

Measurement of R at VEPP-2000*

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Abstract The new e^+e^- storage ring, VEPP-2000, is being commissioned at Budker Institute of Nuclear Physics, Novosibirsk. Measurement of the total cross section $e^+e^- \rightarrow \text{hadrons}$ in the whole VEPP-2000 energy range is one of the main goals of the new experiments. We discuss the goals of the measurement and the expected systematic errors.

Key words hadrons, pion form factor, cross section, muon magnetic moment

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1 Introduction

The new e^+e^- storage ring, VEPP-2000[1], is being commissioned at Budker Institute of Nuclear Physics, Novosibirsk. VEPP-2000 is the successor of VEPP-2M storage ring, which, through the series of experiments, generated vast amount of data on particle physics at energies $\sqrt{s}=0.36\text{--}1.4$ GeV. The new collider covers wider energy range $\sqrt{s}=0.36\text{--}2$ GeV and is expected to provide 10-times higher luminosity, thanks to the novel round-beam technique. The main parameters of the ring are shown in Table 1.

Table 1. Main parameters of VEPP-2000.

circumference	24.38 m
revolution time	82 ns
number of bunches	1
beam current	200 mA
luminosity	10^{31} (1 GeV) \div 10^{32} (2 GeV) $1/\text{cm}^2\text{s}$

Measurement of the total cross section $e^+e^- \rightarrow \text{hadrons}$ in the wide energy range is one of the main goals of experiments at VEPP-2000. It is interesting mainly for two reasons. Measurement of the exclusive modes $e^+e^- \rightarrow \text{hadrons}$ provides valuable information about the properties of the light vector mesons (ρ , ω , ϕ and their excitations). Measurement of the total cross section $e^+e^- \rightarrow \text{hadrons}$, often expressed as the

dimensionless ratio

$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}, \quad (1)$$

is very important for interpretation of the precise electroweak measurements, and, in particular, for evaluation of the Standard Model prediction for the anomalous magnetic moment a_μ of the muon. All known interactions contribute to the value of a_μ . While the effects of electromagnetic and weak forces can be calculated from the first principles, the lowest-order hadronic contribution, due to nonperturbative nature of strong interactions, can only be evaluated by integration of $R(s)$ with the proper kernel function [2]:

$$a_\mu(\text{had}; 1) = \left(\frac{\alpha m_\mu^2}{3\pi} \right)^2 \int_{4m_\pi^2} \frac{R(s)K(s)}{s^2} ds. \quad (2)$$

The contribution of the small s is enhanced via the $1/s^2$ term. Thus the precision of the Standard Model prediction is determined by the accuracy of $R(s)$ measurements at $\sqrt{s} < (2-3)$ GeV.

The experimental value of a_μ , recently measured at Brookhaven National Laboratory with 0.54 ppm precision [3], is approximately 3 standard deviations above the Standard Model expectation, which could indicate the long-sought existence of the New Physics. The precision of the theoretical SM evaluation, ≈ 0.5 ppm [4, 5], dominated by the knowledge of the hadronic contribution $a_\mu(\text{had})$, match the precision of

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the experiment. There is proposal to measure a_μ at FNAL with 0.14 ppm precision [6], which prompted world-wide effort for the more precise measurement of $R(s)$.

At the energy range under discussion, the multiplicity in the final state is low, therefore the only feasible way to measure the total cross section $e^+e^- \rightarrow$ hadrons is to measure the cross section for each final state exclusively and then calculate the sum. The dominant contribution to a_μ (had) comes from $e^+e^- \rightarrow \pi^+\pi^-$ final state (about 74%), followed by $e^+e^- \rightarrow 4\pi$ and resonances $\omega(782)$ and $\phi(1020)$. The estimated requirements for the precision of the cross section measurement for different final states to match the precision of the new FNAL (g-2) measurement are shown in Table 2. The highest precision is required for the dominant mode $e^+e^- \rightarrow \pi^+\pi^-$.

There are several approaches for the cross section measurement. In direct measurements, done at Novosibirsk, the energy scan is performed by changing the beam energy in relatively small (few MeV) steps and collecting the data at different c.m. energies. With the appearance of the φ - and B-factories (detectors KLOE, BABAR, BELLE), a new approach, ISR, was developed [7], in which the data are taken at constant beam energy and the cross section $e^+e^- \rightarrow$ hadrons is extracted from the spectrum of $e^+e^- \rightarrow$ hadrons + γ events. The high precision measurement of $e^+e^- \rightarrow \pi^+\pi^-$ was performed at KLOE [8] and BABAR [9]; many other modes were

measured at BABAR [10]. Here we discuss the energy scan-based measurements of $R(s)$ at VEPP-2M and VEPP-2000.

