Non-Photonic Electron $p_T$ Distributions and Correlations of Electrons from $B$ and $D$ Meson Decays with Charged Hadrons

Xiaoyan Lin

Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
(Dated: November 6, 2018)

We compare the non-photonic electron and $D^0$ meson $p_T$ distributions measured at RHIC with the PYTHIA Monte Carlo event generator in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. A delta fragmentation function much harder than the Peterson function, consistent with recombination scheme for charm meson formation, is needed to match the experimental data. Attempts to fit the non-photonic electrons at high $p_T$ show large uncertainties and the $B$ meson semi-leptonic decays may not be dominant for electron $p_T$ up to 8 GeV/c. Correlations of non-photonic electrons with charged hadrons are studied. We propose an experimental method to quantitatively determine the relative contributions of $D$ and $B$ meson semi-leptonic decays to the non-photonic electrons.

PACS numbers: 24.10.Lx, 14.40.Lb, 13.20.Fc

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 are 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 the nuclear medium. The Peterson function

$$D(z=p_D/p_c) = \frac{1}{z[1-1/z - \varepsilon/(1-z)]^2}$$

has often been used to describe the charm fragmentation function, where the parameter $\varepsilon \approx 0.05$ (default in PYTHIA [6]) is in reasonable agreement with the results from fits to charm production in $e^+e^-$ and $\gamma p$ collisions [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 $z \approx 1$ in Eq. (1) is needed in charm hadroproduction. A more detailed discussion of this observation can be found in [10][11]. Coalescence [12][13] or recombination [14][15][16] models have also been proposed for charmed meson formation by combining a charm quark with a light up or down quark, presumably of soft $p_T$ [17]. 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 charged meson $p_T$ distribution when interpreting non-photonic electron $p_T$ spectra from experimental measurements.

Recently STAR and PHENIX collaborations have observed a suppression of non-photonic electrons much larger than predicted in the $p_T \sim 4 - 8$ GeV/c region [18][19]. This observation challenges theoretical predictions based on energy loss via induced gluon radiation for heavy quarks [20][21]. The fact that the relative contributions of $D$ and $B$ meson semi-leptonic decays to the experimental non-photonic electron spectrum is currently not measured at RHIC severely restricts the understanding of the heavy quark energy loss. A nonzero non-photonic electron $v_2$ has been measured in the $p_T < 2.0$ GeV/c region, while at higher $p_T$ the $v_2$ is observed to decrease with $p_T$ [22]. Quantitative understanding of this feature in heavy quark measurements requires relative charm and bottom contributions to non-photonic electrons.

In this paper we evaluate the $p_T$ distribution of $D$ mesons from PYTHIA v6.22 [7] and compare the PYTHIA results with the STAR measurements [23][24]. The charm quark fragmentation function will be modified from the default Peterson function and the other PYTHIA parameters are tuned in order to describe the experimental $D$ meson data as well as the STAR non-photonic electron spectra [18]. We study the correlations between non-photonic electrons and charged hadrons in order to guide the experimental investigations of the relative contributions to the non-photonic electron spectrum at high $p_T$ from $B$ and $D$ meson decays.

Fig. 1 shows charm quark and $D^0$ meson spectra from PYTHIA calculations and NLO pQCD predictions for charm quark spectra [25] together with the STAR $D^0$ spectrum [26], where the measured $D^0$ data points
The combination of STAR measured D meson spectra into a single D meson spectrum is hampered by the large uncertainties in the ratio $D^*/D^0 = 0.4 \pm 0.09 \pm 0.13$ which is experimentally not well known at RHIC. The STAR D meson spectrum covers a limit $p_T$ range and is not well constrained at high $p_T$. Without further tuning other PYTHIA parameters, we find that the generated bare charm quark spectra from PYTHIA calculations using parameter set I and parameter set II approximately match the STAR D meson $p_T$ distribution. As demonstrated in the left panel of Fig. 1, the PYTHIA calculation with parameter set II also yields a charm quark $p_T$ distribution similar to the NLO pQCD calculations, which coincides with the STAR D meson $p_T$ spectrum as well. It is not the purpose of this paper to show that the PYTHIA calculations with these two parameter sets and NLO pQCD calculations are equivalent in physics contents.

