Study of the Process $e^+e^- \to K_L^0 K_S^0$ in the C.M.Energy Range 1.05 – 1.38 GeV with CMD-2

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Abstract

The cross section of the process $e^+e^- \to K_L^0 K_S^0$ has been measured with the CMD-2 detector using about 950 events detected in the center-of-mass energy range from 1.05 to 1.38 GeV. Above 1.13 GeV the cross section exceeds the expectation based on the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons.

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1 Introduction

The investigation of the process $e^+e^- \to K_L^0 K_S^0$ is important for a number of physics problems. Studies of neutral kaon production provide valuable information about the K-meson structure. Since both I=0 and I=1 vector mesons can decay into a kaon pair, one can search for excitations of the $\rho(770), \omega(782)$ and $\phi(1020)$ by measuring the cross section of the process in the energy range above the $\phi(1020)$ meson [1]. The isovector part of the cross section of the process $e^+e^- \to K\bar{K}$ (both K^+K^- and $K_L^0 K_S^0$ final states should be taken) can be confronted to the $\tau^- \to K^- K^0 \nu_\tau$ decay by using conservation of vector current [2]. Assuming the hypothesis of factorization it can be also used to account for the production of kaon pairs in $B^- \to D^0 K^- K^0$ decays [3]. Finally, the process under study contributes to the total hadronic cross section, so that the values of its cross section are used in the calculation of the hadronic contribution to the muon anomalous magnetic moment [4]. In view of the increasing experimental accuracy in the measurement of this quantity [5], any significant contribution like that from the process $e^+e^- \to K_L^0 K_S^0$ should be measured with adequate precision.

Earlier measurements of the cross section performed in [1,6,7] were based on small data samples and had a systematic accuracy of about 20% or worse. The significant progress in the study of the process $e^+e^- \to K_L^0 K_S^0$ was achieved by the group of the SND detector [8] at the VEPP-2M collider [9]. The experiment was based on the integrated luminosity of 6.3 pb^{-1}. The systematic error of the cross section was estimated to be 10% around 1.04 GeV increasing to about 15% at 1.38 GeV.

In this work we report on the measurement of the $e^+e^- \to K_L^0 K_S^0$ cross section based on 5.7 pb^{-1} of data collected with the CMD-2 Detector [10] at the VEPP-2M collider from 1.05 to 1.38 GeV. The systematic uncertainty on the cross section was about 5% below 1.09 GeV and increased to 10% at the energy 1.38 GeV.

2 Detector and experiment

The CMD-2 detector has been described in detail elsewhere [10]. Its tracking system consists of the cylindrical drift chamber (DC) [11] surrounding the interaction point, and proportional Z-chamber (ZC) [12] for precise polar angle measurement, both also used for trigger. Both chambers are inside a thin (0.38 X_0) superconducting solenoid [13] with a field of 1 T. The barrel electromagnetic calorimeter [14] placed outside the solenoid consists of 892 CsI crystals of $6\times6\times15$ cm^3 size. The muon-range system [15] of the detector, also located outside the solenoid, is based on streamer tubes. The endcap electromagnetic calorimeter [16] based on BGO crystals makes the detector almost hermetic for photons.

The data sample used in the analysis was collected in two scans of the center-of-mass energy range 1.05 – 1.38 GeV. In the first scan, the beam energy was increased from 530 MeV to 690 MeV with a 10 MeV step, while in the second one it was decreased from 685 MeV to 525 MeV with the same energy step.

3 Data analysis

Events of the process $e^+e^- \to K_L^0 K_S^0$ were detected by using a subsequent decay of the K_S^0 meson into a pair of charged pions.

The following selection criteria were used:

- There are two opposite charge tracks from the vertex closest to the beam. Track momenta, assuming that tracks are pions, satisfy the conditions:

$$P_\pi^{min} - 20 < p_{1,2} < P_\pi^{max} + 20,$$

  where P_π^{min}, P_π^{max} are minimum and maximum kinematically possible momenta of a pion from the $K_S^0 \to \pi^+\pi^-$ decay in MeV/c.
- The track polar angles are:

$$0.95 < \theta_{1,2} < \pi - 0.95.$$

- The maximum of the track ionization losses is

$$max(\frac{dE}{dx_1}, \frac{dE}{dx_2}) < 2.2 \frac{dE}{dx_{MIP}},$$

  where $\frac{dE}{dx_{MIP}}$ is the ionization loss of a minimum ionizing particle (see Fig. 1a for events from the energy range 1.05 < $E_{c.m.}$ < 1.09 GeV). The cut is used to remove K^+K^- events as well as events of "beam-wall" interactions.
- The acollinearity angle for pions in the R-ϕ plane is:

$$0.2 < |\pi - |\varphi_1 - \varphi_2|| < 3.0,$$

  and the space angle between pion tracks is

$$\psi > 0.5.$$

  By these criteria events with collinear particles and particles going close to each other were rejected.

