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Hidden and open heavy flavor production at $\sqrt(s) = 200$ GeV in PHENIX

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Heavy flavor production is a sensitive probe of all stages in the evolution of a heavy ion collision system, and in particular heavy quarkonia could be direct probes of quark deconfinement in *A+A* collisions. The characterization of the competing effects on the yield in heavy ion collisions (like energy loss or suppression by collisions with initial partons or co-movers) requires a detailed description of the production, from *p+p* and *p+A* to *A+A* collisions. The unique versatility and increasing performance of the BNL/RHIC collider has provided several beams combinations at $\sqrt{s_{NN}}$ from 7 to 500 GeV. Also, improvements of the PHENIX experiment allow deeper study than has been previously published. This talk aims at presenting recent PHENIX results on J/ψ, ψ' and open charm and beauty productions at $\sqrt{s_{NN}} = 200 GeV$ in several collision systems and focus on the additional degrees of freedom in *p+A* and *A+A* collisions have compared to *p+p* collisions.

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1. Introduction

Heavy quarks are produced in the first steps of a collision, which makes heavy quarkonia an excellent probe of the deconfinement in the quark gluon plasma formed in heavy ion collisions [1].

As the energy of the collision increases, the expected energy density and the lifetime of the expected deconfined phase increases. 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.

The quarkonia states, with their different binding energies have the potential to bring detailed informations on the temperature at the beginning of the collision, but their suppression rate can also be modified by various effects along the evolution of the medium and depending of their formation time. They could then act not only as a thermometer but also as a chronometer. One difficulty is that the calibration of these thermometers/chronometers depends on the conclusion of the study that uses them.

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 [3] and, few years ago polarization measurements at LHC [4] have raised questions about our understanding of the production process. On the other side, the available measurements allow to tune models on a wide domain [5].

But despite of this complexity, open and hidden heavy flavor particles have a rich potential to be sensitive tools for the different effects that apply in the various stages of an beavy ions collision, from initial stage to cold nuclear matter effects, and in the hottest steps of the collision. But for disentangling these effects it is necessary to have a complete set of measurements, in p+ p, p+A and A+A collisions and on a wide domain of collisions energies.

The unique versatility and increasing performance of the BNL/RHIC collider allow to explore these dimensions , with $\sqrt{s_{NN}}$ from 7 to 500 GeV. Also, improvements of the PHENIX experiment allow deeper study than has been previously published. In this talk we present recent results from heavy flavor production and modification at $\sqrt{s_{NN}} = 200 GeV$.

Early PHENIX Au+Au results already suggested a J/ψ suppression at RHIC energies ($\sqrt{s_{NN}} = 200 GeV$), increasing with the centrality of the collision. These results, compatible with the formation of a quark gluon plasma, compare with the Pb-Pb ones at SPS ($\sqrt{s_{NN}} = 17.3 GeV$). 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. The reduced suppression observed at higher collision energy [6, 7], and even maybe a reversed trend in most central collisions, supports this interpretation.

Open heavy flavor (HF) is also a heavy quark pair production, but not exiting through a bound state. The open HF production in Au+Au measured through the single electron yield [8, 9] was found to scale with the number of nucleon nucleon collisions (binary scaling). Open HF was not expected to be sensitive to gluon radiation as for light quarks, but at high p_T , a strong suppression was also observed, together with flow, and both effects can be associated to the interactions in the medium, and are difficult to reproduce simultaneously (see discussion in [9]). Obtaining the information separately for charm and beauty will bring additional information.

2. Experimental setup

The PHENIX experimental set up is described in detail elsewhere [10]. 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 ($1.2 < |y| < 2.2$).

Central and forward rapidity Silicon Vertex Trackers (VTX [11] and FVTX [12]) were installed in PHENIX in 2011 and 2012. VTX (FVTX) covers $|y| < 1.2$ ($1.2 < |y| < 2.2$) in rapidity. The typical segmentation of these 4 layers of strips or pixel, is respectively 50 and 75 μm. This improves strongly the precision of the tracking in the relevant dimension, allowing sensitivity to tracks not originating from the collision point at the submillimetric level, or improving the mass resolution (from 145 to 95 MeV/c^2 for the muon arms).

