Diffractive production of electroweak vector bosons at the LHC

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We analyze diffractive electroweak vector boson production in hadronic collisions and show that the single diffractive W boson production asymmetry in rapidity is a particularly good observable at the LHC to test the concept of the flavor symmetric Pomeron parton distributions. It may also provide an additional constraint for the parton distribution functions in the proton.

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I. INTRODUCTION

The electroweak W and Z boson production in hadronic collision is a particularly valuable process to constrain parton distribution functions (PDFs) in a nucleon. By measuring leptonic products of the weak boson decays, electroweak parameters like $\sin^2\theta_W$, where θ_W is the effective weak mixing angle, or the W/Z boson masses and decay widths can also be determined. At the Born level the W and Z bosons are produced from annihilation of two quarks in the colliding nucleons. In the collinear approximation, the elementary cross sections for these processes have to be convoluted with the nucleons' PDFs. A direct access to these distributions is provided by the measurement of $W^{\pm}$ production asymmetry in rapidity. This quantity reflects the fact that at given rapidity the two charged vector bosons are produced by quarks of different flavors. The measured W asymmetry can be used in the global fit analysis to constrain PDFs, in particular, the ratio of the u and d PDFs. Such measurements were done at the Fermilab Tevatron. The electron charge asymmetry in W boson decays is presented in [1,2], a direct measurement of the W boson asymmetry is reported in [3], the forward-backward asymmetry of the electron from Z boson decays is discussed in [4,5], while a short summary on the W and Z boson production at the Tevatron can be found in [6].

Diffractive hadroproduction of electroweak bosons was observed experimentally at the Tevatron [7] and analyzed theoretically in a series of papers [8–11]. In a single diffractive dissociation case, one of the colliding hadrons remains intact while the other which dissociates into the diffractive state is separated in rapidity from the intact hadron. In the Pomeron model interpretation of this process, the rapidity gap appears due to the exchange of a Pomeron a vacuum quantum number exchange, which in the case of diffractive processes with hard scale reveals partonic structure [12]. Thus, the electroweak bosons are diffractively produced from the annihilation of two quarks, one from the hadron and the other from the Pomeron. The partonic structure of the Pomeron is described by the Pomeron parton distributions, which are usually assumed to be flavor symmetric to account for vacuum quantum numbers of the Pomeron. In the forthcoming analysis, we show that the measurement of the W boson asymmetry in the diffractive pp collisions at the LHC is an ideal process to test the Pomeron model interpretation of the diffractive hadroproduction of electroweak bosons. In addition, this asymmetry may provide an additional constraint for the determination of the PDFs in the proton.

The paper is organized as follows: In Sec. II, we present basic formulas for the weak boson production cross sections and discuss in detail the W boson production in the inclusive $p\bar{p}$ and pp scattering. In Sec. III, we analyze the diffractive W boson production at the LHC and present main results of our analysis.

II. HADROPRODUCTION OF *W* AND *Z* BOSONS

The leading order cross sections for the subprocess $q\bar{q}' \to W, Z$, with *collinear quarks*, are given by [13]

$$\sigma^{q\bar{q}'\to W} = \frac{2\pi G_F}{3\sqrt{2}} M_W^2 |V_{ff'}|^2 \delta(\hat{s} - M_W^2), \tag{1}$$

$$\sigma^{q\bar{q}\to Z} = \frac{2\pi G_F}{3\sqrt{2}} M_Z^2 (V_f^2 + A_f^2) \delta(\hat{s} - M_Z^2), \tag{2}$$

where G_F is the Fermi constant and $V_{ff'}$ is the appropriate Cabibbo-Kobayashi-Maskawa matrix element. In addition, $V_f = T_f^3 - 2Q_f \sin^2\theta_W$ and $A_f = T_f^3$ are the vector and axial couplings of the fermion f to the Z boson, respectively, where $T_f^3 = \pm\frac{1}{2}$ with (+) for the up type quarks and (−) for the down-type quarks and Q_f is given in units of the positron electric charge $e = g_w \sin\theta_W$. These cross sections are convoluted with the quark distribution functions taken at the scale, given by the corresponding vector boson mass, $\mu = M_{W,Z}$. Thus, we obtain for the W bosons

$$\frac{d\sigma_{W^\pm}}{dy} = \sigma_0^W \sum_{qq'} |V_{qq'}|^2 \{q(x_1, \mu)\bar{q}'(x_2, \mu) + \bar{q}(x_1, \mu) q'(x_2, \mu), \}, \tag{3}$$

