Preliminary results on pion form factor at CMD-3 *

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Abstract: The CMD-3 detector has been successfully collecting data at the electron-positron collider VEPP-2000 since December 2010. The first scan below 1 GeV for a $\pi^+\pi^-$ measurement was performed in 2013. The collected data sample corresponds to about 18 pb^{-1} of integrated luminosity in this energy range. Analysis of the $e^+e^- \to \pi^+\pi^-$ cross section is in progress. Preliminary results of this measurement are presented.

Key words: pion form factor, electron positron collider, hadron cross sections

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1 Introduction

The total $e^+e^- \to hadrons$ cross section (or $R(s)$) is important for calculation of various physical quantities: $\alpha_{QED}(M_Z)$ used in precise tests of EW physics, and better precision of this value is required in case of ILC[1]. Also $R(s)$ is essential for the interpretation of precise measurements of the anomalous magnetic moment of the muon $a_\mu = (g-2)/2$[2]. The comparison of this experimental value to the theoretical prediction provides a powerful test of the Standard Model.

The dominant contribution to production of hadrons in the energy range $\sqrt{s} < 1$ GeV comes from the $e^+e^- \to \pi^+\pi^-$ mode. This channel gives the main contribution to the hadronic term and overall theoretical precision of a_μ. And in the light of new g-2 experiments at FNAL and J-PARC, which plan to reduce an error by a factor of 4, it is very desirable to improve systematic precision of the $\pi^+\pi^-$ cross section at least by a factor of two.

At CMD-2 this process was measured in the energy range from 0.37 GeV to 1.38 GeV [3–6]. The 0.6–0.8% systematic uncertainty of this measurement was achieved for $\sqrt{s} < 1$ GeV. For energies above 1 GeV it varies from 1.2% to 4.2%. SND measured the $e^+e^- \to \pi^+\pi^-$ cross section in the energy range 0.39–0.97 GeV with the systematic uncertainty of 1.3% [7].

2 VEPP-2000 and CMD-3

The electron-positron collider VEPP-2000 [8, 9] has been operating at Budker Institute of Nuclear Physics since 2010. The collider is designed to provide luminosity up to 10^{32}cm^{-2}s^{-1} at the maximum center-of-mass energy $\sqrt{s} = 2$ GeV. At present two detectors, CMD-3 [10, 11] and SND [12], are installed in the interaction regions of the collider. In 2010 both experiments started data taking. The physics program [13] includes high precision measurements of the $e^+e^- \to hadrons$ cross sections in the wide energy range up to 2 GeV, studies of known and searches for new vector mesons, studies of $n\bar{n}$ and $p\bar{p}$ production cross sections near threshold and searches for exotic hadrons. It requires a detector with high efficiency for multiparticle events and good energy and angular resolution for charged particles as well as for photons.

CMD-3 (Cryogenic Magnetic Detector) is a general-

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purpose detector, see Fig. 1. Coordinates, angles and momenta of charged particles are measured by the cylindrical drift chamber with a hexagonal cell for uniform reconstruction of tracks.

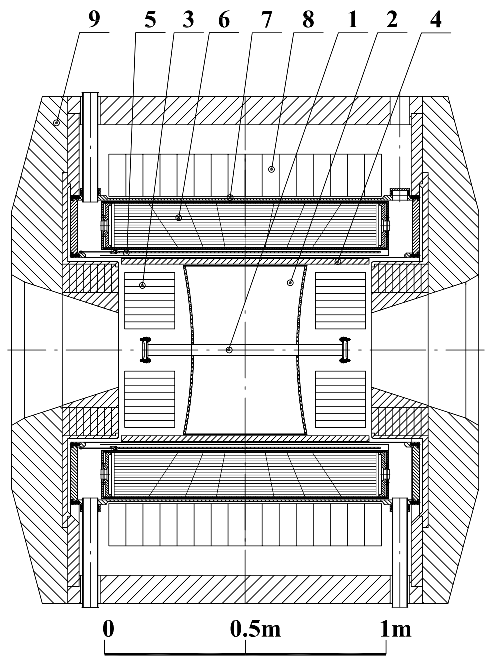

Fig. 1. CMD-3 detector: 1 – beam pipe, 2 – drift chamber, 3 – BGO calorimeter, 4 – Z-chamber, 5 – SC solenoid ($0.13X_0$, 13 kGs), 6 – LXe calorimeter, 7 – TOF system, 8 – CsI electromagnetic calorimeter, 9 – yoke, not shown muon range system

The calorimetry is performed with the endcap BGO calorimeter and the barrel calorimeter. The barrel calorimeter, placed outside of the superconducting solenoid with 1.3 T magnetic field, consists of two systems: ionization Liquid Xenon calorimeter surrounded by the CsI scintillation calorimeter. The total thickness of the barrel calorimeter is about $13.5X_0$. The LXe calorimeter has seven layers with strip readout which give information about a shower profile and are also able to measure coordinates of photons with high accuracy of about a millimeter precision.

