Article

Measurements of D^0 and D^* production in p+p collisions at $\sqrt{s}$ = 510 GeV in STAR experiment

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Abstract: This article focuses on an investigation into the production of D^0 and D^* mesons as a function of transverse momentum in proton-proton (p+p) collisions at a center-of-mass energy of $\sqrt{s}$ = 510 GeV, conducted by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC). Objective of this analysis is to test the perturbative QCD calculations with the charm-anticharm production cross-sections obtained through D^0 and D^* measurements. This report includes ongoing signal extractions of the D^0 and D^* mesons from minimum bias events recorded during the p+p collisions at $\sqrt{s}$ = 510 GeV at STAR in 2017. Signals were reconstructed through the hadronic decay channels of these mesons. Like-sign combination and track rotation methods have been used to estimate the combinatorial background for D^0 measurement from p_T = 0.0 to 2.1 GeV/c. For D^*, wrong-sign and side band combination of the decay daughters were utilized to reconstruct the combinatorial background from p_T = 2.0 to 6.0 GeV/c.

Keywords: heavy-quark production; open-charm hadrons; pQCD; proton+proton collisions; signal extraction

1. Introduction

Heavy-flavour hadrons, which consist of charm and bottom quarks, are crucial for the investigation of Quantum Chromodynamics (QCD) in high-energy hadronic collisions. Studying their production allows for comparisons between experimental results and theoretical models. Firstly, the mass of the heavy quark (m_Q) serves the purpose of a low-energy (or long distance) cut-off, thereby making it possible to calculate the processes within the regime of perturbative QCD (pQCD) up to low transverse momentum (p_T) [1]. Also due to the occurence of multiple hard scales (m_Q, p_T), it is possible to examine the perturbation series across different kinematic regions (i.e., $p_T < m_Q$, $p_T \approx m_Q$, $p_T > m_Q$)[1]. Based on a factorisation scheme, the differential cross section for the inclusive production of a heavy quark Q can be calculated as follows:

$$\sigma^{Q+X} \simeq \sum_{i,j} f_i^A \otimes f_j^B \otimes \mathrm{d}\tilde{\sigma}_{ij\to Q+X} \quad (1)$$

The parton distribution functions (PDF) f_i^A (f_j^B) give the number density of the parton of flavour 'i' ('j') inside the hadron 'A' ('B'). d$\tilde{\sigma}$ is the partonic cross-section which depends on the strong-coupling constant (α_s) [1]. The pQCD calculations of Fixed-Order Next-to-Leading Logarithm (FONLL) can describe the heavy quark production at transverse momenta p_T larger than their mass [2]. But, in the low momentum transfer region (e.g., $p_T < 1$ GeV/c for charm quarks) the strong coupling constant increases drastically where

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pQCD has restricted ability to predict the cross-section. Precise experimental measurements becomes necessary in those situations to improve the theoretical calculations.

The investigation of D meson production in proton+proton (p+p) collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) has attracted considerable interest, as it holds important implications for the comprehension of QCD and the mechanisms underlying charm quark production [3] [4] [5]. The STAR collaboration has reported measurements of D mesons in p+p collisions at $\sqrt{s}$ = 200 GeV. The p_T-differential $c\bar{c}$ production cross sections from D^0 and D^* measurements were compared with FONLL pQCD calculations, as illustrated in Figure 1 [3].

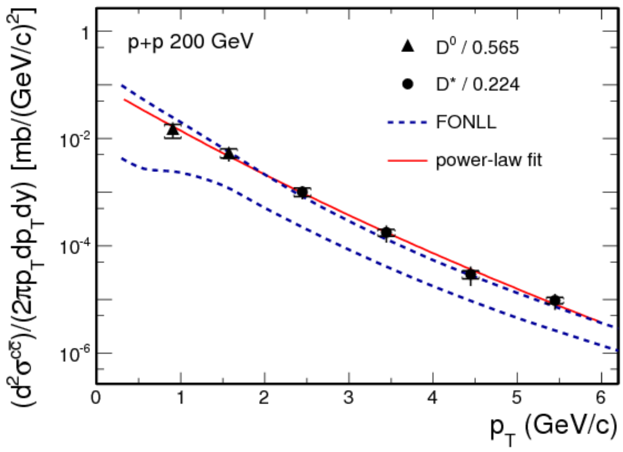

Figure 1. p_T-differential $c\bar{c}$ production cross sections measured in p+p collisions at $\sqrt{s} = 200$ GeV are compared with Fixed Order Next-to-Leading Logarithm (FONLL) pQCD calculations [3].

