

QCD analysis of D^* -meson fragmentation functions and their uncertainties at NNLO *

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In this paper, we present a set of charmed-meson D^* at next-to-leading order (NLO) and, for the first time, at next-to-next-to-leading order (NNLO) accuracy. This new sets of charmed-meson D^* FFs are obtained through global QCD fits to all relevant data sets from single-inclusive e^+e^- annihilation. The “Hessian approach” are applied for the determination of FFs uncertainties as well as the corresponding observables. We compared the resulting D^* FFs with the results in the literature. The theory prediction using the extracted FFs are also compared with the available data sets for single-inclusive $D^{*\pm}$ -meson production in electron-positron annihilation.

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1. Introduction

Studies over the past two decades have provided valuable vital information on the structure of hadrons. Fragmentation functions (FFs) [1, 2, 3, 4, 5, 6, 7] describe the non-perturbative part of hard-scattering processes and along with the parton distribution functions (PDFs) of initial hadrons (in a given hadron-hadron collision) and parton-level differential cross sections are three important ingredients to obtain theoretical predictions for the hadroproduction cross sections [8, 9, 10, 11, 12].

The FFs are studying in hadroproduction processes such as electron-positron (e^+e^-) single-inclusive annihilation (SIA), lepton-hadron semi-inclusive deep inelastic scattering (SI-DIS) and hadron-hadron collisions. Theoretically the cleanest process to extract the fragmentation densities is SIA because we do not require the simultaneous knowledge of PDFs and FFs. Recently, different analysis have been focused on extracting of FFs for light and heavy hadrons at NLO and also NNLO accuracies in perturbative QCD (pQCD) [2, 5, 6, 13, 14]. The calculation of FFs at high order corrections NNLO of pQCD is possible just for electron-positron e^+e^- annihilation while the calculations for the hard processes in SI-DIS and pp collisions at NNLO are not accessible yet.

In this paper, for the first time, a comprehensive QCD analysis is performed to obtain a set of charm- and bottom-quarks into $D^{*\pm}$ -mesons and their uncertainties at NNLO through a global QCD fit to SIA data from ALEPH [15] and OPAL [16] collaborations at LEP. Our analysis is entitled as ‘‘SKM18’’ and using the zero-mass variable flavor scheme (ZM-VFN). It is limited to SIA data only cross sections at NLO and NNLO accuracies.

In Ref [17], the authors have determined non-perturbative charmed-meson FFs at NLO in the general-mass variable flavor number scheme (GM-VFNs), using the SIA data from Belle, CLEO, ALEPH and OPAL Collaborations. Recently, the authors of Ref. [13] have determined the FFs of charged D^* -meson at NLO accuracy using the available data sets for SIA D^* -meson and in proton-proton scattering in which the gluon FF can be well constrained via proton-proton scattering data.

This paper is organized as follows. In Sec. 2, the QCD analyses of hadronization process in electron-positron e^+e^- annihilation are discussed. In this section, we also describe our formalism and parametrizations for the charmed-meson $D^{*\pm}$ FFs at a given input scale as well as the analyzed experimental data sets. In Sec. 3, the results of our $D^{*\pm}$ -FFs and their uncertainties are discussed and compared with other in literature. Our result and conclusion are summarized in Sec. 4.

2. Theory settings and FFs parametrization

According to the factorization theorem of improved QCD-parton model, the differential cross section of electron-positron e^+e^- annihilation can be written as a convolutions of perturbative part of partonic cross sections, $d\sigma_i(x_i, \mu_R, \mu_F)/dx_i$, with the non-perturbative part of $D_i^{D^*}(z, \mu_F^2)$ -FFs, where i stands for one of the flavors of fragmenting partons; $i = g, u, \bar{u}, \dots, b, \bar{b}$. This convolution reads

$$\frac{1}{\sigma_{\text{tot}}} \frac{d}{dx_D} \sigma(e^+e^- \rightarrow D^*X) = \sum_i \int_{x_D}^1 \frac{dx_i}{x_i} D_i^{D^*}\left(\frac{x_D}{x_i}, \mu_F\right) \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma_i}{dx_i}(x_i, \mu_R, \mu_F). \quad (2.1)$$

The renormalization (μ_R) as well as factorization (μ_F) scales are made consists of setting $\mu^2 = \mu_F^2 = Q^2$ in SKM18 analysis. The variable $x_i = 2(p_i \cdot q)/q^2$, where p_i is the four-momentum of parton i . The total cross section up to NNLO for e^+e^- annihilation into hadrons can be written as,

$$\sigma_{tot} = \frac{4\pi\alpha^2(Q)}{Q^2} \left(\sum_i^{n_f} \hat{e}_i^2(Q) \right) (1 + \alpha_s K_{\text{QCD}}^{(1)} + \alpha_s^2 K_{\text{QCD}}^{(2)} + \dots), \quad (2.2)$$