Table 2. Requirements for the next generation measurements of $e^+e^- \rightarrow$ hadrons.

final state	contribution to a_μ	required precision
$e^+e^- \rightarrow \pi^+\pi^-$	$\sim 73\%$	$< 0.3\%$
$e^+e^- \rightarrow \varphi, \omega$	$\sim 10\%$	$< 1.0\%$
$e^+e^- \rightarrow 4\pi$	$\sim 4\%$	$< 3\%$
other below 2 GeV	$\sim 4\%$	$< 3\%$

2 Measurement of R at VEPP-2M

The most precise up-to-date measurement of $\sigma(e^+e^- \rightarrow$ hadrons) done with energy scan technique in the energy range $0.36 < \sqrt{s} < 1.4$ GeV was performed by the CMD-2 [11, 12] and the SND [13, 14] experiments at the electron-positron collider VEPP-2M (Novosibirsk, Russia). The data was taken between 1992 and 2000. The results of the cross section measurements are shown in Fig. 1.

The main sources of systematic errors of the CMD-2 and SND pion form factor measurements are listed in Table 3. The total systematic error of the measurement at $\sqrt{s} < 1$ GeV is 1.3% for SND and 0.6%–0.8% for CMD-2, where the range reflects the detector performance during different data taking seasons. At energies $\sqrt{s} > 1$ GeV the systematic error

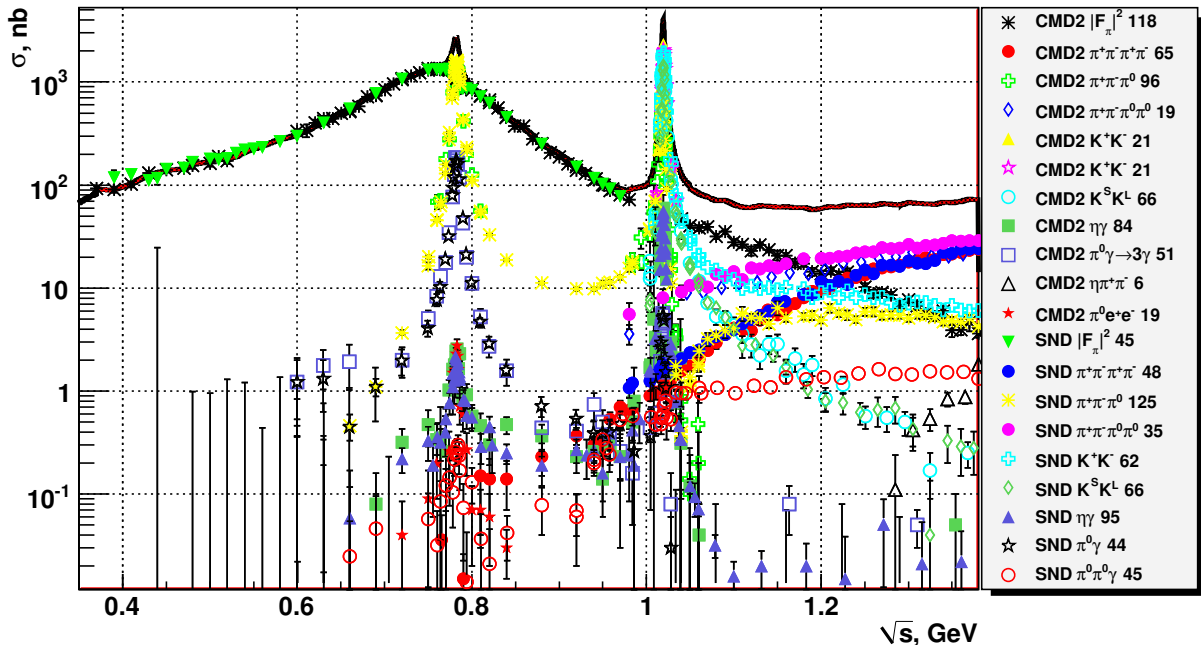


Fig. 1. Measurement of the cross sections $e^+e^- \rightarrow$ hadrons with CMD-2 and SND detectors.

