Implications of CP-violating Top-Higgs Couplings at LHC and Higgs Factories

Archil Kobakhidze$^1$, Ning Liu$^{1,2}$, Lei Wu$^{1,3}$, and Jason Yue$^{1,4}$

$^1$ ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, NSW 2006, Australia

$^2$ Institution of Theoretical Physics, Henan Normal University, Xinxiang 453007, China

$^3$ Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing, Jiangsu 210023, China

$^4$ Department of Physics, National Taiwan Normal University, Taipei 116, Taiwan

Abstract

We utilise the LHC Run-1 and -2 Higgs data to constrain the CP-violating top-Higgs couplings. In order to satisfy the current full Higgs data sets at 2$\sigma$ level, the CP-odd component $C^p_t$ and the CP-even component $C^s_t$ have to be within the ranges $|C^p_t| < 0.37$ and $0.85 < C^s_t < 1.20$, respectively, which is stronger than the LHC Run-1 bound $|C^p_t| < 0.54$ and $0.68 < C^s_t < 1.20$. With the new bound, we explore the impact on the CP-violating top-Higgs couplings in the Higgs production processes $pp \to t\bar{t}h, thj, hh$ at 13 TeV LHC, and $e^+e^- \to hZ, h\gamma$ at future 240 GeV Higgs factories. We find that the cross sections of $pp \to t\bar{t}h$, $pp \to thj$, $pp \to hh$, $e^+e^- \to hZ$ and $e^+e^- \to h\gamma$ can be enhanced up to 1.41, 1.18, 2.20, 1.001 and 1.09 times as large as the SM predictions, respectively. The future precision measurement of the process $e^+e^- \to h\gamma$ with an accuracy of 5% will be able to constrain $|C^p_t| < 0.19$ at most at a 240 GeV $e^+e^-$ Higgs factory.

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I. INTRODUCTION

In the Run-1 of LHC, the existence of the Higgs boson was firmly established\cite{1, 2}. The signal was observed with large significance in four decay channels ($\gamma\gamma$, $ZZ^*$, $WW^*$, $\tau\tau$) and two main production modes (gluon fusion, vector-boson fusion) have been isolated. Currently the LHC is running at a center-of-mass energy of 13 TeV. With the available $\sim 13$ fb$^{-1}$ data, the ATLAS and CMS experiments updated their measurements of the Higgs boson at LHC Run-2. The measured Higgs properties are compatible with the predictions in the Standard Model (SM). Still, due to the large uncertainties, measurements of several Higgs couplings such as that to the top quark, is required to be refined.

Within the Standard Model, the value of the top-Higgs coupling is known to a good accuracy, as it is proportional to the mass of the top quark. Yet, such proportionality can be distorted in models beyond the SM, for example, the non-linear realisation of the electroweak gauge symmetry\cite{3, 4}. Moreover, top-Higgs coupling plays an important role in vacuum stability\cite{5, 6} and electroweak baryogenesis\cite{7–9}. Thus, measurements of the top-Higgs coupling provide a crucial clues to new physics.

The top-Higgs coupling contributes to the main Higgs production channel $gg \rightarrow h$ and the clean Higgs decay channel $h \rightarrow \gamma\gamma$ through the quantum effects at the LHC. These rates are measured to well agree with the SM, therefore serves as strong constraints on the top-Higgs coupling\cite{10–17}. On the other hand, the top-Higgs coupling can affect other important Higgs processes, such as the Higgs pair production at the LHC\cite{18–27}. Therefore, it is meaningful to see how much room is left for the anomalous top-Higgs coupling and its impact on various Higgs processes within the allowed parameter space.

In this work, we perform an updated fit of the most general top-Higgs coupling to the Higgs data collected by LHC Run-1 and -2. Using the bounds on top-Higgs coupling, we examine the effect of anomalous top-Higgs coupling on the production rates of the Higgs processes $pp \rightarrow t\bar{t}h, th_j, hh$ at the LHC and $e^+e^- \rightarrow hZ, h\gamma$ at future lepton colliders, such as ILC, FCC-ee and CEPC.

