PROCEEDINGS OF SCIENCE

Study of the $e^+e^- \to$ hadrons reactions with CMD-3 detector at VEPP-2000 collider

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The CMD-3 detector is taking data at the VEPP-2000 e^+e^- collider (Budker INP, Novosibirsk, Russia). The main goal of experiments with CMD-3 is the measurement of the cross-sections and dynamics of the exclusive modes of e^+e^- annihilation to hadrons. In particular, these results provide an important input for calculations of the hadronic contribution to the muon anomalous magnetic moment. The first round of data taking with the CMD-3 detector was performed in 2011-2013 with about 60 1/pb integrated luminosity in the center-of-mass (c.m.) energy range from 0.32 to 2.0 GeV. The collected data sample exceeds those in all previous experiments.
Here we present the survey of results of data taken in 2011-2013, including a precise measurement of the $e^+e^- \to \pi^+\pi^-$ reaction as well as other hadron final states with up to six pions or states including two kaons.
At the end of 2016 the VEPP-2000 collider resumed operation after upgrade of the injection system, and performance approaching the project luminosity of 10^{32} $cm^{-2}s^{-1}$ at 2 GeV has been demonstrated. Preliminary results of the new 2017 run are also presented.

The European Physical Society Conference on High Energy Physics
5-12 July, 2017
Venice

*Speaker.
†The work is supported by the Russian Science Foundation (project No. 14-50-00580) and by the RFBR grants 16-02-00160-a, 17-02-00327-a, 17-02-00847-a, 17-02-00897-a.

PoS(EPS-HEP2017)407

1. Introduction

The electron-positron collider VEPP-2000 [1] has been operating at Budker Institute of Nuclear Physics since December 2010, and has been upgraded to the new injection system in December 2016. The collider is designed to provide luminosity up to 10^{32}cm^{-2}s^{-1} at the maximum c.m. energy $\sqrt{s} = 2$ GeV. Two detectors, CMD-3 [2] and SND [3], are installed in two interaction regions. The CMD-3 is the general-purpose particle magnetic (1.3 T) detector, equipped with the tracking system, two crystal (CSI and BGO) calorimeters, liquid Xe (LXe) calorimeter, TOF and muon systems. The CMD-3 detector has a high detection efficiency, good energy and angular resolution for charged particles as well as for photons. The integrated luminosity collected by the detector is about 60 pb^{-1} in 2011-2013 runs with additional 50 pb^{-1} after the upgrade. The luminosity is measured with about 1% accuracy [4] using Bhabha events. Figure 1 (left) shows the integrated luminosity averaged over 10% of best runs: green points correspond to new 2017 runs. Increase in the integrated luminosity vs experimental energy is shown in Fig. 1 by green color. The beam energy was continuously measured concurrently with the data taking using a Compton back scattering system [5].

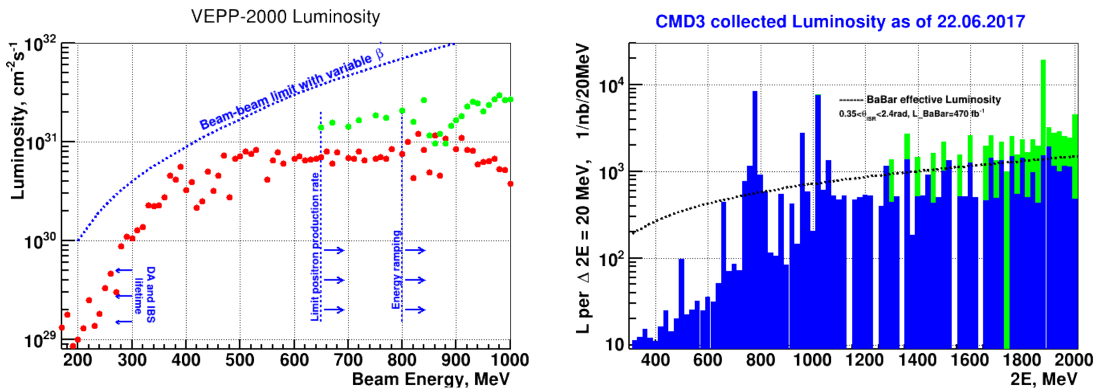

Figure 1: (left) The integrated luminosity averaged over 10% of the best runs vs beam energy: 2017 improvement is shown by green points. (right) The collected integrated luminosity vs energy at the CMD-3 detector. The luminosity collected in 2017 is shown by green color.

