Determining Triple Gauge Boson Couplings from Higgs Data

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In the framework of effective Lagrangians with the $SU(2)_L \times U(1)_Y$ symmetry linearly realized, modifications of the couplings of the Higgs field to the electroweak gauge bosons are related to anomalous triple gauge couplings (TGCs). Here, we show that the analysis of the latest Higgs boson production data at the LHC and Tevatron give rise to strong bounds on TGCs that are complementary to those from direct TGC analysis. We present the constraints on TGCs obtained by combining all available data on direct TGC studies and on Higgs production analysis.

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The direct exploration of the electroweak symmetry breaking sector has recently started with the discovery of a state that resembles the standard model (SM) Higgs boson [1] at the CERN Large Hadron Collider (LHC) [2]. With the increase of available data on this Higgs-like state, we can scrutinize its couplings to determine if it is indeed the state predicted by the SM [3–6]. The observation of departures from the SM predictions for the Higgs couplings can give hints of physics beyond the SM characterized by an energy scale Λ.

A model-independent way to parametrize the low-energy effects of possible SM extensions is by the means of an effective Lagrangian [7], which depends on the low-energy particle content and symmetries. This bottom-up approach has the advantage of minimizing the amount of theoretical hypothesis when studying deviations from the SM predictions [4]. The absence of direct new physics (NP) signals in the present LHC runs so far and the observation of the SM-like Higgs state consistent with being a light electroweak doublet scalar favors that the $SU(2)_L \otimes U(1)_Y$ symmetry is linearly realized in the effective theory which describes the indirect NP effects at LHC energies [8–12]. Except for total lepton number violating effects, the lowest-order operators that can be built are of dimension six. The coefficients of these dimension-six operators parametrize our ignorance of the NP, and they must be determined using all available data.

An important corollary of this approach is that the modifications of the couplings of the Higgs field to the electroweak gauge bosons are related to those of the triple electroweak gauge boson vertices in a model-independent fashion [3,4]. In this Letter, we show that, because of this relation, the analysis of the Higgs boson production data at the LHC and Tevatron is able to furnish bounds on the related triple gauge couplings (TGCs) which are complementary to the direct study of these couplings in gauge boson production.

More specifically, assuming that the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ symmetry is realized linearly, we can write the lowest-order effective Lagrangian for the departures of the SM as

$$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n, \tag{1}$$

where the dimension-six operators $\mathcal{O}_n$ involve gauge bosons, the Higgs boson, and/or fermionic fields with couplings f_n and where Λ is a characteristic scale.

Restricting to P- and C-even operators, there are 20 dimension-six operators relevant to the study of the Higgs couplings [4] barring flavor structure and Hermitian conjugations. Eight of these modify the Higgs couplings to the electroweak gauge bosons plus one operator containing Higgs couplings to gluons. Three out of the 20 operators affect only the Higgs couplings to fermions while the remaining eight modify both the fermionic couplings to the Higgs boson as well as the fermion couplings to the gauge bosons. Triple electroweak gauge couplings are modified by two of these 20 operators, as well as by one operator that only involves the electroweak gauge boson self-couplings, $\mathcal{O}_{WWW}$ [see Eq. (3)].

The use of the equations of motion eliminates three redundant operators from $\mathcal{L}_{\rm eff}$. Moreover, many of these operators are strongly constrained by the precision electroweak measurements which have helped us to establish the SM, such as Z properties at the pole, W decays, low-energy ν scattering, atomic parity violation, flavor changing neutral currents, parity violation in Moller scattering, and $e^+e^- \to f\bar{f}$ at LEP2. For a detailed discussion on the reduction on the number of parameters in our effective Lagrangian, see Ref. [4]. At the end of the day, the effective