- The direct measurements of top-Higgs coupling come mainly from the associated production of the top pair with Higgs boson and the single top associated production with the Higgs boson at the LHC. The former has the larger production rate\cite{28, 37}, but the latter can be used to determine the sign of top-Higgs coupling\cite{12, 38, 49}. 

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• The di-Higgs production is the only way to measure the Higgs self-coupling at the LHC, which is dominated by the gluon-gluon fusion mechanism. The cross section of di-Higgs production is $\sim O(10^3)$ smaller than the single Higgs production at the LHC. This is because that there is a strong cancelation between the box diagrams from top-Higgs coupling and the triangle diagrams from the Higgs self-coupling [51]. So, any changes in top-Higgs coupling will affect the determination of the Higgs self-coupling at the LHC.

• The top-Higgs coupling also contributes to the main Higgs production process, $e^+e^- \rightarrow$
$hZ$, via loops at future Higgs factories. The precision measurement of the production rate of $e^+e^- \to hZ$ therefore possibly constrain the top-Higgs coupling. Another interesting process is $e^+e^- \to h\gamma$ \cite{52,54}, which appears at one-loop level in the SM. Such a process is found to be a sensitive probe in testing the CP nature of the top-Higgs coupling since the CP-violating top-Higgs couplings can induce a large forward-backward asymmetry \cite{55}.

**FIG. 4:** Representative Feynman diagrams of the one-loop virtual corrections to the process $e^+e^- \to hZ$ in next-to-leading order at Higgs Factories.

**FIG. 5:** Representative Feynman diagrams of the process $e^+e^- \to h\gamma$ in leading order at Higgs Factories.

The structure of this paper is organised as follows. In Section II, we will briefly introduce the non-standard top-Higgs interaction and the relevant constraints. In Section III, we present the numerical results and discuss the effects of non-standard top-Higgs coupling in the Higgs production processes $pp \to t\bar{t}h, thj, hh$ at 13 TeV LHC, and $e^+e^- \to hZ, h\gamma$ at future 240 GeV Higgs factories. Finally, the conclusions are drawn in Section IV.

II. CONSTRAINTS ON TOP-HIGGS INTERACTION

In the SM, the top-Higgs coupling is a purely scalar interaction. However, in models beyond the SM, such as the non-linear realisation of the electroweak gauge symmetry, the top-Higgs coupling can comprise both scalar and pseudoscalar components. The most general form of the top-Higgs coupling can be parameterised as follows:

$$\mathcal{L} \supset -\frac{m_t}{v} t(C_t^s + iC_t^p \gamma^5)th,$$  \hspace{1cm} (1)
where $m_t$ is the top quark mass and $v$ is the vacuum expectation value of the Higgs field. In the SM, $C^t_s = 1$ and $C^t_p = 0$ at leading order. But the $\mathcal{CP}$-violating component $C^t_p$ can arise from the high order corrections, whose value is expected to be small [56].

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In general, the $\mathcal{CP}$-violating interactions can contribute to the electron, neutron and mercury electric dipole moments (EDMs). Among them, the electron EDM (eEDM) produces the strongest bound on $C^p_t$ [57]. The dominant contribution to the eEDM comes from the diagram with the exchange of photon, which is given by [58]:

$$
\frac{d_e}{e} = \frac{16}{3} \frac{\alpha}{(4\pi)^3} \sqrt{2} G_F m_e \left[ C^s_t C^p_t f_1(x_{t/h}) + C^n_e C^s_t f_2(x_{t/h}) \right],
$$

where $x_{t/h} := m_t^2/m_h^2$ and the loop functions $f_{1,2}(x)$ can be written as [59]:

$$
f_1(x) = \frac{2x}{\sqrt{1-4x}} \left[ \text{Li}_2 \left( 1 - \frac{1 - \sqrt{1-4x}}{2x} \right) - \text{Li}_2 \left( 1 + \frac{1 + \sqrt{1-4x}}{2x} \right) \right],
$$

