Overview of the CMD-3 recent results at e^+e^- collider VEPP-2000

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Abstract. Since December 2010, the CMD-3 detector has collected data at the electron-positron collider VEPP-2000. The sample of the accumulated data corresponds to about 60 pb^{-1} of integrated luminosity in the c.m. energy from 0.32 up to 2GeV. Preliminary results of the analysis of various processes e^+e^- annihilation to hadrons are presented. It is shown the processes with multihadron events have several intermediate states which must be taken into account to correctly describe the angular and invariant mass distributions as well as cross section dependence versus energy.

1 Introduction

The electron-positron collider VEPP-2000 [1] operates at the Budker Institute of Nuclear Physics since December 2010. The collider is designed to provide luminosity up to 10^{32}cm^{-2}s^{-1} at the maximum center-of-mass energy $\sqrt{s} = 2$ GeV. The new idea of «round beams» firstly applied to get high

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luminosity. Two detectors, CMD-3 [2] and SND [3], are installed opposite to each other in the two beam interaction regions. The current integrated luminosity accumulated by each detector is about 60 pb^{-1}. The main physical tasks for both detectors are to measure the hadronic cross sections in the wide energy range, and searches for the new vector and scalar mesons and as well as for the exotic hadrons.

The precision data of the hadronic cross sections are required for various applications, in particular, to evaluate the anomalous magnetic moment (AMM) of muon, $a_\mu = (g-2)_\mu/2$. The VEPP-2000 energy range gives the major hadronic contribution to AMM ($a_\mu^{had} \sim 92\%$) both to the hadronic vacuum polarization itself and to its uncertainty [4].

The precision measurement of luminosity is a key ingredient of many experiments which study the hadronic cross sections at e^+e^- colliders. So far it is very important to have several QED processes such as $e^+e^- \to e^+e^-$, $\mu^+\mu^-$, $\gamma\gamma$ to have the cross check as it was done by CLEO [5]. The results of the luminosity determination and analysis of various hadronic cross sections are presented.

2 CMD-3 detector

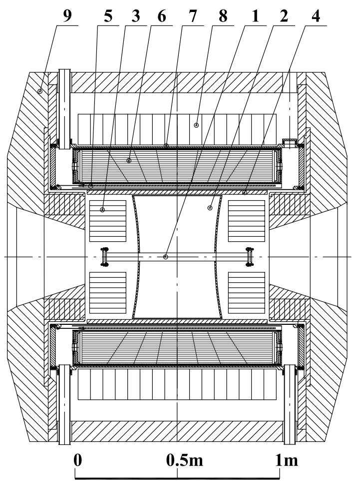

Figure 1. CMD-3 detector: 1 – beam pipe, 2 – drift chamber, 3 – BGO, calorimeter, 4 – Z-chamber,5 – SC solenoid, 6 – LXe calorimeter, 7 – TOF system, 8 – CsI electromagnetic calorimeter, 9 – yoke, not shown the outer muon range system.

Cryogenic Magnetic Detector is shown in Fig. 1. The tracks are measured by the cylindrical drift chamber (DC). In average the momentum resolution goes like $\sigma_p/\text{p} \sim 1 \div 5\%$. The cylindrical MWPC (Z-chamber) tightly embraces DC and provides z-coordinate of the track with accuracy $\sim$ 0.5 mm by measuring the analog information from cathode strips. The signals coming from anode sectors are used for the first level trigger and have time jitter $\sim$ 5 ns.

The calorimeter of the detector consists of three parts. The endcap calorimeter consists of 640 BGO crystals with a thickness 13.4 X_0. The barrel part is placed outside of the thin ($0.08X_0$) superconducting solenoid with 1.3 T magnetic field. The barrel calorimeter consists of two parts: Liquid Xenon calorimeter ($5.4X_0$) and calorimeter with CsI crystals ($8.1X_0$, 1152 crystals) [6] which are arranged in 8 octants. The LXe calorimeter has a tower structure (264 channels) and seven cylindrical double layers with strips (1286 channels). The photon conversion point is measured with precision ∼1÷2 mm. The energy resolution of the barrel calorimeter was measured using Bhabha events and was found to be: $\sigma_E/E \sim 4\div8\%$.

