

Fully charmed tetraquark production in forward rapidity pp collisions at LHC and FCC energies

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(Received 30 November 2025; accepted 24 February 2026; published 9 March 2026)

In this paper, we investigate the production of a fully charmed tetraquark state T_{4c} in pp collisions at forward rapidities through the fragmentation mechanism considering the color glass condensate formalism and the solution of the running coupling Balitsky-Kovchegov equation. The contributions of gluon- and charm-initiated processes are taken into account, and the impact of an intrinsic charm component in the proton's wave function is estimated. Predictions for the transverse momentum distribution of the T_{4c} state are presented assuming different rapidities, distinct quantum numbers of the state and center-of-mass energies. Our results indicate that the higher cross section is associated with the production of a tensor state $T_{4c}(2^{++})$, which is dominated by the gluon-initiated process. In contrast, the production of the axial-vector state $T_{4c}(1^{+-})$ is dominated by the charm-initiated process and is very sensitive to the presence (or not) of an intrinsic charm.

DOI: [10.1103/tq47-w7jn](https://doi.org/10.1103/tq47-w7jn)

I. INTRODUCTION

Since the proposition of the quark model in 1964, by Gell-Mann [1] and Zweig [2], the possible existence of exotic hadrons, composed of four or five quarks, has been largely discussed in the literature (for reviews see, e.g., Refs. [3,4]). In particular, exotic hadrons composed entirely of heavy quarks were originally investigated more than four decades ago in Refs. [5–7]. Despite extensive experimental searches, the first candidate of a fully charmed tetraquark state, denoted T_{4c} , was only observed in 2020 by the LHCb Collaboration in the double J/ψ invariant-mass spectrum [8] and later confirmed by both the ATLAS and CMS Collaborations [9,10]. Such observations have motivated significant efforts focused on the description of the

mass spectra and decay properties of T_{4c} , as well as on the understanding of its dynamical production mechanism, which still is an open question and remains a challenging problem in high-energy physics.

Over the last years, several approaches have been proposed to describe the T_{4c} production in pp , pA , AA , ep , e^+e^- , and $\gamma\gamma$ collisions [11–35]. In particular, the nonrelativistic QCD (NRQCD) framework [36–38] has been used to estimate the fully charmed tetraquark production in hadronic collisions, mainly motivated by the fact that its lowest Fock state $|cc\bar{c}\bar{c}\rangle$ does not receive contributions from valence light quarks and dynamical gluons, justifying the factorization of long-distance dynamics. Such studies have been performed using the collinear factorization approach and have demonstrated that the fragmentation mechanism, where the T_{4c} state is generated through the $g \rightarrow T_{4c}$ and $c \rightarrow T_{4c}$ transitions, becomes dominant for $p_T \gtrsim 20$ GeV [18,33,34], in analogy with heavy-quarkonium production [39,40]. These analyses have focused on the T_{4c} production at central rapidities, where the light cone momentum fractions of the colliding partons are similar ($x_1 \approx x_2 \approx M_{T_{4c}}/\sqrt{s}$). In contrast, at forward rapidities, the fully charmed tetraquark production is expected to be dominated by collisions of projectile partons with

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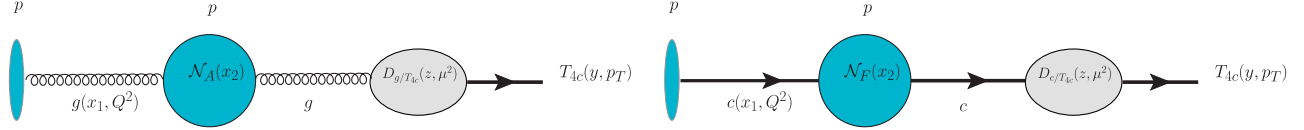


FIG. 1. Gluon- (left) and charm- (right) initiated contribution for the production of a T_{4c} state with transverse momentum p_T and rapidity y in pp collisions.

large light cone momentum fractions ($x_1 \rightarrow 1$) with target partons carrying a very small momentum fraction ($x_2 \ll 1$). In this kinematical region, small- x effects in the description of the QCD dynamics [41] and new large- x contributions to the projectile wave function [42], not taken into account in these previous studies, are expected to become important.

In this paper, we will investigate, for the first time (to the best of our knowledge), the impact of small- and large- x effects on the T_{4c} production. In particular, we will consider the nonlinear corrections to the QCD dynamics, as described by the color glass condensate (CGC) formalism [43], and the possibility that an intrinsic charm component could be present in the projectile wave function, which enhance the probability of finding a charm quark carrying a large momentum fraction x_1 of the projectile hadron. Our analysis is motivated by the recent evidences of an intrinsic charm (IC) component in the proton's wave function [44–46] and by studies performed in Refs. [47–52] that have demonstrated that this contribution can become dominant in the heavy meson production at ultraforward rapidities. In particular, following Ref. [53], we will estimate the contribution of the fragmentation mechanism for the T_{4c} meson production cross section at forward rapidities using the CGC formalism and taking into account gluon-initiated (GI) and charm-initiated (CI) contributions, which can be represented schematically as follows (see Fig. 1):

$$\sigma(pp \rightarrow T_{4c}X) \propto g(x_1, Q^2) \otimes \mathcal{N}_A(x_2) \otimes D_{g/T_{4c}} + c(x_1, Q^2) \otimes \mathcal{N}_F(x_2) \otimes D_{c/T_{4c}}, \quad (1)$$

where $g(x_1, Q^2)$ and $c(x_1, Q^2)$ are the collinear gluon and charm parton distribution functions (PDFs) of the projectile proton, $D_{g/T_{4c}}$ and $D_{c/T_{4c}}$ are the collinear gluon and charm fragmentation functions (FFs) into the T_{4c} state, and the functions $\mathcal{N}_A(x_2)$ and $\mathcal{N}_F(x_2)$ are the adjunct and fundamental forward scattering amplitudes, which encodes all the information about the hadronic scattering and thus about the nonlinear and quantum effects in the hadron wave function. Such amplitudes will be estimated using the CGC formalism, by solving the running coupling Balitsky-Kovchegov (rcBK) equation [54,55]. The first term in Eq. (1) can be associated with the $gg \rightarrow gg$ subprocess and is expected to dominate at high center-of-mass energies and central rapidities. The charm-initiated contribution is, in general, negligible in this same kinematical region. However, the recent results obtained in Ref. [53] for the D meson production at forward rapidities indicated

that this contribution becomes important, especially if an intrinsic charm component is present. One of our goals is to investigate if this conclusion is also valid for the T_{4c} case. In our analysis, we will consider that projectile PDFs are given by the parametrizations derived by the CTEQ and NNPDF groups in Refs. [56–58], with and without the presence of an intrinsic charm component, and a detailed comparison between the associated predictions will be performed. Moreover, we will assume that the FFs for the transition of a charm or a gluon into a T_{4c} state are described by the TQ4Q1.1 parametrization provided in Refs. [33,34,59], which allow us to derive predictions for the three lowest Fock-state T_{4c} configurations: scalar ($J^{PC} = 0^{++}$), axial vector ($J^{PC} = 1^{+-}$), and tensor ($J^{PC} = 2^{++}$). Using these ingredients, we will derive predictions for the transverse momentum distributions associated with the T_{4c} production in pp collisions at the energies of the Large Hadron Collider (LHC) and of the proposed Future Circular Collider (FCC) [60–62].