$$
f_2(x) = (1 - 2x) f_1(x) + 2x (\ln x + 2).$$

Here $\text{Li}_2(x) = -\int_0^x du \ln(1-u)/u$ is the usual dilogarithm. The ACME limit reads [60]:

$$
\left| \frac{d_e}{e} \right| < 8.7 \cdot 10^{-29} \text{ cm},
$$

However, as shown in Eq.[2], such a bound on the coupling $C^p_t$ depend on the assumption of Higgs couplings to the electron, which can vanish by an appropriate tuning of the ratio $C^n_e/C^s_t$. Since the electron-Higgs couplings are practically unobservable at the LHC, we do not impose EDM constraint in this work. The indirect constraints from flavor physics, such as $B_s - \bar{B}_s$ mixing and $B \to X_s \gamma$, remain relatively weak, due to the theoretical uncertainties [57].

![FIG. 6: Two-loop Barr-Zee contributions to the electron EDM.](image-url)
TABLE I: The best-fit values for various Higgs signal strengths \( \mu \) from the CMS and ATLAS 13 TeV experiments, respectively.

| Category       | ATLAS             | CMS             |
|----------------|-------------------|-----------------|
| \( ggF(\gamma\gamma) \) | \(+0.62^{+0.30}_{-0.29} \) [63] | \(+0.77^{+0.25}_{-0.23} \) [65] |
| \( ggF(4\ell) \)          | \(+1.34^{+0.39}_{-0.33} \) [63] | \(+0.96^{+0.40}_{-0.33} \) [66] |
| \( VBF(\gamma\gamma) \)  | \(+2.25^{+0.75}_{-0.75} \) [63] | \(+1.61^{+0.90}_{-0.80} \) [65] |
| \( V_{had}H(\gamma\gamma) \) | \(-0.81^{+2.20}_{-1.88} \) [63] | – |
| \( V_{lep}H(\gamma\gamma) \) | \(+0.68^{+1.71}_{-1.30} \) [63] | – |
| \( t\bar{t}H_{\text{combine}} \) | \(+1.8^{+0.7}_{-0.7} \) [62] | – |
| \( t\bar{t}H(\gamma\gamma) \) | – | \(+1.91^{+1.5}_{-1.2} \) [65] |
| \( t\bar{t}H(3\ell) \)      | – | \(+1.3^{+1.2}_{-1.0} \) [67] |
| \( t\bar{t}H(ss2\ell) \)   | – | \(+2.7^{+1.1}_{-1.0} \) [67] |

Besides, the CP-violating top-Higgs interaction can affect the production rate of \( gg \rightarrow h \) and decay width of \( h \rightarrow \gamma\gamma \). At the LO, the Higgs rates normalised to the SM expectations can be written as:

\[
\frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}} \simeq \left| \frac{1}{4} A_1[m_W] + \left( \frac{3}{4} \right)^2 C_t^s \right|^2 + \left| \left( \frac{3}{4} \right)^2 C_t^p \right|^2
\]

\[
\frac{\sigma(gg \rightarrow h)}{\sigma(gg \rightarrow h)_{\text{SM}}} = \frac{\Gamma(h \rightarrow gg)}{\Gamma(h \rightarrow gg)_{\text{SM}}} \simeq \left| C_t^s \right|^2 + \left| \frac{3}{2} C_t^p \right|^2
\]

with \( A_1[m_W] \approx -8.3 \) for \( m_h \approx 125 \text{ GeV} \). From Eq. 5 we can see that the pseudo-component \( C_t^p \) of \( t\bar{t}h \) has a larger contribution to \( \sigma(gg \rightarrow h) \) than the scalar-component \( C_t^s \). When \( C_t^s \) increases, the ratio of \( \sigma(gg \rightarrow h)/\sigma(gg \rightarrow h)_{\text{SM}} \) becomes larger. However, this observation is not applicable to the ratio \( \Gamma(h \rightarrow \gamma\gamma)/\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}} \), because the contribution of \( C_t^p \) will cancel with \( W \) boson loop.

