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Highlights from PHENIX-I: Initial State and Early Times

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Abstract

We will review the latest physics developments from PHENIX concentrating on cold nuclear matter effects, the initial state for heavy-ion collisions, and probes of the earliest stages of the hot-dense medium created in those collisions. Recent physics results from $p + p$ and $d + Au$ collisions; and from direct photons, quarkonia and low-mass vector mesons in A+A collisions will be highlighted. Insights from these measurements into the characteristics of the initial state and about the earliest times in heavy-ion collisions will be discussed.

1. Introduction

In this overview, we will discuss selected highlights from PHENIX in the areas relating to the initial state and early times, focusing only on those which we believe to be the most significant new results. These will include 1) the suppression of rapidity-separated hadron pairs in $d + Au$ collisions, 2) the contributions of quarkonia and Drell-Yan to the non-photonic single electrons used to detect heavy quarks, 3) the continued suppression of the J/ψ in $Cu + Cu$ collisions to high-p_T, 4) the suppression of Υs in $Au+Au$ collisions, and 5) estimates of the initial temperature from direct photons in $Au + Au$ collisions.

2. Cold Nuclear Matter (CNM) and Gluon Saturation

The physics that modifies hard processes in nuclei relative to those on a free nucleon, often called cold nuclear matter (CNM) effects, includes 1) traditional shadowing either from global fits or from coherence models, 2) gluon saturation at small momentum fraction (x) which is amplified in the nuclear environment, and 3) initial-state energy loss and multiple scattering. For hadron pairs with a rapidity separation between the two hadrons in the pair, where one "triggers" on a mid-rapidity ($|\eta| < 0.35$) hadron and studies correlations with a forward-rapidity ($3.1 < \eta < 3.9$) hadron, there are two pictures which attempt to describe the characteristics of the process. QCD based pictures, such as those used by Vitev [1] that include non-leading-twist shadowing, give suppression of the pairs wrt the mid-rapidity trigger particle. An alternative approach which represents gluon saturation in the color-glass-condensate (CGC) model [2] also gives suppression and gives broadening of the angular correlation peak between the two particles in the pair. In the CGC picture, a mono-jet mechanism becomes important, where a single jet has its momentum balanced by multiple gluons coupling to the saturated gluon field.

Using the new Muon Piston Calorimeters (MPC) in PHENIX we are able to study correlations of rapidity-separated hadron ($h^{\pm}$ or π^0) pairs, where one triggers on a hadron at mid-rapidity and studies correlations with hadrons at forward rapidity in the MPC. For these studies we use

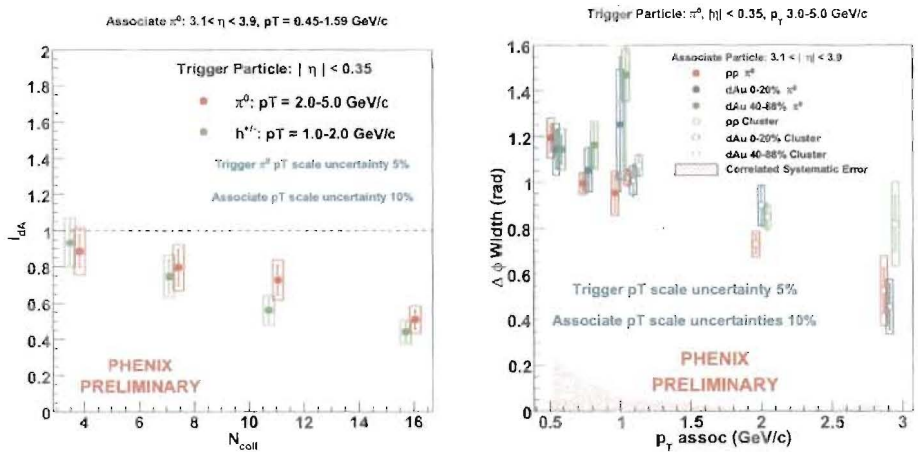

Figure 1: Centrality dependence of I_{dAu} for rapidity-separated hadron pairs (left). Correlation width, $\Delta\phi$, vs p_T of the associated mid-rapidity ($|\eta| < 0.35$) π^0 (filled points) for $p + p$ and for different centrality $d + Au$ collisions, showing no broadening within the substantial uncertainties of the data points (right). Also shown are similar results for higher energy clusters (open symbols) where π^0's and photons are not resolved.

