JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

$J/\psi + \gamma$ simulation at SPD

Final report of the START Programme

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Abstract

In this paper, the process of associative production of $J/\psi + \gamma$ is modeled using the Pythia8 package. The combinatorial background of $J/\psi + \gamma$, the background of inclusive production of $J/\psi X$ and the background of "Minimal Bias" processes were also investigated. A set of cuts was obtained that make it possible to separate the signal process from the background well, but the background from the $J/\psi X$ process turns out to be correlated, which complicates its separation. Thus, the problem of the final separation of the background $J/\psi X$ will not be discussed. Upper estimate of the number of events $J/\psi + \gamma$ per year, taking into account the selection efficiency and taking into account the J/ψ detection efficiency ($\sim 40\%$) $N_{year} \sim 190$.

1 Introduction

The associative production of $J/\psi + \gamma$ in proton collisions has been discussed for about 20 years [1], but there are still no experimentally measured production cross sections. Measuring the associative production of $J/\psi + \gamma$ is very important, as it would allow us to: Firstly, to clarify the distribution of the transverse momentum of the partons in the proton, since theoretical predictions are very sensitive to these distributions [2, 3]; secondly, to clarify Sievers' f-type functions [4] without taking into account d-type functions [5]; and also measuring correlations, for example, by azimuth angle, will allow us to reconstruct the Boer-Mulder function, which will allow us to better know how spin is distributed in the proton.

In the SPD experiment at the NICA collider, it is planned to change the cross-section of the associative production $J/\psi + \gamma$ at the collision energy $\sqrt{s} = 27\ GeV$. Registration of J/ψ-mesons will be carried out by registering decay products - pairs $\mu^+\mu^-$ (branching ratio of particle decay along this channel $Br(J/\psi \to \mu^+\mu^-) = 0.05961 \pm 0.00033$). The task in this paper is to evaluate the signal-background ratio and provide a possible set of kinematic constraints that would allow identifying signal events. The estimates will be performed using reaction simulation in the Pythia8 Monte Carlo generator.Anticipating the description of the results, we say that a problem has been discovered (the problem of background correlation $J/\psi + g$), the solution of which will not be considered in this paper, as it requires the involvement of additional research methods.

2 Models

2.1 CPM in Pythia8

Modeling in Pythia8 is based on the collinear Parton model [6], which was proposed back in 1969. The main idea of the parton model is to consider a hadron in a system with infinite momentum. With this approximation, it is possible to imagine a pair of interacting hadrons in the form of clouds of non-interacting partons. If the interaction time is much less than the lifetime of the virtual state, then the partons can be considered as free particles and assume that one parton from each hadron participates in the interaction. Each parton carries a fraction of the momentum of the hadron with some probability, which is described by parton distribution functions. It is assumed that all the partons of one hadron are coherent, that is, if the interaction did not occur, then the sum of the coherent waves of the partons again forms the original hadron, but if the interaction occurred, the original hadron decays into incoherent partons, which are subsequently hadronized. The approximation of partons as free particles generates an additional condition "the initial partons are on the mass surface". Since gluons are massless particles and in comparison with the collision energy $\sqrt{s} = 27$ GeV, the mass of light quarks u, d, s quarks can be neglected, then the condition will be written: $q_1^2 = q_2^2 = 0$. More about CPM model in [7].

The central theorem of the parton model is the factorization theorem, which states that the cross section of the interaction of hadrons can be expressed in terms of the cross section of the interaction of partons in the form of convolution with parton distribution functions. The approximation of zero transverse momentums of partons is called collinear factorization or collinear parton model (CPM). For CPM, parton momentun are expressed in terms of hadron momentum in the form of $q_1^\mu = x_1 P_1^\mu, q_2^\mu = x_2 P_2^\mu$, here x_1, x_2 is the fraction of the momentum that is "carried away" by parton. The factorization theorem for collinear factorization is written as:

$$\sigma(A + B \to C + D) = \sum_{a,b=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 f(x_1, Q) f(x_2, Q) \hat{\sigma}(a + b \to c + d), \tag{1}$$

where summation is carried out by the types of partons of the initial particles, that is, by quarks of all flavors and gluon, $f(x_i, Q)$ are collinear parton distribution functions, $d\hat{\sigma}$ is the section of the parton process, Q is a hard scale.

