Perspectives of study of direct photon production process at FAIR energy.

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Abstract

The modeling of direct photons production in collisions of antiproton beam with the proton target $\bar{p}p \rightarrow \gamma + X$ is done for the beam energy $E_{beam} = 15$ GeV using the simulation with PYTHIA6.4 generator. Our modeling is performed using two subprocesses: a) quark-antiquark annihilation into a photon and a gluon and b) of gluon-quark scattering leading to a photon emission. The simulation allowed to estimate the values of cross sections of these processes and their main backgrounds. The distributions of the set of kinematic variables which are useful to get the information about proton structure in the available kinematic region were obtained. The background contributions of fake photons in signal events, which can appear from decays of produced hadrons, as well as contribution caused by the background minimum-bias events and other QCD processes, are estimated. The set of cuts which can be useful for separation of signal events containing the direct photons from background ones is proposed.

1 Introduction

The measurements of direct photons production in high energy hadron-hadron interactions have demonstrated already their very notable potential for studying the structure of hadrons and nuclear. The energy region $1 \leq E_{beam} \leq 15$ GeV which can be covered by antiproton beam at the accelerator center FAIR (GSI, Darmstadt) is of interest for research because it is much less investigated as compared to those regions which were studied at the accelerators having more higher energies. Note that the range $5 \leq E_{beam} \leq 15$ GeV has all rights to be referred to as a region of a quite high energy.

In general, the researches at intermediate energies play an important role, because in this energy range the methods of perturbative QCD (pQCD) come into interplay with a rich physics of bound states and resonances. The physics of hadron resonances formation and of their decay is obviously strongly connected with a very important confinement problem, i.e. with the parton dynamics at the so called "large distances". It is clear that the efforts to gain the understanding of the confinement mechanism are of the same great significance as it was, for example, with the discovery of the Higgs boson.

Therefore, a detailed and high precision experimental study of processes, based on using the information about the kinematic distributions of detected particles at beam energies available for FAIR, can help to discriminate between a large variety of existing theoretical pertubative and non-perturbative approaches and models that already exist or under development now. It is obvious that high energy photons (referred to as "prompt" or "direct" photons) belong to

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such kind of particles which can bring a clear and important information about the processes are searched for.

The most interesting role belongs to those prompt photons which are produced directly in the fundamental primary parton-parton collision subprocesses, which initiate the further conversion into the secondary subprocesses of hadronization and emission of stable and unstable particles. The great advantage of direct photons is that they are mostly escape these secondary subprocesses. It happens so due to the obvious fact that the photons participate in interactions with other particles only through the electromagnetic interaction coupling constant α which is essentially smaller than the strong coupling constant $\alpha_s(Q^2)$. Let us remind also that the strong coupling constant governs the interactions of quarks and antiquarks with the gluons in the initial and final state of the same fundamental primary parton-parton collision [1]. Let us also note that the electromagnetic coupling constant, which defines the radiation of a photon from an electromagneticaly charged quark, is well known, while the strong coupling constant is still under study.

The experimental study of direct photon production in hadron-hadron collisions was preceded by the study of production of light elementary particles, mainly the mesons. There was a lot of experiments which have performed the measurements of the processes with π^0, η and ω production. The production of photons from proton-proton (pp) collisions has been the object of many experimental measurements both at FNAL [1] and at the ISR (CERN) [2]. It should be mentioned, that at the same time, no systematic investigations concerning the source of the observed photons has been made and it has been commonly assumed, that these photons are produced through the π^0 and η decays. Nonetheless, it was noted in [1] that the differential cross sections of the process $p+p \to \gamma+X$ (X is *anything*), measured in the range of p_T from 0.2 to 3 GeV/c, has shown a significant deviation from the widely used simple exponential behavior in p_T for incident proton energies above 50 GeV and p_T greater than 1 GeV/c.

Two yeares later the ISR collaboration R412 [3] has declared of their observation, for the first time, of a large and significant production of single photons (and also photon pairs) in the analogous transverse momentum range (1.6 to 3.8 GeV/c), which cannot be explained by π^0 and η decays. The results of the subsequent pioneering experiments [4], [5], [6], [7], [8], [9], [10], [11] [2] were presenting every year new arguments in favor of the production of direct photons and the information about the properties of such processes.

