Probing $WW\gamma\gamma$ and $ZZ\gamma\gamma$ quartic anomalous couplings with 10 pb$^{-1}$ at the LHC

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We report on a possible measurement at the LHC using the first data and a luminosity of 10 pb$^{-1}$ of $W$ and $Z$ pair production via two-photon exchange. This measurement allows to increase the present sensitivity on $WW\gamma\gamma$ and $ZZ\gamma\gamma$ quartic anomalous couplings from the LEP experiments by almost three orders of magnitude.

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In the Standard Model (SM) of particle physics, the couplings of fermions and gauge bosons are constrained by the gauge symmetries of the Lagrangian. The measurement of $W$ and $Z$ boson pair productions via the exchange of two photons allows to provide directly stringent tests of one of the most important and least understood mechanism in particle physics, namely the electroweak symmetry breaking [1]. The non-abelian gauge nature of the SM predicts the existence of quartic couplings $WW\gamma\gamma$ between the $W$ bosons and the photons which can be probed directly at the Large Hadron Collider (LHC) at CERN. The quartic coupling to the $Z$ boson $ZZ\gamma\gamma$ is not present in the SM.

The quartic couplings test more generally new physics which couples to electroweak bosons. Exchange of heavy particles beyond the SM might manifest itself as a modification of the quartic couplings appearing in contact interactions [2]. It is also worth noticing that in the limit of infinite Higgs masses, or in Higgs-less models [2], new structures not present in the tree level Lagrangian appear in the quartic $W$ coupling. For example, if the electroweak breaking mechanism does not manifest itself in the discovery of the Higgs boson at the LHC or supersymmetry, the presence of anomalous — non SM like — couplings might be the first evidence of new physics in the electroweak sector of the SM.

In this Letter, we will demonstrate that it is possible to probe quartic couplings between the $W$ or $Z$ and the photons at the LHC using the first data at low luminosity. The LHC is a proton proton machine with a nominal center-of-mass energy of 14 TeV, located at CERN, Geneva, Switzerland. The first collisions are expected to occur towards the end of 2009 at a reduced center-of-mass energy of 10 TeV. A typical luminosity of 10 (100) pb$^{-1}$ is expected to be accumulated in a few days (weeks).

High energy colliders such as the incoming LHC are the natural place to look for anomalous quartic couplings between the photon and the $W$ or $Z$ bosons. The process we want to study at the LHC is depicted in Fig. 1 and corresponds to $pp \to pWWp$. In this photon-induced process, the two quasi-real photons interact through the exchange of a virtual $W$, leading to a pair of $W$s in the final state. The advantage of this kind of events is that they are extremely clean, there are two $W$s (or $Z$s) which can be detected in the ATLAS or CMS central detectors while the intact proton leave undetected in the beam pipe. The cross section of this Quantum Electrodynamics (QED) process in the standard model is known precisely and is equal to 62 fb at a center-of-mass energy of 10 TeV.

In this Letter, we restrict ourselves to the implementation of the genuine quartic anomalous $\gamma\gamma WW$ and $\gamma\gamma ZZ$ using the lowest dimension operators possible in the Lagrangian. They are of dimension six and preserve by construction the custodial SU(2)$_c$ symmetry required to keep the $\rho = M_W^2/(M_Z^2 \cos^2 \theta_W)$ parameter to its experimental value close to 1 where $M_W$, $M_Z$ and $\theta_W$ are respectively the $W$ and $Z$ boson masses, and the weak...
mixing angle. In addition, they are not related to the anomalous triple gauge couplings in any way. The most general Lagrangians leading to anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ quartic couplings are the following [2]

\[
\mathcal{L}^6_0 = -\frac{e^2 a^W_0}{8 \Lambda^2} F_{\mu\nu} F^{\mu\nu} W^+ W^- - \frac{e^2}{16 \cos^2 \theta_W \Lambda^2} a^Z_0 F_{\mu\nu} F^{\mu\nu} Z^\alpha Z^\alpha - \frac{e^2}{16 \cos^2 \theta_W \Lambda^2} a^C_0 F_{\mu\nu} F^{\mu\nu} Z^\alpha Z^\alpha \]

where $W^{\pm}$ and $Z^\alpha$ are the $W$ and $Z$ boson fields, and $F_{\mu\nu} = \partial_{\mu} A_{\nu} - \partial_{\nu} A_{\mu}$ the electromagnetic tensor. The new scale $\Lambda$ is introduced so that the Lagrangian has the correct dimension 4 and can be interpreted as the scale of new physics. In this Lagrangian, the $W$ and $Z$ parts are allowed to have their specific parameters $a^W_0$, $a^W_C$, $a^Z_0$ and $a^C_0$. Such Lagrangian conserves $C$, $P$ and $T$ parities separately, and represents the most natural extension of the SM.

