Anomalous $WW\gamma$ couplings in γp collision at the LHC

İ. Şahin*
Department of Physics, Zonguldak Karaelmas University, 67100 Zonguldak, Turkey

A. A. Billur†
Department of Physics, Cumhuriyet University, 58140 Sivas, Turkey
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We examine the potential of the $pp \to p\gamma p \to pWqX$ reaction to probe anomalous $WW\gamma$ couplings at the LHC. We find 95% confidence level bounds on the anomalous coupling parameters with various values of the integrated luminosity. We show that the reaction $pp \to p\gamma p \to pWqX$ at the LHC highly improves the current limits.

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I. INTRODUCTION

Gauge boson self-interactions are consequences of the $SU_L(2) \times U_Y(1)$ gauge structure of the standard model (SM). Measurements of these couplings are crucial to test the non-Abelian structure of the electroweak sector. Experimental results obtained from experiments at the CERN LEP and Fermilab Tevatron confirm the SM predictions. Probing these couplings with a higher sensitivity can either lead to additional confirmation of the SM or give some hint for new physics beyond the SM.

In this work we have analyzed the anomalous $WW\gamma$ couplings via single W boson production in a γp collision at the LHC. A quasireal photon emitted from one proton beam can interact with the other proton and produce a W boson through deep inelastic scattering. Since the emitted quasireal photons have a low virtuality they do not spoil the proton structure. Therefore the processes like $pp \to p\gamma p \to pWqX$ can be studied at the LHC (Fig. 1). Photon-induced reactions in a hadron-hadron collision were observed in the measurements of the CDF Collaboration [1–4]. For instance the reactions $p\bar{p} \to p\gamma\gamma\bar{p} \to pe^+e^-\bar{p}$ [1,4], $p\bar{p} \to p\gamma\gamma\bar{p} \to p\mu^+\mu^-\bar{p}$ [3,4], $p\bar{p} \to p\gamma\bar{p} \to pJ/\psi(\psi(2S))\bar{p}$ [3] were verified experimentally. These results raise interest in the potential of the LHC as a photon-photon and photon-proton collider.

The ATLAS and CMS Collaborations have a program of forward physics with extra detectors located at distances of 220 m and 420 m from the interaction point [5,6]. The physics program of this new instrumentation covers soft and hard diffraction, high energy photon-induced interactions, low-x dynamics with forward jet studies, large rapidity gaps between forward jets, and luminosity monitoring [7–24]. One of the main features of these forward detectors is to tag the protons with some momentum fraction loss, $\xi = (|\vec{p}| - |\vec{p}'|)/|\vec{p}|$. Here $\vec{p}$ is the momentum of the incoming proton and $\vec{p}'$ is the momentum of the intact scattered proton. Complementary to proton-proton interactions, the forward detector equipment at the LHC allows us to study photon-photon and photon-proton interactions at energies higher than at any existing collider.

New physics searches in photon-induced interactions at the LHC have been discussed in the literature [17–19,25–33]. A detailed analysis of $WW\gamma$ couplings has been done in [26] via the process $pp \to p\gamma\gamma p \to pW^+W^-p$. This process receives contributions both from anomalous $WW\gamma$ and $WW\gamma\gamma$ couplings. On the other hand the process $pp \to p\gamma p \to pWqX$ isolates $WW\gamma$ coupling and gives us the opportunity to study the $WW\gamma$ vertex independent from $WW\gamma\gamma$. Therefore any signal which conflicts with the SM predictions would be convincing evidence for new physics effects in $WW\gamma$.

II. CROSS SECTIONS AND EFFECTIVE LAGRANGIAN

We consider the following subprocesses of the reaction $pp \to p\gamma p \to pWqX$:

$$\begin{array}{ll}
\text{(i) } \gamma u \to W^+ d, & \text{(ii) } \gamma c \to W^+ s, \\
\text{(iii) } \gamma \bar{d} \to W^+ \bar{u}, & \text{(iv) } \gamma \bar{s} \to W^+ \bar{c}, \\
\text{(v) } \gamma \bar{b} \to W^+ \bar{t}, & \text{(vi) } \gamma d \to W^- u, \\
\text{(vii) } \gamma s \to W^- c, & \text{(viii) } \gamma b \to W^- t, \\
\text{(ix) } \gamma \bar{u} \to W^- \bar{d}, & \text{(x) } \gamma \bar{c} \to W^- \bar{s}.
\end{array} \tag{1}$$

We neglect interactions between different family quarks since the cross sections are suppressed due to small off diagonal elements of the Cabibbo-Kobayashi-Maskawa matrix.

