NNLO charmed-meson fragmentation functions and their uncertainties in the presence of meson mass corrections

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Abstract

The main aim of this paper is to present new sets of non-perturbative fragmentation functions (FFs) for D^0 and D^+ mesons at next-to-leading (NLO) and, for the first time, at next-to-next-to-leading order (NNLO) in the $\overline{\text{MS}}$ factorization scheme with five massless quark flavors. This new determination of FFs is based on the QCD fit to the OPAL experimental data for hadroproduction in the electron-positron single-inclusive annihilation (SIA). We discuss in details the novel aspects of the methodology used in our analysis and the validity of obtained FFs by comparing with previous works in literature which have been carried out up to NLO accuracy. We will also incorporate the effects of charmed meson mass corrections into our QCD analysis and discuss the improvements upon inclusion of these effects. The uncertainties in the extracted FFs as well as in the corresponding observables are estimated using the "Hessian" approach. For a typical application, we use our new FFs to make theoretical predictions for the energy distributions of charmed mesons inclusively produced through the decay of unpolarized top quarks, to be measured at the CERN LHC. As a result of this analysis, suggestions are discussed for possible future studies on the current topic to consider any theory improvements and other available experimental observables.

Mechanism

1: Cross-section

$$\frac{d\sigma}{dx_D}(e^+e^- \to D + X) \quad = \quad \sum_{i=g,u/\bar{u},\cdots,b/\bar{b}} \int_{x_D}^1 \frac{dy}{y} D_i^D\left(\frac{x_D}{y}, \mu_F\right) \frac{d\sigma_i}{dy}(y, \mu_R, \mu_F)\,.$$

2: Parametrization Form

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

3: Definition of χ^2

$$\chi_n^2(p) = \sum_{i=1}^{N_n^{\text{data}}} \left(\frac{\mathcal{N}_n \mathcal{F}_{n,i}^{\text{exp}} - \mathcal{F}_{n,i}^{\text{theo}}(p)}{\mathcal{N}_n \Delta \mathcal{F}_{n,i}^{\text{exp}}}\right)^2$$

4: Experimental data

Table 1 The individual χ^2 values for inclusive and b-tagged cross sections obtained at NLO and NNLO. The total χ^2 and $\chi^2/d.o.f$ fit for D^0 are also shown

Collaboration	Data properties	$\sqrt{s}$ GeV	Data points	χ^2 (NLO)	χ^2 (NNLO)
OPAL	Inclusive	91.2	13	8.36	7.08
	b-tagged	91.2	13	14.62	14
Total: (χ^2/ d.o.f)			26	22.98	21.08
				1.149	1.05

Table 2 As in Table 1, but for D^+

Collaboration	Data properties	$\sqrt{s}$ GeV	Data points	χ^2 (NLO)	χ^2 (NNLO)
OPAL	Inclusive	91.2	13	7.24	6.2
	b-tagged	91.2	13	8.51	8.32
Total: (χ^2/ d.o.f)			26	15.75	14.52
				0.75	0.69

5: Mass corrections

$$\frac{d\sigma}{dx_H}(x_H, s) = \frac{1}{1 - \frac{m_H^2}{s\eta^2(x_H)}} \frac{d\sigma}{d\eta}(\eta(x_H), s),$$

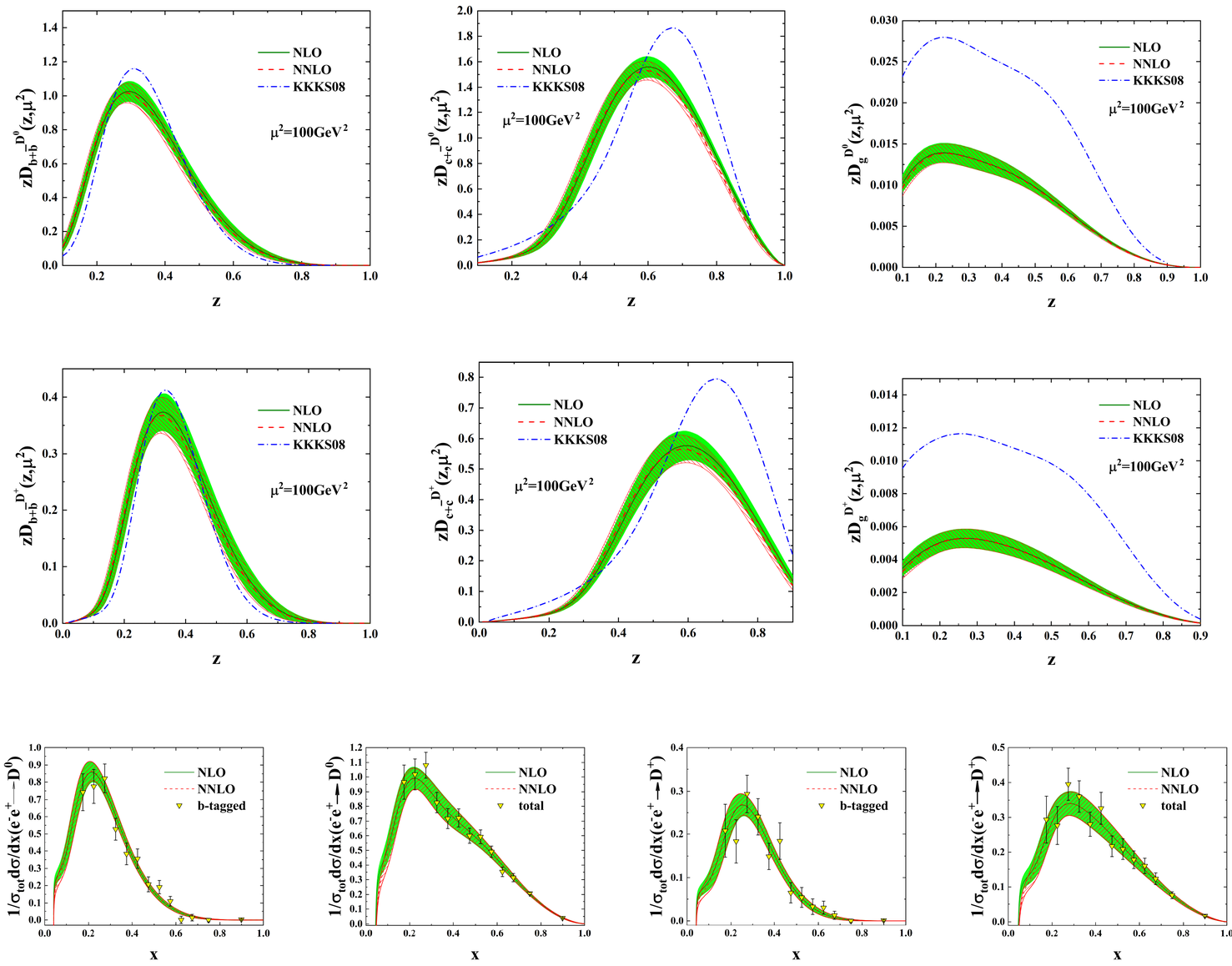
where $\eta = x_H/2 \times (1 - 4m_H^2/(sx_H^2))$ and

