Study of e^+e^- annihilation to hadrons at the VEPP-2000 collider

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Abstract. We present current status of the SND and CMD-3 experiments at the VEPP-2000 e^+e^- collider and recent result of data analysis on the processes $e^+e^- \to \pi^+\pi^-$, $n\bar{n}$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\eta$, $K_S K_L\pi^0$, etc.

1 Introduction

The main goal of experiments at VEPP-2000 [1] is high-precision measurements of the total and exclusive cross sections of e^+e^- annihilation into hadrons. Such measurements provide valuable information about interactions of light quarks. In particular, we study properties of light vector mesons and their excitations, production of $p\bar{p}$ and $n\bar{n}$ pairs, perform searches for rare processes.

High-precision measurements of low energy cross sections also have numerous implications for various fundamental quantities, such as the muon anomalous magnetic moment a_μ, for which a more than 3.5σ deviation is observed from the Standard Model prediction, and the running α. Comparing e^+e^- and τ-decay data allows to perform tests of CVC.

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The VEPP-2000 e^+e^- collider operates in the Budker Institute of Nuclear Physics in Novosibirsk. It covers the center-of-mass energy range from the threshold of hadron production up to 2 GeV. Two detectors, CMD-3 [2] and SND [3] collect data at VEPP-2000.

Most SND and CMD-3 results presented in this report are based on the about 70 pb^{-1} data set recodered during 2010-2013 in the energy region 0.3–2.0 GeV. From 2014 the VEPP-2000 accelerator complex was under reconstruction. The experiments were restarted by the end of 2016 with a new, 10 times more intensive, positron source. In 2017 the detectors performs the 5 month scan of the center-of-mass (c.m.) energy region $\sqrt{s} = 1.68 - 2.005$ GeV with an integrated luminosity of about 50 pb^{-1}. About 70 pb^{-1} were collected during the 2018 run in the range 0.55–1.06 GeV.

SND is a general-purpose non-magnetic detector. Its main part is a three-layer spherical $NaI(Tl)$ calorimeter with 560 individual crystals per layer and 95% solid angle coverage. There is a tracking system around the beam pipe consisting of a nine-layer drift chamber and a one-layer proportional chamber with charge division and cathode strip readout. Outside the calorimeter, a muon detector, consisting of proportional tubes and flat scintillation counters, is placed. An aerogel Cherenkov counter located between the drift chamber and the calorimeter is used as a particle ID detector.

CMD-3 (Cryogenic Magnetic Detector) is a general-purpose detector. Production points, angles and momenta of charged particles are measured by the cylindrical drift chamber with a hexagonal cell for uniform reconstruction of tracks. The calorimetry is performed with the endcap BGO calorimeter and the barrel calorimeter. The barrel calorimeter placed outside the superconducting solenoid providing 1.3 T magnetic field consists of two systems: inner ionization Liquid Xenon calorimeter and outer CsI crystal calorimeter with a total thickness of $13.5X_0$. The LXe calorimeter has seven layers with strip readout, which give information about a shower profile and are also able to measure coordinates of photon conversion with an accuracy of about millimeter.

A high precision beam-energy calibration is crucial for many physical studies performed at VEPP-2000, for example, measurement of the $e^+e^- \to \pi^+\pi^-$ with an accuracy better than 1%. Since 2013 the beam energy is monitored by a system the Compton back-scattering of laser photons on the electron beam [4, 5].

2 Results

Process $e^+e^- \to \pi^+\pi^-$. One of the main goals of the experiments at VEPP-2000 is to reduce the systematic uncertainty of the cross section of two-pion production to the level smaller than 0.5%, corresponding to 0.3–0.4 ppm uncertainty in the a_μ value. The preliminary results on the $e^+e^- \to \pi^+\pi^-$ process obtained by CMD-3 and SND are shown in Fig. 1.

At CMD-3 $\pi^+\pi^-$ events are separated from e^+e^- background either using the particle momenta or the energy deposition in the calorimeter. Two independent ways of event separation provide a cross-check and allow the systematic uncertainty to be kept under control. Data of the 2013 energy scan is used in this analysis. The c.m. energy scan below 1 GeV was performed in 2013. The data sample used in this analysis, collected in 2013, is several times larger than that in the previous CMD-2 measurements, and is comparable in statistics to ISR data of the BABAR and KLOE experiments.

