

Probing the pion-gluon distribution at small x in photon-induced interactions at the LHC

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In this paper, we propose the analysis of the heavy quark photoproduction associated with a leading neutron in hadronic collisions at the LHC as an alternative to probe the pion gluon distribution in a kinematical range not covered by previous experiments. We perform an exploratory study of the charm and bottom photoproduction associated with a leading neutron in proton-proton (pp) and proton-lead (pPb) collisions, and present calculations for the rapidity distributions and cross sections. Our predictions indicate that experimental studies of these processes are feasible, and that a future measurement of this final state will be useful to constrain the pion gluon distribution at small values of the Bjorken x variable and to improve our understanding of the pion structure.

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I. INTRODUCTION

Over the last decades, the study of particle production by photon-photon and photon-hadron interactions in hadronic collisions at the LHC became a reality and is currently one of the more promising ways to investigate the proton and nucleus structure as well to probe for signals of beyond the Standard Model physics [1]. During this period, the four experimental LHC collaborations have released data for exclusive processes (e.g., the exclusive vector-meson photoproduction), where both incident particles remain intact, mainly motivated by the possibility of improving the description of QCD dynamics at high energies [2–4]. More recently, the first data for inclusive processes, where one of the incident hadrons is broken up, have also been released [5–7], providing additional constraints on the description of the hadronic structure as indicated, e.g., in Refs. [3,8–26]. In particular, the recent studies performed in Refs. [24–26] have demonstrated that the analysis of inclusive heavy quark photoproduction in ultraperipheral collisions (UPCs) is an important probe of the gluon distribution of the proton or nucleus target at small values of the Bjorken x variable.

Our goal in this paper is to investigate, for the first time, if the study of inclusive heavy quark photoproduction in UPCs can also be used to probe the pion structure in a kinematical range complementary to that accessed in pion-nucleus scattering at CERN and Fermilab [27–29], and leading neutron electroproduction at HERA [30,31]. In our analysis, we will consider the Sullivan process [32], in which the photon emitted by one of the incoming hadrons scatters off the virtual pion cloud of the hadron target, effectively probing the pion structure. In particular, the heavy quark photoproduction cross section will be determined by the gluonic content of pion (see Fig. 1). Moreover, the final state will be characterized by the presence of a rapidity gap and a leading neutron, which can be tagged using a zero degree calorimeter. In our analysis, we will consider the charm and bottom photoproduction in pp and pPb collisions at the LHC, and will estimate the corresponding rapidity and total cross sections assuming different parametrizations for the pion gluon distribution available in the literature [33–35]. Finally, we will show that the ratio between the charm and bottom rapidity distributions is a sensitive probe of the pion gluon distribution, which can be used to constrain the behavior of this distribution. As we will demonstrate below, the analysis of inclusive process with a leading neutron in UPCs provides an important probe of pion structure, complementary to that obtained by the study of exclusive processes with a leading neutron, originally proposed in Refs. [36,37].

This paper is organized as follows. In the following Section, we present a brief review of the formalism needed to describe the heavy quark photoproduction

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associated with a leading neutron in UPCs. In particular, we will discuss the description of the photon and pion fluxes, as well as the expression for the heavy quark photoproduction cross section. In Sec. III, the x dependence of the pion gluon distribution predicted by the distinct parametrizations used in our calculations will be presented, and we will present our results for the energy dependence of the cross sections for the charm and bottom production in photon-pion interactions. Moreover, predictions for the rapidity distributions and total cross sections associated with the heavy quark photoproduction in pp and pPb collisions will be shown. In Sec. IV, we summarize our main predictions and conclusions.

II. FORMALISM

In this Section, we will present a brief review of the formalism needed to describe the heavy quark photoproduction associated with a leading neutron (HQ + LN) in ultraperipheral collisions. In this exploratory study, we will focus on the direct contribution, in which the photon interacts as a pointlike particle, and postpone the inclusion of the resolved processes, where it fluctuates into a hadronic state, for a future publication. (For a detailed discussion see, e.g., Ref. [38]) The direct photoproduction process is represented in Fig. 1 for pp and pPb collisions, where we also present the main kinematical variables. The basic idea is that in a hadronic collision with center-of-mass energy $\sqrt{s}$, one of the incident protons (or nuclei) can be considered as a source of photons of energy ω , which will interact with the proton target with a squared center-of-mass energy $W_{\gamma p}^2 = 2\omega\sqrt{s}$ [1]. Assuming the Sullivan process [32], the photon scatters off the pion cloud of the proton target, with the squared center of energy for the photon-pion interaction being given by $W_{\gamma\pi}^2 = (1 - x_L)W_{\gamma p}^2$, where x_L is the proton momentum fraction carried by the neutron. Moreover, t is the square of the four-momentum of the exchanged pion, which can be expressed

