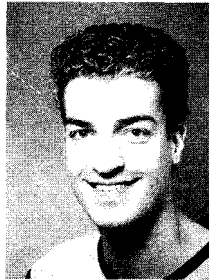


## BOSE-EINSTEIN CORRELATIONS IN $W^+W^-$ EVENTS AT LEP2

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Analyses of Bose-Einstein Correlations in  $W^+W^-$  events at LEP2 by the four LEP collaborations are presented. In particular, Bose-Einstein correlations in  $W^+W^-$  overlap are investigated and the possible existence of these correlations between particles coming from different  $W$ 's, which may influence the  $W$  mass measurements in the fully-hadronic channel  $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ . No evidence for such an inter- $W$  Bose-Einstein correlation is found by L3 and ALEPH. Possible indication of these correlations by DELPHI is mentioned.

### 1 Introduction

Bose-Einstein interference is observed in hadronic  $Z$ -decay as an enhanced production of identical bosons at small four-momentum difference<sup>1</sup>. There is no reason why such an interference should not be present within hadronic  $W$ -decay (intra- $W$  BE interference), as well. Furthermore, since in fully-hadronic  $WW$  events ( $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ ) the  $W$ -decay products overlap in space-time at LEP2 energies, it may be natural, to expect<sup>2</sup> interference also between identical bosons originating from different  $W$ 's (inter- $W$  BE interference). Together with colour reconnection<sup>3</sup>, inter- $W$  BE interference not only forms a potential bias in the determination of the  $W$ -mass, but also may provide a laboratory to measure the space-time development of this overlap. Both recent model predictions<sup>2,3</sup> and recent experimental results<sup>4</sup> are still contradictory, however. In this contribution the recent results on Bose-Einstein Correlations (BEC) in  $WW$  events are presented for the four LEP experiments.

### 2 L3 Analysis

Two-particle correlations can be studied by using the ratio of the two-particle density  $\rho(p_1, p_2) \equiv \frac{1}{N_{ev}} \frac{dn_{pairs}}{dQ}$ , to the product of the two single-particle densities, where  $p_1$  and  $p_2$  are the four-

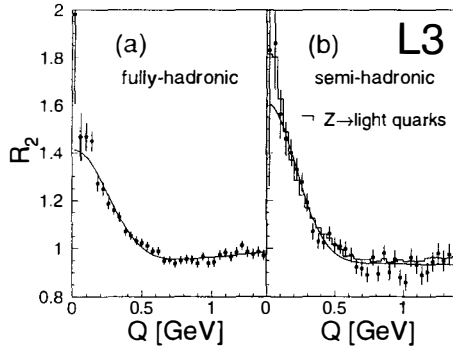


Figure 1: The BE correlation function for the fully-hadronic WW events, (a), and for the semi-hadronic WW events, (b). In (b) the histogram is for the light-quark Z-decay sample.

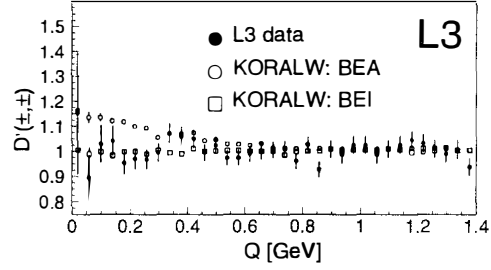


Figure 2: Distribution of the double ratio  $D'$  for like-sign pairs.

momenta of the two particles,  $N_{\text{ev}}$  is the number of events used in the analysis,  $n_{\text{pairs}}$  is the number of identical-particle pairs, and  $Q \equiv \sqrt{-(p_1 - p_2)^2}$  is the four-momentum difference between the two particles. Since we are only interested in BEC here, the product of single-particle densities is replaced by  $\rho_0(p_1, p_2)$ , ideally the two-particle density that would occur in a world without BEC:

$$R_2(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} \quad (1)$$

Taking  $\rho$  from the data recorded at  $\sqrt{s} \simeq 189$  GeV, corrected for detector resolution, acceptance, efficiency, purity of the selection and particle misidentification, and using the Monte Carlo (MC) KORALW<sup>5</sup> without BEC to determine  $\rho_0$ , one finds  $R_2$  as shown in fig.1. The correlation function is shown for the fully hadronic WW events and for the semi-hadronic WW events, *i.e.*, events where one W decays hadronically and the other W decays to a lepton and a neutrino. The enhancement at low values of  $Q$  represents the BE effect and it is parametrized by  $\gamma(1 + \delta Q)(1 + \lambda \exp(-R^2 Q^2))$ , where  $\gamma$ ,  $\delta$ ,  $\lambda$  and  $R$  are the fit parameters. The parameter  $\lambda$  measures the strength of the correlation. The fit results are shown as the solid lines in fig.1. From the figure we observe the tendency that  $\lambda$  for the semi-hadronic channel is somewhat higher than for the fully-hadronic channel ( $0.70 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$  and  $0.55 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})$  respectively), which is in agreement with no or only weak inter-W BEC.

Since, apart from the quark flavour, hadronic W and Z decay is expected to be similar, L3 also analyzed a high statistics hadronic Z-decay sample, collected at  $\sqrt{s} \simeq 91.2$  GeV. A b-tagging procedure is used to reduce the  $b\bar{b}$  fraction in Z decays (as b quarks are not present in W decays) from 22% to 3%. The Bose-Einstein correlation function of the light quark Z-decay sample is plotted in fig.1b as a histogram. As expected, good agreement is observed between this histogram and the correlation function for semi-hadronic WW events.

The method used to study inter-W BEC is based on that proposed in<sup>7</sup>. If the two W's decay independently, the two-particle density in fully-hadronic WW events,  $\rho^{\text{WW}}$ , is given by

$$\begin{aligned} \rho(p_1, p_2)^{\text{WW}} &= \rho(p_1, p_2)^{\text{W}^+} + \rho(p_1, p_2)^{\text{W}^-} + \rho(p_1)^{\text{W}^+} \rho(p_2)^{\text{W}^-} + \rho(p_1)^{\text{W}^-} \rho(p_2)^{\text{W}^+} \quad (2) \\ &= 2\rho(p_1, p_2)^{\text{W}} + 2\rho(p_1)^{\text{W}} \rho(p_2)^{\text{W}} \quad , \quad (3) \end{aligned}$$

where the superscripts, *e.g.*, WW, indicate which W's decay hadronically. Experimentally,  $\rho^{\text{WW}}$  is measured in the fully-hadronic WW events and  $\rho^{\text{W}}$  in the semi-hadronic events. To measure

the product of the single-particle densities, a two-particle density,  $\rho(p_1, p_2)_{\text{mix}}^{W^+W^-}$ , is constructed by pairing particles originating from two different semi-hadronic WW events. By construction these pairs of particles are uncorrelated.

The hypothesis that the two W's decay independently can be tested by testing the validity of eq.(3). In particular, the following test statistic is used

$$D = \frac{\rho^{WW}}{2\rho^W + 2\rho_{\text{mix}}^{W^+W^-}} \quad (4)$$

To diminish artificial distortions due to event mixing, non-BEC and various detector effects, also the double ratio  $D' = D/D_{\text{MC, noBE}}$  is used, where  $D_{\text{MC, noBE}}$  is a MC sample without BEC, or at least without inter-W BEC. Evidently,  $D = D' = 1$  in the absence of inter-W BEC.

Fig.2 shows the distribution of  $D'$  for like-sign track pairs, for the 189 GeV data. A MC sample with only intra-W BEC is used as a reference. Also shown in the figure are the predictions of the MC KORALW, with the BE<sub>32</sub> algorithm<sup>6</sup> and tuned to the Z-data, for the scenario where correlations between all particles are allowed (BEA) and for the scenario where only inside W BEC are allowed (BEI). It is clear that the BEA scenario is disfavoured, while BEI describes the data which are around unity. In particular, the confidence level (CL) for the BEA scenario is 2% and for the BEI scenario it is 96%. Note, that the single ratio distribution gives similar results.