To date there is a lot of new interesting information about direct photon production which came from high energy colliders. Thus, the Tevatron and LHC (for the recent information see, for example [17], [18], [19], [20], which contain the corresponding references) have provided the information about behavior of cross sections of nucleons collision in a region of large transverse momenta which is important for the development of perturbative QCD at high energy and getting the information about the nucleon structure. Also very important results were obtained from study of events with direct photons production in heavy ion collisions. They have been started at CERN SPS (see [14]) and up to date continue in recent measurements at BNL (see [21], [22]) and at CERN [23]. These measurements have shown that the processes with direct photons production play the crucial role in searches and study of Quark-Gluon Plasma.

Meanwhile, in practice, there was not so much progress reached in studying the processes with direct photon production in the region of intermediate beam energy which is important for searches of expected deviations from the perturbative QCD.

The aim of the present paper is to make an estimations of the distributions of the most important kinematical variables of 1.) the produced direct photons and of 2.) the background photons. We use the PYTHIA6.4 generator [24] which includes only those events which are defined by the leading order (LO) subproceses $q\bar{q} \to \gamma + g$ and $qg \to \gamma + q$. In the following,

[1] it can further take a part in the secondary subprocesses which include the interactions between the other so called "underlying partons", which have not participated in the fundamental subprocess.

[2] For more detailed references see [12], [13], [14]. The data compilations can be found in [15], [16].

these events will be called as "signal events", and the photons produced in this subprocess will be called as "signal" photons. The fake photons which are produced in hadron (mainly mesons) decays in the same signal event are called as "decay" photons. The estimation of the contribution of photon emission rate from NLO diagrams [25] would be the subject of further papers.

2 Distributions of the signal photons, produced in $p\bar{p}$ collisions

The sample of 1000000 events was generated using three leading QCD subproceses which have to be, according to PYTHIA, the candidates for production of direct photons. They are: $q\bar{q} \to \gamma + g$, $qg \to \gamma + q$ and $gg \to \gamma + g$. Table 1 shows the values of their cross sections:

Table 1: Signal processes and their cross sections

PYTHIA's number of subprocess	Type of process	Cross section, mb
14	$f + \bar{f} \to g + \gamma$	$1.53 \cdot 10^{-3}$
29	$f + g \to f + \gamma$	$8.18 \cdot 10^{-4}$
115	$g + g \to g + \gamma$	$2.30 \cdot 10^{-7}$

The generated sample allows to make the plots with the distributions of kinematical parameters of the photons. The vertical axis in the most of plots present the number of events expected per the full year of HESR operation having the highest luminousity of $2 \cdot 10^{32} cm^{-2} s^{-1}$.

The main kinematical distributions of signal direct photons are presented on Fig.1.

