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Search for intrinsic charm in vector boson production accompanied by heavy-flavor jets

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Assuming the possible existence of an intrinsic (or valencelike) heavy quark component in the proton distribution functions, we analyze the vector boson Z/W production, accompanied by heavy-flavor jets, in pp collisions at the LHC energies. We present theoretical predictions for differential cross sections of such processes and demonstrate their large sensitivity to parton distribution functions including an intrinsic charm component to the proton in some kinematical regions. Ratio measurements of the $Z+$ heavy-flavor jets differential cross sections over the corresponding spectra in $W+$ heavy jets events are proposed. These ratios are studied as a function of two different observables that maximize their sensitivity to the intrinsic charm component of the proton: the transverse momentum of the leading heavy-flavor jet and the longitudinal momentum fraction x_F^Q of this jet. Such measurements look very promising for the LHC experiments because they can supply unique information about the intrinsic charm hypothesis.

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I. INTRODUCTION

Parton distribution functions (PDFs) give the probability of finding in a proton a quark or a gluon (parton) with a certain longitudinal momentum fraction at a given resolution scale. The PDF $f_a(x,\mu)$ is thus a function of the proton momentum fraction x carried by the parton a at the QCD scale μ. For small values of μ, corresponding to long distance scales of less than $1/\mu_0$, the PDFs cannot be calculated from the first principles of QCD (although some progress has been made using the lattice methods [1]). The unknown functions $f_a(x,\mu_0)$ must be found empirically from a phenomenological model fitted to a large variety of data at $\mu > \mu_0$ in a "QCD global analysis" [2,3]. The PDF $f_a(x,\mu)$ at higher resolution scale $\mu > \mu_0$ can, however, be calculated from $f_a(x,\mu_0)$ within the perturbative QCD using Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Q^2-evolution equations [4].

The limitation in the accuracy at which PDFs are determined constitutes an important source of systematic uncertainty for Standard Model measurements and for multiple searches for New Physics at hadron colliders. The LHC facility is a laboratory where PDFs can be studied and their description improved. Inclusive $W^\pm$ and Z-boson production measurements performed with the ATLAS detector have, for example, introduced a novel sensitivity to the strange quark density at $x \sim 0.01$ [5].

Many pp processes studied at the LHC, including Higgs boson production, are sensitive to the strange $f_s(x,\mu)$, charm $f_c(x,\mu)$, and/or bottom $f_b(x,\mu)$ quark distribution functions. Global analyses usually assume that the heavy-flavor content of the proton at $\mu \sim m_{s,c,b}$ is negligible. Theses heavy quark components arise only perturbatively through gluon splitting as described by the DGLAP Q^2-evolution equations [4]. Direct measurements of the open charm, open bottom, and open strangeness in deep inelastic scattering (DIS) experiments confirmed the perturbative origin of heavy quark flavors [6]. However, the description of these experimental data is not sensitive to the heavy quark distribution at large x ($x > 0.1$).

Analyzing hadroproduction of the so-called leading hadrons, Brodsky *et al.* [7,8] postulated, about 30 years ago, the coexistence of an *extrinsic* and an *intrinsic* contribution to the quark-gluon structure of the proton. The extrinsic (or ordinary) quarks and gluons are generated on a short-time scale associated with large-transverse-momentum processes. Their distribution functions satisfy the standard QCD evolution equations. On the contrary, the intrinsic quark and gluon components are assumed to exist over a time scale which is independent of any probed momentum transfer. They can be associated with a bound-state (zero-momentum transfer regime) hadron dynamics, and one believes that they have a nonperturbative origin. It was argued in Ref. [8] that the existence of intrinsic heavy quark pairs $c\bar{c}$ and $b\bar{b}$ within the proton state can be due to the virtue of gluon-exchange and vacuum-polarization graphs.

A few models have been developed on that basis. The total probability of finding a quark from the postulated intrinsic component of the PDF varies with these models. For example, in the MIT bag model [9], the probability of finding a five-quarks component $|uudc\bar{c}\rangle$ bounded within the nucleon bag, to which is associated an intrinsic charm component to the PDF, can be of about 1%–2%. Another model considers a quasi-two-body state $\bar{D}^0(u\bar{c})\bar{\Lambda}_c^+(udc)$ in the proton [10]. In this scenario, the contribution of intrinsic charm (IC) to the proton PDF (the weight of the relevant Fock state in the proton; see also Refs. [7,8,11]) could be as high as 3.5%, with the upper limitation being due to constraints from DIS HERA data. In these models, the probability of finding an intrinsic bottom state (IB) in the proton can also be estimated but is suppressed by a factor of $m_c^2/m_b^2 \simeq 0.1$ [12] compared to intrinsic charm, where m_c and m_b are respectively the masses of the charm quark ($\simeq$1.3 GeV) and of the bottom quark (4.2 GeV).

It was recently shown that the possible existence of intrinsic strangeness in the proton results in a rather satisfactory description of the HERMES data on $x(f_s(x,Q^2)+f_{\bar{s}}(x,Q^2))$ at $x > 0.1$ and $Q^2 = 2.5\ (\mathrm{GeV/c})^2$ [11,13]. On the other hand, new global QCD analysis of parton distribution functions, including low-energy fixed-target proton and deuteron cross sections that were excluded in previous global analyses, put stringent constraints on the intrinsic charm contribution to the proton [14]. These results are contested by Brodsky *et al.* [15]. The existence of the intrinsic charm (IC) and intrinsic strange (IS) quarks contribution to the proton has up to now been a long-standing debate, and further tests of the viability of this hypothesis must independently be performed in other experiments.

Can the LHC provide a suitable experimental context for the study intrinsic quarks? The typical high-Q^2 energy transfer reached in processes produced in recent high-energy hadron colliders might limit the observability of such phenomena. The percent-level estimations for the intrinsic charm contribution to the PDF obtained from the theoretical predictions quoted above have been calculated at low Q^2 and are decreasing as the Q^2 increases. Recent studies, however, showed that, in high-energy LHC processes where a charm quark in the initial state leads to a heavy quark in the final state, the intrinsic charm contribution to the PDF could lead to an enhanced fraction of heavy mesons (e.g., D-mesons) in the final state compared to when intrinsic quarks are ignored [16]. This fraction is not independent of the phase space probed. It was, for example, shown that selecting high-rapidity and large transverse momentum heavy-flavored jets enhances the $x > 0.1$ PDF contribution to the cross section in the selected phase space and thus the intrinsic charm contribution to the observable number of events [16]. Experimental searches for a possible intrinsic charm signal at high-energy hadron colliders like the LHC are therefore possible.

The aforementioned phenomenology studies were performed with events featuring large transverse momentum photons produced in association with heavy-flavor quarks $Q(\equiv c, b)$ in the final state of pp collisions. In contrary to dijet events where the final state is dominated by gluon jets or by a gluon splitting into a pair of heavy quarks, many photon plus heavy-flavor jets events involve a heavy quark in both the initial and the final states of the events, yielding the sensitivity to intrinsic charm quarks mentioned above. Investigations of prompt photon plus $c(b)$-jet production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV have been carried out at the TEVATRON [17–20]. An excess of $\gamma + c$ events was observed over Standard Model expectations. In particular, it was observed that the ratio of the experimental spectrum of a prompt photon accompanied by a c-jet to the relevant theoretical expectations based on the conventional PDF ignoring intrinsic charm monotonically increases with p_T^γ up to a factor of about 3 when p_T^γ reaches 110 GeV/c. While such a trend is expected from an intrinsic charm contribution to the PDFs, the magnitude of the effect observed in the data is too large. Taking into account the CTEQ66c PDF, which includes the IC contribution obtained within the BHPS model [7,8], the observed excess is about 1.5 times larger than what the addition of an intrinsic charm contribution to the proton predicts [21]. First studies of the $\gamma + b$-jets $p\bar{p}$-production featured no enhancement in the p_T^γ-spectrum [17,20]. A new version of such analysis published by the D0 collaboration in 2012, however, presented the observation of such an enhancement [18], potentially hinting for an intrinsic bottom contribution to the PDFs. Because of the ambiguity in these results, it became imperative to look for intrinsic quarks at the LHC.