The SND presents the measurement of the $e^+e^- \to \pi^+\pi^-$ cross section in the ρ-meson energy region also basing on the 2013 data set. The π/e separation used for event selection is based on calorimeter information. The systematic uncertainty at the ρ-meson peak is estimated to be 0.8%. The VEPP-2000 preliminary results do not contradict to the previous SND results obtained at VEPP-2M [6]. The contribution to the muon anomalous magnetic moment from this process from the energy range 524–885 MeV is cal-

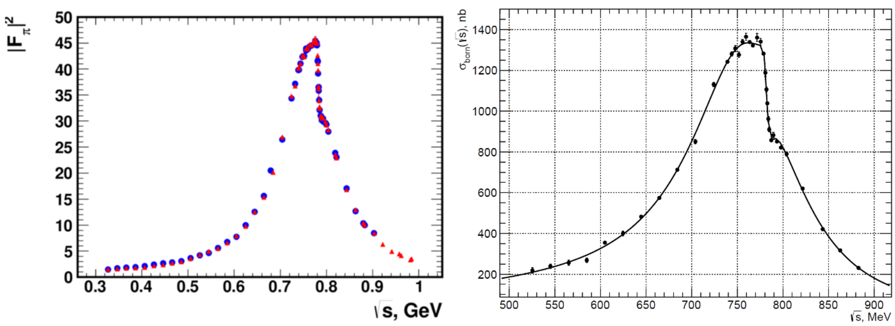

Figure 1. Left: the pion electromagnetic form factor measured by CMD-3. Tte triangles represent the result obtained using e/π separation based on calorimeter information, while the filled circles represent result based on information from the tracker. Right: The $e^+e^- \to \pi^+\pi^-$ cross section measured by SND. The solid curve is the result of the fit to the SND data with the VMD model.

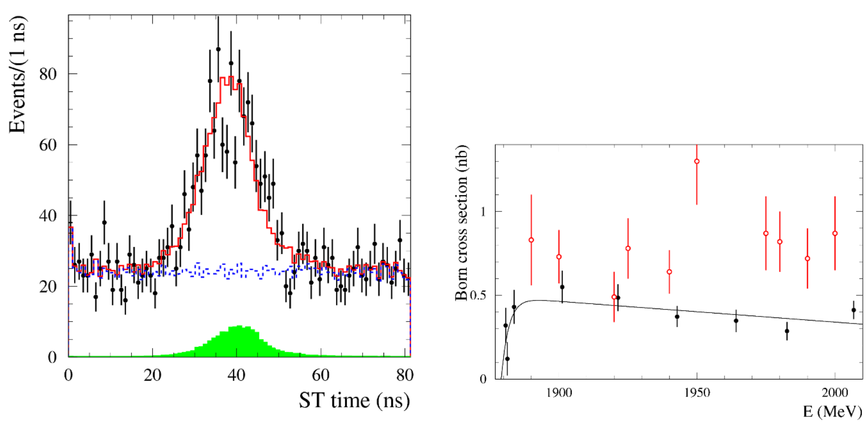

Figure 2. Left: the distribution of the calorimeter time signal relative to the beam crossing signal in the collider for $e^+e^- \to n\bar{n}$ candidate events with $\sqrt{s}$ = 1900 – 2005 MeV (points with error bars). The histogram is a sum of the distributions for signal $e^+e^- \to n\bar{n}$ and background events. The dashed histogram is the cosmic ray background. The shaded histogram is the e^+e^- annihilation background. Right: the cross section of the process $e^+e^- \to n\bar{n}$ measured by SND. The filled circles represent the preliminary results based on the 2017 data set, while the open circles show the previuos measurements based on 2011–2012 data.

culated to be $(414.48 \pm 1.04 \pm 3.49) \times 10^{-10}$, and agrees well with the BABAR value $(414.93 \pm 0.34 \pm 2.07) \times 10^{-10}$ [7].

Process $e^+e^- \to n\bar{n}$. The new preliminary measurement of the $e^+e^- \to n\bar{n}$ cross section is performed by SND using 2017 data. The signature of $e^+e^- \to n\bar{n}$ events in the detector is atypical of e^+e^- annihilation processes. Both neutron and antineutron cross the tracking system without interaction. The neutron gives a low energy deposition in the calorimeter and therefore is not reconstructed, while the antineutron annihilates producing several pions with the total energy up to 2 GeV. The antineutron signal is reconstructed as several photons. The main selection criteria are abcense of charged tracks originated from the interaction region, a large unbalanced event momentum (calculated on energy depositions in the calorimeter crystal), and a large, more than 1 GeV, total energy deposition in the calorimeter. The latter condition is fully rejects beam background and strongly suppress background from cosmic rays.

