Bose-Einstein correlations in WW events at LEP

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The current status of the LEP results on Bose-Einstein correlations is discussed. Emphasis is given to the measurement of Bose-Einstein correlations between decay products from different W's, in an energy range between 172 and 209 GeV, dependent on the experiment. For the first time all four LEP experiments conclude that no evidence for correlations between pions from different W's is seen at the current level of precision.

1 Introduction

Correlations between pairs/multiplets of identical bosons (in the simplified experimental practice, all like-sign particles are considered instead) are a well known phenomenon, yet the understanding of the effect is far from complete. Let us start with the original observation of the effect by Goldhaber and collaborators [1]. In order to give an interpretation to their observations the authors started from the assumption that contributions from different bosons to the measured intensity add incoherently. A strict analogy with the Hanbury-Brown-Twiss effect [2] in astronomy was found. In both cases the measured intensity interference reflects the geometry of the emitter. However, using this scenario too strictly one soon runs into interpretational problems. The shape of the correlation functions measured since Goldhaber's observation until the LEP measurements does not reflect the size of the freeze-out volume at the moment of hadronisation which extends up to several fermi. Most observations, except in heavy ion collisions, indicate source sizes of the order of one fermi.

An alternative model was proposed by Andersson and Ringnér [3], in which the correlations appear as a coherent effect related to the symmetrisation of the quantum-mechanical amplitude corresponding to the full process of particle production in the fragmentation of the Lund string. The strong point here is that the introduction of the Bose-Einstein effect becomes less arbitrary than before. It essentially depends on two fundamental parameters of the Lund model, the string tension κ and the hadronisation cutoff b parameter. In this case one can obtain source sizes compatible with experimental observations. This model has however one fundamental restriction: only bosons from the same string can be subjected to the Bose-Einstein effect, provided that there is no Colour Reconnection at parton level.

For a simple hadronic system like $q\bar{q}$ from a Z^0 decay, it may be impossible to decide between the two possibilities, since the incoherent approach leaves a freedom of the choice of the input particle density, which can be adjusted to reproduce the observed data.

The study of correlations between two close hadronic systems, such as hadronically decaying pairs of WW/ZZ bosons, can eventually help to distinguish between the two possibilities. In the incoherent scenario, the difference between correlations within a single hadronic system, and correlations between the two systems, should depend only on the overlap of the two systems (sources). In the coherent scenario, the correlations between the two systems may not exist at all, even for overlapping sources (as long as there is no interaction -colour flow- between these).

The measurement of inter-W correlations is also important for the estimate of the systematic bias in the measurement of the W mass via the direct reconstruction of measured decay products. A better understanding of the physical origin of the observed correlations is however necessary to ensure a reliable prediction for the uncertainty on the W mass measurement.

2 Analysis methods

It is common practice to investigate BEC between particles coming from different W's by means of a two-particle correlation function in terms of the Lorenz-invariant four-momentum transfer $Q = \sqrt{-(p_1 - p_2)^2}$:

$$R(Q) = \frac{\rho(Q)}{\rho_0(Q)}, \tag{1}$$

where $\rho_0(Q)$ represents the two-particle density without the Bose-Einstein effect. This density is non-existent in nature and is known as the so-called normalization or reference sample problem. We will see that many experiments address this problem in different ways, each with their own degree of model and detector dependence. A widely used implementation of the Bose-Einstein correlation effect in Monte Carlo generators is the LUBOEI [4] code, included in JETSET [5]. Experiments use different versions of this code and tune the Monte Carlo samples to their Z^0 data.

2.1 OPAL analysis

The OPAL collaboration has published an analysis [6] for a total collected statistics of 250 pb^{-1}. In this analysis the two-particle correlation function is constructed using unlike-sign pairs as a reference sample and making a double ratio with the correlation function obtained for a Monte-Carlo sample without Bose-Einstein correlations at all:

$$C(Q) = \frac{N_{\pm\pm}^{data}(Q)}{N_{+-}^{data}(Q)} / \frac{N_{\pm\pm}^{MC}(Q)}{N_{+-}^{MC}(Q)}. \tag{2}$$

This is done for three samples: fully hadronic WW decays, semi-leptonic WW decays and $q\bar{q}$ events selected as fully-hadronic WW events. One can assume that each of these 3 correlation functions can be written as the sum of 3 independent and more interesting correlation functions. For example one can write the correlation function for the fully hadronic sample as

$$C^{had}(Q) = P_{had}^{s}(Q)C^{s}(Q) + P_{had}^{Z^*}(Q)C_{bg}^{Z^*}(Q) + (1 - P_{had}^{s}(Q) - P_{had}^{Z^*}(Q))C^{d}(Q), \tag{3}$$

where $C^s(Q)$, $C^{Z^*}_{bg}(Q)$, $C^d(Q)$ represent the correlation functions for particle pairs originating from the same W, the Z^0 background and for pairs originating from different W's, each with their own probabilities $P(Q)$, obtained from MC samples without Bose-Einstein Correlations. In a next step OPAL makes a simultaneous fit to the three measured correlation function using the expression:

$$C^{s,d,Z}(Q) = N(1 + f_\pi(Q)\lambda^{s,d,Z}e^{-R^2Q^2}), \tag{4}$$

where $f_\pi(Q)$ is the probability that a given particle pair is indeed a pair of pions, obtained from Monte Carlo. Taking into account the distance between the W decay vertices one can impose a constraint on the radii:

$$(R^d)^2 = (R^s)^2 + (correction)^2. \tag{5}$$

This gives a fit result of

$$\lambda^s = 0.69 \pm 0.12(stat) \pm 0.06(syst),$$
$$\lambda^d = 0.05 \pm 0.67(stat) \pm 0.35(syst),$$

leading to the conclusion that with this method and at the current level of precision it is impossible to establish whether BEC between different W's exists or not.

2.2 ALEPH analysis

The ALEPH collaboration has published results [7] for the energy range between 172 and 189 GeV. An update including energies up to 202 GeV was submitted to ICHEP2000 [8]. Similar to OPAL, ALEPH also uses unlike-sign pairs as a reference sample and corrects for resonance decays and detector effects by making a double ratio with a MC sample without BEC at all. Since the $q\bar{q}$ background might fake a possible inter-W BEC signal it was decided to add the background fraction to the MC reference without BEC included. In this way the two-particle correlation function becomes

$$R^*(Q) = \frac{N^{data}_{\pm\pm}(Q)}{N^{data}_{+-}(Q)} / \frac{N^{MC(WW+q\bar{q})}_{\pm\pm}(Q)}{N^{MC(WW+q\bar{q})}_{+-}(Q)} \tag{6}$$

The distribution of $R^*(Q)$ is compared between data and two Bose-Einstein models based on the LUBOEI BE3 algorithm, tuned on Z^0 data, as can be seen in Fig. 1. Fits to this distribution for data and models are made using expression

$$R^*(Q) = \kappa(1 + \epsilon Q)(1 + \lambda e^{-\sigma^2 Q^2}). \tag{7}$$

The results of the fits are compared by integrating over the correlation signal

$$I = \int_0^\infty \lambda e^{-\sigma^2 Q^2} dQ = \frac{\sqrt{\pi}}{2}\frac{\lambda}{\sigma}. \tag{8}$$

For this measurement ALEPH finds that the value of I for the data is compatible with the value of I for the BE3 model in which only intra-W BEC are present. The BE3 model with intra+inter BEC is disfavored at the level of 2.2 σ.

In a second method mixed semi-leptonic events are used as reference sample. Again a double ratio with a MC sample without BEC including the $q\bar{q}$ background is used, and the two-particle correlation function becomes:

$$R^m(Q) = \frac{N^{4qdata}_{\pm\pm}(Q)}{N^{mixed}_{\pm\pm}(Q)} / \frac{N^{MC(4q+q\bar{q})}_{\pm\pm}(Q)}{N^{MC(mixed)}_{\pm\pm}(Q)}. \tag{9}$$

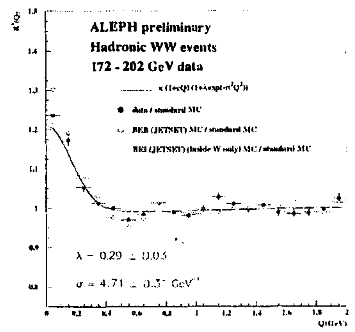

Figure 1: The $R^*(Q)$ distribution for data compared with BE3 model predictions. Only statistical errors are shown. The solid curve shows the fit result to the data.

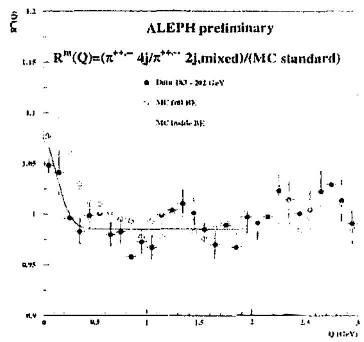

Figure 2: The $R^{m}(Q)$ distribution for data compared with model predictions. The solid curve is the fit result to the data.

This distribution (see Fig. 2) is again fitted with a gaussian parametrisation and integrals are compared. In this case the inter+intra BEC scenario is disfavored at the level of 3.1 σ (stat only).

