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Research Article

Anomalous $tq\gamma$ Couplings in γp Collision at the LHC

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We have examined the constraints on the anomalous $tq\gamma$ ($q = u, c$) couplings through the process $pp \rightarrow p\gamma p \rightarrow pWbX$ at the LHC by considering four forward detector acceptances: $0.0015 < \xi < 0.5$, $0.0015 < \xi < 0.15$, $0.015 < \xi < 0.15$, and $0.1 < \xi < 0.5$, where $\xi = E_\gamma/E$ with E_γ and E the energies of the photon and of the incoming proton, respectively. The sensitivity bounds on the anomalous couplings have been obtained at the 95% confidence level in a model independent effective Lagrangian approach. We have found that the bounds on these couplings can be highly improved compared to current experimental bounds.

1. Introduction

The top quark is the heaviest particle of the standard model (SM). Therefore, the top quark properties and their production process provide a possibility for probing new physics beyond the SM. Furthermore, the impacts of new physics on the top quark couplings are considered to be larger than those on any other fermions, and conflicts with the SM expectations could be measured as described in [1]. A search for rare decays of the top quark is one of such studies. The search for the top quark anomalous interactions via flavour changing neutral currents (FCNC) is of special interest. For the top quark, FCNC decays $t \rightarrow q\gamma$ ($q = u, c$) cannot be seen at the tree level of the SM. These decays can only make loop contributions. As a result, the branching ratios of $t \rightarrow q\gamma$ are very small, and they are at the order of 10^{-10} [2–5]. However, various extensions of the SM, such as the quark-singlet model [6–9], the two-Higgs doublet model [2, 10–14], the minimal supersymmetric model [15–22], supersymmetry [23], the topcolor-assisted technicolor model [24], or extra dimension model [25, 26] could lead to a huge enrichment of those kinds of decays.

The CDF collaboration bounds on the branching ratios at 95% C.L. for the process $t \rightarrow q\gamma$ as follows [27]:

$$\mathrm{BR}(t \longrightarrow u\gamma) + \mathrm{BR}(t \longrightarrow c\gamma) < 3.2\%. \quad (1)$$

Furthermore, the ZEUS collaboration obtained upper limits at 95% C.L. on the anomalous $tq\gamma$ couplings $\kappa_{tu\gamma} < 0.12$ [28]. The large hadron collider (LHC) can produce a large number of top quarks. Therefore, top quark interactions can be examined with high sensitivity. In particular, ATLAS collaboration has predicted a sensitivity of $\mathrm{BR}(t \rightarrow q\gamma) \sim 10^{-4}$ at 5σ level [29].

The FCNC effective Lagrangian among the top quark, two quarks u, c, and the photon γ can be written as [28]

$$L = \sum_{q_i=u,c} g_e e_t \bar{t} \frac{i\sigma_{\mu\nu} p^\nu}{\Lambda} \kappa_{tq_i\gamma} q_i A^\mu. \quad (2)$$

Here $\kappa_{tq_i\gamma}$ is the anomalous coupling for the neutral currents with a photon; Λ is a new physics scale; $\sigma_{\mu\nu} = [\gamma_\mu, \gamma_\nu]/2$; g_e is the electromagnetic coupling constant; e_t is the electric charge of the top quark. Λ is the conventionally taken mass of the top quark (m_t) for the sake of definiteness. Hence, we take $\Lambda = m_t$. Also, we assume in our calculations that $\kappa_{tu\gamma} = \kappa_{tc\gamma}$. Using the anomalous interaction given in (2), the decay width can be obtained as follows:

$$\Gamma(t \longrightarrow q\gamma) = \frac{g_e^2 e_t^2 \kappa_{tq\gamma}^2 m_t^3}{8\pi\Lambda^2} \quad (q = u, c), \quad (3)$$

where we put the masses of the u and c quarks equal to the zero. Branching ratio of the anomalous $t \rightarrow q\gamma$ decay can be

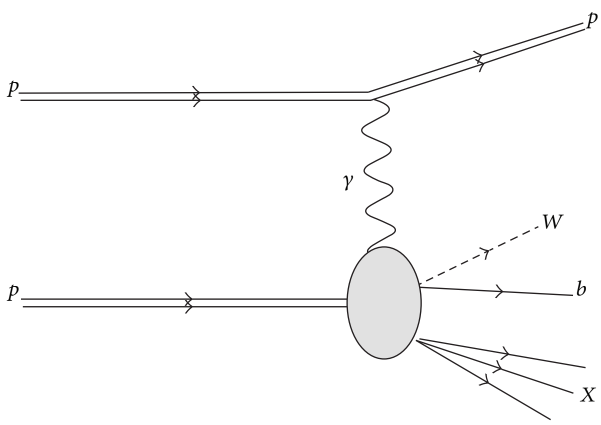

Figure 1: Schematic diagram for the reaction $pp \rightarrow p\gamma p \rightarrow pWbX$.

given by the following equation, since the main decay mode of the top quark is $t \rightarrow bW$:

$$\mathrm{BR}(t \longrightarrow q\gamma) = \frac{\Gamma(t \longrightarrow q\gamma)}{\Gamma(t \longrightarrow bW)}. \quad (4)$$

Using this equation, from the experimental constraints of the CDF collaboration it is easy to obtain magnitude of the upper limit on $\kappa_{tq\gamma} = 0.29$.

In this work, we have examined anomalous FCNC interactions for the process $pp \rightarrow p\gamma p \rightarrow pbWX$ at the LHC. We show a schematic diagram for the this reaction in Figure 1. The subprocess of the main reaction is $\gamma q \rightarrow Wb$. This process is becoming interesting as an additional way to investigate for SM or new physics.