in terms of the measured quantities x_L and transverse momentum p_T of the neutron, as follows:

$$t \simeq -\frac{p_T^2}{x_L} - \frac{(1 - x_L)(m_n^2 - m_p^2 x_L)}{x_L}, \quad (1)$$

where m_p (m_n) is the proton (neutron) mass. In the case of the heavy quark photoproduction, the dominant partonic channel is the photon-gluon interaction, $\gamma g \rightarrow Q\bar{Q}$, with the gluon in the pion g^π carrying a momentum fraction x , which implies $W_{\gamma g}^2 = xW_{\gamma\pi}^2$. As a consequence, the corresponding cross section will be sensitive to the pion gluon distribution $xg^\pi(x, \mu^2)$ at a given value of the Bjorken x variable and hard scale $\mu \propto m_Q$, where m_Q is the heavy quark mass. The final state for the HQ + LN process in UPCs will be characterized by a rapidity gap, associated with the photon exchange, the heavy quark pair and a leading neutron, which carries a large fraction of the proton energy. In principle, such a process can be separated from the dominant heavy quark production by photon-proton interactions by tagging the forward neutron in the final state.

Assuming the equivalent photon approximation [39], the rapidity distribution for the HQ + LN process in an ultraperipheral $h_1 h_2$ collision will be given by

$$\begin{aligned} & \frac{d\sigma[h_1 + h_2 \rightarrow h_i + Q\bar{Q} + X + n]}{dY} \\ &= \left[\omega \frac{dN}{d\omega} \Big|_{h_1} \sigma_{\gamma h_2 \rightarrow Q\bar{Q} + X + n}(\omega) \right]_{\omega_L} \\ &+ \left[\omega \frac{dN}{d\omega} \Big|_{h_2} \sigma_{\gamma h_1 \rightarrow Q\bar{Q} + X + n}(\omega) \right]_{\omega_R}, \end{aligned} \quad (2)$$

where Y is the rapidity of the heavy quark pair, h_i represents the hadron that has emitted the photon and remains intact in the final state, n is the leading neutron, and X is the hadronic state generated by the pion breakup. Moreover, $dN/d\omega|_{h_j}$ is the equivalent photon flux associated with the hadron h_j and $\sigma_{\gamma h \rightarrow Q\bar{Q} + X + n}$ is the cross section for the heavy quark photoproduction associated with a leading neutron. Finally, $\omega_L \propto \exp(+Y)$ and $\omega_R \propto \exp(-Y)$ denote photons associated with the hadrons h_1 and h_2 , respectively.

In our analysis, we will focus on pp and pPb collisions and assume that the equivalent photon fluxes associated with the nucleus and proton are given by [1]

$$\frac{dN_{\gamma/A}(\omega)}{d\omega} = \frac{2Z^2\alpha_{em}}{\pi\omega} \left[\bar{\eta} K_0(\bar{\eta}) K_1(\bar{\eta}) + \frac{\bar{\eta}^2}{2} [K_0^2(\bar{\eta}) - K_1^2(\bar{\eta})] \right], \quad (3)$$

and

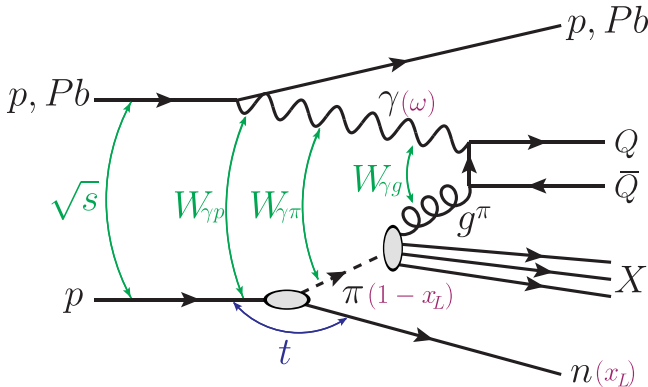


FIG. 1. Heavy quark photoproduction by photon-pion interactions at pp and pPb collisions.

