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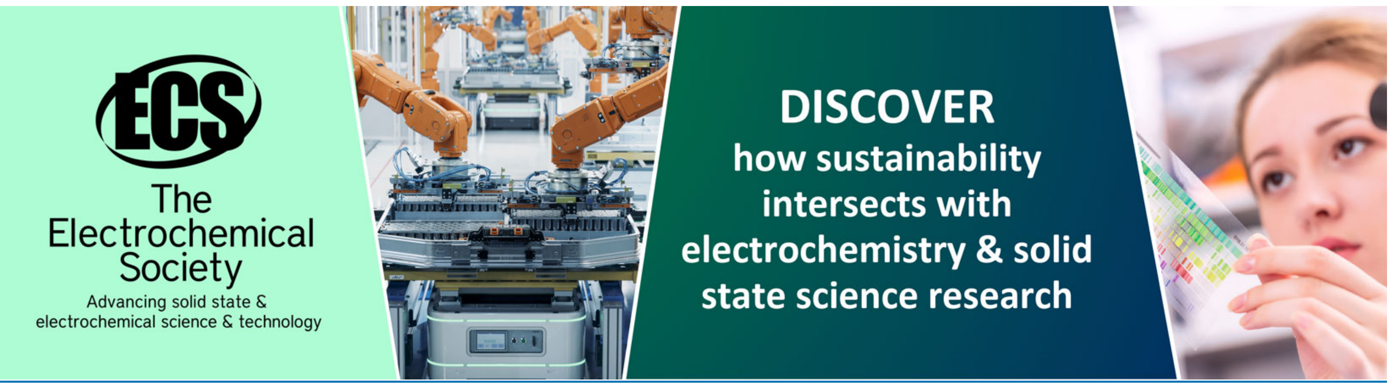

Collider experiment SND and Precision Physics with hadronic e^+e^- cross sections

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Abstract. The Spherical Neutral Detector (SND) is an experiment for e^+e^- annihilation study at low energies 0.2-2 GeV. The light quark anti-quark bound states are the main subject of study at these energies. They express themselves as resonances in the e^+e^- hadronic cross sections. Hadronic cross sections could be recalculated to hadronic vacuum polarization (HVP). The Standard Model predictions today are limited by HVP which is not calculable with modern QCD theory. In this talk we present the review of the hadronic cross sections measurements at SND and new measurements: $e^+e^-\to\pi^+\pi^-$, $\pi^0\gamma$, $\pi^+\pi^-\pi^0$, $\omega\pi^0$, $K^+K^-\eta$, η, $K_SK_L\pi^0$, $\pi^+\pi^-\pi^0\eta$, $\omega\pi^0\eta$ e.t.c.

1. Introduction

The Spherical Neutral Detector (SND) [1,2,3,4] is a general purpose nonmagnetic detector placed at VEPP-2000 e^+e^- collider [5]. The e^+e^- beams are collided head to head inside the detector and new particle system are born with zero total momentum and with energy equal to the e^+e^- total energy. The experiments are performed by an energy range scan between 0.2 and 2 GeV. The beam energy is controlled by the Compton scattering technique [6,7] with relative precision of about 10^{-5}.

During the years 2010-2013 the SND experiment has collected 69 pb^{-1} of data, results presented here are mostly based on the analysis of this statistics. During the years 2014-2016 VEPP-2000 was upgraded and connected to positron source VEPP-5. In the year 2017 the experiments were started with increased luminosity and 50 pb^{-1} were collected in the energy range 1280 – 2000 MeV. At the ϕ-meson energy 1020 MeV the luminosity reached $4\times10^{31}cm^{-2}c^{-1}$ while the project luminosity is $1\times 10^{31}cm^{-2}c^{-1}$ (at 1 GeV c.m.) [5], four times smaller.