In many situations, ultraperipheral collisions and elastic interactions can not be detected at the central detectors. Forward detectors are developed by the ATLAS and CMS collaborations to detect the scattering particles which cannot be caught by the central detectors with limited pseudorapidity. These extra detectors are placed at distance of 220 m–420 m from the central detectors. Usual pp deep inelastic scattering (DIS) incoming protons dissociate into partons. Therefore, DIS interactions have very sophisticated backgrounds. In the DIS process, made-up of jets from the proton remnants, some ambiguities are created which make it hard to detect the new physics signals beyond the SM. However, $\gamma\gamma$ or γp interactions have a clean environment compared to the usual proton-proton DIS, since in $\gamma\gamma$ or γp collisions with almost real photons, a photon is emitted, while the proton remains intact. Because of both of the incoming protons remaining intact, $\gamma\gamma$ collisions provide fewer backgrounds compared to the other processes. However, γp collisions have higher energy and effective luminosity with respect to $\gamma\gamma$ interactions.

In γp collisions, the almost real photons with low virtuality are emitted from only one of the proton beams and it is a good approximation to assume that they are on-mass-shell. Because of the low virtuality of the photons, the structures of the photon emitting protons are not spoilt. Also, almost real photons are scattered with small angles, and then they have a low transverse momentum. Since these photons have very high energy, they can interact with quarks in the other incoming proton's internal structure. On the other hand, intact protons which are emitting photons deflect slightly their path along the beam pipe, and, generally, they cannot be detected in central detectors. One of the main properties of forward detectors is to detect the intact protons with some momentum fraction loss given the formula $\xi = (|\vec{p}| - |\vec{p}'|)/|\vec{p}|$, where $\vec{p}$ and $\vec{p}'$ are momentums of incoming protons and intact scattered protons, respectively. At very high energies, it is a good approximation to write $\xi = E_\gamma/E$ where E, E_γ are the energies of the proton emitting the photon and of the photon, respectively. If the forward detectors are established closer to central detectors, a higher ξ can be obtained. Forward detectors can detect intact outgoing protons in the interval $\xi_{\min} < \xi < \xi_{\max}$. This interval is known as the acceptance of the forward detectors. ATLAS forward detectors have an acceptance of $0.0015 < \xi < 0.15$ [30] and CMS-TOTEM forward detectors are placed closer to the central detectors and the acceptances span $0.0015 < \xi < 0.5$, $0.1 < \xi < 0.5$ [31, 32].

Photon-induced reactions in hadron collider phenomena were recently observed in the measurements of the CDF collaboration [33–39], and these measurements are consistent in both theoretical expectations with $p\bar{p} \rightarrow p\ell^+\ell^-\bar{p}$ through two-photon exchange ($\gamma\gamma \rightarrow \ell^+\ell^-$). Therefore, the photon-induced interactions' potential at the LHC is significant, with its high energetic pp collisions, and high luminosity [30–32, 40–60]. Moreover, two photon reactions $pp \rightarrow p\gamma\gamma p \rightarrow p\mu^+\mu^- p$, $pp \rightarrow p\gamma\gamma p \rightarrow pe^+e^- p$, and $pp \rightarrow p\gamma\gamma p \rightarrow pW^+W^- p$ have been measured by the CMS collaboration from the early LHC data at $\sqrt{s} = 7$ TeV [61–63].

The photon-induced reactions in pp collisions can be obtained in the framework of the equivalent photon approximation (EPA) [64, 65]. In this approximation the equivalent photon spectrum, given the virtuality Q^2 and the energy of the quasireal photons E_γ ($E_\gamma \gg Q^2$), is given as follows:

$$\frac{dN}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}\left[\left(1 - \frac{E_\gamma}{E}\right)\left(1 - \frac{Q^2_{\min}}{Q^2}\right)F_E + \frac{E^2_\gamma}{2E^2}F_M\right], \quad (5)$$

where E is the incoming proton energy ($E_\gamma = \xi E$). The remaining terms are as follows:

$$Q^2_{\min} = \frac{m_p^2 E_\gamma^2}{E(E - E_\gamma)}, \qquad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}$$
$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1 + \frac{Q^2}{Q_0^2}\right)^{-4}, \qquad F_M = G_M^2, \quad (6)$$
$$Q_0^2 = 0.71\ \mathrm{GeV}^2.$$

Here, m_p is the mass of the proton, $\mu_p^2 = 7.78$ is the squared magnetic moment of the proton, F_E and F_M are functions of the electric and magnetic form factors, respectively, and

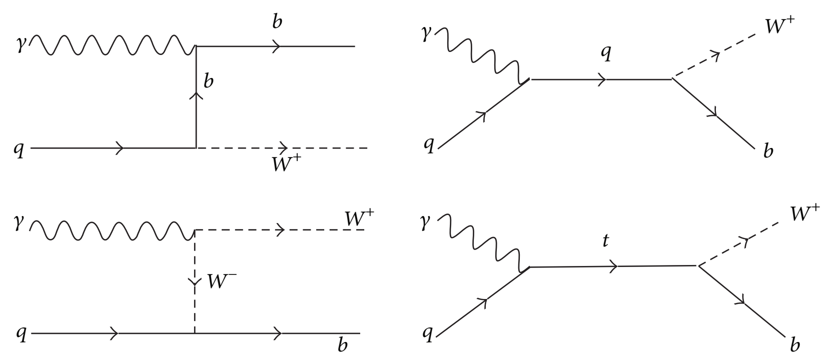

FIGURE 2: Tree level Feynman diagrams for the subprocess $\gamma q \to Wb$ ($q = u, c$) in the presence of the anomalous $tq\gamma$ couplings.

