Extracting the charm cross-section from semileptonic decays into muons

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Abstract

We propose a sensitive measurement of the charm total cross-section at RHIC through muon identification from charm semileptonic decay at low transverse momentum ($p_T$). This can test the binary-collision scaling ($N_{\text{bin}}$) properties of the charm total cross-section and be used to study whether heavy-flavor quarks, which are used as a probe, are produced exclusively at the initial impact in hadron-hadron collisions. The effect of the charm semileptonic decay form factor on extracting the total charm cross section and on the shape of the lepton spectra are also discussed in detail. We conclude that lepton spectra from charmed hadron decays at transverse momentum $p_T \simeq 1.0$ GeV/$c$ are sensitive to the charmed hadron spectrum shape. Therefore, the interactions of heavy quarks with the medium created in relativistic heavy-ion collisions, especially the flow effects, can be extracted from the lepton spectra from charmed hadron decays at low $p_T$.

Key words:

In relativistic heavy-ion collisions, charm quarks are believed to be produced in the early stage via initial gluon fusion and their production cross-section can be evaluated using perturbative QCD [1]. Study of the $N_{\text{bin}}$ scaling properties of the charm total cross-section in p+p, d+Au and Au+Au collisions can test if heavy-flavor quarks, which are used as a probe, are produced exclusively at the initial impact. The interactions of heavy quarks with the medium provide a unique tool for probing the hot and dense matter created in ultra-relativistic heavy-ion collisions at the early times. At RHIC energies, heavy quark energy loss [2], charm quark coalescence [3,4,5,6], the effect of $J/\psi$ production from charm quark coalescence on the interpretation of possible $J/\psi$ suppression due to color screening [7], and charm flow [8,9,10] have been proposed as
important tools in studying the properties of matter created in heavy ion collisions. The last three effects depend strongly on the charm total cross-section and spectrum at low $p_T$.

However, it is difficult to directly reconstruct charmed hadrons and single electrons from charm semileptonic decay in hadron-hadron collisions with high precision at low $p_T$, where the yield accounts for a large fraction of the total cross section [11,12,13]. The difficulties are due to large combinatorial backgrounds in charmed hadron decay channels, and the overwhelming photon conversions in the detector material, and $\pi^0$ Dalitz decays in electron detection. Nevertheless, the charm total cross-sections have been measured in $d+Au$ collisions at RHIC by a combination of the directly reconstructed low $p_T$ $D^0 \to K\pi$ and the non-photonic electron spectra [11], and by electron spectra alone at $p_T > 0.8$ GeV/c [13,14]. Although the systematic and statistical errors are large, the result indicates a much larger charm yield than predicted by pQCD calculations [11,1]. Recently, the measurements of high $p_T$ electrons from heavy-flavor semileptonic decays have posed challenges to our understanding of partonic energy loss in the medium [13,16,15,17]. Since most of the measurements to date at RHIC are from indirect heavy-flavor semileptonic decays, it is therefore important to find novel approaches to improve the measurements and also study in detail how to extract the maximum information about the heavy-flavor spectrum from its lepton spectrum. This includes studying the effects of the form factors of charmed hadron semileptonic decays on the lepton spectra [18].

In this paper, we propose a new method to extract the charm total cross-section by measuring muons from charmed hadron semileptonic decay at low $p_T$ (e.g. $0.16 \lesssim p_T \lesssim 0.26$ GeV/c). Since muons in this $p_T$ range are a very uniform sample of the whole charmed hadron spectrum, the inferred charm total cross-section is insensitive to the detail of the charm spectrum. Once the cross-section is determined, the electron spectrum at higher $p_T$ can be used to sensitively infer the charmed hadron spectral shape. Meanwhile, we survey the form factors used in charm semileptonic decays generated from Particle Data Group [18], in the PYTHIA event generator [11,13,14,19], by pQCD predictions [1] and from the CLEO inclusive measurement [20]. We find that the lepton spectra from these different form factors can be different by a factor of 1.5.

