Highlights from STAR (II)
- Hard Probes of the Initial and Final State -

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Abstract

Highlights of recent results from the STAR collaboration focusing on hard probes of the initial and final state are presented. New results at forward rapidities in d+Au collisions at low $x$ are utilized to study the possible onset of saturation effects at RHIC energies. New reference measurements, $\Upsilon$ production, nuclear-$k_T$ via di-jets in d+Au collisions, and jet quantities in p+p collisions will be discussed. Final state nuclear modifications of $J/\psi$ and identified hadrons in heavy-ion collisions will be presented. In addition to di(multi)-hadron and direct $\gamma$-hadron correlations, new results from full-jet reconstruction in Au+Au collisions will be discussed with respect to the p+p reference measurements. These measurements can be used to put further constraints on the underlying mechanisms of partonic energy loss in heavy-ion collisions at RHIC.

1. Introduction

Hard probes - processes involving large momentum transfers - and their modification in Au+Au collisions with respect to p+p (d+Au) can be used to study the properties of the medium created in a heavy-ion collision at RHIC energies [1]. In order to use hard processes as a well calibrated probe, one must be able to theoretically describe the reference measurements including initial and cold nuclear matter final state effects. The effect of parton energy loss in the final state is a well established observation in heavy-ion collisions at RHIC. It is evident in the suppression of the inclusive charged hadron and non-photonic electron yield at high $p_T$, as well as in the associated yield in di-hadron correlations at high $p_T^{\text{trig}}$ and $p_T^{\text{assoc}}$, accompanied by an enhancement at low $p_T^{\text{assoc}}$, suggesting a dramatic softening of jet fragmentation [2][3][4]. However, these measurements are limited in their sensitivity due to well-known geometric biases (see for example [5]). To overcome these biases one has to better constrain the parton kinematics, which is conceptually possible via direct $\gamma$- and full-jet reconstruction. New results utilizing these methods will be discussed.

In the following, new measurements addressing the initial state effects, such as the possible onset of saturation at low $x$, as well as improved reference measurements will be presented first. These will be followed by a discussion of how these calibrated hard probes become modified in the presence of the dense matter created in heavy-ion collisions at RHIC.

1For the full list of STAR authors and acknowledgements, see appendix in this volume.

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2. Hard Probes of the initial state and p+p reference measurements

2.1. Forward rapidity measurements in p+p and d+Au collisions

Forward rapidity measurements in d+Au collisions can be used to study the possible onset of saturation effects at RHIC energies. The Forward Meson Spectrometer (FMS), new in 2008 (p+p, d+Au), is an electromagnetic calorimeter that probes processes down to $x \approx 10^{-4}$ at $\sqrt{s_{NN}}=200$ GeV at around $\eta \sim 4$ [6], well into the range where saturation effects are expected to set in.

By measuring the azimuthal angular correlations, $\Delta \phi$, of a forward $\pi^0$ and a mid-rapidity $\pi^0$ one expects a clear back-to-back peak in a 2→2 parton scattering picture, whereas if saturation effects play a significant role a broadening of the recoil peak, or even its disappearance (monojet), could occur [7]. These effects can be measured by comparing the $\Delta \phi$ correlations from p+p with d+Au collisions as shown in Fig. 1. Two kinematic selections are shown in Fig. 1, one with a more restrictive cut (bottom panel), suggested by pQCD calculations [8], the other with a lower $p_T$ cut closer to the saturation scale (top panel). The width of the recoil azimuthal correlation peak is larger for d+Au than for p+p and the difference ($\sigma_{dAu} - \sigma_{pp}$) increases from 0.11 ± 0.04 to 0.20 ± 0.03 for the lower $p_T$ cut, qualitatively consistent with a $p_T$ dependent picture of gluon saturation in the Au nucleus (more details in [6]). In addition, the first observation of high-$x_F$ $J/\psi$'s in p+p collisions at $\sqrt{s_{NN}}=200$ GeV have been reported by STAR at the conference [9].

2.2. $\Upsilon$ measurement in d+Au collisions

The production of $\Upsilon$ and their modifications in heavy-ion collisions is a promising tool to study QGP properties at RHIC [10]. In addition to measurements in p+p and Au+Au it is important to study possible cold nuclear matter effects on $\Upsilon$ production in d+Au collisions. The STAR $\Upsilon$ trigger enabled sampling a p+p equivalent luminosity of $\sim 12.5$ pb$^{-1}$ for the 2008 d+Au run at $\sqrt{s_{NN}}=200$ GeV [11]. The measured signal of $\Upsilon(1S + 2S + 3S) \rightarrow e^+e^-$ shown in Fig. 2 has a significance of $\sim 8 \sigma$. The derived cross section at mid-rapidity is $B.R. \times d\sigma/dy = 35 \pm 4 (stat.) \pm 5 (syst.)$ nb, consistent with NLO calculations [12]. The nuclear modification factor $R_{dAu} = 0.98 \pm 0.32 (stat.) \pm 0.28 (syst.)$ suggests that $\Upsilon$ production follows binary scaling in d+Au collisions.
collisions. With increased statistical significance these measurements will serve as an important reference for the upcoming measurement in Au+Au collisions (for more details see [11]).

