A Study of $K_S^0 K_S^0$ Bose-Einstein Correlations in Hadronic Z^0 Decays

The OPAL Collaboration

Abstract

Bose-Einstein correlations in $K_S^0 K_S^0$ pairs have been studied for the first time in e^+e^- annihilations. These correlations were measured through the quantity Q , the four momentum difference of the pair. Out of about half a million Z^0 hadronic decay events a total of about 6000 events with two or more identified K_S^0 mesons were used for the analysis. We observe a threshold enhancement in $K_S^0 K_S^0$ pairs originating from a mixed sample of $K^0 \bar{K}^0$ and $K^0 K^0$ ($\bar{K}^0 \bar{K}^0$) pairs. Although we can not presently exclude that a part of this effect is due to scalar meson decays, our analysis attributes the enhancement to Bose-Einstein correlations. We find the values for the strength of the effect and the radius of the K_S^0 emitting source to be $\lambda = 1.12 \pm 0.33 \pm 0.29$ and $R_o = (0.72 \pm 0.17 \pm 0.19)$ fm respectively, where the first error is statistical and the second systematic.

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1 Introduction

In particle reactions leading to multihadronic final states the interference between a pair of identical bosons, the so called Bose-Einstein Correlation (BEC), is well known. These correlations lead to an enhancement of the number of identical bosons over that of non-identical bosons when the two particles are close to each other in phase space. Experimentally this effect, also known as the GGLP effect, was first observed by Goldhaber et al., [1] in their study of like-sign charged pions in $p\bar{p}$ annihilations at $\sqrt{s} = 2.1$ GeV. In addition to the quantum mechanical aspect of the BEC, these correlations can be used to estimate the dimension of the emitting source of the identical bosons [2]. Some recent reviews which summarize the underlying theoretical concepts of the BEC and the experimental results are given, for example, in references [3, 4].

These correlations have been observed in like-sign charged pion-pairs over a wide energy range and for many different initial state reactions leading to multi-pion final states. More recently, two charged pion correlations have been studied in high energy e^+e^- annihilation at LEP, on and around the Z^0 mass, where the radius of the pion emitting source was measured by OPAL to be $(0.928 \pm 0.019 \pm 0.150)$ fm [5] whereas ALEPH reported $(0.65 \pm 0.04 \pm 0.16)$ fm [6] and DELPHI obtained $(0.62 \pm 0.04 \pm 0.20)$ fm [7].

In contrast to the ample information published on BEC in pion pairs, very few studies have been reported on correlation effects in charged kaon-pairs [8, 9]. This is also the case for the $K^0\bar{K}^0$ correlation studies [10, 11], which had relatively meager statistics in comparison to the pion samples. An apparent reason for this situation stems from the fact that the production rate of strange particles at center of mass energies so far explored is of the order of 10 to 20% of that of pions so that the number of events with two or more identified K-mesons is rather rare. Furthermore, the experimental methods for separating charged kaons from pions or protons were often lacking. In the case of neutral kaons, most experiments study only the $K_S^0 \rightarrow \pi^+\pi^-$ decay mode resulting in a further reduction in statistics. It is expected that the identical boson systems, $K^0\bar{K}^0$ and $\bar{K}^0 K^0$, will manifest Bose-Einstein correlations, similar to neutral or like-sign charged pion pairs, irrespective of the specific decay state chosen. Of special interest however, is the case of the non-identical $K^0\bar{K}^0$ system. Although this is a boson-antiboson system, a BEC-like enhancement is nevertheless expected, as will be shown later, provided one selects the $C = +1$ charge conjugation eigenvalue state of $K_S^0 K_S^0$ or $K_L^0 K_L^0$.

In the present paper we report on a study of the Bose-Einstein correlations in the $K_S^0 K_S^0$ system produced in about half a million Z^0 multihadronic decay events measured with the OPAL detector at LEP. The experimental set-up and data selection are described in Section 2. Section 3 is devoted to the description of the analysis technique, also utilized previously to measure the Bose-Einstein effect in like-sign pion-pairs. In the same section we show that the BEC effect should also be seen in the $K_S^0 K_S^0$ system, independent of whether its origin is a $K^0\bar{K}^0$ or a $\bar{K}^0 K^0$ ($\bar{K}^0 \bar{K}^0$) pair. The physics analysis, the choice of a reference sample and the BEC results are given in Section 4. In Section 5 we discuss the possible contribution from the decays of the $f_o(975)$ and $a_o(980)$ resonances to the BEC effect and compare our results to former BEC studies carried out with kaon and pion-pairs.

