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BOSE–EINSTEIN CORRELATIONS IN HADRONIC *W* DECAYS AT LEP*

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Both experimentalists and theorists dealing with Bose–Einstein correlations (BEC) in high energy interactions find themselves in an awkward situation. The observation of a very weak BEC signal between two hadronizing sources in the reaction $e^+e^- \to W^+W^-$ could well indicate that our understanding of the BEC effect is quite poor. In this paper, an overview of the latest LEP results on BEC between particles from different Ws is given. From the combination of these results, a systematic uncertainty on the measured W mass in the fully hadronic channel is estimated.

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1. Introduction

The phenomenon of Bose–Einstein correlations has been investigated extensively throughout the last decades in various interactions, for various particle species and at ever increasing center-of-mass energies. For a recent review on the subject we refer to [1]. However, after all these years, some open questions remain [2]. One of these is the lack of strong evidence for BEC between particles originating from the decay of different Ws in the reaction $e^+e^- \to W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$.

A priori, there should be no reason why BEC should not occur between particles produced by two largely overlapping sources, at least in the HBT interpretation of BEC [3–5]. Recently, it was noted that at least for a single hadronizing string, the HBT picture does not necessarily apply [6–8]. In a completely coherent particle production mechanism there is even no room for BEC when the original HBT formalism is applied. Therefore the investigation of BEC between particles from different Ws could lead to new insights on the true mechanism behind the BEC effect in high energy interactions. Furthermore, it is known that if inter-W BEC exist, they are of

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relevance to the precise determination of the W mass in the decay channel $W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$ [9–11].

Recently, all four LEP collaborations apply the same method to extract a possible inter-W BEC signal which will be introduced in the next section. In what follows an overview will be given of the latest results, using this method. A combination of these will then be used to estimate a common systematic uncertainty on the W mass determination, assigned to the BEC effect.

2. Formalism

Two decay modes of a produced WW pair are relevant for the following discussion:

$$e^+e^- \to W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4\,, \tag{1}$$

$$e^+e^- \to W^+W^- \to q_1\bar{q}_2l\bar{\nu}_l\,. \tag{2}$$

In the first case, further denoted as WW, both Ws decay hadronically. In the second case, denoted as W, one W decays hadronically and the second decays into a lepton and its corresponding anti-neutrino.

Even in the absence of an inter-W BEC effect, the two-particle correlation function of a fully-hadronic WW event will be non-zero due to correlations inside a single decaying W. An elegant solution is provided in [12] and [6]: In the case of statistically independent WW decay the inclusive two particle density of a fully hadronic WW decay can be expressed as

$$\rho^{WW}(1,2) = 2\rho^{W}(1,2) + 2\rho^{W^+}(1)\rho^{W^-}(2)\,, \tag{3}$$

where the inclusive two-particle density in the variable $Q = \sqrt{-(p_1-p_2)^2}$ is defined as

$$\rho(1,2) = \frac{1}{N_{\mathrm{ev}}}\frac{dn_{\mathrm{pairs}}}{dQ}\,, \tag{4}$$

with N_{ev} being the total number of events, n_{pairs} the number of particle pairs and p_i the four momenta of the particles. In practice, the product of the single particle densities, $\rho^{W^+}(1)\rho^{W^-}(2)$, is replaced by a mixed two-particle density, $\rho^{WW}_{\mathrm{mix}}(1,2)$, obtained by pairing particles from different semi-hadronic WW events. This to ensure that particles coming from differently charged Ws do not correlate.

The validity of Eq. (3) can be easily tested by constructing two variables:

$$\Delta\rho(Q) \;=\; \rho^{WW}(Q) - 2\rho^{W}(Q) - 2\rho^{WW}_{\mathrm{mix}}(Q), \tag{5}$$

$$D(Q) \;=\; \frac{\rho^{WW}(Q)}{2\rho^{W}(Q) + 2\rho^{WW}_{\mathrm{mix}}(Q)}\,, \tag{6}$$

which should be respectively zero or one in the absence of inter-W BEC for all values of Q.

3. Results

From 1997 until 2000 each LEP experiment accumulated between 550 and 690 pb^{-1} at center-of-mass energies from 183–209 GeV. This results in a total collected dataset of $\sim$ 13000 semi-hadronic and $\sim$ 19000 fully hadronic WW decays, after selection. Fig. 1 shows the distributions obtained from Eqs. (5) and (6) from both the L3 and ALEPH collaboration for like sign and unlike-sign particle pairs. Some collaborations, like ALEPH, have opted to calculate the double ratio $D'(Q) = D(Q)_{\mathrm{data}}/D(Q)_{\mathrm{MCnoBEC}}$ in order to reduce experimental biases. Predictions for the LUBOEI BE32 [9,13] model are superimposed on the plots. In this model the BEC effect is implemented by reshuffling of particle momenta and can be switched on for either particles coming from the same W or for all particles in the event. It is clear from Fig. 1 that the model including only BEC for particles coming from the same W is compatible with zero and one for $\Delta\rho(Q)$ and $D'(Q)$ respectively. The model including BEC between all particles shows an enhancement at small Q values, as expected.

