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Study of the process $e^+e^- \to K\bar{K}$ in the center-of-mass energy range 1004-1060 MeV with the CMD-3 detector at e^+e^- VEPP-2000 collider

KOZYREV E. A.[1,2], AMIRKHANOV A. N.[1,2], ANISENKOV A. V.[1,2], M. AULCHENKO V.[1,2], BANZAROV V. S.[1], BASHTOVOY N. S.[1], BERKAEV D. E.[1], BONDAR A. E.[1,2], BRAGIN A. V.[1], EIDELMAN S. I.[1,2], A. EPIFANOV D.[1], EPSHTEYN L. B.[1,2,3], EROFEEV A. L.[1,2], FEDOTOVICH G. V.[1,2], GAYAZOV S. E.[1,2], GREBENUK A. A.[1,2], GRIBANOV S. S.[1,2], GRIGORIEV D. N.[1,4], IGNATOV F. V.[1], IVANOV V. L.[1,2], KARPOV S. V.[1], KASAEV A. S.[1], KAZANIN V. F.[1,2], IRPOTIN A. N.[1], KOROBOV A. A.[1,2], KOVALENKO O. A.[1,2], KOZYREV A. N.[1,2], KOOP I. A.[1], KROKOVNY P. P.[1,2], KUZMENKO A. E.[1,2], KUZMIN A. S.[1,2], LOGASHENKO I. B.[1,2], LUKIN P. A.[1,2], MIKHAILOV K. YU.[1,2], OKHAPKIN V. S.[1], OTBOEV A. V.[1], PESTOV YU. N[1], POPOV A. S.[1,2], RAZUVAEV G. P.[1,2], RUBAN A. A.[1], RYSKULOV N. M.[1], RYZHENENKOV A. E.[1,2], SENCHENKO A. I.[1], SHEBALIN V. E.[1], SHEMYAKIN V. E.[1,2], SHWARTZ A. S.[1,2], SHWARTZ D. B.[1,2], SIBIDANOV A. L.[4], SHATUNOV P. YU.[1], SHATUNOV YU. M.[1], SOLODOV E. P.[1,2], TITOV V. M.[1], TALYSHEV A. A.[1,2], VOROBIOV A. I.[1], YUDIN YU. V.[1,2]

(1. *Budker Institute of Nuclear Physics*, *Novosibirsk* 630090, *Russia*;
2. *Novosibirsk State University*, *Novosibirsk* 630090, *Russia*;
3. *Novosibirsk State Technical University*, *Novosibirsk* 630092, *Russia*;
4. *Falkiner High Energy Physics Department*, *School of Physics*, *University of Sydney*, *Australia*)

Abstract: The $e^+e^- \to K_S^0K_L^0$ and $e^+e^- \to K^-K^+$ cross sections have been measured in the center-of-mass energy range 1004-1060 MeV for 25 energy points with about 2%-3% systematic uncertainties. The analysis is based on 5.5 pb^{-1} of integrated luminosity collected with the CMD-3 detector at the VEPP-2000 e^+e^- collider. The measured cross section is approximated according to vector meson dominance model as a sum of ϕ, ω, ρ-like amplitudes and their excitations, and $\phi(1020)$ meson parameters have been obtained.

Key words: hadrons; electron positron collider; kaon form factor

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Biography: KOZYREV E. A. (corresponding author), born in 1991, PhD. Research field: electro-positron annihilation into hadrons. E-mail: e.a.kozyrev@inp.nsk.su

