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Research Article

Search for the Anomalous Interactions of Up-Type Heavy Quarks in $\gamma\gamma$ Collision at the LHC

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We investigate the anomalous interactions of heavy up-type quark t' in a $\gamma\gamma$ collision at the LHC. We have obtained 95% confidence level (CL) limit of $t'q\gamma$ $(q = u, c)$ anomalous coupling by taking into account three forward detector acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$.

1. Introduction

The Standard Model (SM) ensures a conspicuously successful description of high energy physics at an energy scale of up to a few hundred GeV. However, the number of fermion families is arbitrary in the Standard Model (SM). The only limitation on number of fermion families comes from asymptotic freedom $N \leq 8$. We should use at least three fermion families to obtain CP violation [1] in the SM. CP violation could explain the matter-antimatter asymmetry in the universe. The SM with three families is not enough to show the reel magnitude for matter-antimatter asymmetry of universe. However, this problem can be solved when the number of family reaches four [2]. Also, the existence of three or four families is equally consistent with the updated electroweak precision data [3, 4]. The possible discovery of the fourth SM family may help to respond to some unanswered questions about electroweak symmetry breaking [5–7], fermion's mass and mixing pattern [8–10], and flavor structure of the SM [11–14].

Higgs boson is a theoretical particle that is suggested by the SM. Many experiments were conducted so far to detect Higgs boson. A boson consistent with this boson was a detected in 2012, but it may take quite time to demonstrate certainly whether this particle is indeed a Higgs boson. If the lately surveyed 125 GeV boson is Higgs boson of the SM [15, 16], the presence of the fourth family would be disfavoured [17–19]. Besides, a theory with extended Higgs sector beyond the SM [20] can still include a fourth fermion family even though the 125 GeV boson is one of the forecasted extended Higgs bosons. Moreover, the other models estimate the presence of a heavy quark as a partner to the top quark [21, 22].

Current bounds on the masses of the fourth SM fermion families are given as follows: $m_{t'} > 670$ GeV [23], $m_{b'} > 611$ GeV [24], $m_{l'} > 100.8$ GeV, $m_{\nu'} > 90.3(80.5)$ GeV for Dirac (Majorana) neutrinos [25]. When we analyze our results we have taken into account LHC limits in $\sqrt{s} = 7$ TeV. For this purpose, we have assumed t' mass to be greater than its current experimental limits. The fourth SM quarks would be produced abundantly in pairs at the LHC via the strong interaction for masses below O(1 TeV) [26–29], with fairly large cross sections. The exact designation of their properties can ensure important advantage in the determination of new physics which is established upon high energy scales. Moreover, we can expect a crucial addition from anomalous interactions for production of fourth family quarks. These interactions have been investigated at lepton colliders [30, 31], γe colliders [32], ep colliders [10, 33–35], and hadron colliders [8, 28, 36–45].

