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Kaon Interference in the Hadronic Decays of the Z^0

DELPHI Collaboration

Abstract

The first measurement of like-sign charged kaon correlations in hadronic decays of the Z^0 is presented, based on data collected by the DELPHI detector. The charged kaons are identified by means of ring imaging Cherenkov detectors. A significant enhancement at small values of the four-momentum difference is observed in the ratio of like-sign to unlike-sign KK pairs and in the ratio of like-sign pairs to a simulated reference sample. An update of the measurement of $K^0_S K^0_S$ interference is also presented. An enhancement is found in the production of pairs of K^0_S of similar momenta, as compared with a simulated reference sample. The measured Bose-Einstein correlation parameters λ and r are similar for charged and neutral kaon pairs. The value of the Bose-Einstein correlation strength λ is consistent with unity.

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1 Introduction

Correlations between identical pions have been studied extensively in different types of reactions (see [1]). An enhancement at small relative momenta is usually attributed to the Bose-Einstein (BE) effect. Interference between two neutral kaons has also revealed the influence of BE statistics. In particular, at LEP energies $K^0_S K^0_S$ correlations have been measured in three experiments [2–4]. Correlations between identical charged kaons have been studied in only a few experiments with hadronic or nuclear beams and targets [5].

This paper presents, for the first time, results on correlations between $K^\pm K^\pm$ pairs in e^+e^- annihilations, based on data collected by the DELPHI detector in 1994. The charged kaons are identified by the Ring Image CHerenkov (RICH) detectors. An updated result for $K^0_S K^0_S$ interference is also presented.

The correlation function studied here is defined as

$$R(Q) = \frac{P(q_1, q_2)}{P(q_1)P(q_2)}, \tag{1}$$

where $P(q_1, q_2)$ is the two-particle probability density with the BE effect included and $P(q_1)P(q_2)$ is a reference density where no BE effect is present. The analysis is made in terms of the kinematic variable Q defined by

$$Q^2 = -(q_1 - q_2)^2 = M^2 - 4m_K^2, \tag{2}$$

where q_1 and q_2 are the four-momenta and M is the invariant mass of the pair of kaons. The correlation function $R(Q)$ is parametrised by the function

$$R(Q) = 1 + \lambda \exp(-r^2 Q^2), \tag{3}$$

where the parameter r gives the source size and λ measures the strength of the correlation between the kaons.

2 Experimental procedure

The study is based on a sample of e^+e^- annihilations into hadrons at a centre-of-mass energy around 91.2 GeV, taken with the DELPHI detector [6]. The analysis relies on the information provided by the tracking detectors: the Micro Vertex Detector (VD), the Inner Detector (ID), the Time Projection Chamber (TPC), the Outer Detector (OD) and the Forward Chambers (FCA, FCB).

Charged particles are selected if they have polar angle θ with respect to the beam axis between 25° and 155°, momentum larger than 0.2 GeV/c and smaller than 50 GeV/c, and measured track length in the TPC larger than 50 cm. Hadronic events are selected if they have at least 5 charged particles, total energy of the charged particles (when assigned the pion mass) over 3 GeV in each of the two hemispheres (θ below and above 90°), total energy of all charged particles larger than 15 GeV, total momentum imbalance less than 30 GeV/c, and polar angle of the thrust axis satisfying $|\cos\theta_{\rm th}| < 0.75$.

To ensure that the analysis of $K^\pm$ pairs is restricted to charged particles coming directly from the Z^0 decay, the tracks used to calculate the Q-variable of a pair must have an impact parameter with respect to the mean beam spot for the fill of LEP below 0.1 cm in the transverse plane and 1 cm along the beam direction. These strict cuts on both transverse and longitudinal impact parameters remove most particles from K^0_S and Λ decays.

The $K^\pm$ identification relies on the Barrel Ring Imaging CHerenkov (RICH) detector [7]. A charged particle is identified by measuring the angle of emission of its Cherenkov light, thereby determining its velocity, and its momentum. The $K^\pm$ were selected as in a previous study of inclusive $K^\pm$ production [8]. The present analysis selected charged kaons with momenta larger than 2.5 GeV/c, which are identified with a purity of about 70% (estimated from simulation).

A sample of 1,020,889 events from data collected in 1994 pass the selections above and have both the liquid and the gas RICH operational. There are 108,262 events with at least two charged kaons.

The detector effects on the analysis were estimated using the DELPHI simulation program DELSIM [9]. The events were generated using the JETSET 7.3 Parton Shower model [10] with parameters tuned to DELPHI data [11].

The K^0_S analysis updates earlier results [3], and now includes all DELPHI data collected at LEP from 1991 to 1994. A total of 3,041,134 events satisfied the hadronic event selection. The K^0_S are detected by their decay in flight into $\pi^+\pi^-$. Such decays are normally separated from the Z decay point (primary vertex), which is measured for each event. Candidates for secondary decays, V^0, were found by considering all pairs of particles with opposite charge and applying the selection criteria described in [3].

3 Correlations in the K^+K^+ and K^-K^- system

In the present analysis the K^+K^- two-particle density is used as a reference sample. The measurement of the $R(Q)$ distribution requires the Q distributions for like-sign and unlike-sign kaon pairs. Fig. 1 shows the Q distributions for like-sign (close circles) and for unlike-sign (open circles) charged particle combinations, where all particles were identified as kaons. The unlike-sign distribution is normalized to the like-sign distribution in the interval $0.6 < Q < 1.5$ GeV/c^2.

