Experimental input from e^+e^- machines
to hadronic contribution to muon $(g-2)$

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Abstract

Precise study of the hadrons production in e^+e^- annihilation at low energies provides important information about interactions of light quarks and spectroscopy of their bound states. These studies are especially important for theoretical calculations of the muon $(g-2)$ via the Standard Model because of the present difference between theoretical and experimental values exceeds three standard deviations. In this report we will discuss current status and recent results obtained by the CMD-3 experiment and will give a brief look to status of the BaBar and Belle II experiments.

Contents

1 Introduction

In spite of a long history of hadrons production study in e^+e^- collisions new precise measurements provide important information about interactions of light quarks and spectroscopy of their bound states. One of the most important tasks in this field is a precise determination of the hadronic corrections to the anomalous magnetic moment of the muon, $a_\mu = (g_\mu - 2)/2$. The anomalous magnetic moment of the muon stands as an especially interesting issue in the last decade since high precision measurements of this value, a_μ, performed at Brookhaven National Laboratory [1] differs from theoretical calculations via the Standard Model [2–4] by more than 3.5 standard deviations. If this difference will be confirmed that could be a direct indication of New Physics. Recent review of the status of theoretical calculations is given in [5].

The BNL experiment achieved a relative accuracy in a_μ value of $5 \cdot 10^{-7}$: $a_\mu = (11659208.9 \pm 6.3) \cdot 10^{-10}$. The accuracy of the theoretical calculations via the Standard Model is limited now by the hadronic vacuum polarization term, a_μ^h which requires precise data on the hadronic cross section of e^+e^- annihilation.

In 2017 a new muon (g-2) experiment, FNAL E989, succeeding the BNL E821 started data taking [6,7]. This experiment is based on the same principles as the previous one and reuses the same muon storage ring. Another project based on completely different approach is under development at J-PARC in Japan [8]. Both projects aim to accuracy improvement to about $2 \cdot 10^{-10}$. Then, the precision of the hadronic contribution becomes a crucial issue. The total hadron production cross section needed for a_μ^h calculation is characterized by the ratio R:

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}, \quad \sigma_{\mu^+\mu^-} = \frac{4\pi\alpha^2}{3s}\frac{86.85\,\text{nb}}{s\,[\text{GeV}^2]}. \tag{1}$$

Since a_μ^h is expressed as

$$a_\mu^h = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(S)}{s} R(s), \tag{2}$$

where $K(S) \sim 1$, it is clear that the low energy range provides the dominant contribution to this value.

The data on $R(s)$ available now are obtained in two types of experiments: with the scan of the experiment energy and at the constant energy of the experiment and a detection of the processes with hard photon emitted from the initial state (ISR).

In the energy range below 2 GeV $R(s)$ is determined as a sum of the exclusive cross sections. At higher E_{CM} the inclusive total hadronic cross section is measured. Recent measurements of the energy scan type are performed by CMD-2, SND, KEDR and BES II,III detectors while ISR approach is used by BaBar, KLOE and BES III experiments. In this report we concentrate on the experiments of the first type performed with CMD-3 and SND detectors at VEPP-2000 e^+e^- collider and briefly discuss the results of the BaBar experiment as well as Belle-II perspectives.

2 VEPP-2000 collider and detectors

Until 2010 precise data on the hadronic cross sections obtained in the energy scan mode were provided by experiments at VEPP-2M collider [9–11] with the luminosity up to $3 \times 10^{30} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. Experiments with this collider in the energy range up to 1.4 GeV continued for more than 25 years. The latest cycle of experiments from 1992 to 2000 with two detectors, the CMD-2 [12] and the SND [13], produced most accurate data on e^+e^- annihilation to hadrons in the $0.36 < \sqrt{s} < 1.4$ GeV energy range obtained by the energy scan.