This paper is organized as follows. The next section presents a brief review of the formalism used to estimate the T_{4c} meson production at forward rapidities together with the main ingredients in the calculations of the GI and CI contributions. In particular, we discuss the distinct models for the treatment of the intrinsic charm component and the initial condition of the BK equation used in our analysis, as well as the modeling of the FFs. In Sec. III, we present results for the transverse momentum distribution associated with the T_{4c} meson production in pp collisions at the LHC and FCC energies. Finally, in Sec. IV, we summarize our main results and conclusions.

II. T_{4c} PRODUCTION IN THE FORWARD REGION AT HIGH ENERGIES

In recent years, the T_{4c} production in pp collisions has been investigated considering the collinear factorization, where all partons involved are assumed to be on mass shell, carrying only longitudinal momenta, and their transverse momenta are neglected in the QCD matrix elements [63]. However, the studies of heavy meson production in hadronic collisions, have demonstrated that at high energies the effects of a finite transverse momenta of the incoming partons and nonlinear corrections to the QCD dynamics become important, motivating the proposition of generalized factorization schemes that take into account these effects (see, e.g., Refs. [64–68]). Following Refs. [47,53], we will consider the hybrid factorization scheme [69,70],

which is adequate to describe the scattering of a dilute projectile off a dense target, which is the scenario present at forward rapidities.

As discussed in the Introduction, we will assume that the contribution associated with the fragmentation mechanism

for the T_{4c} production will receive the contribution of GI and CI processes. For the GI contribution, represented in the left panel of Fig. 1, the differential cross section for the production of a T_{4c} state with transverse momentum p_T at rapidity y is expressed in the hybrid formalism by [69,70]

$$\left. \frac{d\sigma_{pp \rightarrow T_{4c}X}}{dy d^2 p_T} \right|_{GI} = \frac{\sigma_0}{2(2\pi)^2} \int_{x_F}^1 dx_1 \frac{x_1}{x_F} \left[g(x_1, Q^2) \tilde{\mathcal{N}}_A \left(\frac{x_1}{x_F} p_T, x_2 \right) D_{g/T_{4c}} \left(z = \frac{x_F}{x_1}, \mu^2 \right) \right], \quad (2)$$

where σ_0 is a constant obtained by fitting the hadron-elektron-ringanlage (HERA) data (see below), $x_{1,2}$ represent the momentum fractions of the projectile and target partons that interact in the scattering process, and x_F is the Feynman x of the produced meson, which are defined by

$$x_{1,2} = \frac{p_T}{z\sqrt{s}} e^{\pm y} \quad \text{and} \quad x_F = x_1 - x_2. \quad (3)$$

On the other hand, for the CI contribution, we will consider the approach proposed in Ref. [47] and rederived in the hybrid formalism in Ref. [70], which implies that the associated differential cross section is given by [47]

$$\left. \frac{d\sigma_{pp \rightarrow T_{4c}X}}{dy d^2 p_T} \right|_{CI} = \frac{\sigma_0}{2(2\pi)^2} \int_{x_F}^1 dx_1 \frac{x_1}{x_F} \left[c(x_1, Q^2) \tilde{\mathcal{N}}_F \left(\frac{x_1}{x_F} p_T, x_2 \right) D_{c/T_{4c}} \left(z = \frac{x_F}{x_1}, \mu^2 \right) \right]. \quad (4)$$

The basic idea is that the incident parton (gluon or charm quark) present in the wave function of the incident proton, described by its PDFs, scatters off with the color background field of the target proton and then fragments into a T_{4c} meson. The interaction is described by the quantities $\tilde{\mathcal{N}}_A$ and $\tilde{\mathcal{N}}_F$, which are the Fourier transform of the adjoint and fundamental forward scattering amplitudes that satisfy the rcBK equation. Finally, $D_{g/T_{4c}}$ and $D_{c/T_{4c}}$ are the gluon and charm FF in a T_{4c} state. Some comments are in order here. First, in this paper we are using the hybrid formalism at the leading order, which have been successful in describing, at least qualitatively, the different particle production spectra at forward rapidities. In recent years, different groups have worked on the calculation of the next-to-leading-order (NLO) corrections to this formalism in order to achieve an accurate description of data. The first results have obtained uncontrolled large NLO corrections in the high transverse momentum region, where p_T becomes much larger than the saturation scale, implying a negative cross section [71–73]. Such result has motivated more detailed studies [74–81], which have proposed different approaches to solve this problem and that predict positive cross sections at large p_T , as the leading-order (LO) solution. In particular, the results derived in Ref. [80] using the resummation formalism indicate that the inclusion of these NLO corrections increases the normalization of the predictions for the light hadron production at forward rapidities in comparison to the LO results, improving the description of data. However, the impact of the NLO corrections on the heavy hadron production is still an open question that deserves a more detailed analysis. A second

comment is that our focus will be on pp collisions, but the formalism presented in this paper can be generalized for a nuclear target (e.g., pPb collisions) by considering the solution of the BK equation for the nuclear case. However, in this case, the results derived, e.g., in Ref. [81] indicate that, in order to describe the nuclear modification factor R_{pPb} and obtain the expected behavior at large p_T , $R_{pPb} \rightarrow 1$, the NLO corrections must be taken into account. Finally, another important aspect that must be emphasized is that some further theoretical efforts [82–87] have been recently performed to go beyond the eikonal approximation assumed in the LO and NLO calculations discussed above. These studies indicated that such next-to-eikonal corrections are important to match the hybrid formalism with the collinear approach at large p_T . In principle, the inclusion of these corrections are expected to modify our predictions, but its impact is still unclear. Surely, such topic deserves to be investigated in the future. In what follows, we will describe in more detail the ingredients used in our calculations, which are performed at leading order and that assume the validity of the eikonal approximation.

A. The parton distribution functions

Over the last decade, the combination of the high precision measurements performed in ep collisions at HERA with LHC data have allowed largely improve the description of the proton structure [88]. Such results imply that the gluon distribution dominates at small values of the Bjorken- x variable, while for large x the proton structure is determined by valence quarks. In addition, sea quarks

created by the QCD evolution are also present. In particular, such evolution also generates $c\bar{c}$ pairs, implying a charm content within the proton, usually denoted as the extrinsic charm component. Recent results also indicate the presence of an intrinsic charm component in the proton wave function [44–46]. The existence of the IC component was first proposed long ago by Brodsky *et al.* (BHPS) in Ref. [89] and since then other models for IC have been discussed [90–93]. The basic idea is that the proton light cone wave function has higher Fock states, one of them being $|qqqc\bar{c}\rangle$, with the probability of finding this configuration given by the inverse of the squared invariant mass of the system. Moreover, the presence of an IC component implies a large enhancement of the charm distribution at large x (> 0.1), which has impact on the production of heavy mesons at forward rapidities. The studies performed in Refs. [47–53], for the case of D meson production in pp collisions, have demonstrated that the charm initiated a contribution is negligible for central rapidities, but becomes important for forward rapidities and can dominate if an intrinsic component of charm is present in the proton's wave function. Such results motivate the analysis of the impact of the IC component on the T_{4c} production.

