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XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2018)

Overview of results from the PHENIX Collaboration

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Abstract

At the Quark Matter 2018 conference, the PHENIX Collaboration gave 10 parallel talks and 19 posters on a wide variety of topics in small and large systems. In these proceedings we discuss a few key results shown at the conference.

1. Nuclear modification of hadron production

We begin with a discussion of nuclear modification of hadron production [1]. Figure 1 shows the nuclear modification factor of charged hadrons in p+Al (left panel) and p+Au (right panel) collisions at $\sqrt{s_{_{NN}}} = 200$ GeV in the most central events (0–5%). The filled circles indicate backward rapidity ($-2.2 < \eta < 1.2$) and the open circles indicate forward rapidity ($1.2 < \eta < 2.4$). The data clearly exhibit a strong enhancement at backward rapidity and a strong suppression at forward rapidity, and both effects are stronger in the collision system with the larger nucleus.

While the strong enhancement at intermediate p_T at backward rapidity (also previously observed at midrapidity) is often attributed to initial state multiple scattering, it has been known for a long time (see e.g. [2, 3]) that there is a strong particle species dependence to it, indicating that there must be some contribution from final state effects.

Nuclear modification can also be studied with two-particle correlations [4]. We consider direct photon-hadron correlations, firstly explaining a few kinematic variables. The trigger particle is a direct photon, whose transverse momentum is $p_T^{\rm trig}$, and the associated particle is a charged hadron, whose transverse momentum is $p_T^{\rm assoc}$. The azimuthal angle between them is $\Delta\phi$, which is exactly π for perfectly back-to-back particles. We relate two additional variables to $p_T^{\rm assoc}$, namely $p_{\rm out} = p_T^{\rm assoc} \sin\Delta\phi$ and $x_E = z_T \cos\Delta\phi$, where the z_T is a frequently used fragmentation variable defined as $z_T = p_T^{\rm assoc}/p_T^{\rm trig}$. The $p_{\rm out}$ is known to have a Gaussian shape in the non-perturbative regime. The evolution of this width as a function of $p_T^{\rm trig}$ is shown in the left panel of Figure 2. The width increases as a function of the hard scale ($p_T^{\rm trig}$), analogously to the increase of the acoplanarity of lepton pairs in the Drell-Yan process as a function of the pair mass. The Gaussian widths of $p_{\rm out}$ are enhanced in p+Al and p+Au relative to p+p, as shown in the right panel of

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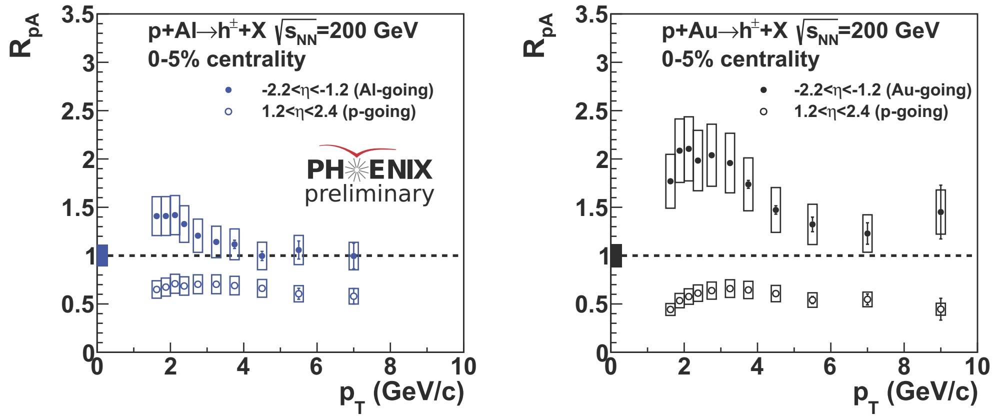

Fig. 1. R_{pA} of charged hadrons at backward (filled circles) and forward (open circles) rapidity in p+Al (left) and p+Au (right) collisions at $\sqrt{s_{NN}}$ = 200 GeV.

