Cold nuclear matter effect measured with high $p_T$ hadrons and jets in 200GeV $d+Au$ collisions in PHENIX

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Cold nuclear matter effect measured with high $p_T$ hadrons and jets in 200GeV $d+Au$ collisions in PHENIX

Takao Sakaguchi, for the PHENIX collaboration

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
E-mail: takao@bnl.gov

Abstract. High $p_T$ $\pi^0$ and $\eta$ as well as jets are measured using high statistics $d+Au$ collision data collected in RHIC Year-2008 run. Both $R_{dA}$ and $R_{cp}$ for three observables are found to be very consistent each other within quoted systematic and statistical uncertainties. It was found that the $R_{dA}$ is strongly centrality dependent as opposed to the expectations from theoretical models. An explanation of the centrality dependence from the experimental point of view is presented.

1. Introduction
It has been of interest that whether or not the initial hard scattering process is modified in relativistic heavy ion collisions, after the suppression of high transverse momentum ($p_T$) hadron yields was discovered in Au+Au collisions at $\sqrt{s_{NN}}=130$ GeV in RHIC Year-2000 run [1]. The first $d+Au$ collision experiment was carried out in RHIC Year-2003 run and confirmed that the suppression attributes to a final state interaction of hard scattered partons with a medium created in Au+Au collisions [2]. After these results were published, many theoretical works have been dedicated to precisely determine the initial state effect that affects to the evaluation of the final state effect such as parton energy loss. Figure 1 shows a nuclear modification ($R_{dA}$) to a free proton PDF from the CTEQ6.1M set [3] in the $MS$ scheme, where $i$ denotes the parton flavor [4]. The hard scattering process is factorized into a fragmentation function, a reaction cross-section, and a parton distribution function (PDF). Since the $d+Au$ collisions will not produce a bulk hot dense medium, the yield difference of the hard scattering probe in $d+Au$ and $p+p$ collisions are predominantly from the modification of PDF. Therefore, the nuclear modification factor $R_{dA}$ ($\equiv (dN_{dA}/dydp_T)/(\langle T_{dA}\rangle d\sigma_{pp}/dydp_T)$) is expected to reflect the modification of PDF. Eskola and companies tried to construct the centrality dependent nuclear PDF using the previously published $\pi^0$ $R_{dA}$ result as shown in Figure 2 [4]. Obviously, the statistical uncertainty is too large to observe the centrality dependence of the nuclear PDF. We analyzed another $d+Au$ collision data set collected in RHIC Year-2008 in order to tackle this interesting subject.

2. Measurements of $\pi^0$, $\eta$, and jets in PHENIX
The schematic view of the PHENIX detector [5] in RHIC Year-2008 is shown in Figure 3. PHENIX sampled an integrated luminosity of 80 nb$^{-1}$ during that run, a factor of 30 increase over...
The RHIC Year-2003 d+Au data set. The minimum bias events are triggered by a coincidence of the signals from the beam-beam counters (BBC) located at the south and north side of the detector system \((3.1 < |\eta| < 3.9)\). We define the forward (positive) rapidity as the Au-going side (pointing to the south BBC). The collision centrality is determined using the charge signal from the south BBC. The underlying average number of binary nucleon-nucleon collisions \((N_{\text{coll}})\) and the number of participant nucleons \((N_{\text{part}})\) are estimated with a Glauber model Monte Carlo simulation. Then the result is combined with a negative binomial distribution (NBD) with parameters \((\mu, k)\) to model the charge distribution from the south BBC. Figure 4 shows the charge distribution in the south BBC (left) and the decomposed \(N_{\text{coll}}\) distributions for each centrality (right), respectively. Due to the auto-correlation between having a high \(p_T\) particle in the central PHENIX spectrometer and the charge multiplicity in the BBC, an additional correction factor is calculated. This is done with the same Glauber Monte Carlo simulation used for the calculation of \(N_{\text{coll}}\).

\(\pi^0\)'s and \(\eta\)'s are reconstructed through 2\(\gamma\)'s measured with eight electromagnetic calorimeters (EMCal) [6, 7]. The EMCal are located most outside of the central arm detector system, which covers an acceptance of \(|\eta| < 0.35\) and a half azimuth. The contribution of random \(\gamma\gamma\) combination is estimated using the mixed event technique, and subtracted from the measured foreground distribution. The drift chamber (DC) and pad chamber (PC) are also used to veto.
charged particles including charged hadrons and electrons. The jets are reconstructed using neutral electromagnetic clusters measured in EMCal and charged particles measured in DC and PC. Those clusters/particles with reconstructed $p_T$ of $p_T > 400$ MeV/$c$ are included in the jet reconstruction procedure. We employed Gaussian filtering algorithm with a filter width of $\sigma=0.3$. This algorithm was also used in $p+p$ and Cu+Cu collision analysis at PHENIX, and cross-checked with anti-$k_T$ algorithm. A mild underlying events in $d+Au$ collisions shifts the

**Figure 4.** BBC south charge (left) and $N_{coll}$ (right) distributions for each centrality obtained from decomposition of the BBC charge distribution.