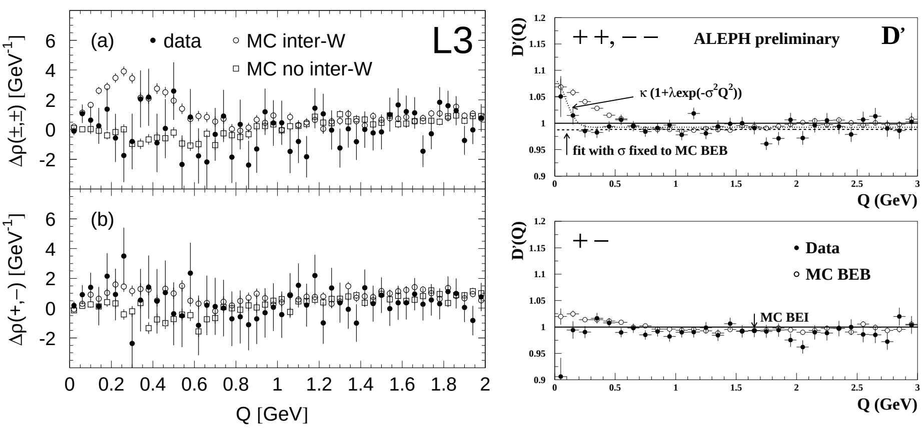

Fig. 1. Left: The $\Delta\rho(Q)$ distribution, measured by the L3 collaboration. Right: The $D'(Q)$ distribution measured by ALEPH. In both figures, the LUBOEI BE32 models, tuned to hadronic Z^0 data for each individual experiment, including either only BEC inside one W or BEC between all identical bosons are superimposed.

Quantitative results can be obtained by either integrating the $\Delta\rho(Q)$ distribution over a certain interval or fitting the $D^{(\prime)}(Q)$ distribution with an analytic expression. The integral of $\Delta\rho(Q)$ gives only a measure for the significance of an inter-W BEC signal, while an analytic fit to $D^{(\prime)}(Q)$ contains information of the geometry behind inter-W BEC. It should however be noted that $D(Q)$ is not a genuine correlation function. In [6] the genuine inter-W correlation function is defined as:

$$\delta_I(Q) = \frac{\Delta\rho(Q)}{2\rho^{WW}_{\rm mix}(Q)}. \tag{7}$$

Both DELPHI and OPAL have studied this genuine inter-W correlation function as shown in Fig. 2. It is clear that DELPHI observes a significant excess at small Q values for like sign particle pairs, while OPAL does not.

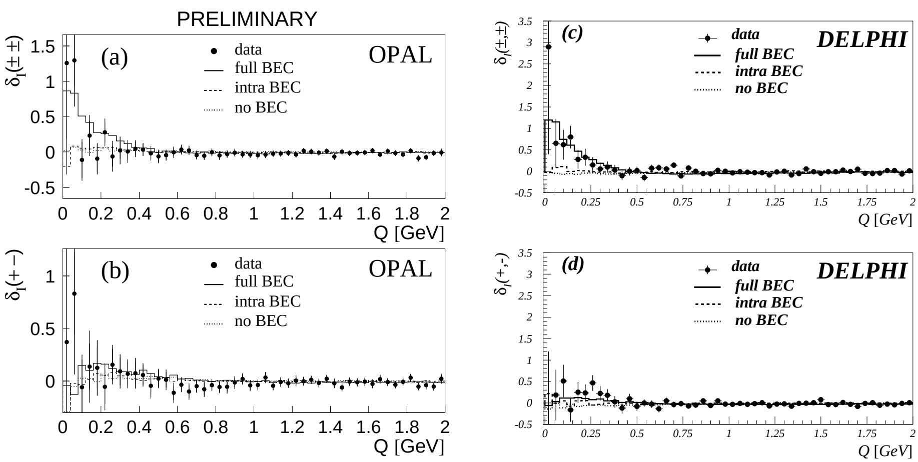

Fig. 2. The genuine inter-W correlation function, $\delta_I(Q)$, for like sign (top) and unlike-sign (bottom) particle pairs analyzed by OPAL (left) and DELPHI (right). Several BEC scenarios implemented with BE32 are superimposed.