VEPP-2000 e^+e^- 对撞机上用 CMD-3 谱仪研究 1004-1060 MeV 能区的 $e^+e^- \to K\bar{K}$ 过程

KOZYREV E. A.[1,2], AMIRKHANOV A. N.[1,2], ANISENKOV A. V.[1,2], M. AULCHENKO V.[1,2], BANZAROV V. S.[1], BASHTOVOY N. S.[1], BERKAEV D. E.[1], BONDAR A. E.[1,2], BRAGIN A. V.[1], EIDELMAN S. I.[1,2], A. EPIFANOV D.[1], EPSHTEYN L. B.[1,2,3], EROFEEV A. L.[1,2], FEDOTOVICH G. V.[1,2], GAYAZOV S. E.[1,2], GREBENUK A. A.[1,2], GRIBANOV S. S.[1,2], GRIGORIEV D. N.[1,4], IGNATOV F. V.[1], IVANOV V. L.[1,2], KARPOV S. V.[1], KASAEV A. S.[1], KAZANIN V. F.[1,2], IRPOTIN A. N.[1], KOROBOV A. A.[1,2], KOVALENKO O. A.[1,2], KOZYREV A. N.[1,2], KOOP I. A.[1], KROKOVNY P. P.[1,2], KUZMENKO A. E.[1,2], KUZMIN A. S.[1,2], LOGASHENKO I. B.[1,2], LUKIN P. A.[1,2], MIKHAILOV K. YU.[1,2], OKHAPKIN V. S.[1], OTBOEV A. V.[1], PESTOV YU. N[1], POPOV A. S.[1,2], RAZUVAEV G. P.[1,2], RUBAN A. A.[1], RYSKULOV N. M.[1], RYZHENENKOV A. E.[1,2], SENCHENKO A. I.[1], SHEBALIN V. E.[1], SHEMYAKIN V. E.[1,2], SHWARTZ A. S.[1,2], SHWARTZ D. B.[1,2], SIBIDANOV A. L.[4], SHATUNOV P. YU.[1], SHATUNOV YU. M.[1], SOLODOV E. P.[1,2], TITOV V. M.[1], TALYSHEV A. A.[1,2], VOROBIOV A. I.[1], YUDIN YU. V.[1,2]

(1. 俄罗斯布德克尔核物理研究所，新西伯利亚 630090，俄罗斯；
2. 国立新西伯利亚大学，新西伯利亚 630090，俄罗斯；
3. 国立新西伯利亚理工大学，新西伯利亚 630090，俄罗斯；
4. 悉尼大学物理学院高能物理系，悉尼，澳大利亚)

摘要：在质心能量 1004-1060MeV 之间的 25 个能量点测量了 $e^+e^- \to K_S^0K_L^0$ 和 $e^+e^- \to K^-K^+$ 截面，系统误差大约为 2%-3%. 分析是基于 VEPP-2000e^+e^- 对撞机上 CMD-3 收集的积分亮度为 5.5 pb^{-1} 的实验数据. 测量的截面可近似看作 ϕ, ω, ρ 类似的振幅及其激发态按照矢量介子主导模型的叠加，得到了 $\phi(1020)$ 介子的共振参数.

关键词：强子；正负电子对撞机；介子形状因子

0 Introduction

Investigation of e^+e^- annihilation into hadrons at low energies provides unique information about interaction of light quarks. Precise measurement of the $e^+e^- \to K\bar{K}$ cross section allows to study properties of the light vector mesons with $J^{PC} = 1^{--}$, and is required for the precise calculation of strong interaction contributions to $(g-2)_\mu$ and $\alpha(M_Z)$ values[1]. A significant deviation of coupling constants ratio $\frac{g_{\phi} \to K^+K^-}{g_{\phi} \to K_SK_L}$ from a theoretical prediction requires new comprehensive measurement of the cross sections[2].

The most precise previous study of the process has been performed by the CMD-2[3-4], SND[5] and BaBar[6-7] detectors. In this paper we present new measurement of the $e^+e^- \to K_S^0K_L^0$ and $e^+e^- \to K^-K^+$ cross section, characterized by statistical advantage and performed in the center-of-mass energy $E_{c.m.}$ range 1004-1060 MeV at 25 energy points. Also the paper contains the results of the cross section interpretation according to the vector meson dominance (VMD) model.