In order to choose the best parametrization for SKM18 global analysis of $D^{*\pm}$ -FFs, we have tested different functional input. Finally we decided adopted the Bowler [18] parametrization form because one can control this parametrization considering the low number of data for $D^{*\pm}$ -meson FFs. Therefore, we parameterize the z distributions of the $c(\bar{c})$ as well as $b(\bar{b})$ quark FFs at their starting scales μ_0 as suggested by Bowler. It is given by:

$$D_i^{D^{*\pm}}(z, \mu_0^2) = N_i z^{-(1+\alpha_i^2)} (1-z)^{\beta_i} e^{-\alpha_i^2/z}. \quad (2.3)$$

As one can see, this parametrization comes with three free parameters; N , α and β . Our fitting procedure is going as follows. At the scale μ_0 , the FFs of gluon and light quarks ($q = u, d, s$) are set to zero, i.e.

$$D_i^{D^{*\pm}}(z, \mu_0^2) = 0, \quad i = u, \bar{u}, d, \bar{d}, s, \bar{s}, g. \quad (2.4)$$

Then, the light and gluon FFs are evolved to the higher scales $\mu^2 > \mu_0^2$ using the DGLAP evolution equations [19] at NLO or NNLO accuracy.

ALEPH [15], OPAL [16], CLEO [20] and Belle [21] Collaborations are reported most of the experimental data for $D^{*\pm}$ in electron-positron (e^+e^-) annihilation. An overview of the data included in SKM18 global analysis of $D^{*\pm}$ FFs is presented in our previous analysis [14] for the total, c -tagged and b -tagged SIA cross sections from ALEPH [15] and OPAL [16] Collaborations. OPAL and ALEPH Collaborations at Large electron-positron (LEP) present their experimental data sets at $Q = M_Z$ which is the mass of the Z boson, while other Collaborations such as Belle and CLEO provide their data in lower energy, i.e. $Q = 10.5$ GeV. In this range of energy, all $D^{*\pm}$ FFs in electron-positron (e^+e^-) annihilation coming from bottom decays are excluded because they are below the mass threshold of b -quark.

The determination of non-perturbative FFs through global QCD fits to the experimental data sets is a statistical procedure that necessarily implies a variety of assumptions. The most important one is the parameterization functions for the charmed-meson FFs at a given input scale as well as and the propagation of the experimental uncertainties into them [2, 3, 4, 22, 23, 24]. The assessment of uncertainties of PDFs and also the corresponding observables have seen significant efforts in very recent QCD analyses (see for example [9, 10, 25, 26]). Among the different approaches in literature, the ‘‘Hessian method’’ [27, 28, 29] is the most reliable ones. The well-known and practical method ‘‘Hessian method’’, has been widely used to extract the uncertainties of the PDFs, polarized PDFs and nuclear PDFs as well as the corresponding observables in our previous analyses [30, 31, 32, 33, 34, 35, 36]. Since, the technical details of the Hessian approach are described in literature, we refer the readers to the mentioned references.

3. Results and discussions

In the following section, we turn to our numerical results for the global analysis of $D^{*\pm}$ -FFs from SIA data. The detailed discussions can be found in Ref. [14], then we will review some important findings. We present our NLO and NNLO FFs analyses for the charm and bottom densities in zero-mass variable flavor number scheme (ZM-VFNS).

The obtained $D^{*\pm}$ FFs and their uncertainties derived using Hessian approach are presented at the input scale $\mu_0^2 = 18.5 \text{ GeV}^2$ in Fig. 1 as well as for a higher values of $\mu^2 = 100 \text{ GeV}^2$ in Fig. 2. The results are correspond to the one- σ uncertainty bands. Our results in Fig. 2 are compared to the central value of KKKS08 analysis [17] as well as very recent analysis by AKSRV17 [13].

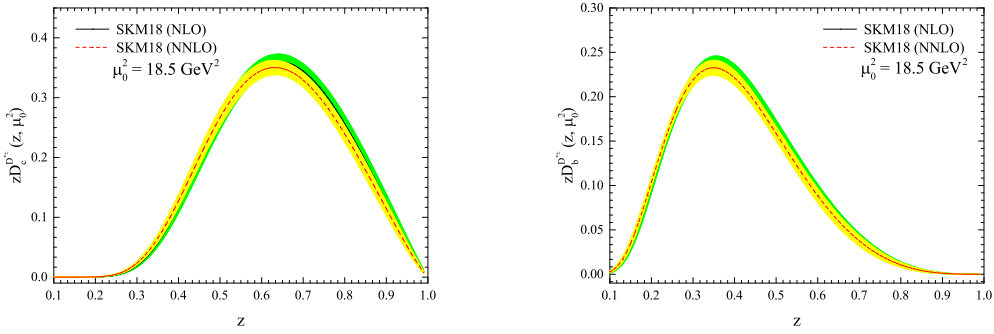


Figure 1: The obtained fragmentation densities and their uncertainties (shaded bands) are shown for the charmed-meson $zD_i^{D^{*\pm}}$ at the initial scale of $\mu_0^2 = 18.5 \text{ GeV}^2$ for c and b FFs both at NLO and NNLO accuracy.