increases, mainly due to the fact that $e^+e^- \rightarrow \mu^+\mu^-$ events were not separated from $e^+e^- \rightarrow \pi^+\pi^-$ events, but rather the corresponding cross section was subtracted from the final answer according to QED calculations with all known effects, like radiative corrections and detector performance, taken into account. At higher energies $e^+e^- \rightarrow \mu^+\mu^-$ cross section dominates over $e^+e^- \rightarrow \pi^+\pi^-$, thus the systematic error of the corresponding correction becomes significant. The statistical precision of the measurement at the particular energy point is typically few times larger than the systematic error, but, when the cross section is integrated for a_μ calculation, the systematic error dominates. It should be noted, that $e^+e^- \rightarrow \pi^+\pi^-$ (signal) and $e^+e^- \rightarrow e^+e^-$ (normalization) final states have similar signatures in the detector, which allows to partially cancel out the detector efficiencies and achieve smaller systematic error for the form factor measurement than for the luminosity.

Table 3. Main sources of systematic errors of the CMD-2 and SND pion form factor measurements at $\sqrt{s} < 1$ GeV.

source of error	CMD-2	SND
event separation	0.2%÷0.4%	0.5%
fiducial volume	0.2%	0.8%
energy calibration	0.1%÷0.3%	0.3%
efficiency correction	0.2%÷0.5%	0.6%
pion losses	0.2%	0.2%
radiative corrections	0.3%÷0.4%	0.5%
other	0.2%	0.5%
total	0.6%÷0.8%	1.3%

The total systematic error of $e^+e^- \rightarrow 4\pi$ measurements [15, 16] is approximately 5%–7% with dominant contributions from acceptance evaluation and corrections for the detector inefficiency.

All hadronic cross sections, measured at VEPP-2M, were normalized to $e^+e^- \rightarrow e^+e^-$ cross section. Direct measurement of $e^+e^- \rightarrow \mu^+\mu^-$ cross section is very interesting as the alternative way of normalization. The cross-section $e^+e^- \rightarrow \mu^+\mu^-$ was measured at VEPP-2M in the two energy ranges $\sqrt{s} < 0.52$ GeV [17] and $\sqrt{s} > 1.04$ GeV [18] with the precision, not enough to use it for normalization of hadronic cross sections. The high precision measurement of $e^+e^- \rightarrow \mu^+\mu^-$ cross section is one of the goals for the next generation of experiments.

3 Measurement of R at VEPP-2000

Two detectors — the upgraded Spherical Neutral Detector (SND) [19] and the newly constructed

Cryogenic Magnetic Detector (CMD-3) [20] — are installed at two interaction points of VEPP-2000 and now are being prepared for the experiments.

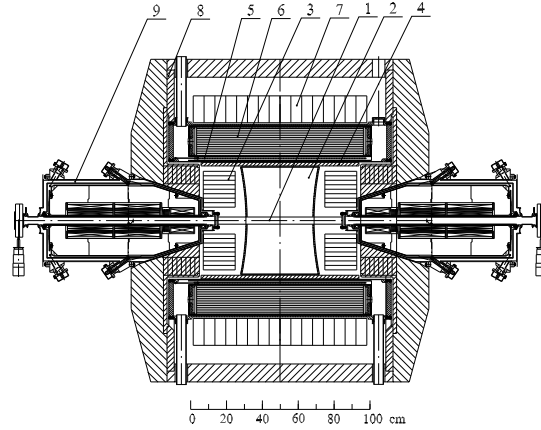


Fig. 2. Cross section of CMD-3. 1 - interaction point; 2 - drift chamber; 3 - end cap BGO electromagnetic calorimeter; 4 - Z-chamber; 5 - superconductive solenoid; 6 - liquid Xenon electromagnetic calorimeter; 7 - CsI electromagnetic calorimeter; 8 - yoke; 9 - VEPP-2000 focusing solenoid.

The CMD-3 detector, shown in Fig. 2, shares some of the subsystems from its predecessor, detector CMD-2, and adds number of new features. The key improvements are: the new drift chamber with 2 times better spatial resolution, the new barrel calorimeter with the first layer made of liquid Xenon, the higher magnetic field.

