Charged particle distributions and nuclear modification at high rapidities in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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(STAR Collaboration)
The measurements of the centrality dependence of $dN/d\eta$ and transverse momentum spectra from mid- to forward rapidity in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV are reported. They provide a sensitive tool for understanding the dynamics of multi-particle production in the high parton-density regime. In particular, we observe strong suppression of the nuclear modification factor $R_{CP}$ at forward rapidities ($d$-side, $\eta = 3.1$) and enhancement at backward rapidity ($\eta = -3.1$). An empirical scaling is obtained for multiplicity and $R_{CP}$ when a shift of the center-of-mass in the asymmetric $d+Au$ collisions with respect to the nucleon-nucleon system is applied.

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I. INTRODUCTION

The $d+Au$ collisions at the Relativistic Heavy Ion Collider (RHIC) provide an important control environment compared to Au+Au collisions. Measurements of the nu-
clear modification factor and back-to-back correlations at mid-rapidity in d+Au collisions suggest that the suppression of particles with high transverse momentum and the disappearance of back-to-back correlations, seen in Au+Au collisions, are due to final-state interactions with the hot, dense medium produced in such collisions, rather than initial-state effects on the Au nucleus. The observed enhancement of the nuclear modification factor in the region of transverse momentum \( p_T > 2 \text{ GeV/c} \) at mid-rapidity in d+Au collisions, referred to as the “Cronin effect”, can be described within a pQCD framework incorporating initial multiple parton scattering and nuclear shadowing. Saturation effects (mostly described as the formation of Color Glass Condensate (CGC)) are expected to be more pronounced at large rapidity \( |\eta| > 3 \) or pseudorapidity \( \eta \) close to the deuteron beam, where the small-\( x \) components of the Au nucleus wave function can be probed. Recent results reported by the BRAHMS collaboration, where a suppression of the nuclear modification factor at forward rapidities is visible, are in qualitative agreement with predictions within the framework of gluon saturation in the CGC. These results indicate a possible dramatic evolution of gluon saturation from mid- to forward rapidity at RHIC. However, it should be noted that these results can be reasonably described by pQCD models and in the framework of final-state parton recombination. On the other hand, as the rapidity of the probe decreases (and at the same time, \( x \) increases), the multiple-scattering contribution to the Cronin effect should decrease. The first results from the PHENIX collaboration show an opposite behaviour which cannot be explained by current model calculations.

In this paper the pseudorapidity and centrality dependence of the nuclear modification factor \( R_{CP} \) will be discussed in connection with the asymmetry in particle production in d+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

II. EXPERIMENTAL SETUP

The STAR experiment at RHIC measures charged hadrons over a wide range of pseudorapidity and transverse momentum. The main detector is a large Time Projection Chamber (TPC) which allows particle identification via \( dE/dx \) within the range of \( |\eta| < 1 \). Charged particle detection in the forward directions is achieved with the two azimuthally symmetric Forward TPCs (FTPCs) which extend the pseudorapidity coverage of STAR to the region \( 2.5 < |\eta| < 4 \). The FTPCs which utilize a radial drift field perpendicular to the magnetic field, achieve a two-track resolution of \( 2 - 2.5 \text{ mm} \) (an order of magnitude better than a TPC using a constant drift field). This allows track reconstruction in the larger rapidity region where track densities are high. In d+Au collisions at a center-of-mass energy of \( \sqrt{s_{NN}} = 200 \text{ GeV} \) a track finding efficiency in the FTPCs of about 90% was reached, independent of centrality, \( \eta \) and \( p_t \) in the phase space region of \( 3 < \eta < 3.5 \) and \( 0.1 < p_t < 3 \text{ GeV/c} \) used for this analysis. The momentum resolution in the FTPCs is also independent of centrality, but shows a strong dependence on \( \eta \) and \( p_t \). For \( \eta \approx 3.1 \), the relative momentum resolution degrades approximately linearly from \( 10\% \) to \( 25 - 30\% \) in the region of \( 0.1 < p_t < 3 \text{ GeV/c} \) and the pseudorapidity resolution is better than 0.02 units in \( \eta \). Background and secondary decay products corrections were estimated using HIJING simulations. The main systematic error quoted in this analysis (if not otherwise mentioned) is caused by the momentum resolution of the FTPCs. This affected mainly the vertex DCA (distance of closest approach) requirement used to select primary charged hadrons in the FTPCs. An estimate of the main systematic error was done by varying the DCA by \( \pm 0.5 \text{ cm} \). A detailed description of the various calibration steps, further corrections and data quality can be found in [20].

