Results from PHENIX

Christine Nattrass for the PHENIX Collaboration[1,*]

[1]University of Tennesse, Knoxville, 1408 Circle Drive, Knoxville TN 37996-1200

Abstract. The PHENIX experiment at the Relatimay invistic Heavy Ion Collider has collected data scanning system sizes from p+p and ^{3}He+Au to Au+Au and U+U at collision energies from $\sqrt{s_{\rm NN}}$ = 7.7 to 510 GeV. The extensive measurements from these data improve our understanding of the Quark Gluon Plasma and the origin of the proton spin. PHENIX's measurements of π^0 mesons, photons, heavy flavor particles, and jets probe the formation of the QGP, and measurements of azimuthal anisotropies are sensitive to collective effects and the initial geometry of the collision. A selection of recent results from PHENIX with an emphasis on results from heavy ion collisions are discussed.

1 Introduction

The PHENIX experiment collected a wealth of data from 2000 to 2016, including data from p+p, p+Al, d+Au, p+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Au+Au, and U+U collisions at energies per nucleon of $\sqrt{s_{\rm NN}}$ = 7.7–510 GeV. The precision detectors and high statistics data samples are used to measure quarkonia at both mid- and foward rapidity, direct photons at mid-rapidity, hydrodynamical flow, and dihadron correlations. These measurements are used to probe the formation of the QGP in small systems, provide tests of QCD in p+p collisions, and constrain the properties of the medium created in A+A collisions.

PHENIX is actively engaged in data and analysis preservation. Over the last year, we have migrated most data from PHENIX papers to the HEPData [1] data base. As of December 15, 2023, 201 out of 218 PHENIX papers (92%) are on HEPData. We are also implementing key analyses in REANA [2], a framework for analysis preservation.

Since the last Quark Matter, the PHENIX collaboration has published nine papers [3–11] and submitted three more [12–14], with several preliminary results presented here. These results are briefly reviewed here, as well as in other proceedings from this conference [15–18].

2 Proton-proton collisions

Recent measurements of the J/ψ have indicated that there is a strong correlation between charged track multiplicity and J/ψ yield in p+p collisions [19], often attributed to multiparton interactions. To disentangle the correlation between the production of charged tracks and impact of the $J\psi$ daughters on the charged particle multiplicity itself, we have measured the production of the $J\psi$ with and without including the decay daughters and using different

*e-mail: christine.nattrass@utk.edu

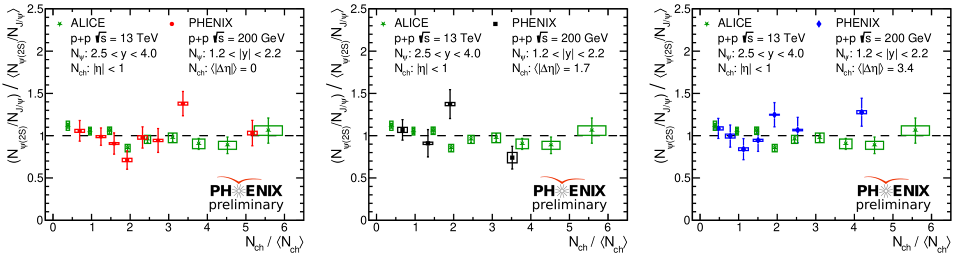

Figure 1. Ratio of $\psi(2S)$ yield to J/ψ yield divided by the average ratio, $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi}\rangle$ as a function of the charged particle multiplicity divided by the average charged particle multiplicity, $N_{ch}/\langle N_{ch}\rangle$, for charged tracks with $\langle\Delta\eta\rangle = 0$ (left), $\langle\Delta\eta\rangle = 1.7$ (middle), and $\langle\Delta\eta\rangle = 3.4$ (right) relative to the J/ψ compared to data from ALICE [19].

rapidity regions for the J/ψ and charged particle yields [15]. The correlation between the J/ψ yield and the charged particle yield is significantly reduced when either a different rapidity region is used or the decay daughters are excluded from the charged particle yield. This observation will help constrain J/ψ production mechanisms in p+p collisions.

The ratio of the yield of the $\psi(2S)$ to the yield of the J/ψ yield divided by the average ratio, $(N_{\psi(2S)}/N_{J/\psi})/\langle N_{\psi(2S)}/N_{J/\psi}\rangle$ as a function of $N_{ch}/\langle N_{ch}\rangle$ is shown in Figure 1 and compared to results from ALICE [19]. Both PHENIX and ALICE results are consistent with a ratio of one and weak multiplicity effects [15]. These measurements could be sensitive to QGP-like effects.

PHENIX also presented new preliminary measurements of the dilepton invariant mass, with separation of prompt and nonprompt pairs and rejection of pairs from photon conversions [18]. The distribution of nonprompt pairs as a function of the distance of closest approach to the primary vertex is consistent with expectations from the production of the J/ψ. These results provide constraints on the QCD and provide a reference for other collision systems.

3 Small systems

Measurements of anisotropic flow in p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV are consistent with the production of small droplets of QGP in small collision systems [20]. These are confirmed by measurements in [8] which use different detectors and pseudorapidity ranges and therefore have different systematic uncertainties.

Measurements of the π^0 nuclear modification factor in small systems [21] indicated that there may be suppression of at high momentum in small systems, although there was also some enhancement observed in peripheral collisions. Measurements of the nuclear modification factor in small systems are complicated by a possible bias in the centrality and the determination of the number of binary collisions, N_{coll}, from Glauber model calculations. This is addressed in [12, 17] by measuring the direct photon yield and calculating N_{coll} experimentally as $N_{coll}^{EXP}(p_T) = \frac{Y_{dAu}^{\gamma^{dir}}(p_T)}{Y_{pp}^{\gamma^{dir}}(p_T)}$. The nuclear modification factor calculated with the experimentally determined number of binary collisions is consistent with one, indicating no suppression, in peripheral d+Au collisions and is suppressed by about 10% in central collisions.