A quasireal photon which enters the subprocess is described by equivalent photon approximation [24,34,35]. The equivalent photon spectrum of virtuality Q^2 and energy E_γ is given by

*inancsahin@karaelmas.edu.tr
†abillur@science.ankara.edu.tr

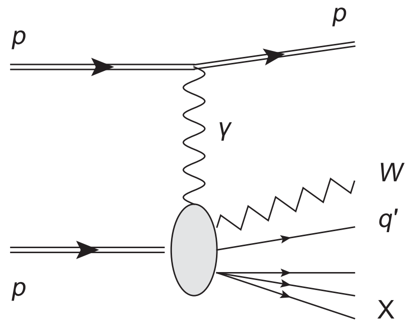

FIG. 1. Schematic diagram for the reaction $pp \to p\gamma p \to pWqX$.

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

where

$$Q^2_{\min} = \frac{m_p^2 E_\gamma^2}{E(E-E_\gamma)}, \qquad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}, \tag{3}$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1+\frac{Q^2}{Q_0^2}\right)^{-4}, \quad F_M = G_M^2, \quad Q_0^2 = 0.71\ \mathrm{GeV}^2. \tag{4}$$

Here E is the energy of the incoming proton beam and m_p is the mass of the proton. The magnetic moment of the proton is taken to be $\mu_p^2 = 7.78$. F_E and F_M are functions of the electric and magnetic form factors. The above equivalent photon approximation formula differs from the pointlike electron positron case by taking care of the electromagnetic form factors of the proton.

The cross section for the complete process $pp \to p\gamma p \to pWqX$ can be obtained by integrating the cross section for the subprocess $\gamma q \to Wq'$ over the photon and quark spectra:

$$\begin{aligned}
\sigma(pp \to p\gamma p \to pWqX) &= \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2 \int_{x_{1\min}}^{x_{1\max}} dx_1 \int_{x_{2\min}}^{x_{2\max}} dx_2 \left(\frac{dN_\gamma}{dx_1 dQ^2}\right) \\
&\quad \times \left(\frac{dN_q}{dx_2}\right)\hat\sigma_{\gamma q\to Wq'}(\hat s) \\
&= \int_{Q^2_{\min}}^{Q^2_{\max}} dQ^2 \int_{\frac{M_{\mathrm{inv}}}{\sqrt{s}}}^{\sqrt{\xi_{\max}}} dz 2z \int_{\mathrm{MAX}(z^2,\xi_{\min})}^{\xi_{\max}} \frac{dx_1}{x_1} \\
&\quad \times \left(\frac{dN_\gamma}{dx_1 dQ^2}\right) N_q(z^2/x_1)\hat\sigma_{\gamma q\to Wq'}(z^2 s).
\end{aligned} \tag{5}$$

Here, $x_1 = \frac{E_\gamma}{E}$ and x_2 is the momentum fraction of the proton's momentum carried by the quark. The second integral in (5) is obtained by transforming the differentials $dx_1 dx_2$ into $dz dx_1$ with a Jacobian determinant $2z/x_1$ where $z = \sqrt{x_1 x_2} \simeq \sqrt{\hat s/s}$. M_{inv} is the total mass of the final particles of the subprocess $\gamma q \to Wq'$. $\frac{dN_q}{dx_2}$ is the quark distribution function of the proton and $N_q(z^2/x_1)$ is $\frac{dN_q}{dx_2}$ evaluated at $x_2 = z^2/x_1$. At high energies greater than the proton mass it is a good approximation to write $\xi = \frac{E_\gamma}{E} = x_1$. The virtuality of the quark is taken to be $Q'^2 = m_W^2$ during calculations. One should note that Q^2 and Q'^2 refer to different particles. In our calculations parton distribution functions of Martin*et al.* [36] have been used.