The $10^{31}\text{cm}^{-2}\text{s}^{-1}$ luminosity was reached by the VEPP-2000 collider. The already collected integrated luminosity is about 60 pb^{-1} per detector in the full energy range, where about 18 pb^{-1} was collected below the ϕ energy. The luminosity at high energy was limited by a deficit of positrons and maximum energy of the booster (825 MeV now), and after upgrade of the accelerator complex we expect the luminosity gain by a factor of ten. The new positron injection facility and achieved operational experience will also improve luminosity at low energy.

The first energy scan below 1 GeV for a $\pi^+\pi^-$ measurement was performed at VEPP-2000 in 2013. The already collected data sample is higher than that in the previous CMD-2 experiment and is similar or better than in the BaBar[14] and KLOE[15, 16] experiments (Fig. 2).

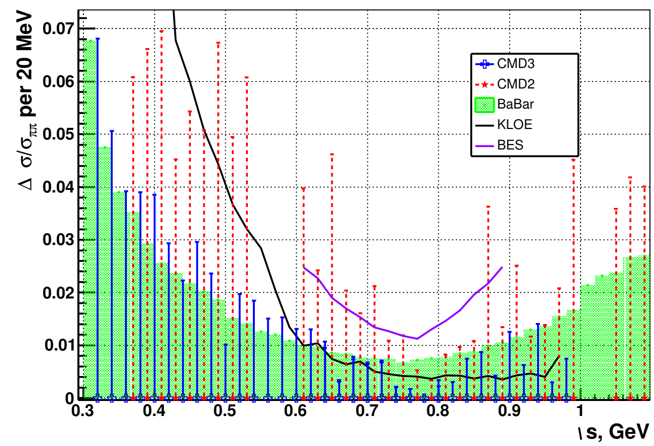

Fig. 2. Statistical precision of $|F_\pi|^2$ from the CMD-3 data in comparison with CMD-2, BaBar, KLOE and BESIII results

3 Data analysis

The $\pi^+\pi^-$ process has a simple event signature with 2 back-to-back charged particles. They can be selected by using the following criteria: two collinear well reconstructed charged tracks are detected, these tracks are close to the interaction point, fiducial volume of event is inside a good region of the DCh. The selected data sample includes events with: $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$, cosmic muons, and it practically doesn't contain any other physical background at energies $\sqrt{s} < 1$ GeV.

These final states can be separated using either the information about energy deposition in the calorimeter or that about particle momenta in the drift chamber, as shown at Fig. 3. At low energies momentum resolution of the drift chamber is sufficient to separate different types of particles. The pion momentum is well aside from the electron one up to energies $E_{beam} \lesssim 450$ MeV, while the $\mu^+\mu^-$ events are separated from others up to $E_{beam} \lesssim 330$ MeV, and at higher energies the number of muons should be fixed relative to the number of electrons according to the QED prediction.

At higher energies the peak of electron shower in the calorimeter is far away from the peak of minimal ionization particles. The separation using energy deposition works best at higher energies and becomes less robust at lower energies. In this method the number of muons can be extracted by event separation or also can be fixed according to QED prediction.

