Measurement of Bose-Einstein correlations at LEP

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A review of Bose-Einstein correlations is presented here using data collected at LEP. Bose-Einstein correlations have been studied in hadronic Z decays produced in e^+e^- interactions at $\sqrt{s} \sim 91$ GeV. They have been observed in pairs of identical pions, charged and neutral, showing a smaller size for the neutral source. Also a multidimensional analysis has been performed that shows an elongation of the source along the direction of the motion of the original quark. At higher centre of mass energies, ($\sqrt{s} \sim 200$ GeV), it was possible to study the Bose-Einstein effect in W-pair production. In particular, Bose-Einstein correlations are investigated between particles coming from different W's as they may influcence the W mass measurement in the four-jet channel.

1. INTRODUCTION

The constructive interference between two identical bosons has been widely studied in hadronic final states produced in e^+e^-, ep, $p\overline{p}$, and heavy ion collisions [1]. It leads to an enhancement of the number of identical bosons over that of non-identical bosons when the two particles are close in phase space. At LEP this effect has been observed in pairs of like-charged pions, kaons and in neutral systems such as $\pi^0$and K^0_S pairs. These Bose-Einstein Correlations (BEC) may influence the properties of multi-hadronic final states and are, therefore, a useful tool to test QCD models. Recently the interest in the BEC of identical charged pions has been extended to their possible effect on the measurement of the mass of the W gauge boson in the reaction $e^+e^- \rightarrow W^+W^-$.

BEC can be studied in terms of the two-particle correlation function:

$$\mathrm{R}_2 = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)} \qquad (1)$$

where $\rho(p_1, p_2)$ is the two-particle density for identical pions with four-momenta p_1 and p_2 subject to the Bose-Einstein symmetry and $\rho_0(p_1, p_2)$ the same density in the absence of BEC. There are several ways to choose the reference sample from which ρ_0 is calculated: a) unlike-charged pion pairs, b) like-charged pion pairs from mixed events and c) like-charged pairs from a Monte Carlo with no BE effect. The advantage of the first two samples is that the experimental systematic errors related to track reconstruction and acceptance are minimised. The problem is that a) suffers from the contribution of pairs coming from resonance decays and from weakly decaying particles, like K^0_S, ρ^0, ω, etc... and in b) the technique of combining two tracks coming from different events removes not only the Bose-Einstein correlations but also the ones arising from energy momentum conservation or long range correlations. To correct for these unwanted features samples a) and b) are normalised to the same ratio obtained from a Monte Carlo sample with no BE effect, i.e. $\mathrm{R}_2^{\mathrm{data}}/\mathrm{R}_2^{\mathrm{MCnoBEC}}$

Assuming a spherically symmetric boson source with a Gaussian density, R_2 can be written as:

$$\mathrm{R}_2 = N(1 + \alpha Q)(1 + \lambda e^{-Q^2R^2}) \qquad (2)$$

where $Q^2 = -(p_1 - p_2)^2$, the parameter R is related to the size of the boson source, λ represents the strength of the correlation and $N(1+\alpha Q)$ is a normalisation factor that takes into account possible long range momentum correlations as well as possible differences in pion multiplicity between the data and the reference sample.

In section 2 a review of the analyses performed at LEP in hadronic Z decays will be presented. Section 3 will be devoted to the study of the

Bose-Einstein effect in WW events and a short summary is given in section 4.

2. BEC IN HADRONIC Z DECAYS

The luminosity collected during the first phase of LEP corresponds to $\sim$ 170 pb^{-1} per experiment at a centre-of-mass energy $\sim$ 91 GeV.