The LHC has high energetic proton-proton collisions with high luminosity. It provides high statistics data. We expect that this collider will answer many open questions in particle physics. Research of exclusive production of proton-proton interactions opens a new field of surveying high energy photon-induced reactions such as photon-photon and photon-proton interactions. ATLAS and CMS Collaborations established a program of forward physics with new detectors located in a region almost 100 m–400 m from the central detectors. These detectors are called very forward detectors. They can detect intact protons which are scattered after the collisions. Very forward detectors can label intact protons with some momentum fraction loss given the formula $\xi = (|\vec{p}| - |\vec{p}\,'|)/|\vec{p}|$. Here, $\vec{p}\,'$ is the momentum of intact scattered proton after the collision and $\vec{p}$ is the momentum of incoming proton. ATLAS Forward Physics Collaboration (AFP) proposed an acceptance of $0.0015 < \xi < 0.15$ for the forward detectors [46]. Two types of measurements will be planned to examine with high precision using the AFP [47–49]: first, exploratory physics (anomalous couplings between γ and W or Z bosons, exclusive production, etc.) and second, standard QCD physics (double Pomeron exchange, exclusive production in the jet channel, single diffraction, $\gamma\gamma$ physics, etc.). These studies will develop the HERA and Tevatron measurements to the LHC kinematical region. Also, CMS-TOTEM forward detector scenario has acceptance regions $0.1 < \xi < 0.5$ and $0.0015 < \xi < 0.5$ [50, 51]. The TOTEM experiment at the LHC is concentrated on the studies of the total proton-proton cross-section, the elastic pp scattering, and all classes of diffractive phenomena. Detectors housed in Roman Pots which can be moved close to the outgoing proton beams allow to trigger on elastic and diffractive protons and to determine their parameters like the momentum loss and the transverse momentum transfer. Moreover, charged particle detectors in the forward domains can detect nearly all inelastic events. Together with the CMS detector, a large solid angle is covered enabling precise studies [52–54]. The forward detectors of ATLAS and CMS were not built in the first phase of the LHC. However, the CMS forward detectors were commissioned in 2009. The first measurement of the forward energy flow has been carried out and forward jets at $|\eta| > 3$ have been analyzed for the first time at Hadron Colliders [55]. Also, two photon reactions $pp \to p\gamma\gamma p \to p\mu^-\mu^+ p$, $pp \to p\gamma\gamma p \to pe^-e^+ p$ were examined with the help of forward detectors by the CMS Collaboration in 2012 [56, 57]. On the other hand, AFP Collaboration has not yet installed the forward detectors. The forward detectors are planned to be built 210 m away from the central detectors in 2013. Additionally, 420 m additional detectors will be installed if physics motivates it later [58]. Forward detectors allow to determine high energy photon-photon process. This process occurred by two almost real photons with low virtuality emitted from protons. The proton structure does not spoil in this process due to low virtuality of photons. Therefore, intact scattered protons after the collision can be detected by the aid of the forward detectors. Searching new physics via photon-induced reactions have been studied in earlier works [59–69].

Photon-photon interaction can be explained by equivalent photon approximation [70, 71]. Emitted quasireal photons by protons with low virtuality produce an X object via $pp \to p\gamma\gamma p \to pXp$ process. The cross section of this process can be found by

$$d\sigma = \int \frac{dL^{\gamma\gamma}}{dW} d\hat{\sigma}_{\gamma\gamma\to X}(W)\, dW, \tag{1}$$

where W is the invariant mass of the two-photon system, $\hat{\sigma}_{\gamma\gamma\to X}$ is the cross section for subprocess $\gamma\gamma \to X$, and $dL^{\gamma\gamma}/dW$ is the luminosity spectrum of photon-photon collisions. $dL^{\gamma\gamma}/dW$ can be given as follows [63]:

$$\frac{dL^{\gamma\gamma}}{dW} = \int_{Q^2_{1,\min}}^{Q^2_{\max}} dQ_1^2 \int_{Q^2_{2,\min}}^{Q^2_{\max}} dQ_2^2 \times \int_{y_{\min}}^{y_{\max}} dy \frac{W}{2y} f_1\left(\frac{W^2}{4y}, Q_1^2\right) f_2\left(y, Q_2^2\right) \tag{2}$$

with

$$y_{\min} = \text{MAX}\left(\frac{W^2}{(4\xi_{\max}E, \xi_{\min}E)}\right), \qquad y_{\max} = \xi_{\max}E, \qquad Q^2_{\max} = 2\,\text{GeV}^2, \tag{3}$$

where f_1 and f_2 are functions of equivalent photon energy spectrum. The photon spectrum with energy E_γ and virtuality Q^2 is given by the following [70]:

$$f = \frac{dN}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}\left[\left(1 - \frac{E_\gamma}{E}\right)\left(1 - \frac{Q^2_{\min}}{Q^2}\right) F_E + \frac{E_\gamma^2}{2E^2} F_M\right], \tag{4}$$

where

$$Q^2_{\min} = \frac{m_p^2 E_\gamma^2}{E\left(E - E_\gamma\right)}, \qquad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2},$$
$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1 + \frac{Q^2}{Q_0^2}\right)^{-4}, \qquad F_M = G_M^2, \tag{5}$$
$$Q_0^2 = 0.71\,\text{GeV}^2.$$

The terms in the previous equations are the following: E is the energy of the proton beam which is related to the photon energy by $E_\gamma = \xi E$, m_p is the proton mass, F_M is function of the magnetic form factor, and F_E is function of the electric form factor and $\mu_p^2 = 7.78$ is the proton magnetic moment.

