Letter

Boost asymmetry of the diboson productions in *pp* collisions

Siqi Yang,[1] Mingzhe Xie,[1] Yao Fu,[1] Zihan Zhao,[1] Minghui Liu,[1] Liang Han,[1] Tie-Jiun Hou,[2] and C.-P. Yuan[3]

[1]*Department of Modern Physics, University of Science and Technology of China, Jinzhai Road 96, Hefei, Anhui 230026, China*
[2]*School of Nuclear Science and Technology, University of South China, Hengyang, Hunan 421001, China*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48823, USA*

(Received 7 July 2022; accepted 21 September 2022; published 30 September 2022)

We propose the boost asymmetry of the diboson productions $q_i\bar{q}_j \to VV'$ in pp collisions ($VV' = W\gamma$, W^+W^-, and WZ) as a new experimental observable, which can provide unique information on the proton structure. The boost asymmetry rises as the difference in the kinematics of the two bosons, that are coupled to the two different quark and antiquark initial states, respectively, and thus reflects different features of the q_i and $\bar{q}_j$ parton densities. By comparing the kinematics of the two bosons, such as the boson energy or rapidity, the diboson events with $\bar{q}_j$ having higher energy than q_i can be distinguished from those with q_i having higher energy than $\bar{q}_j$. This would provide unique information in some special parton momentum fraction regions, which cannot be directly proved by current W and Z measurements at the Large Hadron Collider or other deep inelastic scattering experiments.

DOI: 10.1103/PhysRevD.106.L051301

I. INTRODUCTION

The vector boson productions at the Large Hadron Collider (LHC) are dominated by the initial state quark-antiquark ($q_i\bar{q}_j$) scattering, and thus are highly sensitive to the corresponding parton densities in a large range of the Bjorken variable x, describing the fraction of the parton momentum to the energy of the proton. In the latest global analysis of the parton distribution functions (PDFs) such as the CT18, MSHT20, and NNPDF4.0, the single Z and W production rates measured at 7 and 8 TeV pp collisions have been used and delivered significant impacts [1–3].

Due to the high energy of the proton beam, the vector boson productions at the LHC contain both the $q_i(x_L)\bar{q}_j(x_S)$ contribution where the initial state quarks carry higher energy than the antiquarks ($x_L > x_S$), and the $\bar{q}_j(x_L)q_i(x_S)$ contribution where the antiquarks have higher energy. The ratio between the two cross sections, which we call the quark exchanging fraction, relates to the parton densities of the valence u and d quarks in the small x region, and the sea quarks in the relatively large x region. An example is the forward backward asymmetry (A_{FB}) of the Drell-Yan $pp \to q_i\bar{q}_j \to Z/\gamma^* \to \ell^+\ell^-$ process. Due to the limited knowledge of the dilution effect, which is actually the quark exchanging fraction for the $u\bar{u}$ and $d\bar{d}$ cases, the observed A_{FB} is reduced from its original value arising from the electroweak (EW) symmetry breaking [4], and therefore induces large PDF-induced uncertainty on the determination of the weak mixing angle ($\sin^2\theta^{\ell}_{\mathrm{eff}}$), reported by the ATLAS, CMS, and LHCb measurements [5–7].

The quark exchanging fraction is unique information that is difficult to acquire from other data such as the deep inelastic scattering and the fixed-target Drell-Yan experiments. Therefore, the measurements at the LHC are expected to provide important input to expand our knowledge of proton structure. However, the observed Z and W cross sections are always the mixture of the $q_i(x_L)\bar{q}_j(x_S)$ and $\bar{q}_j(x_L)q_i(x_S)$ contributions, so they could not distinguish the two initial states and fail to give direct constraint on the quark exchanging fraction. It was proposed to use A_{FB} itself to constrain the dilution effect [8–10], but found to have large additional uncertainties due to the correlation with the EW $\sin^2\theta^{\ell}_{\mathrm{eff}}$ parameter [4].

Without a direct constraint, the current PDF global analysis has to provide predictions on the quark exchanging fraction by combining the information of the LHC data and other old experimental results [11]. However, the combined fitting highly relies on the assumption that all the data should be consistent, while on the other hand, it is known that, e.g., the ATLAS 5 TeV, 7 TeV, and 8 TeV W and Z differential cross section data have tensions with other datasets included in the PDF global analysis [12–14].