Lagrangian relevant to the analysis of Higgs couplings and TGCs reads

$$\mathcal{L}_{\rm eff} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_{\rm bot}}{\Lambda^2}\mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2}\mathcal{O}_{e\Phi,33} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW}, \tag{2}$$

with

$$\begin{gathered}\mathcal{O}_{GG} = \Phi^\dagger\Phi G^a_{\mu\nu}G^{a\mu\nu}, \quad \mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi,\\ \mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}), \quad \mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj}),\\ \mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi), \quad \mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi),\\ \mathcal{O}_{WWW} = {\rm Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho]. \end{gathered}\tag{3}$$

Φ is the Higgs doublet with covariant derivative $D_\mu\Phi = (\partial_\mu + i(1/2)g'B_\mu + ig(\sigma_a/2)W^a_\mu)\Phi$, and $v = 246$ GeV is its vacuum expectation value. $\hat{B}_{\mu\nu} = i(g'/2)B_{\mu\nu}$ and $\hat{W}_{\mu\nu} = i(g/2)\sigma^a W^a_{\mu\nu}$ with $SU(2)_L$ $(U(1)_Y)$ gauge coupling g (g') and Pauli matrices σ^a.

The first six operators in Eq. (2) contribute to Higgs interactions with SM gauge boson, bottom quarks, and tau pairs; see Refs. [3,4] for the explicit form of these interactions.

The last three operators in Eqs. (2) and (3) contribute to the TGCs γW^+W^- and ZW^+W^- that can be parametrized as [13]

$$\mathcal{L}_{WWV} = -ig_{WWV}\Big\{g_1^V(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^+_{\mu\nu}W^{-\nu\rho}V^\mu_\rho\Big\}, \tag{4}$$

where $g_{WW\gamma} = e = gs$ and $g_{WWZ} = gc$ with $s(c)$ being the sine (cosine) of the weak mixing angle. In general, these vertices involve six C and P conserving couplings [13]. Notwithstanding, the electromagnetic gauge invariance requires that $g_1^\gamma = 1$, while the five remaining couplings are related to the dimension-six operators $\mathcal{O}_B$, $\mathcal{O}_W$, and $\mathcal{O}_{WWW}$ as $\kappa^V = 1 + \Delta\kappa^V$ and $g_1^Z = 1 + \Delta g_1^Z$ with

$$\begin{aligned}\Delta\kappa_\gamma &= \frac{g^2v^2}{8\Lambda^2}(f_W + f_B), \qquad \lambda_\gamma = \lambda_Z = \frac{3g^2M_W^2}{2\Lambda^2}f_{WWW},\\ \Delta g_1^Z &= \frac{g^2v^2}{8c^2\Lambda^2}f_W, \qquad \Delta\kappa_Z = \frac{g^2v^2}{8c^2\Lambda^2}(c^2f_W - s^2f_B).\end{aligned}\tag{5}$$

In brief, $\mathcal{O}_B$ and $\mathcal{O}_W$ contribute both to Higgs physics and TGCs, which means that some changes of the couplings of the Higgs field to the vector gauge bosons are related to TGCs due to gauge invariance in a model-independent fashion. In the past, the bounds from TGC searches were used to further constrain the Higgs couplings to electroweak gauge bosons [11]. Conversely, with the present precision attained on the determination of the Higgs couplings, it is possible to reverse the argument and derive the bounds that Higgs data imply on TGCs.

Equation (5) implies that only three of the five TGC couplings are independent in our framework. They can be chosen to be $\Delta\kappa_\gamma$, λ_γ, and Δg_1^Z, while λ_Z and $\Delta\kappa_Z$ are determined by the relations

$$\lambda_Z = \lambda_\gamma, \qquad \Delta\kappa_Z = -\frac{s^2}{c^2}\Delta\kappa_\gamma + \Delta g_1^Z. \tag{6}$$

Routinely, the collider experiments search for anomalous TGC parametrized as Eq. (4) through the analysis of electroweak gauge boson production. In most studies, one or at most two couplings at the time are allowed to deviate from the SM predictions, while the others are fixed to their SM values. In particular, several searches were performed by the LEP, followed by Tevatron, and recently LHC experiments in the constrained framework determined by the relations in Eq. (6), which are usually denoted as the "LEP" scenario.

