Open Charm Production in \( pp \) and Heavy Ion Collisions in QCD

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1 Introduction

The RHIC data on charm production are compared with the \( k_T \)-factorization approach predictions, both standard NLO QCD and FONLL. The calculated results underestimate the STAR Collaboration data. The role of possible nuclear effects is discussed.

2 Total Cross Sections

The investigation of heavy quark production in high energy collisions is an important method for studying the quark-gluon structure of hadrons and the possible nuclear effects at early stages of secondary production. The description of hard interactions in hadron collisions within the framework of QCD is possible only with the help of some phenomenological assumptions which reduce the hadron–hadron interaction to the parton–parton one via the formalism of the hadron structure functions. The cross sections of hard processes in hadron–hadron interactions can be written as the convolutions of squared matrix elements of the subprocess calculated within the framework of QCD with the parton distributions in the colliding hadrons.

The most popular phenomenological approach is the NLO QCD collinear approximation [1-4], where the cross sections of QCD subprocesses are calculated in the Next-to-Leading Order (NLO) of \( \alpha_s \) series. The Fixed Order plus Next-to-Leading-Log (FONLL) [5] also resums large perturbative terms proportional to \( \alpha_s^n \log^k(p_T/m) \) with \( k = n, n-1 \), where \( m \) is the heavy quark mass. In these calculations all particles involved are assumed to be on mass shell, carrying only longitudinal momenta, and the cross section is averaged over two transverse polarizations of the incident gluons.
The virtualities $q^2$ of the initial partons are taken into account only through their structure functions.

The standard QCD expression for heavy quark production cross section in a hadron 1 - hadron 2 collision has the form

$$
\sigma^{12-Q\bar{Q}} = \int_{x_{a0}}^{1} dx_a \int_{x_{b0}}^{1} dx_b \cdot G_{a/1}(x_a, \mu_F^2) \cdot G_{b/2}(x_b, \mu_F^2) \cdot \hat{\sigma}^{ab-Q\bar{Q}}(\hat{s}, m_Q, \mu_R^2),
$$

where $\mu_F$ is the QCD factorization scale, $x_{a0} = 4m_Q^2/s$, and $x_{b0} = 4m_Q^2/(sx_a)$. Here $G_{a/1}(x_a, \mu_F^2)$ and $G_{b/2}(x_b, \mu_F^2)$ are the structure functions of partons $a$ and $b$ inside hadrons 1 and 2 respectively, and

$$
\hat{\sigma}^{ab-Q\bar{Q}}(\hat{s}, m_Q, \mu_R^2) = \alpha_s^2(\mu_F^2) \sigma_{ab}^{(0)} + \alpha_s^3(\mu_R^2) \sigma_{ab}^{(1)}
$$

is the cross section of the subprocess $ab \to Q\bar{Q}$ as given by standard QCD as a sum of LO and NLO contributions [1, 2, 4]. These contributions depend on the parton center-of-mass energy $\hat{s} = (p_a + p_b)^2 = x_a x_b s$, the mass of the produced heavy quark $m_Q$ (actually they only depend on $\rho = 4m_Q^2/\hat{s}$), and the QCD renormalization scale $\mu_R^2$.

The possibility to incorporate the incident parton transverse momenta is referred to as the $k_T$-factorization approach [6–9], or the theory of semihard interactions [10–18]. Here the Feynman diagrams are calculated taking into account the virtualities and all possible polarizations of the incident partons. In the small $x$ domain there are no ground to neglect the transverse momenta of gluons, $q_1T$ and $q_2T$, when compared to the quark mass and transverse momenta, $p_{iT}$. Moreover, at very high energies and very high $p_{iT}$ the main contribution to the cross sections comes from the region of $q_1T \sim p_{iT}$ or of $q_2T \sim p_{iT}$ (see [16] for details). The QCD matrix elements of the partonic subprocesses are rather complicated in such an approach. We have calculated them in LO. On the other hand, the multiple emission of soft gluons is included here. All details of the calculations in the $k_T$-factorization approach, presented below, can be found in [18]. In our calculations the charm quark mass was taken as $m_c = 1.4$ GeV and we used QCD scales $\mu_R^2 = \mu_F^2 = m_T^2$, $m_T^2 = m_c^2 + p_T^2$.

We will firstly consider the cross sections of charm production in $pp$ collisions and then we will briefly discuss the situation with nuclear effects.

