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$J/\psi \rightarrow e^+e^-$ decay selection criteria in the CBM experiment

O Yu Derenovskaya\textsuperscript{1}, V V Ivanov\textsuperscript{1,2}

\textsuperscript{1}Joint Institute for Nuclear Research, Dubna, RUSSIA
\textsuperscript{2}National Research Nuclear University “MEPhI”, Moscow, Russia
E-mail: odenisova@jinr.ru

Abstract. Currently the CBM experiment is being developed in GSI (Darmstadt, Germany) at the FAIR accelerator complex in an international collaboration with JINR (Dubna, Russia). Measurements of the $J/\psi \rightarrow e^+e^-$ decay are one of the key objectives of the CBM experiment, the registration of such decays is planned to be conducted in real-time experiment. In the current paper the criteria, that allow for effective selection of signal decay events for AuAu collisions at 10 AGeV, are discussed in detail. This energy corresponds to the first phase of the CBM experiment.

1. Introduction

The CBM (Compressed Baryonic Matter) experiment is heavy-ion experiment dedicated to the investigation of the properties of highly compressed baryonic matter as is produced in nucleus-nucleus collisions at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany [1].

The CBM experimental setup for studying dielectron decays is shown in Fig. 1.

Figure 1. General view of the CBM setup for studying dielectron decays.

The main tracking detector of CBM STS (Silicon Tracking System) is located behind the target between the poles of the superconducting dipole magnet. The STS detector is intended to reconstruct trajectories and momenta of charged particles, as well as reconstruct primary and secondary vertices. The electron/positron identification system includes Ring Imaging CHerenkov (RICH) and Transition Radiation Detectors (TRD). The TRD is also used to reconstruct the trajectories of charged particles registered by the detector. The detector for Time-Of-Flight (TOF) measurement is intended for hadron identification. The Electromagnetic
CALorimeter (ECAL) serves to identify photons. The Projectile Spectator Detector (PSD) calorimeter is used for determining the reaction plane.

The study of charmonium, which is produced in nuclear-nuclear collisions at FAIR energies is one of the key objectives of the CBM experiment. Main difficulty of \( J/\psi \rightarrow e^+e^- \) reconstruction is the extremely low yield of \( J/\psi \) mesons with a low probability (about 6%) of decay into the dielectron channel in the environment of high multiplicity of secondary particles (from 100 to 1000 particles per nucleus-nucleus collision) due to high interaction rate (up to \( 10^7 \) collisions per second). The important and relevant task for CBM collaboration is a fast and efficient selection of the signal events for \( J/\psi \rightarrow e^+e^- \) reconstruction in the real time experiment.

The current paper presents criteria that provide an effective selection of signal events for \( Au+Au \) collisions at 10 AGeV. This energy corresponds to the first phase of the CBM experiment [2].

2. The \( J/\psi \) reconstruction technique

The CBM experimental setup is under development. Therefore, the current study was based on the Monte-Carlo simulated data. Signal decay events and background were simulated separately. The PLUTO [3] generator was used for the signal \( J/\psi \) decay, and the UrQMD [4] generator for the simulation of the background \( AuAu \) events. The so prepared sets of particles were transported through the CBM setup with help of GEANT3 [5] in the CBMROOT framework.

The selection criteria for \( J/\psi \) reconstruction are given below:

a) transverse momentum of the charged particles is more than 1 GeV/c;
b) number of counts in the TRD detector is greater than 2;
c) particles are identified as electrons in the TRD;
d) limit on the deviation of particle trajectory in the TRD \( |d_{c_\mu}| \) is less than 0.035;
e) particles are identified as electrons in the TOF;
f) particles are linked to any of the Cherenkov rings in the RICH detector.

These criteria are applied in order of importance one after another, giving as a result a sample of selected events. The KF Particle Finder [6] is used to reconstruct the signal event topology as the last step.

3. The transverse momentum cut

The reconstruction of trajectories and momenta of charged particles using STS detector is performed as the first step. The cellular automaton algorithm is used for track reconstruction [7]. The Kalman filter is applied to determine the parameters of reconstructed tracks including spatial coordinates and momentum [8].