The current best 95% confidence level (C.L.) limits on the parameters of quartic anomalous couplings were determined by the OPAL Collaboration [4] where the quartic couplings were measured in $e^+e^- \rightarrow W^+W^-\gamma$, $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$ (for $WW\gamma\gamma$ anomalous couplings), and $e^+e^- \rightarrow q\bar{q}\gamma\gamma$ (for $ZZ\gamma\gamma$ couplings) with center-of-mass energies up to 209 GeV and are given in Table [4].

The scattering amplitudes are quadratically divergent for all anomalous coupling parameters. The steep rise of the cross section at high energy leads immediately to the violation of unitarity. The tree level unitarity uniquely restricts the $WW\gamma\gamma$ couplings to the SM values at asymptotically high energies. This implies that any deviation of the anomalous parameters $a^W_0/\Lambda^2$, $a^W_C/\Lambda^2$, $a^Z_0/\Lambda^2$, $a^W_0/\Lambda^2$, $a^C_0/\Lambda^2$ from the SM zero value has to be multiplied by a form factor which vanishes in the high energy limit and which introduces a regularisation of the cross section at the new physics scale. At LEP, where the center-of-mass energy was rather low, the wrong high energy behaviour did not violate unitarity; however, it must be reconsidered at the LHC. We therefore modify the couplings using the form factors that leave the couplings at small energies the same but suppress their effect when the center-of-mass energy $W_{\gamma\gamma}$ increases [2], such as

\[
a \rightarrow \frac{a}{(1 + W^2_{\gamma\gamma}/\Lambda^2)^n}.
\]

The exact form of the form factor is not imposed but rather only conventional and the same holds for a value of the exponent $n$. $\Lambda^2$ corresponds to the scale where new physics should appear. At the LHC, usual values for

\[\text{FIG. 2: Transverse momentum of the leading lepton for the quartic anomalous coupling signal and the different SM backgrounds.}\]
pair production, the dilepton production through $\gamma$ or Pomeron exchange, and the $W$ diffractive production. The $p_T$ distribution of the events with a $WW\gamma\gamma$ anomalous coupling $a_0^W = 4 \times 10^{-4}$ GeV$^2$ (which means a value about two orders of magnitude smaller than the LEP limit) is given in Fig. 2 together with the different backgrounds. After requesting the presence of two reconstructed leptons (electrons or muons) in the main ATLAS detector of $p_T > 10$ GeV, the number of background events for $10 \text{ pb}^{-1}$ is respectively 17.4, 6.0, 0.003 and 0.03 for dilepton production through $\gamma$ exchange, dilepton diffractive production, and $W$ pair production via Pomeron or photon exchange in the detector acceptance. In Fig. 2 we already see that the $p_T$ of the leading lepton extends to much higher values for the signal events than for the background.

Let us now discuss each background in turn. The nondiffractive $W$ pair production is suppressed by requesting the presence of two leptons and nothing else in the ATLAS detector since the inclusive background always shows some hadronic activity in the calorimeter or in the forward part of the tracking detector. This background is thus found to be negligible after the exclusivity cut.

It is worth noticing that this cut requires that we consider only low instantaneous luminosity when only one interaction occurs per bunch crossing. At higher instantaneous luminosity, the proton tagging using dedicated detectors will be needed [10]. The dilepton production through photon exchange (QED process) is suppressed by requesting the presence of a leading lepton with $p_T > 160$ GeV, and of missing energy greater than 20 GeV, which is natural when one requests the presence of two $W$s. The pure SM $W$ pair background (without any anomalous couplings) via photon exchange is small since the value of the cross section is low (62 fb) and it is further suppressed by requiring a reconstructed lepton with $p_T > 160$ GeV. The diffractive production of dileptons or $W$ pairs via double pomeron exchange (DPE) were studied using the FPMC Monte Carlo. The quark and gluon structure of the Pomeron was taken using the H1 parametrisation of the Pomeron [11] with a survival probability at the LHC of 0.03 [12] (the survival probability in the case of $\gamma$-induced processes is 0.9). This background suffers more uncertainties than the photon exchange processes since it is less understood theoretically but it leads to a negligible background after the exclusivity cut. After all cuts, the background is found to be negligible. As an example, the number of events for signal for $a_0^W / \Lambda^2 = 2 \times 10^{-4}$ is 19 before cuts in the detector acceptance and 12 after cuts, showing that the signal is not much affected by the cuts we introduced. The number of events after the different cuts as a function of the value of the anomalous coupling is given in Fig. 2, left, for a luminosity of 10 pb$^{-1}$. We already see that the reach on the anomalous coupling $a_0^W$ and $a_C^W$ is expected to be much better than at LEP by more than two orders of magnitude.

We also studied the effect of the anomalous $ZZ\gamma\gamma$ couplings $a_0^Z$ and $a_C^Z$. The cuts are even simpler since two leptons of the same charge are produced when the $Z$ bosons decay leptonically. We thus request two like sign leptons or three reconstructed leptons and the $p_T$ of the leading lepton is larger than 100 GeV. All background is found to be negligible after those cuts.