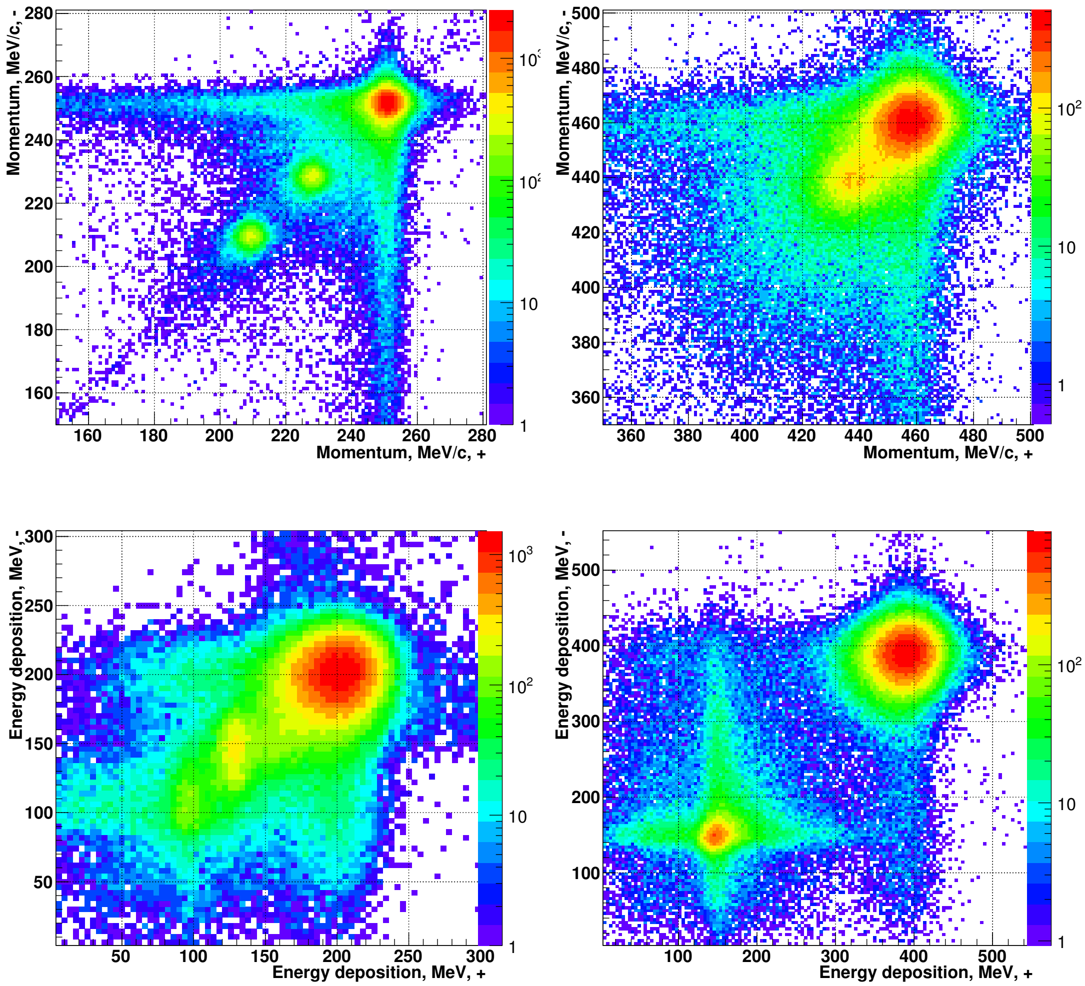

Fig. 3. Distributions of measured momenta in the DCh (top row) and energy deposition in the calorimeter (bottom row) of collinear events at energies E_{beam}=250 MeV (left column) and 460 MeV(right column)

Determination of the number of different particles is done by minimization of the binned likelihood function, where two dimensional PDF functions are constructed in different ways for each type of information.

To construct PDF functions in case of event separation by particle momentum we take as an input the ideal momentum spectra for $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ events from the MC generator for applied selection criteria. Then the generated distributions are convolved with the detector response function which includes effects from momentum resolution, bremsstrahlung of electron at the beampipe, pion decay in flight. The functions themselves are general enough and most of their parameters are free in minimization.

Description of cosmic events is done on base of experimental events with impact parameter outside of the beam interaction region.

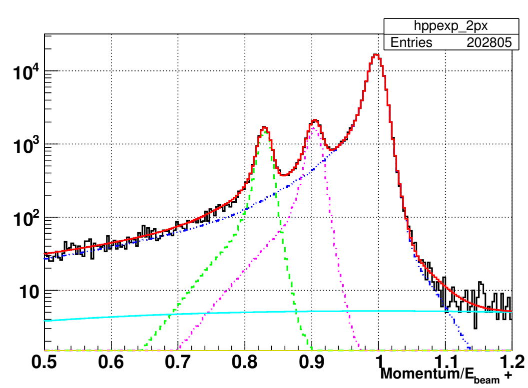

Fig. 4. Momentum distribution of positive charge particles for $E_{beam} = 252.8\,\mathrm{MeV}$, where histogram - data, lines - projection of fitted functions after minimization: the peaks from left to right - π^+, μ^+, e^+, cyan line - cosmic events

Distributions of 3π background events (which gives a small contribution) are taken from full MC simulation. The result of minimization at $E_{beam} = 252.8\,\mathrm{MeV}$ is shown in Fig. 4 and for the point at the ω resonance peak $E_{beam} = 391.48\,\mathrm{MeV}$ in Fig. 5.

