Hindawi Publishing Corporation
Advances in High Energy Physics
Volume 2015, Article ID 590397, 6 pages
http://dx.doi.org/10.1155/2015/590397

*Research Article*

# Search for the Anomalous $tq\gamma$ and $tqH$ Couplings in $\gamma p$ Collision at the LHC

**B. Şahin**

*Department of Physics, Ankara University, Tandogan, 06100 Ankara, Turkey*

Correspondence should be addressed to B. Şahin; banusahin@ankara.edu.tr

Received 28 May 2015; Revised 4 September 2015; Accepted 13 September 2015

Academic Editor: Luca Stanco



We have investigated the constraints on the anomalous $tq\gamma$ and $tqH$ $(q = u, c)$ couplings through the photoproduction processes $pp \to p\gamma p \to pt\gamma X \to pb\ell^+\nu_\ell\gamma X$ and $pp \to p\gamma p \to ptHX \to pb\ell^+\nu_\ell b\bar{b}X$ at the LHC. We have obtained 95% confidence level bounds on the anomalous couplings by considering various values of detector acceptances and integrated luminosities. Improved constraints on the $tq\gamma$ coupling have been obtained compared to current bounds.

## 1. Introduction

Due to its large mass top quark might play a crucial role in electroweak gauge symmetry breaking. However, top quark couplings are expected to be more sensitive to new physics than other particles [1, 2]. Various properties of the top quark have been studied and measured at Tevatron and LHC experiments. A large part of these studies is about new physics effects on the top quark couplings. Studying top quark couplings will be important to test the Standard Model (SM) and deviations of the couplings from the SM expectations would suggest new physics effects. The anomalous top quark interactions can be investigated via Flavour Changing Neutral Currents (FCNC). These couplings are severely suppressed in top quark sector at tree level in the SM framework by GIM mechanism [3, 4]. As an example, $t \to q\gamma$ $(q = u, c)$ FCNC decay can not be seen at the tree level in the SM. The SM diagrams of this top decay occur at one loop level [5]. Flavour changing top quark interactions can appear in the models beyond the SM. Top quark FCNC $tqg$, $tq\gamma$ and $tqH$ ($q = u$ or $c$ quarks) couplings are investigated in various new physics models [4–11].

In order to examine model independent deviations from the SM predictions, effective Lagrangian approach can be used. Effective Lagrangian describing the top quark FCNC interactions with photon and Higgs boson can be written as follows [5, 12]:

$$\begin{aligned} -L_{\text{eff.}} = {} & e\kappa_{tq\gamma}\bar{q}\left(\kappa^{v}_{tq\gamma} + \kappa^{a}_{tq\gamma}\gamma_5\right)\frac{i\sigma_{\mu\nu}q^{\nu}}{m_t}tA^{\mu} \\ & + \frac{g}{2\sqrt{2}}g_{tqH}\bar{q}\left(g^{v}_{tqH} + g^{a}_{tqH}\gamma_5\right)tH + \text{h.c.} \end{aligned} \quad (1)$$

Here $\sigma_{\mu\nu} = [\gamma_\mu, \gamma_\nu]/2$ and $q^\nu$ is the photon momentum. The parameters $\kappa_{tq\gamma}$, $g_{tqH}$ define the anomalous coupling constants which are real and positive and they are normalized as $|\kappa^{v}_{tq\gamma}|^2 + |\kappa^{a}_{tq\gamma}|^2 = 1$, $|g^{v}_{tqH}|^2 + |g^{a}_{tqH}|^2 = 1$.

Experimental limit on the branching ratio at 95% confidence level for the decay $t \to q\gamma$ has been given by CDF collaboration as $\text{BR}(t \to q\gamma) < 3.2\%$ [13]. ZEUS collaboration set upper limit on the anomalous FCNC $tq\gamma$ coupling. This limit has been found to be $\kappa_{tu\gamma} < 0.12$ at 95% CL [14]. CMS experiment at the LHC has placed the most stringent experimental upper bounds on the top quark FCNC branching ratios at 95% CL. These limits are $\text{BR}(t \to u\gamma) < 0.0161\%$ and $\text{BR}(t \to c\gamma) < 0.182\%$ [15, 16].