Figure 2. This conclusively indicates the presence of initial state transverse momentum broadening that increases with centrality.

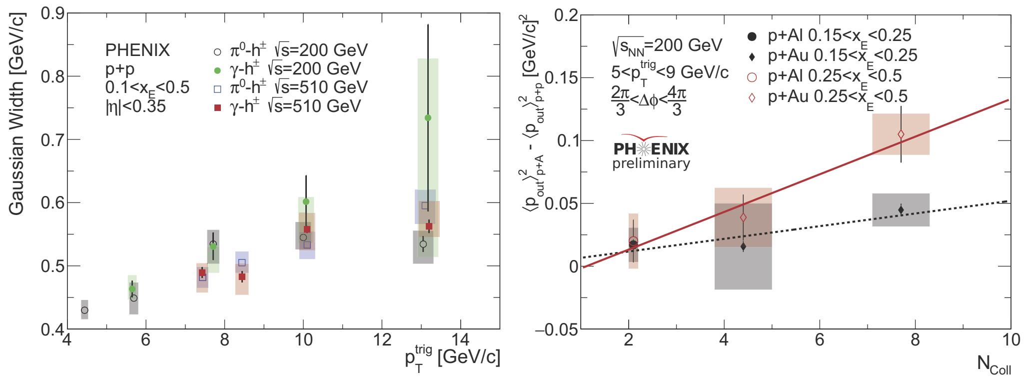

Fig. 2. Left panel: Gaussian width of p_{out} as a function of p_T^{trig} in p+p collisions. Right panel: modification of the Gaussian width of p_{out} in p+Al and p+Au relative to p+p as a function of N_{coll} for two different x_E selections.

2. Heavy flavor

We performed a detailed study of $c\bar{c}$ and $b\bar{b}$ production and the Drell Yan process in p+p collisions at 200 GeV from like-sign and unlike-sign dimuon production [5]. Figure 3 shows the invariant yield of dimuons from $c\bar{c}$ (left) and $b\bar{b}$ (right) as a function of $\Delta\phi = \phi_1 - \phi_2$ in p+p collisions, where ϕ_1 and ϕ_2 are the azimuthal angles of muons coming from the decay of the heavy quarks. Also shown are comparisons to PYTHIA and POWHEG calculations. In PYTHIA, the contributions from the different production mechanisms can be separated, allowing a detailed study of heavy quark production. The contribution from the LO process of pair production is shown in red and the contributions from the NLO processes of flavor excitation and gluon splitting are shown in green and blue, respectively. The $c\bar{c}$ production has comparable contributions from LO and NLO processes while the $b\bar{b}$ production is dominated by the LO process at $\sqrt{s}$ = 200 GeV. At

LHC energies, the NLO contribution to $b\bar{b}$ production is larger. The LO process generates a narrow $\Delta\phi$ distribution while the NLO processes generate a wider $\Delta\phi$ distribution; these characteristics are seen in the data, with the $c\bar{c}$ correlation being considerably wider than the $b\bar{b}$ correlation [6, 7].