1 CMD-3 detector and data set

The Cryogenic Magnetic Detector (CMD-3) is installed in one of two interaction regions of VEPP-2000 collider[8], and is described elsewhere[9]. The detector tracking system consists of the cylindrical drift chamber(DC) and double-layer cylindrical multi-wire proportional Z-chamber, both used for a trigger, and both are installed inside thin (0.2 X_0) superconducting solenoid with 1.3 T field. DC contains 1 218 hexagonal cells and allows to measure charged particle momentum with 1.5%-4.5% accuracy in the 100-1000 MeV/c range, and provides the measurement of the polar (θ) and azimuth (ϕ) angles with 20 mrad and 3.5-8.0 mrad accuracy, respectively. An amplitude information from the DC wires is used to measure the ionization losses dE/dx of charged particles with $\sigma_{dE/dx}\approx$11%-14% accuracy for minimum ionization particles (m. i. p.). A barrel liquid xenon (LXe) with 5.4 X_0 and CsI crystal with 8.1 X_0 electromagnetic calorimeters are placed outside the solenoid. The BGO crystals with 13.4 X_0 are used as the end-cap calorimeters. Return yoke of the detector is surrounded by the scintillation counters, which are required for cosmic events veto.

To study a detector response to investigated processes and obtain a detection efficiency, we have developed a Monte Carlo (MC) simulation of our detector based on GEANT4[10] package, and all simulated events pass all our reconstruction and selection procedures. The MC simulation includes photon jet radiation by the initial electron or positron, calculated according to Ref. [11].

The analysis is based on 5.5 pb^{-1} of integrated luminosity, collected in two scans of ϕ(1020) resonance region at 25 energy points in the $E_{c.m.}$ = 1004-1060 MeV range.

The beam energy E_{beam} has been monitored by using the back-scattering-laser-light system[12] which determines $E_{c.m.}$ at each energy point with about 0.06 MeV accuracy.

2　$e^+e^-\to K\bar{K}$ event selection

At energies under studied K_S^0-meson can be produced only simultaneously with K_L^0-meson. So, signal identification of the process $e^+e^-\to K_S^0K_L^0$ is based on the detection of two pions from the $K_S^0\to\pi^+\pi^-$ decay. For each pair of oppositely charged tracks in the event we perform a kinematic fit with the requirement to have a common vertex, and retain track parameters associated with this vertex. Assuming tracks to be pions, the pair with the best χ^2 from the vertex fit and with the invariant mass in the range 420-580 MeV/c^2 is considered as a K_S^0 candidate. The following requirements are applied to the events with found K_S^0 candidate.

(Ⅰ) The longitudinal and transverse distances of the vertex position are required to have $|Z_{K_S^0}|$ < 10 cm and $|\rho_{K_S^0}|$ < 6 cm, respectively;

(Ⅱ) Each track has momentum 130 < $P_{\pi^\pm}$ < 320 MeV/c corresponding to the kinematically allowed region for pions from the K_S^0 decay;

(Ⅲ) Each track has the ionization losses $dE/dx_{\pi^\pm} < dE/dx_{m.i.p} + 3\times\sigma_{dE/dx_{m.i.p}}$ to reject charged kaons and background protons. The last two requirements are illustrated in Fig. 1 by lines for all detected tracks at the energy point E_{beam} = 505 MeV;

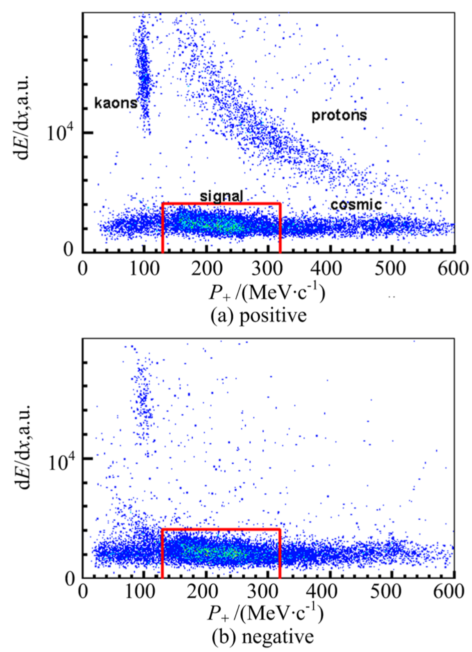

Fig. 1　The ionization losses vs momentum

(Ⅳ) The total reconstructed momentum of the K_S^0 candidate, $P_{K_S^0}$, is required to be within five standard deviations from the nominal momentum at each energy point.