Sensitivity studies of an IC signal in $pp \to \gamma + c(b) + X$ processes at LHC energies was recently done in Ref. [22]. Results indicate that the possible existence of an intrinsic heavy quark component in the proton can be inferred from the measurement of an enhancement (by factor of 2 or 3) of the number of events with a photon of $p_T^\gamma > 150$ GeV/c at high rapidity y_γ in comparison with the relevant number of events expected in the absence of an IC contribution. The problem with $pp \to \gamma + c(b) + X$ processes is, however, that it is experimentally difficult to separate the prompt photon contribution from the nonprompt photon one, therefore adding ambiguities in the results of a measurement. In addition, large experimental uncertainties are expected for the heavy-flavor jet energy measurement and efficiency corrections mitigating the sensitivity to intrinsic charm expected from an actual measurement. In the following, we propose a measurement that will avoid these problems.

A similar IC signal can also be visible in the hard pp processes of vector bosons Z/W production accompanied by heavy-flavor (b and c) jets in certain kinematic regions. These processes do not feature the ambiguities mentioned above regarding $\gamma + c(b) + X$ processes. In this paper, we study the Z/W plus heavy-flavor jet productions in pp collisions at the LHC energies and discuss the potential observation of an intrinsic charm signal, accounting for processes both sensitive and not sensitive to intrinsic charms. In particular, we show an advantage of measuring the ratio of yields of Z-bosons accompanied by c and b heavy-flavor jets to W-bosons in association with the same jets. We discuss how such a ratio must be defined in order to maximize the sensitivity to an intrinsic heavy-flavor quark contribution to the proton and demonstrate that such a measurement controls the systematic uncertainties that mitigate the sensitivity to an IC signal in $pp \to \gamma + c(b) + X$ processes at the LHC.

II. INTRINSIC CHARM AND BEAUTY CONTRIBUTION TO PROTONS IN W/Z PLUS HEAVY-FLAVOR JETS AT THE LHC

At the LHC, with a center-of-mass energy of $\sqrt{s} = 7$–13 TeV, the typical momentum transfer squared (Q^2) in the hard pp processes of photon or vector boson production accompanied by heavy-flavor jets with large transverse momenta is above a few tens of thousands of $(\mathrm{GeV/c})^2$. At these scales, the contribution of the intrinsic charm component to the PDF features an enhancement at $x \geq 0.1$, where the corresponding PDFs turn out to be larger (by more than an order of magnitude at $x \sim 0.3$–0.4) than the sea (extrinsic) charm density distribution in the proton [22,23]. This can be seen in Fig. 1 where we compare the charm distribution in a proton for two values of Q^2 [$Q^2 = 20\,000\ (\mathrm{GeV/c})^2$ and $Q^2 = 150\,000\ (\mathrm{GeV/c})^2$] for a PDF, CTEQ66c, which includes an IC component, and another one, CTEQ66, including only the extrinsic quark contribution. From the figure, one can also see that the high-Q^2 dependence of $xc(x, Q^2)$ does not affect much the IC contribution to the PDF for x values above 0.1.

The sensitivity studies performed with $\gamma + c(b) + X$ processes in the context of the LHC demonstrated that, with the appropriate phase space selections on the final state photon and heavy-flavor jets, one can select a large fraction of events with $x_c > 0.1$ and thus substantially intensify the intrinsic charm PDF contribution to charm hadroproduction, enough for being able to see a signal when compared to the extrinsic contribution alone [22]. In particular, it was shown that if, in at least one of the colliding protons, the momentum fraction of the c-quark x_c is larger than the Feynman variable x_F^γ of the photon, which, in turn, is larger than 0.1, i.e. if

$$x_c \geq x_F^\gamma = \frac{2p_T^\gamma}{\sqrt{s}} \sinh(\eta_\gamma) c \geq 0.1, \tag{1}$$

where p_T^γ is the transverse momentum of photon and η_γ is its pseudorapidity, then the total cross section of the $pp \to \gamma + c + X$ process will be intensified by the intrinsic charm contribution to the PDF (see Fig. 1). As a result, the p_T^γ-spectrum will feature a significant enhancement with respect to the expected spectrum with a nonintrinsic charm contribution in that region of the p_T^γ, η_γ phase space where $x_c \geq x_F^\gamma \geq 0.1$.

Such a region can be selected, for example, by requiring a prompt photon and a final state c-jet with rapidities of respectively $1.5 < |y_\gamma| < 2.4$ and $|y_c| < 2.4$ and by imposing large transverse momenta cuts (> 150 GeV) to the photon and to the leading heavy-flavor jet. The observation of an excess of events selected in this phase space region compared to the standard non-IC component would thus provide compiling evidence for the existence of intrinsic charm and could be used to estimate the increase in the PDF due to the intrinsic charm as a function of x.

Once again, the ambiguity between prompt and nonprompt photons can, however, significantly dilute the signal sensitive to intrinsic charm, and the experimental uncertainties on heavy-flavor jets energy measurement and efficiency corrections can be large enough to mitigate a 20%–30% effect, therefore suppressing the sensitivity of $pp \to \gamma + c(b) + X$ processes to intrinsic charms. The strategy outlined above can, however, equally be applied to test and measure the intrinsic heavy quark contribution to the production of vector bosons $W^\pm, Z^0$ accompanied by heavy-flavor jets (Q_f-jets, with $Q_f = s, c, b$). In these events, the intrinsic quark component would receive its main contribution from $Q_f(\bar{Q}_f) + g \to W^\pm/Z^0 + Q'_f(\bar{Q}'_f)/Q_f(\bar{Q}_f)$ processes for which the leading-order (LO) QCD diagrams are presented in Figs. 2 and 3, in the

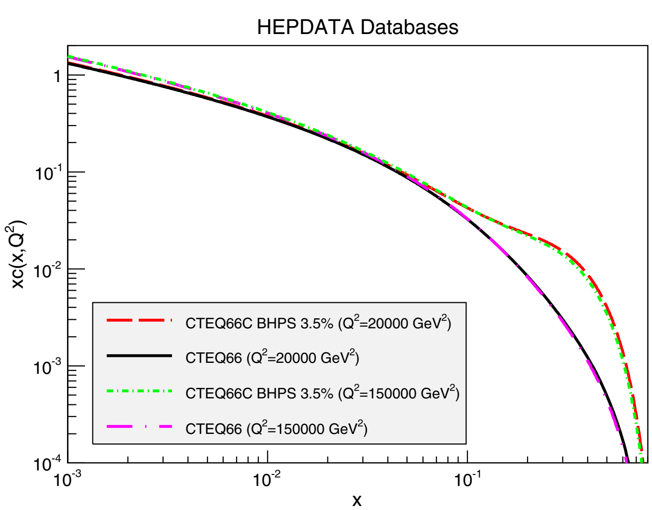

FIG. 1 (color online). Distributions of the charm quark in the proton. The solid line is the standard perturbative sea charm density distribution $xc_{\mathrm{rg}}(x)$ at $Q^2 = 20000\ \mathrm{GeV}^2$, while the long dashed line is for $Q^2 = 150000\ \mathrm{GeV}^2$. The dashed curve corresponds to the charm quark distribution function for the sum of the intrinsic charm density $xc_{\mathrm{in}}(x)$ and $xc_{\mathrm{rg}}(x)$ at $Q^2 = 20000\ \mathrm{GeV}^2$, while the short dashed line is for $Q^2 = 150000\ \mathrm{GeV}^2$ [23].

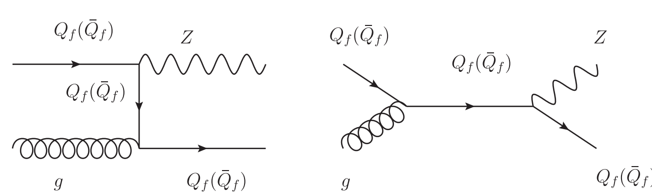

FIG. 2. LO Feynman diagrams for the process $Q_f(\bar{Q}_f)g \to ZQ_f(\bar{Q}_f)$.