Fig. 2 shows the distribution of transverse momentum in the STS: signal events are shown in red, background events are blue. Shaded area corresponds to the selected cases, that is such which have a transverse momentum more than 1 GeV/c.

The major part of signal particles have a large transverse momentum \( p_t \). This is consistent with the fact that kinematic criterion on transverse momentum works especially well when the total mass of daughter particles is much lower than the parent particle mass. Since \( 2m_e \ll m_{J/\psi} \) (here \( m_e \) is the electron mass and \( m_{J/\psi} \) is the \( J/\psi \) meson mass) the limit of \( p_t > 1 \) can significantly suppress the background with a minimum loss of signal events (shaded area on Fig. 2) [9].

4. The number of counts in the TRD detector

In parallel with track reconstruction in the STS it is planned to use the trd data for event selection. The main purpose of the TRD detector is to exclude the pion contribution from the
particle sample. The procedure of pion suppression includes several stages: (1) a reconstruction of trajectories of the particles registered by the TRD coordinate detectors, and (2) particle identification based on the energy losses only in those TRD modules that made a contribution to the reconstructed tracks.

The TRD consists of four stations, each of them registers the intersection of the particle with the detector plane (hit) and its energy loss. A track following technique and Kalman filter are applied for track reconstruction in the TRD [10]. Each track is associated with a set of measurements of the particle energy losses. With the help of mathematical methods, one should determine to which distribution (electrons or pions) these losses are related.

Fig. 3 shows the distribution of the number of hits in the TRD tracks. In order to perform an electron identification the information about the particle energy losses at least at three points is needed. Therefore, for the further analysis only such particles which have the number of hits in the track more than or equal to three are considered.

5. Electron identification in the TRD detector
Fig. 4 shows the distributions of the total energy losses for pions and electrons in the first TRD station. One can see that these distributions highly overlap. Therefore, it is impossible to distinguish between electrons and pions using measurements from one station.

Figure 2. The distribution of transverse momentum in the STS: signal events are red, background events are blue, shaded area corresponds to the selected cases.

Figure 3. The distribution of the number of hits in the TRD-track, shaded area corresponds to the events that pass the further selection.

Figure 4. The distributions of the total energy losses for pions (blue line) and electrons (red line) in the first TRD station.

Figure 5. The distribution of the output values of the neural network for pions (blue line) and electrons (red line).
The possibility of electron and pion identification using an artificial neuron network, a multilayer perceptron (MLP), has been investigated [11, 12]. A three-layered perceptron implemented in the CBMROOT environment is currently employed in the CBM experiment for particle identification using the TRD [13]. Fig. 5 presents the distribution of the output values of the neural network for pions (blue line) and electrons (red line), which shows that the MLP allows reliable electron identification.

6. The limit on the particle deviation in the TRD
Additionally, to suppress the combinatorial background the limit on the deviation of the particle trajectory under the influence of a magnetic field is considered. Since the main magnetic field component is directed along $OY$ axis, the magnetic field deflects electrons and positrons to the different directions in XOZ projection.

The deviation angle $d_{t_x}$ is calculated as follows:

a) the target centre is connected by the straight line with the x-coordinate of the first hit of the corresponding TRD-track,
b) all the hits of the TRD track are connected by the straight line in the plane XOZ,
c) the angle between a) and b) lines are calculated.

Fig. 6 presents the deviation angle distribution for electrons (the blue line) and positrons (the green line) in case of background (a) and signal (b) events respectively. If we impose the limit on the deviation angle of the track $d_{t_x} < 0.035$, it is possible to further suppress the background.

Figure 6. The deviation angle distribution for electrons (the blue line) and positrons (the green line) in case of background (a) and signal (b) events respectively.

Beside that the deviation of the particle trajectory in the TRD can be used to determine the charge sign of the electrons or positrons.

7. Electron identification with TOF detector
In addition to the TRD detector TOF is used to identify high energy electrons and exclude hadrons. ToF can measure the time of flight, which is needed for a certain particle to fly from the target to the ToF detector plane. If you know the particle momentum $p$ and the trajectory length, you can calculate its mass $m$. The squared mass $m^2$ of charged particle dependence of their momentum $p$ is used for particle identification in the TOF (Fig. 7) [12].

