Dependence of Single Particle Distributions on Rapidity and Centrality in d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract

Measurements of identified single particle distributions in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at the RHIC collider are described. The dependence of these distributions on the centrality of the collisions, as well as the rapidity of the detected particles are emphasized in this report.

Keywords: Saturation, d+Au, Cronin Effect

1. Introduction

Early p+A experiments. Collisions of proton beams incident on fixed nuclear targets have been used in the past to study hadronic interactions. The energies of the incident beams ranged from a few GeV to over 800 GeV. Energy loss and baryon transport in nuclear matter were expected to provide a clear window into the workings of strong interactions at the time when Quantum Chromodynamics (QCD) was being formulated. The puzzling image that emerged from these early studies did not show evidence for intranuclear cascade but rather suggested that the projectile interacted at several points within the nuclear target receiving a transverse momentum “kick” at each interaction before undergoing a final violent interaction with a target nucleon. Particle yields from p+A collisions increase with the size of the target and follow a power law dependence in atomic number A: $d\sigma_{pA \rightarrow hX}/d^2p_T = d\sigma_{pp \rightarrow hX}/d^2p_T A^{\alpha(p_T)}$ [1]. The majority of the detected particles were found on the target side of the collision [2, 3].

The Cronin enhancement. Those early experiments on nuclear targets compared particle production as function of the transverse momentum, to the base-line p+p collisions at the same energy in order to highlight differences related to nuclear effects. In general, the comparison would be done between two A and B target systems and it assumes scaling with the
number of binary collisions $N_{coll}$ (incoherent sum of nucleon-nucleon interactions). This comparison is now known as the nuclear modification factor and for d+Au collisions compared to p+p interactions is written as: $R_{dAu} = (dN_{dAu}/dydp_T^2)/(N_{coll}^{dAu}dN_{pp}/dydp_T^2)$. At values of $p_T$ close to zero, the $R_{dAu}$ is smaller than 1 and appears to scale with the number of participant nucleons $N_{part}$. This may be an indication that this behavior is driven by the still unresolved non-perturbative QCD environment. At intermediate values of $p_T$ (from 1 to 4 GeV/c), an enhancement has been measured, which is commonly related to multiple interactions of the projectile in the target that do not produce particles but excite the projectile wave function. This excitation is postulated to be a hardening of the transverse momentum distribution of the projectile partons. At a later time, the excited projectile will fragment and the detected particle will “remember” the transverse parton distribution of the beam.

The DIS program. A new aspect of the p+A collisions resulting from theoretical advances in QCD and experimental results probing deep into the structure of nucleons has gained much relevance in the last 10 to 20 years and is usually referred to as small-x physics. The HERA Deep Inelastic Scattering (DIS) program has explored the structure of protons with unprecedented reach. The QCD based image that comes out of that program shows nucleons in $x$ (the longitudinal momentum fraction carried by a parton) and $Q^2$ (the magnitude of the 4-vector momentum of the probe, a virtual photon in the case of DIS which determines the probing resolution). At high values of $x$ the parton distribution is dominated by the constituent u, d and s quarks. As the values of $x$ tends toward zero, the population of partons becomes a mixture of gluons and quark-antiquark pairs that emerge as fluctuations from the vacuum [4]. At the limit of even smaller values of $x$, gluons are the dominant entities, and the HERA measurements found that the gluon density grows as a power in $1/x$ [5]. An end to that growth has not yet been measured, but unitarity imposed on the wave function of the target makes the end of that growth all but inevitable. The growth of the gluon density is postulated to have two components: a linear term produced by gluon splitting, and a non-linear one related to gluon fusion as expressed in eq. 1:

$$dG/dy \sim G - G^2.$$  \hspace{1cm} (1)

As the value of the momentum fraction $x$ in the target reaches sufficiently small values and the growth of the gluon density governed by eq. 1 has ended,
the target is said to be in the so called Color Glass Condensate (CGC) a slowly varying system of color fields that presents a maximal cross section to any projectile \[6\]. A boundary to the CGC is expected to depend on \(1/x\) as well as the size of the target \(A\):

\[
Q_{sA}^2 = A^{1/3}Q_0^2(x_0/x)^\lambda = A^{1/3}Q_0^2x_0^\lambda e^{\lambda y}.
\]

When one describes p+A collisions at the partonic level, the momentum fraction of the target parton depends on the rapidity of the produced particle, and for simplicity, it is written as \(x_2 = (2p_T/\sqrt{s})e^{-y}\). In the CGC framework it is possible to search for the onset of saturation (\(p_T\) below or close to \(Q_{sA}^2\)) by studying particle production as function of rapidity and centrality \[7, 8\]. The High Rapidity section of this report is an attempt to summarize the measurements performed in d+Au collisions with relevance to small-x physics.

