Study of the process $e^+e^- \to \pi^+\pi^-\gamma$ with the CMD-3 detector at the e^+e^- collider VEPP-2000

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Abstract. Existing Monte-Carlo generators with radiative corrections to the $e^+e^- \to \pi^+\pi^-$ process are usually developed under the assumption that pions can be treated as pointlike particles. We study the $e^+e^- \to \pi^+\pi^-\gamma$ process with final-state radiation and test this assumption using simulated events from the MCGPJ generator based on the scalar QED hypothesis. In order to increase a fraction of events with FSR, the analysis was performed in the energy region to the left from the ρ-meson peak (660÷785 MeV) that is based on the integrated luminosity of about 8.4 pb^{-1}. The experimental data for the photon energy spectrum agree with the simulation results at 1% level.

1 Introduction

The physics program of experiments with the CMD-3 includes precise measurements of the cross sections of the $e^+e^- \to hadrons$ processes [1]. Such experiments are necessary, e.g., for the calculation of the hadronic contribution (α_μ^{had}) to the anomalous magnetic moment of the muon ($\alpha_\mu=(g-2)/2$). The value of α_μ is of great importance as a Standard Model test. Among hadronic channels the process $e^+e^- \to \pi^+\pi^-$ is particularly important because it gives the main contribution to the value α_μ^{had} (~72%) in the low energy region (S < 2

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GeV^2) [2]. Radiative corrections to the $e^+e^- \to \pi^+\pi^-$ process are calculated under the assumption of pointlike pions. In this work we study the $e^+e^- \to \pi^+\pi^-\gamma$ process with photon radiation from the final state and test the hypothesis about pointlike pions used in the Monte-Carlo Generator Photon Jets (MCGPJ) [3].

The photon in the $e^+e^- \to \pi^+\pi^-\gamma$ event can be emitted by initial particles or from final state. Initial particles radiate mainly into a narrow cone along the particle movement path, but about 10% of the photons are emitted at the large angle, therefore it is impossible to separate events with radiation from the initial state from events with radiation from the final state based on the photon angular distribution. But there is an energy region to the left from the ρ-meson peak where radiation from the initial state causes a $e^+e^- \to \pi^+\pi^-$ cross section drop. The study of the $e^+e^- \to \pi^+\pi^-\gamma$ process in this energy region allows an increase of the relative fraction of events with the radiation from the final state.

For the test of the assumption about pointlike pions we analyzed an experimental photon-energy spectrum and compared it with the simulated one, which we produced using MCGPJ.

2 CMD-3 detector and dataset

The Cryogenic Magnetic Detector (CMD-3) is a general-purpose detector [4]. Coordinates, angles and momenta of charged particles are measured by the cylindrical drift chamber (DC) with accuracy about 120 μm in the $r - \varphi$ plane and 2 mm along the beam axis. The cylindrical multiwire double-layer proportional Z-chamber provides z-coordinate determination with accuracy ~0.5 mm. The calorimeter consists of three parts. The endcap BGO calorimeter consists of 680 crystals with a thickness 13.4 X_0. The barrel part is placed outside of the thin 0.08 X_0 superconducting solenoid with 1.3 T magnetic field and consists of the Liquid Xenon calorimeter (5.4 X_0) and CsI crystals with a thickness of 8.1 X_0 (1152 crystals) which are arranged in eight octants. The energy resolution of the barrel calorimeter was measured using Bhabha events and was found to be $\sigma_E/E \sim 4 \div 8\%$.

The analysis was carried out on the part of the statistics obtained at CMD-3 in the period from 04.12.2012 to 15.07.2013. Ten energy points in the c.m. energy region from 660 MeV to 785 MeV with the largest luminosity were chosen for the analysis. The total integrated luminosity in the processed data was ~ 8.4 pb^{-1}.

3 Study of the process $e^+e^- \to \pi^+\pi^-\gamma$

3.1 Preliminary selection

For preliminary selection we imposed restrictions on the distributions of the main parameters of the processes for selection of events $e^+e^- \to X^+X^-\gamma$, where X is an arbitrary charged particle.