The database 15.09 of Lilith-1.1.3 [61] have been updated with the new Higgs data listed in Tab. I in the fit, which was performed under the reduced coupling mode. The total number of degrees of freedom, \( n_{\text{dof}} \), is given by the difference between the number of observables, \( n_{\text{obs}} \), and the number of scan parameters, \( n_{\text{para}} \). In our fit, we have in total \( n_{\text{obs}} = 48 \) (35) and \( n_{\text{para}} = 2 \) after (before) LHC Run-2, corresponding to \( n_{\text{dof}} = 46 \) (33).

In Fig. 7 we show the Higgs data constraints on the CP-violating top-Higgs couplings...
FIG. 7: Higgs data fit results of $C^s_t$ and $C^p_t$ for LHC Run-1 (left panel) and Run-1 with Run-2 (right panel). The orange diamond and cyan bullet correspond to the SM value of top-Higgs coupling and the best fit value, respectively. The color map is the value of $\Delta \chi^2$.

after (before) LHC Run-2. All other Higgs couplings are assumed to take the SM values. Points with $\Delta \chi^2 < 2.30$ (6.18, 11.83) correspond to points in a two-dimensional $1\sigma$ ($2\sigma$, $3\sigma$) region in the Gaußian limit. The left panel shows the bounds due to the LHC Run-1 data sets ($\sim 25$ fb$^{-1}$, 7 + 8 TeV). The best fit values of $C^p_t$ and $C^s_t$ give $\chi^2_{\text{min}}/n_{\text{dof}} = 28.96/33$. The bounds $|C^p_t| < 0.54$ and $0.85 < C^s_t < 1.2$ are required to be consistent with the Higgs data at $2\sigma$ level. In the right panel, the LHC Run-1 data sets have been combined with the available LHC Run-2 data sets ($\sim 13$ fb$^{-1}$, 13 TeV), which is shown in Table. The stronger $2\sigma$ limits of $|C^p_t| < 0.37$ and $0.68 < C^s_t < 1.2$ are obtained by using the combined data. This is mainly because that the current signal strengths of diphoton final states in the gluon fusion channel is less than unity, which favors smaller values of $C^p_t$. The best fit values of $C^p_t$ and $C^s_t$ give $\chi^2_{\text{min}}/n_{\text{dof}} = 41.90/46$. Negative values of $C^s_t$ are excluded in both fits.

III. COLLIDER IMPLICATIONS

Given the importance of the top-Higgs coupling in measuring the properties of the Higgs boson, we examine its impact on the production rates of the processes $pp \rightarrow t\bar{t}h$, $thj$, $hh$ at the LHC and $e^+e^- \rightarrow hZ$, $h\gamma$ at future lepton colliders within the allowed parameter ranges
of \( C_t^s \) and \( C_t^p \).

In the numerical calculations, we take the input parameters of the SM as \(^68\):

\[
m_t = 173.07 \text{ GeV}, \quad m_W = 80.385, \quad m_Z = 91.19 \text{ GeV},
\]
\[
m_e = 0.519991 \text{ MeV}, \quad \sin^2 \theta_W = 0.2228, \quad \alpha(m_Z)^{-1} = 127.918.
\]

\[(6)\]

The value of the Higgs mass is taken as \( m_h = 125 \text{ GeV} \). For the strong coupling constant \( \alpha_s(\mu) \), we use the 2-loop evolution with the QCD parameter \( \Lambda^{\alpha_f=5} = 226 \text{ MeV} \). The CTEQ6M parton distribution functions (PDF) \(^69\) are chosen for the calculations. We set the renormalisation scale \( \mu_R \) and factorisation scale \( \mu_F \) to be \( \mu_R = \mu_F = (\Sigma m_f)/2 \). All the amplitudes are generated by \texttt{FeynArts-3.9} \(^70\), and are further reduced by \texttt{FormCalc-8.3} \(^71\). The loop functions are numerically calculated by \texttt{LoopTools-2.8} \(^72\). We keep the electron mass and checked that all the UV divergences in the one-loop processes \( e^+e^-hZ \) and \( e^+e^-h\gamma \) are canceled. The infrared (IR) divergences can appear in the virtual correction of \( e^+e^- \to hZ \), which is removed with the two cutoff phase space slicing method \(^73\) used in our previous works \(^74\)–\(^76\). To show the impact of the CP-violating top-Higgs couplings, we define the signal strength \( \mu \) as,

