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New emerging results in Higgs precision analysis updates 2018 after establishment of third-generation Yukawa couplings

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ABSTRACT: We perform global fits of the Higgs boson couplings to all the 7 TeV, 8 TeV, and 13 TeV data available up to the Summer 2018. New measurements at 13 TeV extend to include the Higgs signal strengths exclusively measured in associated Higgs production with top-quark pair and the third-generation Yukawa couplings now have been established. Some important consequences emerge from the global fits. (i) The overall average signal strength of the Higgs boson stands at 2σ above the SM value ($\mu = 1.10 \pm 0.05$). (ii) For the first time the bottom-quark Yukawa coupling shows a preference of the positive sign to the negative one. (iii) The negative top-quark Yukawa coupling is completely ruled out unless there exist additional particles running in the $H\text{-}\gamma\text{-}\gamma$ loop with contributions equal to two times the SM top-quark contribution within about 10 %. (iv) The branching ratio for nonstandard decays of the Higgs boson is now below 8.4% at the 95% confidence level.

KEYWORDS: Phenomenological Models

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1 Introduction

Ever since the discovery of a standard model (SM) like Higgs boson in 2012 [1, 2], the main focus of the LHC experiments has been put on fully establishing its identity. Though the initial data sets till the summer 2013 indicated that it might be different from the SM Higgs boson [3], the data sets collected till the summer 2014 showed that the data is best described by the SM Higgs boson [4]. Ever since then more production channels and decay channels of the Higgs boson are established. On the production side, in addition to gluon fusion (ggF), vector-boson fusion (VBF), the associated production with a $V = W/Z$ boson (VH), and the associated production with a top-quark pair (ttH) have been extensively investigated [5, 6]. On the decay side, $H \rightarrow b\bar{b}$ [7, 8] and $H \rightarrow \tau\tau$ [9, 10] were also very recently established in single measurements.¹ It is the right timing to perform the global fits to all Higgs-boson signal strengths in various scenarios of new physics, generically labeled by **CPC** n and **CPV** n in this work with n standing for the number of fitting parameters.

In this work, we analyze the direct Higgs data collected at the Tevatron and the LHC adopting the formalism suggested in ref. [3] to study the impact of the established third-generation Yukawa couplings on the nature of 125 GeV Higgs. More precisely, we use 3

¹We note that, in combined measurements of CMS and ATLAS, $H \rightarrow \tau\tau$ was already established in Run I [11].

signal strengths measured at the Tevatron [12, 13] and, for the Higgs-boson data at 7 and 8 TeV, we use 20 signal strengths and the correlation matrix obtained in the combined ATLAS and CMS analysis [11]. On the other hand, for the 13 TeV data, we use 41 signal strengths in total. Since any information on correlations between ATLAS and CMS data and those among various channels is not currently available, it is assumed that each data at 13 TeV is Gaussian distributed and correlations among them are ignored accordingly. And, when we combine them, we simply take a χ^2 method. For the details of the 13 TeV data, we refer to appendix B.

Some very interesting results emerge from the new global fits, which were not realized previously.

1. The combined average signal strength of the Higgs boson now stands at a $2\text{-}\sigma$ deviation from the SM value, namely $\mu_{\text{exp}} = 1.10 \pm 0.05$.
2. For the first time the bottom-Yukawa coupling shows statistical difference between the positive and negative signs. Thanks to the discriminating power of the Higgs-gluon vertex S^g the positive sign of the bottom-Yukawa is more preferred than the negative one.
3. Previously in 2014 the fits still allowed the negative sign of the top-Yukawa coupling at the 95% confidence level (CL). Now with more precisely measured signal strengths together with the establishment of the associated production with the top-quark pair, the negative island of the top-Yukawa is now entirely ruled out, except in the scenarios with non-zero ΔS^γ . Even with $\Delta S^\gamma \neq 0$, it has to be adjusted within 10 % of two times the SM top-quark contribution. This tuning is going to be more and more severe as more data accumulate.
4. The nonstandard (or invisible decay) branching ratio of the Higgs boson is now reduced to less than 8.4% at the 95% CL which improves substantially from the previous value of 19%. This is obtained by varying only $\Delta\Gamma_{\text{tot}}$.

The organization of the paper is as follows. In the next section, we describe briefly our formalism to make this work more self-contained. In section 3, we show the data for the Higgs signal strengths. In section 4, we show the results for all the fits. We conclude in section 5. In appendix A, we describe the correspondence between the coupling modifiers of our work with those of the LHCHSWG [14, 15] and of a recent ATLAS paper [16]. In appendix B, we list all the 13 TeV Higgs boson data that we use in our global fitting.

2 Formalism

In order to make the current presentation more self-contained, we include here brief description of the formalism that we use in calculating the signal strengths and chi-squares. We follow the conventions and notations of CPsuperH [17–19] for the Higgs couplings to the SM particles assuming the Higgs boson is a generally CP-mixed state without carrying any definite CP-parity.

- *Higgs couplings to fermions:*

$$\mathcal{L}_{H\bar{f}f} = - \sum_{f=u,d,l} \frac{gm_f}{2M_W} \sum_{i=1}^3 H \bar{f} \left(g_{H\bar{f}f}^S + i g_{H\bar{f}f}^P \gamma_5 \right) f. \quad (2.1)$$

For the SM couplings, $g_{H\bar{f}f}^S = 1$ and $g_{H\bar{f}f}^P = 0$.

- *Higgs couplings to the massive vector bosons:*

$$\mathcal{L}_{HVV} = g M_W \left(g_{HWW} W_\mu^+ W^{-\mu} + g_{HZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) H. \quad (2.2)$$

For the SM couplings, we have $g_{HWW} = g_{HZZ} \equiv g_{HVV} = 1$, respecting the custodial symmetry.

- *Higgs couplings to two photons:* the amplitude for the decay process $H \rightarrow \gamma\gamma$ can be written as

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi v} \left\{ S^\gamma(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^\gamma(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}, \quad (2.3)$$

where $k_{1,2}$ are the momenta of the two photons and $\epsilon_{1,2}$ the wave vectors of the corresponding photons, $\epsilon_{1\perp}^\mu = \epsilon_1^\mu - 2k_1^\mu(k_2 \cdot \epsilon_1)/M_H^2$, $\epsilon_{2\perp}^\mu = \epsilon_2^\mu - 2k_2^\mu(k_1 \cdot \epsilon_2)/M_H^2$ and $\langle \epsilon_1 \epsilon_2 k_1 k_2 \rangle \equiv \epsilon_{\mu\nu\rho\sigma} \epsilon_1^\mu \epsilon_2^\nu k_1^\rho k_2^\sigma$. The decay rate of $H \rightarrow \gamma\gamma$ is proportional to $|S^\gamma|^2 + |P^\gamma|^2$. Including some additional loop contributions from new particles, the scalar and pseudoscalar form factors, retaining only the dominant loop contributions from the third-generation fermions and $W^\pm$, are given by²

$$\begin{aligned} S^\gamma(M_H) &= 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^S F_{sf}(\tau_f) - g_{HWW} F_1(\tau_W) + \Delta S^\gamma, \\ P^\gamma(M_H) &= 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^\gamma, \end{aligned} \quad (2.4)$$

where $\tau_x = M_H^2/4m_x^2$, $N_C = 3$ for quarks and $N_C = 1$ for taus, respectively. The additional contributions ΔS^γ and ΔP^γ are assumed to be real in our work, as there are unlikely any new charged particles lighter than $M_H/2$.

Taking $M_H = 125.09$ GeV, we find that

$$\begin{aligned} S^\gamma &\simeq -8.34 g_{HWW} + 1.76 g_{H\bar{t}t}^S + (-0.015 + 0.017 i) g_{H\bar{b}b}^S \\ &\quad + (-0.024 + 0.022 i) g_{H\bar{\tau}\tau}^S + (-0.007 + 0.005 i) g_{H\bar{c}c}^S + \Delta S^\gamma \\ P^\gamma &\simeq 2.78 g_{H\bar{t}t}^P + (-0.018 + 0.018 i) g_{H\bar{b}b}^P \\ &\quad + (-0.025 + 0.022 i) g_{H\bar{\tau}\tau}^P + (-0.007 + 0.005 i) g_{H\bar{c}c}^P + \Delta P^\gamma \end{aligned} \quad (2.5)$$

giving $S_{\text{SM}}^\gamma = -6.62 + 0.044 i$ and $P_{\text{SM}}^\gamma = 0$.

²For the loop functions of $F_{sf,pf,1}(\tau)$, we refer to, for example, ref. [17].

