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Dzhelepov Laboratory of Nuclear Problems

**FINAL REPORT ON THE
START PROGRAMME**

**Study, validation, and development of event
generators for prompt photon production**

Supervisor:

Dr. Igor Denisenko

Student:

Butskikh Gleb, Russia
Samara University

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Abstract

In this paper, we investigate the direct photon production in unpolarized proton-proton collisions in the energy range close to NICA collider energies. We compare the results obtained using the Monte Carlo generator developed by us and the Pythia8 library together with the experimental data. We estimate the ratio of signal to background photons, considering the direct, decay and fragmentation photons.

1 Introduction

Monte Carlo methods play a key role in modern high-energy physics, particularly in the modeling and analysis of complex particle interactions. One such method is the generation of events at the parton level, which allows us to investigate the internal structure of hadrons and the mechanisms of their interactions [1]. Collisions of polarized (longitudinally and transversely) protons and deuterons with high luminosity (up to 10^{32} $\text{cm}^{-2}\text{s}^{-1}$) at the NICA Collider provide the opportunity to study a wide variety of spin and polarization-dependent effects in hadron-hadron collisions, including:

1. Reactions with the production of Drell-Yan lepton pairs.
2. Processes with the production of direct photons.
3. Spin effects in reactions with the production of baryons, mesons and others [2].

2 Monte-Carlo event generation

The main task of a Monte Carlo generator [3, 4] is to model the primary interaction in the beam collision region. The generated long-living particles are propagated through the detector using dedicated software to simulate its response. Analysis of the detector response allows to estimate the experiment capabilities to study processes under consideration.

The event generation is performed in several stages, corresponding to the physical processes that ultimately lead to experimentally observed particles. In proton-proton and proton-antiproton collisions, the following processes are necessary to fully describe the experimental data: parton interactions, parton showers, and hadronization processes.

At the same time, event generators can be used to predict physical observables (differential cross sections, etc.) for the ideal detector via the Monte Carlo method. The predictions are subjected to statistical uncertainties controlled by the used statistics.

To simulate the "hard" processes of high-energy physics, both our generator and PYTHIA use generator uses the collinear parton model. According to this theory, the

interaction of parent hadrons occurs through the interaction of their component partons, each of which carries a fraction of the longitudinal momentum of the parent parton [5].

The implementation of this model requires computing multidimensional integrals over parton momentum fractions and phase space, where the calculation using the Monte Carlo method is based on the following basic principle: the value of the integral can be written using the average of the integral expression:

$$I = \int_{x_1}^{x_2} dx f(x) = (x_2 - x_1) \langle f(x) \rangle. \quad (1)$$

Therefore, if we take N random numbers that are evenly distributed between x_1 and x_2 , then the average value of the function $f(x)$ will be determined by the value of I in formula:

$$I \approx (x_2 - x_1) \frac{1}{N} \sum_{i=1}^N f(x_i). \quad (2)$$

To evaluate the accuracy of the calculation, we can use the central limit theorem: the distribution $\langle f(x) \rangle$ will tend to be Gaussian with a standard deviation $\sigma_{mc} = \frac{\sigma}{\sqrt{N}}$, where σ is the standard deviation of $f(x_i)$. Then the value of the integral is the average value of the weight:

$$W_i = (x_2 - x_1) f(x_i), \quad (3)$$

$$I \approx I_N = \frac{1}{N} \sum_{i=1}^N W_i. \quad (4)$$

Let's define the dispersion as $V_n \equiv \sigma^2$, write down the formula:

$$V_N = \frac{1}{N} \sum_i W_i^2 - \left[\frac{1}{N} \sum_i W_i \right]^2, \quad (5)$$

from which $\sigma_{MC} = \sqrt{\frac{V_N}{N}}$ and totally we get formula calculation of the integral by the Monte Carlo method [6]:

$$I \approx I_N \pm \sqrt{\frac{V_N}{N}}, \quad (6)$$

3 Direct photon production

In this chapter we compare results from Pythia [7] and from our Monte-Carlo generator, based on Collinear Parton Model(CPM). The direct photon production at the energies of closed to NICA collider energies is dominated by Compton scattering process $q + g \rightarrow \gamma + q$, about 94%. Another process is quark-antiquark annihilation $q + \bar{q} \rightarrow \gamma + g$, about 6%, where $q=d, u, s, c, b$. These relations of the invariant cross section with to p_T are shown in Figure 1.

