Bose-Einstein Correlations Between Particles from Different Ws in $e^+e^- \to W^+W^-$ Events

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Abstract

Preliminary results are presented for the correlation functions $R(Q)$ for like-sign particle pairs for fully hadronic WW and for mixed decay WW channels using the data collected by the DELPHI detector at LEP at the center-of-mass energies of 183 and 189 GeV. The parameters λ and r characterizing the Bose-Einstein effect, measured in fully hadronic events are in agreement with parameter values in semileptonic events.

The comparison of the distributions for real fully hadronic events and for fully hadronic events where correlations between decay products from different Ws are absent (constructed by an event mixing technique) shows an excess of like-sign particle pairs at low four-momenta difference in the data for fully hadronic events. It can be interpreted as evidence for Bose-Einstein correlations between identical particles from different Ws.

1 Introduction

The possible presence of interference due to colour reconnection and Bose-Einstein correlations (BEC) (see for example [1, 2] and references therein) in hadronic decays of WW pairs has been discussed on a theoretical basis, in the framework of the measurement of the W mass: this interference [1] can induce a systematic uncertainty on the W mass measurement in the 4-jet mode comparable with the expected accuracy of the measurement. The subject became very popular due to the prediction [3] that BEC could shift up to 100 MeV the measured W mass.

The effects of Bose-Einstein Correlations between identical bosons have been studied extensively in different types of reactions and for different bosons species. Although many studies exist, one still misses a complete understanding of the influence of this quantum mechanical effect on a multi-particle system generated in a high energy collision. The description itself for a given multi-particle system is complicated by the fact that one would need to know how to symmetrize the amplitude for the system.

The observable most often used for the investigation of the BEC in multi-particle final states is the two-particle correlation function. Other observables are affected and can also be exploited. The WW events allow a comparison of the characteristics of the W hadronic decays when both Ws decay in fully hadronic modes (in the following we shall often refer to this as to the $(4q)$ mode) with the case in which the other W decays semileptonically ($(2q)$ mode for brevity). In the absence of interference between the products of the hadronic decay of the Ws, the single particle distributions in $(4q)$ mode should be equal to twice the $(2q)$ mode after removing the final state lepton or its decay products.

2 Investigation of Bose-Einstein Effects

BEC manifest themselves as an enhancement in the production of pairs of identical bosons close in phase space.

To study the enhanced probability for emission of two identical bosons, the correlation function R is used. For pairs of particles, it is defined as

$$R(p_1,p_2) = \frac{P(p_1,p_2)}{P_0(p_1,p_2)}\,, \tag{1}$$

where $P(p_1,p_2)$ is the two-particle probability density, subject to Bose-Einstein symmetrization, p_i is the four-momentum of particle i, and $P_0(p_1,p_2)$ is a reference two-particle distribution which, ideally, resembles $P(p_1,p_2)$ in all respects, apart from the lack of Bose-Einstein symmetrization.

If $f(x)$ is the space-time distribution of the source, $R(p_1,p_2)$ takes the form

$$R(p_1,p_2) = 1 + |G[f(x)]|^2\,,$$

where $G[f(x)] = \int f(x)e^{-\imath(p_1-p_2)\cdot x}\,dx$ is the Fourier transform of $f(x)$. Thus, by studying the correlations between the momenta of pion pairs, one can determine the distribution of the points of origin of the pions. Experimentally, the effect is often described in terms of the variable Q, defined by $Q^2 = (p_1 - p_2)^2 = M^2(\pi\pi) - 4m_\pi^2$, where M is the invariant mass of the two pions. The correlation function can then be written as

$$R(Q) = \frac{P(Q)}{P_0(Q)}, \tag{2}$$

which is frequently parametrized by the function

$$R(Q) = 1 + \lambda e^{-r^2Q^2}\,. \tag{3}$$

In the above equation, in the hypothesis of a spherically symmetric pion source, the parameter r gives the RMS radius of the source and λ is the strength of the correlation between the pions.

3 Modelling BEC in WW decays.

Bose-Einstein correlations can be included in PYTHIA/JETSET by using the LUBOEI code, where they are introduced as a final state interaction [4]. After the generation of the pion momenta, the values generated for all identical pions are modified by an algorithm that reduces their momentum vector differences.

This code has been shown [5] to reproduce well the two particle correlation functions measured in Z decays if Bose-Einstein correlations are switched on with a gaussian parametrization for pions that are produced either promptly or as decay products of short-lived resonances and if the parameter values $\lambda = 1$ and $r = 0.5$ fm are used. The measured values of the parameters, using a mixed track reference sample, for such 'direct' pions in Z decays were $\lambda = 1.06 \pm 0.17$, $r = 0.49 \pm 0.05$ fm [5]. The value λ=1 for direct pions corresponds to $\lambda \sim 0.35$ for all pions or $\lambda \sim 0.25$ for all particles [5, 8].