- *Higgs couplings to two gluons*: similar to $H \rightarrow \gamma\gamma$, the amplitude for the decay process $H \rightarrow gg$ can be written as

$$\mathcal{M}_{ggH} = -\frac{\alpha_s M_H^2 \delta^{ab}}{4\pi v} \left\{ S^g(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^g(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\}, \quad (2.6)$$

where a and b ($a, b = 1$ to 8) are indices of the eight SU(3) generators in the adjoint representation. The decay rate of $H \rightarrow gg$ is proportional to $|S^g|^2 + |P^g|^2$.³ Again, including some additional loop contributions from new particles, the scalar and pseudoscalar form factors are given by

$$\begin{aligned} S^g(M_H) &= \sum_{f=b,t} g_{H\bar{f}f}^S F_{sf}(\tau_f) + \Delta S^g, \\ P^g(M_H) &= \sum_{f=b,t} g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^g. \end{aligned} \quad (2.7)$$

The additional contributions ΔS^g and ΔP^g are assumed to be real again.

Taking $M_H = 125.09$ GeV, we find that

$$\begin{aligned} S^g &\simeq 0.688 g_{H\bar{t}t}^S + (-0.037 + 0.050 i) g_{H\bar{b}b}^S + \Delta S^g, \\ P^g &\simeq 1.047 g_{H\bar{t}t}^P + (-0.042 + 0.051 i) g_{H\bar{b}b}^P + \Delta P^g, \end{aligned} \quad (2.8)$$

giving $S_{\text{SM}}^g = 0.651 + 0.050 i$ and $P_{\text{SM}}^g = 0$.

- *Higgs couplings to Z and γ* : the amplitude for the decay process $H \rightarrow Z(k_1, \epsilon_1)\gamma(k_2, \epsilon_2)$ can be written as

$$\mathcal{M}_{Z\gamma H} = -\frac{\alpha}{2\pi v} \left\{ S^{Z\gamma}(M_H) [k_1 \cdot k_2 \epsilon_1^* \cdot \epsilon_2^* - k_1 \cdot \epsilon_2^* k_2 \cdot \epsilon_1^*] - P^{Z\gamma}(M_H) \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\} \quad (2.9)$$

where $k_{1,2}$ are the momenta of the Z boson and the photon (we note that $2k_1 \cdot k_2 = M_H^2 - M_Z^2$), $\epsilon_{1,2}$ are their polarization vectors. The scalar and pseudoscalar form factors can be found in ref. [3].

Finally, we define the ratios of the effective Higgs couplings to gg , $\gamma\gamma$, and $Z\gamma$ relative to the SM ones as follows:

$$C_g \equiv \sqrt{\frac{|S^g|^2 + |P^g|^2}{|S_{\text{SM}}^g|^2}}; \quad C_\gamma \equiv \sqrt{\frac{|S^\gamma|^2 + |P^\gamma|^2}{|S_{\text{SM}}^\gamma|^2}}; \quad C_{Z\gamma} \equiv \sqrt{\frac{|S^{Z\gamma}|^2 + |P^{Z\gamma}|^2}{|S_{\text{SM}}^{Z\gamma}|^2}}. \quad (2.10)$$

Note that the ratios of decay rates relative to the SM are given by $|C_g|^2$, $|C_\gamma|^2$, and $|C_{Z\gamma}|^2$, respectively.

The theoretical signal strength may be written as the product

$$\hat{\mu}(\mathcal{P}, \mathcal{D}) \simeq \hat{\mu}(\mathcal{P}) \hat{\mu}(\mathcal{D}) \quad (2.11)$$

³Note that the production rate of $gg \rightarrow H$ at the Higgs peak is also proportional to $|S^g|^2 + |P^g|^2$ in our formalism.

where $\mathcal{P} = \text{ggF, VBF, VH, ttH}$ denote the production mechanisms and $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\bar{\tau}$ the decay channels. More explicitly, we are taking

$$\begin{aligned}\hat{\mu}(\text{ggF}) &= \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{|S_{\text{SM}}^g(M_H)|^2}, \\ \hat{\mu}(\text{VBF}) &= g_{HWW, HZZ}^2, \\ \hat{\mu}(\text{VH}) &= g_{HWW, HZZ}^2, \\ \hat{\mu}(\text{ttH}) &= (g_{H\bar{t}t}^S)^2 + (g_{H\bar{t}t}^P)^2;\end{aligned}\tag{2.12}$$

and

$$\hat{\mu}(\mathcal{D}) = \frac{B(H \rightarrow \mathcal{D})}{B(H_{\text{SM}} \rightarrow \mathcal{D})}\tag{2.13}$$

with

$$B(H \rightarrow \mathcal{D}) = \frac{\Gamma(H \rightarrow \mathcal{D})}{\Gamma_{\text{tot}}(H) + \Delta\Gamma_{\text{tot}}}\tag{2.14}$$

Note that we introduce an arbitrary non-SM contribution $\Delta\Gamma_{\text{tot}}$ to the total decay width. Incidentally, $\Gamma_{\text{tot}}(H)$ becomes the SM total decay width when $g_{H\bar{f}f}^S = 1$, $g_{H\bar{f}f}^P = 0$, $g_{HWW, HZZ} = 1$, $\Delta S^{\gamma, g, Z\gamma} = \Delta P^{\gamma, g, Z\gamma} = 0$.

The experimentally observed signal strengths should be compared to the theoretical ones summed over all production mechanisms:

$$\mu(\mathcal{Q}, \mathcal{D}) = \sum_{\mathcal{P}=\text{ggF, VBF, VH, ttH}} C_{\mathcal{Q}\mathcal{P}} \hat{\mu}(\mathcal{P}, \mathcal{D})\tag{2.15}$$

where $\mathcal{Q}$ denote the experimentally defined channel involved with the decay $\mathcal{D}$ and the decomposition coefficients $C_{\mathcal{Q}\mathcal{P}}$ may depend on the relative Higgs production cross sections for a given Higgs-boson mass, experimental cuts, etc.

The χ^2 associated with an uncorrelated observable is

$$\chi^2(\mathcal{Q}, \mathcal{D}) = \frac{[\mu(\mathcal{Q}, \mathcal{D}) - \mu^{\text{EXP}}(\mathcal{Q}, \mathcal{D})]^2}{[\sigma^{\text{EXP}}(\mathcal{Q}, \mathcal{D})]^2},\tag{2.16}$$

where $\sigma^{\text{EXP}}(\mathcal{Q}, \mathcal{D})$ denotes the experimental error. For n correlated observables, we use

$$\chi_n^2 = \sum_{i,j=1}^n (\mu_i - \mu_i^{\text{EXP}}) (V^{-1})_{ij} (\mu_j - \mu_j^{\text{EXP}}),\tag{2.17}$$

where V is a $n \times n$ covariance matrix whose (i, j) component is given by

$$V_{ij} = \rho_{ij} \sigma_i^{\text{EXP}} \sigma_j^{\text{EXP}}$$

with ρ denoting the relevant $n \times n$ correlation matrix. Note $\rho_{ij} = \rho_{ji}$, $\rho_{ii} = 1$, and if $\rho_{ij} = \delta_{ij}$, χ_n^2 reduces to

$$\chi_n^2 = \sum_{i=1}^n \frac{(\mu_i - \mu_i^{\text{EXP}})^2}{(\sigma_i^{\text{EXP}})^2},$$

i.e., the sum of χ^2 of each uncorrelated observable.

Channel	Signal strength μ	$M_H(\text{GeV})$	Production mode				$\chi^2_{\text{SM}}(\text{each})$
	c.v $\pm$ error		ggF	VBF	VH	ttH	
Tevatron (Nov. 2012)							
Combined $H \rightarrow \gamma\gamma$ [12]	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	—	2.60
Combined $H \rightarrow WW^{(*)}$ [12]	$0.85^{+0.88}_{-0.81}$	125	78%	5%	17%	—	0.03
VH tag $H \rightarrow b\bar{b}$ [13]	$1.59^{+0.69}_{-0.72}$	125	—	—	100%	—	0.67
$\chi^2_{\text{SM}}(\text{subtot}):$							3.30

Table 1. (*Tevatron: 1.96 TeV*) The signal strengths data from Tevatron (10.0 fb^{-1} at 1.96 TeV).