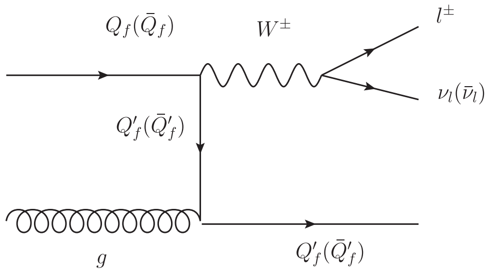

FIG. 3. Example of a LO Feynman diagram for the process $Q_f(\bar{Q}_f)g \to W^\pm Q'_f(\bar{Q}'_f)$, where $Q_f = c, b$ and $Q'_f = b, c$ respectively.

case of the Z and W production, respectively. Here $Q'_f = c, b, c$ if $Q_f = s, c, b$.

At next-to-leading order (NLO) in QCD, $W/Z + Q_f$ diagrams, often more complicated than the ones presented in Figs. 2 and 3, must also be considered. As can be seen in Fig. 4, the heavy-flavor jets in the final state of these diagrams come from a gluon splitting somewhere along the event chain and do thus not feature any intrinsic quark contribution. If the cross section of these diagrams is large enough, the conclusions about the sensitivity of a measurement to the intrinsic charm at the LHC will be affected. It is thus important to consider QCD NLO calculations in the current study.

To this end, we calculated the p_T-spectra of heavy-flavor jets (b and c) in association with a vector boson calculated at NLO in pp collisions at $\sqrt{s} = 8$ TeV using the parton-level Monte Carlo generator MCFM version 6.7 [24]. The NLO corrections include the splitting of a gluon into a pair of heavy-flavor quarks and thus provides a better description of such process than what is yielded by parton showers, at least for the first splitting. The lack of further parton radiation and of hadronization in MCFM will affect the shape of the hadronic recoil to vector bosons and the p_T-spectra of the leading heavy-flavor jet in the various $V + c$ and $V + b$ ($V = W$ or Z) events, but it affects the predictions with and without intrinsic charm contributions to the PDF in the exact same way. Conclusions that will be derived from MCFM about the IC sensitivity studies to be presented below are thus not affected by the fact that MCFM provides only a fixed-order calculation with no parton shower nor further nonperturbative corrections. A test of this statement is provided after the presentation of the sensitivity studies performed with MCFM. For the various processes considered, the vector boson is required to decay leptonically, in order to allow experimental studied to trigger on these events, and the pseudorapidity of the heavy quark jet is required to satisfy $|\eta_Q| > 1.5$, to probe high-x PDFs.

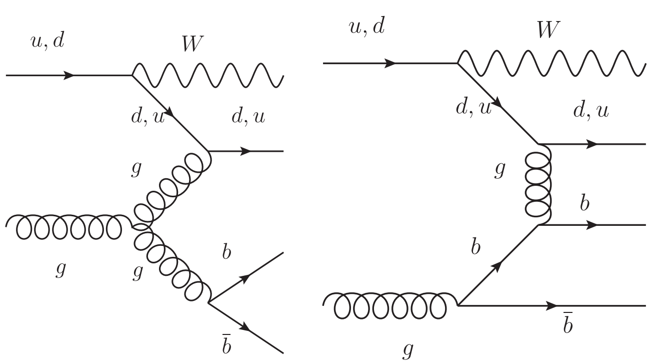

FIG. 4. Some NLO Feynman diagrams for the process $Q_f(\bar{Q}_f)g \to W^\pm Q'_f(\bar{Q}'_f)$, where $Q_f = c, b$ and $Q'_f = b, c$ respectively. Left: gluon-splitting; Right: t-channel type of W-scattering with one gluon exchange in the intermediate state.

By selecting $Z + c$-jet events, where the c-jet is required to be rather forward ($1.5 < |y_c| < 2.0$), we can see on the left panel of Fig. 5 that the c-jet transverse momentum spectrum of events with a 3.5% intrinsic charm contribution to the PDF (CTEQ66c) features an excess, increasing with the c-jet p_T, compared to the corresponding differential cross section when only extrinsic heavy-flavor components of the PDF are considered (CTEQ66). These differential cross section distributions have been obtained at NLO from the MCFM processes 262. From the right panel of the same figure, showing the ratio of the two spectra obtained with and without an IC contribution, we can see that the excess in the c-jet p_T-spectrum due to the IC is of ~5% for p_T of 50 GeV and rises to about 220% for $p_T \sim 300$ GeV. This effect can thus be observed at the LHC if the c-jet p_T differential cross section in $Z + c$ events can be measured with sufficient precision.

In the case of the W production in association with heavy-flavor jets, the intrinsic charm contribution would be observed in a $W + b$-jet final state due to the change of flavor in the charged current. In MCFM, the NLO $W + b$ Feynman diagrams for which the LO part is depicted in Fig. 3 correspond to the processes 12 and 17 [24]. They provide the contribution to $W + Q'$ which is sensitive to IC. The p_T-spectrum of the b-jet is presented, for the sum of these two processes, in Fig. 6 (left), where one calculation (squares) has been obtained at NLO in QCD with the CTEQ66c PDF that includes an IC contribution (about 3.5%), and the other calculation (triangles) uses the CTEQ66 PDF, which does not include IC. On the right panel of Fig. 6, the ratio of these two spectra (with and without an IC contribution to the PDF used in the $W + b$ production calculations) is presented. From this figure, one can see that the inclusion of the IC contribution to the PDF leads to an increase in the b-jet spectrum by a factor of about 1.9 at $p_T > 250$ GeV/c. This is comparable to what was observed in the $Z + c$ case of Fig. 5.

Similarly, the $W + c$ final state would be sensitive to the intrinsic strange while the $Z + b$ final state would be sensitive to the intrinsic bottom. These processes are, however, suboptimal for finding intrinsic quarks at the LHC. As mentioned above, the contribution of the IB to the

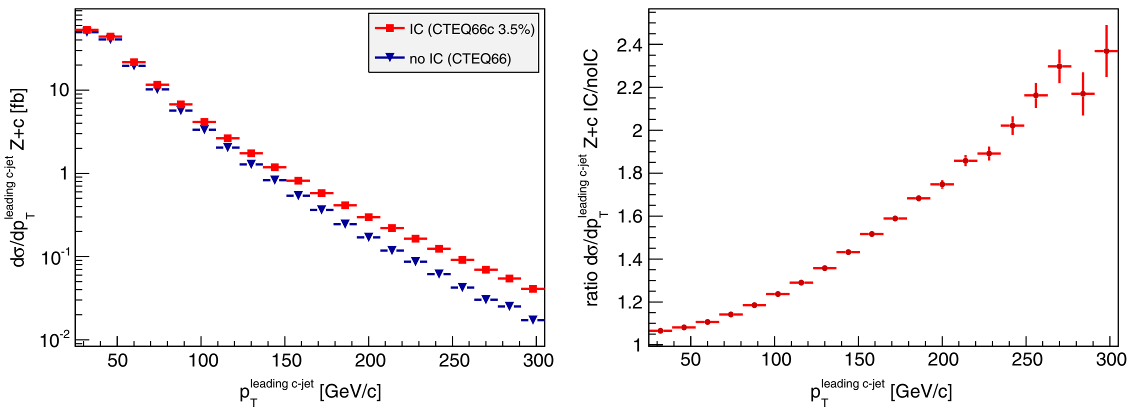

FIG. 5 (color online). Left: Comparison of the p_T-spectra for the NLO $pp \to Z + c$ process 262 [24] obtained with PDF including an intrinsic charm component (CTEQ66c) and PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two spectra.