Modifications of the charm meson production in heavy-ion collisions with respect to p+p provide insights into the presence of Quark Gluon Plasma (QGP) medium. The D meson nuclear modification factor (R_{AA}) in heavy-ion collisions at RHIC has been studied to understand the suppression effects due to the presence of the QGP [6] [7]. The results indicate a strong suppression of D meson yields at high transverse momentum, which is a signature of the medium's influence on heavy quark dynamics. The p_T-differential invariant yield of D^0 mesons in Au+Au collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV, across various centralities, along with the nuclear modification factor for D^0 mesons, is presented in Figure 2.

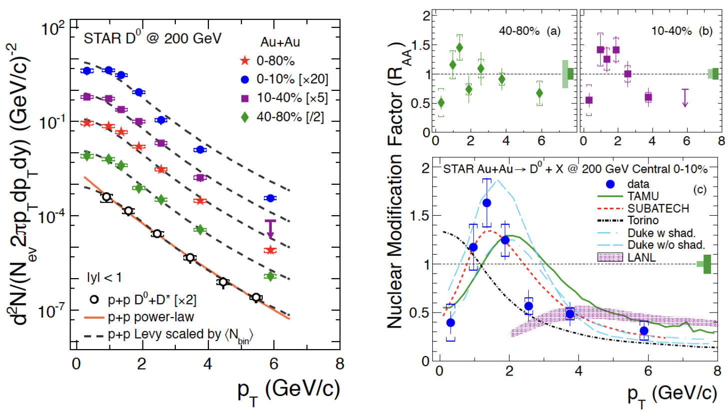

Figure 2. p_T-differential D^0 invariant yield in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for various centralities (left) and the D^0 meson nuclear modification factor R_{AA} (right) [8].

2. Measurement of Open-Charm Mesons with STAR

In 2017, STAR collected about 1.11 billion minimum-bias events for p+p collisions at $\sqrt{s}$ = 510 GeV which allows very precise heavy flavor meson measurements. In this section, the methodology of the signal extraction of open-charm mesons D^0 and D^* from this data are described.

As D^0 and D^* mesons decay before reaching the detectors, it is not possible to directly observe those. Therefore, it is necessary to reconstruct those through their decay products. In this analysis, the following decay channels have been utilized: $D^0(\bar{D^0}) \rightarrow K^{\mp}\pi^{\pm}$(Branching Ratio $= 3.947 \pm 0.030\%$) and $D^{*\pm} \longrightarrow D^0(\bar{D^0})\pi_s^{\pm}$(Branching Ratio $= 67.7 \pm 0.5\%$) $\longrightarrow K^{\mp}\pi^{\pm}\pi_s^{\pm}$ [9]. Here, π_s denotes the soft pions directly decaying from D^*. It is important to note that the Heavy Flavor Tracker (HFT) [10] of the STAR experiment was not operational during the 2017 run. So, the secondary vertex (the decay vertex of D^0) reconstruction by looking into the D^0 decay topology was out of the scope of this analysis which would have been useful to remove the huge combinatorial background while reconstructing the invariant mass of D^0 from the daughter particles.

A set of event selection cuts were applied on this minimum bias triggered data. The events were selected so that the position of the primary vertex along the beam axis $\mathrm{V}_{\mathrm{z[TPC]}}$ determined using the Time Projection Chamber (TPC) [11] is no further than 60 cm from the center of STAR. A cut on the difference of vertex z coordinate measured by TPC ($\mathrm{V}_{\mathrm{z[TPC]}}$) and by Vertex Position Detector [12] ($\mathrm{V}_{\mathrm{z[VPD]}}$) have been imposed to ensure tracks from events identified by both VPD and TPC are accepted which is also effective to remove plie-up vertices.