2.1. Charged pions

All LEP collaborations have studied the Bose-Einstein effect in charged pions [2–5] coming from hadronic Z decays. The distribution of R_2 displayed in Figure 1 corresponds to the analysis performed by the L3 collaboration on a data sample corresponding to an integrated luminosity of about 78 pb^{-1}, where 2 million hadronic events were selected. In this case the reference sample consists of Monte Carlo generated events without the Bose-Einstein effect. An enhancement at

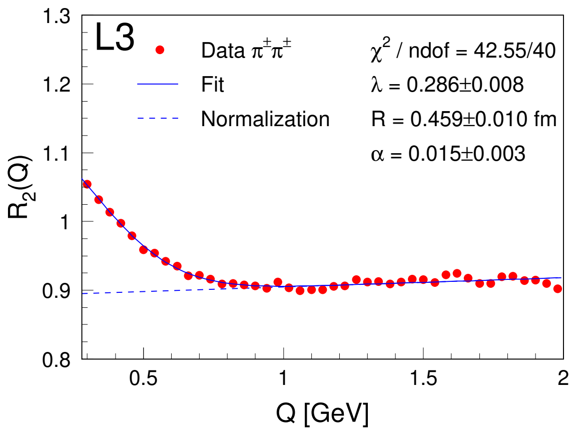

Figure 1. Distribution of R_2 using $\pi^{\pm}\pi^{\pm}$pairs.

low Q values, expected from the Bose-Einstein symmetry, is clearly visible. The function $\mathrm{R}_2(Q)$ from Equation 2 is fitted to this ratio in the interval 300 MeV $< Q <$ 2 GeV. The result of the fit shows that the strength of the correlation is significantly different from zero.

2.2. Neutral pions

The Bose-Einstein effect has rarely been studied in neutral pions and it has been done for the first time in e^+e^- annihilations [5]. Neutral pions in hadronic events are reconstructed with a mass resolution of 7.4 MeV from photon pairs detected in the L3 electromagnetic calorimeter. The π^0 purity of the candidate sample is of the order of 54% and the π^0 selection efficiency is approximately 17%. Figure 2 shows the correlation function, R_2, for neutral pion pairs using as reference sample Monte Carlo events with no Bose-Einstein correlations.

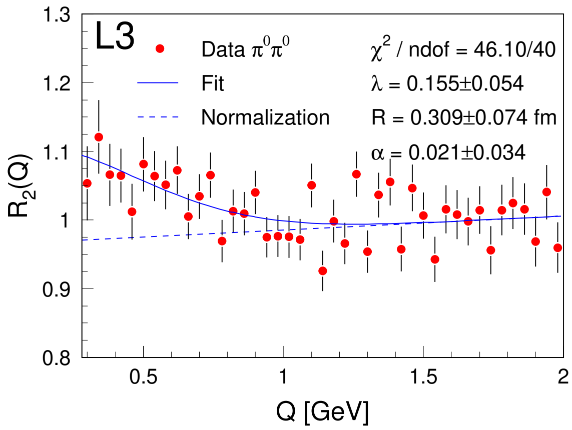

Figure 2. Distribution of R_2 using $\pi^0\pi^0$pairs.

The radius of the neutral pion source is found to be smaller than that of the charged pions:

$$\mathrm{R}_{\pm\pm} - \mathrm{R}_{00} = 0.150 \pm 0.075(\mathrm{stat.}) \pm 0.068(\mathrm{syst.})\mathrm{fm} \quad (3)$$

This result is in qualitative agreement with the string fragmentation model [6], which predicts that two neutral pions can lie together in the same string whereas two like-charged pions cannot.

2.3. Multidimensional analysis of the source

The form of the correlation function in more than one dimension has been a major subject

Table 1
Results of the multidimensional analysis of the BEC source, with the statistical and systematic errors.