LEP experiments were sensitive to anomalous TGCs through the W^+W^- and single γ and W productions which yielded information on both WWZ and $WW\gamma$ vertices [14]. We depict in Fig. 1 the bounds obtained in Ref. [14] from the combined analysis of the LEP collaborations in the LEP scenario for $\lambda_\gamma = \lambda_Z = 0$.

Tevatron experiments have also set bounds on TGCs from the combination of WW, WZ, and $W\gamma$ productions

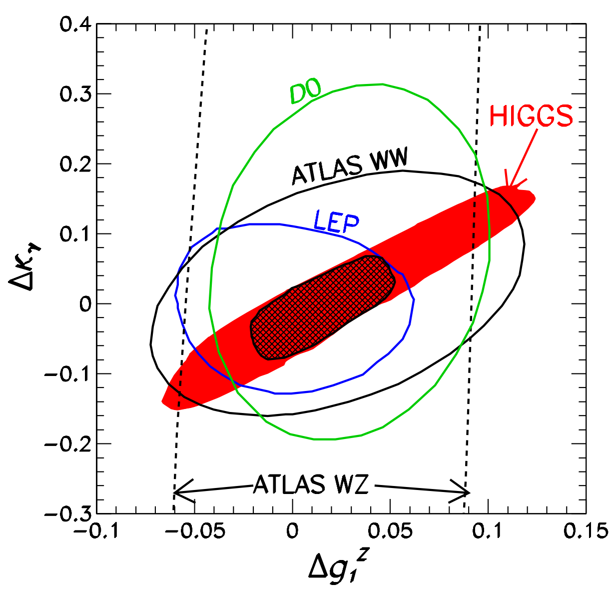

FIG. 1 (color online). The 95% C.L. allowed regions (2 d.o.f.) on the plane $\Delta\kappa_\gamma \otimes \Delta g_1^Z$ from the analysis of the Higgs data from the LHC and Tevatron (filled region) together with the relevant bounds from different TGC studies from collider experiments as labeled in the figure. We also show the estimated constraints obtainable by combining these bounds (hatched region).

in $p\bar{p}$ collisions. In the most recent results [15], D0 combined these data sets containing 0.7 to 8.6 fb^{-1} of integrated luminosity. CDF has presented results from WZ production [16] with an integrated luminosity of 7.1 fb^{-1} and from W^+W^- with 3.6 fb^{-1} [17]. We show in Fig. 1 the bounds obtained from the D0 combined analysis in Ref. [15] for the LEP scenario. These bounds were derived by the experiments for $\lambda_\gamma = \lambda_Z = 0$. Also, D0 results were obtained assuming a form factor for the anomalous TGC $1/(1 + (\hat{s}/\Lambda^2))^2$ with $\Lambda = 2$ TeV. (It is well known that the introduction of anomalous couplings will spoil delicate cancellations in scattering amplitudes, eventually leading to unitarity violation above a certain scale Λ. The way to cure this problem, according to the literature, is to introduce an energy-dependent form factor that dumps the anomalous scattering amplitude growth at high energy.)