A new TOF system [7] has been installed between calorimeters to detect products of the antineutron annihilation under their interaction with the matter of calorimeter. This system has more fine granularity and time resolution with respect to the previous one.

The muon range system is mounted outside of the magnetic yoke and consists of 36 scintillation counters in the barrel part and 8 counters at the endcaps and has time resolution ∼1 ns.

3 Luminosity measurement

The energy range from 1 to 2GeV was scanned upward and downward with a step of 50MeV. At each energy point the integrated luminosity of about $500nb^{-1}$ was accumulated. In the case of scanning downward, the energy points at which the data were collected have been shifted by 25MeV with respect to the previous case. The experiments were performed from January to June 2011 and, similarly, in 2012. The beam energy was monitored to a precision of about 1÷3MeV by measuring of the track curvature in DC of the Bhabha events. For several points the energy was measured using Compton back scattering technique, which provides accuracy of about tenth keV [8]. These results were used also to calibrate the first method of energy measured.

Two types the «CHARGED» and the «NEUTRAL» first level triggers were used while data have been taking. A combinations of the signals from DC cells and ZC sectors, which roughly reproduce "track", start a special processor «TRACKFINDER» (TF). The combinations of signals from calorimeters with different energy thresholds actuated the «CLUSTERFINDER» (CF) processor. A positive decision of either processor allowed the recording of current event onto a hard disk with capacity about 2 TB. In the course of data accumulation, the mean frequency of trigger actuations ranged ∼200 ÷ 400 Hz. The sample of collinear Bhabha events e^+e^- were selected for luminosity determination, using the information about energy deposition of these events in calorimeters.

The process $e^+e^- \to \gamma\gamma$ was also used, since it has essential advantages [9] with respect to the first one. It is free of radiation of the final state particles and its Coulomb interaction, the corresponding Feynman graphs do not contain photon propagators affected by the vacuum polarization effects. These advantages are the main motivation to exploit this process as an independent tool for luminosity determination.

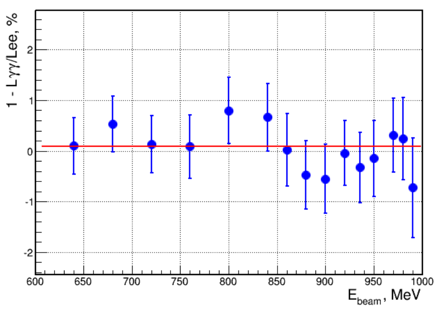

Figure 2. The ratio of the relative difference of the luminosities vs beam energy (scan 2012). Red line - fit: 0.2 ± 0.3%

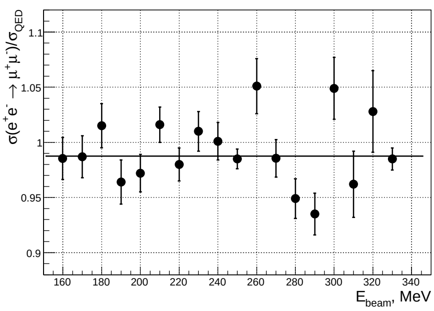

Figure 3. Result of the measurement of muon pair production in comparison with the QED prediction. Horizontal line - fit: 0.995 ± 0.005

The collected integrated luminosity above the ϕ mass is about 34.5pb^{-1}, 8.3 and 8.4pb^{-1} at the ω and ϕ resonances, respectively, and 9.4pb^{-1} from a scan below the ϕ. The peak luminosity $\sim 2 \cdot 10^{31}$ cm^{-2}s^{-1} is limited while by a positrons injection rate and it will gain by a factor of ten after upgrade of the injection facility.