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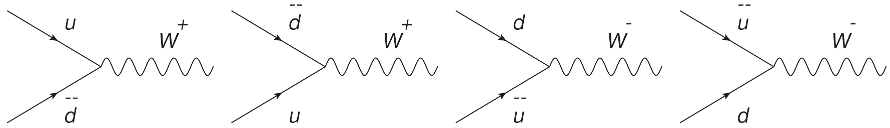

FIG. 1. The leading order diagrams for the $W^{\pm}$ boson production.

where the factorization scale $\mu = M_W$, and q, $\bar{q}$ denote quark/antiquark distributions. In addition,

$$\sigma_0^W = \frac{2\pi G_F}{3\sqrt{2}} \frac{M_W^2}{s}, \qquad x_1 = \frac{M_W}{\sqrt{s}} \mathrm{e}^{y}, \qquad x_2 = \frac{M_W}{\sqrt{s}} \mathrm{e}^{-y}, \tag{4}$$

where y is the W *boson rapidity*. Obviously, $y = \frac{1}{2} \times \ln(x_1/x_2)$ and from the condition $0 < x_{1,2} < 1$, the following constraint results:

$$-y_{\max} < y < y_{\max}, \tag{5}$$

with $y_{\max} = \ln(\sqrt{s}/M_W)$. The cross section for the Z boson is obtained from Eq. (3) by replacing

$$|V_{qq'}|^2 \rightarrow \delta_{qq'}(V_q^2 + A_q^2) \equiv \delta_{qq'} C_q. \tag{6}$$

In the forthcoming analysis we neglect the Cabbibo suppressed s quark part of the W production cross sections and consider only two flavors: u and d. Thus, for the partonic processes shown in Fig. 1, we find

$$\frac{d\sigma_{W^+}}{dy} = \sigma_0^W |V_{ud}|^2 \{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)\}, \tag{7}$$

$$\frac{d\sigma_{W^-}}{dy} = \sigma_0^W |V_{ud}|^2 \{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)\}, \tag{8}$$

$$\frac{d\sigma_Z}{dy} = \sigma_0^Z \{C_u u(x_1)\bar{u}(x_2) + C_d d(x_1)\bar{d}(x_2) + (x_1 \leftrightarrow x_2)\}, \tag{9}$$

where the parton distributions are taken at the scale $\mu = M_{W,Z}$. The $W^{\pm}$ boson production asymmetry in rapidity is defined as follows:

$$A(y) = \frac{d\sigma_{W^+}(y)/dy - d\sigma_{W^-}(y)/dy}{d\sigma_{W^+}(y)/dy + d\sigma_{W^-}(y)/dy}. \tag{10}$$

A. $p\bar{p}$ collisions

Assuming that the fraction x_1 refers to the proton and the fraction x_2 refers to the antiproton in the $p\bar{p}$ scattering, the W production cross sections are related to the nucleon parton distributions in the following way (see Fig. 1):

$$\begin{aligned} \frac{d\sigma_{W^+}}{dy} &\sim u_p(x_1)\bar{d}_{\bar{p}}(x_2) + \bar{d}_p(x_1)u_{\bar{p}}(x_2) \\ \frac{d\sigma_{W^-}}{dy} &\sim d_p(x_1)\bar{u}_{\bar{p}}(x_2) + \bar{u}_p(x_1)d_{\bar{p}}(x_2). \end{aligned} \tag{11}$$

From the charge conjugation symmetry we have

$$\begin{aligned} &d_{\bar{p}}(x) = \bar{d}_p(x), \\ &u_{\bar{p}}(x) = \bar{u}_p(x) \quad \text{and} \quad \bar{d}_{\bar{p}}(x) = d_p(x), \\ &\bar{u}_{\bar{p}}(x) = u_p(x), \end{aligned} \tag{12}$$

thus, we find

$$\begin{aligned} \frac{d\sigma_{W^+}}{dy} &\sim u_p(x_1)d_p(x_2) + \bar{d}_p(x_1)\bar{u}_p(x_2) \\ \frac{d\sigma_{W^-}}{dy} &\sim d_p(x_1)u_p(x_2) + \bar{u}_p(x_1)\bar{d}_p(x_2). \end{aligned} \tag{13}$$

