Electron Spectra for $D$ and $B$ Meson Semi-leptonic Decays at RHIC from PYTHIA with Modified Heavy Quark Fragmentation

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We present a study of charmed hadron transverse momentum distribution from $p+p$ collisions at \(\sqrt{s_{NN}} = 200\) GeV using the PYTHIA Monte Carlo event generator. The PHENIX tuned PYTHIA parameter set based on electron measurements alone yields a $D$ meson $p_T$ distribution softer than the preliminary STAR experimental data from $d+Au$ collisions scaled by the number of binary collisions. In order to match the STAR $p_T$ spectrum, the higher order QCD effects in PYTHIA have to be taken into account, and a fragmentation function of charm quarks much harder than the default Peterson function is needed. Electrons from beauty quark semi-leptonic decays are found significantly below the contribution from charm quark decays for the $p_T$ region up to 8 GeV/c in our modified fragmentation scheme, while in the default fragmentation scheme the $B$ decay electrons dominate at $p_T$ above 4 GeV/c. We propose an experimental measurement of electron and charged hadron correlation to differentiate these scenarios.

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Heavy quarks are believed to be produced through initial parton-parton, mostly gluon-gluon, scatterings in nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) energies. Theoretical calculations of heavy quark production within the perturbative Quantum Chromo-Dynamics (pQCD) framework is considered more reliable because the heavy quark mass sets a natural scale for the pQCD. Charm quark production is sensitive to the incoming parton flux for the initial conditions of nuclear collisions $^{[1]}$ $^{[2]}$. The transport dynamics of the heavy quarks in nuclear medium such as flow $^{[3]}$ and energy loss $^{[4]}$ $^{[5]}$ can probe QCD properties of the dense matter created in nucleus-nucleus collisions. Therefore, heavy quark measurements provide unique insights into QCD properties of the new state of matter produced in nucleus-nucleus collisions.

The heavy quark production in $p+p$ or $p+A$ collisions provides a reference for heavy meson formation and for nuclear modification factors of heavy quarks in nuclear medium. The charm fragmentation function has been measured in $e^+e^-$ and $\gamma p$ collisions and was fit by the Peterson function $^{[6]}$ (defined later in the paper) with a parameter $\epsilon \approx 0.05$ (default in PYTHIA $^{[7]}$) $^{[8]}$. However, in charm hadroproduction, it was observed that the $c$-quark $p_T$ distributions of next-to-leading-order (NLO) pQCD calculations agree well with the measured open charm $p_T$ spectrum $^{[9]}$, indicating that a much harder fragmentation function peaked at $z \approx 1$ is needed in charm hadroproduction. A more detailed discussion of this observation can be found in $^{[10]}$. Coalescence $^{[11]}$ or recombination $^{[12]}$ $^{[13]}$ models have also been proposed for charmed meson formation by combining a charm quark with a light up or down quark, presumably with soft $p_T$ $^{[14]}$. Thus the charmed hadron $p_T$ would coincide with the bare charm quark $p_T$ distribution in this hadronization scheme. These various hadron formation schemes can lead to significantly different interpretation of electron $p_T$ spectra from experimental measurements.

Recently the PHENIX collaboration reported a measurement of non-photonic electrons from heavy quark semi-leptonic decays from $pp$ and $AA$ collisions $^{[15]}$ $^{[16]}$. The measured electron yields appear to follow approximately a binary scaling. Such a scaling would imply that the charm quarks have a small energy loss in the dense medium created at RHIC. However, such an interpretation is subject to the ambiguity that the electron contribution from $B$ quarks, which is predicted to have a much smaller energy loss than that of charm quarks $^{[17]}$, is unknown experimentally in the $p_T$ region above 3-4 GeV/c. In order to evaluate heavy quark energy loss using non-photonic electron measurement, contributions from $D$ and $B$ meson decays have to be investigated.

In this paper we evaluate the $p_T$ distribution of $D$ mesons from PYTHIA v6.22 $^{[18]}$ and compare the PYTHIA results with the STAR preliminary measurements $^{[13]}$. The charm quark fragmentation function will be modified from the default Peterson function and the PYTHIA parameters are tuned in order to match the PYTHIA results on $p_T$ distribution with the experimental data. The electrons from $D$ meson decays are compared with STAR preliminary electron $p_T$ distribution $^{[19]}$. We present a method to qualitatively estimate the significance of $B$ meson decays to the electron spectrum at high $p_T$ and to verify the scheme of modified heavy quark fragmentation function as an explanation for hard $p_T$ distribution of $D$ meson in $pp$ collisions at RHIC.

In our PYTHIA calculations, we started with a PHENIX tuned parameter set $^{[15]}$, and changed the value of PARP(67) to 4, which enhances c-quark production probability through gluon splitting $^{[20]}$. In addition, we also modify the parameter in the Peterson function so that PYTHIA calculation approximately follows the shape of the STAR measured open charm $p_T$ spectrum.
Fig. 1: $D^0$ and c-quark spectra from PYTHIA calculations compared with STAR preliminary data from d+Au collisions scaled by $N_{bin} = 7.5$.