The relative difference of the luminosities determined with two processes versus energy is presented in Fig. 2, where only statistical errors are shown (SCAN 2012). The horizontal line is a fit for this ratio and in average it is about 0.2±0.3%. The main sources which contribute to systematic error are: contribution due to the different angular resolutions for Bhabha events and $\gamma\gamma$ is estimated as ~0.8%; correction, which takes into account inclination of the beam axis with respect to detector is about ~0.4%; DC z-coordinate calibration contributes about 0.3 %; beam energy is measured with precision of σ_E < 50 keV using Compton back scattering of the laser light; radiative corrections are calculated according to [10] with the accuracy about 0.2%. Presently we estimate the current luminosity systematic uncertainty as ~1% for energies higher than 1 GeV.

4 Processes with multihadrons in final states

One of the main goal of the CMD-3 experiment is to reduce a systematic uncertainty of the cross section of two pion production to 0.3-0.4%. The $\pi^+\pi^-$ events are separated either using the particles momentum or their energy deposition in calorimeter. Two ways of event separation will provide cross-check and is expected allow to keep the systematic error under control. The first energy scan below 1GeV was performed in 2013. The collected statistics is a few times higher than we had in the previous CMD-2 measurements and it is at the level of ISR statistics accumulated by BaBar and KLOE. The process $e^+e^- \to \mu^+\mu^-$ is very importance since it provides overall systematic test of the event separation accuracy. Preliminary results for the cross section $\sigma(e^+e^- \to \mu^+\mu^-)$ are shown in Fig. 3 with respect to the QED prediction. Horizontal line is a fit for the double ratio $\sigma_{\mu\mu}^{exp}/\sigma_{\mu\mu}^{QED}/\sigma_{ee}^{exp}/\sigma_{ee}^{QED}$ which was found to be 0.995±0.005. At the moment this result demonstrates our potential power of the event separation procedure. Study of different systematic uncertaintices is going on.

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

It is known the CMD-2 and BaBar results for cross sections at the ϕ-peak region disagree at the level ~4% for charged channel, so a new measurement are required. The $e^+e^- \to K_S^0 K_L^0$ and $e^+e^- \to K^+K^-$ cross sections were measured in the c.m. energy range 1.004-1.060 GeV at 25 energy points. The neutral mode detection is based on the search of two central tracks with common vertex in DC from the $K_S^0 \to \pi^+\pi^-$ decay. The number of events is defined by the fit of two pions invariant mass distribution [11].

The registration of the charged mode is based on the search of two central collinear tracks of kaons with defined momentum in DC. Each track should has ionization losses significantly larger than mip due to relatively small velocity of kaons under study. After these requirements the level of remaining background is less than 0.5%. The detection efficiency of each kaon was determined with data and as well as with MC and deliver a deviation less 1.5%.

The obtained cross sections for the neutral (published) and charged mode (preliminary) are presented in Fig. 4 and Fig. 5, correspondingly. The measured cross section is approximated according to VDM model as a sum of ϕ, ω, ρ-like amplitudes and their excitations. The interference of non-resonant amplitudes with the amplitude of ϕ meson scales in ten times and shown too at the bottom of graphs. The neutral and charged channels were approximated simultaneously, as a result the following values of the ϕ meson parameters have been obtained: $m_\phi = 1019.464 \pm 0.060$ MeV/c^2,

$\Gamma_\phi = 4.240 \pm 0.017$ MeV, $\frac{B_{\phi\to K^+K^-}}{B_{\phi\to K^0_S K^0_L}} = 1.573 \pm 0.06$. The obtained parameters have accuracy comparable or better than it was obtained in previous experiments.

