

QCD Predictions for Charm and Bottom Production at RHIC

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We present up-to-date QCD predictions for open charm and bottom production at RHIC in nucleon-nucleon collisions at $\sqrt{s} = 200$ GeV. The electron spectrum resulting from heavy flavor decays is also evaluated for direct comparison to the PHENIX and STAR data. These predictions seek to establish a rigorous benchmark, including the theoretical uncertainties, against which nuclear collision data can be compared to obtain evidence for nuclear effects.

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The PHENIX [1] and STAR [2, 3] Collaborations at the Relativistic Heavy Ion Collider (RHIC) have recently presented data for production of heavy quarks in pp and $d+Au$ collisions at $\sqrt{S_{NN}} = 200$ GeV, both in the form of explicitly reconstructed D mesons, and as an electron spectrum from semi-leptonic decay of the heavy hadrons. These data must be compared to QCD predictions, to establish the extent to which they can be successfully described, before moving forward and trying to determine the presence of dense matter effects in nucleus-nucleus collisions.

Recent improvements in heavy quark production theory and experimental measurements at colliders, especially for bottom production, have shown that the perturbative QCD framework works rather well, see Refs. [4], provided a number of precautions are taken in performing the phenomenological analysis and the proper modern tools are employed. In particular, the advantages of comparing the theoretical prediction and the data directly at the level of the experimental observables have been clearly outlined.

The purpose of this work is to repeat these analysis for RHIC, and to provide therefore a benchmark prediction against which the data can be compared.

We calculate the transverse momentum (p_T) distributions of charm and bottom quarks, the charm and bottom hadron distributions resulting from fragmentation and, finally, the electrons produced in semi-leptonic decays of the hadrons [5]. Theoretical uncertainties, estimated as extensively as possible, constitute an intrinsic component of the prediction. Our final result is thus not a single curve, but rather an uncertainty band which has a reasonably large probability of containing the ‘true’ theoretical prediction.

The theoretical prediction of the electron spectrum includes three main components: the p_T and rapidity distributions of the heavy quark Q in pp collisions at $\sqrt{S} = 200$ GeV, calculated in perturbative QCD; fragmentation of the heavy quarks into heavy hadrons, H_Q , described by phenomenological input extracted from e^+e^- data; and the decay of H_Q into electrons according to spectra available from other measurements. This cross section is schematically written as

$$\frac{Ed^3\sigma(e)}{dp^3} = \frac{E_Q d^3\sigma(Q)}{dp_Q^3} \otimes D(Q \rightarrow H_Q) \otimes f(H_Q \rightarrow e)$$

where the symbol \otimes denotes a generic convolution.

The distribution $Ed^3\sigma(Q)/dp_Q^3$ is evaluated at Fixed-Order plus Next-to-Leading-Log (FONLL) level, implemented in Ref. [6]. In addition to including the full fixed-order NLO result [7], the FONLL calculation also resums [8] large perturbative terms proportional to $\alpha_s^n \log^k(p_T/m)$ to all orders with next-to-leading logarithmic (NLL) accuracy (i.e. $k = n, n-1$) where m is the heavy quark mass. The perturbative parameters are m and the value of the strong coupling, α_s . We take $m_c = 1.5$ GeV and $m_b = 4.75$ GeV as central values and vary the masses in the range $1.3 < m_c < 1.7$ GeV for charm and $4.5 < m_b < 5$ GeV for bottom to estimate the mass uncertainties. The five-flavor QCD scale is the CTEQ6M value, $\Lambda^{(5)} = 0.226$ GeV. The perturbative calculation also depends on the factorization (μ_F) and renormalization (μ_R) scales. The scale sensitivity is a measure of the perturbative uncertainty. We take $\mu_{R,F} = \mu_0 = \sqrt{p_T^2 + m^2}$ as the central value and vary the two scales independently within a ‘fiducial’ region defined by $\mu_{R,F} = \xi_{R,F} \mu_0$ with $0.5 \leq \xi_{R,F} \leq 2$ and $0.5 \leq \xi_R/\xi_F \leq 2$ so that $\{(\xi_R, \xi_F)\} = \{(1,1), (2,2), (0.5,0.5), (1,0.5), (2,1), (0.5,1), (1,2)\}$. The envelope containing the resulting curves defines the uncertainty. The mass and scale uncertainties