In our analysis, we will consider the PDFs obtained in the global analysis performed in Refs. [56–58], with and without the presence of an intrinsic charm component in the proton wave function. Although these two groups have basically used the same set of data, the parametrizations have been derived using distinct methodologies and different assumptions for the initial conditions. As a consequence, they predict different behaviors for the charm and gluon distributions, as can be verified in Fig. 2, where we present a comparison between the charm and gluon PDFs predicted by the CT18 (left panel) and NNPDF (right

panel) parametrizations for a fixed hard scale $Q = 2m_c$. The parametrizations that assume a presence of an IC component (CT18FC BHPS and NNPDF40 IC) imply an enhancement of the charm distribution at large x (> 0.1) (lower curves in Fig. 2) in comparison to the no IC predictions (CT18NLO no IC and NNPDF40 PC). We have that the corresponding gluon distributions are also modified by the inclusion of intrinsic charm, as observed in the upper curves of Fig. 2. Moreover, we have that the amount of charm quarks at large x is larger in the NNPDF40 parametrization in comparison to the CT18FC one. In the next section, we will calculate the T_{4c} production at large rapidities assuming these distinct parametrizations, which will allow us to estimate the dependence of our predictions on the choice of PDF for the projectile proton, as well as the impact of an intrinsic charm component on the transverse momentum distributions. The bands in Fig. 2 illustrate the PDF-related uncertainties at the input energy scale $Q = 2m_c$.

B. The scattering amplitudes

For the adjunct and fundamental forward dipole scattering amplitude, we will consider that both quantities are related in the impact parameter space by the relation $\mathcal{N}_A(x, r) = 2\mathcal{N}_F(x, r) - \mathcal{N}_F^2(x, r)$, where r is the dipole size, and estimate $\mathcal{N}_F(x, r)$ by solving the BK equation [54,55] including running coupling corrections [94], denoted rcBK, which represents the simplest nonlinear evolution equation for the dipole-hadron scattering amplitude, being actually a mean field version of the first equation of the Balitsky hierarchy [54]. We will consider the solution obtained assuming an initial condition inspired by the McLerran and Venugopalan (MV) [95] model, given by

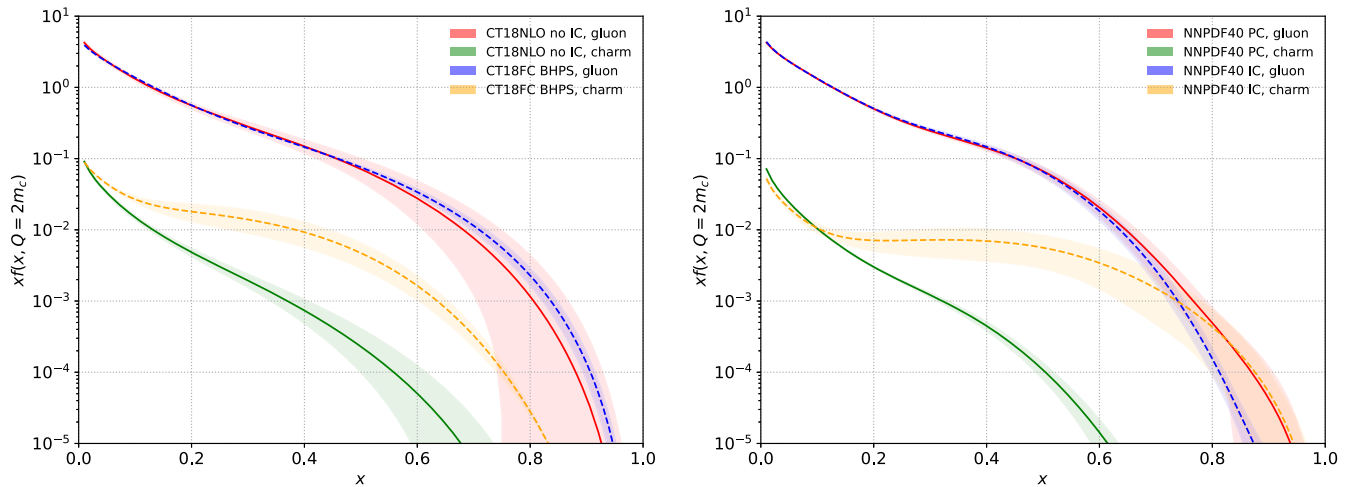


FIG. 2. Predictions of the different intrinsic charm models for the x dependence of the charm (lower blue curves) and gluon (upper red curves) distributions, as obtained by the CT18 (left) and NNPDF (right) parametrizations [56,57].

$$\mathcal{N}_F(x_0 = 0.01, r) = 1 - \exp \left[-\frac{(r^2 Q_{s,0}^2)^\gamma}{4} \ln \left(\frac{1}{\Lambda r} + e \right) \right] \quad (\text{MV-like}), \quad (5)$$

where $\Lambda = \Lambda_{\text{QCD}}(n_f = 3)$ and the free parameters, the initial saturation scale $Q_{s,0}$, and the anomalous dimension γ have been determined by fitting the HERA data [96,97]. As in Refs. [53,98,99], we will assume a MV-like initial condition with $Q_{s,0}^2 = 0.1597 \text{ GeV}^2$ and $\gamma = 1.118$. Moreover, we will assume the values of σ_0 obtained in Ref. [97]. For a more detailed discussion about the scattering amplitudes, we refer the interested reader to Ref. [53].

C. The TQ4Q1.1 fragmentation functions

Finally, the gluon and charm FFs employed in this work are taken from the recent TQ4Q1.1 determinations [33,34,59]. These functions describe the collinear fragmentation of gluons and heavy quarks into fully heavy tetraquarks in the three lowest Fock-state configurations: scalar ($J^{PC} = 0^{++}$), axial vector ($J^{PC} = 1^{+-}$), and tensor ($J^{PC} = 2^{++}$). They are constructed from initial-scale inputs [18,28] calculated within the NRQCD effective theory [36–38], assuming single-parton fragmentation at leading power, and evolved through a threshold-consistent next-to-leading-order Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution implemented in the heavy-flavor nonrelativistic evolution scheme [100,101]. This hybrid evolution framework ensures smooth matching across heavy-flavor thresholds and a consistent treatment of multi-flavor dynamics. Moreover, the TQ4Q1.1 release provides a systematic assessment of theoretical uncertainties.

