Overview of charm production at RHIC

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Abstract. In this presentation, I discussed a) the charm total cross-section and its comparisons to measurements at other beam energies and pQCD calculations; b) the semileptonic decay of charmed hadrons and the sensitivity of non-photonic leptons to charm quark collective flow and freeze-out; c) semileptonic decayed electron spectrum at high transverse momentum, its comparison to FONLL in p+p and d+Au collisions, and heavy-quark energy loss in Au+Au collisions.

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 $N_{bin}$ 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 $p_T$.

Since the beginning of RHIC operation, PHENIX and STAR collaborations have made pioneer measurements in charm related physics [11, 12, 13, 14, 15, 16]. New measurements presented at this conference are:

(i) muon spectra at forward rapidity ($1.4 < |y| < 2.2$) from charm semileptonic decay by PHENIX Collaboration [16]. This enables us to study the rapidity dependence of nuclear effects of charm production.

(ii) muon spectra at low $p_T$ ($0.17 < p_T < 0.25$ GeV/$c$) from charm semileptonic decay by STAR Collaboration [15]. This improves the charm total cross-section measurements and better constrains the charm spectrum for studying the charm radial flow.

‡ The overviews of charm elliptic flow and quarkonium can be found elsewhere [17, 18]
1. Charm total cross-section

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 ($\sim 85\%$) of the total cross section $\sigma_{NN}$. The difficulties are due to short decay distance ($c\tau \simeq 100 \mu m$) and 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 $p_T$ $D^0 \rightarrow K\pi$ and the non-photonic electron spectra $\gamma$, and by non-photonic electron spectra alone at $p_T > 0.8$ GeV/c $\pi$. Although the systematic and statistical errors are large, the result indicates a much larger charm yield than predicted by pQCD calculations $\gamma$. It was argued that results with small renormalization (fragmentation) scales shown as solid line in Fig. are not reliable calculations $\gamma$. A new method $\gamma$ was proposed to extract the charm total cross-section by measuring muons from charmed hadron semileptonic decay at low $p_T$ (e.g. $0.16 < p_T < 0.26$ 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.

1.1. Are we (RHIC) consistent?

PHENIX and STAR collaborations have used several methods and techniques to extract total charm cross section in $p+p$, $d+Au$ and $Au+Au$ collisions $\gamma$. The total cross-section measured at $\sqrt{s_{NN}} = 200$ GeV can be summarized as Fig. and Fig. In general, the measurements have smaller errors in $Au+Au$ collisions than in
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p+p or d+Au collisions. The agreements between PEHNIX and STAR are better in light systems than in central Au+Au collisions. The non-photonic electron spectra by PHENIX have smaller systematic errors than the corresponding STAR measurements while STAR Collaboration have two additional measurements from direct charmed hadron reconstruction and low-momentum muon spectra. These reflect the strengths of the detectors, accordingly. There is substantial discrepancy of charm total cross-section between those extracted from PHENIX’s non-photonic electron spectra and the combined (hadronic and semileptonic) fit results from STAR’s measurements. The results in p+p and d+Au collisions show consistency within the errors. However, the discrepancy is about a factor of 2 in central Au+Au collisions while both have errors at 20% level. Part of the discrepancy may be explained by the different coverage of the two experiments [20]. Measurements from PHENIX non-photonic electron spectra cover < 15% of the dN/dy of the charm yields. Fig. 2 right panel illustrates the possible difference between measurements at low $p_T$ and higher $p_T$. It shows the dependence of the muon yield on power-law parameter $\langle p_T \rangle$ for a fixed total charm yield (details at Ref. [20]). The yield is normalized to yields at $\langle p_T \rangle = 1.3$ GeV/c. Fig. 2 demonstrates that over a wide range in $\langle p_T \rangle$, the muon yield is within $\pm 15\%$. 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. 2. On the other hand, the large discrepancy is difficult to be accounted for within reasonable range of parameters (e.g. $\langle p_T \rangle$ need change from 1.4 to 0.9 GeV/c for a factor of 2 change in extrapolated total yield) when both experimental errors are small in central Au+Au collisions. In addition, no obvious contradiction was observed from the electron spectra themselves and those are shown in Fig.3 and Fig.4 (details in later sections). With upgrades by PHENIX and STAR collaborations targeting at drastic improvement of precise secondary vertex detectors and continuous improvements of statistics and reduction/understanding of systematical errors, we may be able to better understand the difference in near future [21].