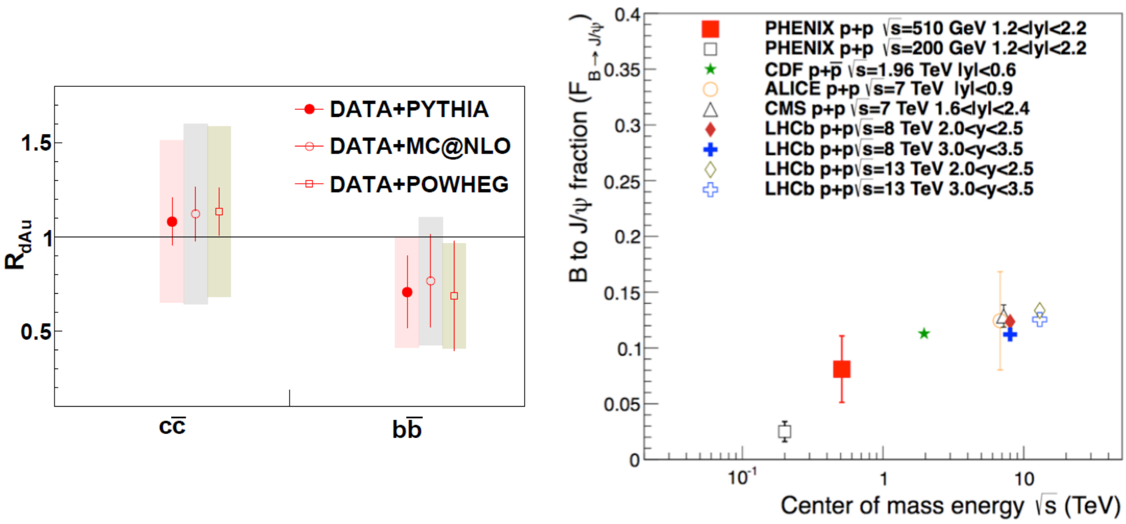

Figure 1: $R_{\rm dAu}$ of $b\bar{b}$ and $c\bar{c}$ yields extracted from dielectron production using various models for the mass-p_T distributions (left). Evolution of $F_{B\to J/\psi}$ as a function of $\sqrt{s_{NN}}$ from RHIC to LHC energies, in moderate rapidity domains (right)

In heavy ions collisions, the nuclear modification factor $R_{\rm AB}$ is generally used: it is the ratio of invariant yields in the collisions of nuclei A and B to those in p+p collisions, scaled by the number of nucleon nucleon collisions expected [13] in a geometrical Glauber model, depending on the "impact parameter", the distance between the trajectories of the two colliding nuclei which defines the "participant zones" in the two nuclei.

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3. Open heavy flavor production

A way to separate beauty from charm production has been developped [14] in the e^+e^- mass-p_T distribution. Once the other components have been determined, it is possible to separate $b\bar{b}$ and $c\bar{c}$ in the remaining continuum, thanks to their different mass-p_T distributions. Figure 1 displays the values obtained for $R_{\rm dAu}$ for $c\bar{c}$ and $b\bar{b}$ which are all compatible with unity, and not sensitive to the differences [14] between the models used for the simulations. The Large error bars could also accommodate the increase observed for single electrons in d+Au [15].

Thanks to the FVTX, allowing through the radial distance of closest approach DCA$_{\rm R}$ to estimate the fraction of tracks not pointing to the collision vertex , PHENIX has measured the fraction of J/ψs coming from B-hadrons decays, $F_{B\to J/\psi}$, for J/ψs within $1.2 < |y| < 2.2$ and $p_T > 0$ in p + p collisions at $\sqrt{s_{NN}} = 510 GeV$ [16] and in p + p and Cu+Au collisions at $\sqrt{s_{NN}} = 200 GeV$ [17]. The results in p + p collisions at $\sqrt{s_{NN}} = 200$ and $510 GeV$ compared to the world data, at similar moderate rapidity and low p_T , are displayed in figure 1 and show both a certain saturation at high energies, and a clear increase with RHIC energies. Values at $\sqrt{s_{NN}} = 200$ and $510 GeV$ are found consistent with expectations [16, 17] of FONLL (fixed order next to leading logarithm) and CEM (color evaporation model) models.