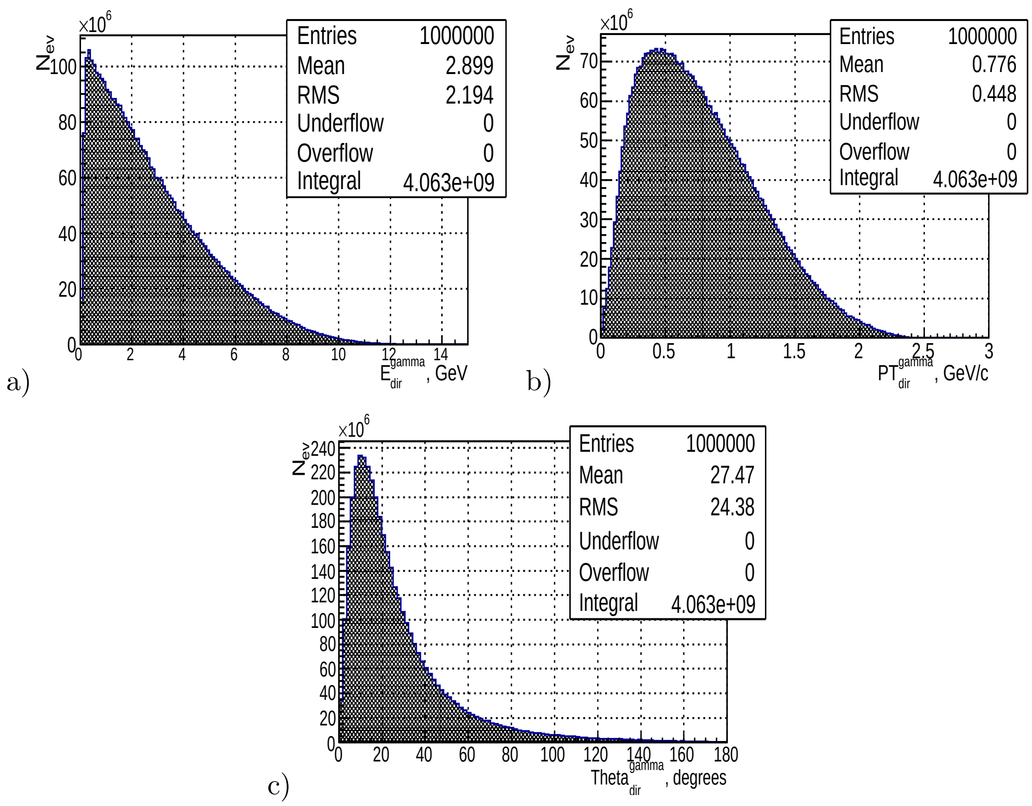


Figure 1: *Distributions of direct photons:* **a)** *Energy E^{γ}_{dir};* **b)** *Transverse momentum PT^{γ}_{dir};* **c)** *Polar angle Θ^{γ}_{dir}*

As it can be seen from the Fig.1a, the energy of photons is distributed in a region $0 < E^{\gamma}_{dir} < 12$ GeV with a mean value of $< E^{\gamma}_{dir} >= 2.9$ GeV. Their PT's values range is $0 < PT < 2.3$ GeV/c (fig.1b) with a mean value of $< PT^{\gamma}_{dir} >= 0.77$ GeV/c, and the polar angle Θ_{dir} (fig.1c), calculated from the beam direction, cover the range of $0 < \Theta_{dir} < 140$ degrees with a mean value of $< \Theta_{dir} >= 27$ degrees.

It is important to note, that swiching on and off the initial state radiation doesn't influence on the shape of distributions.

3 Structure functions

The distributions of Bjorken x-variable are shown in Fig.2 for up- (xU plot), down-(xD plot), strange-(xS plot) quarks and gluons-(xG plot). They represent the corresponding quark components of the proton structure function which was used in the present simulation with CTEQ3L PDF.