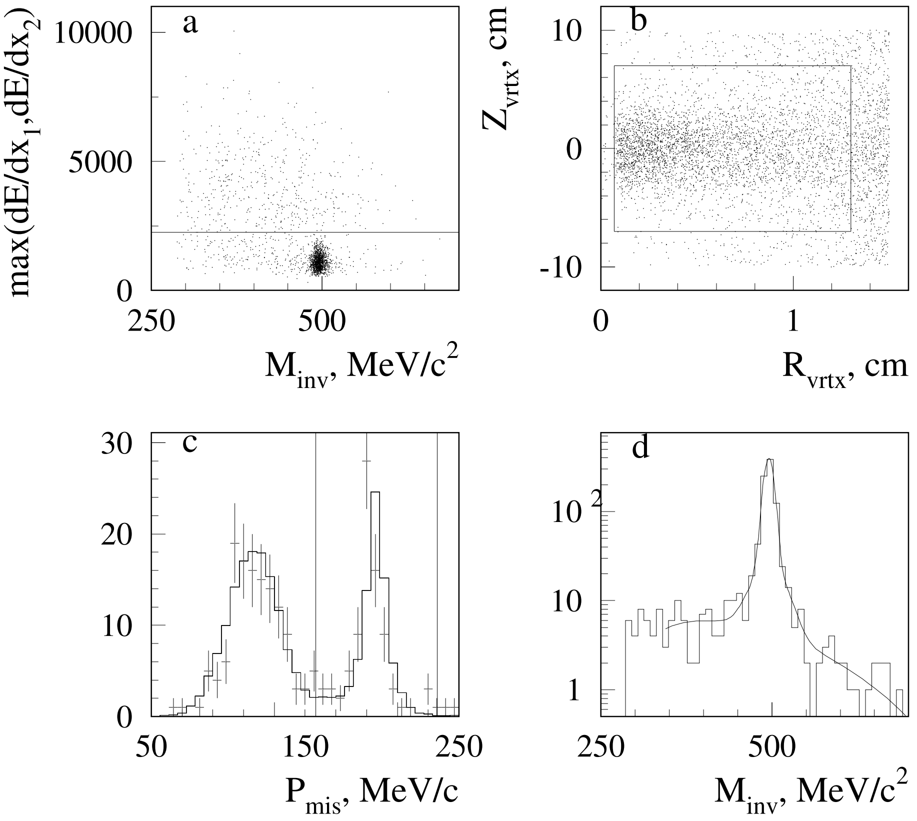

Fig. 1. Distributions used for the selection of $e^+e^- \to K_L^0 K_S^0$ events: a. Particle ionization losses versus the invariant mass of two tracks; b. Z-coordinate of the vertex versus the distance from the beam point to the vertex in the $R - \varphi$ plane; c. Missing momentum (the histogram is simulation, the points are experimental events); d. Invariant mass of two tracks.

- The Z-coordinate of the vertex is less than 7.0 cm and the radius of the vertex in the R-φ plane (R_{vrtx}) satisfies the condition:

$$0.07 < R_{vrtx} < 1.3 \text{ cm}.$$

  The described cuts are shown in Fig. 1b for the energy range $1.05 <$ E$_{c.m.}$ $<$ 1.09 GeV.

In the energy region above the $\phi(1020)$, production of a neutral kaon pair is often accompanied by emission of a hard photon by initial electrons ("return to resonance" effect). The distribution of the missing momentum of two tracks defined as $P_{mis} = |\vec{P}_1 + \vec{P}_2|$ is shown in Fig. 1c for E$_{c.m.}$ $= 1.07$ GeV. In agreement with the Monte Carlo simulation, the left peak in Fig. 1c corresponds to "return to resonance" events, while the right one describes events without hard photon emission. In the present work events with "return to resonance" were excluded from analysis by the requirement:

$$\left|P_{mis} - \sqrt{E_{beam}^2 - m_{K^0}^2}\right| < 40 \text{ MeV/c},$$

where 40 MeV/c corresponds to five standard deviations of the experimental resolution for the P_{mis} value. The selection criteria are shown in Fig. 1c by the vertical lines.

