PROCEEDINGS OF SCIENCE

Measurement of hadronic cross sections at VEPP-2000

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The first round of data taking with the CMD-3 and SND detectors at the VEPP-2000 e+e collider (BINP, Novosibirsk, Russia) was performed in 2011-2013. The main goal of experiments at VEPP-2000 is measurements of cross sections and studies of dynamics of exclusive modes for $e^+e^- \to hadrons$. In particular, these results provide important input for calculations of the hadronic contribution to the muon anomalous magnetic moment.

Here we present the survey of analysis of data taken in 2011-2013. About 60 pb^{-1} per detector were taken in the c.m. energy range from 0.32 to 2.0 GeV. The beam energy was continuously measured concurrently with data taking using Compton backscattering. In 2016 VEPP-2000 resumed operations after upgrade with a design luminosity of 10^{32} cm^{2}s^1 at 2 GeV.

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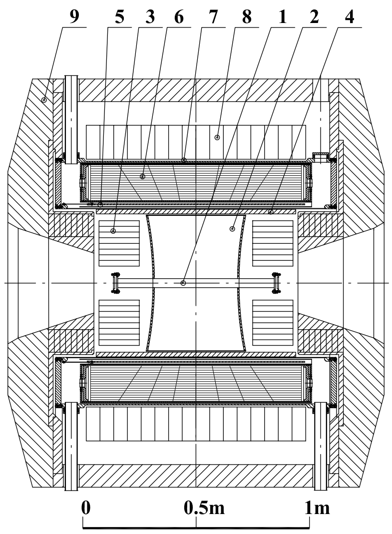

Figure 1: CMD-3 detector: 1 – beam pipe, 2 – drift chamber, 3 – BGO calorimeter, 4 – Z-chamber, 5 – superconducting solenoid, 6 – LXe calorimeter, 7 – TOF system, 8 – CsI calorimeter, 9 – yoke. The muon range system, not shown, is placed outside the yoke.

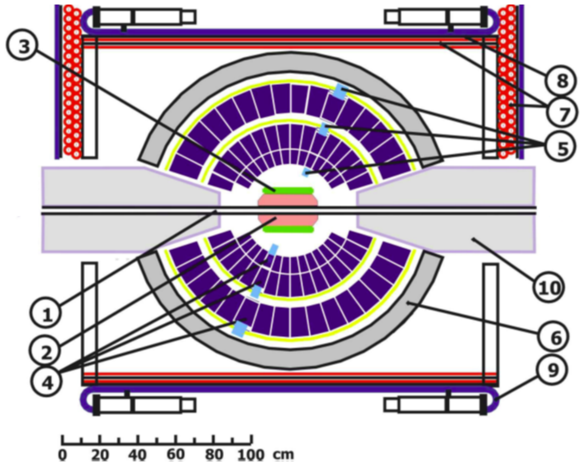

Figure 2: The SND detector: 1 - beam pipe, 2 - tracking system, 3 - aerogel Cherenkov counters, 4 - NaI(Tl) crystals, 5 - phototriodes, 6 - iron muon absorber, 7-9 - muon detector, 10 - focusing superconducting solenoids.

1. The experimental setup

The electron-positron collider VEPP-2000[1] started operation at Budker Institute of Nuclear Physics (Novosibirsk, Russia) in 2010. The machine covers the c.m. energy range from $\sqrt{s} = 0.32$ GeV to 2.0 GeV and employs the novel technique of round beams to reach a design luminosity up to 10^{32} cm^{-2}s^{-1} at 2 GeV.

Detectors CMD-3[2] and SND[3] are installed at the two interaction regions of VEPP-2000.

