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Anomalous Wtb couplings in γp collision at the LHC

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We study the possibility for the process $pp \to p\gamma p \to pW^- t(W^+ \bar{t})X$ with anomalous Wtb couplings in a model-independent effective Lagrangian approach at the LHC. We find 95% confidence level bounds on the anomalous coupling parameters for various values of the integrated luminosity. The improved constraints on the anomalous Wtb couplings have been obtained compared to current limits.

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I. INTRODUCTION

The Standard Model (SM) has been very successful in explaining the data taken from former colliders such as CERN LEP or Fermilab Tevatron. Testing SM at the CERN LHC will either lead to additional confirmation of the SM or give some hints for new physics beyond the SM. Because of the large mass of the top quark, its couplings are expected to be more sensitive to new physics than other particles [1,2]. Especially, Wtb vertex deserves special attention since the top quark is expected to decay almost completely via this interaction. Thus, studying top-quark couplings will be substantial to test the SM, and a deviation of the top couplings from the expected values would imply the existence of new physics.

In this work, we have analyzed anomalous Wtb couplings via single top quark production in γp collision at the LHC. This reaction is probable at the LHC via elastic photon emission from one of the incoming protons. The emitted photon can collide with the other proton and produce a final state of WtX through deep inelastic scattering (Fig. 1). We employ the equivalent photon approximation (EPA) [3–5] for elastic photon emission from the proton. In the EPA, emitted photons have a low virtuality, and it is a good approximation to assume that they are on-mass-shell. For this reason, these photons are sometimes called quasireal photons. When a proton emits a quasireal photon, it remains intact and scatters with a very small angle from the beam pipe. The ATLAS and CMS Collaborations at the LHC have a program with very forward detectors. It is aimed to investigate soft and hard diffraction, low-x dynamics with forward jet studies, high energy photon-induced interactions, large rapidity gaps between forward jets, and luminosity monitoring [6–23]. These detectors will be located in a region nearly 220–420 m from the interaction point, and they can detect protons in a continuous range of momentum fraction loss [24,25]. Momentum fraction loss of the proton is defined as $\xi = (|\vec{p}| - |\vec{p}'|)/|\vec{p}|$. Here, $\vec{p}$ is the momentum of the incoming proton, and $\vec{p}'$ is the momentum of the intact scattered proton. Therefore, equipped with very forward detectors, the LHC can, to some extent, be considered a high-energy photon-photon or photon-proton collider.

Photon-induced reactions have been experimentally observed through $p\bar{p} \to \gamma\gamma p\bar{p} \to \ell^+\ell^- p\bar{p}$ processes in hadron-hadron collisions [26–28], $ep \to eXp$ in ep collisions [29–34], and pair production in AA collisions [35–38]. These experiments raise interest on the potential of the LHC as a photon-photon and photon-proton collider and motivate phenomenological works on photon-induced reactions at the LHC as a probe of new physics [16–18,39–49].

II. LAGRANGIAN AND CROSS SECTIONS

Anomalous Wtb couplings can be investigated in a model-independent way by means of the effective Lagrangian approach [50–56]. We employ the following effective Lagrangian describing anomalous Wtb couplings:

$$L = \frac{g_W}{\sqrt{2}}\Big[W_\mu \bar{t}(\gamma^\mu F_{1L} P_- + \gamma^\mu F_{1R} P_+)b - \frac{1}{2m_W} W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(F_{2L}P_- + F_{2R}P_+)b\Big] + \text{H.c.}, \quad (1)$$

where

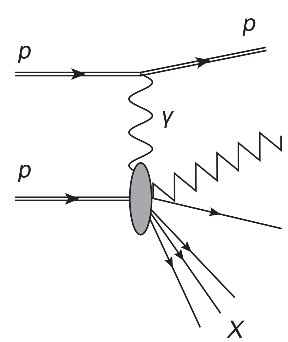

FIG. 1. Schematic diagram of the process $pp \to p\gamma p \to pWtX$.