Notice that interchanging $x_1 \leftrightarrow x_2$ $(y \rightarrow -y)$ we have $d\sigma_{W^+}/dy \leftrightarrow d\sigma_{W^-}/dy$, and

$$\frac{d\sigma_{W^+}(y)}{dy} = \frac{d\sigma_{W^-}(-y)}{dy}. \tag{14}$$

This is clearly seen in Fig. 2 (left) where the weak boson production cross sections are shown for the proton-antiproton collisions at the Tevatron energy $\sqrt{s} = 1.8$ TeV (in which case $y_{\max} \approx 3.1$). We use the LO MSTW08 parametrization [14] of the parton distribution functions. From relation (14), the W boson production asymmetry $A(y)$ is odd function rapidity, see Fig. 2 (right).

In $p\bar{p}$ collisions, the W-charge asymmetry in rapidity is also defined

$$A_{W^+}(y) = \frac{d\sigma_{W^+}(y)/dy - d\sigma_{W^+}(-y)/dy}{d\sigma_{W^+}(y)/dy + d\sigma_{W^+}(-y)/dy}. \tag{15}$$

From the above-mentioned symmetry, we have the following chain of equalities:

$$A_{W^+}(y) = A_{W^-}(-y) = A(y). \tag{16}$$

These asymmetries are useful for the determination of the parton distributions since assuming for simplicity the local isospin symmetry of the sea quark distributions, $\bar{d}_p(x) = \bar{u}_p(x)$, we obtain from relations (13)

$$A(y) = \frac{u_p(x_1)d_p(x_2) - d_p(x_1)u_p(x_2)}{u_p(x_1)d_p(x_2) + d_p(x_1)u_p(x_2) + 2\bar{u}_p(x_1)\bar{u}_p(x_2)}. \tag{17}$$

For most of the parton distribution parametrizations, the term $2\bar{u}_p(x_1)\bar{u}_p(x_2)$ in the denominator can be neglected, and we find

$$A(y) \simeq \frac{u_p(x_1)d_p(x_2) - d_p(x_1)u_p(x_2)}{u_p(x_1)d_p(x_2) + d_p(x_1)u_p(x_2)}. \tag{18}$$