$$\frac{dN_{\gamma/p}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega} \left[1 + \left(1 - \frac{2\omega}{\sqrt{s}} \right)^2 \right] \times \left(\ln \Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{2}{3\Omega^2} + \frac{1}{3\Omega^3} \right) \quad (4)$$

where $\omega = m_Q e^Y$, $\bar{\eta} = \omega(R_A + R_p)/\gamma_L$, $\Omega = 1 + [(0.71 \text{ GeV}^2)/Q_{\min}^2]$, and $Q_{\min}^2 = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{s})]$, with K_0 and K_1 being the modified Bessel functions and γ_L the Lorentz factor. For pPb collisions, the cross section is dominated by γp interactions due to the factor Z^2 in the nuclear photon flux.

In order to describe the cross section $\sigma_{\gamma h \rightarrow Q\bar{Q}+X+n}$ we will assume the Sullivan process [32], which implies that it can be expressed as follows (see, e.g., Ref. [40])

$$\sigma_{\gamma p \rightarrow Q\bar{Q}+X+n}(W_{\gamma p}^2) = \mathcal{K} \cdot \int dx_L dt f_{\pi/p}(x_L, t) \cdot \sigma_{\gamma \pi \rightarrow Q\bar{Q}+X}(W_{\gamma \pi}^2), \quad (5)$$

where $\mathcal{K}$ represents the absorption factor associated with soft rescatterings between the produced and spectator particles¹ and $f_{\pi/p}(x_L, t)$ is the pion flux. The main assumption here is that the splitting $p \rightarrow \pi^+ n$, the photon-pion interaction and the absorptive effects can be factorized. The general form of the pion flux is given by

$$f_{\pi/p}(x_L, t) = \frac{1}{4\pi} \frac{2g_{p\pi p}^2}{4\pi} \frac{-t}{(t - m_\pi^2)^2} (1 - x_L)^{1-2\alpha(t)} [F(x_L, t)]^2 \quad (6)$$

where $g_{p\pi p}^2/(4\pi) = 14.5$ is the $p\pi p$ coupling constant, m_π is the pion mass, $\alpha(t)$ is the pion intercept, and the form factor $F(x_L, t)$ accounts for the finite size of the nucleon and pion. Following Refs. [40,42], we will assume an exponential form factor given by

$$F(x_L, t) = \exp[b(t - m_\pi^2)], \quad \alpha(t) = t \quad (7)$$

with $b = 0.3 \text{ GeV}^{-2}$. As demonstrated in Refs. [40,42], such choice allow us to describe the current leading neutron electroproduction HERA data [30,31]. It is important to emphasize that assuming the validity of the factorization hypothesis and the universality of the fragmentation process, the data of leading neutron production in pp collisions can be used to constrain $f_{\pi/p}$, reducing the dependence of our predictions on this assumption. Finally, in this exploratory study, the heavy quark photoproduction in photon-pion interactions will be estimated at leading order, which implies that the associated cross section will be given by [43]

$$\sigma^{\gamma \pi \rightarrow Q\bar{Q}X}(W_{\gamma \pi}^2) = \int_{x_{\min}}^1 dx \sigma^{\gamma g \rightarrow Q\bar{Q}}(W_{\gamma g}^2) g^\pi(x, \mu^2), \quad (8)$$

with $x_{\min} = 4m_Q^2/W_{\gamma \pi}^2$ and

$$\sigma^{\gamma g \rightarrow Q\bar{Q}}(W_{\gamma g}^2) = \frac{2\pi\alpha_{em}\alpha_s(\mu^2)e_Q^2}{W_{\gamma g}^2} \times \left[\left(1 + \beta - \frac{\beta^2}{2} \right) \ln \left(\frac{1+\nu}{1-\nu} \right) - (1+\beta)\nu \right], \quad (9)$$

where $\nu = \sqrt{1-\beta}$ and $\beta = 4m_Q^2/W_{\gamma g}^2$. In our calculations, we will assume $\mu = 2m_Q$, with $m_c = 1.5 \text{ GeV}$ and $m_b = 4.5 \text{ GeV}$, and $\mathcal{K} = 0.8$, which allows us to describe the HERA data for the leading neutron electroproduction [40].