The new VEPP-2000 e^+e^- collider for the center-of-mass energy range from 0.3 to 2 GeV has been operating at BINP (Novosibirsk) from 2010 [14]. This machine exploits an idea of the round beams developed at the BINP that has to provide the project luminosity up to $10^{32} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at 2 GeV. To achieve this target a special magnetic structure of the ring including two focusing solenoids with 12 T magnetic field installed at both sides of each interaction region was designed. The collider operates with one electron and one positron bunches containing up to 10^{11} particles. Main characteristics of VEPP-2000 is given in the Table 1. A special system based on the Compton back scattering of laser photons is used to measure the beam energy [16]. The accuracy of these measurements is 30-50 keV.

Table 1: Main project parameters of VEPP-2000

E_{beam}, MeV	510	1000
Π, cm	2235	
I^+, I^-, mA	34	200
$\epsilon \cdot 10^5$, cm·rad	0.5	1.6
β_x, β_z, cm	6.3	6.3
ξ_x, ξ_z	0.075	0.075
Ł, cm^{-2}s—1	$1 \cdot 10^{31}$	$1 \cdot 10^{32}$

Two detectors, CMD-3 and upgraded SND [15], are running at two interaction regions of the collider. In the first experimental run conducted from 2010 to 2013 integrated luminosity of about 55 pb^{-1} per detector was collected. Then experiments at VEPP-2000 were resumed in 2017 after a three year shutdown taken for the new intensive positron injection source implementation as well as for an upgrade of the 1 GeV booster.

The CMD-3, shown schematically in Fig. 1, is a compact multipurpose detector combining magnetic spectrometry with high resolution calorimetry. The main instrument of the SND detector, presented in Fig. 2, is a high resolution calorimeter based on NaI(Tl) scintillation crystals with $0.95 \times 4\pi$ uniform acceptance. The calorimeter consists of three layers of counters that provides high quality electron/pion separation. The SND is equipped by the tracking drift chamber, aerogel Cherenkov counters for pion/kaon separation and muon system. During 2017-18 experiments the VEPP-2000 achieved luminosity of $5 \times 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at 2 GeV and
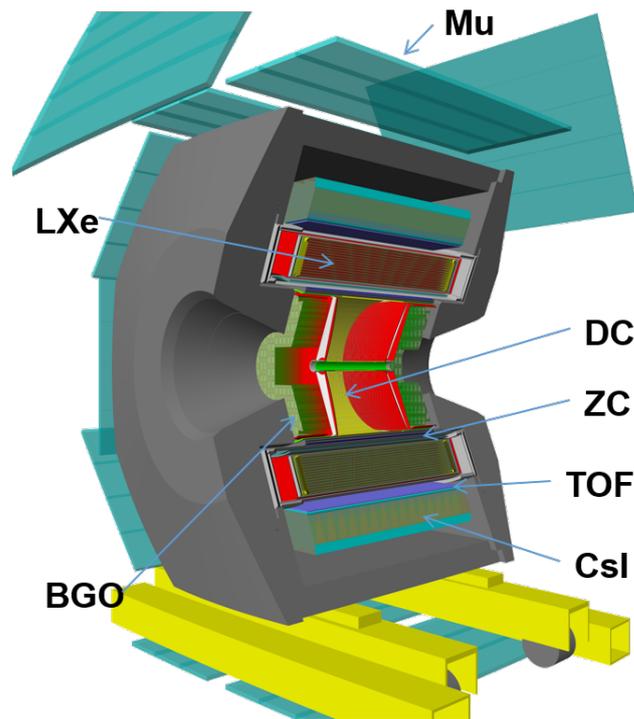
Figure 1: The CMD-3 detector. DC – drift chamber, ZC – multiwire proportional chamber used for the trigger and z-coorsinate measurement, LXe – liquid Xe calorimeter, CsI – calorimeter based on scintillation CsI crystals, TOF– time-of-flight system, BGO – end cap calorimeter based on BGO scintillation crystals.
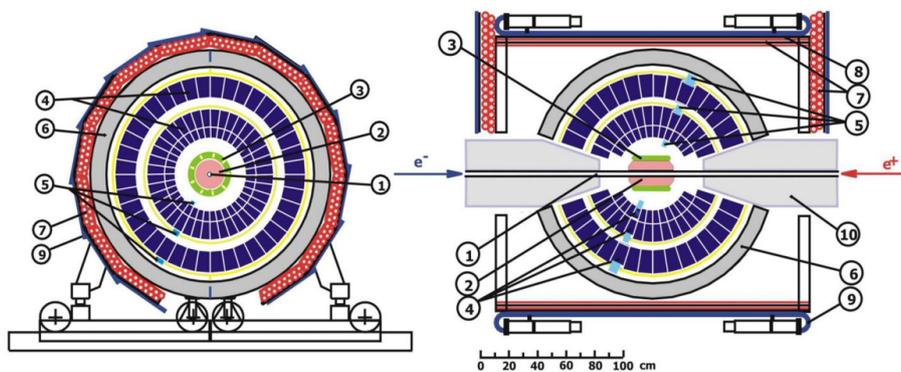
Figure 2: The SND detector. 1 – vacuum chamber, 2 – tracking DC, 3 – aerogel n=1.13, 1.05, 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – absorber, 7 – muon detector, 10 – SC solenoids.