Production mode	Decay mode				
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^+\tau^-$
ggF	$1.10^{+0.23}_{-0.22}$	$1.13^{+0.34}_{-0.31}$	$0.84^{+0.17}_{-0.17}$	—	$1.0^{+0.6}_{-0.6}$
VBF	$1.3^{+0.5}_{-0.5}$	$0.1^{+1.1}_{-0.6}$	$1.2^{+0.4}_{-0.4}$	—	$1.3^{+0.4}_{-0.4}$
WH	$0.5^{+1.3}_{-1.2}$	—	$1.6^{+1.2}_{-1.0}$	$1.0^{+0.5}_{-0.5}$	$-1.4^{+1.4}_{-1.4}$
ZH	$0.5^{+3.0}_{-2.5}$	—	$5.9^{+2.6}_{-2.2}$	$0.4^{+0.4}_{-0.4}$	$2.2^{+2.2}_{-1.8}$
ttH	$2.2^{+1.6}_{-1.3}$	—	$5.0^{+1.8}_{-1.7}$	$1.1^{+1.0}_{-1.0}$	$-1.9^{+3.7}_{-3.3}$
$\chi_{\text{SM}}^2(\text{subtot}): 19.93$					

Table 2. (*LHC: 7+8 TeV*) Combined ATLAS and CMS data on signal strengths from table 8 of ref. [11].

Production mode	Decay mode					$\mu_{\text{combined}}^{\text{prod}}$	$\chi_{\text{SM}}^2(\chi_{\text{min}}^2)$
	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ^{(*)}$	$H \rightarrow WW^{(*)}$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau^+\tau^-$		
ggF	$1.02^{+0.12}_{-0.11}$	$1.09^{+0.11}_{-0.11}$	$1.29^{+0.16}_{-0.16}$	$2.51^{+2.43}_{-2.01}$	$1.06^{+0.40}_{-0.37}$	$1.11^{+0.07}_{-0.07}$	5.42(3.15)
VBF	$1.23^{+0.32}_{-0.31}$	$1.51^{+0.59}_{-0.59}$	$0.54^{+0.32}_{-0.31}$	—	$1.15^{+0.36}_{-0.34}$	$1.02^{+0.18}_{-0.18}$	7.53(7.51)
VH/WH	$1.42^{+0.51}_{-0.51}$	$0.71^{+0.65}_{-0.65}$	$3.27^{+1.88}_{-1.70}$	$1.07^{+0.23}_{-0.22}$	$3.39^{+1.68}_{-1.54}$	$1.15^{+0.20}_{-0.19}$	7.05(6.44)
ZH	—	—	$1.00^{+1.57}_{-1.00}$	$1.20^{+0.33}_{-0.31}$	$1.23^{+1.62}_{-1.35}$	$1.19^{+0.32}_{-0.30}$	0.45(0.02)
ttH	$1.36^{+0.38}_{-0.37}$	$0.00^{+0.53}_{-0.00}$	—	$0.91^{+0.45}_{-0.43}$	—	$0.93^{+0.24}_{-0.24}$	5.96(5.86)
ttH (excl.)	$1.39^{+0.48}_{-0.42}$	—	$1.59^{+0.44}_{-0.43}$	$0.77^{+0.36}_{-0.35}$	$0.87^{+0.73}_{-0.73}$	$1.16^{+0.22}_{-0.22}$	4.17(3.62)
$\mu_{\text{combined}}^{\text{dec}}$	$1.10^{+0.10}_{-0.10}$	$1.05^{+0.11}_{-0.11}$	$1.20^{+0.14}_{-0.13}$	$1.05^{+0.19}_{-0.19}$	$1.15^{+0.24}_{-0.23}$	$1.10^{+0.06}_{-0.06}$	
$\chi_{\text{SM}}^2(\chi_{\text{min}}^2)$	6.83(5.72)	9.13(8.88)	9.48(7.32)	1.56(1.51)	3.58(3.20)		30.58(27.56)

Table 3. (*LHC: 13 TeV*) Combined ATLAS and CMS (13 TeV) data on signal strengths. The $\mu_{\text{combined}}^{\text{dec}}$ ($\mu_{\text{combined}}^{\text{prod}}$) represents the combined signal strength for a specific decay (production) channel by summing all the production (decay) modes, and χ_{min}^2 are the corresponding minimal chi-square values. In the VH/WH row, the production mode for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)}$ is VH while it is WH for $H \rightarrow WW^{(*)}$ and $H \rightarrow \tau^+\tau^-$; for the remaining decay mode $H \rightarrow b\bar{b}$, we combine the two signal strengths from WH and VH, see table 12.

3 Results on Higgs signal strength data

In our work, we use the direct Higgs data collected at the Tevatron and the LHC. We use 3 signal strengths measured at the Tevatron, see table 1. The Higgs-boson data at 7 and 8 (7+8) TeV used in this analysis are the signal strengths obtained from a combined ATLAS and CMS analysis [11], see table 2. We also take into account the correlation matrix given in figure 27 of ref. [11]. On the other hand, the 13 TeV data are still given separately by

ATLAS and CMS and in different production and decay channels.⁴ In total, the number of signal strengths considered is $3(1.96 \text{ TeV}) + 20(7 + 8 \text{ TeV}) + 41(13 \text{ TeV}) = 64$.

Precaution is noted before we show the combined results of ATLAS and CMS. In each of the data, there are statistical, systematic, and theoretical uncertainties. Especially, the latter one, e.g., uncertainties coming from factorization scale, renormalization scale, higher order corrections, is correlated between ATLAS and CMS. Since no such information is available at the time of writing, we only combine them with a simple χ^2 method and assuming each data is Gaussian distributed. Our finding of 2 sigma excess in the overall signal strength is to be taken cautiously.

At 7+8 TeV, we use the combined average signal strengths given in ref. [11] in which the experimental correlations are considered. At 1.96 TeV and 13 TeV, we combine signal strengths of various channels using a simple χ^2 method and assuming each is Gaussian distributed. The combined signal strength at 1.96 TeV is 1.44 ± 0.55 and, at 13 TeV, the combined ATLAS and CMS signal strengths for each production and decay channel are presented in table 3. Before we go to the global fits, we would like to point out a few peculiar features in the data sets, and the average signal strengths.

1. The combined overall signal strength at 7+8 TeV is $\mu_{7+8\text{TeV}} = 1.09^{+0.11}_{-0.10}$ [11], which is larger than the SM value by slightly less than 1σ .
2. At 13 TeV, from table 3, it is clear that all decay channels show slight excess over the SM value of 1.0, especially the $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^*$ channels.
3. Again from table 3, almost all production modes, except for ttH, show excess above the SM, especially the gluon fusion (ggF).
4. The 13 TeV data shows similar deviations in both ATLAS and CMS results: $\mu_{13\text{TeV}}^{\text{ATLAS}} = 1.09 \pm 0.08$ and $\mu_{13\text{TeV}}^{\text{CMS}} = 1.1^{+0.09}_{-0.08}$. By combining these two results we obtain

$$\mu_{13\text{TeV}} = 1.10 \pm 0.06$$

which is about 1.67σ above the SM.

5. Finally, we combine all the signal strengths for the Tevatron at 1.96 TeV, and for 7 + 8 and 13 TeV ATLAS and CMS, and thus obtain

$$\mu_{\text{All}} = 1.10 \pm 0.05$$

which indicates a 2σ deviation from the SM value.

We summarize the results in table 4.

Here and in the following section, we will present two statistical measures: (i) goodness of fit quantifying the agreement within observables in a given fit, and (ii) p -value of a given

⁴For the details of the 13 TeV data sets used in this work, see appendix B.

Energy	ATLAS	CMS	Combined
1.96 TeV [table 1]			1.44 ± 0.55
7+8 TeV [11]	$1.20^{+0.15}_{-0.14}$	$0.97^{+0.14}_{-0.13}$	$1.09^{+0.11}_{-0.10}$
13 TeV [table 3]	1.09 ± 0.08	$1.11^{+0.09}_{-0.08}$	1.10 ± 0.06
			1.10 ± 0.05

Table 4. Combined average signal strengths for the Tevatron at 1.96 TeV, and for ATLAS and CMS at 7 + 8 TeV and 13 TeV.

fit hypothesis against the SM null hypothesis. Goodness of fit is expressed in terms of an integral, which is given by

$$\text{Goodness of fit} = \int_{\chi^2}^{\infty} f[x, n] dx$$

where the probability density function is given by

$$f[x, n] = \frac{x^{n/2-1} e^{-x/2}}{2^{n/2} \Gamma(n/2)},$$

n is the degree of freedom, and $\Gamma(n/2)$ is the gamma function. The rule of thumb is that when the value of χ^2 per degree of freedom is less than around 1, it is a good fit.

On the other hand, the p -value of the given fit hypothesis (test hypothesis) with m fitting parameters against the SM null hypothesis is given by

$$p\text{-value} = \int_{\Delta\chi^2}^{\infty} f[x, m] dx,$$

where $\Delta\chi^2$ in the lower limit of the integral is equal to chi-square difference between the best-fit point of the fit hypothesis and the SM one: $\Delta\chi^2 = \chi_{\text{SM}}^2 - \chi_{\text{min}}^2$. This p -value represents the probability that the test hypothesis is a fluctuation of the SM null hypothesis. A large p -value means that the test hypothesis is very similar to the SM null hypothesis. For example, in table 5 the **CPC1** case (with 1 fitted parameter) has a $\Delta\chi^2 = 53.81 - 51.44 = 2.37$ corresponding to a p -value of 0.124. For **CPC2** case (with 2 fitted parameters) has $\Delta\chi^2 = 53.81 - 51.87 = 1.94$ corresponding to a p -value of 0.379. From these two fits we can easily see that the SM null hypothesis is more similar to the **CPC2** best fit-point. According to the p -values in table 5, the SM is more consistent with the fits with more parameters.