New physics contributions to $WW\gamma$ couplings can be investigated in a model independent way by means of the effective Lagrangian approach. The theoretical basis of such an approach relies on the assumption that at higher energies beyond where the SM is tested, there is a more fundamental theory which reduces to the SM at lower energies. The SM is assumed to be an effective low-energy theory in which heavy fields have been integrated out. Such a procedure is quite general and independent of the new interactions at the new physics energy scale. The charge and parity conserving effective Lagrangian for $WW\gamma$ interaction can be written following the papers [37,38]:

$$\begin{aligned}
\frac{iL}{g_{WW\gamma}} &= g_1^\gamma (W^\dagger_{\mu\nu}W^\mu A^\nu - W^{\mu\nu}W^\dagger_\mu A_\nu) + \kappa W^\dagger_\mu W_\nu A^{\mu\nu} \\
&\quad + \frac{\lambda}{M_W^2} W^\dagger_{\rho\mu} W^\mu_\nu A^{\nu\rho},
\end{aligned} \tag{6}$$

where

$$g_{WW\gamma} = e, \qquad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu, \qquad V_\mu = W_\mu, A_\mu$$

and dimensionless parameters g_1^γ, κ, and λ are related to the magnetic dipole and electric quadrupole moments. The tree-level SM values for these parameters are $g_1^\gamma = 1$, $\kappa = 1$, and $\lambda = 0$. For on-shell photons, $g_1^\gamma = 1$ is fixed by electromagnetic gauge invariance to its SM value at tree level.

The vertex function for $W^+(p_1)W^-(p_2)A(p_3)$ generated from the effective Lagrangian (6) is given by

$$\begin{aligned}
\Gamma_{\mu\nu\rho}(p_1, p_2, p_3) &= e\Big[g_{\mu\nu}\Big(p_1 - p_2 - \frac{\lambda}{M_W^2}[(p_2.p_3)p_1 - (p_1.p_3)p_2]\Big)_\rho \\
&\quad + g_{\mu\rho}\Big(\kappa p_3 - p_1 + \frac{\lambda}{M_W^2}[(p_2.p_3)p_1 - (p_1.p_2)p_3]\Big)_\nu \\
&\quad + g_{\nu\rho}\Big(p_2 - \kappa p_3 - \frac{\lambda}{M_W^2}[(p_1.p_3)p_2 - (p_1.p_2)p_3]\Big)_\mu \\
&\quad + \frac{\lambda}{M_W^2}(p_{2\mu}p_{3\nu}p_{1\rho} - p_{3\mu}p_{1\nu}p_{2\rho})\Big],
\end{aligned} \tag{7}$$

where $p_1 + p_2 + p_3 = 0$.

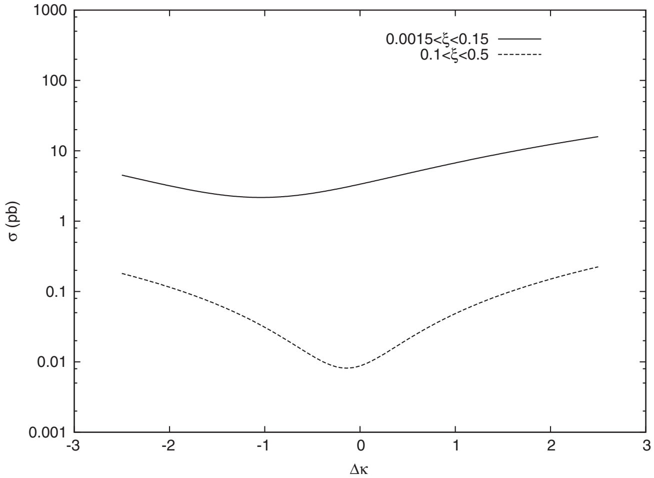

FIG. 2. The integrated total cross section of the process $pp \to p\gamma p \to pWqX$ as a function of anomalous coupling $\Delta\kappa = \kappa - 1$ for two different forward detector acceptances stated in the figure. We consider the sum of all subprocesses given in Eq. (1). The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