In this study, we have examined the anomalous interaction of up-type t' quark via the $pp \to p\gamma\gamma p \to pq\bar{q}p$ ($q = u, c$) process by considering three forward detector acceptances; $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$.

2. Anomalous Interaction of t' Quark

The fourth family t' quark can interact with the ordinary quarks q_i via SM gauge bosons ($\gamma, g, Z^0, W^{\pm}$). The lagrangian of this interaction is expressed by

$$L = -g_e Q_{t'} \overline{t'} \gamma^{\mu} t' A_{\mu} - g_s \overline{t'} T^a \gamma^{\mu} t' G^a_{\mu} - \frac{g_Z}{2} \overline{t'} \gamma^{\mu} \left(g_V - g_A \gamma^5\right) t' Z^0_{\mu} - \frac{g_e}{2\sqrt{2}\sin\theta_W} V_{t'Q_i} \overline{t'} \gamma^{\mu} \left(1-\gamma^5\right) q_i W^{\pm}_{\mu} + h.c., \quad (6)$$

where g_e is the electromagnetic coupling constant, g_s is the strong coupling constant, g_Z is the weak neutral current coupling constant, g_A and g_V are the vector and axial-vector type couplings of the neutral weak current with t' quark, T_a are the Gell-Mann matrices, and $Q_{t'}$ is the electric charge of t' quark. The vector fields $A_{\mu}, G_{\mu}, Z^0_{\mu}$, and $W^{\pm}_{\mu}$ represent photon, gluon, Z^0-boson, and $W^{\pm}$-boson, respectively. Finally, the $V_{t'Q_i}(Q_i = d, b, s, b')$ are the elements of the extended CKM mixing matrix. In [19] they found that the maximum value of the fourth generation quark mass is ~300 GeV for a Higgs boson mass of ~125 GeV, which is already in conflict with bounds from direct searches. Therefore, we have considered that t' is a heavy quark instead of fourth generation quark. The t' quark is heavier than the top quark. It is accepted as the heaviest particle, and it is couple the flavor changing neutral currents, leading to an enhancement in the resonance processes at the LHC. The interaction Lagrangian for the anomalous interactions between the t' quark, ordinary quarks u, c, t, and the gauge bosons γ, g, Z is given as follows:

$$L = \sum_{q_i=u,c,t} \frac{\kappa_{\gamma q_i}}{\Lambda} Q_{q_i} g_e \overline{t'} \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i=u,c,t} \frac{\kappa_{Z q_i}}{\Lambda} \frac{g_Z}{2} \overline{t'} \sigma_{\mu\nu} q_i Z^{\mu\nu} + \sum_{q_i=u,c,t} \frac{\kappa_{g q_i}}{\Lambda} g_s \overline{t'} \sigma_{\mu\nu} T_a q_i G^{\mu\nu}_a + h.c., \quad (7)$$

where κ_{γ}, κ_Z, and κ_g are the anomalous couplings with photon, Z boson, and gluon, respectively. Λ is new physics scale and $\sigma_{\mu\nu} = i[\gamma^{\mu}, \gamma^{\nu}]/2$. $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}_a$ are the field stress tensor of the photon, Z boson, and gluons, respectively. Jets that originate from light quarks (u, d, and s) differ from heavy quarks (c and b) in the final state at the LHC. Therefore, anomalous $\kappa_{\gamma u}$ coupling can be distinguished from $\kappa_{\gamma c}$ coupling via the process $\gamma\gamma \to q\overline{q}$, if anomalous couplings $\kappa_{\gamma c}$ are not equal to $\kappa_{\gamma c}$. It can be understood that the bound on product $\kappa_{\gamma u} \times \kappa_{\gamma c}$ through the process $\gamma\gamma \to u\overline{c}$ can be also examined. However, we consider that $\kappa_{\gamma u}$ is equal to $\kappa_{\gamma c}$ in our paper. For the fourth family leptons $l'l\gamma$ coupling was calculated in the literature for the photon-photon fusion at the LHC [72]. Also, $b'q\gamma$ coupling can be examined through the process $\gamma\gamma \to q\overline{q}(q = d, s)$. But study of the $b'd\gamma$ and $b's\gamma$ couplings is difficult for this process since d and s quarks cannot be distinguished from each other.