The following criteria were used : two opposite charged tracks were reconstructed in the DC; the number of hits of each track exceeded 10; the distance from the intersection of tracks to the beam axis in the r-φ plane was less than 0.1 cm; the distance from the intersection of tracks to the interaction point along the beam axis did not exceed 6 cm; one or more photons clusters (not attached to the tracks) registered in the calorimeter; energy deposition in the photon cluster exceeded 50 MeV; the acollinearity angle between tracks in the scattering plane 0.06 rad < $|\Delta\theta| = |\theta_1 - (\pi - \theta_2)|$ <1 rad; the acollinearity angle between tracks in the azimuthal plane 0.025 rad < $|\Delta\varphi| = |(\pi - |\varphi_1 - \varphi_2|)|$ <1 rad; tracks and photons cluster registered in the barrel part of detector $1 < \theta_i < \pi - 1$; the angle between photon and missing momentum did not exceed 0.4 rad; the absolute value of the missing mass squared less than 9000 MeV^2. The last criterion was used for suppression of the $e^+e^- \to \pi^+\pi^-\pi^0$ events.

The kinematic reconstruction of each event was carried out. The χ^2 of kinematic reconstruction must be smaller than 50. In events with two or more photons the photon with smallest χ^2 was chosen for the spectrum production.

In the energy region to the left from the ρ-meson peak the main background processes are $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \pi^+\pi^-\pi^0$.

3.2 Background suppression

To suppress the $e^+e^- \to e^+e^-\gamma$ and $e^+e^- \to \mu^+\mu^-\gamma$ we used parameters W, M and dE.

$$W = W_1 \times W_2 \tag{1}$$

Where $W_{\rm i} = E_{\rm i} / P_{\rm i}$ – ratio of the energy deposition in the calorimeter to the momentum measured in the DC, M – mass of the charged particle.

$$\mathrm{M} = \sqrt{\frac{T^4 - 2T^2\left(P_1^2 + P_2^2\right) + \left(P_1^2 - P_2^2\right)^2}{4T^2}} \tag{2}$$

Where $T = 2E_{\rm beam} - \omega_\gamma$, $E_{\rm beam}$ – measured energy of the beam, $P_{\rm i}$ – momentum of the charged particle measured in DC, ω_γ – energy of the photon.

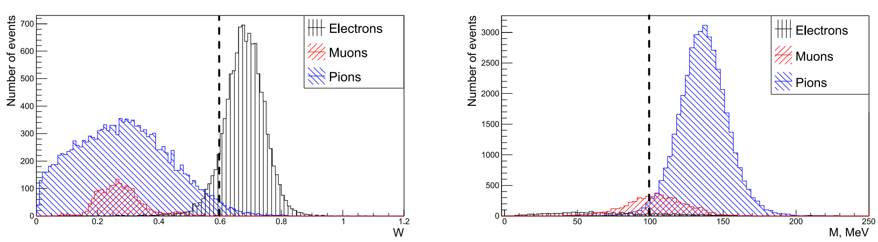

Fig. 1. (left) The value of parameter W for simulated events after preliminary selection. (right) Mass of charged particle for simulated events after preliminary selection and W cut. Dashed lines indicate selection criteria.

$$dE = 2E_{\rm beam} - E_1 - E_2 - P_{\rm miss} \tag{3}$$

The energies of the particles were constructed with the pion mass assumption.

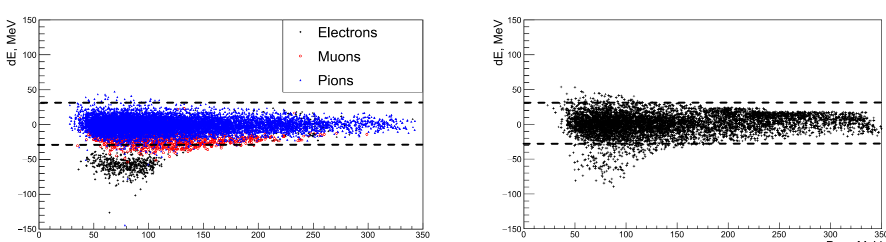

Fig. 2. The distribution of events remaning after applying W and M selection criteria and preliminary selection. (left) The simulation of the signal events and physical background. (right) The experimental data. Dashed lines indicate selection criteria.