For calculating in the leading order of the perturbation theory, since we neglect the transverse momentums of the initial particles, it can be shown from the law of conservation of 4-momentum that the correlation sections will be trivial in CPM, that is, each correlation section will be a delta function with the corresponding argument value:

$$i = 1, 2;\ q_i^\mu = x_i P_i^\mu;\ P_i^{x,y} = 0 \ \Rightarrow\ (q_{J/\psi} + q_\gamma)_T = 0;\ \Delta\phi = \phi_{J/\psi} - \phi_\gamma = \pi\ rad;\ |y_{J/\psi} - y_\gamma| = 0.$$

But the experiment shows that trivial cross-sections by correlations are not a physical situation. As a result, there are several reasons why correlations will not be trivial:

- The transverse momentum of the initial particles is not equal to 0.
- Taking into account the next leading order of perturbation theory.
- The uncertainty of determining particle momentum is not 0 due to the imperfection of experimental equipment (In modeling, we will take the uncertainty value 1.5%).

In the Pythia8 generator, the fact that the initial $p_T \neq 0$ is taken into account in a rather unusual way. The components of the transverse momentums of particles generated in a hard process are additionally multiplied by the Gaussian

$$s = x,\ y;\ f(q_T^s) = \exp\left[-(q_T^s)^2/(2\sigma^2)\right]/(\sigma\sqrt{2\pi})$$

with some width that depends on the scale of processes

$$\sigma = \frac{\sigma_{soft} * Q_{half} + \sigma_{hard} * Q}{Q_{half} + Q} * \frac{m}{m + m_{half} * y_{damp}},\ y_{damp} = (E/m)^{r_{red}}.$$

where m is the mass of the system, σ_{soft} is the smudge width p_T of the initial particles in the soft interaction limit, σ_{hard} is the smudge width p_T of the initial particles in the hard interaction limit, Q_{half} is defined as the midpoint between the hard and soft interactions scale, m_{half} is defined as the midpoint between the smallest and largest mass of the system. Indeed, the simulation shows that we are not modeling back-to-back (Fig. 1).

2.2 Background processes

Background events will be considered of several types:

- The combinatorial background in the $J/\psi+\gamma$ reaction includes events of the associative production signal reaction, but a deliberately non-associated photon is chosen as a candidate for a hard photon. It is easy to take such information for particles, since our modeling is called "MC truth".
- Background $J/\psi X$ – as in the previous one, J/ψ-meson and photon pairs from hadronization can be taken as signal events.
- Minimal bias(MB) events that will be modeled using the softQCD process class – there is a possibility that charged pions can be mistaken for muons, respectively, there are quite a lot of candidates for J/ψ mesons that are made up of pairs of $\mu^+\pi^-$, $\pi^+\mu^-$, $\pi^+\pi^-$. Photons are born mainly from decays of π^0 (with a probability of 98.798%), which are born through hadronization.