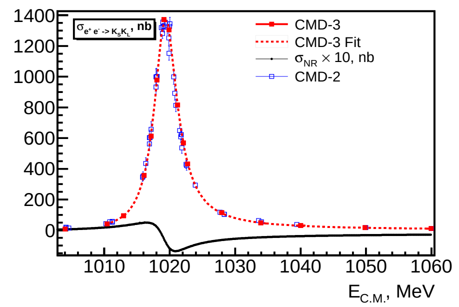

Figure 4. The cross section of the process $e^+e^- \to K_L KS$ around ϕ-meson energy region. CMD-2, CMD-3 and BaBar data are presented.

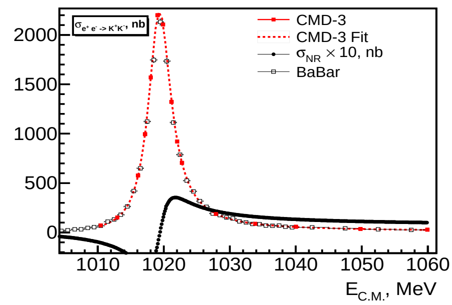

Figure 5. The cross section of the process $e^+e^- \to K^+K^-$ around ϕ-meson energy region. CMD-2, CMD-3 and BaBar data are presented.

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

To select events under study the following requires were applied: two track in DC with two or more photons in calorimeter. For each pair of photons the kinematics reconstruction was done under assumption that these photons are the product of the π^0 decay. If kinematics of these four particles satisfies energy-momentum conservation and ionization losses in DC corresponds to charged kaons the combination with the smallest χ^2 is chosen. The physical background coming from the processes $e^+e^- \to \pi^+\pi^-\pi^0$, $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ and significantly suppressed by using dE/dx information. The events of the processes $e^+e^- \to K^+K^-2\pi^0$ and $e^+e^- \to K^+K^-3\pi^0$ rejected by the kinematics cuts. The detection efficiency was determined by MC simulation with RC. Preliminary results of the cross section measurement are plotted in Fig. 6. Study of the dynamics production this system confirms two mechanism - production $K^{*\pm}K^{\mp}$ or $\Phi\pi^0$.

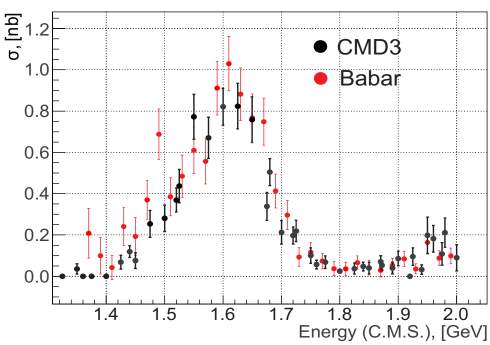

Figure 6. $e^+e^- \to K^+K^-\pi^0$ cross section. Black squares — this analysis, only statistical errors are shown; red dots – CMD-2.

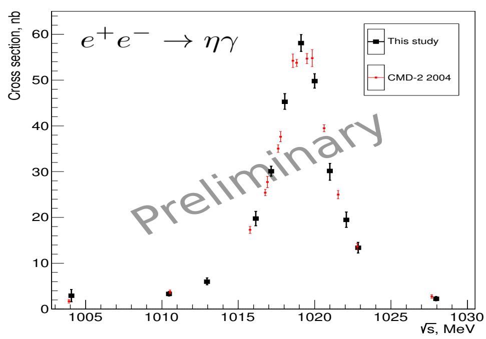

Figure 7. $e^+e^- \to \eta\gamma$ cross section. Black squares — this analysis, only statistical errors are shown; red dots — CMD-2.

4.3 Study of the processes $e^+e^- \to \eta\gamma$ and $e^+e^- \to \pi^0\gamma$

These processes with 3γ in final state were studied with the whole VEPP-2000 energy range. The signal events should have at least three photons and no tracks in DC. The kinematic reconstruction with total energy-momentum conservation was performed to better estimate photon parameters and reject background calorimeter clusters. The number of signal events is determined from fit of the two photon invariant mass spectrum where peaks at the pseudoscalar meson masses are seen. The main background comes from QED process with three photon annihilation and they are suppressed significantly by kinematics cuts.