The discovery of the Higgs boson in 2012 at the LHC provides opportunity of searching Higgs boson couplings. Anomalous top decay to $u$ or $c$ quark and a Higgs boson is investigated at the LHC. The ATLAS [17] and CMS [12] collaborations have searched $t \to qH$ decay in $t\bar{t}$ events.

95% CL upper limits on the FCNC branching ratios have been obtained by ATLAS and CMS collaborations. These branching ratios are 0.79% and 0.56%, respectively.

The partial decay widths for FCNC top quark decays are given by

$$\Gamma\left(t \longrightarrow q\gamma\right) = \frac{2\alpha}{9}\kappa_{tq\gamma}^{2} m_t$$
$$\Gamma\left(t \longrightarrow qH\right) = \frac{\alpha}{32 s_W^2} g_{tqH}^{2} m_t \left[1 - \frac{m_H^2}{m_t^2}\right]^2. \qquad (2)$$

Branching ratios of the anomalous decays $t \rightarrow q\gamma$ and $t \rightarrow qH$ can be calculated by the following equations:

$$\mathrm{BR}\left(t \longrightarrow q\gamma\right) = \frac{\Gamma\left(t \longrightarrow q\gamma\right)}{\Gamma_{\text{tot.}}},$$
$$\mathrm{BR}\left(t \longrightarrow qH\right) = \frac{\Gamma\left(t \longrightarrow qH\right)}{\Gamma_{\text{tot.}}}. \qquad (3)$$

Here, the top quark full width is taken to be $\Gamma_{\text{tot.}} \approx 2$ GeV [18]. The corresponding branching ratios are given by

$$\mathrm{BR}\left(t \longrightarrow q\gamma\right) = 0.151\kappa_{tq\gamma}^{2},$$
$$\mathrm{BR}\left(t \longrightarrow qH\right) = 2.125 \times 10^{-2} g_{tqH}^{2}. \qquad (4)$$

Using (4) and experimental limits on the branching ratios we can obtain the experimental upper limits on the anomalous couplings $\kappa_{tq\gamma}$ and $g_{tqH}$.

In this work, we have analyzed the anomalous $tq\gamma$ and $tqH$ FCNC couplings for the processes $pp \rightarrow p\gamma p \rightarrow pt\gamma X \rightarrow pb\ell^{+}\nu_{\ell}\gamma X$ and $pp \rightarrow p\gamma p \rightarrow ptHX \rightarrow pb\ell^{+}\nu_{\ell}b\bar{b}X$ in $\gamma p$ collision at the LHC. These reactions are probable via elastic photon emission from one of the incoming protons and subprocesses $\gamma q \rightarrow t\gamma \rightarrow b\ell^{+}\nu_{\ell}\gamma$ and $\gamma q \rightarrow tH \rightarrow b\ell^{+}\nu_{\ell}b\bar{b}$ can occur at the LHC (Figures 1 and 2). We use the equivalent photon approximation (EPA) [19–21] for elastic photon emission from the incoming proton. Emitted photons have low virtuality and it is a good approximation to suppose that they are on mass-shell. These photons are called quasireal. Intact proton which emits a quasireal photon is scattered with a small angle from the beam pipe. At the LHC, ATLAS and CMS Collaborations have a program with very forward detectors which can detect intact scattered protons. These forward detectors are placed away from the interaction point and they can detect intact protons with a small momentum fraction loss [22, 23]. Momentum fraction loss of the proton is given by the formula $\xi = (|\vec{p}| - |\vec{p}'|)/|\vec{p}|$, where $\vec{p}$ is the momentum of the incoming proton and $\vec{p}'$ is the momentum of the intact scattered proton. This fraction can be written approximately as $\xi = E_\gamma/E$ at high energies. Here $E_\gamma$, $E$ are the energies of the photon and the photon emitting proton, respectively. Forward detectors have a capability to detect intact outgoing protons in the interval $\xi_{\min} < \xi < \xi_{\max}$. This interval is called the acceptance of the forward detectors.

