

BOSE-EINSTEIN CORRELATIONS IN W-PAIR EVENTS AT LEP

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An overview of measurements of Bose-Einstein correlations in W-pair events at LEP is given. The results presented are based on data collected at centre-of-mass energies between 172 and 202 GeV. The review concentrates on the search for Bose-Einstein correlations between pions from different W's in $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$ events. No agreement is reached in the results of the four experiments.

1 Introduction

The existence of Bose-Einstein correlations (BEC) in reactions leading to hadronic final states is well known. BEC are observed as an enhancement of the production of multiple identical bosons close in momentum space, first reported for pairs of charged pions in $p\bar{p}$ collisions¹. They have also been studied for two or more identical bosons in hadronic Z decays at LEP², including π^\pm , K_s^0 and K^\pm .

This talk reviews recent studies of BEC^{3,4,5,6} for charged pion pairs produced in $e^+e^- \rightarrow W^+W^-$ events at LEP. ‘‘Intra-W’’ BEC (or BEI, BEC Inside a W) between pions from the same $W \rightarrow q\bar{q}$ decay are observed unambiguously. As expected, these closely resemble BEC in $Z \rightarrow q\bar{q}$ decays, when only udsc quark flavours are considered.

Since the average separation between the two W decays at LEP2 is $\lesssim 0.1$ fm, smaller than the hadronisation scale of ~ 1 fm, ‘‘inter-W’’ BEC (or BEB, BEC Between W's) could also be expected between pions from different W's in $WW \rightarrow q\bar{q}q\bar{q}$ (4q) events. The theoretical framework is, however, still unclear. In the absence of exact nonperturbative QCD calculations for the symmetrized production amplitude of multiple mesons from hadronic W decays, BEC are described only by phenomenological models. Many models exist, with contradictory predictions⁷ about BEB. This note will therefore concentrate on the experimental measurements of BEB in W-pair events at LEP.

The question whether BEB exist is par-

ticularly important as the cross-talk between the two W decays could bias the W mass (m_W) measurement in 4q events. Different models of BEC predict different values for the shift⁷. Using MC events with full detector simulation, the LEP experiments obtain⁸ m_W biases from 20 to 67 MeV, conservatively taken as systematic errors on the individual measurements. In the LEP combination, a common BEC systematic error of 25 MeV in the 4q channel is assumed⁹. The impact of this error is more than halved when combining 4q events to $WW \rightarrow \ell\nu q\bar{q}$ (2q) events. While presently the BEC error is not the limiting factor to the LEP measurement of m_W , a better understanding of BEC in W decays is important in view of the future reduction of the other, currently larger, systematics.

2 Overview of analysis methods

BEC in identical boson pairs are often studied by the two-particle correlation function

$$R(Q) = \frac{\rho(Q)}{\rho_0(Q)} \quad . \quad (1)$$

Here, ρ is the two-boson density in the presence of BEC, while the reference ρ_0 should ideally describe pair-production if there were no BEC. Since BEC are largest at small four-momentum difference $Q = \sqrt{-(p_1 - p_2)^2}$, in a simplified approach the effect can be studied in terms of this variable alone¹⁰.

In the studies reviewed in this note, Bose-Einstein (BE) enhancements of production rates are parametrised using functions like

$$R(Q) \sim (1 + \lambda e^{-r^2 Q^2}) \quad , \quad (2)$$

which describe source distributions of radius r and BE “strength” λ . Fit results for r and λ will not be compared here, since the various analyses differ in detector acceptance, choice of fit function and definition of R .

The choice of the reference ρ_0 and the definition of R are distinctive features of each BEC analysis. The simplest is to derive ρ_0 from MC events with no BEC (“standard MC”). Data can also be used: for instance, the density for unlike-sign pion pairs, ρ^{+-} , is often taken as a reference to study BEC in like-sign pairs, $\rho^{++,-}$. Since unlike-sign pion pairs are not free from correlations other than BEC, such as those due to resonance decays, the correlation function is frequently computed as a double ratio of the form

$$R^{\text{d.r.}}(Q) = \frac{(\rho^{++,-}/\rho^{+-})^{\text{data}}}{(\rho^{++,-}/\rho^{+-})^{\text{standard MC}}}, \quad (3)$$

where resonance correlations in the MC cancel those in data. Additional corrections may be introduced to describe final-state Coulomb interactions¹¹, different in like- and unlike-sign pairs and usually absent in the MC.

In the study of BEB, instead of comparing 4q data to a reference with no BEC at all, one can finally define¹² a function like

$$R^{\text{mix}}(Q) = \frac{(\rho^{++,-})^{4q}}{(\rho^{++,-})^{\text{“mixed” } 2q}}, \quad (4)$$

where a reference with BEI and no BEB is obtained by “mixing” hadronically decaying W ’s from pairs of different 2q data events. Different mixing procedures exist; in general, the two W ’s, chosen of opposite charges, are boosted to be approximately back-to-back in the lab frame, as in 4q events. A double-ratio version of Eq. (4) can also be used.

