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

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Abstract

We examine the potential of $pp \rightarrow p\gamma p \rightarrow pWqX$ 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 $pp \rightarrow p\gamma p \rightarrow pWqX$ at the LHC highly improve the current limits.

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I. INTRODUCTION

Gauge boson self-interactions are consequences of the $SU_L(2) \times SU_Y(1)$ 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 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 $\gamma p$ collision at the LHC. A quasi-real photon emitted from one proton beam can interact with the other proton and produce W boson through deep inelastic scattering (DIS). Since the emitted quasi-real photons have a low virtuality they do not spoil the proton structure. Therefore the processes like $pp \rightarrow p\gamma p \rightarrow pWqX$ can be studied at the LHC (Fig.1). Photon induced reactions in a hadron-hadron collision were observed in the measurements of CDF collaboration [1–4]. For instance the reactions:

- $p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow pe^+e^-\bar{p}$ [1, 4], $p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow p\mu^+\mu^-\bar{p}$ [2, 4], $p\bar{p} \rightarrow p\gamma\bar{p} \rightarrow pJ/\psi(\psi(2S))\bar{p}$ [3],
- $p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow pe^+e^-\bar{p} [1, 4], p\bar{p} \rightarrow p\gamma\gamma\bar{p} \rightarrow p\mu^+\mu^-\bar{p} [2, 4], p\bar{p} \rightarrow p\gamma\bar{p} \rightarrow pJ/\psi(\psi(2S))\bar{p} [3],$

were verified experimentally. These results raise interest on the potential of LHC as a photon-photon and photon-proton collider.

ATLAS and CMS collaborations have a program of forward physics with extra detectors located at distances of 220m and 420m 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 incoming proton and $\vec{p}'$ is the momentum of intact scattered proton. Complementary to proton-proton interactions, forward detector equipment at the LHC allows 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 being discussed in the literature [17, 19, 25–33]. A detailed analysis of $WW\gamma$ couplings has been done in [26] via the process $pp \rightarrow p\gamma\gamma p \rightarrow pW^+W^-p$. This process receives contributions both from anomalous $WW\gamma$ and $WW\gamma\gamma$ couplings. On the other hand the process $pp \rightarrow p\gamma p \rightarrow pWqX$
isolates $WW\gamma$ coupling and gives us the opportunity to study $WW\gamma$ vertex independent from $WW\gamma\gamma$. Therefore any signal which conflicts with the SM predictions would be a convincing evidence for new physics effects in $WW\gamma$.

II. CROSS SECTIONS AND EFFECTIVE LAGRANGLIAN

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

(i) $\gamma u \rightarrow W^+d$  \hspace{0.5cm} (vi) $\gamma d \rightarrow W^-u$

(ii) $\gamma c \rightarrow W^+s$  \hspace{0.5cm} (vii) $\gamma s \rightarrow W^-c$

(iii) $\gamma\bar{d} \rightarrow W^+\bar{u}$  \hspace{0.5cm} (viii) $\gamma b \rightarrow W^-t$

(iv) $\gamma\bar{s} \rightarrow W^+\bar{c}$  \hspace{0.5cm} (ix) $\gamma\bar{u} \rightarrow W^-\bar{d}$

(v) $\gamma\bar{b} \rightarrow W^+\bar{t}$  \hspace{0.5cm} (x) $\gamma\bar{c} \rightarrow W^-\bar{s}$

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

Quasi-real photon which enters the subprocess is described by equivalent photon approximation (EPA) \cite{24, 34, 35}. Equivalent photon spectrum of virtuality $Q^2$ and energy $E_\gamma$ is given by

$$\frac{dN_\gamma}{dE_\gamma dQ^2} = \frac{\alpha}{\pi} \frac{1}{E_\gamma Q^2} \left[ (1 - \frac{E_\gamma}{E})(1 - \frac{Q_{\text{min}}^2}{Q^2})F_E + \frac{E_\gamma^2}{2E^2}F_M \right]$$  \hspace{0.5cm} (2)

where

$$Q_{\text{min}}^2 = \frac{m_p^2 E_\gamma^2}{E(E - E_\gamma)}, \hspace{0.5cm} F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2}$$  \hspace{0.5cm} (3)

