EPJ Web of Conferences **199**, 02027 (2019) https://doi.org/10.1051/epjconf/201919902027
MESON 2018

Recent results of the hadronic cross section measurements with the CMD-3 detector at e^+e^- collider VEPP-2000

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Abstract. A brief review of the recent results on the hadronic cross section measurements with the CMD-3 detector at the e^+e^- collider VEPP-2000 is given. Focus is made on the processes with charged kaons in multihadron events, which have a strong impact on strange meson spectroscopy and form factors that are important ingredients in the Dalitz plot analysis. Experimental data relevant to the topic are presented from the broad energy range covered by VEPP-2000 and compared to earlier measurements by the different collaborations. The analysis is based on the integrated luminosity of about 100 pb^{-1} collected in 2011, 2012 and 2017.

1 Introduction

High-precision measurements of the exclusive $e^+e^- \to hadrons$ cross sections are required for many applications, in particular, to evaluate the hadronic contribution to the muon anomalous magnetic moment (AMM). The major hadronic contribution to AMM comes from energy range covered by the VEPP-2000, that determined the hadronic vacuum polarization itself (∼92%) and its uncertainty.
The exclusive $K^+K^-(n\pi)$ final states are of special interest since their production involves rich intermediate dynamics which allows to test the isotopic relations and to measure parameters of these intermediate states. In addition, these results are required for the strange meson spectroscopy and form factors that are important ingredients in the Dalitz plot analysis. Recent preliminary results of the analysis of some hadronic processes are presented.

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2 CMD-3 detector and experiment

The Cryogenic Magnetic Detector (CMD-3) is a general-purpose detector [1]. Coordinates, angles and momenta of charged particles are measured by the cylindrical drift chamber (DC) with accuracy about 120 μm in the $r - \phi$ plane and 2 mm along the beam axis. The amplitude information from the DC wires is used to measure specific ionization losses (dE/dx) in DC. The cylindrical multiwire double-layer proportional Z-chamber provides z-coordinate determination with accuracy ~0.5 mm. The calorimeter consists of three parts. The endcap BGO calorimeter consists of 680 crystals with a thickness 13.4 X_0. The barrel part is placed outside of the thin 0.08 X_0 superconducting solenoid with 1.3 T magnetic field and consists of the Liquid Xenon calorimeter (5.4 X_0) and CsI crystals with a thickness of 8.1 X_0 (1152 crystals) which are arranged in eight octants. The energy resolution of the barrel calorimeter was measured using Bhabha events and was found to be σ_E/E ~ 4 ÷ 8%. More detailed information is given elsewhere [1].

The energy range from 1 to 2 GeV was scanned again up and down in 2017 and the collected data correspond to the integrated luminosity of ~60 pb^{-1}. After upgrade of the positron injection complex the peak luminosity ~ $5 \cdot 10^{31} cm^{-2} s^{-1}$ was reached. During all runs the beam energy has monitored using Compton backscattering technique with accuracy ~50 keV [2]. Two independent first-level triggers "CHARGED", based on DC and ZC information and "NEUTRAL", based on the EMC were used. A positive decision of any trigger generates a signal for the data acquisition system. Samples of collinear Bhabha e^+e^- as well as of $\gamma\gamma$ events were selected for luminosity measurements. Electrons, muons and gamma candidates are selected using the energy deposited in the EMC and charged-track momentum measured in the DC. Photon candidates are defined as clusters in the EMC not associated with charged tracks in DC. The specific selection criteria for every channel are applied and each candidate undergoes a kinematic fit constraint, both to select the signal and to estimate the background contamination. Preliminary results on the ratio of the luminosities measured with $e^+e^- \to e^+e^-$ and $\gamma\gamma$ events are consistent within ~1% [3].

3 Study of the processes $e^+e^- \to K_S K_L$ and $e^+e^- \to K^+K^-$

The most precise previous study of these processes was performed by the CMD-2, KLOE and BaBar detectors. In this paper we present a new measurement of the $e^+e^- \to K_S K_L$ and $e^+e^- \to K^+K^-$ cross sections with CMD-3. These measurements are required since up to now at the ϕ peak are inconsistent between experiments at the level of ~ 4%.