Fully simulated data showed that when Q is above 0.15 GeV/c^2, $R(Q)$ is not affected by the detector. However there are significant losses of like-sign combinations for smaller Q. Therefore the analysis was restricted to Q values above 0.15 GeV/c^2.

To measure the correlation for charged kaon pairs, the contamination of non-kaon pairs must be subtracted. Using the JETSET 7.3 PS model [10] to generate hadronic events, and with full simulation of these events in the detector [9], 58% of the pairs are found to be kaon pairs and the remaining 42% are predominantly $K\pi$ pairs. The background Q distribution for non-kaon pairs was obtained from the same data by requiring the kaon hypothesis for one particle and non-kaon for the other. The simulation shows that the composition of this sample of non-kaon pairs is 8% kaon pairs and 92% others. The fractions of pairs quoted are for all combinations (like sign plus unlike sign). The difference between the fractions for like-sign and unlike-sign combinations and the errors on these fractions (due to limited statistics for the simulated events) are less than the systematic uncertainties on the fractions.

For convenience, the first selection is henceforth called the kaon pair selection (with 58% of kaon pairs and 42% others) and the second is called the non-kaon pair selection (with 8% kaon pairs and 92% others). The lower part of Fig. 1 shows the Q-distribution for the non-kaon pair selection for like-sign (black squares) and unlike-sign pairs (open squares). These distributions were normalized to the contamination of non-kaon pairs (42%) in the kaon pair selection. The distributions for non-kaon pairs were subtracted from the distributions for kaon pairs to obtain the Q distributions for pure kaon pairs. The resulting distributions for like-sign and unlike-sign pure kaon pairs are shown in Fig.

2a. The distribution for K$^+$K$^-$ pairs is normalized to the like-sign kaon distribution in the interval $0.6 < Q < 1.5$ GeV/c^2.

In order to remove the effect of the $\phi(1020)$ in the unlike-sign reference sample the following procedure was adopted. The $Q_{K^+K^-}$ spectrum (Fig. 2a) was fitted to the form

$$N_{K^+K^-}(Q) = \alpha_1.BW(Q).BG(Q) + \alpha_2.BG(Q) \tag{4}$$

with $BW(Q)$ the relativistic Breit-Wigner shape and the background term parametrised as

$$BG(M) = (M - M_{th})^{\alpha_3}\exp(-\alpha_4 M - \alpha_5 M^2), \tag{5}$$

where M and Q are related by equation (2), the α_i are fitted parameters, and M_{th} is the threshold invariant mass of the two kaons (for more details of the fitting procedure used, see for example Ref. [12]).

In the fitting procedure, the ϕ mass was fixed to the PDG value [13] while the width was allowed to vary. The measured width of the ϕ was 9.5 MeV, which includes the experimental resolution. The parameters α_1 and α_2 are then used to assign to the K$^+$K$^-$ combinations the weight

$$W(M) = \frac{\alpha_2}{\alpha_1.BW(M) + \alpha_2}. \tag{6}$$

The resulting K$^+$K$^-$ Q-distribution without ϕ contamination is shown in Fig. 2b together with the Q-distribution for like-sign kaon pairs. There is an excess of same sign KK events for Q below 0.5 GeV/c^2, which can be interpreted as a BE enhancement. The ratio

$$R(Q) = \frac{N(K^\pm K^\pm)}{N(K^+K^-)} \tag{7}$$

after all the above corrections is shown in Fig. 3a.

The best fit to the expression

$$R(Q) = 1 + \lambda\exp(-r^2Q^2) \tag{8}$$

gives the values:

$$\lambda = 0.82 \pm 0.11(stat) \pm 0.25(syst) \tag{9}$$

$$r = 0.48 \pm 0.04(stat) \pm 0.07(syst)\ \text{fm}, \tag{10}$$

with $\chi^2 = 13$ for 11 degrees of freedom and correlation coefficient 0.8. This fit is shown by the curve on Fig. 3a.

It has to be remarked that the ratio (7) calculated using JETSET events without BE correlations and without ϕ contamination in the K$^+$K$^-$ Q-distribution is practically constant in the region $0.15 < Q < 1.5$ GeV/c^2. This confirms the validity of using the K$^+$K$^-$ two-particle density as a reference sample.

The systematic errors quoted in eq. (9) and eq. (10) include the uncertainties due to:

- the fractions of non-kaon pairs which were obtained from simulated events. The fraction of non-kaon pairs (with central value 0.42) was varied between 0.33 and 0.51. This variation was estimated by comparing the fraction of decay pions from K^0_S passing the charged kaon selection criteria from real and from simulated events. The error due to this source was estimated to be ±0.15 for λ and ±0.02 fm for r.
- the variation of the reference sample due to ϕ contamination. The K$^+$K$^-$ Q-distribution without ϕ contamination was also estimated by another fit to the $Q_{K^+K^-}$ spectrum using equation (5) but with the ϕ region (between 0.20 and 0.34 GeV/c^2)

excluded from the fit. For each point in the region with Q below 0.45 GeV/c^2, the average of the two measurements was used and half the difference between the two values was considered as the systematic error. The systematic error was added to the statistical error in quadrature. For the first data point in Fig. 3a, this procedure decreases $R(Q)$ by about 20% and increases the error by about a factor two. The uncertainty from this source was estimated to be ± 0.14 for λ and ± 0.01 for r.