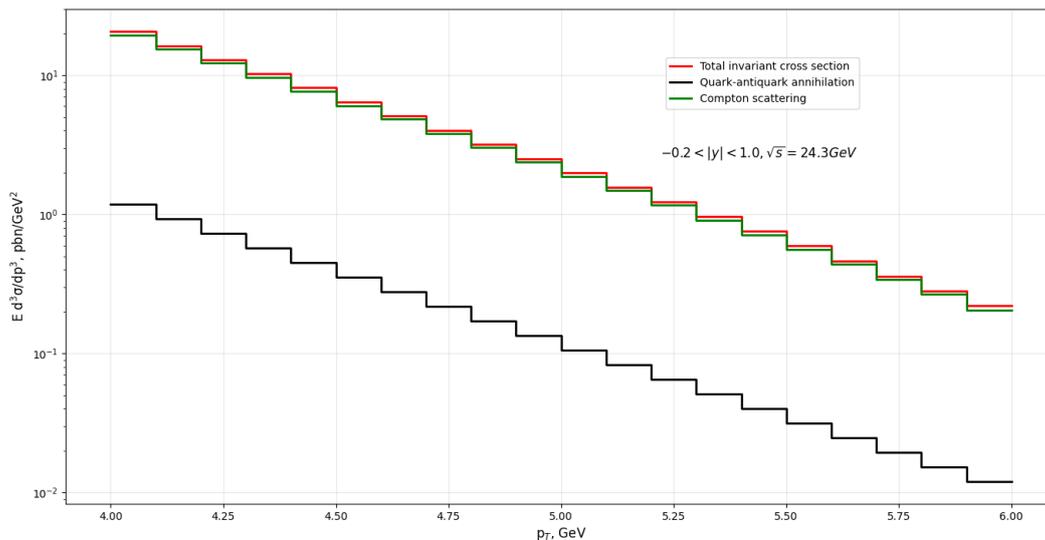


Figure 1: Relative contributions of Compton and annihilation direct photon production processes obtained in our CPM generator.

We consider the collinear parton model, therefore we will define a formula by which the differential invariant cross section is calculated. Let us write down the calculation formulas for the case of direct photon production in hadron-hadron collisions, where by direct photons we mean photons produced directly in the hard interaction process of partons. Let the two initial protons have 4-momenta P_1^μ and P_2^μ collide with energy $\sqrt{S} = \sqrt{(P_1 + P_2)^2}$ in center-of-mass. Then their 4 momenta are written as $P_1^\mu = (\frac{\sqrt{S}}{2}, 0, \frac{\sqrt{S}}{2})$

and $P_2^\mu = (\frac{\sqrt{S}}{2}, 0, -\frac{\sqrt{S}}{2})$. Then, according to the collinear approximation, the partons emitted one by one by each of the hadrons carry away the fractions of the longitudinal momentum x_1 and x_2 . So, their 4-momenta are represented as $q_i = P_i x_i, i = 1, 2$. Using the hypothesis of factorization of soft and hard QCD processes, or, in other words, large and small distances, we write an expression for the cross section of the generation of direct photons with a 4-momenta p_γ in the hard scattering process of partons $a + b \rightarrow \gamma + c$:

$$d\sigma^{CPM} = \int dx_1 f_a(x_1, \mu^2) \int dx_2 f_b(x_2, \mu^2) d\hat{\sigma}(a(q_1)b(q_2) \rightarrow \gamma(p_\gamma)c), \quad (7)$$