The Physical Program of VEPP-2000 includes:

i. Precise measurement of the quantity $R=\sigma(e^+e^- \to hadrons)/ \sigma(e^+e^- \to\mu^+\mu^-)$
ii. Study of hadronic channels: $e^+e^- \to 2h, 3h, 4h \ldots, h= \pi,K,\eta$

iii. Study of 'excited' vector mesons: ρ' ,ρ'', ω', φ', etc.
iv. CVC tests: comparison of $e^+e^- \to$hadrons (T=1) cross section with τ-decay spectra
v. Study of nucleon-antinucleon pair production – nucleon electromagnetic form factors, search for $N\overline{N}$ resonances.

Below 2 GeV the quantity $R=\sigma(e^+e^- \to \text{hadrons})/\ \sigma(e^+e^- \to \mu^+\mu^-)$ is usually measured as the sum of exclusive channel cross sections. Using the sum rules R could be recalculated to Hadronic Vacuum Polarization (HVP) [8]. The HVP is one of the components that is used for the muon (g-2) prediction [9]. At present the muon (g-2) deviates from Standard Model prediction by 3.9σ [10]. The uncertainty of the SM prediction is dominated by the HVP uncertainty and by the uncertainty of the e^+e^- hadronic cross sections.

2. Precise cross-section measurements

In this section some recently measured $e^+e^- \to$hadrons cross sections are observed.

The $e^+e^- \to \pi^+\pi^-$ process gives the largest contribution to the muon (g-2). The most precise measurements of this process were done by ISR method at BaBar [11] and KLOE and some tension between their results was observed [10]. The uncertainty for $e^+e^- \to \pi^+\pi^-$ was dominated by the BABAR-KLOE difference. Here we present new direct measurement of this channel.

Some channels like $e^+e^- \to \pi^+\pi^-\pi^0\eta$, $\omega\pi^0\eta$ were not studied before although they reveal very interesting internal dynamics. The radiative decays of the vector mesons are used to fix the quark content of these mesons.

The radiative widths are determined from the $e^+e^- \to X\gamma$ cross sections. Here we present the most accurate measurement of $e^+e^- \to \pi^0\gamma$ cross section.

2.1. The process $e^+e^- \to \pi^0\gamma$

Recently the SND collaboration has published the most accurate up to date $e^+e^- \to \pi^0\gamma$ cross section measurement [12] which is based on the old VEPP-2M data. The results are in agreement with previous SND [13,14] and CMD-2 [15] measurements, but have better accuracy.
There was a tension between branching fraction ratio B $(\omega \to \pi^0\gamma)$/ B $(\omega \to \pi^+\pi^-\pi^0)$ measured by KLOE [16] and by SND and CMD-2 experiments. Due to the new VEPP-2M measurements by SND this tension is increased to 3.4σ. The next branching ratios were obtained from the data fit: $B(\rho \to \pi^0\gamma) = (4.20\pm0.52) \times 10^{-4}$, $B(\omega \to \pi^0\gamma) = (8.88\pm0.18)\%$, $B(\varphi \to \pi^0\gamma) = (1.367\pm0.072) \times 10^{-3}\%$.

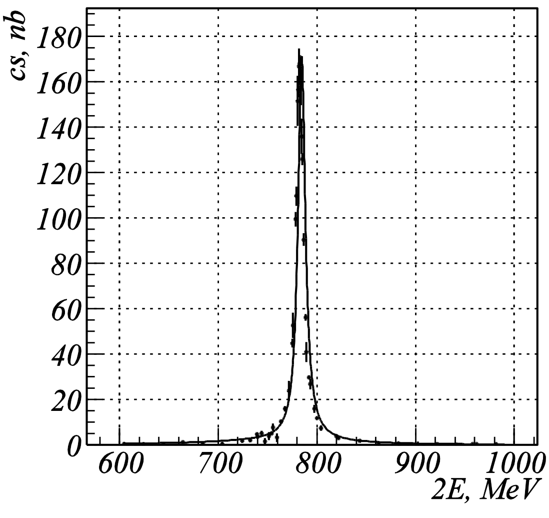

Figure 1. The $e^+e^- \to \pi^0\gamma$ cross section measured by SND using new VEPP-2000 data.