Tracks are reconstructed in TPC from registered hits - therefore the higher the number of hits, the more precise is the final track [11]. Only tracks reconstructed from more than 18 points were kept in this analysis. The ratio of the number of TPC fit points to the maximum possible number of TPC fit points, exceeding 0.52, was employed to mitigate the occurrence of split tracks, wherein a single track is erroneously reconstructed as two distinct tracks. A 1.5 cm limit on DCA (Distance of Closest Approach) was found to be effective on removing pile-up tracks. Particles were needed to have a certain minimal value of transverse momentum (p_T) to be accepted for the sake of higher reconstruction efficiency. Also, tracks within the acceptance of the TPC and Time of Flight (TOF) detector [13] were selected by imposing a cut on the pseudorapidity $|\eta|$. An overview of these track quality cuts and event selection cuts have been demonstrated in Table 1.

Table 1. Summary of event and track selection criteria used in this analysis.

Event Selection Cuts	$\left\vert \mathrm{V}_{\mathrm{z[TPC]}} - \mathrm{V}_{\mathrm{z[VPD]}} \right\vert < 4.0$ cm $\mathrm{V}_{\mathrm{z[TPC]}} < 60$ cm $\mathrm{V}_{\mathrm{x[TPC]}} \in (-0.3, 0.14)$ cm $\mathrm{V}_{\mathrm{y[TPC]}} \in (-0.26, 0.02)$ cm
Track Quality Cuts	number of TPC fit points > 18 $\frac{\text{number of TPC fit points}}{\text{number of max possible TPC fit points}} > 0.52$ global DCA < 1.5 cm $p_T > 0.2$ GeV/c [1] $\lvert\eta\rvert < 1$

[1] To select π_s candidates directly decaying from D^*, p_T cut was reduced to 0.1 GeV/c to select lower momentum tracks

Next, the daughter particle candidates were identified by utilizing the TPC and TOF detectors. The identification of charged particles is achieved through the measurement of energy loss within the TPC gas. The measured energy loss is compared to the expected one. Particle identification in TOF is done by comparing measured value of inverse velocity $1/\beta_{\mathrm{TOF}}$ with the expected theoretical value $1/\beta_{\mathrm{th}}$. β_{th} is obtained from the particle momentum p measured by TPC and expected rest mass m using the formula $\beta_{\mathrm{th}} = p/\sqrt{p^2 + m^2c^2}$ [13].

In order to enhance observed signals, D^0 and $\bar{D}^0$ were analyzed together. Unlike-sign pion and kaon candidates were paired and the invariant mass of the resulting pair was computed. Pion-kaon pairs with a rapidity outside the interval of (-1, 1) were excluded from consideration. As most of the $K\pi$ pairs do not come from $D^0(\bar{D}^0)$ decay, one has to deal with a huge combinatorial background. The combinatorial background was reconstructed using two independent methodologies: (i) like-sign combination where candidates for pions were paired with kaon candidates of identical charge and (ii) track rotation where one of the tracks was rotated so that its momentum was pointing in opposite direction: $(E, p_x, p_y, p_z) \longrightarrow (E, -p_x, -p_y, -p_z)$, thus destroying all correlation and decay kinematics.

Now, in order to form a D^* candidate, a soft pion candidate (π_s) was combined with the unlike-sign $K\pi$ pair if the invariant mass of the pair $M_{K^{\mp}\pi^{\pm}}$ falls between 1.8 and 1.95 GeV/c^2. The invariant mass of the $K^{\mp}\pi^{\pm}\pi_s^{\pm}$ triplet was subsequently calculated, and a histogram was populated with the mass difference. Furthermore, the combinatorial background was reconstructed utilizing two distinct and independent methods: wrong-sign combination method and side-band method. In the wrong-sign combination, the soft pion was paired with the D^0 daughter pion of the opposite charge. In the side-band method, the $M_{K^{\mp}\pi^{\pm}}$ had been lying between two side-bands: 1.64 - 1.74 GeV/c^2 and 2.01 - 2.11 GeV/c^2, i.e. outside the D^0 mass window.

3. Results

The D^0 signal was extracted by fitting the background subtracted invariant mass distribution with a sum of gaussian and linear function. The raw yield was determined by calculating the area under the Gaussian distribution superimposed on a linear function, which was employed to accurately model the residual background with sufficient precision. Like-sign background subtracted mass distribution of D^0 candidates with $0.0 \leq p_T \leq 1.1$ GeV/c, $1.1 \leq p_T \leq 1.6$ GeV/c and $1.6 \leq p_T \leq 2.1$ GeV/c are shown in Figure 3.