It should be noted that the sensitivity to the inter-W BEC effect is quite small due to the small fraction of particle pairs coming from different Ws that result in small Q values. Therefore it is worth combining the measurements of all four LEP experiments. Due to different track resolutions, acceptances and selection criteria, the data can not be combined directly. This is solved at present by performing a χ^2 combination of the observed fraction of the full BE32 model, including correlations between all identical bosons, defined as:

$$\Lambda_{\rm frac} = \frac{\rm data - model(noBE)}{\rm model(BEfull) - model(noBE)}. \tag{8}$$

The obtained result and its total error is translated into a W mass shift by

$$\Delta M_W = (\Lambda_{\rm frac} + \sigma(\Lambda_{\rm frac})) \times [M_W({\rm BEfull}) - {\rm M_W(noBE)}]. \tag{9}$$

The individual measurements and the combined LEP result on inter-W BEC, translated into the observed fraction of the LUBOEI BE32 model are shown in Fig. 3. The combined observed fraction of 23% results in a small W mass shift due to inter-W BEC of 8 ± 5 MeV.

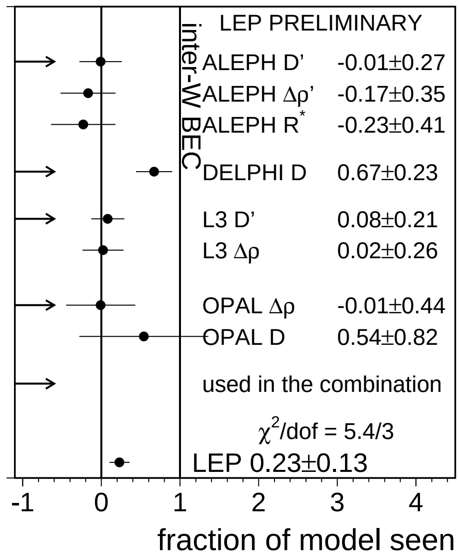

Fig. 3. The fraction of the full BE32 model seen by each experiment, using different techniques. The results with arrows are considered for combination.

So far the fraction of the full BE32 model is computed using the measured correlation strength, Λ, only. In the simplest case of a Goldhaber parametrization [4], combining the information on the correlation strength with the measured radius R could give a more correct estimate of the impact on M_W. If R increases, the resulting W mass shift is expected to decrease, since fewer particles participate in the BEC effect.

A first indication that the measured inter-W BEC R parameter might be larger in data than in the BE32 model, tuned at the Z^0 peak, has been found by DELPHI. There the $D(Q)$ distribution was fitted with an exponential expression of the form:

$$N(1 + \delta Q)(1 + \Lambda \mathrm{e}^{-RQ})\,. \tag{10}$$

The one, two and three sigma contours of the fitted Λ versus R parameter are shown in Fig. 4. Although $D(Q)$ is not a genuine correlation function, this gives an indication that the DELPHI data prefers a larger source size for inter-W BEC than the corresponding LUBOEI models.

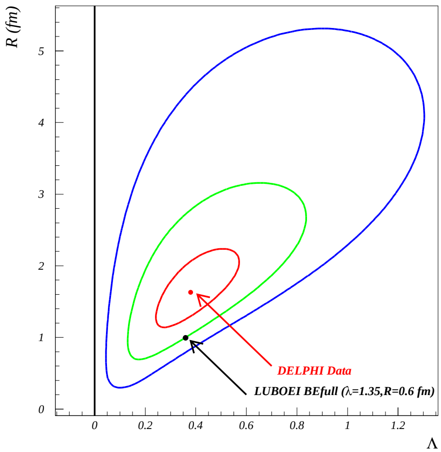

Fig. 4. The one, two and three sigma contours of the measured correlation strength Λ and R parameter, taken from a fit by DELPHI to $D(Q)$ with expression 10.

4. Conclusion

All four LEP experiments have been looking for BEC between particles coming from different Ws in the reaction $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$. Only very weak evidence for this effect has been found when all LEP data is combined. This confirms the original Lund idea that when two separate strings hadronize in a coherent way, there is no possibility for BEC between particles originating from the decay of those two primary strings. This is a very surprising result, knowing that in heavy ion reactions where many strings are hadronized, strong BEC are observed. The results from DELPHI deviate from the rest of the LEP experiments. They find an inter-W BEC signal with a total significance of the order of 2.9 σ. A weak indication that the measured radius for inter-W BEC is smaller than the one observed for one hadronizing string is also found.

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