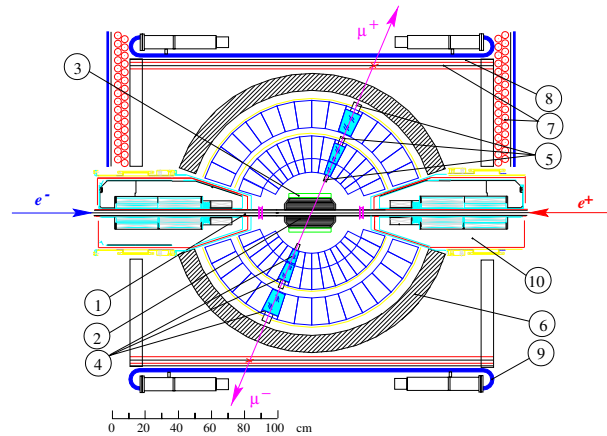


Fig. 3. Cross section of SND. 1 - VEPP-2000 vacuum chamber; 2 - tracking system; 3 - aerogel counters; 4 - NaI(Tl) electromagnetic calorimeter; 5 - vacuum phototriodes; 6 - iron absorber; 7-9 - muon system; 10 - VEPP-2000 focusing solenoid.

The SND detector, shown in Fig. 3, is the upgrade of the detector, previously installed at VEPP-2M. It

inherits the most expensive element of the predecessor, the spherical NaI calorimeter, and adds new or improved systems, most notably the new drift chamber and the Cherenkov counters for particle identification.

Both CMD-3 and SND use the completely redesigned data acquisition systems and frontend electronics, necessary for the high data rate at VEPP-2000 and for precise determination of the detector efficiencies. More details about the detectors can be found elsewhere [21].

The improved features of the detectors for VEPP-2000 should allow to overcome some of the limitations of the VEPP-2M measurements of $e^+e^- \rightarrow$ hadrons cross sections.

Event separation. The most demanding measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section is based on the selection of event sample with the signature of two back-to-back particles and its further separation

on the e^+e^- , $\mu^+\mu^-$ and $\pi^+\pi^-$ final states. One of the main drawbacks of CMD-2 and SND data analyzes is inability of robust separation between μ and π in the whole energy range. There are many factors which should improve quality of event separation at the new detectors: the new particle identification system of SND; 2 times thicker barrel calorimeter of CMD-3 (compared to CMD-2); measurement of the longitudinal shower profile with the CMD-3 LXe calorimeter; 2 times better momentum resolution of the CMD-3 drift chamber (compared to CMD-2). Potential ability to measure $e^+e^- \rightarrow \mu^+\mu^-$ cross section in the whole energy range of VEPP-2000 should open completely new field of opportunity: the possibility to normalize to dimuon cross section, rather than to traditional Bhabha cross section; the possibility for direct measurement of the vacuum polarization; independent systematic tests. The improved quality of the CMD-3 detector is illustrated in Figs. 4 and 5.

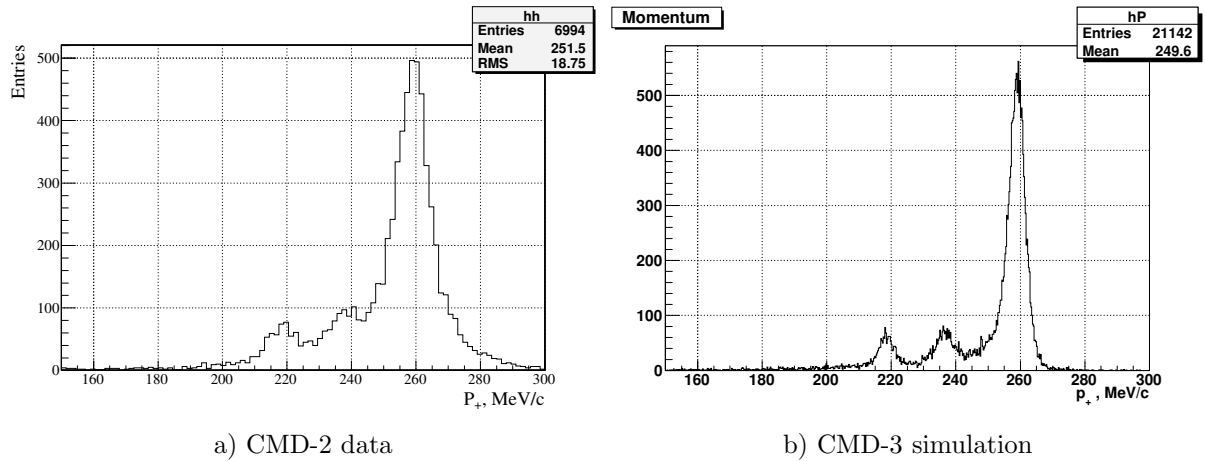


Fig. 4. Momentum resolution of CMD-2 and CMD-3 detectors at the c.m. energy $\sqrt{s} = 0.52$ GeV. The three peaks correspond to $\pi^+\pi^-$, $\mu^+\mu^-$ and e^+e^- final states.

