Monte-Carlo simulation of lepton pairs production in 
”$p\bar{p} \rightarrow \mu^+\mu^- + X$” events at $E_{\text{beam}} = 5$ GeV

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Abstract. Muon pairs production via the quark-antiquark annihilation process in collisions of antiproton beam with $E_{\text{beam}} = 5$ GeV (which corresponds to the center-of-mass energy of the $p\bar{p}$ system $E_{\text{cm}} = 3.363$ GeV) with the proton target in PANDA experiment is modeled by using of PYTHIA6.4 generator. The considered quark level subprocess goes through the production of virtual photon which converts into lepton pair ($q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$). Quark-antiquark annihilation process of hadron-hadron collision 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 provide an important information about the intrinsic transverse momentum $k_T$ that appears due to the Fermi motion of quarks inside the nucleon. The distributions of different kinematical variables of final state muons are presented. The problems due to the presence of fake leptons that appear from meson decays, as well as due to the background caused by minimum bias events are also discussed. The set of cuts which allows to separate the signal events with lepton pairs from the backgrounds is proposed.

Introduction
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 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 LoI [3], TPR [4] and “Physics book” [5] of PANDA experiment at HESR (High-Energy Storage Ring at FAIR). This study may provide an interesting information about quark dynamics inside the nucleon [2].

Observations and Interpretation
This work is a continuation of the work [1], [2] done to study the lepton pairs production in the processes $pp \rightarrow \mu^+\mu^- + X$ at the beam energy $E_{\text{beam}} = 14$ GeV. Here we consider the same process but in the case of beam energy $E_{\text{beam}} = 5$ GeV (which corresponds to the center-of-mass energy of the $p\bar{p}$ system $E_{\text{cm}} = 3.363$ GeV) which is the lowest possible for simulation of this kind of process with PYTHIA6.4 [6]. The main goal of this work for the moment is an estimation of the leptons kinematical distributions and search for the cuts criteria for signal and background separation.
We use PYTHIA6.4 to generate 100000 $p\bar{p}\rightarrow \mu^+\mu^-$ events which include the 2 $\rightarrow$ 2 quark level $q\bar{q}\rightarrow \gamma^* \rightarrow \mu^+\mu^-$ subprocess. The simulation is done starting from the assumption of the ideal muon detection system and electromagnetic calorimeter covering full phase space without taking into account the influence of magnetic field. We consider the case where both initial-state radiation (ISR) and final-state radiation (FSR) are switched on simultaneously by choosing the corresponding values of PYTHIA parameters. Also we have used the CTEQ3L parametrization of parton distributions and the default value of the parameter, which allows one to take into account the primordial $k_T$-effect (i.e. quarks Fermi motion).

The study of kinematical characteristics of lepton pair as a whole system was also done. Figures 1 and 2 show, correspondingly, the distributions of the invariant masses of initial-state quark-antiquark pairs $M_{inv}^{q\bar{q}}=\sqrt{(P_{q\bar{q}})^2}$ and the invariant mass of the final-state $\mu^+\mu^-$ pair $M_{inv}^{\mu^+\mu^-} = \sqrt{(P_{\mu^+\mu^-})^2} = Q^2$, where $Q^2 = q^2 = (P_{\mu^+} + P_{\mu^-})^2$. Both invariant mass distributions look rather similar. It is shown in Fig.2 that the spectrum of the invariant mass of the lepton pair decreases rather fast and vanishes at $M_{inv}^{\mu^+\mu^-} = 1.45$ GeV. The square of the invariant mass $(M_{inv}^{\mu^+\mu^-})^2 = Q^2 = q^2 = (P_{\mu^+} + P_{\mu^-})^2$ has the meaning of the square of the momentum transferred from the hadronic system of initial quark-antiquark pair to the electromagnetic system of the final state lepton pair. From these figures it can be seen that it can have the values in the region $Q^2 \leq 2.1 \text{ GeV}^2$.