where $d\hat{\sigma}$ hard Compton scattering or annihilation cross section; $f_{a(b)}(x_{1,2}, \mu^2)$ stand for the collinear distributions of partons a(b) in the protons, depending on the factorization scale μ , which is usually chosen to be of the order of the largest transverse momentum in the process, in this case $p_{\gamma T}$. We define the Mandelstam variables in the processes under consideration: $\hat{s} = (q_1 + q_2)^2, \hat{t} = (q_1 - p_\gamma)^2, \hat{u} = (q_2 - p_\gamma)^2$. Then the cross section of the hard photon production process can be written as:

$$d\hat{\sigma} = \frac{1}{16\pi^2 I} \frac{d^3 p_{\gamma T}}{E_\gamma} \overline{|M(a(q_1)b(q_2) \rightarrow \gamma(p_\gamma)c)|^2} \delta(\hat{s} + \hat{t} + \hat{u}), \quad (8)$$

where $\overline{|M(a(q_1)b(q_2) \rightarrow \gamma(p_\gamma)c)|^2}$ is the squared matrix element for the hard parton-scattering process $a + b \rightarrow \gamma + c$ and δ -function corresponds to the 4-momenta conservation in a hard process; $I = 2x_1 x_2 S$ – flux factor;

$\hat{s}, \hat{t}, \hat{u}$ are determined by the following formulas:

$$\begin{aligned} \hat{s} &= x_1 x_2 S, \\ \hat{t} &= -p_T^2 (1 + e^{y_\gamma - y_c}), \\ \hat{u} &= -p_T^2 (1 + e^{y_c - y_\gamma}), \end{aligned}$$

Finally, we get the collinear parton model formula used in our Monte Carlo event generator:

$$\sigma_{total} = \int_0^1 dy_\gamma \int_0^1 dy_c \int_0^{\sqrt{S}} dp_T \frac{f_a f_b}{8\pi x_1 x_2 S^2} \overline{|M(a(q_1)b(q_2) \rightarrow \gamma(p_\gamma)c)|^2}, \quad (9)$$

where

$$x_1 = \frac{p_T}{\sqrt{S}}(e^{y_\gamma} + e^{y_e}), \quad (10)$$

$$x_2 = \frac{p_T}{\sqrt{S}}(e^{-y_\gamma} + e^{-y_e}). \quad (11)$$

To facilitate comparison with experimental data, which are typically presented as invariant cross-section distributions, it was necessary to establish a normalization procedure for the generated results. In terms of the kinematic variables, the invariant cross section can be expressed as:

$$\sigma_{inv} = E \frac{d^3\sigma}{dp^3} \quad (12)$$

This expression defines the invariant differential cross section, which can also be formulated as

$$\sigma_{inv} = \frac{d^3\sigma}{dp_x dp_y \frac{dp_z}{E}} = \frac{d^3\sigma}{dp_x dp_y dy}, \quad (13)$$

and in the polar coordinates of p_x , p_y , if the system is azimuthally isotropic in the transverse plane, this can be transformed to

$$\sigma_{inv} = \frac{d^3\sigma}{p_T dp_T dy d\phi} = \frac{d^2\sigma}{2\pi p_T dp_T dy}, \quad (14)$$

As a result, we got a formula for invariant cross section if we take ranges of p_T and y :

$$\sigma_{inv} = \frac{\sigma_{total}}{N_{events}} \frac{1}{2\pi \Delta p_T \Delta y} \sum_{i=1}^{N_0} \frac{1}{p_{T,i}} \quad (15)$$

where σ_{total} denotes the total process cross section, N_{events} is the number of generated events, Δp_T defines the transverse momentum range for averaging, N_0 counts the number of particles within the bin, and $\sum_{i=1}^{N_0} \frac{1}{p_{T,i}}$ constitutes the sum of inverse transverse momentum weights for all photons in the bin [11].

To simulate prompt photon production in Pythia8, two relevant process flags were activated: "PromptPhoton:qg2qgamma = on" and "PromptPhoton:qqbar2ggamma = on".