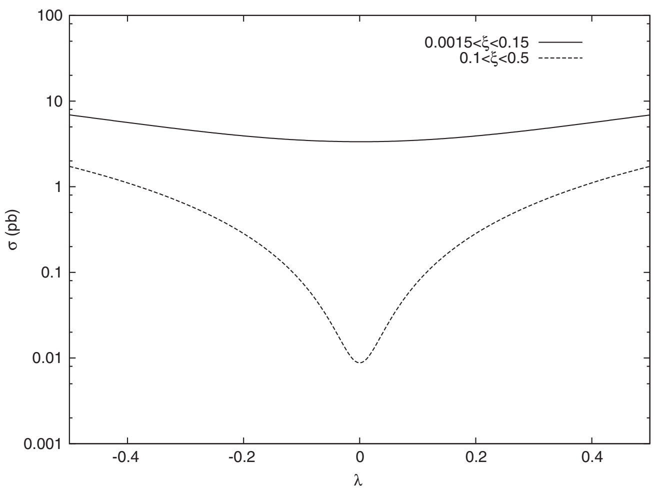

FIG. 3. The same as Fig. 2 but for the coupling λ.

During calculations we consider three different forward detector acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$, and $0.1 < \xi < 0.5$. The ATLAS Forward Physics (AFP) Collaboration proposed an acceptance of $0.0015 < \xi < 0.15$ [5,6]. On the other hand, the CMS-TOTEM forward detector scenario spans $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$ [17,39].

In Figs. 2 and 3 we plot the integrated total cross section of the process $pp \to p\gamma p \to pWqX$ as a function of anomalous couplings $\Delta\kappa = \kappa - 1$ and λ for the acceptances $0.0015 < \xi < 0.15$ and $0.1 < \xi < 0.5$. We sum all the contributions from subprocesses given in Eq. (1). We do not plot the cross section for the acceptance $0.0015 < \xi < 0.5$ since there is only a minor difference between the curves for $0.0015 < \xi < 0.5$ and $0.0015 < \xi < 0.15$. In these figures we observe that although the $0.1 < \xi < 0.5$ case gives small cross sections, deviations of the cross sections from their SM values are large. This feature is especially remarkable for the cross section as a function of the coupling λ.

III. SENSITIVITY TO ANOMALOUS COUPLINGS

A detailed investigation of the anomalous couplings requires a statistical analysis. To this purpose we have obtained 95% confidence level (C.L.) bounds on the anomalous coupling parameters $\Delta\kappa = \kappa - 1$ and λ using a one-parameter χ^2 test. The χ^2 function is given by

$$\chi^2 = \left(\frac{\sigma_{\rm SM} - \sigma(\Delta\kappa, \lambda)}{\sigma_{\rm SM}\delta}\right)^2, \tag{8}$$

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 as the signal $N = 0.9{\rm BR}(W \to \ell\nu)\sigma_{\rm SM}L_{\rm int}$, where $\ell = e$ or μ and 0.9 is the survival probability factor [17,18]. ATLAS and CMS have central detectors with a pseudorapidity coverage $|\eta| < 2.5$. Therefore we place a cut of $|\eta| < 2.5$ for electrons and muons from decaying W and also for final quarks from subprocess $\gamma q \to Wq'$.

In Tables I and II, we show 95% C.L. sensitivity bounds on the anomalous coupling parameters $\Delta\kappa$ and λ for various integrated luminosities and forward detector acceptances of $0.0015 < \xi < 0.5$, $0.0015 < \xi < 0.15$, and $0.1 < \xi < 0.5$. During statistical analysis only one of the anomalous couplings is assumed to deviate from the SM at a time. We see from the tables that bounds on $\Delta\kappa$ for $0.0015 < \xi < 0.5$ and $0.0015 < \xi < 0.15$ cases are almost same. They are more than an order of magnitude better

TABLE I. Ninety-five percent C.L. sensitivity bounds of the coupling $\Delta\kappa$ 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.

Luminosity	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
10 fb^{-1}	(− 0.017, 0.016)	(− 0.017, 0.017)	(− 0.428, 0.146)
30 fb^{-1}	(− 0.010, 0.009)	(− 0.010, 0.010)	(− 0.378, 0.095)
50 fb^{-1}	(− 0.007, 0.007)	(− 0.007, 0.007)	(− 0.360, 0.078)
100 fb^{-1}	(− 0.005, 0.005)	(− 0.005, 0.005)	(− 0.340, 0.058)
200 fb^{-1}	(− 0.004, 0.004)	(− 0.004, 0.004)	(− 0.325, 0.043)

TABLE II. The same as Table I but for the coupling λ.