- the inclusion of $f_0(980)$ decay kaons in the K^+K^- reference sample. The $f_0(980)$ correction was calculated as in [3]. The uncertainty from this source was estimated to be ± 0.11 for λ and ± 0.01 for r.
- the final state Coulomb interactions. Correcting by the Gamow factor [15] increases λ by 0.09 and does not change r. One calculation [16] suggests that the Gamow factor overestimates the size of the final state interaction. Hence it was decided not to correct the λ parameter for Coulomb interactions but to include a systematic error of ± 0.09 for λ due to this source.
- another choice of the reference sample. An alternative reference sample was calculated from simulated events without BE correlations and was normalized to the distribution of real events in the interval $0.6 < Q < 1.5$ GeV/c^2. The resulting $R(Q)$ distribution is shown in Fig. 3b, together with the fit by equation (3). The fitted values of λ and r are:

$$\lambda = 0.78 \pm 0.13 \tag{11}$$

$$r = 0.42 \pm 0.04 \text{ fm}\,. \tag{12}$$

The relative uncertainties due to this different choice of the reference sample were estimated as the difference between these values and the values measured using the unlike-sign uncorrelated background, i.e. ± 0.04 for λ and ± 0.06 fm for r.

The total systematic error was calculated by adding all contributions in quadrature.

4 Correlations in the $K^0_S K^0_S$ system

The $\pi^+\pi^-$ invariant mass spectrum from the accepted K^0_S candidates is shown in Fig. 4(a). A clear signal of about 541,000 K^0_S is seen over a background of about 14% within ± 10 MeV/c^2 of the peak. In an interval of ± 10 MeV/c^2 around the nominal K^0 mass, the average detection efficiency for K^0_S to $\pi^+\pi^-$, determined from a simulated sample and weighted by the momentum spectrum predicted by JETSET PS, is 26.4%.

From a sample of simulated data the background from Λ decays into $p\pi^-$ was found to be uniform in the $\pi^+\pi^-$ mass spectrum. The level of this background is about 2% under the peak. The contribution from photon conversions was found to be negligible.

The number of K^0_S pairs was evaluated using the same procedure as in reference [3]. The correlation between Δm_1 and Δm_2 (the absolute differences between the invariant mass of the K^0_S candidate and the known K^0_S mass) is shown in Fig. 4(b). The "signal region", defined by $\Delta m_1, \Delta m_2 < 10$ MeV/c^2, contains 75,065 pairs. The number of true pairs in the signal region can be estimated as in [3], giving after background subtraction $55,498 \pm 280(stat)$ $K^0_S K^0_S$ pairs among which $25,501 \pm 188(stat)$ have $Q < 2$ GeV/c^2.

In the present analysis, simulated events were used to supply the reference sample. Other methods are possible, based on the use of particles from different events to provide an uncorrelated sample. Such 'mixed event' methods have been useful in charged pion analyses [19], but have been found to be problematic in their application to K^0_S data [2]. A sample of 2,548,000 simulated Z^0 decays was generated using the JETSET model without

BE symmetrization for the K^0. These data were passed through the detailed DELPHI simulation and the simulated electronic signals processed through the same programs as the real data.

To measure the correlation function, we define the ratio $R_{meas}(Q) = \mathcal{N} \times N_R(Q)/N_S(Q)$, where N_R and N_S are the number of K^0_S pairs per interval of Q for real and simulated data after appropriate background subtraction, and $\mathcal{N}$ is a normalization factor computed as the ratio of N_S and N_R in the range between 0.667 GeV/c^2 and 2 GeV/c^2. $N_R(Q)$ and $N_S(Q)/\mathcal{N}$ are shown in Fig. 5. The correlation function $R_{meas}(Q)$ is plotted in Fig. 6. An enhancement is clearly visible in the region $Q < 0.6$ GeV/c^2.

The best fit to the expression

$$R(Q) = 1 + \lambda \exp(-r^2 Q^2) \tag{13}$$

gives the values:

$$\lambda = 0.61 \pm 0.16(stat) \pm 0.16(syst) \tag{14}$$

$$r = 0.55 \pm 0.08(stat) \pm 0.12(syst) \text{ fm}, \tag{15}$$

with $\chi^2 = 23$ for 10 degrees of freedom and correlation coefficient 0.8. The systematic errors were calculated by adding in quadrature all the contributions described in [3].

Decays of mesons like $f_0(980)$ and $a_0(980)$, which are not present in the simulated sample, can fake the correlation effect, producing two K^0_S very close in momentum. A correction for $f_0(980)$ production (see our previous paper [3]), using the measured $f_0(980)$ production rate [12], shows that the $f_0(980)$ can account for only a small part of the measured BE excess.