2 The Experiment

Experimental Set-up

The OPAL detector is designed to measure outgoing particles coming from e^+e^- annihilations at high energies. Details concerning the OPAL detector and its performance are given elsewhere [12] so here we will describe briefly only those detector elements pertinent to the present analysis, namely, the central tracking chambers. These consist of a precision vertex detector, a large jet chamber and additional z-chambers surrounding the jet chamber. The vertex detector, a 1 m long cylindrical drift chamber of 470 mm diameter, surrounds the beam pipe and consists of an inner layer of 36 cells each with 12 sense wires and an outer layer of 36 small angle (4°) stereo cells each with 6 sense wires. The jet chamber has a length of 4 m and a diameter of 3.7 m. It is divided into 24 sectors, each equipped with 159 sense wires ensuring a large number of measured points even for particles emerging from a secondary vertex. The z-chambers consist of 24 drift chambers, 4 m long, 50 cm wide and 59 mm thick. They are subdivided in 8 cells each with 6 sense wires perpendicular to those of the jet chamber and provide an exact measurement of the z coordinate along the beam direction¹. They cover polar angles from 44° to 136° and 94% of the azimuthal angle. All the chambers are contained in a solenoid providing an axial magnetic field of 0.435 T.

Data Selection

The present study was carried out with 499,000 hadronic Z^0 decay events corresponding to an integrated luminosity of about 20.8 pb^{-1} collected during 1990 and 1991 at center of mass energies on and around the Z^0 mass. The criteria used for the selection of the Z^0 hadronic decay event sample were described previously [13]. In addition, we have accepted only multi-hadron events recorded while the jet and z-chambers were fully operational. At least 5 well reconstructed charged tracks were required for each event.

The method for finding K_S^0 decays into $\pi^+\pi^-$ was essentially the same as that used in a former OPAL study of inclusive Z^0 decays into K_S^0 mesons [14]. It started by systematically pairing tracks of opposite charge. These tracks had to fulfil the following conditions: a minimum transverse momentum of 150 MeV/c with respect to the beam direction and more than 50 % of the possible jet chamber hits (at least 20). Each track was also required to have more than 3 z-chamber hits or a reconstructed end point inside the jet chamber, determined by using the last wire with a hit. These requirements ensure a good mass resolution by improving the measurement of the polar angle. Furthermore, the radial distance of the track to the beam axis at the point of closest approach was required to exceed 3 mm to reduce the large combinatorial background.

Intersection points of track pairs in the radial plane were considered to be secondary vertex candidates. Additional cuts were then imposed on these pairs. The radial distance from the intersection point to the primary vertex had to be larger than 1 cm and the reconstructed momentum vector of the K_S^0 candidate in the plane perpendicular to the beam axis had to point to the beam axis within 2° . In the case where both intersections of the track pair passed these cuts, the one closer to the beam axis was taken.

¹A right-handed coordinate system is adopted by OPAL, where the x axis points to the center of the LEP ring, and positive z is along the electron beam direction. The angles θ and ϕ are the polar and azimuthal angles, respectively.

All the track-pairs which passed these cuts were refitted with the constraint that they originate from a common 3-dimensional vertex. Pairs with an invariant mass of less than 100 MeV/ c^2 , when assuming both tracks to be electrons, were taken to be photon conversions and were rejected.

The mass distribution of the reconstructed K_S^0 decays is shown in Fig. 1 assuming both tracks to be pions. As can be seen, a prominent peak is observed at the K^0 mass value. The distribution was fitted with a Gaussian shape plus a polynomial expression for the background. The measured K^0 mass value thus obtained was 496.9 ± 0.1 MeV/ c^2 , consistent² with the world average of 497.671 MeV/ c^2 [15]. The obtained width of $\sigma = 7.0 \pm 0.1$ MeV/ c^2 , corresponds to our experimental mass resolution. In order to reduce the background we have introduced a cut on the measured K^0 mass of ± 25 MeV/ c^2 from the mean fitted value. This cut reduced the background to $(11 \pm 1)\%$ coming mainly from accidentally reconstructed secondary vertices and from some (about 2%) misidentified Λ -hyperons. Correspondingly the estimated background in this sample in terms of pairs of K_S^0 candidates, which in the following will be referred to as $K_S^0 K_S^0$ pairs, was then $(21 \pm 1)\%$ that is, a signal of $(79 \pm 1)\%$. In this way we were left with a total of 5501 events having two identified $K_S^0 \rightarrow \pi^+ \pi^-$ decays, 465 with three K_S^0 decays and 23 events with a higher K_S^0 candidate multiplicity.

3 Analysis Tools

Bose-Einstein correlations in particle physics are in general described in terms of a normalized correlation function C defined as:

$$C(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_o(p_1, p_2)} \quad (1)$$

where p_1 and p_2 are the four momenta of the two bosons, $\rho(p_1, p_2) = (1/\sigma)(d^8\sigma/d^4p_1 d^4p_2)$ is the measured density for two identical bosons and $\rho_o(p_1, p_2)$ is the two particle density in the absence of BEC which we will refer to as the reference sample distribution.

In conjunction with the studies of BEC in pion pairs several parametrizations of the correlation function C can be found [3, 4, 16]. For the correlation function C we have used the Lorentz invariant variable Q

$$Q^2 = -(p_1 - p_2)^2 \quad (2)$$

which was also used in previous studies of the BEC in e^+e^- multihadronic annihilations [4]. For two identical particles Eq. 2 can be rewritten as

$$Q^2 = M^2 - 4m^2 \quad (3)$$

where M^2 is the invariant mass squared of the two particles and m is the rest mass of each of them.