III. MEASUREMENTS

A. Mean transverse momentum

To quantify the influence of momentum resolution on the transverse momentum spectra simulated charged pions were embedded in real d+Au events, adding up to 5% of the total event multiplicity in the FTPCs. Initially flat input distributions were weighted according to the measured transverse momentum distributions as function of centrality and transverse momentum. Background and secondary decay products corrections were estimated using HIJING simulations. The transverse momentum distributions corrected for momentum resolution, background and secondary decay products measured in the East-FTPC (Au-side; \( \eta \approx -3.1 \)) and West-FTPC (d-side; \( \eta \approx 3.1 \)) are shown in Fig. 1. Background and secondary decay products were estimated using HIJING simulations. A slight increase of \( p_t \) centrality is visible on the Au-side, whereas on the d-side virtually no centrality dependence of \( p_t \) is present.

B. \( R_{CP} \) in the forward directions

Another variable of interest is the ratio of central to peripheral inclusive d+Au spectra

\[
R_{CP}(p_t) = \frac{(d^2N/dp_t d\eta/\langle N_{bin} \rangle)|_{\text{central}}}{(d^2N/dp_t d\eta/\langle N_{bin} \rangle)|_{\text{periph}}}, \tag{1}
\]
where $d^2N/dp_t d\eta$ is the differential yield per event and $\langle N_{bin} \rangle$ the mean number of binary collisions for the corresponding centrality class, calculated using a Monte Carlo Glauber model [8] (see Table I). For the $R_{CP}$ measurements the transverse momentum range could be expanded to 3 GeV/c (instead of 1 GeV/c for the transverse momentum measurements in section III.A) due to the centrality independence of the momentum resolution. Therefore, the effect of momentum resolution on the transverse momentum spectra cancels out in the $R_{CP}$ ratio.

Comparing forward to backward rapidities, it can be seen in Fig. 2 that $R_{CP}$ is increasing with $p_t$ for $p_t < 3$ GeV/c on the Au-side. Also $R_{CP}$ is larger on the Au-side,
FIG. 3: (Color online) Charged hadron pseudorapidity distribution per event in the TPC and FTPC acceptance for 0-20%, 20-40%, 40-100% central and minimum bias d+Au events (triangles). The error bars include both statistical and systematic error. Also overlayed are measurements from BRAHMS (crosses) and PHOBOS (circles). In addition predictions from HIJING, AMPT and the saturation model are also plotted compared with STAR measurements.

which indicates that the Cronin effect is more pronounced on the Au-side of a d+Au collision. Strong centrality dependence of $R_{CP}$ on the d-side of the collisions is another interesting feature seen in Fig. 2. This observation was also reported by the BRAHMS collaboration. However, no significant centrality dependence is observed on the Au-side of a d+Au collision. The $R_{CP}$ measurements from the FTPCs are in good overall agreement with measurements from BRAHMS on the d-side [11] for $p_t > 1$ GeV/c and in agreement with PHENIX on the Au-side [14] of a d+Au collision (see Fig. 2). The discrepancy between the BRAHMS and STAR $R_{CP}$ measurements on the d-side at $\eta \approx 3$ for $p_t < 1$ GeV/c can not be completely resolved at this time. The discrepancy can be partially attributed to the different centrality classes used by the two experiments to calculate the $R_{CP}$. BRAHMS uses 60-80% as the most peripheral bin whereas STAR uses the 40-100% centrality class. Also, the BRAHMS centrality selection is biased towards peripheral collisions in forward rapidities as discussed in section III C. Furthermore, different low-$p_t$ cut-offs may affect the low $p_t$ measurements, where the difference between BRAHMS and STAR is most prominent.