**The RHIC d+Au program.** The d+Au collisions at RHIC were in part included in the program as a contrasting system to the hot medium being formed in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV. The first result from d+Au at RHIC did not show the suppression found in Au+Au in what is understood as the absence of “jet quenching” in cold matter. Instead the nuclear modification factor measured at mid-rapidity brought back the focus on the Cronin effect, which later was found to be different when measured for baryons and mesons. The yields of charged particles were found to be suppressed in the projectile fragmentation region in a manner consistent with the onset of saturation in the Au wave function.

At RHIC, d+Au and p+p collisions at \(\sqrt{s_{NN}} = 200\) GeV were, for the first time in p+A physics history, collected in collider mode. At top RHIC energy these collisions provide well separated fragmentation regions, and as such, constitute a leap in data quality and physics reach. Figure 1 shows the pseudo-rapidity distribution of charged particles measured in d+Au collisions at RHIC by the PHOBOS Collaboration \[9\].

The pseudo-rapidity density of the very early p+A experiments suggested a projectile traversing the target without being affected. This feature of the data was dubbed “nuclear transparency” in p+A collisions. The RHIC results are showing a much clearer picture that negates the existence of such transparency. When compared to similar pseudo-rapidity distribution extracted from p+p collisions at the same energy, as is done if Fig. 2, one finds a triangular shape extending from \(\eta = 0\) to close to the deuteron beam
Figure 1: Pseudo-rapidity distributions of charged particles measured in d+Au collisions at RHIC $\sqrt{s_{NN}}=200$ GeV for data samples of different centrality as well as a Minimum Bias sample [9].

Figure 2: Centrality dependence of the $dN_{ch}/d\eta$ ratio of d+Au collisions relative to that extracted from inelastic p+p collisions at the same energy by the PHOBOS Collaboration.

rapidity, which can be explained by a scenario where each detected particle “drags” uniform trails of particles at lower rapidities as suggested by Brodsky, Gunion, and Kühn [10]. The particle production on the target fragmentation side ($\eta < 0$) is completely different; as it was the case at lower energies, most of the particle yield detected originates from that region and when compared to p+p yields, one finds a clear change in the growth rate, deeper into the target fragmentation ($\eta < -3$).

The RHIC d+Au collisions have been studied with a complement of four experiments: STAR with its full azimuth coverage and its large acceptance Time Projection Chamber (TPC) which covers 2 units in pseudo-rapidity ($|\eta| < 1$). PHENIX, the second large detector at RHIC, designed with emphasis on electron, photon and muon detection. PHOBOS, with its almost complete coverage for measurements of charged particle multiplicity, and finally, BRAHMS with its two conventional rotatable spectrometers that measure fully identified charged particles starting from mid-rapidity and extending well into the fragmentation region of the deuteron beam. These four
experiments collected their data under similar trigger conditions. STAR defined its minimum-bias trigger by requiring at least one beam neutron in the Au side Zero Degree Calorimeter (ZDC). (The ZDC counters are located at 18 meters on both sides of the nominal interaction point). The Beam-Beam Counter (BBC) \((3.3 < |\eta| < 5.0)\) was used to measure the luminosity and to define the vertex of the collisions. The STAR minimum-bias trigger measures \(95 \pm 3\%\) of hadronic d+Au cross section \((2.21 \pm 0.09\) \). The PHENIX minimum-bias trigger was defined by hits on their BBC detector \((3.0 < |\eta| < 3.9)\) and a vertex cut: \(|z| < 30\) cm. This trigger accepts \(88 \pm 4\%\) of all inelastic d+Au that satisfy the vertex condition. PHOBOS triggers with 16 scintillator paddles installed with azimuthal symmetry and cover \(3 < |\eta| < 4.5\). The BRAHMS minimum-bias trigger was defined with plastic scintillators placed at \(\pm 1.6, \pm 4.2, \text{and} \pm 6.6\) meters from the nominal interaction point, which cover \(3.2 < |\eta| < 5.3\) and can trigger on \(91 \pm 3\%\) of the d+Au inelastic cross section \((2.4\) \). The centrality of the STAR events is defined with raw (uncorrected) multiplicity of charged particles measured in the Au side Forward TPC (FTPC-Au) \((-3.8 < \eta < -2.8)\). PHOBOS used the signal from their three ring detectors \((3.0 < |\eta| < 5.4)\). PHENIX defines centrality with the charged particle multiplicity in the Au side BBC. BRAHMS defines centrality with Si strips and scintillator tile multiplicity counters \((-2 < \eta < 2)\).

