

Quarkonia and heavy flavors latest PHENIX results

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Abstract Heavy quarkonia are direct probes of deconfinement in the quark gluon plasma formed in heavy ion collisions. Other effects also occur, such as modification of the parton distributions in cold nuclear matter, and a multidimensional description is necessary to disentangle the various contributions. Characterization of the production processes in p+p and p or d induced collisions with ions is critical in the extraction of the additional effects in ion-ion collisions. The Relativistic Heavy Ion Collider has delivered a wide range of systems and energies, from p+p to Au+Au through d+Au and Cu+Au, from 7.6 to 200 GeV (N-N collision energy), allowing the PHENIX experiment to start exploring these experimentally available dimensions for open and hidden charm and beauty as a function of rapidity and transverse momentum. Recent PHENIX results on heavy flavor production measured through lepton pairs or singles, including J/ψ , ψ' , χ_c , Υ and open charm and beauty, are presented.

1. Introduction

Heavy quarks and quarkonia are produced in the first steps of a collision, and they are sensitive to the whole evolution of the system, and in particular to the initial stage, which makes heavy quarkonia an excellent probe of the quark gluon plasma formed in heavy ion collisions [1]. As a bound pair of rare quarks, charmonia and bottomia should be direct probes of the deconfined nature of the medium, even possibly a QGP thermometer.

As the energy of the collision increases, the expected energy density and the lifetime of the expected deconfined phase increase. But other effects make the quarkonium picture more complex. Breaking of the bound quarkonium pair, or modifications of their kinematic characteristics, could come from collisions with nucleons or particles produced during the collision. Also, even though they were discovered several decades ago, quarkonia production is not yet fully understood (see for instance [2]). In the last 20 years Tevatron results and, recently, polarization measurements at LHC [3] have raised questions about our understanding of the production process.

The situation is complex, with a range of possible physics processes and strengths. But the recent start of LHC and the increasingly precise and detailed results coming from RHIC are putting more constraints on models of heavy flavor modification in nuclear collisions.

2. Expérimental set up

The PHENIX experimental set up is described in detail in [4].

Open and hidden heavy flavor yields are deduced from measurements of electrons at mid-rapidity ($-0.35 < y < 0.35$), and muons at forward and backward rapidity ($1.2 < |y| < 2.2$).

As a function of the centrality of the collision between two nuclei A and B, the modification of the yield is characterized by R_{AB} , the ratio of invariant yields in A+B collisions to those in p+p collisions, scaled by the number of nucleon nucleon collisions estimated in a geometrical Glauber model.

3. Quarkonia production

Quarkonia are measured using electron and muon pairs. Early PHENIX Au-Au results already suggested a J/ψ suppression at RHIC energies ($\sqrt{s}=200$ GeV), increasing with the centrality of the collision. These results, compatible with the formation of a quark gluon plasma, were comparable with the Pb-Pb ones at SPS ($\sqrt{s}=17.3$ GeV). This was confirmed by higher statistics PHENIX measurements, showing also that suppression was stronger at forward rapidity. Recent observations [5] at $\sqrt{s}=39$ GeV and 62.4 GeV showed similar suppression. This apparent stability from SPS to RHIC could hide a more complex phenomenon: the increase of energy density leading to more suppression, but also to more coalescence or recombination due to higher yields of the underlying heavy quark population [6]. The reduced suppression observed at higher collision energy [7] supports this interpretation.

For the smaller colliding system Cu+Cu, results [8] have been found to be very consistent with Au-Au for the same numbers of participating nucleons. For the d-Au system a decrease in the direction of the lighter partner (forward rapidity) is systematically observed. This is a general trend, observed for the bulk of the production [10]. Recent results from d+Au collisions with high statistical precision [11] bring a new sensitivity in the p_T and y dimensions. Calculations based on the NLO EPS09 nuclear PDF (nPDF) are found to not reproduce the p_T and y distributions simultaneously [11]. On the other hand a multiple scattering and energy loss model has an impressive ability [12] to reproduce the changes of distributions over wide p_T ranges at mid and forward rapidity, at all collision energies.

In Figure 1 the R_{dAu} for the J/ψ , measured in the central rapidity region, is shown to depend weakly on the centrality, while that for the ψ' [13] displays unexpectedly strong suppression for the most central collisions. Stronger suppression of the ψ' than the J/ψ has been observed at lower energies, where the difference seems to be consistent with breakup by collisions with nucleons. But at RHIC breakup by nucleons is unable to explain the large suppression because the two quarkonia are expected [14] to cross the target nucleus too early in their development to have a different sensitivity to breakup effects. Beside their interest as a reference for heavy ion collisions, p(d)+A quarkonia results across a wide range of rapidities provide sensitivity to the time spent in the target nucleus by the quarkonia precursor. This allowed [15], a separation of the J/ψ data into regimes dominated by breakup and energy loss - respectively associated with the forward rapidity domains of the heavy or light colliding partners - in addition to the nuclear effects on the PDF.