The suppression of $R_{CP}$ and $R_{dAu}$ at higher rapidities on the d-side is in qualitative agreement with predictions of the saturation model [12]. Models based on pQCD which incorporate initial-state parton scattering and energy loss can also describe the behaviour of $R_{CP}$ at higher rapidities [8, 9]. Furthermore, in the framework of parton recombination in the final state, $R_{CP}$ at forward rapidities can be described as well [13].

C. Charged particle density asymmetry

In Fig. 3b, the pseudorapidity distribution $dN_{ch}/d\eta$ of charged hadrons per event in the TPC and FTPC acceptance is shown for minimum bias and for the 0-20%, 20-40%, and 40-100% most central events. For comparison, measurements of the pseudorapidity distribution from BRAHMS and PHOBOS are also plotted. The measured $dN_{ch}/d\eta$ distributions for minimum bias d+Au events are in good agreement for all three experiments. However, with increasing centrality, a significant difference in the particle density at negative pseudorapidity values $\eta < -3$ between STAR and PHOBOS is visible. On the other hand, the measurements in the mid-pseudorapidity region are in good agreement. When comparing central events, for the $\eta < -3$ region the BRAHMS $dN_{ch}/d\eta$ distribution is lower than the STAR measurements; at mid-rapidity it is higher. A possible explanation could be the different methods used for centrality selection. Centrality selection for the STAR-TPC was done via the $N_{ch}$ multiplicity in the FTPC and vice versa, to avoid autocorrelations caused by fluctuations in the measured multiplicity. Simulation studies show that with a pseudorapidity gap of 2 units between the detectors this method is insensitive to autocorrelations [20]. Use of the FTPC $N_{ch}$ multiplicity on the Au-side instead leads to a visibly higher particle density in the $dN_{ch}/d\eta$ distribution for $\eta < -3$, causing a significant bias in the centrality definition [20]. This observation explains the higher particle density measured by PHOBOS for the Au-side of a d+Au collision, because their centrality was determined via the multiplicity in the pseudorapidity region of $-4 < \eta < -3.5$. For BRAHMS the enhancement in the particle density at midrapidity could be due to the fact that the multiplicity in the central region $|\eta| < 2.2$ was used to define centrality. However, within the systematic errors the results of all three experiments are consistent with each other.

In addition, the measured pseudorapidity distributions were compared with model predictions. Calculations based on gluon saturation in the Color Glass Condensate [12] as well as results of HIJING [19] and a Multi-Phase Transport Model (AMPT) [26] are shown in Fig. 3b. All
model calculations are in good overall agreement with the measured $dN_{ch}/d\eta$ distributions for different centrality classes. In particular, the models are able to reproduce the increasing asymmetry of charged particle densities with increasing centrality.

IV. COLLISION ASYMMETRY AND YIELD SUPPRESSION

In the following section the centrality dependence of $R_{CP}$ at high rapidities $|\eta| \approx 3.1$ will be discussed in connection with the observed asymmetry of the produced particle density in d+Au collisions at transverse momenta $p_t < 3$ GeV/c. In Fig. 2 the $R_{CP}$ from HIJING simulations for different centralities with and without shadowing is shown. It is evident from Fig. 2 that HIJING reproduces the overall behaviour of $R_{CP}$ at $|\eta| \approx 3.1$. In addition, it can be concluded that the influence of shadowing for $p_t > 1$ GeV/c only affects the measurements on the Au-side. Since the $p_t$ spectrum on the d-side is more or less independent of centrality – except for an overall scale – (see Fig. 1a and b) and comparable with p+p collisions, the suppression of $R_{CP}$ on the d-side (see Fig. 2) could be due to the asymmetry in particle production in d+Au collisions with respect to the symmetric p+p collisions (see Fig. 3). To take the asymmetry in d+Au collisions into account, a new variable $\eta_{CM}$ is introduced, which is defined as the weighted mean of the $dN_{ch}/d\eta$ distribution for each centrality class ($\eta_{CM} = \eta_{CM}(N_{part})$). $\eta_{CM}$ was extracted from the published PHOBOS results [24] and should represent the shift of the center-of-mass in the asymmetric d+Au collisions with respect to the nucleon-nucleon center-of-mass system (see Table II). Even though the PHOBOS data are biased towards higher multiplicity on the Au-side as discussed in section III C they were used to determine $\eta_{CM}$ to maintain a model independent approach (also they are the only measurements available covering the full $\eta$ range). The $dN_{ch}/d\eta$ distribution for inelastic p+p collisions [22] in this new reference system - obtained by shifting with $\eta_{CM}$ - are shown in Fig. 4. One observes that the d+Au $dN_{ch}/d\eta$ distributions normalized with $<N_{part}/2>$ (see Table I) at high rapidities are consistent with the shifted p+p values. Also, the centrality dependence can be qualitatively explained. Therefore, $\eta_{CM}$ seems to be an appropriate variable to describe the asymmetry in particle production in d+Au collisions assuming that this asymmetry is caused by the nuclear stopping of the deuteron while traversing through the gold nucleus. Similar approaches to describe the pseudorapidity distributions in d+Au can be found in [21, 27, 28].