The correlation function $C(Q)$ at $Q = 0$ attains the value 1 in the absence of BEC and the value 2 in the presence of BEC of two identical bosons. However, in the case of like-sign charged pions, i.e. $\pi^+\pi^+$ or $\pi^-\pi^-$ pairs, the experimental values [4] are found to be between 1 and 2. This deviation from the expected theoretical value of 2 may indicate that not all pairs of particles are emitted from purely incoherent sources. Furthermore, not all particle pairs used

²The quoted errors are statistical only. The difference between the measured K_S^0 mass and the world average can be explained by the uncertainty in the mean value of the OPAL magnetic field.

are formed from identical bosons which further reduces the value of $C(Q = 0)$. If the particle source is assumed to have a Gaussian shape, $C(Q)$ can be parametrized as follows [3]:

$$C(Q) = (1 + \lambda e^{-Q^2 R^2}) \quad (4)$$

where the parameter R is related to the boson emitter size R_o in fm through the relation $R_o = \hbar c R$. The parameter λ , often called the strength or chaoticity parameter, measures the strength of the effect and can vary between 0 and 1. In practice the data are fitted to an expression of the type

$$C(Q) = N(1 + f(Q)\lambda e^{-Q^2 R^2})\phi(Q) \quad (5)$$

where N is a normalization factor and $\phi(Q)$ is a term of the type $(1 + \delta Q + \epsilon Q^2)$. It accounts for the rise of the correlation function at large Q values due to long range two-particle correlations, imposed, for example, by charge and energy conservation and phase space constraints. In order to keep λ as the strength parameter only for the boson under study, one introduces a function $f(Q)$, to be determined experimentally. This function should account for the background effects and their possible Q dependence. Here it should also be noted that, unlike the case of charged pion pairs, no Coulomb corrections are needed since the $K_S^0 K_S^0$ pair is a system of neutral particles.

For the BEC study of charged pion or charged kaon final states, the identical boson-pair system is simply guaranteed by the requirement that they have the same charge sign. In the case of the BEC study of $K_S^0 K_S^0$ pairs the origin may come either from a pair of identical $K^0 K^0$ ($\bar{K}^0 \bar{K}^0$) mesons or from a non-identical $K^0 \bar{K}^0$ boson-antiboson system. From a sample of Monte Carlo generated events, to be discussed later, we have estimated that about 2/3 (3/4 for $Q < 1$ GeV) of our data sample of two K_S^0 events originate from a $K^0 \bar{K}^0$ pair and the rest from pairs of K^0 or $\bar{K}^0$ mesons. This being the case, when trying to estimate the expected BEC effect one needs to discuss separately these two sources of the $K_S^0 K_S^0$ pairs. In the following discussion we neglect effects due to CP violation.

1) $K^0 K^0$ and $\bar{K}^0 \bar{K}^0$ Decays

In this case we deal with identical bosons which should show the BEC effect in all their decay combinations. In particular the BEC effect should also be observed in the $K_S^0 K_S^0$ pairs studied in this work.

2) $K^0 \bar{K}^0$ Decay

The system $K^0 \bar{K}^0$ is an eigenstate of the charge conjugation operator C having two possible eigenvalues $C = +1$ and $C = -1$. The probability amplitude $|K^0; \bar{K}^0\rangle$ can be written as:

$$|K^0; \bar{K}^0\rangle = \frac{1}{\sqrt{2}} |K^0; \bar{K}^0\rangle_{C=+1} + \frac{1}{\sqrt{2}} |K^0; \bar{K}^0\rangle_{C=-1} \quad (6)$$

It consists of a pair of non-identical bosons which should *a priori* not show any BEC effect. Following Lipkin [17] we can write the probability amplitude for a given charge conjugation eigenvalue C as follows:

$$\frac{1}{\sqrt{2}} |K^0; \bar{K}^0\rangle_{C=\pm 1} = \frac{1}{2} |K^0(\mathbf{p}); \bar{K}^0(-\mathbf{p})\rangle \pm \frac{1}{2} |\bar{K}^0(\mathbf{p}); K^0(-\mathbf{p})\rangle \quad (7)$$

where $\mathbf{p}$ is now the three momentum vector defined in the $K^0\bar{K}^0$ center of mass system. In the limit of $Q = 0$, where the BEC should be maximal, $\mathbf{p} = 0$ and Eq. 6 reads

$$\frac{1}{\sqrt{2}} |K^0; \bar{K}^0\rangle_{C=\pm 1} = \frac{1}{2} |K^0(0); \bar{K}^0(0)\rangle \pm \frac{1}{2} |\bar{K}^0(0); K^0(0)\rangle \quad (8)$$

This means that, at $Q = 0$, the probability amplitude for the $C = -1$ state is zero whereas that of the state $C = +1$ is maximal. This will be also the case for boson-antiboson pairs such as $\pi^+\pi^-$ or K^+K^- .

