Preliminary results on CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$ cross section

Fedor Ignatov[1,⋆], I.B.Logashenko[1,2], R.R.Akhmetshin[1], A.N.Amirkhanov[1,2], A.V.Anisenkov[1,2], V.M.Aulchenko[1,2], V.S.Banzarov[1], N.S.Bashtovoy[1], D.E.Berkaev[1,2], A.E.Bondar[1,2], A.V.Bragin[1], S.I.Eidelman[1,2], D.A.Epifanov[1,2], L.B.Epshteyn[1,2,3], A.L.Erofeev[1,2], G.V.Fedotovich[1,2], S.E.Gayazov[1,2], A.A.Grebenuk[1,2], S.S.Gribanov[1,2], D.N.Grigoriev[1,2,3], V.L.Ivanov[1,2], S.V.Karpov[1], A.S.Kasaev[1], V.F.Kazanin[1,2], A.A.Korobov[1,2], I.A.Koop[1], A.N.Kozyrev[1,2], E.A.Kozyrev[1,2], P.P.Krokovny[1,2], A.E.Kuzmenko[1,2], A.S.Kuzmin[1,2], P.A.Lukin[1,2], A.P.Lysenko[1], K.Yu.Mikhailov[1,2], V.S.Okhapkin[1], E.A.Perevedentsev[1,2], Yu.N.Pestov[1], A.S.Popov[1,2], G.P.Razuvaev[1,2], Yu.A.Rogovsky[1,2], A.A.Ruban[1], N.M.Ryskulov[1], A.E.Ryzhenenkov[1,2], V.E.Shebalin[1,2], D.N.Shemyakin[1,2], B.A.Shwartz[1,2], D.B.Shwartz[1,2], A.L.Sibidanov[4], Yu.M.Shatunov[1], E.P.Solodov[1,2], A.A.Talyshev[1,2], A.I.Vorobiov[1], Yu.V.Yudin[1,2]

[1] *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, 630090, Russia*
[2] *Novosibirsk State University, Novosibirsk, 630090, Russia*
[3] *Novosibirsk State Technical University, Novosibirsk, 630092, Russia*
[4] *University of Victoria, Victoria, British Columbia, Canada V8W 3P6*

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. Status of this measurement are presented.

1 Introduction

The total $e^+e^- \to hadrons$ cross section (or $R(s)$) gives an input through dispersion integral to the calculation of various fundamental quantities: the running fine structure constant $\alpha_{QED}(M_Z)$[1], hyperfine splitting in muonium [2], the anomalous magnetic moment of the muon $(g_\mu - 2)/2$[3]. The $(g_\mu - 2)/2$ value provides a powerful test of the Standard Model with intriguing $3 \div 4$ sigma deviation between the most recent experimental measurement and the theoretical prediction. The main theoretical uncertainty comes from hadronic part of the anomaly, where the value and error are dominated by low energy $R(s)$ below $\sqrt{s} < 2$ GeV and, particularly, the $e^+e^- \to \pi^+\pi^-$ channel gives the biggest contribution (73% of a_μ^{had}). In the light of new g-2 experiments at FNAL and J-PARC, which plan to reduce the error by a factor of 4, it is very desirable to improve systematic precision of the $\pi^+\pi^-$ cross section by at least a factor of two. At the moment the systematic precision of 0.6–0.8% for the direct energy scanning approach was achieved by the CMD-2 experiment [4–7], but with somehow limited statistical precision. After this result the new developed ISR method at detectors KLOE(0.8% systematic precision)[15, 18], BaBar(0.5%)[16] and BES(0.9%)[17] provided successive progress in measurement of this cross-section with less limitations on statistic.