the ratio I_{dAu}, which is the pair efficiency wrt to the mid-rapidity "trigger" hadron for $d + Au$ divided by that for $p + p$,

$$I_{dAu} = \frac{N^{pair}_{d+Au}[(\eta = 3.5) + (\eta = 0)]/N^{trig}_{d+Au}(\eta = 0)}{N^{pair}_{p+p}[(\eta = 3.5) + (\eta = 0)]/N^{trig}_{p+p}(\eta = 0)}$$

Preliminary results [3] for the centrality dependence (in terms of number of collisions, N_{coll}) of I_{dAu} in Fig. 1 (left) show increasing suppression for more central collisions. The angular correlations of the pairs were also studied, but showed no broadening in the relative angle $\Delta\Phi$ outside the substantial uncertainties in the present preliminary result, Fig. 1 (right).

We have also studied hadron pairs in $d+Au$ collisions where both hadrons are at mid-rapidity, this time in terms of J_{dAu} which is basically the same as R_{dAu} for a single particle, but in this case for pairs,

$$J_{dAu} = \frac{(PairYield)_{dAu}}{< N_{coll} > (PairYield)_{pp}}$$

These pairs exhibit a very large Cronin-like enhancement, i.e. they scale faster than N_{coll} ($J_{dAu} > 1$) and both J_{dAu} and the angular correlation width decrease for larger p_T [4].

3. Open Heavy Quarks

Recent studies of the contribution of quarkonia and Drell-Yan to the spectrum of single electrons from heavy quarks have determined that for transverse momenta above about 5 GeV/c these contributions can amount to up to 16% of the total non-photonic electron yield [5]. The contributions of J/ψ, Υ, and Drell-Yan are shown in Fig. 2 (left) and one can see that the J/ψ gives the dominant contribution. After subtracting off these estimates of the contributions to the

$p + p$ collision data, with careful attention to their uncertainty, shown in Fig. 2 (right), the net yield of electrons from heavy quark decay has moved from a little above, to slightly below, the FONLL model's upper uncertainty limit. Similar corrections, but with larger uncertainties have been applied for $Au + Au$ collisions. However, because both $p + p$ and $Au + Au$ are lowered by about the same amount, the resulting nuclear depencence in $Au + Au$ collisions, R_{AA}, is not significantly changed.

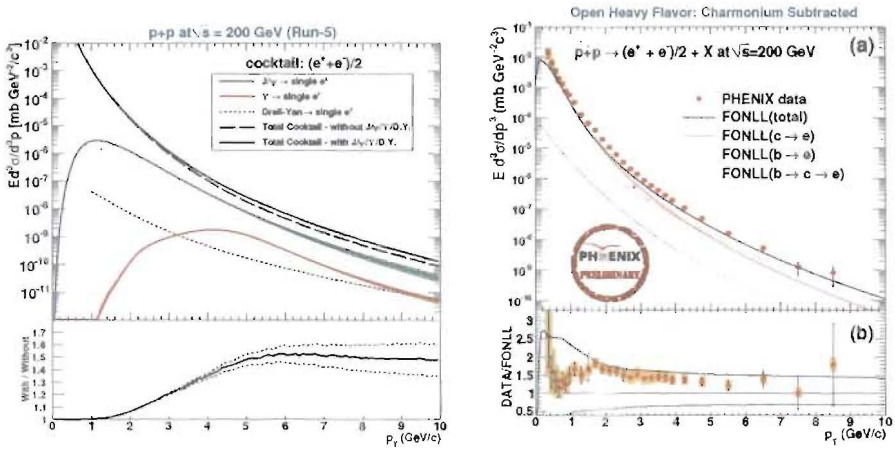

Figure 2: Contributions of quarkonia and Drell-Yan to the background for single electrons from heavy meson decays and the relative change wrt to the background before their inclusion (left). Single electron spectrum from heavy quarks corrected for these contributions compared to a FONLL calculation [6] (right).

