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Bose-Einstein Results from L3*

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Two studies using Bose-Einstein correlations are reported. The first, a three-dimensional analysis of hadronic Z decays, finds that the pion source is not spherical, but elongated along the thrust direction. The second study compares $e^+e^- \to W^+W^-$ events at $\sqrt{s} = 189\,\mathrm{GeV}$ where only one W decays hadronically with events where both do. No evidence is found for Bose-Einstein correlations between pions from different W bosons.

1 Elongation of the Pion Source in Hadronic Z decays

Using the L3 detector[1] at LEP, we have performed two analyses using Bose-Einstein correlations. The first concerned hadronic decays of the Z. It used about 1 million hadronic Z events at $\sqrt{s} \approx 91.2\,\mathrm{GeV} \approx M_\mathrm{Z}$. A three-dimensional analysis of pairs of identically charged pions was performed in the longitudinal center of mass system of the pion pair, with the longitudinal direction along the thrust axis of the event. This system has the advantage that the longitudinal and one of the transverse spatial dimensions are independent of the temporal dimension of the pion source, allowing, since azimuthal symmetry may be assumed, a measurement of the transverse and longitudinal source dimensions. Since this study has now been published,[2] only the main results will be stated here: Using an azimuthally symmetric Gaussian parametrization we extracted the incoherence parameter, λ, and the spatial radii. A better fit was obtained using the Edgeworth expansion[3,4] of the Gaussian parametrization. The transverse radius was found to be significantly smaller than the longitudinal radius:

$$R_\mathrm{trans}/R_\mathrm{long} = 0.81 \pm 0.02^{+0.03}_{-0.19}$$

Similar analyses have been performed by DELPHI[5] and OPAL.[6]

2 Inter-W Bose-Einstein Correlations

The second analysis[7] studies Bose-Einstein (BE) correlations in $e^+e^- \to W^+W^-$. BE interference is observed in hadronic Z-decay as an enhanced production of identical bosons at small four-momentum difference, Q. This effect is expected also in hadronic W-decay (intra-W BE interference). Since in fully hadronic WW events ($W^+W^- \to q_1\overline{q}_2q_3\overline{q}_4$) the W-decay products overlap in space-time at LEP-2 energies, it is reasonable to expect[8] BE correlations (BEC) between particles coming from different W's (inter-W BE interference). Such correlations, as well as so-called color reconnection, could bias the W mass measurements in the four-jet channel. This analysis is designed to investigate whether inter-W BEC exist. These results are preliminary.

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2.1 Method

The method used to study Bose-Einstein correlations (BEC) between identical hadrons originating from different W's (inter-W BEC) is mainly based on that proposed by Chekanov, De Wolf, and Kittel.[9]

Assuming for the moment that the two W's decay independently, one can write[9] the two-particle density in the four-momenta p_1 and p_2,

$$\rho(p_1, p_2) = \frac{1}{N_{\text{ev}}} \frac{\mathrm{d}n_{\text{pairs}}}{\mathrm{d}Q} \quad , \tag{1}$$

where N_{ev} is the number of events, n_{pairs} is the number of particle pairs and $Q \equiv \sqrt{-(p_1 - p_2)^2}$ is the four-momentum difference between the two particles, as

$$\rho_{4\text{q}}(p_1, p_2) = \rho^+(p_1, p_2) + \rho^-(p_1, p_2) + \rho^+(p_1)\rho^-(p_2) + \rho^-(p_1)\rho^+(p_2) \quad , \tag{2}$$

where the first (second) term is the density for two particles from the W^+ (W^-) and the last two terms, with products of the single-particle densities, are the density for one particle from each of the W's. This can be rewritten, assuming $\rho^+ = \rho^-$, as

$$\rho_{4\text{q}}(p_1, p_2) = 2\rho_{2\text{q}}(p_1, p_2) + 2\rho_{2\text{q}}(p_1)\rho_{2\text{q}}(p_2) \tag{3}$$

where $\rho_{2\text{q}}$ is the density for particles from a single W. If, on the other hand, the decays of the two W's are not independent, eq. 3 will not hold.

Experimentally, $\rho_{4\text{q}}(p_1, p_2)$ and $\rho_{2\text{q}}(p_1, p_2)$ can be measured using fully hadronic and semi-hadronic ($\mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\ell\nu$), respectively. We determine the product of the single particle densities by measuring the two-particle density in mixed events. These events are constructed from pairs of semi-hadronic events where the leptonic W decays are discarded and the remaining hadronic decays are aligned along their thrust axes. Furthermore, we demand that the total visible energy of the two W's have a value of $\sqrt{s} \pm 10\,\text{GeV}$. The resulting mixed events have an average multiplicity in agreement with the average multiplicity of real four-jet events. Thus eq. 3 becomes

$$\rho_{4\text{q}}(p_1, p_2) = 2\rho_{2\text{q}}(p_1, p_2) + 2\rho_{\text{mix}}(p_1, p_2) \quad . \tag{4}$$

The independence of the W decays is tested by testing the validity of eq. 4. Of course, BEC are not the only possible correlations. However, BEC affect only identical bosons at small Q. Therefore, eq. 4 is examined for both like-sign and unlike-sign pairs as a function of Q. The advantage of this method is that it measures inter-W correlations directly from the experimental data, without any need for normalisation by a Monte-Carlo model.