⋆e-mail: ignatov@inp.nsk.su

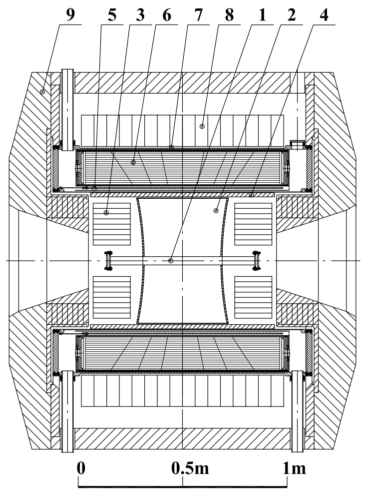

Figure 1. CMD-3 detector: 1 – beam pipe, 2 – drift chamber, 3 – BGO calorimeter, 4 – Z-chamber, 5 – SC solenoid ($0.13X_0$, 13 kGs), 6 – LXe calorimeter, 7 – TOF system, 8 – CsI electromagnetic calorimeter, 9 – yoke, not shown muon range system

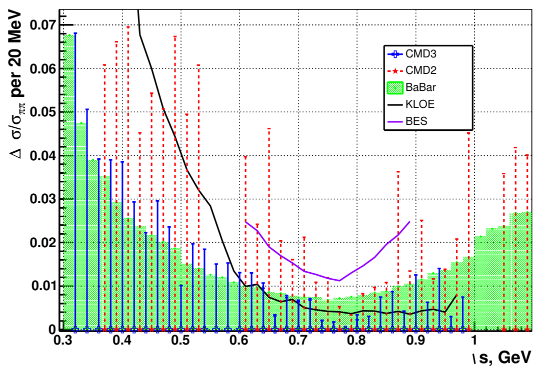

Figure 2. Statistical precision of $|F_\pi|^2$ from the CMD-3 data in comparison with CMD-2, BaBar, KLOE and BESIII results

2 VEPP-2000 and CMD-3

The electron-positron collider VEPP-2000 [9, 10] 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. Two detectors CMD-3 [11, 12] and SND [13] are installed at the interaction regions of the collider. In 2010 both experiments started data taking. The physics program [14] includes high precision measurements of the $e^+e^- \to hadrons$ cross sections in the wide energy range up to 2 GeV, where rich intermediate dynamics involved, 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-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.

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 about a millimeter precision.

The first energy scan below 1 GeV for a $\pi^+\pi^-$ measurement was performed at VEPP-2000 in 2013. The collected data sample is higher than that in the previous CMD-2 experiment and is similar or better than in the BaBar[16] and KLOE[15, 18] experiments (Fig. 2).

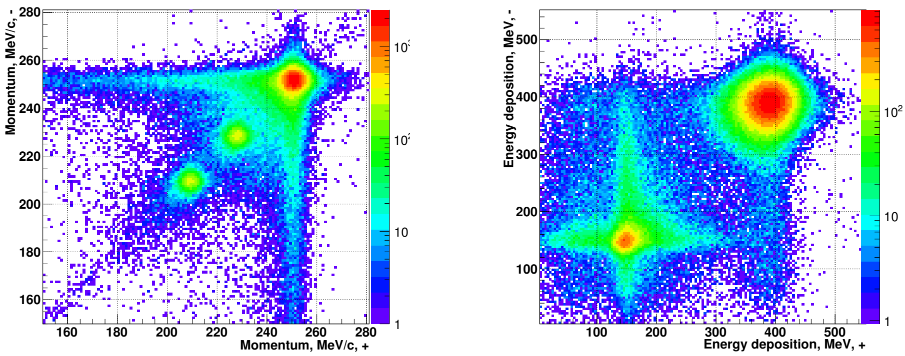

Figure 3. Distributions of collinear events of measured momenta in the DCh at energy E_{beam}=250 MeV (left) and energy deposition in the calorimeter at E_{beam}=460 MeV (right)

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 $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ pairs and 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 $\sqrt{s} \lesssim 0.9$ GeV, while the $\mu^+\mu^-$ events are separated from others up to $\sqrt{s} \lesssim 0.66$ GeV. 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 better at higher energies and becomes less robust at lower energies.

In both methods the number of muons can be extracted by event separation or also can be fixed according to QED prediction. 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 it is taken 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. This function are general enough themselves 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. Distributions of 3π background events (which gives only < 1% contribution at ω peak) are taken from full MC simulation.

