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Heavy-flavor hadron decays producing muon cross sections in pp collisions at high transverse momentum

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The focus of this work was on investigating and comparing two methods for calculating the cross sections of muons produced by the decay of heavy-flavor hadrons in pp collisions, which cover the interval $2 < p_T < 20$ GeV/c at a center-of-mass energy of $\sqrt{s} = 7$ TeV. One method involves using the fixed-order plus next-to-leading logarithms (FONLL) approach to scale the measured p_T-differential cross section of muons from heavy-flavor hadron decay in pp collisions at a center-of-mass energy of $\sqrt{s} = 5.02$ TeV. The other method involves using FONLL calculations to extrapolate the published measured p_T-differential cross section at $\sqrt{s} = 7$ TeV to higher p_T. In these two methods, we can use the published measured p_T-differential cross section at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV, which cover the interval $2 < p_T < 20$ GeV/c and $2 < p_T < 12$ GeV/c, respectively. In terms of consistency within uncertainties, the results from both methods were compared not only to pQCD-based FONLL calculations but also to each other. Because they provide the necessary pp reference, these calculations are critical for determining the nuclear modification factor of muons from heavy flavor decays in heavy-ion collisions.

KEYWORDS

General properties of QCD, FONLL, heavy-flavor hadron decays, muon, cross sections, pp collisions, high transverse momentum

1 Introduction

The production of heavy quarks, due to their large mass, is a result of the initial hard parton scatterings that occur in high-energy collisions. The study of these events is conducted within the realm of perturbative quantum chromodynamics (pQCD), and the calculations are based on the factorization approach. The approach involves the evaluation of the hard parton scattering cross section as a perturbative series of the strong interaction's coupling constant, combined with the parton distribution function (PDF) of the fragmentation function of heavy quarks to heavy-flavor hadrons and the colliding protons. These production cross sections are predicted at the next-to-leading order using the fixed-order plus next-to-leading logarithms approach [1–4]. The systematic uncertainties in these theoretical production cross sections are dominated by uncertainties in renormalization and factorization scales. The results in the forward rapidity region ($2.5 < y < 4$) allow for a test of pQCD predictions in a region of small Bjorken x, which can reach as low as 10^{-5}, where the gluon distribution functions are affected by large uncertainties [5].

The comprehensive study of charm, beauty, and heavy-flavor hadron decay leptons, which has been conducted over a broad range of energies at the Tevatron, RHIC, and LHC ([6–17]), has shown that their production cross sections are in good agreement with pQCD-based predictions. This holds true both in the forward and central rapidity regions and across a wide range of transverse momentum (p_T). The precise measurement of heavy-flavor production cross sections in pp collisions serves as the foundation for exploring the impact of cold nuclear matter effects as well as effects associated with the hot and strongly interacting medium in proton–nucleus and nucleus–nucleus collisions. These studies are essential in gaining a deeper understanding of the properties of the quark–gluon plasma.

In this study, our primary sources of data are from ALICE, one is the muon production cross section of produced heavy-flavor hadrons in pp collisions at 7 TeV, which cover the interval 2< p_T < 12 GeV/c [19]. Another is the muon production cross section of produced heavy-flavor hadrons in pp collisions at 5.02 TeV, which cover the interval 2< p_T < 20 GeV/c [20]. The results encompass the range 2< p_T < 20 GeV/c, with the beauty contribution being predominant over the charm contribution at high transverse momenta (p_T > 5 GeV/c) [4]. Furthermore, the present results have been obtained in a much broader p_T range than earlier ALICE results for cross sections of muons from heavy-flavor hadron decays [18, 19].

Our article is organized as follows: in Section 2, we give a brief introduction to the FONLL prediction and uncertainty propagation. In Section 3, we show the energy scaling and p_T extrapolation method to calculate heavy-flavor hadron decays producing muon cross sections in $\sqrt{s}$ = 7 TeV pp collisions at high transverse momentum. In Section 4, we present the forward rapidity transverse momentum muon cross section for energy scaling and the p_T extrapolation method. Furthermore, we show that the results from the energy scaling and p_T extrapolation method are consistent, within uncertainty. Finally, a summary is given in Section 5.