We first study the charmed hadron semileptonic decay form factor and its effect on the lepton spectrum. Fig. 1 shows the electron momentum spectra from charmed meson decays at rest generated using the Particle Data Table [18], PYTHIA [11,13,14,19], pQCD calculations [1] and from the CLEO preliminary inclusive measurement [20]. The spectrum generated by the PDG is according to the form factor of charmed meson decays to pseudoscalar $K + l + \nu$, vector meson $K^* + \nu$ and non-resonance $(K\pi) + l + \nu$ where the $K^*$ mass is used for
the \((K\pi)\) system. The decay partial widths \((\Gamma)\) of the three dominant decay channels are:

1. \(K + l + \nu\) with pseudo scalar meson in final state \((D^{\pm} 7.8\%)\)

\[
\frac{d\Gamma}{dq^2} \propto \frac{p_k^3}{(1 - q^2/M^* c^2)^2}
\]

where \(q^2\) is the invariant mass of the virtual \(W \rightarrow \nu l\), \(p_k\) is the momentum of the kaon, and \(M^* = 0.189 \text{ GeV}/c^2\) is a parameterization of the effective pole mass in the decay.

2. \((K\pi) + l + \nu\) with non-resonant \(K\pi\) in final state \((D^{\pm} 4.0\%)\)

We use the \(K^*\) mass \((0.892 \text{ GeV}/c^2)\) for the \(K\pi\) invariant mass and the form factor is the same as in the decay to the pseudo scalar meson.

3. \(K^* + l + \nu\) with vector meson in final state \((D^{\pm} 5.5\%)\)

\[
\frac{d\Gamma}{dq^2 d \cos \theta_l} \propto \frac{p_v q^2}{M^2} [(1 - \cos \theta_l)^2 |H_+(q^2)|^2 + \frac{4}{3} (1 + \cos \theta_l)^2 |H_-(q^2)|^2 + \frac{8}{3} \sin^2 \theta_l |H_0(q^2)|^2]
\]

where \(\theta_l\) is the decay angle between the lepton and the vector meson, \(p_v\) is the vector meson momentum,

\[
H_{\pm}(q^2) = (M + m)A_1(q^2) \mp \frac{2Mp_v}{M + m} V(q^2)
\]

and

\[
H_0(q^2) = \frac{1}{2mq} [(M^2 - m^2 - q^2)(M + m)A_1(q^2) - \frac{4M^2p_v^2}{M + m} A_2(q^2)]
\]

where \(A_{1,2}, V\) take the form of \(1/(1 - q^2/M^*_A)^2\) with \(M^*_A = 2.5 \text{ GeV}/c^2\), \(M^*_V = 2.1 \text{ GeV}/c^2\) and \(r_V = V(0)/A_1(0) = 1.62 \pm 0.08\), \(r_2 = A_2(0)/A_1(0) = 0.83 \pm 0.05\) \([18,21]\).

For different charmed hadrons, we assume that the relative branching ratios among these three channels are the same, and their decay electron spectra are the same. The overall charmed hadron to electron branching ratio \(\Gamma(c \rightarrow e)/\Gamma(c \rightarrow anything)\) is 10.3\% \([18]\). There is a possible \(~5\%) difference between electron and muon decays due to phase space which was not taken into account in this analysis. Electrons at high momentum are mainly from decay channel (1) \(K + l + \nu\) because the kaon is lighter than the \(K^*\) and the form factor of the decay channel to a vector meson \((K^* + l + \nu)\) favors a low momentum lepton and higher momentum neutrino. Since PYTHIA uses a simplified vector meson decay form factor \([19]\), it tends to produce a softer electron spectrum. Both the parameterization by Cacciari \([1]\) and formulae from the PDG agree with CLEO’s preliminary electron spectrum. In addition, we also find that although the charmed mesons \((D^{\pm} \text{ and } D^0)\) from \(\Psi(3770)\) decay have a momentum of
244 MeV/c only and without correction of final state radiation [20], it affects slightly its subsequent electron spectrum.

We use our electron momentum spectra and that of Cacciari to generate electron spectra from charmed decay at RHIC. A power-law function of the charmed hadron transverse momentum spectrum was obtained from minimum-bias Au+Au collisions [16]. Fig. 2 shows the ratios of those electron spectra divided by the spectrum using PYTHIA decay form factors [19,11]. The slightly soft form factor of the charm semileptonic decay in PYTHIA convoluted with a steeply falling charm spectrum produces an electron $p_T$ spectrum in Au+Au collisions at RHIC, which can be lower than the correct one by up to a factor of 1.5 at high $p_T$. Part of the discrepancy between experimental results and PYTHIA in electron spectra [11,13] can be explained by the decay form factor. Taking $D^\pm$ and $D^0$ from $\Psi(3770)$ decay as if it were at rest, results in slight change on the electron spectrum.