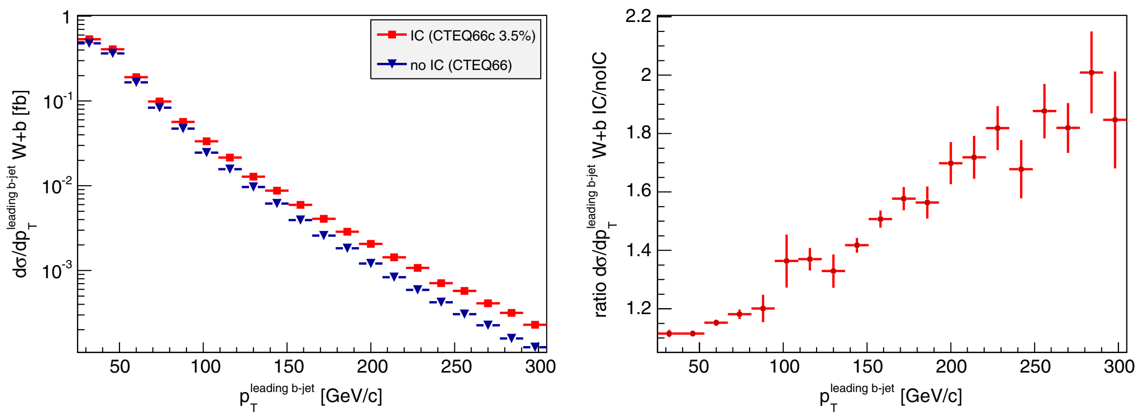

FIG. 6 (color online). Left: Comparison of the p_T-spectra for the NLO $pp \to W + b$, processes 12 + 17 [24] obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two spectra.

PDF is suppressed by a factor of $(\frac{m_c}{m_b})^2$ and is thus subdominant compared to the intrinsic charm. The contribution of the IS can be of the same order of magnitude as the IC according to Refs. [11,13]. The Q^2 evolution for this component has, however, not been calculated up to now and thus contains many unknowns. This is why this paper concentrates on the intrinsic charm component of the proton.

The above results of Figs. 5 and 6 seem *a priori* very encouraging regarding the capacity of the LHC to provide an observation of an intrinsic charm contribution to the PDFs in $W/Z + Q_f$ events, but the real situation is unfortunately more complex than this. The W-boson plus one or more b-quark jets production, calculated at NLO in the four-flavor scheme, for which two of the diagrams are represented in Fig. 4, must also be included. These corresponds to the MCFM processes 401/406 and 402/407 [24]. Their total cross section is about 50 times larger than the $W + b$ processes sensitive to the IC. As a result, the total $W + b$ production is not sensitive to an intrinsic charm component of the PDF, as can be seen in Fig. 7, where the sum of all processes contributing to $W + b$ has been taken. Fortunately the $Z + c$ processes do not suffer from a similar large dilution of the intrinsic quark component because the $Q_f + g \to Z + Q_f$ processes, which are sensitive to the IC, are not Cabibbo suppressed.

Another difficulty consists of the experimental identification of heavy-flavor jets in order to select, for example, $Z + c$-jet events in a very large $Z +$jets sample. Algorithms disentangling heavy-flavor jets from light-quark jets typically exploit the longer lifetime of heavy-quark hadrons that decay away from the primary vertex of the main process but close enough to allow for a reconstruction of the tracks of the decay products of the heavy-flavor hadron in the inner part of the detector. Such algorithms are typically not capable of explicitly distinguishing c-jets from b-jets; only the efficiency for identifying the heavy-flavor nature of the jet would differ between c-jets and b-jets. For example, one of the ATLAS heavy-flavor tagging algorithms (MV1) yields

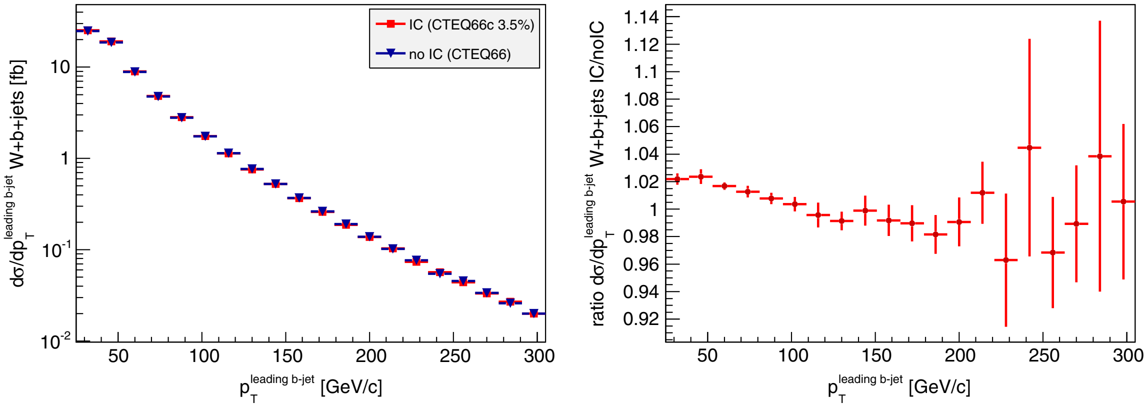

FIG. 7 (color online). Left: Comparison of the p_T-spectra for the NLO $pp \to W + b + \text{jet}$ processes 401/406 and 402/407 [24] obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two spectra.

an efficiency of 85% for b-jet identification and 50% for c-jet (for a working point where the light flavor rejection is 10) [25]. As a result of such heavy-flavor jet tagging algorithm, the selected $Z + Q$ final state will be a mixture of $Z + c$ and $Z + b$.

A priori, one would expect that $Z + b$ events are sensitive to the intrinsic bottom and therefore act only as a small background to intrinsic charm studies, when the two processes cannot be experimentally distinguished. The situation is, however, more complicated than this. Because of sum rules, an intrinsic charm component would affect the total b-quark contribution to the proton, and the $Z + b$-jet final state therefore becomes sensitive to the intrinsic charm as well. As can be seen in Fig. 8, this contribution is in the opposite direction of the intrinsic charm effect on $Z + c$ processes presented in Fig. 5. In addition, the heavy-flavor tagging efficiency is lower for c-jets than it is for b-jets, therefore increasing the weight of the negative $Z + b$ contribution to the total Z plus heavy-flavor tagged jets signal. The question is thus if $Z + Q$-jet events are still sensitive to the intrinsic charm.

To answer this question, we once again used MCFM to calculate the p_T-spectra of the heavy-flavor jets at NLO for $Z + c$ (process 262) and for $Z + b$ (process 261) [24]. This includes the contribution from both heavy-flavor scattering and pair production from gluon splitting. In all processes, the Z-boson is required to decay leptonically, and a pseudorapidity cut of $1.5 < |\eta_Q| < 2.0$ is applied on the heavy-flavor jets. We also applied the b tagging and c-jet tagging efficiency on the corresponding jet, as a function of the p_T of the jet, as reported in Ref. [25]. The resulting spectrum from all the processes is then summed. In Fig. 9, we can see that, despite the negative contribution of $Z + b$ processes and the effect of heavy-flavor tagging efficiency, the contribution of the intrinsic charm has a significant impact on the shape and normalization of the heavy-flavor jet spectrum, suggesting that it can be tested at the LHC.

To be able to observe and quantify the intrinsic charm contribution to the proton, the size of the effect presented in Fig. 9 must be significantly larger than the total statistical plus systematic uncertainty in each bin of the measured heavy-flavor jet spectrum. The experimental uncertainties

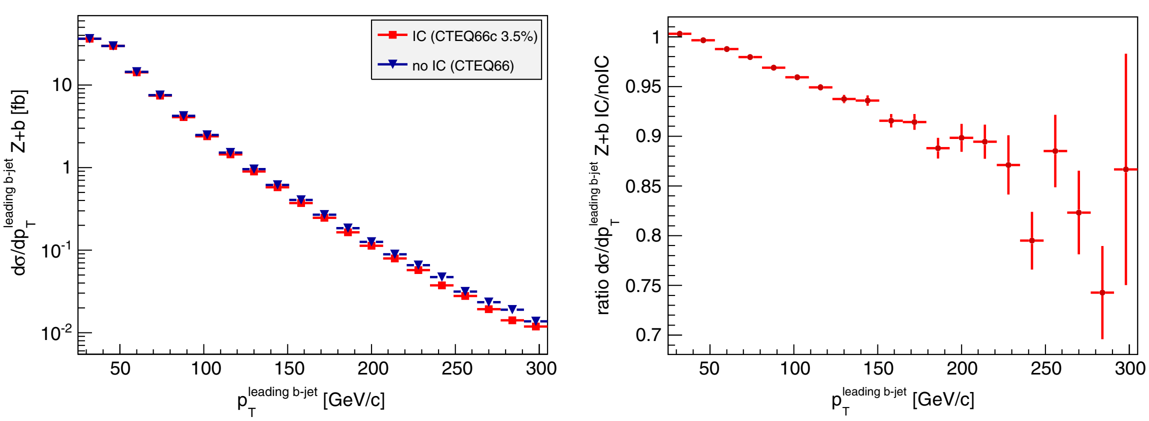

FIG. 8 (color online). Left: Comparison of the p_T-spectra for the total NLO $pp \to Z + b$ process 261 obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two spectra.