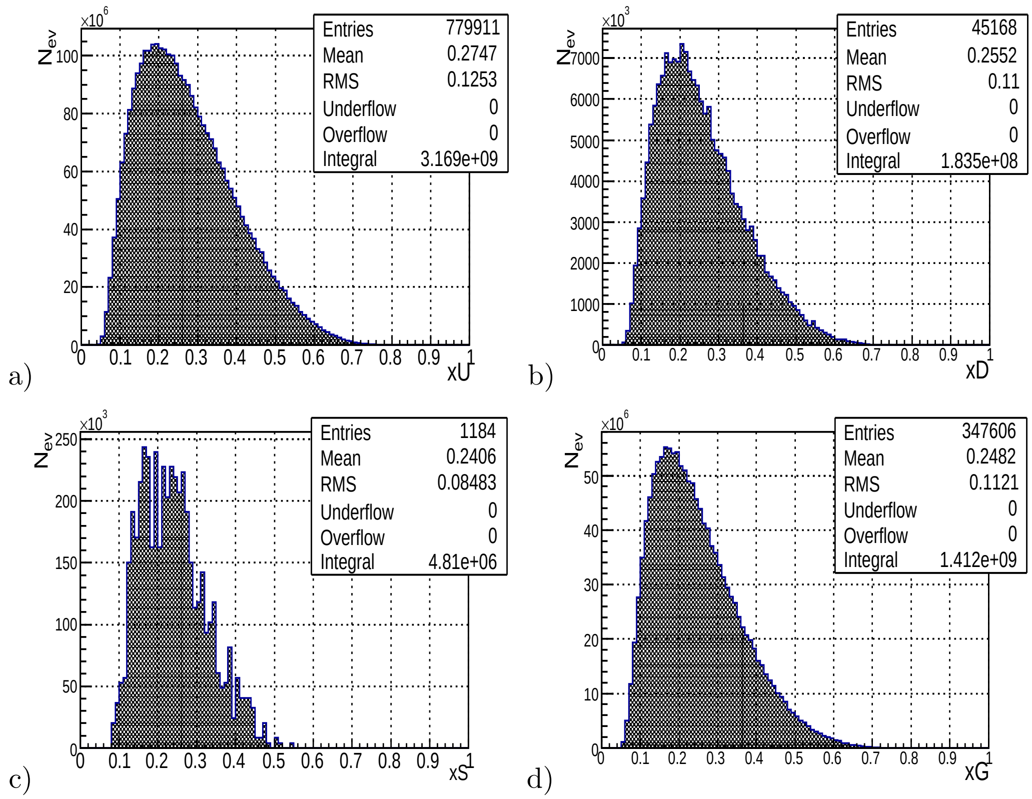


Figure 2: *x distributions of valence:* **a)** *up quarks;* **b)** *down quarks;* **c)** *strange quarks; and* **d)** *of gluons.*

It is seen that xU plot for up-quarks (i.e. **a)** plot) and the xG plot for gluons (i.e. **d)** plot) [3], give the main contributions. The plot xD with the d-quarks contribution (i.e. **c)** plot) shows that the contribution of down qarks is significantly less (by factor about 0,058) as compared with the contribution of up-quarks. The contribution of strange quarks, which is shown in xS plot (i.e. **c)** plot), demonstrates the smallest contribution.

The most ineresting for us is the information about the size of the x-region which will be available at the FAIR energies. The plots of Figure 2 show that x-varaiable will span the interval $0.06 < x < 0.7$.

[3]Their number of entries on the histogram should be divided by factor 2

4 Fake photons in signal events

The signal events, defined by the $q\bar{q} \to \gamma + g$ and $qg \to \gamma + q$ subproceses, should also contain some hadrons in the final state. Fortunately, their number would be essentialy restricted by the upper limit caused by the beam energy $E_{beam} = 15$ GeV. This circumstance may simplify greatly the identification of final state particles and the physical analysis due to reduction of the phase space and, therefore, due 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 photons which may fake the signal ones, produced in a signal annihilation subproceses. Here, the PYTHIA events generator option for getting the information about the parent particles, which serve as the origin of the outgoing decay products, will be used.

The study of the sources of fake photons have shown that the contribution of neutral pion π^0 decay is a dominat one. It provides a much higher (more than one order) contribution than all of other decay channels. The next contribution, which is more than about one order less, comes from the η, and then follow in decending order ω, Σ^0, η' decays and the decays of other mesons.

4.1 The kinematical distributions of background photons in signal events

The main kinematical distributions of background photons in signal events are presented in the Figure 3. They are obtained basing on the same sample of 1 000 000 signal events generated by PYTHIA and which were used in Section 2. One can see from the statistics frame in the upper part of the plots that the contribution of all the fake photons, including the contribution from the neutral pions, which was discussed before, can be by factor of about 2.75 larger than the number of of signal direct photons.

From Fig.3**a** one can see that the energy of the fake photons covers the range $0 \leq E^{\gamma}_{dec} \leq 5$ GeV and it has the average value of $< E^{\gamma}_{dec} > = 0.7$ GeV. At the same time, the range of the transverse momentum (Fig.3**c**) is $0 \leq PT^{\gamma}_{dec} \leq 1$ GeV/c and it has the average value of $< PT^{\gamma}_{dec} > = 0.17$ GeV/c.

The comparison of the plots shown in Figure 3 for the energy E^{γ}_{dec} and the transverse momentum PT^{γ}_{dec} distributions of fake photons with the analogous plots of **a**) and **b**) at Fig.1 for signal photons shows that they are very different, while the angle distributions Fig3**e** are, practicaly, have the same shape in Figs.1**c** and 3**e**. It covers also the same range $0 \leq \Theta^{\gamma} \leq 180^{o}$ and has the average value $< \Theta^{\gamma} >= 28^{o}$.