There are several LHC machine set-ups at which ALFA (Absolute Luminosity For ATLAS) and AFP (ATLAS Forward Proton) detectors could take data. They are typically

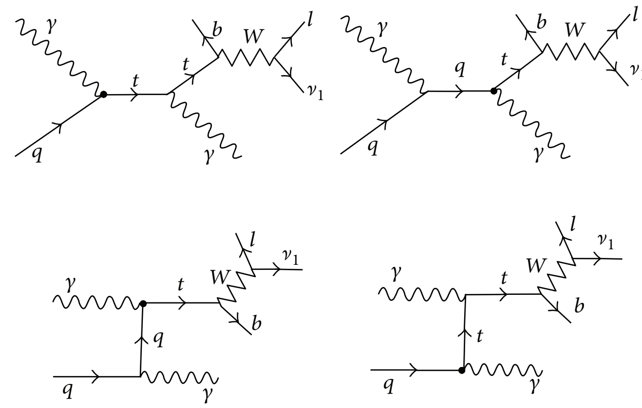

Figure 1: Tree level Feynman diagrams for the process $\gamma q \rightarrow t\gamma \rightarrow b\ell^{+}\nu_{\ell}\gamma$.

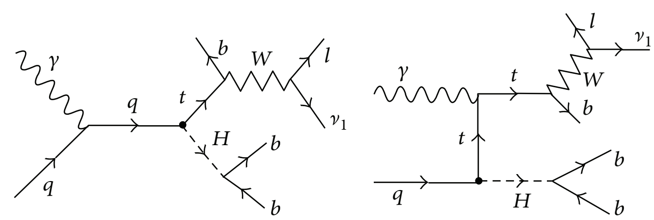

Figure 2: Tree level Feynman diagrams for the process $\gamma q \rightarrow tH \rightarrow b\ell^{+}\nu_{\ell}b\bar{b}$.

described by the value of the betatron function at the interaction point, $\beta^*$ [24]. Various values of $\beta^*$ can be considered for the different settings. The low $\beta^*$ value is a common setting for the LHC high luminosity runs. The expected acceptance regions of the ATLAS and CMS-TOTEM forward detectors can be considered as $0.015 < \xi < 0.15$ and $0.03 < \xi < 0.2$ for the low $\beta^*$ optics [25].

Photon-induced processes have been observed via the process $p\bar{p} \rightarrow \gamma\gamma p\bar{p} \rightarrow \ell^{+}\ell^{-}p\bar{p}$ in $p\bar{p}$ collisions [26–28]. Moreover, the process $ep \rightarrow eXp$ in $ep$ collisions [29–34] and several two-photon reactions have been investigated in $pp$ collisions [35–38]. These studies raise interest in the photon-induced reactions as photon-photon and photon-proton collisions.

## 2. Cross Sections and Sensitivity to Anomalous Couplings

Photon-induced reactions can be investigated in the framework of the EPA. The equivalent photon spectrum of $E_\gamma$ energy and $Q^2$ virtuality is given by [19–21]

$$\frac{dN_\gamma}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}\left[\left(1 - \frac{E_\gamma}{E}\right)\left(1 - \frac{Q_{\min}^2}{Q^2}\right)F_E + \frac{E_\gamma^2}{2E^2}F_M\right]. \qquad (5)$$

Here

$$
\begin{aligned}
Q_{\min}^2 &= \frac{m_p^2 E_\gamma^2}{E\left(E-E_\gamma\right)}, \\
F_E &= \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}, \\
G_E^2 &= \frac{G_M^2}{\mu_p^2} = \left(1+\frac{Q^2}{Q_0^2}\right)^{-4}, \\
F_M &= G_M^2, \\
Q_0^2 &= 0.71\,\mathrm{GeV}^2.
\end{aligned}
\tag{6}
$$

In (5), $E$ is the incoming proton beam energy and $m_p$ is mass of the proton. The magnetic moment of the proton is $\mu_p^2 = 7.78$.

