

Summary of the latest PHENIX Heavy Ion Results

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The PHENIX Experiment at the Relativistic Heavy Ion Collider of the Brookhaven National Laboratory has been taking data for over 10 years. The accumulated data sets span multiple beam energies and collision systems that provide an increasingly detailed picture of the hot and dense medium produced in central heavy ion collisions. This is a summary of our latest results for direct photons, cold nuclear matter effects and a beam energy scan.

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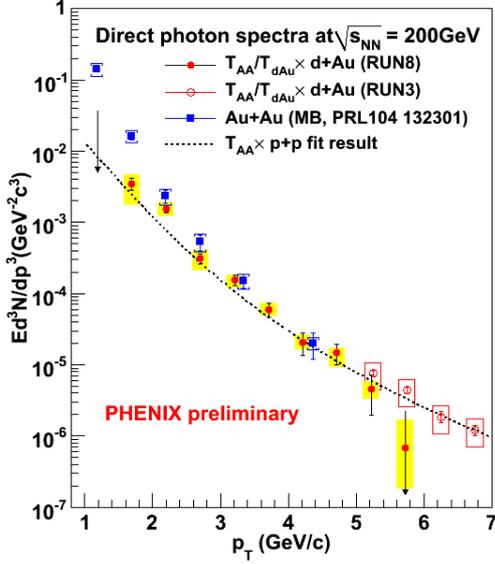


Figure 1: Invariant yield of direct photons as function of p_T . The red (blue) symbols show the invariant yields for $d + Au$ ($Au + Au$) collisions, the dashed line shows the scaled $p + p$ fit curve. While the $d + Au$ data agree with the scaled $p + p$ data, the $Au + Au$ data show an excess at low p_T .

1. Direct photon v_2

Direct photons are produced during the entire space-time history of relativistic heavy ion collisions [1, 2]. Due to their small coupling they leave the collision region mostly without further interaction which makes them a direct probe of all stages of the collision. The transverse momentum ranges populated by various production mechanisms overlap, but event by event azimuthal asymmetries can provide additional information and the means to distinguish between sources of direct photons [3, 4]. At higher p_T ($p_T > 4 \text{ GeV}/c$) four sources of direct photons are predicted, each with a characteristic signature in v_2 . Photons from initial hard scattering are expected to be emitted isotropically ($v_2 = 0$). Fragmentation photons should have $v_2 > 0$ since the energy loss of the originating parton is smaller in the reaction plane. Bremsstrahlung and jet-conversion photons should have a negative v_2 because the average path length is larger perpendicular to the reaction plane. At low p_T ($1 < p_T < 4 \text{ GeV}/c$) thermal photons dominate the picture. They were first mea-

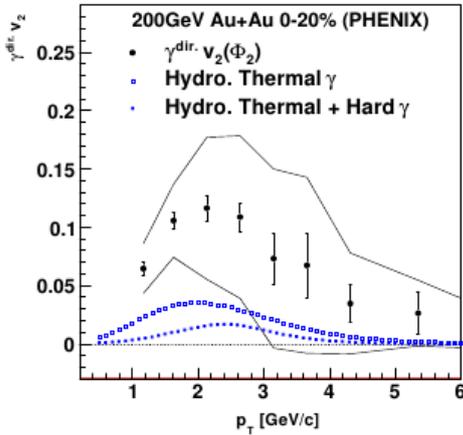


Figure 2: Azimuthal asymmetry (v_2) of direct photons as a function of p_T in the 20% most central $Au + Au$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ [6]. The error bars indicate the statistical uncertainty, the lines the systematic uncertainty. The data are compared to a hydrodynamic calculation [7]. The open symbols include only thermal photons, the closed symbols take also prompt photons into account which is a more realistic scenario

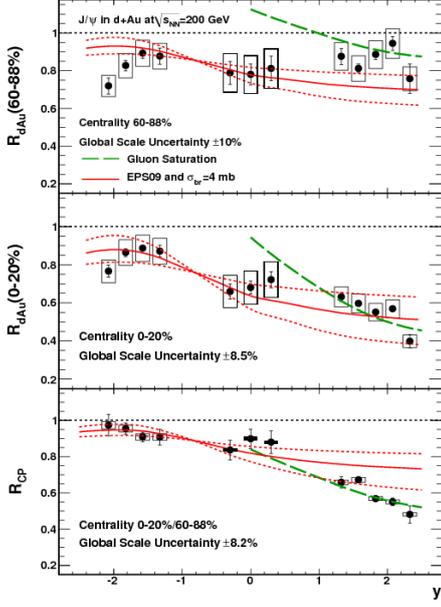


Figure 3: The nuclear modification factors R_{dAu} for peripheral (top) and central (middle) events, and R_{CP} as function of rapidity. The red line indicates a calculation using the EPS09 nuclear modified PDF set [10], the red dashed lines show the differences within the EPS09 nPDFs for a single parameter change that gives the largest variation. The green dashed line shows a calculation incorporating gluon saturation at small- x [12, 13]