The subtruction of remaining background is based on time measurements in the calorimeter. Figure 2 shows the distribution of the calorimeter time signal formed in the first-level trigger relative the beam crossing signal in the collider for $e^+e^- \to n\bar{n}$ candidate events. It is fitted by a sum of a peaked signal distribution, and a flat cosmic-background distribution, and a peaked distribution for background e^+e^- annihilation process. The latter background is estimated using data recorded below the $n\bar{n}$ threshold.

The measured $e^+e^- \to n\bar{n}$ cross section is shown in fig. 2 in comparison with the previous SND measurement based on 2011-2012 data [8]. The difference between the new and old measurement is explined by incorrect $n\bar{n}$ simulation, and beam and cosmic-ray background subtruction in the previous analysis. The systematic uncertainty of the current measurement is mainly due to imperfect MC simulation of detector responce for antineutrons and is estimated to be 20%.

Process $\eta \to e^+e^-$. The decays of pseudoscalar mesons $P \to l^+l^-$ into a pair of leptons are rare. In the Standard Model, they occur through a two-photon intermediate state. A model-independent lower limit for the decay probability, so-called unitary limit, is calculated from the meson two-photon width. For $\eta \to e^+e^-$ deaay $B_{UL}(\eta \to e^+e^-) = 1.78 \times 10^{-9}$. The current best upper limit on the decay probability $B(\eta \to e^+e^-) < 2.3 \times 10^{-6}$ was set in the HADES experiment [9].

At SND the inverse reaction $e^+e^- \to \eta$ is used to measure this decay [5]. We analyse data with an integrated luminosity of 654 nb^{-1} recorded in 2018 at $\sqrt{s} = m_\eta c^2$. The η meson is reconstructed via its decay to $3\pi^0$. No η candidate events are observed in data, and the upper limit $B(\eta \to e^+e^-) < 6.7 \cdot 10^{-7}$ is set at 90% confidence level,which is about 3 times lower than the previous limit.

Process $e^+e^- \to \pi^+\pi^-\pi^0\eta$. The process $e^+e^- \to \pi^+\pi^-\pi^0\eta$ has complex internal structure. There are at least four mechanisms for this reaction: $\omega(782)\eta$, $\phi(1020)\eta$, $a_0(980)\rho$, and structureless $\pi^+\pi^-\pi^0\eta$. The known $\omega\eta$ and $\phi\eta$ contributions explain about 50–60% of the cross section below 1.8 GeV. Above 1.8 GeV the dominant mechanism is $a_0\rho$. The preliminary SND results on the cross sections for the $e^+e^- \to \pi^+\pi^-\pi^0\eta$ process and its components are shown in Fig. 3 in comparison with the BABAR [10] and CMD-3 [11] measurements.

Process $e^+e^- \to \eta K^+K^-$. The process $e^+e^- \to \eta K^+K^-$ is studied by SND in the $\eta \to \gamma\gamma$ decay mode [12]. The SND results shown in Fig. 5 is in reasonable agreement with the previous BABAR measurement [13] and have and have comparable accuracy. The energy dependence of the cross section is determined predominantly by the contribution of the $\phi(1680)$ resonance.

Process $e^+e^- \to K_SK_L\pi^0$. The cross section for the process $e^+e^- \to K_SK_L\pi^0$ has been measured by SND in the energy range 1.3–2.0 GeV [14]. The comparison of the SND data with the only previous measurement by the BABAR Collaboration [15] is presented in Fig. 4. Only statistical errors are shown. The systematic uncertainty of the SND data is 12–13%, while the BABAR systematic uncertainty increases from 10% at 1.7 GeV and below to about 20% at 2 GeV. Near the maximum of the cross section (1.7 GeV) the SND points lie below the BABAR points, but agree within systematic errors. The same trend persists at higher energies, up to 2 GeV. The largest difference, about 2 standard deviations including systematic uncertainties, between the SND and BABAR data is observed at the energy points 1.875 and 1.925 GeV. The dominant mechanism of the $e^+e^- \to K_SK_L\pi^0$ reaction at $\sqrt{s} < 2$ GeV is $K^*(892)^0K^0$.

Process $e^+e^- \to \eta\pi^+\pi^-$. The cross section for the process $e^+e^- \to \eta\pi^+\pi^-$ has been measured by SND in the c.m. energy range from 1.07 to 2.00 GeV in the decay mode $\eta \to$