These properties make the TQ4Q1.1 sets particularly well suited for applications in the forward rapidity regime, where hybrid (CGC-based) factorization applies. In this kinematic region, the hard partonic subprocess and the subsequent collinear fragmentation are cleanly factorized: the small- x evolution of the dense target is encoded in the unintegrated gluon distribution, while the moderate- x projectile dynamics is naturally described by the collinear FFs. This complementarity allows the TQ4Q1.1 determinations to provide reliable nonperturbative inputs for the description of forward exotic-hadron production within the hybrid formalism. The TQ4Q1.1 sets are part of a broader program dedicated to the high-energy study of production mechanisms for heavy quarkonia [102–104] and rare [105] and exotic hadrons [27,106,107] within a unified collinear framework.

For the sake of illustration, Fig. 3 displays the z dependence of the TQ4Q1.1 FFs directly obtained from the JETHAD code [108,109]. They describe gluon (left panels) and charm (right panels) fragmentation into fully charmed tetraquarks with scalar [$T_{4c}(0^{++})$], axial-vector [$T_{4c}(1^{+-})$], and tensor [$T_{4c}(2^{++})$] quantum numbers. Each

curve corresponds to a distinct factorization scale μ_F , while the filled bands represent the propagated uncertainties associated with the nonperturbative long-distance matrix elements (LDMEs); for more details, see Sec. II C of Ref. [34]. Possible contributions from color-octet channels are neglected, as they are expected to be suppressed by at least 2 orders of magnitude relative to the singlet ones, due to both dynamical and hadronization constraints [34]. We also note that double-parton scattering, although relevant at low transverse momentum in multi-quark final states [17], is expected to be suppressed at moderate to large transverse momentum, where leading-power, single-parton fragmentation remains the dominant production mechanism.

To highlight the impact of perturbative evolution, the TQ4Q1.1 FFs are shown at representative factorization scales $\mu_F = 30, 60$, and 90 GeV , evolved from the input value $Q_0 = 5m_c$. At Q_0 , the [$g \rightarrow T_{4c}(1^{+-})$] function vanishes by construction, being generated radiatively through DGLAP evolution, whereas the scalar and tensor channels already feature nonzero gluon components. For uniformity, only evolved distributions are displayed.

The gluon-induced functions show broad support at small z . For scalar and tensor states, they decrease monotonically with increasing z and lack any high- z enhancement, while the axial-vector channel develops a distinct radiative hump in the intermediate region ($0.15 \lesssim z \lesssim 0.7$) that shifts slightly upward with increasing μ_F . This feature, more evident in the charm sector, reflects the intrinsic shape dynamically generated by DGLAP evolution in the absence of a nonperturbative input. The heavy-quark functions exhibit complementary patterns. In the scalar and tensor cases, they start from finite values at small z , drop rapidly, and develop a mild large- z enhancement, consistent with hard-fragmentation behavior, typical of heavy-quarkonium production [110]. Conversely, the axial-vector channel peaks sharply at intermediate-to-large z ($0.75 \lesssim z \lesssim 0.9$) and vanishes as $z \rightarrow 0$, revealing its strong preference for hard fragmentation and reduced soft-emission phase space. In all cases, the axial-vector fragmentation probabilities are suppressed by over an order of magnitude relative to the scalar and tensor ones, in both gluon and quark channels. This hierarchy aligns with NRQCD expectations: the antisymmetric spin-color configuration of the 1^{+-} state yields smaller LDMEs and weaker overlap with leading gluon-production mechanisms, whereas the absence of orbital excitation enhances the scalar and tensor compatibility with collinear NRQCD selection rules.

III. RESULTS

In what follows, we will estimate the fragmentation contribution for the transverse momentum distribution of a T_{4c} state produced in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ (LHC) and $\sqrt{s} = 100 \text{ TeV}$ (FCC, nominal). Our calculations will be performed considering different values of the rapidity y ,

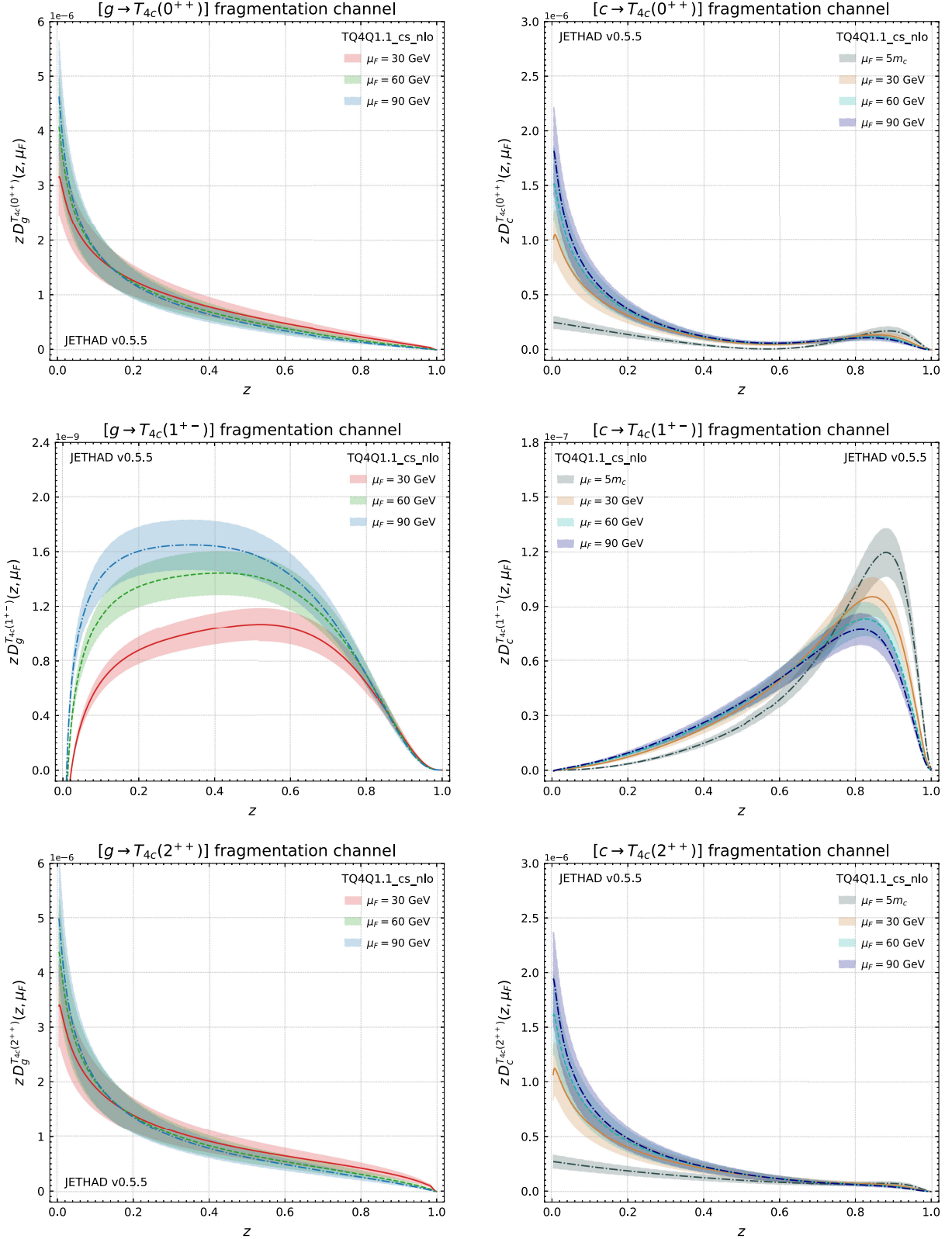


FIG. 3. Dependence on z of the TQ4Q1.1 functions describing the gluon (left) and charm (right) fragmentation channels into scalar tetraquarks $T_{4c}(0^{++})$ (upper), axial-vector tetraquarks $T_{4c}(1^{+-})$ (middle), and tensor tetraquarks $T_{4c}(2^{++})$ (lower), calculated at various factorization scales μ_F . Filled bands represent the uncertainties associated with LDMEs.