The total cross sections for the processes $pp \rightarrow p\gamma p \rightarrow pt\gamma X \rightarrow pb\ell^+\nu_\ell\gamma X$ and $pp \rightarrow p\gamma p \rightarrow ptHX \rightarrow pb\ell^+\nu_\ell b\bar{b}X$ can be found by integrating the subprocesses over the quark and photon distributions:

$$
\begin{aligned}
&\sigma\left(pp \longrightarrow p\gamma p \longrightarrow pt\gamma X \longrightarrow pb\ell^+\nu_\ell\gamma X\right) \\
&\quad = \sum_{q=u,c}\int_{\xi_{1\min}}^{\xi_{1\max}} dx_1 \int_0^1 dx_2 \left(\frac{dN_\gamma}{dx_1}\right)\left(\frac{dN_q}{dx_2}\right) \\
&\quad\cdot \left[\hat{\sigma}_{\gamma q \to t\gamma \to b\ell^+\nu_\ell\gamma}(\hat{s})\right] \\
&\sigma\left(pp \longrightarrow p\gamma p \longrightarrow ptHX \longrightarrow pb\ell^+\nu_\ell b\bar{b}X\right) \\
&\quad = \sum_{q=u,c}\int_{\xi_{1\min}}^{\xi_{1\max}} dx_1 \int_0^1 dx_2 \left(\frac{dN_\gamma}{dx_1}\right)\left(\frac{dN_q}{dx_2}\right) \\
&\quad\cdot \left[\hat{\sigma}_{\gamma q \to tH \to b\ell^+\nu_\ell b\bar{b}}(\hat{s})\right].
\end{aligned}
\tag{7}
$$

In these equations, $x_1 = E_\gamma/E$ and $x_2$ is the momentum fraction of the proton's momentum carried by the quark ($u$ or $c$). $dN_q/dx_2$ is the $u$ or $c$ quark distribution function. In our calculations we have used Martin, Stirling, Thorne, and Watt distribution functions [39].

In the total cross section calculations, two different forward detector acceptance ranges have been considered: $0.015 < \xi < 0.15$ and $0.03 < \xi < 0.2$. In Figures 3 and 4, we have plotted the integrated total cross sections of the processes $pp \rightarrow p\gamma p \rightarrow pt\gamma X \rightarrow pb\ell^+\nu_\ell\gamma X$ and $pp \rightarrow p\gamma p \rightarrow ptHX \rightarrow pb\ell^+\nu_\ell b\bar{b}X$ as a function of anomalous couplings $\kappa_{tq\gamma}$, $g_{tqH}$, respectively. Because the total cross sections are very close to each other for $0.015 < \xi < 0.15$ and $0.03 < \xi < 0.2$, we have plotted one of them. We observe from these figures that the total cross sections increase with increasing anomalous coupling. We also see from the figures that sensitivity of the cross section to anomalous coupling $g_{tqH}$ is comparably weak.

We have considered all SM backgrounds in the sensitivity calculations of the anomalous couplings $\kappa_{tq\gamma}$ and $g_{tqH}$. SM backgrounds to our processes are the following: $\gamma q \rightarrow b\ell^+\nu_\ell\gamma$ and $\gamma q \rightarrow b\ell^+\nu_\ell H$ ($H \rightarrow b\bar{b}$), where $q = u, c$ quarks and $\ell = e, \mu$. Total cross sections of the SM backgrounds were evaluated using CalcHEP [40]. The integrated cross section of the background process $\gamma q \rightarrow b\ell^+\nu_\ell\gamma$ is $\sigma = 2.165\times 10^{-5}$ pb for the acceptance region $0.015 < \xi < 0.15$. We can obtain the number of events for $L = 30\,\mathrm{fb}^{-1}$, $N_{\mathrm{SM}} = 0.7\times 0.6\times 2.165\times 10^{-5}\times 30000 = 0.27$. As can be seen from the number of events calculation, this cross section gives approximately 0 events for $L = 30\,\mathrm{fb}^{-1}$ and 2 events for $L = 200\,\mathrm{fb}^{-1}$.