We determine the number of signal events for data and simulation by approximation of two pion invariant mass, shown in the Fig. 2 (at the beam energy 505 MeV for simulation (a) and data (b). The short dotted line corresponds to a signal profile, and the long dotted line is for the background), by a sum of signal and background profiles. The signal shape is described by the sum of three Gaussian functions with parameters fixed from the simulation, but with additional Gaussian smearing to account for the detector response. A background, predominantly caused by collider processes $e^+e^- \to \pi^+\pi^-2\pi^0$, $4\pi^\pm$, 3π, K^+K^- and cosmic muons, is described by second order polynomial function and is presented in both data and MC-simulation. The background in simulation corresponds to tails of signal with wrong reconstructed parameters of pions. By varying shapes of the functions used, we estimate uncertainty in number of extracted signal events not more than 1.1%.

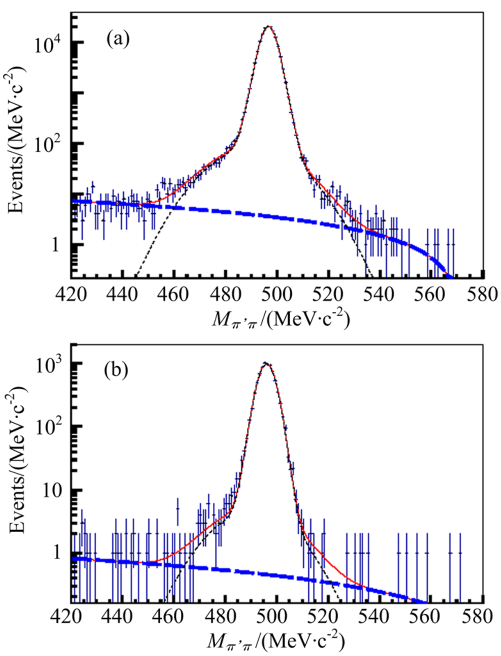

Fig. 2 The approximation of the invariant mass of two pions

The detection efficiency $\epsilon(K_S^0K_L^0)$ is obtained by dividing the number of MC simulated events after reconstruction and selections described above, by the total number of generated $K_S^0K_L^0$ pairs. Fig. 3 shows the obtained detection efficiency (squares) vs c. m. energy. The energy behavior as well as the absolute value ($\approx 35\%$) is predominantly due to pions polar angle selection criterion. The efficiencies of single tracks of charged kaons ($\varepsilon(K^+)$, $\varepsilon(K^-)$); The efficiency of both kaons detection ($\varepsilon(K^+K^-)$)-circles; The efficiency of K_S-meson ($\varepsilon(K_S^0)$)-squares.

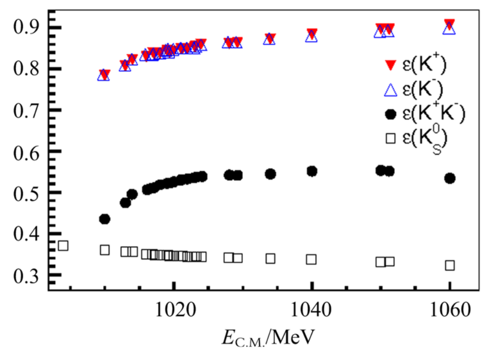

Fig. 3 The detection efficiency vs energy from simulation

The detection of the charged mode ($e^+e^- \to K^-K^+$) is based on the search of two central collinear tracks of kaons in DC with defined momentums approximately equal to $\sqrt{E_{c.m.}^2/4 - m_{K^+}^2}$ with accuracy of detector resolution. Additional selection reveals that kaon track has ionization losses significantly larger than the ones of m. i. p. due to relatively small velocity of kaons under study $\beta = 0.2$-0.4 (as shown in Fig. 1). The level of remaining background is less than 0.5%.