assuming distinct PDF parametrizations and taking into account the GI and CI channels. Moreover, we will present predictions for the three lowest Fock-state T_{4c} configurations: scalar ($J^{PC} = 0^{++}$), axial vector ($J^{PC} = 1^{+-}$), and tensor ($J^{PC} = 2^{++}$). The CMS Collaboration has recently reported [111] the first measurement of the quantum numbers of a family of fully charmed tetraquark candidates, with results being consistent with a $J^{PC} = 2^{++}$ assignment. This observation provides valuable support for the existence of tensor T_{4c} states, but further studies are required to fully establish the quantum structure and possible existence of additional T_{4c} states with different quantum numbers.

Initially, in Fig. 4 we present the dependence of the transverse momentum distribution on the quantum numbers of the T_{4c} state in pp collisions at the LHC (left panel) and FCC (right panel) energies. The predictions have been

derived considering the CT18 no IC parametrization and assuming $y = 5$, but the behaviors are observed for other choices. As expected, the cross section increases with the center-of-mass energy. Moreover, our results indicate that the predictions for the $T_{4c}(2^{++})$ and $T_{4c}(0^{++})$ states are similar, while the production of a $T_{4c}(1^{+-})$ is suppressed by 2 orders of magnitude. Such suppression is directly associated with the smaller probability of a charm and gluon fragmentation into this state in comparison to scalar and tensor states, already observed in Fig. 3. In what follows, we will focus on the $T_{4c}(2^{++})$ state.

In Fig. 5 we present a comparison between the predictions associated with the contributions of the GI and CI processes for the transverse momentum distribution of a $T_{4c}(2^{++})$ state produced in pp collisions at the LHC (left panel) and FCC (right panel) energies. The results have

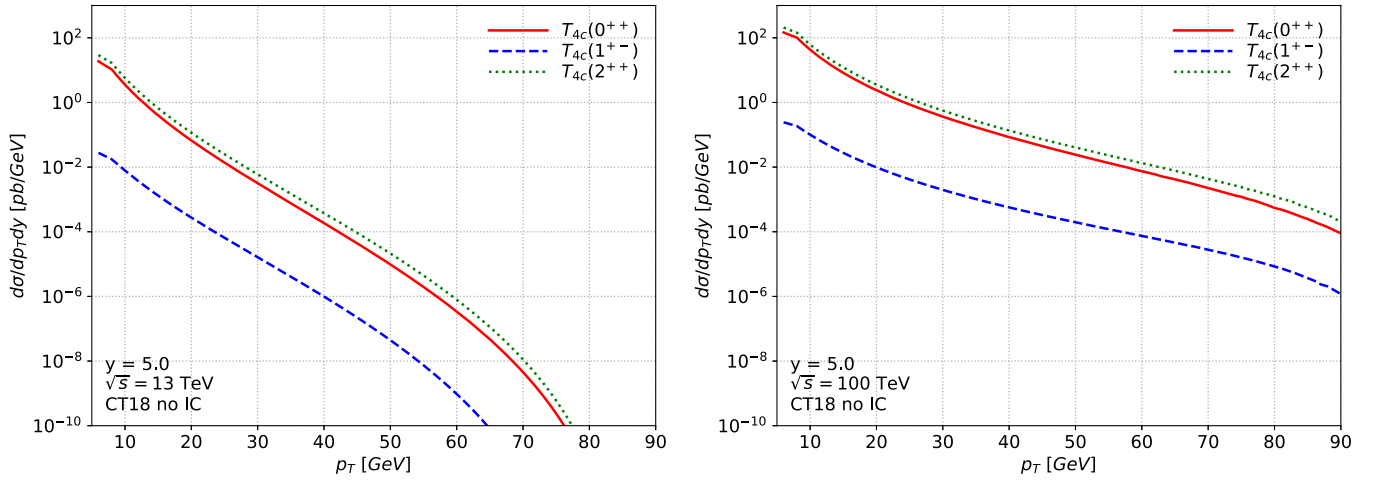


FIG. 4. Dependence of the transverse momentum distribution on the quantum numbers assumed for the T_{4c} state. Results for the T_{4c} production in pp collisions at the LHC (left) and FCC (right) energies and fixed rapidity ($y = 5.0$).

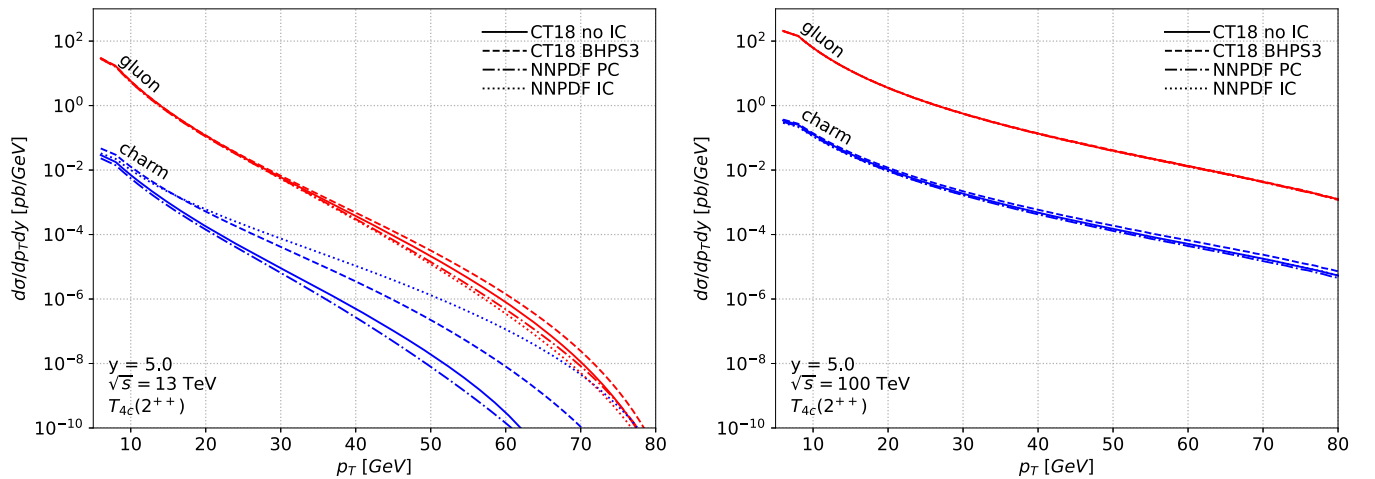


FIG. 5. Contributions of the GI and CI processes for the transverse momentum distribution associated with the $T_{4c}(2^{++})$ production in pp collisions at the LHC (left) and FCC (right) energies and fixed rapidity ($y = 5.0$). Results derived considering the solution of the rcBK equation and distinct PDFs.