E, E_γ are the energies of the proton emitting the photon and of the photon, respectively. The cross section for the main process $pp \to p\gamma p \to pWbX$ can be found by integrating $\gamma q \to Wb$ subprocess cross section over the photon and quark spectra:

$$\sigma(pp \longrightarrow p\gamma p \longrightarrow pWbX) = \sum_{q=u,c} \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2 \int_{\xi_{\min}}^{\xi_{\max}} d\xi \times \int_{x_{\min}}^{x_{\max}} dx \left(\frac{dN_\gamma}{d\xi dQ^2}\right)\left(\frac{dN_q}{dx}\right)\widehat{\sigma}_{\gamma q \to Wb}(\widehat{s}), \quad (7)$$

where x is the momentum fraction of the proton's momentum carried by the quark. dN_q/dx is the quark distribution function of the proton. Also, we have taken the $Q^2_{\max} = 2\,\text{GeV}^2$ since $Q^2_{\max}$ greater than $2\,\text{GeV}^2$ does not make a significant contribution to this integral. From (7) the following equation can be obtained:

$$\sigma(pp \longrightarrow p\gamma p \longrightarrow pWbX) = \sum_{q=u,c} \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2 \int_{M_{\text{inv}}/\sqrt{s}}^{\sqrt{\xi_{\max}}} dz 2z \times \int_{\text{MAX}(z^2,\xi_{\min})}^{\xi_{\max}} \frac{d\xi}{\xi}\frac{dN_\gamma}{d\xi dQ^2} N_q\left(\frac{z^2}{\xi}\right)\widehat{\sigma}_{\gamma q \to Wb}(\widehat{s}), \quad (8)$$

where M_{inv} is total mass of the final state particles of the $\gamma q \to Wb$ subprocess and $\widehat{s} = z^2 s$ with $z = \xi x$. In our paper, we have used Martin et al. parton distribution functions [66]. During calculations, we have taken the quark virtuality $Q'^2 = m_t^2$. In all the results presented in this work, we impose a cut of pseudorapidity $|\eta| < 2.5$ for final state particles from subprocess $\gamma q \to Wb$ since central detectors of the ATLAS and CMS have a pseudorapidity $|\eta|$ coverage of 2.5.

2. Phenomenological Analysis

The subprocess $\gamma q \to Wb$ consists of s, t, and u channel tree-level SM diagrams. Additionally, there is a one tree-level Feynman diagram containing anomalous $tq\gamma$ coupling in Figure 2. The total polarization summed amplitude squared is given in Appendix. In our calculations, it is assumed that the center of mass energy of the LHC is 14 TeV.

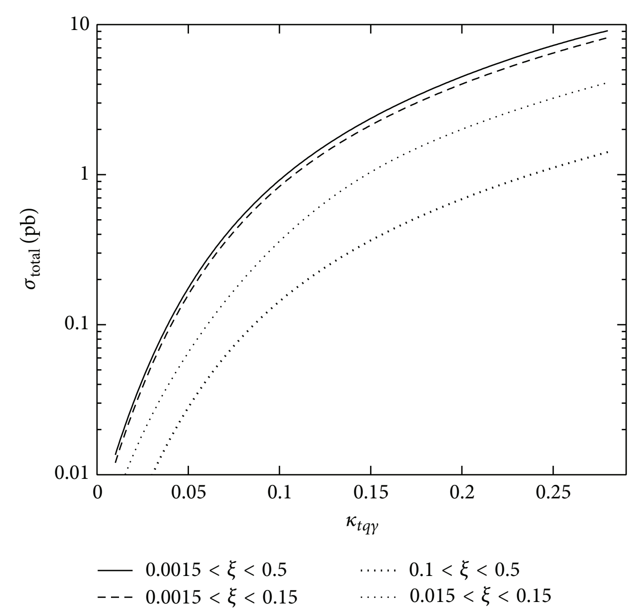

FIGURE 3: The total cross sections of $pp \to p\gamma p \to pWbX$ as a function of anomalous $tq\gamma$ coupling ($\kappa_{tq\gamma}$) for four different forward detector acceptances stated in the figure. It is assumed that the center of mass energy of the LHC is 14 TeV. Also, we impose cuts $|\eta| < 2.5$ and $p_t > 30$ GeV.

The total cross sections as a function of $\kappa_{tq\gamma}$ for four acceptance regions $0.0015 < \xi < 0.5$, $0.0015 < \xi < 0.15$, $0.1 < \xi < 0.5$, and $0.015 < \xi < 0.15$ are presented in Figure 3. We see from this figure that total cross sections for the $0.0015 < \xi < 0.5$ and $0.0015 < \xi < 0.15$ are close to each other. In Figure 4, we have plotted the SM and total cross sections of $pp \to pWbX$ as functions of the transverse momentum cut (p_t cut or $p_{t,\min}$) of the final state particles for $\kappa_{tq\gamma} = 0.01$ and two forward detectors acceptance regions: $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. Figure 5 same as Figure 4 but for the other acceptances regions: $0.0015 < \xi < 0.15$ and $0.015 < \xi < 0.15$. As seen from these figures, in actual

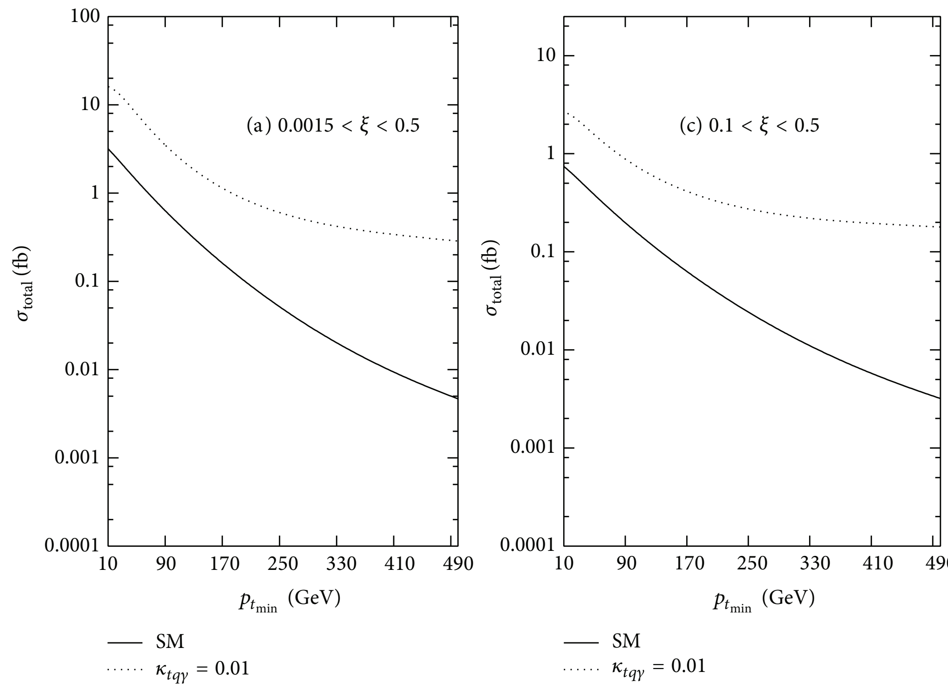

FIGURE 4: Cross sections of $pp \to p\gamma p \to pWbX$ as a function of the transverse momentum cut on the final state particles for two forward detector acceptances: $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. Solid lines are for the SM and the dotted lines are for the total cross sections with $\kappa_{tq\gamma} = 0.01$. We impose cuts $|\eta| < 2.5$ and $p_t > 30$ GeV.