Therefore, it would be important to have experimental observables which can provide constraints directly on the quark exchanging fraction at the LHC.

In this paper, we propose a set of new experimental observables, the boost asymmetries $A_{\text{boost}}^{VV'}$, in the $pp \to q_i\bar{q}_j \to VV'$ processes, including $VV' = W\gamma$, W^+W^-, and WZ at the LHC. By observing $A_{\text{boost}}^{VV'}$, the initial states of $q_i(x_L)\bar{q}_j(x_S)$ and $\bar{q}_j(x_L)q_i(x_S)$ can be distinguished from each other, so that the quark exchanging fraction can be directly determined. We also perform an impact study of introducing the $A_{\text{boost}}^{VV'}$ observables to the PDF global analysis. It is demonstrated that the uncertainties of the relevant parton densities can be significantly reduced.

II. THE BOOST ASYMMETRY IN THE VV' EVENTS

At the LHC, the diboson events are produced dominantly by the $q_i\bar{q}_j$ initial state via the t- and u-channel contributions, of which the Feynman diagrams are shown in Fig. 1. The two bosons are separately coupled to the quarks and antiquarks, and consequently the kinematics of the two different bosons reflect the energy of the corresponding quark or antiquark respectively. The boson kinematic can usually be represented by the rapidity (Y) of the boson or the lepton from the boson decay. For the $W\gamma$, W^+W^-, and WZ processes where the two bosons can be experimentally distinguished, the events can be divided into $|Y_V| > |Y_{V'}|$ and $|Y_V| < |Y_{V'}|$ categories. The boost asymmetry is defined to describe the relative difference between the two categories:

$$A_{\text{boost}}^{VV'} = \frac{N(|Y_V| > |Y_{V'}|) - N(|Y_V| < |Y_{V'}|)}{N(|Y_V| > |Y_{V'}|) + N(|Y_V| < |Y_{V'}|)} \qquad (1)$$

where N is the number of observed events. Due to q_i and $\bar{q}_j$ having different energy densities, the observation of A_{boost} is expected to have nonzero values. In the following subsections, we will discuss how $A_{\text{boost}}^{VV'}$ reflects the information of the quark exchanging fractions.

A. $A_{\text{boost}}^{VV'}$ in the $W\gamma$ and WZ processes

The $W^\pm\gamma$ production is dominated by the two different $u\bar{d}$ and $d\bar{u}$ initial states respectively, where W and γ can

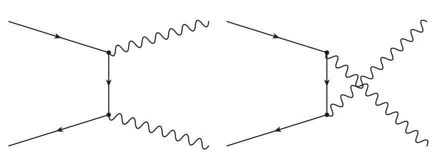

FIG. 1. The Feynman diagrams of the t-channel (left) and u-channel (right) processes in the $pp(q_i\bar{q}_j) \to VV'$ production. The s-channel diagram, needed for some production mode to form a gauge invariant set, is not shown here.

couple to either quarks or antiquarks. Since the $W^+\gamma$ and $W^-\gamma$ processes can be measured independently, it is possible to probe the different energy spectrum of $u\bar{d}$ and $d\bar{u}$ initial states. For example, according to different boson-quark-couplings ($V - q$) and parton densities ($q(x)$), the $u\bar{d}$ contribution in $W^+\gamma$ events can be further divided into four parts as: $N_{\gamma-\bar{d}(x_S)}^{W-u(x_L)}$, $N_{\gamma-\bar{d}(x_L)}^{W-u(x_S)}$, $N_{\gamma-u(x_S)}^{W-\bar{d}(x_L)}$, and $N_{\gamma-u(x_L)}^{W-\bar{d}(x_S)}$. When u carries higher energy than $\bar{d}$, i.e., in the two $u(x_L)\bar{d}(x_S)$ cases, it statistically gives $|Y_\gamma| > |Y_W|$ via $N_{\gamma-u(x_L)}^{W-\bar{d}(x_S)}$ where W couples to $\bar{d}(x_S)$ and γ couples to $u(x_L)$; meanwhile, it may raise $|Y_\gamma| < |Y_W|$ via $N_{\gamma-\bar{d}(x_S)}^{W-u(x_L)}$, and thus partially cancel the asymmetry. However, the cross section of $N_{\gamma-\bar{d}(x_S)}^{W-u(x_L)}$ is smaller than that of $N_{\gamma-u(x_L)}^{W-\bar{d}(x_S)}$, because the $\gamma - u$ coupling results in a larger contribution than the $\gamma - d$ coupling by a factor of about 4. Therefore, the cancellation on the asymmetry is not significant. In the same way, when $\bar{d}$ carries higher energy than u, i.e., in $u(x_s)\bar{d}(x_L)$ cases, it statistically gives $|Y_\gamma| < |Y_W|$ via $N_{\gamma-u(x_S)}^{W-\bar{d}(x_L)}$, and also would be partially canceled by the $N_{\gamma-\bar{d}(x_L)}^{W-u(x_S)}$ contribution.