In the right panel of Fig. 1, the $D^0$ $p_T$ distribution from PYTHIA calculations using the default Peterson fragmentation function is shown as open circles for parameter set I and crosses for parameter set II. The default Peterson function refers to the value of the parameter $\varepsilon$ in Peterson function 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 $D^0$ spectrum together with $D^*$ spectrum. We modified the value of the parameter $\varepsilon$ to $10^{-5}$ for both charm and beauty quarks. In this case the fragmentation function is nearly $\delta(1-z)$. The results are shown as stars for parameter set I and triangles for parameter set II in the right panel of Fig. 1. The PYTHIA calculations using the modified Peterson fragmentation function ($\varepsilon = 10^{-5}$) with parameter set I and set II can reasonably reproduce the measured D meson $p_T$ distribution.

![FIG. 1: (color online) Charm quark (left) and $D^0$ (right) spectra from PYTHIA calculations compared with next-to-leading-order pQCD predictions for charm quark spectra and the STAR measured $D^0$ spectrum from d+Au collisions scaled by $N_{bin} = 7.5$.](image1)

![FIG. 2: (color online) Electron spectra from PYTHIA calculations with the modified Peterson function for charm quarks and beauty quarks compared with background subtracted single electron spectrum measured by STAR from p+p collisions and the prediction for theoretical uncertainty electron band. Left panel: The spectra are from parameter set II. Right panel: The spectra are from parameter set I.](image2)
While the $k_T$ broadening can make the charm $p_T$ distribution harder at low beam energies [11], the intrinsic $k_T$ has little effect on the $p_T$ distribution at RHIC energies [23]. A harder fragmentation function is needed for the hadronization of charm quarks if the pQCD calculation is to describe the measured STAR data.

The STAR independent measurements of the reconstructed $D^0$ meson and single electrons from heavy quark semi-leptonic decays measured with TOF and TPC are consistent [23]. The electron measurement there only covers up to $p_T < 4$ GeV/c and has no sensitivity to the $B$ meson contribution. We also checked the consistency between $D$ meson data and non-photonic single electron data in p+p collisions within our PYTHIA calculations. Fig. 4 shows the electron spectra from PYTHIA calculations using the modified Peterson fragmentation function for charm quarks and beauty quarks with parameter set II in the left panel and parameter set I in the right panel. The parameters for beauty quarks in set II and set I are all the same as for charm quarks except $m_b = 4.8$ GeV/$c^2$. 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 decays are normalized by the ratio of $\sigma_b/\sigma_c$ based on the NLO pQCD calculation [23]. The band corresponds to the theoretical uncertainty of this ratio (0.45% - 0.60%) [23], where the theoretical error may be an underestimate according to recent calculations [23]. We used the value at the center of this range to calculate the sum of the electrons. Fig. 4 also shows the comparison to the STAR measured non-photonic single electron data in p+p collisions [18] and the FONLL calculation for the theoretical uncertainty band of the electron spectrum from charm and bottom in p+p collisions [23]. The FONLL prediction of electron spectrum gives a fair description of the shape of the measured spectra. But there is a discrepancy in the overall scale and the FNOLL calculation is significant below the STAR data at high $p_T$. More discussions can be found in [18]. The PYTHIA calculations with parameter set II and modified heavy quark fragmentation function can simultaneously describe the STAR direct $D$ meson $p_T$ distribution [23, 24] and the STAR EMC non-photonic electron data [18]. This modified scheme indicates that the contribution of electrons from $B$ meson decays is not dominant for the measured $p_T$ region up to 8 GeV/c assuming $\sigma_b/\sigma_c \sim 0.45\% - 0.60\%$ based on NLO pQCD calculation. The measurement of electron $p_T$ distribution alone has a reduced sensitivity to the $p_T$ distribution of $D$ mesons as shown in reference [18]. Within the statistical and systematic errors of the electron data, the PYTHIA calculation with parameter set I and the modified Peterson function for both $c$ and $b$ quarks can yield an electron $p_T$ distribution similar to the measurement [18]. In this case, as shown in the bottom panel of Fig. 4, electrons from $b$ quark decays are not the dominant source for the $p_T$ region up to 6 GeV/c. It is critical that the $B$ and $D$ meson decay contributions to non-photonic electrons to be separated experimentally.