exceeding $10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1 GeV. Each detector collected about 120 pb^{-1} in this new run. Considerable statistics was taken within an energy range around the nucleon-antinucleon pair production.

3   A measurement of the $e^+e^- \to \pi^+\pi^-$ cross section

The dominant contribution to the a_μ^h value as well as the uncertainty of this value come from the $\pi^+\pi^-$ channel at the range below 2 GeV. By now the most precise data on the $e^+e^- \to \pi^+\pi^-$ in the low energy range were obtained by CMD-2 [20] and SND [21] by the energy scan and with ISR approach by the BaBar [17], KLOE [18] and BES III [19] experiments. The precision in all these measurements is dominated by the systematic uncertainties which all groups estimated to be about 1%. To be consistent with the target precision of the new (g-2) experiments the systematic uncertainty in $\pi^+\pi^-$ cross section should be improved by at least two times.

Another reason to perform these measurements again is certain discrepancies between data of different experiments exceeding the stated uncertainties. Thus, new and more precise measurements of the $e^+e^- \to \pi^+\pi^-$ cross section is an important part of the experiments at VEPP-2000.

To study this process events with two collinear (back-to-back) tracks with opposite charges originated from the interaction region are selected. Then the most difficult task is a precise separation of e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ events. In the CMD-3 experiment this separation can be done by two methods: based on the particle momentum measurement or using the energy deposition in the calorimeter. Using both approaches provides a possibility of the systematics control. Preliminary results (still blinded!) of CMD-3 study of the $\pi^+\pi^-$ channel based on 9.4 pb^{-1} of integrated luminosity performed by two approaches is presented in Fig. 3. The result is still
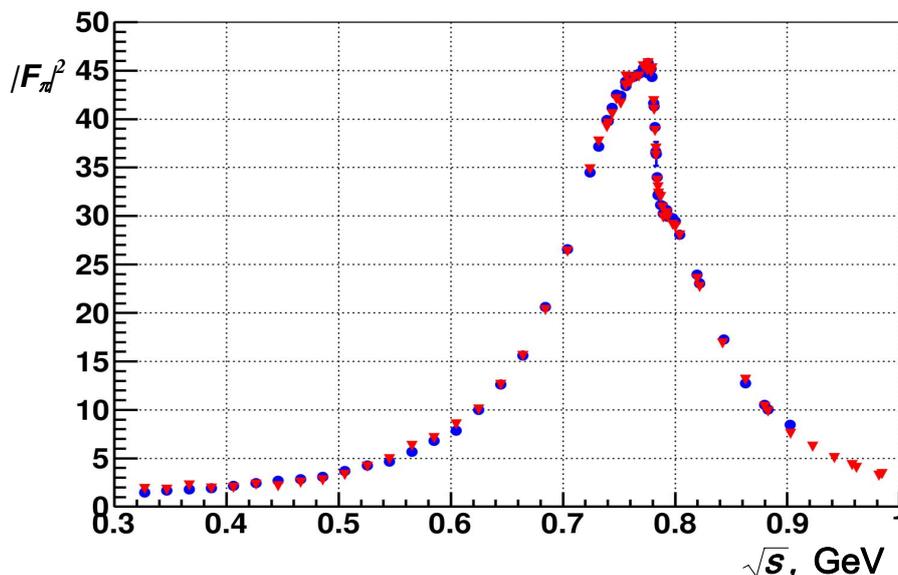
Figure 3: Preliminary results (still blinded!) of CMD-3 study of the $\pi^+\pi^-$ channel. Triangles (red) – separation by energy deposition in the calorimeter ; circles (blue) – separation by the particle momenta.