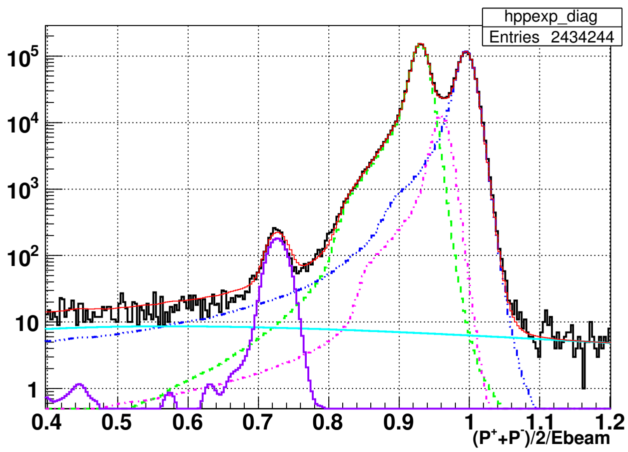

Fig. 5. Average momentum distribution for events with $|\Delta P|/E_{beam} < 0.038$, $E_{beam} = 391.48\,\mathrm{MeV}$, where histogram - data, lines - projection of fitted functions after minimization: the peaks from left to right $3\pi, 2\pi, 2\mu, e^+e^-$,cyan line - cosmic events

In case of event separation by energy deposition of particles: the PDF distributions of energy deposition are taken from MC or data itself. Each process is fitted by its own analytical function, and then these functions are used during minimization with some free parameters. Electron distributions are described by a function with most of parameters free. Muon description is taken from simulation and convolved with additional smearing as free parameter (it's planned to select muons totally from data). And cosmic events are selected from experimental data by the vertex position. The pion particles can be cleanly selected from huge $\omega, \phi \to 3\pi$ data samples. The example of energy deposition of selected pions is shown in Fig. 6.

Full energy deposition in LXe with CsI calorimeters is used at the moment. An example of the minimization result at $E_{beam} = 387.5\,\mathrm{MeV}$ is shown in Fig. 7.

As further development, one can use a neural net for event classification. This can help to exploit information about the shower profile from 7 strip layers in the LXe and energy deposition in the CsI calorimeter.

The comparison of two approaches with the pion formfactor after event separation is shown in Fig. 8. In the figure additional corrections, common to two methods (e.g., the trigger efficiency), are not applied.

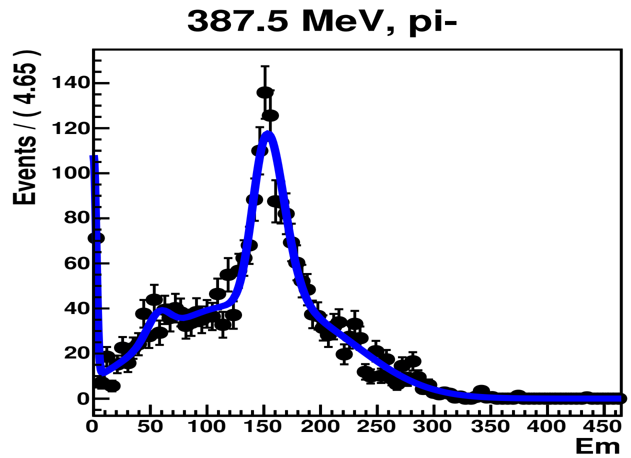

Fig. 6. Energy deposition in the calorimeter of π^- from 3π events with $P_{\pi^-} = 387.5\,\mathrm{MeV/c}$