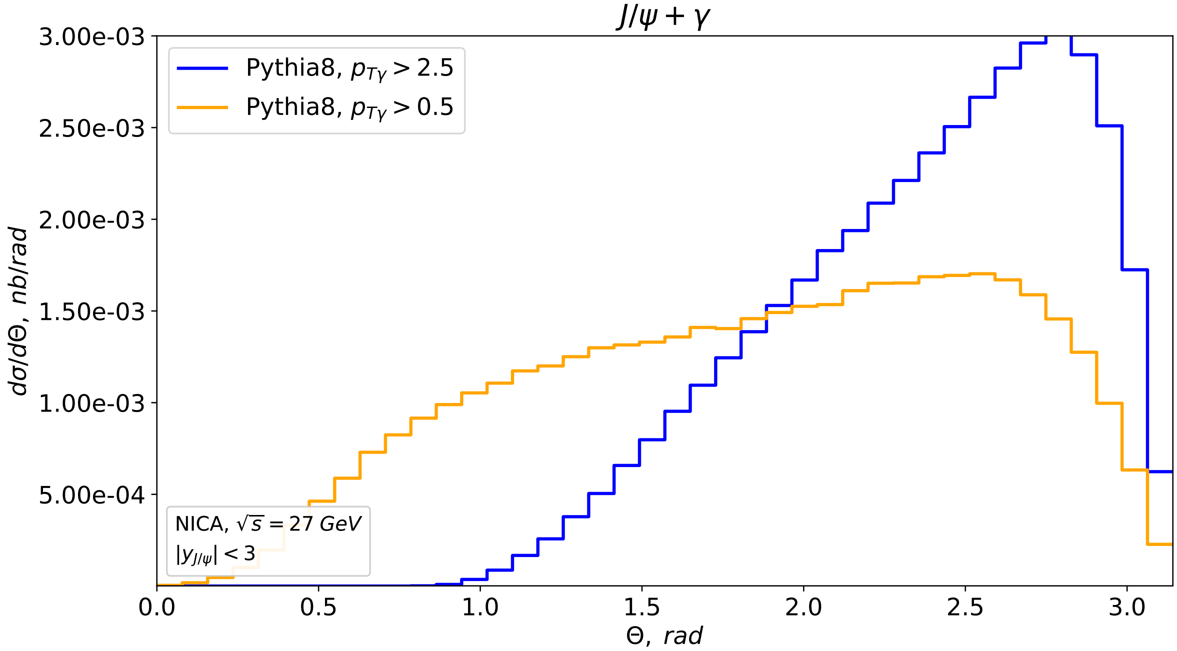


Figure 1: A graph of the differential cross section depending on the angle between the final particles under different cuts on the transverse momentum of the photon.

The weight method was used for the background of the minimal bias events. The weight method will significantly increase the background statistics. That is, the candidate particles in the components of the candidate J/ψ were assigned weight, pions 0.01, muons 1. The weight makes sense of the probability with which we define this particle as a muon, that is, there is a probability to define $\pi^{\pm}$ as $\mu^{\pm}$. The candidate in J/ψ is given a weight equal to the product of the weights of the components:

$$\begin{pmatrix} Weight & 0.01 & 1 & 1 & ... \\ Particle & \pi^{+} & \mu^{+} & \mu^{+} & ... \end{pmatrix} \otimes \begin{pmatrix} Weight & 1 & 0.01 & 0.01 & ... \\ Particle & \mu^{-} & \pi^{-} & \pi^{-} & ... \end{pmatrix}$$

$$\Downarrow$$

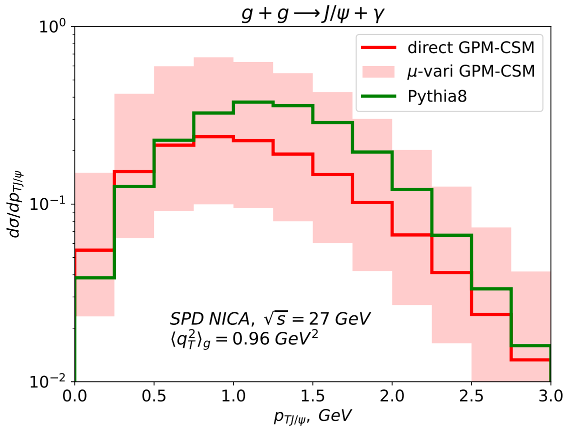
$$\begin{pmatrix} Weight(product) & 0.01 & 1 & 1e-4 & ... \\ Pair & (\pi^{+},\mu^{-}) & (\mu^{+},\mu^{-}) & (\pi^{+},\pi^{-}) & ... \end{pmatrix}$$

The number of events that were simulated for the signal and backgrounds (N): for signal reaction and combinatorial background, respectively ($N = 5 \times 10^{7}$), for background reaction $J/\psi + g$ ($N = 5 \times 10^{7}$), for background events minimal bias ($N = 10^{9}$).

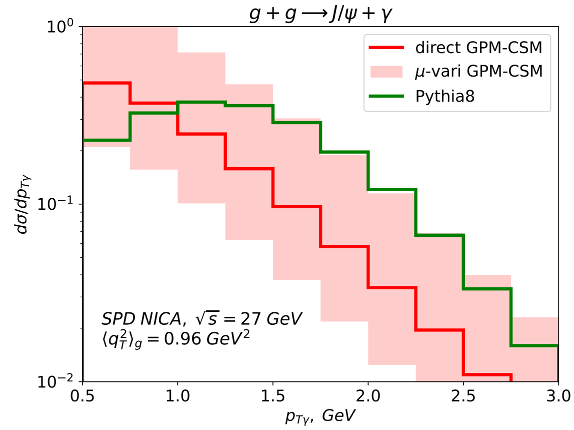
3 Results

3.1 Estimation of the number of events per year

A theoretical calculation of the cross section was carried out in the GPM model with kinematic conditions $\sqrt{s} = 27\ GeV,\ |y| < 3,\ p_{T\gamma} > 0.5\ GeV$. The data obtained are in good agreement with the modeling in Pythia8, which is expected, since modeling in Pythia8 is a calculation in a collinear model with the addition of additional p_T distribution of final particles (Fig. 2a, 2b).