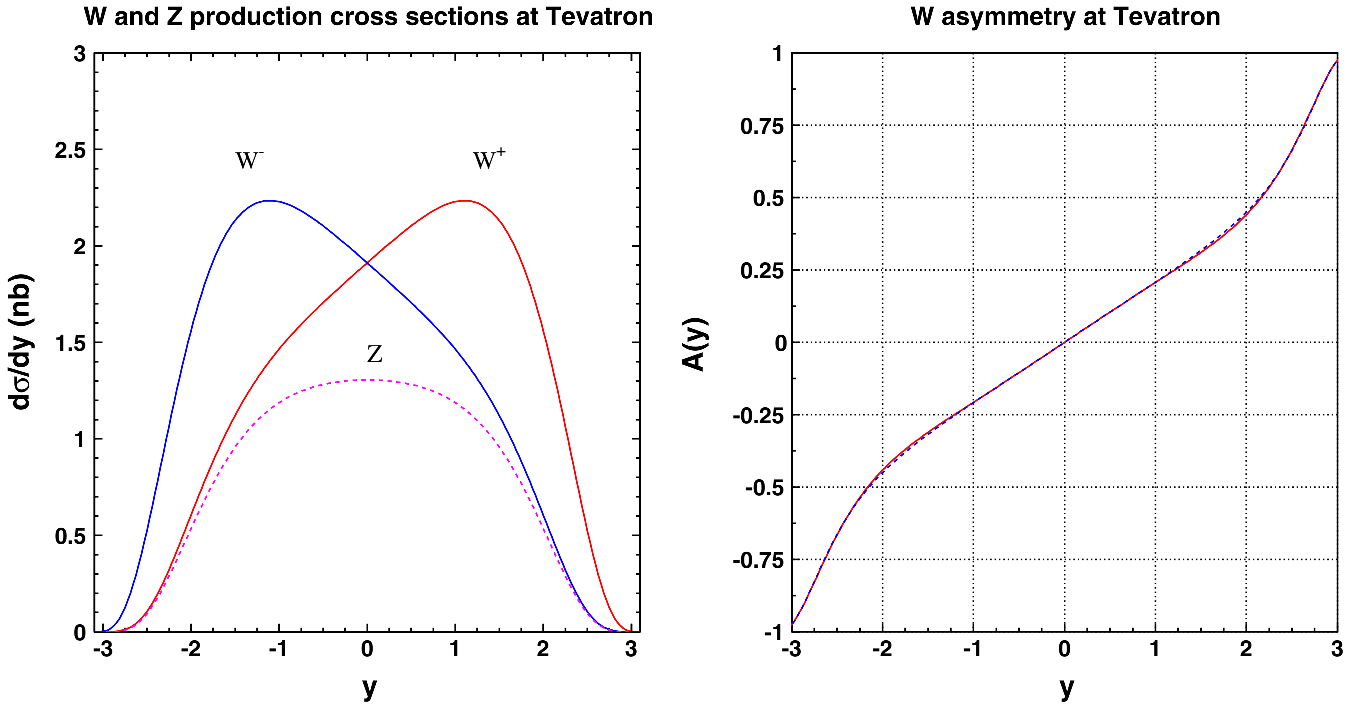

FIG. 2 (color online). Left: the W and Z boson production cross sections at Tevatron as functions of the boson rapidity y for the MSTW08 parton distributions. Right: the W boson asymmetry (solid line) together with the approximate relation (18) [dashed line].

The quality of this relation is shown in Fig. 2 (right) where the solid curve shows Eq. (17), while the dashed curve corresponds to relation (18), computed for the LO MSTW08 parametrization.

Relation (18) is the basis of the current analyses of the Tevatron data on the W production asymmetry for the determination of the ratio $d_p(x)/u_p(x)$, since from Eq. (18) we find at the scale $\mu = M_W$

$$\frac{d_p(x_1)/u_p(x_1)}{d_p(x_2)/u_p(x_2)} \simeq \frac{1 - A(y)}{1 + A(y)}. \tag{19}$$

B. pp collisions

For pp collisions, the W production cross sections look as follows:

$$\frac{d\sigma_{W^+}}{dy} \sim u_p(x_1)\bar{d}_p(x_2) + \bar{d}_p(x_1)u_p(x_2)$$
$$\frac{d\sigma_{W^-}}{dy} \sim d_p(x_1)\bar{u}_p(x_2) + \bar{u}_p(x_1)d_p(x_2). \tag{20}$$

Because of symmetric proton beams, the transformation $x_1 \leftrightarrow x_2$ leaves $d\sigma_{W^\pm}$ unchanged, which is reflected in the symmetry of these cross sections under the rapidity reflection $y \longrightarrow -y$. This is clearly seen in Fig. 3 (left) where the cross sections for the LHC energy $\sqrt{s} = 14$ TeV (in which case $y_{\max} \approx 5.1$) are shown for the LO MSTW08 parton distributions. Assuming for simplicity the local isospin symmetry for the sea quark distributions, $\bar{u}_p(x) = \bar{d}_p(x)$, we find

$$A(y) = \frac{(u_p(x_1) - d_p(x_1))\bar{u}_p(x_2) + \bar{u}_p(x_1)(u_p(x_2) - d_p(x_2))}{(u_p(x_1) + d_p(x_1))\bar{u}_p(x_2) + \bar{u}_p(x_1)(u_p(x_2) + d_p(x_2))}, \tag{21}$$

which is evidently even function of rapidity, see Fig. 3 (right). In the limit $x_1 \sim 1$ and $x_2 \ll 1$ or $x_1 \sim x_2 \ll 1$, the sea quark distribution $\bar{u}(x_1)$ is small and the second terms in the numerator and denominator of Eq. (21) can be neglected. Thus, we obtain

