J/ψ Elliptic Flow, High $p_T$ Suppression and Υ Measurements in A+A Collisions by the PHENIX Experiment.

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Abstract

Three measurements that broaden the scope of the experimental investigation of quarkonia modifications in heavy ion collisions are presented. Although the current statistical precision on the first two measurements does not allow one to draw significant conclusions, J/ψ elliptic flow and high $p_T$ suppression results are important proofs of principle measurements, and make the case for higher luminosities at RHIC. Finally, the first measurement of an upper limit on the nuclear modification $R_{AA}$ of dielectrons in the Υ mass region in Au+Au collisions is presented. The results show a significant suppression with an upper limit of $< 0.64$ at 90% CL.

1. Introduction

J/ψ suppression measurements in heavy ion collisions have long been used as a test of deconfinement in the Quark Gluon Plasma (QGP) formed in heavy ion collisions. J/ψ rates in heavy ion collisions are now known to be subject to a number of competing mechanisms of production and suppression. These mechanisms can be categorized into Cold Nuclear Matter (CNM) such as breakup through nuclear interaction and shadowing and QGP induced mechanisms including the looked for melting induced by Debye screening, and recombination.

The use of J/ψ to study dissociation phenomenon due to Debye screening in the QGP requires the understanding and good control of every other mechanism. It is therefore essential to broaden the scope of experimental observables. Here the focus will be on three particularly challenging measurements, where results are in their beginning stages at RHIC. The critically important measurement of CNM effects is not covered, as it was the subject of another talk at this conference [1, 2].

2. Momentum dependence of J/ψ suppression

The momentum dependence of J/ψ suppression is a very useful indication of some of the initial and final state effects. On the one hand, initial state multiple scattering which is present in proton/deuteron–ion and ion–ion collisions is expected to broaden the $p_T$ spectrum with respect to the reference proton–proton spectra, due to a random walk of the colliding partons in the transverse plane to the collision axis thorough elastic scattering before the final inelastic interaction that creates the $c\bar{c}$ state. This effect is known as the Cronin effect. On the other hand, recombination, if it takes place in the QGP is expected to result in a softer $p_T$ spectrum than in proton–proton collisions. This comes from the expectation that only $c$ and $\bar{c}$ pairs close in...
momentum space actually combine, and that the low $p_T$ charm quarks dominate the spectrum. Measuring $J/\psi$ suppression at the highest possible $p_T$ is essential since different model predictions show the most variation in this region. Figure 1(1) shows the currently available $J/\psi R_{AA}$ versus $p_T$ in 0-20% central Cu+Cu collisions. The data clearly disfavors the hot wind model [3], whereas more statistical precision is required to discriminate between the other models [4].

Figure 1: Left: $J/\psi$ suppression in 0-20% central Cu+Cu collisions vs. $p_T$ at mid ($|y| < 0.35$) rapidity region. Right: Elliptic flow of $J/\psi$ vs. $p_T$ in the PHENIX mid and forward (1.2 < $|y|$ < 2.2) rapidity regions.

3. $J/\psi$ elliptic flow

The physics motivation for the measurement of the $J/\psi$ elliptic flow comes from the observation that semileptonic decay electrons from heavy flavor show a strong flow that is thought to be accounted for by a strong thermalization of the underlying heavy quarks [5]. As a result, $J/\psi$ created by recombination of independent charm quarks will inherit the flow of their constituents, whereas direct $J/\psi$ possess at most a very small $v_2$ due to geometrical effects in their absorption. The measurement of $J/\psi$ elliptic flow has thus the potential to discriminate between different recombination scenarios, as illustrated by the theoretical curves shown in Figure 1(right), predicted by models that incorporate various degrees of regeneration [6]. Unfortunately the current measurement of $J/\psi$ $v_2$ from PHENIX at mid and forward rapidities, shown in the same figure, are limited by statistics and do not favor any particular scenario.

4. Insight from higher mass states

In this section, the efforts to measure the nuclear modification of $b\bar{b}$ resonances are described. The $b\bar{b}$ states are more tightly bound than the $c\bar{c}$ states. As a result most lattice QCD calculations predict a much higher melting temperature for the lowest $\Upsilon$ state than for the $J/\psi$, despite discrepancies on the actual value of the melting temperatures [7]. The tighter binding also implies that $b\bar{b}$ state should suffer less CNM breakup. Pinning down the $\Upsilon$ nuclear modification factor $R_{AA}$ will provide new constraints in the study of quarkonium modifications.