been derived considering four distinct PDF parametrizations, two of them taking into account the intrinsic charm component. Initially, let us discuss the results for the LHC (left panel). As expected from Fig. 2, the magnitude of the CI channel is sensitive to the IC, with the NNPDF IC implying a larger enhancement. In particular, such parametrization implies that the charm and GI processes become of the same order at large transverse momentum p_T . At the FCC energy (right panel), the predictions are similar in the transverse momentum range considered, which is expected, since the impact of an IC component occurs at large x , which is only reached at larger p_T when the center-of-mass energy is increased.

In the previous figures for the transverse momentum distribution, we have assumed the central TQ4Q1.1 FFs and that the factorization and renormalization scales are equal and given by $\mu_R = \mu_F = \mu = M_{T_{4c}}$. Before presenting our predictions for distinct rapidities, it is important to evaluate the dependence of our results on these assumptions. In Fig. 6 (upper panels), we illustrate the dependence

on the factorization scale by varying μ in the range $\mu = M_{T_{4c}}/2 - 2M_{T_{4c}}$. The results are presented for the LHC (left panel) and FCC (right panel) energies, different PDFs, and a fixed rapidity ($y = 5$). We have that the uncertainty band increases at larger values of the transverse momentum and is smaller at the FCC energy in the p_T range considered. In Fig. 6 (lower panels), we present the dependence on the nonperturbative LDMEs, which determine the fragmentation functions. Our results indicate that this ingredient has a larger impact on our predictions. We have verified that a similar conclusion is also obtained for other rapidities. As a consequence, in that follows, we will only present the uncertainty band associated with the LDMEs.

The dependence of our predictions for the transverse momentum distributions on the rapidity is presented in Fig. 7. We consider the $T_{4c}(2^{++})$ production in pp collisions at the LHC (left panels) and FCC (right panels) energies, and the results have been derived by summing the GI and CI contributions and assuming different PDF

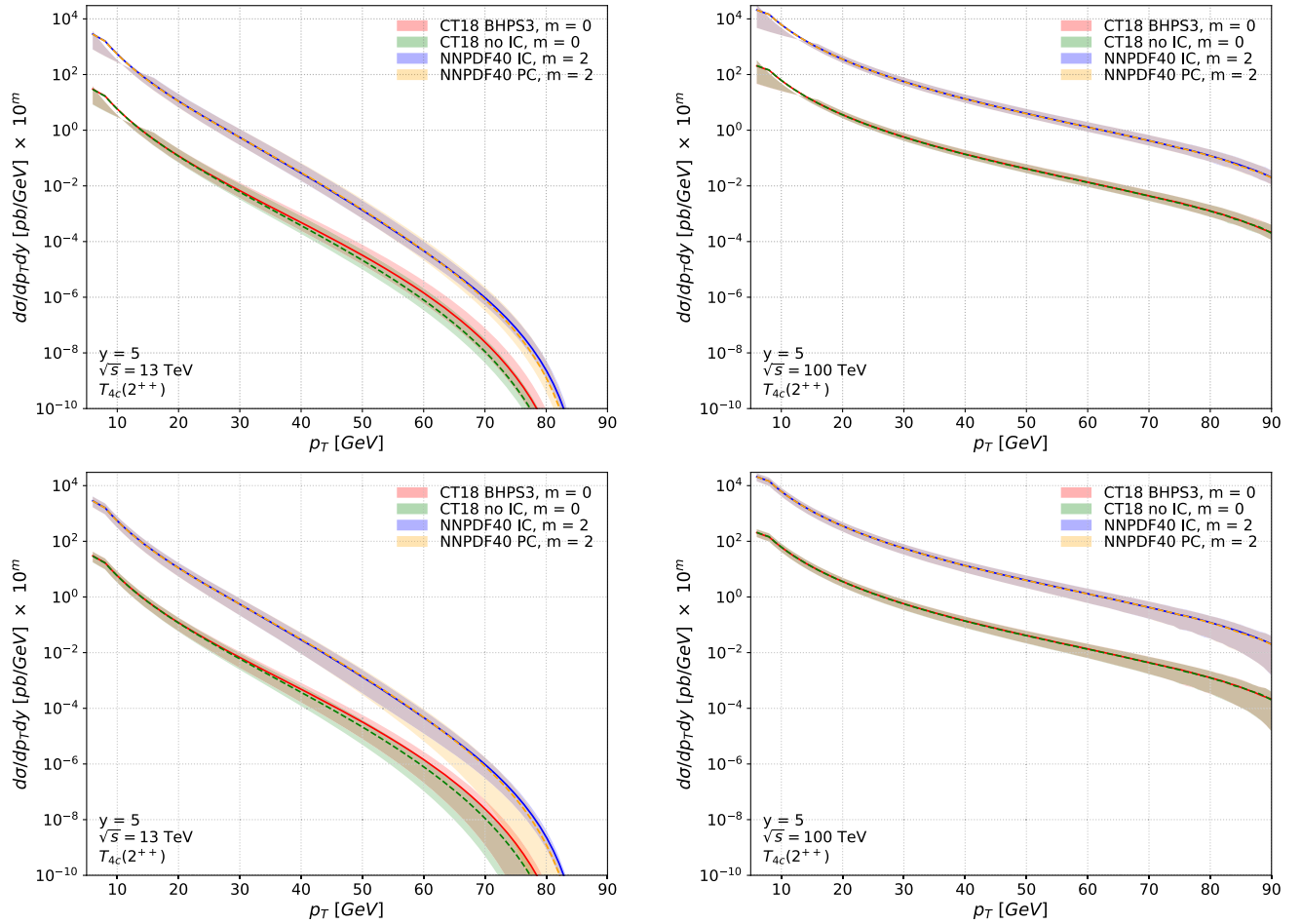


FIG. 6. Dependence of our predictions for the transverse momentum distribution associated with the $T_{4c}(2^{++})$ production in pp collisions at the LHC (left) and FCC (right) energies on the factorization scale (upper) and nonperturbative long-distance matrix elements (lower). Results derived considering the solution of the rcBK equation and the CT18 and NNPDF parametrizations.