It is also a useful model to test detector effects, and to test the reliability of the experimental techniques.

In the present analysis the LUBOEI algorithm with the same values of λ and r was applied to generate WW events to calculate predictions for the case where Bose-Einstein correlations are present. Various modifications of the LUBOEI code, i.e. the original version, version BE_3 and version BE_{32} were used in the present analyses. The versions BE_3 and BE_{32} differ in the rescaling procedures of momentum and energy after modification of the particle momenta. For more details on the LUBOEI code and the modifications, see [2]. For each version, two scenarios were considered: a) where Bose-Einstein correlations were included for particles from the same and from different Ws (herafter called full BE) and b) where Bose-Einstein correlations were included only for particles from the same Ws (hereafter called inside BE) [6]. In the version a) Bose-Einstein correlations between particles from different Ws are included in the same way as Bose-Einstein correlations between particles from the same Ws.

4 Event Selection

We selected 1427 WW fully hadronic events. The purity and efficiency of the selection, estimated using simulated events, were about 87% and 73%, respectively. The 686 events were selected for mixed decay WW channel. The purity and efficiency were about 96% and 49%, respectively.

5 Results and Discussion

5.1 Correlation Functions for Like-Sign Particles for Fully Hadronic and for Mixed Decay WW channels

To compute the correlation function $R(Q)$ (Eq. 2), the two-particle probability density $P(Q)$ was calculated and $P_0(Q)$, the reference two-particle distribution. The reference distribution $P_0(Q)$ was calculated using events generated by PYTHIA (without Bose-Einstein correlations included) after full simulation of the DELPHI detector and after the same selection criteria were applied as for real data. The $R(Q)$ distributions were normalised to unity in the region $Q > 0.8$ GeV$/c^2$ where no Bose-Einstein effects are expected. It has to be remarked that the use of a Monte-Carlo reference sample for the WW fully hadronic channel implies the assumption that color reconnection effects [7] are negligible.

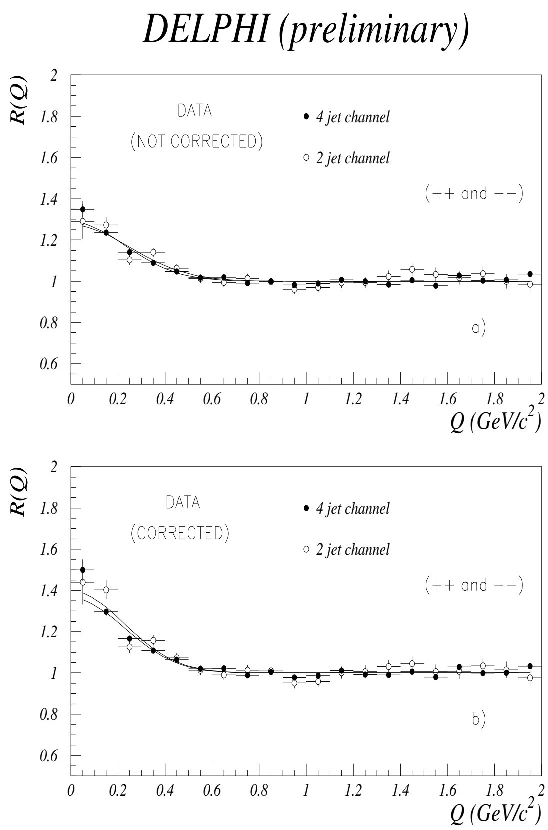

Figure 1: (a) The uncorrected correlation functions $R(Q)$ for like-sign pairs for the mixed decay channel (open circles) and for the fully hadronic decay channel (closed circles). (b) The same as in (a), but after corrections. The curves in the figures are the fit results using expression (4).

The $R(Q)$ distributions for like-sign combinations of mixed decay and fully hadronic WW channels is shown in Fig. 1a(uncorrected on detector effects) and 1b(corrected). A fit to the correlation functions $R(Q)$ using the expression

$$R(Q) = 1 + \lambda e^{-r^2 Q^2} \tag{4}$$

was performed, where the parameter r represents the source size and λ the strength of the correlation between the particles. The fit yielded the values:

$$\lambda_{2q} = 0.399 \pm 0.060(stat) \pm 0.026(syst) \tag{5}$$

$$r_{2q} = 0.622 \pm 0.061(stat) \pm 0.022(syst) \text{ fm}\,. \tag{6}$$

for the semileptonic channel and

$$\lambda_{4q} = 0.365 \pm 0.036(stat) \pm 0.047(syst) \tag{7}$$

$$r_{4q} = 0.622 \pm 0.042(stat) \pm 0.031(syst) \text{ fm}\,. \tag{8}$$

for the fully hadronic decay channel.