As one can conclude from the presented results, the most difference between SKM18, KKKS08 as well as the AKSRV17 analysis is in the extracted gluon FF. The charm and bottom FFs from SKM18 analysis are in agreement with KKKS08 and AKSRV17, however the charm FF in KKKS08 are slightly higher than other.

4. Summary

In this article, we have presented the non-perturbative FFs of partons into the $D^{*\pm}$ -meson at NLO perturbative QCD as well as at NNLO. These sets of FFs have been obtained from global analyses of single-inclusive electron-positron (e^+e^-) annihilation data sets. In order to consider the heavy quark contributions, SKM18 analyses have been done in the ZM-VFN scheme in which all quarks are treated as massless partons. Our phenomenological analyses are significant in, at least, two major respects. Firstly, we applied all SIA experimental data sets in SKM18 NLO and NNLO QCD analyses. Secondly, for the first time, we considered the NNLO accuracy in SKM18 global fit. The obtained results show that SKM18 calculations at NNLO come with much smaller theoretical uncertainties relative to the NLO calculations which could reflect the stability of the NNLO analysis. In addition, we found that the experimental uncertainties for the $D^{*\pm}$ -FFs and SIA

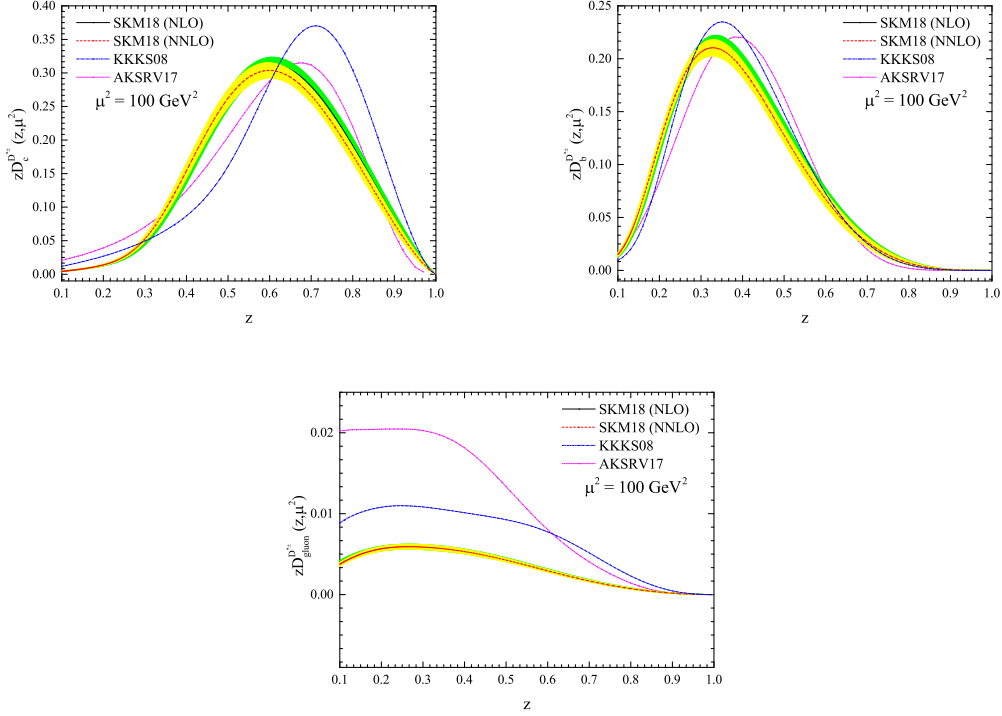


Figure 2: Fragmentation densities including their uncertainties (shaded bands) are shown for the charge meson $zD_i^{D^{*\pm}}$ at $\mu^2 = 100 \text{ GeV}^2$ for c , b and gluon FFs both at NLO and NNLO accuracy. SKM18 results are also compared with the KKKS08 analysis [17] as well as very recent analysis by AKSRV17 [13].

cross sections are similar in size both for the NLO and NNLO approximations. These findings are significantly in agreements with previous results reported in the literature. The theory prediction for the SIA cross section based on SKM18 $D^{*\pm}$ -meson FFs are in good agreements with all data analyzed.

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