Monte-Carlo simulation of lepton pairs production in "\( p\bar{p} \rightarrow e^+e^- + X \)" events at PANDA experiment.

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Abstract. Electron-positron pairs production via the quark-antiquark annihilation process in collisions of antiproton beam having \( E_{\text{beam}} = 15 \) GeV with the proton target in PANDA experiment is modeled by using the PYTHIA6.4 Monte-Carlo event generator and PandaRoot framework. The considered quark level subprocess pass through the production of virtual photon which converts into the lepton pair \( q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^- \). The spectrum of the final state leptons in this process of quark-antiquark annihilation obviously depends on the form of parton distributions inside colliding protons and may provide an interesting information about the quark dynamics inside the hadron. The measurement of the total transverse momentum of a lepton pair as a whole system may give an important information about the intrinsic transverse momentum \( k_T \) that appears due to the Fermi motion of quarks inside the nucleon. In the article the distributions of different kinematical variables of final state electrons/positrons are presented. The influence of the detector environment on the presence of fake leptons is demonstrated. The signal leptons registration efficiency is calculated. The background contribution is also discussed.

Introduction
The intermediate energy experiment PANDA \( (E_{\text{beam}} \leq 15 \) GeV) may play an important role because it allows to study the energy range where the perturbative methods of QCD (pQCD) come into interplay with a rich physics of resonance production. A detailed and high-precision experimental study at PANDA may allow to discriminate between a large variety of existing nonperturbative approaches and models that already exist or are under the development now. Dilepton events may serve as a powerful tool to get out the information about the parton distribution functions (PDFs) in hadrons [1]. The plans to study this process are included into the “Physics book” [2] of PANDA experiment at HESR (High-Energy Storage Ring at FAIR). This study may provide an interesting information about quark dynamics inside the nucleon [3].

This paper is a continuation of the work [1], [3] done to study the lepton pairs production in the processes \( p\bar{p} \rightarrow \mu^+\mu^- + X \) and \( p\bar{p} \rightarrow e^+e^- + X \) at the beam energy \( E_{\text{beam}} = 14 \) GeV. Here we consider the last process but for the case of beam energy \( E_{\text{beam}} = 15 \) GeV (which corresponds to the center-of-mass energy of the \( p\bar{p} \) system \( E_{\text{cm}} = 5.474 \) GeV). The simulation is done with PYTHIA6.4 [4] and the PandaRoot [5] framework which takes into account the PANDA detector geometry and fulfills the global simulation of the detector by using the implemented Geant4 [6] program. The main goal of the current work was to monitor the influence of detector environment on leptons propagation and their final distributions.
Observations and Interpretation

We have used PYTHIA6.4 to generate 10000 $p\bar{p} \rightarrow e^+e^- + X$ events which include the $2 \rightarrow 2$ quark level $q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$ subprocess. This simulation has shown that one can expect to gain about $7 \cdot 10^6$ such lepton pairs production events per year for the luminosity $L = 2 \cdot 10^5mb^{-1}s^{-1}$, which corresponds to the cross section $\sigma = 4.59 \cdot 10^3 pb$ and the assumption of the full year of detector operation. Electron-positron pairs from these events were used for the further study with the program of full simulation PandaRoot with Geant4.

It was found that the number of events where one of the signal leptons is not registered in detector amount to 1285 for 10000 generated events. There are also 127 events in which no one of signal leptons was registered. That means we can expect the registration of only 85.8% of signal events. The number of signal events where both of the signal leptons satisfy the criteria $P_{e} > 0.2$ GeV/c and $P_{T} > 0.2$ GeV/c is 62.6%.

Also we have performed the comparison of kinematical distributions of signal leptons after passing through the detector with the corresponding initial ones obtained with PYTHIA. In the following pictures the distributions of leptons obtained with the simulation by PandaRoot and Geant4 are shown by pink histograms. For comparison, distributions of the same leptons obtained at the level of the generation by PYTHIA, i.e. before passing through the detector, are shown in the same pictures by violet lines. At the final distributions, having the pink color, are shown only those electrons and positrons which belong to those events in which both signal leptons are registered. All of the statistical boxes contain the information corresponding to GEANT simulation.