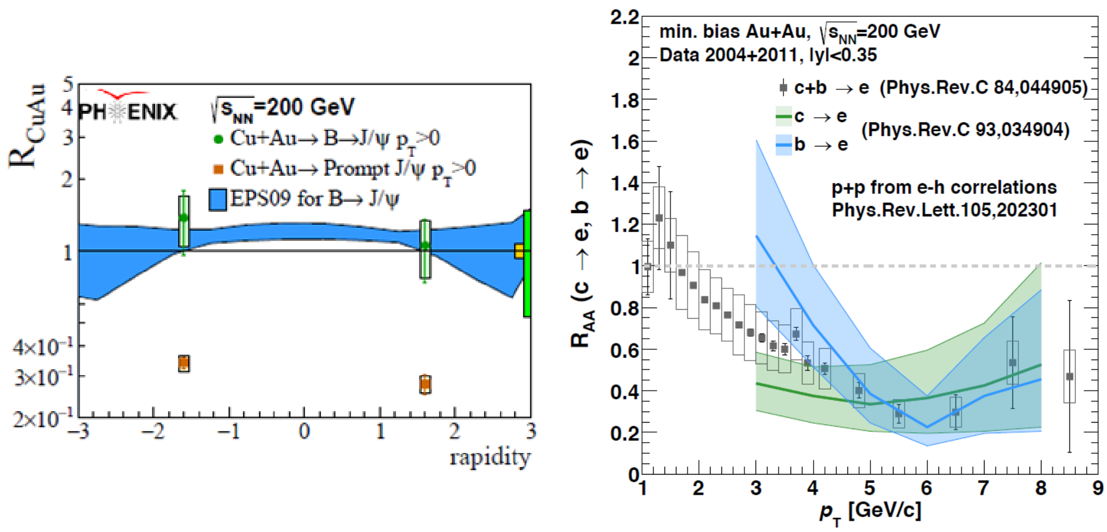

Figure 2: R_{CuAu} evolution of the ratio of J/ψ produced by B decay (left), and R_{AuAu} evolution of the charm and bottom components in single electron spectra (right).

In Cu+Au, the nuclear modification factor $R_{\rm CuAu}$ of J/ψs from B-hadron decays shown in figure 2, is found [17] compatible with unity , that is, a "binary scaling". $R_{\rm CuAu}$ is also consistent with expectations from nuclear PDF as given by EPS09, which seems even to suggest a small increase. In contrast the prompt J/ψs production is suppressed by a factor 3.

In the PHENIX central arm the extraction of beauty and charm components in the single electron yield [11] has been applied to a fraction of the Au+Au 2014 data, using the same method based on the distance of closest approach (DCA$_{\rm T}$) estimated thanks to tracking in VTX . These preliminary results are presented in figure 2 for the most central 200GeV Au+Au collisions. The b-quark production is much less suppressed than the c-quark one between 3 and 5 GeV/c p_T . In addition, for these central collisions the c-quark yield is found more suppressed than for minimum bias collisions. Transport models reproduce qualitatively the decrease of $R_{\rm AuAu}$ with p_T and the mass ordering, but the predicted differences are smaller, the models overpredict the beauty suppression, which emphasizes the interest of the incoming analyses with the full set of data.