2 Fixed-order plus next-to-leading logarithms prediction and uncertainty propagation

2.1 Fixed-order plus next-to-leading logarithms

The FONLL approach is widely used in high-energy physics to study the properties of heavy-flavor hadrons, such as charm and beauty mesons, and to make predictions of their differential decay rates into muons. Predictions for c and b quark production at the LHC have been presented in [4]. Recently, the ALICE collaboration has produced comparisons of distributions of leptons from heavy hadrons with FONLL predictions, i.e., muons in the forward rapidity region 2.5 < y < 4 [20] and electrons in the central region $|y|$ < 0.8 [21].

In the FONLL [7] framework, the fixed order (FO) and next-to-leading logarithms (NLL) calculations are combined [1]. Schematically, the FONLL matching can be written as

$$\text{FONLL} = \text{FO} + (\text{RS} - \text{FOM0}) \times G(m_Q, p_T), \quad (1)$$

where FO is the massive NLO calculation, RS is the massless resummed calculation, and FOM0 is the massless limit of FO. The subtraction of the massless limit FOM0 from the resummed (RS) approach ensures the $\alpha_s \log(p_T/m)$ terms, present in both the fixed-order (FO) and RS calculations, are not double-counted. The function $G(m_Q, p_T)$ is a damping function that serves to prevent artificially massless higher-order terms from providing an unphysically large contribution to the cross-section calculation.

2.2 Uncertainty determination at the muon level with FONLL

Figure 4 shows the p_T-differential production cross section at the muon level for charm and beauty, which has been obtained by taking into account the fragmentation and semi-muonic decays with the appropriate branching ratios.

There are three kinds of muon sources for the processes of heavy flavor hadron decay muons ($\mu \leftarrow c, b$):

1. Muons from charm quarks: this source of muons is generated through the decay of charm quarks, with the decay chain represented as $\mu \leftarrow D \leftarrow c$.
2. Muons from beauty quarks: this source of muons is generated through the decay of beauty quarks, with the decay chain represented as $\mu \leftarrow B \leftarrow b$.
3. Muons from the indirect decay of beauty quarks: this source of muons is generated through the indirect decay of beauty quarks, with the decay chain represented as $\mu \leftarrow D \leftarrow B \leftarrow b$.

We named these three kinds of muons as charm μ, beauty μ, and feed down μ, respectively. In order to make a fair comparison with experimental data, it is necessary to sum the production cross sections for all three types of muons. However, the uncertainties associated with each of these sources are not independent, so a straightforward quadratic propagation of errors is not possible. The procedure outlined in [22] is utilized for the proper propagation of uncertainties:

1. The central values of the production cross section of these three kinds of muons are combined to obtain the central value of the production cross section for muons from open heavy-flavor decays.
2. When determining the masses of quarks, it is possible to choose three distinct values for both m_c and m_b, resulting in a total of nine distinct combinations. By analyzing the maximum and minimum differences between these combinations, along with the central cross section value, it is feasible to derive the upper and lower bounds of uncertainty associated with the quark masses.
3. By independently adjusting the QCD scales for muons originating from charm and those from beauty (the beauty μ and feed down μ) while keeping the other parameters unchanged, it is possible to estimate the upper and lower uncertainties from the QCD scales, σ^{max}_{scales} and σ^{min}_{scales}. For each case, there are seven combinations of renormalization scales (μ_R) and factorization scale (μ_F) values which satisfy the conditions $0.5\mu_0 < \mu_R, \mu_F < 2\mu_0$, $0.5 < \mu_R/\mu_F < 2$ [1]. μ_0 is obtained by quadratically adding p_T at the parton level and quark mass. Finally, by combining the charm and beauty together, we can get a total of 49 combinations for the QCD scales by mixing the QCD scales.