The number of events was determined from the fit of the invariant mass distribution with a sum of two Gaussians describing the signal and a smooth function describing background. To determine parameters of the background function as well as variances of the signal Gaussians, the following procedure was used. The whole data sample was subdivided into three energy bins: 1.05–1.19, 1.20–1.29 and 1.30–1.38 GeV. The approximation above was performed in each of the three bins and the obtained parameters of the fitting functions were later fixed during the approximation at each energy point within the corresponding bin. An example of such an approximation in the energy range 1.05–1.19 GeV is shown in Fig. 1d.

After applying the cuts described above and background subtraction, 948±33 $K_L^0 K_S^0$ events were selected.

At each energy point the cross section is determined from the following formula:

$$\sigma = \frac{N}{L\varepsilon(1+\delta_{rad})},$$

where N is the number of selected events, ε is the detection efficiency, L is the integrated luminosity determined from events of Bhabha scattering at large angles according to [17], and $(1+\delta_{rad})$ is a radiative correction due to initial state radiation calculated according to [18]. The detection efficiency $\varepsilon = \varepsilon_{rec}\varepsilon_{trig}\varepsilon_{geom}$, where ε_{rec} is the reconstruction efficiency, ε_{trig} is the trigger efficiency, and ε_{geom} is the acceptance.

The reconstruction efficiency (ε_{rec}) was determined from the experimental data. To this end "test" events, in which a K_L^0 produced a cluster in the CsI calorimeter, were selected. Using the angles of this cluster as well as the angles of the clusters produced by pions from the $K_S^0 \to \pi^+\pi^-$ decay, and requiring one track in DC, one obtains a clean sample of events for efficiency determination. Analysis shows that the reconstruction efficiency is energy independent. The same procedure was applied to simulation and also gave an energy independent reconstruction efficiency. The efficiency values in the data sample and simulation are slightly different, therefore a correction for this difference was applied to the experimental reconstruction efficiency. A similar procedure was used to determine the trigger efficiency (ε_{trig}). More detail about this analysis can be found in [19]. The acceptance (ε_{geom}) was determined from Monte Carlo simulation.

The beam energy at each point was evaluated from the value of the magnetic field in the bending magnets using the method described in [20]. The systematic uncertainty in the beam energy value was estimated to be $\frac{\Delta E}{E} = 4 \cdot 10^{-4}$ according to the analysis of the long-term stability of energy performed in [17]. The number of events, integrated luminosity, detection efficiency, radiative correction and cross section at each energy point are listed in Table 1. It is this cross section (the "dressed" one) that should be used in the approximation of the energy dependence with resonances. For applications to various dispersion integrals like that for the leading order hadronic contribution to the muon anomalous magnetic moment, one should use the "bare" cross section. The latter is obtained from the "dressed" one by multiplying it by the vacuum polarization factor $|1 - \Pi(s)|^2$, where $\Pi(s)$ is the photon polarization operator calculated taking into account the effects of both leptonic and hadronic vacuum polarization.

Figure 2 shows the energy dependence of the cross section obtained in this work together with the results of our study of the $\phi \to K_L^0 K_S^0$ decay from [21] (the data in the 1.00 – 1.04 GeV energy range). Also shown are the results of the previous experiments that studied the process $e^+e^- \to K_L^0 K_S^0$ above the ϕ meson region. Good agreement between the results of these measurements is observed.