1.2. Are we alone? What’s right and what’s wrong?

It has been shown that the charm cross-sections in hadron collisions at lower energy have large errors and in many cases are inconsistent. We examined the experimental data and how the total cross-section was extracted. We found that in most of the cases, the charm total cross-sections were inferred from measurements covering small phase space using formulae to extrapolate to the full phase space. In some cases, the functions used for extrapolation were not consistent and resulted in large discrepancy. In addition, the systematic error from the extrapolation has not been properly implemented. In X. Dong’s thesis [22], we tabulated all the measurements and got rid of those with large extrapolation or inferred from correlations. Although it eliminated many measurements, those kept show better consistency and were listed in ref. [22]. Now we can compare the experimental data from low energy to high energy to the pQCD calculations. At RHIC energies, the data points are in general above the default pQCD predictions. The
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Figure 2. Left panel: Differential $\bar{c}$ cross-section per nucleon-nucleon collision ($dN/dy$) as function of the number of collision participant nucleons ($N_{\text{part}}$). The solid line is default NLO pQCD and FNOLL calculations. The shaded band indicates uncertainty of the predictions. The data points are from PHENIX and STAR collaborations. Right panel: 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 $0.16 < p_T < 0.26 \text{ GeV/c}$ and $|y_l| < 0.5$. Dashed line shows electron yields with $p_T > 1.0 \text{ GeV/c}$.

usual wisdom is that there is a factor of 2 uncertainty from pQCD calculations by varying the renormalization and fragmentation scales within a factor of 2. We noted that cross sections inferred from cosmic ray measurements are also much higher than the pQCD predictions. The cosmic ray showers required large charm total cross-section to account for the large muon yields and electromagnetic showers within the cosmic ray shower with incident nucleon energy at a few teens of TeV. On the other hand, the results at lower energy are consistent with pQCD calculations as shown in Fig. 1 and charmed hadrons at $p_T > 5 \text{ GeV/c}$ at Tevatron is within a factor of 2 above pQCD calculation [19]. We have also compared the non-photonic electron spectra from ISR energies to RHIC and to Tevatron energies. We found that there is no obvious inconsistency among the electron spectra. The direct $D^0$ measurement for $p_T > 5 \text{ GeV/c}$ in $p + \bar{p}$ collisions by CDF Collaboration was fitted to a power-law function and the semileptonic decayed electron spectrum was from the extrapolated spectrum. Detail of this study has been shown in Ref. [22, 23].

2. Are leptonic spectra sensitive to charm flow?

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. $0.16 < p_T < 0.26 \text{ GeV/c}$). 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
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factors used in charm semileptonic decays generated from Particle Data Group [24], in
the PYTHIA event generator [11, 12, 13, 25], by pQCD predictions [1] and from the
CLEO inclusive measurement [26]. We find that the lepton spectra from these different
form factors can be different by a factor of 1.5.

2.1. Form factors

The spectrum generated by the PDG is according to the form factor of charmed meson
decays to pseudoscalar $K + l + \nu$, vector meson $K^* + l + \nu$ and non-resonance $(K\pi) + l + \nu$
where the $K^*$ mass is used for the $(K\pi)$ system. Since PYTHIA uses a simplified vector
meson decay form factor [25], it tends to produce a softer electron spectrum. Both the
parameterization by Cacciari [1] and formulae from the PDG agree with CLEO’s electron
spectrum [26]. In addition, we also find that although the charmed mesons ($D^\pm$ and
$D^0$) from $\Psi(3770)$ decay have a momentum of 244 MeV/c only and without correction
of final state radiation [26], it affects slightly its subsequent electron spectrum.

2.2. Freeze-out

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 in Ref. [20] shows that
there is a factor of 3 difference at $p_T = 1.5$ GeV/c between late freeze-out ($T_{fo} = 100$
MeV, $\beta_{max} = 0.9$) [27] and early freeze-out ($T_{fo} = 160$ MeV, $\beta_{max} = 0.6$) [28]. 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 [15, 14], 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 [20].
In fact, with the measurements by PHENIX and STAR collaborations presented in
this conference, it was demonstrated that we are able to obtain freeze-out parameters
based on a blast-wave assumption with reasonable errors [15] (also shown as solid line in
Fig.4). However, 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 [8].