5 Summary and Conclusions

The first observation of like–sign charged kaon correlations in hadronic e^+e^- annihilations at the Z mass has been made using data collected by the DELPHI detector during 1994. The charged kaons are identified with the RICH detectors. The correlation function shows an enhancement, which we interpret as due to the Bose-Einstein interference between identical bosons, and which can be represented by a Gaussian as in equation (8) with parameters

$$\lambda = 0.82 \pm 0.11 \pm 0.25 \tag{16}$$

$$r = 0.48 \pm 0.04 \pm 0.07 \text{ fm}. \tag{17}$$

Low-Q correlations between pairs of K^0_S from the decay of the Z^0 have been observed with the DELPHI detector at LEP, using a sample of about 55,000 pairs coming from more than 3 million selected hadronic events. The results show an enhancement, interpreted as due to Bose-Einsten interference, which can be parametrised by a Gaussian as in equation (8) with parameters

$$\lambda = 0.61 \pm 0.16 \pm 0.16 \tag{18}$$

$$r = 0.55 \pm 0.08 \pm 0.12 \text{ fm}. \tag{19}$$

Assuming that the strength of the Bose-Einstein effect can be parametrised by $\lambda \leq 1$ for interfering pairs, and if only like-strangeness identical neutral kaons contribute to the observed enhancement at low Q, then λ values considerably smaller than 1 would be expected for $K^0_S K^0_S$ pairs. According to JETSET PS, 28% of the low-Q $K^0_S K^0_S$ pairs come

Combination	λ	r fm	Ref.
$K^\pm K^\pm$	0.82±0.11±0.25	0.48±0.04±0.07	this analysis
$K^0_S K^0_S$	1.14±0.23±0.32	0.76±0.10±0.11	[2]
	0.61±0.16±0.16	0.55±0.08±0.12	this analysis
	1.4±0.3±0.4	0.71±0.07±0.15	[4]
$\pi^\pm\pi^\pm$	0.35±0.04	0.42±0.04	[19]
	0.40±0.02	0.50±0.02	[21]
$\pi^0\pi^0$	0.37±0.03±0.12	0.40±0.03±0.13	[20]
$\pi^\pm\pi^\pm$ (prompt pions)	1.06±0.05±0.16	0.49±0.01±0.05	[22]

Table 1: Parameters λ and r in the Gaussian parametrisation in e^+e^- interactions at LEP, for different like-sign particles.

from identical K^0 K^0 (or $\overline{K^0}$ $\overline{K^0}$) pairs; about 70% of these pairs originate from prompt sources. If the positive interference at low Q affected only the K^0 K^0 (or $\overline{K^0}$ $\overline{K^0}$) pairs, the expected value for λ would be $\simeq 0.2$. Thus it is unlikely that only identical neutral kaons are responsible for the observed enhancement at low Q. Our results support the hypothesis [18] that K^0_S coming from K^0 $\overline{K^0}$ pairs also exhibit constructive interference at $Q \simeq 0$.

The values of λ and r measured at LEP for particle pairs using a Gaussian parametrisation for $R(Q)$ are presented in Table 1.[†] The values of the λ and r parameters for charged kaon pairs are in agreement with those obtained for $K^0_S K^0_S$. The correlation strength λ is expected to be bigger for charged kaon pairs than for $K^0_S K^0_S$, if $K^0_S K^0_S$ pairs coming from K^0 $\overline{K^0}$ do not interfere at low Q. Similar λ values for charged kaon pairs and for $K^0_S K^0_S$ pairs yield additional support to the prediction [18] of a dynamic enhancement at low Q in $K^0_S K^0_S$ coming from K^0 $\overline{K^0}$.

The radius of emission of kaons is consistent with that measured for pions. The average value of λ for kaon pairs calculated by using all four measurements at LEP is $\lambda_{KK} = 0.85 \pm 0.18$, which is considerably higher than the ones for all pions and in good agreement with the value obtained for prompt pions [22]. It may also be remarked that a non-negligible fraction of kaons is expected to come from the decay of long-lived charm and bottom states, and these are not expected to interfere with prompt kaons within the observed range of Q values. Correcting for this effect using the JETSET PS model would increase λ by about 40−50%.

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[†] For charged pions the parameters λ and r, shown with only statistical errors, are the ones obtained with an event-mixing reference sample. The decay products of the η and η' mesons strongly influence the values of λ and r when these parameters are estimated by using an unlike-sign reference sample [22].

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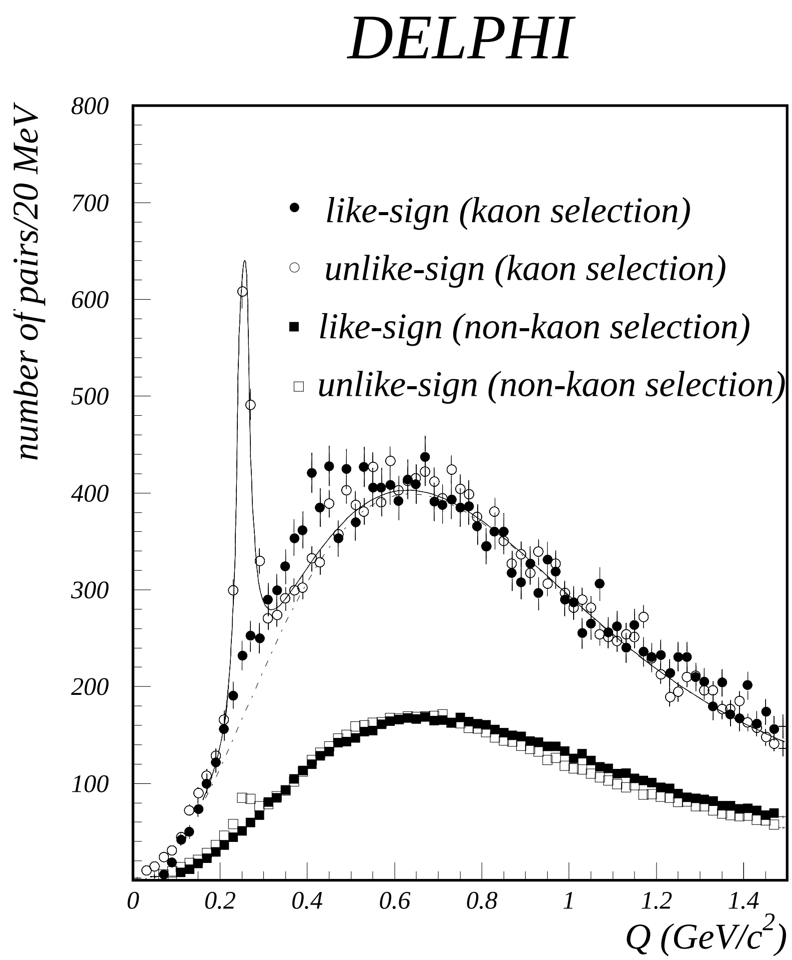