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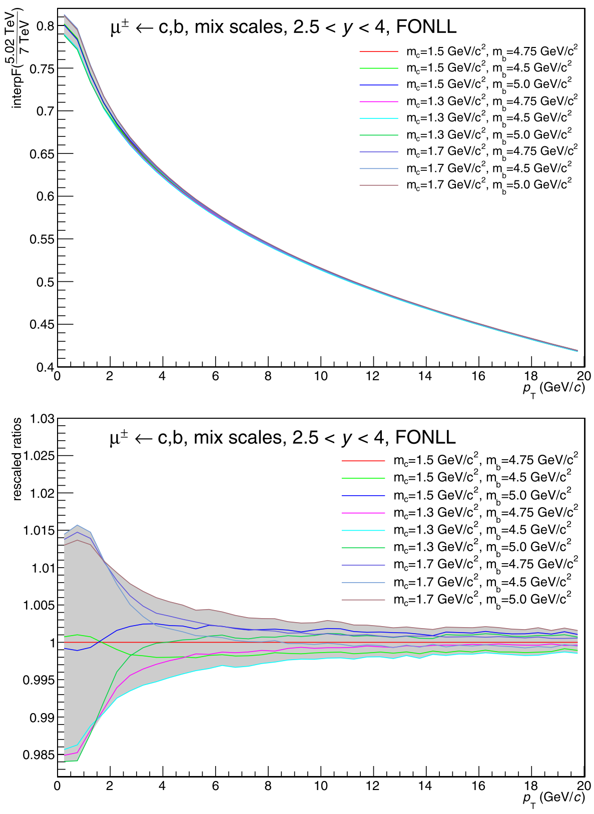

FIGURE 1
Upper: FONLL scaling factor from 5.02 TeV to 7 TeV for the measurement of the p_T-differential cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in pp collisions with different combinations of quark masses indicated in the figure. Bottom: corresponding relative systematic uncertainty.

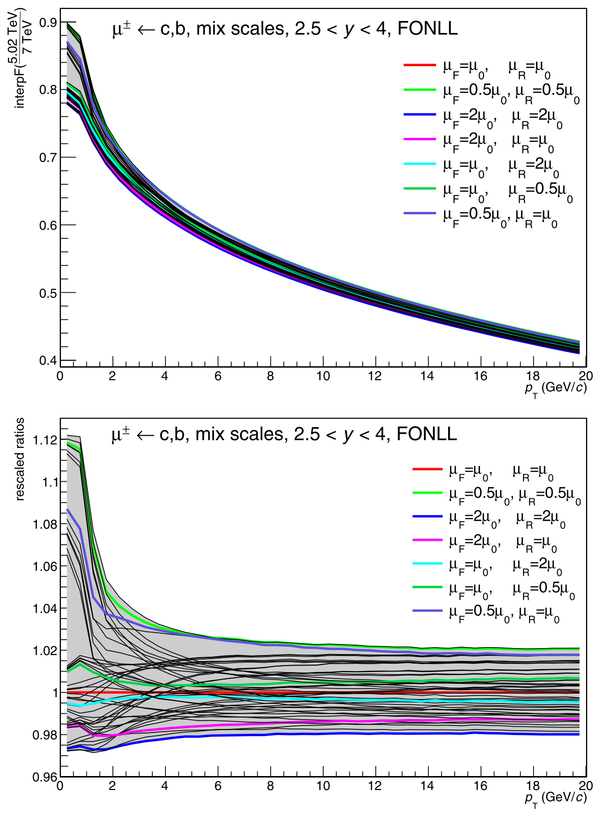

FIGURE 2
Upper: FONLL scaling factor from 5.02 TeV to 7 TeV for the measurement of the p_T-differential cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in pp collisions with different combinations of QCD scales, as indicated in the figure. Bottom: corresponding relative systematic uncertainty.

After completing all of the aforementioned steps, the upper and lower uncertainties of the production cross sections of muons from heavy-flavor decays are obtained by quadratically adding the corresponding quark masses and QCD scales uncertainties. Because the QCD scales and quark masses uncertainties dominate in our chosen p_T region, the uncertainties from PDFs are negligible in this work.

3 Energy scaling and p_T extrapolation method

3.1 pp reference at $\sqrt{s}$ = 7 TeV: energy scaling

In order to obtain the reference cross section at $\sqrt{s} = 7$ TeV, the scaling factor that will be applied to the p_T-differential cross section of muons from heavy-flavor decays measured in pp collisions at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 7 TeV is calculated using FONLL predictions [22]. Figure 1 shows the scaling factor obtained by combining different sets of c and b quark masses and assuming that quark masses are unchanged at 5.02 TeV and 7 TeV. The scaling factor depends on p_T, in particular in the low p_T range ($p_T < 2$ GeV/c). It decreases from approximately 0.7 to 0.4 in the p_T range 2–20 GeV/c (Figure 1, upper panel). The relative uncertainty with different combinations of quark masses is depicted in the bottom panel of Figure 1. Changes in the quark masses introduce a systematic uncertainty smaller than 1% for $2 < p_T < 20$ GeV/c.