The selection criteria for described above parameters were obtained from the simulation of the signal process. $W < 0.6$, $M > 100$ MeV, $|dE| < 30$ MeV.

After all restrictions applied the detection efficiency of signal events was 0.25%.

4 Data-MC comparison

To compare the data with the theoretical predictions we simulated processes of the signal and the physical background ($e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \pi^+\pi^-\pi^0$) using the CMD3SIM program developed on the basis of the GEANT4 package [5]. The processes of the physical background were simulated with weights corresponding to the cross sections of the simulated processes. The CMD3SIM contains a description of all CMD - 3 systems and provides a complete simulation of the detector. The comparison was carried out with the same restrictions on the final state for the experiment and simulation.

According to the simulation, the cumulative application of the selection criteria described above allows us to distinguish events of $e^+e^- \to \pi^+\pi^-\gamma$ with the 6% impurity. ($e^+e^- \to e^+e^-\gamma$ (<1%), $e^+e^- \to \mu^+\mu^-\gamma$ (5÷6%) and $e^+e^- \to \pi^+\pi^-\pi^0$ (<<1%)).

The level of agreement between the experiment and simulation was determined from the ratio of the experimental photon-energy spectrum to the simulated one. The photon energy ω_γ at each energy point was normalized to the beam energy $E_{\rm beam}$. The result of the analysis is shown in Fig.3.

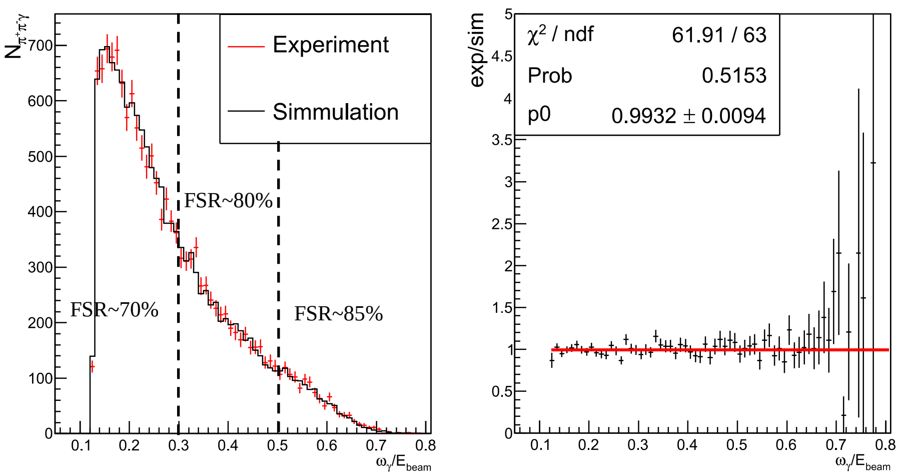

Fig. 3. (left) The photon energy spectrum in relative units for the data and simulation. Dashed lines indicate photon energy regions with the approximate content of FSR events. (right) The ratio of the data and simulation.

5 Summary

The analysis of the process $e^+e^- \to \pi^+\pi^-\gamma$ was carried out in the energy region 660÷785 MeV and based on the integrated luminosity about 8.4 pb^{-1}. The applied selection criteria allow to extract signal events of the process $e^+e^- \to \pi^+\pi^-\gamma$ with 6% of background events. The simulation is in good agreement with the experiment for $e^+e^- \to \pi^+\pi^-\gamma$ and for $e^+e^- \to \mu^+\mu^-\gamma$. The ratio is stable in each energy region. The assumption of the pointlike pions makes an insignificant contribution to the $e^+ e^- \to \pi^+\pi^-$ cross section measurement uncertainty (~ 0.01%) because the radiative correction to the $e^+ e^- \to \pi^+\pi^-$ process is about 1% [6].

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