The LHC experiments are providing bounds on TGCs [18]. ATLAS studied TGCs in W^+W^- [19], WZ [20], and $W\gamma$ and $Z\gamma$ [21] fully leptonic channels at 7 TeV with an integrated luminosity of 4.6 fb^{-1}. CMS has also constrained TGCs using 7 TeV data on the leptonic channels in WW [22] with 4.92 fb^{-1}, $W\gamma$ and $Z\gamma$ with 5.0 fb^{-1} [23], and WW and WZ productions with two jets in the final state [24] and 5.0 fb^{-1}. We present in Fig. 1 the most sensitive results from the LHC searches in the LEP scenario, i.e., the WW and WZ studies from ATLAS [19,20] (these bounds were derived by ATLAS for $\lambda_\gamma = \lambda_Z = 0$). Notice that the limits on the WWZ vertex from the WZ channel [20] were obtained by a two parameter analysis in terms of $\Delta\kappa_Z$ and Δg_1^Z, and we expressed these bounds in terms of $\Delta\kappa_\gamma$ and Δg_1^Z using Eq. (6). Results on $W\gamma$ searches from both ATLAS and CMS [21,23] are only sensitive to $WW\gamma$, i.e., to $\Delta\kappa_\gamma$ and λ_γ, leading thus to horizontal bands in Fig. 1. However, they are still weaker than the bounds shown from WW and WZ productions. All LHC bounds in Fig. 1 were obtained without the use of form factors.

We now turn our attention to TGC bounds from Higgs data. In Ref. [4], an analysis of the latest Higgs data from the LHC and Tevatron collaborations has been recently updated in this framework to constrain the six-dimensional space spanned by f_g, f_{WW}, f_W, f_B, $f_{\rm bot}$, f_τ. Equation (5) allows us to translate the constraints on f_W and f_B from this analysis to bounds on $\Delta\kappa_\gamma$, $\Delta\kappa_Z$, and Δg_1^Z of which only two are independent. We show the results of the fitting to the Higgs data only in Fig. 1 where we plot the 95% C.L. allowed region in the plane $\Delta\kappa_\gamma \otimes \Delta g_1^Z$ after marginalizing over the other four parameters relevant to the Higgs analysis, f_g, f_{WW}, $f_{\rm bot}$, and f_τ. In other words, we define

$$\begin{aligned}\Delta\chi^2_H(\Delta\kappa_\gamma, \Delta g_1^Z) \\ = \min_{f_g,f_{WW},f_{\rm bot},f_\tau} \Delta\chi^2_H(f_g, f_{WW}, f_{\rm bot}, f_\tau, f_B, f_W). \qquad (7)\end{aligned}$$

So we are not making any additional assumption about the coefficients of the six operators which contribute to the Higgs analysis. Notice also that these bounds obtained from the Higgs data are independent of the value of $\lambda_\gamma = \lambda_Z$. We define the two-dimensional 95% C.L. allowed region from the condition $\Delta\chi^2_H(\Delta\kappa_\gamma, \Delta g_1^Z) \le 5.99$.

Clearly, the present Higgs physics bounds on $\Delta\kappa_\gamma \otimes \Delta g_1^Z$ in Fig. 1 exhibit a non-negligible correlation. This stems from the strong correlation imposed on the high values of f_W and f_B from their tree-level contribution to $Z\gamma$ data, a correlation which is indubitably translated to the $\Delta\kappa_\gamma \otimes \Delta g_1^Z$ plane. The 1σ (68% C.L.) 1 d.o.f. allowed ranges read

$$\begin{gathered}-0.04 \le \Delta g_1^Z \le 0.02, \qquad -0.11 \le \Delta\kappa_\gamma \le 0.02, \\ \text{which imply } -0.02 \le \Delta\kappa_Z \le 0.03. \qquad (8)\end{gathered}$$

Figure 1 also shows that the present constraints on $\Delta\kappa_\gamma \otimes \Delta g_1^Z$ from the analysis of Higgs data are stronger than those coming from direct TGC studies at the LHC. Nevertheless, what is most important is that this figure illustrates the complementarity of the bounds on NP effects originating from the analysis of Higgs signals and from studies of the gauge boson couplings. To estimate the potential of this complementarity, we combine the present bounds derived from Higgs data with those from the TGC analysis from LEP, Tevatron, and LHC shown in Fig. 1. In order to do so, we reconstruct an approximate Gaussian $\chi_i^2(\Delta\kappa_\gamma, \Delta g_1^Z)$, which reproduces each of the 95% C.L. regions for the TGC analysis in the figure (i = LEP, D0, ATLAS WW, ATLAS WZ); i.e., we obtain the best fit point and two-dimensional covariance matrix which better reproduce the curve from the condition $\chi_i^2 = 5.99$. So we write

$$\chi^2_{\rm comb} = \chi^2_H(\Delta\kappa_\gamma, \Delta g_1^Z) + \sum_i \chi_i^2(\Delta\kappa_\gamma, \Delta g_1^Z). \qquad (9)$$