A new measurement of the process $e^+e^-\to\pi^0\gamma$ has been performed in the experiment with the SND detector at the e^+e^- collider VEPP-2000 using the data collected at the years 2013-2015 (figure 1). The $e^+e^-\to\pi^0\gamma$ cross section has been measured in the center-of-mass energy range from 0.60 to 0.98 GeV. From the fit to the cross section data we have determined preliminary branching fractions $B(\rho\to\pi^0\gamma) = (5.94\pm0.93)\times10^{-4}$, $B(\omega\to\pi^0\gamma) = (8.55\pm0.13)\%$.

2.2. *The process $e^+e^-\to\pi^+\pi^-$*

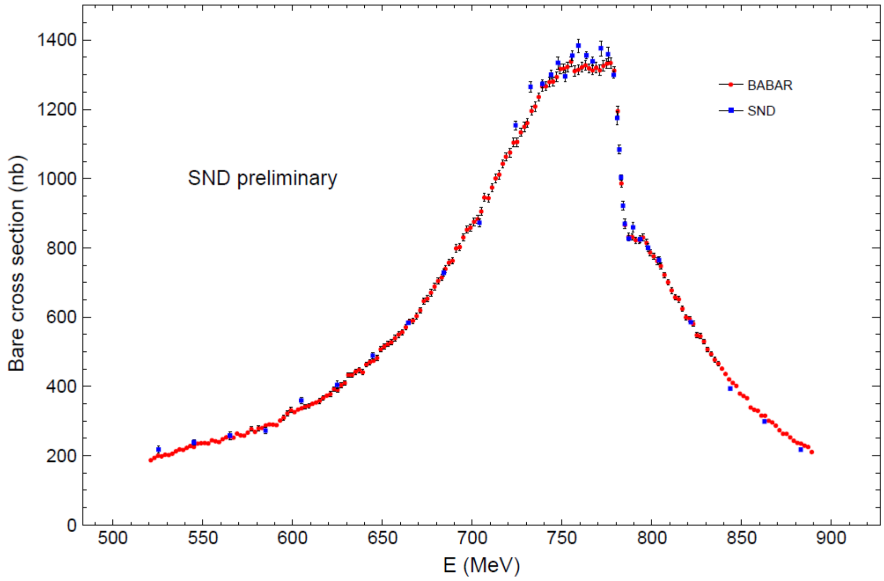

Figure 2. Cross section of the process $e^+e^-\to\pi^+\pi^-$ measured by SND at VEPP-2000 in comparison with BaBAR result [17].

The $e^+e^-\to\pi^+\pi^-$ cross section is the largest hadronic cross section below 1 GeV. A preliminary result for $e^+e^-\to\pi^+\pi^-$ cross section measurement in the c.m. energy range 520–880 MeV was obtained recently. Our result in comparison with most precise previous measurement by BABAR [17] is shown in figure 2.

2.3. *The process $e^+e^-\to\pi^+\pi^-\pi^0$*

The $e^+e^-\to\pi^+\pi^-\pi^0$ cross section was measured in an experiment with the SND detector at VEPP-2000 [23]. For the analysis 22 pb^{-1} of the data collected at the year 2011 and 12 pb^{-1} of the data collected at the year 2012 were used. The fit to the cross section was performed taking into account ω, φ, ω', ω'' mesons (figure 3).

