Experimental research of $\pi^0$ meson production in U+U collision at 192 GeV

A. Ya. Berdnikov, Ya. A. Berdnikov, D. O. Kotov, P. V. Radzevich, S. V. Zharko
Peter the Great St.Petersburg Polytechnic University (SPbPU), Russia, 195251, St.Petersburg, Polytechnicheskaya, 29
E-mail: radzevichp@gmail.com

Abstract. To study properties of quark-gluon plasma (QGP) is one of the main tasks of modern High Energy Physics. One of the signatures of QGP formation is jet quenching, which was observed as a suppression of particle yields (compared to the yield of the same particles in proton-proton collisions) at high transverse momentum region in central collisions of ultra-relativistic heavy nuclei. Jet quenching is the effect of the final state of heavy nuclei collision which is usually explained through parton energy loss in hot and dense medium. Experimentally the jet quenching is studied with nuclear modification factor. This paper presents invariant transverse momentum spectra and nuclear modification factors for $\pi^0$ mesons in different classes of centrality in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV. Spectra and factors are measured in a wide $p_T$ range up to 18 GeV/c for different classes of centrality. In central U+U collisions suppression of neutral $\pi$-mesons is the same as the suppression of neutral $\pi$-mesons in Au+Au collisions at the similar collision energy and similar numbers of participants.

1. Introduction

High transverse momentum ($p_T$) hadrons are produced from the fragmentation of hard scattered quarks and gluons (partons) in the collisions of ultra-relativistic protons ($p+p$). This phenomenon is well described with the framework of perturbative quantum chromodynamics (pQCD) [1]. Over against, production of high-$p_T$ hadrons in the collisions of ultra-relativistic heavy nuclei ($A+A$) is modified by the hot and dense medium – quark-gluon plasma (QGP) and cannot be described with pQCD formalism. High-$p_T$ partons traverse through the produced medium and lose their energy, which results in production of hadrons with reduced energy. This effect is called jet-quenching [2,3] and is manifested by suppressed production of hadron yields relative to yields measured in elementary $p+p$ collisions.

The measurement of $\pi^0$ meson production spectra allows to study jet-quenching effect with a good precision, because $\pi^0$ can be identified up to the highest $p_T$ with relatively small uncertainties. In 2012, PHENIX experiment collected data from U+U collisions at $\sqrt{s_{NN}} = 192$ GeV. This collision system provides the largest energy density available at RHIC, which gives a unique possibility to obtain additional restrictions on the parameters of various theoretical models and measure properties of QGP with a higher accuracy.

2. Data Analysis

This paper reports on the measurement of neutral pion production in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV at RHIC. The whole analysis uses $9.4 \times 10^8$ events taken by the PHENIX experiment [4]. Collision centrality is determined from the correlation between the number of charged particles detected in the Beam-Beam Counters (BBC, $|\eta|<0.35$). A Glauber model Monte-Carlo simulation of the BBC responses is used to estimate the associated average number of participating nucleons ($<N_{part}>$) and binary nucleon-nucleon collisions ($<N_{coll}>$) for each centrality bins. There are two sets of data due to different deformation parameterization of U ion in the Wood-Saxon distribution [5,6]. Neutral pions are measured in the $\pi^0 \rightarrow \gamma \gamma$ decay channel with the photons reconstructed in the Electromagnetic
Calorimeter (EMCal), which is located in the two central arms of PHENIX (|η| ≤ 0.35). The EMCal [7] consists of two subsystems: six sectors of lead-scintillator sandwich calorimeter (PbSc) and two sectors of lead-glass Cherenkov calorimeter (PbGl). Different types of the EMCal have different energy resolution, segmentation and linearity, and the use of both types of them provides excellent cross-check of the final results.

A detailed description of the analysis, including extraction of the raw π⁰ yield, correction for acceptance, assignment of detector energy resolution and dead areas, estimation of π⁰ reconstruction efficiency have been described in another paper [8].