It is well known that the K^0 and the $\bar{K}^0$ mesons are described in terms of the two CP eigenstates, K_S^0 with CP=+1 and K_L^0 with CP=-1. This being the case, then when the $K^0\bar{K}^0$ pair is detected through the K_S^0 and K_L^0 decays, the eigenvalue C of the $K^0\bar{K}^0$ system is determined. Thus, as Q approaches zero, an enhancement would be observed in the probability to detect $K_S^0K_S^0$ pairs and $K_L^0K_L^0$ pairs ($C = +1$) whereas a depletion would occur in the $K_S^0K_L^0$ pairs ($C = -1$). Since the present work is restricted to $K_S^0K_S^0$ pairs, which picks out only the $C = +1$ state, a BEC enhancement is expected. Note, however, that if all the decay modes of the $K^0\bar{K}^0$ pairs were detected, then according to Eq. 7, no BEC effect will be observed at $Q = 0$. This however should not be a surprise because the $K^0\bar{K}^0$ system is not composed of identical bosons.

In conclusion, when studying the $K_S^0K_S^0$ pairs, as in this work, a BEC-like enhancement should be observed similar to that of like-sign charged pions and charged kaons, even if the $K_S^0K_S^0$ pairs originate from a $K^0\bar{K}^0$ boson-antiboson system.

4 Physics Analysis and Results

The invariant mass distribution M_{KK} of all K_S^0 -pairs is shown in Fig. 2a. This distribution, which reaches its maximum near threshold, is seen to decrease smoothly as M_{KK} increases apart from some concentration of events around 1.5 GeV/ c^2 . This mass enhancement may be associated with the isoscalar $J^{PC} = 2^{++}$ $f_2'(1525)$ resonance. In addition some indication is also present in the data for the production of the $f_o(1710)$ resonance with the same quantum numbers. Furthermore, two lower mass resonances, the $f_o(975)$ and $a_o(980)$, are known to exist below the $K\bar{K}$ threshold and their relation to our analysis will be discussed later on. Note that the $\phi(1020)$ does not decay to $K_S^0K_S^0$.

To construct the correlation function $C(Q)$ it is necessary to have a reference sample distribution $\rho_o(Q)$ which should simulate the data distribution $\rho(Q)$, shown in Fig. 2b (full circles), in all its features except the BEC. In the various studies of the $\pi^\pm\pi^\pm$ system the immediately available and obvious reference sample was that obtained from the $\pi^+\pi^-$ pairs in the same data events. Such a data based reference sample does not exist for the BEC investigations of $K_S^0K_S^0$ -pairs. In particular the system $K_S^0K_L^0$, which is identical in its kinematic properties to the $K_S^0K_S^0$ -pairs, is excluded not only for experimental difficulties (the long life-time of K_L^0) but also due to the presence of the destructive interference discussed in Sec. 3.

In principle one can consider the data of $K^\pm K_S^0$ or K^+K^- pairs as reference samples. However in our experiment, as in many others, the identification of charged kaons is limited to a restricted momentum range. Furthermore, the K^+K^- system is plagued by the presence of the $\phi(1020)$ vector meson lying near $Q = 0$. For these reasons we have considered in this work only two possible reference samples, namely, a generated Monte Carlo sample and the event mixing method applied to data events.

For the generation of a Monte Carlo reference sample we have used the JETSET 7.3 program [18] with its BEC option switched off and its free parameters set to values which best describe the OPAL multi-hadron event shape distributions [19]. The generated events were passed through a detailed detector simulation [20] and were analyzed with the same programs as our data events. A JETSET generated sample has previously been successfully applied to the OPAL inclusive K_S^0 analysis [14]. In this version of the Monte Carlo program however, no provision has been made to account for the decay of resonances into a $K_S^0 K_S^0$ final state. For the present analysis we utilized a sample of about 570,000 events. To verify that the Monte Carlo events are adequate to be used as a reference sample, we have checked that its features pertaining to events with more than one K_S^0 candidate in the final state, which are relatively insensitive to the BEC effect, were in good agreement with the data. This agreement is seen for example in Fig. 3a where a comparison is made between the Monte Carlo distribution of the angle between the $K_S^0 K_S^0$ pair and that obtained from the data. A similar agreement is seen in Fig. 3b where the sum of the momentum values of the two K_S^0 candidates is plotted. In the insert of the same figure this sum of momenta is plotted for the low pair masses with $M_{KK} \leq 1.1 \text{ GeV}/c^2$ where the BEC is expected to be concentrated. Finally in Fig. 2b we show the Monte Carlo Q distribution in the range $0 \leq Q \leq 2.0 \text{ GeV}$ where it is compared with the corresponding distribution for the data.