	L3	OPAL	DELPHI
r_{side}/r_l	$0.80 \pm 0.02^{+0.03}_{-0.18}$	$0.82 \pm 0.02^{+0.01}_{-0.05}$	
$r_\perp/r_\parallel$			$0.62 \pm 0.02 \pm 0.05$

of theoretical study in recent years. In Monte Carlo generators, spherical symmetry is usually assumed, while elongation can be expected in the case of string fragmentation [7]. Multidimensional analyses have been done in heavy-ion and hadron-hadron collisions and they are now performed at LEP [4,8]. To probe the actual shape of a boson source, Bose-Einstein Correlations are studied in terms of the various components of Q in a chosen reference system. For the LEP analysis the Longitudinal Centre-of-Mass System (LCMS) is used [9] where the correlation function can be parametrised as:

$$\mathrm{C}_2 \simeq 1 + \lambda e^{-Q_l^2 \mathrm{r}_l^2 - Q_{out}^2 \mathrm{r}_{out}^2 - Q_{side}^2 \mathrm{r}_{side}^2} \qquad (4)$$

where r_l and r_{side} represent pure space components (longitudinal and transverse) and r_{out} is a mixture between the time and space (transverse) components. L3 and OPAL perform a three dimensional analysis of the source while DELPHI studies the shape as a function of $Q_\parallel = Q_l$ and $Q_\perp = \sqrt{Q_{out}^2 + Q_{side}^2}$. Figure 3 shows the two-dimensional correlation function measured by DELPHI using 8.1×10^5 hadronic events. The results summarised in table 1 indicate that the transverse size of the boson source in e^+e^- annihilations is smaller than the longitudinal one.

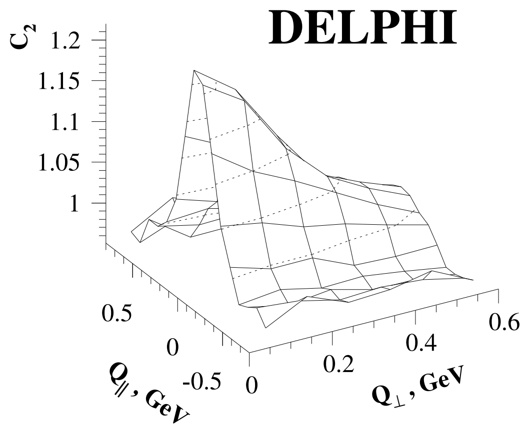

Figure 3. Correlation function as a function of $Q_\parallel$ and $Q_\perp$.

2.4. Three particle correlations

In systems with more than two identical bosons, BEC are also expected to be present. These higher order correlations may affect multihadron production. Furthermore, information not present in two particle correlations can be derived from higher order correlations, such as asymmetries in the particle source shape. Detection of "genuine" multi-boson BEC is complicated as they have to be isolated from the lower order boson correlations and therefore require large data samples. Three particle correlations have been reported at LEP between three identical charged pions [10]. They have been studied as a function of Q_3, where $Q_3^2 = Q_{12}^2 + Q_{23}^2 + Q_{32}^2$, using the three particle correlation function R_3:

$$\mathrm{R}_3 = \frac{\rho_3(p_1, p_2, p_3)}{\rho_0(p_1, p_2, p_3)} \qquad (5)$$

where ρ_3 represents the three particle density and ρ_0 the same density in the absence of the Bose-Einstein effect. The genuine three boson correlation, C_3, is obtained by subtracting from R_3 the term which contains the two-boson correlations contribution. Figure 4 shows the three particle correlation measured by OPAL using 4×10^6 hadronic Z decays.

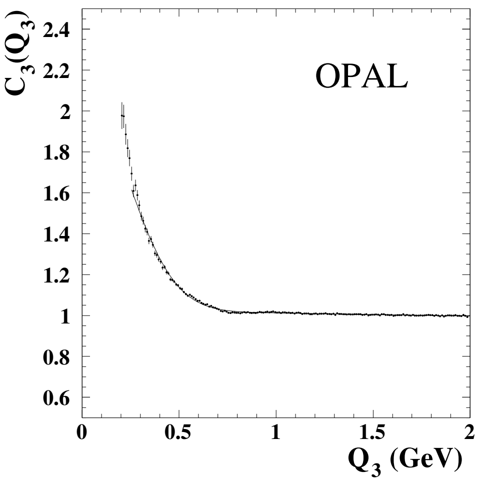

Figure 4. Three particle correlation function, C_3.