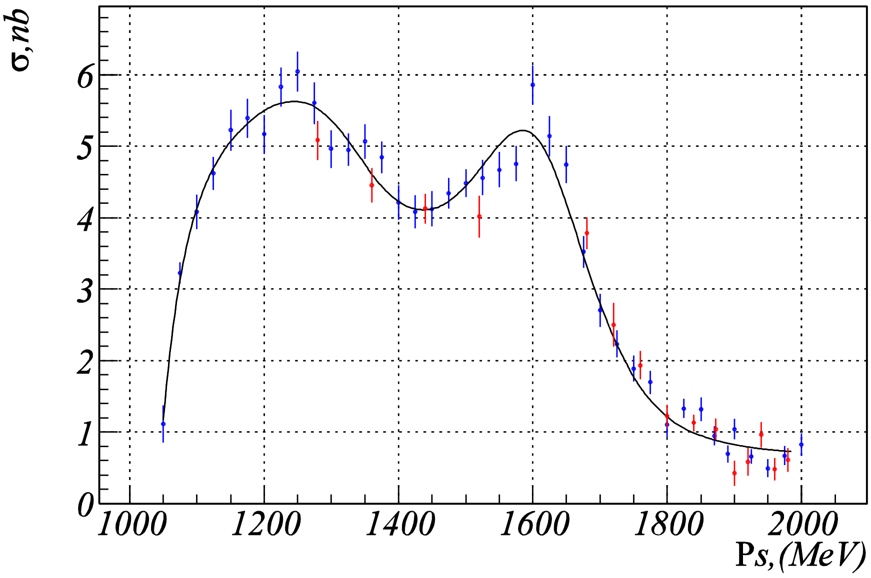

Figure 3. Cross section of the process $e^+e^-\to\pi^+\pi^-\pi^0$ measured by SND at VEPP-2000. Red dots – year 2012, blue dots – year 2011.

2.4. The process $e^+e^- \to \eta K^+K^-$

The cross section of the process $e^+e^- \to \eta K^+K^-$ was measured by the SND detector in the c.m. energy range 1.55 – 2.00 GeV [24]. The agreement between our measurement and the BABAR most precise result [18] is seen (figure 4 left). The energy dependence of the $e^+e^- \to \eta K^+K^-$ cross section can be described by the $\varphi(1680)$ resonance contribution. The K^+K^- invariant mass distribution supports the hypothesis that $e^+e^- \to \eta K^+K^-$ transition is dominated by the $\eta\varphi$ intermediate state (figure 4 right).

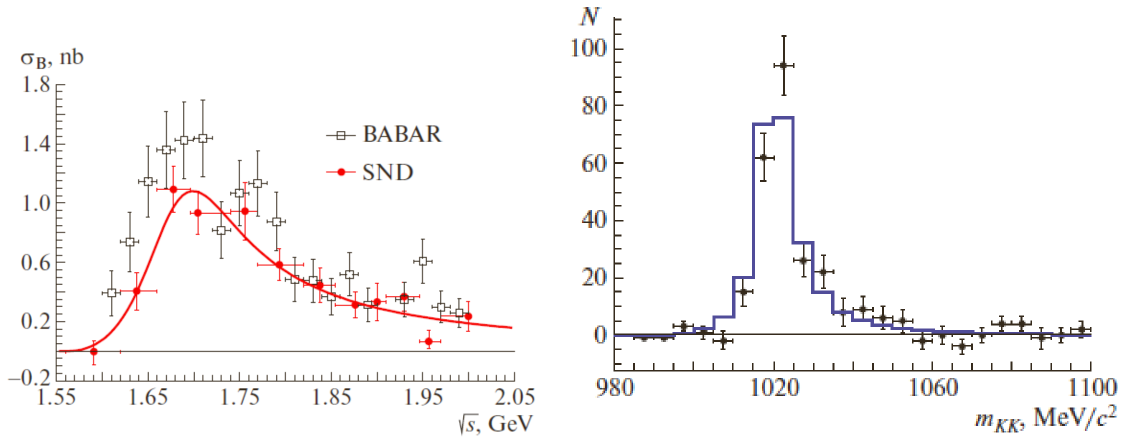

Figure 4. Cross section of the process $e^+e^- \to \eta K^+K^-$ measured by SND at VEPP-2000 (left). The invariant mass distribution of the K-meson pairs for the process $e^+e^- \to \eta K^+K^-$ (right).