5.2 Measurement of BEC Between Particles from Different Ws Using an Event Mixing Technique

The first measurements of Bose-Einstein correlations in $e^+e^- \to W^+W^-$ events, performed by DELPHI [10] using a subtraction method, do not show any evidence of correlation between like-sign pions from different Ws at the level of statistics collected at 172 GeV center-of-mass energy. Similar results were obtained by ALEPH using the same method at 172 and 183 GeV center-of-mass energy data [11]. The above mentioned method appears to be less sensitive to BEC between different Ws than an event mixing method used in the present analysis. Moreover the subtraction method has a large sensitivity to the normalization.

To perform a direct measurement sensitive to BEC between particles from different Ws, an analysis was made using a reference sample which contains only BEC for particles coming from a single W boson, not for particle pairs from different Ws. Such reference sample was constructed by an event mixing technique using the selected real semileptonic events.

A reference sample of $(4q)$-like events was constructed by mixing two $(2q)$ events. From each selected semileptonic event, the hadronic part was boosted to the rest frame of the W candidate. An event was constructed from two single Ws by boosting the particles of such single W candidates in opposite directions using the velocities and directions of flight of the W candidates according to energy-momentum conservation using the values of fitted W mass of these single Ws. Note that no informations from real $(4q)$ events were used to constract $(4q)$-like events in order to avoid the introduction of the possible biases from interconnection effects which may exist in real $(4q)$ events. These mixed events have an average multiplicity which is exactly twice that of Ws from semileptonic events. The inclusive momentum spectra of the mixed events are fully consistent with the spectra of $(4q)$ events and with the spectra of $(2q)$ events multipled by two (not shown).

We define the ratio

$$g(Q) = \frac{P(Q)_{4q}}{P(Q)_{mix}}, \tag{9}$$

where $P(Q)_{4q}$ is the Q-distribution of real $(4q)$ events and $P(Q)_{mix}$ is the Q-distribution of $(4q)$-like events obtained by mixing two real $(2q)$ events. The function $g(Q)$ does not have the usual meaning of correlation function between particles from different Ws, because pairs from different Ws were not isolated. Note that a deviation of $g(Q)$ from unity would indicate a fractional excess or lack of the number of pairs in real $(4q)$ events.

To ensure that the event mixing did not introduce artificial distortions, the analyses were repeated with a full simulation sample without BEC. The double ratio

$$g'(Q) = \frac{g(Q)}{g^{MCnoBE}(Q)}, \tag{10}$$

should have any distortion removed.

The ratio $g(Q)$ obtained for the data is shown in Fig. 2a (closed circles) together with the prediction of DELSIM where no BEC were included (open circles). The double ratio $g'(Q)$ is shown in Fig. 2b. A BE-like excess in the number of pairs is seen in the low Q region. In order to quantify this, the $g'(Q)$ were fitted to the gaussian shape

$$g'(Q) = 1 + \Delta e^{-k^2Q^2}\,. \tag{11}$$

where Δ and k were free parameters. The Δ represents the fractional excess of number of pairs in fully hadronic $(4q)$ events at Q=0 . The fit by eq. (11) yielded

$$\Delta \quad = \quad 0.059 \pm 0.016(stat). \tag{12}$$

The bias due to detector effects and selection criteria was studied using events generated by PYTHIA and using the same generated events which were passed through the full detector simulation and were subject to the same selection criteria as the data.

The ratio of the functions $g'(Q)$ obtained at generator level and after full detector simulation and selection criteria, was used as a correction factor for the $g'(Q)$ of the data. The average value of the two correction factors (obtained for full and inside Ws BEC) was used and half the difference was considered