To select the neutral mode we search pairs of two tracks forming a vertex with a good χ^2 and which are at least 2 mm away from the event primary vertex with a condition that the $\pi^+\pi^-$ invariant mass is within the nominal K_S mass. We observe 6.1×10^5 events of the process $e^+e^- \to K_S K_L$ in the 1004–1060 MeV c.m. energy range and measure the cross section with a 1.8% systematic uncertainty [4]. The obtained parameters of the ϕ meson are in good agreement with previous experiments. The values of Γ_ϕ and $\Gamma_{\phi\to ee} B_{\phi\to K_S K_L}$ are the most precise among all existing measurements. High precision in the cross section measurement allows the first quantitative estimate of the contributions from the ρ and ω mesons to the studied energy region.

Detection of the charged mode is based on the search of two central collinear tracks of kaons with close momentum values and specific ionization losses in the DC. We select $1.7\cdot10^6$ events of the process $e^+e^- \to K^+K^-$ and measure the cross section with a systematic error of about 2%. Our value of $\Gamma_{\phi\to ee} B_{\phi\to K^+K^-}$ is larger than the BaBar result by 1.8 standard deviations while the corresponding value of $B_{\phi\to ee}B_{\phi\to K^+K^-}$ is larger than the PDG one, predominantly based on the CMD-2 measurement, by 2.7 standard deviations. The obtained values of the ϕ meson mass and width agree with the results of other experiments including our recent study of the process $e^+e^- \to K_S K_L$. The observed deviation of the $\rho(770)$ and $\omega(782)$ amplitudes, $r_{\rho/\omega} = 0.95 \pm 0.03$, from a naive theoretical prediction, allows to estimate the accuracy of the used VMD-based phenomenological model as better than 5%. The obtained ratio $\frac{g_{\phi K^+K^-}}{g_{\phi K_S K_L}\sqrt{Z(m_\phi^2)}} = 0.990 \pm 0.017$ is consistent with isospin symmetry [5]. The obtained accuracy will be further improved in future experiments.

4 Study of the process $e^+e^- \to K^+K^-\pi^0$

To select events under study we require two central tracks in the DC with specific ionization losses and two or more photons in the EMC. For each pair of photons the kinematics reconstruction was performed and if kinematics of these four particles satisfy energy-momentum conservation, the combination with the smallest χ^2 is chosen. The number of signal events is determined by a fit of the π^0 peak using the invariant mass distribution of the two "best" photons. The main physical background comes from the processes $e^+e^- \to \pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$ which are significantly suppressed by using dE/dx information, whereas the events of the processes $e^+e^- \to K^+K^-2\pi^0$ and $e^+e^- \to K^+K^-\eta$ are rejected by the kinematic cuts. The detection efficiency was determined with MC simulation taking into account radiative corrections. Preliminary results on the cross section are shown in Fig. 1 along with BaBar data.

5 Study of the process $e^+e^- \to \eta\pi^+\pi^-\pi^0$

It is the first measurement of the cross section of the $e^+e^- \to \eta\pi^+\pi^-\pi^0$ process. We identify $\eta\pi^+\pi^-\pi^0$ candidates using all decay modes of η. Candidates for the process under study are required to have two good tracks with opposite charges, and four or more clusters in the calorimeters, not related to the tracks, assumed to be photons. The total number of selected events was found to be 2769±95. The production dynamics was studied in detail to calculate the detection efficiency and improve our understanding of the spectroscopy of light mesons. It was observed that the main intermediate states for the studied process are $\omega(782)\eta$, $\phi(1020)\eta$ and $a_0(980)\rho(770)$. Our data sample is too small for standard amplitude analysis. So, we extract a contribution of the narrow intermediate resonances, $\eta\omega(782)$ (824±41 events) and $\eta\phi(1020)$ (214±46 events) and then investigate other contributions, assuming low interference with the narrow states above. As a result, we clearly see a signal with the $a_0(980)\rho(770)$ state. The Born cross section are shown in Fig. 2. The systematic uncertainty was estimated as 11%. More detailed analysis can be found in [6].

6 Study of the processes $e^+e^- \to K^+K^-\eta$ and $e^+e^- \to K^+K^-\omega$

The $e^+e^- \to K^+K^-\eta$ process has been earlier studied by BaBar. It was shown that the main production mechanism is $e^+e^- \to \phi(1680) \to \phi(1020)\eta$. We consider an η meson as a recoil particle with respect to the detected charged kaons, thus all decay modes of η are used. The missing mass distribution of the K^+K^- system is used to determine the number of signal events by fitting the η meson peak. As a result, we select 3824± 62 signal events and preliminary results of the cross section of the $e^+e^- \to \phi(1020)\eta$ process are shown in Fig. 3 as well as Babar data [7].