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$$W_{\mu\nu} = D_\mu W_\nu - D_\nu W_\mu, \qquad D_\mu = \partial_\mu - ieA_\mu$$

$$P_{\mp} = \frac{1}{2}(1 \mp \gamma_5), \qquad \sigma^{\mu\nu} = \frac{i}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu). \tag{2}$$

It should be noted that the Lagrangian (1) also gives rise to anomalous $Wtb\gamma$ couplings. In the SM, the $(V-A)$ coupling F_{1L} corresponds to the Cabibbo-Kobayashi-Maskawa matrix element V_{tb}, which is very close to unity, and F_{1R}, F_{2L} and F_{2R} are equal to zero.

For off-shell top and/or bottom quarks, the Lagrangian in Eq. (1) is not the most general one; it should be extended with k^μ and $\sigma^{\mu\nu}k_\nu$ terms where k is the sum of the momenta of the t and b quarks. However, if Wtb couplings arise from gauge-invariant effective operators, single top production and decay can be described in full generality using the on-shell Lagrangian in Eq. (1) for the Wtb vertex, even in the process where the top and bottom quarks are far from their mass shell [57]. If the W boson is off-shell, then there are additional terms containing $\partial_\mu W^\mu$ [56]. These terms are omitted in the Lagrangian; they can be recovered by applying the equation of motion through operators of the original Lagrangian [58].

Measurements at the D0 detector at Fermilab Tevatron provide stringent direct constraints on these couplings [59–62]. The most stringent bounds on the anomalous couplings F_{1R}, F_{2R}, and F_{2L} are given by $|F_{1R}|^2 < 0.50$, $|F_{2R}|^2 < 0.05$ and $|F_{2L}|^2 < 0.11$ at 95% C. L. assuming that $F_{1L} = 1$ [62]. Recent results from an early LHC data are comparable, but still have weaker bounds with respect to the Tevatron [63]. We see from the Tevatron and LHC data that the bound on the coupling F_{2L} is weaker than the bound on F_{2R}, and the bound on the coupling F_{1R} is weaker than the others [59–63]. The $(V+A)$ coupling F_{1R} is stringently bounded by the CLEO $b \to s\gamma$ data [64,65] from an indirect analysis. The limit from the CLEO data is given by $|F_{1R}| < 4\times 10^{-3}$ at the 2σ level [65]. It is explicit that indirect constraints are much more restrictive than direct constraints [66,67].

In the literature, there has been a great amount of work on Wtb couplings through single and pair top-quark production. The single top-quark production cross section was discussed below and above the $t\bar{t}$ threshold for the processes $e^+e^- \to Wtb$ [68,69] and $e^+e^- \to e\bar{\nu}tb$ at the CERN LEP [70,71]. Top-quark single and pair production processes were studied for a future linear e^+e^- collider and its $\gamma\gamma$ and $e\gamma$ modes [72–80] and also for γp collisions in TESLA + HERAp and CLIC + LHC options [81–83]. Anomalous Wtb couplings have also been probed at the LHC and Tevatron [57,59–63,67,84–93].

The equivalent photon spectrum of virtuality Q^2 and energy E_γ is given by the following formula [3–5]:

$$\frac{dN_\gamma}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}\left[\left(1-\frac{E_\gamma}{E}\right)\left(1-\frac{Q^2_{\min}}{Q^2}\right)F_E + \frac{E_\gamma^2}{2E^2}F_M\right], \tag{3}$$

where

$$Q^2_{\min} = \frac{m_p^2 E_\gamma^2}{E(E-E_\gamma)}, \qquad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1 + \frac{Q^2}{Q_0^2}\right)^{-4}, \qquad F_M = G_M^2.$$

In Eq. (3), E is the energy of the incoming proton beam, and m_p is mass of the proton. The magnetic moment of the proton is taken to be $\mu_p^2 = 7.78$ and $Q_0^2 = 0.71\ \mathrm{GeV}^2$ [3,16,23]. The photon spectrum which is integrated from a kinematic minimum $Q^2_{\min}$ up to $Q^2_{\max}$ is given by [16]

$$dN(E_\gamma) = \frac{\alpha}{\pi}\frac{dE_\gamma}{E_\gamma}\left(1-\frac{E_\gamma}{E}\right)\left[\varphi\left(\frac{Q^2_{\max}}{Q_0^2}\right) - \varphi\left(\frac{Q^2_{\min}}{Q_0^2}\right)\right]. \tag{4}$$