To test eq. 4 we can test whether

$$\Delta\rho(Q) = \rho_{4\text{q}}(Q) - [2\rho_{2\text{q}}(Q) + 2\rho_{\text{mix}}(Q)] \tag{5}$$

is zero. Alternatively, we can test whether

$$D(Q) = \frac{\rho_{4\text{q}}(Q)}{2\rho_{2\text{q}}(Q) + 2\rho_{\text{mix}}(Q)} = \frac{\Delta\rho(Q)}{2\rho_{2\text{q}}(Q) + 2\rho_{\text{mix}}(Q)} + 1 \tag{6}$$

is 1. To suppress possible artificial distortions due to event mixing, we also use the double ratio $D'(Q) = D(Q)/D(Q)_{\text{MC, noBE}}$ where $D_{\text{MC, noBE}}$ is determined from a Monte-Carlo sample without BEC. A deviation at small Q of $D(\pm,\pm)$ or $D'(\pm,\pm)$ from unity or of $\Delta\rho(\pm,\pm)$ from zero can be interpreted as evidence for inter-W BEC.

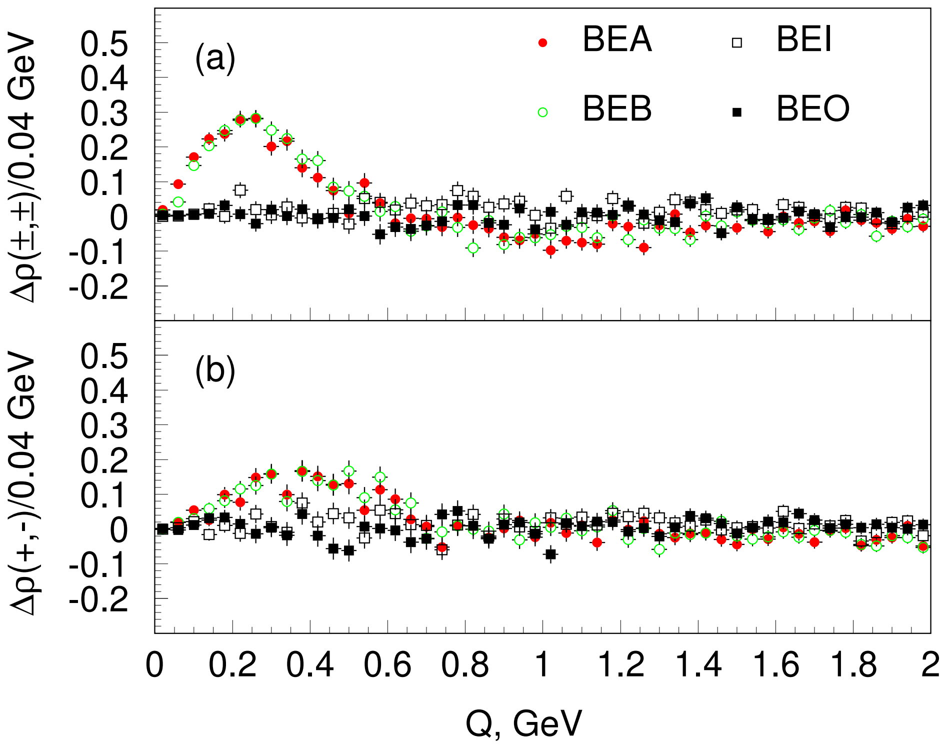

Figure 1: Distributions according to generator-level PYTHIA of (a) $\Delta\rho(\pm,\pm)$ and (b) $\Delta\rho(+,-)$ for BEC between all particles (BEA), only between particles from the same W (BEI), only between particles from different W's (BEB) and when the BEC are switched off (BEO). BEC are simulated using the BE_{32} algorithm.

2.2 Demonstration by PYTHIA

To check the method described in the previous section, we examined the relevant distributions obtained at the generator level of the Monte Carlo generator PYTHIA[10] using both the LUBOEI and the BE_{32} algorithms.[11] Four BE scenarios were investigated: BEC between all particles (BEA); only between particles from the same W (BEI); only between particles coming from different W's (BEB); and without any BEC (BEO). No color-reconnection was included and only charged pions were taken into account. The results for $\Delta\rho$ are shown in Fig. 1.

A clear enhancement at small Q is observed for like-sign pairs (Fig. 1a) when inter-W BEC are present (BEA and BEB scenarios). Moreover, the distribution is the same for these two cases. When no inter-W BEC (BEI and BEO scenarios) are present the distribution is flat and zero. This distribution thus behaves as expected.