Figure 1: Q-distributions for like-sign (black circles) and for unlike-sign (open circles) kaon pairs. The full line is a fit by equation (4) to unlike-sign pairs. The background after subtracting the $\phi(1020)$ is shown as the dashed curve. The lower plots show the Q-distributions for like-sign (black squares) and unlike-sign (open squares) pairs for the non-kaon pair selection.

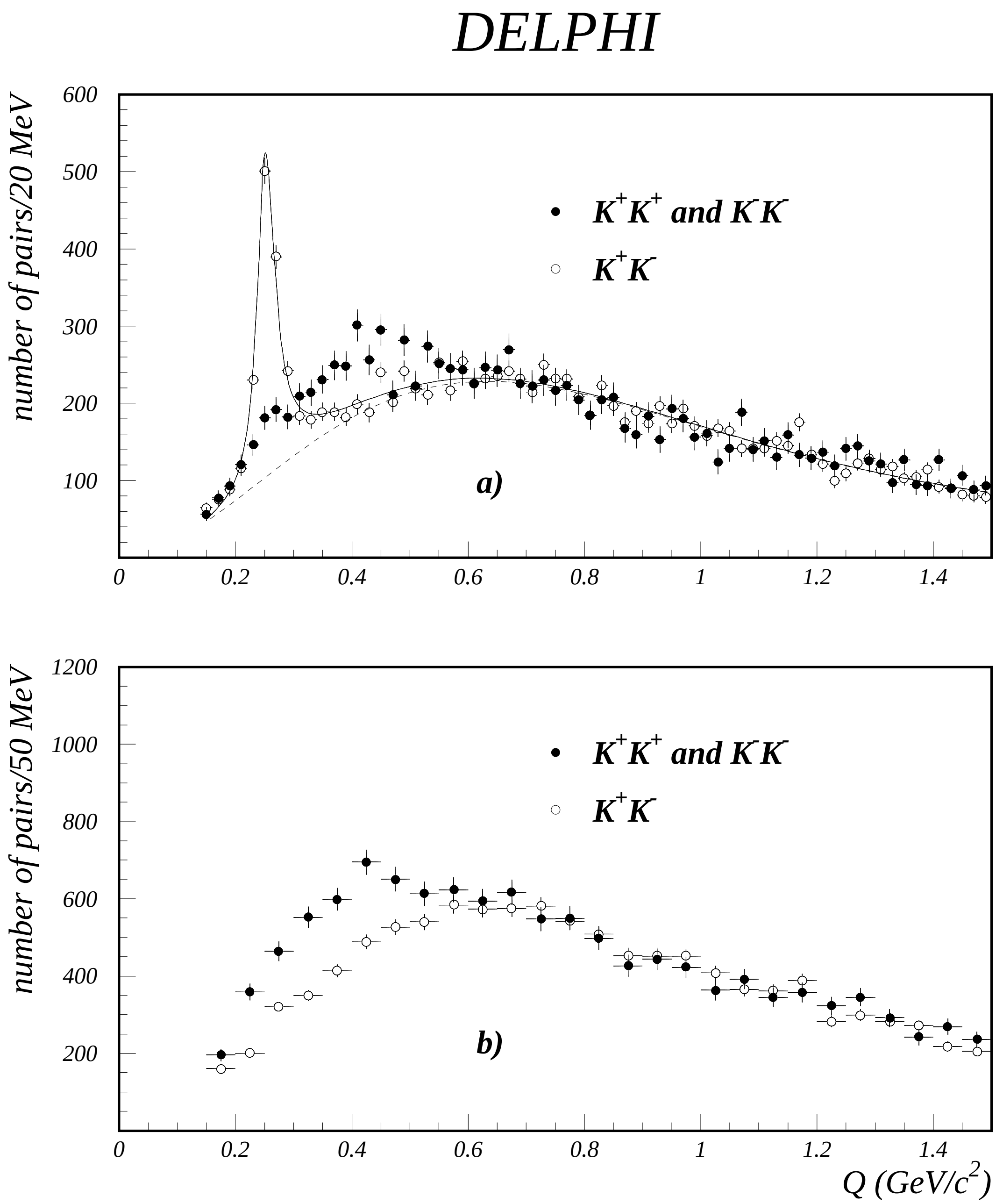

Figure 2: (a) Q distributions after subtracting the non-kaon contaminations for like-sign (black circles) and for unlike-sign (open circles) kaon pairs. The full curve is a fit by equation (4) to unlike-sign kaon pairs. The background after subtracting the $\phi(1020)$ is shown as the dashed curve. (b) Same as Fig. 2a but without ϕ contamination in unlike-sign charged kaon pairs.