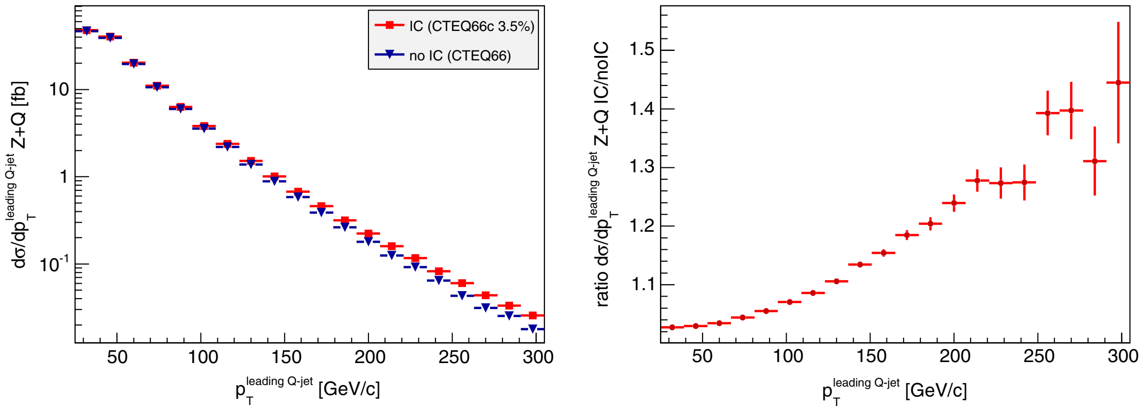

FIG. 9 (color online). Left: Comparison of the p_T-spectra for the total NLO $pp \to Z + b(\bar{b})$ process plus $pp \to Z + c(\bar{c})$ (processes 261 and 262 [24]) obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Heavy-flavor jet tagging efficiencies have been applied to the c-jets and the b-jets. Right: Ratio of these two spectra.

on background estimates, jet energy scale and resolution effects, and heavy-quark tagging efficiency are typically large, as can be inferred from the latest ATLAS [26,27] and CMS [28,29] publications on $Z + b$ and $W + b$ measurements. Recently, ATLAS published a measurement of the $W +$ jets to $Z +$ jets differential cross section ratio as a function of a plethora of observables [30]. The results indicate a substantial reduction of the main systematic uncertainties with respect to the absolute differential cross section measurements also performed by the ATLAS Collaboration [31,32]. This strategy to offset systematic uncertainties can be exploited to measure the intrinsic charm contribution to the proton, because the b-jet and c-jet spectra in $W + Q$ and $Z + Q$ processes follow similar p_T and rapidity distributions, thus allowing for a cancellation of both jet energy measurement and efficiency correction uncertainties. Before claiming that such a ratio has a higher sensitivity to the IC than the absolute cross section measurement, we must, however, first demonstrate that the $Z + Q$ sensitivity to the intrinsic charm is not washed out by taking the ratio to $W + Q$ processes.

To test this, similarly to what was done for $Z + Q$, we used MCFM to calculate, at NLO in QCD, the p_T-spectra of the leading Q-heavy-flavor jets $(b + c)$ produced in association with the $W^{\pm}$-boson in hard pp $\sqrt{s} = 8$ TeV collisions. The Wb, Wc, and Wbj contributions of MCFM (processes 12, 13, 14, 17, 18, 401, 402, 406, and 407) have been summed, and the b-jet and c-jet tagging efficiencies have been applied. In all cases, the W-boson is decaying leptonically, and Q-jets are required to satisfy $1.5 < |\eta_Q| < 2.0$. As can be seen in Fig. 10, comparing the heavy-flavor jet p_T-spectra when the intrinsic charm is included or not in the PDF (CTEQ66c vs CTEQ66), the sensitivity of $W + Q$ to the intrinsic charm is small. Taking the ratio of $Z + Q$ to $W + Q$ should therefore not smear out the effects observed in $Z + Q$ alone. To verify this, the ratio

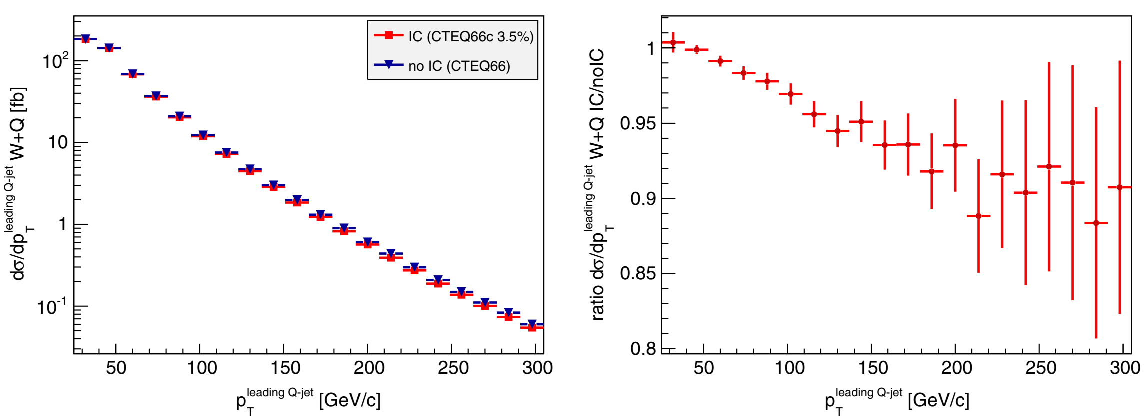

FIG. 10 (color online). Left: Comparison of the p_T-spectra for the total NLO $pp \to W + b$ plus $pp \to W + c$ plus $pp \to W + bj$ processes (12, 17, 13, 18, 401, 402, 406, and 407 [24]) obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Heavy-flavor jet tagging efficiencies have been applied to the c-jets and the b-jets. Right: Ratio of these two spectra.

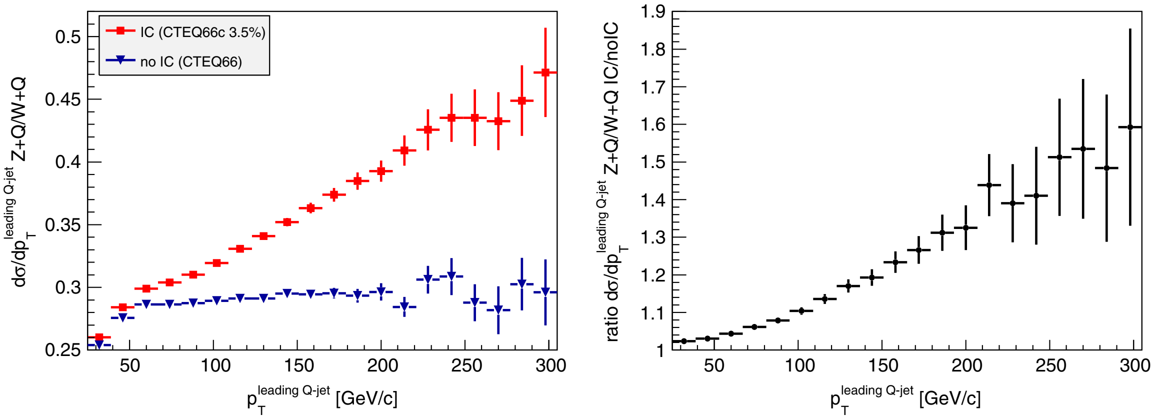

FIG. 11 (color online). Left: Comparison of the ratio of the p_T-spectra for the $Z+Q$ to $W+Q$ NLO processes obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Heavy-flavor jet tagging efficiencies have been applied to the c-jets and the b-jets. Right: Ratio of these two ratios of spectra.