Note that the relationship between Y_W and Y_γ does not exactly reflect the relationship between u and $\bar{d}$ energy. Apart from the cancellation effect mentioned above, the freedom in the kinematic of internal quark propagators, the contributions from the s-channel processes and higher order effects, and the interference between them would also smear the boost asymmetry. In practice, the W boson kinematic is usually replaced by the rapidity of the leptons from the decay, and thus further smears A_{boost} due to the missing neutrino. Nevertheless, these smearing effects of diminishing A_{boost} observation are more related to the EW calculations which can be precisely predicted, and thus independent with the parton densities of the initial state quarks. As a conclusion, A_{boost} in the $W^+\gamma$ events is dominated by the quark exchanging fraction of $u(x_L)\bar{d}(x_S)$ over $u(x_S)\bar{d}(x_L)$. Similarly, A_{boost} in the $W^-\gamma$ events contains the information of the quark exchanging fraction of $d(x_L)\bar{u}(x_S)$ over $d(x_S)\bar{u}(x_L)$.

To give numerical results, a sample of $pp \to W\gamma \to \ell\nu\gamma$ is generated at $\sqrt{s} = 13$ TeV using a PYTHIA event generator [15], with a size of the data sample in full phase space corresponding to about 1 ab^{-1} data produced at the LHC. The boost asymmetry is specifically defined as

$$A_{\text{boost}}^{W\gamma} = \frac{N(|Y_\gamma| > |Y_\ell|) - N(|Y_\gamma| < |Y_\ell|)}{N(|Y_\gamma| > |Y_\ell|) + N(|Y_\gamma| < |Y_\ell|)} \qquad (2)$$

in terms of the rapidity of γ and ℓ of the final states. The predicted values of $A_{\text{boost}}^{W\gamma}$ in the $W^+\gamma$ and $W^-\gamma$ events from CT18, MSHT20, and NNPDF4.0 [1–3],

TABLE I. The boost asymmetry and the corresponding PDF-induced uncertainties predicted from CT18, MSHT20, and NNPDF4.0, in the $W^+\gamma \to \ell^+\nu\gamma$ and $W^-\gamma \to \ell^-\nu\gamma$ events. PDF uncertainties correspond to 68% C.L.

	$W^+\gamma$ events	$W^-\gamma$ events
$A_{\rm boost}^{W\gamma}$ prediction in CT18	0.457 ± 0.006(PDF)	−0.119 ± 0.008(PDF)
$A_{\rm boost}^{W\gamma}$ prediction in MSHT20	0.446 ± 0.004(PDF)	−0.114 ± 0.005(PDF)
$A_{\rm boost}^{W\gamma}$ prediction in NNPDF4.0	0.444 ± 0.004(PDF)	−0.111 ± 0.004(PDF)

together with the corresponding PDF uncertainties, are summarized in Table I.

The asymmetry $A_{\rm boost}^{W\gamma}$ in the $W^+\gamma$ event has a positive large value, namely γ is more boosted than the W boson, because of three reasons. Firstly, since the probability of the valence u quark having higher energy is greater than that of the sea $\bar{d}$ quark, $N_{\gamma-u(x_L)}^{W-\bar{d}(x_S)}$ which gives $|Y_\gamma| > |Y_\ell|$, would surpass $N_{\gamma-u(x_S)}^{W-\bar{d}(x_L)}$ which gives $|Y_\gamma| < |Y_\ell|$. Secondly, the cancellation of $N_{\gamma-\bar{d}(x_S)}^{W-u(x_L)}$ to the dominating $N_{\gamma-u(x_L)}^{W-\bar{d}(x_S)}$ is suppressed due to the charge-determined $\gamma - q$ couplings. Thirdly, the massless γ would be more boosted than the massive W boson. As a result, the boost asymmetry is enhanced.