These results motivate further studies of quarkonia in small systems. Measurements of the yield of the $\psi(2S)$ to the yield of theJ/ψ yield as a function of the number of binary

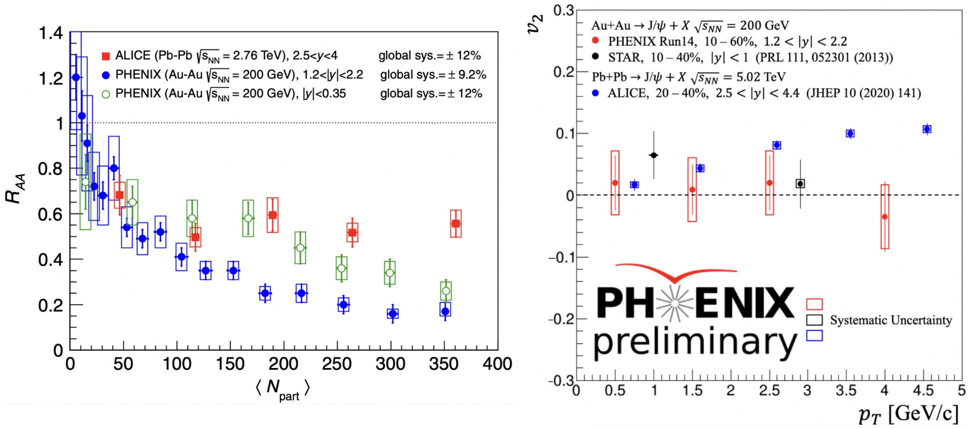

Figure 2. Left: Nuclear modification factor R_{AA} for the J/ψ for midrapidity and forward rapidities in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV compared to data from ALICE [23] at forward rapidities. Right: Anisotropic flow parameter v_2 at forward rapidities in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV compared to data from STAR [24] at midrapidity in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV and ALICE [22] at forward rapidities in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

collisions [11, 15] show no clear energy dependence and suggest possible final state effects at backward rapidities.

4 Gold-gold collisions

Direct photons constrain the temperature reached in heavy ion collisions. PHENIX has measured direct photons across multiple collision systems and energies [6, 18]. New measurements in Au+Au collisons at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV feature roughly ten times higher statistics [13], enabling precision constraints on direct photon yields. The higher yields and reduction in systematic uncertainties lead to higher precision measurements of the azimuthal anisotropy of direct photons [18], which is consistent with zero at high momentum.

New measurements of the J/ψ nuclear modification factor and azimuthal anisotropy are shown in Figure 2. These demonstrate stronger J/ψ suppression at both forward and midrapidies at RHIC than observed at the LHC and an azimuthal anisotropy consistent with zero, incontrast to the non-zero azimuthal anisotropy observed at the LHC [22]. This is consistent with less J/ψ regeneration at RHIC than the LHC.

Figure 3 shows the v_2 as a function of transverse momentum p_T of charged hadrons and muons from heavy flavor decays at forward rapidities in the muon arms. The charged hadron v_2 is consistent with that at midrapidities and the v_2 from muons from heavy flavor decays is consistent with that from electrons from heavy flavor decays at midrapidity. This is the first ever measurement of open heavy flavor elliptic flow at forward rapidities at RHIC.

Preliminary measurements of π^0 hadron correlations in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV demonstrate enhancement of low momentum hadrons relative to correlations in p+p collisions [16]. These measurements are consistent with a hybrid model with a wake from the medium response to the jet.

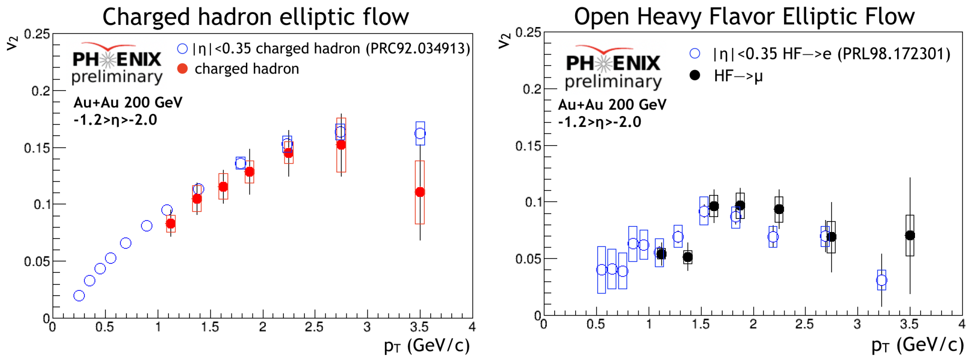

Figure 3. Left: Charged hadron elliptic flow at forward rapidities compared to charged hadron elliptic flow at midrapidity. Right: Elliptic flow of muons from heavy flavor decays at forward rapidities compared to electrons from heavy flavor decays at midrapidity.

5 Conclusions

We have measured quarkonia and the dilepton invariant mass in *p*+*p* collisions, which can be used to test QCD and constrain phenomenological calculations of particle production. We have measured anisotropic flow in small systems consistent with the formation of small droplets of QGP and we have measured the nuclear modification factor using an experimentally determined number of binary collisions, which may indicate that there is jet suppression in small systems. Measurements of quarkonia in small systems suggest possible final state effects at backward rapidities. Several new measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV can provide quantitative constraints on the properties of the medium, including new measurements of direct photon spectra and azimuthal anisotropy, quarkonia production, azimuthal anisotropies of open heavy flavor, and dihadron correlations.

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