(a) Comparison of the theoretical calculation of the differential cross section by the transverse momentum J/ψ $g+g \to J/\psi+\gamma$ in the GPM-CSM model [8, 9, 10] with the calculation of the reaction in Pythia8.



(b) Comparison of the theoretical calculation of the differential cross section by the transverse momentum γ $g+g \to J/\psi+\gamma$ in the GPM-CSM model [8, 9, 10] with the calculation of the reaction in Pythia8.

According to the obtained theoretical total cross section ($\sigma = 0.33\ nb$), given that the luminosity of $L = 10^{32}\ s^{-1}cm^{-2} = 0.1\ s^{-1}nb^{-1}$, it is possible to estimate the expected amount signal events per year, without taking into account the effectiveness of selection: $N_{year} = \sigma * L * T * Br \sim 22200$.

3.2 Event selection

To separate the signal reaction events from the background ones, let's imagine a fairly good set of cuts found. The efficiency coefficients will be presented further in the comparative table. We will apply the cuts sequentially to justify their expediency. Consider the standard cut $|\cos(\theta_{\mu^+})|,\ |\cos(\theta_{\mu^-})| < 0.9$ (Fig. 3). Its expediency lies in the fact that a large number of MB events are close to the corners, that is, they mostly fly without deviating much from the original axis of the beam.

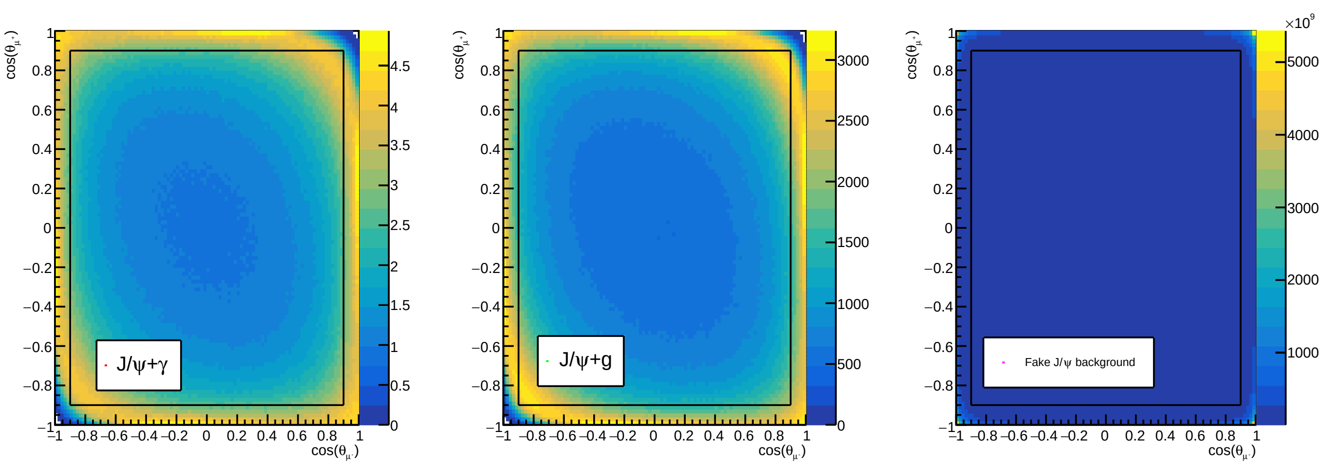


Figure 3: The standard cut when selecting J/ψ. $|\cos(\theta_{\mu^+})|,\ |\cos(\theta_{\mu^-})| < 0.9$.