\[
\mu_i = \frac{\sigma_{i}^{CPV}}{\sigma_{i}^{SM}}
\]

where \( i \in \{t\bar{t}h, \; thj, \; hh, \; hZ, \; h\gamma\} \). The advantage of this ratio is that it has a weak dependence on the renormalization scale.

\[\text{A. } t\bar{t}h, \; thj \; \text{and} \; hh \; \text{production at LHC}\]

In Fig. 8, we show the signal strength \( \mu_{t\bar{t}h, \; thj, \; hh} \) at 13 TeV LHC on the plane of \( C_t^s \) and \( C_t^p \). The yellow contour corresponds to the 2\( \sigma \) limit from Higgs data fit in Fig. 7. From Fig. 8, we can see that the cross sections of \( t\bar{t}h, \; thj \; \text{and} \; hh \) can be enhanced up to 1.41, 1.18 and 2.2 times as large as the SM predictions respectively within the current allowed parameter space. For \( C_t^p = 0 \) and \( C_t^s > 1 \), the cross section of the processes \( pp \to t\bar{t}h, \; tjh, \; hh \) becomes larger with the increase of \( C_t^s \). For \( C_t^s = 1 \), the presence of the pseudo-component \( C_t^p \) will enhance the cross sections of all these Higgs production processes at the LHC. Besides, the signal strength \( \mu_{t\bar{t}h} \) is symmetric around the parameter point \( C_t^s = C_t^p = 0 \), while \( \mu_{tjh} \) and \( \mu_{hh} \) is asymmetric because the processes \( pp \to tjh, \; hh \) can be induced without the top-Higgs coupling.
FIG. 8: The signal strength $\mu_{tth}$, $h\not to$, $hh$ at 13 TeV LHC on the plane of $C'^s_t$ and $C'^p_t$. The yellow contour corresponds to the allowed $2\sigma$ limit in Fig. 7.

B. $hZ$ and $h\gamma$ production at $e^+e^-$ colliders

FIG. 9: Same as Fig. 8 but for the signal strength $\mu_{hZ}$, $h\gamma$ at future $e^+e^-$ colliders with $\sqrt{s} = 240$ GeV.

In Fig. 9 we present the signal strength $\mu_{hZ}$, $h\gamma$ at a $e^+e^-$ collider with $\sqrt{s} = 240$ GeV on the plane of $C'^s_t$ and $C'^p_t$. It is seen here that the CP violating top-Higgs couplings can enhance the SM cross sections of $e^+e^- \rightarrow hZ$, and $e^+e^- \rightarrow h\gamma$ by 0.1% and 9% respectively within the current allowed parameter space. For $C'^p_t = 0$ and $C'^s_t > 1$, the cross section of the process $e^+e^- \rightarrow hZ$ becomes larger with the increase of $C'^s_t$, while the cross section of
the process $e^+e^- \rightarrow h\gamma$ decreases because of the cancelation between top quark loop and $W$ boson loop. It should be noted that the presence of the pseudo-component $C^p_t$ only enhances the cross section of $e^+e^- \rightarrow h\gamma$. The cross section of $e^+e^- \rightarrow hZ$ is independent of $C^p_t$. The future precision measurement of the process $e^+e^- \rightarrow h\gamma$ with an accuracy of 5% will be able to constrain $|C^p_t| < 0.19$ at most at a 240 GeV $e^+e^-$ Higgs factory.