Figs.3 and 4 contain the distributions of up- and down-quarks at $E_{beam} = 5$ GeV, respectively. They demonstrate that the contribution of up-quarks dominates over the down quarks, while both of them cover practically the same region of $x$’s: $0.15 \leq x \leq 0.6$. Let us emphasize that
the measurements in this region of positive (“time-like”) \( q^2 \equiv (P^l_+ + P^l_-)^2 = Q^2 \geq 0 \) would be a good extension of studies planned to be done at JLab in the region of negative (“space-like”) values of \( q^2 = (P^l_{in} - P^l_{out})^2 \leq 0 \).

![Figure 5. Muon’s energy \( E_\mu \).](image)

![Figure 6. Muon’s transverse momentum \( P^\mu_T \).](image)

![Figure 7. Muon’s angle \( \Theta^\mu \).](image)

The distributions of the number of generated signal events \( N_{ev} \) versus the muon energy \( E^\mu_{ev} \) as well as versus the modulus of the transverse momentum \( P^\mu_T \) and of the polar angles \( \Theta^\mu_{ev} \), measured from the z-axis directed along the beam line, are given in the Figs.5-7. At PYTHIA level of simulation (for “ideal” detector) the distributions for positive and negative leptons are identical. One can see from Fig.5 that the most part of leptons energy is contained in the interval \( 0 < E^\mu_{ev} < 3 \) GeV. Its spectrum has a mean value \( <E^\mu_{ev}> = 1.09 \) GeV and a peak at \( E^\mu_{peak} \approx 0.3 \) GeV. The \( P^\mu_T \) spectrum (Fig.6) has an analogous peak at \( P^\mu_T \approx 0.4 \) GeV. The main part of \( P^\mu_T \) spectrum is confined within a rather narrow interval \( 0 < P^\mu_T < 1 \) GeV. The number of events spectrum versus the polar angle \( \Theta^\mu_{ev} \) (Fig.8) has a peak around \( \Theta^\mu_{peak} \approx 20^\circ \) and the mean value \( <\Theta^\mu_{ev}> = 41.4^\circ \). One sees that while 98% of signal leptons fly in the forward direction \( \Theta^\mu < 90^\circ \), there is still 2% of them which fly into the back hemisphere \( \Theta^\mu > 90^\circ \).

The next Figures include the correlation plots done for the signal leptons having the largest energy in the lepton pair, \( \mu_{fast} \), and for the leptons having a smaller energy in the pair, \( \mu_{slow} \). We shall call them, correspondingly, as “fast” and ”slow” muons.

![Figure 8. \( \Theta^\mu_{slow} - E^\mu_{slow} \) correlation.](image)

![Figure 9. \( \Theta^\mu_{fast} - E^\mu_{fast} \) correlation.](image)

Figures 8-9 contain two projections of 3-Dimensional ”Angle-Energy” correlation plots for slow \( \Theta^\mu_{slow} - E^\mu_{slow} \) (left plot) and fast \( \Theta^\mu_{fast} - E^\mu_{fast} \) (right plot) muons in signal pairs onto \( \Theta - E \) planes. This allows to show the boundary contours of regions with different density of number of
The color code on Zaxis in each correlation plot shows the correspondence between the contour color and the density of events ($N_{\text{ev}}$ per year).

After a discussion of individual lepton distributions let us turn to the distributions that characterize the produced pair of leptons as a whole system. The next Figures 10-11 show the Energy-Energy $E_{\mu\text{slow}} - E_{\mu\text{fast}}$ (left plot) and Angle-Angle $\Theta_{\mu\text{slow}} - \Theta_{\mu\text{fast}}$ (right plot) correlations.

**Figure 10.** $E_{\mu\text{slow}} - E_{\mu\text{fast}}$ correlation.  
**Figure 11.** $\Theta_{\mu\text{slow}} - \Theta_{\mu\text{fast}}$ correlation.

**Backgrounds**

The signal events, defined by the $q\bar{q} \rightarrow \mu^+\mu^-$ subprocess, also may contain up to 8 hadrons in the final state. Fortunately, their number is essentially restricted by the upper limit on the PANDA beam energy. This circumstance may simplify greatly the identification of final state particles and the physical analysis due to reduction of the phase space and therefore to the reduction of the number of hadrons and other particles which may be produced in event directly or in the decay cascades of other hadrons. These hadrons may decay within the detector volume and thus produce the background leptons which may fake the signal leptons produced in a signal annihilation subprocess.