The existing data on total cross section of charm production at high energies are presented in Fig. 1. One can see the difference in results by PHENIX and by STAR Collaborations. This difference is discussed in details in [25, 26].

All experimental points except those by STAR Collaboration and the cosmic ray ones are in reasonable agreement with NLO QCD calculations (dash-dotted curve), where the GRV95 parton distributions [27] were used, and which are compatible with more modern analysis (see discussion in [28]). The $k_T$-factorization approach result (solid curve) underestimates the data at comparatively low energies because it contains only gluon-gluon fusion contribution and is close to the NLO QCD collinear approximation curve at higher energies.
Figure 1: Total cross section of charm production in $pp$ and $\bar{p}p$ collisions at $p \geq 400$ GeV/c. Experimental fixed target data are taken from [19] and [20], UA2 Collaboration data from [21], all they are shown by points. Squares correspond to PHENIX data [22, 23] and triangle to STAR data [24]. The data of cosmic rays taken from [25] are shown by diamonds. The solid curve shows the result of $k_T$-factorization approach, dashed curve corresponds to NLO QCD with only gluon-gluon fusion contribution, and dash-dotted curve to total NLO QCD result.

3 The $p_T$-Distributions

STAR Collaboration obtains also the $p_T$-distributions of $D$-mesons produced in $d+Au$ collisions and scaled to $pp$ collisions at $\sqrt{s} = 200$ GeV. These data, taken from [29] are presented in Fig. 2. together with theoretical calculations. The NLO QCD result shown by dashed curve is in evident disagreement with the data on the same level as in Fig. 1. The upper curve of FONLL calculations for charmed quark production taken from [29] (dash-dotted curve) also underestimates the data. The result of the $k_T$-factorization approach (solid curve) has reasonable slope in $p_T$-dependence but also underestimates the data. The level of disagreement in this case is, however, smaller than in the case of total cross sections. This should be connected with the fact that a rather large contribution to the total cross section comes from low-$p_T$ region ($p_T \leq 1$ GeV/c) where both experimental and theoretical uncertainties are rather large.

It is necessary to note that in Fig. 2 we compare the experimental points for $D$-meson production with theoretical curves for charmed quark distributions. Contrary
Figure 2: STAR Collaboration data for $p_T$-distributions of $D$-mesons produced in $d + Au$ collisions and scaled to $pp$ collisions at $\sqrt{s} = 200$ GeV together with calculations in $k_T$-factorization approach (solid curve), NLO QCD (dashed curve), and FONLL [29] (dash-dotted curve).

to the mention in [29], together with fragmentation processes where the momentum of $D$-meson is smaller than the momentum of $c$-quark, there exist recombination processes where the momentum of $D$-meson is larger than the momentum of $c$-quark. The existence of recombination processes in charm production seems to be evident from the experimental data on the asymmetry in yields of the so-called favoured and unfavoured $D$-mesons, see discussions in [30–33]. As a matter of fact the produced heavy and light quarks have very different transverse momenta but the difference in the components of their velocities can be not so large. Possibly, the fragmentation and recombination processes in charm quark hadronization balance each other in the processes with not very high $p_T$, e.g. the calculated Feynman-$x$ distributions of produced charm quarks in $\pi p$ collisions are in good agreement with the experimental distributions of produced $D$-mesons (see Fig. 5 in [34]).

The total cross section of charm production was not measured at Tevatron-collider energies. However there exist data on $p_T$-distributions of $D$-mesons at these energies [35]. They are presented in Fig. 3 where it is shown that they are in good agreement with NLO QCD calculations for charm quarks (dashed curve) based on GRV95 parton distributions. The solid curve corresponds to the $k_T$-factorization approach and it slightly overestimates the data, but the agreement should become better in the future when the contribution of charmed antibaryons will be added to the experimental data.
The results of FONLL calculations [29] with fragmentation functions for $D$-mesons production presented in [35], slightly underestimate the yields of $D$-mesons. Thus all QCD approaches (see also [36]), except of the extremal ones, e.g. the one presented in [37], are in reasonable agreement with experimental data at $\sqrt{s} = 1.96$ TeV.

![Graph](image)

Figure 3: The cross sections for $D$-meson production in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV [35] with $|y_1| \leq 1$ together with calculations in $k_T$-factorization approach (solid curve) and NLO QCD (dashed curve).