Luminosity	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
10 fb^{-1}	(− 0.043, 0.044)	(− 0.051, 0.052)	(− 0.017, 0.017)
30 fb^{-1}	(− 0.032, 0.033)	(− 0.039, 0.040)	(− 0.013, 0.013)
50 fb^{-1}	(− 0.028, 0.029)	(− 0.034, 0.035)	(− 0.011, 0.011)
100 fb^{-1}	(− 0.024, 0.025)	(− 0.029, 0.030)	(− 0.009, 0.009)
200 fb^{-1}	(− 0.020, 0.021)	(− 0.024, 0.025)	(− 0.008, 0.008)

TABLE III. Ninety-five percent C.L. sensitivity bounds of the couplings $\Delta\kappa$ and λ for various forward detector acceptances and integrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 7$ TeV.

	Luminosity	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$	$0.1 < \xi < 0.5$
Limits on $\Delta\kappa$	1 fb^{-1}	(− 0.081, 0.075)	(− 0.086, 0.080)	(− 1.084, 0.305)
	2 fb^{-1}	(− 0.057, 0.054)	(− 0.060, 0.057)	(− 1.010, 0.231)
Limits on λ	1 fb^{-1}	(− 0.144, 0.145)	(− 0.176, 0.178)	(− 0.078, 0.078)
	2 fb^{-1}	(− 0.121, 0.122)	(− 0.148, 0.150)	(− 0.066, 0.066)

than the bound obtained from the $0.1 < \xi < 0.5$ case. On the other hand, bounds on λ are more restrictive in the $0.1 < \xi < 0.5$ case with respect to the $0.0015 < \xi < 0.5$ and $0.0015 < \xi < 0.15$ cases. In Tables I and II, we consider a center-of-mass energy of $\sqrt{s} = 14$ TeV for the proton-proton system. But the LHC will not operate at $\sqrt{s} = 14$ TeV before the year 2013. Therefore it is valuable to search its sensitivity at $\sqrt{s} = 7$ TeV. To this purpose we present Table III where the sensitivity bounds are obtained at $\sqrt{s} = 7$ TeV with an integrated luminosity of 1–2 fb^{-1}.

The current bounds on anomalous $WW\gamma$ couplings are provided by the Fermilab Tevatron and CERN LEP. The most stringent bounds obtained at the Tevatron are [40]

$$-0.51 < \Delta\kappa < 0.51, \qquad -0.12 < \lambda < 0.13 \tag{9}$$

at 95% C.L. The combined fits of the four LEP experiments improve the precision to [41]

$$-0.098 < \Delta\kappa < 0.101, \qquad -0.044 < \lambda < 0.047 \tag{10}$$

at 95% C.L. Although the LEP bounds are more precise than the bounds from the Tevatron, LEP results are obtained via the reactions $e^-e^+ \to W^-W^+$, $e^-e^+ \to e\nu W$, and $e^-e^+ \to \nu\bar{\nu}\gamma$ where the first two reactions receive contributions both from $WW\gamma$ and WWZ couplings. Therefore in general, limits given in (10) cannot be regarded as a bound on pure $WW\gamma$ couplings.

IV. CONCLUSIONS

The LHC with forward detector equipment gives us the opportunity to study photon-photon and photon-proton interactions at energies higher than at any existing collider. The reaction $pp \to p\gamma p \to pWqX$ provides a rather clean channel compared to pure deep inelastic scattering reactions 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 photons' momenta. This may be useful in reconstructing the kinematics of the reaction.

The reaction $pp \to p\gamma p \to pWqX$ at the LHC with a center-of-mass energy of 14 TeV probes anomalous $WW\gamma$ couplings with a better sensitivity than the LEP and Tevatron experiments. Our limits are also better than the limits obtained in $pp \to p\gamma\gamma p \to pW^+W^-p$ at the LHC [26]. We also investigate the potential of the LHC with a center-of-mass energy of 7 TeV. We deduce that the reaction $pp \to p\gamma p \to pWqX$ with a center-of-mass energy of 7 TeV and an integrated luminosity of 1 fb^{-1} probes anomalous $WW\gamma$ couplings with a better sensitivity than the Tevatron and with a comparable sensitivity with respect to the LEP.

A prominent advantage of the reaction $pp \to p\gamma p \to pWqX$ is that it isolates anomalous $WW\gamma$ couplings. It allows us to study $WW\gamma$ couplings independent from WWZ as well as from $WW\gamma\gamma$.

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