Here, the function φ is defined as follows:

$$\varphi(x) = (1+ay)\left[-ln(1+x^{-1}) + \sum_{k=1}^{3}\frac{1}{k(1+x)^k}\right] + \frac{(1-b)y}{4x(1+x)^3} + c\left(1+\frac{y}{4}\right)\left[\ln\frac{1+x-b}{1+x} + \sum_{k=1}^{3}\frac{b^k}{k(1+x)^k}\right], \tag{5}$$

where

$$y = \frac{E_\gamma^2}{E(E-E_\gamma)}, \qquad a = \frac{1}{4}(1+\mu_p^2) + \frac{4m_p^2}{Q_0^2} \approx 7.16$$

$$b = 1 - \frac{4m_p^2}{Q_0^2} \approx -3.96, \qquad c = \frac{\mu_p^2 - 1}{b^4} \approx 0.028. \tag{6}$$

In the EPA, emitted photons have a low virtuality, and the photon spectrum has an asymptotic behavior for large values of virtuality Q^2. In the EPA which we have considered, typical photon virtuality is $\langle Q^2\rangle \approx 0.01\ \mathrm{GeV}^2$ [3]. Above this average virtuality value, spectrum function rapidly decreases, and the contribution to the integral above $Q^2_{\max} \approx 2\ \mathrm{GeV}^2$ is negligible. To be precise, the difference between SM cross sections for $Q^2_{\max} = 2\ \mathrm{GeV}^2$ and $Q^2_{\max} = 64\ \mathrm{GeV}^2$ is at the order of 10^{-5} pb. Therefore, during calculations, we set $Q^2_{\max} = 2\ \mathrm{GeV}^2$.

We consider the subprocesses $\gamma b \to W^- t$ and $\gamma\bar{b} \to W^+\bar{t}$ of our main process $pp \to p\gamma p \to pW^-t(W^+\bar{t})X$. In the SM, single production of the top quark via the process $\gamma b \to W^- t$ is described by three tree-level diagrams. Each of the diagrams contains a Wtb vertex. In the effective Lagrangian approach, there are four tree-level diagrams; one of them contains an anomalous γbtW vertex, which is absent in the SM (Fig. 2).

The total cross section for the process $pp \to p\gamma p \to pW^-t(W^+\bar{t})X$ can be obtained by integrating the cross section for the subprocesses over the photon and quark distributions:

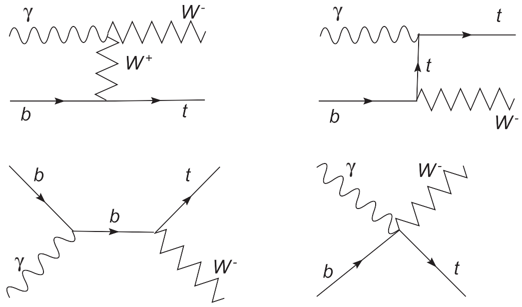

FIG. 2. Tree-level Feynman diagrams for the process $\gamma b \rightarrow W^- t$.

$$\sigma(pp \rightarrow p\gamma p \rightarrow pW^- t(W^+\bar{t})X) = \int_{\xi_{1\min}}^{\xi_{1\max}} dx_1 \int_0^1 dx_2 \left(\frac{dN_\gamma}{dx_1}\right) \times \left(\frac{dN_q}{dx_2}\right)[\hat{\sigma}_{\gamma b\rightarrow W^- t}(\hat{s}) + \hat{\sigma}_{\gamma\bar{b}\rightarrow W^+\bar{t}}(\hat{s})]. \quad (7)$$

In this formula, $x_1 = \frac{E_\gamma}{E}$, and x_2 is the fraction which represents the ratio between the $b(\bar{b})$ quark and incoming proton's momentum. $\frac{dN_q}{dx_2}$ is the $b(\bar{b})$ quark distribution function. We ignore interactions between different families of quarks since the cross sections are suppressed due to small off-diagonal elements of the Cabibbo-Kobayashi-Maskawa matrix. In the total cross section calculations, we have used Martin, Stirling, Thorne, and Watt distribution functions [94].