In that representation, the suppression of the particle density on the d-side and the enhancement on the Au-side in asymmetric d+Au collisions with respect to the symmetric p+p collisions (see Fig. 4) can be expressed by defining $S_{dAu}(\eta, \eta_{CM})$ as the ratio of the p+p reference $dN_{ch}^{pp}/d\eta$ distribution shifted with $\eta_{CM}$ and the unshifted $dN_{ch}^{pp}/d\eta$ distribution:

$$S_{dAu}(\eta, \eta_{CM}) = \frac{dN_{ch}^{pp}/d\eta|_{\eta-\eta_{CM}}}{dN_{ch}^{pp}/d\eta|_{\eta}} (\eta, \eta_{CM}).$$ (2)

Our ansatz is then that the suppression and enhancement of $R_{dAu}$ (and $R_{CP}$) is mainly caused by this geometric asymmetry. It would follow from this ansatz that the difference in the observed centrality dependence of $R_{dAu}$ should be accounted for by simply scaling with $S_{dAu}(\eta, \eta_{CM})$ (Eq. 2). The BRAHMS $R_{dAu}$ measurements [11] at different pseudorapidities ($\eta=0, 1, 2.2$ and 3.2) on the d-side are then consistent with a universal behaviour, reaching binary scaling at $p_t > 3$ GeV without a significant Cronin enhancement at intermediate $p_t$.

A similar procedure can be applied to describe $R_{CP}$ measurements for different centrality classes and pseudorapidities on the d- and Au-side of a d+Au collision. One has to modify $S_{dAu}(\eta, \eta_{CM})$ (Eq. 2) to take the asymmetry in particle production - still visible in peripheral d+Au collisions (see Fig. 4) - into account. This is realized by taking the peripheral d+Au $dN_{ch}/d\eta$ distribution as reference and shifting the denominator in Eq. 2.

### Table II: $\eta_{CM}$ defined as the weighted mean of the PHOBOS $dN_{ch}/d\eta$ distribution for various centrality classes [24].

| Centrality class | $\eta_{CM}$ |
|------------------|--------------|
| 0-20%            | -1.29        |
| 20-40%           | -0.98        |
| 40-60%           | -0.68        |
| 60-80%           | -0.37        |
| 80-100%          | -0.14        |
| 40-100%          | -0.48        |
| 0-100%           | -0.92        |

FIG. 4: (Color online) Pseudorapidity distribution of charged hadrons in the FTPC acceptance for 0-20%, 20-40%, 40-100% central d+Au events scaled with Npart (open triangles). p+p measurements [22] unshifted (triangles) and shifted by $\eta_{CM}$ (lines) are overlay (for further details see text).
according to the peripheral $\eta_{CM}$ value:

$$S_{CP}(\eta, \eta_{CM}) = \frac{dN_{pp}^{ch}/d\eta|_{\eta-\eta_{CM}}}{dN_{pp}^{ch}/d\eta|_{\eta-\eta_{CM,\text{periph.}}}} (\eta, \eta_{CM}).$$ \hspace{1cm} (3)