4 Results on global fits

We perform global fits in which one or more parameters are varied. They are categorized into CP-conserving (**CPC**) and CP-violating (**CPV**) fits, because the current data still allows the observed Higgs boson to be a mixture of CP-even and CP-odd states. Assuming generation independence for the normalized Yukawa couplings of $g_{H\bar{f}f}^{S,P}$, we use the following notation for the parameters in the fits:

$$\begin{aligned} C_u^S &= g_{H\bar{u}u}^S, & C_d^S &= g_{H\bar{d}d}^S, & C_\ell^S &= g_{H\bar{\ell}\ell}^S; & C_w &= g_{HWW}, & C_z &= g_{HZZ}; \\ C_u^P &= g_{H\bar{u}u}^P, & C_d^P &= g_{H\bar{d}d}^P, & C_\ell^P &= g_{H\bar{\ell}\ell}^P. \end{aligned} \quad (4.1)$$

In most of the fits, we keep the custodial symmetry between the W and Z bosons by taking $C_v \equiv C_w = C_z$. However, in the last CP-conserving scenario (**CPCX4**), we adopt $C_w \neq C_z$, which is motivated by the data.

4.1 CP conserving fits

In CP-conserving fits, we are varying $C_u^S, C_d^S, C_\ell^S, C_{v;w,z}, \Delta S^g, \Delta S^\gamma$, and $\Delta\Gamma_{\text{tot}}$ while taking $C_u^P = C_d^P = C_\ell^P = \Delta P^\gamma = \Delta P^g = 0$. All the CP-conserving fits considered in this work are listed here:

- **CPC1**: vary $\Delta\Gamma_{\text{tot}}$ while keeping $C_u^S = C_d^S = C_\ell^S = C_v = 1$ and $\Delta S^\gamma = \Delta S^g = 0$.
- **CPC2**: vary ΔS^γ and ΔS^g while keeping $C_u^S = C_d^S = C_\ell^S = C_v = 1$ and $\Delta\Gamma_{\text{tot}} = 0$.
- **CPC3**: vary $\Delta S^\gamma, \Delta S^g$ and $\Delta\Gamma_{\text{tot}}$ while keeping $C_u^S = C_d^S = C_\ell^S = C_v = 1$.
- **CPC4**: vary $C_u^S, C_d^S, C_\ell^S, C_v$ while keeping $\Delta S^\gamma = \Delta S^g = \Delta\Gamma_{\text{tot}} = 0$.
- **CPC6**: vary $C_u^S, C_d^S, C_\ell^S, C_v, \Delta S^\gamma, \Delta S^g$ while keeping $\Delta\Gamma_{\text{tot}} = 0$.
- **CPCN2**: vary C_u^S, C_v while keeping $C_d^S = C_\ell^S = 1$, and $\Delta S^\gamma = \Delta S^g = \Delta\Gamma_{\text{tot}} = 0$.
- **CPCN3**: vary $C_u^S, C_v, \Delta S^\gamma$ while keeping $C_d^S = C_\ell^S = 1$ and $\Delta S^g = \Delta\Gamma_{\text{tot}} = 0$.
- **CPCN4**: vary $C_u^S, C_v, \Delta S^\gamma, \Delta S^g$ while keeping $C_d^S = C_\ell^S = 1$ and $\Delta\Gamma_{\text{tot}} = 0$.
- **CPCX2**: vary $C_v, \Delta\Gamma_{\text{tot}}$ while keeping $C_u^S = C_d^S = C_\ell^S = 1$, and $\Delta S^\gamma = \Delta S^g = 0$.
- **CPCX3**: vary $C_u^S, C_v, \Delta S^g$ while keeping $C_d^S = C_\ell^S = 1$ and $\Delta S^\gamma = \Delta\Gamma_{\text{tot}} = 0$.
- **CPCX4**: vary $C_u^S, C_w, C_z, \Delta S^g$ while keeping $C_d^S = C_\ell^S = 1$ and $\Delta S^\gamma = \Delta\Gamma_{\text{tot}} = 0$.

Note that **CPC1** to **CPC6** were those originally in our first Higgcision paper [3] while **CPCN2** to **CPCN4** were those studied in our 2014 update paper [4]. The **CPCX2** to **CPCX4** are new in this work. The reason why we study more scenarios here is because we want to fully understand the effects of having ΔS^g alone, in order to discriminate the contribution from the bottom-Yukawa coupling to Higgs production. In doing so we find that the effect of the bottom-Yukawa coupling becomes sizable in the Higgs-gluon-gluon vertex: numerically flipping the sign of bottom-Yukawa coupling can cause more than 10% change in $|S^g|$ while it is less than 0.5% in $|S^\gamma|$.

4.1.1 CPC1 to CPC6

The fitting results for **CPC1** to **CPC6** are shown in table 5. The corresponding figures for confidence regions are depicted in figure 1 to figure 5. In the following, we are going through each fit one by one.

In **CPC1**, the best-fit value for $\Delta\Gamma_{\text{tot}}$ is

$$\Delta\Gamma_{\text{tot}} = -0.285^{+0.18}_{-0.17} \text{ MeV}$$

Cases	CPC1	CPC2	CPC3	CPC4	CPC6
Parameters	Vary $\Delta\Gamma_{\text{tot}}$	Vary ΔS^γ ΔS^g	Vary ΔS^γ $\Delta S^g, \Delta\Gamma_{\text{tot}}$	Vary C_u^S, C_d^S , C_ℓ^S, C_v	Vary $C_u^S, C_d^S, C_\ell^S, C_v$ $\Delta S^\gamma, \Delta S^g$
After ICHEP 2018					
C_u^S	1	1	1	$1.001^{+0.056}_{-0.055}$	$1.033^{+0.079}_{-0.082}$
C_d^S	1	1	1	$0.962^{+0.101}_{-0.101}$	$0.945^{+0.109}_{-0.105}$
C_ℓ^S	1	1	1	$1.024^{+0.093}_{-0.093}$	$1.018^{+0.095}_{-0.094}$
C_v	1	1	1	$1.019^{+0.044}_{-0.045}$	$1.012^{+0.047}_{-0.048}$
ΔS^γ	0	$-0.226^{+0.32}_{-0.32}$	$-0.150^{+0.32}_{-0.33}$	0	$-0.128^{+0.368}_{-0.369}$
ΔS^g	0	$0.016^{+0.025}_{-0.025}$	$-0.003^{+0.034}_{-0.031}$	0	$-0.032^{+0.061}_{-0.057}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	$-0.285^{+0.18}_{-0.17}$	0	$-0.247^{+0.31}_{-0.27}$	0	0
χ^2/dof	51.44/63	51.87/62	51.23/61	50.79/60	50.46/58
goodness of fit	0.851	0.817	0.809	0.796	0.749
p -value	0.124	0.379	0.461	0.554	0.764

Table 5. CPC: the best-fitted values in various CP conserving fits and the corresponding chi-square per degree of freedom and goodness of fit. The p -value for each fit hypothesis against the SM null hypothesis is also shown. For the SM, we obtain $\chi^2 = 53.81$, $\chi^2/dof = 53.81/64$, and so the goodness of fit = 0.814.

Figure 1. CPC1: $\Delta\chi^2$ from the minimum versus $\Delta\Gamma_{\text{tot}}$ with only $\Delta\Gamma_{\text{tot}}$ varying in the fit. The best-fit point is denoted by the triangle.

which is 1.6σ below zero. The p -value of this fit is 0.851, which is indeed better than the SM (p -value = 0.814). This finding is consistent with the average signal strength $\mu_{\text{All}} = 1.10 \pm 0.05$. Nevertheless, we do not recall any new physics models that reduce the total decay width. From the fit we can determine the upper limit for $\Delta\Gamma_{\text{tot}}$. The 95% CL allowed range for $\Delta\Gamma_{\text{tot}} = -0.285^{+0.38}_{-0.32}$, as shown in figure 1. Assuming the fit is consistent with the SM, the 95% CL upper limit for $\Delta\Gamma_{\text{tot}} = 0.38$ MeV (we simply take the central value equal to zero and use the upper error as the upper limit), which translates to

Figure 2. CPC2: the confidence-level regions of the fit by varying ΔS^γ and ΔS^g only in (a) $(\Delta S^\gamma, \Delta S^g)$ plane and (b) in the corresponding (C_γ, C_g) plane. The contour regions shown are for $\Delta\chi^2 \leq 2.3$ (red), 5.99 (green), and 11.83 (blue) above the minimum, which correspond to confidence levels of 68.3%, 95%, and 99.7%, respectively. The best-fit point is denoted by the triangle.

a branching ratio

$$B(H \rightarrow \text{nonstandard}) < 8.4\%,$$

which improves significantly from the previous value of 19% [4].