Most open-heavy flavor meson measurements at RHIC to date are not able to separate contributions to the single electrons from charm and beauty, while theoretical predictions of energy loss and flow in the hot-dense medium created in high-energy heavy ion collisions are generally quite different for charm and beauty. Recently a new method has been employed, where one studies the correlations of hadrons near the observed electron and exploits the fact that the decay of a charm meson into an electron and hadron produces a broader correlation and lower efficiency for observing the pair than that of a beauty meson. Using this technique, the fraction of $(b \to e)/(b + c \to e)$ has been determined [7] and is shown vs p_T in Fig. 3 (left).

PHENIX has also measured open-heavy flavor mesons at forward rapidity via their decay to single muons, but so far not with enough precision to define the shape of the cross section vs rapidity. However, three different methods in PHENIX now yield consistent cross sections in $p + p$ collisions at mid rapidity: single electrons via cocktail subtraction, a converter method, and with di-electrons. Using the beauty fraction determined above, a beauty cross section of $\sigma_{b\bar{b}} = 3.2^{+1.2}_{-1.1}(stat)^{+1.4}_{-1.3}(sys)\ \mu b$ has also been determined [7].

Finally, the first proof-of-principle measurement of charm pairs via electron-muon correlations in $p + p$ collisions has been made [8] and is shown in Fig. 3 (right). The peak at π radians in $\Delta\Phi$ is from these correlated pairs. This method promises to provide another independent measurement of charm in the near future, as luminosities increase and allow substantial yields for this rare signal.

4. Quarkonia Production and Suppression

The simultaneous theoretical description of both the cross section and the polarization of the J/ψ in hadron production has long been a challenge. A new analysis of the 2006 PHENIX $p + p$ data agrees well with the previous results, has significantly higher precision, and agrees well with the Lansberg s-channel cut color-singlet model [9]. The decay polarization of the J/ψ measured by PHENIX at mid and forward rapidity is shown in Fig. 4 (left), where the Lansberg model reproduces the small polarization falling with p_T at mid rapidity (red points), but predicts a larger polization than the null polarization seen at forward rapidity (by 2-3 sigma) [10]. Improved polarization measurements at forward rapidity in several bins in p_T are expected soon, and may help clarify the situation.

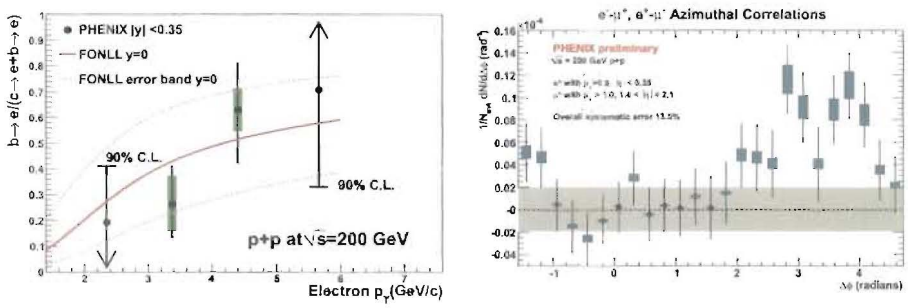

Figure 3: Fraction of beauty, $(b \rightarrow e)/(b + c \rightarrow e)$, vs single-electron transverse momentum compared to FONLL calculations [6] (left). Early electron-muon pair charm signal for $p + p$ collisions (right).