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = (1 + \frac{Q^2}{Q_0^2})^{-4}, \hspace{0.5cm} F_M = G_M^2, \hspace{0.5cm} Q_0^2 = 0.71\text{GeV}^2$$  \hspace{0.5cm} (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 EPA 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 $pp \rightarrow p\gamma p \rightarrow pWqX$ can be obtained by integrating the cross section for the subprocess $\gamma q \rightarrow Wq'$ over the photon and quark.
spectra

\[ \sigma (pp \rightarrow p\gamma p \rightarrow pWqX) = \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ^2 \int_{x_1_{\text{min}}}^{x_1_{\text{max}}} dx_1 \int_{x_2_{\text{min}}}^{x_2_{\text{max}}} dx_2 \]

\[ \times \left( \frac{dN_\gamma}{dx_1 dQ^2} \right) \left( \frac{dN_q}{dx_2} \right) \hat{\sigma}_{\gamma q \rightarrow Wq'}(\hat{s}) \]

\[ = \int_{Q^2_{\text{min}}}^{Q^2_{\text{max}}} dQ^2 \int_{\xi_{\text{max}}}^{\xi_{\text{max}}} d\xi \int_{M_{\text{inv}}(z^2, \xi_{\text{min}})}^{M_{\text{inv}}(z^2, \xi_{\text{min}})} \frac{dx_1}{x_1} \]

\[ \times \left( \frac{dN_\gamma}{dx_1 dQ^2} \right) N_q(z^2/x_1) \hat{\sigma}_{\gamma q \rightarrow Wq'}(z^2 s). \]  

(5)

Here, \( x_1 = \frac{E_\gamma}{E} \) and \( x_2 \) is the momentum fraction of the proton’s momentum carried by the quark. 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 \( z = \sqrt{x_1 x_2} \simeq \sqrt{\hat{s}} \). \( M_{\text{inv}} \) is the total mass of the final particles of the subprocess \( \gamma q \rightarrow Wq' \). \( \frac{dN_q}{dx_2} \) 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 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, Stirling, Thorne and Watt 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 rely 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

\[ \frac{iL}{g_{WW\gamma}} = g_1^\gamma (W_\mu W^\mu A^\nu - W_\mu W_\nu A^\mu A^\nu) + \kappa W_\mu W_\nu A^\mu A^\nu + \frac{\lambda}{M_W^2} W_\rho W_\mu W^\rho W^\mu A^\nu \]

(6)

where

\[ g_{WW\gamma} = e \quad , \quad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \quad , \quad V_\mu = W_\mu, A_\mu \]

and dimensionless parameters \( g_1^\gamma, \kappa \) and \( \lambda \) 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

\[
\Gamma_{\mu\nu\rho}(p_1, p_2, p_3) = e \left[ g_{\mu\nu} \left( p_1 - p_2 - \frac{\lambda}{M_W^2} [ (p_2 \cdot p_3) p_1 - (p_1 \cdot p_3) p_2 ] \right)_\rho + g_{\mu\rho} \left( \kappa p_3 - p_1 + \frac{\lambda}{M_W^2} [ (p_2 \cdot p_3) p_1 - (p_1 \cdot p_2) p_3 ] \right)_\nu + g_{\nu\rho} \left( p_2 - \kappa p_3 - \frac{\lambda}{M_W^2} [ (p_1 \cdot p_3) p_2 - (p_1 \cdot p_2) p_3 ] \right)_\mu + \frac{\lambda}{M_W^2} (p_2 \rho p_3 \nu p_1 \mu - p_3 \rho p_1 \nu p_2 \mu) \right],
\]

(7)

where \( p_1 + p_2 + p_3 = 0 \).

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

In Fig.2 and Fig.3 we plot the integrated total cross section of the process \( pp \rightarrow p\gamma p \rightarrow pWqX \) as a function of anomalous couplings \( \Delta\kappa = \kappa - 1 \) and \( \lambda \) for the acceptances \( 0.0015 < \xi < 0.15 \) and \( 0.1 < \xi < 0.5 \). We sum all the contributions from subprocesses given in equation (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 \( 0.1 < \xi < 0.5 \) case gives small cross sections, deviations of the cross sections from their SM values are large. This feature especially remarkable for the cross section as a function of the coupling \( \lambda \).