3 Experimental results at LEP2

The analyses presented use data collected by the four experiments at 172–202 GeV (Tab. 1). Signal efficiency and background contamination are 70–90% and 20% (mainly $q\bar{q}$) for 4q, 50–75% and 6% for 2q events. Up to ~ 7000 selected WW events per experiment are used, including both channels.

Exper.	\sqrt{s} [GeV]	\mathcal{L} [pb^{-1}]	Status
ALEPH ³	172–202	479	Prel.
DELPHI ⁴	183–202	437	Prel.
L3 ⁵	189	177	Publ.
OPAL ⁶	172–189	250	Prel.

Table 1. Data samples used in the analyses presented. The L3 analysis is submitted for publication, those from the other experiments are preliminary.

All analyses are performed on pairs of like-sign charged pions, with generally loose pion selection criteria. In each event, every pion enters several pairs, which introduces bin-to-bin correlations in some distributions. Where necessary, these are corrected for by all experiments, using various techniques.

The four experiments simulate BEC using different MC models, differently tuned. WW MC events with BEC are needed for model-dependent analyses or cross-checks of model-independent assumptions. BEC also exist in the $q\bar{q}$ background, although they may differ in the four experiments depending on the anti-b tagging criteria used in the selection. The simulation of BEC in $q\bar{q}$ events selected as 4q is especially important, as³ they look more similar to BEC for 4q events in BEI+BEB MC than in BEI-only MC.

In ALEPH³, a double ratio R^* of like- and unlike-sign pion pairs for data over standard MC is used, similar to that of Eq. (3). The analysis of BEB is based on the comparison of R^* for data to that expected from MC with BEI-only or BEI+BEB, simulated according to a specific model of BEC tuned on Z data. Background is added to the WW signal in computing R^* for the MC. Fits to the $R^*(Q)$ distributions are performed using a function similar to Eq. (2). The results are compared in terms of the integral of the BE signal, $I = \int_0^\infty \lambda e^{-r^2 Q^2} dQ = \frac{\sqrt{\pi} \lambda}{2r}$. The value for I in the BEI-only MC is compatible with that in data, while I in data and in the MC with BEI+BEB are inconsistent at the level of 2.2σ . This includes systematics, dominated by the tuning of BEC MC parameters using Z data. It is concluded that data

support the BEI model considered, while the BEB model is disfavoured. An alternative analysis, using a double ratio R^m of 4q and mixed 2q events in data over standard MC, yields qualitatively similar results (Fig. 1).

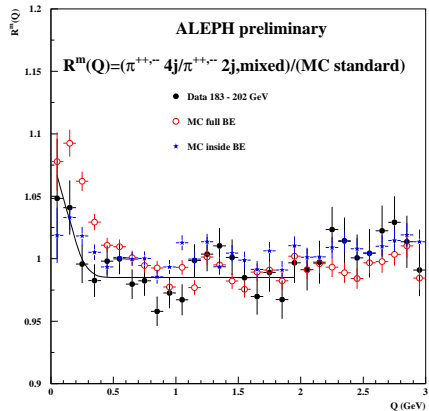


Figure 1. ALEPH³ distributions of R^m for data, BEI-only MC (“inside”) and BEI+BEB MC (“full”).

In the DELPHI analysis⁴, also presented in another talk¹³, correlation functions for like-sign pion pairs R_{4q} and R_{4q}^{mix} are built for both 4q events and mixed 2q events, as single ratios over standard MC (Fig. 2a). Unlike-sign pairs are also used for qualitative comparisons (Fig. 2b). Expected backgrounds are subtracted from data in computing R_{4q} and R_{4q}^{mix} . By construction, $R_{4q}(Q)$ and $R_{4q}^{\text{mix}}(Q)$ are thus expected to be equal (different) in the absence (presence) of BEB. Signal MC events with BEC (BEI-only, or BEI+BEB) are used to verify these hypotheses and for systematic studies. A simultaneous fit to $R_{4q}(Q)$ and $R_{4q}^{\text{mix}}(Q)$ determines a common BE source radius and two different BE strengths, which are expected to be equal in the absence of BEB. The fit to their difference $\Delta\lambda^{\text{mix}} = \lambda_{4q} - \lambda_{4q}^{\text{mix}}$ yields

$$\Delta\lambda^{\text{mix}} = 0.062 \pm 0.025 \pm 0.021 \quad . \quad (5)$$

It is concluded that data support BEB at the level of $\sim 2\sigma$. The largest systematic errors come from the check that $\Delta\lambda^{\text{mix}} = 0$ in BEI-only MC, and from bin-to-bin correlations.