Using interaction Lagrangian in (7) anomalous decay widths of t' quarks can be obtained as follows:

$$\Gamma\left(t' \longrightarrow q\gamma\right) = \frac{2\kappa^2_{\gamma}}{\Lambda} \alpha_e Q^2_{q_i} m^3_{t'}, \quad (8)$$

where $m_{t'}$ is the mass of the t' quark and α_e is the electromagnetic coupling constant.

The subprocess $\gamma\gamma \to q\overline{q}$ consists of t and u channel tree-level SM diagrams. Additionally, there are two Feynman diagrams containing t' quark propagators in t and u channels. The whole polarization summed amplitude square of this process has been calculated as follows:

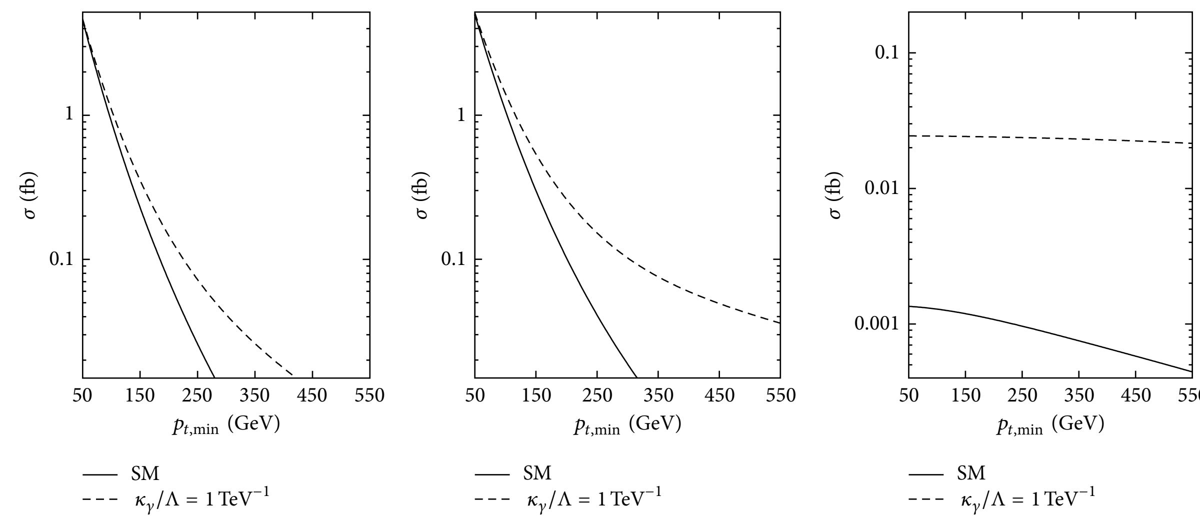
$$|M|^2 = 8 g^4_e Q^4_{q_i} \left(\frac{t}{u} + \frac{u}{t}\right) - 64 g^4_e Q^4_{q_i} \left(\frac{\kappa_{\gamma}}{\Lambda}\right)^2 \times \left(\frac{u^2}{u - m^2_{t'}} + \frac{t^2}{t - m^2_{t'}}\right) + 128 g^4_e Q^4_{q_i} \left(\frac{\kappa_{\gamma}}{\Lambda}\right)^4 \times \left[\frac{2stum^2_{t'}}{\left(u - m^2_{t'}\right)\left(t - m^2_{t'}\right)} + \left(tu + m^2_{t'} s\right) \times \left(\frac{u^2}{\left(u - m^2_{t'}\right)^2} + \frac{t^2}{\left(t - m^2_{t'}\right)^2}\right)\right], \quad (9)$$

where s, t, and u are the Mandelstam variables and we omit the mass of ordinary quark ($q_i = u, c$). We have supposed $\sqrt{s} = 14$ TeV to be center of mass energy of the proton-proton system during calculations.