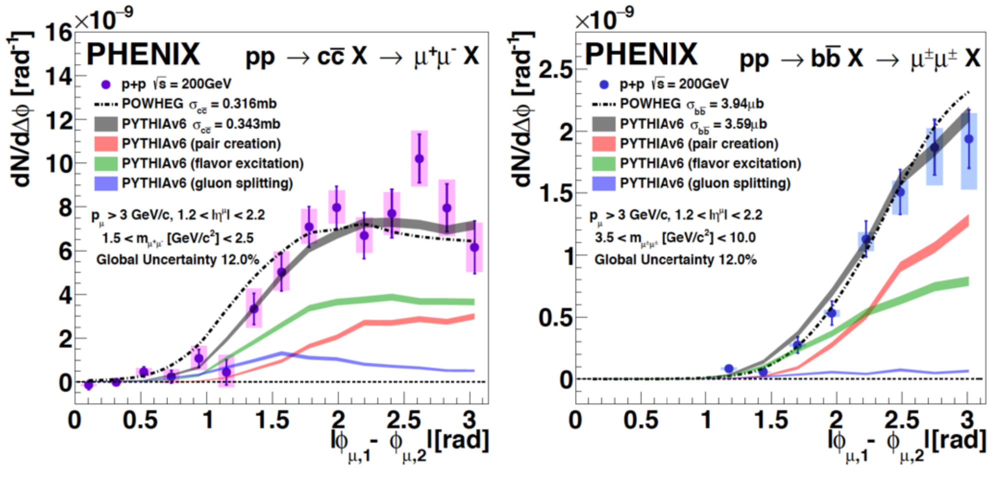

Fig. 3. Invariant yield of $c\bar{c}$ (left) and $b\bar{b}$ (right) as a function of the angular separation of the pair in p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV.

We have measured single electrons from c and b decays in AuAu collisions at $\sqrt{s_{NN}}$ = 200 GeV [8]. The c-decay electrons and b-decay electrons were separated from the DCA measurement. The analysis follows a similar procedure as is done with the determination of the c and b spectra, e.g. Ref [9]. Figure 4 shows the v_2 of electrons from charm and bottom decays as a function of electron p_T in the left and right pane, respectively.

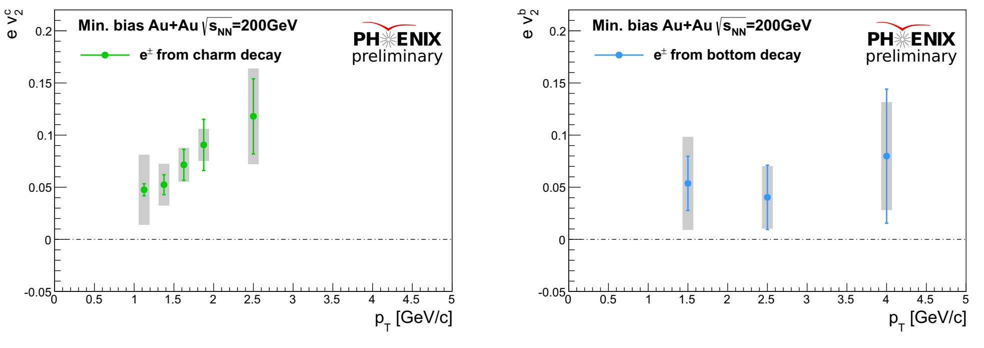

Fig. 4. v_2 of electrons coming from charm quarks (left) and bottom quarks (right) as a function of electron p_T in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

We have also measured single muons from c and b decays in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Figure 5 shows, as blue points, the v_2 of muons from heavy flavor (charm and bottom) decays as a function of muon p_T for $-2.2 < \eta < -1.4$ (left panel) and $1.4 < \eta < 2.2$ (right panel). Also shown, as red points, is the charged hadron v_2 as a function of hadron p_T in the same η selections. Although the comparison isn't perfect due to the decay kinematics of the heavy flavor mesons into muons, the v_2 values are quite similar each other, raising the possibility of a common mechanism for generating the azimuthal anisotropy of light and heavy quarks. This is quite similar to what has been seen in A+A collisions.