2.5. The process $e^+e^- \to K_SK_L\pi^0$

The $e^+e^- \to K_SK_L\pi^0$ cross section is measured in the center-of-mass energy range E=1.3-2.0 GeV [25]. The analysis is based on the data sample with an integrated luminosity of 33.5 pb^{-1} collected with the SND detector at the VEPP-2000 e^+e^- collider. Systematic uncertainty of the measurement is 12%. A disagreement with BABAR measurement [19] at energies E > 1.8 GeV was found. On the other side our measurement is in agreement with the cross section calculated by using the isospin relations: $\sigma(e^+e^- \to K_SK_L\pi^0)= \sigma(e^+e^- \to K_SK^\pm\pi^\pm)- \sigma(e^+e^- \to K^+K^-\pi^0)+ Br(\varphi\to K_SK_L)\sigma(e^+e^- \to \varphi\pi^0)$ (figure 5).

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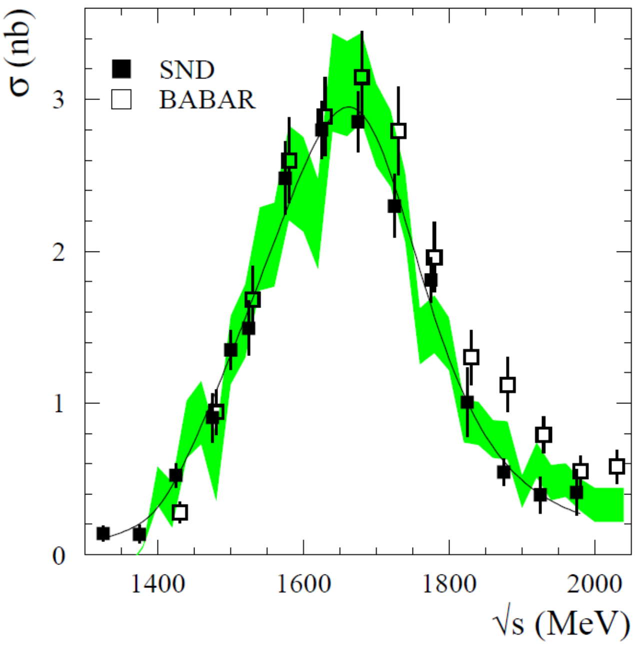

Figure 5 The $e^+e^- \to K_S K_L \pi^0$ cross section is measured by the SND at VEPP-2000. The band represents the cross section calculated by using the isospin relations.

2.6. Search for η →e⁺e⁻

A search for the rare process $\eta \to e^+e^-$ (figure 6) was performed with the help of the inverse reaction $e^+e^- \to \eta \to \pi^0\pi^0\pi^0$. An integrated luminosity of 108 nb^{-1}collected by the SND detector in the η meson region was used. The limit for the branching ratio was set $Br(\eta \to e^+e^-) < 2.9 \cdot 10^{-6}$.

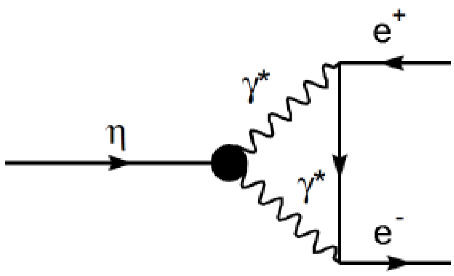

Figure 6 Feynman diagram for the process $\eta \to e^+e^-$.

2.7. The process $e^+e^- \to \omega\eta\pi^0$

The cross section of the process $e^+e^- \to \omega\eta\pi^0$ was measured for the first time (figure 7 right) [20]. The cross section value in the energy range 1.8 – 2 GeV is around 2 nb, it contribute approximately 5% of the total hadronic cross section in this energy range. The threshold of this reaction is located at 1.75 GeV. From the analysis of the $\eta\pi^0$ invariant mass distribution it was found that $\omega a_0(980)$ intermediate state dominates in this process (figure 7 right).