The leading order background process comes from QCD-induced reactions (pomeron exchange). Pomerons emitted from incoming protons can interact with each other, and they can occur at the same final state. However, survival probability for a pomeron exchange is quite smaller than survival probability of induced photons. Therefore, pomeron background is expected to have minor effect on sensitivity bounds [73, 74].

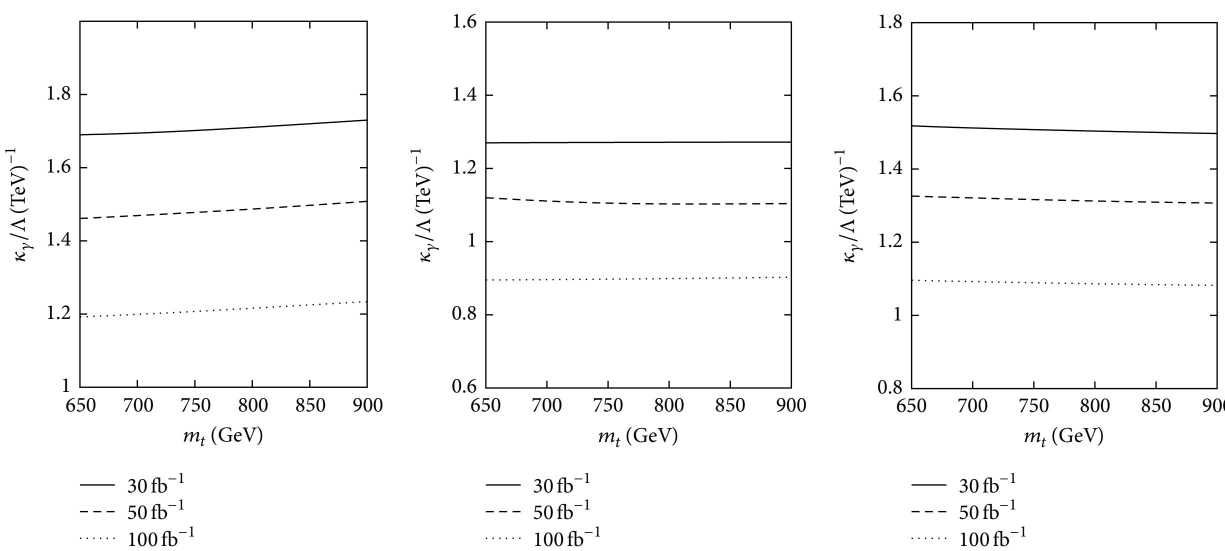
In Figure 1, we have plotted the SM and total cross sections of $pp \to pq\overline{q}p$ ($q = u, c$) process as a function $p_{t,\min}$(p_t cut) transverse momentum of final state quarks for three forward detector acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$. Here, $m_{t'}$ and κ_{γ}/Λ are taken to be 700 GeV, 1 TeV $^{-1}$, respectively. From these figures, we see that the SM and total cross sections can be distinguished from each other at large values of the p_t cut. Then, it can be understood that imposing higher values of p_t cut can reduce the SM background. These cuts allow to obtaining better sensitivity bounds.

In this motivation, we show the SM event numbers of $pp \to pq\overline{q}p$ for different values of p_t cut and luminosities in Tables 1, 2, and 3 for acceptance regions $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$, respectively. During statistical analysis we use two different techniques. In the first approach we apply cuts on the p_t of the final state quarks to suppress the SM cross section. We make the number of SM event smaller than 0.5. Then it is very appropriate to set