In case of event separation by energy deposition of particles the PDF distributions are taken mostly from 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 general function with most of parameters free. Muon description is taken from cosmic events, which 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. Full energy deposition in combined LXe and CsI calorimeters is used at the moment. A further methods are under development to exploit full power of layered barrel

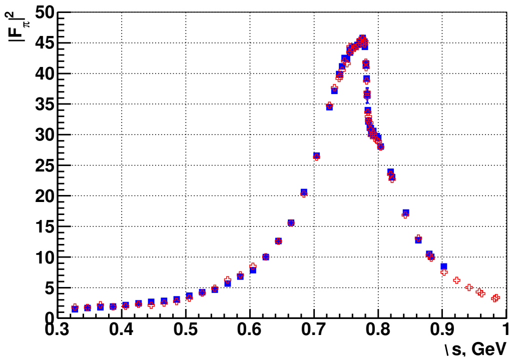

Figure 4. Preliminary results on F_π^2 from CMD-3. Open crosses – separation done on the calorimeter information, filled squares – on particle momentum. Some additional corrections, common to two methods (e.g., the trigger efficiency), are not applied

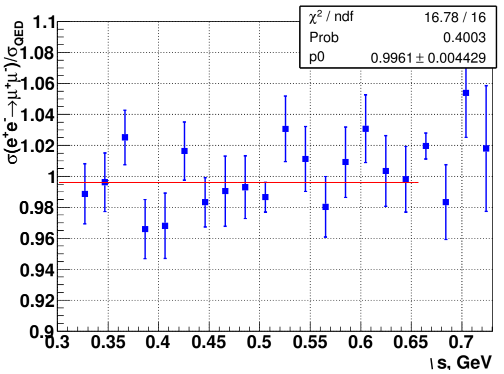

Figure 5. Preliminary result of the measurement of muon pair production in comparison with the QED prediction

calorimeter. The available independent measurements in 7 strip layers of the LXe and energy deposition in the CsI calorimeter give better discrimination power between different particles due to different interaction process involved (electromagnetic shower, ionization process, nuclear interaction).

The preliminary result on the pion formfactor is shown in Fig. 4 with the comparison of two approaches using either momentum information or energy deposition. In the figure additional corrections, common to two methods (e.g., the trigger efficiency), are not applied. These two methods overlap in the wide energy range and provide a cross-check of each other, allowing to reach in future a systematic error of event separation at the level of 0.2%. 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. 5.

The only significant physical background in the selected data sample is 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.

4 Systematic uncertainty

The final goal of the CMD-3 measurement of $\pi^+\pi^-$ cross section is to reduce an overall systematic uncertainty in this channel up to 0.35%. The target systematic error is expected to come 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.

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 $100\,\mu$m, 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 $|\delta Z/Z| < 6 \times 10^{-4}$ for the 2013 season, which corresponds to 0.1% systematic error of luminosity determination at $\theta_{track} = 1$ rad. An additional crosschecks of Z scale measurement (vertex distribution of particles converted on detector elements, polar angle distribution and so on) will allow to strengthen confidence in 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 [19] helps to 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. Most of this inefficiency is canceled in normalization ratio of number of pion versus to number of electron. The pion specific loss comes from two sources: nuclear interaction and decay in flight. Less than 0.5% of pions have nuclear interaction in the drift chamber, mostly on vacuum tube. All such events are lost after selection cuts are applied. This inefficiency doesn't depend on a detector performance, and can be safely taken from the simulation with contribution to total systematic precision as 0.1%. With more tension on this contribution in total sum, than this part can be additionally cross-checked from $\omega, \phi \to 3\pi$ data samples. 1.5-7% of pions decay in volume of the drift chamber, and than half of them passed selections criteria. This inefficiency depends on track reconstruction efficiency and correspondingly depend on behavior of detector performance with time. The pion momentum spectra have two visible feature in tails: left one correspond to lower momentum of electrons after pion decay, and another when reconstructed track was build from two segment before and after decay (electron after decay has mostly same direction as initial pion because of boost). The decay in flight inefficiency can be controlled by number of events in tails in comparison with simulation. At the moment the agreement is at level 10%, which contributes to total systematic error as 0.6-0.3%. This contribution will be improved with better DCH understanding, which include accounting of detail per drift cell inefficiencies, noise level, etc.

The systematic contribution from $e/\mu/\pi$ separation is estimated now as 0.1-0.5% when using momentum information and up to 1.5% in case of by energy deposition, and it should be greatly improved with exploiting of full power of the combined barrel calorimeter.