III. RESULTS

In what follows, we will present our results for the rapidity distributions and cross sections for the charm and bottom photoproduction associated with a leading neutron in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ and pPb collisions at $\sqrt{s} = 8.1 \text{ TeV}$. Such predictions will be derived assuming three different parametrizations for the pion gluon distribution, which are available in the LHAPDF library.² In particular, we will consider the GRV [33], JAM21 [35], and xFitter [34] parametrizations, which are based on different assumptions for the initial conditions of the DGLAP evolution and consider distinct datasets to constrain the free parameters. In Fig. 2 we present a comparison between the predictions of these parameterizations for the gluon distribution, derived considering two distinct values of the hard scale μ . In addition to the central value, the uncertainty band on the JAM21 and xFitter gluon parametrizations is also presented. Such uncertainty is not available in the GRV case. We have that all parametrizations predict the increase of the distribution at small x , but the increasing is dependent on the parametrization. Moreover, the uncertainty band increases for smaller values of x , which is directly associated with the fact that the current data for Drell-Yan and leading neutron DIS processes are not able to constrain the pion gluon distribution in the kinematical range.

The impact of the distinct parametrizations for the pion gluon distributions on the energy dependence of the cross section for the heavy quark photoproduction in photon-pion interactions is presented in Fig. 3. Results for the charm (bottom) pair production are presented in the left (right) panel. The cross sections increase with the energy, since smaller values of x are probed at larger W , and decrease for heavier quarks. Moreover, the predictions are

¹For a detailed discussion about the absorptive effects see Ref. [41].

²<https://www.lhapdf.org>.

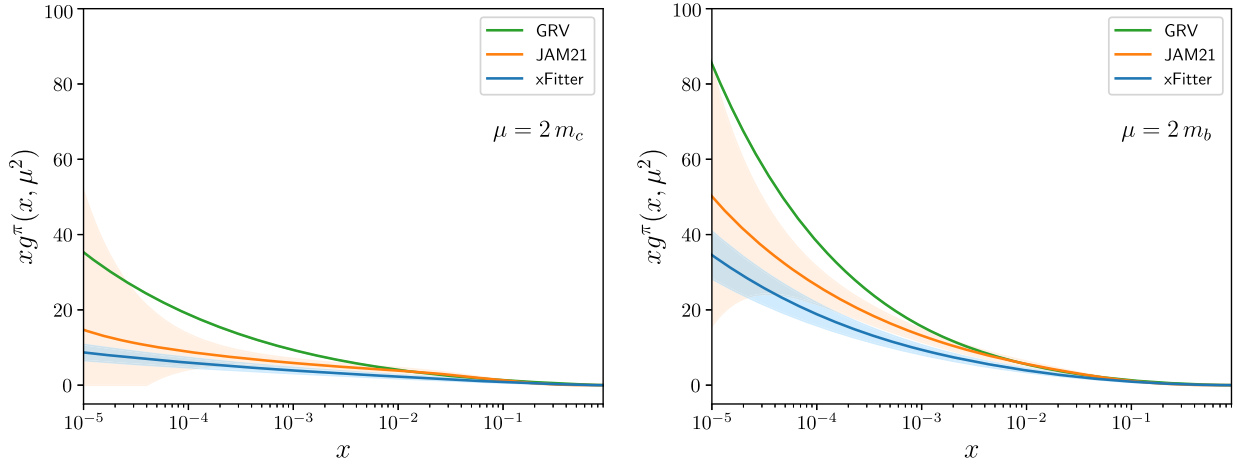


FIG. 2. Comparison between the pion gluon distributions predicted by the GRV, JAM21 and xFitter parametrizations [33–35]. Results for two distinct values of the hard scale μ .

sensitive to the parametrization assumed as input in the calculations.