In our calculations, three different forward-detector acceptance ranges have been discussed: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$. The former one was proposed by the ATLAS Forward Physics Collaboration [24,25]. The second acceptance range was proposed by the CMS-TOTEM forward-detector scenario [95]. Since the forward detectors can detect protons in a continuous range of ξ, one can impose some cuts and choose to work in a subinterval of the whole acceptance region. Hence, we also consider an acceptance of $0.1 < \xi < 0.5$ which is a subinterval of the CMS-TOTEM acceptance range.

In Figs. 3–6, we show the integrated total cross section of the process $pp \rightarrow p\gamma p \rightarrow pW^- tX$ as a function of anomalous couplings F_{2R}, F_{2L}, F_{1R}, and ΔF_{1L} for the acceptances of $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$. Here, the anomalous coupling ΔF_{1L} is defined by $\Delta F_{1L} \equiv F_{1L} - 0.99$. In Figs. 3 and 4, we observe that the cross section approximately has the same dependence to both F_{2R} and F_{2L} couplings. We see from

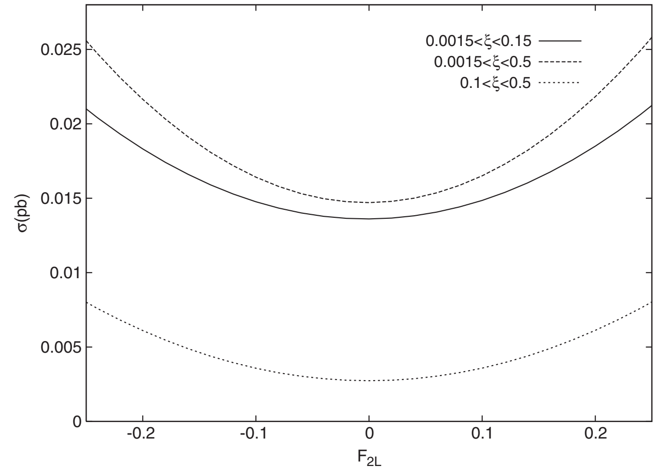

FIG. 4. The integrated total cross section of the process $pp \rightarrow p\gamma p \rightarrow pWtX$ as a function of anomalous coupling F_{2L} for three different detector acceptances stated in the figure. The center-of-mass energy is taken to be $\sqrt{s} = 14$ TeV.

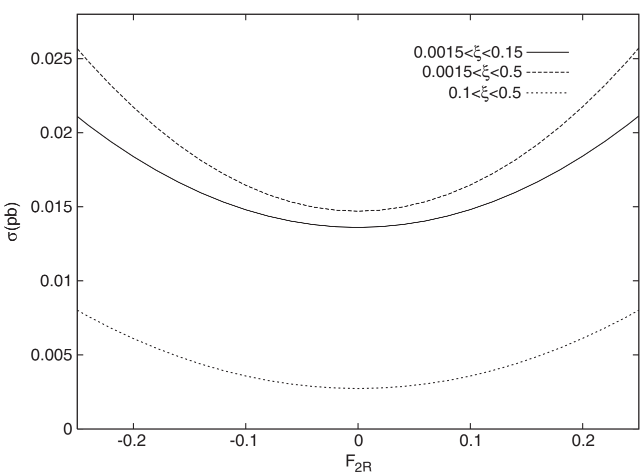

FIG. 3. The integrated total cross section of the process $pp \rightarrow p\gamma p \rightarrow pWtX$ as a function of anomalous coupling F_{2R} for three different detector acceptances stated in the figure. The center-of-mass energy is taken to be $\sqrt{s} = 14$ TeV.