Another important source of systematics is a theoretical precision of radiative corrections [20]. Additional studies like crosschecks of different calculation approaches and further proof from comparison with experimental data are necessary in this field. The high statistics collected with CMD-3 allowed us to observe a discrepancy in momentum distribution of experimental data vs theoretical spectra from MCGPJ generator[21], which is used in this analysis. The source of the discrepancy was understood: the collinear approximation for photon jets was not good enough to describe differential cross-section in the $P^+ \times P^-$ momentum distributions when both final leptons has energy much below initial value (when 2 final photons are involved in kinematic).

Comparison between the MCGPJ[21] and BabaYaga@NLO[22] generators was performed. The integrated cross-section for the cuts applied is well consistent at the level better than 0.1% between both tools, and BabaYaga@NLO better describes the data in momentum distribution. While this discrepancy mostly doesn't affect analysis by energy deposition, it becomes crucial if momentum distribution information is used.

Several steps for improving the MCGPJ were done, main one was including of photon jets angular distribution in the generator. The consistency between both generators become much better, but it is still present deviation at level ~ 10% in momentum tails. This discrepancy gives additional $0.0 \div 0.4\%$ systematic uncertainty on number of $\pi^+\pi^-$ events extracted from momentum distributions (less influenced on lowest energy and more at peak of ρ). As seen from influence of two photon contributions to momentum spectra, to reach precision $\lesssim$ 0.1%, it becomes very desirable to have exact NNLO $e^+e^- \to e^+e^-(\gamma\gamma)$ generator.

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 for the cross section measurements than was achieved by other experiments. Data analysis is in progress.

A new positron injection complex was commissioned during 2013-2016 years. It already gives increased luminosity by few times at $\sqrt{s} > 1.2$ GeV during the 2017 data taken season, with further improvement underway. It is also expected that the new positron injection facility and achieved operational experience will 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.

We thank the VEPP-2000 team for excellent machine operation.

This work is supported in part by the Russian Science Foundation (project 14-50-00580) and Russian Foundation of Basic Research (17-02-00847).

References

[1] F. Jegerlehner, Nucl. Phys. Proc. Suppl. **162** (2006): 22
[2] A. Czarnecki, S. I. Eidelman and S. G. Karshenboim, Phys. Rev. D **65** (2002) 053004
[3] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, J. Phys. G **38** (2011): 085003
[4] R. R. Akhmetshin *et al.*, Phys. Lett. B **578** (2004):285
[5] V. M. Aulchenko *et al.*, JETP Lett. **82** (2005): 743
[6] R. R. Akhmetshin *et al.*, JETP Lett. **84** (2006): 413
[7] R. R. Akhmetshin *et al.*, Phys. Lett. B **648** (2007): 28
[8] M. N. Achasov *et al.*, J. Exp. Theor. Phys. **103** (2006): 380
[9] P. Y. Shatunov *et al.*, Phys. Part. Nucl. Lett. **13** (2016) no.7, 995.
[10] D. Shwartz *et al.*, PoS ICHEP **2016** (2016) 054.
[11] V. M. Aulchenko *et al.*, BUDKER-INP-2001-45
[12] B. Khazin,Nucl. Phys. Proc. Suppl. **181-182** (2008): 376
[13] M. N. Achasov *et al.*,Nucl. Instrum. Meth. A **598** (2009): 31
[14] S. Eidelman,Nucl. Phys. Proc. Suppl. **162** (2006): 323
[15] F. Ambrosino *et al.*, Phys. Lett. B **670** (2009): 285
[16] J. P. Lees *et al.*, Phys. Rev. D **86** (2012): 032013
[17] M. Ablikim *et al.*, Phys. Lett. B **753** (2016) 629
[18] F. Ambrosino *et al.*, Phys. Lett. B **700** (2011): 102
[19] E. V. Abakumova *et al.*,Phys. Rev. Lett. **110** (2013): 140402
[20] S. Actis *et al.*, Eur. Phys. J. C **66** (2010): 585
[21] A. B. Arbuzov *et al.*, Eur. Phys. J. C **46** (2006): 689
[22] G. Balossini *et al.*, Nucl. Phys. B **758** (2006): 227