Let us now consider ultraperipheral collisions at the LHC. As discussed in the Introduction, in these collisions, the incoming hadrons can be considered as sources of photons of energy ω , whose distribution is described by the equivalent photon flux. The maximum photon energy can be derived considering that the maximum possible momentum in the longitudinal direction is modified by the Lorentz factor, γ_L , due to the Lorentz contraction of the hadrons in that direction [1]. It implies $\omega_{\max} \approx \gamma_L/R_h$ and, consequently, $W_{\gamma p}^{\max} = \sqrt{2\omega_{\max}\sqrt{s}}$. Therefore, for pp/pPb collisions at $\sqrt{s} = 13/8.1$ TeV, we have that the maximum photon-proton center-of-mass energy, $W_{\gamma p}^{\max}$, will be of the order of 8.2/1.4 TeV [1], i.e., LHC probes a range of photon-proton center-of-mass energies unexplored by HERA. Such a conclusion is also valid for photon-pion

interactions, which implies that the study of heavy quark photoproduction associated with a leading neutron in UPCs allows us to investigate the pion structure in the high energy limit.

In Fig. 4 we present our predictions for the rapidity distributions for the charm and bottom photoproduction associated with a leading neutron in pp collisions at the LHC, derived assuming different parametrizations for the pion gluon distribution. The results are obtained by calculating Eq. (2). The first term in Eq. (2) is determined by the photon flux for a photon with energy $\omega \propto e^Y$ and the heavy quark photoproduction cross section for a given photon-proton center-of-mass energy $W_{\gamma p}$. While $\sigma_{\gamma p \rightarrow Q\bar{Q}+X+n}$ increases with $W_{\gamma p}$, the photon flux strongly decreases when the photon energy is of the order of $\omega_{\max} \approx \gamma_L/R_p$, becoming almost zero for larger photon energies. As a consequence, this contribution increases

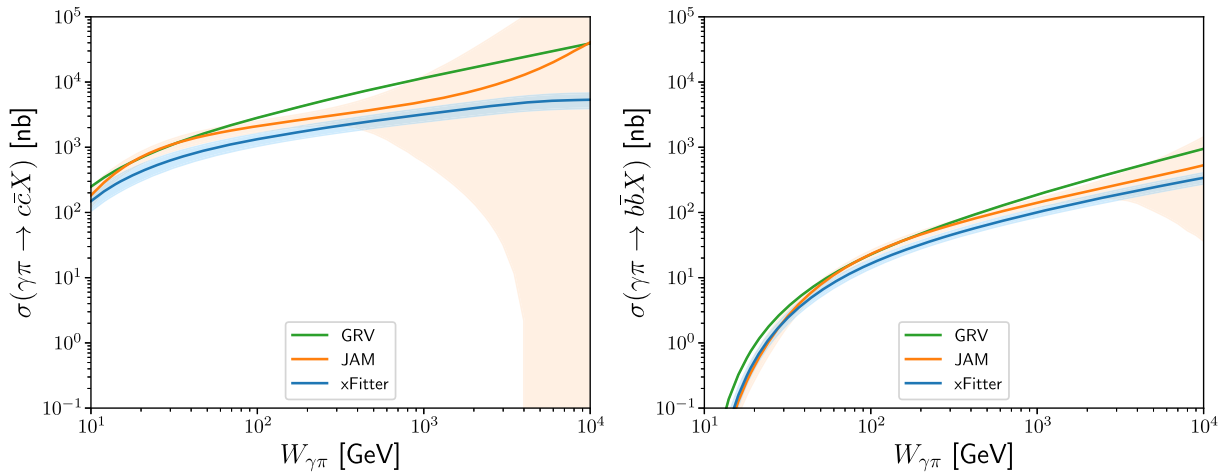


FIG. 3. Energy dependence of the total cross section for the charm (left panel) and bottom (right panel) pair production in photon-pion interactions.