New results for the J/ψ from the 2008 $d + Au$ run with approximately thirty times larger integrated luminosity than that of the previous (2003) $d + Au$ results are beginning to emerge, with the first preliminary result in terms of R_{CP},

$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} / < N_{coll}^{0-20\%} >}{N_{inv}^{60-88\%} / < N_{coll}^{60-88\%} >},$$

shown in Fig. 4 (right) vs rapidity for three different centrality bins [10, 11]. One sees essentially no nuclear dependence at backward rapidity, a little at mid rapidity, and increasing suppression with centrality at forward rapidity in the nuclear shadowing region (large rapidity corresponds to small momentum fraction down to about $x = 2 \times 10^{-3}$ and is in the shadowing region). PHENIX is working on more comprehensive results for the near future in terms of R_{dAu}, the nuclear dependence wrt to $p + p$ - the much higher statistical precision of this new data requires precision systematics and more careful analysis.

New preliminary results for J/ψ R_{AA} in $Cu + Cu$ collisions show continuing suppression up to at least 7 GeV/c in p_T. In Fig. 5 (left) this suppression is compared to several theoretical models, including the "hot-wind" AdS/CFT inspired model [12] which is inconsistent with the data. Eventually, due to the Cronin effect seen in $d + Au$ collisons, which causes a change from suppression to enhancement at high-p_T, one would expect R_{AA} to return to one at large p_T, but there is no evidence of that yet from these results.

With the increasing luminosities provided by the RHIC machine, PHENIX is now beginning to accumulate useful number of Υs for various kinds of collisions. From the 2006 $p + p$ run,

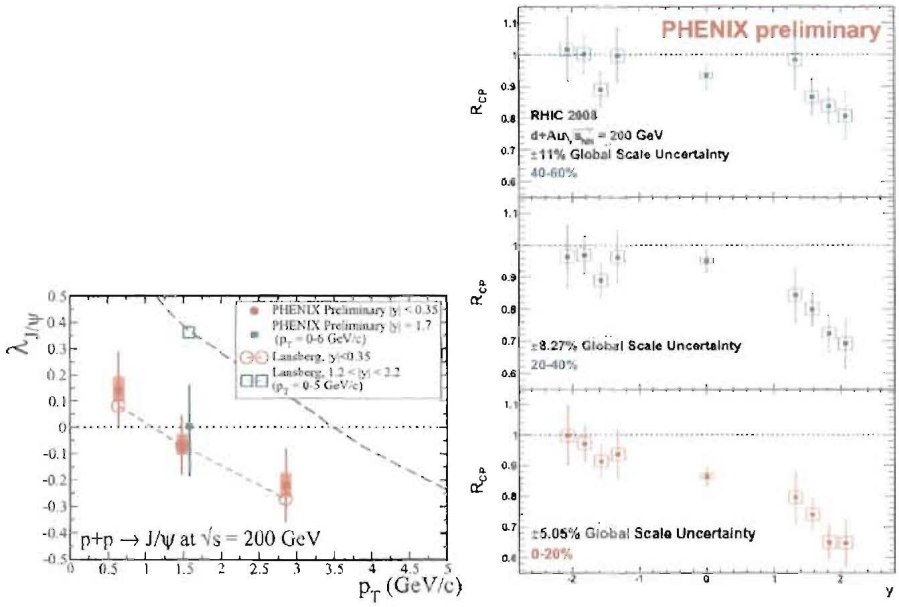

Figure 4: Polarization vs p_T in the helicity frame for J/ψ production in 200 GeV $p+p$ collisions with mid-rapidity points as red circles and forward rapidity points as blue squares (left). R_{CP} vs rapidity for J/ψ production in 200 GeV $d+Au$ collisions for three different centrality bins, with the most central collisions (0-20%) on the bottom (right).

as shown in Fig. 5 (right), we now have a preliminary cross section for dielectron events in the $\Upsilon(1S+2S+3S)$ mass region [8.5,11.5 GeV/c^2] of $BR * d\sigma/dy$ ($|y| < 0.35$) = 114^{+46}_{-45} pb . A small number of dielectron pairs from Drell-Yan and from open beauty pairs may also contribute in that mass region, but this contribution is estimated to be less than 15% and is included in the systematic uncertaintiy. Using a similar signal for $Au+Au$ collisions, shown in Fig. 6 (left), and doing a very careful statistical analysis which takes into account the small numbers of counts in both the $Au+Au$ and $p+p$ Υ mass regions, we have obtained the probability distribution for R_{AuAu} in this mass region shown in Fig. 6 (right). From this an upper limit of $R_{AuAu} < 0.64$ at 90% C.L. is determined [14].