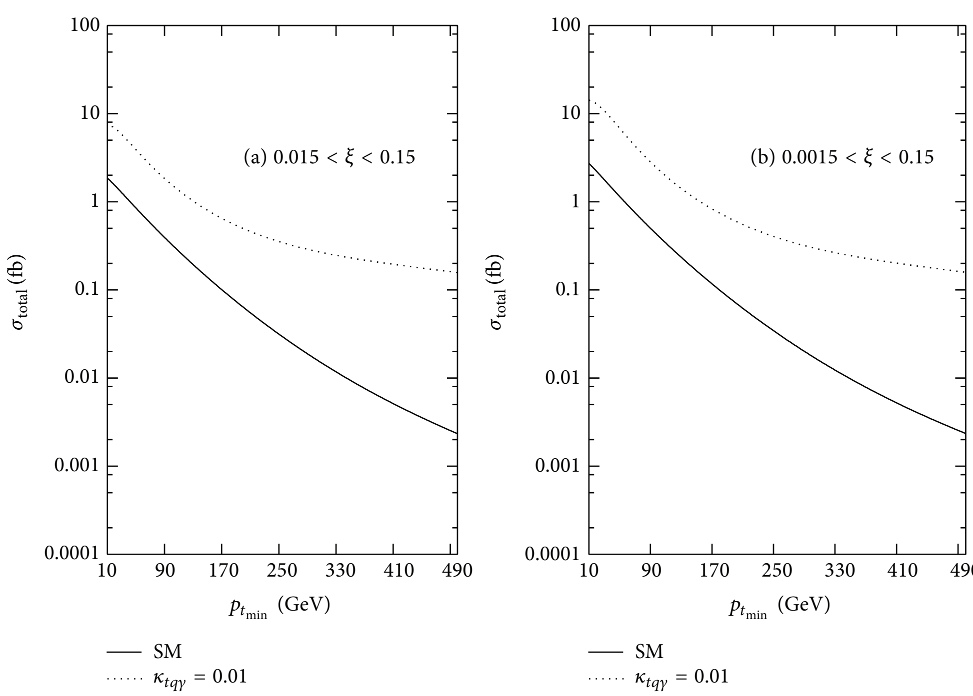

FIGURE 5: Cross sections of $pp \to p\gamma p \to pWbX$ as a function of the transverse momentum cut on the final state particles for two forward detector acceptances: $0.015 < \xi < 0.15$ and $0.0015 < \xi < 0.15$. Solid lines are for the SM and the dotted lines are for the total cross sections with $\kappa_{tq\gamma} = 0.01$. We impose cuts $|\eta| < 2.5$ and $p_t > 30$ GeV.

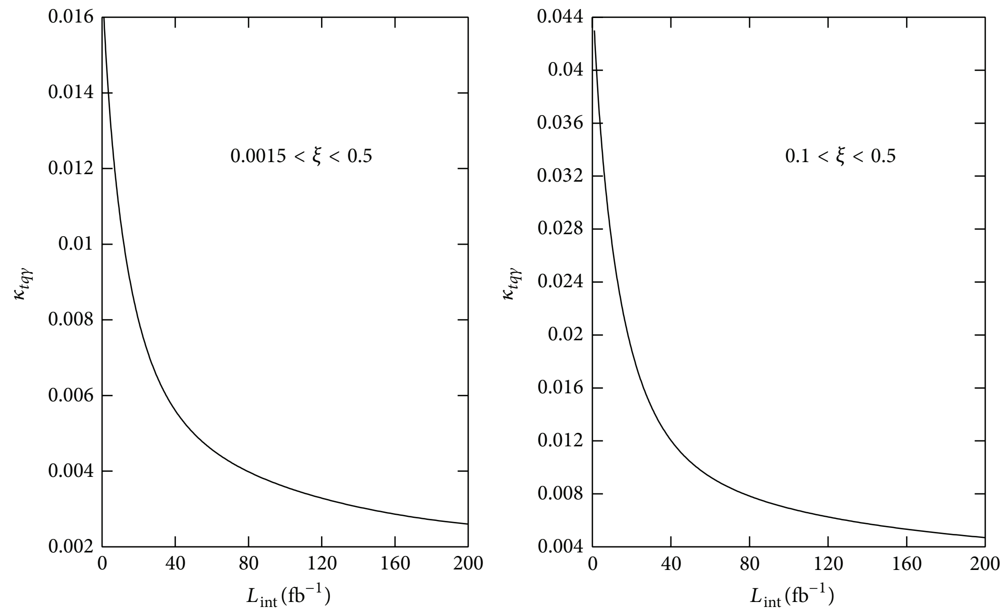

Figure 6: 95% C.L. sensitivity bounds for $\kappa_{tq\gamma}$ as a function of integrated LHC luminosity for two forward detector acceptances: $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. We impose the following cuts: $p_t > 30$ GeV and $|\eta| < 2.5$.