The recent measurement of χ_c in d-Au [13] is an additional step towards the study of the relationship between the characteristics of the quarkonia, in particular their binding energy, and the CNM suppression, at these energies.

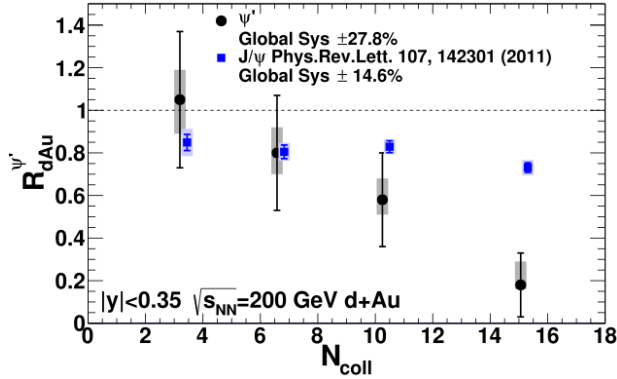


Figure 1 J/ψ and ψ' R_{dAu} with respect to centrality. ψ' displays an unexpected additional suppression.

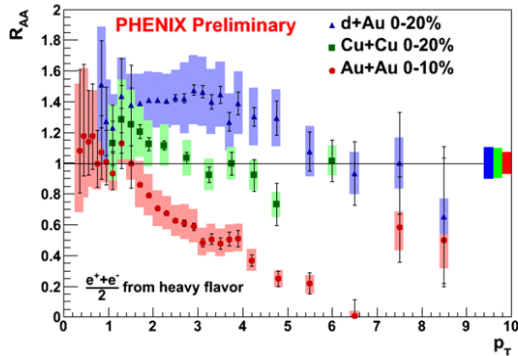


Figure 3 evolution from d -Au to $Au+Au$ of R_{AA} for open heavy flavor production at central rapidity

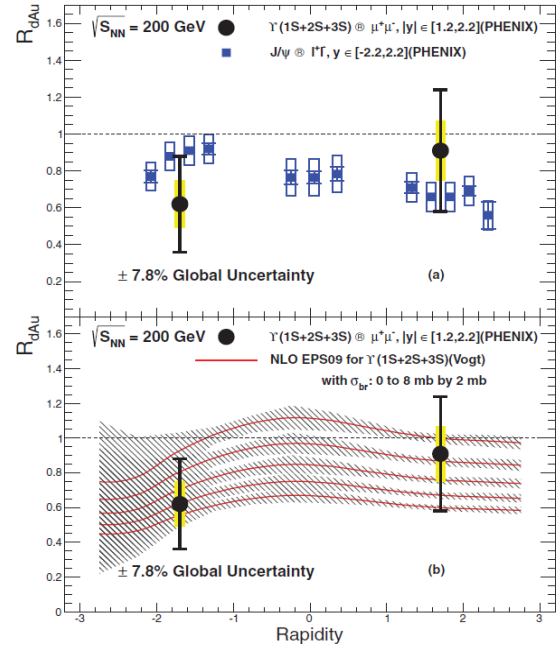


Figure 2 (from [16])

R_{dAu} for Υ , with respect to rapidity, and compared to
a) R_{dAu} for J/ψ
b) calculation based on NLO EPS09 and breakup cross sections

Figure 2 [16] displays R_{dAu} versus rapidity, for the Υ , compared to J/ψ (top) and to a model calculation (bottom). In contrast to the J/ψ , the Υ suppression appears stronger in the backward region. The large error bars preclude physics conclusions at this stage, but it is noteworthy that the calculation [17] suggests a stronger decrease in the backward region. This could be linked to the breakup effect but also to the EMC effect in the gluon structure functions [18]. This EMC gluon effect can be accessed mainly through Υ measurements at these energies.

4. Open heavy flavour production

Open heavy flavor (HF) originate from the same production mechanism as heavy quarkonia (for instance [19] reproduces quarkonia measurements with a calculation tuned on open flavor). The produced b and c quarks combine with light quarks leading to B and D excited mesons, mostly decaying to ground states, which then can decay in the semileptonic channels. This HF lepton source has to be separated from the leptons coming from lower mass mesons, and, in the case of electrons,

from photon decays. In PHENIX it is done [20][21] using a Monte Carlo simulation of these backgrounds, and for the muon arms by using the variation of their decay rate with distance from the production point to the hadron absorber in front of the muon arm. For electrons in the central arm, the measurement of background at low p_T using foils as a photon converter is also employed.