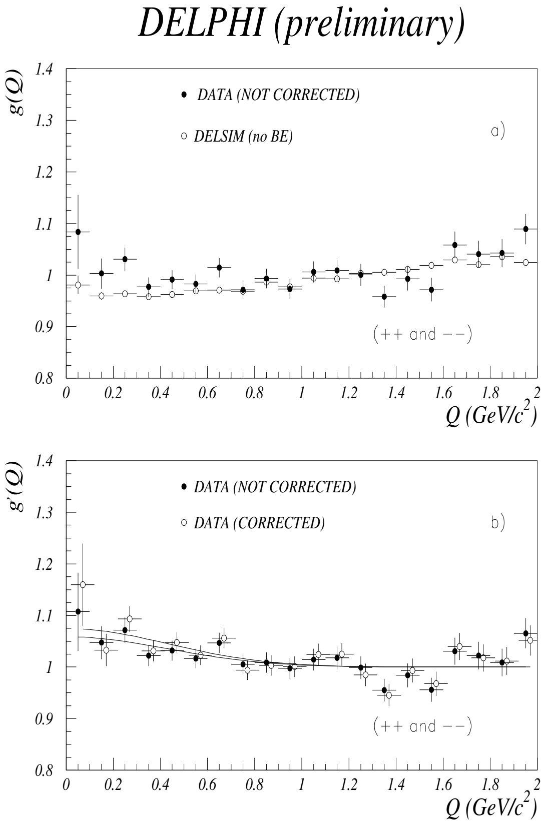

Figure 2: (a) The ratio $g(Q)$ for like-sign pairs for the WW data (closed circles) and for DELSIM without BEC (open circles). (b) the double ratio $g'(Q)$ for the data before and after corrections (closed and open circles, respectively).

as a systematic error. The multiplication factor for the statistical error on the value of Δ due to bin-to-bin correlations was found to be 1.25. Thus, the final value of the parameter Δ is

$$\Delta = 0.073 \pm 0.025(stat) \pm 0.018(syst). \tag{13}$$

The measured $g'(Q)$ distribution and model predictions are shown in Fig. 3. The data points are at uncorrected level, the corresponding distributions were also used for the model predictions. The model modifications vary in the range indicated by the shaded area (upper shaded area for full BEC and lower one for inside BEC). The predicted $g'(Q)$ for BEC inside Ws only are below the measured $g'(Q)$, while the model with full BEC is in good agreement with the data.

6 Summary

The correlation functions for like-sign and unlike-sign particles were measured for mixed and for fully hadronic WW channels using data collected with the DELPHI detector during the 1997 and 1998 run with integrated luminosity of 208.5 pb^{-1} at center-of-mass energies of 183 and 189 GeV. The values of Bose-Einstein correlation (BEC) strenght(λ) and radius(r) were

$$\lambda_{4q} = 0.365 \pm 0.036(stat) \pm 0.047(syst) \tag{14}$$

$$r_{4q} = 0.622 \pm 0.042(stat) \pm 0.031(syst)\ \mathrm{fm}\,. \tag{15}$$

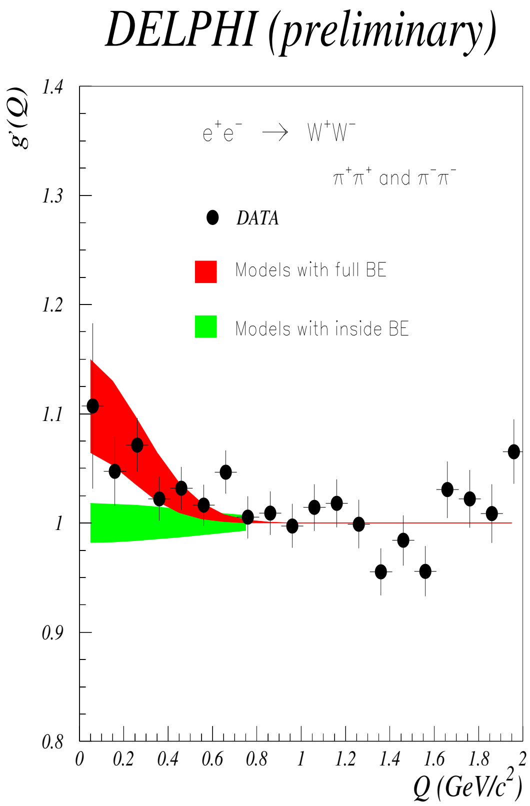

Figure 3: The uncorrected double ratio $g'(Q)$ for the data for like-sign pairs. The model predictions are shown by the shaded areas.

for the fully hadronic decay channel and

$$\lambda_{2q} = 0.399 \pm 0.060(stat) \pm 0.026(syst) \tag{16}$$

$$r_{2q} = 0.622 \pm 0.061(stat) \pm 0.022(syst) \text{ fm}\,. \tag{17}$$

for the mixed decay channel.

The λ and r values for the fully hadronic decay channel are consistent with those for the mixed decay channel indicating the existence of BEC between particles from different Ws.

A direct measurement of correlations between pions from different Ws was performed using an event mixing technique to construct a reference sample which contains only correlations for particles from a single W boson. An excess of like-sign particle pairs of

$$\Delta = 7.3 \pm 2.5(stat) \pm 1.8(syst) \quad \% \tag{18}$$

was found in the fully hadronic decay channel at low four-momenta difference. The predictions of the LUBOEI model with full BEC agree with the data.

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