To obtain a quantitative result,  $D'$  is fitted by  $(1 + \varepsilon Q)(1 + \Lambda \exp(-k^2 Q^2))$ , where  $\varepsilon$ ,  $\Lambda$  and  $k$  are the fit parameters. The  $\Lambda$  parameter measures the strength of inter-W BEC. The result of the fit is  $\Lambda = 0.001 \pm 0.026(\text{stat}) \pm 0.015(\text{syst})$ . This can be interpreted as evidence against BEC between identical particles originating from different W's.

### 3 Delphi Analysis

The Delphi collaboration has analyzed the data recorded at  $\sqrt{s} \simeq 183, 189$  and 192-200 GeV. The Bose-Einstein correlation function is estimated by  $R_2 = N_{\text{data}}^{\pm\pm} / N_{\text{MC, noBE}}^{\pm\pm}$ , where  $N^{\pm\pm}$  is the number of like-sign track pairs. For the reference sample PYTHIA<sup>8</sup> generated events without BEC are used, and the correlation function is corrected for detector effects. Normalizing  $R_2$  to unity in the region  $Q > 0.8$  GeV, gives the correlation function for the semi- and fully-hadronic WW events as shown in fig.3. Also shown in the figure are MC predictions of PYTHIA with the original LUBOEI algorithm BE<sub>0</sub><sup>6</sup>, tuned to the Z-data. The semi-hadronic WW events are well described by this MC. For the fully-hadronic channel only the BEA scenario describes the data, while the BEI scenario is disfavoured by  $2.9\sigma$ .

Moreover, fitting the correlation function of the fully- and semi-hadronic WW events and of a light quark Z-decay sample, by  $1 + \lambda \exp(-R^2 Q^2)$ , results in  $\lambda_{\text{fully}} = 0.302 \pm 0.021(\text{stat}) \pm 0.019(\text{syst})$ ,  $\lambda_{\text{semi}} = 0.270 \pm 0.035(\text{stat}) \pm 0.010(\text{syst})$  and  $\lambda_{\text{Zudsc}} = 0.309 \pm 0.008(\text{stat})$ . This is an indication for the existence of inter-W BEC.

This indication is confirmed by constructing the following correlation function:

$$R_2^{\text{constr}} \equiv \frac{[N_{\text{semi}}^{\pm\pm} + cN_{\text{mix}}^{\pm\pm}]_{\text{data}}}{[N_{\text{semi}}^{\pm\pm} + cN_{\text{mix}}^{\pm\pm}]_{\text{MC, noBE}}} \quad (5)$$

where  $N_{\text{mix}}^{\pm\pm}$  is constructed by combining tracks from different semi-hadronic WW events and  $c$  is a relative normalization factor between  $N_{\text{semi}}^{\pm\pm}$  and  $N_{\text{mix}}^{\pm\pm}$ . So, by construction this correlation function is free from inter-W correlations. Fitting this function by  $1 + \lambda \exp(-R^2 Q^2)$  gives  $\lambda_{\text{constr}} = 0.214 \pm 0.029(\text{stat}) \pm 0.008(\text{syst})$ . Comparing this value with  $\lambda_{\text{fully}}$  one observes a inter-W BE effect of  $2.4\sigma$ .

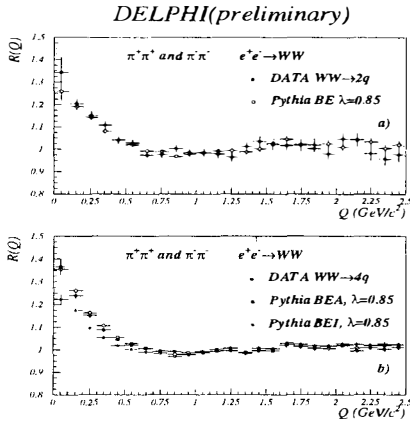


Figure 3: The BE correlation function for semi-hadronic WW events, (a), and for fully-hadronic WW events, (b).