Next, a good cut was found in the axes of the muon candidate momentum modules $f(p_{\mu^-}) <$

p_{μ^+}, $f(p_{\mu^-}) = 2/(p_{\mu^-} - a) + a$, $a = 0.11$ (Fig. 5). Such the cut is not applied on a permanent basis, but its physical nature becomes clear if we remember that the muon momentums that are generated through the decay of J/ψ are limited from below by the mass of $m_{J/\psi} = 3.096\ GeV$ according to the law of conservation of energy.

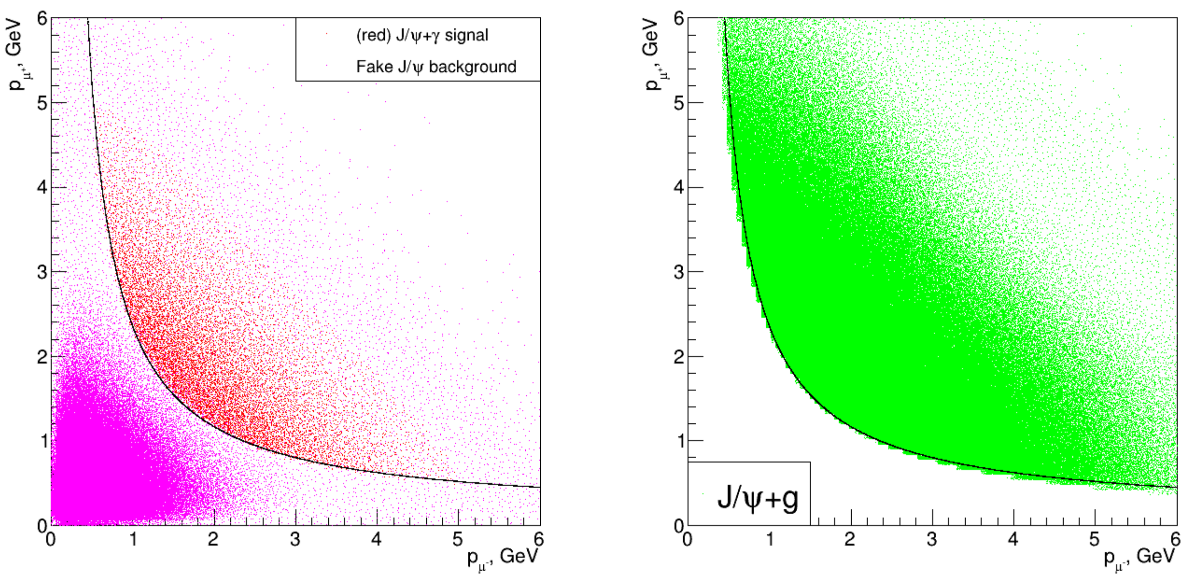


Figure 4: Non-standard cat in the axes of the momentum modules of muon candidates. $f(p_{\mu^-}) < p_{\mu^+}$, $f(p_{\mu^-}) = 2/(p_{\mu^-} - a) + a$, $a = 0.11$

With the constraints already considered, it can be seen that inclusive J/ψ can be well distinguished (Fig. 5), but since we are interested in $J/\psi + \gamma$, it is necessary to investigate whether it is possible to separate associative production from inclusive. We will also select candidates in J/ψ with an invariant mass close to the mass of J/ψ.

To reduce the signal-background ratio $J/\psi + \gamma - J/\psi X$ is possible if we consider the histograms of the distribution of events modulo the transverse momentum of photons (Fig. 6). The photons associated with J/ψ turn out to be more hard and at large $p_{T\gamma} \sim 2.3GeV$ the signal-background ratio is of the order of ~ 1, so we choose a new cut $p_{T\gamma} > 2.5\ GeV$. A large number of MB events will also be cut off. It should also be noted that the combinatorial background from the reaction $g + g \to J/\psi + \gamma$ refuses to be completely filtered out and does not participate in further constructions, respectively, the efficiency coefficient will be zero for the combinatorial background.

Consider the natural idea that the associated photon should be well isolated from other photons and jets of charged particles, since the jets are generated mainly by leptons, which are decay products of the J/ψ meson. The dependence of the number of particles on the angle between the photon candidate for the associated photon and all other photons and charged particles was investigated (Fig. 7a). Thus, we can generalize the selection principle - we require that in the vicinity of the candidate for the associated photon in some solid angle, which corresponds to a linear angle, which we will call the "isolation angle", there are no photons and charged particles (Fig. 7b). It is necessary, however, to remember that with too strict cut, the signal selection efficiency will not be sufficient to restore data dependencies, so the isolation angle is chosen $0.5\ rad$. This choice allows us to save the signal statistics and discard background events of associative birth to a sufficient extent.