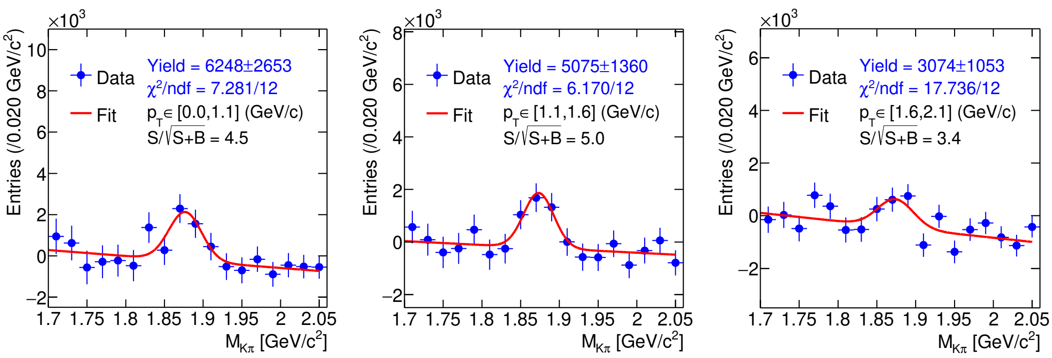

Figure 3. Like-sign background subtracted invariant mass distributions of D^0 candidates in three p_T bins fitted with Gaussian+linear function.

The D^* signals after subtracting the combinatorial background reconstructed by wrong-sign pairs and side-band method in the p_T bins 2.0 - 3.0 GeV/c, 3.0 - 4.2 GeV/c, 4.2 - 6.0 GeV/c are shown in Figure 4 and Figure 5 respectively. These signals were also extracted by fitting the background subtracted invariant mass distribution with a sum of Gaussian and linear function for each p_T bin. Again, the raw yields were estimated from the area under the Gaussian distribution.

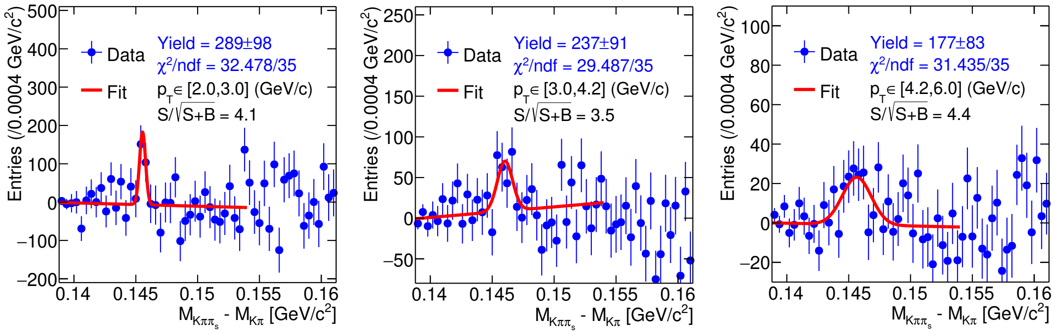

Figure 4. Wrong-sign background subtracted invariant mass distributions of D^* candidates in three p_T bins fitted with Gaussian+linear function.

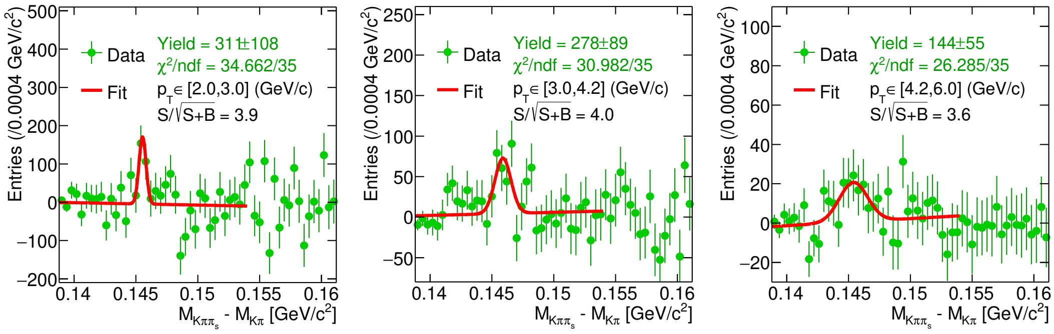

Figure 5. Side-band background subtracted invariant mass distributions of D^* candidates in three p_T bins fitted with Gaussian+linear function.