(a) $0.0015 < \xi < 0.15$ (b) $0.0015 < \xi < 0.5$ (c) $0.1 < \xi < 0.5$

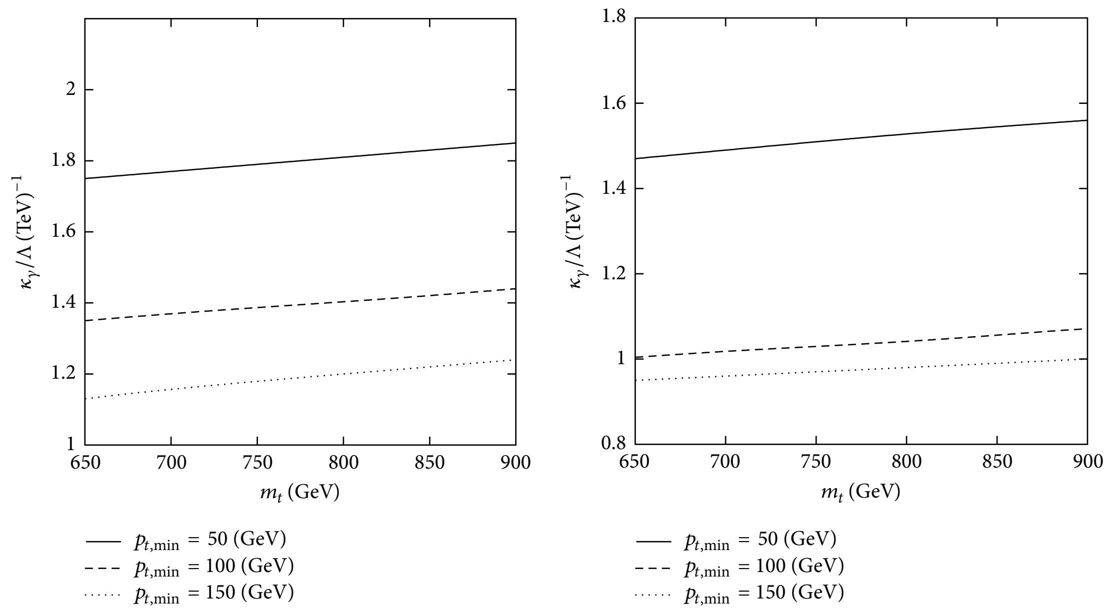
FIGURE 1: The SM and total cross sections of $pp \to pq\bar{q}p$ ($q = u, c$) process as a function transverse momentum cut ($p_{t,\min}$) on the final state quarks for three forward detector acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$. $m_{t'}$ and κ_γ/Λ is taken to be 700 GeV, $1\,\mathrm{TeV}^{-1}$, respectively.



(a) $0.0015 < \xi < 0.15$ (b) $0.0015 < \xi < 0.5$ (c) $0.1 < \xi < 0.5$

FIGURE 2: The parameter plane of $m_{t'}$ and κ_γ/Λ at 95% CL using Poisson analysis for three different luminosities: 30, 50, and $100\,\mathrm{fb}^{-1}$. In (a) and (b), we use the different p_t values for every acceptance region to obtain less than 0.5 event number of SM: (a) $p_t = 380$ GeV for acceptance region $0.0015 < \xi < 0.15$; (b) $p_t = 452$ GeV for acceptance region $0.0015 < \xi < 0.5$. In (c), we applied a p_t cut of $p_t = 50$ GeV for acceptance region $0.1 < \xi < 0.5$.

bounds on the couplings using a Poisson distribution since the number of SM events with these cuts is small enough. From our calculations, p_t cuts are obtained as 380 GeV and 452 GeV for two acceptance regions $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ in order to be less than 0.5 the number of SM event, respectively. Since the invariant mass of the final state quarks for $0.1 < \xi < 0.5$ is greater than 1400 GeV, the SM cross section is very small. Hence, it does not need a high p_t cut for $0.1 < \xi < 0.5$ acceptance region. Moreover, ATLAS and CMS have central detectors with a pseudorapidity $|\eta| < 2.5$ for the tracking system at the LHC. Therefore, for all of the calculations in this paper, we also apply $|\eta| < 2.5$ cut. The parameter plane $m_{t'}-\kappa_\gamma/\Lambda$ is plotted at 95% CL using Poisson analysis for the three different acceptances $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$ in Figure 2. In Figures 2(a) and 2(b), we use the different p_t values for every acceptance region to obtain less than 0.5 event number of SM: (a) $p_t = 380$ GeV for $0.0015 < \xi < 0.15$; (b) $p_t = 452$ GeV



(a) $0.0015 < \xi < 0.15$

(b) $0.0015 < \xi < 0.5$

Figure 3: The parameter plane of $m_{t'}$ and κ_γ/Λ for the two different acceptances: $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ at 95% CL using χ^2 analysis. Here, $p_{t,\min}$ transverse momentum cuts ($p_{t,\min}$) are taken to be 50, 100, and 150 GeV, respectively.

