Cronin effect at RHIC

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Abstract. The Cronin effect is studied with identified particle spectra from 200GeV d+Au collision at RHIC. The nuclear modification factor R_{dAu} of baryons (proton etc.) rise faster than those of mesons (pions, kaons and phi etc.) and show a baryon/meson scaling behavior similar to that found at Au+Au collisions at same energy. The particle-species dependence of the Cronin effect is observed to be significantly smaller than that at lower energies. The eta asymmetry is also reported and shows contrary trends to prediction based on initial multiple parton scattering model. These measurements indicate that the final state effect plays an important role in the Cronin effect.

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1. INTRODUCTION AND MOTIVATION

The Cronin effect [1] in high energy p+A and A+A collisions has gained renewed interest since many novel physical phenomena were discovered on the Relativistic Heavy Ion Collider (RHIC), especially the large suppression of hadron production at high p_T [3]. As an important baseline, p+A (d+A) collisions were proposed to clarify the role of initial/final state effect in A+A collisions. Thus Cronin effect, as one of the two main nuclear effect in p+A (d+A) collisions, must be firmly understood in order to reliably interpret the physics (partonic energy loss effect, etc.) in A+A collisions.

Cronin effect was first discovered in 1970s [1], featuring an enhancement of hadron production at intermediate p_T range in p+A relative to pp, when scaled by number of binary collisions. Partonic scattering at the initial impact [4] has been interpreted as main source of this effect. Models based on this picture can reproduce the Cronin effect of inclusive hadron production in d+Au collisions, as well as the suppression of charged hadron in Au+Au collisions at RHIC when coupling with partonic energy loss (jet quenching) model [5]. However, based on initial multiple parton scattering and independent fragmentation, one would expect same Cronin effect for different particle type (see, $p(\overline{p})$ and pions). This is not the case since the first discovery of Cronin effect, where experimentally the Cronin effect for $p(\overline{p})$ is larger than that for pions. On the other hand, some recent works have tried to interpret the Cronin effect as a final state effect, such as recombination [6] and coherent multiple scattering [7]. The recombination model has successfully reproduce the particle type dependence of hadron production at intermediate p_T in Au+Au collisions [8].

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The particle production in d+Au collisions at different rapidities can reflect the dynamics of nuclear and Bjorken-x dependence of the Cronin effect (and shadowing). The calculation based on initial multiple parton scattering is also employed to study the pseudo-rapidity dependence of particle production. A unique rapidity asymmetry of particle production in d+Au collisions is predicted [9], where the backward-to-forward (Au-side to d-side) particle ratio is greater than unity at low p_T , goes below unity at intermediate p_T, and approaches unity again at high p_T. Some other models based on gluon saturation [10] or parton recombination [11] predict a backward-to-forward particle ratio that is opposite to the predictions based on incoherent multiple partonic scattering.

Due to these complications, detailed measurements of particle production - the centrality dependence, pseudo-rapidity and p_T distribution - in d+Au collisions are needed for understanding the Cronin effect, and therefore underlying physics in Au+Au collisions. In this proceeding, identified hadron spectra for pion and proton, the pseudo-rapidity asymmetry of inclusive charged hadron, as well as some preliminary results from ϕ meson production from 200GeV d+Au collisions at RHIC, will be presented. Comparison to various model predictions will be made and the physics implication on Cronin effect will be discussed.

2. EXPERIMENT SETUP

The detector used for these studies was the Solenoidal Tracker at RHIC (STAR) [12]. The main tracking device is the Time Projection Chamber (TPC) which provides momentum information and particle identification for charged particles up to $p_T \sim 1.1$ GeV/c by measuring their ionization energy loss (dE/dx) [13]. Detailed descriptions of the TPC and d+Au run conditions have been presented in Ref [18].

A prototype time-of-flight detector (TOFr) based on multi-gap resistive plate chambers (MRPC) [14] was installed in STAR in the d+Au run. It extends particle identification up to $p_T \sim 3$ GeV/c for p and $\bar{p}$. By combining the particle identification capability of dE/dx from TPC and time-of-flight from TOFr, we are able to extend pion identification to ~ 3 GeV/c [15]. More information about the TOF system can be found in [16].

Charged particle multiplicity within $-3.8 < \eta < -2.8$ was measured by the Forward TPC [18] in the Au beam direction and served as the basis for d+Au centrality tagging scheme, as described in [5]. A separate centrality tag, which requires that a single neutron impinge on the Zero Degree Calorimeter [17] in the deuteron beam direction (ZDC-d), was also used.