$R_{CP}$ measurements from the FTPCs at $|\eta| \approx 3.1$ for different centrality classes scaled with $S_{CP}(\eta, \eta_{CM})$ are shown in Fig. 5. These results suggest that the observed enhancement of $R_{CP}$ on the Au-side for different centrality classes can be explained by an enhancement of particle production caused by the nuclear stopping of the deuteron and described by a shift of the center-of-mass in the d+Au collisions. The suppression of $R_{CP}$ on the d-side is explained analogously. Universal scaling behaviour of $R_{CP}$ scaled with $S_{CP}(\eta, \eta_{CM})$ at $|\eta| \approx 3.1$ is visible for $p_t > 1$ GeV/c in the FTPC measurements (see Fig. 5). In addition scaled BRAHMS $R_{CP}$ measurements for the top 20% central d+Au events at different pseudorapidities are also overlaid in Fig. 5. Universal scaling behaviour of scaled $R_{CP}$ is seen in both STAR and BRAHMS measurements reaching binary scaling for $p_t > 2$ GeV/c. The deviation from the supposed scaling for the BRAHMS $R_{CP}$ measurements at midrapidity (and also the discrepancy to the STAR midrapidity measurements) might be explained by the different centrality definitions, where a bias to higher particle multiplicities might be present in the BRAHMS data as discussed in section IIIIC. It should be noted that systematic errors in the scaling due to uncertainties in the determination of $\eta_{CM}$ were not estimated in this analysis. One would expect an overall normalization uncertainty, but the main feature of scaling should be preserved. The simple data driven picture outlined in this paper was meant to point out the importance of the collision geometry in d+Au collisions.

V. CONCLUSIONS

Centrality dependence of the $dN/d\eta$ distributions in $\sqrt{s_{NN}}=200$ GeV d+Au collisions is presented. Within errors, $dN/d\eta$ cannot discriminate between different model calculations. However, our data show an increase of $(p_t)$ as a function of centrality on the Au-side, whereas on the d-side no centrality dependence is visible. This result together with the suppression of $R_{CP}$ on the d-side and its enhancement on the Au-side relative to mid-rapidity cannot be described consistently by current model calculations [14]. A similar study of comparing particle production at high $p_t$ in d- and Au-side at mid-rapidity [20] has ruled out models based on incoherent initial multiple partonic scattering and independent fragmentation. It also showed that models based on nuclear shadowing incorporating extremes of gluon shadowing at low $x$ can not account for the difference in particle production in d- and Au-side at high $p_t$ at mid-rapidity.

This paper demonstrated, that in a simple stopping picture the main features of the pseudorapidity and centrality dependence of $R_{CP}$ (and $R_{dAu}$) at higher rapidities can be explained by the suppression (enhancement) of particle yields in d+Au relative to p+p collisions and peripheral d+Au collisions. Simulation studies show a small effect of shadowing in HIJING on $R_{CP}$, especially on the d-side, supporting this geometric picture. This result is also confirmed by measurements of $R_{pPb}$ by NA49 [30] at an order of magnitude lower energies, where shadowing and gluon saturation are expected to be small, which show qualitatively the same characteristic centrality and rapidity ($x_F$) dependence and are consistent with the stopping picture.

Taking the asymmetry in particle production – characterized by a shift of the center-of-mass in the asymmetric d+Au collisions with respect to the nucleon-nucleon or peripheral d+Au center-of-mass system – into account, $R_{CP}$ (and $R_{dAu}$) show a universal scaling behaviour independent of centrality and pseudorapidity in d+Au collisions at RHIC energies. On the other hand, the success of the CGC saturation approach [31] and stopping picture in quantitatively describing BRAHMS $R_{CP}$ (and $R_{dAu}$) measurements could be interpreted as a link between saturation as the possible origin of nuclear stopping. In that case deviations from the observed empirical scaling in asymmetric collision systems at different energies can help to quantify the onset of saturation effects in heavy-ion collisions.

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[32] \[ R_{AB}(p_T) = \frac{(d^2N/dp_Td\eta)}{(T_{AB}d^2\sigma^{pp}/dp_Td\eta)}, \] where \( d^2N/dp_Td\eta \) is the differential yield per event in the nuclear collision A+B and \( T_{AB} = \langle N_{bin} \rangle \sigma^{pp}_{inel} \) describes the nuclear geometry with respect to the p+p reference measurements.