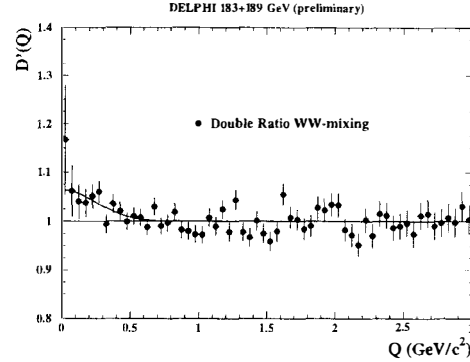


Figure 4: Distribution of the double ratio for like-sign pairs.

Moreover, a double ratio is constructed of the data collected at  $\sqrt{s} \simeq 183$  and 189 GeV. This ratio is determined in an almost similar way as L3, see eq.(4). The main difference is in the mixing procedure. The result of this double ratio is shown in fig.4. Fitting this ratio by  $1 + \Lambda \exp(-k^2 Q^2)$ , results in  $\Lambda = 0.064 \pm 0.040(\text{stat})$ .

All the results of Delphi show a preference for the hypothesis of inter-W BEC.

#### 4 Aleph Analysis

Aleph uses the unlike-sign particle pairs from the experimental events as a reference to determine the Bose-Einstein correlation function. Since this introduces a bias due to the presence of dynamical fluctuations, such as the decay of resonances, the density for unlike-sign pairs is multiplied by the ratio of the densities for like- and unlike-sign pairs determined from a MC model without BEC:

$$R_2(Q) \equiv \left( \frac{N^{\pm\pm}(Q)}{N^{+-}(Q)} \right)_{\text{data}} \cdot \left( \frac{N^{+-}(Q)}{N^{\pm\pm}(Q)} \right)_{\text{MC, noBE}} \quad (6)$$

The result of this correlation function is shown in fig.5, where the black dots correspond to the data collected at  $\sqrt{s} \simeq 172, 183, 189$  and 192-202 GeV, for the fully-hadronic WW events.

A MC model, using the BE<sub>3</sub> algorithm<sup>6</sup>, has been tuned to the Z-data, and a pure sample of light quark Z-decays has then been extracted in the data as well as in the MC, by means of an anti-b-tagging procedure. Residual discrepancies between data and MC for the light-quark sample have been corrected bin-by-bin. The prediction of this tuned and corrected MC, appears to reproduce the data in the semi-hadronic WW channel. More importantly, the same MC also reproduces the BEC in the fully-hadronic WW events, assuming inter-W BEC to be absent (BEI scenario). A model allowing inter-W BEC (BEA scenario) is disfavoured by  $2.2\sigma$ , calculated from a fit to the four first bins. The two MC scenarios are also shown in fig.5.

The disfavour of inter-W BEC is confirmed by the computation of the double ratio  $D'$ , constructed in an almost similar way as L3 and Delphi. Again, the main difference is in the mixing procedure. The double ratio is shown in fig.6 for the data, a MC with the BEA and one

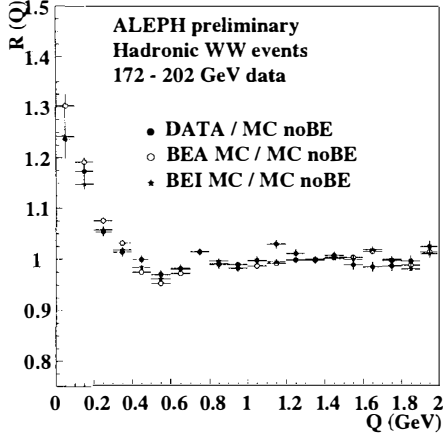


Figure 5: The BE correlation function for the fully-hadronic WW events.