2. Results from 2011-2013 runs

The analysis of data, collected in 2011-2013, is in process and a number of results on exclusive cross sections was published by the CMD-3 Collaboration. All major channels are under analysis including channels with up to six pions or two kaons and two pions in the final state. Here we review the published results and show some of the recent preliminary results.

The CMD-3 collaboration published several results with a few charged particles in the final state: $e^+e^- \to 3(\pi^+\pi^-)$ [6], $e^+e^- \to K^+K^-\pi^+\pi^-$ [7], $e^+e^- \to K_S K_L, K_S \to \pi^+\pi^-$ [8] and $e^+e^- \to 2(\pi^+\pi^-)$ [9] around the ϕ-meson, $e^+e^- \to \pi^+\pi^-\pi^0\eta$ [10], and $e^+e^- \to p\bar{p}$ [11].

Preliminary results for the pion form factor from the $e^+e^- \to \pi^+\pi^-$ cross section measurement are shown in Fig. 2 (left). We use two independent methods for separation of two-pion events from the e^+e^- and $\mu^+\mu^-$ pairs: using only DC information or using only calorimeter response. We already estimate the DC selection accuracy below or close to 1%, which is cross checked with the cross section of the $e^+e^- \to \mu^+\mu^-$ process. The result is shown in Fig. 2 (right) with respect to the QED prediction, and provides an important overall systematic test of the measurement. A study of the systematic uncertainties of the calorimeter response is in progress, and we plan to "open the box" and present final result soon.

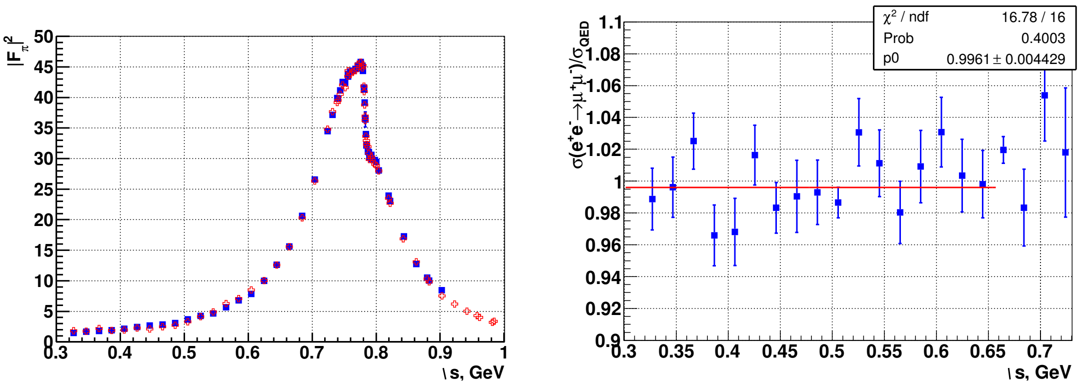

Figure 2: (left) Preliminary results of the pion form factor measurement; squares - particle separation with momenta, points - particle separation with energy deposition in calorimeter; (right) Results of the measurement of muon pair production in comparison with the QED prediction.