Although Υs have long been touted as the standard candle for the melting of quarkonia in the Quark Gluon Plasma (QGP), i.e. that they would not be screened up to very high temperatures, it is clear that there are a number of simple non-QGP effects that could easily cause a suppression at or below the upper limit determined above. These include 1) the suppression of Υ states seen in fixed target experiments [13] which would give about 0.81^2 in R_{AuAu}, 2) the fact that only about 52% of the Υ_{1S} do not come from feeddown from the higher mass (2S, 3S) Υ states and B decays [15], and 3) that we do not resolve the three Υ states (1S+2S+3S) and the 1S is only about 73% of this [16].

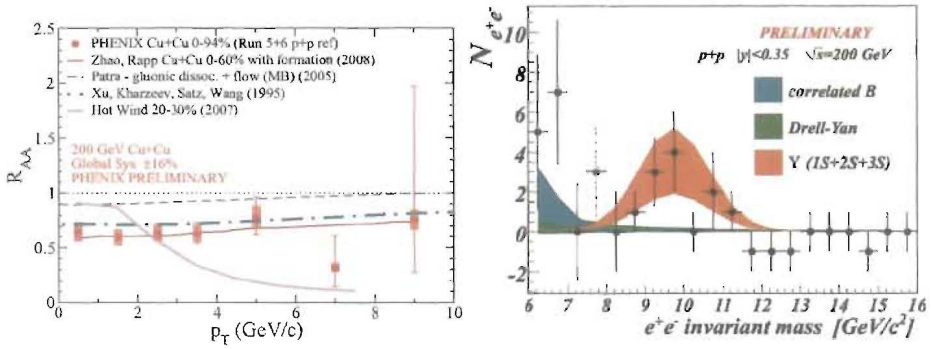

Figure 5: R_{CuCu} vs p_T for mid-rapidity J/ψs out to 9 GeV/c compared to several theoretical models [12, 17] (left). Invariant mass spectrum at mid rapidity for $p + p$ collisions at high mass showing the Υ family and other components of the spectrum.

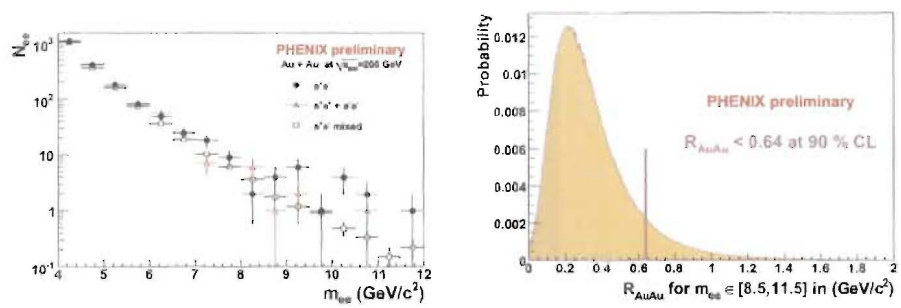

Figure 6: Di-electron pair mass at mid rapidity for 200 GeV Au+Au collisions in the Υ mass region, where e^+e^- pairs are shown as black points, like-sign pairs as red points, and mixed e^+e^- background pairs in green (left). The probability distribution vs R_{AuAu} determined from the $Au + Au$ and $p + p$ data (right).

5. Initial State and Temperature

Direct photon production in nucleus-nucleus collisions, although a difficult measurement, is a clean probe of the initial-state gluon distributions in the colliding nuclei. The latest measurements in PHENIX show no modification wrt $p + p$ collisions except for transverse momenta above about 12 GeV/c. These modifications are likely due to CNM effects (Cronin) and isopin (neutrons vs protons) [18].