IV. CONCLUSIONS

In this paper, we updated the bound on the CP-violating top-Higgs couplings by combining the LHC Run-1 and -2 Higgs data sets. We find that the CP-odd component $C^p_t$ and the CP-even component $C^e_t$ have been constrained within the ranges $|C^p_t| < 0.37$ and $0.85 < C^e_t < 1.20$ at 2σ level, which is stronger than the previous LHC Run-1 bound $|C^p_t| < 0.54$ and $0.68 < C^e_t < 1.20$. Under the new bound, we examine the impact of the CP-violating top-Higgs couplings in the Higgs production processes $pp \rightarrow t\bar{t}h, thj, hh$ at 13 TeV LHC, and $e^+e^- \rightarrow Zh, h\gamma$ at a future 240 GeV Higgs factory. We note that the cross sections of $pp \rightarrow t\bar{t}h$, $pp \rightarrow thj$, $pp \rightarrow hh$, $e^+e^- \rightarrow hZ$ and $e^+e^- \rightarrow h\gamma$ can be still enhanced up to 1.41, 1.18, 2.2, 1.001 and 1.09 times as large as the SM predictions, respectively. The future precision measurement of the process $e^+e^- \rightarrow h\gamma$ with an accuracy of 5% will be able to constrain $|C^p_t| < 0.19$ at most at a 240 GeV $e^+e^-$ Higgs factory.

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[1] G. Aad et al.(ATLAS Collaboration), Phys. Lett. B 710, 49 (2012).
[2] S. Chatrchyan et al.(CMS Collaboration), Phys. Lett. B 710, 26 (2012).
[3] S. R. Coleman, J. Wess and B. Zumino, Phys. Rev. 177, 2239 (1969). doi:10.1103/PhysRev.177.2239

[4] C. G. Callan, Jr., S. R. Coleman, J. Wess and B. Zumino, Phys. Rev. 177, 2247 (1969). doi:10.1103/PhysRev.177.2247

[5] M. Sher, Phys. Rept. 179, 273 (1989). doi:10.1016/0370-1573(89)90061-6

[6] G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori and A. Strumia, JHEP 1208, 098 (2012) doi:10.1007/JHEP08(2012)098 [arXiv:1205.6497 [hep-ph]].

[7] X. Zhang, S. K. Lee, K. Whisnant and B. L. Young, Phys. Rev. D 50, 7042 (1994) doi:10.1103/PhysRevD.50.7042 [hep-ph/9407259].

[8] A. Kobakhidze, L. Wu and J. Yue, JHEP 1604, 011 (2016) doi:10.1007/JHEP04(2016)011 [arXiv:1512.08922 [hep-ph]].

[9] F. P. Huang, P. H. Gu, P. F. Yin, Z. H. Yu and X. Zhang, Phys. Rev. D 93, no. 10, 103515 (2016) doi:10.1103/PhysRevD.93.103515 [arXiv:1511.03969 [hep-ph]].

[10] A. Kobakhidze, arXiv:1208.5180 [hep-ph].

[11] K. Cheung, J. S. Lee and P. Y. Tseng, Phys. Rev. D 90, 095009 (2014) doi:10.1103/PhysRevD.90.095009 [arXiv:1407.8236 [hep-ph]].

[12] A. Kobakhidze, L. Wu and J. Yue, JHEP 1410, 100 (2014) doi:10.1007/JHEP10(2014)100 [arXiv:1406.1961 [hep-ph]].

[13] M. J. Dolan, P. Harris, M. Jankowiak and M. Spannowsky, Phys. Rev. D 90, 073008 (2014) doi:10.1103/PhysRevD.90.073008 [arXiv:1406.3322 [hep-ph]].

[14] S. Khatibi and M. Mohammadi Najafabadi, Phys. Rev. D 90, no. 7, 074014 (2014) doi:10.1103/PhysRevD.90.074014 [arXiv:1409.6553 [hep-ph]].

[15] Y. T. Chien, V. Cirigliano, W. Dekens, J. de Vries and E. Mereghetti, JHEP 1602, 011 (2016) doi:10.1007/JHEP02(2016)011 [arXiv:1510.00725 [hep-ph]].

