Measurement of Open Heavy Flavor Production with Single Muons in p+p and d+Au Collisions at RHIC

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Abstract. Heavy flavor production in hadronic collisions is dominated by gluonic processes and so is a sensitive probe of the gluon structure function in the nucleon and its modification in nuclei. A study of heavy flavor production in p+p and d+Au collisions in various kinematic regions presents an opportunity to probe cold nuclear medium effects; parton shadowing, color glass condensate, initial state energy loss, and coherent multiple scattering in final state interactions. The PHENIX muon arms cover both forward and backward directions in the rapidity range of 1.2 < |η| < 2.4. We investigate single muon production from open heavy flavor and light mesons decay in p+p and d+Au collisions at forward and backward rapidity.

1. Introduction:

Heavy quarks are believed to be mostly created from initial gluon fusion in hadronic collisions. Since they are massive, heavy flavor hadrons are proposed to be ideal probes to study the early stage dynamics in heavy-ion collisions.

Measurements of heavy quark production in p+p interactions at collider energies serve as important tests for perturbative Quantum Chromo Dynamics (pQCD), while measurements in d+Au collisions serve to calibrate the effects of the cold nuclear medium. Both observations create a very important baseline for understanding the hot-dense matter created in Au+Au collisions. Since the initial formation of open and closed charm are both sensitive to initial gluon densities, open charm production serves as an appropriate normalization for J/ψ production.

In √s_{NN} = 200 GeV d+Au collisions at RHIC, measurements at forward rapidity (deuteron direction) probe the shadowing region with momentum fractions in Au near x_2 = 0.01 while the anti-shadowing region is probed in backward rapidity (Gold going direction) with momentum fractions in Au near x_1 = 0.1. Recent models of gluon shadowing [1], color glass condensate [2] and recombination [3] are implemented to understand the hadron and open charm production at forward rapidity. All of these three models predict suppression in the small x region. It is very important to have
precise measurements of open heavy flavor and hadron production to disentangle these different models.

2. Experimental technique

The PHENIX experiment [4] has measured open charm production through observation of semi-leptonic decays at forward and backward rapidity with the PHENIX muon spectrometer. The PHENIX muon arms cover both forward and backward directions in the rapidity range of $1.2 < |\eta| < 2.4$, which covers both shadowing and anti-shadowing regions.

The decay of heavy flavor is prompt, and produces a track with an origin at the collision vertex. Another source of prompt muon-like tracks is hadrons that punch through the shielding in front of the muon spectrometer. The acceptance of the spectrometer for these prompt tracks is relatively independent of the vertex location $z$. Another background source is the weak decay of those same hadrons before reaching the shielding – these non-prompt muon tracks have an origin separated from the collision vertex, and the acceptance for these tracks is strongly $z$-dependent.

A PYTHIA simulation shows around 75% of prompt muons with $p_T > 0.9$ GeV/c come from open charm decay in d+Au collisions, while 11% come from open bottom decay. Prompt muons are produced close to the collision vertex. We can separate heavy flavor decays and light hadron decays experimentally by studying the shape of the vertex distribution.

The normalized event vertex distribution of reconstructed muons is given by

$$\frac{1}{N_{MB}^{MB, measured}} \frac{d^3N(z, \eta, P_T^{\mu \pm})}{dz dP_T^{\mu \pm} d\eta} \propto \{ \alpha(P_T, \eta)(z - z_{0eff}^0) + \beta(P_T, \eta) \}$$

where $z$ is the event vertex and $z_{0eff}^0 = \pm 41$cm for north and south arms, respectively. $\alpha(P_T, \eta)$ and $\beta(P_T, \eta)$ are determined from event vertex distribution. The distribution of detected muons from light hadron decay is collision vertex dependent due to the acceptance of the muon spectrometers, and this is described by the $\alpha$ parameter. The prompt muon and the hadron punch through tracks will contribute to the vertex independent part and this is described by the $\beta$. The data were used to subtract the hadron punch through. The PHENIX muon spectrometer includes a ”muon identifier” consisting of thick iron sheets with detectors in the gaps between the sheets. Muons are more likely to penetrate into the deeper gaps than are hadrons. By analyzing the hadrons stopped at gap 2 and 3, one can estimate the hadron contribution at gap 4 using an attenuation model [5]. With this statistical method, we can measure the yield of muon from heavy flavor decays with the PHENIX muon arms.

3. Open Charm results for p+p collisions

The invariant differential cross section for prompt muon production at forward rapidity ($1.5 < \eta < 1.8$) has been measured by the PHENIX experiment over the transverse
momentum range \(1 < p_T < 3 \text{ GeV/c} \) in \(\sqrt{s_{NN}} = 200 \text{ GeV} \) \(p+p\) collisions at the Relativistic Heavy Ion Collider.

The resulting muon spectrum from heavy flavor decays is compared to PYTHIA and a next-to-leading order perturbative QCD calculation showing in Figure 1. PHENIX muon arm data (at forward and backward rapidity) is compatible with the PHENIX charm measurement at \(y = 0\) [6], and it exceeds predictions from PYTHIA and FONLL.

4. Nuclear Modification Factor in d+Au collisions

The nuclear modification factor of d+Au collisions is defined as the particle yield per nucleon-nucleon collision relative to the yield in p+p collisions. The nuclear modification factors with muons from light hadron decay and from heavy flavor decay are shown in Figure 2 and Figure 3. Muons from both light hadron decay and prompt single muon production show suppression at forward rapidity and enhancement in the backward direction.

5. Summary and Outlook

FONLL and PYTHIA 6.205 under-predict the prompt \(\mu\) yield at forward rapidity in \(p+p\) collisions at 200 GeV/c. We observe a significant cold nuclear medium effect in forward and backward rapidity in d+Au collisions at 200 GeV/c. For both muons from open heavy flavor decays and light hadron decays, a suppression in forward rapidity is observed. It is consistent with CGC and power correction model [7]. The mechanism of the observed enhancement at backward rapidity needs more theoretical investigation. Anti-shadowing and recombination could lead to such enhancement.

We need a more precise d+Au measurement to understand the cold nuclear medium effects as a baseline for understanding the hot dense matter produced in Au+Au collisions.
Figure 2. Left: $R_{dAu}$ for hadrons vs $\eta$; Right: $R_{dAu}$ for hadrons vs $p_T$. South Arm is Au-going direction and North Arm is deuteron-going direction.

Figure 3. Invariant spectra of the prompt muons (left) and nuclear modification factor of prompt muons (right) in d+Au collisions. The theoretical curves are come from power correction model at $\eta = 1.25$ and 2.5 \[7\].

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References

[1] Eskola, Kolhinen, Vogt, Nucl. Phys. A696 (2001) 729-746.
[2] L. McLerran and R Venugopalan, Phys. Rev. D49, 2233(1994); Phys. Rev. D49 3352(1994)
[3] R.C. Hwa, C.B.Yang and R.J. Fries, Phys.Rev C71, 024902(2005)
[4] K. Adcox et al., Nucl. Instrum. Methods A499, 469(2003)
[5] Y. Kwon for PHENIX collaborations, nucl-ex/0510011
[6] S.S. Adler et. al, PHENIX collaborations, Phys. Rev. Lett. 96, 032001 (2006)
[7] J. Qiu, I. Vitev, Phys.Lett. B632, (2006)507-511
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