The significance of both of the D^0 and D^* signals were calculated as $S/\sqrt{S+B}$, where S is the raw yield of the signal and B is the raw yield of the background.

4. Discussion

In this analysis, D^0 and D^* measurements in p+p collisions at $\sqrt{s} = 510$ GeV has been presented. These open-charm mesons were reconstructed through their hadronic decay channels at STAR. D^0 candidates were reconstructed from p_T = 0.0 to 2.1 GeV/c. Wrong-sign and Side-band methods were used to estimate the combinatorial background of the D^* candidates' invariant mass spectrum from p_T = 2.0 to 6.0 GeV/c. Signals were extracted with a significance more than 3. These raw yields will be corrected by considering the particle-misidentification rates in TPC and TOF. The primary objective of this analysis was to measure the charm production cross-section in proton-proton collisions at a center-of-mass energy of $\sqrt{s}$ = 510 GeV. To obtain that one also needs to take into account the efficiency of the experiment, trigger biases, and systematic uncertainties. The measured transverse momentum differential invariant charm production cross section will be subjected to a fit to the Lévy power-law function [14] in order to extract the charm pair production cross section at mid-rapidity, and subsequently compared to predictions derived from the FONLL framework.

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References

1. Andronic, A., Arleo, F., Arnaldi, R. et al. Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions. *Eur. Phys. J. C* **2016**, *76*, 107.

2. Nelson, Randy J., Ramona Vogt and Anthony D. Frawley. Narrowing the uncertainty on the total charm cross section and its effect on the J/ψ cross section. *Phys. Rev D* **2012**, *87*, 014908.
3. Adamczyk, L., et al. (STAR Collaboration), Measurements of D^0 and D^* Production in p + p Collisions at $\sqrt{s}$ = 200 GeV, *Phys. Rev. D* **2012**, *86*, 072013.
4. Acharya, S., et al. (ALICE Collaboration), Measurement of D^0 , D^+ , D^{*+} and D_s^+ production in pp collisions at $\sqrt{s}$ = 5.02 TeV with ALICE, *Eur. Phys. J. C* **2019**, 79, 388.
5. Acharya, S., et al (ALICE Collaboration), Measurement of D-meson production at mid-rapidity in pp collisions at $\sqrt{s}$ = 7 TeV, *Eur. Phys. J. C* **2017** 77, 550.
6. Nahrgang, M., Aichelin, J., Bass, S., Gossiaux, P. B., and Werner, K., Heavy flavor observables at RHIC and LHC, *Nucl. Phys. A* **2014**, *931*, 575–580.
7. Xie, G. (STAR Collaboration), Nuclear Modification Factor of D^0 Meson in Au + Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV, *Nucl. Phys. A* **2016**, *956*, 473–476.
8. Adamczyk, L., et al. (STAR Collaboration), Observation of D^0 Meson Nuclear Modifications in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV, *Phys. Rev. Lett* **2014** 113, 142301.
9. Navas, S., et al. (Particle Data Group), Review of particle physics, *Phys. Rev. D* **2012**, *110*, 030001.
10. Kapitán, J., Open charm measurement with HFT at STAR, *Indian J Phys* **2011**, *85*, 177–181.
11. Anderson, M., et al., The STAR Time Projection Chamber: A Unique Tool for Studying High Multiplicity Events at RHIC, *Nucl. Instrum. Meth. A* **2003**, 499, 659–678.
12. Llope, W. J., et al., The STAR Vertex Position Detector, *Nucl. Instrum. Meth. A* **2014**, *759*, 23–28.
13. Shao, M., et al., Extensive particle identification with TPC and TOF at the STAR experiment, *Nuclear Instruments & Methods in Physics Research Section A-accelerators Spectrometers Detectors and Associated Equipment* **2005**, *558*, 419-429.
14. Wong, Cheuk-Yin and Grzegorz Wilk, Tsallis fits to p_T spectra and multiple hard scattering in pp collisions at the LHC, *Phys. Rev. D* **2013**, *11*, 114007.