2. Mid-rapidity

The STAR Collaboration has produced a systematic study of particle production at mid-rapidity with moderate transverse momentum reach from all collision systems studied at RHIC so far; p+p, d+Au and Au+Au. In particular, the invariant yields for identified charged particles produced in minimum-bias d+Au and p+p collisions at the same energy are shown in Fig. 3 as a sample of the high quality of the data. In order to compare the behavior of these systems, they performed fits to particle spectra based in the Blast Wave formalism, even if the smaller systems p+p and d+Au are not expected to show radial flow. The average transverse momentum \(\langle p_T \rangle\) of pions displayed as a function of charged particle density in pseudo-rapidity space in Fig. 4 shows a smooth linear growth spanning from p+p all the way to the most central Au+Au collisions. In contrast, the corresponding quantity extracted for kaons and protons shows values for p+p and d+Au that are visibly higher than the corresponding extrapolations from Au+Au.
collisions as they approach the most peripheral collisions. The most peripheral Au+Au collisions have the same value of $\langle p_T \rangle$ as the p+p collisions. As stated in the STAR publication, the different behavior for kaons and protons in d+Au collisions may come from jet contributions (in Au+Au jet contribution is softened by quenching) or initial state multiple interactions in the Au target.

The PHENIX Collaboration has performed a study of the Cronin effect at mid-rapidity with charged particles, both with the full d+Au collision events as well as events where a beam neutron was detected in the deuteron side ZDC or a beam proton in the Forward Calorimeter North, which is also located in the deuteron fragmentation region. These tagged events divide into two samples where only one nucleon in the deuteron beam interacted: p+Au or n+Au. In what follows both samples are used together and those collisions are designated as nucleon+Au (N+Au). The nuclear modification factors $R_{dAu}$ and $R_{NAu}$ for different centralities are shown in Fig. 5. The centrality of the event is defined with the multiplicity of charged particles incident in the BBC (in the Au fragmentation region) which is a related to the number of participant Au target nucleons. The N+Au sample of collisions is biased towards peripheral collisions but the number of Au participant nucleons can be extracted from a Glauber model Monte Carlo calculation used as well to

![Figure 3: STAR identified charged particle yields extracted from a Minimum bias sample of d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as well as Non Single Diffractive (NSD) p+p at the same energy [11].](image1)

![Figure 4: (color online) Average $p_T$ for $\pi$, K and protons as function of $dN_{ch}/dy$ in p+p d+Au and Au+Au collisions at different centralities. Statistical and systematic error added in quadrature.](image2)
extract collision parameters for the d+Au collisions. The similarity of the 
$p_T$ dependence of the $R_{dAu}$ and $R_{NAu}$ factors is clear and it may be related 
to the fact that the Cronin effect is tied to the partonic component of the 
nucleons.

Figure 5: PHENIX $R_{dAu}$ and $R_{NAu}$ for 
charged hadrons in four different centrality 
samples A: 0-20%, B: 20-40%, C: 40-60%, D: 
60-88% of d+Au cross-section [12].

Figure 6: $R_{dAu}$ (open symbols) and $R_{NAu}$
(closed symbols) for charged particles in 
three momentum ranges as function of $\nu$−1 [12].