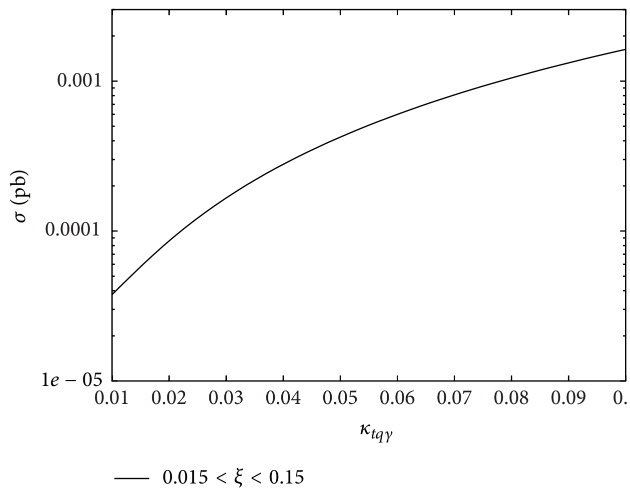


FIGURE 3: Total cross section of $pp \rightarrow p\gamma p \rightarrow pt\gamma X \rightarrow pb\ell^+\nu_\ell\gamma X$ as a function of anomalous coupling $\kappa_{tq\gamma}$. Forward detector acceptance is taken to be $0.015 < \xi < 0.15$.

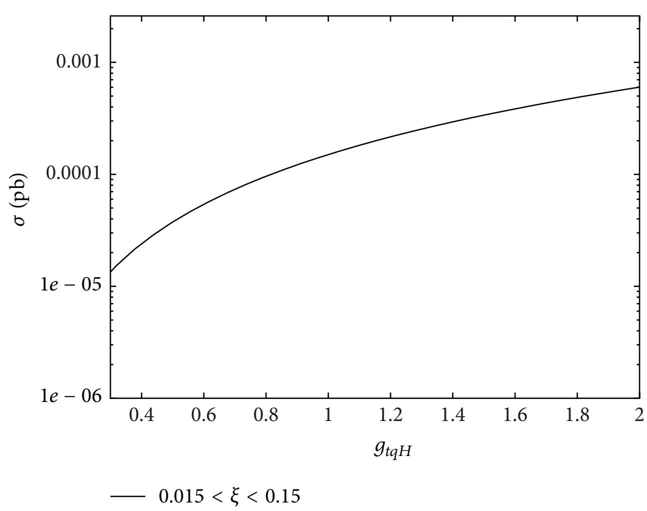


FIGURE 4: Total cross section of $pp \rightarrow p\gamma p \rightarrow ptHX \rightarrow pb\ell^+\nu_\ell b\bar{b}X$ as a function of anomalous coupling $g_{tqH}$. Forward detector acceptance is taken to be $0.015 < \xi < 0.15$.

We see that the number of events of the SM backgrounds is very small. However, if the number of events is bigger than 1, it can not be ignored. The cross sections of these background processes are proportional to the square of CKM matrix elements. $\gamma u \rightarrow b\ell^+\nu_\ell\gamma$ subprocess contains $Wub$ and $\gamma c \rightarrow b\ell^+\nu_\ell\gamma$ contains $Wcb$ vertex. Because the CKM matrix

Table 1: 95% CL bounds on the anomalous coupling $\kappa_{tq\gamma}$ 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$^{-1}$) | $0.015 < \xi < 0.15$ | $0.03 < \xi < 0.2$ |
|---|---|---|
| 30 | 0.038 | 0.049 |
| 50 | 0.029 | 0.038 |
| 100 | 0.026 | 0.033 |
| 200 | 0.021 | 0.027 |

Table 2: 95% CL bounds on the anomalous coupling $g_{tqH}$ 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$^{-1}$) | $0.015 < \xi < 0.15$ | $0.03 < \xi < 0.2$ |
|---|---|---|
| 30 | 1.259 | 1.495 |
| 50 | 0.975 | 1.158 |
| 100 | 0.689 | 0.819 |
| 200 | 0.487 | 0.579 |

elements are off-diagonal for these vertices, cross sections of the SM backgrounds are expected to be small.

Integrated cross section of the process $\gamma q \rightarrow b\ell^+\nu_\ell H$ ($H \rightarrow b\bar{b}$) is $\sigma = 1.093 \times 10^{-8}$ pb at the region $0.015 < \xi < 0.15$. This cross section gives 0 events for $L = 30$–$200\,\mathrm{fb}^{-1}$. Above discussions which are related to CKM matrix elements are valid also here.