In **CPC2**, we vary ΔS^g and ΔS^γ — the vertex factors for Hgg and $H\gamma\gamma$, respectively. This scenario accounts for additional charged particles running in the loop of $H\gamma\gamma$ vertex and additional colored particles running in the loop of Hgg vertex. The best-fit point $(\Delta S^\gamma, \Delta S^g) = (-0.226, 0.016)$ shows an increase of 3.4% and 2.4% in $|S^\gamma|$ and $|S^g|$, respectively. We note that the error of ΔS^g is now ± 0.025 , which is numerically smaller than the SM bottom-quark contribution of -0.037 to the real part of S^g , see eq. (2.8), alerting that we have reached the sensitivity to probe the sign of the bottom-quark Yukawa coupling in gluon fusion. The p -value of the best-fit point is about as the SM one. In figure 2, we show the confidence-level regions of the fit for $\Delta\chi^2 \leq 2.3$ (red), 5.99 (green), and 11.83 (blue) above the minimum, which correspond to confidence levels of 68.3%, 95%, and 99.7%, respectively. The corresponding regions for (C^γ, C^g) are also shown in the right panel.

In **CPC3**, $\Delta\Gamma_{\text{tot}}$, ΔS^g , and ΔS^γ are the varying parameters. The best-fit point shows that the data prefer modification of $\Delta\Gamma_{\text{tot}}$ to accommodate the data rather than the other two parameters. It implies that the excesses are seen in most channels, not just the diphoton channel. Nevertheless, the p -value of this fit is very similar to **CPC2** and the SM. On the other hand, the better p -value of **CPC1** indicates that the data prefer enhancement in all channels, instead of a particular one. The confidence-level regions of the fit are shown in figure 3.

The **CPC4** fit allows $C_v, C_u^S, C_d^S, C_\ell^S$ to vary, and it shows two most dramatic changes from previous results [3, 4]. (i) The “island” on the negative of C_u^S in the (C_u^S, C_v) plane completely disappears, shown in the left panels of figure 4. (ii) The middle panels show that C_d^S now prefers the positive sign to the negative one. It is more clear from the middle-lower panel that the point $C_d^S = -1$ has $\Delta\chi^2 > 2$ above the minimum at $C_d^S = +1$. This is the first time that the data prefer positive bottom-Yukawa coupling to the negative one. The key observation here is that when we change the sign of bottom-Yukawa

Figure 3. CPC3: the confidence-level regions of the fit by varying ΔS^γ , ΔS^g , and $\Delta\Gamma_{\text{tot}}$. The color code is the same as in figure 2.

Figure 4. CPC4: (Upper) The confidence-level regions of the fit by varying C_v , C_u^S , C_d^S , and C_ℓ^S . The color code is the same as figure 2. (Lower) $\Delta\chi^2$ from the minimum versus Yukawa couplings.

Figure 5. CPC6: the confidence-level regions of the fit by varying ΔS^γ , ΔS^g , C_v , C_u^S , C_d^S , and C_ℓ^S . The color code is the same as figure 2.

coupling, the vertex factor S^γ only changes by $0.03/6.64 = 0.0045$, which is too small compared with experimental uncertainty. On the other hand, the vertex factor S^g changes by $0.074/0.651 = 0.11$, which now becomes comparable to experimental uncertainty. This is the reason why the positive bottom-Yukawa is more preferred in the scenario with $\Delta S^g = 0$. Yet, the current data precision still do not show any preference for the sign of tau-Yukawa coupling, as shown in the right panels of figure 4.

CPC6 is the most general scenario that we consider. Now confidence regions, as in the upper panels of figure 5, show that both signs (± 1) of top-Yukawa C_u^S , bottom-Yukawa C_d^S , and tau-Yukawa C_ℓ^S are equally good in describing the data, because of the compensations from ΔS^g and ΔS^γ . For the positive sign of C_u^S , there are 4 possible combinations of C_d^S and C_ℓ^S with $\Delta S^\gamma \sim 0$,⁵ see the lower-left panel of figure 5. Together with the two minima at $\Delta S^g = -0.03 (-0.10)$ and $-1.32 (-1.39)$ for $C_d^S \sim 1 (-1)$ as shown in lower-middle panel of figure 5, one has 8 minima. Similarly, for the negative sign of C_u^S , there are also 8 minima with $\Delta S^\gamma \sim 3.4$. In total, therefore, there are 16 degenerate minima in the **CPC6** fit. In table 5, we only show the minimum at $C_{u,d,\ell}^S \sim 1$ and $\Delta S^{\gamma,g} \sim 0$. A substantial improvement from previous results is that the confidence-level regions shown in figure 5 are now well separated islands, while in previous results [4] those islands are “connected”. For example, in the plane of (C_u^S, C_v) , the negative and positive islands of C_u^S are now separated but they were connected in previous results. It means that previously $C_u^S = 0$ was allowed but not in the current data.

Before moving to **CPCN** fits, we note that the negative top-quark Yukawa coupling is allowed only in the presence of non-zero ΔS^γ which can offset the flipped top-quark contribution to S^γ . The required tuning is now $\delta(\Delta S^\gamma) \simeq \pm 0.4$ at 1σ level, which is about 10% of the change in ΔS^γ due to the negative top-quark Yukawa coupling. The tuning will be more and more severe as more data accumulate.

⁵In this work, we neglect the other possibility of $\Delta S^\gamma \sim 13$ (17) for positive (negative) C_u^S .

Cases	CPCN2	CPCN3	CPCN4			
	Vary C_u^S, C_v	Vary C_u^S, C_v	Vary C_u^S, C_v			
Parameters	ΔS^γ		$\Delta S^\gamma, \Delta S^g$			
After ICHEP 2018						
C_u^S	$1.017^{+0.039}_{-0.037}$	$1.016^{+0.039}_{-0.038}$	$1.042^{+0.077}_{-0.081}$	$1.042^{+0.078}_{-0.081}$	$-1.042^{+0.081}_{-0.078}$	$-1.042^{+0.081}_{-0.078}$
C_d^S	1	1	1	1	1	1
C_ℓ^S	1	1	1	1	1	1
C_v	$1.030^{+0.028}_{-0.028}$	$1.025^{+0.034}_{-0.035}$	$1.027^{+0.034}_{-0.036}$	$1.027^{+0.034}_{-0.036}$	$1.028^{+0.034}_{-0.036}$	$1.028^{+0.034}_{-0.036}$
ΔS^γ	0	$-0.090^{+0.36}_{-0.36}$	$-0.129^{+0.37}_{-0.37}$	$-0.129^{+0.37}_{-0.37}$	$3.524^{+0.41}_{-0.42}$	$3.523^{+0.41}_{-0.42}$
ΔS^g	0	0	$-0.021^{+0.057}_{-0.055}$	$-1.34^{+0.066}_{-0.065}$	$0.095^{+0.055}_{-0.057}$	$1.414^{+0.066}_{-0.066}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	0	0	0	0	0	0
χ^2/dof	51.16/62	51.10/61	50.96/60			
goodness of fit	0.835	0.813	0.791			
p -value	0.266	0.439	0.583			

Table 6. CPCN: the best-fitted values in various CP conserving fits and the corresponding chi-square per degree of freedom and goodness of fit. The p -value for each fit hypothesis against the SM null hypothesis is also shown. For the SM, we obtain $\chi^2 = 53.81$, $\chi^2/dof = 53.81/64$, and so the goodness of fit = 0.814.

Figure 6. CPCN2: the confidence-level regions of the fit by varying C_u^S and C_v . The color code is the same as in figure 2.

4.1.2 CPCN2 to CPCN4

We can see in **CPC2** to **CPC6**, the bottom-Yukawa and tau-Yukawa couplings are not very sensitive to the overall fits, though the bottom-Yukawa shows slight preference on the positive side in **CPC4**. Here we attempt to use the more effective parameters in the fits. The best-fits points and their p -values are shown in table 6, and their corresponding figures in figure 6 to 8.