The total cross-section is calculated according to the formula $\sigma(e^+e^- \to P\gamma) = N/[L\,\varepsilon_{NT}\,\varepsilon_{det}\,(1+\delta_{rad})\,B(P \to 2\gamma)]$, where P stands for π^0 or η, N is the number of signal events, L — integrated luminosity, δ_{rad} — radiation correction, ε_{det} — detection efficiency defined with Monte Carlo simulation, $B(P \to 2\gamma)$ — branching ratio, and ε_{NT} is a neutral trigger efficiency studied with an $e^+e^- \to e^+e^-\gamma$ process. The preliminary results of the cross section measurement at ϕ-meson energy range is presented in Fig 7.

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

The cross section measurement of the process $e^+e^- \to K^+K^-\pi^+\pi^-$ is based on the integrated luminosity of 22 pb^{-1} in the c.m. energy range from 1.5 to 2.0 GeV and early was measured by the BaBar via ISR. Nevertheless the direct measurements are very important, since some contributes to a_μ are based on isospin relations of various $K\overline{K} + n\pi$ final states. Any uncertainty of this approach will be crucial for the a_μ accuracy.

The signal events should have three or four tracks in DC coming from interaction region and obey to the energy-momentum conservation. Two tracks corresponding to kaons should have the large ionization losses dE/dx in DC. Fig. 8 shows the difference between measured total energy and c.m.

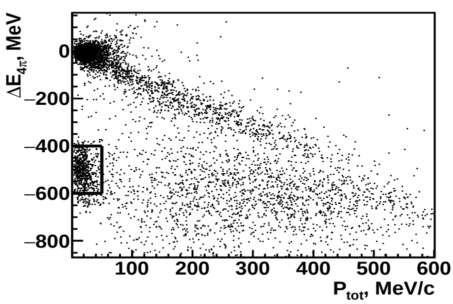

Figure 8. The difference between the total energy and c.m. energy (ΔE_4) versus the total momentum for the four-track events. The upper cluster of dots represents $\pi^+\pi^-\pi^+\pi^-$ while the lower one - $K^+K^-\pi^+\pi^-$ events.

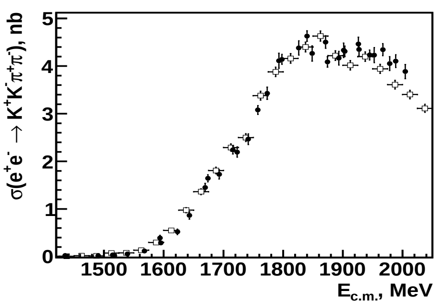

Figure 9. Dots - the $e^+e^- \to K^+K^-\pi^+\pi^-$ cross section measured with the CMD-3. The BaBar results are shown by open circles.

energy $\Delta E_4 = E_{tot} - E_{c.m.}$ vs the total momentum for all events with four tracks. The signal events are located near in origin of coordinates. The cluster of events with a zero total momentum but shifted up along the vertical axis, corresponds to $\pi^+\pi^-\pi^+\pi^-$ events.

The similar procedure was used to select signal events with the three-track in DC. As a result, ~13300 four-track events and ~16000 three-track events were selected. To calculate a detection efficiency, the $K^+K^-\pi^+\pi^-$ events were simulated with a primary generator using the GEANT4 package and then reconstructed with the same software as experimental data.

The cross section as a function of energy shown in Fig. 9, and well agrees with the previous BaBar measurement [13] presented by open circles. Systematic error was studied in detail and currently is estimated as 6% and mainly due to model dependence of the detection efficiency. More detail analyses can be found in publication [14]

4.5 Six pion production

Production of six pions in e^+e^- annihilation was studied at DM2 [15] and BaBar [16]. The DM2 experiment observed a "dip" in the cross section of the process $3(\pi^+\pi^-)$ near 1.9 GeV, confirmed later by the BaBar. The origin of the "dip" remains unclear, but the most popular explanation is based on a hypothesis of a presence of the under-threshold $(p\overline{p})$ resonance discussed in many theoretical papers [17].