$$A(y) \simeq \frac{u_p(x_1) - d_p(x_1)}{u_p(x_1) + d_p(x_1)}. \tag{22}$$

From the $x_1 \leftrightarrow x_2$ symmetry, the same relation holds true when the argument of the parton distributions in Eq. (22) is changed to x_2. These approximate relations are shown by the two dashed curves in Fig. 3 (right). Thus, from the measurement of the W asymmetry in the pp collisions, the $d_p(x)/u_p(x)$ ratio at the scale $\mu = M_W$ can be extracted,

$$\frac{d_p(x)}{u_p(x)} \simeq \frac{1 - A(y)}{1 + A(y)}, \tag{23}$$

down to $x_1 \simeq M_W/\sqrt{s} \approx 0.006$ for the LHC energy. Relation (22) can also be written in terms of the valence (val) and sea (sea) quark distributions

$$u_p(x) = u_{\text{val}}(x) + u_{\text{sea}}(x), \qquad \bar{u}_p(x) = u_{\text{sea}}(x)$$
$$d_p(x) = d_{\text{val}}(x) + d_{\text{sea}}(x), \qquad \bar{d}_p(x) = d_{\text{sea}}(x), \tag{24}$$

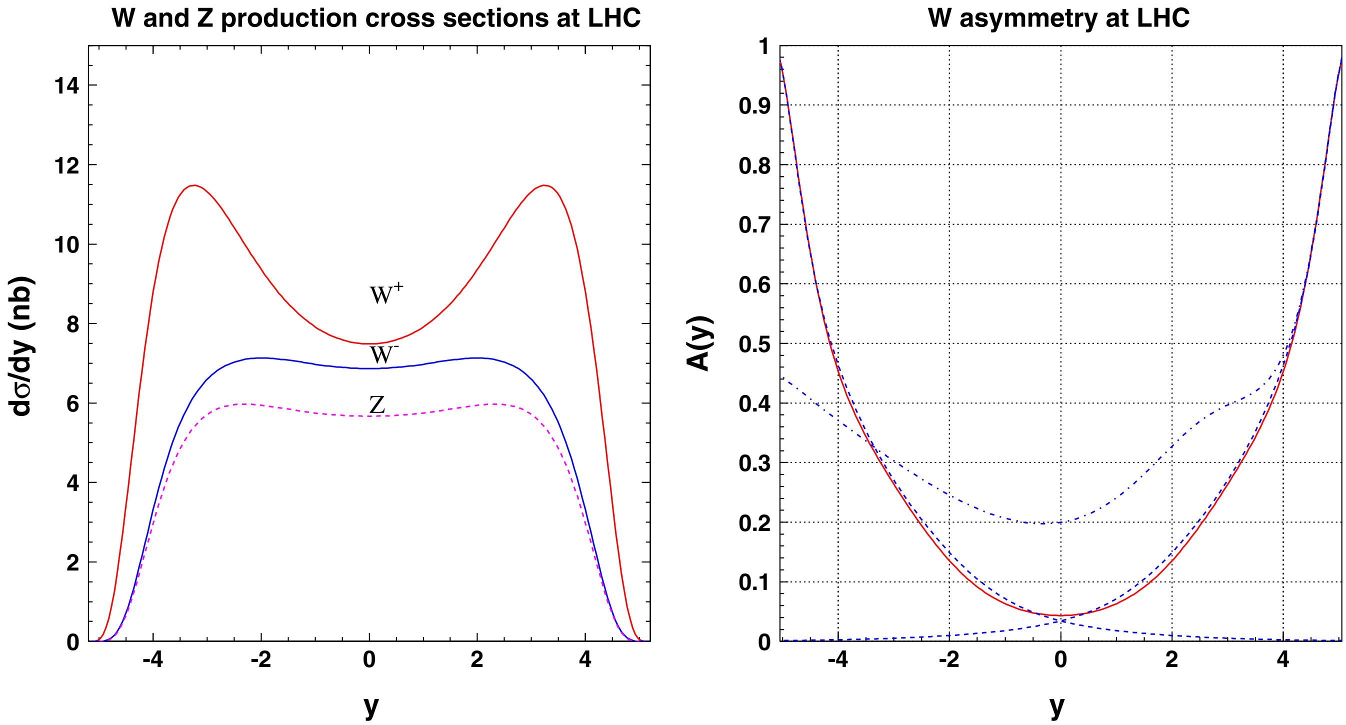

FIG. 3 (color online). Left: the W and Z boson production cross sections at the LHC as functions of the boson rapidity y for the LO MSTW08 parton distributions. Right: the W boson asymmetry (solid curve) together with relation (22) computed at $x = x_1$ and $x = x_2$ (two dashed lines) and for the valence quark distributions at $x = x_1$ (dash-dotted line).