Table 1. Systematic uncertainties for $\pi^0$, $\eta$, and jet $p_T$ measurement.

| Source                  | Type   | $\pi^0$ 5 GeV/$c$ | $\eta$ 5 GeV/$c$ | $\pi^0$ 10 GeV/$c$ | $\eta$ 10 GeV/$c$ | $\pi^0$ 15 GeV/$c$ | $\eta$ 15 GeV/$c$ | $\pi^0$ 20 GeV/$c$ | $\eta$ 20 GeV/$c$ |
|-------------------------|--------|-------------------|------------------|-------------------|------------------|-------------------|-------------------|-------------------|-------------------|
| Peak extraction         | B      | 2%                | 2%               | 2%                | 2%               | 2%                | 2%                | 2%                | 2%                |
| Acceptance              | C      | 2.5%              | 2.5%             | 2.5%              | 2.5%             | 2.5%              | 2.5%              | 2.5%              | 2.5%              |
| PID efficiency          | B      | 7%                | 8%               | 8.5%              | 9%               | 8%                | 8%                | 8%                | 8%                |
| Energy scale            | B      | 7.5%              | 8%               | 8%                | 8%               | 8%                | 8%                | 8%                | 8%                |
| Photon conversion       | C      | 2%                | 2%               | 2%                | 2%               | 2%                | 2%                | 2%                | 2%                |
| Cluster merging         | B      | 0%                | 0%               | 8%                | 18%              | 8%                | 18%               | 8%                | 18%               |

| Source                  | Type   | 9-12 GeV/$c$ | 12-15 GeV/$c$ | 15-20 GeV/$c$ | 20+ GeV/$c$ |
|-------------------------|--------|--------------|---------------|--------------|-------------|
| Trigger efficiency      | B      | 5-8%         | 5-8%          | 5%           | 5%          |
| Unfolding               | B      | 4-10%        | 4-10%         | 4-6%         | 4-6%        |
| Residual fake rate      | B      | 5%           | 5%            | 5%           | 5%          |
| Acceptance              | C      | 3%           | 3%            | 3%           | 3%          |
| Vertex dependence       | C      | 1%           | 1%            | 1%           | 1%          |

measured $p_T$ to a higher value than the true one. This effect is evaluated and corrected for by embedding jets into real events. A small residual fake rate ($<5\%$) was observed for $p_T > 9$ GeV/$c$ and was accounted in a systematic uncertainty. The systematic uncertainties for $\pi^0$, $\eta$, and jets $p_T$ measurements are summarized in Table 1. The type-B errors are the errors correlated from
$p_T$ to $p_T$. The type-C errors are the errors of overall normalizations.

3. Results
The $p_T$ spectra of $\pi^0$ and $\eta$ are shown in Figures 5 and 6, respectively. With the better statistics in RHIC Year-2008 run, we extended $p_T$ reach by more than 5 GeV/c. As going to higher $p_T$ ($p_T > \sim 12$ GeV/c), the opening angle of $\pi^0 \rightarrow \gamma \gamma$ becomes so small that they cannot be resolved in EMCal because of its limited granularity. It is called as the cluster merging effect. An $\eta$ has a four times larger opening angle ($\theta_{\gamma \gamma} \propto \frac{M}{p_T}$) and thus the merging of two $\gamma$’s does not happen until $\sim 50$ GeV/c. Due to this effect, the ratio of raw $\eta$ to $\pi^0$ yield increases at higher $p_T$ [7]. The $p_T$ spectra of jets is shown in Figure 7. Jets are reconstructed from multi-particles, resulting in reaching to much higher $p_T$, as high as 45 GeV/c, with the same integrated luminosity. We computed the $R_{dA}$ for $\pi^0$, $\eta$, and jets as shown in Figure 8.

Although jets and single identified hadrons can not be directly compared at the same $p_T$, they are agreeing each other very well within quoted uncertainties. For reader’s sake, it may be useful to note that the mean $z(\equiv \frac{p_T^{had}}{p_T^{jet}})$ for $\pi^0$ and $\eta$ is $\sim 0.7$. It was found that the $R_{dA}$ is strongly centrality dependent; the most central collisions show a small suppression, while the most peripheral collisions show a sizable enhancement, compared to the expectation from $p + p$ collisions. It should also be noted that the enhancement in the peripheral collisions increases as
Figure 8. $R_{dA}$ for $\pi^0$, $\eta$ and jets in $d+Au$ collisions for various centralities.

