Measurement of electrons from heavy-flavor decays from $p+p$, $d+Au$, and Cu+Cu collisions in the PHENIX experiment

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Abstract

Charm and bottom quarks are formed predominantly by gluon fusion in the initial hard scatterings at RHIC, making them good probes of the full medium evolution. Previous measurements at RHIC have shown large suppression and azimuthal anisotropy of open heavy-flavor hadrons in $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Explaining the simultaneously large suppression and flow of heavy quarks has been challenging. To further understand the heavy-flavor transport in the hot and dense medium, it is imperative to also measure cold nuclear matter effects which affect the initial distribution of heavy quarks as well as the system size dependence of the final state suppression. In this talk, new measurements by the PHENIX collaboration of electrons from heavy-flavor decays in $p+p$, $d+Au$, and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV are presented. In particular, a surprising enhancement of intermediate transverse momentum heavy-flavor decay leptons in $d+Au$ at mid and backward rapidity are also seen in mid-central Cu+Cu collisions. This enhancement is much larger than the expectation from anti-shadowing of the parton distributions and is theoretically unexplained.

Keywords: Open heavy flavor, System size dependence

1. Introduction

Heavy quarks, charm and bottom, are produced in the initial hard scattering. Therefore, they are good probes to study the evolution of the medium produced in heavy ion collisions. In addition, the predominant process of heavy quark production at RHIC energy, gluon fusion, is sensitive to initial state modifications such as shadowing. The PHENIX experiment has excellent capabilities to measure leptons from heavy-flavor decay both in the central arms at mid-rapidity ($|\eta| < 0.35$) and the muon arms at forward rapidity ($1.2 < |\eta| < 2.2$). The previous PHENIX results in $p+p$ collisions, considered as a baseline measurement for the results from other collisions, show a good agreement with FONLL calculation within uncertainties $^1$. In order to quantify medium effects compared to the $p+p$ collisions, the nuclear modification factor is defined as the ratio of invariant yields scaled by the number of binary collisions for a certain centrality range ($\langle N_{coll} \rangle$),

$$R_{AA}^{(dA)} = \frac{\langle N_{coll} \rangle}{\langle N_{coll} \rangle} \frac{dN_{AA}^{(dA)}/dp_T}{dN_{pp}/dp_T}. \tag{1}$$

In central $Au+Au$ collisions, where the number of binary collisions is almost 1000, a large suppression of heavy-flavor decay electron production compared to the scaled $p+p$ result is observed $^2$. Even though it is clear that suppressing effects are dominant in the largest collision system at RHIC, it is still important to understand other nuclear effects which are also convoluted in. Since RHIC has the flexibility to use various beam species, we can study which nuclear effects are dominant in a certain size of collision system such as $d+Au$ and Cu+Cu.

$^1$A list of members of the PHENIX Collaboration and acknowledgements can be found at the end of this issue.
2. $d+Au$ collisions

The $d+Au$ collision system is considered as a control experiment to study initial state effects, because suppressing effects from the hot and dense medium in heavy ion collisions can be minimized in this low multiplicity collision system. PHENIX has measured heavy-flavor decay electrons at mid-rapidity [3] and heavy-flavor decay muons at forward ($d$-going direction) and backward (Au-going direction) rapidity [4] based on large statistics of data collected in 2008. Figure 1 shows $R_{dA}$ as a function of $p_T$ for heavy-flavor decay electrons in the most central (top) and most peripheral (bottom) centrality classes measured at mid-rapidity [3]. Heavy-flavor decay electron production is clearly enhanced at moderate $p_T$ region in central $d+Au$ collisions ($\langle N_{\text{coll}} \rangle \approx 15.1$), however almost no modification ($R_{dA} \sim 1$) is observed in peripheral $d+Au$ collisions ($\langle N_{\text{coll}} \rangle \approx 3.2$). By comparing with the central Au+Au results, we can determine that suppressing effects are dominant only in heavy ion collisions.