$$\frac{d\sigma}{d\eta}(\eta, s) = \sum_i \int_\eta^1 \frac{dy}{y} \frac{d\hat{\sigma}}{dy} D_i^H\left(\frac{\eta}{y}, \mu_F\right).$$

Reference

Eur. Phys. J. C **79**, no.12, 999 (2019) [arXiv:1904.09832 [hep-ph]].

Results



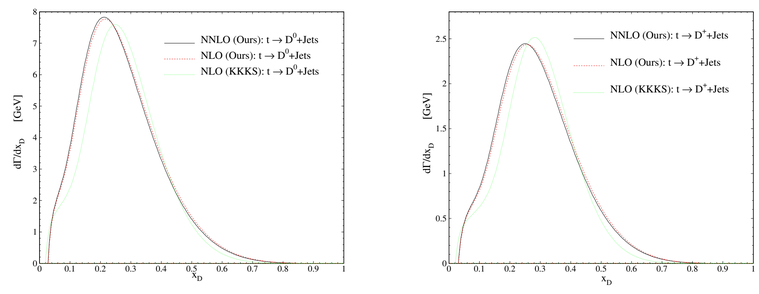
The application of FFs

1: Top quark decay

$$t \to b + W^+(g) \to W^+ + D^0/D^+ + X,$$

2: The energy distribution of charmed mesons

$$\frac{d\Gamma}{dx_D} = \sum_{i=b,g} \int_{x_i^{min}}^{x_i^{max}} \frac{dx_i}{x_i} \frac{d\Gamma}{dx_i}(\mu_R, \mu_F) \times D_i^{D^+}\left(\frac{x_D}{x_i}, \mu_F\right),$$



Discuss and Conclusion

In the present study, a new determination of nonperturbative FFs for D^0 and D^+ mesons are presented at NLO and, for the first time, at NNLO in perturbative QCD considering the hadron mass effects. Of all the available data sets for D^0 and D^+ productions in e^+e^- annihilation, i.e. OPAL, CLEO and Belle, the D^0/D^+-FFs are determined by fitting the data taken by the OPAL Collaboration at LEP, because the data from Belle is now removed due to an unrecoverable error in the measurements and including the CLEO data sets in the analysis might be a reason for tension.

Discuss and Conclusion

The uncertainties of extracted FFs and SIA cross sections are also estimated using the standard 'Hessian" approach. The determination of uncertainty includes the error estimation for the tolerance criterion of $\chi^2 = 1$. We judged the quality of our fit by comparing with the prior result presented by the KKKS08 Collaboration and also showed how they describe the available data for charmed meson productions. Considering the χ^2 values, we have shown that the inclusions of higher order QCD corrections and hadron mass effects could slightly improve the fit quality.

As a typical application of extracted FFs, we employed the NLO and NNLO FFs to make our theoretical predictions for the scaled-energy distributions of D^0/D^+-mesons inclusively produced in top quark decays.

To describe the novelty and innovation of our work, it should be noted that this study introduces the following improvements. It is one of the first attempts to contain higher order QCD corrections into the D^0/D^+ mesons FFs considering reliable data. The previous results, focused on the D-mesons FFs, are unreliable due to using the Belle data in their analyses. Our work also includes the effects of hadron mass corrections into the FF analysis. Hence, the findings of this paper could make several contributions to the current literature. For future study, it would be interesting to include other sources of experimental observables which carry more information on quark and gluon FFs. Apart from the data, this study is possible if other theoretica