We have analyzed the $e^+e^- \to K^+K^-$ production around the ϕ-meson, and compare the cross section obtained with about 2% accuracy with other measurements. Our data are in agreement with BaBar measurements, and we confirm large inconsistency with the old CMD-2 result, which we expect to be reanalyzed. By comparison of these measurements with our published results on $e^+e^- \to K^0_S K^0_L$, we can extract the isospin-one-amplitude contribution to the $e^+e^- \to K^+K^-$ cross section. Figure 3 shows the difference of the K^+K^- and $K^0_S K^0_L$ production cross sections, corrected for the phase space and charge interaction. The observed interference signal allows to extract the dominating $\rho(770)$ amplitude, which contributes 0.95 ± 0.03 of the value predicted by the SU(3) symmetry. Our results for the K^+K^- and $K^0_S K^0_L$ production rate are in good agreement with the isospin symmetry: the ratio of coupling constants with the Coulomb factor taken into account is

$$\frac{g_{\varphi K^+K^-}}{g_{\varphi K_S K_L}\sqrt{Z(m^2_\varphi)}} = 0.990 \pm 0.017.$$

Many other exclusive cross sections like $e^+e^- \to \pi^+\pi^-\pi^0$, $e^+e^- \to \pi^+\pi^-\omega$, $e^+e^- \to \pi^+\pi^-\phi$, $e^+e^- \to K^+K^-\pi^0$, $e^+e^- \to K^+K^-\eta$, $e^+e^- \to 2(\pi^+\pi^-)$, $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ etc. in the VEPP2000 energy range are under study and results will be published soon.

3. Preliminary results from 2017 run

In 2017 the VEPP2000 collider has resumed operation with the new injection complex. We have no limitation with the number of positrons any longer. We have collected about 50 pb^{-1} in 5 months of operation in the c.m. energy scan from 1680 to 2007 MeV. About 4 pb^{-1} has

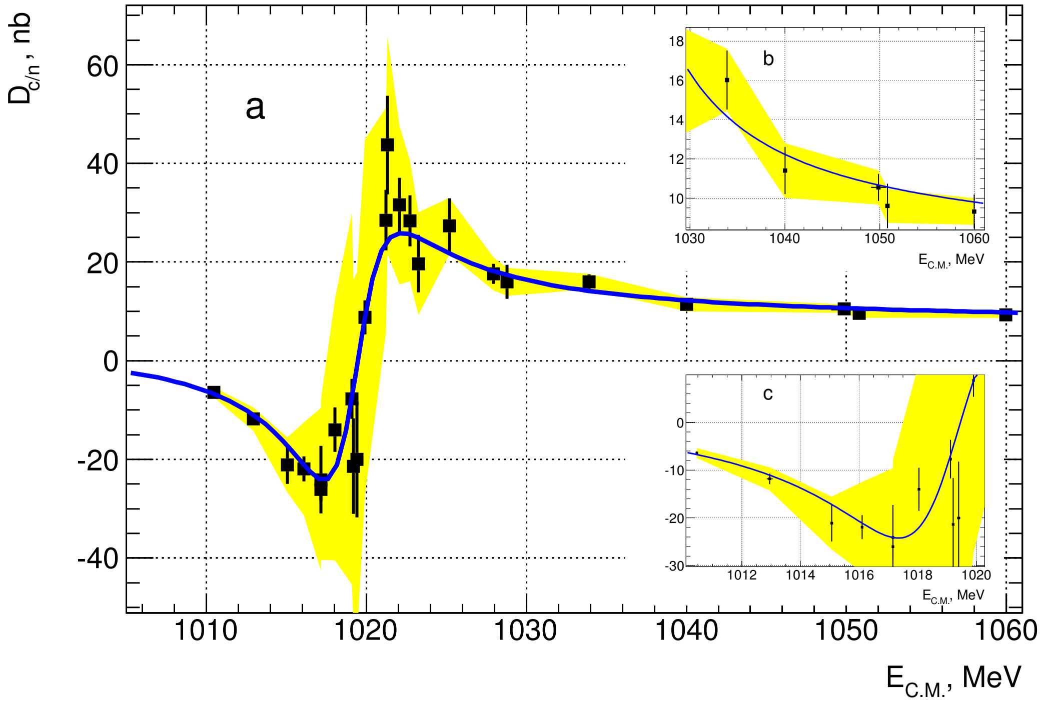

Figure 3: The difference of the charged and neutral cross sections defined as $D_{c/n} = \sigma_{e^+e^-\to K^+K^-} \times \frac{\beta^3_{K^0}(s)}{\beta^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \delta_{K^0_S K^0_L} \times \sigma_{e^+e^-\to K^0_S K^0_L}$. The shaded area corresponds to the systematic uncertainties in data, the solid line shows the fit described in the text.

been collected at E$_{c.m.}$=2007 MeV to to search for direct production of $D^*(2007)^0$ in the e^+e^- annihilation. An observation of such production at any level above the SM prediction $B(D^{*0} \to e^+e^-) \sim O(10^{-19})$ would be a clear signal of physics beyond SM [12].