The analysis based on 22 pb^{-1} of integrated luminosity collected in the c.m. energy range from 1.5 to 2 GeV. Candidates for the process under study are required to have five or six tracks in DC. For six- or five-track candidates the total energy and total momentum are calculated, assuming all tracks to be pions. To estimate the background MC simulation of the major processes $2(\pi^+\pi^-\pi^0)$ and $2(\pi^+\pi^-)\pi^0$ was performed and was found to be smaller than 1%. To determine the number of events with one missing particles, a sample with five selected tracks was used too. These events have energy deficit correlated with the total (missing) momentum. The analysis in detail of the process under study can be found in [18].

To measure the cross section of the process $e^+e^- \to 2(\pi^+\pi^-\pi^0)$ the sample of events with the four charged and two neutral pions were selected. To select neutral pions the spectrum of invariant mass of all two photon combinations was studied inside energy gap from $60 < m_{\gamma\gamma} < 200$ MeV/c^2 and combination with the nearest to the pion mass is chosen. The number of events under study at each

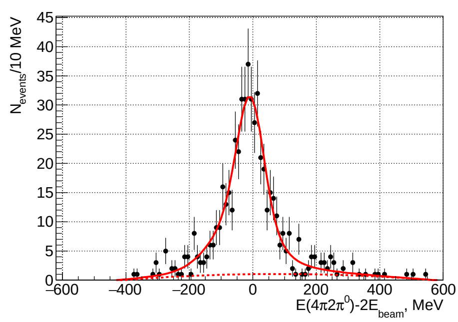

Figure 10. The number of events vs the total energy of the system $2(\pi^+\pi^-\pi^0)$. Signsl- fit with a sum of three Gaussian functions, background - fit with quadratic polynomial.

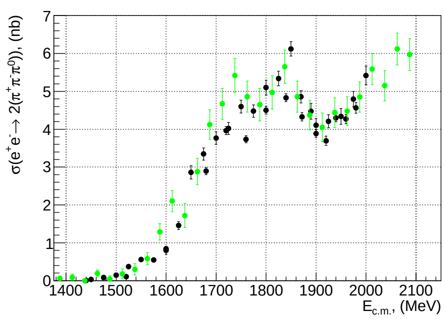

Figure 11. . Cross section of the process $e^+e^- \to 2(\pi^+\pi^-\pi^0)$ vs energy. Black points - CMD3, green - BaBar.

energy point was determined by fit of the distributions shown in Fig. 10 with a sum of three Gaussian functions for signal events and quadratic polynomial for background. The cross section calculates according to the number of determine events and takes into account RC and detection efficiency. The preliminary results for the cross section are presented in Fig. 11. The analysis of the data is going on now.

4.6 Cross sections measurement of the $e^+e^- \to \eta\pi^+\pi^-$ and $e^+e^- \to \omega\pi^+\pi^-$ processes

The process $e^+e^- \to \eta\pi^+\pi^-$ was studied in two decay modes of η: 2γ and $\pi^+\pi^-\pi^0$. The signal events should have two tracks and at least two photons. The shape of two photons invariant mass distribution was fix from MC and used to determine the number of the $\eta\pi^+\pi^-$ events at each energy point. The result of such fit at 1500 MeV is shown in Fig. 12. The preliminary results for the Born cross section are shown in Fig. 13. The systematic uncertainty for this process is about 5.2% and due uncertainty of detection efficiency, which depends of angular distribution of the final particles which, in one turn, affected of intermediate states through goes this process. At the current statistics it is not possible to make conclusion about significant presence of the $\rho(1700)$. These two processes were studied when

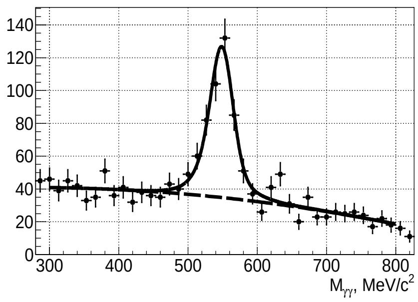

Figure 12. Two photons invariant mass at the energy of 1500 MeV.