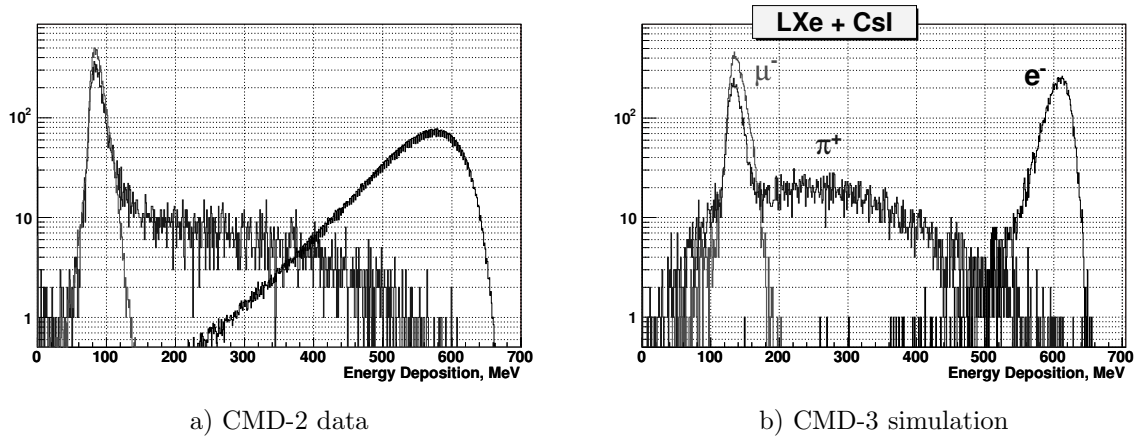


Fig. 5. Energy resolution of CMD-2 and CMD-3 barrel calorimeter at the c.m. energy $\sqrt{s} = 1.18$ GeV. The three histograms correspond to $\pi^+\pi^-$, $\mu^+\mu^-$ and e^+e^- final states.

Energy calibration. In the energy scan approach it is crucial to know the absolute value of the beam energy to high precision. The requirement is the most strict for the measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section below 1 GeV, where 0.1% shift of the beam energy can lead to 1% systematic error. In order to eliminate the corresponding contribution to the systematic error of R measurement, the absolute beam energy should be known at any moment to $\sim 10^{-4}$ relative precision.

There are two approaches to reach this goal at VEPP-2000. The magnetic field in the storage ring elements is constantly monitored by 16 NMR probes and is used for real-time determination of the beam energy. The absolute calibration of the system will be done with the resonant depolarization technique. The second approach is to use the Compton backscattering for constant monitoring of the beam energy [22]. The system is being constructed and planned to be installed in 2010-2011.

Fiducial volume. The same Z-chamber, as was used at CMD-2, is installed at CMD-3, thus providing the same acceptance uncertainty (about 0.2% for $e^+e^- \rightarrow \pi^+\pi^-$ measurement). The LXe calorimeter of CMD-3 detector has strip structure made with 0.1 mm accuracy. Therefore it can be used for an independent determination of the acceptance with the accuracy compatible with that of Z-chamber, providing the important cross-check. The new tracking system of SND detector has better precision of z -measurement compared to the predecessor, thus the acceptance uncertainty is expected to be improved.

Detector and trigger efficiency. Both detectors use newly developed data acquisition systems, able to collect data at about 1 kHz rate. That should allow to use softer selection criteria in the first-level trigger and collect not only the signal events, but also events, necessary for the systematic studies. The electronics of the trigger system is designed to make decision using several independent algorithms and to provide all input and intermediate data in the main data stream. That should allow to determine precisely the trigger efficiency.