[16] V. Cirigliano, W. Dekens, J. de Vries and E. Mereghetti, Phys. Rev. D 94, no. 1, 016002 (2016) doi:10.1103/PhysRevD.94.016002 [arXiv:1603.03049 [hep-ph]].

[17] V. Cirigliano, W. Dekens, J. de Vries and E. Mereghetti, Phys. Rev. D 94, no. 3, 034031 (2016) doi:10.1103/PhysRevD.94.034031 [arXiv:1605.04311 [hep-ph]].

[18] M. J. Dolan, C. Englert and M. Spannowsky, Phys. Rev. D 87, no. 5, 055002 (2013) doi:10.1103/PhysRevD.87.055002 [arXiv:1210.8166 [hep-ph]].

[19] K. Nishiwaki, S. Niyogi and A. Shivaji, JHEP 1404, 011 (2014) doi:10.1007/JHEP04(2014)011
[20] C. Han, X. Ji, L. Wu, P. Wu and J. M. Yang, JHEP 1404, 003 (2014) doi:10.1007/JHEP04(2014)003 [arXiv:1307.3790 [hep-ph]].

[21] N. Liu, S. Hu, B. Yang and J. Han, JHEP 1501, 008 (2015) doi:10.1007/JHEP01(2015)008 [arXiv:1408.4191 [hep-ph]].

[22] F. Goertz, A. Papaefstathiou, L. L. Yang and J. Zurita, JHEP 1504, 167 (2015) doi:10.1007/JHEP04(2015)167 [arXiv:1410.3471 [hep-ph]].

[23] S. Dawson, A. Ismail and I. Low, Phys. Rev. D 91, no. 11, 115008 (2015) doi:10.1103/PhysRevD.91.115008 [arXiv:1504.05596 [hep-ph]].

[24] C. Shen and S. h. Zhu, Phys. Rev. D 92, no. 9, 094001 (2015) doi:10.1103/PhysRevD.92.094001 [arXiv:1504.05626 [hep-ph]].

[25] L. Wu, J. M. Yang, C. P. Yuan and M. Zhang, Phys. Lett. B 747, 378 (2015) doi:10.1016/j.physletb.2015.06.020 [arXiv:1504.06932 [hep-ph]].

[26] C. T. Lu, J. Chang, K. Cheung and J. S. Lee, JHEP 1508, 133 (2015) doi:10.1007/JHEP08(2015)133 [arXiv:1505.00957 [hep-ph]].

[27] Q. H. Cao, B. Yan, D. M. Zhang and H. Zhang, Phys. Lett. B 752, 285 (2016) doi:10.1016/j.physletb.2015.11.045 [arXiv:1508.06512 [hep-ph]].

[28] W. J. Marciano and F. E. Paige, Phys. Rev. Lett. 66, 2433 (1991). doi:10.1103/PhysRevLett.66.2433

[29] R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, R. Pittau and P. Torrielli, Phys. Lett. B 701, 427 (2011) doi:10.1016/j.physletb.2011.06.012 [arXiv:1104.5613 [hep-ph]].

[30] C. Degrande, J. M. Gerard, C. Grojean, F. Maltoni and G. Servant, JHEP 1207, 036 (2012) Erratum: [JHEP 1303, 032 (2013)] doi:10.1007/JHEP07(2012)036, 10.1007/JHEP03(2013)032 [arXiv:1205.1065 [hep-ph]].

[31] N. Liu, Y. Zhang, J. Han and B. Yang, JHEP 1509, 008 (2015) doi:10.1007/JHEP09(2015)008 [arXiv:1503.08537 [hep-ph]].

[32] M. R. Buckley and D. Goncalves, Phys. Rev. Lett. 116, no. 9, 091801 (2016) doi:10.1103/PhysRevLett.116.091801 [arXiv:1507.07926 [hep-ph]].

[33] Q. H. Cao, S. L. Chen and Y. Liu, [arXiv:1602.01934 [hep-ph]].