sured in [5] which showed a substantial excess in this region relative to the scaling of $p + p$ yields (Fig. 1). Using this measured excess it is now possible to extract the azimuthal asymmetry v_2 of direct photons from the inclusive photon v_2 which is dominated by decay photons. Fig. 2 shows the measurement of the direct photon v_2 as a function of p_T for the 20% most central collisions at $\sqrt{s_{NN}} = 200$ GeV [6]. The magnitude of v_2 at $p_T \approx 2$ GeV/c is comparable to the elliptic flow measured for hadrons [8]. At high p_T where isotropically emitted prompt photons dominate, v_2 approaches zero as expected. A comparison to a hydrodynamic calculation [7] shows that the measurement lies significantly above the model calculation. The discrepancy is even larger for a more realistic case in which prompt photons are included. This is a challenge for theory calculations and it is clear that the v_2 data for direct photons provide strong additional constraints on models.

2. Cold Nuclear Matter (CNM) effects

Imperative for the interpretation of heavy ion results is the measurement of cold nuclear matter effects in $d(p) + A$ collisions. J/Ψ s offer a unique probe of cold nuclear matter effects in heavy ion collisions. As gluon-gluon fusion is the dominant J/Ψ production process at RHIC, they can offer insight into gluon shadowing and anti-shadowing as well as gluon saturation at low- x . Given that we can separate events by impact parameter we can gather information on the geometric dependence of the nuclear modification. The PHENIX experiment measures J/Ψ s through 2 decay channels: di-electrons at midrapidity and di-muons at forward/backward rapidities. Fig. 3 shows the nuclear modification factor R_{dAu} as function of rapidity for central (top) and peripheral (middle) events as well as the ratio R_{CP} between central and peripheral events (bottom) [9]. The quantity R_{CP} has the advantage that many systematic uncertainties cancel in the ratio. These are compared to the EPS09 nuclear PDF set [10] using a breakup crosssection of $\sigma_{br} = 4mb$, chosen to match the unbiased backward rapidity R_{dAu} data (red line) [11]. One sees a reasonable agreement at backward and midrapidities but a significant deviation in R_{CP} at forward rapidities which hints at a centrality

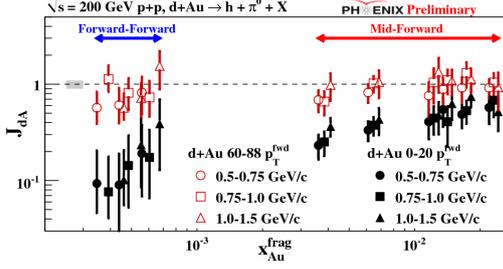


Figure 4: J_{dA} , the ratio of di-hadron production in $d + Au$ collisions to the binary scaled $p + p$ result versus x_{Au}^{frag} a measure for the x_{Bj} of the parton in the Au nucleus for peripheral (60–88%) and central (0–20%) events. The vertical bars indicate the statistical uncertainty

dependence of nuclear effects. A calculation which incorporates gluon saturation effects at small- x (green dashed line) [12, 13] is able to reproduce the suppression and its centrality dependence at forward rapidities but its predicted small enhancement at midrapidity due to double gluon exchange processes is not seen.

Low- x gluon saturation has been predicted to be most apparent in di-hadron correlations in $d(p) + A$ collisions at forward (Au-going) rapidity where x can be reasonably constrained [14, 15]. PHENIX has recently measured di-hadron correlations of neutral pions in this kinematic region [16]. Fig. 4 shows the ratio of di-hadron production in $d + Au$ collisions to the binary-scaled $p + p$ result (J_{dA}) as a function of x_{Au}^{frag} a measure of the x_{Bj} of the parton in the Au nucleus. While there is no suppression for peripheral events we observe a significant suppression in central events which increases when probing more forward rapidities.

3. Beam Energy Scan

The large suppression of π^0 production which was first observed in $\sqrt{s_{NN}} = 130$ GeV Au + Au collisions [17] is one of the most significant manifestations of the new state of matter produced in