The $\Delta\rho$ distributions for unlike-sign pairs (Fig. 1b) shows a small effect for BEA and BEB and no effect for BEI and BEO. This small effect is understood as an artifact of the BE_{32} algorithm; its shifting of momenta of particles to obtain the desired two-particle correlation for identical particles also modifies the distributions of non-identical particles. This effect is much larger for LUBOEI.

Thus, despite its small signal, inter-W BEC can be observed in the $\Delta\rho$ distribution, where the scenarios BEA and BEB show an enhancement at small Q while the BEI and BEO scenarios do not. A similar conclusion is reached for D and D'.

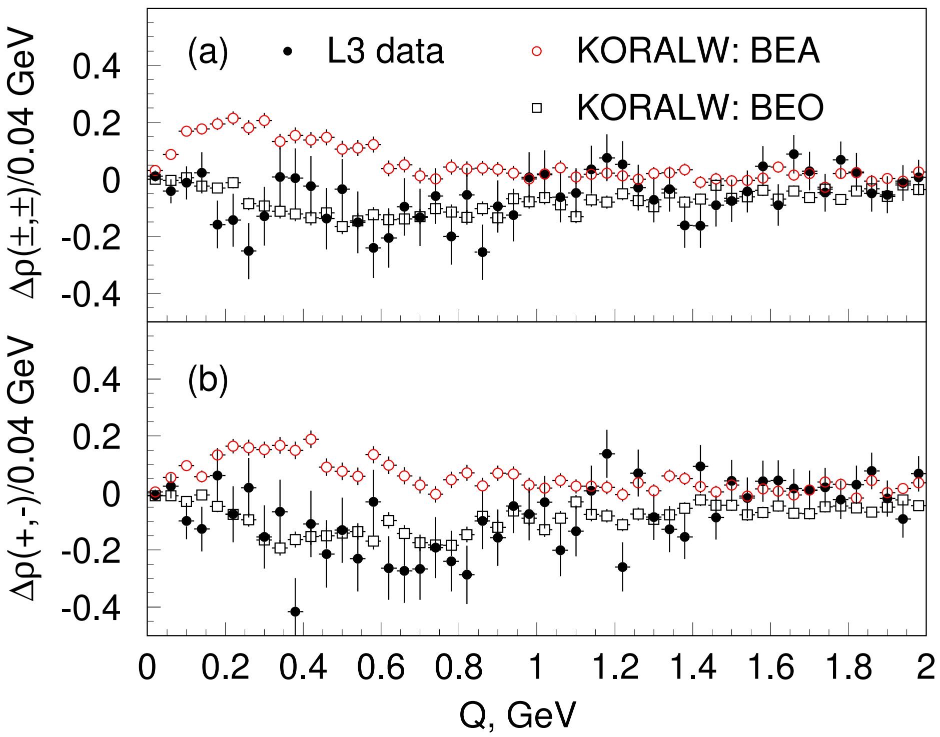

Figure 2: Distributions according to the uncorrected L3 data of (a) $\Delta\rho(\pm,\pm)$ and (b) $\Delta\rho(+,-)$. Also shown are the Monte Carlo predictions of KORALW after full detector simulation with BEC (LUBOEI) between all particles (BEA) and without BEC (BEO).

2.3 Results

The data, corresponding to about 176 pb^{-1}, were recorded by L3[1] in 1998 at $\sqrt{s} = 189$ GeV. After selection, there are 1026 semi-hadronic and 1514 fully hadronic W^+W^- events, which contain about 52k and 302k well-measured like-sign pairs, respectively.

The resulting distributions for $\Delta\rho$ are shown in Fig. 2. Also shown are the predictions of KORALW[12] after the events generated by this Monte Carlo have been passed through the L3 detector simulation program,[13] reconstructed and subjected to the same selection criteria as the data. Two scenarios are shown: (1) BEC between all particles in an event (BEA) and (2) no BEC (BEO).

The data agree well with KORALW without BEC, both for like-sign and unlike-sign pairs, and are inconsistent with KORALW with BEC from LUBOEI. KORALW shows an enhancement in the $\Delta\rho$ distribution for the BEA scenario. This enhancement occurs for like-sign pairs as a consequence of BEC; an enhancement also occurs in unlike-sign pairs as an artifact of LUBOEI.

2.4 Summary

The possible existence of BEC between particles originating from different W's was studied using 1514 fully- and 1026 semi-hadronic WW-events, collected by L3 at $\sqrt{s} = 189$ GeV.

From the two-particle densities for real fully-hadronic events and for fully-hadronic events without inter-W BEC (constructed by an event mixing technique from real semi-hadronic events), we obtained the distributions of $\Delta\rho(\pm,\pm)$, $D(\pm,\pm)$ and $D'(\pm,\pm)$. None of these distributions show any excess at small values of Q. An excess is to be expected from inter-W BEC. On the other hand, the distributions agree very well with KORALW without BEC. Thus there is no evidence for BEC between identical particles originating from different W's (inter-W BEC).

Acknowledgments

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