To interpret the results of the present analysis, the energy dependence of the cross section was approximated in the frame of Vector Dominance Model [22] with the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons according to the following SU(3) based formula:

$$\sigma(s) = \frac{1}{s^{5/2}} \cdot \frac{q^3(s)}{q^3(m_\phi^2)} \cdot \left| -\frac{\Gamma_\phi m_\phi^3 \sqrt{\sigma(\phi \to K_L^0 K_S^0) m_\phi}}{D_\phi(s)} - \right.$$
$$- \frac{\sqrt{\Gamma_\phi \Gamma_\omega m_\phi^2 m_\omega^3 6\pi B(\omega \to e^+e^-) B(\phi \to K_L^0 K_S^0)}}{D_\omega(s)} +$$
$$\left. + \frac{\sqrt{\Gamma_\phi \Gamma_\rho m_\phi^2 m_\rho^3 6\pi B(\rho \to e^+e^-) B(\phi \to K_L^0 K_S^0)}}{D_\rho(s)} \right|^2 ,$$

where $\sigma(\phi \to K_L^0 K_S^0)$ is the ϕ meson peak cross section, $q(s) = \sqrt{s/4 - m_{K^0}^2}$ is the neutral kaon momentum, $D_V(s) = (m_V^2 - s + \imath\sqrt{s}\Gamma_V(s))$ is the propagator of the vector meson V. The energy dependence of the total width for a meson V was chosen as in [23]. Masses and total widths of the resonances were taken from [24]. The following value of the $\phi(1020)$ meson peak cross section was obtained from the fit:

Table 1
The number of events, integrated luminosity, detection efficiency, radiative correction, "dressed" cross section, vacuum polarization factor and "bare" cross section of the process $e^+e^- \to K_L^0 K_S^0$. The first error in the cross section value is statistical and the second is systematic one.

$\sqrt{s}$, MeV	N	$\mathcal{L}$, nb^{-1}	ε	$(1+\delta_{rad})$	σ, nb	$\|1-\Pi(s)\|^2$	σ^0, nb
1050.0	310.9±17.8	117.7±0.7	0.151	0.996	17.56±1.00± 1.97	0.948	16.65±0.95±1.87
1060.0	124.1±11.3	76.8±0.6	0.146	0.950	11.65±1.06± 0.64	0.953	11.10±0.97±0.61
1070.0	76.1±8.9	81.8±0.5	0.141	0.926	7.13±0.84± 0.35	0.956	6.82±0.80±0.33
1080.0	39.3±6.6	59.6±0.5	0.136	0.914	5.30±0.90± 0.26	0.958	5.08±0.86±0.25
1090.0	53.0±7.5	85.2±1.3	0.132	0.909	5.18±0.73± 0.25	0.959	4.97±0.70±0.24
1100.0	29.0±5.5	57.5±0.5	0.128	0.906	4.35±0.81± 0.21	0.961	4.19±0.78±0.20
1110.0	33.5±6.1	83.3±0.5	0.124	0.905	3.58±0.65± 0.29	0.962	3.44±0.62±0.28
1120.0	$18.2^{+4.9}_{-4.2}$	59.4±0.7	0.120	0.905	$2.82^{+0.75}_{-0.65}\pm0.23$	0.963	$2.71^{+0.72}_{-0.62}\pm0.22$
1130.0	$14.7^{+4.2}_{-3.6}$	62.8±0.5	0.116	0.905	$2.23^{+0.63}_{-0.55}\pm0.18$	0.963	$2.15^{+0.61}_{-0.53}\pm0.18$
1140.0	$25.5^{+5.7}_{-5.0}$	87.4±0.5	0.113	0.905	$2.85^{+0.61}_{-0.54}\pm0.23$	0.964	$2.75^{+0.59}_{-0.52}\pm0.22$
1150.0	$17.8^{+4.8}_{-4.1}$	63.2±0.5	0.109	0.906	$2.85^{+0.74}_{-0.62}\pm0.23$	0.965	$2.75^{+0.71}_{-0.60}\pm0.21$
1160.0	$17.2^{+4.8}_{-4.1}$	113.0±0.7	0.106	0.906	$1.58^{+0.44}_{-0.37}\pm0.14$	0.965	$1.52^{+0.42}_{-0.36}\pm0.13$
1170.0	$13.9^{+4.2}_{-3.5}$	71.8±0.5	0.103	0.907	$2.07^{+0.59}_{-0.50}\pm0.17$	0.966	$2.00^{+0.57}_{-0.48}\pm0.16$
1180.0	$15.1^{+4.6}_{-3.9}$	114.9±0.7	0.100	0.907	$1.45^{+0.42}_{-0.36}\pm0.12$	0.966	$1.40^{+0.41}_{-0.35}\pm0.12$
1190.0	$20.9^{+5.3}_{-4.6}$	132.5±1.1	0.097	0.908	$1.79^{+0.44}_{-0.37}\pm0.15$	0.966	$1.72^{+0.42}_{-0.36}\pm0.14$
1204.6	$19.7^{+5.6}_{-4.9}$	270.1±1.1	0.094	0.909	$0.85^{+0.23}_{-0.21}\pm0.07$	0.967	$0.82^{+0.23}_{-0.21}\pm0.07$
1225.0	$26.9^{+6.0}_{-5.3}$	286.7±1.5	0.089	0.910	$1.16^{+0.24}_{-0.21}\pm0.11$	0.967	$1.12^{+0.24}_{-0.21}\pm0.11$
1250.6	$21.3^{+5.7}_{-5.3}$	492.3±2.3	0.083	0.912	$0.57^{+0.14}_{-0.14}\pm0.05$	0.968	$0.55^{+0.14}_{-0.14}\pm0.05$
1275.0	$18.7^{+5.8}_{-5.0}$	468.6±1.5	0.079	0.913	$0.55^{+0.17}_{-0.14}\pm0.05$	0.968	$0.53^{+0.17}_{-0.14}\pm0.05$
1295.8	$20.2^{+6.0}_{-5.2}$	589.2±2.7	0.075	0.915	$0.50^{+0.14}_{-0.12}\pm0.05$	0.968	$0.48^{+0.14}_{-0.12}\pm0.05$
1325.3	$11.2^{+6.2}_{-5.4}$	994.9±3.1	0.071	0.916	$0.17^{+0.09}_{-0.08}\pm0.02$	0.968	$0.16^{+0.09}_{-0.08}\pm0.02$
1368.3	$20.7^{+6.6}_{-5.9}$	1338.7±3.4	0.066	0.919	$0.25^{+0.08}_{-0.07}\pm0.02$	0.968	$0.24^{+0.08}_{-0.07}\pm0.02$