We study the process $e^+e^- \to K^+K^-\omega$ on the base of the runs of 2011 and 2012 considering π^0 from $\omega\to 3\pi$ decay as a recoil particle. K/π separation is performed in the same way as in the

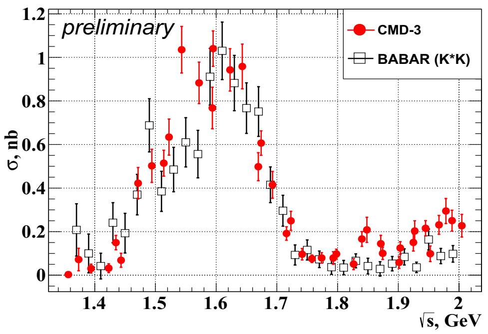

Figure 1. Cross sections of the process $e^+e^- \to K^+K^-\pi^0$ with the BaBar data. CMD-3 results - red dots, BaBar, measured in the $\eta \to 2\gamma$ mode are plotted by squared markers.

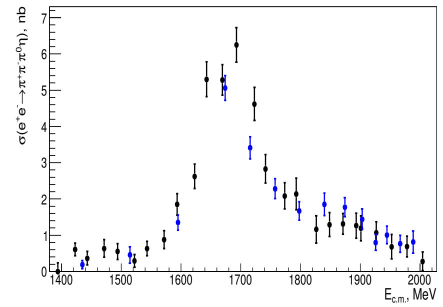

Figure 2. The $e^+e^- \to \eta\pi^+\pi^-\pi^0$ cross section. Black and blue colors are for the 2011 and 2012 data, respectively.

$K^+K^-\eta$ case. The only difference is that we consider only 3- and 4-track events, requiring to have two kaon candidates in an event. The major background processes are $e^+e^- \to K^+K^-\pi^+\pi^-$ and $e^+e^- \to K^+K^-\eta$. Suppression of the $K^+K^-\pi^+\pi^-$ final state is performed using cuts on the $2K\pi$ (for 3-track events) and $2K2\pi$ (for 4-track events) missing masses. We perform signal/background separation by fitting the $m_{\text{missing, 2K}}$ near the $\omega(782)$ peak, where the $K^+K^-\eta$ background contribution is negligibly small. In total, in the experiment 967±35 of signal events were extracted.

To calculate the radiative corrections, we fit the cross section with the shape obtained by the direct integration of the sqared matrix element of $e^+e^- \to \phi(1680) \to K^+K^-\omega(782) \to K^+K^-3\pi$ production in the 5-body phase space. Cross section of this process is plotted in Fig. 4. We esimate the current systematic uncertainty as 5%.

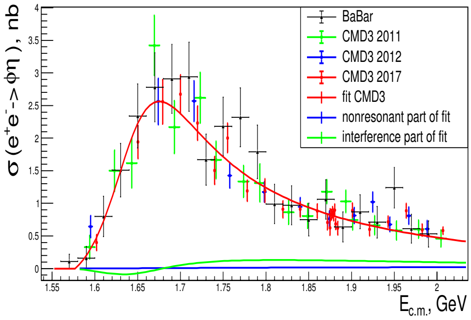

Figure 3. Cross section of the process $e^+e^-\to\phi(1020)\eta$ with the BaBar data - black triangles, CMD-3 - green, blue and red points.

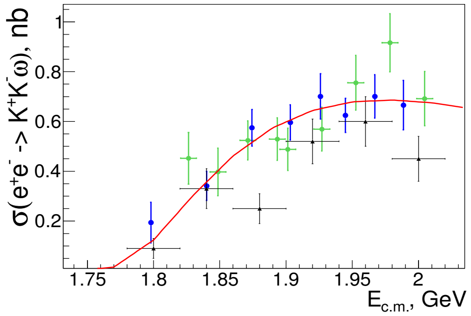

Figure 4. Cross section of the process $e^+e^-\to K^+K^-\omega(782)$ with the BaBar data presented by black triangles, CMD-3 - green and blue (2017). The fit - approximation of CMD-3 data.