In L3⁵, the correlation functions for like-sign charged pions are built taking mixed 2q

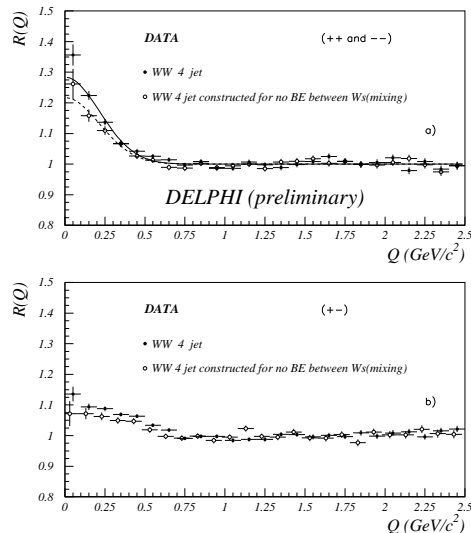


Figure 2. DELPHI⁴ distributions of R_{4q} (black circles) and R_{4q}^{mix} (hollow circles) for a) like-sign and b) unlike-sign pion pairs, as a function of Q .

events as a reference. A single ratio D is built as in Eq. (4). The main analysis uses a double ratio D' , where D for data is divided by that for BEI-only MC events. Backgrounds are subtracted from data in the calculation of D' . By construction, it is thus expected that $D'(Q) = 1$ in the absence of BEB. Signal MC with BEI-only is used to verify this hypothesis (Fig. 3a). Unlike-sign pairs are also used for qualitative comparison (Fig. 3b). The $D'(Q)$ distribution is fitted for the BEB strength Λ , expecting $\Lambda = 0$ in the absence of BEB. The fit yields

$$\Lambda = 0.001 \pm 0.026 \pm 0.015 \quad , \quad (6)$$

indicating that data are compatible with the absence of BEB. Systematics are dominated by the selection of charged tracks and the inclusion of the low-purity $\tau\nu q\bar{q}$ channel. The fit is repeated for MC events with a model of BEB, yielding $\Lambda = 0.127 \pm 0.007$, where only statistical errors are given. The BEB model considered is disfavoured by more than 4σ .

In OPAL⁶, $WW \rightarrow \ell\nu q\bar{q}$, $WW \rightarrow q\bar{q}q\bar{q}$ and non-radiative high-energy $(Z/\gamma)^* \rightarrow q\bar{q}$ decays are analysed. Correlation functions for these samples, built from double ratios as

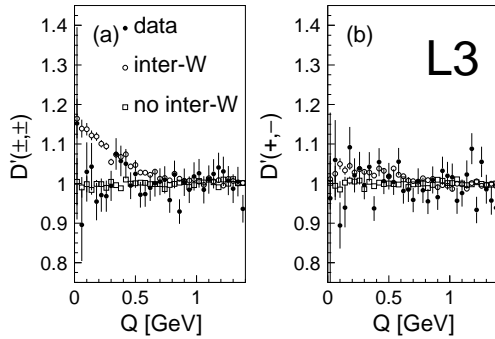


Figure 3. $L3^5$ distributions of D' for like-sign (a) and unlike-sign (b) pion pairs. Data are compared to BEI-only (“intra-W”) and BEI+BEB (“inter-W”) MC.

in Eq. (3) and adjusted for resonance multiplicities observed in data, are unfolded as sums of contributions from three categories: pion pairs coming from the same W, from different W’s, or from hadronic Z decays. BEC parameters for each category are determined in a simultaneous fit, correcting for the differences in BEC between $q\bar{q}$ events selected as $(Z/\gamma)^*$ and those selected as WW. The BEC strength for the second category, λ^{diff} , directly measures BEB and is expected to be zero in their absence. MC events with BEC are only used for qualitative comparison to the data (Fig. 4). Fits are performed with different assumptions about BEC source sizes in the three categories. The main fit yields

$$\lambda^{\text{diff}} = 0.05 \pm 0.67 \pm 0.35 \quad , \quad (7)$$

where systematics mainly come from tracking for low- Q like-sign pairs and the HERWIG simulation of resonances. While the result is compatible with the absence of BEB, OPAL conclude that, at the current precision, they are unable to determine whether BEB exist.

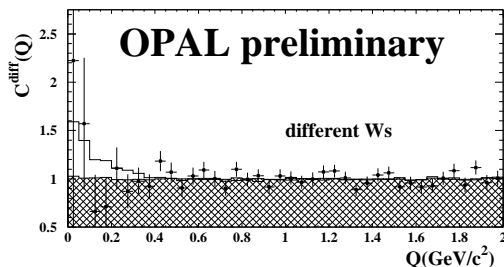


Figure 4. Unfolded correlation for pions from different W’s in OPAL⁶. Data (crosses) are compared to MC with BEI-only (hatched), or BEI+BEB (open).

4 Conclusions

Bose-Einstein correlations between like-sign charged pion pairs produced in W-pair events at LEP are studied by the four experiments using different techniques. The existence of BEC for pions coming from the same W is firmly established, while no agreement is reached in the results of the four experiments about the possible existence of BEC between pions coming from different W’s. The existence of inter-W BEC is supported by DELPHI at the 2σ level, whereas models of inter-W BEC are disfavoured by L3 and ALEPH at the 4σ and 2.2σ level, respectively. No conclusion is reached by OPAL at the present level of statistical accuracy.

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