It is interesting to compare the $d+Au$ results from different rapidities, because gluons of different momentum fractions in the Au nucleus, such as those within the shadowing and the anti-shadowing regions, can be accessed in different rapidity regions. The heavy-flavor decay muon measurement at backward rapidity shows a similar enhancement with the results at mid-rapidity, but a suppression is seen only at forward rapidity [4]. One interesting observation is that any model calculation considering initial state effects, i.e., modification of nuclear parton distribution function and initial $k_T$ broadening, can not simultaneously reproduce the data at forward and backward rapidity. Furthermore, there is no current theoretical approach with initial state effects to successfully explain the enhancement of heavy-flavor decay electron production seen at mid-rapidity. Recently, PHENIX has measured angular anisotropies and long-range correlations in central $d+Au$ collisions at RHIC energy [5,6], and a model calculation considering radial flow qualitatively reproduces the enhancement of heavy-flavor decay electron production [7]. From these facts, the enhancement of heavy-flavor decay lepton production seen at mid and backward rapidity in central $d+Au$ collisions could possibly result from final state interaction.
3. Cu+Cu collisions

The Cu+Cu collision system size is in between the d+Au and Au+Au collision systems, and heavy-flavor decay electron measurements in this intermediate system can provide a connection between the enhancement in d+Au collisions and the suppression in Au+Au collisions. Based on large statistics data collected in 2005, PHENIX has measured heavy-flavor decay electrons in various centrality classes at mid-rapidity [8]. Figure 2 shows $R_{AA}$ in the most peripheral (left) and central (center) centrality classes and $R_{CP}$ (right) of heavy-flavor electrons in Cu+Cu collisions where $R_{CP}$ is defined as

$$R_{CP} = \frac{N_{\text{peripheral}}}{N_{\text{coll}}} \cdot \frac{dN_{\text{central}}/dp_T}{dN_{\text{peripheral}}/dp_T}.$$  

In peripheral Cu+Cu collisions ($\langle N_{\text{coll}} \rangle \approx 5.1$), heavy-flavor decay electron production is clearly enhanced in the intermediate $p_T$ region, which is similar to the results in central d+Au collisions, and a slight suppression is observed at $p_T < 3$ GeV/c in central Cu+Cu collisions ($\langle N_{\text{coll}} \rangle \approx 182.7$). A comparison between the most central and peripheral results ($R_{CP}$), which takes into account the enhancement in peripheral Cu+Cu collisions, shows a clear suppression of heavy-flavor decay electron production. Therefore, we can conclude that suppressing effects are dominating in central Cu+Cu collisions, whereas there is a clear enhancement in peripheral Cu+Cu collisions.

4. System size dependence

Based on the heavy-flavor decay electron measurements in various collision systems, we can see how modifications (nuclear effects) evolve as system size grows. Figure 3 shows $R_{AA}$ as a function of $p_T$ between selections of d+Au, Cu+Cu, and Au+Au systems with similar number of participants ($\langle N_{\text{part}} \rangle$). The two left panels
show comparisons of $R_{AA}$ between central $d+Au$ and peripheral $Cu+Cu$ collisions. Both $d+Au$ and $Cu+Cu$ results show a similar trend of enhancement. In the two right panels, $R_{AA}$ from central $Cu+Cu$ and mid-central $Au+Au$ collisions also show similar $p_T$ shapes of heavy-flavor decay electron production compared to the same $p+p$ reference.

In order to look at a trend of the entire collision system, Figure 4 shows $R_{AA}$ as a function of $\langle N_{\text{coll}} \rangle$ measured at mid-rapidity for two $p_T$ ranges in $d+Au$, $Cu+Cu$, and $Au+Au$ collision systems. A reasonably smooth trend is seen from $d+Au$ and peripheral $Cu+Cu$ collisions, where enhancement effects are dominating, to central $Cu+Cu$ and $Au+Au$ collisions, where suppression effects take over.

5. Summary

PHENIX has measured heavy-flavor decay leptons in various collision systems, $p+p$, $d+Au$, $Cu+Cu$, and $Au+Au$ collisions, across a wide rapidity range. The heavy-flavor decay electron results at mid-rapidity show a trend of decreasing $R_{AA}$ with increasing system size from the enhancement seen in $d+Au$ and peripheral $Cu+Cu$ collisions to suppression in $Au+Au$ collisions. The enhancement seen in central $d+Au$ collisions at mid and backward rapidity regions is larger than the expectation from initial state effects, and a model calculation inspired by recent results of hydrodynamic behavior in $d+Au$ collisions raises the possibility of final state interaction. A new silicon vertex tracking system (VTX and FVTX) has measured a very large $Au+Au$ dataset in 2014. Based on precise vertex position information, new measurements such as $D/B$ separation are expected, and these results will help to understand the production and modification of charm and bottom quarks.

References

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