3. RESULTS AND DISCUSSIONS

The pion and proton are identified by TOF up to $p_T = 3$ GeV/c in 200GeV d+Au collisions. The p_T distribution of particle yields for pion and proton are shown in Fig. 1 [19]. The errors shown in the plot are statistical (predominately smaller than the size of data symbols). The bin-to-bin systematic errors are $\sim 8\%$, while the normalization

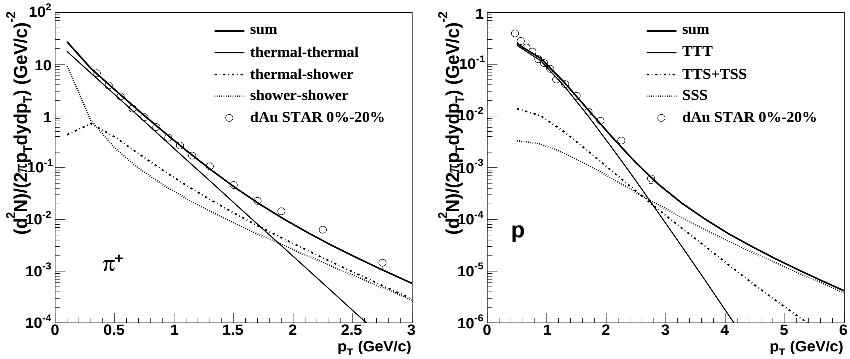

FIGURE 1. The invariant yields for π^+ (left) and proton (right) at $0\% - 20\%$ d+Au collisions as a function of p_T. The open circles are data points. The curves are the calculation results from recombination model. Sum represents the total contribution from recombination model. Thermal-thermal (or TTT) represents the soft contribution. The thermal-shower (or TTS+TSS) represents the contribution from the interplay between soft and hard components. The shower-shower (or SSS) represents the hard contribution.

uncertainty is around 10%. Using the method described in [11], the pion and proton spectra in d+Au collisions from the recombination model calculation are also plotted in the figure, shown as the curves on top of the data points. These plots show that the recombination model can reproduce the spectra of both pion and proton in minimum-bias (and centrality selected, not shown here) d+Au collisions.

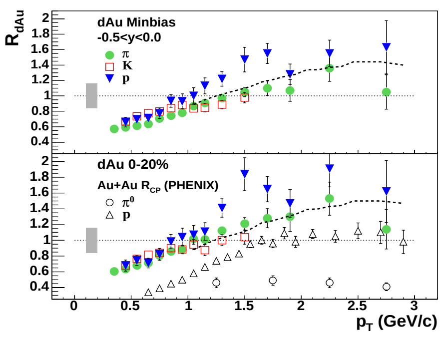

FIGURE 2. The identified particle $R_{dAu}(p_T)$ for minimum-bias and top 20% d+Au collisions. The filled triangles are for $p+\bar{p}$, the filled circles are for $\pi^+ + \pi^-$ and the open squares are for $K^+ + K^-$. Dashed lines are R_{dAu} of inclusive charged hadrons from [5]. The open triangles and open circles are R_{CP} of $p+\bar{p}$ and π^0 in Au+Au collisions measured by PHENIX [20]. Errors are statistical. The gray band represents the normalization uncertainty of 16%.

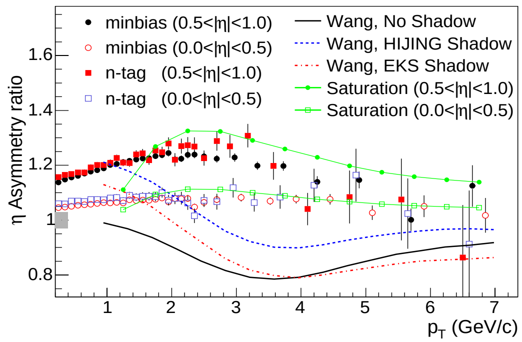

FIGURE 3. The ratio of charged hadron spectra in the backward rapidity to forward rapidity region for minbias and ZDC-d neutron-tagged events in 200GeV d+Au collisions. Calculations based on initial multiple partonic scattering [9] ($y = -1/y = 1$) for minbias events are also shown for cases with no shadowing (solid curve), HIJING shadowing (dashed curve) [23], and EKS shadowing (dot-dashed curve) [24]. Calculations in a gluon saturation model [10] for minbias events are shown for $0.5 < |\eta| < 1.0$ (filled circles with solid line) and for $0.0 < |\eta| < 0.5$ (open squares with solid line)

Nuclear modification factor in d+Au collisions are measured through comparison to the p+p spectrum, defined as

$$R_{dAu}(p_T) = \frac{d^2N^{dAu}/(2\pi p_T dp_T dy)}{T_{dAu} d^2\sigma^{pp}_{inel}/(2\pi p_T dp_T dy)}, \tag{1}$$

where $T_{dAu} =< N_{bin} > /\sigma^{pp}_{inel}$ describes the nuclear geometry. The results of $\pi^+ + \pi^-$, $K^+ + K^-$ and $p^+ + \bar{p}$ for minbias and central (20%) d+Au collisions are plotted in Fig. 2 [21], showing characteristic Cronin effect [1][22] in particle production with R_{dAu} less than unity at low p_T and above unity at $p_T \geq 1.0$ GeV/c. In both cases, the R_{dAu} of protons rise faster than R_{dAu} of pions and kaons. It is notable that the R_{dAu} of protons and anti-protons are greater than unity in both central and minimum-bias d+Au collisions while the proton and antiproton production follows binary scaling in all centralities in Au+Au collisions [20].