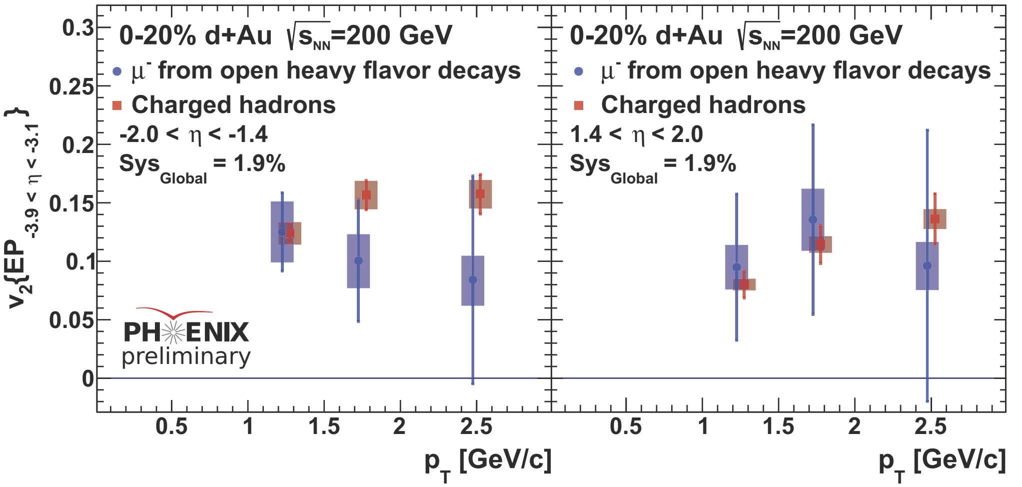

Fig. 5. v_2 of muons coming from heavy flavor quarks as a function of muon p_T for backward (left) and forward (right) rapidity in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

3. Evidence for collectivity in small systems

We have performed a detailed study of v_n in a variety of small collision systems. In our small systems analyses we primarily use the event plane method for the determination of v_n. It is important to note that, in all cases, the event plane resolution is low enough that the contributions from the fluctuations are the same as they are for two-particle techniques. For that reason, all theoretical comparisons are made with $v_n\{2\}$.

We have studied the v_2 of identified charged hadrons in small systems [10]. Figure 6 shows v_2 as a function of p_T of identified charged hadrons $\pi^\pm$ and p and $\bar{p}$ in p+Au (left), d+Au (middle), and ^{3}He+Au (right) collisions at $\sqrt{s_{NN}}$ = 200 GeV [11]. Also shown are hydrodynamical predictions from superSONIC [12]. The low-p_T behavior is well-described by the theory, suggesting a common velocity field that gives a larger $\langle p_T \rangle$ boost to heavier particles. The intermediate-p_T behavior is less well-described—the superSONIC model uses Cooper-Frye hadronization, in contrast to AMPT [13] (not shown) which uses spatial coalescence and describes the intermediate-p_T data better.

We have studied the v_2 and v_3 of charged hadrons in small systems [14]. The p+Au system has no intrinsic geometry, meaning the initial shape is driven entirely by fluctuations. Contrariwise, the d+Au system has very large intrinsic ellipticity but no intrinsic triangularity, and ^{3}He+Au has both intrinsic ellipticity and triangularity. If the correlations are geometrical in origin, we would expect d+Au and ^{3}He+Au to have similar v_2 which would in turn be larger than that in p+Au. Similarly, we would expect p+Au and d+Au to have similar v_3 where as that in ^{3}He+Au would be significantly larger. These qualitative expectations match the data perfectly. Figure 7 shows v_2 and v_3 as a function of p_T of charged hadrons in p+Au (left), d+Au (middle), and ^{3}He+Au (right) collisions at $\sqrt{s_{NN}}$ = 200 GeV [15]. Also shown in the figure are hydrodynamical calculations in both the superSONIC and iEBE-VISHNU [16] models. The hydrodynamical theory calculations describe the data extremely well.

Shown at this conferences [17] and posted to the arXiv [18] shortly thereafter are calculations of $v_2\{2\}$ and $v_3\{2\}$ in p+Au, d+Au, and ^{3}He+Au in the CGC-inspired dilute-dense framework. These calculations describe the v_2 data quite well. The v_3 data are not described quite as well—in the CGC calculation there is a hierarchy based strictly on system size, whereas the data are better described by a hierarchy that matches