2.5. Other analyses done at LEP

Other studies performed at LEP, such as BEC in neutral and charged Kaon pairs, multiplicity dependence of the Bose-Einstein correlations and invariant mass dependence of the particle correlations, can be found in [11].

3. BEC IN $e^+e^- \rightarrow W^+W^-$ EVENTS

W pairs were produced during the second phase of LEP as the centre-of-mass energy increased to $\sim$ 200 GeV. The hadronic decays of the W provided a new scenario to investigate the Bose-Einstein effect inside the W's (intra-BE interference). Furthermore, since in fully hadronic WW events ($e^+e^- \rightarrow W^+W^- \rightarrow q\overline{q}q\overline{q}$), the W decay products overlap in space-time, interference between identical bosons originating from different W's can be expected. This inter-W interference may provide a laboratory to measure the space-time development of this overlap. Moreover, this effect, like colour reconnection can be a source of bias in the determination of the W mass in the four jet channel.

3.1. Intra-W correlations

In the semileptonic channel,WW$\rightarrow q\overline{q}l\nu$, Bose-Einstein correlations are studied in the $q\overline{q}$ system. Figure 5 shows the correlation function, $R^*(Q)$, for semileptonic WW events, calculated using unlike-charged pion pairs as reference sample and taking the double ratio between data and Monte Carlo to restore other sources of correlation not present in the reference sample:

$$R^*(Q) = R_2^{\rm data}/R_2^{\rm MC} \qquad (6)$$

where R_2 is given by equation 1. These results are compared with the correlation function obtained using Monte Carlo events in which the Bose-Einstein correlations have been generated using a tuned version of the model of Lönnblad and Sjöstrand [13], and taking care of the low content in b quarks present in W events. The result of the fit to the data points, assuming a spherical source, gives a value of the strength of the correlation significantly different from zero. The same effect is observed by the other LEP collaborations [12].

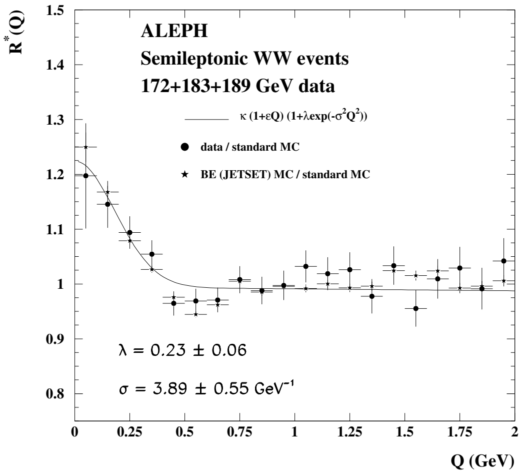

Figure 5. $R^*(Q)$ for data and Monte Carlo with Bose-Einstein correlations for semileptonic WW events. The solid curve shows the result of the fit to the data.

3.2. Inter-W correlations

The main interest of the study of Bose-Einstein correlations in W events is to disentangle whether correlations between particles coming from different W's exist when the two W's decay hadronically [15]. If they exist the momentum transfer between the two W's can affect the W mass determination in the four jet channel.

The hypothesis that the two W's decay independently can be tested studying either the deviation from zero of the following relation [14]:

$$\Delta\rho(Q) = \rho^{\mathrm{WW}}(Q) - 2\rho^{\mathrm{W}}(Q) - \rho^{\mathrm{WW}}_{\mathrm{mix}}(Q) \qquad (7)$$

or, alternatively, a deviation from unity of the ratio:

$$D(Q) = \frac{\rho^{\mathrm{WW}}(Q)}{2\rho^{\mathrm{W}}(Q) + \rho^{\mathrm{WW}}_{\mathrm{mix}}(Q)} \qquad (8)$$

where ρ^{WW}, ρ^{W} and $\rho^{\mathrm{WW}}_{\mathrm{mix}}$ represent the two particle densities for particle pairs coming from a fully hadronic event, the hadronic part of a semileptonic event and pairs from two different semileptonic events which are combined to simulate a fully hadronic event.