Since the parameters for the form factor from the PDG are extracted from experimental data, and the form factor describes data well, we will select this form factor with D at rest, to generate lepton spectra for the remainder of the paper unless otherwise specified. A power-law function is used to create
Fig. 2. Charm-decay electron spectra for three different form factors divided by the spectrum using the PYTHIA form factor. The histogram represents the ratio using the PDG form factor. The solid line is Cacciari’s parameterization, and the dashed line is from PDG and takes a form factor from $\Psi(3770) \rightarrow D \rightarrow e$. See text for detail.

The charm-decayed hadron $p_T$ spectra. The function takes the form:

$$\frac{dN}{2\pi dy p_T dp_T} = \frac{dN}{dy} \frac{2(n-1)(n-2)}{\pi(n-3)^2\langle p_T\rangle^2} \left(1 + \frac{2p_T}{\langle p_T\rangle(n-3)}\right)^{-n},$$

where $dN/dy$ is the yield and $n$ and $\langle p_T \rangle$ are the parameters controlling the shape of the spectrum. Fig. 3 shows the charm-decayed hadron $p_T$ spectrum before and after requiring its decayed muons at $0.16 < p_T < 0.26$ GeV/$c$. The similarity of the spectral shape shows that the muon selection reasonably uniformly samples the entire charm-decayed hadron spectrum. The muons in this $p_T$ range sample 14% of the charm-decayed hadron spectrum. The muon yield is about 1/70 of the charm-decayed yield due to an additional 10.5% decay branching ratio. Fig. 4 shows the dependence of the muon yield on $\langle p_T \rangle$ for a fixed total charm yield. The yield is normalized to yields at $n = 10$ and $\langle p_T \rangle = 1.3$ GeV/$c$. We also note that the muon yield has a very weak dependence on $n$ which demonstrates that over a wide range in $\langle p_T \rangle$, the muon yield is within ±15%. This is in contrast to the large variation of the electron yield integrated above $p_T$ of 1.0 GeV/$c$, where a factor of 8 variation is seen in Fig. 4. This may explain the difference between results from Au+Au, p+p and d+Au collisions [22], pointing to a softer charm spectrum in Au+Au collisions. On the other hand, once $dN/dy$ is determined by the low $p_T$ muons, the electron yield at higher $p_T$ is very sensitive to the $\langle p_T \rangle$ of the charm-decayed hadron spectrum. If the lepton spectrum at low $p_T$ can be measured, the electron yield at higher $p_T$ essentially
determines the charm $\langle p_T \rangle$. In fact, the dependence on $\langle p_T \rangle$ is almost linear. At lower beam energies at RHIC, the electron background is too high to make a meaningful charm measurement [23] due to the overwhelming photon conversions in the detector material and background from $\pi^0$ Dalitz decays. The alternative muon measurement can be used to extract the charm total cross-section and study the energy excitation function of charm production [11,1]. In central Au+Au collisions, $c \rightarrow \mu$ in this $p_T$ range is estimated to be about 0.1 per event due to the high production of charm quarks at RHIC. If the charm-decay muon yields are verified to follow binary collision scaling in p+p, d+Au, minimum-bias and central Au+Au collisions, we will be able to use it as an experimental measure of $N_{bin}$ for peripheral collisions where Glauber model calculations[24] result in a large uncertainty on $N_{bin}$.

The key issue then is how to identify and measure the charm lepton spectrum at very low $p_T$ in the absence of high precision measurements of directly reconstructed charmed hadrons. First, we will demonstrate the feasibility by simple estimates and then using more detailed Monte Carlo simulations from a combination of two types of detectors: the Time Projection Chamber (TPC) and Time-of-Flight (TOF) detectors.

The ionization energy loss difference between $\pi$ and $\mu$ is about 12% at $p = 0.2$ GeV/c and is much smaller at higher momentum [18]. Typical TPC $dE/dx$ resolutions are 4% at NA49/SPS, 8% at STAR/RHIC and a projected 6% at ALICE/LHC. This means that the separation between $\pi$ and $\mu$ is about
Fig. 4. Lepton yields relative to the fixed total charm cross section as function of power-law parameters $\langle p_T \rangle$ for a charmed hadron transverse momentum spectrum. Solid line shows muon yields with a kinematics selection $0.16 < p_T < 0.26$ GeV/$c$ and $|y_l| < 0.5$. Dashed line shows electron yields with $p_T > 1$ GeV/$c$.