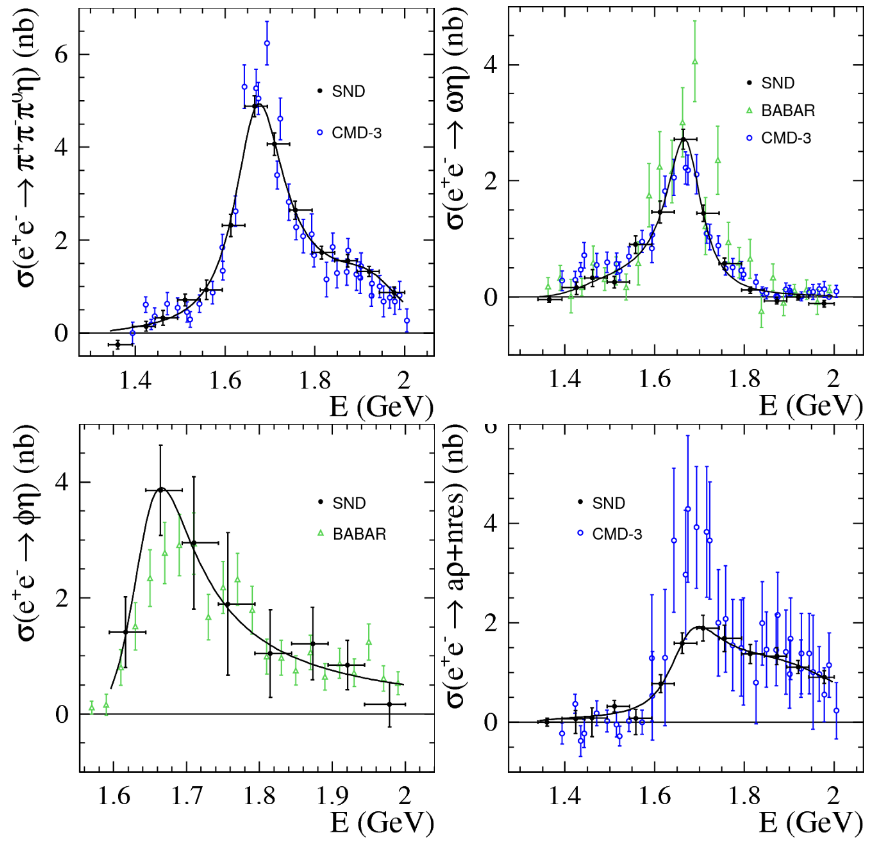

Figure 3. The preliminary SND results on the $e^+e^- \to \pi^+\pi^-\pi^0\eta$, $e^+e^- \to \omega\eta$, $e^+e^- \to \phi\eta$, and $e^+e^- \to a_0(980)\rho + nres$ cross sections in comparison with the BABAR [10] and CMD-3 [11] measurements. The curve is the result of the VMD fit.

$3\pi^0$ [16]. In the range 1.22–2.00 GeV the measured cross section is found to be in good agreement with the previous SND measurement in the $\eta \to \gamma\gamma$ decay mode. Therefore, the two measurements have been combined. The result is shown in Fig. 6. The cross-section energy dependence is fitted with the VMD model with 2, 3 and 4 ρ-like states. The quality of the fit with two resonances, $\rho(770)$ and $\rho(1450)$, is quite poor, $P(\chi^2) = 2\%$, while the fits with the additional $\rho(1700)$ resonance describe data well. The $\rho(1700)$ contribution appears as a shoulder on the $\rho(1450)$ peak near 1.75 GeV. The SND data on the $e^+e^- \to \eta\pi^+\pi^-$ cross section are in agreement with the previous most precise data obtained by the BABAR Collaboration [17], but have better accuracy.

3 Conclusions

The goal of the CMD-3 and SND experiments CMD-3 at the VEPP-2000 is to provide exclusive measurements of reactions e^+e^- annihilation to hadrons in the energy range 0.3–2.0 GeV.

In 2011-2013 the detectors have collected about 70 pb^{-1} each in the whole 0.32–2.0 GeV energy range available at VEPP-2000. During 2014-2016 machine and detectors have

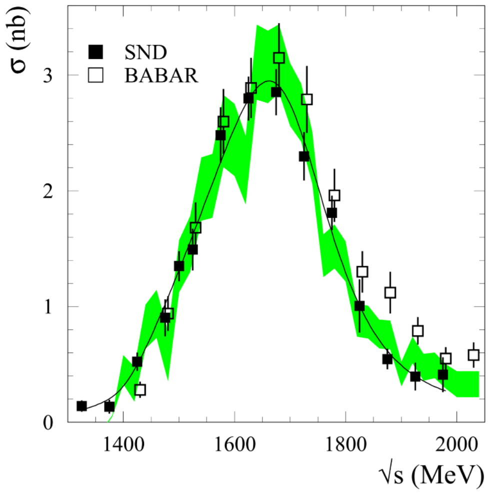

Figure 4. The cross section for the process $e^+e^- \to K_S K_L \pi^0$ measured by SND (filled squares) in comparison with the BABAR data [15] (open squares). The curve represents the result of the fit to SND data with the VMD model. The band represents the prediction for the $e^+e^- \to K_S K_L \pi^0$ cross section obtained using isospin relations from the BABAR measurements of the $e^+e^- \to K_S K^\pm \pi^\mp$, $e^+e^- \to K^+K^-\pi^0$, and $e^+e^- \to \phi\pi^0$ cross sections [13].