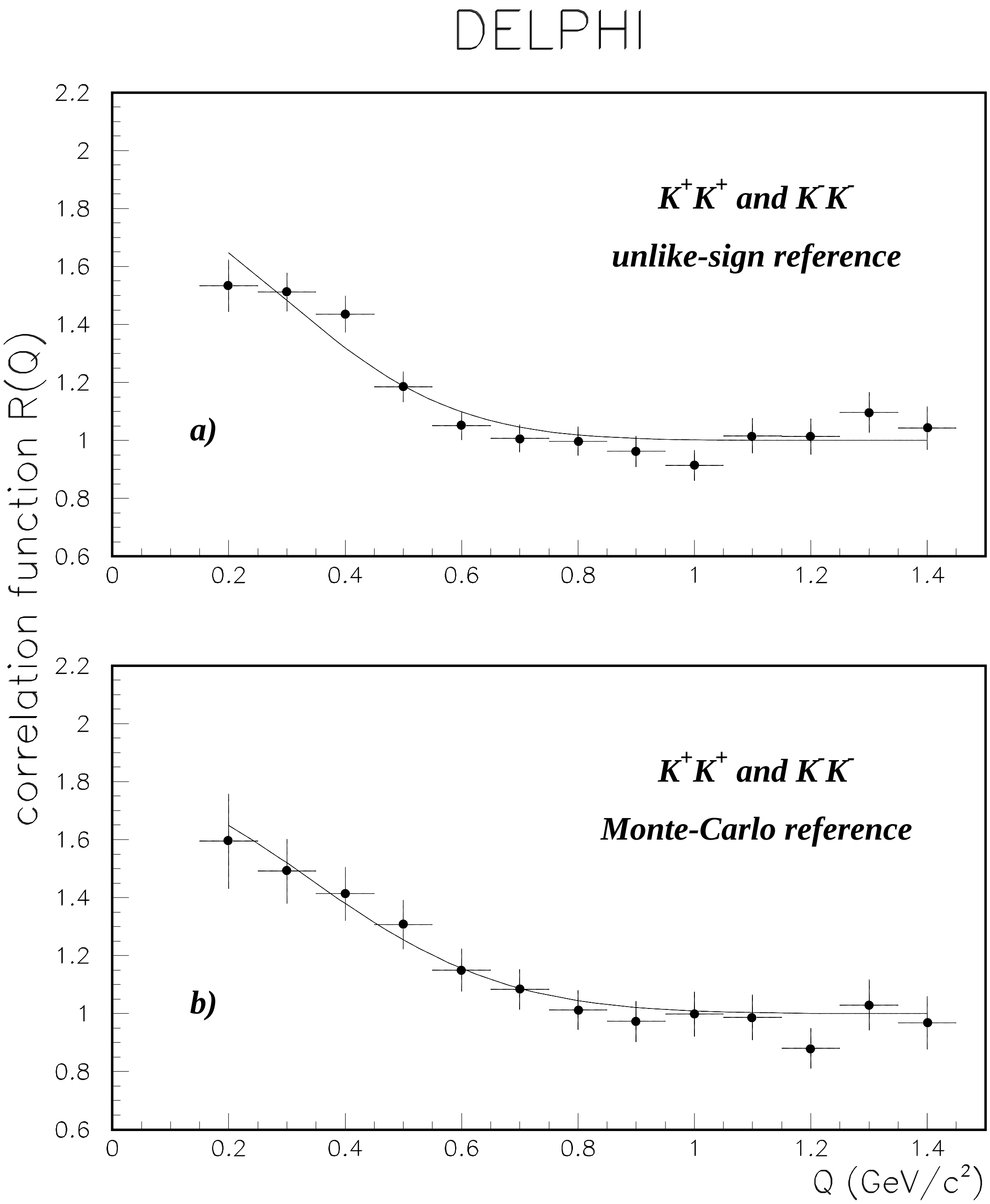

Figure 3: The ratio $R(Q)$ for charged kaons: (a) for the unlike-sign reference sample and (b) for the Monte-Carlo reference sample. The curves show the results of the fits using equation (3).