Figure 6 is a summary of the previous figure where an average of the 
nuclear modification factors $R_{dAu}$ and $R_{NAu}$ in three ranges of transverse 
momentum is shown as function of the number of sequential nucleon-nucleon 
collisions. A QCD based description of the Cronin effect has a projectile 
nucleon interacting several times with the nuclear target, each interaction 
broadens the transverse momentum distribution of the projectile partons. 
Eventually, the projectile has a hard interaction or hadronizes into other 
particles whose transverse momentum distribution will display the history of 
the previous interactions. Most of the models describing Cronin effect will 
parametrize the target contribution to the $k_T$ broadening as proportional 
to the number of sequential interactions minus one $\nu − 1$. Where $\nu =$\n$\langle N_{coll}/N_{part} \rangle$ in d+Au collisions and $\nu = N_{coll}$ for N+Au. The Cronin 
effect is most pronounced in the high $p_T$ range, where, within the systematic 
uncertainties, it reaches a constant value of $\sim 20%$ above $\nu = 5$ and remains 
flat for more central collisions. Both d+Au and N+Au have the same $\nu$ 
dependence.
The nuclear modification factors extracted with identified particles have shown a different behavior between baryons and mesons. Figure 7 shows that the $R_{dAu}$ for protons deviates from binary collisions scaling by as much as 40% whereas pions and kaons show an enhancement of at most 10%. The difference in the magnitude of the Cronin effect between protons and pions has been seen at lower energies [14], and it is stronger that the one measured at RHIC energies. This difference continues to be unexplained and both the STAR and PHENIX collaborations have published several studies that add information about the Cronin effect and its difference between baryon and mesons. Figure 8 compiles those studies showing the $R_{dAu}$ ratio constructed for $\rho$, $K^{*\pm}$ and $K^{*0}$ extracted from d+Au and p+p collisions at mid-rapidity by STAR [15], and the $\phi$ [16] and $\omega$ [17] mesons studied by PHENIX. The figure includes a curve joining the measured STAR $R_{dAu}$ for charged pions. Within errors, it appears as all measured mesons behave just as pions, even though the $\rho$ tends to have smaller values above 2 GeV/c.

### 3. High rapidity

The BRAHMS experimental setup consists of two conventional rotatable spectrometers. The Mid-Rapidity Spectrometer (MRS) tracks charged particles from 90 to 35 degrees with two Time-Projection Chambers and two
Time-of-Flight detectors. The Forward Spectrometer (FS) measures charged particles produced at angles ranging from 30 to 2.3 degrees. As the momenta of those particles can reach values as high as 30 GeV/c, the momentum measurement is done with a complement of four magnets, two TPCs and two drift chambers. Particle identification at high momentum is done with the Ring Imaging Cherenkov detector. Lower momentum charged particles are identified using two Time-of-Flight detectors. Figure 9 shows the minimum-bias yields for positive and negative pions, kaons and protons measured with the MRS and FS spectrometers in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These distributions are fully corrected for spectrometer acceptance, decays in flight and absorption in the spectrometers’ material. The largest systematic un-
certainty in these results is related to the matching between magnetic field settings at any angular setting of the spectrometers and is estimated to be have an upper value of 10%.

![Figure 10: The nuclear modification factor $R_{dAu}$ for charged pions detected in the most central sample of events (0-30%) at three different values of rapidity. The reference p+p charged pion distributions were also measured with the BRAHMS spectrometers during RHIC run 5. At $y=3$, the published $R_{dAu}$ for negative charged hadrons [18], is shown with open square symbols for comparison.](image)

Figure 10 shows the nuclear modification factor $R_{dAu}$ comparing the invariant yields of charged pions in the most central sample of d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV ($N_{coll} = 12.6$), to similar yields measured in p+p collisions at the same energy collected with the BRAHMS spectrometers. The two panels to the left of the figure show the $R_{dAu}$ at two rapidity values near mid-rapidity ($y=0$ and $y=0.9$) measured with the MRS spectrometer. The low $p_T$ suppression is a feature of all these measurements and will not be described any further, above 1.5 GeV/c, the Cronin enhancement is visible at mid-rapidity but its magnitude remains below 20%. At $y=0.9$ there is a hint for the presence of the same enhancement, but the extent of the pion identification range does not allow for a definite statement. The right panel in the same figure shows a drastic change in the ratio, this time, it grows from a value at the lowest $p_T$ that is consistent with $N_{part}$ scaling but remains below one and reaches a value of $\sim 0.6$ at the highest $p_T$ bin (3 GeV/c). This suppression in the yield of pions measured in d+Au collisions with respect to similar yields seen in p+p collisions is well explained and reproduced with
arguments that involve the values of the saturation scale $Q_s^2$ in the CGC formalism. As mentioned above, the onset of saturation, or the location of a boundary in transverse momentum space where non-linear effects in the gluon fields are present at their full strength, depends both on the rapidity of the measurements and the atomic number A of the target. The evolution of the gluon density, which is governed by equations similar to eq. [1] will make the numerator yields change slowly with rapidity if the d+Au system at RHIC top energy is close to saturation. Meanwhile the p+p system at the same energy will have yields growing quickly with rapidity because the $p_T$ of the measurements is well above the corresponding saturation scale. (The p+p system is considered dilute and is well described by perturbative QCD.)