We have also considered the use of the HERWIG Monte Carlo generator [21] with the detailed OPAL detector simulation which previously was able to describe the inclusive K_S^0 production seen in the OPAL data [14]. However we found that this generated sample fails to describe multi- K_S^0 systems. In particular the distribution of the angle between the $K_S^0 K_S^0$ pair shows marked differences between HERWIG and the data over the whole angular region. A similar failure of HERWIG to describe the two particle system in OPAL data has already been observed in the energy-energy correlation function study [22]. We have therefore not used the HERWIG Monte Carlo as a reference sample.

In the event mixing method one combines a $K_S^0 K_S^0$ pair originating from two different e^+e^- annihilation events which therefore should be void of BEC. This method, in its simplest application, is unsuitable at high energies where a distinct hadron jet structure is present. In order to try and correct the method for this deficiency we have adopted the following procedure. First we have utilized only pairs of multihadronic events which had two identified K_S^0 decays each. Next we rotated the $K_S^0 K_S^0$ pair of one event so that its higher momentum K_S^0 coincided in its direction with the higher momentum K_S^0 of the second event. We then calculated the Q values from the two possible mixed $K_S^0 K_S^0$ pairs. In order to verify whether the mixed event method is able to serve as a reference sample, we have first applied it to the generated sample. A comparison between the Monte Carlo mixed event Q distribution to that obtained from the Monte Carlo sample using $K_S^0 K_S^0$ pairs of the same event revealed a large and significant difference in particular at the low Q values ($< 0.2 \text{ GeV}$) which are most sensitive to the BEC. This discrepancy arises because event mixing not only destroys the Bose-Einstein correlations, but also all other conceivable correlations such as those coming from gluon emission and the fragmentation process. Difficulties of the event mixing method due to the hadron jet topology at high energies have already been noted previously in a BEC study of like-sign charged pion pairs [6]. In kaon pairs these difficulties may well be aggravated due to the lower number of pair combinations per event. The reference sample was thus chosen to be derived from about 570,000 JETSET Monte Carlo events which did not include the BEC, using the $K_S^0 K_S^0$ pairs of the same event, as displayed in Fig. 2b.

The correlation function $C(Q)$, defined by Eq. 1, was obtained by dividing the data dis-

tribution, bin by bin, by the reference sample distribution shown in Fig. 2b. The reference sample is normalized to the total number of the $K_S^0 K_S^0$ pairs in the data within the range of $0.65 \leq Q \leq 1.1$ GeV and $1.55 \leq Q \leq 2.0$ GeV. This range was chosen in such a way as to avoid, on one hand, the resonance region from 1.1 to 1.55 GeV and, on the other hand, the BEC effect range. The resulting $C(Q)$ distribution is shown in Fig. 4a in the range $0 \leq Q \leq 2.0$ GeV and in Table 1.

Q [GeV]	correlation function $C(Q)$
0. – 0.2	1.71 ± 0.36
0.2 – 0.35	1.29 ± 0.14
0.35 – 0.5	1.09 ± 0.09
0.5 – 0.65	1.01 ± 0.08
0.65 – 0.8	0.92 ± 0.06
0.8 – 0.95	1.02 ± 0.07
0.95 – 1.1	0.98 ± 0.07
1.1 – 1.25	1.10 ± 0.08
1.25 – 1.4	1.00 ± 0.08
1.4 – 1.55	1.31 ± 0.11
1.55 – 1.7	1.11 ± 0.10
1.7 – 1.85	1.00 ± 0.10
1.85 – 2.0	1.07 ± 0.11

Table 1: The measured correlation function $C(Q)$ in 13 bins for $0. \leq Q \leq 2.0$ GeV. The errors represent the combined statistical uncertainty of the data and Monte Carlo samples.

The Q resolution, as found in the Monte Carlo generated sample, was better than 20 MeV over the whole Q range under study. In the data sample this resolution is expected to be slightly wider but still much narrower than the chosen Q bin size. It can be seen from Fig. 4a that, for $Q \geq 0.5$ GeV, the distribution is consistent with unity if the Q range of the $f_2'(1525)$ and $f_0(1710)$ mesons is disregarded. At smaller Q values an enhancement is seen as the correlation function $C(Q)$ increases and reaches a value of about 1.7 at $Q \approx 0.1$ GeV. This behavior is very similar to the BEC seen in the $\pi^\pm \pi^\pm$ systems³. We then fitted the expression given in Eq. 5 to the data. Since it was found that $\phi(Q)$ was essentially independent of Q in the range of $0 \leq Q \leq 2.0$ GeV where the fits were carried out, we have set $\epsilon = 0$, so that Eq. 5 reduces to

$$C(Q) = N(1 + f(Q)\lambda e^{-Q^2 R^2})(1 + \delta Q) \quad (9)$$

For the $C(Q)$ fits to the data we have used the least χ^2 method and set $f(Q)$ to a constant, namely $f(Q)=0.79$, since it was found from the Monte Carlo studies that the non $K_S^0 K_S^0$ background was essentially independent of Q .