[34] F. Maltoni, E. Vryonidou and C. Zhang, [arXiv:1607.05330 [hep-ph]].

[35] A. V. Gritsan, R. Rontsch, M. Schulze and M. Xiao, Phys. Rev. D 94, no. 5, 055023 (2016).
3899/12/125004 [arXiv:1402.3050 [hep-ph]].

[53] H. Y. Ren, Chin. Phys. C 39, no. 11, 113101 (2015) doi:10.1088/1674-1137/39/11/113101 [arXiv:1503.08307 [hep-ph]].

[54] Q. H. Cao, H. R. Wang and Y. Zhang, Chin. Phys. C 39, no. 11, 113102 (2015) doi:10.1088/1674-1137/39/11/113102 [arXiv:1505.00654 [hep-ph]].

[55] G. Li, H. R. Wang and S. h. Zhu, Phys. Rev. D 93, no. 5, 055038 (2016) doi:10.1103/PhysRevD.93.055038 [arXiv:1506.06453 [hep-ph]].

[56] J. A. Aguilar-Saavedra, Nucl. Phys. B 821, 215 (2009) doi:10.1016/j.nuclphysb.2009.06.022 [arXiv:0904.2387 [hep-ph]].

[57] J. Brod, U. Haisch and J. Zupan, JHEP 1311, 180 (2013) doi:10.1007/JHEP11(2013)180 [arXiv:1310.1385 [hep-ph]], [arXiv:1310.1385].

[58] S. M. Barr and A. Zee, Phys. Rev. Lett. 65, 21 (1990) Erratum: [Phys. Rev. Lett. 65, 2920 (1990)], doi:10.1103/PhysRevLett.65.21

[59] D. Stockinger, J. Phys. G 34, R45 (2007) doi:10.1088/0954-3899/34/2/R01 [hep-ph/0609168].

[60] J. Baron et al. [ACME Collaboration], Science 343, 269 (2014) doi:10.1126/science.1248213 [arXiv:1310.7534 [physics.atom-ph]].

[61] J. Bernon and B. Dumont, Eur. Phys. J. C 75, no. 9, 440 (2015) doi:10.1140/epjc/s10052-015-3645-9 [arXiv:1502.04138 [hep-ph]].

[62] ATLAS-CONF-2016-068.

[63] ATLAS-CONF-2016-081.

[64] ATLAS-CONF-2016-068.

[65] CMS-PAS-HIG-16-020.

[66] CMS-PAS-HIG-16-033.

[67] CMS-PAS-HIG-16-022.

[68] J. Beringer et al., Particle Data Group, Phys. Rev. D 86, 010001 (2012) and 2013 partial update for the 2014 edition.

[69] P. M. Nadolsky, H. -L. Lai, Q. -H. Cao, J. Huston, J. Pumplin, D. Stump, W. -K. Tung and C. -P. Yuan, Phys. Rev. D 78, 013004 (2008), [arXiv:0802.0007 [hep-ph]].

[70] T. Hahn, Comput. Phys. Commun. 140, 418 (2001).

[71] T. Hahn, M. Perez-Victoria, Comput. Phys. Commun. 118, 153 (1999).

[72] G. J. van Oldenborgh, Phys Commun 66, 1 (1991).
[73] B. W. Harris and J. F. Owens, Phys. Rev. D 65, 094032 (2002) doi:10.1103/PhysRevD.65.094032 [hep-ph/0102128].

[74] N. Liu, Phys. Lett. B 707, 137 (2012) doi:10.1016/j.physletb.2011.12.032 arXiv:1112.3702 [hep-ph].

[75] N. Liu, J. Ren and B. Yang, Phys. Lett. B 731, 70 (2014) doi:10.1016/j.physletb.2014.02.023 arXiv:1310.6192 [hep-ph].

[76] N. Liu, J. Ren, L. Wu, P. Wu and J. M. Yang, JHEP 1404, 189 (2014) doi:10.1007/JHEP04(2014)189 arXiv:1311.6971 [hep-ph].