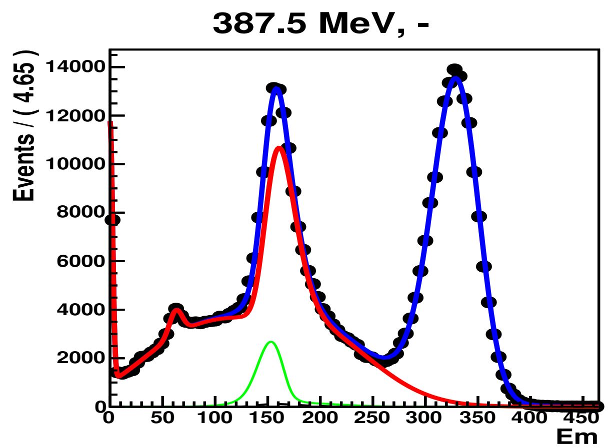

Fig. 7. Result of event separation based on energy deposition information at $E_{beam} = 387.5\,\mathrm{MeV}$. Projection to negative charge particle, where dots - data, blue line is the fit, red line - contribution from $\pi^+\pi^-$, green line - $\mu^+\mu^-$

These two methods overlap in the wide energy range and provide a cross-check of each other, allowing to reach a systematic error of event separation at the level of 0.2%.

The only significant physical background in the selected data sample is pions from 3π events at the ω energy. The total contribution from these events $N_{3\pi}/N_{ee} < 0.85\%$ is small even at the peak of ω. These events are independently identified in particle separation based on momentum distributions. The $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ cross section obtained as a by-product of this analysis agrees well with published results by CMD2 and SND experiments. The geometrical acceptance was calculated using Monte-Carlo with 3π in the phase space model, and the reconstruction efficiency is mostly the same as for studied collinear events and will be canceled during $N_{3\pi}/N_{ee}$ normalization.

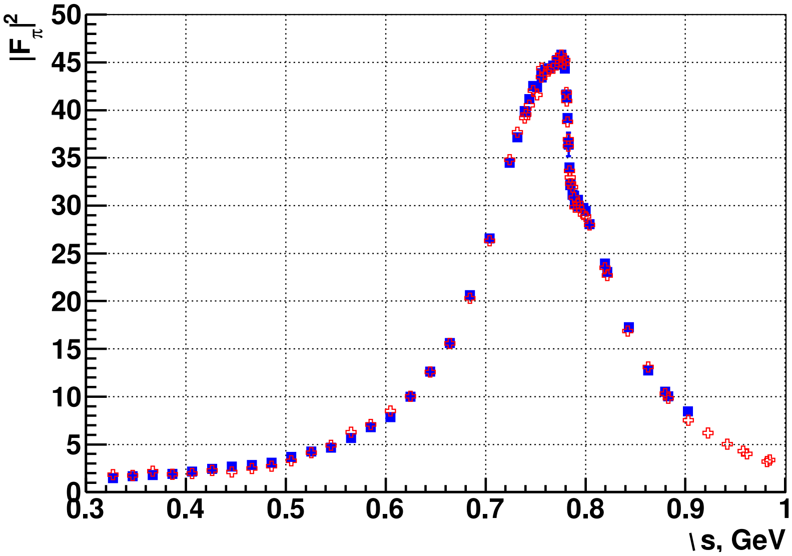

Fig. 8. Preliminary results on F_π^2 from CMD-3. Open crosses – separation done on the calorimeter information, filled squares – on particle momentum. Some additional corrections, common to two methods (e.g., the trigger efficiency), are not applied

4 Systematic uncertainty

The systematic error of $\pi^+\pi^-$ channel is expected to be mainly from the following sources: 0.2% - $e/\mu/\pi$ separation, 0.2% - pion specific correction, 0.1% - radiative corrections, 0.1% - fiducial volume, 0.1% - beam energy determination. The final goal of the CMD-3 experiment is to reduce a overall systematic uncertainty in this channel up to 0.35%.

In the CMD-3 detector, a polar angle of tracks is measured by the DC chamber with help of the charge division method with the z-coordinate resolution of about 2 mm. This measurement is unstable by itself as it depends on calibration and thermal stability of electronic board parameters. An independent calibration should be applied relative to another system, such as the ZC-chamber or the LXe calorimeter. The ZC chamber is a 2-layer multiwire chamber installed at the outer radius of the DC chamber. It has a strip readout along Z coordinate, where the strip size is 6 mm and the z-coordinate resolution is about 0.7 mm for tracks with 1 radian inclination. Also the CMD-3 detector has the unique LXe calorimeter where ionization is collected in 7 layers with a cathode strip readout, where the combined strip size is 10-15 mm and coordinate resolution is about 2 mm. Both subsystems have precision for strip position better than 100 μm, which should gives less than a 0.1% systematic contribution to luminosity determination.