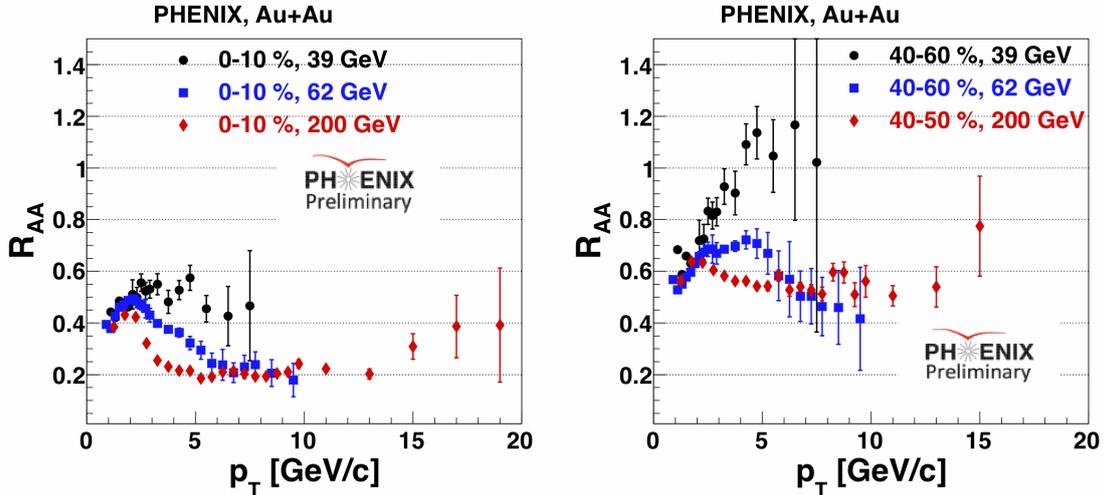


Figure 5: The nuclear modification factor R_{AA} of π^0 production for central (left) and mid-peripheral (right) Au + Au collisions as function of p_T at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV. The error bars represent the quadratic sum of the statistical and point to point systematic uncertainties. The necessary $p + p$ reference for $\sqrt{s_{NN}} = 39$ GeV was extrapolated from the E706 experiment at the Tevatron [18].

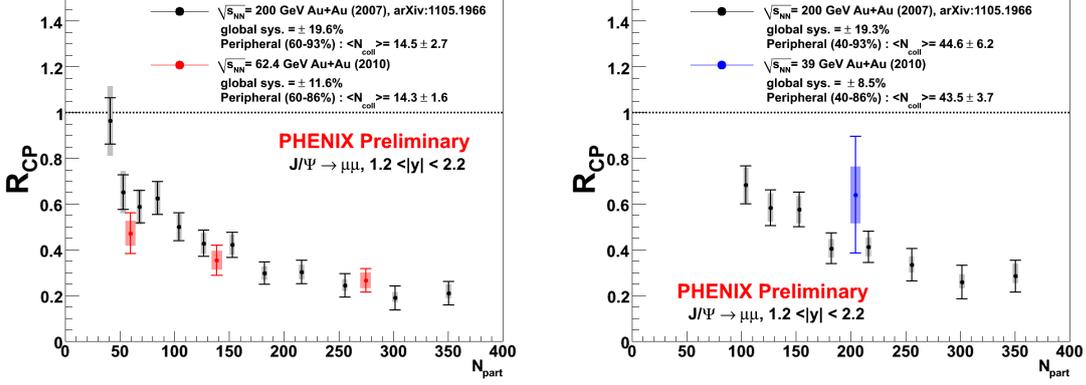


Figure 6: R_{CP} for J/Ψ production as function of the number of participants (N_{part}) for $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV in the rapidity range $1.2 < |y| < 2.2$.

ultra relativistic heavy ion collisions. One of the goals of the beam energy scan program is to search for the onset of this suppression. Fig. 5 shows the nuclear modification factor R_{AA} for central and mid-peripheral collisions at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV. All data sets exhibit a large suppression in central collisions suggesting that the new state of matter is produced even at $\sqrt{s_{NN}} = 39$ GeV. In mid-peripheral collisions a large suppression over the full p_T range is only observed for $\sqrt{s_{NN}} = 62.4$ and 200 GeV while there is no suppression for the $\sqrt{s_{NN}} = 39$ GeV data.

Quarkonia have long been proposed as a sensitive probe of the color screening length and deconfinement [19]. The modification by the hot dense medium will lead to a suppression of quarkonium production compared to $p + p$ collisions. Fig. 6 shows the J/Ψ R_{CP} for $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV. The suppression is of similar magnitude for all energies which is consistent with what was observed at SPS energies [20]. This picture gets complicated by the different magnitude of CNM effects [9, 21] which might account for a larger fraction of the total suppression at SPS energies compared to RHIC energies.

4. Conclusion

We have measured a significant azimuthal asymmetry (v_2) for direct photons in the $1 < p_T < 4 \text{ GeV}/c$ range which is comparable to the v_2 observed for hadrons. It drops to zero at higher momenta where isotropically emitted prompt photons dominate. Its magnitude poses a serious challenge to theoretical calculations. We have measured sizable cold nuclear matter effects in forward J/Ψ and di-hadron production which have to be taken into account when interpreting heavy ion results. The suppression of π^0 production in central events is similar for $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV but we observe no suppression in mid-peripheral events at $\sqrt{s_{NN}} = 39$ GeV. For J/Ψ production the suppression is of similar level for all three beam energies within the uncertainties.

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