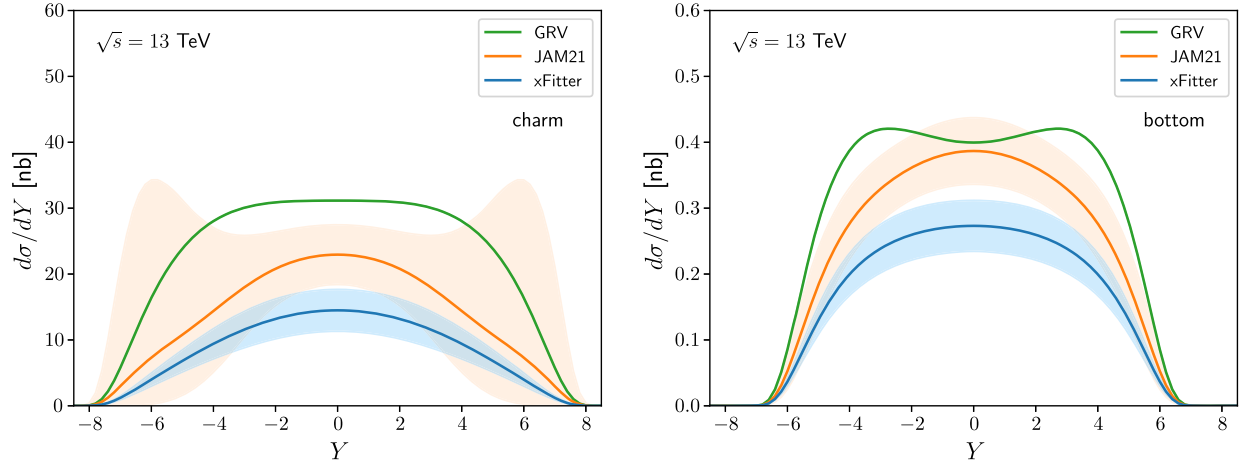


FIG. 4. Rapidity distributions for the charm (left panel) and bottom (right panel) pair photoproduction associated with a leading neutron in pp collisions at $\sqrt{s} = 13$ TeV. Results derived assuming different parametrizations for the pion gluon distribution.

with the rapidity up to a maximum and becomes zero at very large Y . On the other hand, the second term in Eq. (2) increases for negative values of rapidity, since in this case $\omega \propto e^{-Y}$. For pp collisions, the contributions of both terms in Eq. (2) are identical and symmetric in rapidity. Moreover, we have that the increasing with rapidity is determined by the energy dependence of the heavy quark photoproduction cross section, being dependent on the pion gluon distribution considered. Therefore, the difference between the predictions presented in Fig. 4 is larger for larger values of $|Y|$. However, the results are also distinct at midrapidities ($Y \approx 0$), with the central predictions for the charm production associated with the JAM21 and xFitter parametrizations differing by a factor ≈ 2 . A similar difference is also observed in the case of bottom production (right panel). It is important to emphasize that it should be possible to identify the pion-going direction by tagging the forward neutron, which will allow us to use this

information to separate the contribution of each term in Eq. (2), allowing a more precise determination of the pion gluon distribution since the ambiguity about what of the incident protons was the photon emitter is eliminated. Such an aspect will be explored in a future publication.

In Fig. 5 we present our results for pPb collisions. In this case, the rapidity distribution receives contributions of photon-proton and photon-nucleus interactions. However, due to the Z^2 factor present in the nuclear photon flux, the distribution is dominated by the photon-proton contribution. As a consequence, the associated rapidity distribution is asymmetric and larger in magnitude in comparison with the pp case. We have that the difference between the predictions increases with the rapidity, with the position of the maximum of distribution being dependent on the parton distribution function (PDF) parametrization.

In Table I we present our results for the charm and bottom photoproduction cross sections with a leading