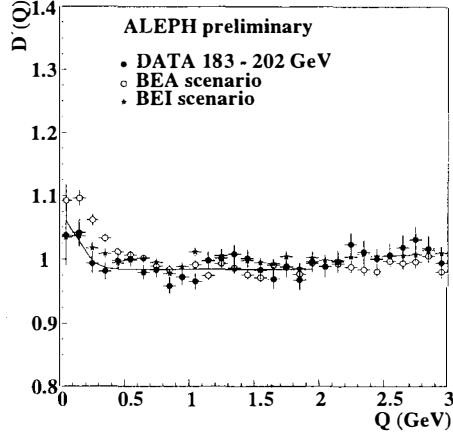


Figure 6: Distribution of the double ratio for like-sign particle pairs.

with the BEI scenario. Good agreement is obtained between data and the BEI scenario; The BEA scenario, *i.e.* inter-W BEC, is disfavoured. Note that the small enhancement at low  $Q$  for the BEI scenario is shown to be caused by  $Z \rightarrow q\bar{q}(\gamma)$  background events.

## 5 Opal Analysis

The Opal collaboration has studied BEC in the three event samples:  $W^+W^- \rightarrow q_1\bar{q}_2\ell\nu$ ,  $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$  and  $Z \rightarrow q\bar{q}$  selected as fully-hadronic WW events. The idea is that each of these processes may have different BEC. Therefore, the Bose-Einstein correlation function, eq.(6), is rewritten as a combination of contributions from the various pure pion classes. For example, the Bose-Einstein correlation function for the fully-hadronic WW events is written as:

$$R_2^{\text{had}}(Q) = P_{\text{had}}^{\text{same}}(Q)R^{\text{same}}(Q) + P_{\text{had}}^Z(Q)R_{\text{had}}^Z(Q) + (1 - P_{\text{had}}^{\text{same}}(Q) - P_{\text{had}}^Z(Q))R^{\text{diff}}(Q) \quad , \quad (7)$$

where  $R^{\text{same}}$ ,  $R^{\text{diff}}$  and  $R^Z$  are the Bose-Einstein correlation functions for the class of pions from the same W, different W and from hadronic Z decays, respectively.  $P_{\text{had}}^{\text{same}}$  and  $P_{\text{had}}^Z$  are the probabilities, computed from MC models without BEC, that the pair is coming from a certain event class. Also for the semi-hadronic WW events and the hadronic Z events one can write the correlation function as a superposition of the different classes. Doing a simultaneous fit with the data collected at  $\sqrt{s} \simeq 172, 183$  and  $189$  GeV, where the parametrization for each class is given by:

$$R_2(Q) = \gamma(1 + f_\pi(Q)\lambda \exp(-Q^2 R^2)) \quad , \quad (8)$$

where  $f_\pi$  is the probability that a selected track pair is really a pair of pions, results in:  $\lambda^{\text{same}} = 0.70 \pm 0.10(\text{stat})$  and  $\lambda^{\text{diff}} = -0.14 \pm 0.36(\text{stat})$ , when assuming a common source size  $R$ . Imposing the theoretical prediction  $(R^{\text{diff}})^2 = (R^{\text{same}})^2 + 4\beta^2\gamma^2\tau^2$ , which takes into account the distance between the W decay vertices, where  $\beta$ ,  $\gamma$  and  $\tau$  are, respectively, the velocity, the Lorentz factor and the life time of the W, results in  $\lambda^{\text{same}} = 0.69 \pm 0.12(\text{stat}) \pm 0.06(\text{syst})$  and  $\lambda^{\text{diff}} = 0.05 \pm 0.67(\text{stat}) \pm 0.35(\text{syst})$ . It is clear that intra-W BEC exist, but at this level of statistics, it is impossible to establish whether inter-W BEC exist, or not.

## 6 Summary

Different methods and variables have been used by the four LEP collaborations to study BEC in the fully- and semi-hadronic WW events. Computing the Bose-Einstein correlation function for these events, all experiments observe the existence of these correlations between particles originating from a single W (intra-W BEC). However, opposite conclusions are obtained by L3 and Aleph on one side, and Delphi on the other side, when it comes to the (non-)existence of BEC between particles originating from different W's (inter-W BEC). L3 and Aleph disfavour inter-W BEC whereas Delphi favours them. The results of Opal are inconclusive at the level of statistical precision.

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