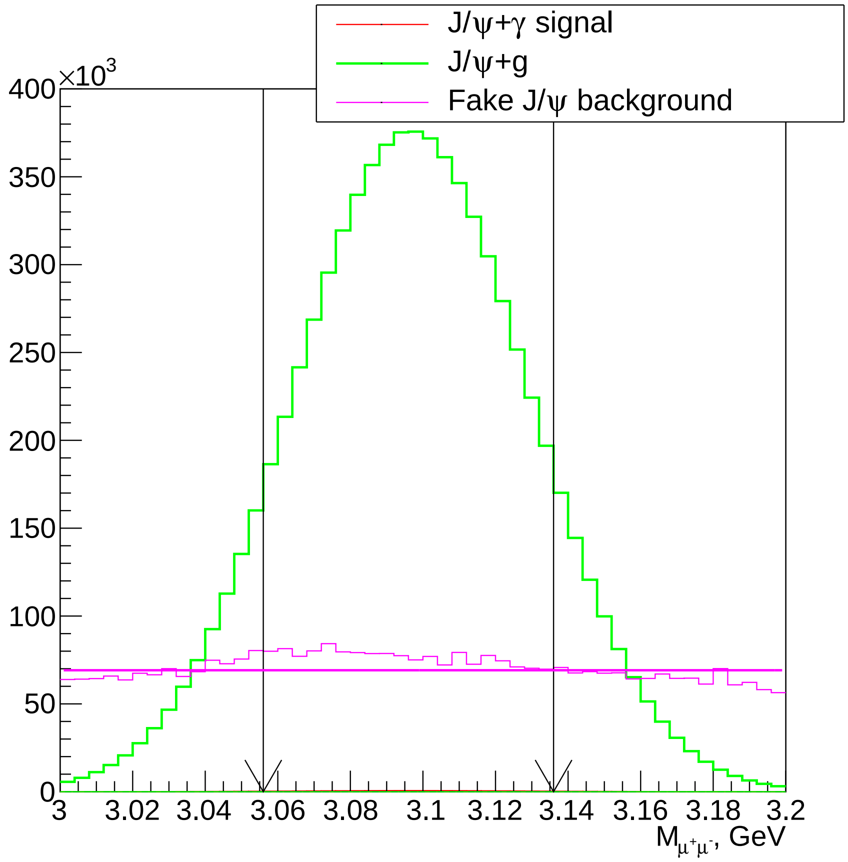


Figure 5: Histogram of the invariant mass of the pair $\mu^+\mu^-$, the decay peak of J/ψ. Illustration map $|M_{(\mu^+\mu^-)} - m_{J/\psi}| < 40\ MeV$.

We present the efficiency coefficients of signals and backgrounds after each of the requirements, as well as the total selection efficiencies, which are the products of the efficiency coefficients for each map:

Taking into account all the cuttings discussed above, we will construct a histogram of correlations by the difference of azimuthal angles (Fig. 8). Note that it was expected that the backgrounds would not be correlated, so it would be possible to separate the background-substrate to the correlated signal part, but, as mentioned in the introduction, the problem of background correlation from the reaction $J/\psi + g$ is found (Fig. 8a). This problem will not be solved in this work, since in order to successfully subtract the correlated background of the reaction $J/\psi + g$, it is necessary to obtain experimental data on the inclusive production of J/ψ at the energy $\sqrt{s} = 27\ GeV$ and also well know the distribution of π^0-mesons product in various processes. It should also be said that although 10^9 events were modeled for the background of $softQCD$, the statistics still turn out to be insufficient, and it is impossible to judge the nature of the dependence by the remaining events. But, of course, it is expected that the background of $softQCD$ will not be correlated, which is well observed if the requirements for events are relaxed (Fig. 8b).