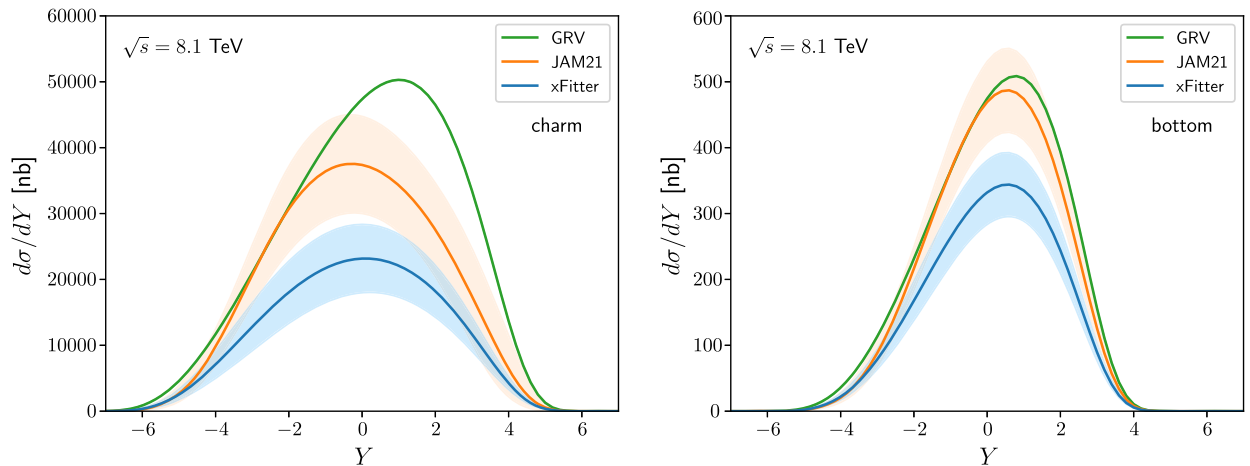


FIG. 5. Rapidity distributions for the charm (left panel) and bottom (right panel) pair photoproduction associated with a leading neutron in pPb collisions at $\sqrt{s} = 8.1$ TeV. Results derived assuming different parametrizations for the pion gluon distribution.

TABLE I. Predictions for the charm and bottom photoproduction cross section associated with a leading neutron in pp collisions at $\sqrt{s} = 13$ TeV and pPb collisions at $\sqrt{s} = 8.1$ TeV. Results derived assuming different rapidity ranges and using distinct pion PDF parametrizations.

Final state	Rapidity range	PDF parametrization	$\sigma(pPb)$ (μb)	$\sigma(pp)$ (nb)
$c\bar{c}$	$[-7, 7]$	GRV	3.02×10^2	3.47×10^2
$c\bar{c}$	$[-7, 7]$	JAM21	2.24×10^2	2.14×10^2
$c\bar{c}$	$[-7, 7]$	xFitter	1.42×10^2	1.34×10^2
$c\bar{c}$	$[-2, 2]$	GRV	1.78×10^2	1.19×10^2
$c\bar{c}$	$[-2, 2]$	JAM21	1.39×10^2	8.36×10^1
$c\bar{c}$	$[-2, 2]$	xFitter	8.59×10^1	4.91×10^1
$c\bar{c}$	$[2, 4.5]$	GRV	6.86×10^1	6.97×10^1
$c\bar{c}$	$[2, 4.5]$	JAM21	3.64×10^1	3.97×10^1
$c\bar{c}$	$[2, 4.5]$	xFitter	2.43×10^1	3.12×10^1
$b\bar{b}$	$[-7, 7]$	GRV	2.29×10^0	4.32×10^0
$b\bar{b}$	$[-7, 7]$	JAM21	2.11×10^0	3.47×10^0
$b\bar{b}$	$[-7, 7]$	xFitter	1.54×10^0	2.50×10^0
$b\bar{b}$	$[-2, 2]$	GRV	1.68×10^0	1.61×10^0
$b\bar{b}$	$[-2, 2]$	JAM21	1.62×10^0	1.50×10^0
$b\bar{b}$	$[-2, 2]$	xFitter	1.16×10^0	1.05×10^0
$b\bar{b}$	$[2, 4.5]$	GRV	3.48×10^{-1}	9.79×10^{-1}
$b\bar{b}$	$[2, 4.5]$	JAM21	2.90×10^{-1}	7.02×10^{-1}
$b\bar{b}$	$[2, 4.5]$	xFitter	2.06×10^{-1}	5.41×10^{-1}

neutron in pp collisions at $\sqrt{s} = 13$ TeV and pPb collisions at $\sqrt{s} = 8.1$ TeV, derived assuming different rapidity ranges and using distinct pion PDF parametrizations. In particular, predictions for the rapidity range covered by typical central ($-2.0 \leq Y \leq 2.0$) and forward ($2.0 \leq Y \leq 4.5$) detectors are presented. We have that the pPb predictions are ≈ 3 orders of magnitude larger than for pp collisions. Moreover, the bottom cross sections are one order of magnitude smaller than for the charm production. Finally, our results indicate that the predictions are sensitive to the pion gluon distribution assumed in the calculations. Such conclusion strongly motivates the improvement of the theoretical description of the process, as well the extension

of our analysis for the production of identified heavy-flavor-hadrons, as, e.g., D - and B mesons.