The simulation of prompt photon production in our Monte Carlo generator is realized

through the selection of specific squared matrix elements[12]. The active quark flavours are determined using the LHAPDF6 framework [13]. The squared modulus of the amplitude for the hard parton-scattering process for the process $q + \bar{q} \rightarrow \gamma + g$ reads:

$$\overline{|M|}^2_{q\bar{q}\rightarrow\gamma g} = \frac{128}{9}\pi^2\alpha\alpha_s Z_q^2 \frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}} \quad (16)$$

And also the squared modulus of the amplitude for process $q + g \rightarrow \gamma + q$ are:

$$\overline{|M|}^2_{qg\rightarrow\gamma q} = -\frac{16}{3}\pi^2\alpha\alpha_s Z_q^2 \frac{\hat{t}^2 + \hat{s}^2}{\hat{t}\hat{s}} \quad (17)$$

$$\overline{|M|}^2_{qg\rightarrow g\gamma} = -\frac{16}{3}\pi^2\alpha\alpha_s Z_q^2 \frac{\hat{u}^2 + \hat{s}^2}{\hat{u}\hat{s}} \quad (18)$$

Here Z_q is the quark charge. α is Sommerfeld's fine-structure constant and $\alpha \approx \frac{1}{137}$; The strong coupling constant $\alpha_s = \alpha_s(\mu^2)$ is the fundamental coupling parameter in quantum chromodynamics that quantifies the strength of the strong interaction between quarks and gluons. We choose the collinear distribution functions $f_{a(b)}(x_{1,2}, \mu^2)$ of partons using the LHAPDF library. We take into account the only u, d, s, c, b quark flavours for both direct photon production processes. So, their flavour numbers are 1, 2, 3, 4, 5 and also in Compton scattering process we use gluon and it's number is 21. And the function of choosing the flavour of particle we use also from the LHAPDF framework. Also we chose the desired particles in Pythia, by their identification number.

As PYTHIA can take into account the effects of initial and final state radiation and intrinsic phenomenological primordial transverse momentum, we tested three Pythia configurations for the comparison with the existing experimental data. They read: default, with disabled primordial k_T with flag "`BeamRemnants:primordialKT = off`", with disabled primordial k_T , ISR and FSR using flags: "`PartonLevel:ISR = off`" and "`PartonLevel:FSR = off`". The our CPM generator configuration corresponds to the Pythia one with disabled primordial k_T , ISR, and FSR. Turning off primordial k_T disables Gaussian modeling of initial partonic transverse momentum. Turning off ISR and FSR also disables initial and final state radiation. Direct photon distributions from Pythia and different experi-

ments with \sqrt{S} from 23.75 GeV to 63.0 GeV were compared.

The list of experiments [8–10] considered in the work is presented in Table 1.

Name of Experiment	\sqrt{S}
CERN UA6	24.3 GeV
CERN NA24	23.75 GeV
CERN R806	63 GeV