The influence of the pQCD scale variations on the FONLL scaling factor was investigated in two cases: 1) the seven combinations for the QCD scales by mixing the QCD scales if we use the same scales for charm and beauty (correlated scales, colored lines in Figure 2) and 2) the 42 combinations for the QCD scales by mixing the QCD scales if we use different scales for charm and beauty (uncorrelated scales, black lines in Figure 2). At low p_T ($p_T < 2$ GeV/c), the uncertainty of the scaling factor reaches approximately 12%, while in the interval $2 < p_T < 20$ GeV/c, it is smaller than 4%.

In summary, the FONLL scaling factor, as a function of p_T, obtained for different sets of quark masses (green boxes) and pQCD scales (red boxes), as just discussed, is shown in Figure 3 (upper panel). The relative systematic uncertainty of the scaling factor is also shown in the bottom panel of the figure (gray band); we can observe that the QCD scale uncertainty evidently dominates over the quark mass uncertainties.

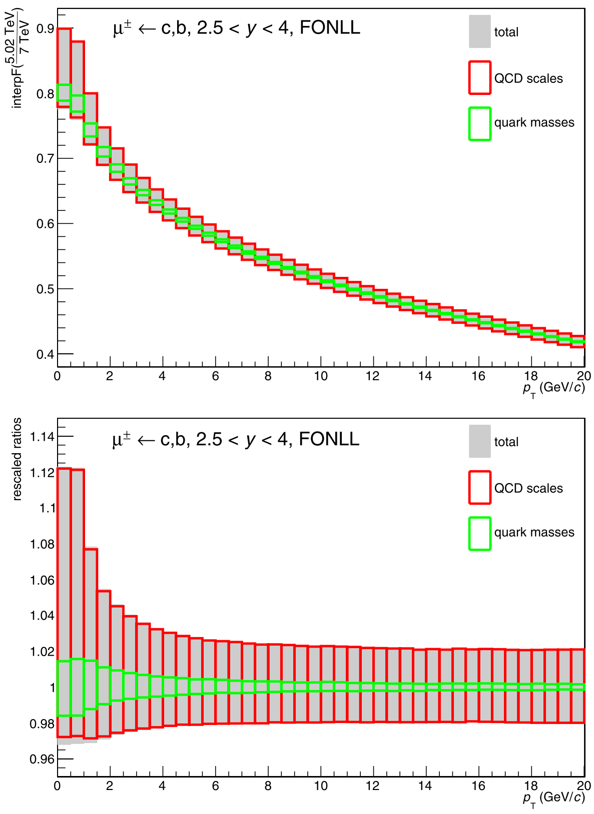

FIGURE 3
Upper: FONLL scaling factor from 5.02 TeV to 7 TeV for the measurement of the p_T-differential cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in pp collisions with different combinations of QCD scales (red boxes) and quark masses (green boxes). The gray band is the total systematic uncertainty. Bottom: corresponding relative systematic uncertainty.

3.2 pp reference at $\sqrt{s}$ = 7 TeV: p_T extrapolation

The p_T-differential cross section of heavy-flavor decay muons in $2 < p_T < 12$ GeV/c in pp collisions at $\sqrt{s}$ = 7 TeV is published [19]. We use FONLL calculations to extrapolate the published measured p_T-differential cross section in a higher p_T region.

First, we determine the ratio between the published $\sqrt{s}$ = 7 TeV data and FONLL; the error of this ratio point combines uncertainty from data and FONLL. Then, we use a constant line to fit the ratio between data and FONLL in different ranges: $2 < p_T < 12$ GeV/c, $3 < p_T < 12$ GeV/c, and $4 < p_T < 12$ GeV/c.