of the p_T-spectra of the leading heavy-flavor jet (b, c) produced in $Zb+Zc$ and $Wb+Wc+Wbj$ processes has been calculated using a PDF including IC and another one without any IC contribution to the proton. The result of the calculation is presented in Fig. 11. As can be seen in this figure, the sensitivity to the IC signal observed in $Z+Q$ is maintained in the ratio, which can amount to about 160% of the extrinsic only contribution at p_T of about 270–300 GeV/c. This ratio measurement would, at least partially, cancel a number of large experimental systematic uncertainties, especially since, in our proposal, $V+c$-jets and $V+b$-jets are both considered as a signal and not treated as a background with respect to the other. This would allow for a clear signal at the LHC if the IC contribution is sufficiently high (here we considered a 3.5% contribution). In the case where no excess is observed, limits on the IC contribution to the proton can be obtained from such measurement. Note that ratio predictions obtained with MCFM would agree with predictions that include a parton shower and a modeling of the hadronization because such effects cancel in the ratio for jets above ∼100 GeV, as reported by ATLAS in Ref. [30]. To illustrate that the parton shower inclusion does not change our conclusions, we calculated, at LO using the PYTHIA8 generator [33], the ratio, for the $pp \to Z+c(\bar{c})$ process, of the c-jet p_T-spectrum with and without the IC for a set of predictions including a parton shower and another one ignoring it. These results are presented in Fig. 12. As can be seen on the figure, parton showers do not affect the sensitivity of our proposed measurements to an intrinsic quark component to the proton.

As discussed above, a high p_T and relatively high rapidity heavy-flavor jet enhances the probability to have a heavy-flavor quark in the initial state with a high-x fraction, ensuring that the effect of intrinsic quarks on the cross section is more prominent. This is the reason why we proposed to measure the ratio of the $Z+Q$ to $W+Q$

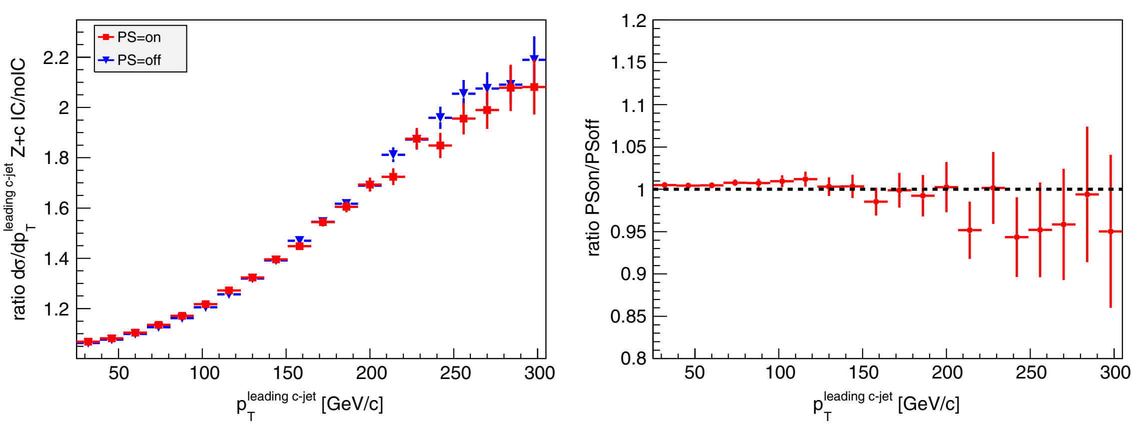

FIG. 12 (color online). Left: Ratio of the c-jet p_T-spectra for the $Z+c$ process obtained at LO with PYTHIA8 and the PDF including an intrinsic charm component (CTEQ66c) over the same spectra obtained from the PDF not including the intrinsic charm (CTEQ66). This ratio is obtained for a calculation that includes the modeling of the parton shower, (PS = on, red squares) and another calculation ignoring the parton shower (PS = off, blue triangles). Right: Ratio of PS = on to PS = off.

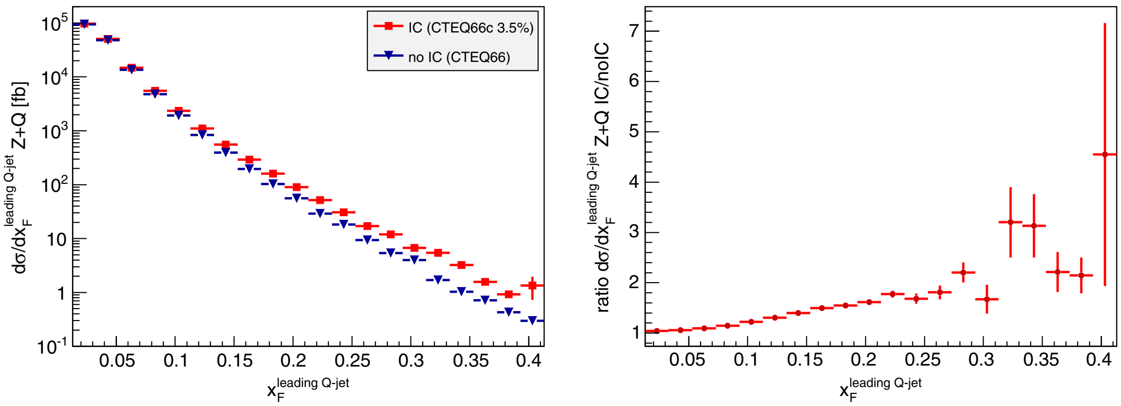

FIG. 13 (color online). Left: Comparison of the x_F^Q-spectra for the total NLO $pp \to Z + b(\bar{b})$ process plus $pp \to Z + c(\bar{c})$ (processes 261 and 262 [24]) obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two spectra.

differential cross sections as a function of the transverse momentum of the leading heavy-flavor jet measured within a specific rapidity interval. As indicated by Eq. (1), a large-x heavy-flavor quark will in general be achieved by a high value of the Feynman variable x_F^V of the final state vector boson V recoiling to the hadronic system. While such variable cannot be reconstructed at the detector level in $W + Q$ events because of the presence of an undetectable neutrino in the final state, it is possible to construct a quantity highly correlated to such a Feynman variable by using the leading heavy-flavor jet in the final state, rather than the vector boson. We therefore propose to investigate the sensitivity to the IC of the ratio of the $Z + Q$ to $W + Q$ differential cross sections as a function of the pseudo-Feynman variable of the leading heavy-flavor jet defined as

$$x_F^Q = \frac{2p_T^{\mathrm{Lead}Q\text{-jet}}}{\sqrt{s}} \sinh(\eta_{\mathrm{Lead}Q\text{-jet}}), \qquad (2)$$

where $p_T^{\mathrm{Lead}Q-\mathrm{jet}}$ is the transverse momentum of the leading heavy-flavor jet in the final state and $\eta_{\mathrm{Lead}Q-\mathrm{jet}}$ is the pseudorapidity of this jet.

