Diffractive gauge boson production at the LHC as a probe of the flavor content of the Pomeron

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The production of the W and Z bosons in single diffractive processes at the LHC is investigated taking into account the ATLAS, CMS and LHCb acceptances and considering different assumptions for the flavor content of the Pomeron. The total cross sections and pseudorapidity distributions are estimated for pp collisions at $\sqrt{s} = 13$ TeV. Our results indicate that a future experimental analysis of the ratio between the W and Z cross sections can be used to probe the flavor content of the Pomeron.

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The study of hadronic collisions at the LHC provides a unique environment for precise measurements of poorly understood phenomena. In particular, the study of hard diffractive processes at the LHC is expected to provide important insight for improving the theoretical description of the diffractive physics and the nature of the Pomeron ($\mathbb{P}$), which is a long-standing puzzle in particle physics [1]. This object, with the vacuum quantum numbers, was introduced phenomenologically in the Regge theory as a simple moving pole in the complex angular momentum plane, to describe the high-energy behavior of the total and elastic cross sections of the hadronic reactions. On the other hand, the diffractive deep inelastic scattering (DDIS) at HERA is quite well described assuming the validity Regge factorization of the diffractive processes, as suggested long ago by Ingelman and Schlein (IS) [2] and not yet proven in pQCD (See Ref. [3] for a recent criticism and alternative approach). The IS approach essentially considers that the diffractive processes can be described in terms of the probability of the proton to emit a color singlet object—the Pomeron—and the subsequent interaction of the partons inside such Pomeron with the virtual photon emitted by the incident electron. This introduces the Pomeron parton distribution functions, which can be extracted from data where a hard final state is produced and a leading hadron is detected. During the last years, several groups have used the HERA data to extract the gluon and quark distributions of the Pomeron considering different assumptions for the initial conditions and the DGLAP evolution at leading and next-to-leading orders [4–10]. The main conclusion of these different analyzes is that the Pomeron structure is dominated by gluons, with the quark content being non-negligible. One important assumption present in these studies is that the flavor content of the Pomeron is equal for up, down and strange quarks, i.e., $u_{\mathbb{P}} = d_{\mathbb{P}} = s_{\mathbb{P}} = q_{\mathbb{P}}$ with $q_{\mathbb{P}} = \bar{q}_{\mathbb{P}}$. Such assumption arise due to the fact that the HERA data do not allow us to separate the contribution of the distinct light quarks for the Pomeron structure. Our goal in this paper is to demonstrate that the diffractive gauge boson production at the LHC can improve our understanding of the flavor content of the Pomeron.

The recent studies of $W^{\pm}$ and Z^0 production in hadronic collisions are in general dedicated to the calculation of the production of this final state in inclusive reactions, where both initial protons dissociate in the interaction. However, these gauge bosons can also be produced in diffractive interactions, where one (or both) of the protons remain intact and empty regions in pseudo-rapidity, called rapidity gaps, separate the intact very forward proton(s) from the gauge boson state (For previous studies, see, e.g., Refs. [11–18]). In this paper, we will focus in the gauge boson production in single diffractive processes, represented in Fig. 1. In the IS approach, denoted often as the "resolved Pomeron model," the Pomeron is assumed to have a well defined partonic structure and the hard process takes place in a Pomeron-proton or proton-Pomeron interaction in the case of single diffractive processes. At

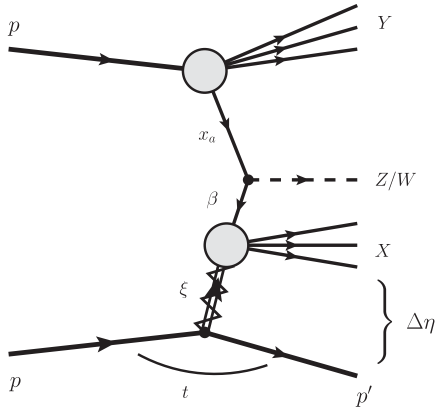

FIG. 1. Single diffractive production of gauge bosons in pp collisions.