From the the shapes of the PT^{γ}_{dec} distribution of fake photons shown on Fig.3**c** and the corresponding plot of Fig.1**a** for direct photons, one can see that the cut on transverse momentum about $PT^{\gamma} > 0.6$ GeV/c may allow to eliminate the fake photons at the cost of a bit less than a half of signal direct photons loss.

The right-hand column of Fig.3 includes the plots **b**) and **d**) which contain the values of the Vx- (Vy-distribution is identical to that one of Vx) and Vz- components of the 3-vector **V** which points the position (in mm) of fake photon production vertex. The logarithmic scales of Vx- and Vz- axes show that the most of fake photons in the signal events are produced very close to the point of direct photons production (interaction point).

Fig3**f** shows the spectrum of the number of fake photons per event. It is seen that the number of signal events, which do not have at all the fake photons (bin0), is quite large, and the range of the number of fake photons in event ($N^{\gamma}_{dec}/event$) spreads up to eighteen $0 < N^{\gamma}_{dec}/event < 18$.

4.2 Separation of background photons in signal events

To reduce the fake photons background we propose the next two selection cuts:

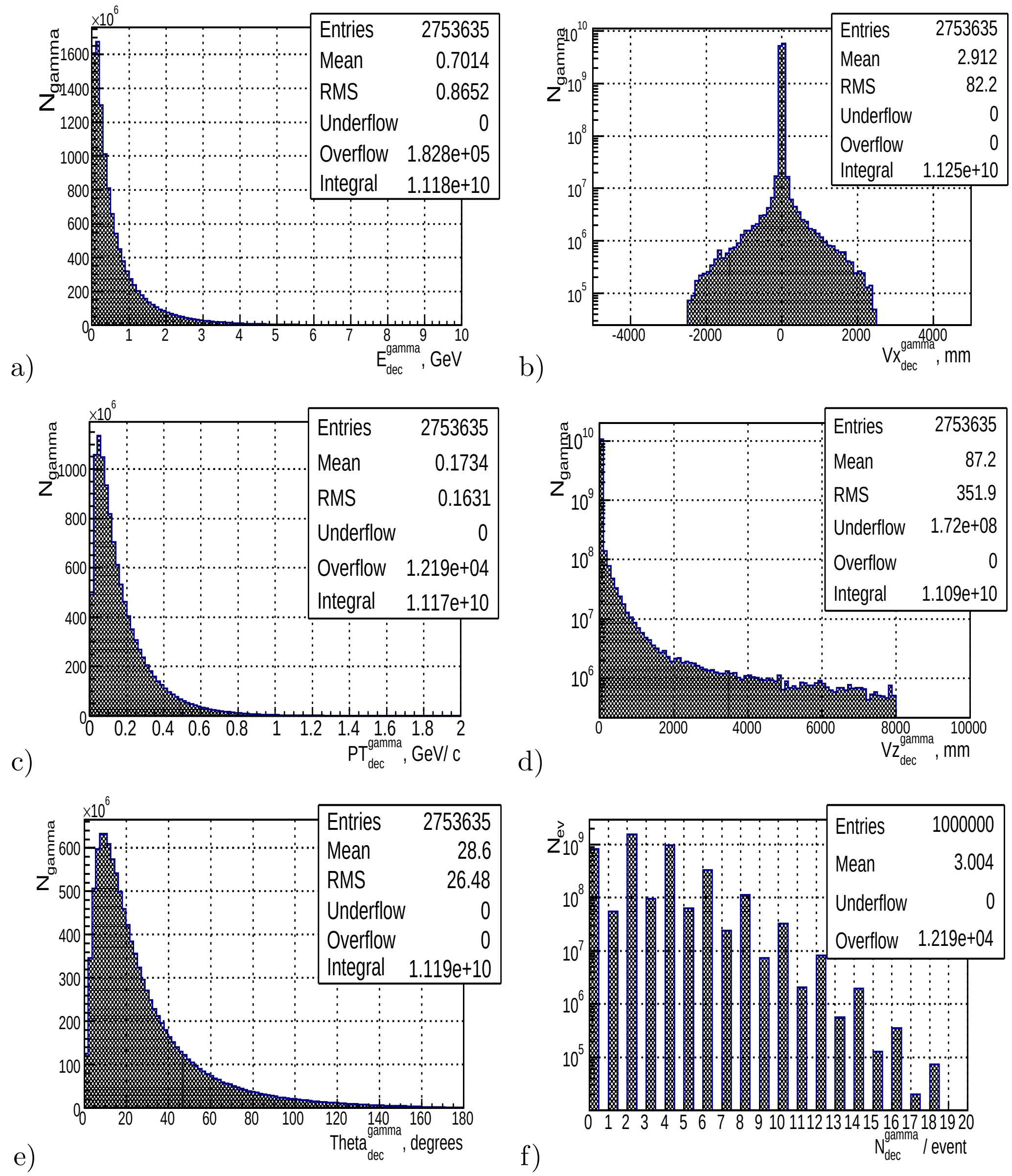