2.3. Full-jet reconstruction in p+p and d+Au collisions

The study of jet properties and the underlying event in p+p collisions is important for our understanding of QCD and the not well understood process of hadronization, as well as providing a baseline for jet measurements in heavy-ion collisions.

Full jet reconstruction in STAR is performed by using charged particles, measured in the TPC, and neutral particles in the EMC at mid-rapidity. Modern jet-finding algorithms such as $k_T$ and Anti-$k_T$ recombination, and a seedless cone algorithm, SISCone, from the FastJet package [13] were used to reconstruct jets and to estimate systematic effects [14, 15, 16]. The jet energy resolution in p+p collisions can be obtained by either using PYTHIA simulations (PYTHIA 6.410 Tune A [17]) passed through STAR’s simulation and reconstruction algorithms, or via the jet energy balance of back-to-back di-jets in p+p data. Both methods result in a comparable jet energy resolution of ~ 20% for reconstructed jet with $p_T > 10$ GeV/c [14]. The uncorrected charged particle fragmentation function (FF) as a function of $z = p_T^{hadron}/p_T^{jet}$ for different resolution parameters, $R$, and jet energies show reasonable agreement with PYTHIA for all jet...
algorithms (see Fig. 3 left panel for $R = 0.7$). This agreement especially for larger $R$ suggests that there are only minor NLO contributions beyond the PYTHIA LO calculations at RHIC energies. We also studied the underlying event (UE) in p+p collisions following the CDF technique [18]. Fig. 3 (right panel) shows the charged particle density in the UE. One can conclude that the UE is largely independent of the jet energy. By comparing different selections and subsets in the UE analysis, which have different sensitivities to initial and final state radiation contributions, we observe only minor contributions from large angle initial/final state radiation (further details in [14]).

Deploying full-jet reconstruction algorithms and methods to subtract background contributions in the FastJet package we performed a measurement of nuclear $k_T$ effects in d+Au collisions via di-jets [19]. To estimate the effect of jet energy resolution and possible background contributions of the underlying event in d+Au collisions on $k_{T,\text{raw}} = p_{T,1} \sin(\Delta \phi)$, we compared PYTHIA simulations and PYTHIA jets (including detector simulation) embedded in d+Au minimum bias events. This study suggests that jet energy resolution and possible background contributions in d+Au have only minor effects on the measured quantity [19]. We estimate a $\sigma_{k_{T,\text{raw}}} = 3.0 \pm 0.1(\text{stat}) \pm 0.4(\text{sys})$ GeV/c in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Further di-jet studies for different centralities in d+Au and p+p collisions will be pursued to estimate the nuclear $k_T$ effects.

3. Hard Probes of the final state

3.1. Nuclear modification of $J/\psi$ at high-$p_T$ in Cu+Cu collisions

Suppression of $J/\psi$ meson production in heavy-ion collisions has been proposed as a signature of QGP formation [10]. The measured suppression at $\sqrt{s_{NN}} = 200$ GeV comparable to the observed magnitude at CERN-SPS energies is surprising and may be due to counterbalancing of larger dissociation with recombination of $c$ and $\bar{c}$ in the medium, which are more abundant at higher energies (see [12] and references within). To interpret the $J/\psi$ suppression, an understanding of quarkonium production in hadronic collisions is required. No model at present can fully explain the $J/\psi$ production in elementary collisions. $J/\psi$ measurements at high-$p_T$ in p+p and Au+Au collisions may provide further insight into the underlying process of quarkonium production [9, 21]. In Fig. 4 the nuclear modification factor $R_{AA}$ for $J/\psi$ as a function of $p_T$ in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV is shown. The $R_{AA}$ increases as a function of $p_T$ and is consistent with unity for $p_T > 5$ GeV/c. The $J/\psi$ is the only hadron measured in heavy-ion collisions at RHIC which does not exhibit a significant suppression at high $p_T$. The absence of $J/\psi$ suppression at high $p_T$, in contrast to a significant suppression of open charm, might indicate that high
$p_T$ $J/\psi$ production is dominated by the color singlet channel (for more details on confronting theoretical calculations with the data see [21]). From high $p_T$ $J/\psi$-hadron azimuthal correlations in p+p collisions one can estimate the contribution from B-meson feed-down to inclusive $J/\psi$ production to be $(13 \pm 5)$% for $p_T > 5$ GeV/c.