4 Summary and future

Taking into account the selection efficiency and taking into account the detection efficiency of J/ψ (40%), the number of signaling events per year $N_{year} was estimated \sim 190$. The problem of correlation

CUTs	$J/\psi + \gamma$	$J/\psi + g$	MB
$\lvert cos(\theta)\rvert < 0.9$	0.67	0.65	0.75
$f(p_{\mu^-}) < p_{\mu^+}$	0.986	0.987	0.07
$\lvert M_{(\mu^+\mu^-)} - m_{J/\psi}\rvert < 40\ MeV$	0.78	0.78	0.01
$p_{T\gamma} > 2.5GeV$	0.06	4×10^{-5}	10^{-4}
isolation	0.6	0.07	0.4
full efficiency	1.8×10^{-2}	1.1×10^{-6}	2×10^{-8}

Table 1: Table of efficiency coefficients for signals and backgrounds. The coefficients are given for each of the requirements and the total efficiency is also presented, which is the product of the coefficients for each requirement.

of the background of inclusive production of J/ψ mesons was discovered, its solution is possible using the background subtraction procedure, which in turn is possible in the presence of experimental data of inclusive production and experimental data on distributions of π^0 mesons. There is also the problem of an additional photonic background, which appears due to the finite size of the detectors: we can count one high-energy π^0-meson as a high-energy photon. Of course, for more realistic modeling, taking into account the restoration of vertices, tracks and events, we need to conduct modeling in packages that would take into account the geometry of the detector, errors during reconstruction attempts, but the computer power at our disposal does not allow us to conduct such a simulation in an adequate time.

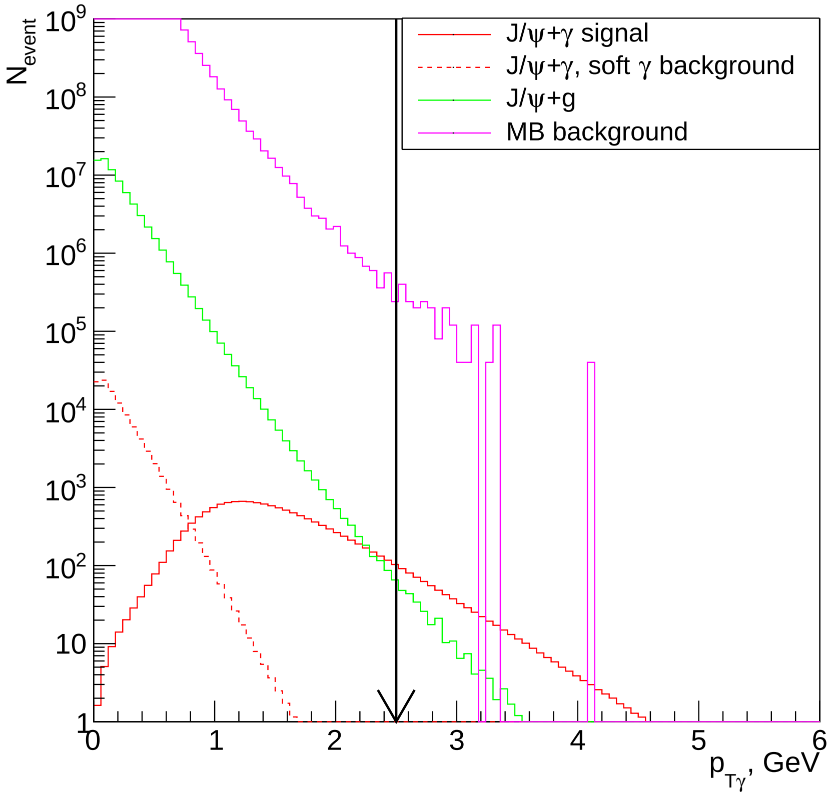
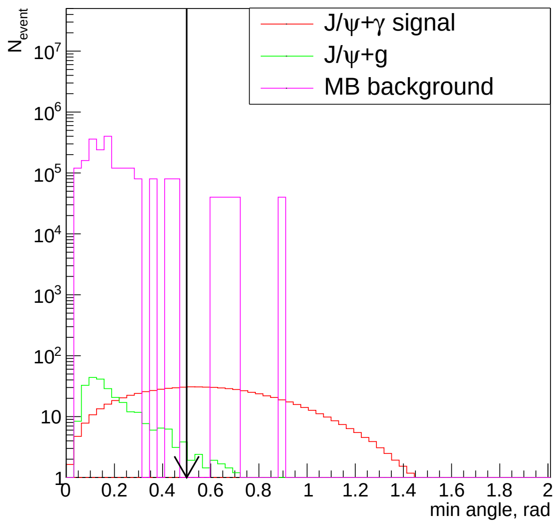
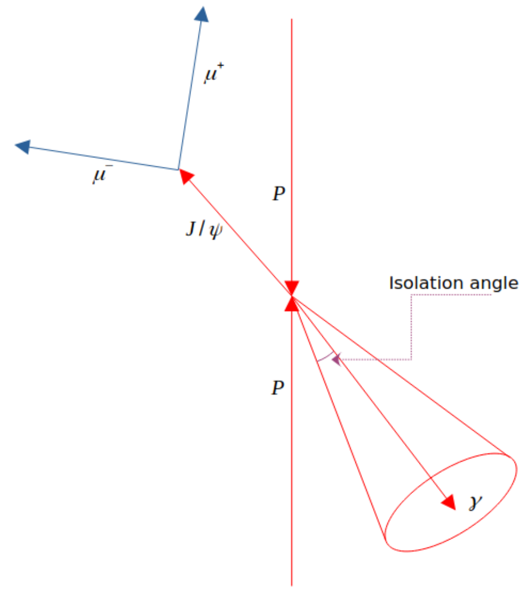