Reconstruction of γ and π^0 . The liquid-xenon calorimeter of the CMD-3 detector provides ~ 1 mm spatial resolution for the point of γ conversion in the calorimeter. That should make it possible to use $e^+e^- \rightarrow \gamma\gamma$ for independent luminosity measurement. That also should allow to significantly improve the π^0 reconstruction efficiency and mass resolution, which are the main factors in reducing systematic error and background for processes with neutral pions in the

final state.

Radiative corrections. The CMD-2 collaboration developed computer code, MCGPJ (Monte-Carlo Generator of Photon Jets) [23], for calculation of radiative corrections to $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \pi^+\pi^-$ processes. To increase the accuracy of the cross section calculation, the structure function approach is used to take into account enhanced multi-photon contributions coming from the collinear region. Originally, the total systematic uncertainty for each of the processes was estimated to be 0.2%, and this estimation was used in VEPP-2M measurements.

Over last few years, the MCGPJ code was extended to other final states and was extensively compared with other independent Monte-Carlo generators — BHWIDE, BabaYaga, KKMC [24]. There is work under development to take into account additional missing terms, to reach the total systematic uncertainty for each of the processes of 0.1% or better.

The calculation of radiative corrections for $e^+e^- \rightarrow \pi^+\pi^-$ channel is based on the assumption of scalar QED, where pions are considered as the point-like objects. One of the tasks at VEPP-2000 will be to prove experimentally the validity of this approach.

High statistics. Expected high experimental statistics, to be available at VEPP-2000, should help to reduce the systematic uncertainty of the measurements as well. The statistical error, compatible or smaller than the systematic error, is expected to be achieved for each energy point, allowing for conclusive comparison between different experiments on point-by-point level.

The possibility to use soft trigger settings should allow to collect enough statistics of events, intended for the different kinds of systematic studies: experimental tests of the radiative correction calculations, studies of the nuclear interactions of pions, studies of the trigger and reconstruction efficiencies, etc.

One of the main sources of the systematic errors for the multihadron processes $e^+e^- \rightarrow 4\pi, 5\pi, \dots$ is the uncertainty of the detector acceptance due to incomplete knowledge of the intermediate dynamics of the process. With high statistics to be available, it will be possible to study the mechanism of the particular process through analysis of the angular and energy distributions of the final particles, thus reducing the systematic error of the cross section measurement.

With the high statistics, expected at VEPP-2000, it might be possible to use ISR approach in addition to the energy scan approach in the same experiments. This may provide the useful cross-check between two

approaches.

The expected systematic uncertainties for the $e^+e^- \rightarrow \pi^+\pi^-$ and $e^+e^- \rightarrow 4\pi$ are listed in Table 4.

Table 4. Expected sources of systematic errors of $e^+e^- \rightarrow \pi^+\pi^-$ and $e^+e^- \rightarrow 4\pi$ cross section measurements at CMD-3.

source of error	$2\pi, \sqrt{s} < 1 \text{ GeV}$	$4\pi, \sqrt{s} > 1.1 \text{ GeV}$
event separation	0.2%	1%
fiducial volume	0.2%	2%
energy calibration	0.1%	–
efficiency correction	0.1%	1%
pion losses	0.1%	–
luminosity	–	0.3%
radiative corrections	0.1%	1%
total	0.35%	2.5%

4 Conclusion

In the series of experiments at VEPP-2M collider, CMD-2 and SND detectors performed the best di-

rect measurements of the cross sections of exclusive modes of $e^+e^- \rightarrow \text{hadrons}$. The overall improvement by a factor of 2-3 in the value of $R(s)$ compared to the previous measurements was achieved. Two new detectors, CMD-3 and SND, are being prepared to start data taking in 2010 at VEPP-2000 collider in Novosibirsk. With the upgraded detectors and the high luminosity of the collider, another improvement by a factor of 2-3 seems to be feasible. In addition to the new measurement of $R(s)$, new kinds of the related studies will be possible: measurement of $e^+e^- \rightarrow \mu^+\mu^-$ cross section, detailed analysis of the radiative tails, luminosity normalization to $e^+e^- \rightarrow \gamma\gamma$, etc.

Detailed comparison of the new high precision measurements at VEPP-2000 with the results of high statistics ISR measurements at KLOE and BABAR will provide an important cross-check. With all these new results combined, the accuracy of the evaluation of the lowest order hadronic contribution to anomalous magnetic moment of the muon will match the requirements for the new ($g-2$) experiment.

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