leading order, the gauge boson production is determined by the annihilation processes $q\bar{q} \to G$ ($G = W$ or Z). Higher-order contributions are not considered here and can be taken into account effectively by a K factor. In order to estimate the hadronic cross sections, we have to convolute the cross section for this partonic subprocess with the inclusive and diffractive parton distribution functions. In the collinear factorization formalism, the single diffractive gauge boson production cross section can be expressed by

$$\sigma^{SD}(pp \to YGX \otimes p) = \sum_{a,b} \int dx_a \int dx_b [f_a^D(x_a,\mu^2) f_b(x_b,\mu^2) + f_a(x_a,\mu^2) f_b^D(x_b,\mu^2)] \hat{\sigma}_{ab\to G}, \quad (1)$$

where $\otimes$ represents a rapidity gap in the final state, Y the product of the proton dissociation, X the Pomeron remnants and $f_i(x_i,\mu^2)$ and $f_i^D(x_i,\mu^2)$ are the inclusive and diffractive parton distribution functions, respectively. In our study, we use the inclusive parton distributions as given by the CT10 parametrization [19]. In Eq. (1), the $p\mathbb{P}$ and $\mathbb{P}p$ interactions are included. Moreover, $\hat{\sigma}_{ab\to G}$ denotes the hard partonic interaction producing a gauge boson. The r Pomeron model considers the diffractive quark distributions as a convolution of the Pomeron flux emitted by the proton, $f_{\mathbb{P}}(x_{\mathbb{P}})$, and the parton distributions in the Pomeron, $q_{\mathbb{P}}(\beta,\mu^2)$, where β is the momentum fraction carried by the partons inside the Pomeron. The Pomeron flux is given by

$$f_{\mathbb{P}}^p(\xi) = \int_{t_{\min}}^{t_{\max}} dt \frac{A_{\mathbb{P}} e^{B_{\mathbb{P}} t}}{\xi^{2\alpha_{\mathbb{P}}(t)-1}}. \quad (2)$$

The normalization of the flux is such that the relation $\xi \int_{t_{\mathrm{cut}}}^{t_{\min}} dt f_{\mathbb{P}/p}(\xi,t) = 1$ holds at $\xi = 0.003$, where $|t_{\mathrm{cut}}| = 1$ GeV is limited by the measurement and $|t_{\min}| \simeq (m_{\mathrm{p}}\xi)^2/(1-\xi)$ is the kinematic limit of accessible momentum $|t|$. The Pomeron flux factor is motivated by Regge theory, where the Pomeron trajectory assumed to be linear, $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$, and the parameters $B_{\mathbb{P}}$, $\alpha'_{\mathbb{P}}$ and their uncertainties are obtained from fits to H1 data [6]. In the present analysis, the H1 Fit B is used, which has the slope parameter set to $B_{\mathbb{P}} = 5.5\ \mathrm{GeV}^{-2}$ and $\alpha'_{\mathbb{P}} = 0.06\ \mathrm{GeV}^{-2}$, while $\alpha_{\mathbb{P}}(0) = 1.111 \pm 0.007$. Consequently, the diffractive quark distributions are given by

$$q^D(x,\mu^2) = \int d\xi d\beta \delta(x-\xi\beta) f_{\mathbb{P}}(\xi) q_{\mathbb{P}}(\beta,\mu^2) = \int_x^1 \frac{d\xi}{\xi} f_{\mathbb{P}}(\xi) q_{\mathbb{P}}\left(\frac{x}{\xi},\mu^2\right). \quad (3)$$

The quark distributions of the Pomeron have been extracted from the HERA DIS measurements for the diffractive proton structure function $F_2^{D(4)}$ assuming that $u_{\mathbb{P}} = d_{\mathbb{P}} = s_{\mathbb{P}} = q_{\mathbb{P}}$, with $q_{\mathbb{P}} = \bar{q}_{\mathbb{P}}$. However, at leading order, we have that

$$\mathrm{F}_2^{\mathrm{D}(4)} \propto \left(\frac{2}{3}\right)^2 u_{\mathbb{P}} + \left(\frac{1}{3}\right)^2 d_{\mathbb{P}} + \left(-\frac{1}{3}\right)^2 s_{\mathbb{P}}, \quad (4)$$