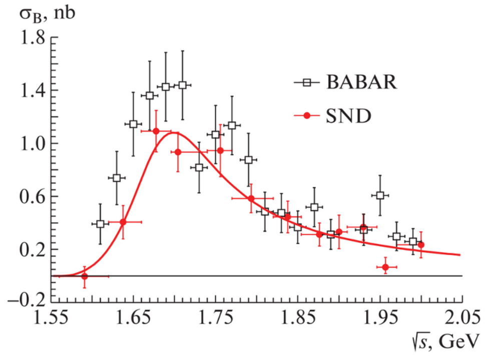

Figure 5. The $e^+e^- \to \eta K^+K^-$ cross section measured by SND in comparison with the BABAR measurement [13]. The curve represents the results of the VMD fit to the SND data.

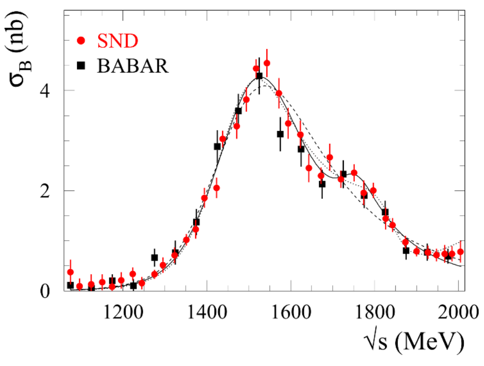

Figure 6. The $e^+e^- \to \eta\pi^+\pi^-$ cross section measured by SND and BABAR [17]. The solid, dashed, and dotted curves are the results of the VMD fit with 2, 3 and 4 ρ-like states.

been upgraded and at the end of 2016 detectors resumed data taking. In 2017-2018 the detectors have recorded about 120 pb^{-1} data samples in the energy region 0.5–2.005 GeV. Many analyses have been published. Many more are in the line.

This work is supported by the RFBR grants 15-02-05674-a, 16-02-00014, 16-02-00160-a, 16-02-00327, 17-02-00897, 17-02-00847, 18-02-00147, and 18-02-00382. Part of this work related to the photon reconstruction algorithm in the electromagnetic calorimeter for multiphoton events is supported by the Russian Science Foundation (project No. 14-50-00080).

References

[1] A. Romanov *et al.*, in *Proceedings of Particle Accelerator Conference PAC 2013*, Pasadena, CA USA, 14 (2013)
[2] V. M. Aulchenko *et al.*, BUDKER-INP-2001-45;
B. Khazin, Nucl. Phys. Proc. Suppl. **181-182**, 376-280 (2008)
[3] M. N. Achasov *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **598**, 31 (2009);
V. M. Aulchenko *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **598**, 102 (2009)
[4] E. V. Abakumova *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **744**, 35 (2014)
[5] M. N. Achasov *et al.* (SND Collaboration), arXiv:1806.07609 [hep-ex]
[6] Achasov M N *et al.*, J. Exp. Theor. Phys. **103**, no. 3, 380-384 (2006)
[7] Lees J P *et al.*, Phys. Rev. D **86**, 032013 (2012)
[8] M. N. Achasov *et al.* (SND Collaboration), Phys. Rev. D **90**, 112007 (2014)
[9] G. Agakishiev *et al.* (HADES Collaboration), Phys. Lett. B **731**, 265 (2014)
[10] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. D **73**, 052003 (2006)
[11] R. R. Akhmetshin *et al.* (CMD-3 Collaboration), Phys. Lett. B **773**, 150-158 (2017)
[12] M. N. Achasov *et al.*, (SND Collaboration), Physics of Atomic Nuclei **81**, no.2, 205-213 (2018)
[13] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. D **77**, 092002 (2008)
[14] M. N. Achasov *et al.* (SND Collaboration), Phys. Rev. D **97**, no.3, 032011 (2018)
[15] P. Lees *et al.* (BaBar Collaboration), Phys. Rev. D **95**, 052001 (2017)
[16] M. N. Achasov *et al.*, (SND Collaboration), Phys. Rev. D **97**, no.1, 012008 (2018)
[17] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. D **76**, 092005 (2007); **77**, 119902(E) (2008)