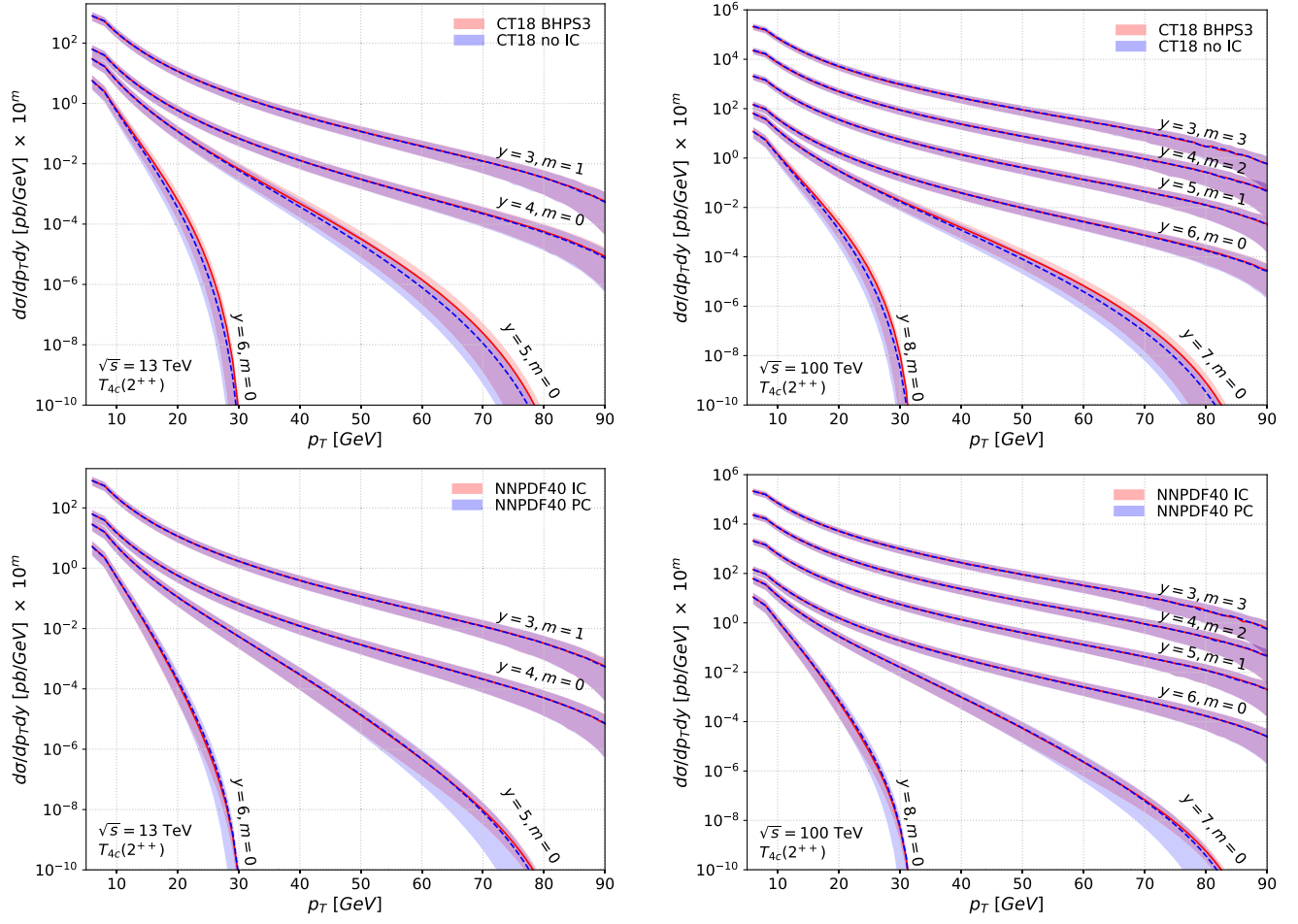


FIG. 7. Transverse momentum distribution for the $T_{4c}(2^{++})$ production in pp collisions at the LHC (left) and FCC (right) energies and different rapidities, derived considering the solution of the rcBK equation and the CT18 (upper) and NNPDF (lower) parametrizations.

parametrizations. The distribution increases with the energy and decreases with the rapidity. In particular, the behavior is strongly modified with the increasing of rapidity, due to the reduction of the available phase space for a fixed center-of-mass energy. Moreover, we have that the predictions associated with the distinct PDFs are similar, which is expected for this state due to the dominance of the GI channel.

Let us now consider the production of a $T_{4c}(1^{+-})$ state. As verified in the previous section, the charm fragmentation is dominant for this state, different from the scalar and tensor states, which makes the $T_{4c}(1^{+-})$ production more sensitive to an IC component in the proton wave function. In Fig. 8 we present our predictions for the transverse momentum distribution of a $T_{4c}(1^{+-})$ state produced in pp collisions at the LHC (left panel) and FCC (right panel) energies, derived using the CT18 and NNPDF parametrizations. We have that the distribution is strongly enhanced when an IC component is presented, especially at larger rapidities, with the magnitude of the enhancement being dependent on the PDF parametrization considered.

Finally, in Table I, we present our predictions for the total cross sections associated with the production of the different fully charmed tetraquark states in pp collisions at the LHC and FCC energies through the fragmentation mechanism. The results, presented in picobarns, have been derived integrating over the transverse momentum p_T of the T_{4c} state in the range $p_T \geq 20$ GeV and over the forward rapidity range covered by the LHCb detector ($2.0 \leq y \leq 4.5$). Moreover, we present the predictions for the distinct PDF parametrizations used in our analyses and taking into account the uncertainty associated with the LDMEs. As expected from the results for the transverse momentum distributions, the cross section increases with the energy and is larger for the $T_{4c}(2^{++})$ state. Moreover, for the LHC energy, the presence of an IC component implies a small enhancement of the cross section in the rapidity range considered. In contrast, at the FCC, the predictions with and without an IC are very similar, which is expected, since the impact of an IC component for this energy only occurs at very large p_T , while the integrated cross section is dominated by small values of transverse