We have studied the azimuthal correlations between heavy quark semi-leptonic decay electrons and inclusive charged hadrons. Fig. 5 shows the $\Delta\phi$ distributions between non-photonic electrons and inclusive charged hadrons, with different electron trigger $p_T$ cuts and the associated hadron $p_T > 0.1$ GeV/c. The distributions are scaled by the number of electron triggers. These plots are from PYTHIA calculation with parameter set II and the modified heavy quark fragmentation function. The solid lines in Fig. 5 are for electrons from $B$ meson decays and...
We further studied the particle production within a cone around triggered high $p_T$ electrons from heavy quark decays. We focused on the scalar summed $p_T$ distributions of inclusive 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 $|\varphi_h - \varphi_e| < 0.35$ ($\eta$ is pseudorapidity and $\varphi$ is azimuthal angle). The summed $p_T$ distributions of inclusive charged hadrons in three triggered electron $p_T$ ranges are shown in Fig. 4. The distributions are scaled to unit. The dashed lines are for $D$ decays and the solid lines are for $B$ decays. These plots are from PYTHIA calculation with parameter set II and the modified heavy quark fragmentation function. We also can see that there is a significant difference between $B$ decays and $D$ decays. The summed $p_T$ distributions for $D$ meson decays are much wider than those for $B$ meson decays. This difference can also be used to distinguish $B$ and $D$ decay contributions. We use the summed $p_T$ histograms from $B$ decays and $D$ decays to fit the summed $p_T$ histogram from PYTHIA inclusive case to determine the $B$ decay contribution. The results are shown in Table II. The results are consistent with those directly from the electron spectra. The ratios for the same trigger $p_T$ ranges are different between Table III and Table IV. It is because we removed those electrons which have no hadrons in the cone around them when we calculated the bottom contribution from the electron spectra for Table III. This removes different fractions from $B$ and $D$ decays, which has to be corrected by simulations. This was done to make the results directly from the electron spectra comparable to the results from hadron summed $p_T$ histogram fitting. It will be more valuable for the small acceptance experiments to investigate the $B$ decay contribution using summed $p_T$ histogram fitting.

In conclusion, we found that in order to match the STAR measured $p_T$ shape of $D$ mesons from d+Au collisions at RHIC using the PYTHIA Monte Carlo generator, a harder charm quark fragmentation function must be used. Since the $D$ meson production at high $p_T$ is not well constrained by the STAR data and the measurement of electrons alone has a reduced sensitivity on the $p_T$ shape of $D$ mesons, PYTHIA calculations with parameter set I and set II can simultaneously describe the $p_T$ distributions of $D$ mesons and non-photonic electrons from semi-leptonic decays of heavy quarks. These

---

**Table I: Fractions of $B$ meson decay contributions from electron spectra and $\Delta \varphi$ distribution fitting in PYTHIA calculations with parameter set II and modified Peterson fragmentation function for charm and beauty quarks.**

| $p_T^{\text{trig}}$ (GeV/c) | From Spectra (%) | From Fitting (%) |
|-----------------------------|-----------------|-----------------|
| 2.5 - 3.5                   | 12.64 ± 0.04    | 12.64 ± 1.37    |
| 3.5 - 4.5                   | 21.65 ± 0.12    | 21.65 ± 2.55    |
| 4.5 - 5.5                   | 30.50 ± 0.26    | 30.50 ± 4.76    |
| 5.5 - 6.5                   | 36.66 ± 0.48    | 36.66 ± 7.87    |
| 6.5 - 8.5                   | 42.24 ± 0.71    | 42.24 ± 11.10   |
| 8.5 - 10.5                  | 49.82 ± 1.72    | 49.82 ± 25.11   |