Different fit ranges were used to extract the $K_{7\mathrm{TeV}}$ factor, as reported in Table 1. Finally, the pp reference in the $12 < p_T < 20$ GeV/c range is obtained using the $K_{7\mathrm{TeV}}$ value (Table 1), which is 1.28. Then, the pp reference in the p_T extrapolated region is

$$\frac{d\sigma^{\mu\leftarrow HF}_{pp(7TeV)}}{dp_T} = K_{7TeV} \times \frac{d\sigma^{FONLL}_{pp(7TeV)}}{dp_T}. \quad (2)$$

TABLE 1 Scaling factor $K_{7\mathrm{TeV}}$ to extrapolate the measured pp reference to the high p_T region.

GeV/c	2–12	3–12	4–12
$K_{7\mathrm{TeV}}$	1.28	1.26	1.25

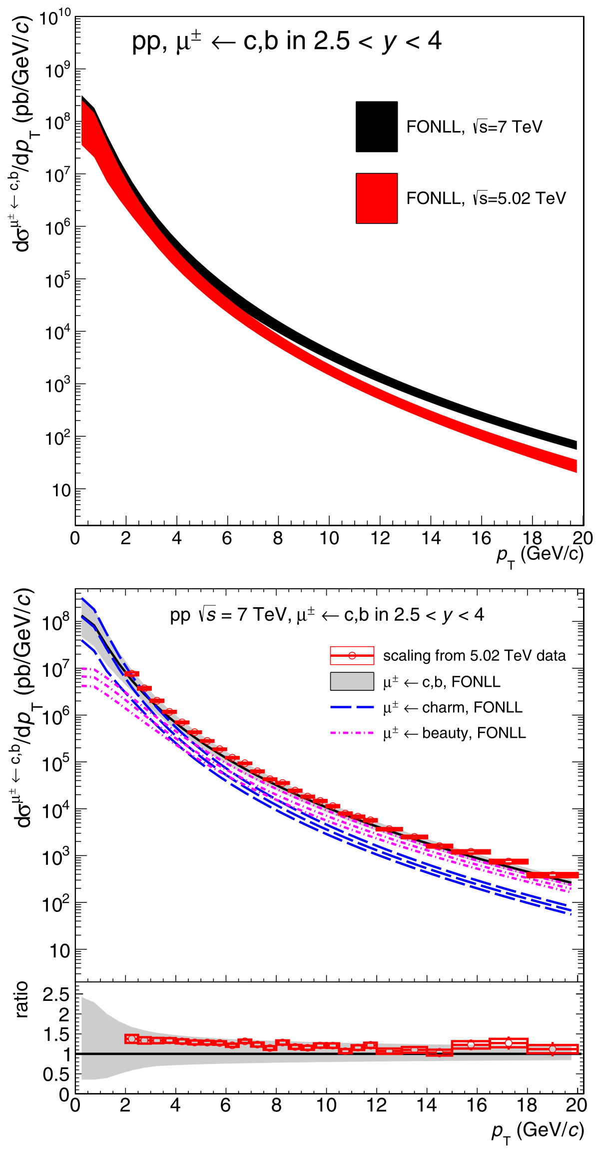

FIGURE 4
Upper: p_T-differential cross section of muons from heavy-flavor hadron decays in pp collisions at $\sqrt{s}$ = 5.02 TeV and 7 TeV from FONLL. Bottom: p_T-differential cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in $\sqrt{s}$ = 7 TeV pp collisions with the energy scaling method.

4 Results and discussion

The upper panel of Figure 4 displays the production cross section of muons from heavy-flavor decays in pp collisions at 5.02 TeV and 7 TeV, obtained from FONLL predictions. The p_T-differential cross section of muons from heavy-flavor hadron decays at $\sqrt{s}$ = 7 TeV, which covers $2 < p_T < 20$ GeV/c, is shown in the bottom panel of Figure 4. The energy