Figure 3 shows the p_T evolution of R_{AA} for electrons, in central collisions for three systems. High p_T Au-Au displays a strong suppression. That was unexpected for heavy quarks due to the dead cone effect in heavy particle energy loss. The d+Au collision data allow estimation of CNM effects. In contrast to the Au+Au data, they mostly show enhancement at mid p_T . Cu+Cu collisions are intermediate between d+Au and Au+Au. When integrated in p_T , a continuous evolution from enhancement to suppression is observed from d-Au peripheral to Au-Au central.

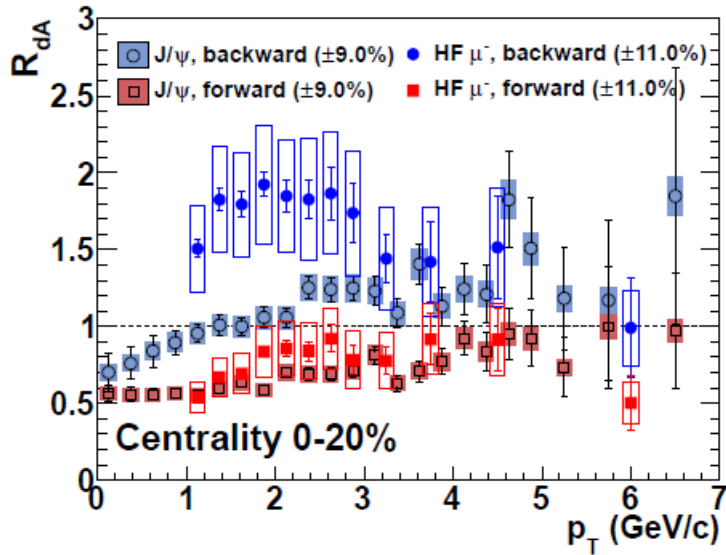


Figure 4 For the most central collisions, Heavy flavor $R_{dAu}(p_T)$, displays a backward enhancement. Whereas the J/ψ $R_{dAu}(p_T)$ [11] decreases at low p_T , and displays a smaller forward/backward ratio.

The modification of open HF for d-Au at mid-rapidity lies in between that observed in the backward and forward regions. As shown in Figure 4, for the most central collisions, $R_{dAu}(p_T)$ displays [22] an increased enhancement in the backward region, and a suppression in the forward one. This behavior is different from the one observed for quarkonia [11] shown for comparison in Figure 4. The J/ψ at low p_T is always suppressed, and the difference between backward/forward rapidities is smaller. The differences might be due to different dominant effects at forward and backward rapidities [15]. In the forward region the similar R_{dAu} of J/ψ and HF could reflect the same shadowing and/or energy loss effect with no nuclear breakup at the very short target crossing time, whereas in the backward region the suppression of the J/ψ relative to HF could be due to breakup of expanding quarkonia.

5. Summary

Thanks to the exploration in various colliding systems and energies made possible by RHIC, a more detailed landscape is emerging in ultrarelativistic collisions with heavy ions. Even dimensions like the

time evolution of the system seem to become experimentally accessible, thanks to the diversity of probes provided by the quarkonia families and their various formation times, seen from the target nucleus.

Open HF is a reference for quarkonia production, as well as an extremely interesting probe of the energy loss of heavy quarks in the QGP through the observed Au+Au high p_T suppression. The suppression pattern of J/ψ with the centrality of the nucleus nucleus collisions remains similar from 200 to 20 GeV collision energy, at the current precision. More p+p and h+A measurements are required to go further. But the d+Au at 200 GeV results have already provided some perspective. As a function of centrality in d+Au collisions, quarkonia and open HF production are modified, with strong suppression in the forward (light partner) rapidity domain. At backward rapidity however there is notably different behavior: the decrease in R_{dAu} of the Υ , and the increase for open HF. The evolution with p_T also puts constraints on models. The ψ' is more suppressed than the J/ψ , possibly due to its different binding energy. But this difference is not expected at these energies given the small nuclear crossing time scale of the charmonia precursor, which would lead to a similar breakup cross section due to nucleon collisions. The explanation is not clear yet, but may involve the small binding energy of the ψ' making it very sensitive to the small hot regions produced in d+Au collisions.

The increase of precision and kinematic range has led to stronger constraints on models but also revealed more complexity, and raises new questions. With the vertex detector recently added, allowing experimental separation of open bottom and charm contributions at all rapidities in PHENIX, the near future addition of a new forward calorimeter, and the proposal to measure data from a range of p+A collisions as well as Au+Au with these new detectors, the next generation of results will bring additional information to constrain models and advance our understanding of the mechanisms that influence heavy flavor production in p+A and Au+Au collisions.

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