First, the sensitivity of $Z + Q$ events to the intrinsic charm is presented in the left panel of Fig. 13 as a function of this pseudo-Feynman variable of the leading heavy-flavor jet. The x_F^Q-spectrum has been obtained from the total NLO $pp \to Z + b(\bar{b})$ plus $pp \to Z + c(\bar{c})$ contributions calculated with MCFM (processes 261 and 262 [24]) for collisions at $\sqrt{s} = 8$ TeV. The distribution displayed with a red square has been obtained using the CTEQ66c PDF that includes an intrinsic charm component, while the distribution displayed as blue inverted triangles has been obtained with the CTEQ66 PDF that only contains an extrinsic charm component. The left panel of Fig. 14 features the equivalent calculation performed on $pp \to W + b$ plus $pp \to W + c$ and $pp \to W + bj$ contributions (processes 12, 17, 13, 18, 401, 402, 406, and 407 [24]). The ratios of the x_F^Q-spectrum obtained with an IC contribution

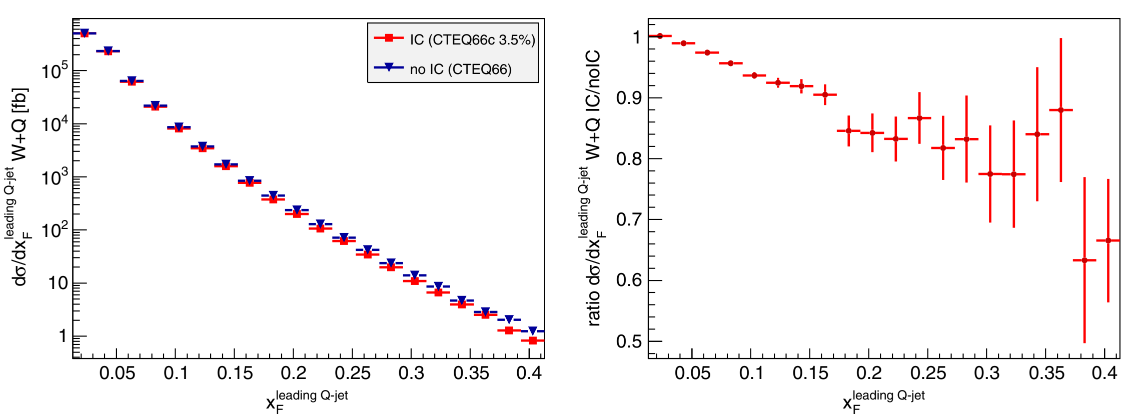

FIG. 14 (color online). Left: Comparison of the x_F^Q-spectra for the total NLO $pp \to W + b$ plus $pp \to W + c$ plus $pp \to W + bj$ processes (12, 17, 13, 18, 401, 402, 406, and 407 [24]) obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two spectra.

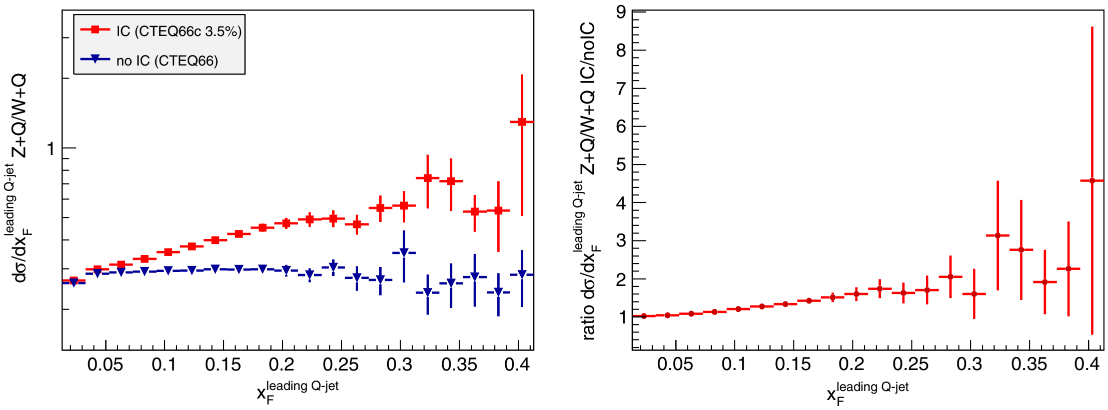

FIG. 15 (color online). Left: Comparison of the ratio of the x_F^Q-spectra for the $Z+Q$ to $W+Q$ NLO processes obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). Right: Ratio of these two ratios of spectra.

(about 3.5%) to the same spectrum obtained without any intrinsic charm contribution to the proton for both $Z+Q$ and $W+Q$ are presented in the right panels of Fig. 13 and Fig. 14 respectively. From these distributions, one can see that the pseudo-Feynman observable x_F^Q features an even bigger sensitivity to the IC than what was observed in $Zb+Zc$ production of the leading Q-jet transverse momentum observable, while the $W+Q$ processes still feature very little sensitivity to the IC. Figure 15 presents the $Z+Q$ to $W+Q$ ratio sensitivity to the IC as a function of the pseudo-Feynman variable x_F^Q. In this figure, heavy-flavor tagging has been applied to both $Z+Q$ and $W+Q$ processes. An IC contribution of 3.5% yields a change by a factor of 2 to 4 in the $Z+Q$ to $W+Q$ cross section ratio at $x_F^Q \simeq 0.3$–0.4 compared to the calculation where the PDFs do not include any IC component. The number of events in that kinematic region runs from about a few hundred up to a few thousand events, for both $Z+Q$ and $W+Q$ processes. This results in a reduced statistical uncertainty on the $Z+Q$ to $W+Q$ ratio compared to the proposed ratio measured as a function of the transverse momentum of the leading heavy-flavor jet in the phase space region discussed above. Because the shapes of the pseudo-Feynman variable and of the Q-jet transverse momentum distributions are significantly different, they have a different sensitivity to the various experimental and theoretical systematic uncertainties affecting their measurements. With both being sensitive to an intrinsic charm contribution to the proton, we thus have two complementary ratio observables to be measured at the LHC in order to observe an IC contribution to the proton, or determine an upper limit on it.

As discussed above, the leading heavy-flavor jet transverse momentum and rapidity distributions are similar for the b-jet and c-jet in $Z+Q$ and $W+Q$ events. As a consequence, the experimental uncertainties on Q-jet energy measurements and heavy-flavor tagging efficiencies will get significantly reduced in the ratio measurements proposed above. The Feynman diagrams contributing to $Z+Q$ and $W+Q$ processes are, however, quite different. It is therefore important to verify that a similar cancellation of the theory uncertainty also occurs in this ratio, therefore not impeding the conclusion about the IC that can be obtained with such a ratio. The dominant theoretical systematic uncertainty on a NLO cross section calculation obtained at fixed order in perturbative QCD comes, by far, from the uncertainty introduced by the choice of renormalization (μ_R) and factorization (μ_F) scales in the calculation. In the current calculations performed with MCFM [24], the central predictions were obtained with a dynamic scale $\mu_R = \mu_F = H_T$, where H_T is the scalar sum of the transverse momentum of all the particles (p_{Ti}) in the final state ($H_T = \sum_i^n p_{Ti}$). To assess the sensitivity of the calculations to this choice of scale, cross sections have been calculated with two other choices of scale, $H_T \cdot 2$ and $H_T/2$, and results compared to the nominal predictions. In the left panel of Fig. 16, we can see the $Z+Q$ predictions for three different choices of renormalization and factorization scales with an IC contribution of 3.5%, all divided by the same $Z+Q$ prediction (nominal H_T) with no intrinsic charm contribution included in the PDF. As can be seen on this figure, the systematic uncertainty on the $Z+Q$ predictions due to the scale uncertainty is substantial, ranging from about 5% to 20% and increasing with the leading Q-jet transverse momentum. This is nevertheless much smaller than the size of the intrinsic charm effect that is of about 50% for an IC contribution of 3.5%. On the right panel of Fig. 16, we can see that the impact of the scale uncertainty on the ratio of $Z+Q$ to $W+Q$ cross sections is significantly smaller than on the absolute $Z+Q$ cross section, being between 2% and 5% for the main part of the spectrum, more or less constant for all values of the leading heavy-flavor-jet transverse momentum and significantly smaller than the expected statistical uncertainty at large p_T. The ratio will thus feature a better sensitivity to the intrinsic charm (or tighter limits on the maximum contribution of the IC to the proton) than the actual $Z+Q$ cross section.

