Study of $\pi^+\pi^-\pi^+\pi^-$ production with CMD-3 detector at the VEPP-2000 collider

A. A. Korobov[1,2,*], R. R. Akhmetshin[1,2], A. N. Amirkhanov[1,2], A. V. Anisenkov[1,2], V. M. Aulchenko[1,2], V. Sh. Banzarov[1], N. S. Bashtovoy[1], D. E. Berkaev[1,2], A. E. Bondar[1,2], A. V. Bragin[1], S. I. Eidelman[1,2,5], 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], F. V. Ignatov[1,2], V. L. Ivanov[1,2], S. V. Karpov[1], A. S. Kasaev[1], V. F. Kazanin[1,2], I. A. Koop[1,2], A. A. Korobov[1,2], A. N. Kozyrev[1,3], E. A. Kozyrev[1,2], P. P. Krokovny[1,2], A. E. Kuzmenko[1,2], A. S. Kuzmin[1,2], I. B. Logashenko[1,2], A. P. Lysenko[1], P. A. Lukin[1,2], K. Yu. Mikhailov[1], V. S. Okhapkin[1], A. V. Otboev[1], E. A. Perevedentsev[1,2], Yu. N. Pestov[1], A. S. Popov[1,2], G. P. Razuvaev[1,2], A. A. Ruban[1], N. M. Ryskulov[1], A. E. Ryzhenenkov[1,2], A. V. Semenov[1,2], A. I. Senchenko[1], Yu. M. Shatunov[1], V. E. Shebalin[1,2], D. N. Shemyakin[1,2], B. A. Shwartz[1,2], D. B. Shwartz[1,2], A. L. Sibidanov[1,4], E. P. Solodov[1,2], V. M. Titov[1], A. A. Talyshev[1,2], A. I. Vorobiov[1], and 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, BC, Canada V8W 3P6
[5]Lebedev Physical Institute RAS, Moscow, 119333, Russia

Abstract. The cross section of the process $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ has been measured using an integrated luminosity of 17 pb^{-1} collected with the CMD-3 detector in the center-of-mass energy range 650-1000 MeV. High-precision measurements of various hadronic cross sections are of great interest in relation with the problem of the muon anomalous magnetic moment g-2. This measurement can be also used to test the relation between the cross section of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ and the spectral function for the $\tau^- \to \pi^-\pi^0\pi^0\pi^0$ decay predicted by the conservation of vector current (CVC).

1 Introduction

The VEPP-2000 electron-positron collider has been operated at Budker Institute of Nuclear Physics in the center-of-mass (c.m.) energy range from $\sqrt{s} = 320$ MeV to 2000 MeV. Production of four charged pions in e^+e^- annihilation has been studied before with rather high statistics at the CMD-2 [4] and SND detectors [5] as well as using initial-state radiation (ISR) with BaBar [6] at which a low systematic uncertainty of about 3% was achieved for the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section in the wide c.m. energy range. Earlier experiments are discussed in [7]. In this work the cross section of the process $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ has been measured using an integrated luminosity of 17 pb^{-1} collected with the CMD-3 detector in the c.m. energy range 650-2000 MeV. Also studied are the internal dynamics of four-pion

*e-mail: korobovfech@gmail.com

production. High-precision measurements of various hadronic cross sections are of great interest in relation with the problem of the muon anomalous magnetic moment g-2. The $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section can be also used to test relations between e^+e^- annihilation and τ lepton decays based on conservation of vector current.

The general-purpose detector CMD-3 described in detail elsewhere[1] is installed in one of the two interaction regions of the VEPP-2000 e^+e^- collider. Its tracking system consists of the cylindrical drift chamber (DC)[8] and double-layer multiwire proportional Z-chamber, both also used for a trigger. The electromagnetic calorimeter (EMC) includes three systems. The liquid xenon (LXe) barrel calorimeter with a thickness of 5.4 X_0 has a fine electrode structure, providing 1-2 mm spatial resolution [9], and shares the cryostat vacuum volume with the superconducting solenoid. The barrel CsI crystal calorimeter with a thickness of 8.1 X_0 is placed outside the LXe calorimeter, and the endcap BGO calorimeter with a thickness of 13.4 X_0 is installed inside the solenoid [10].
The luminosity is measured using events of Bhabha scattering at large angles [11] with about 1% accuracy. The c.m. energy has been monitored by using the Back-Scattering-Laser-Light system [12] with about 0.06 MeV systematic uncertainty. To obtain a detection efficiency, we have developed Monte Carlo (MC) simulation of our detector based on the GEANT4[13] package, in which the interaction of generated particles with the detector and its response are implemented. MC simulation includes soft-photon radiation by the electron or positron, calculated according to Ref. [14].

