Abstract

Neutral pions have been measured in $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{\text{NN}}}=200$ GeV up to 20 GeV$/c$ in the RHIC Year-2014 run. The nuclear modification factor $R_{AA}$ was measured and compared with that from $d+\text{Au}$ collisions. The integrated $R_{AA}$ as a function of $N_{\text{part}}$ was calculated for $d+\text{Au}$, $^3\text{He}+\text{Au}$ and $\text{Au}+\text{Au}$ collisions at $\sqrt{s_{\text{NN}}}=200$ GeV, and found to converge for $N_{\text{part}} >12$, while a clear system ordering $R_{d\text{Au}} > R_{^3\text{He}\text{Au}} > R_{\text{AuAu}}$ was observed for $N_{\text{part}} <12$. The fractional momentum loss for the most central $^3\text{He}+\text{Au}$ collisions was also estimated.

Keywords: 

1. Introduction

The small collision systems such as $p/d+A$ collisions have been considered a good laboratory to quantify cold nuclear matter effects, a necessary baseline for understanding the effects of the hot and dense medium produced in $A+A$ collisions. The observation of the ridge-like structure in the long-range azimuthal correlations in $p+\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV at the LHC [1, 2], however, called into question the view of such systems as consisting merely of cold nuclear matter. The study at the LHC was followed by the PHENIX experiment at RHIC, and a finite $v_2$ of hadrons in 0–5 % central $d+\text{Au}$ collisions using both the two-particle angular correlation method and the event-plane method were shown [3, 4]. These observations led the community to explore any phenomena found in $A+A$ collisions, in $p/d+A$ collisions.

The energy loss of hard scattered partons produced in the initial stage of the collisions, so-called jet quenching, has been one of the key observations in confirming the production of the QGP. The first evidence of this phenomena was found in the yield suppression of high transverse momentum ($p_T$) hadrons, the fragments of the hard scattered partons. The measurement of high $p_T$ identified hadrons have been improved over the last decade, and reached to the level that a precise quantitative comparison of the data and theoretical models became realized [5, 6]. A recent study also found that the energy loss scales with the particle multiplicity ($dN/d\eta$) [7]. Obviously, the high $p_T$ hadrons will be a powerful tool to investigate the parton degree of freedom in the small systems like $p/d+A$ collisions as well. In addition, a systematic study of the high $p_T$ hadron spectra from small to large collision systems will be able to explore the onset of QGP as a function of the collision systems. In this paper, we show the new measurement of the high $p_T$ $\pi^0$ in $^3\text{He}+\text{Au}$ collisions and compared with the ones from $d+\text{Au}$ and $\text{Au}+\text{Au}$ collisions and discuss the systematics of the yield suppression and enhancement of the high $p_T$ hadrons.

2. Detector and Dataset

PHENIX recorded an integrated luminosity of 25 nb$^{-1}$ in $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{\text{NN}}}=200$ GeV in the RHIC Year-2014 run. The detector setup was the same as the one in the RHIC Year-2012 run as shown in Fig. [1]. The detailed description of the PHENIX detector system can be found elsewhere [8]. The $\pi^0$ was
reconstructed via $\pi^0 \rightarrow \gamma\gamma$, by primarily using a lead- 
scintillator sandwich type electromagnetic calorimeter 
(PbSc EMCal). The threshold of cluster energy is set 
to 0.2 GeV and the photon clusters were selected using 
a shower shape cut. Then, an energy asymmetry cut of 
$\alpha = (E_1 - E_2)/(E_1 + E_2) < 0.8$ was applied on selecting 
pairs of photons from $\pi^0$ decay. The efficiency and acceptance of the $\pi^0$ were estimated using a GEANT-
based detector simulation software.

Two types of the trigger selections were used to trig-
gger events; one is the coincidence of the signals from 
the two Beam-Beam counters (BBC) located at $3.1 < |\eta| < 3.9$ covering the full azimuth (minimum bias trigger), 
and the other is the coincidence of the minimum bias trigger and a high energy tower hit in the EMCal 
(ERT trigger). The events used in this analysis were $2 \times 10^{10}$ minimum bias triggered events, and $4.5 \times 10^{10}$ 
minimum-bias-equivalent ERT events, totaling in the integrated luminosity of $22 \text{ nb}^{-1}$. The minimum bias 
trigger is not 100% efficient to the inelastic collisions 
because of the limited acceptance and efficiency of the 
BBC. This inefficiency increases as the collision system 
becomes smaller. They were already studied in $d+Au$ 
collisions by comparing the BBC charge with a Glauber 
Monte Carlo simulation folded with a negative binomial 
distribution [9]. From this comparison, we determined 
that the trigger efficiency is 88% for $d+Au$ collisions. 
We followed the same method, and determined the trig-
gger efficiency of $^3\text{He}+Au$ collisions also as 88%. In 
case of 200 GeV Au+Au collisions, the efficiency was 
94%. When dividing the events into centralities, an ad-
ditional bias factor plays a role. The bias is originated 
from the anti-correlation of the available energies for 
producing particles in midrapidity where the EMCal is 
installed, and the backward rapidity where the BBC sits. 
We estimated the bias factors for the $^3\text{He}+Au$ collisions, 
also by following the method used for $d+Au$ collisions, 
and determined as 0.95, 1.02, 1.02, 1.03, and 0.89 for 
0–20, 20–40, 40–60, 60–88, and 0–100% $^3\text{He}+Au$ 
collisions, respectively [9]. We divided uncorrected yields 
by these factors.