CMD-3 (Cryogenic Magnetic Detector) is a general-purpose detector (Fig. 1). The cylindrical drift chamber with hexagonal cells is surrounded by the Z-chamber, a MWPC with a dual anode and cathode readout, used for precise determination of the fiducial volume for charged particles. The barrel electromagnetic calorimeter [4], placed outside the superconducting solenoid (0.13X_0, 13 kGs), is composed of two systems: the Liquid Xenon calorimeter (about 5.4X_0), surrounded by the CsI crystal calorimeter [5] (about 8.1X_0). The LXe calorimeter has 7 layers and utilizes dual readout: the anode signals are used for a measurement of the total energy deposition, while signals from the cathode strips provide information about a shower profile and are used for a measurement of photon coordinates with high precision (about 1-2 mm). The endcap BGO crystal calorimeter (about 13.4X_0) operates in the main magnetic field. The time-of-flight system, made of plastic scintillators with PMT readout, is placed between the two layers of the barrel calorimeter. The detector is surrounded by the muon range system.

The SND (Fig.2) is a general-purpose nonmagnetic detector. The core of the detector is a three-layer spherical electromagnetic calorimeter with 1640 NaI(Tl) crystals. Directions and dE/dx of charged particles are measured by a tracking system based on a nine-layer drift chamber. The particle identification is provided by a system of aerogel Cherenkov counters. The calorimeter is surrounded by a muon detector.

The primary goal of two experiments is a measurement of cross sections of various modes of $e^+e^- \to hadrons$ in the whole energy range available at VEPP-2000. The total cross section of $e^+e^- \to hadrons$ is closely related to the problem of the muon anomalous magnetic moment, a_μ.

A high-precision measurement of a_μ provides a powerful test of the Standard Model (SM). The most recent measurement of a_μ, done at BNL with 0.54 ppm precision [6], is 2.2÷2.5 ppm, or ~ 3.5 standard deviations above the Standard Model expectation a_μ(SM), which is known to about 0.42 ppm. While this discrepancy may be interpreted as a contribution from non-SM fields, its statistical power is not enough to claim the discovery. In order to reach better precision for $a_\mu(\mathrm{NewPhysics}) = a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM})$, the precision of both the experimental value and Standard model expectation should be improved. The new experiment [7] aimed at measuring a_μ to 0.14 ppm is currently under construction at FNAL planning to start data taking in 2017. The accuracy of $a_\mu(SM)$ evaluation is determined by the knowledge of the hadronic (QCD) contribution a_μ(had), which, in the lowest order, is calculated using dispersion relations by integrating $\sigma(e^+e^- \to hadrons)$. The dominant contribution to the integral comes from the low energy range, available at VEPP-2000, and there is no theoretical way to predict $\sigma(e^+e^- \to hadrons)$ at these energies. Thus, the accuracy of $a_\mu(SM)$ evaluation is determined by the precision of $\sigma(e^+e^- \to hadrons)$ measured at VEPP-2000 energies.

It is nearly impossible to directly measure the total (inclusive) cross section $e^+e^- \to hadrons$ at low energies to a high precision, due to low multiplicity (and, correspondingly, large correlations between final particles) and diverse internal dynamics. The only feasible way is to measure this cross section exclusively for each final state and to calculate the sum.

2. Data taking in 2011-2013

The data were taken in three independent seasons. In 2011 and 2012 seasons the data were collected at energies above the φ meson — in the c.m. energy range from 1.0 GeV to 2.0 GeV, with a 25 MeV step in 2011 and slightly more coarse step in 2012. About 30 pb^{-1} were collected per detector, with about 10 pb^{-1} per detector above the $p\bar{p}$ threshold. The 2013 season was dedicated to a c.m. energy scan below 1.0 GeV, down to 0.32 GeV, in 20 MeV steps, except for the $\omega(782)$ region, where finer steps up to 2 MeV were used. About 20 pb^{-1} were collected per detector, with about 8 pb^{-1} near the $\omega(782)$ peak. Before each season enough data were taken near the φ peak to calibrate the systems and energy scale.

During the 2012 season the beam energy monitoring system[8, 9] has been installed and commissioned. The system allows to continuously monitor beam energy concurrently with data taking with relative precision $< 10^{-4}$ using Compton backscattering of laser photons at the electron beam.