Some final comments are in order. The results presented above indicated that a future experimental analysis of the heavy quark photoproduction associated with a leading neutron can be useful to constrain the behavior of the pion gluon distribution at small x . However, a natural question is how reliable our predictions are, since they are dependent on the modeling of the absorptive effects and pion flux as well as of the order of the perturbative calculation and value assumed for the hard scale. As discussed in the previous Section, the description of the absorptive effects has been improved in recent years and its magnitude can, in

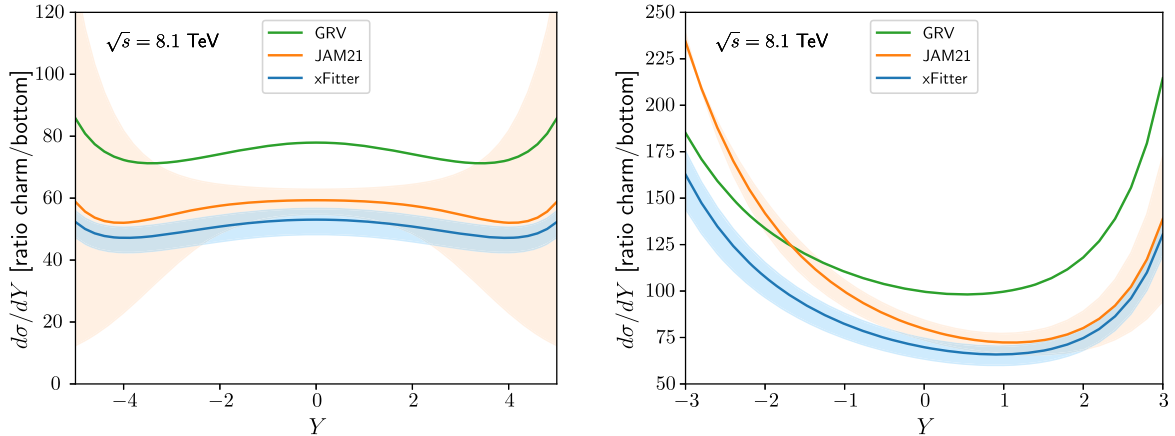


FIG. 6. Predictions for the ratio between the charm and bottom rapidity distributions in pp (left panel) and pPb (right panel) collisions. Results derived assuming distinct pion PDFs.

principle, be constrained in a phenomenological way using the HERA, as performed in the current paper. Similarly, the pion flux can also be constrained using the HERA and LHC data for leading neutron processes. On the other hand, the photon-pion cross section can be evaluated at next-to-leading order, which would reduce the dependence of the predictions on the choices for the factorization and renormalization scales. Such a task is currently being performed. We have verified that the normalization of our predictions is dependent on the model assumed for the pion flux and on the values for $\mathcal{K}$ and μ , but the difference associated with the distinct pion PDFs is not affected, i.e., our main conclusion remains valid. One way to circumvent this dependence, while the description of main ingredients in the calculation is being improved, is to consider the ratio between the rapidity distributions for the charm and bottom production. Such a ratio is not dependent on the absorptive effects, and we have verified that the predictions are not affected by the value of μ and by the order of the perturbative calculation. The corresponding predictions for pp and pPb collisions are presented in Fig. 6. We have that the ratio is also dependent on the pion PDF and that its analysis in pPb collisions can be very useful to impose additional constraints in the description of the pion structure at high energies.

IV. SUMMARY

Despite the theoretical and experimental advances during the last decades, a comprehensive understanding of the partonic structure of the pion remains incomplete. In particular, the behavior of the sea quarks and gluon distributions at small values of the Bjorken x variable is currently poorly understood. In the near future, the electron-ion collider and the proposed electron-ion collider in China are expected to measure the pion structure functions

assuming the Sullivan process and tagging the leading neutron, providing additional constraints in these distributions. In this paper we have considered an alternative to probe the pion structure at the existing Large Hadron Collider by studying photon-induced interactions, which become dominant in ultraperipheral hadronic collisions. We have proposed the analysis of the heavy quark photo-production associated with a leading neutron and carried out an exploratory study of the charm and bottom production in pp and pPb collisions. The rapidity distributions and cross sections have been estimated assuming different parametrizations for the pion gluon distribution. We predicted large cross sections and demonstrated that the rapidity distribution is sensitive to the behavior of the pion gluon distribution at small values of x . In addition, we have proposed the analysis of the ratio between the charm and bottom rapidity distributions, which is almost independent of the assumptions for the absorptive effects and the modeling of the pion flux. Our results indicate that the proposed process is a promising way to improve our understanding of the pion structure. Such results strongly motivate the improvement of the theoretical description of the process as well its implementation in a Monte Carlo event generator. Both subjects will be explored in forthcoming publications.

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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