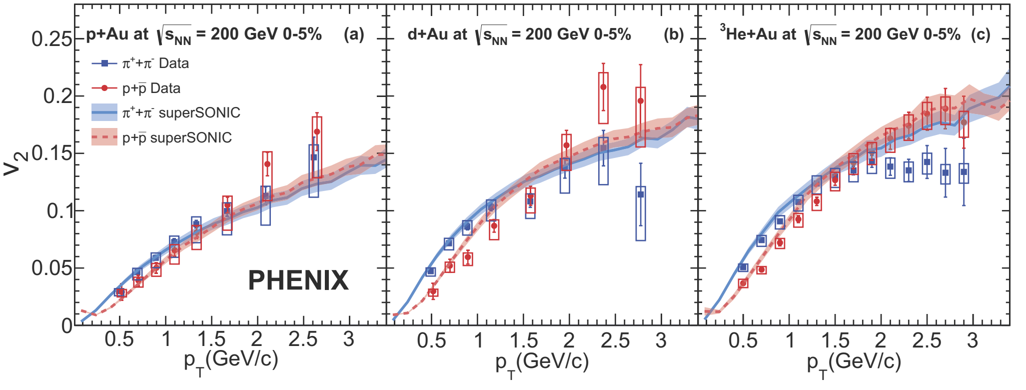

Fig. 6. v_2 vs p_T of identified particles in p+Au (left), d+Au (center), and ^{3}He+Au (right) collisions at $\sqrt{s_{NN}}$ = 200 GeV.

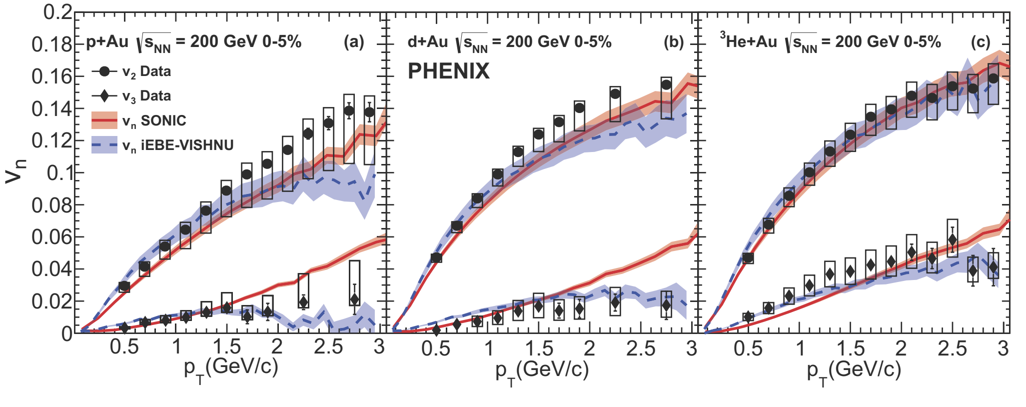

Fig. 7. v_2 and v_3 vs p_T of charged hadrons in p+Au (left), d+Au (center), and ^{3}He+Au (right) collisions at $\sqrt{s_{NN}}$ = 200 GeV.

whether the system has intrinsic triangularity. In this sense, the hydrodynamical picture is favored by the data.

4. Scaling of low-p_T direct photon production

Ultimately, any theory of heavy-ion collisions (be they heavy-heavy, light-heavy, or light-light) should simultaneously describe as many different observables as possible. In the hydrodynamical picture, one expects thermal production of photons and therefore an enhancement relative to a pure pQCD baseline. This can manifest as an enhancement in the nuclear modification factor.

We have studied low-p_T direct photon production in Au+Au at $\sqrt{s_{NN}}$ = 39, 64, and 200 GeV in various centralities and in Cu+Cu, d+Au, p+Au, and p+p at 200 GeV [19]. Shown in the left panel of Figure 8 is the invariant yield of photons dN_γ/dy as a function of the charged hadron multiplicity ($dN_{\rm ch}/d\eta$). Shown as the band is the p+p data scaled by $N_{\rm coll}$ and a fit to the heavy-ion data (dashed line) [20]. The small systems data (p+Au and d+Au) fall in between the two lines, suggesting a possible onset of thermal radiation.