A new method has been used recently to extract the yield of photons in the low-p_T thermal region where the production of these photons is inferred from the low-mass ($M_{ee} < 300\ GeV/c^2$) $1 < p_T < 5\ GeV/c$ e^+e^- spectrum [19]. These low-mass photons show an enhancement over the scaled $p + p$ reference, as shown in Fig. 7 (left). If interpreted as thermal photons from the hot-dense medium and fit to an exponential slope, an average temperature of the medium (for central collisions) of $T_{avg} = 221 \pm 23 \pm 18\ MeV$ is obtained. Since this is the average over the expansion, one can ask within various theoretical descriptions for that expansion, what the initial termperature is. Fig. 7 (right) shows various initial temperatures vs the formation time assumed in each theoretical picture. All models indicate an initial temperature of at least 300 MeV, well

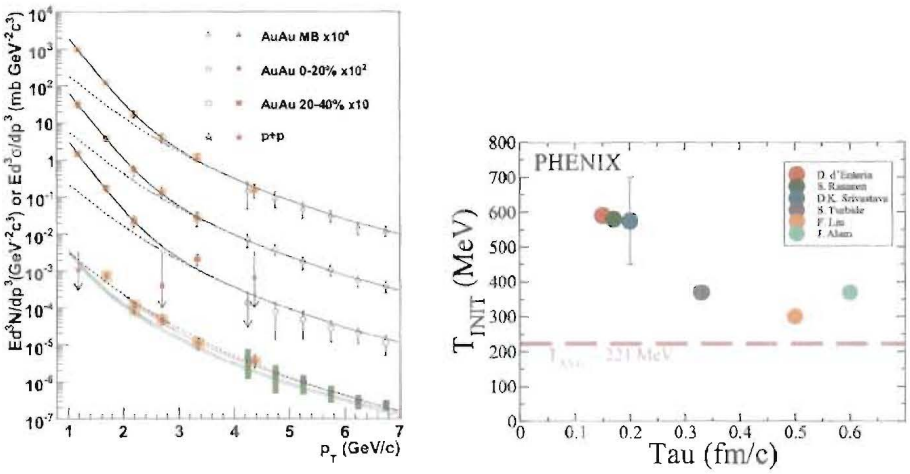

Figure 7: Direct photon spectra vs p_T in $p + p$ and $Au + Au$ collisions at 200 GeV, with the scaled $p + p$ reference compared to the data from various centrality $Au + Au$ data as a black dashed line. The enhancement over the $p + p$ reference at small p_T for $Au + Au$ collisions is fit to an exponential (solid black lines) to extract an inverse slope and an effective temperature (left). Estimates of the initial temperature of the hot-dense medium from several different models for the expansion of that medium, given the average temperature of 221 MeV determined from the central $Au+Au$ spectra (right).

above the predicted QGP phase transition at 170 MeV.

6. Summary

We highlight here some of the recent PHENIX results that we believe to be most interesting in areas that relate to the initial state and early times, including:

1. Quarkonia contribute substantially to the electrons from heavy flavor for $p_T > 5\ GeV/c$ and should be taken into account when comparing to theoretical predictions.
2. Beauty decays give 50% or more of the single electrons for $p_T > 4\ GeV/c$, so any differences between beauty and charm for energy loss and flow may become apparent at these p_T values.
3. J/ψ polarization measurements at mid rapidity agree with the Lansberg color singlet model, but at forward rapidity the p_T-integrated value does not.
4. For $Cu + Cu$ collisions, J/ψs continue to be strongly supressed up to $p_T \simeq 8\ GeV/c$.
5. Events in the $\Upsilon(1S + 2S + 3S)$ mass region at mid rapidity are suppressed in $Au + Au$ collisions by at least 36%, but this is not unexpected given cold nuclear matter effects and the likely strong suppression for central $Au + Au$ collisions of the higher mass Υ states.
6. Direct photons measured in the thermal region for central $Au + Au$ collisions indicate intial temperatures of at least 300 MeV, well above the expected QGP phase transition.

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