which implies that the constraint $4u_{\mathbb{P}} + d_{\mathbb{P}} + \bar{s}_{\mathbb{P}} = 6q_{\mathbb{P}}$ must be satisfied. Defining the auxiliary functions

$$R_{ud} = \frac{u_{\mathbb{P}}}{d_{\mathbb{P}}}, \qquad R_{sd} = \frac{s_{\mathbb{P}}}{d_{\mathbb{P}}}, \quad (5)$$

the diffractive PDFs can be expressed as follows:

$$u_{\mathbb{P}}(\beta,\mu^2) = \frac{6R_{ud}}{1+R_{sd}+4R_{ud}} \cdot q_{\mathbb{P}}(\beta,\mu^2)$$
$$d_{\mathbb{P}}(\beta,\mu^2) = \frac{6}{1+R_{sd}+4R_{ud}} \cdot q_{\mathbb{P}}(\beta,\mu^2)$$
$$s_{\mathbb{P}}(\beta,\mu^2) = \frac{6R_{sd}}{1+R_{sd}+4R_{ud}} \cdot q_{\mathbb{P}}(\beta,\mu^2). \quad (6)$$

For $R_{ud} = R_{sd} = 1$, we recover the default HERA diffractive distributions. In order to test the dependence of the gauge boson production on the flavor content of the Pomeron, in what follows we will consider some different assumptions for the value of the ratios R_{ud} and R_{sd}, which we assume to be scale independent. In particular, as in Ref. [16], we will consider that these ratios can also assume, independently, the values 0.5 and 2.0, and will compare with the default predictions. As demonstrated in Ref. [16], these different assumptions has direct impact on the W charge asymmetry. Our goal is to extend this previous analysis for the Z boson production and present, for the first time, predictions for the rapidity distributions and ratio between cross sections considering the kinematic range probed by the ATLAS, CMS and LHCb detectors and the typical cutoffs present in the selection of the single diffractive events.

Before we present our results, some comments are in order. First, at large values of the Pomeron momentum fraction ξ, subleading contributions associated to Reggeon exchange can be important in some regions of the phase space (For a discussion see e.g., Refs. [16,20]). In what follows, we will focus our analysis in the kinematical region where $\xi \leq 0.12$, in which the Reggeon contribution is negligible. Second, in order to estimate the diffractive cross sections in pp collisions, one also have to take into account of the soft rescattering corrections associated to reinteractions (often referred to as multiple scatterings) between spectator partons of the colliding proton that implies the breakdown of the factorization assumed in Eq. (1) [21]. One possible approach to treat this problem is to assume that the hard process occurs on a short enough timescale such that the physics that generate the additional particles can be factorized and accounted by an overall factor, denoted gap survival factor $\langle |S|^2 \rangle$, multiplying the cross section calculated using the collinear factorization and the diffractive parton distributions extracted from HERA data. The modeling and magnitude of this factor still is a theme of intense debate [22,23]. In general, the values of $\langle |S|^2 \rangle$ depend on the energy, being typically of order 1%–5% for LHC energies. Such an approach has been largely used in the literature to estimate the hard diffractive processes at the LHC with reasonable success to describe the current data. In what follows, we will assume the validity of this approach, with $\langle |S|^2 \rangle = 0.05$ for single diffractive processes (for a more detailed discussion, see e.g., [18]).