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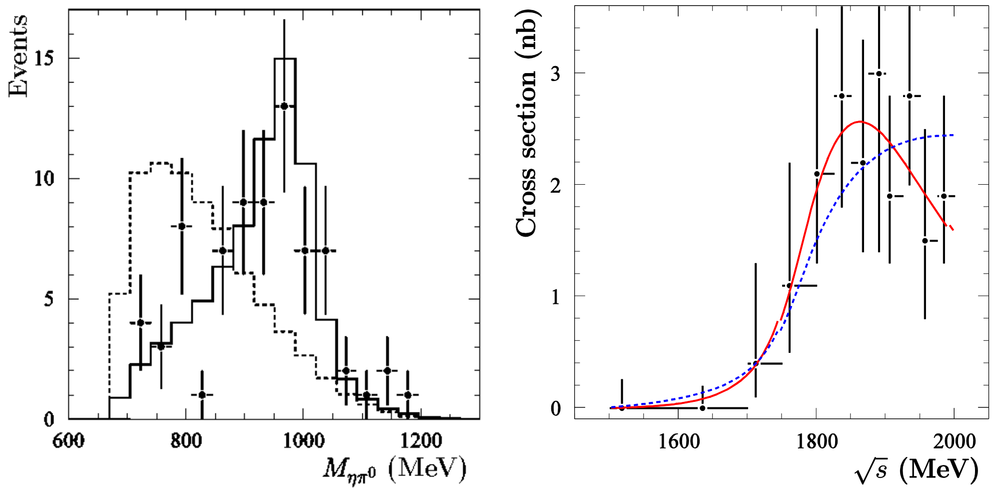

Figure 7 Invariant mass distribution of the $\eta\pi^0$ system for the $e^+e^- \to \omega\eta\pi^0$ process (left). Solid histogram is MC for $\omega a_0(980)$ intermediate state. Dashed histogram is MC for uniform events distribution over phase space. Points represent the data (right). The $e^+e^- \to \omega\eta\pi^0$ cross section measured by SND. Solid (dashed) line represents fit to data with (without) one resonance.

2.8. *The process $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$*

The cross section of the process $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ was measured with high accuracy in the energy range 1 – 2 GeV (figure 8). The statistical uncertainty is 2 – 16 % while the systematical uncertainty is 1 – 9 %. The results of the cross section measurement are in agreement with the previous measurements but have better accuracy.

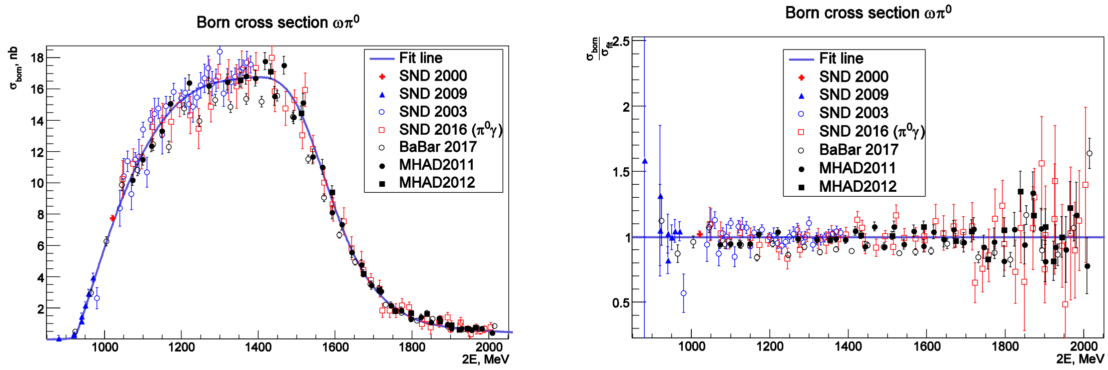

Figure 8 The $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ cross section measured by SND (left) and it's comparison to other measurements (right). Solid line represents the fit to data with VMD model.