On the contrary, $A_{\rm boost}^{W\gamma}$ in the $W^-\gamma$ event has a smaller negative value. In this $\bar{u}d$ process, γ can acquire higher energy by coupling to the valence d quark, but the dominating contribution $N_{\gamma-d(x_L)}^{W-\bar{u}(x_S)}$ is suppressed by the γ-d-$\bar{d}$ vertex. The W boson can acquire higher energy via $N_{\gamma-\bar{u}(x_S)}^{W-d(x_L)}$, but its boost is limited due to its heavy mass. Consequently, neither W nor γ could significantly lead the boost after the cancellation.

Similarly, $A_{\rm boost}$ can be defined in the WZ events, and is also sensitive to the quark exchanging fraction of $u\bar{d}$ and $d\bar{u}$. Due to the smaller cross section and full lepton decay branching ratios of the W and Z boson, the boost asymmetry in the WZ processes is less significant than that in the $W\gamma$ ones. However, the $A_{\rm boost}^{WZ}$ observation would be more feasible than $A_{\rm boost}^{W\gamma}$ at the LHCb, where the precise photon measurement is not practicable. Thus the LHCb $A_{\rm boost}^{WZ}$ observation may provide complementary information in a much forward phase space, which cannot be covered by the acceptance of the ATLAS and CMS detectors.

B. $A_{\rm boost}$ in the W^+W^- process

The W^+W^- process is dominated by the $u\bar{u}$ and $d\bar{d}$ initial states, and has different sensitivities to the quark exchanging fraction from the $W\gamma$ and WZ events. The W^+ boson is always coupled to the positive charged u or $\bar{d}$ quark, while the W^- boson is coupled to the negative charged $\bar{u}$ or d quark. Therefore, there is no cancellation due to the exchange of the boson-to-quark couplings in the W^+W^- event. Instead, the cancellation rises between the $u\bar{u}$ and $d\bar{d}$ contributions. In the $u\bar{u}$ subprocess, the large cross section part $N_{W^--\bar{u}(x_S)}^{W^+-u(x_L)}$ statistically gives W^+ the higher energy, while the higher energy W^- events are mainly produced by the small cross section $N_{W^--\bar{u}(x_L)}^{W^+-u(x_S)}$ contribution, so that W^+ leads the boost. On the contrary, in the $d\bar{d}$ subprocess, it is the large cross section $N_{W^+-\bar{d}(x_S)}^{W^--d(x_L)}$ part that gives W^- the higher energy, while the small cross section $N_{W^+-\bar{d}(x_L)}^{W^--d(x_S)}$ has W^+ as the higher energy, so that W^- leads the boost. Since the overall cross section and boost kinematics of $u\bar{u}$ differ from those of $d\bar{d}$, the observed boost asymmetry in the W^+W^- is expected to be nonzero, and can be defined in terms of the rapidity of the leptons of the W boson decay in the final state as

$$A_{\rm boost}^{WW} = \frac{N(|Y_{\ell^+}| > |Y_{\ell^-}|) - N(|Y_{\ell^+}| < |Y_{\ell^-}|)}{N(|Y_{\ell^+}| > |Y_{\ell^-}|) + N(|Y_{\ell^+}| < |Y_{\ell^-}|)}. \quad (3)$$

The boost asymmetry in the W^+W^- event was previously discussed in Ref. [16], of which it was expected to have some sensitivity in new physics search. In this work, we will demonstrate that $A_{\rm boost}^{WW}$ is a useful observable in the PDF global analysis. The numerical predictions of PYTHIA with various PDFs are listed in Table II.