3.2. Jet flavor conversion in Au+Au collisions

To study the color charge effect of parton energy loss in heavy-ion collisions one can utilize the nuclear modification of identified hadrons ($\pi$, $K$ and $p$) at high $p_T$. Figure 5 shows the nuclear modification factor $R_{AA}$ in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV as a function of $p_T$ for $\pi$, $K$ and $p$ [23]. One observes that the $R_{AA}$(K) and $R_{AA}$(p) are larger than $R_{AA}$(\pi) in contradiction to predictions from energy loss calculations [24]. The observed ordering of $R_{AA}$ for identified hadrons is consistent with predictions from calculations including jet flavor conversion in the hot dense medium [25] (see dashed lines in Fig. 5). In addition the identified hadron high-$p_T$ spectra in p+p collisions are in agreement with NLO calculations and can be used to put constraints on the fragmentation functions (detailed discussion in [23]).

3.3. Di- and Multi-hadron correlations

The observation of the near-side ridge (long range $\Delta\eta$ correlation) has motivated many theoretical attempts to explain this phenomena (for a summary see [26]). A recent model, the Correlated Emission Model (CEM) [27], suggested that the ridge is formed from correlated particle emission due to aligned jet propagation and medium flow. As a consequence it predicts an asymmetric ridge $\Delta\phi$ correlation depending on the orientation with respect to the reaction plane $\phi_S = \phi_{\text{trig}} - \Psi_{RP}$. The measured ridge asymmetry (for details see [26]) as shown in Fig. 6 (left panel) is qualitatively consistent with the CEM predictions suggesting that the ridge formation might be caused by jet-flow alignment. Updates concerning 3-particle near-side $\Delta\eta$-$\Delta\eta$ correlations, using the charge properties of the associated hadrons to separate the ridge and jet components, can be found in [26]. To study if the ridge is also present on the away-side, a technique was developed where one uses a pair of correlated high-$p_T$ hadron triggers to determine the jet-axis and study the associated hadron distribution (A) with respect to both triggers (T1 and T2) (details concerning the method can be found in [28]). Selecting a “symmetric” di-jet triggered case, $5 < p_T(T1) < 10$ GeV/c and $p_T(T2) > 4$ GeV/c, with $p_T(A) > 1.5$ GeV/c one observes no modification of the $\Delta\eta$ and $\Delta\phi$ correlations with respect to d+Au reference measurements, indicating that for this kinematical selection there is no evidence of a ridge or a conical structure.
on the away-side. For the symmetric di-jet selection the associated $p_T$ spectra for both trigger sides are consistent (Fig. 6, right panel) and in agreement with d+Au measurements suggesting no, or only little, energy loss in the medium (more details in [28]).

3.4. Constraining the parton kinematics

The measurements discussed above are limited in their sensitivity to jet quenching effects due to well-known geometric biases. To gain sensitivity and to be able to distinguish between different underlying energy loss mechanisms, one has to better constrain the parton kinematics. This can be achieved via direct $\gamma$- and full-jet reconstruction measurements.

3.4.1. Direct $\gamma$-hadron fragmentation functions

Conceptually clean measurements to constrain the parton kinematics are direct $\gamma$-hadron (jet) correlations. Studies are however, limited in statistics, due to the small cross-section of that process. Details concerning the analysis can be found in [29]. In Fig. 7 the ratio of the integrated yield of associated charged hadron ($h^\pm$) per trigger in Au+Au relative to d+Au on the away-side (D_{0-10%}/D_{d+Au}) for $\pi^0$ and direct $\gamma$ ($8 < p_T^{\pi^0} < 16$ GeV/c) as function of $z_T = p_T^{\pi^0}/p_T^{\gamma}$ is shown. In the measured $z_T$ kinematics there is no apparent difference in the suppression of $\pi^0$-h$^\pm$ and direct $\gamma$-h$^\pm$ correlations. Naively one would expect a difference due to the trigger bias of the high-$p_T$ $\pi^0$'s, which would result in a longer pathlength of the recoil jet in the $\pi^0$-h$^\pm$ case. The absence of this effect might be due to a significant contribution of punch through or tangential jets in the measured kinematical regime, which would leave the fragmentation function unmodified. The measurements are in agreement with theoretical calculations (see [29] and references within), but to distinguish between the different models one has to extend the measurement to lower $z_T$, which we plan to pursue.

3.4.2. Full-jet reconstruction in Au+Au collisions

Full-jet reconstruction in heavy-ion collisions is an alternative approach to constrain the parton kinematics over a larger range of jet energies as compared to direct $\gamma$-hadron (jet) correlations. The challenges in these measurements are to correct for contributions from the underlying heavy-ion event. In central Au+Au events at $\sqrt{s_{NN}}=200$ GeV the background energy in a cone
The text discusses the examination of schematic conjectures of energy loss, and incorporates the complete set of photon production channels. It presents utilizing hard probes to study the initial and final state effects. The possible onset of saturation effects, as well as new and improved baseline measurements of the initial state, were...
discussed. The presented data of nuclear modifications in the final state can be used to gain further insights into the production mechanisms of heavy-flavor. Full-jet reconstruction extends significantly the kinematical reach to study jet quenching effects and modifications of jet quantities in the presence of the hot, dense medium created in heavy-ion collisions at RHIC. These measurements will put further constraints on the underlying partonic energy loss mechanisms.

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