blinded, the study of the sources of systematic uncertainties and necessary correction are on-going. The Fig. 4 shows the ratio $R = \sigma(e^+e^- \to \mu^+\mu^-)/\sigma_{QED}$. The data is in good agreement with QED calculations that confirms the consistency of the analysis procedure..

To separate e^+e^- and $\pi^+\pi^-$ events the SND uses the total energy deposition as well as its distribution over layers of the calorimeter. This provides high efficiency of separation. Preliminary results of the pion form factor measurements by SND experiment is shown in Fig. 5. This results well agree with the previous SND measurements.
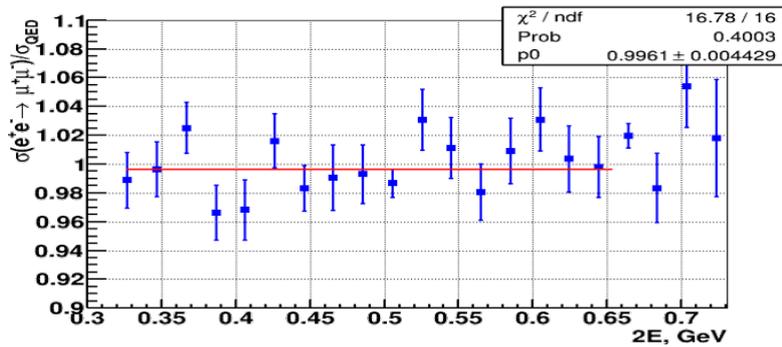
Figure 4: The ratio $R = \sigma(e^+e^- \rightarrow \mu^+\mu^-)/\sigma_{QED}$
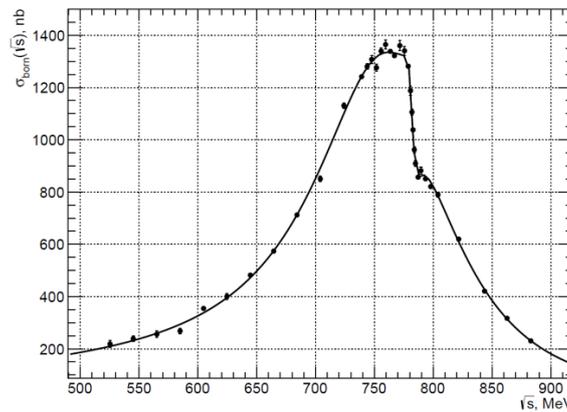
Figure 5: Preliminary results of the pion form factor measurements by SND experiment. The solid line correspond to the fit of the data by the ρ-meson shape with $\rho - \omega$ interference.

4 Other hadronic channels

High luminosity of the VEPP-2000 collider and two multipurpose detectors provide a possibility to study many channels of e^+e^- annihilation to hadrons. By now results on about 20 channels were published by both collaborations and analyses of more than 20 other processes are ongoing.