The combined 95% C.L. region is obtained with the condition $\Delta\chi^2_{\rm comb} \le 5.99$. The combined 1σ 1 d.o.f. allowed ranges read

$$\begin{gathered}-0.002 \le \Delta g_1^Z \le 0.026, \qquad -0.034 \le \Delta\kappa_\gamma \le 0.034, \\ \text{which imply } -0.002 \le \Delta\kappa_Z \le 0.029. \qquad (10)\end{gathered}$$

Summarizing, the present data on the Higgs-like particle are consistent with the assumption that the observed state belongs to a light electroweak doublet scalar and that the $SU(2)_L \otimes U(1)_Y$ symmetry is linearly realized, as demonstrated in Ref. [4]. Under these assumptions, indirect NP effects associated with the EWSB sector can be written in terms of an effective Lagrangian whose lowest-order operators are of dimension six. The coefficients of these dimension-six operators parametrize our ignorance of these effects, and our task at hand is to determine them using all the available data. In this general framework, the modifications of the couplings of the Higgs field to electroweak gauge bosons are related to the anomalous triple gauge boson vertex. In this Letter, we have shown that at present, the analysis of the Higgs boson production data at the LHC and Tevatron is able to furnish bounds on the related TGCs which, in some cases, are tighter than those obtained from direct triple gauge boson coupling analysis. In the near future, the LHC collaborations will release their analysis of TGC with the largest statistics of the 8 TeV run. The combination of those with the present results from Higgs data has the potential to furnish the strongest constraints on NP effects on the EWSB sector.

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[1] F. Englert and R. Brout, Phys. Rev. Lett. **13**, 321 (1964); P. W. Higgs, Phys. Rev. Lett. **13**, 508 (1964); Phys. Lett. **12**, 132 (1964); G. Guralnik, C. Hagen, and T. Kibble, Phys. Rev. Lett. **13**, 585 (1964); P. W. Higgs, Phys. Rev. **145**, 1156 (1966); T. Kibble, Phys. Rev. **155**, 1554 (1967).

[2] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **716**, 30 (2012); G. Aad *et al.* (ATLAS Collaboration), Phys. Lett. B **716**, 1 (2012).

[3] T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile, and M. C. Gonzalez-Garcia, Phys. Rev. D **86**, 075013 (2012).

[4] T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile, and M. C. Gonzalez-Garcia, Phys. Rev. D **87**, 015022 (2013); This analysis has been updated including the results presented by the LHC collaborations in March 2013, see also http://hep.if.usp.br/Higgs.

[5] For other post-discovery analyses of the *X*-particle couplings, see also J. Ellis and T. You, J. High Energy Phys. 09 (2012) 123; I. Low, J. Lykken, and G. Shaughnessy, Phys. Rev. D **86**, 093012 (2012); P. P. Giardino, K. Kannike, M. Raidal, and A. Strumia, Phys. Lett. B **718**, 469 (2012); M. Montull and F. Riva, J. High Energy Phys. 11 (2012) 018; J. R. Espinosa, C. Grojean, M. Muhlleitner, and M. Trott, J. High Energy Phys. 12 (2012) 045; D. Carmi, A. Falkowski, E. Kuflik, T. Volansky, and J. Zupan, J. High Energy Phys. 10 (2012) 196; S. Banerjee, S. Mukhopadhyay, and B. Mukhopadhyaya, J. High Energy Phys. 10 (2012) 062; F. Bonnet, T. Ota, M. Rauch, and W. Winter, Phys. Rev. D **86**, 093014 (2012); T. Plehn and M. Rauch, Europhys. Lett. **100**, 11 002 (2012); A. Djouadi, arXiv:1208.3436; B. Batell, S. Gori, and L. T. Wang, J. High Energy Phys. 01 (**2013**) 139; G. Moreau, Phys. Rev. D **87**, 015027 (2013); G. Cacciapaglia, A. Deandrea, G. D. La Rochelle, and J.-B. Flament, arXiv:1210.8120; A. Azatov and J. Galloway, Int. J. Mod. Phys. A **28**, 1330004 (2013).