The first figures show the distributions of the number of generated signal leptons $N_{ev}$ versus their momentum components $P_{x \pm}$ (Fig.1), $P_{y \pm}$ (Fig.2) and $P_{z \pm}$ (Fig.3). Distributions over $P_{x}$ and $P_{y}$ are identical to each other and follow the initial distributions at PYTHIA level except some loss of events, denoted above. Distribution of longitudinal component shows the excess over PYTHIA results in the region of small $0 < P_{z \pm} < 0.6$ GeV/c and some reduction of number of events at the medium values of $1 < P_{z \pm} < 9$ GeV/c.

![Figure 1. $P_{x \pm}$](image1)

![Figure 2. $P_{y \pm}$](image2)

![Figure 3. $P_{z \pm}$](image3)

The next figures demonstrate distributions of the signal $e^+/e^-$ over their transverse momentum $P_{T \pm}^e$ (Fig.4) and full momentum $P_{\pm}$ (Fig.5). One can see that PandaRoot spectra shift to the region of lower momenta as comparing to the PYTHIA ones. In the region of small transverse momentum $0 < P_{T \pm}^e < 0.25$ GeV/c the number of events obtained by PandaRoot slightly exceeds the initial distributions. At the higher $P_{T \pm}^e > 0.4$ GeV/c their number is reduced significantly. The distribution over full momentum P shows the excess over PYTHIA results in the region of small $0.3 < P_{z \pm} < 0.8$ GeV/c and some reduction of number of events at the medium values of $1 < P_{z \pm} < 9$ GeV/c.

The distribution of the number of generated signal leptons $N_{ev}$ versus their polar angle $\Theta_{\pm}$, measured from the z-axis directed along the beam line, is given at Fig.6. The distribution over the polar angle $\Theta_{\pm}$ shows the maximum at the values about 15 degrees, whereupon it sharply falls...
Entries 16612
Mean 0.7068
RMS 0.4444
Underflow 0
Overflow 40
Integral 1.657e+04, GeV/c

Figure 4. Transverse momentum $P_T e^\pm$.

Entries 16612
Mean 2.454
RMS 1.966
Underflow 0
Overflow 92
Integral 1.652e+04, GeV/c

Figure 5. Full momentum $P e^\pm$.

up to the values about 120 degrees. Fig.7 presents the distribution over the azimuthal angle $\phi e^\pm$ which shows a relatively uniform shape. Both angular distributions, accounting for the statistical errors and decrease of the number of registered particles, repeat the initial distributions obtained with PYTHIA.

Entries 16612
Mean 26.68
RMS 21.61
Underflow 0
Overflow 0
Integral 1.661e+04

Figure 6. Polar angle $\Theta e^\pm$.

Figure 7. Azimuthal angle $\phi e^\pm$.

Figures 8, 9 and 10 present the registration efficiencies over the electron/positron transverse momentum $Eff_{P_T e^\pm}$, full momentum $Eff_{P e^\pm}$ and polar angle $Eff_{\Theta e^\pm}$ correspondingly. The efficiency of registration $Eff$ is calculated as a ratio of the number of leptons registered in a definite momentum (angle) region while modeling in PandaRoot to that ones which were initially generated in the same momentum (angle) region in PYTHIA.

Figure 8. Transverse momentum registration efficiency $Eff_{P_T e^\pm}$.

Figure 9. Full momentum registration efficiency $Eff_{P e^\pm}$.

Figure 10. Polar angle registration efficiency $Eff_{\Theta e^\pm}$.