taking the following form (assuming isospin symmetry)

$$A(y) \simeq \frac{u_{\rm val}(x_1) - d_{\rm val}(x_1)}{u_{\rm val}(x_1) + d_{\rm val}(x_1) + (u_{\rm sea}(x_1) + d_{\rm sea}(x_1))}. \quad (25)$$

For $x_1 \to 1$ the sea quark distributions in the denominator can be neglected and relation (23) gives

$$\frac{d_{\rm val}(x)}{u_{\rm val}(x)} \simeq \frac{1 - A(y)}{1 + A(y)}. \quad (26)$$

The quality of this relation for the LO MRTW09 parametrization is shown in Fig. 3 by the dash-dotted line computed from Eq. (22) with the valence quark distributions at $x = x_1$ (a symmetric curve can be found for $x = x_2$). We see that for $y > 4$ ($x > 0.3$) relation (26) can be used for the determination of the $d_{\rm val}/u_{\rm val}$ ratio at the scale $\mu = M_W$.

III. DIFFRACTIVE PRODUCTION OF *W* BOSONS

In the diffractive case, the electroweak bosons are produced in a restricted region of rapidity with a rapidity gap without particles between the proton which stayed intact and the diffractive system from the dissociated proton. In this process boson mass is a hard scale allowing for perturbative QCD interpretation as in the nondiffractive case. However, the nature of the vacuum quantum number exchange, which leads to the rapidity gap, is nonperturbative. It is usually modeled using the Regge theory notion—a Pomeron. In the model of Ingelman and Schlein [12] the Pomeron is endowed with a partonic structure described by the Pomeron parton distributions $q_{\mathbb{P}}$, which replace the standard inclusive parton distributions on the dissociated proton side. Since the Pomeron carries vacuum quantum numbers, these distributions have to be flavor symmetric

$$u_{\mathbb{P}}(x) = \bar{u}_{\mathbb{P}}(x) = d_{\mathbb{P}}(x) = \bar{d}_{\mathbb{P}}(x) = s_{\mathbb{P}}(x) = \bar{s}_{\mathbb{P}}(x) = \ldots \equiv q_{\mathbb{P}}(x), \quad (27)$$

where $x = x_2/x_{\mathbb{P}}$ with $x_{\mathbb{P}} = M_D^2/s$ being a fraction of the proton's momentum transferred into the diffractive system of mass M_D. With such a definition, x is a fraction of the Pomeron momentum carried by the parton taking part in the W boson production. From the condition $0 < x, x_{\mathbb{P}} < 1$, one finds that the W boson rapidity is in the range

$$-y_{\rm max} + \ln(1/x_{\mathbb{P}}) < y < y_{\rm max}, \quad (28)$$

and the rapidity gap has the length $\Delta = \ln(1/x_{\mathbb{P}})$.

Thus, in the single diffractive case, the W production cross sections are related to quark distributions in the following way:

$$\frac{d\sigma_{W^+}}{dy dx_{\mathbb{P}}} \sim (u_p(x_1) + \bar{d}_p(x_1)) q_{\mathbb{P}}(x_2/x_{\mathbb{P}}), \quad (29)$$

$$\frac{d\sigma_{W^-}}{dy dx_{\mathbb{P}}} \sim (d_p(x_1) + \bar{u}_p(x_1)) q_{\mathbb{P}}(x_2/x_{\mathbb{P}}). \quad (30)$$

In more general approach, the Pomeron parton distribution should be replaced by diffractive parton distributions [15–19], which in the Pomeron model interpretation have the Regge factorized form

$$q_D(x_2, x_{\mathbb{P}}) = f(x_{\mathbb{P}}) q_{\mathbb{P}}(x_2/x_{\mathbb{P}}), \tag{31}$$

where $f(x_{\mathbb{P}})$ is called Pomeron flux. Independent of this interpretation, however, the diffractive quark distributions should also be flavor symmetric. In Fig. 4 (left) we show the W and Z production cross sections with the LO MSTW08 proton parton distributions and the Pomeron parton distributions from the analysis [20]. The effect of the Pomeron is clearly visible in the left hemisphere—the rapididty gap is formed and the $W^{\pm}$ asymmetry strongly decreases. These cross sections should be multiplied by a gap survival factor, $S^2 = 0.09$ [21], which takes into account soft interactions destroying the rapidity gap.