3. Does it make senses: Color and Flavor?

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 [12, 13, 29, 22].
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3.1. \( p+p / \text{FONLL} \) is 5.5 at high \( p_T \)?

It has been perceived that pQCD can reasonably calculate charm production because its quark mass is much larger than the non-perturbative scale. However, we have shown that the total cross section seems to be above pQCD calculations in several cases. On the other hand, the agreement should be better at higher \( p_T \). Fig. 3 shows the measurements of non-photonic electron spectra and muon spectra in \( p+p \) collisions divided by the First-Order-Next-to-Leading-Log (FONLL) calculations as function of \( p_T \). The pQCD calculations have a factor of 2 uncertainty. Although the experimental data have large errors at low \( p_T \), it is in general larger than the prediction. In particular, the STAR data from Electromagnetic calorimeter and the PHENIX data from muon detector are a factor of 5 above the FONLL calculations. This presents a puzzling issue since charged hadron and pions at high \( p_T \) can be quite well reproduced by NLO pQCD calculations.

3.2. Color and flavor dependence of energy loss

Let us ignore the discrepancy between data and pQCD in \( p+p \) collisions and study the nuclear modification function \( (R_{AA}) \) in \( \text{Au+Au} \) collisions. PHENIX and STAR collaborations has shown that \( R_{AA} \) of non-photonic electron (presumably from charm and bottom decays) is much smaller than 1 for \( p_T \gtrsim 2 \text{ GeV/c} \) shown in Fig. 4. In fact, it is very similar to that of pions with \( R_{AA} \simeq 0.2 \). Jet-quenching models incorporating collisional and radiation energy loss can not account for such large suppression. This may be due to the large contribution of bottomed hadrons to the non-photonic electron in the model calculations, which assume that charm and bottom production scale the same way from pQCD to match data in \( p+p \) collisions.

If we look at the \( R_{AA} \) at quark level for gluons, light quarks, and charm quarks, it is
obvious that the difference between light quarks and charm quarks is quite small (much less than a factor of two at low $p_T$ and similar at high $p_T$) calculated by Ref. [29]. The largest difference is between light quarks and gluons. This means that the deadcone effect of heavy quarks traversing the medium has much smaller effect on the nuclear modification factor than the color-charge factor of $9/4$ between gluons and quarks. To study this, it is important to find differential experimental probes sensitive to gluon and light quark energy loss. It has been proposed [33] that anti-protons at high $p_T$ (10 GeV/c) in A+A collisions are mainly from gluon fragmentation while pions are dominated by light quark fragmentation. By measuring $R_{AA}$, $\bar{p}/p$ and $\bar{p}/\pi$ ratios, we will be able to access the difference between gluon and quark energy loss. This was done by STAR Collaboration in a recent publication [31] using the relativistic rise of ionization energy loss in TPC to separate protons and pions [34]. The results show that there is no difference between proton and pion $R_{AA}$ (or $R_{CP}$) and little centrality dependence of $\bar{p}/\pi$ ratio has been found [31].

We now witness a set of data showing that the nuclear modification factors are the same among hadrons that are presumed to be fragments from separated gluons, light quarks and heavy quarks. This apparently contradicts the prediction from jet quenching models, which successfully explain the light hadron production at high $p_T$ and dijet correlations [30]. It doesn’t necessarily mean that the general framework of jet quenching is invalid. This may imply that interesting phenomena are present besides the general idea of energy loss of energetic partons traversing dense medium.

Experimentally, we need to measure the charm total cross-section with energy scan to map out its energy dependence and help constrain the pQCD calculations and charm coalescence into $J/\Psi$. We also will be able to study radial and elliptic flows of heavy flavors with upgrades by PHENIX and STAR collaborations. We need to separately measure the nuclear modification factors of charmed and bottomed hadrons and possible

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**Figure 4.** The nuclear modification function ($R_{AA}$) of non-photonic electron spectra vs. transverse momentum. Curves show different freeze-out assumptions in a blast-wave model. The data points are from PHENIX and STAR collaborations.
heavy-quark tagged jets to study the charm and bottom quark energy loss.

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