$$\sigma(\phi \to K_L^0 K_S^0) = (1376 \pm 6 \pm 23) \text{ nb},$$
$$\chi^2/n.d.f = 1.69.$$

The value of the peak cross section is in good agreement with that from our $\phi \to K_L^0 K_S^0$ study [21]. A relatively large value of the χ^2 arises from the energy range above 1.13 GeV where, as seen from Fig. 2, most of the

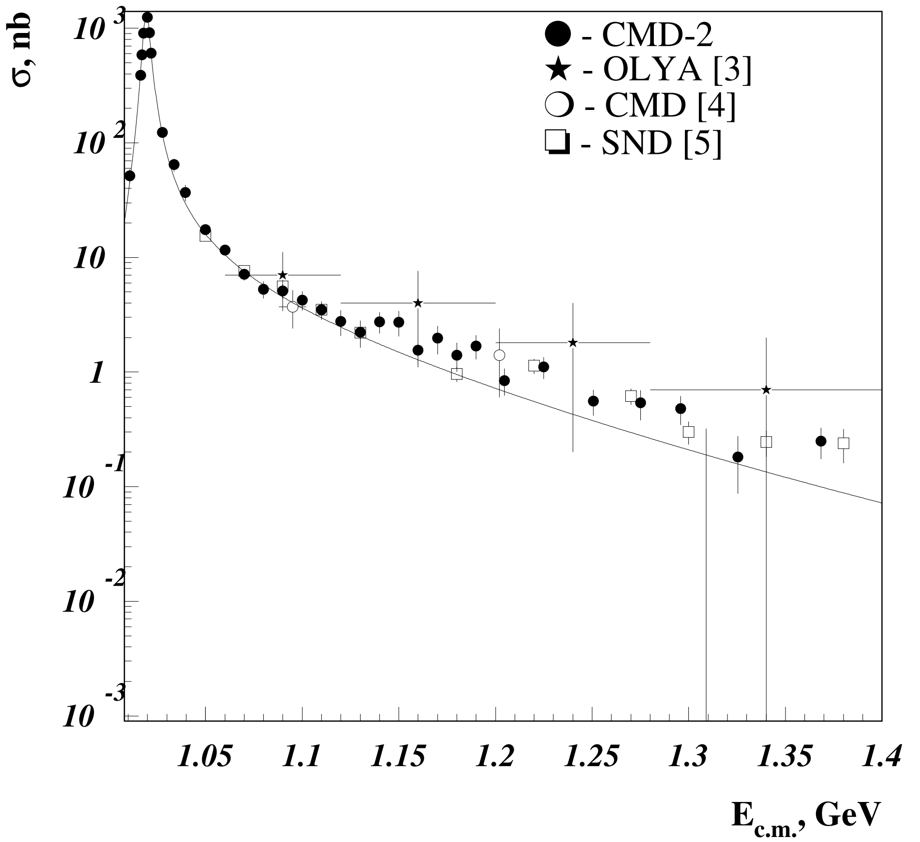

Fig. 2. The cross section of the process $e^+e^- \to K_L^0 K_S^0$ in the energy range $E_{c.m.}$ = 1.05 – 1.38 GeV, measured in different experiments. The curve is the Vector Dominance Model prediction with the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons.

experimental points lie above the approximation curve. The observed excess could be explained, for example, by higher resonances contributing to the production of pairs of neutral kaons. This assumption is confirmed by the combined analysis of our results with those from the DM1 detector obtained in the energy range 1.4 – 2.18 GeV [1], see Fig. 3. To describe the energy dependence of the cross section near $E_{c.m.