Figure 6: The histogram is the distribution of events by the transverse momentum of photons.

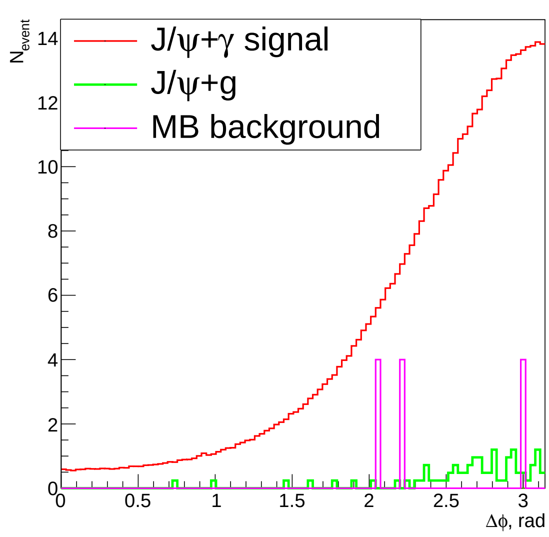


(a) A histogram of the number of particles depending on the angle between the candidate associated photon and any other photon or charged particle.

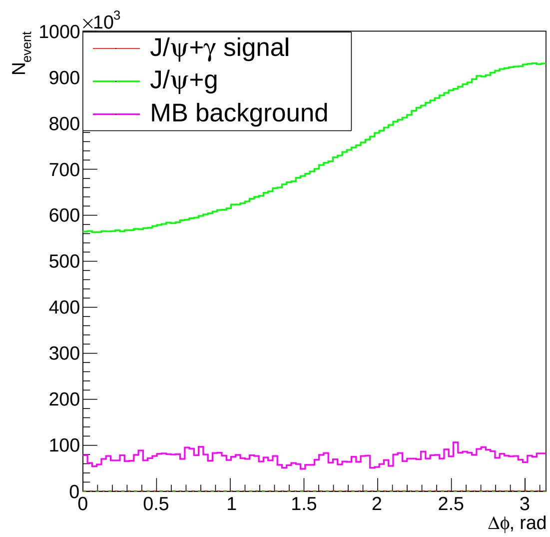


(b) Diagram which schematically illustrating the direction of departure of the photon, charged particles, the position of the insulation angle and the corresponding solid angle.

Figure 7: The histogram – 7a and the schematic diagram – 7b describe the criterion for the isolation requirements of the associated photon.



(a) Histogram of the number of particles, depending on the difference in azimuthal angles of the candidate particles in the associated J/ψ and γ. The events are subject to the full set of requirements considered, presented in (Tab. 1)



(b) Histogram of the number of particles, depending on the difference in azimuthal angles of the candidate particles in the associated J/ψ and γ. The requirements imposed on events are relaxed compared to (Fig. 8a), only present cut $|\cos(\theta)| < 0.9$, $f(p_{\mu^-}) < p_{\mu^+}$.

Figure 8: Histograms of correlations by the difference of azimuthal angles of final particles under different requirements imposed on events.

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