Figure 3: *Left column - distributions of the number of fake photons versus their:* **a)** *energy* E^{γ}_{dec}*;* **c)** *transverse momentum* PT^{γ}_{dec} *and* **e)** *polar angle* θ^{γ}_{dec}*. Right column - distributions of:* **b)** *x-coordinate of fake* γ *production vertex* **d)** *z-coordinate of fake* γ *production vertex and* **f)** *the total number* N^{γ}_{bkg} *of fake photons per signal event.*

1.) Gamma isolation criteria:

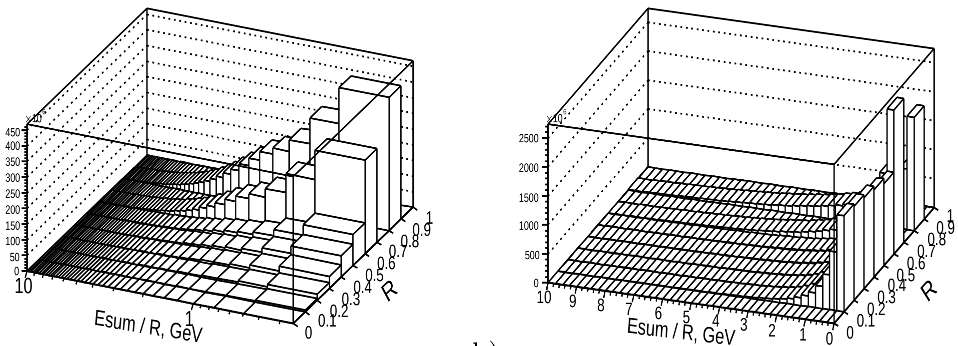
we select only those photons for which the summed energy E_{sum} of all the charged particles around the photon within the cone of the radius $R=\sqrt{\Delta^2_{\varphi}+\Delta^2_{\eta}}=0.2$ in the $\eta-\varphi$ space is less than 0.25 GeV, i.e. $E_{sum} \leq 0.25$ GeV. [4]

2.) Restriction on photon PT^{γ}:

we select only photons having the transverse momentum higher than 0.2 GeV/c, i.e. $PT^{\gamma} \geq$ 0.2 GeV/c.

[4] Here $\Delta_{\varphi}=\varphi_{\gamma}-\varphi_p$ is the difference of the photon's (γ) azimuth angle φ_{γ} and the azimuth angle φ_p of the particle (p). Analogously, $\Delta_{\eta}=\eta_{\gamma}-\eta_p$ is the difference of the photon and the particle pseudorapidities. The azimuth angle φ and the polar (zenith) angle θ (counted from the beam direction, are used to determine the direction of particle 3-momentum). The particle pseudorapidity η is defined as $\eta=-\ln tg(\theta/2)$.