2.9. *The process $e^+e^- \to \pi^+\pi^-\pi^0\eta$*

The process $e^+e^- \to \pi^+\pi^-\pi^0\eta$ has at least four mechanisms: $\omega\eta$, $\varphi\eta$, $a_0(980)\rho$, and structureless $\pi^+\pi^-\pi^0\eta$. The known $\omega\eta$ and $\varphi\eta$ mechanisms together give about 50-60% contribution to the cross section below 1.8 GeV. Above c.m. energy 1.8 GeV $a_0(980)\rho$ is the dominant mechanism. Preliminary result on the $e^+e^- \to \pi^+\pi^-\pi^0\eta$ cross section is shown at figure 9 (left). The cross section for the sub process $e^+e^- \to \omega\eta$ was measured separately [21] and it is shown in figure 9 (right) in comparison with the BABAR measurement [22]. Our results are more accurate and disagree with the BABAR data above c.m. energy 1.6 GeV. The $e^+e^- \to \varphi\eta$ and $e^+e^- \to a_0(980)\rho$ cross sections are shown at figure 10 and structure less $\pi^+\pi^-\pi^0\eta$ is shown at figure 11.

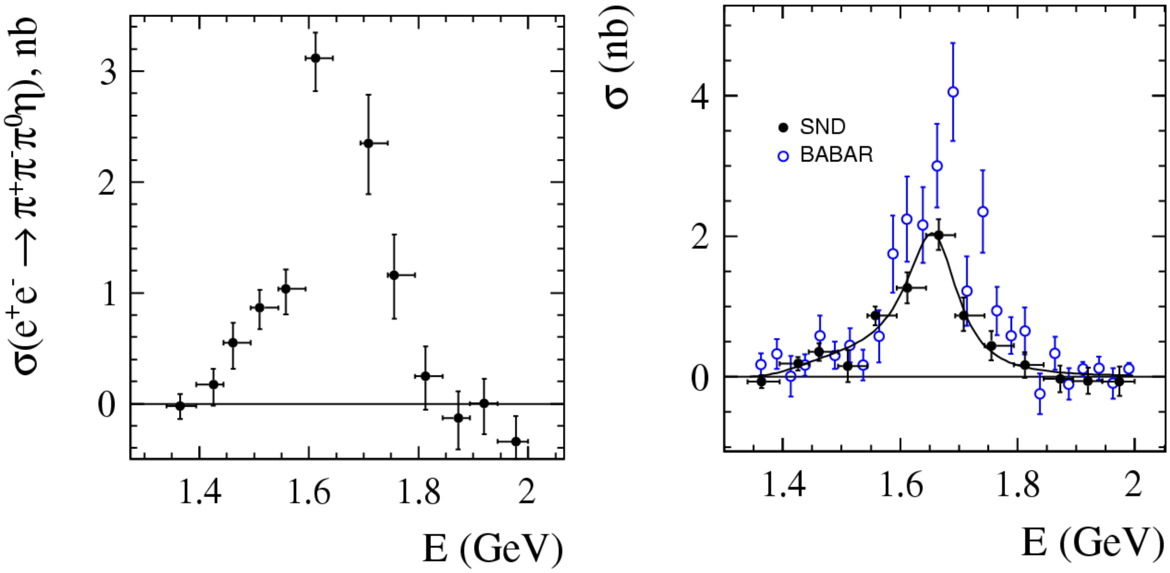

Figure 9 Left panel: The $e^+e^- \to \pi^+\pi^-\pi^0\eta$ cross section measured by SND (preliminary). Right panel: The $e^+e^- \to \omega\eta$ cross section measured by SND in comparison with BABAR data [22]. The curve is the result of the VMD fit.

