Bose-Einstein correlations in WW pair production at LEP

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The search for the presence of Bose-Einstein correlations (BEC) between identical bosons coming from the decay of different W’s in the reaction $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}_2q_3q_4$ is recently of high interest. It is relevant for a precise determination of the W mass at LEP in the fully-hadronic decay channel and can provide insight in hadronisation mechanisms. A novel method, allowing data to be directly compared with itself by means of mixing tracks from different events, is applied by all LEP experiments. The latest results obtained by the L3 and DELPHI collaboration are presented.

1 Introduction

Correlations between final state particles in high energy collisions have been extensively studied since the Goldhaber et al. experiment. They can be due to phase space, energy-momentum conservation, resonance production, or are dynamical in nature. In the particular case of identical bosons, the correlations are enhanced by the Bose-Einstein effect. These Bose-Einstein Correlations (BEC) are a consequence of quantum statistics. The net result is that multiplets of identical bosons are produced with smaller energy-momentum differences than non-identical ones.

The interest of studying BEC in the reaction $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}_2q_3q_4$, and more in particular BEC between identical bosons coming from different W’s is twofold. Due to the short life-time of a W boson ($\tau_c \sim 0.1$ fm), compared to the distance needed to produce final state particles (0.5 - 1. fm), it is natural to expect a large space-time overlap between the decay products of the W’s. As a consequence, BEC could exist between identical bosons coming from different W’s, hence violating the assumption that the two W’s decay independently. Together with colour reconnection, the poor understanding of the inter-W BEC effect introduces a large systematic uncertainty in the measurement of the W mass by means of direct reconstruction.
in the fully-hadronic decay channel. The current statistical uncertainty of the combined LEP measurement in this channel amounts to 36 MeV, while the systematic uncertainty due to the inter-W BEC effect is of the same order. In addition, the observation of a possible inter-W BEC effect is of high interest to our understanding of hadronisation models, since, at present, all assume independent hadronisation of the W decay products.

After five successful years of LEP2 running, each of the four LEP experiments collected around 10000 WW events at centre-of-mass energies ranging from 189 to 209 GeV, nevertheless a measurement of inter-W BEC is mainly bound by statistics. The most promising technique, based on and is currently applied by all four LEP experiments. The L3 collaboration was the first to publish their results obtained by this method. DELPHI has nearly finalised their analysis while activities in ALEPH and OPAL are still ongoing. Therefore, in what follows, only the results obtained by L3 and DELPHI will be discussed.

2 Formalism

The method proposed in provides an elegant way to investigate the presence of inter-W BEC. It allows real data to be directly compared with itself, hereby eliminating fragmentation and detector uncertainties, and is based on the following reasoning.

In the case of two stochastically independent hadronically decaying W’s, the single and two-particle inclusive densities obey the following relations:

\[
\rho_{WW}(1) = \rho_{W^+}(1) + \rho_{W^-}(1),
\]

\[
\rho_{WW}(1,2) = 2\rho_{W}(1,2) + 2\rho_{W^+}(1)\rho_{W^-}(2),
\]

where \(\rho_{W}(1)\) denotes the inclusive single particle density of one W and \(\rho_{W}(1,2)\) the inclusive two-particle density of one W. The densities \(\rho_{WW}(1)\) and \(\rho_{WW}(1,2)\) then correspond to the single, resp. two-particle inclusive density of a fully hadronic WW event. The terms \(\rho_{WW}(1,2)\) and \(\rho_{W}(1,2)\) can be extracted from, respectively, fully-hadronic and semi-leptonic WW decays. The product of the single particle densities \(\rho_{W}(1)\rho_{W}(2)\) is, in practical applications, replaced by a two-particle density \(\rho_{mix}\), obtained by combining particles from two hadronic W decays taken from different semi-leptonic events.

Expressed in the variable \(Q = \sqrt{-(p_1 - p_2)^2}\), Eq. 2 can be re-written as

\[
\rho_{WW}(Q) = 2\rho_{W}(Q) + 2\rho_{mix}(Q).
\]

Using this expression one can construct two test observables to search for correlations between decay products from different W’s. The observables considered are:

\[
\Delta\rho(Q) = \rho_{WW}(Q) - 2\rho_{W}(Q) - 2\rho_{mix}(Q),
\]

\[
D(Q) = \frac{\rho_{WW}(Q)}{2\rho_{W}(Q) + 2\rho_{mix}(Q)}.
\]

Any deviation from zero of \(\Delta\rho(Q)\), or any deviation from one of \(D(Q)\), is an indication for non-independent WW decay.