Table 1. List of experiments

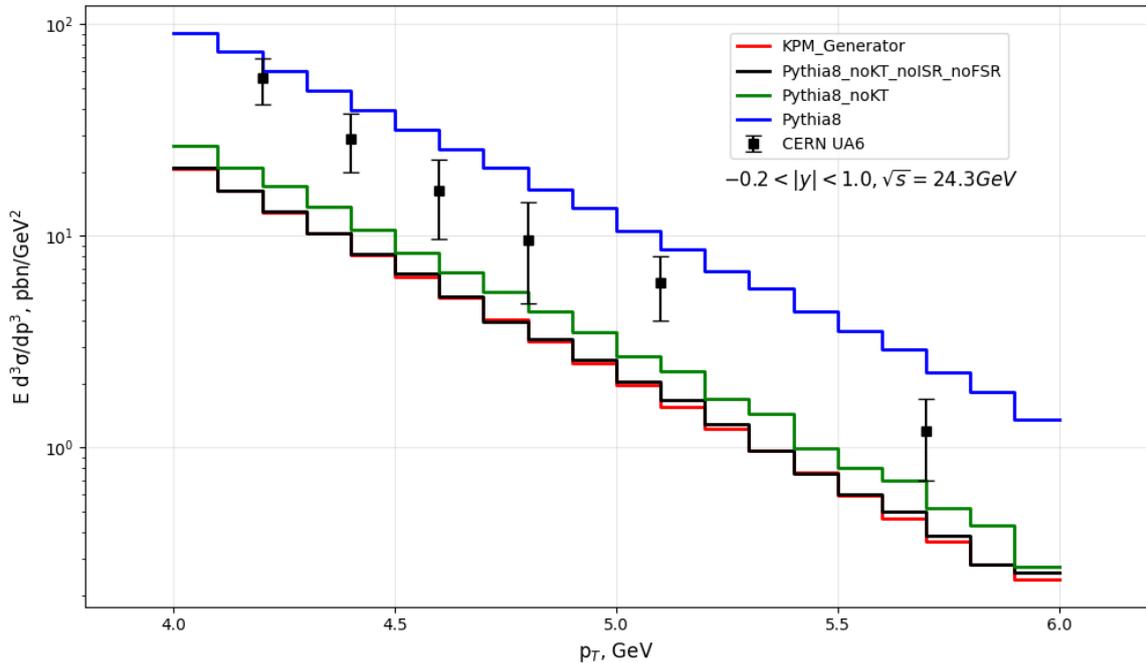


Figure 2: Comparison of CPM generator data with Pythia8 in experiment CERN UA6.

A simulation of the direct photon production spectrum was performed using transverse momentum in the CERN UA6, NA24, R806 experiments at $\sqrt{S} = 24.3, 23.75, 63$ GeV respectively in the CMS of colliding protons. The results are presented in Figures 2, 3, 4 as histograms of the differential invariant cross section distribution as a function of photon transverse momentum. The data from the collaborations are presented as points with error bars. We observe that the simulation results in CPM generator are same as in Pythia without ISR, FSR and primordial k_T . From this we can draw a conclusion about the accuracy of modeling the process of production of direct photons in generator and its applicability in further calculations.

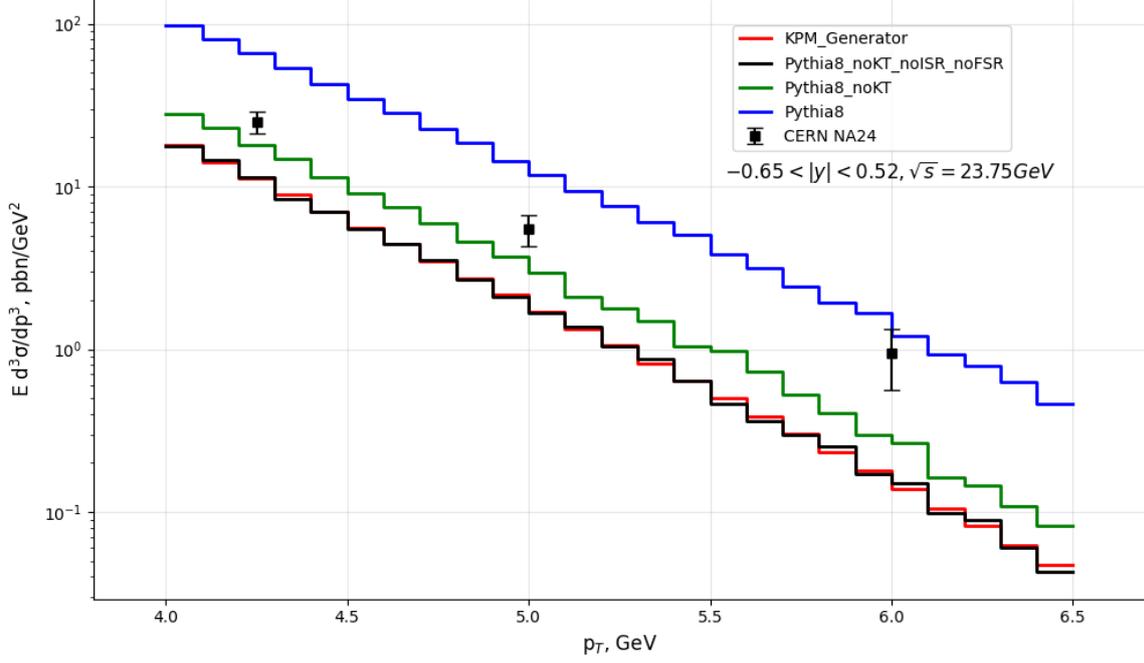


Figure 3: Comparison of CPM generator data with Pythia8 in experiment CERN NA24.