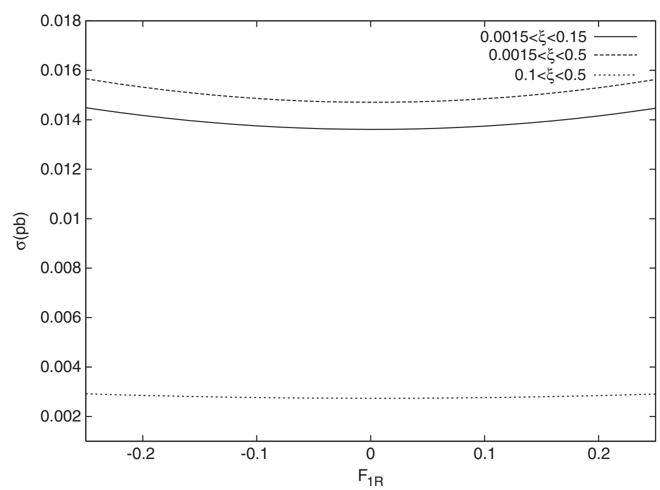

FIG. 5. The integrated total cross section of the process $pp \rightarrow p\gamma p \rightarrow pWtX$ as a function of anomalous coupling F_{1R} for three different detector acceptances stated in the figure. The center-of-mass energy is taken to be $\sqrt{s} = 14$ TeV.

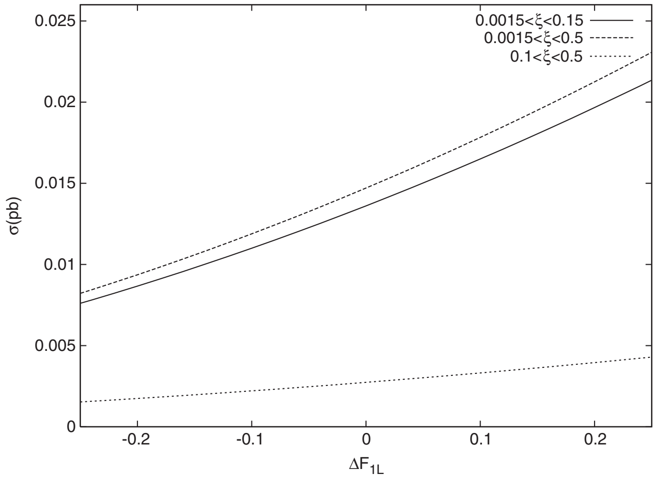

FIG. 6. The integrated total cross section of the process $pp \to p\gamma p \to pWtX$ as a function of anomalous coupling ΔF_{1L} for three different detector acceptances stated in the figure. The center-of-mass energy is taken to be $\sqrt{s} = 14$ TeV.

Fig. 5 that sensitivity of the cross section to anomalous coupling F_{1R} is comparably weak.

III. SENSITIVITY TO ANOMALOUS COUPLINGS

We estimate the sensitivity of the process $pp \to p\gamma p \to pW^- t(W^+ \bar{t})X$ to anomalous couplings F_{2R}, F_{2L}, F_{1R}, and ΔF_{1L} using a simple one-parameter χ^2 criterion for integrated luminosities of $L_{\rm int} = 10$, 30, 50, 100, 200 fb^{-1} and $\sqrt{s} = 14$ TeV. The χ^2 function is given by

$$\chi^2 = \left(\frac{\sigma_{\rm SM} - \sigma(\Delta F_{1L}, F_{1R}, F_{2L}, F_{2R})}{\sigma_{\rm SM}\delta}\right)^2, \qquad (8)$$

where $\delta = \frac{1}{\sqrt{N}}$ is the statistical error. The expected number of events has been calculated considering the leptonic decay channel of the W boson and leptonic decay of the top quark as the signal $N = {\rm BR}(W^- \to \ell^- \bar{\nu}_\ell)\,{\rm BR}(t \to W^+ b \to \ell^+ \nu_\ell b)\sigma_{\rm SM} L_{\rm int}$, where $\ell = e$ or μ. ATLAS and CMS have central detectors with a pseudorapidity coverage $|\eta| < 2.5$. Therefore, we consider an acceptance window of $|\eta| < 2.5$ for final-state electrons, muons, and b quarks. Branching ratios appearing in the number of events are defined as ${\rm BR} = \frac{\Gamma}{\Gamma_{\rm total}}$ where $\Gamma_{\rm total}$ is the full width and Γ is the decay rate for the corresponding channel with a cut of $|\eta| < 2.5$ for final decay products.