The single diffractive gauge boson production at the LHC will be estimated using the forward physics Monte Carlo (FPMC) event generator [24]. This Monte Carlo allows us to produce event samples for the diffractive $W \to \nu\mu$ and $Z \to \mu\mu$ processes and to obtain realistic predictions for the boson $W^{\pm}$ and Z production with one leading intact hadron, taking into account the acceptance of the LHC detectors. The distributions are obtained for pp collisions at $\sqrt{s} = 13$ TeV considering the LHCb, CMS and ATLAS acceptances and a nondiffractive background in the $W^{\pm}$ and Z production. The events have been generated assuming the following combinations for the ratios $R_{ud} = u_{\mathbb{P}}/d_{\mathbb{P}}$ and $R_{sd} = s_{\mathbb{P}}/d_{\mathbb{P}}$: (0.5,0.5), (0.5,1), (2,1) and (2,2). An integrated luminosity of 100 pb^{-1} (CMS and ATLAS) and 6 fb^{-1} (LHCb) is assumed. In the case of the CMS and ATLAS detectors, the following selection criteria have been considered: the muons must have $p_T(\mu^{\pm}) > 30$ GeV at the central region inside the interval $|\eta(\mu^{\pm})| < 2.4$ and the transverse mass of the W bosons, given by, $M_T = \sqrt{(E_{T,\mu} + E_{T,\nu_\mu})^2 - (p_{T,\mu} + p_{T,\nu_\mu})^2}$, is required to be greater than 40 GeV. On the other hand, in the case of the LHCb detector, we assume that the muons with $p_T(\mu^{\pm}) > 20$ GeV must be at the forward region inside the pseudorapidity window of $2.0 < \eta(\mu^{\pm}) < 4.5$. Moreover, a VELO gap requirement in the backward region is performed using charged particles with momentum greater than 100 MeV inside the rapidity range $-1.5 > \eta > -3.5$ acceptance. Finally, a HERSCHEL gap requirement in the backward region is performed using charged and neutral particles with momentum greater than 500 MeV inside the $-5.5 > \eta > -8.0$ acceptance [25].

In Table I, we present our predictions for the total cross sections considering the acceptances of the ATLAS, CMS and LHCb detectors and different assumptions for the flavor content of the Pomeron. For comparison, we also present the results for the full LHC rapidity range. We have that the predictions for the W^+ production can differ by a factor $\lesssim 3$ depending of the values for R_{ud} and R_{sd}. For Z production, the difference between the predictions is smaller than a factor 1.5. Moreover, our results indicate that the cross sections are not strongly sensitive to the ratio R_{sd}. Such conclusion is also obtained from the analysis of the results presented in Fig. 2 for the pseudorapidity μ^+ distributions. We have that the reduction of u quarks in the Pomeron, and corresponding enhancement of d quarks, present in the assumption $R_{ud} = 1/2$ imply a larger cross section in comparison to the default $R_{ud} = 1$ one. On the other hand, $R_{ud} = 2$ imply a smaller cross section. Similar behavior also is present in the single diffractive Z production, as observed in the results presented in Fig. 3. However, the impact of the different assumptions for the

TABLE I. Predictions for the single diffractive cross sections for the W^+ and Z production considering the ATLAS, CMS and LHCb acceptances and different assumptions for the flavor content of the Pomeron.

	$\sigma^{SD}(pp \to W^+ p)$ [pb]			$\sigma^{SD}(pp \to Zp)$ [pb]		
Flavor content	Full rapidity range	ATLAS/CMS	LHCb	Full rapidity range	ATLAS/CMS	LHCb
$u_{\mathbb{P}} = s_{\mathbb{P}} = d_{\mathbb{P}}$	115.8	13.6	2.0	59.7	3.1	0.18
$u_{\mathbb{P}}/d_{\mathbb{P}} = 0.5$, $s_{\mathbb{P}}/d_{\mathbb{P}} = 0.5$	147.1	18.0	3.2	61.3	3.7	0.21
$u_{\mathbb{P}}/d_{\mathbb{P}} = 0.5$, $s_{\mathbb{P}}/d_{\mathbb{P}} = 1$	142.2	17.6	2.9	58.6	3.9	0.20
$u_{\mathbb{P}}/d_{\mathbb{P}} = 2$, $s_{\mathbb{P}}/d_{\mathbb{P}} = 1$	94.9	9.1	1.3	60.5	2.5	0.17
$u_{\mathbb{P}}/d_{\mathbb{P}} = 2$, $s_{\mathbb{P}}/d_{\mathbb{P}} = 2$	96.0	9.0	1.4	58.5	2.7	0.16