In the first fit we have left the four quantities λ, R_o, δ and N free. Next we reduced the free parameters to three, namely, to λ, R_o and δ where the factor N was determined by the requirement that the area under the fitted $C(Q)$ curve be equal to that given by the data points. Due to the fact that the value obtained for the parameter δ was found to be consistent with

³A similar behavior is also seen at the JETSET 7.3 generator level when the parameters addressed to the BEC in $K_S^0 K_S^0$ pairs are set to those determined from the pion studies [5].

zero both for the 4 and 3-parameter fits, we have further set $\delta = 0$ and repeated the analysis with a 2-parameter fit to λ and R_o . The results of these fits are presented in Table 2 where DOF stands for the number of Degrees Of Freedom. All fits have acceptable values for χ^2/DOF and, within errors, result in consistent values for the parameters λ and R_o . In the following we will refer to our final 2-parameter result as the reference fit.

Type of Fit	χ^2/DOF	λ	R_o (fm)	δ (GeV $^{-1}$)	N
4-parameter (λ, R_o, δ, N)	1.9/6	1.13 ± 0.47	0.61 ± 0.16	0.10 ± 0.11	0.89 ± 0.11
3-parameter (λ, R_o, δ)	2.9/7	1.01 ± 0.49	0.71 ± 0.18	0.01 ± 0.04	—
2-parameter (λ, R_o)	3.4/8	1.12 ± 0.33	0.72 ± 0.17	—	—

Table 2: Results of the χ^2 fits of $C(Q)$, as defined in Eq. 9, to the data in the range of $Q=0$ to $Q=2.0$ GeV. The region of the $f'_2(1525)$ and $f_o(1710)$ resonances, $1.1 \leq Q \leq 1.55$ GeV, has been omitted from the fit. The errors are statistical only.

Fit conditions	χ^2/DOF	λ	R_o (fm)
[a] reference fit	3.4/8	1.12 ± 0.33	0.72 ± 0.17
[b] modified track selection	4.5/8	1.10 ± 0.41	0.71 ± 0.22
[c] K_S^0 mass cut: ± 20 MeV/ c^2	3.4/8	1.06 ± 0.38	0.78 ± 0.23
[d] K_S^0 mass cut: ± 30 MeV/ c^2	3.9/8	1.11 ± 0.29	0.64 ± 0.13
[e] Q -range: 0 to 1.1 GeV	1.4/5	1.07 ± 0.28	0.66 ± 0.16
[f] Q -range: 0 to 2.0 GeV	12.0/11	1.18 ± 0.37	0.80 ± 0.18
[g] $f(Q)=0.73 + 0.06 \cdot Q$	3.4/8	1.20 ± 0.36	0.73 ± 0.17

Table 3: Results from a study of the χ^2 fit dependence on the selection criteria and the fit conditions (see text). The errors are statistical only.

To estimate the dependence of our final results on the K_S^0 selection criteria we have repeated the analysis modifying these criteria within plausible ranges. The results of the corresponding 2-parameter fits are summarized in Table 3. First, the track selection was changed by limiting the acceptance range to tracks with a polar angle between 44° and 136° (row [b] in Table 3). We then changed the cut on the reconstructed mass of the K_S^0 from ± 25 MeV/ c^2 to ± 20 MeV/ c^2 (row [c]) and ± 30 MeV/ c^2 (row [d]). It is interesting to note that when we widen this cut to ± 75 MeV/ c^2 or more, we observe a significant decrease of the enhancement, indicating thereby that the effect does not come from the background.

To examine the dependence of our fit on the Q range chosen for normalization and fit, we modified it as follows. First, we select the Q range of $0 \leq Q \leq 1.1$ GeV to avoid the range of influence of the $f'_2(1525)$ and $f_o(1710)$ mesons altogether (row [e]). Next we used for the normalization and the fit the full Q -range 0 to 2.0 GeV thereby including the resonance region (row [f]). Finally, in row [g], we used for $f(Q)$, instead of a constant, a linear function in Q . We determined the slope from Monte Carlo studies of the background under the K_S^0 peak and chose the maximum slope allowed within one standard deviation from the mean value. As can be seen from Table 3, all the fit results are in good agreement. To estimate the systematic error

from the variation of the selection and the fit conditions we assumed the deviations from the reference fit values to be independent. Adding them in quadrature we obtained an uncertainty of ± 0.13 and ± 0.14 fm for the λ and R_o values respectively.