The collinear configuration of the process allows to test MC simulation by the determination of the efficiencies of each kaon in data as well as in MC. The experimental efficiencies of single positive and negative tracks ($\varepsilon(K^+)$, $\varepsilon(K^-)$) are shown by triangles in Fig. 3 and increases from 78% to 90% across the energy region under study. The deviation of efficiencies of single tracks in data from MC is less then 1%. Circles in the figure correspond to total simulated detection efficiency ($\varepsilon(K^+K^-)$) of K^+K^- final state, constituted by geometrical efficiency due to polar angle selection ($\approx 73\%$) as well as by the values of $\varepsilon(K^+)$, $\varepsilon(K^-)$.

3 Cross section of $e^+e^- \to K\bar{K}$ and systematic uncertainties

The experimental Born cross section of the $e^+e^- \to K\bar{K}$ process has been calculated for each energy point according to the expression:

$$\sigma^{born} = \frac{N^{exp}}{\epsilon_{reg}\epsilon_{trig}L(1+\delta_{rad})}\delta^{en.\,disper} \qquad (1)$$

where ϵ_{reg} is a detection efficiency, ϵ_{trig} is a trigger efficiency, L is the integrated luminosity, $1+\delta_{rad}$ is a radiative correction, and $\delta^{en.\,disper.}$ represents a correction due to the energy dispersion of the electron-positron beams.

The trigger efficiency is studied using responses of two independent triggers, charged and neutral, for selected signal events, and is found to be close to unity $\epsilon_{trigg} = 0.998 \pm 0.001$. The integrated luminosity L is determined by the processes $e^+e^-\to e^+e^-$ and $e^+e^-\to\gamma\gamma$ with about 1%[13] accuracy. The initial state radiative correction $1+\delta_{rad}$ is calculated using structure function method with an accuracy better than 0.3%[14]. The dispersion of the electron-positron c. m. energy is about 300 keV, significant in comparison with the width of ϕ meson, and we introduce the correction of the cross section, which has a maximum value of 1.028 ± 0.007 for both channel in the peak of ϕ resonance. The resulting cross sections are shown in Fig. 4.

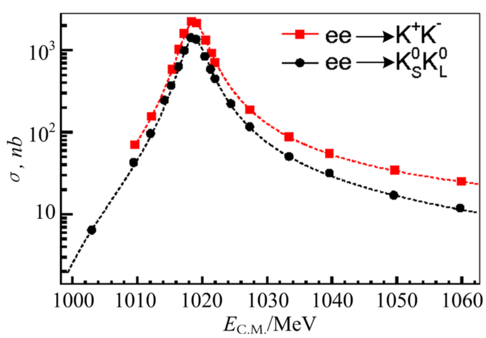

Fig. 4 Preliminary results of measurement

The uncertainty in $e^+e^-\to K_S^0K_L^0$ cross section is dominated by the signal extraction procedure used two pion mass approximation (Fig. 2). Moreover, MC simulation doesn´t exactly reproduce all detector responses, and we perform some additional study to obtain corrections for data-MC difference in the detection efficiency. We observe good data-MC agreement for the charged pion detection inefficiency ($\approx 1\%$), introduce no efficiency correction, and estimate uncertainty in the detection as 0.5%. By variation of corresponding selection criteria we estimate uncertainty due to the data-MC difference in the angular and momentum resolutions as 0.4%, and other selection criteria contribute 0.5%.

The uncertainty in $e^+e^-\to K^+K^-$ cross section is dominated by inexact knowledge of angular acceptance of kaons. This systematic uncertainty (3%) is examined using Z-chamber which surrounds DC. Unlike pions in neutral channel the charged pair of kaons have much more ionization losses and collinear configuration that leads to strong correlation in detector response to charged kaons tracks.

The systematic errors of the $e^+e^-\to K_S^0K_L^0$ and $e^+e^-\to K^+K^-$ cross sections measurement, discussed above, are summarized in Tab. 1, and in total estimated as 1.8% and 3.2%, respectively.