The W boson production asymmetry (10) is a particularly good observable since it is insensitive to the gap survival probability [22] which multiplies both the cross sections $d\sigma_{W^{\pm}}/dy dx_{\mathbb{P}}$. The flavor symmetric Pomeron parton distributions also cancel, and we obtain for the W asymmetry in the diffractive case

$$A^D(y) = \frac{u_p(x_1) - d_p(x_1) + \bar{d}_p(x_1) - \bar{u}_p(x_1)}{u_p(x_1) + d_p(x_1) + \bar{d}_p(x_1) + \bar{u}_p(x_1)}, \tag{32}$$

where the parton distributions are taken at the scale $\mu = M_W$. Notice that $A^D(y)$ is independent of $x_{\mathbb{P}}$, i.e., the length of the rapidity gap. Substituting decomposition (24), we find

$$A^D(y) = \frac{u_{\rm val}(x_1) - d_{\rm val}(x_1)}{u_{\rm val}(x_1) + d_{\rm val}(x_1) + 2(u_{\rm sea}(x_1) + d_{\rm sea}(x_1))}. \tag{33}$$

This is an exact result obtained only under the assumption (27). In Fig. 4 (right) we show the asymmetry (33) [solid line] together with the W boson asymmetry (21) in the inclusive case (dashed line).

In order to understand our result, it is interesting to compare Eq. (33) with the approximate asymmetry (25), valid in the right hemisphere for $y > 0$. For large rapidities, when the sea quark distributions can be neglected, these two asymmetries are equal while for $y \approx 0$, when the valence quark distributions in the denominator are negligible, $A^D(y) \approx A(y)/2$. This is clearly seen in Fig. 5 where the ratio $A^D(y)/A(y)$, with $A(y)$ given by Eq. (21), is shown. Approaching the rapidity gap, the asymmetry $A^D(y) \rightarrow 0$ while $A(y)$ rises. Thus, the ratio shown in Fig. 5 is close to zero at the edge of the rapidity gap.

The pattern shown in Fig. 5 is quite general and depends only on the assumption on flavor symmetry of the Pomeron parton distributions, Eq. (27). Therefore, it would be interesting to test experimentally the very concept of the flavor