experiments both angular distribution and the p_t cut can be used to improve the sensitivity bounds since contributions of the new physics and the SM are well separated from each other for high p_t cut regions. Moreover, the acceptance region $0.1 < \xi < 0.5$ has almost the same features as the other acceptance regions with a high p_t cut. It can be concluded that a high lower bound of the acceptance region mimics an extra p_t cut. Therefore, in this paper we estimate sensitivity of the $pp \rightarrow p\gamma p \rightarrow pWbX$ process to be $tq\gamma$ anomalous couplings using two different statistical analysis methods. First, we use a Poisson distribution, which is the appropriate sensitivity analysis since the number of SM events with these cuts is small enough. In this statistical analysis, the number of observed events is assumed to be equal to the SM prediction $N_{\text{obs}} = S \times E \times \text{BR} \times L \times \sigma_{\text{SM}} = N_{\text{SM}}$. Here S is the survival probability factor, E is the jet reconstruction efficiency, and L is the integrated luminosity. We have taken a survival probability factor of $S = 0.7$ [67], and the b jet reconstruction efficiency of $E = 0.6$. We consider W boson decay leptonically; hence, here BR is the branching ratio of W boson to leptons. In the second statistical analysis, we have used the χ^2 criterion without a systematic error which is given by

$$\chi^2 = \left(\frac{\sigma_{\text{SM}}^i - \sigma_{\text{NEW}}^i}{\sigma_{\text{SM}}^i \delta} \right)^2, \tag{9}$$

where σ_{NEW} is the total cross section including SM and new physics and δ is the statistical error. We show the sensitivity of the 95% C.L. parameter $\kappa_{tq\gamma}$ as a function of integrated LHC luminosity for $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$ in Figure 6 and $0.0015 < \xi < 0.5$, $0.0015 < \xi < 0.15$ in Figure 7. We set $p_t > 30$ GeV and $|\eta| < 2.5$ in these figures.

During calculations, we considered all tree-level SM contributions for the subprocess $\gamma q \rightarrow Wb$ (Figure 2). These generate major backgrounds. On the other hand, the leading order background to this process might be coming from the pomeron-quark interaction. A pomeron emitted from one of the incoming proton beams can collide with the other proton's quarks and the same final state particles can take place. However, when examined in detail it can be seen that this background process is expected to have a quite small influence on limits of the anomalous coupling. In DIS process, the virtuality of the struck quark is quite high. In this work, we take the virtuality of the struck quark $Q^2 = m_t^2$. Hence, when a pomeron collides with a quark it may be dissociated into partons. Pomeron remnants can be caught by the calorimeters and this background can be removed. Moreover, the survival probability for a pomeron exchange is quite smaller than the survival probability of induced photons. Hence, even if the background from pomeron exchange cannot be eliminated, it does not affect the bounds on anomalous coupling [30, 59].

In low luminosity values, the pileup of events is negligible in γp interactions at the LHC. However, these backgrounds can be suppressed by using exclusivity conditions, kinematics, and timing constraints at high luminosity [30, 68–70]. For these purposes, we give the sensitivity bounds for between luminosity values of 1–200 fb^{-1} in Figures 6 and 7. As seen from these figures, SM backgrounds could be smaller than 10 depending on the integrated luminosity. Therefore, in these kinematical regions we have used Poisson analysis for the $N_{\text{SM}} < 10$ and we have used χ^2 criterion for $N_{\text{SM}} > 10$. We understand from the figures that the best sensitivity has been obtained in the $0.0015 < \xi < 0.5$ case. In Figure 8 we show the 95% C.L. lower bounds for $\kappa_{tq\gamma}$ as a function

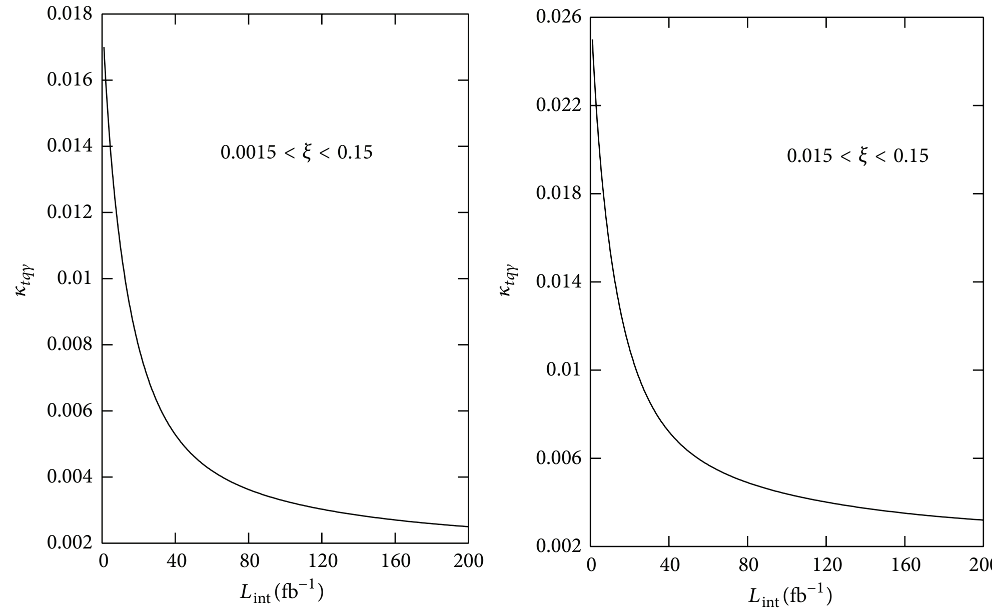

Figure 7: 95% C.L. sensitivity bounds for $\kappa_{tq\gamma}$ as a function of integrated LHC luminosity for two forward detector acceptances: $0.0015 < \xi < 0.15$ and $0.015 < \xi < 0.15$. We impose the following cuts: $p_t > 30$ GeV and $|\eta| < 2.5$.