The sensitivity on anomalous coupling is depicted in Fig. 3, right, where the 5$\sigma$ discovery contours are displayed in the plane ($a_0^Z$, $a_C^Z$), or ($a_0^W$, $a_C^Z$) for two different values of the accumulated luminosity of 10 and 100 pb$^{-1}$. The reach on the different anomalous couplings is also given in Table I. At LHC energies, the cross sections are the same for negative and positive values of the anomalous couplings and the obtained sensitivities are symmetric. We note that the LEP sensitivity on quartic anomalous couplings can be increased by two or three orders of magnitude depending on the coupling with a low luminosity of 10 or 100 pb$^{-1}$. By comparison, the gain on trilinear gauge coupling is not that stringent with respect to LEP.

| Couplings | OPAL limits [GeV$^{-2}$] | Sensitivity @ $L = 10$ (100) pb$^{-1}$ |
|-----------|-------------------------|------------------------------------------|
| $a_0^W / \Lambda^2$ | (-0.020, 0.020) | 2.2 $\times 10^{-4}$ | 5$\sigma$ | (7.3 $\times 10^{-5}$) |
| $a_C^Z / \Lambda^2$ | (-0.052, 0.037) | 5.9 $\times 10^{-4}$ | 5$\sigma$ | (2.4 $\times 10^{-4}$) |
| $a_0^Z / \Lambda^2$ | (-0.007, 0.023) | 1.0 $\times 10^{-3}$ | 5$\sigma$ | (3.7 $\times 10^{-4}$) |
| $a_C^W / \Lambda^2$ | (-0.029, 0.029) | 3.0 $\times 10^{-4}$ | 5$\sigma$ | (1.3 $\times 10^{-3}$) |

TABLE I: Limits on anomalous coupling coming from the LEP OPAL experiment. Sensitivity at low luminosity. The 5$\sigma$ discovery potentials as well as the 95% C.L. limits are given for 10 pb$^{-1}$ and 100 pb$^{-1}$ in parenthesis.

In this Letter, we described a new study to be performed using the first data at the LHC at a center-of-mass energy of 10 TeV using a luminosity of 10 or 100 pb$^{-1}$. Through the measurements of $WW$ and $ZZ$ productions via photon exchange at the LHC when the $Z$ or $W$ bosons decay leptonically, it is possible to improve the sensitivity on the $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings by almost three orders of magnitude with respect to the LEP sensitivity. This will be one of the most stringent tests of the electroweak symmetry breaking at the beginning of the LHC which will happen before the search for the Higgs boson and might lead to a first evidence for effects beyond the Standard Model via the indirect effects of a heavy scalar particle or an indirect test of Higgs-less models.
FIG. 3: Left: Number of signal events after cuts as a function of the value of the quartic anomalous coupling for 10 pb$^{-1}$ at the LHC. Right: 5σ discovery contours for the WW and ZZ quartic anomalous couplings at $\sqrt{s} = 10$ TeV for luminosities of 10 and 100 pb$^{-1}$.

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[1] P. J. Dervan, A. Signer, W. J. Stirling, A. Werthenbach, J. Phys. G26 (2000); W. J. Stirling, A. Werthenbach, Eur. Phys. J. C14 (2000) 103.
[2] O. J. P. Eboli, M. C. Gonzales-Garcia, S. M. Lietti, S. F. Novaes, Phys. Rev. D63 (2001) 075008; G. Cvetic, B. Koegerler, Nucl. Phys. B363 (1991) no2-3,401-424; A. Hill, J.J. van der Bij, Phys. Rev. D36 (1987) 3463;
[3] G. Belanger, F. Boudjema, Phys. Lett. B288 (1992) 201.
[4] G. Abbiendi et al., OPAL Collaboration, Phys. Rev. D70 032005 (2004).
[5] T. Pierzhala and K. Piotrzkowski, Nucl. Phys. Proc. Suppl. 179-180 (2008) 257.
[6] M. Boonekamp, V. Juranek, O. Kepka, C. Royon, Forward Physics Monte Carlo, Proceedings of the Workshop of the Implications of HERA for LHC physics, DESY-Pro2009-02, see http://cern.ch/fpmc
[7] E. Boos et al, Nucl. Instrum. Meth. A534 (2004) 250.
[8] G. Marchesini et al., Comp. Phys. Comm. 67, 465 (1992).
[9] ATLFast++ package for ROOT, http://root.cern.ch/root/Atlfast.html
[10] C. Royon, Proceedings for the DIS 2007 Workshop, Munich, arXiv:physics.ins-det/0706.1796 (2007); M.G. Albrow et al., arXiv:hep-ex/0806.0302 (2008).
[11] A. Aktas et al. [H1 Collaboration], Eur. Phys. J. C 48 (2006) 715.
[12] J. D. Bjorken, Phys. Rev. D47, (1993) 101; A. B. Kaidalov, V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C21 (2001) 521; A. Kupco, C. Royon and R. Peschanski, Phys. Lett. B 606, 139 (2005).
[13] O. Kepka and C. Royon, Phys. Rev. D78 073005 (2008).