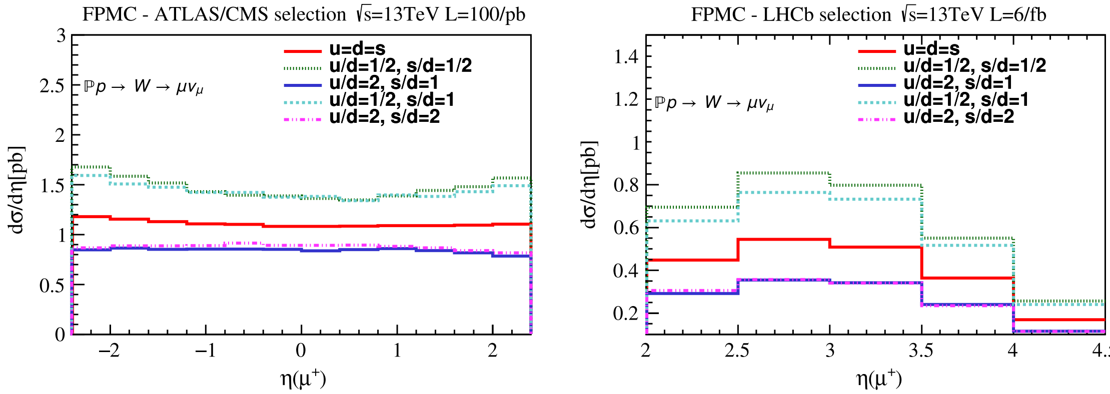

FIG. 2. Differential cross section as function of $\eta(\mu^+)$ for the single diffractive W^+ production in pp collisions at $\sqrt{s} = 13$ TeV considering the ATLAS/CMS (left) and LHCb (right) acceptances and different assumptions for the flavor content of the Pomeron.

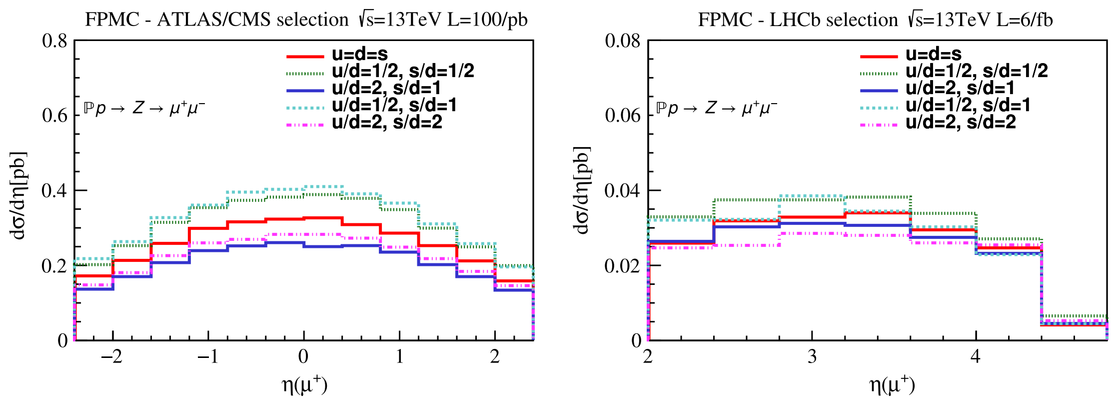

FIG. 3. Differential cross section as function of $\eta(\mu^+)$ for the single diffractive Z production in pp collisions at $\sqrt{s} = 13$ TeV considering the ATLAS/CMS (left) and LHCb (right) acceptances and different assumptions for the flavor content of the Pomeron.

flavor content of the Pomeron is smaller, in agreement with the results presented in the Table I. We have that the shape of the distributions is not sensitive to these assumptions. That is an important shortcoming to probe the flavor content of the Pomeron, due to the current theoretical uncertainty on the value of the absorptive corrections for the diffractive processes.

An alternative to surpass this shortcoming is to consider the ratio between cross sections, which cancel several of the experimental and theoretical systematic uncertainties. In