2.3 L3 analysis

The L3 analysis relies on a rigorous mathematical treatment [11] and generalizations thereof [12] and is published [9] for the collected data at 189 GeV. A new update has been given for this conference, including the 192-202 GeV data. In their formalism one can write the two-particle densities for independently decaying W's as

$$\rho^{WW}(1,2) = 2\rho^{W}(1,2) + 2\rho^{WW}_{mix}, \tag{10}$$

where the second term on the right-hand side of Eq. 10 is obtained by mixing 2 semi-leptonic events. In the absence of inter-W BEC the ratio of the left-hand side and right-hand side of Eq. 10, which is called D, should be compatible with one. After subtracting 18.6% $q\bar{q}$ background from the fully hadronic term $\rho^{WW}(1,2)$, using the LUBOEI BE0 model, L3 makes a double ratio by dividing the D distribution for the data by the same distribution obtained with a MC sample without any BEC included. This variable is called D' and is fitted with a gaussian expression. Both distributions are shown in Fig. 3. The fitted value for the correlation strength Λ is compatible with zero:

$$\Lambda = 0.013 \pm 0.018(stat) \pm 0.015(syst).$$

Comparison with the inter+intra BEC BE32 model tuned at the Z^0 data gives a deviation from the data of 4.7 σ.

2.4 DELPHI analysis

The DELPHI analysis has been updated [10] for a total collected statistics of 531 pb^{-1} including energies from 189-209 GeV. DELPHI used the same formalism as L3 and also studies the

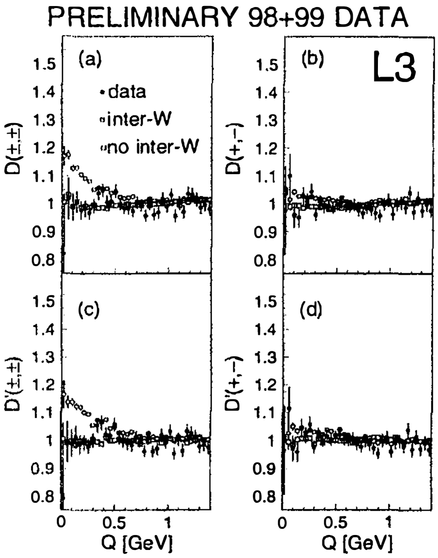

Figure 3: The D and D' distribution for data compared with BE32 model predictions. Only statistical errors are shown. Bin-to-bin correlations are not considered

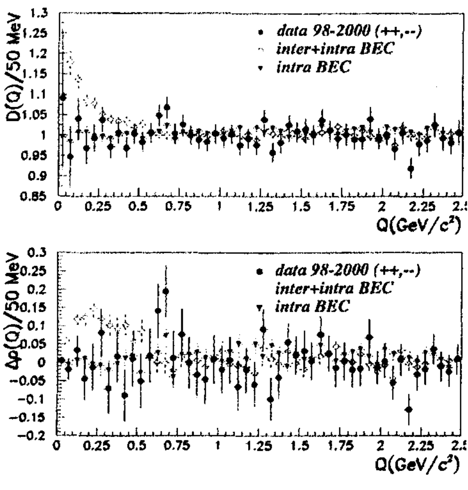

Figure 4: The D and $\Delta\rho$ distribution for the DELPHI data compared with BE32 model predictions. Only statistical errors are shown. Bin-to-bin correlations are not considered.

difference between the right-hand side and left-hand side of Eq. 10, which is called $\Delta\rho(Q)$. This distribution, together with the D distribution, is shown in Fig. 4. The $q\bar{q}$ background contamination in the data amounts to 15% and is subtracted using the BE32 model tuned on Z^0 data. Since this background subtraction is a delicate point, DELPHI tried to investigate how well the BE32 model describes the $q\bar{q}$ events which are selected as WW events. This was done using 4 jet Z^0 events and high energy $q\bar{q}$ events with an anti-WW tag. The largest disagreement between the model and data did not exceed the 10% level. This study is still ongoing. In order to stay as model independent as possible DELPHI does not construct a D' distribution and makes a fit directly to the D variable with the following expression:

$$D(Q) = N(1 + \epsilon Q)(1 + \Lambda e^{-\sigma Q}) \tag{11}$$

After fixing σ to 1.01 fm, as was fitted for the inter+intra BEC model prediction, DELPHI finds a value of Λ^{dat} compatible with zero.

$$\Lambda^{dat} = -0.038 \pm 0.057(stat) \pm 0.06(syst)$$

The systematic error is still under study and contains for the moment only the contributions from the background subtraction (0.05) and from the mixing method (0.03). However, it is assumed that these two contributions are the dominant ones. When comparing the fitted value of Λ of the data with the inter+intra BEC BE32 model prediction, DELPHI disfavors the model at the level of 3.2 σ.

3 Summary

It is important to note that for the first time the 4 LEP experiments obtain consistent conclusions. The LUBOEI models tuned on the Z^0 data from each experiment, and which include

BEC between different W's, are excluded by all experiments with varying significance. The LEP experiments are on the way to converge on measurement techniques as proposed in [11,12] ,which is very promising. It is my question to the W-mass measurement community whether they will still use these models to estimate their systematic errors. What is clear for me is that WW events will not tell us much more about the ongoing discussion on incoherence and coherence, and the easy but rather restrictive variable Q might not be the ideal one to be used. Certainly a study of multi-string events from LEP1 would be very interesting to address this problem [12].

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