One can see that at the low values of $PT < 0.1$ GeV/c the value of registration efficiency $Eff_{P_T e^\pm}$ > 1 that can be caused by the production of some additional low energetic $e^+/e^-$ in a result of interaction with the detector environment. At the higher transverse momentum the value of registration efficiency evenly falls linearly up to $Eff_{P_T e^\pm} \approx 0.4 - 0.6$ and the $Eff_{P_T e^\pm}$ spectrum stops at the value of $PT = 2.35$ GeV/c.
The value of $e^+/e^-$ full momentum registration efficiency $Eff_{P_{e^+}}$ sharply grows at the values $P < 0.4$ GeV/c from $Eff_{P_{e^+}} = 0.6$ to the value of 1.2, that can be explained by the reason described above. Then the distribution curve practically linearly falls up to the value of $Eff_{P_{e^+}} = 0.5$.

From Fig.10 showing the electron/positron registration efficiency $Eff_{\Theta e^\pm}$ over their polar angle $\Theta^{e\pm}$, one can see that the value of this efficiency has almost the same value $Eff_{\Theta e^\pm} \approx 0.83$ (that corresponds to the whole loss of the number of signal events) in the polar angle region $0 < \Theta^{e\pm} < 80^\circ$ with some fall up to the value $Eff_{\Theta e^\pm} \approx 0.6$ in the region of $\Theta^{e\pm} \approx 7^\circ$, with the following uniform (with account of statistical errors) fall to $Eff_{\Theta e^\pm} \approx 0.4$ at $\Theta^{e\pm} \approx 160^\circ$.

**Backgrounds**

The main source of the background to the process of lepton pairs production are the so called minimum bias events, i.e. the events with low PT [1], [3] as well as different kind of QCD events. The total cross section of minimum-bias events is about $6 \times 10^6$ times higher than the cross section of the signal event, i.e. there are about $10^5$ background events per one signal event. The total cross section of QCD processes is also significant, but it is about 5 order of magnitude less than the one of the minimum-bias events.

We took $10^5$ background events initially simulated in PYTHIA and passed them through the detector using Geant4 in PandaRoot. The comparative kinematical distributions of the $e^+/e^-$ obtained in PYTHIA and PandaRoot are represented further. The final state electrons in background processes in PYTHIA appear from the hadron and meson decays according to the Lund fragmentation model. In PandaRoot they are produced from the analogous decays laid in Geant program.

As one can see from the obtained distributions, the electrons/positrons produced from decays of different particles in detector volume happen to be more energetic in comparison with analogous ones simulated in PYTHIA. On the other hand, their number is significantly reduced in comparison with PYTHIA predictions. Namely, they have in average on 0.5 GeV/c higher momentum in transverse plane ($P_x$ (Fig.11), $P_y$ (Fig.12) and $PT_{bkg}$ (Fig.14)), and about 1 GeV/c higher momentum in longitudinal component ($P_z$ (Fig.13) and correspondingly $P$ (Fig.15)).
The distribution of the background leptons obtained by PandaRoot over the polar angle $\Theta^e\pm$ (Fig.16) has the similar shape with electrons/positrons, obtained in PYTHIA simulation, but has some clear excess in direction of 5-35 degrees with the peaks on 3-5 and 9-11 degrees.

The distribution of the background electrons/positrons over the zenith angle $\phi^e\pm$ (Fig.17) has evidently non uniform character with a prevalence in the region of 0 and 180 degrees, as well as with the holes close to 80 (-80) and -100 degrees.

The analysis of 100000 generated background events, discussed above, has shown that in these $10^5$ background events 68803 electrons/positrons were produced. The number of background events where no one of electron/positron was registered amount to 55448, i.e. 55.4%. The number of background events including 1 electron/positron is 29311, i.e. 29.3%. Thus the number of events having 2 and more electrons/positrons is 15241, i.e. 15.3%. The number of events, which satisfy to the selection criterion – the presence of exactly 2 leptons of different charge with $P^e\pm > 0.2$ GeV/c and $P_T^e\pm > 0.2$ GeV/c provides the maximum in the region of 3-4 GeV/c over momentum and 10-21 degrees over the polar angle.

The correlation plot of electron/positron distribution over their full momentum $P$ and the polar angle $\Theta^e\pm$ (Fig.18) shows the maximum in the region of 3-4 GeV/c over momentum and 10-21 degrees over the polar angle.

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