3 L3 results

The L3 collaboration has recently published results using the method described above. Their \(\Delta\rho(Q)\) and \(D(Q)\) distributions are shown in Fig. both for like-sign and unlike-sign particle pairs. It can be seen in this figure that an excess at low Q values is observed for a scenario with inter-W BEC, while no excess is seen in the case where no inter-W BEC is implemented. The
Monte Carlo implementation of the Bose-Einstein effect was realised by means of the LUBOEI BE32 model, described in [3] and tuned to the L3 data. In order to quantify a possible inter-W BEC effect in the data, two methods are applied. The first consists of integrating the $\Delta \rho(Q)$ distribution to obtain

$$J = \int_0^{Q_{\text{max}}} \Delta \rho(Q)dQ,$$

where the value $Q_{\text{max}}$ is taken where the two MC scenarios have converged to less than one standard deviation. The obtained value of $J$ for like-sign pairs amounts to

$$J(\pm, \pm) = 0.3 \pm 0.33(\text{stat}) \pm 0.15(\text{syst}).$$

In addition, the distribution $D'(Q)$ is computed, defined as

$$D'(Q) = \frac{D(Q)_{\text{data}}}{D(Q)_{\text{MC, no inter}}},$$

where the denominator is the $D(Q)$ distribution taken for a MC sample without inter-$W$ BEC. This double ratio is used in order to eliminate possible distortions, introduced by event selections and track mixing. Finally the $D'(Q)$ distribution is fitted with the following expression

$$D'(Q) = (1 + \delta Q)(1 + \Lambda \exp(-k^2 Q^2)),$$

where a non-zero value of $\Lambda$ would indicate the presence of inter-$W$ BEC. The obtained value of this parameter amounts to

$$\Lambda = 0.008 \pm 0.018(\text{stat}) \pm 0.012(\text{syst}),$$

thus being compatible with the absence of an inter-$W$ BEC effect.

4 DELPHI results

The DELPHI collaboration has revised their analysis, using the same formalism as described above. The analysis described in [9] was optimised as a function of the purity of the selected
Figure 2: The $D(Q)$ distribution for like-sign particle pairs obtained by the DELPHI experiment (left). The red line indicates the prediction of a Monte Carlo Model including only BEC within one $W$ (BEins). The blue line gives the prediction where also BEC between particles from different $W$’s are included. The shaded band indicates the result of the fit, using Eq. 11 to the real data. On the right, the one, two and three sigma contours are given for the fitted $\Lambda$ and $R$ parameters.

fully-hadronic $WW$ decays. By increasing the purity of the selected events, the systematic uncertainty due to the subtraction of $q\bar{q}(\gamma)$ events decreases, but the amount of statistics is reduced as well. The sensitivity of the analysis was further increased by weighing particle pairs, according to their probability to originate from different $W$’s. This weighing procedure is model independent and weights can be extracted from data itself, using mixed events. Most emphasis is given to a fit of the $D(Q)$ distribution with the following expression:

$$D(Q) = N(1 + \Lambda e^{-R Q})(1 + \delta Q),$$

where the $R$ parameter is either fixed to a value obtained from a MC sample, using the BE$_{32}$ model, tuned to the DELPHI data, including inter-$W$ BEC, or where all fit parameters are left free. The result of both fits can be seen in Fig. 2. On the left-hand side of Fig. 2 the $D(Q)$ distribution for like-sign pairs obtained from the data is shown. The blue band indicates the result of the fit, using Eq. 11 with a fixed $R$ parameter, taking into account the statistical uncertainties and the correlations between all remaining free parameters. The $\Lambda$ value obtained by this approach amounts to

$$\Lambda(\pm, \pm) = 0.241 \pm 0.075(stat) \pm 0.038(syst),$$

$$\Lambda(\pm, \pm) = 0.123 \pm 0.050(stat) \pm 0.042(syst),$$

for like-sign and unlike-sign particle pairs respectively.

The BE$_{32}$ model, including BEC between all particles yielded the following result:

$$\Lambda(\pm, \pm) = 0.360 \pm 0.012(stat),$$

$$\Lambda(\pm, \pm) = 0.0785 \pm 0.0057(stat).$$

On the right-hand side of Fig. 2, the one, two and three sigma contours of the fitted $\Lambda$ and $R$ parameters are shown. The central value obtained from the BE$_{32}$ model with inter-$W$ BEC
is shown as well. For like-sign and unlike-sign particle pairs the obtained \( \Lambda \) values using this fit are respectively

\[
\begin{align*}
\Lambda(\pm, \pm) &= 0.38 \pm 0.16(\text{stat}) \pm 0.038(\text{syst}), \\
\Lambda(+, -) &= 0.131 \pm 0.059(\text{stat}) \pm 0.045(\text{syst}).
\end{align*}
\]

\text{(16) (17)}

**Conclusion**

Both L3 and DELPHI have finalised their analysis, looking for Bose-Einstein correlations between identical bosons coming from different \( W \)'s. L3 sees no indication of the effect, while DELPHI observes an indication of inter-\( W \) BEC for like-sign particle pairs at the level of three standard deviations. The result of the DELPHI fit indicates that the effect tends to be concentrated in a very small region in \( Q \), indicating that very few pairs contribute to the effect. This might be good news for the \( W \) mass measurement, where a small amount of particle pairs subjected to the inter-\( W \) BEC effect are expected to give a small influence on the reconstructed \( W \) mass in the fully hadronic channel. Results from the OPAL and ALEPH collaborations are eagerly awaited in order to perform a complete LEP combination of the obtained results.

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