Tab. 1 Summary of systematic errors in the $e^+e^-\to K\bar{K}$ cross section measurement

source systematic error	$e^+e^-\to K_S^0K_L^0$	$e^+e^-\to K^+K^-$
signal extraction	1.1	0.3
detection efficiency	1.0	3
radiative correction	0.3	0.3
energy dispersion correction	0.3	0.3
trigger efficiency	0.1	0.1
luminosity	1.0	1.0
total	1.8	3.2

4 Cross section interpretation

Our data in the studied energy range allows to obtain $\phi(1020)$ parameters with good accuracy. We approximate the energy dependence of the cross section according to a vector meson dominance (VMD) model as a sum of ϕ, ω, ρ-like amplitudes[15]:

$$\sigma_{e^+e^-\to K\bar{K}}(s) = \frac{8\pi\alpha}{3s^{5/2}}p_K^3\frac{Z(s)}{Z(m_{\phi^2})}\cdot$$
$$\left|\frac{g_{\phi\gamma}g_{\phi KK}}{D_\phi(s)} \pm \frac{g_{\rho\gamma}g_{\rho KK}}{D_\rho(s)} + \frac{g_{\omega\gamma}g_{\omega KK}}{D_\omega(s)} + A_{\phi',\rho',\omega'}\right| \quad (2)$$

where $s=E^2_{c.m.}$, p_K is a kaon momentum, $Z(s)=1+\frac{\pi\alpha}{2\beta}$ is the Sommerfeld-Gamov-Sakharov factor for charged kaons with velocity $\beta=\sqrt{1-4m_K/s}$, $D_V(s)=m_V^2-s-i\sqrt{s}\Gamma_V(s)$, m_V, and Γ_V are mass and width of major intermediate resonances: $V=$

$\rho(770)$, $\omega(782)$, $\phi(1020)$. The sign before ρ-amplitude is plus for charged channel and minus for neutral one due to quark structure of kaons and ρ-meson. The energy dependence of the decay width is expressed via sum of branching fractions and phase space energy dependence $P_{V\to f}(s)$ of all decay modes as (see Refs. [5-15]):

$$\Gamma_V(s) = \Gamma_V \sum_{V\to f} B_{V\to f} \frac{P_{V\to f}(s)}{P_{V\to f}(m_V^2)}.$$

The coupling constants of the intermediate vector meson V with initial and final states can be presented as:

$$g_{V\gamma} = \sqrt{\frac{3m_V^3\Gamma_{Vee}}{4\pi\alpha}},\ g_{VK\bar{K}} = \sqrt{\frac{6\pi m_V^2\Gamma_V B_{VK\bar{K}}}{p_V^3(m_V)}},$$

where Γ_{Vee} and $B_{VK\bar{K}}$ are electronic width and decay branching fraction to pair of kaons.

In our approximation we use values of mass (Tab. 1), total width, and electronic width of $\rho(770)$ and $\omega(782)$: $\Gamma_{\rho\to ee} = 7.04 \pm 0.06$ keV, $\Gamma_{\omega\to ee} = 0.60 \pm 0.02$ keV[16]. The branching fractions of $\rho(770)$ and $\omega(782)$ to a pair of kaons are unknown, and we use the relation $g_{\omega K_S^0K_L^0} = -g_{\rho K_S^0K_L^0} = g_{\phi K_S^0K_L^0}/\sqrt{2}$, based on the quark model with "ideal" mixing and exact SU(3) symmetry of u-, d-, s-quarks[15]. In order to take into account possible breaking of the assumption both $g_{\rho K_S^0K_L^0}$ and $g_{\phi K_S^0K_L^0}$ are multiplied by the union constant $r_{\rho/\omega}$.

The amplitude $A_{\phi',\rho',\omega'}$ denotes a contribution of excited $\omega(1420)$, $\rho(1450)$ and $\phi(1680)$ vector meson states to the $\phi(1020)$ mass region. Using BaBar[6-7] data above 1.06 GeV for the $e^+e^-\to K_S^0K_L^0$ and $e^+e^-\to K^+K^-$ reactions we fix the contribution of higher energy states.