Let us shortly discuss the nuclear effects in charm production at RHIC. First of all we can say that EMC-effect, i.e. the nuclear deformation of parton distributions [38] should increase the total cross sections for charm production, calculated in the NLO QCD linear approximation at RHIC energy by 5-10 % [39] in comparison with a linear A-dependence.

The data of PHENIX and STAR Collaborations scaled to binary interactions are presented together in [26]. One can see the absence of nuclear effects from $pp$ to central Au-Au collisions from PHENIX data, and from d-Au to central Au-Au collisions from STAR data, both on the level of 20% accuracy. Concerning the PHENIX data presented in [25], there is no visible dependence of the charm production cross section on the number of collision participant nucleons, $N_{part}$, in Au-Au collisions at different centralities.

There exists a factor $\sim 2-3$ discrepancy [26] in the total cross sections of charm production obtained by PHENIX and STAR Collaborations. Surely, the explanation of this discrepancy is completely connected to some experimental problem. However, meanwhile experiments don’t clarify this point, two possibilities can be imagined:
i) if we trust PHENIX data, the NLO QCD reasonably describes all experimental data except of two cosmic ray points presented in Fig. 1, and then nuclear effects in total cross sections of charm production are small;

ii) if, on the contrary, we trust STAR data, nuclear effects increase the total cross sections of charm production about 4-5 times. If the $N_{\text{part}}$ dependence of these nuclear effects saturates very fast, even the cosmic ray data could be included in the theoretical description. The origin of so large nuclear effects can be connected with large non-perturbative contributions in high density states (which can be larger than perturbative contributions), e.g. string fusion [40], percolation [41], or colour glass condensate effects [42, 43] in the interactions with nuclei.

In these approaches, above some scale $\eta_c$ [41] given by the critical percolation string density, the strong colour field inside the cluster formed by the overlapping strings produces $Q\bar{Q}$ pairs via the Schwinger mechanism as a single string produces light $q\bar{q}$ pairs. In the same way, in the colour glass condensate approach [42, 43] the significant scale is the saturation momentum $Q_s$ which grows with energy and nuclear size. When $Q_s > m_T(\sigma)$, the classical colour field is strong and produce pairs $Q\bar{Q}$. The production pattern for heavy quarks becomes similar to that of the light quarks and an overall enhancement of heavy quark production cross section is thus expected.

4 Summary

1. The $k_T$-factorization approach predictions are in reasonable agreement with NLO QCD for the total cross section of charm production at RHIC energies. We obtain a reasonable description of the PHENIX data and we are in contradiction with STAR data.

2. It seems that the main part of our disagreement with STAR data comes from low-$p_T$ region ($p_T \leq 1$ GeV/c) where both experimental and theoretical uncertainties are rather large.

3. The predicted $p_T$-distribution of the produced charm at high $p_T$ in the $k_T$-factorization approach is higher than NLO QCD and FONLL predictions. The $k_T$-factorization approach only slightly underestimates the experimental STAR data.

4. PHENIX data are compatible with the absence of any nuclear effects in charm production, whereas STAR data need rather strong nuclear effects at RHIC energies.

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References


Discussion

A. Capella (LPTHE-Orsay): What kind of nuclear effects in parton distributions do you refer to when you say that they are expected to increase the total cross section for charm production at RHIC by 5-10% with respect to an A-linear increase?

C. Merino: We think of nuclear effects connected with the experimental difference between quark distributions in free and bound nucleons, and with the theoretical analysis of using these quark distributions as input to the evolution equations.

I. Sarcevic (University of Arizona): Would the nuclear effects in charm production at RHIC energies depend on $p_T$ and/or $y$?

C. Merino: As these nuclear corrections in charm production are a new effect it is still premature to say anything about their $p_T$ and/or $y$ dependency, if any.

E.G. Ferreiro (Universidade de Santiago de Compostela): You claim that if STAR data (and not PHENIX data) are correct this is an indication that nuclear effects increase the total cross section for charm production by a 4-5 factor. Wouldn’t this claim be in contradiction with the fact you also explained that STAR data show not nuclear effects from $d$-$Au$ to central $Au$-$Au$ collisions?

C. Merino: There wouldn’t be any contradiction if the discussed nuclear effects were very fast saturated (before $d$-$Au$, in the transition from nucleon-nucleon to nucleus-nucleus collisions).