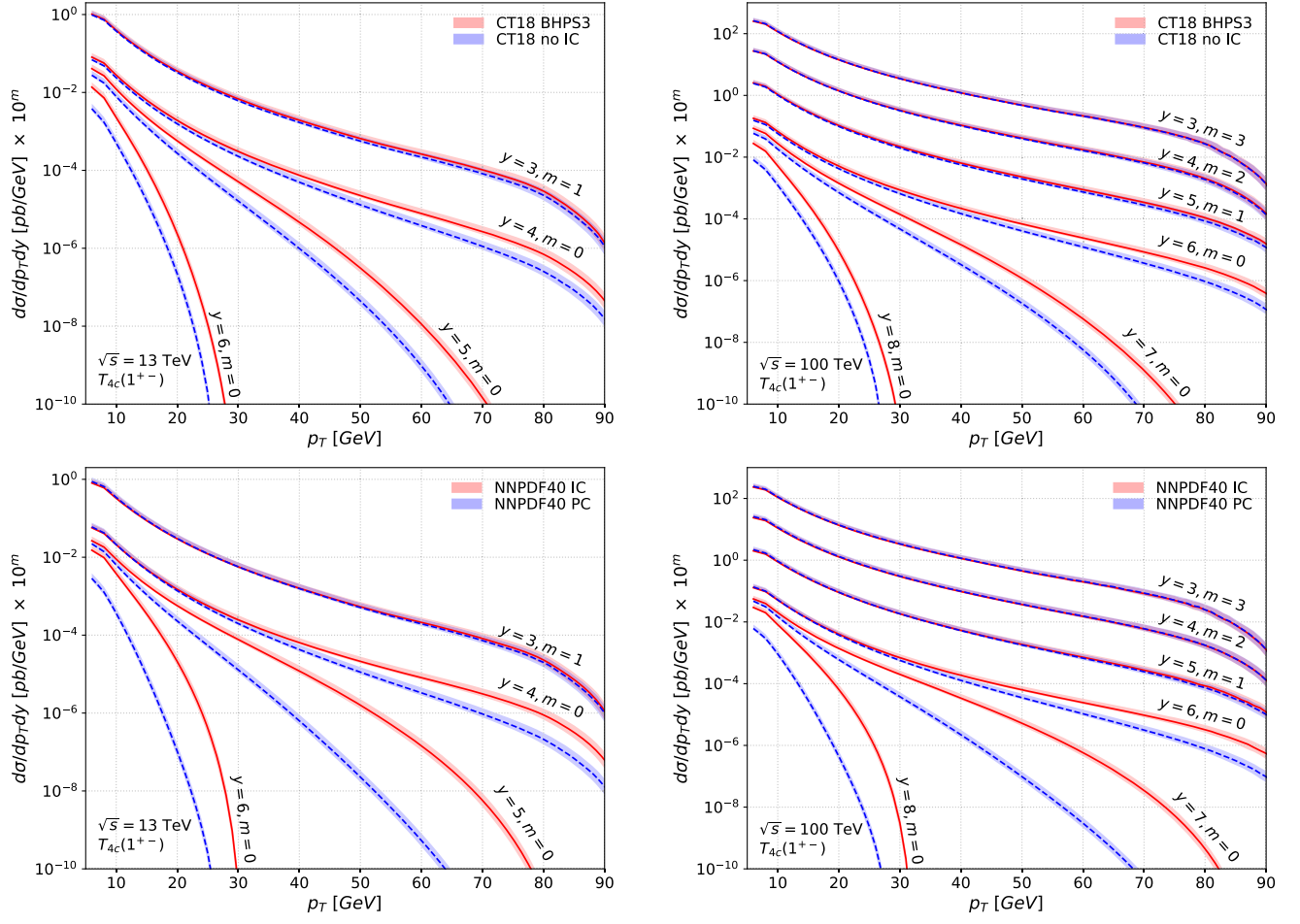


FIG. 8. Transverse momentum distribution for the $T_{4c}(1^{+-})$ production in pp collisions at the LHC (left) and FCC (right) energies and different rapidities, derived considering the solution of the rcBK equation and the CT18 (upper) and NNPDF (lower) parametrizations.

momentum. The results presented in Table I indicate that the cross section for the $T_{4c}(2^{++})$ production is of the order of 2 nb at the LHC, which implies $\gtrsim 10^9$ events if an

integrated luminosity of 3000 fb^{-1} is considered. As a consequence, a future experimental analysis of this final state is, in principle, feasible.

TABLE I. Predictions for the production cross sections of the different fully charmed tetraquark states for the LHC ($\sqrt{s} = 13 \text{ TeV}$) and FCC ($\sqrt{s} = 100 \text{ TeV}$). Results, in picobarns, derived assuming $p_T \geq 20 \text{ GeV}$ and $2.0 \leq y \leq 4.5$, considering distinct PDF parametrizations and taking into account the uncertainty associated with the LDMEs.

State	PDF parametrization	σ_{LHC} (pb)	σ_{FCC} (pb)
$T_{4c}(0^{++})$	CT18 no IC	760.70–1904.28	5257.51–12106.06
	CT18 BHPS3	771.67–1927.26	5212.69–11976.89
	NNPDF40 PC	746.88–1873.38	5225.36–12037.64
	NNPDF40 IC	750.89–1833.17	5260.52–12133.35
$T_{4c}(1^{+-})$	CT18 no IC	6.46–9.14	43.21–59.21
	CT18 BHPS3	7.33–10.30	43.65–59.72
	NNPDF40 PC	5.96–8.46	41.56–56.99
	NNPDF40 IC	6.20–8.73	40.56–55.69
$T_{4c}(2^{++})$	CT18 no IC	1214.94–2921.03	8105.39–17857.29
	CT18 BHPS3	1231.31–2954.36	7998.99–17590.97
	NNPDF40 PC	1194.20–2876.16	8078.51–17791.60
	NNPDF40 IC	1200.73–2891.00	8116.32–17911.80

IV. SUMMARY

Understanding exotic hadrons remains one of the central challenges in hadronic physics, with the production mechanisms of fully heavy tetraquark states being the subject of intense theoretical scrutiny. Previous studies have analyzed the fragmentation-driven production of these states within the NRQCD formalism, demonstrating that this channel becomes dominant at large transverse momentum. However, such analyses have predominantly focused on central rapidity configurations in pp collisions. In this work, we have extended the investigation to the forward rapidity regime, where additional effects are expected to shape the production rates. In particular, forward kinematics probes asymmetric Bjorken- x configurations ($x_1 \gg x_2$), thereby enhancing sensitivity to nonlinear QCD dynamics at small x and to the large- x structure of the projectile. To model this dilute-dense scattering environment, we employed hybrid factorization for both gluon- and charm-initiated channels, using the CGC formalism to describe the parton-target interaction. We further incorporated different models of the intrinsic component in the proton wave function and provided predictions for the production of T_{4c} states with different quantum numbers. Our phenomenological analysis included transverse momentum distributions at various rapidities and collider energies, ranging from the 13 TeV LHC to the nominal 100 TeV FCC. We found that the largest cross sections are associated with tensor states, predominantly produced via the gluon-initiated mechanism. In contrast, axial-vector

states are dominantly produced via charm-initiated fragmentation, making them particularly sensitive to the large- x charm content of the projectile. As such, the $T_{4c}(1^{+-})$ fragmentation production [33] emerges as a valuable probe of the intrinsic charm hypothesis, especially in forward kinematics where charm-initiated contributions gain greater relevance.

ACKNOWLEDGMENTS

V. P. G. was partially supported by CNPq, FAPERGS, and INCT-FNA (Process No. 408419/2024-5). Y. N. L. was partially financed by the São Paulo Research Foundation (FAPESP), Brazil (Process No. 2024/17836-9). A. V. G. is grateful to Universidade do Estado de Santa Catarina for its hospitality and financial support and is partially supported by CNPq through the INCT-FNA Grant No. 408419/2024-5 and the Universal Grant No. 405458/2025-8. The authors acknowledge the National Laboratory for Scientific Computing (LNCC/MCTI, Brazil), through the ambassador program (UFGD), subprojects FCNAE and SADFT for providing HPC resources of the SDumont supercomputer. F. G. C. was supported by the Atracción de Talento Grant No. 2022-T1/TIC-24176 from the Comunidad Autónoma de Madrid, Spain.

DATA AVAILABILITY

No data were created or analyzed in this study.

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