Fit conditions	χ^2/DOF	λ	R_o (fm)
[a] reference fit	3.4/8	1.12 ± 0.33	0.72 ± 0.17
[b] $\Lambda_{QCD} = 0.28$ GeV	3.0/8	1.04 ± 0.32	0.69 ± 0.16
[c] $\Lambda_{QCD} = 0.31$ GeV	3.4/8	1.32 ± 0.37	0.77 ± 0.16
[d] $Q_o = 0.70$ GeV	3.6/8	1.25 ± 0.34	0.75 ± 0.15
[e] $Q_o = 1.80$ GeV	4.7/8	1.26 ± 0.34	0.74 ± 0.15
[f] $\sigma_q = 0.32$ GeV	14.6/8	1.12 ± 0.38	0.91 ± 0.22
[g] $\sigma_q = 0.40$ GeV	2.5/8	1.07 ± 0.30	0.65 ± 0.14
[h] $a = 0.13$	3.3/8	1.31 ± 0.36	0.75 ± 0.15
[i] $a = 0.30$	4.7/8	1.26 ± 0.34	0.74 ± 0.15
[j] $(\frac{V}{V+P})_S = 0.43$	4.9/8	1.05 ± 0.37	0.65 ± 0.18
[k] $(\frac{V}{V+P})_S = 0.68$	4.6/8	1.38 ± 0.41	0.85 ± 0.19

Table 4: Results from a study of the χ^2 fit dependence on several parameters of the JETSET 7.3 reference sample which control the momentum distribution of hadrons. The errors are statistical only.

As observed in previous BEC studies of charged pion pairs, an obvious important source of systematic errors comes from the particular choice of the reference sample. These systematic errors were estimated in the di-pion studies from a comparison of several acceptable reference samples. Here however, we are limited to only one reference sample as discussed above.

This being the case we adopted the following method to estimate the systematic uncertainties. Event samples were generated with the JETSET 7.3 program by varying, one at a time, its free parameters by one standard deviation from the optimized values given in Ref. [19]. The following parameters were varied: the QCD cut off parameter Λ_{QCD} , the Q_o parameter which specifies the minimum parton virtuality to which partons may evolve, σ_q which controls the transverse momentum spectrum of hadrons and the parameter a which determines the longitudinal momentum spectrum. Finally we varied the ratio of strange vector mesons to vector plus pseudoscalar mesons. The higher value is derived from the mean value and the errors given in [23], while the lower value was presented by this experiment in [24]. The resulting Q distributions were then divided by the standard generated distribution before detector simulation. Through this division we obtained values which have been used as Q dependent weights to modify the standard reference sample with full detector simulation. Finally with these modified distributions we repeated the BEC analysis. The values of the changed parameters and the fit results are given in Table 4.

We estimated the systematic uncertainties coming from our choice of the reference sample from the variation of the parameters given in Table 4. These were found to be strongly correlated. Therefore we evaluated the systematic errors by taking the maximum deviations from the reference fit values. These were found to be ± 0.26 for the λ value and ± 0.13 fm for the R_o value. Due to the unacceptable fit obtained for $\sigma_q = 0.32$ we omitted the values given in row [f] from our systematic errors study. Finally we added in quadrature the contributions from

the variations of the selection and the fit conditions to the reference sample uncertainties, such that our final values for the parameters λ and R_o are:

$$\lambda = 1.12 \pm 0.33 \pm 0.29 \quad R_o = (0.72 \pm 0.17 \pm 0.19) \text{ fm}$$

The first quoted error is statistical and the second systematic. The results of the 2-parameter χ^2 reference fit are also illustrated in Fig. 4b in a 2-dimensional plot of λ versus R_o . The contours represent the λ and R_o values having confidence levels of 50% and 90% as calculated from the statistical errors. As can be seen, even though the values of λ and R_o are somewhat correlated, a value of $\lambda = 0$ is excluded with more than 90% confidence level.

5 Summary and Conclusions

An enhancement at small values of Q is seen in our sample of $K_S^0 K_S^0$ pairs produced in the reaction $e^+e^- \rightarrow Z^0 \rightarrow K_S^0 K_S^0 + X$. We attribute this enhancement to Bose-Einstein correlations. In principle, the scalar mesons $f_o(975)$ and $a_o(980)$, established via their decays to $\pi\pi$ and $\eta\pi$, respectively, can contribute to the $K_S^0 K_S^0$ mass distribution in the neighbourhood of the $K\bar{K}$ threshold. To estimate the contribution of meson decays one requires the knowledge of the production rate in Z^0 decays, the decay rate to $K\bar{K}$ and a model to describe the $K\bar{K}$ mass spectrum above threshold. At the current time none of these factors are known with sufficient certainty. Furthermore, the former analyses of this decay mode have not addressed the question of a BEC enhancement in the $K_S^0 K_S^0$ channel. We have looked for evidence for scalar mesons in the K^+K^- mass spectrum [24] but can draw no conclusions due to the limited sensitivity. Therefore, no reliable quantitative estimate is possible from these analyses. Nevertheless, we cannot presently exclude that a part of the enhancement is in fact due to the scalar meson decays.