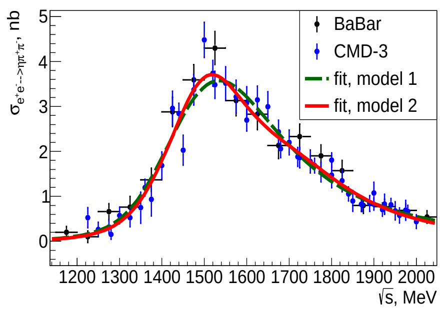

Figure 13. The $e^+e^- \to \eta\pi^+\pi^-$ Born cross section measured in the $\eta \to \gamma\gamma$ channel. The results are presented together with BaBar data.

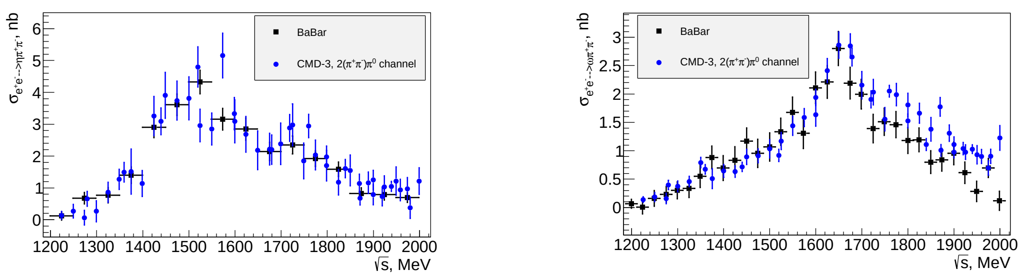

Figure 14. The $e^+e^- \to \eta\pi^+\pi^-$ and $e^+e^- \to \omega\pi^+\pi^-$ Born cross sections measured when η and ω decays into three pions $\pi^+\pi^-\pi^0$. The results are presented together with BaBar data.

η and ω decay to the three pions: $\pi^+\pi^-\pi^0$. To determined the signal events the form of the $\pi^+\pi^-\pi^0$ invariant mass distribution for the system $2\pi^+2\pi^-\pi^0$ has been studied using Monte Carlo simulation and was used to count the number of the signal events under study. The signal events were clearly seen which correspond to η and ω decay into three pions. The preliminary results for the Born cross sections of the $e^+e^- \to \eta\pi^+\pi^-$ and $e^+e^- \to \omega\pi^+\pi^-$ processes are shown in Fig. 14. The current systematic uncertainty for these channels we estimated as 15% and mainly due to the difference between angular distributions of charged particles in simulation and experiment. The significant difference appears in the region of the low polar angles of the charged π-mesons. The study of this problem will improve simulation and make track reconstruction efficiency more realistic.

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

The analysis of the process $e^+e^-\to K^+K^-\eta$ was based on 19 pb^{-1} of an integrated luminosity collected by the CMD-3 detector in 2011–2012 in the $E_{\text{c.m.}}$ range from 1.59 to 2.01 GeV. On the base of these statistics we observed the contribution of $\phi(1020)\eta$ intermediate state only. Candidates for the events of the signal process were required to have two, three or four tracks in the DC, coming out of the beams intersection point. The kaon/pion separation was performed with the use of $f_{K/\pi}(p, dE/dx)$ functions [14], representing the probability density for charged kaon/pion with the momentum p to produce the energy losses dE/dx in the DC. We considered η-meson as a recoil particle, which allowed us to avoid the loss of statistics due to the selection of the specific η decay mode. But such an inclusive approach lead to the complication of the signal/background separation. Therefore the major background processes were studied and were found to be $e^+e^-\to K^+K^-\omega(782)$, $e^+e^-\to K^+K^-\pi^+\pi^-$, $e^+e^-\to\phi f_0(500)$, $K^{*\pm}(892)K^{\mp}\pi^0\to K^+K^-\pi^0\pi^0$, $e^+e^-\to 2\pi^+2\pi^-2\pi^0$. We perform the signal/background separation and 1296±43 signal events were extracted. The resulting $e^+e^-\to\phi(1020)\eta$ cross section is shown in the Fig. 15 along with the BaBar results. The overall systematic uncertainty of the cross section measurement was estimated to be 6%. Via the cross section approximation the $\phi(1680)$-meson parameters have been determined. The analysis of the process $e^+e^-\to K^+K^-\omega(782)$ was based on 12