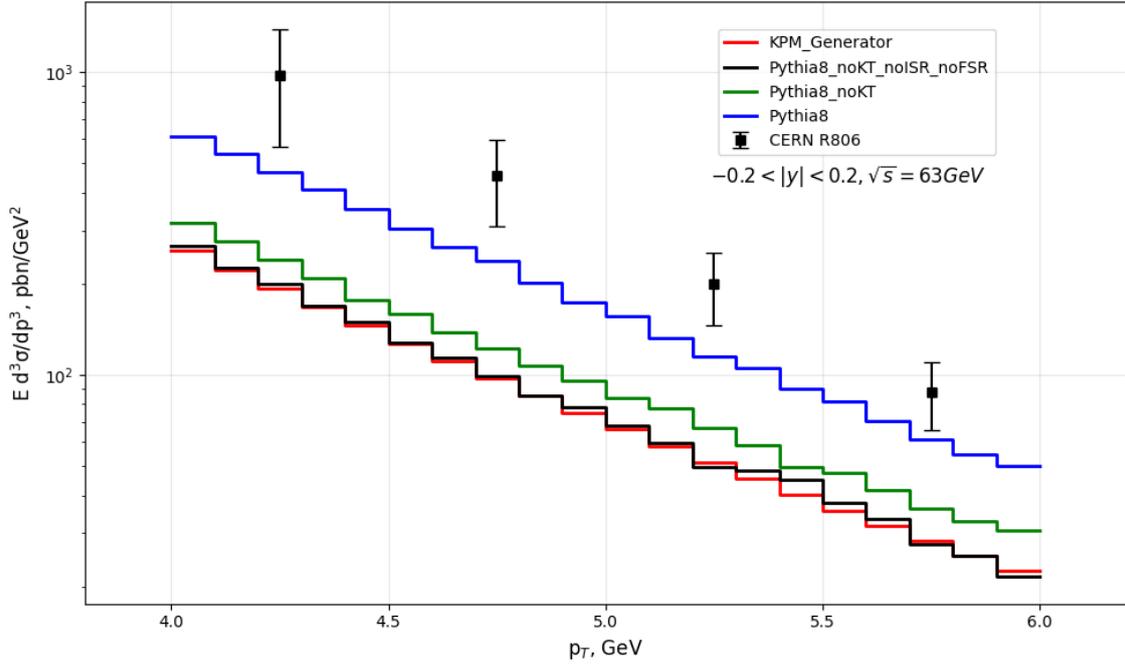


Figure 4: Comparison of CPM generator data with Pythia8 in experiment CERN R806.

4 Decay and fragmentation photons

The study of photon spectra in proton-proton collisions is of considerable interest for understanding the kinematic characteristics of various photon generation mechanisms. In the intermediate transverse momentum region $p_T=4.6$ GeV, the main contribution to

the photon spectrum comes from three main mechanisms: direct photons, decay photons, and fragmentation photons[14, 15]. Direct photons were discussed in the previous chapter. Fragmentation photons arise from the fragmentation of high-transverse-momentum partons into photons which is described via fragmentation functions [16]. Decay photons are produced as a result of electromagnetic decays of hadrons, predominantly $\pi^0 \rightarrow \gamma\gamma$ (98.8%), $\eta \rightarrow \gamma\gamma$ (39.4%) and other mesons [17]. Their spectrum is related to the spectrum of the parent hadrons. In this paragraph we compare invariant differential cross-section of p_T of decay, direct and fragmentation photons at $p_T = 4.6$ GeV, for the collision energy of the WA70 experiment [18].