} \approx 1.6$ GeV, the following amplitude was added to the amplitudes of $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons:

$$A_X = \frac{\sqrt{\frac{m_X^7 \Gamma_X^2 \sigma(X \to K_L^0 K_S^0) q^3(m_\phi^2)}{q^3(m_X^2)}}}{m_X^2 - s + \imath\sqrt{s}\Gamma_X} \cdot e^{\imath\delta_X}.$$

The parameters $\sigma(X \to K_L^0 K_S^0)$, M_X, Γ_X,δ_X as well as the $\phi(1020)$ peak cross section were obtained from the approximation:

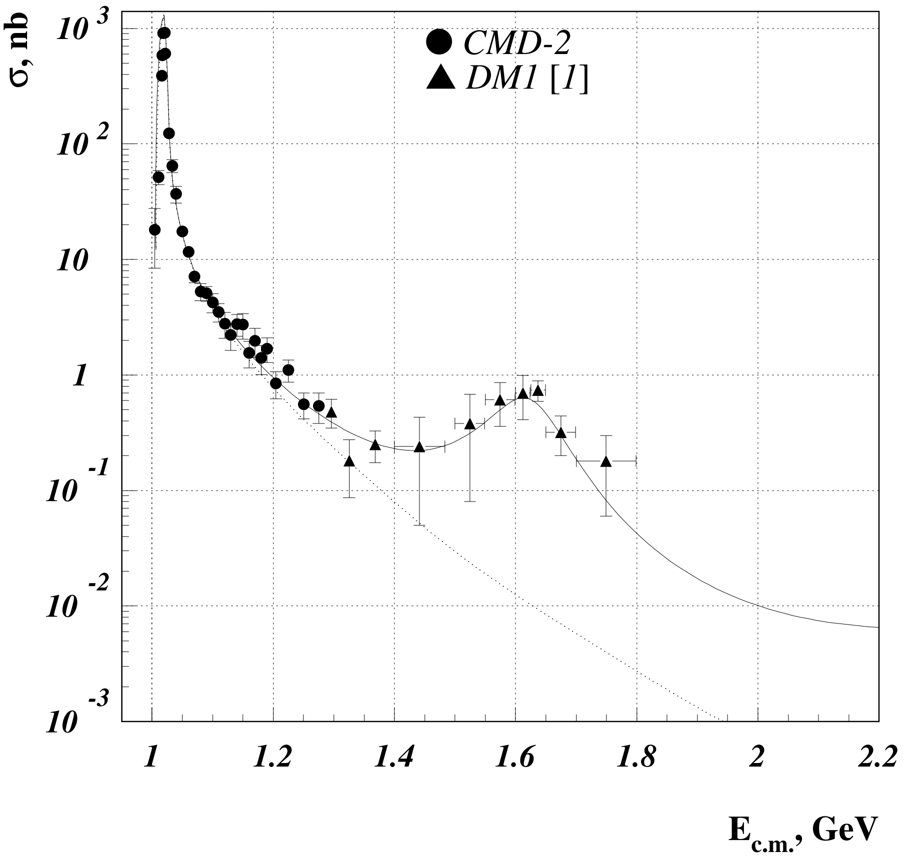

Fig. 3. The cross section of the process $e^+e^- \to K_L^0 K_S^0$ in the energy range $E_{c.m.}$ = 1.05 – 1.80 GeV compared to the Vector Dominance Model predictions: $\rho(770)$, $\omega(782)$, $\phi(1020)$ mesons (the dotted curve) and $\rho(770)$, $\omega(782)$, $\phi(1020)$ and X (the solid curve).