1.5$\sigma$ to $3\sigma$. Typical TOF timing resolution is about $\sigma_t = 100$ ps at a distance of $l = 2m$. Therefore, the separation of $\pi$ and $\mu$ measured in time is: $\Delta t = (\sqrt{m_\pi^2/p^2 + 1} - \sqrt{m_\mu^2/p^2 + 1}) \times l \times c \simeq 600$ ps. This is about a $6\sigma$ separation, which decreases rapidly as $\gamma^3$ at higher momentum.

For our more detailed simulations, we used the HIJING event generator [25] to simulate Au+Au collisions in the STAR detector at RHIC to demonstrate how muons can be identified and how the background can be subtracted. The same approach can be used for detectors with similar configurations, such as CDF and ALICE. Muons were identified by measuring the energy loss in the Time Projection Chamber and the velocity in the Time-of-Flight patch at STAR [23,26]. From the $dE/dx$ and Time-of-Flight resolutions, we conclude that the $dE/dx$ difference between pions and muons is about 1.5$\sigma$ and the mass resolution is about 5$\sigma$ at $p_T \simeq 0.2$ GeV/$c$. This provides a pion rejection factor of $> 500$, $\sim 25$ from each detector. The left panel of Fig. 5 shows the $m^2 = (p/\beta/\gamma)^2$ distribution from TOF after TPC $dE/dx$ selections [23] for muon candidates and pure pion candidates. A clean muon peak can be identified within a mass window of $0.008 < m^2 < 0.014$. The tail of the pion background can be evaluated by selecting pure pion candidates with a $dE/dx$ cut and the result is shown as a dashed histogram in Fig. 5. The residual pions can be subtracted statistically from the distribution of the distance of the closest approach (DCA) to the collision vertex with the muon mass window.
applying to the pure pion sample [26].

The STAR Collaboration have performed analyses of all the V0 and other weak-decay strange hadrons and has published many papers on these topics [27]. Those decay topologies have shorter decay distances and comparisons between data and simulation show good agreement. Our analyses of DCA distributions are the similar and should lead to a good match between data and simulation [26]. Measurements of the muon spectra from charmed hadron semileptonic decays at low $p_T$ are not affected by the $\pi^0$ Dalitz decays and photon conversions that an equivalent electron measurement is. The dominant background muons from pion/kaon weak decays are subtracted using the DCA distribution. Other sources of background ($\rho \rightarrow \mu^+\mu^-$, $\eta \rightarrow \gamma\mu^+\mu^-$, etc.) are found to be negligible from the HIJING simulation. Fig. 5 shows the DCA distribution of muons from pion and kaon decays in minimum-bias Au+Au collisions. Also shown is the DCA distribution of particles at the same $p_T$ originating from the collision vertex. The integrated yields of these two distributions reflect the appropriate muon(from charm)-to-hadron ratio with hadron yields estimated from HIJING and the charm-to-muon yield from d+Au collisions scaled by the corresponding $N_{\text{bin}}$. It is clear that the two distributions are very different and muons from charm decay can be reliably obtained from this method with high precision when the DCA distribution from real data is fitted to the combination of these signal and background distributions. Since charm production is expected to scale with $N_{\text{bin}}$ while low-$p_T$ pions scale with number of the participant nucleons, $N_{\text{part}}$, we expect a better signal-to-background ratio in central Au+Au collisions. Additional vertex detectors, such as the Silicon Strip Detector (SSD) [28] and/or the Heavy Flavor Tracker (HFT) [29], can greatly enhance this capability because the DCA of the muon from pion/kaon decay is determined by the decay distance and track geometry while for the muon from charm decay, the DCA accuracy is currently due to tracking resolution and can be reduced to $\lesssim 100 \mu m$ with a good vertex detector. In principle, the 20% systematic uncertainties presented by the STAR Collaboration [26] can probably be further reduced. It will then provide a complementary charm measurement in the era of directly reconstructing charmed hadrons from a displaced secondary vertex.