In Table 5 we present our λ and R_o values together with those three results previously reported in BEC studies of kaon-pairs and in recent studies of charged pion pairs at LEP. In comparing our results with those listed in Table 5 one should keep the following in mind:

- 1) The former experiments were carried out in hadron-hadron reactions. This is the first time that Bose-Einstein correlations have been observed between $K_S^0 K_S^0$ pairs in e^+e^- annihilations. It should be noted that the λ values for $\pi^\pm\pi^\pm$ correlations obtained in hadronic reactions are in general lower than those obtained in e^+e^- annihilations [4].
- 2) The former experiments have used the variables q_t, q_o of Ref. [16] which tend to yield higher values of R_o than those obtained through the analysis of the Q variable used here [4].
- 3) Our result for R_o is consistent with that reported by the only previous BEC study of $K_S^0 K_S^0$ pairs, described in Ref. [11]. However, that experiment has not extracted a value for the chaoticity parameter λ .
- 4) Finally it also should be mentioned that a meaningful comparison is handicapped because the various experiments have used different types of reference sample and different methods, if at all, to offset the background and account for Coulomb effects. For this reason we give in Table 5 in brackets our values for λ and R_o without the background correction.

Notwithstanding these reservations, our result for the chaoticity parameter λ is in agreement with those obtained for charged kaon-pairs. On the other hand, our R_o value is consistent with the one obtained previously for the $K_S^0 K_S^0$ system but lower than those obtained for the $K^\pm K^\pm$ pairs.

Experiment	Reaction	$\sqrt{s}$ (GeV)	Variable	λ	R_o (fm)
$K^\pm K^\pm$, Ref. [8]	$pp, \bar{p}p, \alpha\alpha$	53 - 126	q_t, q_o	0.58 ± 0.31	2.4 ± 0.9
$K^\pm K^\pm$, Ref. [9]	pp	27.4	q_t, q_o	0.57 ± 0.26	1.87 ± 0.33
$K_S^0 K_S^0$, Ref. [11]	$\bar{p}p$	2.0	q_t, q_o	—	0.9 ± 0.2
$K_S^0 K_S^0$, this study	e^+e^-	91	Q	1.12 ± 0.33 (0.89 ± 0.26)	0.72 ± 0.17 (0.71 ± 0.17)
$\pi^\pm \pi^\pm$, ALEPH Ref. [6]	e^+e^-	91	Q	0.51 ± 0.04	0.65 ± 0.04
$\pi^\pm \pi^\pm$, DELPHI Ref. [7]	e^+e^-	91	Q	0.40 ± 0.03	0.62 ± 0.04
$\pi^\pm \pi^\pm$, OPAL Ref. [5]	e^+e^-	91	Q	1.08 ± 0.05	0.93 ± 0.02

Table 5: Results for λ and R_o obtained from BEC studies of like-sign charged kaons, charged pions and K_S^0 pairs using the Goldhaber variable Q and the variables q_t and q_o of Kopylov and Podgoretskii [16]. These are defined as follows: if $q = p_1 - p_2 = (q_o, \mathbf{q})$ then q_t denotes the component of $\mathbf{q}$ perpendicular to $\mathbf{p}_1 + \mathbf{p}_2$, where $\mathbf{p}_1$, $\mathbf{p}_2$ and $\mathbf{q}$ are the three momenta vectors. Given in brackets is the result of our analysis without the correction for background effects. The errors given are statistical only.

Finally it is of interest to compare our results for the dimension of the K_S^0 source and its chaoticity parameter to those found for the pion source in e^+e^- annihilations at the same energy. As can be seen from Table 5, our values for λ and R_o are similar to those obtained for like-sign charged pions.

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Figure Captions

Figure 1: The $\pi^+\pi^-$ invariant mass distribution of the K_S^0 candidates in OPAL data.

Figure 2: a) The invariant mass distribution M_{KK} and b) the dN/dQ distribution for OPAL data $K_S^0 K_S^0$ pairs (full circles) compared to the same distribution obtained from the Monte Carlo simulated events (line histogram). Due to the relatively small statistics at Q values near 0 GeV, we have taken a wider bin for the first one in order to keep its statistical error comparable to those at higher Q values. The area under the Monte Carlo distribution is normalized to the data sample.

Figure 3: Comparison of the data to JETSET Monte Carlo generated events: a) The distribution of the cosine of the angle between the two K_S^0 candidates, $\cos(K_S^0, K_S^0)$. b) The sum of the momentum values of the two K_S^0 candidates. The insert illustrates the same distribution for the low mass range $M_{KK} \leq 1.1$ GeV/ c^2 only. The areas are normalized to unity. The data points (full circles) are compared with the corresponding distribution (lined histogram) obtained from the Monte Carlo sample void of the BEC effect. The statistical errors for the Monte Carlo sample are of about the same size as that of our data.

Figure 4: a) The measured correlation function $C(Q)$ in the range $0.0 \leq Q \leq 2.0$ GeV. The error bars represent the combined statistical uncertainty of the data and Monte Carlo samples. The solid line represents the best fit to the data using Eq. 5 with a 2-parameter χ^2 fit. The region of the $f_2'(1525)$ and the $f_o(1710)$ has been omitted from the fit (see text).
b) λ versus R_o obtained in a 2-parameter χ^2 fit of $C(Q)$ to the data. The cross represents our best values and the contours around it represent the allowed regions for a 50% and 90% confidence level using the statistical errors only.

Figure 1

Figure 2

Figure 3

Figure 4