The plots presented on the Fig.4 illustrate the action of the photon isolation criterion used for the definition of the first cut. They show the distributions of the total energy of the charged particles which are contained within the cones of the radius R around the photon momentum. The comparison of the plot **a**) (for the signal photons) with the plot **b**) (for the background photons) show that the signal photons have much smaller summarized energy content within the cone of $R \leq 0.2$ than the energy content around the fake photons. The choice of the values $E_{sum} \leq 0.25$ GeV within R= 0.2 allows to minimize the number of background fake photons on 67%, with the 1.2% loss of the signal events.



a) b)

Figure 4: *Demonstration of photon isolation criterion. Distributions of the summarized energy* E_{sum} *within the cone of the radius R=0.1, 0.2, 0.3.... around:* **a)** *signal photons,* **b)** *background photons.*

The second cut $PT^{\gamma} \geq 0.2$ GeV/c allows to reduce the background to 1.3%, thus achiving the signal to background ratio S/B = 73.9 by the additional loss of 6.5% of signal events. The value of $PT^{\gamma} \geq 0.25$ GeV/c allows to suppress the fake photons background in signal events completely.

5 Background processes to the process of direct photon production $p\bar{p} \to \gamma + X$.

The main contribution to background for the process of direct photon production comes from the processes, presented in the Table 2 in order of their cross section decrease. As it can be seen (from the comparison with the Table1), their cross sections are in orders higher than the signal process cross section. So it is especially important to find out the criteria for their suppression.

Table 2: Background processes and their cross sections

PYTHIA's number of subprocess	Type of process	Cross section, mb
95	Low-pT scattering	$3.37 \cdot 10^{1}$
92	Single diffractive (XB)	1.72
93	Single diffractive (AX)	1.72
94	Double diffractive	$2.48 \cdot 10^{-1}$
28	$f + g \to f + g$	$1.67 \cdot 10^{-2}$
68	$g + g \to g + g$	$4.89 \cdot 10^{-3}$
11	$f + f' \to f + f'(QCD)$	$8.76 \cdot 10^{-3}$
12	$f + \bar{f} \to f' + \bar{f}$	$1.11 \cdot 10^{-3}$
13	$f + \bar{f} \to g + g$	$1.07 \cdot 10^{-3}$
53	$g + g \to f + \bar{f}$	$1.29 \cdot 10^{-4}$

The distributions of the photons from the background events over their energy, transverse momentum, zenith angle and the number of the photons per event are presented in the Fig.5. From them one can see, that the photons in the background events are rather low energetic (mostly < 2 GeV with the range of energy $0 \leq E^{\gamma}_{bkg} \leq 4$ GeV and the mean value $< E^{\gamma}_{bkg} >$ $= 0.64$ GeV), have low transverse momenta (mostly $PT^{\gamma}_{bkg} < 0.4$ GeV/c with the range $0 \leq PT^{\gamma}_{bkg} \leq 0.7$ GeV/c and the mean value $< PT^{\gamma}_{bkg} > = 0.15$ GeV/c). Fig.5**b** shows the polar angle distribution for the background photons. Similar to the signal photons $0 \leq \theta^{\gamma}_{bkg} \leq 180^o$, $< \theta^{\gamma}_{bkg} >= 30.3^o$. From the Fig.5**d** one can see that background events may include up to 18 photons. Let us note that some (11.2 %) of the processes considered as background ones, may not include photons at all (see Fig.5**d** bin 0).