3. Results
Figure 1 shows the π⁰ invariant p_T-spectra for four different centrality classes and minimum bias collisions. Invariant transverse momentum spectra of π⁰-mesons are measured in a wide p_T range (up to 18 GeV/c in minimum bias collisions). The main sources of systematic uncertainties are yield extraction, efficiency corrections, and energy scale, none of which exhibit a significant centrality dependence. The PbSc and PbGl detectors have quite different systematic uncertainties with all but one of them (off-vertex π⁰) uncorrelated. Obtained results show that main systematic uncertainty comes from possible mismatch in absolute energy scales (5% at low and intermediate p_T to 10% at high p_T) and reproduction of cluster merging effect between data and simulation (influence only at the highest p_T, ~15%).

To quantify the comparison of spectra in heavy ion and p+p collisions, the nuclear modification factor is used. Nuclear modification factors of π⁰ mesons is calculated with formula:

\[ R_{AA}(p_T) = \frac{1}{\langle N_{col} \rangle} \frac{dN_{AA}(p_T)}{dN_{p+p}(p_T)}, \]  

Figure 1. Invariant transverse momentum spectra measured for π⁰ mesons in U+U collisions at 192 GeV in minimum bias(●), 0-20%(■), 20-40%(▲), 40-60%(▼), 60-80%(○) centrality intervals. Statistical uncertainties are smaller than the marker size. Open boxes correspond to systematic uncertainties.
where \( dN_{AA}(p_T) \) (\( dN_{pp}(p_T) \)) – particle yield, measured in \( A+A \) (\( p+p \)) collisions, \( \langle N_{coll} \rangle \) – average number of binary inelastic nucleon-nucleon collisions. If \( R_{AA}<1 \) (\( R_{dd}>1 \)), particle production is suppressed (enhanced) in comparison to elementary nucleon-nucleon collisions. Contrariwise, if \( R_{dd}=1 \), there are no collective effects in \( A+A \) collisions.

Figure 2 shows \( \pi^0 \) nuclear modification factors measured for different sets of the collision parameters [10,11] in minimum bias \( U+U \) collisions and different \( U+U \) centrality intervals as a function of \( p_T \). \( R_{AA} \) are compared to the previous results obtained in Au+Au collisions at 200 GeV [9] at similar values of \( N_{coll} \). Presented values of \( R_{AA} \) are consistent between two collision systems within the uncertainties of the measurements.

Figure 3 shows the integrated nuclear modification factor in \( U+U \) and \( Au+Au \) [9] for \( \pi^0 \) as a function of numbers of nucleons participating in the nuclei interactions (\( N_{part} \)). The suppression increases monotonically with \( N_{part} \) without any sign of saturation within uncertainties. In peripheral collisions (\( N_{part} < 80 \)) \( \pi^0 \) mesons seem to be slightly more suppressed but still agree within uncertainties.

4. Summary
PHENIX has measured neutral pion production in \( U+U \) collisions at \( \sqrt{s_{NN}}=192 \) GeV at mid rapidity in the transverse momentum range of \( 1<p_T<18 \) GeV/c, using RHIC Run-12 data. In central collisions the yield is suppressed by a factor of \(~5\) at \( p_T>5 \) GeV/c compared to the binary scaled \( p+p \) reference. The suppression prevails with little or no change up to 18 GeV/c. In central \( U+U \) collisions \( \pi^0 \) production is suppressed in the same way as in \( Au+Au \) at similar number of binary collisions, which suggests that suppression level depends on the size of the interaction region and not on its shape. In peripheral \( U+U \) collisions low \( p_T \) \( \pi^0 \) mesons seem to be slightly more suppressed but still agree within uncertainties.
Figure 3. Integrated nuclear modification factor in U+U SET 1 (●), SET 2 (♦) and Au+Au (▲) collisions at $p_T>5$ GeV/$c$ for $\pi^0$ as a function of numbers of participants. Error bars and open boxes show statistical and systematic uncertainties, respectively. Boxes at unity show scaling uncertainty.

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