The peak VEPP-2000 luminosity, seen during 2011-2013 data taking, was significantly below the design luminosity — from about a factor of 2 at $\sqrt{s} = 1.2$ GeV to a factor of 10 at the maximum energy of 2 GeV. It is mainly explained by two factors: the deficit of positrons starting from $\sqrt{s} \approx 1.2$ GeV and above, and the limit of the booster ring energy at 0.825 GeV, which forces to ramp beam up and down at each injection into the main ring. To overcome these limitations, an upgrade of VEPP-2000 started in the second half of 2013, which among other things included switching to a ten times more powerful positron source and increase of maximum energy of the booster ring to 1

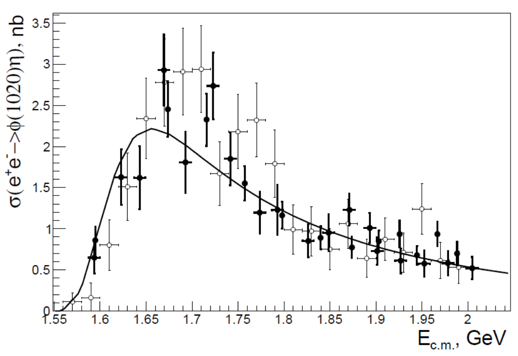

Figure 3: Preliminary results on $e^+e^- \to K^+K^-\eta$ cross section from CMD-3 (black dots), in comparison with the BABAR measurement (open circles).

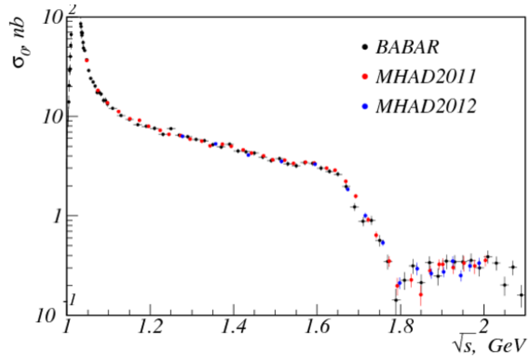

Figure 4: Preliminary results on $e^+e^- \to K^+K^-$ cross section [19] from SND

GeV. The upgrade has been completed in 2016 and the commissioning of the collider and detectors started. Regular data taking is expected to be resumed in 2017.

3. Overview of the results from 2011-2013 data

The analysis of data, collected in 2011-2013, is in process and a number of results on exclusive cross sections were published by both groups. All major channels are under analysis including channels with up to 6 pions or 2 kaons and 2 pions in the final state. Here we review the published results and show some of the recent preliminary results.

Due to presence of the solenoidal magnetic field, CMD-3 has a natural advantage in detection of charged particles. The CMD-3 collaboration published several results with a few charged particles in the final state: $e^+e^- \to 3(\pi^+\pi^-)$ [10], $e^+e^- \to K^+K^-\pi^+\pi^-$ [11], $e^+e^- \to K_SK_L$ [12] around the φ-meson with $K_S \to \pi^+\pi^-$ and $e^+e^- \to p\bar{p}$ [13].

The spherically symmetric calorimeter of SND detector provides an excellent ability for detection of events with several γ's in the final state. A number of results for such final states were published by the SND collaboration: $e^+e^- \to \pi^+\pi^-\pi^0$ [14] above the φ meson, $e^+e^- \to \pi^+\pi^-\eta$ [15], $e^+e^- \to \omega\pi^0$ [16] in the 5γ and $e^+e^- \to \eta\gamma$ [17] in the 7γ mode, $e^+e^- \to n\bar{n}$ [18].

Both detectors have good ability of K/π separation. The CMD-3 uses dE/dx in the drift chamber (slow kaons) and in the LXe calorimeter (fast kaons). The preliminary result of CMD-3 on the cross section measurement for one of the channels with kaons, $e^+e^- \to K^+K^-\eta$, is shown in Fig. 3. SND has a dedicated PID system, the aerogel Cherenkov counters. The preliminary result on the $e^+e^- \to K^+K^-$ cross section from SND is shown in Fig. 4.