Figure 9. $R_{cp}$ for $\pi^0$, $\eta$ and jets in $d+Au$ collisions for various centralities. The 60-88% centrality is taken as the denominator.
going to higher $p_T$. This trend shows that the nuclear PDF may be strongly dependent of impact parameters as opposed to what was predicted by theoretical models. In order to investigate the suppression/enhancement trend with reduced systematic uncertainties, the ratio of the yield in central to peripheral collisions ($R_{cp}$) is computed and shown in Figure 9. In this ratio, the error from $p+p$ baseline measurement will be excluded. It was found that the $\pi^0$, $\eta$, and jet $R_{cp}$ show the same trend and are consistent each other within even smaller uncertainties. The decreasing trend as going to higher $p_T$ is consistent with the fact that the $R_{dA}$ is enhanced in peripheral collisions and suppressed in central collisions.

4. Global feature in $d+Au$ collisions
Before one concludes that the nuclear PDF is strongly impact parameter dependent, one may want to revisit some global features in $d+Au$ collisions such as triggering or centrality definition. In any collisions, one has to generate a trigger using signals from detectors whose efficiencies are not 100% in reality. The efficiency of a trigger is often particle multiplicity dependent. Therefore, when triggering minimum bias events in small collision system such like $d+Au$, the peripheral collisions are most biased. In Figure 10, we tried to sketch the collision dynamics for events with low and high $p_T$ observables in peripheral collisions. As explained before, we trigger minimum bias events and define their centrality classes based on the charge signals from the south side BBC (Au-going direction). As seen in Figure 10, the soft-process-dominated events emit

**Figure 10.** Collision dynamics for events with low $p_T$ (top) and high $p_T$ (bottom) observables.
particles isotropically. Therefore, the BBC charge is proportional to the centrality. However, in the case that hardest jets are produced, less energy will be available for soft production at high $\eta$, e.g., at the BBC location. This leads to a possible $p_T$ dependence of the trigger efficiency in most peripheral collisions. We performed a simulation study for the simplest case, $p+p$ collisions, using PYTHIA [8] and AMPT [9] event generators to see this effect. The left side of the Figure 11 shows the number of BBC hits as a function of jet $E_T$ obtained from a PYTHIA simulation. Since the collision system is symmetric, we took the BBC hit distributions from both south and north sides. The error bars show RMS of the distributions. As going to higher $E_T$, the number of hits in BBC decreases, and the trigger efficiency of events is reduced as shown in the right side of the same figure. At $\sim 30 \text{ GeV}/c$ the trigger efficiency becomes 70\%.

Figure 12 shows an AMPT simulation of $p+p$ minimum bias collisions. In this figure, the number of BBC hits and the trigger efficiency are plotted against the $p_T$ of $\pi^0$'s. The yield of $\pi^0$'s starts
decreasing at $\sim 4 \text{ GeV/c}$, and reaches to $\sim 30\%$ deficit at $14 \text{ GeV/c}$. The trend and magnitude are found to be consistent with what PYTHIA simulation showed, by taking the difference of the energy scale between jets and $\pi^0$'s into account. This implies a trigger bias is expected from a simple hard scattering kinematics, and manifests both in jet $E_T$ and single hadron $p_T$. We are now looking for a same effect in the $d+Au$ collision case using the simulations.

5. Summary and Outlook

High $p_T$ $\pi^0$ and $\eta$ as well as jets are measured using high statistics $d+Au$ collision data collected in RHIC Year-2008 run. Both $R_{dA}$ and $R_{cp}$ for three observables are found to be very consistent each other within quoted systematic and statistical uncertainties. It was found that the $R_{dA}$ is strongly centrality dependent as opposed to the expectations from theoretical models. A possible explanation is given based on the kinematics of hard scattering process. A simulation study in $p+p$ collision case using PYTHIA and AMPT event generators is presented for supporting the explanation. The study for $d+Au$ collisions is on-going.

Recently, a dedicated workshop on $d+A$ and $p+A$ collisions at RHIC and LHC was organized [10]. In the workshop, it was pointed out that the collision dynamics in $d+Au$ collisions is a sequence of $2 \to 2$ hard processes, therefore, the statistical treatment of collisions, such like using $N_{\text{coll}}$ may lead a problem. We expect a rich physics in this small collision system.

References

[1] K. Adcox et al. [PHENIX Collaboration], Phys. Rev. Lett. 88, 022301 (2002) [nucl-ex/0109003].
[2] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 072303 (2003) [nucl-ex/0306021].
[3] D. Stump, J. Huston, J. Pumplin, et al., JHEP 0310, 046 (2003) [hep-ph/0303013].
[4] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904, 065 (2009) [arXiv:0902.4154 [hep-ph]].
[5] K. Adcox et al. [PHENIX Collaboration], Nucl. Instrum. Meth. A 499, 469 (2003).
[6] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 87, 034911 (2013) [arXiv:1208.2254 [nucl-ex]].
[7] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 82, 011902 (2010) [arXiv:1005.4916 [nucl-ex]].
[8] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605, 026 (2006) [hep-ph/0603175].
[9] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, Phys. Rev. C 72, 064901 (2005) [nucl-th/0411110].
[10] http://www.bnl.gov/jqr2013/index.php