The first kind of background contains the muons which may be produced additionally to a signal $\mu^+\mu^-$ pair in the signal events due to hadron decays. According to simulation by PYTHIA the fraction of signal processes, which include fake muons, is about 1.2%. Criteria for separation of such background were proposed in [1],[3]. The choice of the events with two muons, having: a) different charges, b) $E_{\mu} > 0.2$ GeV, $PT_{\mu} > 0.2$ GeV and c) the production vertex is close to the interaction point, allows to get rid of events having the fake decay muons by the loss of 15.8% of signal events.

The main background comes from minimum-bias events (i.e. low PT scattering, single diffractive processes etc.), which total cross section is more than $7 \cdot 10^8$ times higher than the cross section of the signal event.

Comparison of figures of background muon distribution with their analogs for the signal muons shows that background muons are less energetic that the signal ones. The average value of the signal muons energy $<E_{\mu}> = 0.97$ GeV corresponds to such a point of the background muons spectrum where the contributions of the last ones is practically absent. Analogically the average value of PT-distribution of signal muons $<PT_{\text{sig}}>$ = 0.33 GeV corresponds to such a point where $PT_{\text{dec}}$ spectrum disappears. From the muon production vertex distributions one can see that the largest part of the background muons are produced far away from the interaction point and the vertices of their production are distributed over the detector volume.
From distribution of the number of muons per background event one can see that in a case of beam energy of $E_{\text{beam}} = 5$ GeV there can be up to 6 muons per event (while for $E_{\text{beam}} = 14$ GeV this number can reach 7 muons per event).

To get rid of minimum-bias events contribution the following set of five cuts (see also [1],[3]) was used:

1. We choose the events with 2 muons in the final state with $E_{\mu_{\text{dec}}} > 0.2$ GeV, $PT_{\mu_{\text{dec}}} > 0.2$ GeV;
2. These muons have the opposite charges;
3. Their production vertex is close to the interaction point;
4. Their invariant mass $M_{\text{inv}}(\mu^+\mu^-) > 0.9$ GeV;
5. Muons are isolated, i.e. the summarized energy of charged particles within the cone around the muon momentum, having the radius which can cover about three cells of PANDA calorimeter, is less than 0.5 GeV.

The table below shows the dependence of signal to background ratio (S/B) on the application of the chosen five cuts for two cases of using the lower bound for muon transverse momentum, i.e. one with $PT_{\mu} > 0.2$ GeV and the other one with $PT_{\mu} > 0.5$ GeV. Efficiency shows the relation $N_{\text{cut}}^{\text{cat}}/N_{\text{bkg}}^{\text{cat}}$, thus the less is efficiency the more effective is the cut.

| N of cut | S/B ratio for $PT_{\mu} > 0.2$ GeV | Efficiency | S/B ratio for $PT_{\mu} > 0.5$ GeV | Efficiency |
|----------|---------------------------------|------------|---------------------------------|------------|
| 1        | $1.02 \cdot 10^{-6}$           | $1.47 \cdot 10^{-3}$ | $2.37 \cdot 10^{-6}$ | $4.22 \cdot 10^{-4}$ |
| 2        | $1.13 \cdot 10^{-6}$           | 0.906      | $2.57 \cdot 10^{-6}$ | 0.921      |
| 3        | $3.70 \cdot 10^{-4}$           | $3.04 \cdot 10^{-3}$ | $6.09 \cdot 10^{-4}$ | $4.21 \cdot 10^{-3}$ |
| 4        | $6.58 \cdot 10^{-2}$           | 0.056      | $7.04 \cdot 10^{-3}$ | 0.086      |
| 5        | 1.5                             | 0.004      | 2                               | 0.003      |

These results of backgrouns study are very preliminary because they are done for the case of “ideal” detector. Nevertheless they are rather promising and give the confidence in a good signal and background separation. The numbers of S/B ratio may be increased by adjustment the value of each of the cuts parameters. More precise study would be done using the PANDARoot simulation.

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