Shown in the right panel of Figure 8 is the nuclear modification factor $R_{\rm pAu}$ of photons in 0–5% p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Also shown are a pure pQCD calculation (dashed blue line) and a hydrodynamical calculation with thermal radiation (solid blue line). Although the systematic uncertainties are large, the data clearly indicate an enhancement and thus favor the hydrodynamical case, presenting some of the best experimental evidence to date for the formation of QGP droplets in small collision systems. Furthermore, it is worth noting that the same hydrodynamical calculation of the photon $R_{\rm pAu}$ [16] is also shown to be in excellent agreement with the v_2 and v_3 of inclusive charged hadrons, shown above. Nevertheless, alternate explanations are possible, and additional theoretical calculations in different frameworks are very much welcomed.

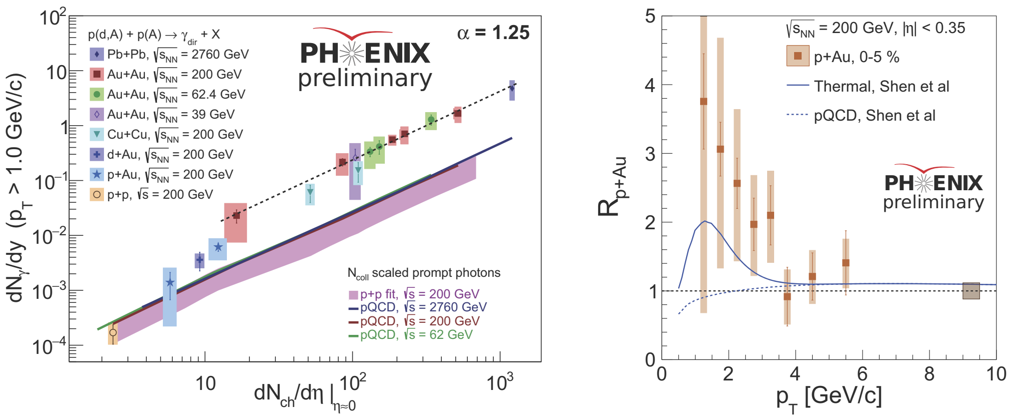

Fig. 8. Left panel: invariant yield of photons as a function of multiplicity for various collision systems. The lower line is the extrapolated p+p data, the upper line is the extrapolated Right panel: R_{pA} of direct photons in p+Au collisions for 0–5% centrality.

5. Brief summary

At the Quark Matter 2018, the PHENIX Collaboration gave 10 contributed talks and 19 posters covering a wide variety of topics. In these proceedings we have given a short overview of a few of the covered topics.

We showed heavy flavor measurements in a variety of collision systems. We find that, in p+p collisions, NLO effects are significant in $c\bar{c}$ production but that $b\bar{b}$ production is dominated by pair production (LO). We also presented flow measurements of electrons coming from both c and b decays.

We showed modification of charged hadron spectra in light nuclear species p+Al and p+Au, showing both the Cronin enhancement at forward and backward rapidity. We also showed the modification of the Gaussian width of p_{out} in p+Al and p+Au collisions. With these and prior measurements, we find conclusively that there are both initial and final state effects in small collision systems.

Lastly, we showed a variety of measurements in small systems. This includes identified charged hadron v_2 as well as inclusive charged hadron v_2 and v_3 in p+Au, d+Au, and ^{3}He+Au collisions. We find that the behavior of all of these observables is remarkably consistent with hydrodynamics. We also find the inclusive charged hadron v_2 and v_3 is somewhat consistent with recent calculations in the dilute-dense framework of the CGC. While the hydrodynamical theory describes the data better, it is clear that further study is warranted and the need for additional discriminating observables is essential. We also showed v_2 of muons from heavy flavor quark decays in d+Au collisions, where we find that the behavior of heavy quarks is quite similar to that of light quarks, similar to what has been found in large collisions systems. Further, we showed that there is strong enhancement of photon production in p+Au collisions relative to p+p collisions and that this enhancement is consistent with expectations from hydrodynamical theory.

Ultimately, the theory of heavy-ion collisions must describe all observables in all collisions simultaneously. We vigorously encourage all avenues of theoretical investigation.

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