3. Results

Fig. 2 shows the invariant spectra of the $\pi^0$ as a function of $p_T$ in $^3\text{He}+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV. The

we plotted the integrated $R_{AA}$ for $^{3}\text{He}+\text{Au}$ and $d+\text{Au}$ collisions as a function of number of participant nucleons ($N_{\text{part}}$) as shown in Fig. 7.

The integrated $R_{AA}$ for three $p_{T}$ ranges, namely $p_{T}>5\text{ GeV/c}$, $>8\text{ GeV/c}$, and $>10\text{ GeV/c}$, agree each other for all the points, suggesting that the $R_{AA}$ is flat over $p_{T}$ within the quoted uncertainties. At the higher $N_{\text{part}}$, the $d+\text{Au}$ and $^{3}\text{He}+\text{Au}$ collisions show the very similar $N_{\text{part}}$ dependence, while at the lower $N_{\text{part}}$, a clear distinction between two collision systems are seen; the ones in $d+\text{Au}$ collisions show larger enhancement, suggesting a larger Cronin effect or less suppression (energy loss). We can study the trend even more systematically by comparing those with the $R_{AA}$’s from the peripheral Au+Au collisions, i.e., 60–70, 70–80, and 80–93% centrality. In the previous publication, we measured the $R_{AA}$ for $p_{T}>5\text{ GeV/c}$ as $\sim0.78$, $\sim0.87$, and $\sim0.84$, for $N_{\text{part}}$ of $26.7\pm3.7$, $13.7\pm2.5$, and $5.6\pm0.8$, respectively [6]. From these numbers, we found that the $R_{AA}$’s from the three collisions systems

$$x^{0}+X, \sqrt{s_{NN}} = 200 \text{ GeV}$$

Figure 3: $R_{AA}$ for 0–100% $^{3}\text{He}+\text{Au}$ collisions with the one from $d+\text{Au}$ collisions.

$\pi^{0}$ + X, $\sqrt{s_{NN}} = 200 \text{ GeV}$

Figure 4: $R_{AA}$ for 0–20% $^{3}\text{He}+\text{Au}$ collisions with the one from $d+\text{Au}$ collisions.

the both systems are remarkably similar within quoted uncertainties for all the centrality classes. However, a small systematic difference is seen, especially at the low $p_{T}$ region ($p_{T}<5\text{ GeV/c}$).

In order to systematically compare the enhancement/suppression of the invariant yields in two systems, we measured the $\pi^{0}$ spectra from the $p+p$ collisions measured in the RHIC Year-2005 run as the baseline. Fig. 3 shows the $R_{AA}$ for the minimum bias $^{3}\text{He}+\text{Au}$ collisions. The $R_{AA}$ for the minimum bias $^{3}\text{He}+\text{Au}$ collisions are shown, again

$$\pi^{0}+X, \sqrt{s_{NN}} = 200 \text{ GeV}$$

Figure 5: $R_{AA}$ for 20–40% $^{3}\text{He}+\text{Au}$ collisions with the one from $d+\text{Au}$ collisions.

$$\pi^{0}+X, \sqrt{s_{NN}} = 200 \text{ GeV}$$

Figure 6: $R_{AA}$ for 40–60% $^{3}\text{He}+\text{Au}$ collisions with the one from $d+\text{Au}$ collisions.

the primordial production ($p+p$ collisions), we computed the nuclear modification factor ($R_{AA}$) for all the five event classes. We used the $\pi^{0}$ spectra from the $p+p$ collisions measured in the RHIC Year-2005 run as the baseline. Fig. 3 shows the $R_{AA}$ for the minimum bias $^{3}\text{He}+\text{Au}$ collisions. The $R_{AA}$ for the minimum bias $^{3}\text{He}+\text{Au}$ collisions are shown, again
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$\pi^0 + X, \sqrt{s_{NN}} = 200$ GeV

Figure 7: $R_{AA}$ for 60–88% $^3$He+Au collisions with the one from $d+Au$ collisions.

$\pi^0 + X, \sqrt{s_{NN}} = 200$ GeV

Figure 8: Integrated $R_{AA}$ for $d+Au$ and $^3He+Au$ collisions.

4. Summary

Identified $\pi^0$ has been measured in $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the RHIC Year-2014 up to 20 GeV/c in four centrality classes as well as in the minimum bias events. The $R_{AA}$ was computed and compared with those from $d+Au$ collisions, and found that they are consistent with quoted uncertainties, however, small difference was seen between two systems, especially at the low $p_T$. The integrated $R_{AA}$ from $d+Au$, $^3$He+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were found to converge for $N_{part} > 12$, while a system ordering of $R_{dAu} > R_{HeAu} > R_{AuAu}$ was observed for $N_{part} < 12$, suggesting a similar medium may be created for the system for $N_{part} > 12$. We also found the most central $^3$He+Au collisions exhibited $\delta p_T/p_T \sim 0.03$. The measurement in $p+Au$ collisions at RHIC will help completing this systematic study and could point the onset of QGP in terms of the collision system size.

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