Finally, we would like to discuss the boost asymmetry in the $Z\gamma$ production. It is also dominated by $u\bar{u}$ and $d\bar{d}$ initial states, and thus could have the same sensitivities to the quark exchanging fractions as the W^+W^- events. However, the sensitivity is almost completely canceled due to the exchange of the boson-quark coupling, namely the interchanging possibilities of either higher energy $q(x_L)$ or $\bar{q}(x_L)$ radiating a photon or Z boson are equal. Even though there is still a sizable asymmetry, as shown in Table III, such asymmetry is purely raised by the mass difference between Z and γ and has very little sensitivity to the quark densities. This is also indicated by the much smaller PDF uncertainties in Table III than those of $A_{\rm boost}^{W\gamma}$ and $A_{\rm boost}^{WW}$. Therefore, for the $Z\gamma$ production at the LHC, even though it has a relatively larger cross section than W^+W^- and is easy

TABLE II. The boost asymmetry and the corresponding PDF-induced uncertainties predicted in the $W^+W^- \to \ell^+\nu\ell^-\nu$ event at the 13 TeV LHC, predicted from CT18, MSHT20, and NNPDF4.0. PDF uncertainties correspond to 68% C.L.

$A_{\rm boost}^{WW}$ prediction in CT18	-0.051 ± 0.005(PDF)
$A_{\rm boost}^{WW}$ prediction in MSHT20	-0.051 ± 0.004(PDF)
$A_{\rm boost}^{WW}$ prediction in NNPDF4.0	-0.051 ± 0.002(PDF)

TABLE III. The boost asymmetry and the corresponding PDF-induced uncertainties in the $Z\gamma$ event at the 13 TeV LHC, predicted by CT18, MSHT20, and NNPDF4.0. PDF uncertainties correspond to 68% C.L.

$A^{Z\gamma}_{\mathrm{boost}}$ prediction in CT18	$0.124 \pm 0.0008(\mathrm{PDF})$
$A^{Z\gamma}_{\mathrm{boost}}$ prediction in MSHT20	$0.124 \pm 0.0005(\mathrm{PDF})$
$A^{Z\gamma}_{\mathrm{boost}}$ prediction in NNPDF4.0	$0.126 \pm 0.0003(\mathrm{PDF})$

to be measured, it would not provide as large PDF-sensitivity boost asymmetry as in the $W\gamma$ and WW events.

III. IMPACT STUDY OF INTRODUCING $A^{VV'}_{\mathrm{boost}}$ INTO THE PDF GLOBAL FITTING

In this section, we present an impact study of introducing $A^{VV'}_{\mathrm{boost}}$ into the PDF global fitting, by using pseudodata samples of $W\gamma$ and WW events corresponding to 1 ab^{-1} data at the 13 TeV LHC as new experimental input. The error PDF updating method package (ePump) [17] is used which can efficiently update the PDF with a new data input in the way equivalent to the PDF global fitting based on the Hessian approach. The central and error set predictions of CT18 PDFs on $A^{W\gamma}_{\mathrm{boost}}$ and A^{WW}_{boost} are used as inputs to ePump.

The results of using $A^{W\gamma}_{\mathrm{boost}}$ to do the PDF updating are shown in Fig. 2. With information of the quark exchanging fractions introduced, the uncertainties on the valence-u, valence-d, $\bar{u}$, and $\bar{d}$ PDFs are largely reduced. The proposed boost asymmetry contains unique information of the valence quarks in the small x_S region and the sea quarks in the large x_L region. As depicted in the figures, the uncertainties of the sea $\bar{u}$ and $\bar{d}$ quark PDFs significantly reduced in the large x_L region, while the valence u and d ones have better precision in the small x_S region. Although $A^{W\gamma}_{\mathrm{boost}}$ can also offer constraints on $q_i(x_L)\overline{q_j}(x_S)$, the single Z and W observations at the LHC would certainly cover such information with much larger statistics. For example, it was concluded in Ref. [18] that the up and down valence quark PDFs can be better constrained in the large x_L region by the high mass Drell Yan data. Therefore, the improvements on the small x_S region antiquarks and the large x_L region valence quarks are not significant by using the boost asymmetry.