Table 1: The SM event numbers of $pp \rightarrow pq\bar{q}p$ process for different values of p_t transverse momentum cuts ($p_{t,\min}$) and luminosities. Here, acceptance region is taken to be $0.0015 < \xi < 0.15$.

$p_{t,\min}$ (GeV)	30 fb^{-1}	50 fb^{-1}	100 fb^{-1}
50	124.05	206.75	413.5
100	14.68	24.46	48.94
150	3.58	5.97	11.95
200	1.21	2.02	4.05
300	0.23	0.37	0.75
400	0.06	0.1	0.19

Table 2: The SM event numbers of $pp \rightarrow pq\bar{q}p$ process for different values of p_t transverse momentum cuts ($p_{t,\min}$) and luminosities. Here, acceptance region is taken to be $0.0015 < \xi < 0.5$.

$p_{t,\min}$ (GeV)	30 fb^{-1}	50 fb^{-1}	100 fb^{-1}
50	134.9	224.8	449.6
100	17.5	29.2	58.4
150	4.69	7.8	15.6
200	1.73	2.9	5.8
300	0.39	0.65	1.3
400	0.12	0.21	0.42
500	0.05	0.08	0.16

for $0.0015 < \xi < 0.5$ as mentioned above. In Figure 2(c), we applied a p_t cut of $p_t = 50$ GeV for $0.1 < \xi < 0.5$ for detection of the final state quarks in central detectors.

Table 3: The SM event numbers of $pp \rightarrow pq\bar{q}p$ process for different values of p_t transverse momentum cuts ($p_{t,\min}$) and luminosities. Here, acceptance region is taken to be $0.1 < \xi < 0.5$.

$p_{t,\min}$ (GeV)	30 fb^{-1}	50 fb^{-1}	100 fb^{-1}
50	0.037	0.06	0.12
100	0.036	0.057	0.115
150	0.034	0.05	0.1

Second analyze technique, we have used to one-parameter χ^2 analyze when the SM event number larger than 10. The χ^2 function is given as follows:

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma_{NP}}{\sigma_{SM}\delta}\right)^2, \tag{10}$$

where σ_{SM} is the cross section of SM, σ_{NP} is the cross section containing new physics effects, and $\delta = 1/\sqrt{N_{SM}}$ is the statistical error. In Figure 3, the parameter plane $m_{t'} - \kappa_\gamma/\Lambda$ is plotted at 95% CL using χ^2 analysis for the two different acceptances $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$. For the $0.1 < \xi < 0.5$ acceptance region we cannot use χ^2 analysis due to SM event number being smaller than 10 as seen from Table 3. We have found from Figure 3 that $0.0015 < \xi < 0.5$ acceptance region provides more restrictive limit than $0.0015 < \xi < 0.15$ acceptance region because new physics effect comes from high energy region.

3. Conclusions

Forward detector equipments at the LHC can discern intact scattered protons after the collision. Hence, we can distinguish exclusive photon-photon processes with respect to deep inelastic scattering which damages the proton structure. Since photon-photon interaction has very clean environment, it is important to examine new physics for a given detector acceptance region through photon-induced reactions. Moreover, this interaction can isolate to κ_γ coupling from the other gauge boson couplings. In these motivations, we have researched the anomalous interaction of t' quark via $pp \rightarrow p\gamma\gamma p \rightarrow pq\bar{q}p$ process at the LHC to investigate anomalous $t'q\gamma$ coupling. Our results show that the sensitivity of the anomalous $\kappa_\gamma/\Lambda = 0.85\,\text{TeV}^{-1}$ coupling can be reached at $\sqrt{s} = 14\,\text{TeV}$ and $L_{\text{int}} = 100\,\text{fb}^{-1}$ for the $m_{t'} = 650\,\text{GeV}$, $0.0015 < \xi < 0.5$. As a result, the exclusive $pp \rightarrow p\gamma\gamma p \rightarrow pq\bar{q}p$ reaction at the LHC offers us an important opportunity to probe anomalous couplings of t' quark.

Conflict of Interests

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

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