In **CPCN2**, we vary only C_v and C_u^S . This fit offers a slightly better p -value than the SM. While in **CPCN3**, we also vary ΔS^γ in addition to C_v and C_u^S . We find that it

Figure 7. CPCN3: (Upper) The confidence-level regions of the fit by varying ΔS^γ , C_u^S , and C_v . The color code is the same as in figure 2. (Lower) $\Delta\chi^2$ versus C_u^S (left) and $\Delta\chi^2$ versus ΔS^γ (right).

has little improvement over the **CPCN2** in terms of total χ^2 but, with one less degree of freedom, the p -value indeed decreases. As shown in figure 7, there are two minima: the minimum near $(C_u^S, \Delta S^\gamma) = (1, 0)$ provides a better solution by $\Delta\chi^2 \approx 2$ than the other one near $(C_u^S, \Delta S^\gamma) = (-1, 3.2)$. The ΔS^γ can compensate the flip in sign of C_u^S in the vertex factor S^γ . However, when C_u^S flips the sign, $|S^g|$ increases by more than 10% leading to a worse fit.

In **CPCN4**, we vary the four most efficient fitting parameters C_v , C_u^S , ΔS^γ , and ΔS^g . Therefore, in contrast to **CPCN3**, the ΔS^g here can compensate the sign change in C_u^S , such that there are four minima in this fit with the same p -value, as shown in table 6 and figure 8.

4.1.3 CPCX2 to CPCX4

We perform some more fits, which were not considered in our previous works. The best-fit points for **CPCX2** to **CPCX4** are shown in table 7 and the corresponding figures in figure 9 to figure 11.

The **CPCX2** fit involves C_v and $\Delta\Gamma_{\text{tot}}$. Both parameters shift from the corresponding SM values in order to enhance the signal strengths. The confidence-level regions are shown in figure 9.

In addition to C_v and C_u^S (similar to **CPCN2**), the **CPCX3** fit also varies ΔS^g . The result is very similar to **CPCN2**, but ΔS^g has two solutions with the same p -values: see figure 10.

Figure 8. CPCN4: (Upper) The confidence-level regions of the fit by varying ΔS^g , ΔS^γ , C_u^S , and C_v . The color code is the same as in figure 2. (Lower) $\Delta\chi^2$ versus C_u^S (left), $\Delta\chi^2$ versus ΔS^γ (middle), and $\Delta\chi^2$ versus ΔS^g (right).

Cases	CPCX2	CPCX3		Cases	CPCX4	
Parameters	Vary $C_v, \Delta\Gamma_{\text{tot}}$	Vary C_u^S, C_v ΔS^g		Parameters	Vary C_u^S, C_w $C_z, \Delta S^g$	
After ICHEP 2018						
C_u^S	1	$1.04^{+0.08}_{-0.08}$	$1.04^{+0.08}_{-0.08}$	C_u^S	$1.045^{+0.078}_{-0.081}$	$1.045^{+0.078}_{-0.081}$
C_d^S	1	1	1	C_d^S	1	1
C_ℓ^S	1	1	1	C_ℓ^S	1	1
C_v	$1.020^{+0.051}_{-0.049}$	$1.03^{+0.03}_{-0.03}$	$1.03^{+0.03}_{-0.03}$	C_w	$1.040^{+0.033}_{-0.034}$	$1.040^{+0.032}_{-0.034}$
-				C_z	$1.015^{+0.048}_{-0.049}$	$1.015^{+0.048}_{-0.049}$
ΔS^γ	0	0	0	ΔS^γ	0	0
ΔS^g	0	$-0.02^{+0.06}_{-0.05}$	$-1.34^{+0.07}_{-0.06}$	ΔS^g	$-0.020^{+0.056}_{-0.054}$	$-1.345^{+0.067}_{-0.067}$
$\Delta\Gamma_{\text{tot}}$ (MeV)	$-0.134^{+0.43}_{-0.36}$	0	0	$\Delta\Gamma_{\text{tot}}$ (MeV)	0	0
χ^2/dof	51.25/62	51.08/61		χ^2/dof	50.84/60	
goodness of fit	0.833	0.813		goodness of fit	0.820	
p -value	0.278	0.435		p -value	0.5631	

Table 7. CPCX: the best-fitted values in various CP conserving fits and the corresponding chi-square per degree of freedom and goodness of fit. The p -value for each fit hypothesis against the SM null hypothesis is also shown.

In the **CPCX4** fit, we relax the requirement of $C_w = C_z$ because we can see from the 13 TeV data that the signal strengths for $H \rightarrow WW^*$ are generically larger than those for $H \rightarrow ZZ^*$, see table 3. The result is shown in table 7. The best-fitted values for C_w and C_z are within 1σ and $C_w > C_z$ as demanded by the data. Again there are two solutions for ΔS^g : see figure 11. We note that, compared to C_z which is only constrained by $H \rightarrow ZZ^*$ decay, C_w is constrained by both VBF and WH production as well as $H \rightarrow \gamma\gamma$

Figure 9. CPCX2: the confidence-level regions of the fit by varying C_v and $\Delta\Gamma_{\text{tot}}$. The color code is the same as in figure 2.

Figure 10. CPCX3: the confidence-level regions of the fit by varying C_v , C_u^S and ΔS^g . The color code is the same as in figure 2.

and $H \rightarrow WW^*$ decays. This leads to the narrower $\Delta\chi^2$ curve in C_w than in C_z , as shown in lower frames of figure 11.

4.2 CP violating fits

For the CP-violating fits, we consider the following 4 scenarios:

- **CPV2:** vary C_u^S , C_u^P .
- **CPV3:** vary C_u^S , C_u^P , C_v .
- **CPV4:** vary ΔS^γ , ΔS^g , ΔP^γ , ΔP^g .
- **CPVN3:** vary C_u^S , C_u^P , $\Delta\Gamma_{\text{tot}}$.

The current Higgs boson data ruled out a pure pseudoscalar [20, 21], but the data cannot rule out a mixed state [22]. Noting that the CP-odd coupling to gauge bosons only arises

Figure 11. CPCX4: (Upper) The confidence-level regions of the fit by varying C_w , C_z , ΔS^g , and C_u^S . The color code is the same as in figure 2. (Lower) $\Delta\chi^2$ versus C_w (left), $\Delta\chi^2$ versus C_z (middle), and $\Delta\chi^2$ versus $C_w - C_z$ (right).

Cases	CPV2		CPV3	CPV4	CPVN3	
Parameters	Vary C_u^S, C_u^P		Vary C_u^S, C_u^P C_v	Vary $\Delta S^\gamma, \Delta S^g$ $\Delta P^\gamma, \Delta P^g$	Vary C_u^S, C_u^P $\Delta\Gamma_{\text{tot}}$	
After ICHEP 2018						
C_u^S	$1.00^{+0.07}_{-0.11}$	$1.00^{+0.07}_{-0.11}$	$1.02^{+0.04}_{-0.10}$	1	$0.99^{+0.07}_{-0.10}$	$0.99^{+0.07}_{-0.10}$
C_d^S	1	1	1	1	1	1
C_ℓ^S	1	1	1	1	1	1
C_v	1	1	$1.03^{+0.03}_{-0.03}$	1	1	1
ΔS^γ	0	0	0	$0.26^{+13.56}_{-0.81}$	0	0
ΔS^g	0	0	0	$0.016^{+0.025}_{-}$	0	0
$\Delta\Gamma_{\text{tot}}$ (MeV)	0	0	0	0	$-0.27^{+0.34}_{-0.28}$	$-0.27^{+0.34}_{-0.28}$
C_u^P	$0.19^{+0.14}_{-0.52}$	$-0.19^{+0.52}_{-0.14}$	$0.00^{+0.28}_{-0.28}$	0	$0.11^{+0.19}_{-0.41}$	$-0.11^{+0.41}_{-0.19}$
ΔP^γ	0	0	0	$-2.54^{+9.72}_{-4.65}$	0	0
ΔP^g	0	0	0	$0.00^{+0.69}_{-0.69}$	0	0
χ^2/dof	52.07/62		51.16/61	51.87/60	51.42/61	
goodness of fit	0.812		0.811	0.763	0.804	
p -value	0.419		0.449	0.747	0.495	

Table 8. CPV: the best-fitted values in various CP violating fits and the corresponding chi-square per degree of freedom and goodness of fit. The p -value for each fit hypothesis against the SM null hypothesis is also shown.

Figure 12. CPV2: the confidence-level regions of the fit by varying C_u^S and C_u^P . The color code is the same as in figure 2.

Figure 13. CPV3: the confidence-level regions of the fit by varying C_u^S , C_u^P , and C_v . The color code is the same as in figure 2.