For some hadronic channels it is possible to measure the same cross section in different final states. Preliminary results on the $e^+e^- \to \pi^+\pi^-\eta$ cross section from CMD-3 are shown in Fig. 5. Two independent measurements are done, with $\eta \to 3\pi$ and $\eta \to 2\gamma$; the results are in good agreement.

Recently, the SND collaboration released two new results. The world-best measurement of the cross section $e^+e^- \to \omega\eta$ [20] disagrees with a previous measurement from BABAR. This

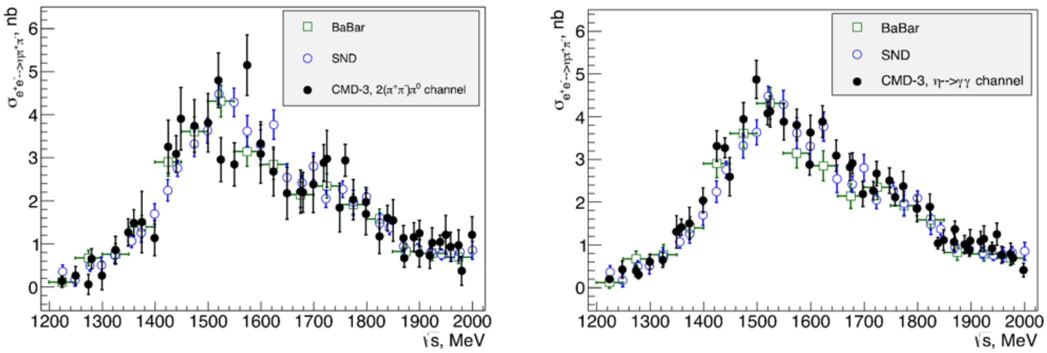

Figure 5: Preliminary results on the cross section $e^+e^- \to \pi^+\pi^-\eta$ measured by CMD-3 in two final states, with η decaying to 3π (left) and $\gamma\gamma$ (right).

hadronic mode is a part of a more general $e^+e^- \to \pi^+\pi^-\pi^0\eta$ final state, which is under further analysis at both detectors. The cross section $e^+e^- \to \omega\pi^0\eta$ [21], studied in the 7γ final state, was measured for the first time.

The dominant hadronic cross section below φ is $e^+e^- \to \pi^+\pi^-$, and it has to be measured to high precision, well below 1%, to improve accuracy of the calculation of the hadronic contribution to a_μ. The amount of data collected in 2013 is several times larger compared to the previous measurements done at VEPP-2M, the predecessor of VEPP-2000.

The data analysis is based on selection of events with two back-to-back tracks and accurate identification of the signal $e^+e^- \to \pi^+\pi^-$ and monitoring $e^+e^- \to e^+e^-$, $\mu^+\mu^-$ events. The CMD-3 strategy is to use two independent approaches, both based on the likelihood fit of the measured distributions to extract the number of events of each kind. The first approach uses the momenta of two particles; the momentum resolution of the CMD-3 drift chamber is enough to use this approach up to the ρ peak (and, with additional restrictions, up to $\sqrt{s} = 0.9$ GeV). The second approach uses the energy deposition of two particles; this technique is more complicated, but it can be used in the whole VEPP-2000 energy range. It requires the energy deposition p.d.f.s for muons and pions, which are extracted from the data using cosmic events and decays $\omega \to \pi^+\pi^-\pi^0$ and $\varphi \to \pi^+\pi^-\pi^0$.

The accurate measurement of $e^+e^- \to \pi^+\pi^-$ cross section requires high-precision calculation of radiative corrections. With high statistics of 2013, the MC generator MCGPJ, used by CMD-3, was carefully compared to the data. Small discrepancies were observed at the tails of momentum distributions, which can lead to a percent-level systematic error in the cross section. The source of the discrepancy was understood and the more accurate version of the generator is now under development. With the updated generator, and after more careful calibration of the drift chamber, the sub-percent precision is expected for the data collected in 2013.

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