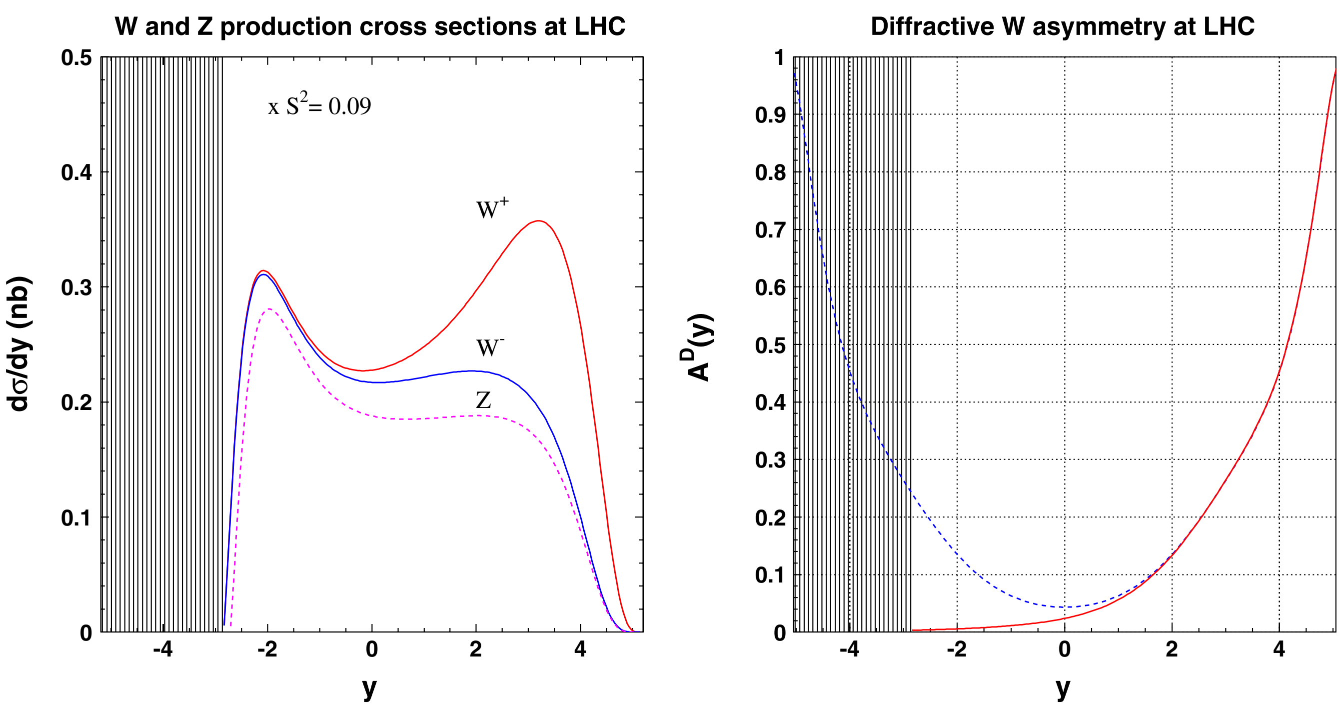

FIG. 4 (color online). Left: the single diffractive W/Z boson production cross sections at the LHC as functions of boson rapidity. The results have to be multiplied by the gap survival factor $S^2 = 0.09$. Right: the W asymmetry in $p\mathbb{P}$ collisions (solid line), given by Eq. (32), together with the asymmetry (21) in pp collisions (dashed line). The shaded areas indicate the rapidity gap $\Delta = 2.3$ for $x_{\mathbb{P}} = 0.1$.

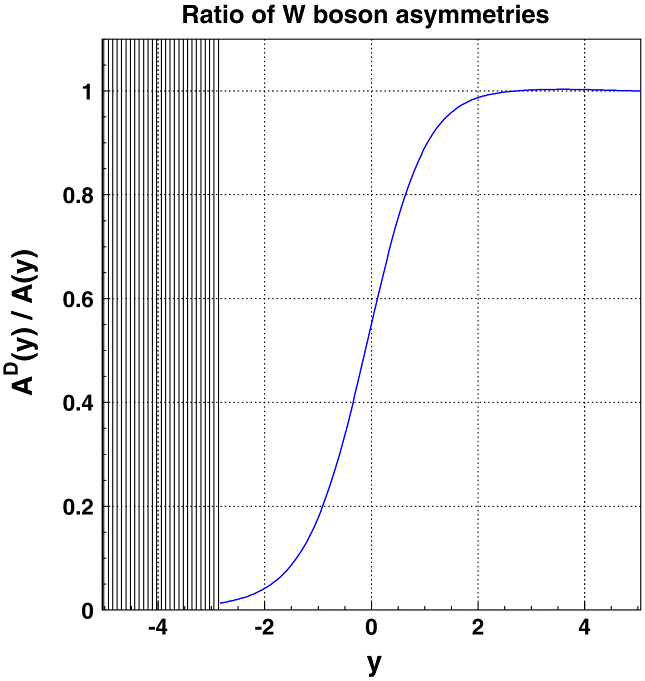

FIG. 5 (color online). The ratio of the W boson production asymmetries in the diffractive and nondiffractive pp scattering.

symmetric Pomeron parton distributions by measuring the ratio of the two W asymmetries in the diffractive and nondiffractive pp scattering. Systematic errors will cancel in such a ratio which should allow for quite precise determination of this quantity. We are looking forward to the experimental verification of the presented results at the LHC.

IV. SUMMARY

The measurement of the W boson production asymmetry in the diffractive pp collisions is a valuable method to test the concept of the flavor symmetric Pomeron parton distributions. If it is true, the W asymmetry in the single diffractive case provides an additional constraint for the parton distribution functions in the proton.

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