Figure 14. CPV4: the confidence-level regions of the fit by varying ΔS^γ , ΔS^g , ΔP^γ , and ΔP^g . The color code is the same as in figure 2.

from loop corrections, we only allow the top-quark Yukawa coupling and the vertex factors for Hgg and $H\gamma\gamma$ to develop sizeable CP-odd couplings. Therefore, CP violation is signaled by the simultaneous existence of C_u^S and C_u^P as in **CPV2**, **CPV3**, and **CPVN3** or of $\Delta S^{\gamma,g}$ and $\Delta P^{\gamma,g}$ in **CPV4**. The results for **CPV2** to **CPVN3** are shown in table 8 and the corresponding figures in figure 12 to figure 15.

The simplest choice **CPV2** happens in the coexistence of CP-even and CP-odd top-Yukawa couplings: C_u^S and C_u^P . Since the signal strengths are CP-even quantities, in general, they do not contain any CP-odd products of $C_u^S \times C_u^P$ and $S^{g,\gamma} \times P^{g,\gamma}$ even though the products are non-vanishing. This is why the confidence-level regions appear like a circle

Figure 15. CPVN3: the confidence-level regions of the fit by varying C_u^S , C_u^P , and $\Delta\Gamma_{\text{tot}}$. The color code is the same as in figure 2.

or an arc of a circle in the planes of (C_u^S, C_u^P) , $(\Delta S^\gamma, \Delta P^\gamma)$, and $(\Delta S^g, \Delta P^g)$. In figure 12, we show two best-fit points with equal p -value for **CPV2**, indeed the arc joining these two points essentially has the same p -value.

We vary C_u^S , C_u^P , and C_v in **CPV3** fit. The confidence-level regions, shown in figure 13, shrink a lot from previous results [4]. Previously, the blue region forms a closed ellipse, but now all regions hardly form a closed ellipse, showing the data are getting much more stringent than before.

We vary ΔS^g , ΔS^γ , ΔP^g , and ΔP^γ in **CPV4**. As explained in our previous work [3], the solutions to ΔS^g and ΔP^g , as well as to ΔS^γ and ΔP^γ appear to be an ellipse. It is quite clear in figure 14. The best-fit points are in fact an arc inside the red region that passed through the triangle. Note that we are not considering the scenarios with too large values of $|\Delta S^\gamma|$ in our fits. Otherwise, the left frame of figure 14 may complete an ellipse as in the middle frame.

In the **CPVN3** fit, we try a different combination of parameters: C_u^S , C_u^P , and $\Delta\Gamma_{\text{tot}}$. With the help of $\Delta\Gamma_{\text{tot}}$ the “banana” shaped regions originally in CPV2 now become fattened.

4.3 Predictions for $H \rightarrow Z\gamma$

Before we close this section, we examine how large $C_{Z\gamma}$ can be in the scenarios with $\Delta S^\gamma = 0$, assuming the absence of additional particles running in the H - γ - Z loop. The results are shown in figure 16. We observe that $C_{Z\gamma}$ can be as large as 1.2 which may imply $B(H \rightarrow Z\gamma) \lesssim 1.4 B(H_{\text{SM}} \rightarrow Z\gamma)$.

5 Conclusions

We have performed global fits to the Higgs couplings to gauge bosons and fermions, using all the data from the Tevatron, 7+8 TeV and 13 TeV data from ATLAS and CMS. Overall, the allowed parameter space regions shrink substantially from those in 2014. Notably, the data precision is now sensitive to the bottom-Yukawa coupling and the overall average signal strength shows a 2 - σ deviation from the SM value.

Let us summarize the major findings or improvements from previous results.

1. The combined average signal strength for the Higgs boson now stands at a 2 - σ deviation from the SM value, namely $\mu_{\text{exp}} = 1.10 \pm 0.05$.

Figure 16. Predictions for $C_{Z\gamma}$ for the scenarios in which $\Delta S^\gamma = 0$. [Upper]: **CPC1** (left), **CPCN2** (middle), **CPCX2** (right); [Middle]: **CPCX3** (left), **CPC4** (middle), **CPCX4** (right); [Low]: **CPV2** (left), **CPV3** (middle), **CPVN3** (right). The color code is the same as in figure 2 except **CPC1** for which $\Delta\chi^2 \leq 1$ (red), 4 (green), and 9 (blue) above the minimum.

2. For the first time the bottom-Yukawa coupling shows statistical difference between the positive and negative signs. Thanks to the discriminating power of the Higgs-gluon vertex S^g the positive sign of the bottom-Yukawa is more preferred than the negative one.
3. Previously in 2014 the fits still allowed the negative sign of the top-Yukawa coupling at 95% CL. Now with more precisely measured signal strengths together with the establishment of the associated production with the top-quark pair, the negative island of the top-Yukawa is now entirely ruled out, except in the scenarios with non-zero ΔS^γ .
4. The nonstandard (or invisible decay) branching ratio of the Higgs boson is now reduced to less than 8.4%, which improves substantially from the previous value of 19%. This is obtained by varying only $\Delta\Gamma_{tot}$. It would be relaxed if more parameters are allowed to vary in the fit.
5. When we relax the custodial symmetry requirement (C_w not necessarily equal to C_z), we find that the coupling C_w is larger than C_z though still within 1σ , and more constrained than C_z .

6. We have also made the predictions for $H \rightarrow Z\gamma$ by showing the effective coupling $C_{Z\gamma}$. In most scenarios, it is predicted to be SM-like. The most extreme allowed value would $C_{Z\gamma} \simeq 1.2$, which gives a branching ratio 40% larger than the SM value.

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A Relation between our formalism and the kappa formalism

Here in this appendix we compare the definitions of coupling modifiers taken in our formalism to those defined by LHCHXSWG, and make the correspondence taking the specific examples of the loop-induced Hgg and $H\gamma\gamma$ couplings.

In the LHCHXSWG YR3 [14] and YR4 [15], as well as in a very recent paper by ATLAS [16], the definition of κ_g is given by

$$\kappa_g^2(\kappa_b, \kappa_t, M_H) \equiv \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(M_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(M_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(M_H)}{\sigma_{ggH}^{tt}(M_H) + \sigma_{ggH}^{bb}(M_H) + \sigma_{ggH}^{tb}(M_H)} \quad (\text{A.1})$$

where $\sigma_{ggH}^{tt}(M_H)$ and $\sigma_{ggH}^{bb}(M_H)$ denote the squares of the top and bottom contributions to the $gg \rightarrow H$ production, respectively, and $\sigma_{ggH}^{tb}(M_H)$ the top-bottom interference. On the other hand, κ_g can be also defined through the $H \rightarrow gg$ decay process:

$$\kappa_g^2 \equiv \frac{\Gamma(H \rightarrow gg)}{\Gamma^{\text{SM}}(H \rightarrow gg)}. \quad (\text{A.2})$$

The LHCHXSWG is performing analyses through $gg \rightarrow H$ production at 8 TeV beyond the leading order and, taking $M_H = 125$ GeV, they find [14, 15]

$$\begin{aligned} \kappa_{g,\text{YR3}}^2 &= 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b \\ \kappa_{g,\text{YR4}}^2 &= 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2. \end{aligned} \quad (\text{A.3})$$

The difference between $\kappa_{g,\text{YR3}}^2$ and $\kappa_{g,\text{YR4}}^2$ can be attributed to the choices of the QCD and factorization scales and the PDF set, the different renormalization scheme for the masses of the fermions entering into the loops, etc. On the other hand, in the recent paper by ATLAS, the simpler κ_g^2 based on the Higgs decay $H \rightarrow gg$ is taken and they find [16]:

$$\kappa_{g,\text{ATLAS}}^2 = 1.11\kappa_t^2 + 0.01\kappa_b^2 - 0.12\kappa_t\kappa_b \quad (\text{A.4})$$

which is closer to $\kappa_{g,\text{YR3}}^2$.

In our work, we only perform LO analysis and κ_g^2 is given by

$$\kappa_g^2 = C_g^2 = \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{|S_{\text{SM}}^g(M_H)|^2} \quad (\text{A.5})$$

independently of whether one considers $gg \rightarrow H$ production or $H \rightarrow gg$ decay. Using the numerical expression eq. (2.8) which is obtained by taking $M_H = 125.09 \text{ GeV}$ and $\Delta S^g = P^g = 0$, we have

$$\kappa_{g,\text{OURS}}^2 \simeq 1.11C_t^2 + 0.01C_b^2 - 0.12C_tC_b, \quad (\text{A.6})$$

which is very consistent with $\kappa_{g,\text{ATLAS}}^2$ based on $H \rightarrow gg$ decay with the identification of $C_f = \kappa_f$.

One of the important findings of our work is the preferred sign of the bottom-Yukawa coupling C_b . The observable effect on signal strength due to flipping of the sign of C_b comes from the *interference* term ($\propto C_tC_b$ or $\kappa_t\kappa_b$), but not the square of the bottom-Yukawa term. Thus, all three expressions of $\kappa_{g,\text{YR3}}^2$, $\kappa_{g,\text{YR4}}^2$, and $\kappa_{g,\text{ATLAS}}^2$ and our expression of $\kappa_{g,\text{OURS}}^2$ yield a similar change of order $O(10)\%$ due to the flipping of the sign of the bottom-Yukawa coupling.