Very interesting phenomena were observed near the $p\bar{p}$, $n\bar{n}$ production threshold. In 2017 CMD-3 and SND has performed the scan at the $N\bar{N}$ threshold with a step smaller than machine energy spread (1.2 MeV in total energy). The $e^+e^- \rightarrow p\bar{p}$ cross section demonstrates exponentially fast rising in about 1 MeV interval. An explanation of this behavior is suggested in [22].

On the base of 2017 detail scan the SND experiment presented preliminary results on $e^+e^- \rightarrow n\bar{n}$ near threshold shown in Fig. 6. A difference between new results and earlier ones [23] can be explained by large systematic uncertainties in these data are caused mostly by ambiguities in the simulation of low energy antiproton interaction with matter. Systematic uncertainty of the latest measurements was considerably improved but are still of about 20%.

In the new detail scan the CMD-3 confirmed observed earlier [24] fast drop of the $e^+e^- \rightarrow 3(\pi^+\pi^-)$ cross section at the $N\bar{N}$ production threshold as seen in Fig. 7 [25]. It was found that one more channel shows similar behaviour – $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ as seen in Fig. 8. However, other channels, for example $2(\pi^+\pi^-)$, do not demonstrate any structure at
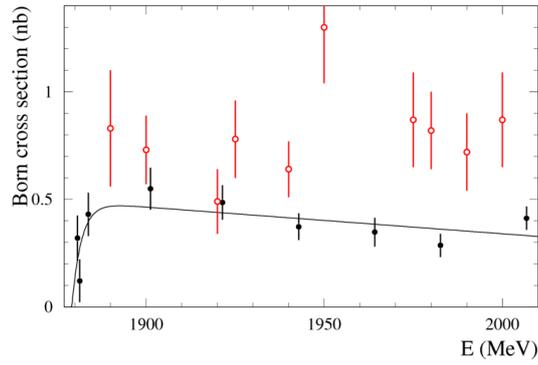
Figure 6: Preliminary results of the $e^+e^- \to n\bar{n}$ production (black circles). Previous SND measurements [23] are shown by open circles.
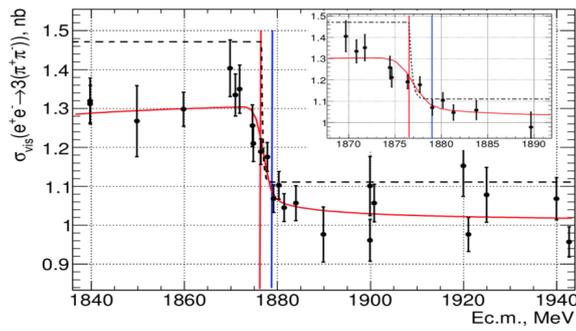
Figure 3: The $e^+e^- \to 3(\pi^+\pi^-)$ visible cross section measured with the CMD-3 detector. Solid curve shows fit with Born cross section (dashed curve) convoluted with 1.2 MeV energy spread and radiation function. The vertical lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

Figure 7: Cross section of $e^+e^- \to 3(\pi^+\pi^-)$ process measured by CMD-3 [25]. The solid line is a fit with empirical function. The vertical lines indicate the $p\bar{p}$ and $n\bar{n}$ thresholds.
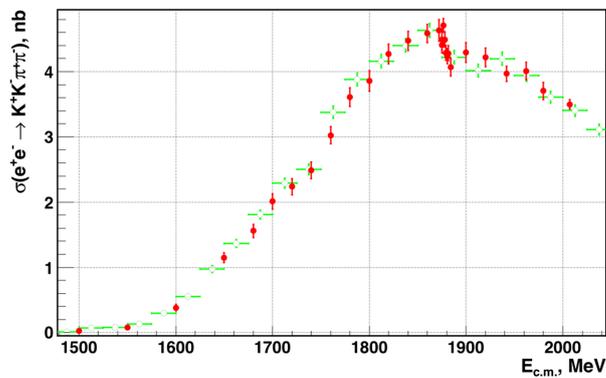
Figure 8: Cross section of $e^+e^- \to K^+K^-\pi^+\pi^-$ process measured by CMD-3

$N\bar{N}$ production threshold.