7 Study of the process $e^+e^- \to K^+K^-\pi^+\pi^-$

This process has been earlier studied by the BaBar and CMD-3 [7, 8] in the c.m. energy range from 1.5 to 2.0 GeV. New results presented here are based on statistics collected in 2017. The energy range around $N\bar{N}$ threshold was scanned carefully and the beam energy has been monitored with accuracy ~ 50 keV. A similar procedure to select candidates under study, described in [8], was used. The signal events should have four tracks coming from the interaction point and two of them must correspond to kaons. The sample of selected events was used to calculate the cross section vs energy and it is consistent with the previous BaBar and CMD-3 measurements. For the first time we observe unexpected "sharp behavior' of the cross section near 1.9 GeV, similar to that for the six-pion channel (see Fig. 5). The cross section changes quickly by ~0.5 nb inside a narrow energy gap, again similar to that for six pions. It is the first hint that nature of this phenomenon is identical in both cases, but up to now remains unclear. For example, it is not seen in the channel with four charged pions and it is still a puzzle.

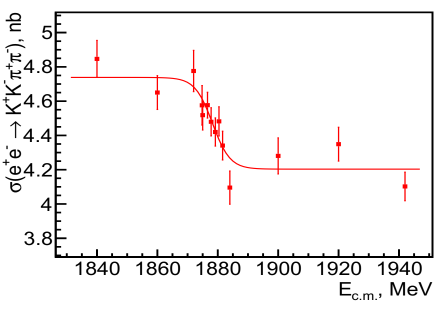

Figure 5. Preliminary result for the cross section of the $e^+e^- \to K^+K^-\pi^+\pi^-$ process near the $N\bar{N}$ threshold.

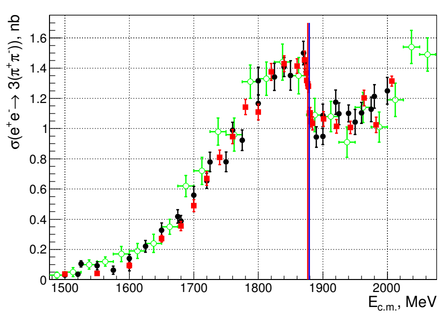

Figure 6. The $e^+e^- \to 3(\pi^+\pi^-)$ cross section measured with the CMD-3 in 2017 run (red squares), previous measurements are shown by black dots, BaBar results - open green circles. The vertical lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

8 Production of six charged pions in the $e^+e^- \to 3(\pi^+\pi^-)$ reaction

This process was measured by the DM2 experiment and later by BaBar and CMD-3. The CMD-3 results published in [9] are based on 22 pb^{-1} of the integrated luminosity collected in the c.m. energy range from 1.5 to 2 GeV. In 2017 the second energy scan was done and ~ 60 pb^{-1} has been collected. Especially we focus our study on the energy region around the $N\bar{N}$ threshold. To search for the events under study we have applied the same procedure as in [9]. The cross section is calculated according to the number of determined events taking into account radiative corrections and detection efficiency and is presented in Fig. 6. The new measurements are consistent with the previous one and more convincingly demonstrate the sharp cross section behavior around the nucleon-antinucleon threshold. Unfortunately, the beam energy spread on the average is about 1 MeV and we are unable to distinguish fine structure due to different masses of protons and neutrons.

9 Summary and Conclusion

The current integrated luminosity collected by the CMD-3 detector is about 100 pb^{-1}. The recorded data sample is comparable or higher than in all previous experiments in this energy region. Due to huge collected statistics we plan to measure the hadronic cross sections with systematic significantly smaller than is in the earlier experiments. For the first time we observed unexpected “sharp behavior” of the cross section for the process $e^+e^- \to K^+K^-\pi^+\pi^-$ near the $N\bar{N}$ threshold. We studied more carefully the six-pion process around the $N\bar{N}$ threshold and confirmed our previous result. Data analysis is in progress.

The authors are grateful to the VEPP-2000 team for excellent machine operation. Part of this work related to the photon reconstruction algorithm in the electromagnetic calorimeter is supported by the Russian Science Foundation (project 14- 50-00080). The work is partially supported by the Russian Foundation for Basic Research (grants RFBR 15-02-05674-a, RFBR 16-02- 00160-a, RFBR 17-02-00897, RFBR 17-02-00847).

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