Fig. 1 shows our PYTHIA calculations together with the STAR open charm spectrum [18], where the measured open charm data points from d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have been divided by $N_{bin} = 7.5$ - the number of binary collisions. The PYTHIA spectra have been normalized to the measured $dN/dy$ for $D^0$ at mid-rapidity $(0.0265 \pm 0.0036(stat.) \pm 0.0071(syst.))$.

The charm quark $p_T$ distribution labeled by stars in Fig. 1 is from PYTHIA calculation with PHENIX tuned parameters and PARP(67)=4. We will refer this set of parameters as high-$p_T$-tuned parameters in the rest of the paper. The PARP(67)=4 was introduced to take into account higher order effects in pQCD calculation. We found that the change mainly affects c-quark production at high $p_T$. Due to the large uncertainties in scaling $D^*$ and $D^{\pm}$ to $D^0$ ($D^*/D^0 \approx D^{\pm}/D^0 = 0.4 \pm 0.09 \pm 0.13$), the STAR measurement of $D$ $p_T$ shape has large systematic uncertainties in the high $p_T$ region. Without fine tuning any other PYTHIA parameters, we found that the bare charm quark spectrum approximately match the STAR open charm $p_T$ distribution. This also indicates that PARP(67)=4 somehow does generate a $p_T$ distribution similar to the actual NLO pQCD calculation [21], which coincides with the STAR $p_T$ spectrum as well [18]. It is not the purpose of this paper to show that the PYTHIA calculation with our parameter set and NLO pQCD calculation are equivalent. The PYTHIA calculation with the high-$p_T$-tuned parameter set seems to reproduce the same observation seen when comparing NLO pQCD calculation for c-quark to measured open charm data [10]. We will further modify the fragmentation function in PYTHIA and investigate the consequences on single electron measurements.

The solid squares in Fig. 1 depict $D^0$ $p_T$ distribution from PYTHIA calculation with the high-$p_T$-tuned parameters and default Peterson fragmentation function in PYTHIA. The default Peterson function refers to the value of the parameter $\varepsilon$ in Peterson function

$$D(z;p_T/p_c) \propto \frac{1}{z^2(1/z - \varepsilon/(1-z))^2}$$

being 0.05 for charm quarks and 0.005 for beauty quarks. The default Peterson fragmentation for charm quarks is too soft to reproduce the measured open charm spectrum. We modified the value of the parameter $\varepsilon$ to make the fragmentation function harder. The result is shown as open circles in Fig. 1. The $D^0$ spectrum roughly coincides with the measured data. Here the value of $\varepsilon$ we used is $10^{-5}$ for both charm quarks and beauty quarks. In this case the fragmentation function is very like $\delta(1-z)$. Hence, the charm quark hardly loses its momentum during fragmentation. The PYTHIA calculation with high-$p_T$-tuned parameter set and modified $p_T$ spectrum labeled by stars in Fig. 1. The $D^0$ distribution from PYTHIA calculation with high-$p_T$-tuned parameters and modified Peterson function for charm quarks and beauty quarks compared with background subtracted single electron spectrum measured by STAR EMC from d+Au collisions scaled by $N_{bin} = 7.5$. (b) Electron spectra from PYTHIA calculation with the high-$p_T$-tuned parameters and default Peterson function for charm quarks and beauty quarks.
Peterson fragmentation function ($\varepsilon = 10^{-5}$) can reasonably depict the measured open charm data. A harder fragmentation function is needed for the hadronization of charm quarks if the pQCD calculation is to describe the STAR preliminary data.

The STAR independent measurements of the reconstructed $D^0$ and single electrons from heavy quark semileptonic decays measured with TOF and TPC are consistent [22]. The electron measurement there only covers up to $p_T < 4 \text{ GeV}/c$ and has no sensitivity to the $B$ meson contribution. We also checked the consistency between open charm data and non-photonic single electron data in d+Au collisions measured by STAR EMC [19] within our PYTHIA calculation. The results are shown in Fig. 2. The PYTHIA spectra of electrons from charm meson decays are scaled by the same factor used to scale the PYTHIA $D^0$ spectra to the measured $dN/dy(D^0)$ at mid-rapidity. The electron spectra from beauty meson decay are normalized by the ratio of $\sigma_{h\mu}/\sigma_{c\mu}$ based on the NLO pQCD calculation [21]. The band corresponds to the theoretical uncertainty of this ratio, which is in the region of 0.45% - 0.60%. We used the value at the center of this range to calculate the sum of the electrons from both charm and beauty meson decays. The EMC electron data points are divided by $N_{bin}$. The electron spectra from the PYTHIA calculation with the high-$p_T$-tuned parameters and modified Peterson function for charm quarks and beauty quarks are shown in the upper panel of Fig. 2. The PYTHIA calculation with the high-$p_T$-tuned parameter set and modified heavy quark fragmentation function can simultaneously describe the STAR direct open charm $p_T$ distribution and the STAR EMC electron data reported at the Quark Matter 2004 conference. Our calculation indicates that the contribution of electrons from $B$ meson decays is not dominant for the measured $p_T$ region up to 8 $\text{ GeV}/c$.