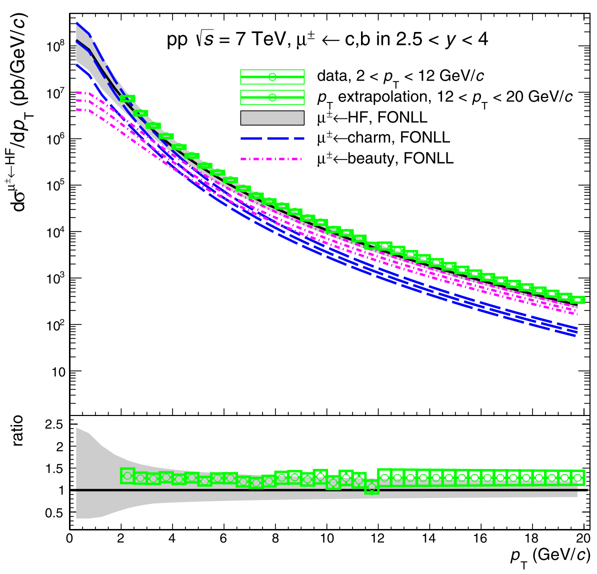

FIGURE 5
Heavy-flavor hadron decay muons that cover the interval $2 < p_T < 12$ GeV/c at $\sqrt{s}$ = 7 TeV are from published measurements [19]; then, we calculate the heavy-flavor hadron decay muons that cover the interval $12 < p_T < 20$ GeV/c at $\sqrt{s}$ = 7 TeV using the p_T extrapolation method.

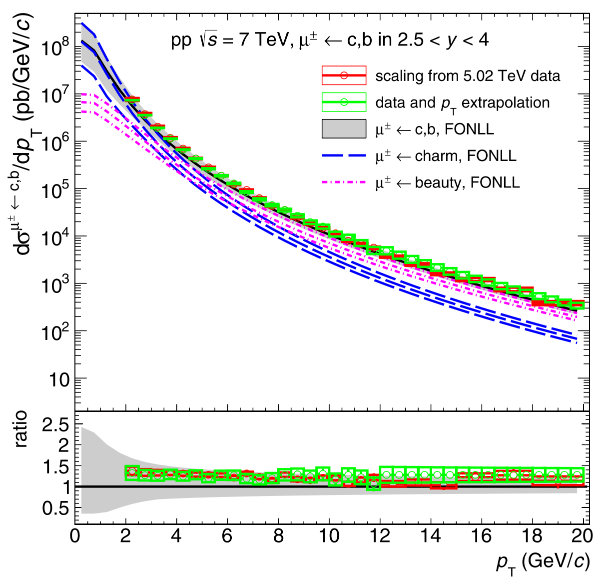

FIGURE 6
p_T-differential cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in $\sqrt{s}$ = 7 TeV pp collisions with energy scaling and the p_T extrapolation method.

scaling factor is calculated from the ratio between FONLL predictions and published measurements (Section 3.1). The uncertainty of heavy-flavor hadron decay muons p_T-differential cross section at $\sqrt{s}$ = 7 TeV covers $12 < p_T < 20$ GeV/c and does not include the uncertainty from 5.02 TeV data; its uncertainty is also contained in FONLL calculations with different sets of factorization and renormalization scales and quark masses, which is discussed in Section 3.1 (see also Ref. [22]).

The results are in agreement with FONLL calculations within uncertainties, although the data lie at the upper limit of the model predictions, as already observed at other center-of-mass energies.

With the p_T extrapolation method, the p_T-differential cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in pp collisions at $\sqrt{s}$ = 7 TeV is shown in Figure 5. In the extrapolated region, $12 < p_T < 20$ GeV/c, the systematic uncertainty of the pp reference includes the uncertainty of the scaling factor $K_{7\text{TeV}}$ and that of FONLL calculations (quark masses, QCD scales). The total uncertainty is within 16%–19% in the whole p_T range, $12 < p_T < 20$ GeV/c, depending on p_T.

5 Summary

In summary, with the published measurements and FONLL predictions, we use the energy scaling and p_T extrapolation method to calculate the cross section of muons from heavy-flavor hadron decays at forward rapidity ($2.5 < y < 4$) in pp collisions at $\sqrt{s}$ = 7 TeV. As compared to previously published measurements, which cover the p_T range from 2 to 12 GeV/c, the present results have an extended p_T coverage, $2 < p_T < 20$ GeV/c. These results provide an important reference for the study of the effects of hot and dense matter on the production of muons from heavy-flavor hadron decays in heavy-ion collisions at the same center-of-mass energy. We also compare the results based on two methods with theoretical model predictions. The results in Figure 6 show that, within the error range, the two results are consistent with each other and agree well with the pQCD calculations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

ZZ analyzed the simulation data and wrote the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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