The measurement of $\Upsilon$ is however more challenging at RHIC than $J/\psi$ due to the smaller bottom production cross section, and as a result requires much higher integrated luminosity to attain the same level of statistical significance as a $J/\psi$ measurement. Figure 2 shows the foreground and combinatorial background invariant mass spectra in the high mass region in p+p (left) and
Au+Au (right) interactions and corresponding combinatorial background. Most of the available data from the 2006 p+p RHIC run and 2007 Au+Au RHIC run at 200 GeV were included here. The net like and unlike pair yields in p+p and Au+Au in the mass region from 8.5 GeV/c$^2$ to 11.5 GeV/c$^2$ are summarized in Table 1.

| Unlikely sign | Like sign | J/ψ yield |
|---------------|-----------|------------|
| [8.5-11.5] GeV/c$^2$ | [8.5-11.5] GeV/c$^2$ | |
| p+p           | 12        | 1          | 2653 ± 70 (stat) ± 345 (syst) |
| Au+Au         | 17        | 5          | 4166 ± 442 (stat) ± 304 (syst) |

Table 1: Net J/ψ yield and like and unlikely sign pair yields in the [8.5-11.5] GeV/c$^2$ mass range for p+p and Au+Au collisions.

In order to take advantage of canceling systematic uncertainties, the $R_{AA}$ in the $\Upsilon$ mass region was calculated by taking its ratio to that of the J/ψ, $R_{AA} = 0.42 ± 0.025$ (stat) ± 0.051 [8].

$$R_{AA}([8.5, 11.5]) = \left( \frac{N([8.5, 11.5])_{AA}/A\epsilon(\Upsilon)_{AA}}{N_{col} \times N([8.5, 11.5])_{pp}/A\epsilon(\Upsilon)_{pp}} \right) \left( \frac{N(J/\psi)_{AA}/A\epsilon(J/\psi)_{AA}}{N_{col} \times N(J/\psi)_{pp}/A\epsilon(J/\psi)_{pp}} \right)$$

(1)

and rearranging to get

$$R_{AA}([8.5, 11.5]) = \frac{(N[8.5, 11.5]/N(J/\psi))_{AA}}{(N[8.5, 11.5]/N(J/\psi))_{pp}} \times R_{AA}(J/\psi)$$

(2)

where the acceptance and efficiencies cancel out in the double ratio. This approach has the advantage that efficiency calculation systematics cancel in the ratio $N([8.5, 11.5])/N(J/\psi)$ within a given data set. The probability distribution for $R_{AA}([8.5, 11.5])$ shown in Figure 3 is calculated by a convolution of the Poissonian probability distributions for $N[8.5, 11.5]/N(J/\psi)$ in Au+Au and p+p deduced from the values in Table 1 and smeared by the Gaussian distributed error of $R_{AA}(J/\psi)$. From this distribution, the upper limit on $R_{AA}([8.5, 11.5])$ at 90% confidence level is determined to be 64% [9].
Figure 3: The statistical probability distribution of the $R_{AA}$ of the signal from correlated pairs as obtained from Eq. An upper limit at 90% confidence level of 0.64 is inferred from this distribution.

The following considerations have to be taken into account when trying to interpret this value. The first is that the contributions of other correlated physics backgrounds like open beauty and Drell-Yan are estimated to be quite small, of the order of 15% or less from an extrapolation of the lower mass spectrum in p+p. Although physics background subtraction was not performed before calculating the upper limit given here, its contribution seems to be small. The other consideration is that the high mass counts integrate a mass range that was determined as the experimental width covered by the $\Upsilon(1S), \Upsilon(2S)$ and $\Upsilon(3S)$ states. It also includes a feed down contribution from excited states such as the $\chi_b$. The suppression observed is therefore a cumulative effect of the above mentioned resonances, which, except for the 1S ground state are predicted by many lattice QCD calculations to have a melting temperature close to that of $J/\psi$. Finally, any interpretation of this result should take into consideration the cold nuclear matter effects such as break up and shadowing on the high mass resonances.

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