**Table II: Fractions of $B$ meson decay contributions from electron spectra and summed $p_T$ histogram fitting in PYTHIA calculations with parameter set II and modified Peterson fragmentation function for charm and beauty quarks.**

| $p_T^{\text{trig}}$ (GeV/c) | From Spectra (%) | From Fitting (%) |
|-----------------------------|-----------------|-----------------|
| 2.5 - 3.5                   | 8.25 ± 0.05     | 8.25 ± 1.50     |
| 3.5 - 4.5                   | 14.94 ± 0.13    | 14.94 ± 2.54    |
| 4.5 - 5.5                   | 22.60 ± 0.29    | 22.60 ± 4.13    |
calculations predict that the beauty quark decay electrons are not a dominant contribution over the entire $p_T$ region up to 6-8 GeV/c depending on parameters. The relative contributions to non-photonic electrons from $B$ and $D$ decays have to be determined experimentally. We studied the correlations of non-photonic electrons and inclusive charged hadrons, which can distinguish between $D$ and $B$ decay contributions to the non-photonic electrons due to their different decay kinematics. We have proposed an experimental method to estimate the relative $D$ and $B$ decay contributions.

The author wishes to thank An Tai, Huan Z. Huang, Lianshou Liu and Chuck Whitten for their helpful discussions, Ramona Vogt for suggestions and providing FONLL data. This work was supported in part by NSFC under project 10575042.

[1] J.A. Appel, Annu. Rev. Nucl. Part. Sci. 42 (1992) 367.
[2] B. Müller and X.N. Wang, Phys. Rev. Lett. 68 (1992) 2437.
[3] V. Greco, C.M. Ko and R. Rapp, Phys. Lett. B 595 (2004) 202.
[4] Y.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B 519 (2001) 199.
[5] Ben-Wei Zhang et al., Phys. Rev. Lett. 93 (2004) 072301.
[6] C. Peterson et al., Phys. Rev. D 27 (1983) 105.
[7] T. Sjöstrand, Comput. Phys. Commun. 135 (2001) 238.
[8] P. Nason and C. Oleari, Nucl. Phys. B 565 (2000) 245; L. Gladilin (for ZEUS Collaboration), hep-ex/0309044.
[9] M. Adamovich et al., Beatrice Collaboration, Nucl. Phys. B 495 (1997) 3; G.A. Alves et al., E769 Collaboration, Phys. Rev. Lett. 77 (1996) 2392.
[10] R. Vogt et al., Nucl. Phys. B 383 (1992) 643.
[11] S. Frixione et al., Adv. Ser. Direct. High Energy Phys. 15 (1998) 609.
[12] Z.W. Lin and C.M. Ko, Phys. Rev. Lett. 89 (2002) 202302.
[13] Z. Lin and D. Molnar, Phys. Rev. C 68 (2003) 044901.
[14] R.J. Fries et al., Phys. Rev. Lett. 90 (2003) 202303.
[15] R.C. Hwa and C.B. Yang, Phys. Rev. C 67 (2003) 034902.
[16] V. Greco et al., Phys. Rev. Lett. 90 (2003) 202302.
[17] R. Rapp and E.V. Shuryak, Phys. Rev. D 67 (2003) 074036.
[18] J. Adams et al., STAR Collaboration, nucl-ex/0607012.
[19] S.S. Adler et al., PHENIX Collaboration, Phys. Rev. Lett. 96 (2006) 032301.
[20] N. Armesto et al., Phys. Rev. D 71 (2005) 054027.
[21] M. Djordjevic et al., Phys. Lett. B 632 (2006) 81.
[22] Y. Akiba (for the PHENIX Collaboration), nucl-ex/0510008.
[23] J. Adams et al., STAR Collaboration, Phys. Rev. Lett. 94 (2005) 062301.
[24] An Tai (for the STAR Collaboration), J. Phys. G: Nucl. Part. Phys. 30 (2004) S809-S817.
[25] R. Vogt, Int. J. Mod. Phys. E 12 (2003) 211-270.
[26] K. Adcox et al., PHENIX Collaboration, Phys. Rev. Lett. 88 (2002) 192303.
[27] E. Norrbin and T. Sjöstrand, Eur. Phys. J. C 17 (2000) 137.
[28] M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. 95 (2005) 122001.
[29] R. Vogt, hep-ph/0203151.
[30] S. Batsouli et al., Phys. Lett. B 557 (2003) 26.