$$
\begin{aligned}
\sigma(\phi \to K_L^0 K_S^0) &= (1375 \pm 6 \pm 23)\ \text{nb}, \\
\sigma(X \to K_L^0 K_S^0) &= 0.73 \pm 0.33\ \text{nb}, \\
M_X &= 1623 \pm 20\ \text{MeV/c}^2, \\
\Gamma_X &= 139 \pm 60\ \text{MeV}, \\
\delta_X &= 160^\circ \pm 42^\circ, \\
\chi^2/n.d.f &= 0.91.
\end{aligned}
$$

The value of the $\phi(1020)$ peak cross section changes from 1376 nb to 1375 nb after the contribution of a higher resonance is taken into account. This change agrees with the estimation of the systematic uncertainty of the cross section (of about 1.5 nb) due to the model dependence of the cross section value [25]. The approximation curve is shown in Fig. 3 by the solid line. The theoretical curve describing the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons, is shown in Fig. 3 by the dotted line. One can see that after adding the amplitude

Table 2
Main sources of the systematic errors

Source	Contribution,%
Selection criteria	3.5–6
Background subtraction	2–7
Luminosity	2
Detection efficiency	2
Radiative corrections	1
Total	5 – 10

A_X, the approximation of the experimental data is much better. The obtained values of the mass and width of the X state are consistent with those of the $\phi(1680)$ meson [24]. However, as noted above, both isovector and isoscalar states could contribute to the cross section of the neutral kaon production in the energy range 1.0 – 2.0 GeV. To unambiguously identify the nature of the observed enhancement as well as to determine the relative weights of the I=0 and I=1 final states, one should simultaneously study both $K^0_L K^0_S$ and K^+K^- final states with a significantly higher data sample, particularly in the energy range above 1.4 GeV. The detailed investigation of other final states of e^+e^- annihilation in this energy range will be also needed to shed light on the light quark spectroscopy in the vector sector. Such studies will be possible at the VEPP-2000 collider [26] now under construction at the Budker Institute of Nuclear Physics.

The main sources of the systematic uncertainties are listed in Table 2. The uncertainty caused by the selection criteria was estimated by varying the cuts for pion momenta, acollinearity angle $|\Delta\phi|$ and Z-coordinate of the vertex by one standard deviation. It showed that the cross section changed by 3.5% below 1.1 GeV and by 6% above this energy. To estimate the uncertainty because of the background shape, the following procedure was used. The invariant mass distribution of two tracks was approximated in a narrow mass range from 440 to 560 MeV/c^2, the parameters of the function describing background were determined and the obtained number of signal events was compared to that after the standard approximation in the invariant mass range from 340 to 700 MeV/c^2. The variation of the cross section was 2% in the energy range 1.05–1.09 GeV smoothly rising to 7% in the higher energy range. The systematic error of the luminosity is caused by the radiative corrections to the Bhabha scattering cross section as well as selection of Bhabha events [17]. The uncertainty of the detection efficiency is dominated by the statistical error of the approximating constant in experiment [19]. The uncertainty on the radiative correction comes from the accuracy of the theoretical formulae used in the calculation (1%) as well as from the missing momentum resolution. To take into account the influence of the latter effect, selection criteria using this parameter were varied by one standard deviation. The resulting change was significant at 1.05 and 1.06 GeV only where it was 10% and 2.5% respectively whereas at all other energies it was negligible. The overall systematic uncertainty of the cross section is obtained by adding the individual contributions in quadrature. It grows up with energy from 5% in the energy range $E_{c.m.} = 1.05$–1.09 GeV to 10% in the energy range $E_{c.m.} = 1.27$–1.38 GeV.

4 Conclusion

Using 948±33 reconstructed events, detected by the CMD-2, the cross section of the process $e^+e^- \to K_L^0 K_S^0$ was measured in the energy range from 1.05 to 1.38 GeV. It is shown that the cross section energy dependence in the energy range $E_{c.m.} > 1.13$ GeV could not be explained by the Vector Dominance Model with the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons only.

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