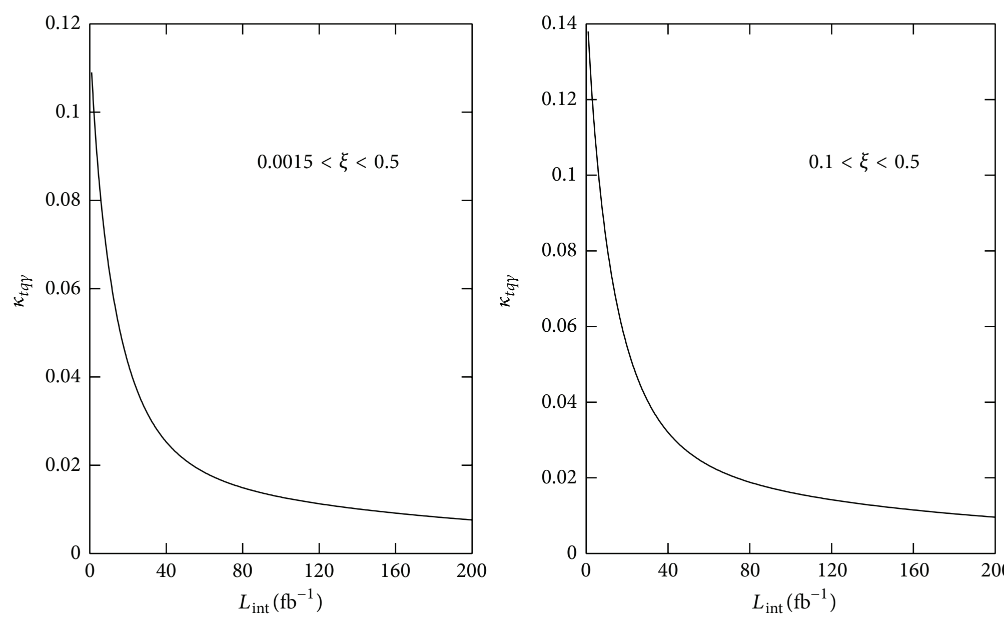

Figure 8: 95% C.L. sensitivity bounds for $\kappa_{tq\gamma}$ as a function of integrated LHC luminosity for two forward detector acceptances: $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. We impose the following cuts: $p_t > 500$ GeV and $|\eta| < 2.5$.

of integrated LHC luminosity for $0.0015 < \xi < 0.5$, $0.1 < \xi < 0.5$, and $p_t > 500$ GeV. Figure 9 same as Figure 8 but for $0.0015 < \xi < 0.15$ and $0.015 < \xi < 0.15$. In this high p_t cut region, SM events are smaller than 10 for all of the luminosity values as seen from Figures 4 and 5. Hence, in Figures 8 and 9 we use only Poisson analysis. These figures show that the obtained sensitivity bounds in Figures 6 and 7 are better than in Figures 8 and 9. However, high p_t cut regions have a very clean environment. Therefore, any signal which conflicts with the SM expectations would be a credible clue for there being something beyond the SM.

3. Conclusions

By using very forward detectors, the LHC can be designed as a high energy photon-photon and photon-proton collider. There is no existing high energy photon-photon

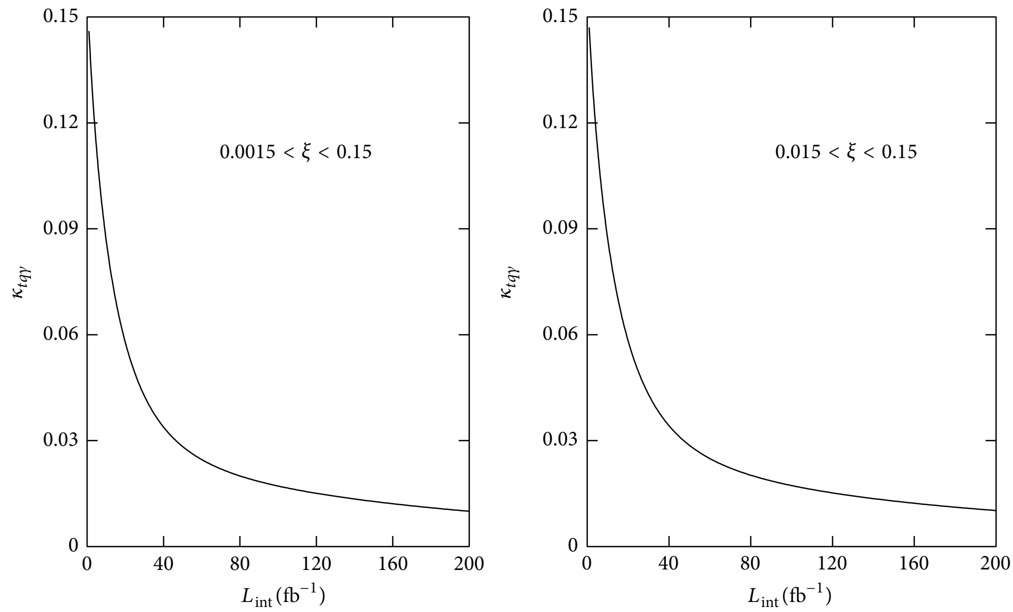

Figure 9: 95% C.L. sensitivity bounds for $\kappa_{tq\gamma}$ as a function of integrated LHC luminosity for two forward detector acceptances: $0.0015 < \xi < 0.15$ and $0.015 < \xi < 0.15$. We impose the following cuts: $p_t > 500$ GeV and $|\eta| < 2.5$.

and photon-proton collider with this property. The process $pp \to p\gamma p \to pWbX$ provides fewer backgrounds than the pure DIS process due to one of the incoming protons being intact after the collision. The detection of the intact protons in forward detectors makes it possible to determine the momentum of the quasireal photons. This situation may be useful in determining the kinematics of the process. Moreover, anomalous $tq\gamma$ couplings might also be uniquely revealed in single top photoproduction [30].