### 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 \( \lambda \) using one-parameter \( \chi^2 \) test. The \( \chi^2 \) function is given by,

\[
\chi^2 = \left( \frac{\sigma_{SM} - \sigma(\Delta\kappa, \lambda)}{\sigma_{SM} \delta} \right)^2
\]

(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 \( N = 0.9 \text{BR}(W \to \ell\nu)\sigma_{\text{SM}} L_{\text{int}} \), where \( \ell = e \) or \( \mu \) 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 table I and II we show 95% C.L. sensitivity bounds on the anomalous coupling parameters \( \Delta\kappa \) and \( \lambda \) 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 than the bound obtained from \( 0.1 < \xi < 0.5 \) case. On the other hand, bounds on \( \lambda \) are more restrictive in \( 0.1 < \xi < 0.5 \) case with respect to \( 0.0015 < \xi < 0.5 \) and \( 0.0015 < \xi < 0.15 \) cases. In table I and II we consider a center of mass energy of \( \sqrt{s} = 14\text{TeV} \) for the proton-proton system. But the LHC will not operate at \( \sqrt{s} = 14 \text{ TeV} \) before the year 2013. Therefore it is valuable to search its sensitivity at \( \sqrt{s} = 7 \text{ TeV} \). To this purpose we present table III where the sensitivity bounds are obtained at \( \sqrt{s} = 7 \text{ TeV} \) with an integrated luminosity of 1-2 fb\(^{-1}\).

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

\[
-0.51 < \Delta\kappa < 0.51 \quad -0.12 < \lambda < 0.13
\]

at 95% C.L.. The combined fits of the four LEP experiments improves the precision to \([41]\)

\[
-0.098 < \Delta\kappa < 0.101 \quad -0.044 < \lambda < 0.047
\]

at 95% C.L.. Although the LEP bounds are more precise than the bounds from the Tevatron, LEP results are obtained via the reactions \( e^-e^+ \to W^-W^+, \quad e^-e^+ \to e\nu W \) and \( e^-e^+ \to \nu\bar{\nu}\gamma \) where first two reactions receive contributions both from \( WW\gamma \) and \( WWZ \) couplings. Therefore in general, limits given in \([40]\) can not be regarded as a bound on pure \( WW\gamma \) couplings.
IV. CONCLUSIONS

LHC with a 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 $pp \rightarrow p\gamma p \rightarrow pWqX$ provides a rather clean channel compared to pure DIS reactions due to absence of one of the incoming proton remnants. Furthermore detection of the intact scattered protons in the forward detectors allows us to reconstruct quasi-real photons momenta. This may be useful in reconstructing the kinematics of the reaction.

The reaction $pp \rightarrow p\gamma p \rightarrow pWqX$ 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 also better than the limits obtained in $pp \rightarrow p\gamma\gamma p \rightarrow pW^+W^-p$ 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 $pp \rightarrow p\gamma p \rightarrow pWqX$ 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 Tevatron and with a comparable sensitivity with respect to LEP.

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

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

FIG. 2: The integrated total cross section of the process $pp \rightarrow p\gamma p \rightarrow pWqX$ as a function of anomalous coupling $\Delta \kappa = \kappa - 1$ for two different forward detector acceptances stated on the figure. We consider the sum of all subprocesses given in equation (1). The center of mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.
FIG. 3: The same as figure 2 but for the coupling $\lambda$.

TABLE I: 95% 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 $\sqrt{s} = 14\text{TeV}$.

| Luminosity | $0.0015 < \xi < 0.5$                     | $0.0015 < \xi < 0.15$               | $0.1 < \xi < 0.5$               |
|------------|----------------------------------------|-------------------------------------|--------------------------------|
| $10fb^{-1}$| (-0.017 , 0.016)                        | (-0.017 , 0.017)                    | (-0.428 , 0.146)               |
| $30fb^{-1}$| (-0.010 , 0.009)                        | (-0.010 , 0.010)                    | (-0.378 , 0.095)               |
| $50fb^{-1}$| (-0.007 , 0.007)                        | (-0.007 , 0.007)                    | (-0.360 , 0.078)               |
| $100fb^{-1}$| (-0.005 , 0.005)                        | (-0.005 , 0.005)                    | (-0.340 , 0.058)               |
| $200fb^{-1}$| (-0.004 , 0.004)                        | (-0.004 , 0.004)                    | (-0.325 , 0.043)               |
TABLE II: The same as table I but for the coupling $\lambda$.

| 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: 95% C.L. sensitivity bounds of the couplings $\Delta \kappa$ and $\lambda$ 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 $\lambda$: |
| $1 fb^{-1}$ | (-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) |