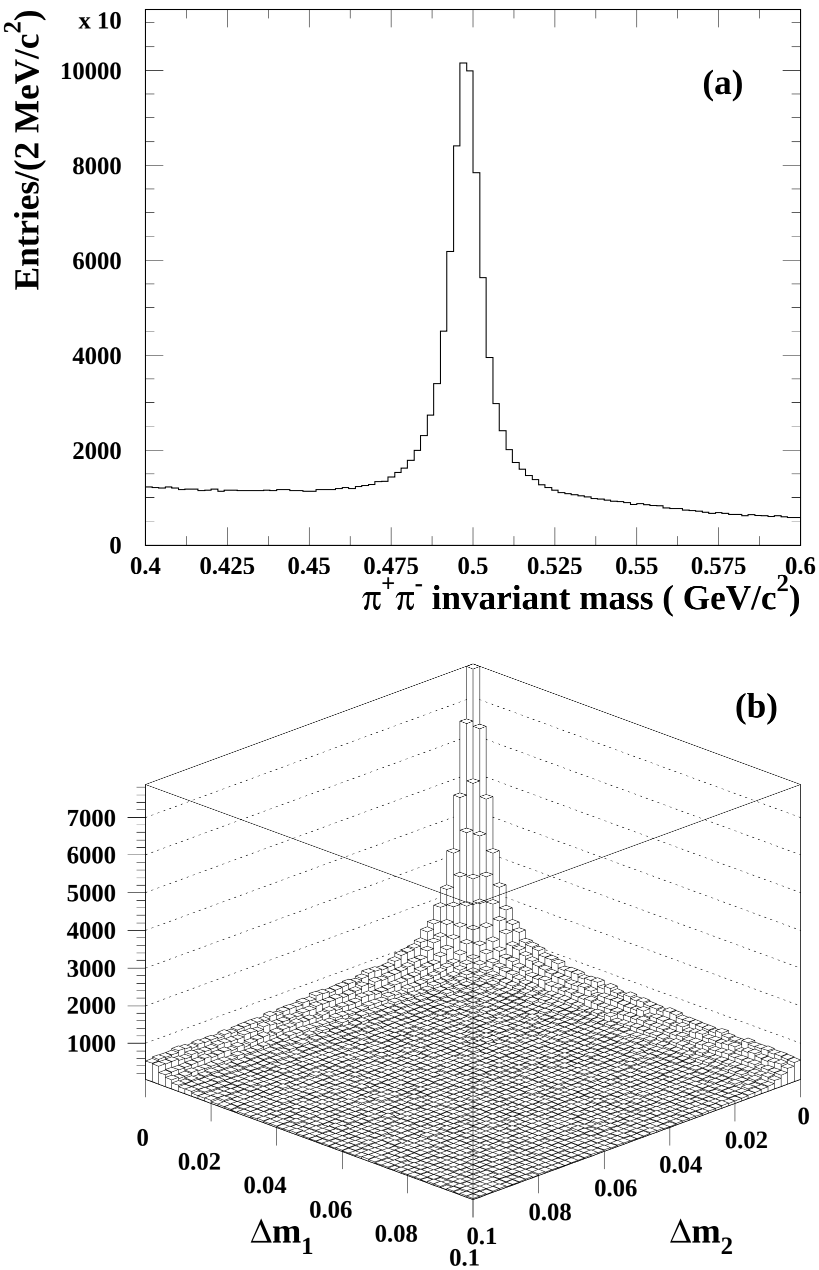

Figure 4: (a) $\pi^+\pi^-$ invariant mass spectrum for the accepted secondary vertices used in the present analysis. (b) Two-dimensional plot of the absolute value of the difference from the nominal K^0_S mass Δm (GeV/c^2) when two or more K^0_S candidates are present in the same event.