The limits for the anomalous coupling parameters are given in Tables I, II, III, and IV for integrated luminosities of $L_{\rm int} = 10$, 30, 50, 100, 200 fb^{-1} and forward-detector acceptances of $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$. We see from the tables that the $0.1 < \xi < 0.5$ case provides more restrictive bounds on both F_{2R} and F_{2L} couplings compared to the $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ cases. On the other hand, limits on F_{1R} and ΔF_{1L} couplings in the $0.1 < \xi < 0.5$ case are weaker than the limits in the $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ cases. The limits presented in tables are reasonable. In the effective Lagrangian (1), anomalous couplings F_{1R} and F_{1L} are originated from dimension-4 effective operators, but anomalous couplings F_{2R} and F_{2L} are originated from dimension-5 effective operators. Therefore, energy dependence of the terms in the cross section proportional to F_{2R} and F_{2L} are expected to be higher than the Standard Model and also the terms in the cross section proportional to F_{1R} and F_{1L}. Hence, the main new physics contribution from couplings F_{2R} and F_{2L} comes from the high-energy region

TABLE I. 95% C. L. sensitivity bounds of the coupling F_{2R} for various forward detector acceptances and integrated LHC luminosities. The center of mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

L(fb^{-1})	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
10	−0.117; 0.116	−0.138; 0.138	−0.110; 0.110
30	−0.089; 0.088	−0.105; 0.105	−0.084; 0.084
50	−0.078; 0.078	−0.093; 0.092	−0.074; 0.074
100	−0.066; 0.065	−0.078; 0.077	−0.062; 0.062
200	−0.055; 0.055	−0.066; 0.065	−0.052; 0.052

TABLE II. 95% C. L. sensitivity bounds of the coupling F_{2L} for various forward detector acceptances and integrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

L(fb^{-1})	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
10	−0.118; 0.115	−0.140; 0.136	−0.110; 0.110
30	−0.090; 0.087	−0.107; 0.103	−0.084; 0.084
50	−0.079; 0.077	−0.094; 0.090	−0.074; 0.074
100	−0.067; 0.064	−0.080; 0.076	−0.062; 0.062
200	−0.056; 0.054	−0.067; 0.063	−0.052; 0.052

TABLE III. 95% C. L. sensitivity bounds of the coupling F_{1R} for various forward detector acceptances and integrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

$L(\text{fb}^{-1})$	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
10	−0.396; 0.400	−0.404; 0.408	−0.603; 0.609
30	−0.300; 0.304	−0.307; 0.310	−0.457; 0.464
50	−0.264; 0.268	−0.270; 0.273	−0.402; 0.409
100	−0.222; 0.226	−0.227; 0.230	−0.337; 0.344
200	−0.186; 0.190	−0.190; 0.194	−0.283; 0.290

TABLE IV. 95% C. L. sensitivity bounds of the coupling ΔF_{1L} for various forward detector acceptances and integrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

$L(\text{fb}^{-1})$	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
10	−0.084; 0.077	−0.087; 0.080	−0.207; 0.171
30	−0.047; 0.045	−0.049; 0.047	−0.114; 0.102
50	−0.036; 0.035	−0.038; 0.037	−0.087; 0.080
100	−0.026; 0.025	−0.027; 0.026	−0.060; 0.057
200	−0.018; 0.018	−0.019; 0.018	−0.042; 0.041

$0.1 < \xi < 0.5$. On the contrary, the main SM contribution comes from the low-energy region $0.0015 < \xi < 0.15$. The limits on F_{2R} and F_{2L} are expected to be better in the less-forward region $0.1 < \xi < 0.5$ since the invariant mass of the incoming photon and b quark is large, and the SM background is low in that region.

IV. CONCLUSION

Our limits on the couplings F_{2R} and F_{2L} are approximately a factor from 2 to 4 and 3 to 6 better than the limits from direct constraints at the Tevatron, respectively, depending on the luminosity [62]. On the other hand, our best limit on F_{1R} is a factor of 3.7 more restricted compared to Tevatron direct constraint [62].

Physics studied at the LHC is significantly enhanced via the forward-physics programs of ATLAS and CMS collaborations. Equipped with forward detectors, the LHC gives us new options to examine high-energy photon-proton interactions. With respect to pure deep inelastic scattering processes, photon-proton interactions provide a quite clean channel due to the absence of one of the incoming proton remnants. Furthermore, detection of the intact scattered protons in the forward detectors allows us to reconstruct quasireal photon momenta. This provides an advantage in the reconstruction of the kinematics.

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