We fit the cross sections of $e^+e^-\to K_S^0K_L^0$ and $e^+e^-\to K^+K^-$ with float m_ϕ, Γ_ϕ, $\Gamma_{\phi\to e^+e^-}\times B_{\phi\to K_S^0K_L^0}$, $\Gamma_{\phi\to e^+e^-}\times B_{\phi\to K^+K^-}$ and $g_{\rho/\omega}$ parameters. The obtained fit is shown in the Fig. 4 with the following parameters, which contain statistical errors as well as systematic and model-dependent uncertainties:

$$\left.\begin{aligned}
&m_\phi = 1019.464 \pm 0.060\ \text{MeV/c}^2\\
&\Gamma_\phi = 4.247 \pm 0.015\ \text{MeV}\\
&\Gamma_{\phi\to ee}B_{\phi\to K_S^0K_L^0} = 0.429 \pm 0.009\ \text{keV}\\
&\Gamma_{\phi\to ee}B_{\phi\to K^+K^-} = 0.679 \pm 0.022\ \text{keV}\\
&r_{\rho/\omega} = 0.76 \pm 0.11\\
&g_{V\to K^+K^-}/g_{V\to K_S^0K_L^0} = 0.995 \pm 0.035
\end{aligned}\right\} \quad (3)$$

The difference of charged and neutral cross-sections for 24 energy points defined as $R_{c/n} = \sigma_{e^+e^-\to K^+K^-}\times\frac{p_{K^0}^3(s)}{p_{K^\pm}^3(s)}\times\frac{1}{Z(s)} - \sigma_{e^+e^-\to K_S^0K_L^0}$ is shown in Fig. 5. The difference $R_{c/n}$ is predominantly caused by interference term of resonance amplitudes of ϕ-meson and isovector ρ-meson. The shaded area corresponds to 1.8% and 3.2% systematic uncertainties in data for neutral and charged channel respectively. The result of the fit discussed above is shown by solid line that leads to agreement $\chi^2 = 37$. It should be mentioned that the case with $A_{\phi',\rho',\omega'} = 0$ and naive theoretical prediction $g_{V\to K^+K^-} = g_{V\to K_S^0K_L^0}$, $r_{\rho/\omega} = 1$ also gives an adequate description of experimental $R_{c/n}$. This case is characterized by $\chi^2 = 51$ and shown by the short dotted line, while long dotted lines correspond to the same theoretical prediction with $r_{\rho/\omega} = 0.5$ or 1.5 and differ strongly from data.

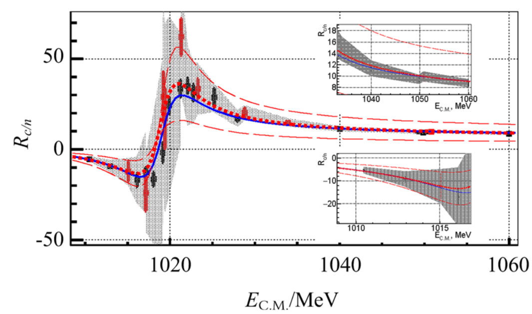

Fig. 5 The difference of charged and neutral cross-sections

5 Conclusion

Using pions from the $K_S^0\to\pi^+\pi^-$ decay and collinear charge kaons in DC we observed 6.5×10^5 and 1.6×10^6 events of the $e^+e^-\to K_S^0K_L^0$ and $e^+e^-\to K^+K^-$ processes respectively in the 1004-1060 MeV c. m. energy range, and measured its cross section with 1.8%-3.2% systematic error. Using VMD model the parameters of ϕ-meson are preliminary measured (Eq. (3)). The obtained deviation of ρ, ω amplitudes from naive theoretical prediction $r_{\rho/\omega} = 0.76 \pm 0.11$ allows to estimate the precision of used VMD-based phenomenological model as 25 %. Moreover, obtained ratio $g_{V\to K^+K^-}/g_{V\to K_S^0K_L^0} = 0.995 \pm 0.035$ demonstrates the precision of SU(2)-symmetry better than 3.5 %.

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