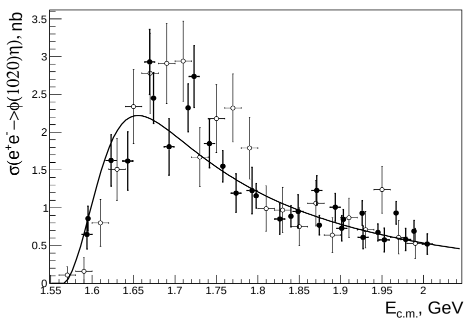

Figure 15. Cross section of the process $e^+e^-\to\phi(1020)\eta$. The BaBar data - open circles, CMD-3 - filled circles. The fit - joint approximation of CMD-3 and BaBar data.

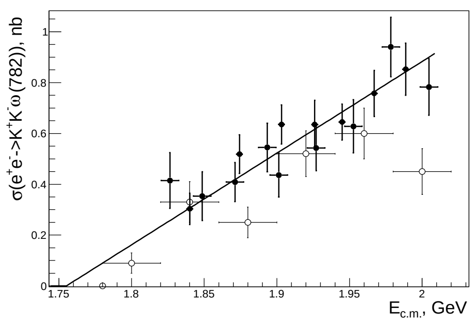

Figure 16. Cross section of the process $e^+e^-\to K^+K^-\omega(782)$. The BaBar data - open circles, CMD-3 - filled circles. The fit - approximation of CMD-3 data.

pb^{-1} of an integrated luminosity collected by the CMD-3 detector in 2011–2012 in the $E_{\text{c.m.}}$ range from 1.8 to 2.01 GeV. Candidates for the events of the signal process were required to have three or four tracks in the DC, flying out of the area of the beams intersection. The kaon/pion separation was performed in the same way, as in the $e^+e^-\to K^+K^-\eta$ process analysis. We studied the process in the $\omega(782)\to\pi^+\pi^-\pi^0$ decay mode, considering π^0 as a recoil particle. The major background processes were found to be $e^+e^-\to K^+K^-\eta$ and $e^+e^-\to K^+K^-\pi^+\pi^-$, but their contribution was almost completely suppressed by the cuts on the invariant and missing masses of kaons and pions. After background suppression we performed a direct subtraction of the estimated number of background events and in total in the experiment we obtained 886±30 signal events. The resulting $e^+e^-\to K^+K^-\omega(782)$ cross section is shown in the Fig. 16 along with the BaBar results. The overall systematic uncertainty of the cross section measurement was estimated to be 6%.

5 Summary and conclusion

CMD-3 detector will operate with a goal to get $\sim 1 fb^{-1}$ in 5-10 years and provides the new precise results on the hadron production. The current integrated luminosity was measured using two well known QED processes $e^+e^- \to e^+e^-, \gamma\gamma$ and systematic accuracy is estimated as 1%. Two type of the first level triggers «CHARGED» and «NEUTRAL» deliver the independent information that allowed to determine the detection efficiencies and to estimate their uncertainties. Data analysis is in progress, the already collected data sample provides the same or better statistical precision for the hadronic cross sections than in previous experiments were achieved.

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