Since the SM contribution to the processes is absent, we use Poisson distribution as a statistical analysis method. The expected number of events has been calculated from the formula $N = S \times E \times \sigma \times L_{\mathrm{int}}$. Here, $L_{\mathrm{int}}$ is the integrated luminosity, $E$ is the jet reconstruction efficiency, and $S$ is the survival probability factor. We have taken into account survival probability factor of $S = 0.7$ [41] and jet reconstruction efficiency of $E = 0.6$. CMS and ATLAS have central detectors with pseudorapidity coverage $|\eta| < 2.5$. Therefore, we place pseudorapidity cut of $|\eta| < 2.5$ for final state leptons and quarks.

The 95% confidence level bounds on the anomalous coupling parameters are given in Tables 1 and 2 for integrated luminosities of $L_{\mathrm{int}} = 30, 50, 100, 200\,\mathrm{fb}^{-1}$ and forward detector acceptances of $0.015 < \xi < 0.15$, $0.03 < \xi < 0.2$. We see from the tables that $0.015 < \xi < 0.15$ acceptance region provides more sensitive bounds on both $\kappa_{tq\gamma}$ and $g_{tqH}$ couplings compared to other acceptance values. On the other hand, we see that limits on the coupling $\kappa_{tq\gamma}$ are more stringent than the limits on $g_{tqH}$.

One can calculate the experimental constraints on the anomalous couplings $\kappa_{tq\gamma}$, $g_{tqH}$ by using (4) and experimental bounds on the FCNC branching ratios. We have obtained the most stringent bounds on the FCNC couplings at luminosity value of $200\,\mathrm{fb}^{-1}$ and acceptance of $0.015 < \xi < 0.15$. The CDF and CMS collaborations obtained the most stringent experimental bounds on the $\kappa_{tq\gamma}$ coupling at 95% CL. These limits are $\kappa_{tq\gamma} < 0.46$ and $\kappa_{tq\gamma} < 0.11$ [13, 15]. Our results for $0.015 < \xi < 0.15$ improve the bounds on $\kappa_{tq\gamma}$ coupling by up to a factor of 22 and 5 with respect to CDF and CMS experimental bounds.

The most stringent experimental upper bounds on the coupling $g_{tqH}$ have been obtained by ATLAS and CMS collaborations [12, 17]. Limits are $g_{tqH} < 0.61$ and $g_{tqH} < 0.52$, respectively. We see from Table 2 that our bounds for $L = 50$–$200\,\mathrm{fb}^{-1}$ and $0.015 < \xi < 0.15$ are at the same order with respect to experimental bounds.

The main experimental challenge of running at high luminosity is the effect of pile-up, which can generate fake signal events within the acceptances of the proton detectors as a result of the coincidence of two or more separate interactions in the same bunch crossing [23, 42, 43]. However these backgrounds can be subtracted or suppressed by several methods: jet area method, jet vertex fraction, soft term fraction, and charged hadron subtraction. Very high luminosities at the LHC will require focusing on methods to reduce pile-up fluctuations. These methods are listed as follows: optimized calorimeter input signals, grooming, and jet areas subtraction; jet substructure is to reject fake pile-up jets. Studies are underway to mitigate pile-up effects and improve existing algorithms to maximize performance.

## 3. Conclusion

We have analysed the potential of the $pp \rightarrow p\gamma p \rightarrow pt\gamma X \rightarrow pb\ell^+\nu_\ell\gamma X$ and $pp \rightarrow p\gamma p \rightarrow ptHX \rightarrow pb\ell^+\nu_\ell b\bar{b}X$ processes at the LHC to probe anomalous $tqH$ and $tq\gamma$ couplings. Improved bounds have been obtained for the anomalous $tq\gamma$ coupling. On the other hand limits on the $tqH$ coupling are weaker with respect to $tq\gamma$ coupling in photon-proton collision at the LHC.

The LHC equipped with forward detectors gives us new opportunity to investigate high-energy photon-photon and photon-proton interactions. As regards deep inelastic scattering reactions, photon-proton interactions ensure a quite clean channel. Moreover, detection of the intact scattered protons in forward detector enables us to determine quasireal photon momenta. This case is useful for the reconstruction kinematics of the process.

## Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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