For the background there is a large contribution from protons (Fig. 7,a). In order to remove the protons from the sample we apply the method which is used in KF Particle Finder [6]. The particles which lie in the corridor marked with red lines are selected for the further analysis (Fig. 7,c).
Figure 7. The distribution of the squared mass of charged particle dependence of their momentum for background (a) and signal (b) events respectively; c) the boundaries using for the electron selection (red lines).

8. Electron identification with RICH detector
The selected tracks are extrapolated to the RICH detector [14]. The primary function of this detector is electron identification and pion suppression in the momenta range from 0.5 to 10 GeV/c. The principle of the RICH operation is based on the detection of the Cherenkov radiation emitted during the passage of a relativistic charged particle through the detector radiator.

Fig. 8 shows the result of registration of the charged particles in one AuAu-collision in the RICH detector. Dots show places of registration of the Cherenkov radiation by the photomultipliers on the RICH plane and the reconstructed rings.

Figure 8. The result of registration of the one AuAu-collision in the RICH detector.

Further, we consider only those particles which are linked to any of the reconstructed Cherenkov ring.

9. The construction of the invariant mass spectrum
The KF Particle Finder was used to reconstruct the signal event topology [6]. This package is designed for the search and reconstruction of short-lived particles by the products of their decay. The set of $J/\psi$ candidates are formed by combining all selected (using the criteria described
above) electrons with all selected positrons. In order to reduce the contribution of background, only particles emerged from the target are considered.

The observed number of signal events $N(s)$ may be estimated using the following formula:

$$N(s) = N(i) \cdot M \cdot BR \cdot Eff,$$

where $N(i)$ is the number of central AuAu collisions at 25 AGeV ($\sim 10^{12}$ events); $M$ is the probability of $J/\psi$ production in a central collision ($M = 5 \times 10^{-6}$ for the mentioned collisions) [15]; $BR$ is the branching ratio of the $J/\psi$ decay into dielectrons (6%) [16]; $Eff$ is the efficiency of the signal registration by the CBM setup. This normalization has been used to construct the $J/\psi$ distribution.

The combinatorial background was formed as a result of modeling the central UrQMD events for the mentioned above collisions. Since it is extremely time-consuming to generate $10^{12}$ collisions, the event-mixing technique was used to obtain the sufficient statistics. This method involves combining each background electron after applying all the criteria described above from the considered event with all positrons from other events. This approach allows to increase the statistics corresponding to the background spectrum quadratically.

The resulting invariant-mass spectrum of $J/\psi$ mesons in AuAu collisions at 10 AGeV energy is shown in Fig. 9. The spectrum has been obtained by summing two distributions: signal and background. The reconstruction efficiency is about 11.6%. The calculated signal to the background ratio is about 0.14.

![Figure 9. The reconstructed invariant-mass spectrum of $J/\psi$ for central AuAu collisions at 10 AGeV.](image)

10. Results

Table 1. The loss of signal events and the corresponding background suppression factor in each stage.

| Criteria | Signal loss (%) | background suppression |
|----------|----------------|------------------------|
| a        | 16             | 92                     |
| b        | 18             | 26                     |
| c        | 28.5           | 99.5                   |
| d        | 7.5            | 16                     |
| e        | 1.1            | 54                     |
| f        | 1.6            | 61.5                   |
| Total    | 55             | 99.9                   |
Table 1 shows the loss of signal events and the corresponding background suppression in each stage independently. This means that all the coefficients for each individual criterion was calculated to a sample formed as a result of applying the preceding criterion. First column are criteria: a) transverse momentum more than 1 GeV/c, b) number of counts in the TRD detector is greater than 2, c) particles are identified as electrons in the TRD, d) limit on the deviation of particle trajectory in the TRD $|d_{\tau}|$ is less than 0.035, e) particles are identified as electrons in the TOF, f) particles are linked to any of the Cherenkov rings in the RICH. The total values of the signal losses and the background suppression are in the last line.

The developed criteria lead to almost complete rejection of the background contribution, while selecting major part of the signal events.

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