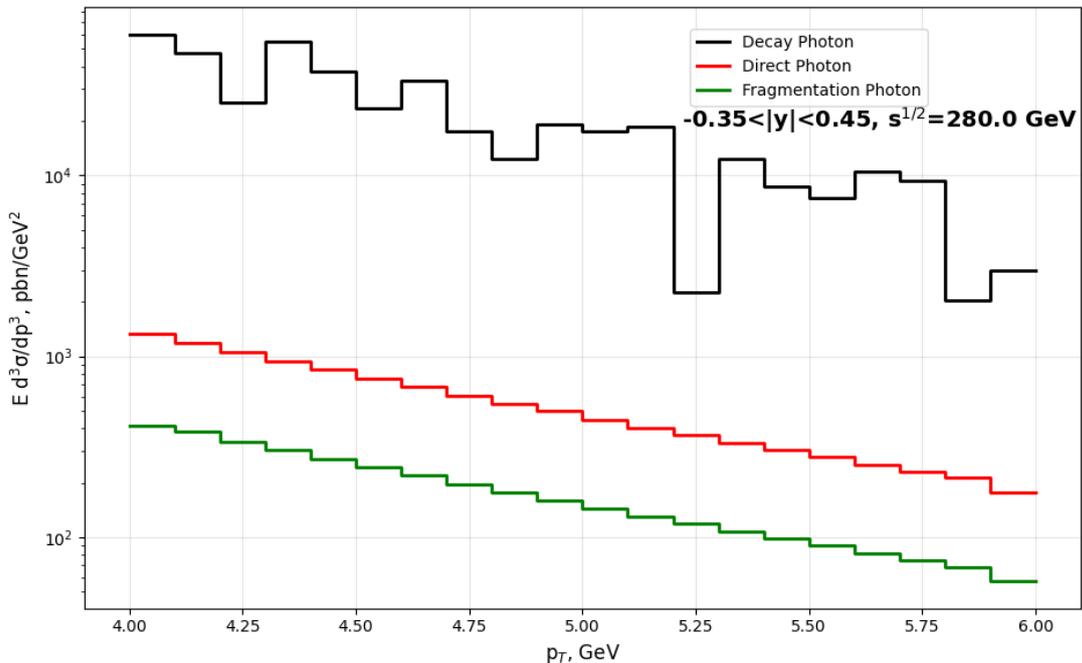


Figure 5: Comparison of direct, fragmentation and decay photon data with Pythia8 at energies $\sqrt{S} = 280$ GeV.

The simulation decay photon production using Pythia8 were switched on two correspondent process flags:

```
"SoftQCD:all = off",
```

```
"SoftQCD:nonDiffractive = on".
```

Also we should include two flags for $\pi^0 \rightarrow \gamma\gamma$ process

```
"111:onMode = off",
```

```
"111:onIfMatch = 22 22",
```

if we want to compare process of π^0 -meson decay.

The simulation fragmentation photon production using Pythia8 were used three flags:

```
"TimeShower:QEDshowerByQ =on",
```

```
"HadronLevel:Hadronize = on",
```

```
"TimeShower:QEDshowerByGamma = on".
```

In the figure 5 we find the invariant cross section of direct and fragmentation photons are significantly lower than the decay one. This fact points out to the necessity of effective subtraction algorithm of decay photons, at first. At second, one should reduce the contribution of fragmentation photons. Both these subtractions can be performed by using the kinematic selection criteria.

5 Conclusion

In this study we examined the direct photon production, encompassing both signal processes and principal background photon sources. Three distinct Pythia configurations were evaluated: the default setup; a configuration with primordial k_T disabled; and a configuration with primordial k_T , ISR, and FSR all disabled. The resulting photon spectra demonstrate satisfactory agreement with available experimental data at center-of-mass energies comparable to the NICA energy range in cases of restricted in ISR, FSR and kT configurations. We also estimated the main sources of background of direct photons being the fragmentation and decay photons using the PYTHIA simulations, and found them to be highly significant. The effective procedure of background cancellation is required. We present the results obtained using the developed by us Monte Carlo event generator based on the pure CPM. They obviously coincide with the results of PYTHIA simulation without ISR, FSR and intrinsic transverse momenta. The validation of the simple calculation using our event generator opens the opportunity to expand it implementing the more complex transverse-momentum-dependent factorization, such as generalized parton model. The work on this topic is in progress.

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