In these motivations, we have analysed the potential of the $pp \to p\gamma p \to pWbX$ at the LHC to probe anomalous $tq\gamma$ couplings for four forward detector acceptances $0.0015 < \xi < 0.5$, $0.0015 < \xi < 0.15$, $0.015 < \xi < 0.15$, and $0.1 < \xi < 0.5$. We determined that this photon-induced process has an important potential to examine anomalous $tq\gamma$ couplings. We have investigated the sensitivity bounds for $p_t > 30$ GeV and $p_t > 500$ GeV regions. The sensitivity bounds on $tq\gamma$ coupling are better than the current experimental results even at luminosity value of $1\,\text{fb}^{-1}$. For this luminosity value, bounds on $tq\gamma$ coupling can be improved 18 times with respect to present experimental data as seen from Figure 6.

On the other hand, we show that obtained results improve the sensitivity bounds by up to a factor of 116 for $0.0015 < \xi < 0.5$ with respect to current experimental data as seen from Figure 6. Furthermore, for $p_t > 500$ GeV, the results improve the sensitivity bounds on $tq\gamma$ couplings by up to a factor of 38 for $0.0015 < \xi < 0.5$. These high p_t cut regions can give extra opportunities to search for new physics with very low backgrounds. As a result, forward detectors provide an enhancement of the physics studied at the LHC.

Appendix

With the total polarization summed amplitude squared which consists of SM, new physics and interference parts have been obtained in functions of the Mandelstam invariants $\hat{s}$, $\hat{t}$, and $\hat{u}$ as follows:

$$|M_1|^2 = -\frac{g_e^2 g_w^2 V_{bq}^2 e_u^2}{m_w^2 s}\left(m_w^4 - \left(\hat{s} - \hat{t} + \hat{u}\right) m_w^2 + \left(\hat{s} - m_b^2\right)\hat{u}\right),$$

$$\begin{aligned}|M_2|^2 = {}& \frac{g_e^2 g_w^2 V_{bq}^2 e_b^2}{m_w^2\left(\hat{t} - m_b^2\right)^2} \\ & \times \left(-2\hat{t} m_b^4 + \left(5m_w^4 + \left(\hat{s} - 5\hat{t} - \hat{u}\right) m_w^2 + \hat{t}\left(2\hat{s} + 3\hat{u}\right)\right)\right. \\ & \left. \times m_b^2 + \hat{t}\left(-m_w^4 + \left(-\hat{s} + \hat{t} + \hat{u}\right) m_w^2 - \hat{t}\hat{u}\right)\right),\end{aligned}$$

$$\begin{aligned}|M_3|^2 = {}& \frac{g_e^2 g_w^2 V_{bq}^2}{4m_w^4\left(\hat{u} - m_w^2\right)^2} \\ & \times \left(\left(m_w^2 - \hat{u}\right)\left(3m_w^2 - \hat{u}\right)\left(m_b^2 + m_w^2 - \hat{t} - \hat{u}\right)\left(\hat{u} - \hat{t}\right)\right. \\ & + s\left(-3m_w^6 + \left(3\hat{s} - 14\hat{t} + 4\hat{u}\right) m_w^4\right. \\ & - \hat{u}\left(4\left(\hat{s} + \hat{t}\right) + \hat{u}\right) m_w^2 + \left(\hat{s} + 2\hat{t}\right)\hat{u}^2 \\ & \left.\left. + m_b^2\left(11m_w^2 - 3\hat{u}\right)\left(m_w^2 + \hat{u}\right)\right)\right),\end{aligned}$$