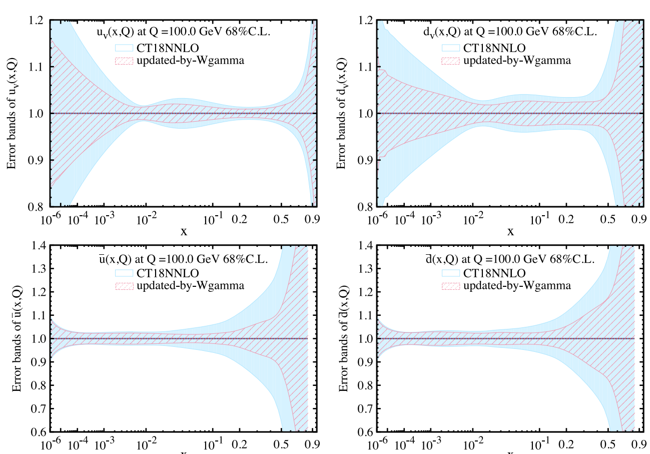

FIG. 2. Ratios of the central values and uncertainties to the CT18 central predictions of the valence u, valence d, $\bar{u}$, and $\bar{d}$ PDFs, before and after the PDF updating using $A^{W\gamma}_{\mathrm{boost}}$. The blue band corresponds to the uncertainty before updating and the red band is after updating.

The impact of using A^{WW}_{boost} is less significant. Firstly, the cross section of the W^+W^- process is much smaller than the $W\gamma$ process. Secondly, unlike the $W\gamma$ measurement which can distinguish the $u\bar{d}$ and $d\bar{u}$ initial states, the W^+W^- process cannot separate the $u\bar{u}$ from the $d\bar{d}$ ones. Thirdly, the sensitivity is of A^{WW}_{boost} is further reduced due to the double neutrinos in both of the W boson decays. Its leading effect, based on the CT18 updating, is on the valence u and d quark PDFs as shown in Fig. 3. However, a potential impact of measuring A^{WW}_{boost} is expected beyond its own sensitivity. As discussed in the Introduction, the A_{FB} observation in the single Z Drell-Yan process at the LHC is believed to have high sensitivity on the quark exchanging fraction of $u\bar{u}$ and $d\bar{d}$, but not available in practice due to the strong correlation with $\sin^2\theta^{\ell}_{\mathrm{eff}}$. Reported in Ref. [19], the A_{FB} spectrum at the LHC has been analytically factorized with proton structure parameters representing the relevant parton information, so that the structure parameters can be determined together with $\sin^2\theta^{\ell}_{\mathrm{eff}}$ by simultaneous fit, with the correlation automatically taken into account. It is pointed out that the precision of the simultaneous fit is expected to be significantly improved if other data could be introduced in the fit, which ought to be $\sin^2\theta^{\ell}_{\mathrm{eff}}$ independent and providing the information on the quark exchanging fraction exactly the same as A_{FB} provides. The observable A^{WW}_{boost} is an ideal input satisfying the requirement proposed in Ref. [19], and thus can be used to improve the precision both on the PDF and $\sin^2\theta^{\ell}_{\mathrm{eff}}$ by further reducing the correlation between them in the A_{FB} measurement.

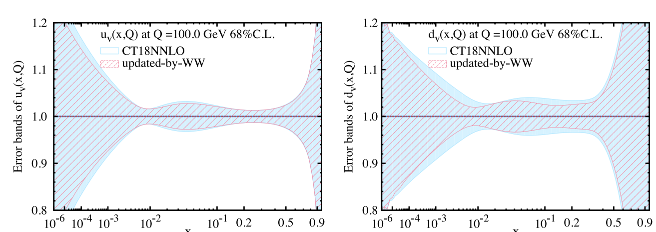

FIG. 3. Ratios of the central value and uncertainties to the CT18 central values of the valence u and valence d PDFs, before and after the PDF updating using A^{WW}_{boost}. The blue band corresponds to the uncertainty before updating and the red band is after updating.

The numerical results presented in this work are based on the PYTHIA event generator, with the CT18 NNLO PDFs. Generally, PYTHIA does not include full higher-order matrix elements. However, it provides good approximation via the parton-shower approach, as long as the measurement of the boost asymmetry is not restricted for the events with a large transverse momentum or with special requirement on the number of the associated jets. More specifically, in this work, the PYTHIA prediction is given by the LO matrix element with parton showers (to approximate some QCD resummation effects), while the PDFs are at the NNLO. Hence, the precision of the total rate only has the LO accuracy, while the prediction of the shape of various kinematic distributions, including the boost asymmetry, can be closer to high order predictions. The detailed numbers given in the discussion could be different when higher order calculations and other PDFs are used in this test. However, the phenomenal conclusion that $A_{\rm boost}^{VV'}$ can provide important information to the PDFs should be independent with the choice of event generators and PDFs. In this work, $A_{\rm boost}^{VV'}$ is defined in terms of the boson and lepton rapidity. It could be defined with other kinematic variables such as boson and lepton energy under a specific experimental apparatus, if needed.