5 BaBar recent results and Belle II first look to ISR

The BaBar group has been studying low energy hadronic processes via ISR for a long time [26]. By now 22 final states were studied and about 20 papers on this subject were published. These results are presented in Fig. 9. Recently preliminary results on the processes
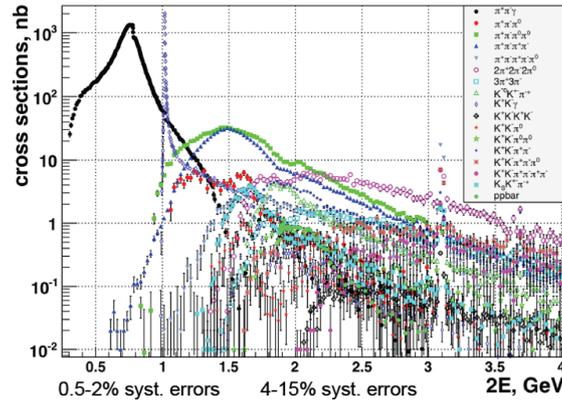
Figure 9: Study of the processes from ISR at BaBaR.

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0$ and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ were presented. These results are reported by E. Solodov at this workshop [27].

In the Spring-Summer of 2018 the first physics run was conducted by the Belle II experiment. Among other processes a first look to ISR events was done.

To selects such events the following criteria were applied: one photon with the CM energy exceeding 3 GeV and two tracks from the interaction region (IR) with the total energy in a range $10 < E_{tot} < 11$ GeV were required. In addition the E/p ratio should be less than 0.8 for each track, where E is the energy deposition in the calorimeter while p is a momentum measured by tracker. The invariant mass of two charged particles expecting the pion mass for each is shown in Fig. 10 in comparison with MC simulation performed with Phokhara procedure [28].
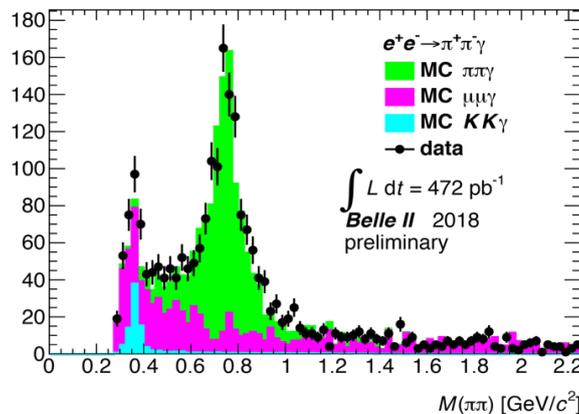
Figure 10: Study of the processes from ISR at Belle II.

6 Conclusion

The VEPP-2000 resumed operation in 2017 after a three year shutdown taken for new intensive positron injection source implementation as well as to upgrade the 1 GeV booster. New accelerator principles put on the base of this machine, "round beams", were successfully proved. Hopefully, in the next 5-10 years the VEPP-2000 will produce the integrated luminosity of about 1 fb^{-1} which should provide new precise interesting results on the hadron production in e^+e^- annihilation.

The BaBar experiment continues to produce new interesting data on hadron production in e^+e^- collisions using ISR approach. Recently Belle II experiment starts to collect data. First look to ISR events showed a good possibility of this experiment to give large contribution to this field.

Acknowledgements

This work is partially supported by the Russian Foundation for Basic Research grants 16-02-00160-a, 17-02-00327-a, 17-02-00847-a, 17-52-50064-a 18-32-01020 and 18-02-00147-a.

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