Determination of the fiducial volume could be made independently with help of the LXe and Z-chamber subsystems. It allows an efficient monitoring of detector operation stability during data taking. This monitoring shows compatibility between two subsystems inside the range $|\delta Z/Z| < 6\times10^{-4}$ for the 2013 season, which corresponds to 0.1% systematic error of luminosity determination at $\theta_{track} = 1\,\mathrm{rad}$. An addition of other crosschecks of Z scale measurement (radiography of detector elements from conversion of particles, momentum versus polar angle correlation and so on) will allow to keep a systematic uncertainty from this source at the 0.1% level.

Measurement of beam energy by Compton backscattering of the laser photons with precision $\sigma_E < 50$ keV [17] will keep a systematic uncertainty from this source below 0.1%.

The reconstruction inefficiency in the CMD-3 detector is about 0.2–1%, which is 3–10 times better than was achieved by the CMD-2 experiment. Moreover, we plan to study in more details pion specific loss because of decay in flight and nuclear interaction using $\phi,\omega \to 3\pi$ experimental data.

Another important source of systematics is a theoretical precision of radiative corrections [18]. Additional studies like crosschecks of different calculation approaches and further proof from comparison with experimental data are necessary in this field. Comparison between the MCGPJ[19] and BabaYaga@NLO[20] generators was performed. The integrated cross-section for applied cuts is well consistent at the level better than 0.1% between both tools, but strong difference in the $P^+ \times P^-$ momentum distributions observed. Also observed is some discrepancy between experimental data and fitted functions when using event separation by momentum information, where the initial input comes from the MCGPJ generator, while BabaYaga@NLO describes the data better. One of the next steps for improvement of the MCGPJ generator can be addition of the angular distribution for photon jets. While this discrepancy mostly doesn't affect analysis by energy deposition, it becomes crucial if momentum distribution information is used. We expect that the overall uncertainty from MC tools can be reduced to 0.1%.

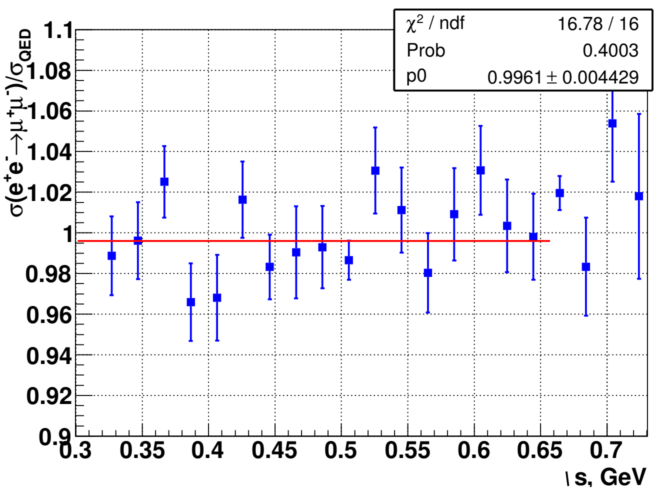

Fig. 9. Preliminary result of the measurement of muon pair production in comparison with the QED prediction

One of the tests in this analysis is a measurement of the $e^+e^- \to \mu^+\mu^-$ cross section at low energy, where separation was performed using momentum information. Preliminary results of this test are consistent with the QED prediction with an overall precision of 0.5% as shown in Fig. 9.

5 Conclusions

VEPP-2000 accelerator successfully operates with a goal to get $\sim 1\,\mathrm{fb}^{-1}$ in 5-10 years which should provide new precise results on hadron production. The CMD-3 and SND detectors were upgraded, with significantly improved performance and monitoring capabilities of different detector subsystems. The first scan below 1 GeV for a $\pi^+\pi^-$ measurement was done in 2013. The already collected data sample has the same or better statistical precision of cross sections than was achieved by other experiments. Data analysis is in progress.

A new positron injection complex will be commissioned during this winter. The luminosity will be increased by a factor of 10 up to $10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $2E = 2$ GeV . It is expected that the new positron injection facility and achieved operational experience will also improve the luminosity at low energies for the $\pi^+\pi^-$ scan. High statistics will allow us to study and to control better different systematic contributions, with a final goal of 0.35% precision for the $\sigma(\pi^+\pi^-)$ cross section measurement.

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