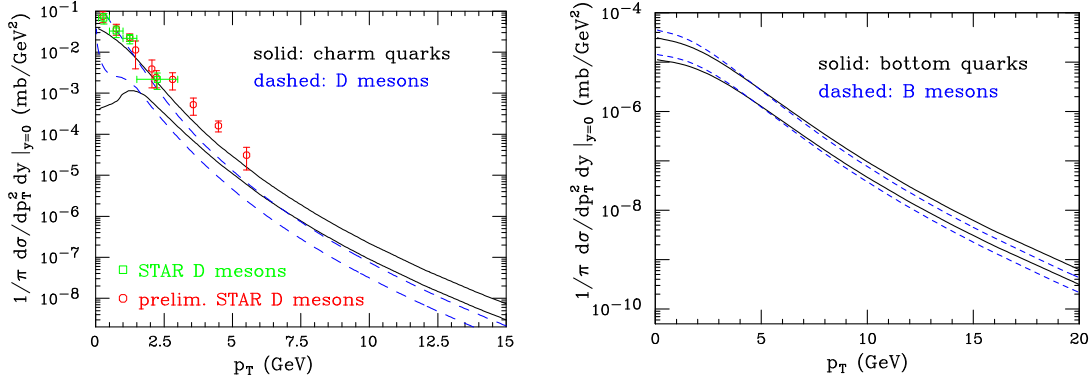


Figure 1: Left-hand side: The theoretical uncertainty bands for c quark and D meson p_T distributions in pp collisions at $\sqrt{s} = 200$ GeV, using $\text{BR}(c \rightarrow D) = 1$. The final [2] and preliminary [3] STAR d+Au data (scaled to pp using $N_{\text{bin}} = 7.5$) are also shown. Right-hand side: The same for b quarks and B mesons.

are then added in quadrature. These inputs lead to a FONLL total $c\bar{c}$ cross section in pp collisions of $\sigma_{c\bar{c}}^{\text{FONLL}} = 256_{-146}^{+400} \mu\text{b}$ at $\sqrt{s} = 200$ GeV, and to a total $b\bar{b}$ cross section of $1.87_{-0.67}^{+0.99} \mu\text{b}$.

The fragmentation functions, $D(c \rightarrow D)$ and $D(b \rightarrow B)$, where D and B indicate a generic admixture of charm and bottom hadrons, are consistently extracted from e^+e^- data in the context of FONLL [9, 10]. Using the Peterson *et al.* fragmentation function, with standard parameter choices $\epsilon_c \simeq 0.06 \pm 0.03$ and $\epsilon_b \simeq 0.006 \pm 0.003$, does not provide a valid description of fragmentation in FONLL, since the hadronization is too soft. In fact, Ref. [9] showed that replacing the Peterson fragmentation description with an appropriate one constitutes one of the main improvements which help reconcile the bottom transverse momentum distribution measured at the Tevatron with the theoretical prediction.

The measured spectra for primary $B \rightarrow e$ and $D \rightarrow e$ decays are modeled and assumed to be equal for all bottom and charm hadrons, respectively. The contribution of electrons from secondary B decays, $B \rightarrow D \rightarrow e$, was also included but is mostly negligible. The decay spectra are normalized using the branching ratios for bottom and charm hadron mixtures: $\text{BR}(B \rightarrow e) = 10.86 \pm 0.35\%$, $\text{BR}(D \rightarrow e) = 10.3 \pm 1.2\%$, and $\text{BR}(B \rightarrow D \rightarrow e) = 9.6 \pm 0.6\%$.

The left-hand side of Fig. 1 shows the theoretical uncertainty bands for c quarks and D mesons, obtained by summing the mass and scale uncertainties in quadrature. The band is broader at low p_T due to the large value of α_s and the behavior of the CTEQ6M parton densities at low scales as well as the increased sensitivity of the cross section to the charm quark mass.

Figure 2 compares the RHIC data to the total uncertainty band for $D \rightarrow e$, $B \rightarrow e$ and $B \rightarrow D \rightarrow e$ decays to electrons. The upper and lower limits of the band are obtained by summing the upper and lower limits for each component. It is worth noting that, while for the central parameter sets, the $B \rightarrow e$ decays begin to dominate the $D \rightarrow e$ decays at $p_T \simeq 4$ GeV, a comparison of the individual bands (not shown) shows that the crossover may occur over a rather broad range of electron p_T . The relative c and b decay contributions may play an important part in understanding the electron R_{AA} in nucleus-nucleus collisions which seems to suggest strong energy loss effects on heavy flavors [11, 12].

In conclusion, we have performed a phenomenological analysis of heavy quark production in

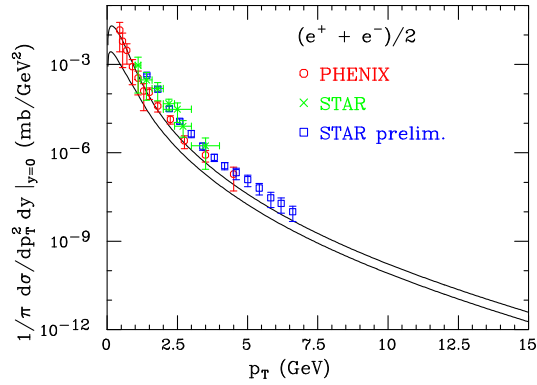


Figure 2: The final prediction for the theoretical uncertainty band of the electron spectrum from charm and bottom in pp collisions. Data from PHENIX [1] and STAR (final [2] and preliminary [3]) are also shown.

$\sqrt{S} = 200$ GeV pp collisions at RHIC. The results are presented in the form of a theoretical uncertainty band for the transverse momentum distribution of either bare charm (bottom), D (B) mesons, or electrons originating from the decay of charm and bottom hadrons. This band stems, at the perturbative level, from a next-to-leading order result improved by next-to-leading log resummation at large transverse momenta. These result should not be multiplied by any K factor before comparison with data. Rather, agreement within the uncertainties of the measurements will support the applicability of standard QCD calculations to heavy quark production at RHIC. Alternatively, a significant disagreement will suggest the need to complement this evaluation with further ingredients.

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