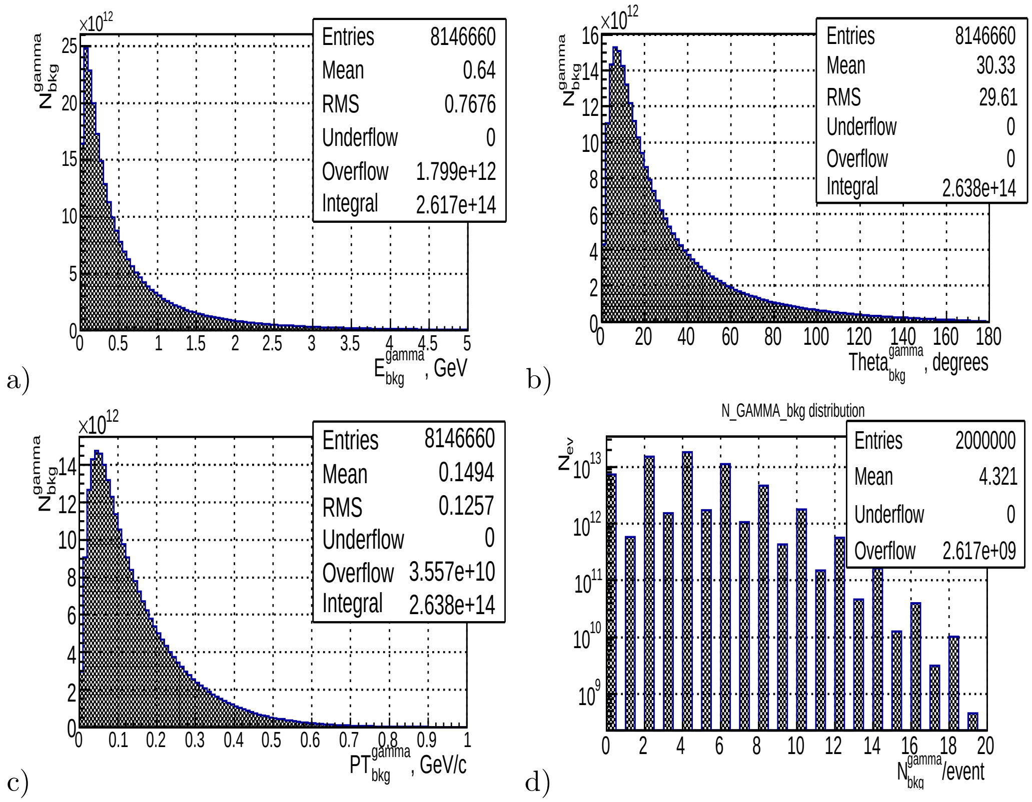


Figure 5: *Left column - distributions of the number of background photons versus their:* **a)** *energy* E^{γ}_{bkg}*;* **c)** *transverse momentum* PT^{γ}_{bkg}*. Right column- distributions of:* **b)** *polar angle* θ^{γ}_{bkg}*;* **d)** *the total number* N^{γ}_{bkg} *of the photons per the background event.*

For the background suppression we propose, similar to the signal process case, the next criteria:

1.) Isolation criterion for the leading photon (photon with the highest energy in event): we select only those events in which the summed energy $E_{sum} \leq 0.25$ GeV of all the charged particles around the leading photon within the cone of the radius $R=\sqrt{\Delta^2_{\varphi} + \Delta^2_{\eta}} = 0.2$ in the $\eta - \varphi$ space. This criterion allows to suppress up to 83.7 % of background events.

2.) Transverse momentum cut on the leading photon $PT^{\gamma} > 0.2$ GeV/c. This criterion allows to suppress most of the rest of background (up to 4.9 % of background events).

The proposed cuts demonstrate the similar results for all the types of the background processes, shown above, and look promissing for the signal separation. But the account of detector effects may significantly change the picture. So, it is necessary the further investigation with use of Geant.

6 Summary.

The present paper contains the results of modeling of the most important processes of direct photons production in antiproton-proton collision $\bar{p}p \to \gamma + X$ for the case of antiproton beam having the energy E_{beam} = 15 GeV. The set of kinematical distributions such as the energy, the transverse momentum and the angle of the signal photons was build. These distributions have shown the size of kinematical regions which can be expected for the study. Estimation of the x-region, which can be available for the study of the nucleon structure functions, is also presented.

The sources of background which is caused by the presence of the fake photons in the final state of the signal processes are studied in detail. The way to get rid of them was proposed. Two cuts were worked out. They are the "gamma isolation criteria" and the "photon PT^{γ} restriction" which allow to reach a good suppression of the influence of fake photons in the signal events. It was shown that the application of the similar method to the case when the background caused by the other QCD and minimum-bias processes can also help to reach a good background suppression. The next modeling by application of GEANT tools for account of the detector influence should be a useful step.

7 Acknowledgements.

The work was carried out with the financial support of SAEC "Rosatom" and Helmholtz Association for A.N.Skachkova.

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