[6] For results using the data released in Moriond 2013, see A. Falkowski, F. Riva, and A. Urbano, arXiv:1303.1812; J. Ellis and T. You, arXiv:1303.3879; P. P. Giardino, K. Kannike, I. Masina, M. Raidal, and A. Strumia, arXiv:1303.3570; A. Djouadi and G. Moreau, arXiv:1303.6591.

[7] S. Weinberg, Physica (Amsterdam) **96A**, 327 (1979).

[8] W. Buchmuller and D. Wyler, Nucl. Phys. **B268**, 621 (1986); C. N. Leung, S. Love, and S. Rao, Z. Phys. C **31**, 433 (1986); B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, J. High Energy Phys. 10 (2010) 085.

[9] A. De Rujula, M. Gavela, P. Hernandez, and E. Masso, Nucl. Phys. **B384**, 3 (1992).

[10] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Rev. D **48**, 2182 (1993); K. Hagiwara, R. Szalapski, and D. Zeppenfeld, Phys. Lett. B **318**, 155 (1993); K. Hagiwara, S. Matsumoto, and R. Szalapski, Phys. Lett. B **357**, 411 (1995).

[11] M. Gonzalez-Garcia, Int. J. Mod. Phys. A **14**, 3121 (1999); F. de Campos, M. C. Gonzalez-Garcia, and S. F. Novaes, Phys. Rev. Lett. **79**, 5210 (1997); M. C. Gonzalez-Garcia, S. M. Lietti, and S. F. Novaes, Phys. Rev. D **57**, 7045 (1998); O. J. P. Eboli, M. C. Gonzalez-Garcia, S. M. Lietti, and S. F. Novaes, Phys. Lett. B **434**, 340 (1998); M. C. Gonzalez-Garcia, S. M. Lietti, and S. F. Novaes, Phys. Rev. D **59**, 075008 (1999); O. J. P. Eboli, M. C. Gonzalez-Garcia, S. M. Lietti, and S. F. Novaes, Phys. Lett. B **478**, 199 (2000).

[12] G. Passarino, Nucl. Phys. **B868**, 416 (2013).

[13] K. Hagiwara, R. Peccei, D. Zeppenfeld, and K. Hikasa, Nucl. Phys. **B282**, 253 (1987).

[14] LEP collaborations and LEP TGC Working Group, Report No. LEPEWWG/TGC/2003-01.

[15] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **718**, 451 (2012).

[16] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **86**, 031104 (2012).

[17] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **104**, 201801 (2010).

[18] For a study of the sensitivity to TGCs in the early LHC runs, see O. J. P. Eboli, J. Gonzalez-Fraile, and M. C. Gonzalez-Garcia, Phys. Lett. B **692**, 20 (2010), and references therein.

[19] G. Aad *et al.* (ATLAS Collaboration), arXiv:1210.2979.

[20] G. Aad *et al.* (ATLAS Collaboration), Eur. Phys. J. C **72**, 2173 (2012).

[21] G. Aad *et al.* (ATLAS Collaboration), arXiv:1302.1283.

[22] CMS Collaboration, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005.

[23] CMS Collaboration, https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11009.

[24] S. Chatrchyan *et al.* (CMS Collaboration), Eur. Phys. J. C **73**, 2283 (2013).