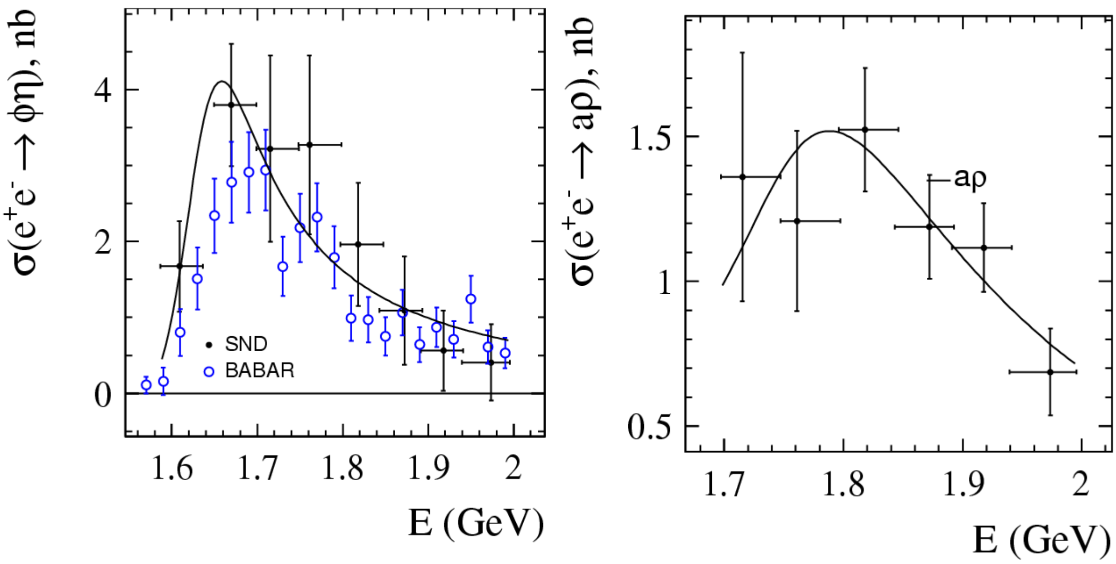

Figure 10 The $e^+e^- \to \varphi\eta$ (left) and $e^+e^- \to a_0(980)\rho$ (right) cross sections measured by the SND at VEPP-2000.

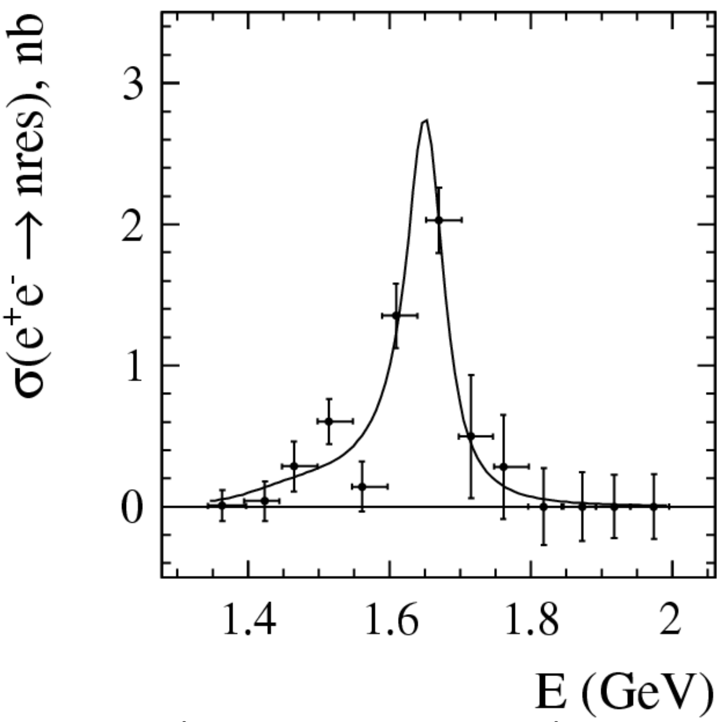

Figure 11. The structureless $\pi^+\pi^-\pi^0\eta$ contribution to $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta$ process cross section.

3. Conclusion

During the year 2017 the SND detector accumulated about 50 pb^{-1} of integrated luminosity at the VEPP-2000 e^+e^- collider in the c.m. energy range 0.3-2 GeV. Data analysis on hadron production is in progress. The results of analysis of processes $e^+e^-\rightarrow\pi^+\pi^-$, $\pi^0\gamma$, $\pi^+\pi^-\pi^0$, $\omega\pi^0$, $K^+K^-\eta$, η, $K_SK_L\pi^0$, $\pi^+\pi^-\pi^0\eta$, $\omega\pi^0\eta$ are presented. After VEPP-2000 upgraded the data taking runs are resumed and the main goal is to achieve 1 fb^{-1} of integrated luminosity.

4. Acknowledgement

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