Fig. 3 [25] shows the p_T dependence of the asymmetry for minimum bias and ZDC-d neutron-tagged events. The asymmetry is obtained by taking ratios of inclusive backward (Au-side) to forward (d-side) p_T spectra. The ratio was taken between the $-1.0 < \eta < -0.5$ and $0.5 < \eta < 1.0$ as well as $-0.5 < \eta < 0.0$ and $0.0 < \eta < 0.5$ regions. The overall systematic uncertainty (indicated by the band) is less than 3%. The ratio taken within $|\eta| < 0.5$ is nearly constant in p_T, while at higher pseudo-rapidity the ratio slowly increases with p_T up to about p_T = 2.5 GeV/c, maximized at approximately 1.25, and then approaches unity beyond p_T = 5 GeV/c, indicating the absence of nuclear effects at high p_T . For the ZDC-d neutron-tagged events, the ratio exhibits nearly the same p_T dependence as minimum bias events.

Also shown in Fig. 3 are the calculation of the asymmetry in the incoherent multiple partonic scattering framework [9] with various nuclear shadowing parameterizations [23][24], as well as minimum bias gluon saturation results [10]. The measurements

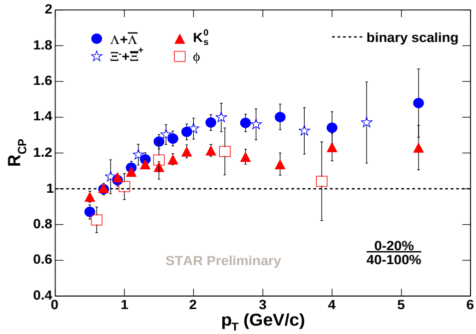

FIGURE 4. The ratio of central($0 \sim 20\%$) collisions over peripheral($40 \sim 100\%$) collisions (R_{CP}) normalized by N_{bin} for ϕ, Λ, Ξ and K_s^0 in d+Au collisions at 200GeV d+Au collisions.

show an opposite trend at intermediate p_T to the theoretical calculations in [9] and thus suggest that multiple scattering of partons in the initial state alone cannot reproduce the observed pseudo-rapidity asymmetry. The gluon saturation prediction exhibits a stronger p_T dependence of pseudo-rapidity asymmetry than actually observed, over-predicting the magnitude of the asymmetry at high pseudo-rapidities. However, it does show the same trend of increasing asymmetry with increasing centrality. The idea of recombination [11], as a final state effect, can also give calculations qualitatively consistent with the measurements of the pseudo-rapidity asymmetry as a function of p_T (not shown in this article). More measurements and quantitative comparisons to these models will be interesting and important to understand the particle production at intermediate p_T.

The parton coalescence/recombination model has been successfully applied in describing the scaling behavior of particle production at intermediate p_T in Au+Au collisions, based on meson/baryon type. It was suggested this final state effect can be pronounced even in d+Au collisions [11], a system considered to be predominated by initial state effect. ϕ meson is a good candidate to test whether particle species dependence still exists in d+Au system, since it has a mass similar to that of the Λ baryon. Preliminary R_{CP} measurements of ϕ meson are shown in Fig. 4 [26], as a function of p_T. Also shown for comparison are R_{CP} for Λ, Ξ and K_s^0. The R_{CP} of baryons are larger than those of mesons at intermediate p_T, which imply the particle production at this p_T region is divided by the particle's types. R_{dAu} measurements [26], which is not shown here, give similar implication. This particle species dependence seems to indicate significant final state effect at d+Au collisions.

4. CONCLUSIONS

In summary, Cronin effect is studied at 200GeV d+Au collisions at RHIC. Pion and proton are identified up to $p_T = 3$ GeV/c. Their spectra are reported and can be reproduced by the recombination model. R_{dAu} of protons rises faster than that of pions and kaons. Ratios of backward-to-forward pseudo-rapidity transverse momentum distributions are above unity for p_T below 5 GeV/c. The initial multiple scattering of partons alone cannot reproduce the observed pseudo-rapidity asymmetry, while the latest calculations in gluon saturation model and parton recombination model stand in qualitative agreement with the measurements. Preliminary results of the nuclear modification factors for ϕ meson in 200 GeV d+Au collisions show that the R_{CP} and R_{dAu} are divided into two groups in intermediate pt range, where the R_{CP}/R_{dAu} of baryons (Λ, Ξ and proton) are larger than that of mesons (ϕ, K_s^0, pion and kaon). This is similar to that observed in Au+Au collisions, where the recombination model has been successfully applied. Based on all these measurements, we can we conclude that the Cronin effect in $\sqrt{s_{NN}}$ = 200 GeV d+Au collisions is not the initial state effect only, and the final state effect plays an important role. Understanding of the Cronin effect should involve both effects simultaneously.

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