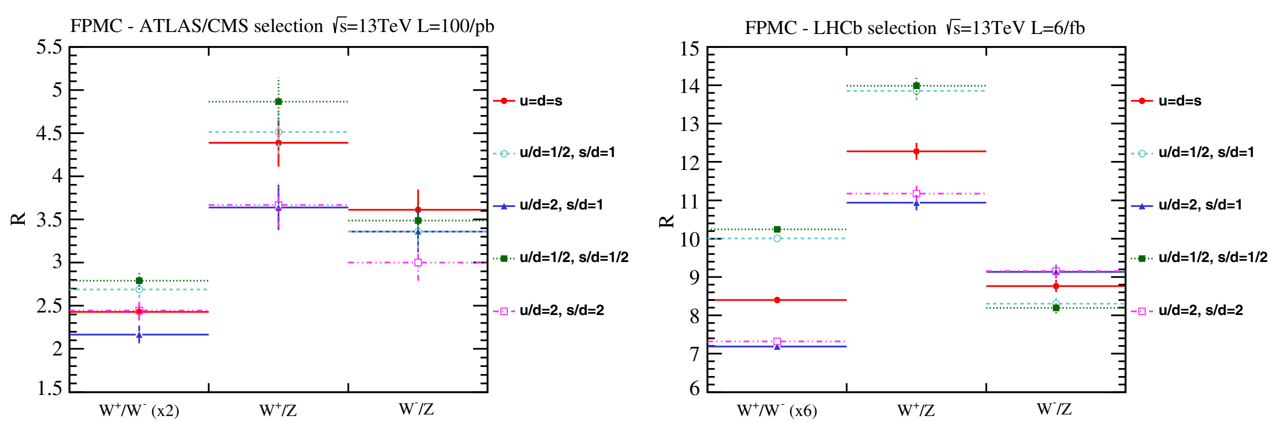

FIG. 4. Predictions for the ratios $\sigma^{SD}_{W^+}/\sigma^{SD}_{W^-}$, $\sigma^{SD}_{W^+}/\sigma^{SD}_{Z}$ and $\sigma^{SD}_{W^-}/\sigma^{SD}_{Z}$ considering the ATLAS/CMS (left) and LHCb (right) acceptances. The CMS/ATLAS (LHCb) predictions for $\sigma^{SD}_{W^+}/\sigma^{SD}_{W^-}$ have been rescaled by a factor 2 (6) to allow the comparison with the other ratios.

particular, as the absorptive corrections are expected to be similar for the diffractive $W^{\pm}$ and Z production, such ratios should not be sensitive to the modelling of these effects. In Fig. 4, we present our predictions for the ratios $\sigma^{SD}_{W^+}/\sigma^{SD}_{W^-}$ $\sigma^{SD}_{W^+}/\sigma^{SD}_{Z}$ and $\sigma^{SD}_{W^-}/\sigma^{SD}_{Z}$ considering the ATLAS/CMS (left) and LHCb (right) acceptances. Since LHCb has no forward proton detectors, we included in the ratio predictions the nondiffractive contribution as predicted by PYTHIA 8 [26]. Our results indicate that the ratios between the W and Z cross sections are sensitive to the flavor content of the Pomeron, with the magnitude being dependent of the charge of the W boson. From the analysis of these results, we propose the measurement of both ratios, $\sigma^{SD}_{W^+}/\sigma^{SD}_{Z}$ and $\sigma^{SD}_{W^-}/\sigma^{SD}_{Z}$, as a strategy the constrain the modelling of the flavor content of the Pomeron.

Finally, let us summarize our main results and conclusions. The description of the diffractive processes is still an important open question. In particular, the quark content of the Pomeron has been poorly constrained by the HERA data. In this paper, we have investigated the single diffractive gauge boson production as a probe of the flavor content of the Pomeron. We have used the forward physics Monte Carlo and obtained realistic predictions for the single diffractive W^{+} and Z production taking into account the acceptance of the ATLAS, CMS and LHCb detectors. In the case of the ATLAS and CMS detectors, we have assumed the tagging of one of the protons in the final state, which allow the direct separation of the single diffractive events. On the other hand, in the LHCb case, we have considered a gap requirement in the VELO and HERSCHEL detectors. Our results indicate that the magnitude of the distributions is sensitive to the assumptions about the content of u, d and s quarks in the Pomeron. As the shape of the distributions are not strongly modified by these assumptions, we have proposed the analysis of the ratio between cross sections in order to reduce the impact of the absorptive corrections in our predictions. Our results indicate that a future experimental analysis of the ratio between the W and Z cross sections can be used to probe the flavor content of the Pomeron.

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