The measurement of electron $p_T$ distribution alone has a reduced sensitivity to the $p_T$ distribution of $D$ mesons as shown in reference [22]. Within the large statistical and systematic errors of the electron data, it is possible to use high-$p_T$-tuned PYTHIA calculation and the default Peterson function for both $c$ and $b$ quarks to yield an electron $p_T$ distribution similar to the measurement at high $p_T$. In this case, as shown in the bottom panel of Fig. 2, electrons from $b$ quark decays are the dominant source for $p_T$ greater than 4 $\text{ GeV}/c$.

In order to differentiate these two scenarios, we studied the correlation between charm/beauty semileptonic decay electrons and charged hadrons in PYTHIA with these two sets of parameter in Peterson function. First, we select an electron decayed from $B$ or $D$ mesons at a given electron $p_T$ cut, and make a cone around the direction of the electron. Then we study the scalar summed $p_T$ distributions of these charged hadrons in the cone ($p_T$ refers to the transverse momentum in the laboratory frame). Here the cone is defined by $|\eta_h - \eta_e| < 0.35$ and $|\phi_h - \phi_e| < 0.35$ ($\eta$ is pseudorapidity and $\phi$ is azimuthal angle). The summed $p_T$ distributions of charged hadrons at three different electron $p_T$ cuts are shown in Fig. 3.
TABLE I: Fractions of $B$ meson decay contribution at three electron $p_T$ cuts from two different PYTHIA calculations with high-$p_T$-tuned parameters. Modified Peterson function and default Peterson function are each used for both charm quarks and beauty quarks.

| $p_T$ (GeV/c) | 2.0 | 3.5 | 5.0 |
|--------------|-----|-----|-----|
| Modified Peterson function | 17% | 22% | 32% |
| Default Peterson function | 17% | 54% | 69% |

The distributions are normalized to unity. The solid lines in Fig. 3 are electrons from $B$ meson decays and the dashed lines are electrons from $D$ meson decays. We found that the summed $p_T$ distributions do not change significantly between the default Peterson function and our modified fragmentation function. When electron $p_T$ cut goes from 2.0 GeV/c to 5.0 GeV/c, the summed $p_T$ distributions broaden for both $B$ meson decay case and $D$ meson decay case. However, the change is more drastic for the $D$ meson decay case.

The upper panel of Fig. 4 shows the sum of $D$ decay case and $B$ decay case weighted by fractions of electrons from $D$ and $B$. Here the distributions are normalized such that the values in the first bin are the same. In the left upper panel, the fractions come from PYTHIA calculations with the high-$p_T$-tuned parameters and modified Peterson function for charm quarks and beauty quarks, while the fractions in the right upper panel of Fig. 4 are from PYTHIA calculations with the high-$p_T$-tuned parameters, but default Peterson function for charm quarks and beauty quarks. The values of the fractions are shown in Table I. When electron $p_T$ increases, if $B$ meson decays become dominant, the summed $p_T$ distribution of charged hadrons changes slightly as shown in the right upper panel of Fig. 4. However, if the $D$ meson decay contribution is always dominant, the summed $p_T$ distribution broadens drastically as shown in the left upper panel of Fig. 4. Ratios are shown in the bottom panels in Fig. 4. The solid circles are the ratios of $p_T > 5.0$ GeV/c case over $p_T > 2.0$ GeV/c case. The open circles are the ratios of $p_T > 3.5$ GeV/c case over $p_T > 2.0$ GeV/c case. Experimental observation of these ratios can be used to determine the relative significance of $B$ and $D$ decay electrons.

In conclusion, we found that in order to match the STAR measurement of $p_T$ shape of $D$ mesons from d+Au collisions at RHIC using PYTHIA Monte Carlo generator, higher order QCD effects have to be taken into account (PARP(64)=4) and a harder charm quark fragmentation function must be used. The high-$p_T$-tuned PYTHIA calculation with the modified fragmentation function can simultaneously describe the $p_T$ distributions of $D$ mesons and non-photonic electrons from semileptonic decays of heavy quarks. Because the measurement of electrons alone has a reduced sensitivity on the $p_T$ shape of $D$ mesons, the high-$p_T$-tuned PYTHIA calculation with default Peterson fragmentation function for both $c$ and $b$ quarks can match the STAR electron measurement at high $p_T$ within large statistical and systematic errors. This calculation predicts that the $B$ decayed electrons dominate at the high $p_T$ ($> 4$ GeV/c) region. However, in the proposed scheme of modified charm and beauty quark fragmentation, the beauty quark decay electrons are not a dominant contribution over the entire $p_T$ region up to 8 GeV/c. Using PYTHIA as a guidance we found that the summed $p_T$ of charged hadrons within a narrow cone of heavy quark decayed electrons can be used to differentiate these scenarios.

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