4. Quarkonia production

The discovery of the additional suppression [18] of the ψ' came as a surprise. Indeed at lower energies it has been observed, but was not expected at RHIC, since the formation time of the resonances of about 0.35 fm/c is one order of magnitude above the average path in the nucleus, given the lenght contraction, and the various states then are expected to suffer identical effects in their crossing of the nucleus. Recently this result has been extended [19] to forward and backward rapidity in p(^{3}He)+A collisions. Previous ratio of ψ'/ψ ratios at central rapidity in d+Au and p+p is shown in figure 3. In the forward p(^{3}He)-going direction, within uncertainties the ψ'/ψ ratio does not display additional suppression . However, in the backward A-going direction, the weaker bound ψ' is more additionally suppressed than it is at central rapidity. These trends are qualitatively consistent with interaction with co-moving particles [20], as presented by a line in the picture.

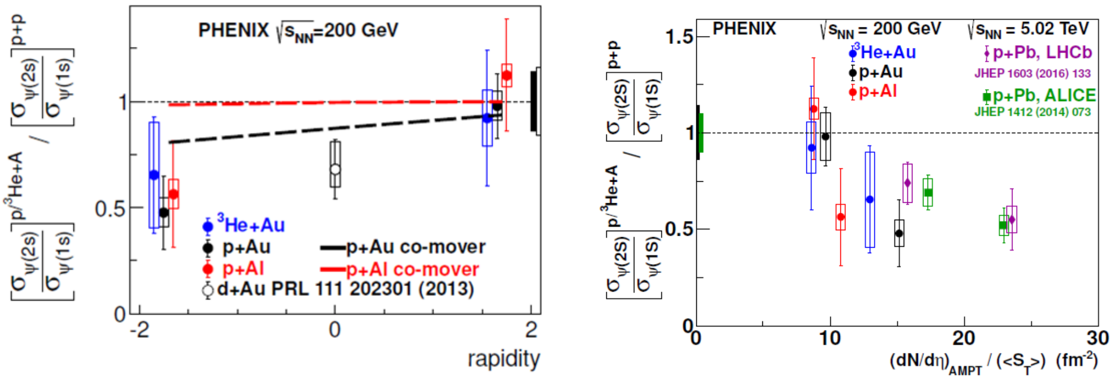

Figure 3: $R_{\rm AB}$ evolution in pAu, pAl and HeAu of the fraction ψ/ψ' in produced by B decay (left), and its comparison as a function of the multiplicity of particles in the collision for several experiments (right).

ψ'/ψ ratios are consistent (figure 3) with the ones at LHC plotted against dN/dy (estimated with AMPT). Co-movers effect could also explain [21] part of the additional suppressions observed for bottomonium states in A-A collisions at LHC. The co-movers effect then appears to have an important role, competing with the melting by color screening that can also explains by itself the suppressions observed [22] in A-A, or with effects like breakup in p-A [23]. It also emphasizes a unique role of the heavy ion collisions in their potentiality to give access to some time evolution, through the effects suffered from the medium.

5. Summary

Thanks to VTX and FVTX Vertex detectors, PHENIX gained access separately to charm and beauty, and to ψ' excited state. In Au+Au at $\sqrt{s_{NN}} = 200 GeV$, bottomium displays a similar suppression than charm, at high p_T , but at low p_T (3-5 GeV/c) is less suppressed. J/ψ non prompt production by $B \to J/\psi$ decay shows the rise of the bottom production at 200 and 500 GeV, consistently with FONLL and CEM models. In Cu+Au at 200GeV and at lower p_T , bottom production measured through $B \to J/\psi$ decays is not suppressed, consistently with expectations from EPS09 nPDF binary scaling. In d+Au , $b\bar{b}$ and $c\bar{c}$ extraction from electrons pairs confirms a R_{dAu} compatible with unity or above.

Quarkonia are suppressed in A-A collisions. Recent results on ψ'/ψ ratio in p-A collisions at $1.2 < |y| < 2.2$ show that the surprising additional suppression of ψ' is probably linked partially to interactions with co-movers particles. This maybe questions possibilities to go further on the theoretical detailed description of the space and time evolution of the partons or particles produced, and their effect on production/suppression rates of the different quarkonia and formation times.

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