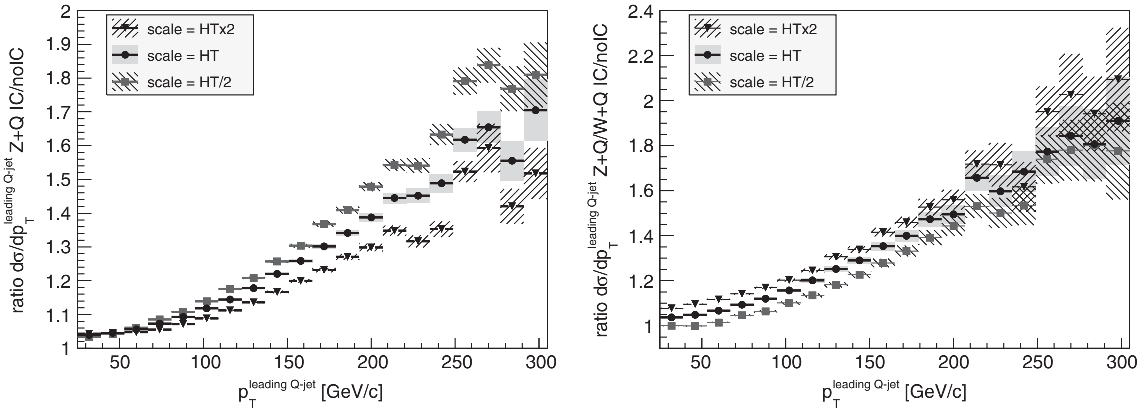

FIG. 16. Left: ratio of the p_T-spectra for $Zb + Zc$ NLO processes obtained with the PDF including an intrinsic charm component (CTEQ66c) and the PDF having only an extrinsic component (CTEQ66). The spectrum with the IC is obtained with three different choices of dynamical scales, $H_T \cdot 2$, H_T, and $H_T/2$, but the denominator of this ratio, the spectrum derived with the PDF not including the IC, is obtained only with the nominal scale H_T. Right: similar plot as on the left panel, but obtained for the cross section ratio of the $Z + Q$ over the $W + Q$ processes, rather than for the absolute $Z + Q$ cross section.

Similar results have been obtained for the pseudo-Feynman variable x_F^Q. Note that this figure presents a very conservative sensitivity test to scale uncertainties. In an actual measurement, a comparison between two predictions, one obtained with PDFs including an IC component to the proton and one ignoring intrinsic quarks in PDFs, would be made. The choice of scales made in both predictions should be the same, therefore leaving a ratio of predictions with the IC to predictions without the IC essentially independent of such a choice.

III. CONCLUSION

In this paper we have shown that the possible existence of an intrinsic heavy quark component to the proton can be seen not only in the forward open heavy-flavor production of pp-collisions (as it was believed before), but it can also be observed in the semi-inclusive pp-production of massive vector bosons in association with heavy-flavor jets (b and c). In particular, it was shown that the IC contribution can produce much more $Z + c$-jet events (a factor 1.5–2) than what is predicted from the extrinsic contribution to the PDF alone, when the heavy-flavor jet has a transverse momentum of $p_T > 100$ GeV/c and a pseudorapidity satisfying $1.5 < |\eta_Q| < 2.0$. We then showed that this conclusion stays true when the $Z + b$ negative contribution and the inefficiencies in the experimental identification of heavy-flavor jets are taken into account. We also investigated the sensitivity of the pseudo-Feynman variable x_F^Q for the leading heavy-flavor jet to an IC contribution to the proton and found that such a spectrum is complementary to the Q-jet p_T distribution and features an even larger sensitivity to the IC.

We then showed that, because of the dominant contribution of gluon-splitting processes, the production of W-bosons accompanied by heavy-flavor jets is not sensitive to intrinsic quarks. All the calculations were performed at NLO within perturbative QCD using the fixed-order parton-level MCFM program. The fact that these predictions do not include the parton shower and hadronization does not affect the results presented in this paper because the main gluon splitting giving heavy-flavor jets is included in these calculations, and further gluon emission affects the IC and non-IC contributions in a very similar way. This was numerically tested at LO using the example of the $pp \to Z + c(\bar{c})$ process within PYTHIA8.

We took advantage of these studies to propose a set of promising measurements sensitive to the intrinsic charm contribution to the proton. The new idea is to use the ratio of the leading heavy-flavor jet spectra in inclusive heavy-flavor $Z + Q$ to $W + Q$ events to verify the predictions about an IC contribution to the proton (or to set limits on such contribution) and to reproduce a similar measurement as a function of the pseudo-Feynman variable defined in Eq. (2). We stress that ratio measurements as proposed above reduce many sources of experimental and theoretical systematic uncertainties such as background due to the light jet production, heavy-flavor jet energy and tagging measurements, and QCD prediction rescaling. Such measurements can already be made with ATLAS and CMS available data.

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[1] J. W. Negele *et al.*, Nucl. Phys. B, Proc. Suppl. **128**, 170 (2004); W. Schroers, Nucl. Phys. **A755**, 333 (2005).

[2] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky, and W. K. Tung, J. High Energy Phys. 07 (2002) 012; D. R. Stump, J. Huston, J. Pumplin, W. K. Tung, H. L. Lai, S. Kuhlmann, and J. F. Owens, J. High Energy Phys. 10 (2003) 046.

[3] R. S. Thorne, A. d. Martin, W. G. Stirling, and R. G. Roberts, arXiv:hep-ph/0407311.

[4] V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. **15**, 438 (1972); G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1997); Yu. L. Dokshitzer, Sov. Phys. JETP **46**, 641 (1977).

[5] ATLAS Collaboration, Phys. Rev. Lett. **109**, 012001 (2012).

[6] A. Aktas *et al.* (H1 Collaboration), Eur. Phys. J. C **45**, 23 (2006); arXiv:hep-ex/0507081.

[7] S. Brodsky, P. Hoyer, C. Peterson, and N. Sakai, Phys. Lett. **93B**, 451 (1980).

[8] S. Brodsky, C. Peterson, and N. Sakai, Phys. Rev. D **23**, 2745 (1981).

[9] J. F. Donoghue and E. Golowich, Phys. Rev. D **15**, 3421 (1977).

[10] J. Pumplin, Phys. Rev. D **73**, 114015 (2006).

[11] J.-C. Peng and W.-C. Chang, *Proc. Sci.*, QNP2012 (2012) 012.

[12] M. V. Polyakov, A. Schafer, and O. V. Teryaev, Phys. Rev. D **60**, 051502 (1999).

[13] G. I. Lykasov, I. V. Bednyakov, M. A. Demichev, and Yu. Yu. Stepanenko, Nucl. Phys. B, Proc. Suppl. **245**, 215 (2013).

[14] P. Jimenez-Delgado, T. Hobbs, J. Londegan, and W. Melnitchouk, Phys. Rev. Lett. **114**, 082002 (2015).

[15] S. Brodsky and S. Gardner, arXiv:1504.00969v1.

[16] G. I. Lykasov, V. A. Bednyakov, A. F. Pikelner, and N. I. Zimine, Europhys. Lett. **99**, 21002 (2012).

[17] V. M. Abazov *et al.*, Phys. Rev. Lett. **102**, 192002 (2009).

[18] V. M. Abazov *et al.*, Phys. Lett. B **714**, 32 (2012).

[19] V. M. Abazov *et al.*, Phys. Lett. B **719**, 354 (2013).

[20] T.Altonen *et al.*, Phys. Rev. D **81**, 052006 (2010).

[21] T. P. Stavreva and J. F. Owens, Phys. Rev. D **79**, 054017 (2009).

[22] V. A. Bednyakov, M. A. Demichev, G. I. Lykasov, T. Stavreva, and M. Stockton, Phys. Lett. B **728**, 602 (2014).

[23] P. M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, and C.-P. Yuan, Phys. Rev. D **78**, 013004 (2008).

[24] J. M. Campbell and R. K. Ellis, Phys. Rev. D **65**, 113007 (2002); http://mcfm.fnal.gov/.

[25] ATLAS Collaboration, Report No. ATLAS-CONF-2013-109; Report No. ATLAS-CONF-2014-046.

[26] ATLAS Collaboration, J. High Energy Phys. 10 (2014) 141.

[27] ATLAS Collaboration, J. High Energy Phys. 06 (2013) 084.

[28] CMS Collaboration, J. High Energy Phys. 06 (2014) 120.

[29] CMS Collaboration, Phys. Lett. B **735**, 204 (2014).

[30] ATLAS Collaboration, Phys. Lett. B **708**, 221 (2012); ATLAS Collaboration, Eur. Phys. J. C **74**, 3168 (2014).

[31] ATLAS Collaboration, Eur. Phys. J. C **75**, 82 (2015).

[32] ATLAS Collaboration, J. High Energy Phys. 07 (2013) 032.

[33] T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput. Phys. Commun. **178**, 852 (2008).