IV. CONCLUSION

We propose the boost asymmetry in the $W\gamma$, WZ, and W^+W^- events at the LHC as new experimental observables to constrain the PDFs. The kinematics of the two different bosons separately reflect the parton information of quarks and antiquarks in the initial state, respectively, and result in an asymmetry on the boosted boson. Such boost asymmetry can be used to constrain the quark exchanging fractions directly, which cannot be observed in the current single W and Z measurements. The observation on $A_{\rm boost}$ in the $W\gamma$ and WZ events is sensitive to the quark exchanging fraction of $u\bar{d}$ and $d\bar{u}$, while in the WW events it is sensitive to that of $u\bar{u}$ and $d\bar{d}$ initial states. The $W^{\pm}\gamma$ events are particularly useful because the different strength of photon couplings to up and down quarks can further enhance the asymmetry. Impact study shows a reduction on the PDF uncertainties of relevant quarks when introducing $A_{\rm boost}$ into the PDF global analysis. The asymmetries would be helpful not only for PDF improvement but also to other related topics such the measurement of $A_{\rm FB}$ and the EW $\sin^2\theta_{\rm eff}^{\ell}$ parameter.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under Grants No. 11721505, No. 11875245, No. 12061141005, and No. 12105275, and supported by the "USTC Research Funds of the Double First-Class Initiative." This work was also supported by the U.S. National Science Foundation under Grant No. PHY-2013791. C.-P. Yuan is also grateful for the support from the Wu-Ki Tung endowed chair in particle physics.

[1] T. J. Hou, J. Gao, T. J. Hobbs, K. Xie, S. Dulat, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, and C. Schmidt *et al.*, Phys. Rev. D **103**, 014013 (2021).
[2] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin, and R. S. Thorne, Eur. Phys. J. C **81**, 341 (2021).
[3] R. D. Ball *et al.* (NNPDF Collaboration), Eur. Phys. J. C **82**, 428 (2022).
[4] Y. Fu, S. Yang, M. Liu, L. Han, T. J. Hou, C. Schmidt, C. Wang, and C. P. Yuan, Chin. Phys. C **45**, 053001 (2021). arXiv:2008.03853.
[5] ATLAS public note at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-037/.
[6] A. M. Sirunyan *et al.* (CMS Collaboration), Eur. Phys. J. C **78**, 701 (2018).
[7] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 11 (2015) 190.
[8] A. Bodek, J. Han, A. Khukhunaishvili, and W. Sakumoto, Eur. Phys. J. C **76**, 115 (2016).
[9] E. Accomando, J. Fiaschi, F. Hautmann, and S. Moretti, Phys. Rev. D **98**, 013003 (2018); **99**, 079902(E) (2019).
[10] E. Accomando, J. Fiaschi, F. Hautmann, and S. Moretti, Eur. Phys. J. C **78**, 663 (2018); **79**, 453(E) (2019).
[11] T. J. Hou, Z. Yu, S. Dulat, C. Schmidt, and C. P. Yuan, Phys. Rev. D **100**, 114024 (2019).
[12] M. Aaboud *et al.* (ATLAS Collaboration), Eur. Phys. J. C **79**, 128 (2019); **79**, 374(E) (2019).
[13] M. Aaboud *et al.* (ATLAS Collaboration), Eur. Phys. J. C **77**, 367 (2017).
[14] G. Aad *et al.* (ATLAS Collaboration), Eur. Phys. J. C **79**, 760 (2019).
[15] Christian Bierlich *et al.*, arXiv:2203.11601.
[16] E. Re, M. Wiesemann, and G. Zanderighi, J. High Energy Phys. 12 (2018) 121.
[17] C. Schmidt, J. Pumplin, C. P. Yuan, and P. Yuan, Phys. Rev. D **98**, 094005 (2018).
[18] C. Willis, R. Brock, D. Hayden, T. J. Hou, J. Isaacson, C. Schmidt, and C. P. Yuan, Phys. Rev. D **99**, 054004 (2019).
[19] S. Yang, Y. Fu, M. Liu, L. Han, T. J. Hou, and C. P. Yuan, Phys. Rev. D **106**, 033001 (2022).