 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] in the longitudinal, out and side components of the two-particle four-momentum difference Q and the corresponding size parameters $r_{\rm L}, r_{\rm out}, r_{\rm side}$, DELPHI [16] and L3 [17] find a pion-source elongation along the thrust axis in the longitudinal cms. [19] This is in contradiction with the assumption of a spherically symmetric correlation function in most of the models.

2. *Position-momentum correlation*: The correlation length of $0.7 < r_{\rm L} < 0.8$ fm [16, 17] (often 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 $r_{\rm L}$ (see Fig. 1 of [20])! So far, this function has been measured only in hadron-hadron [21] and heavy-ion collisions, [22] but its measurement in Z decay will tell us its average shape in space-time, and, therefore, how the overlap of WW has to be visualized!

3. *Non-Gaussian correlation function*: Strong deviation from a Gaussian behavior is known from hadron-hadron collisions, [23] but also exists at the Z. [15] Generalizing the Gaussian to an Edgeworth expansion [24] shows [17] that the correlation is indeed stronger than Gaussian at small Q. While maintaining the elongation, the CL value of the fit increases by a factor 10.

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

5. *Genuine higher-order correlations* exist in hadron-hadron collisions [23, 26] and also in Z decay. [27, 28] 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 a decrease of the correlation-strength parameter λ is well known from heavy-ion and higher-energy ISR and collider results (e.g. [29] and refs. therein). At least the decrease of λ can be understood from the overlap of an increasing number of independent mechanisms (e.g. strings or clusters). OPAL [30] finds a similar dependence in Z decay, where it can 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 (since it introduces an artificial length scale [32, 33]), 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*: A 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 has been derived of the form [35] $W(p_1,\dots p_n) = \sum_{\{P_n\}} \prod_{i=1}^{n} K_2(Q_{iP_n(i)})$, 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. Higher-order correlations are included, but either assume [38] a quantum optical model, already shown to be wrong, [26, 41] or factorization not allowing for phases between the terms in the product above. As in [31], the weight is imposed a posteriori, so is not part of the MC model, itself. Retuning is necessary, but this can, in practice, be achieved by just retuning the multiplicity distribution. [40] 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.

3. *Symmetrizing:* An ordering in space-time exists for the hadron momenta within a string. [42, 43] 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 $\{p_j\}$, $j = 1,\dots n$ 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 $M_n = \exp(i\xi A_n)$ with $\mathrm{Re}(\xi) = \kappa, \mathrm{Im}(\xi) = b/2$, 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 $\kappa = 1$ GeV/fm .

The production of two identical bosons (1,2) is governed by the symmetric matrix element $\sqrt{2}M = M_{12} + M_{21} = \exp(i\xi A_{12}) + \exp(i\xi A_{21})$. There is an area difference and, consequently, a phase difference between M_{12} and M_{21} of $\Delta A = |A_{12} - A_{21}|$ (see Fig. 2 of [20]). Using this matrix element, one obtains $R_{\mathrm{BE}} \approx 1 + \langle\cos(\kappa\Delta A)/\cosh(b\Delta A/2)\rangle$, 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_I 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 is 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 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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