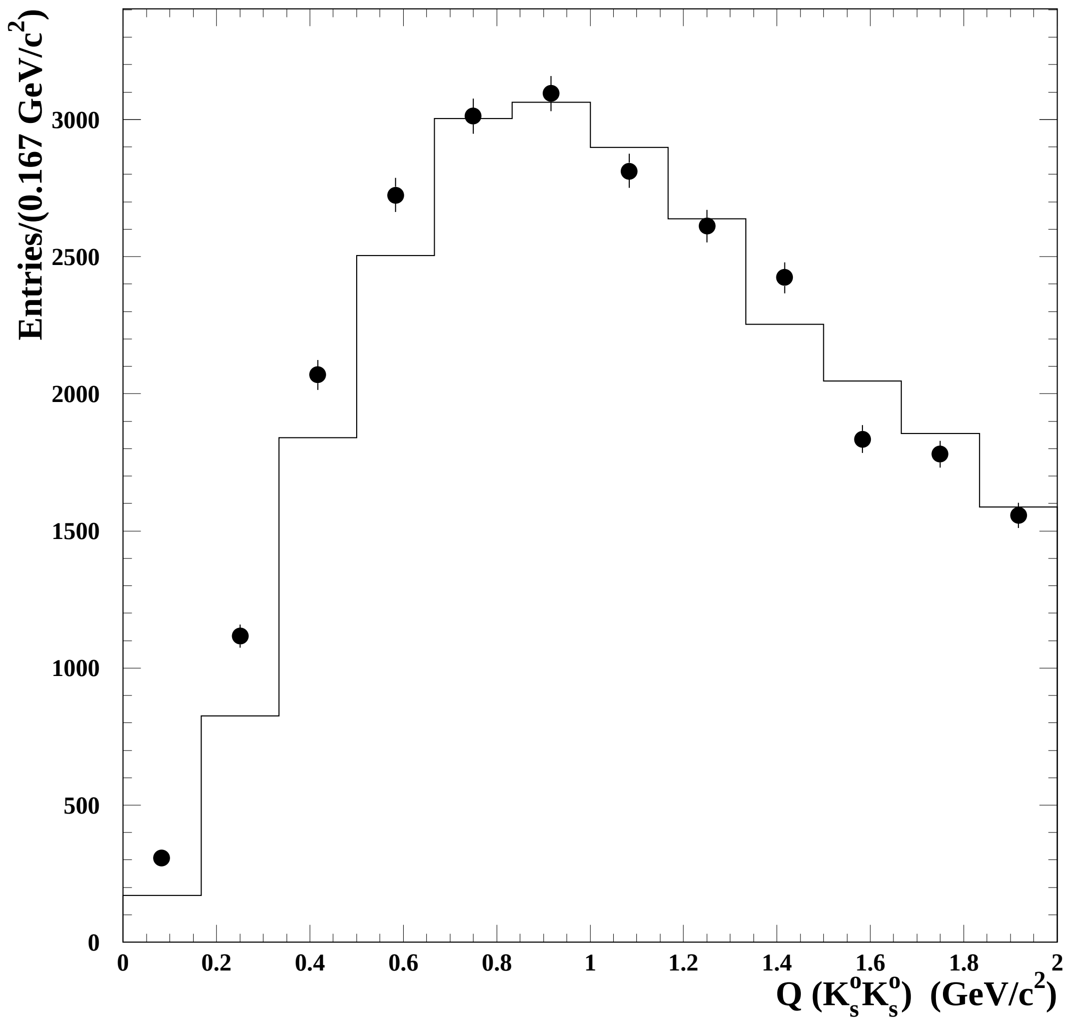

Figure 5: Distribution of K^0_S pairs in data (points) and simulation without Bose-Einstein interference (histogram), as a function of Q. The simulated sample is normalized to the data sample in the range $0.667 - 2.0$ GeV/c^2.

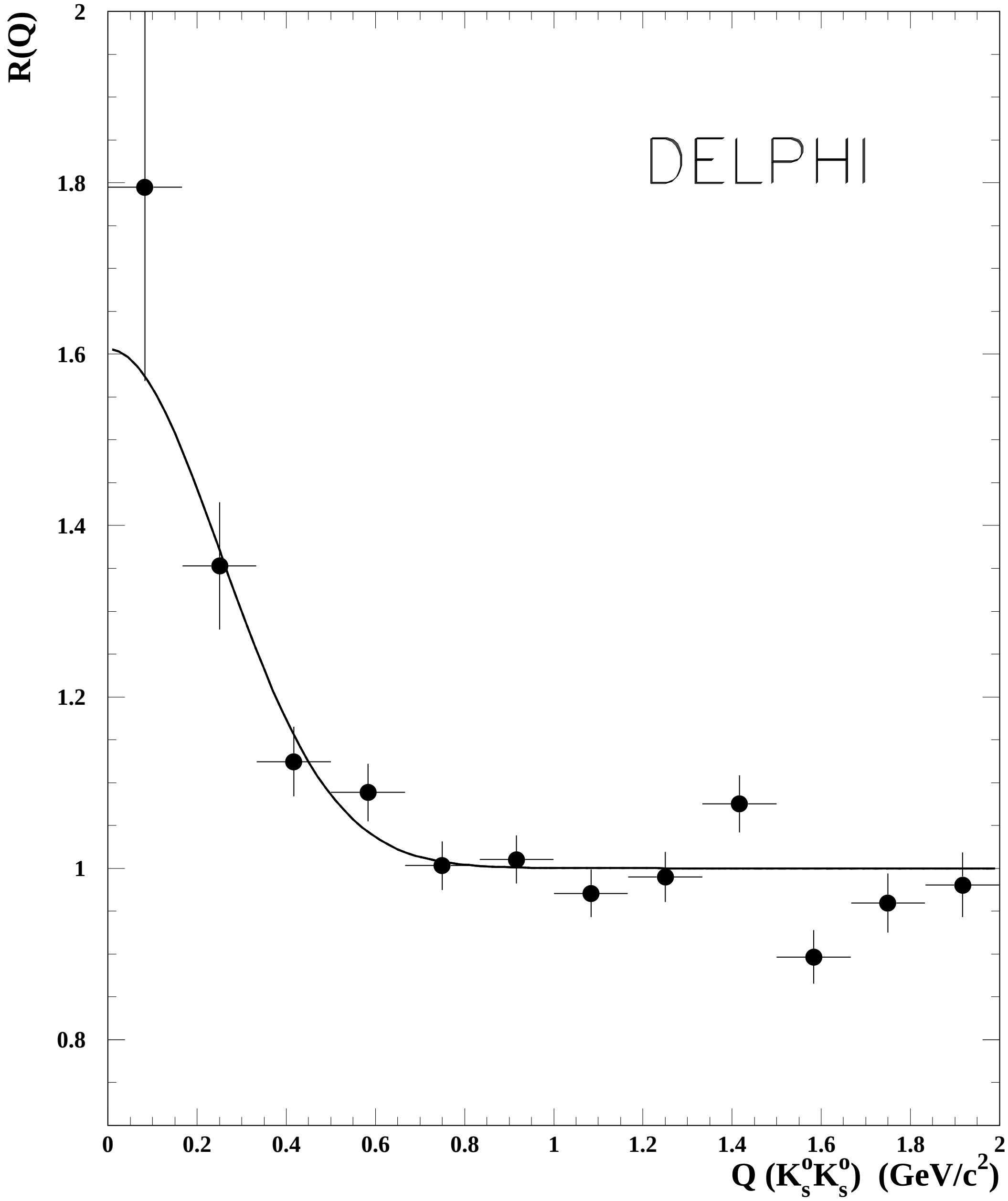

Figure 6: Ratio $R_{meas}(Q)$. The curve shows the best fit to equation (3).