The PHOBOS Collaboration has also studied the rapidity dependence of the nuclear modification factor $R_{dAu}$ with charged particles tracks in their mid-rapidity spectrometer and their results are summarized in Fig. where they found that the suppressions starts already one unit of pseudo-rapidity away from $\eta = 0$ [20].

![Figure 11: The nuclear modification factors for charged particles measured by the PHOBOS Collaboration in d+Au collisions and a parametrization of UA1 p+p spectra in three pseudo-rapidity bins close to mid-rapidity [20].](image)

The STAR Collaboration has studied the production of neutral pions with a lead glass array called Forward Pion Detectors (FPD) which covers a range in rapidity $3.0 < \eta < 4.2$ [22]. Their data sample includes $\pi^0$ with $20 < E_{\pi} < 55$ GeV where the energy scale is calibrated better than 1%.

The minimum-bias $R_{dAu}$ extracted with $\pi^0$ by STAR at $\langle \eta \rangle = 4.0$ is shown in Fig. [12] together with the published BRAHMS for negative charged
Figure 12: (color online) Nuclear modification factors $R_{dAu}$ for minimum-bias collisions. STAR neutral pions shown with filled circles [22] at an average rapidity equal to 4.00. The BRAHMS ratios for negative hadrons are shown with open circles and open squares at $\eta = 2.2$ and $\eta = 3.2$ respectively.

hadrons at $\eta = 2.2$ and 3.3. The suppression seen in the BRAHMS data at high rapidity is also present in the STAR results and is even more pronounced at $\eta = 4.0$.

As mentioned above, the saturation scale has an $A$ dependence that is written more accurately as depending on the number of participating Au nucleons [19]:

$$Q_{sA}^2(b) = Q_{sA}^2(0) N_{part.Au}(b)/N_{part.Au}(0). \quad (3)$$

Using eq. (3) would imply a factor of almost 4 in the value of the saturation scale $Q_{sat}^2$ between the central and peripheral events. The effect of such increase is apparent in Fig. 13 where central events are compared to peripheral ones with a ratio similar to the nuclear modification factor $R_{dAu}$, but this time the p+p reference is replaced by the most peripheral sample of events, 60-80%. This ratio commonly referred to as $R_{cp}$ has similar rapidity dependence as the $R_{dAu}$ ratio.

The PHENIX Collaboration has extracted the $R_{cp}$ ratio at moderately high rapidity in both projectile and target fragmentation regions, using their Muon Arms [21]. The coverage in the projectile fragmentation region (deuteron beam) is $1.4 < \eta < 2.0$ corresponding to $x_2$ in the Au target ranging from
Figure 13: The $R_{cp}$ ratio calculated with pions produced at different rapidities. The numerator of this ratio is populated with central events, which are normalized by the number of binary collisions calculated to be equal to $N_{coll} = 12.6$. The denominator is extracted from the 60-80% sample of peripheral events normalized by $N_{coll} = 3.5$.

0.001 to 0.03. The coverage for the Au fragmentation is $-2.0 < \eta < -1.4$ which probes $x_2$ from 0.04 to 0.5 where anti-shadowing and the EMC effect may have relevance. The measurement is based on two techniques: the first uses hadrons that make it past the muon absorbers and reach some depth in the MuID detector, called Punch Thru Hadrons (PTH); the second technique involves detected muons produced by the decay of $\pi$ and K before the absorber, called Hadron Decay Muon (HDM). Measurements of absolute yields are not possible, but the ratio of yields at different centralities is. Figure 14 summarizes those measurements and shows a very clear difference between the projectile and target fragmentation regions and confirms the BRAHMS measurements at $\eta = 2$.

4. Summary

We have attempted to summarize the most salient measurements of the single particle inclusive spectra extracted from d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC. The Cronin effect is present around mid-rapidity but its magnitude is smaller than the one seen at lower energy in fixed target measurements. The magnitude of the Cronin enhancements appears to reach an upper limit as the collisions become more central. There is a clear difference
between $R_{dAu}$ factors calculated with baryons and mesons. As the rapidity of the detected particles approaches the deuteron beam rapidity, the $R_{dAu}$ factors are strongly suppressed. In the context of the CGC, that suppression is interpreted as an indication that the saturation scale at the relevant values of $x_2$ has values in the range of the measured $p_T$, which in turn implies that at RHIC energies the wave function of the target is saturated.

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