2 Selection of $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ events

Candidates for the process under study should have four tracks of charged particles in the DC with the following requirements: the ionization losses of each track in the DC are consistent with the pion hypothesis; a minimum distance from a track to the beam axis in the transverse plane is less than 0.25 cm; a minimum distance from a track to the center of the interaction region along the beam axis Z is less than 12 cm. Reconstructed momenta and angles of the tracks for four-track candidates are used for further selection. The background in the studied energy region comes from the processes $e^+e^- \to \pi^+\pi^-\pi^0$, $e^+e^- \to e^+e^-e^+e^-$ and $e^+e^- \to e^+e^-$ with extra tracks from decays or nuclear interaction of pions as well as from a conversion of the photons from the π^0 decay in the detector material. To reduce the background from the reaction $e^+e^- \to \pi^+\pi^-\pi^0$, we require a pion hypothesis for each track in e/π separation. After this requirement the remaining contribution from three pions to the number of four-track candidates is less than 5%. The number of signal events is determined using the following criteria:

- $30 > 2E_{beam} - \sum_{i=1}^{4} \sqrt{p_i^2 + m_\pi^2} > -20$ MeV
- $|\sum_{i=1}^{4} \vec{p}_i| < 100$ MeV

These criteria are shown in the 2D distribution in Fig. 2.

3 Electron-pion separation

To suppress background from the processes containing electrons and positrons, we use ionization losses in DC, and track energy deposition in calorimeters. We divided the whole momentum range into two parts: below and above 100 MeV/c. We use ionization losses in DC to separate electrons and pions if the track momentum is below 100 MeV/c. If it is above 100 MeV/c and $E_{cal} - 12/11 * p_{tr} + 70 < 0$ we assume a pion hypothesis for such tracks. We use a clean sample of $e^+e^- \to \pi^+\pi^-\pi^0$ to test the e/π separation procedure. Since there is a

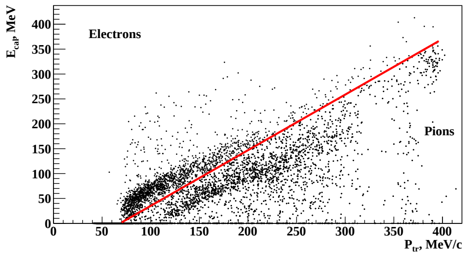

Figure 1. Momentum dependence for track energy deposition in the calorimeter. The red line is the e/π separation criterion.

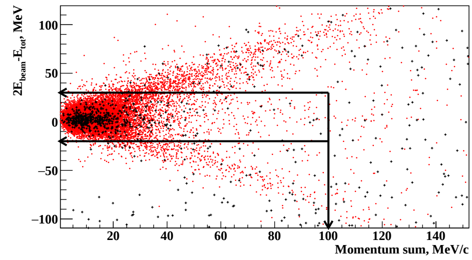

Figure 2. 2D-distribution on total momentum and $2E_{\text{beam}} - E_{\text{tot}}$ in data (black plus) and MC (red dots). The thick line shows boundaries of these parameters.

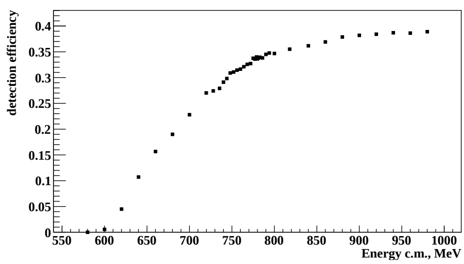

Figure 3. Energy dependence of the detection efficiency

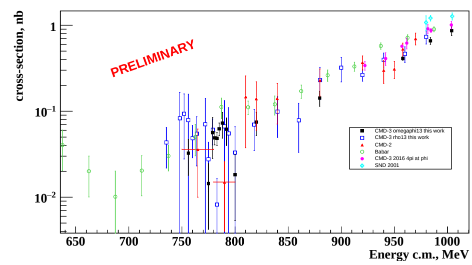

Figure 4. Comparison of our preliminary results on $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section with the previous experiments:open circle - BaBar,triangle - CMD-2, full square- this work (1st scan), open square - this work (2nd scan), full circle - CMD-3 phi, open squares - SND

difference between simulation and experiment for the energy deposition of negative tracks in the calorimeter, we use the data for this quantity. We assume that this difference is related to simulation of nuclear interaction. The following criteria are used in experimental data:

- Track is referred to as a pion if $E_{cal} - 12/11 * p + 70 < 0$ and $p > 100$ MeV/c
- Track is referred to as a pion if $|f(x) - \frac{dE}{dx}| < 1500$ and $p < 100$ MeV/c, where $f(p) = \frac{5.58*10^9}{(p+40)^3} + 2.21 * 10^3 - 3.77 * 10^{-1} * p$

The following criteria are used in MC data:

- Track is referred to as a pion according to pion identification dependence on track momentum separately for π^+ and π^-.
- Track is referred to as a pion if $|f(x) - \frac{dE}{dx}| < 1500$ and $p < 100$ MeV, where $f(p) = \frac{5.58*10^9}{(p+40)^3} + 2.21 * 10^3 - 3.77 * 10^{-1} * p$

4 Simulation and detection efficiency

To determine the detection efficiency for four-pion events, we use simulation data. To simulate $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ events we use the VDM model with the $a_1\pi$ intermediate state. We simulate 100000 $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ events at each energy point. We used simulation with radiative corrections. Energy dependence of the detection efficiency is shown in Fig.3. The detection efficiency can be as high as 40% around E_{cm}=1 GeV.

5 Preliminary results

We used the following formula to measure $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross-section: $\sigma = \frac{N_{sig}}{L*\epsilon*(1+\delta)}$, where L is integrated luminosity at this energy, ϵ is detection efficiency, $1+\delta$ is the radiative correction calculated according to [14]. We measure the cross section at 100 energy points. In the energy range from threshold up to 1 GeV the cross section rapidly rises. We managed to suppress the $e^+e^- \to \pi^+\pi^-\pi^0$ background around ω mass. Energy dependence of the $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ cross section is shown in Fig. 4. Also shown are the results of the previous experiments. Our results are consistent with the previous experiments. The uncertainties shown are statistical only. A study of systematic effects is in progress.

6 Acknowledgements

We thank the VEPP-2000 personnel for the excellent machine operation. This work is partially supported by the Russian Foundation for Basic Research grants RFBR 17-02-00327-a, RFBR 17-52-50064.

References

[1] B.I. Khazin et al. (CMD-3 Collaboration), Nucl. Phys. B (Proc. Suppl.) **181-182**, 376 (2008).

[2] M. N. Achasov et al. (SND Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. **A449**, 125 (2000).

[3] F. Jegerlehner and A. Nyffeler, Phys. Rep. **477**, 1 (2009).

[4] R. R. Akhmetshin et al. (CMD-2 Collaboration), Phys. Lett. **B595**, 101 (2004).

[5] M. N. Achasov et al. (SND Collaboration), JETP **96**, 789 (2003).

[6] B. Aubert et al. (BaBar Collaboration), Phys. Rev. **D85**, 112009 (2012).

[7] R. R. Akhmetshin et al. (CMD-2 Collaboration), Phys. Lett. **B475**, 190 (2000).

[8] F. Grancagnolo et al., Nucl. Instr. Meth. A**623**, 114 (2010).

[9] A. V. Anisyonkov et al., Nucl. Instr. Meth. A**598**, 266 (2009).

[10] D. Epifanov (CMD-3 Collaboration), J. Phys. Conf. Ser. **293**, 012009 (2011); V. M. Aulchenko et al., JINST **10**, P10006 (2015); V. E. Shebalin et al., JINST **9**, C10013 (2014).

[11] R. R. Akhmetshin et al., Nucl. Phys. B (Proc. Suppl.) **225-227**, 69 (2012); G. V. Fedotovich et al., Phys. At. Nucl. **78**, 591 (2015).

[12] V. Abakumova et al., Phys. Rev. Lett. **110**, 140402 (2013).

[13] S. Agostinelli et al. (GEANT4 Collaboration), Nucl. Instr. Meth. **A506**, 250 (2003).

[14] E. A. Kuraev and V. S. Fadin, Sov. J. Nucl. Phys. **41**, 466 (1985); S. Actis et al., Eur. Phys. J. **C66**, 585 (2010).