$$
\begin{aligned}
\left|M_4\right|^2 ={}& \frac{g_e^2 g_w^2 \kappa_{tq\gamma}^2 e_t^2 V_{tb}^2}{m_w^2 \Lambda^2 \left(\left(\hat{s}-m_t^2\right)^2+\Gamma_t^2 m_t^2\right)} \\
&\times \hat{s}\left(\left(-m_w^4+\left(\hat{s}-\hat{t}+\hat{u}\right) m_w^2+\left(m_b^2-\hat{s}\right) \hat{u}\right) m_t^2\right. \\
&\left.+\hat{s}\left(-m_w^4+\left(\hat{s}+\hat{t}-\hat{u}\right) m_w^2+\left(m_b^2-\hat{s}\right) \hat{t}\right)\right), \\
2 \operatorname{Re}\left(M_1^{\dagger} M_2\right) ={}& \frac{g_e^2 g_w^2 V_{bq}^2 e_u e_b}{m_w^2 \hat{s}\left(\hat{t}-m_b^2\right)} \\
&\times\left(\left(\hat{s}-3 \hat{t}-\hat{u}\right) m_b^4\right. \\
&+\left(4 m_w^4+\left(\hat{s}-\hat{t}+\hat{u}\right) m_w^2-2 \hat{s}^2\right. \\
&\left.+\hat{u}^2+4 \hat{s} \hat{t}+\hat{s} \hat{u}+3 \hat{t} \hat{u}\right) \\
&\times m_b^2-\left(m_w^2-\hat{s}-\hat{t}\right)\left(\hat{s}-\hat{t}\right)^2 \\
&-\left(\hat{s}+\hat{t}\right) \hat{u}^2 \\
&\left.+\left(-4 m_w^4+\left(\hat{s}+\hat{t}\right) m_w^2-2 \hat{s} \hat{t}\right) \hat{u}\right), \\
2 \operatorname{Re}\left(M_1^{\dagger} M_3\right) ={}& \frac{g_e^2 g_w^2 V_{bq}^2 e_u}{4 m_w^4 \hat{s}\left(m_w^2-\hat{u}\right)} \\
&\times\left(2\left(\hat{s}+4 \hat{t}-4 \hat{u}\right) m_w^6\right. \\
&+\left(\hat{s}^2+13 \hat{t} \hat{s}-7 \hat{u} \hat{s}-12 \hat{t}^2+12 \hat{u}^2\right) \\
&\times m_w^4+\left(-3 \hat{s}^3+\left(\hat{u}-6 \hat{t}\right) \hat{s}^2\right. \\
&+\left(-3 \hat{t}^2-3 \hat{u} \hat{t}+2 \hat{u}^2\right) \hat{s} \\
&\left.+4\left(\hat{t}-\hat{u}\right)\left(\hat{t}+\hat{u}\right)^2\right) m_w^2 \\
&+\hat{s} \hat{u}\left(\hat{s}+\hat{t}-\hat{u}\right)\left(\hat{s}+\hat{t}+\hat{u}\right) \\
&+m_b^2\left(-4\left(\hat{s}-2 \hat{t}+2 \hat{u}\right) m_w^4\right. \\
&+\left(7 \hat{s}^2+5 \hat{t} \hat{s}-3 \hat{u} \hat{s}-4 \hat{t}^2+4 \hat{u}^2\right) \\
&\left.\left.\times m_w^2+\hat{s} \hat{u}\left(-\hat{s}-3 \hat{t}+\hat{u}\right)\right)\right), \\
2 \operatorname{Re}\left(M_1^{\dagger} M_4\right) ={}& \frac{m_t e_u g_e^2 g_w^2 \kappa_{tq\gamma} e_t V_{bq} V_{tb}\left(m_t^2-\hat{s}\right)}{\Lambda m_w^2\left(\left(\hat{s}-m_t^2\right)^2+\Gamma_t^2 m_t^2\right)} \\
&\times\left(-3 m_w^4+\left(3 \hat{s}-\hat{t}+\hat{u}\right) m_w^2\right. \\
&\left.+\left(m_b^2-\hat{s}\right)\left(\hat{t}+2 \hat{u}\right)\right), \\
2 \operatorname{Re}\left(M_2^{\dagger} M_3\right) ={}& \frac{g_e^2 g_w^2 V_{bq}^2 e_b}{4 m_w^4\left(\hat{u}-m_w^2\right)\left(\hat{t}-m_b^2\right)} \\
&\times\left(2\left(4 \hat{s}+\hat{t}-4 \hat{u}\right) m_w^6\right. \\
&+\left(-12 \hat{s}^2+13 \hat{t} \hat{s}+\left(\hat{t}-4 \hat{u}\right)\left(\hat{t}-3 \hat{u}\right)\right) \\
&\times m_w^4 \\
&+\left(4 \hat{s}^3+\left(4 \hat{u}-3 \hat{t}\right) \hat{s}^2\right. \\
&-\left(6 \hat{t}^2+3 u t+4 u^2\right) s \\
&\left.-3 t^3-4 u^3+2 t u^2+t^2 u\right) m_w^2 \\
&+t u\left(s+t-u\right)\left(s+t+u\right)+m_b^2 \\
&\times\left(6 m_w^6-\left(21 \hat{s}+\hat{t}+9 \hat{u}\right) m_w^4\right. \\
&+\left(-5 \hat{s}^2+13 \hat{t} \hat{s}+3 \hat{u} \hat{s}+8 \hat{t}^2+6 \hat{u}^2\right) \\
&\times m_w^2 \\
&\left.+\hat{u}\left(-\hat{s}^2-3 \hat{t} \hat{s}-4 \hat{t}^2+\hat{u}^2+\hat{t} \hat{u}\right)\right) \\
&+m_b^4\left(4 m_w^4-\left(3 \hat{s}+5\left(\hat{t}+\hat{u}\right)\right) m_w^2\right. \\
&\left.\left.+\left(\hat{s}+3 \hat{t}-\hat{u}\right) \hat{u}\right)\right), \\
2 \operatorname{Re}\left(M_2^{\dagger} M_4\right) ={}& \frac{m_t e_b g_e^2 g_w^2 \kappa_{tq\gamma} e_t V_{bq} V_{tb}}{\Lambda m_w^2\left(\hat{t}-m_b^2\right)\left(\left(\hat{s}-m_t^2\right)^2+\Gamma_t^2 m_t^2\right)} \\
&\times\left(\left(m_t^2-\hat{s}\right)\right. \\
&\times\left(\left(\hat{s}-\hat{u}\right) m_b^4\right. \\
&+\left(m_w^4+\left(3 \hat{s}+\hat{t}-\hat{u}\right) m_w^2\right. \\
&\left.-2 \hat{s}^2+\hat{u}^2+\hat{s} \hat{u}\right) m_b^2 \\
&+\left(m_w^2-\hat{s}\right) \hat{u}^2+\left(m_w^2-\hat{s}\right)^2 s \\
&\left.-m_w^2\left(m_w^2-\hat{s}+\hat{t}\right) \hat{u}\right) \\
&\left.+4 \Gamma_t m_t\left(m_b^2+m_w^2-\hat{s}\right) \epsilon^{p_1 p_2 p_3 p_4}\right), \\
2 \operatorname{Re}\left(M_3^{\dagger} M_4\right) ={}& \frac{m_t g_e^2 g_w^2 \kappa_{tq\gamma} e_t V_{bq} V_{tb}}{2 \Lambda m_w^2\left(\hat{u}-m_w^2\right)\left(\left(\hat{s}-m_t^2\right)^2+\Gamma_t^2 m_t^2\right)} \\
&\times\left(\left(m_t^2-\hat{s}\right)\right. \\
&\times \hat{s}\left(-m_w^4+\left(\hat{s}-8 \hat{t}+\hat{u}\right) m_w^2\right. \\
&\left.-\hat{s} \hat{u}+m_b^2\left(7 m_w^2+\hat{u}\right)\right) \\
&+\left(m_w^2-\hat{u}\right) \\
&\times\left(4 \Gamma_t m_t \epsilon^{p_1 p_2 p_3 p_4}-\left(m_t^2-\hat{s}\right)\right. \\
&\left.\left.\times\left(m_b^2+m_w^2-\hat{t}-\hat{u}\right)\left(\hat{t}-\hat{u}\right)\right)\right),
\end{aligned}
\tag{A.1}
$$

where g_e and g_w are the electromagnetic and weak coupling constants, m_b is the b quark mass, and m_w is the W boson mass. p_1, p_2, p_3, and p_4 are the momentums of the photon, incoming quark, W boson, and b quark, respectively. V_{bq} and V_{tb} are the corresponding CKM matrix elements. $e_u(e_b)$ is the electric charge of the $u(b)$ quark. Also, Γ_t is the total decay width of the top quark. We have neglected the mass of the incoming quarks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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