With the improved charm semileptonic decay form factor [1] and possible high precision measurements of muons at low $p_T$, we re-evaluate the sensitivity of the lepton spectrum to the original charm spectrum as has been performed previously [10]. In our approach, we take the extracted charm spectrum from d+Au collisions as a baseline charm spectrum for nucleon-nucleon collisions [11]. A power-law function was fitted to the $D^0 p_T$ spectrum combined with its associated decay electron spectrum for the d+Au collision data [11]. A blast-wave similar to Ref. [10] with freeze-out temperature and freeze-out velocity parameters obtained from multistrange baryons ($T_{\text{fo}} = 160 \text{ MeV}$, $\beta_{\text{max}} = 0.6$) was used to generate a charm spectrum [30]. The blast-wave as-
Fig. 5. Left panel: Particle mass $m^2 = (p/\beta/\gamma)^2$ from Time-of-Flight detector after TPC $dE/dx$ selections of muon candidates (solid) and primary pion candidates (dashed). Right panel: Primary particle DCA distribution (dashed line) and muon DCA distribution from background after TPC $dE/dx$ and TOF $m^2$ selections from HIJING simulations through realistic STAR detector configuration. The DCA distributions of muons from charmed hadron decay are practically identical to the primary particle in this detector configuration.

Assumption is likely not appropriate for lepton $p_T > 2$ GeV/c and therefore we focused our study for $p_T > 2$ GeV/c. The spectrum was divided by the spectrum from d+Au. Fig. 6 shows the ratios of these spectra to the baseline spectra of charmed hadrons and leptons, respectively. The semileptonic decay greatly smears the spectrum and reduces the difference between the different spectrum shapes. However, it is clear that a reasonably realistic blast-wave parameterization of charmed mesons in Au+Au collisions is very different from that in d+Au collisions. There is also a significant difference between spectra with different flow (blast-wave function) parameters at $0.5 < p_T < 1.5$ GeV/c. Fig. 6 shows that there is a factor of 3 difference at $p_T = 1.5$ GeV/c between late freeze-out ($T_{fo} = 100$ MeV, $\beta_{max} = 0.9$) and early freeze-out ($T_{fo} = 160$ MeV, $\beta_{max} = 0.6$). Current measurements of non-photonic electron spectra and direct charm spectra seem to be consistent with a decreasing trend even at $p_T \simeq 1.0$ GeV/c [16], which is likely due to multiple collisions and thermalization at low $p_T$ with early freeze-out [9] and not due to pQCD energy loss. However, since the overall normalization is not known, an early freeze-out scenario can be interpreted as suppression of the charm total cross-section as well. This ambiguity can be resolved by a measurement of the total cross-section. In addition, the errors on the current measurements are large in this $p_T$ range. We advocate improving the measurements of electrons in this $p_T$ range to assess if charm thermalizes in the medium and has similar flow and freeze-out as multistrange hadrons [8].

In summary, we propose a sensitive measurement of the charm total cross-section at RHIC. The charm-decay muons at $p_T \simeq 0.2$ GeV/c can be identified by energy loss in a Time Projection Chamber and velocity from a Time-of-Flight detector. The background from pion/kaon decays can be subtracted
Fig. 6. Charmed meson spectrum of blast-wave form with $T_{fo} = 160$ MeV and $\beta_{max} = 0.6$ (dashed line) divided by the spectrum with a power-law parameterization of d+Au data from STAR [11], and corresponding electron spectrum ratio. These represent an early freeze-out scenario. The dash-dotted line is for an electron spectrum from a later freeze-out assumption with $T_{fo} = 100$ MeV and $\beta_{max} = 0.9$.

using the distribution of the distance of the closest approach to the collision vertex. We present simulations using HIJING within the realistic environment of the STAR detector. Detailed studies show that charm-decay muon spectra at low $p_T$ are proportional to the total charm cross-section. There is very weak dependence of the muon yields at the level of $\pm 15\%$ on charmed hadron shape over a wide range of spectrum parameters. Detailed comparison of different form factors of the charm semileptonic decay shows up to a factor of 1.5 difference in the resulting lepton spectra between PYTHIA and more realistic form factors. A power-law spectrum and a blast-wave-type spectrum possibly present in Au+Au is different by about 30\% at $p_T \approx 1$ GeV/c. We conclude that the lepton spectrum at low $p_T$ from charmed hadron decays is sensitive to the charm spectrum. Therefore, electron spectra at $0.5 < p_T < 1.5$ GeV/c can be used to study charm quark thermalization and radial flow.

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