The advantage of this method is that it gives access to inter-W correlations directly from the experimental data, and is model independent except for background subtraction.

Figure 6 shows the $D(Q)$ and $\Delta\rho$ variables calculated for like-sign pairs, after background subtraction, using 531 pb^{-1} collected by the DELPHI detector in the energy range from 189 to 209 GeV. The data are compared to Monte Carlo events assuming two different scenarios: one with inter and intra-W correlations and the other assuming only intra-W correlations. The first model shows an enhancement at low values of Q for $D(Q)$ and $\Delta\rho$ not observed in data while there is good agreement between data and the scenario with only intra-W correlations.

An estimation of the strength of the inter-W correlation can be obtained by fitting the D or D' distributions ($D' = D_{\mathrm{data}}/D_{\mathrm{MC,noBEC}}$) to the following function:

$$D(Q) \simeq 1 + \Lambda e^{-Q^2R^2} \qquad (9)$$

where Λ represents the strength of the inter-W correlation. Figure 7 shows the value of Λ obtained by L3 after a fit to the D' distribution for data at different centre-of-mass energies, together with the average value. A similar fit was performed in a Monte Carlo sample generated with inter-W correlations. The result of this fit corresponds to the vertical band situated at the right of the figure. The data significantly disagree with this value, but are consistent with $\Lambda = 0$.

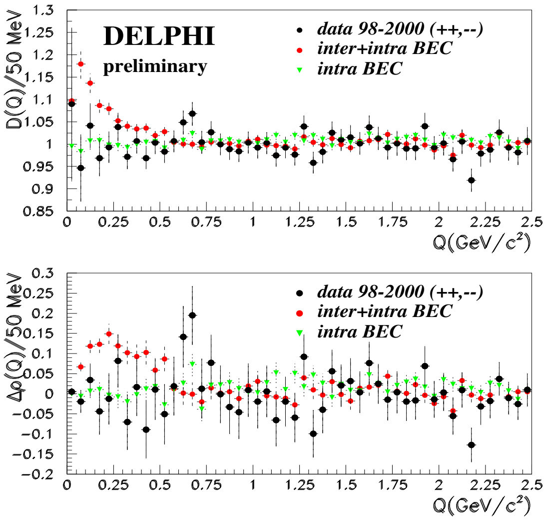

Figure 6. $D(Q)$ (top) and $\Delta\rho$ (bottom) variables for like-sing pairs as measured by DELPHI.

4. CONCLUSIONS

A very detailed study on the Bose-Einstein correlations has been done at LEP using the data collected at $\sqrt{s}\sim$ 91 GeV and $\sqrt{s}\sim$ 200 GeV. BEC have been observed between pairs of like-charged pions as well as neutral pions with an indication of smaller radius for the neutral source compared to the charged one. There is evidence for the elongation of the BEC source along the direction of the motion of the original quark; such effect is not taken into account currently in the modelling of hadronic final states. The contribution coming from three particle correlations has also been

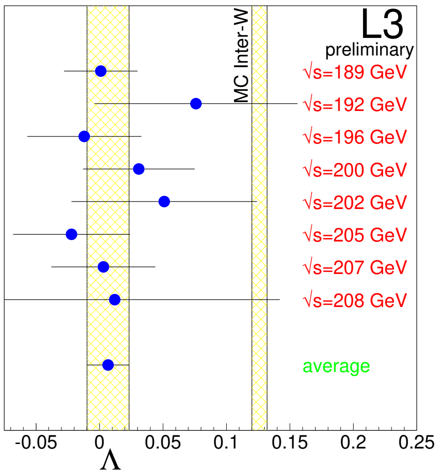

Figure 7. Value of the Λ parameter at different centre-of-mass energies. The error is statistical only.

isolated.

At higher energies, W production has allowed the study of the same effect in hadronic decays of the W. It has been established that BEC correlations exist between pions inside the same W, but there is no evidence for BEC between particles coming from different W's when the two W's decay hadronically.

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