Similarly, LHCHXSWG gives the definition for κ_γ :

$$\kappa_\gamma^2 \equiv \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma_{\gamma\gamma}^{ij}(M_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(M_H)} \simeq 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$$

where the pairs (i, j) are bb , tt , $\tau\tau$, WW , bt , $b\tau$, bW , $t\tau$, tW , and τW . The above numerical expression is compared with that obtained by the use of eq. (2.5) after taking $M_H = 125.09 \text{ GeV}$ and $\Delta S^\gamma = P^\gamma = 0$:

$$\begin{aligned} \kappa_\gamma^2 \simeq & 1.583C_W^2 + 0.070C_t^2 - 0.667C_WC_t + 0.006C_WC_b \\ & + 0.009C_WC_\tau + 0.003C_WC_c - 0.001C_tC_b - 0.002C_tC_\tau, \end{aligned}$$

and we find excellent consistency. We note that our formalism takes on the advantage that it can admit pseudoscalar form factor P^g and P^γ into the effective Hgg and $H\gamma\gamma$ vertices.

B 13 TeV data: tables 9, 10, 11, 12, 13, and 14

In this appendix, we list all the details of 13 TeV Higgs signal strengths used in our global fitting.

Channel	Signal strength μ c.v $\pm$ error	M_H (GeV)	χ_{SM}^2 (each)
ATLAS (79.8 fb $^{-1}$ (13 TeV)): figure 8 of [23] (Jul. 2018)			
ggF	$0.97^{+0.15}_{-0.14}$ [23]	125.09	0.04
VBF	$1.40^{+0.43}_{-0.37}$ [23]	125.09	1.17
VH	$1.08^{+0.59}_{-0.54}$ [23]	125.09	0.02
ttH	$1.12^{+0.43}_{-0.37}$ [23]	125.09	0.11
CMS (35.9 fb $^{-1}$ (13 TeV)): figure 17 of [24] (Apr. 2018)			
ggF	$1.10^{+0.20}_{-0.18}$ [24]	125.4	0.31
VBF	$0.8^{+0.6}_{-0.5}$ [24]	125.4	0.11
VH	$2.4^{+1.1}_{-1.0}$ [24]	125.4	1.96
ttH	$2.2^{+0.9}_{-0.8}$ [24]	125.4	2.25
			subtot: 5.97

Table 9. (*LHC: 13 TeV*) Data on signal strengths of $H \rightarrow \gamma\gamma$ by the ATLAS and CMS after ICHEP 2018. The χ^2 of each data with respect to the SM is shown in the last column. The sub-total χ^2 of this decay mode is shown at the end.

Channel	Signal strength μ c.v $\pm$ error	M_H (GeV)	χ_{SM}^2 (each)
ATLAS (79.8 fb $^{-1}$ at 13 TeV): table 9 of [25] (Jun. 2018)			
ggF	$1.04^{+0.16}_{-0.16}$ [25]	125	0.06
VBF	$2.8^{+0.94}_{-0.94}$ [25]	125	3.67
VH	$0.9^{+1.01}_{-1.01}$ [25]	125	0.01
ttH †	$< 4.04(95\%)$ [25]	125	—
CMS (77.4 fb $^{-1}$ at 13 TeV): figure 10 of [26] (Jul. 2018)			
ggF	$1.15^{+0.18}_{-0.16}$ [26]	125.09	0.88
VBF	$0.69^{+0.75}_{-0.57}$ [26]	125.09	0.17
VH $_{\text{had}}$	$0.00^{+1.16}_{-0.00}$ [26]	125.09	0.74
VH $_{\text{lep}}$	$1.25^{+2.46}_{-1.25}$ [26]	125.09	0.04
ttH	$0.00^{+0.53}_{-0.00}$ [26]	125.09	3.56
			subtot: 9.13

† : this data point is not included in our χ^2 analysis.

Table 10. (*LHC: 13 TeV*) The same as table 9 but for $H \rightarrow ZZ^{(*)}$.

Channel	Signal strength μ c.v $\pm$ error	M_H (GeV)	χ^2_{SM} (each)
ATLAS (36.1 fb $^{-1}$ (13 TeV)): page 8 of [27] (Mar. 2018)			
ggF	$1.21^{+0.22}_{-0.21}$ [27]	125	1.00
VBF	$0.62^{+0.37}_{-0.36}$ [27]	125	1.05
CMS (35.9 fb $^{-1}$ at 13 TeV): figure 9 of [28] (Mar. 2018)			
ggF	$1.38^{+0.21}_{-0.24}$ [28]	125.09	2.51
VBF	$0.29^{+0.66}_{-0.29}$ [28]	125.09	1.16
WH	$3.27^{+1.88}_{-1.70}$ [28]	125.09	1.78
ZH	$1.00^{+1.57}_{-1.00}$ [28]	125.09	0.00
subtot: 7.50			

Table 11. (*LHC: 13 TeV*) The same as table 9 but for $H \rightarrow W^+W^-$.

Channel	Signal strength μ c.v $\pm$ error	M_H (GeV)	χ^2_{SM} (each)
ATLAS (79.8 fb $^{-1}$ (13 TeV)) figure 3 of [29] (Aug. 2018)			
WH	$1.08^{+0.47}_{-0.43}$ [29]	125.0	0.03
ZH	$1.20^{+0.33}_{-0.31}$ [29]	125.0	0.42
CMS (77.2 fb $^{-1}$ (13 TeV)) [7, 30] (Aug. 2018)			
ggH	$2.51^{+2.43}_{-2.01}$ [30]	125.09	0.56
VH	$1.06^{+0.26}_{-0.26}$ [7]	125.09	0.05
ttH	$0.91^{+0.45}_{-0.43}$ [30]	125.09	0.04
subtot: 1.11			

Table 12. (*LHC: 13 TeV*) The same as table 9 but for $H \rightarrow b\bar{b}$.

Channel	Signal strength μ c.v $\pm$ error	M_H (GeV)	χ^2_{SM} (each)
ATLAS (36.1 fb $^{-1}$ at 13 TeV) [10] (Jun. 2018)			
ggH	$0.98^{+0.62}_{-0.51}$ [10]	125.09	0.00
VBF	$1.18^{+0.59}_{-0.55}$ [10]	125.09	0.11
CMS (35.9 fb $^{-1}$ at 13 TeV) figure 6 of [31] (Jun. 2018)			
ggH	$1.12^{+0.53}_{-0.50}$ [31]	125.09	0.06
VBF	$1.13^{+0.45}_{-0.42}$ [31]	125.09	0.10
WH	$3.39^{+1.68}_{-1.54}$ [31]	125.09	2.41
ZH	$1.23^{+1.62}_{-1.35}$ [31]	125.09	0.03
subtot: 2.70			

Table 13. (*LHC: 13 TeV*) The same as table 9 but for $H \rightarrow \tau^+\tau^-$.

Channel	Signal strength μ c.v $\pm$ error	M_H (GeV)	χ^2_{SM} (each)
ATLAS (79.8 fb $^{-1}$ (13 TeV)): figure 5 of [6] (Jun. 2018), (36.1 fb $^{-1}$ (13 TeV)): figure 16 of [32] (Apr. 2018)			
$\gamma\gamma$	$1.39^{+0.48}_{-0.42}$ (79.8 fb $^{-1}$) [6]	125.09	0.86
$ZZ^{(*)\dagger}$	$< 1.77(68\%)$ (79.8 fb $^{-1}$) [6]	125.09	—
$WW^{(*)}$	$1.5^{+0.6}_{-0.6}$ (36.1 fb $^{-1}$) [32]	125.09	0.69
bb	$0.84^{+0.64}_{-0.61}$ (36.1 fb $^{-1}$) [33]	125.09	0.06
$\tau\tau$	$1.5^{+1.2}_{-1.0}$ (36.1 fb $^{-1}$) [32]	125.09	0.25
CMS (35.9 fb $^{-1}$ (13 TeV))			
$WW^{(*)}$	$1.69^{+0.68}_{-0.61}$ [5]	125.09	1.28
bb(hadronic)	$0.9^{+1.5}_{-1.5}$ [34]	125.09	0.00
bb(leptonic)	$0.72^{+0.45}_{-0.45}$ [35]	125.09	0.39
$\tau\tau$	$0.15^{+1.07}_{-0.91}$ [5]	125.09	0.63
			subtot: 4.17

† : this data point is not included in our χ^2 analysis.

Table 14. (*LHC: 13 TeV*) The same as table 9 but for exclusive ttH production mode.

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