Another $\approx 10\text{pb}^{-1}$ has been collected in the $N\bar{N}$ threshold scan with a step comparable with the beam energy spread of 1.2 MeV. Figure 4 (left) shows our preliminary results for the $e^+e^- \to 3(\pi^+\pi^-)$ cross section measurement. All analysis procedures are the same as in our publication [6], and we confirm our previous observation of a very sharp cross section drop at the $N\bar{N}$ threshold. Moreover, an energy scan with a small step allows to investigate a structure of this drop.

Figure 4 (right) shows a visible (no radiative corrections are applied) cross section of six-pion production around the $N\bar{N}$ threshold. For a demonstration we fit the structure with a "Fermi" function

$$\sigma_{\text{Born}}(E_{c.m.}) = a + \frac{b}{1 + exp(\frac{(E_{c.m.} - E_{step})}{\sigma_{step}})}, \tag{3.1}$$

convolved with the energy spread and the radiative effects: the obtained value of the drop $\text{E}_{\text{step}} = 1876.81 \pm 0.07$ MeV is consistent with the $p\bar{p}$ production threshold (1876.544092 MeV), but not with the $n\bar{n}$ (1879.130758 MeV), with a width $\sigma_{\text{step}} = 1.496 \pm 0.063$ MeV. A Born cross section, $\sigma_{\text{Born}}(E_{c.m.})$, obtained in the fit is shown by the dashed line in Fig. 4 (right). Unfortunately, the

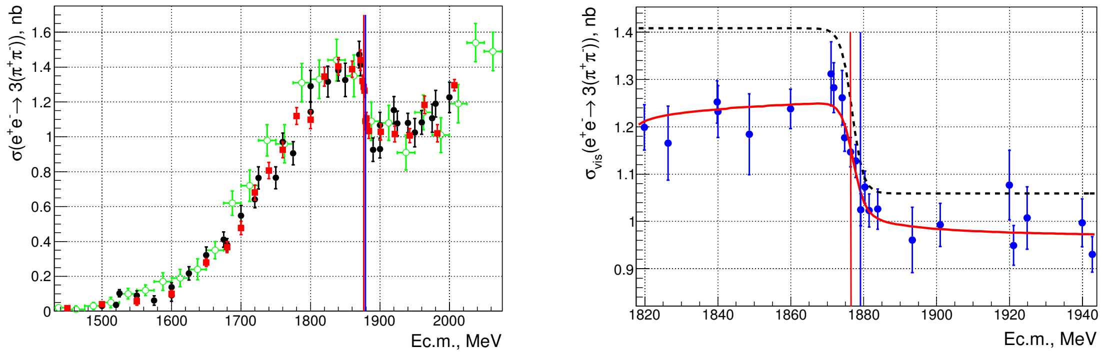

Figure 4: (left) Preliminary results of the $e^+e^- \to 3(\pi^+\pi^-)$ cross section measurement; squares - new 2017 data, points - published CMD-3 data [6], open circles - BaBar data. (right) Visible $e^+e^- \to 3(\pi^+\pi^-)$ cross section. Vertical lines show the $p\bar{p}$ and $n\bar{n}$ production thresholds. Lines show the fits explained in the text.

machine-induced c.m. energy spread does not allow a more detailed study of a possible fine cross section structure at the $N\bar{N}$ threshold.

Note that the drop cannot be explained by an interference of any resonance amplitude with the "continuum" cross section, and is related to the $e^+e^- \to p\bar{p}$ and $e^+e^- \to n\bar{n}$ cross sections rise [11, 13], which are under investigation with our new data as well as many other hadron productions.

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