Constraining wrong-sign $hbb$ couplings with $h \to \Upsilon \gamma$

Tanmoy Modak,\textsuperscript{1} Jorge C. Romão,\textsuperscript{2} Soumya Sadhukhan,\textsuperscript{1} João P. Silva,\textsuperscript{2} and Rahul Srivastava\textsuperscript{1,3}

\textsuperscript{1}The Institute of Mathematical Sciences, Chennai, India
\textsuperscript{2}CFTP, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049 Lisboa, Portugal
\textsuperscript{3}Physical Research Laboratory, Ahmedabad, India
(Dated: July 28, 2016)

The rare decay $h \to \Upsilon \gamma$ has a very small rate in the Standard Model, due to a strong cancellation between the direct and indirect diagrams. Models with a changed $hbb$ coupling can thus lead to a great increase in this decay. Current limits on two Higgs doublet models still allow for the possibility that the $hbb$ coupling might have a sign opposite to the Standard Model; the so-called “wrong-sign”. We show how $h \to \Upsilon \gamma$ can be used to put limits on the wrong-sign solutions.

PACS numbers: 12.60.Fr, 14.80.Ec, 14.80.-j

I. INTRODUCTION

With the discovery at LHC of the first spin 0 particle \textsuperscript{1,2}, one must now probe its couplings in detail, searching for discrepancies with the Standard Model (SM) Higgs. Of particular interest is the possibility that the $hbb$ coupling could have a magnitude close to the SM value, but opposite sign; the “wrong-sign” solution. Current data is consistent with this possibility \textsuperscript{3–5}.

There is great interest in the two Higgs doublet model (2HDM) \textsuperscript{6,7}. Most attention is devoted to models with a discrete $Z_2$ symmetry, softly broken by a term with a real coefficient. These models have two charged scalars $H^\pm$, one pseudoscalar $A$, a heavy scalar $H$, and a light scalar $h$, which we identify as the 125 GeV scalar from LHC. There are four types of such models. Of these, only Type II and Flipped are consistent with wrong-sign solutions \textsuperscript{8–10}.

Naturally, a sign change does not affect the $h \to b \bar{b}$ rate, which, in most models of the 125 GeV scalar, is very close to its total width. Thus, the effect of the wrong-sign must be sought indirectly, for example through its one-loop contribution to the glue-glue production $gg \to h$ and di-photon decay $h \to \gamma \gamma$. However, there, loops with intermediate bottom quarks compete with much larger contributions from loops with top quarks ($gg \to h$) or with top quarks and with gauge bosons ($h \to \gamma \gamma$). As a result, these processes will have values close to the SM, and only a very precise measurement of order 5\% in $pp \to h \to \gamma \gamma$ will enable experiments to disentangle the normal sign from the wrong-sign solutions \textsuperscript{9,11}.

In contrast, the rare decay $h \to \Upsilon \gamma$ involves two diagrams which have almost the same magnitude in the SM. The decay is very suppressed in the SM (compared, for example, with $h \to J/\psi \gamma$) due to an accidental cancellation between the two diagrams \textsuperscript{12,13}. A change in the $hbb$ sign will destroy the precise cancellation and will have a dramatic effect in this decay, making $h \to \Upsilon \gamma$ the prime candidate to probe the wrong-sign solutions. The importance of such a measurement on the wrong-sign solutions of the 2HDM is the subject of this article.

In Section \textsuperscript{II} we introduce our notation, and in Section \textsuperscript{III} we present the details of the $h \to \Upsilon \gamma$ decay and perform a full simulation within the real 2HDM. In Section \textsuperscript{IV} we draw our conclusions.
II. WRONG-SIGN SOLUTION IN THE 2HDM

A. Notation

In this article we consider a CP-conserving 2HDM with a discrete $Z_2$ symmetry, broken softly by a real term, reviewed extensively for example in [6, 7]. The scalar potential may be written as

$$V_H = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 \left[ \Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right]$$

$$+ \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1)$$

$$+ \frac{\lambda_5}{2} \left[ (\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right],$$

with all coefficients real. The vacuum expectation values (vevs) are also real and written as $v_1/\sqrt{2}$ and $v_2/\sqrt{2}$. The fields may be parametrized in terms of the mass eigenstates as

$$\Phi_1 = \left( \frac{1}{\sqrt{2}} \left[ v c_\beta + (-s_\alpha h + c_\alpha H) + i (c_\beta G^0 - s_\beta A) \right] \right),$$

$$\Phi_2 = \left( \frac{1}{\sqrt{2}} \left[ v s_\beta + (c_\alpha h + s_\alpha H) + i (s_\beta G^0 + c_\beta A) \right] \right),$$

where $c_\theta$ ($s_\theta$) is the cosine (sine) of any angle $\theta$ in subscript, $\tan \beta = v_2/v_1$, and $v = \sqrt{v_1^2 + v_2^2} = (\sqrt{2}G_F)^{-1/2}$. The fields $G^\pm$ and $G^0$ are the would-be Goldstone bosons.

We assume that the lightest scalar ($h$) is the 125 GeV resonance found at LHC. Its couplings with the gauge bosons are

$$\mathcal{L}_{hvV} = \sin (\beta - \alpha) h \left[ m_Z^2 \frac{Z^\mu Z_\mu}{v} + 2 m_W^2 \frac{W^\mu W^-_\mu}{v} \right].$$

The SM limit corresponds to $\sin (\beta - \alpha) = 1$. We are interested in models with wrong-sign solutions for the fermion couplings. Given current experiments, only Type II and Flipped are consistent with this possibility [8–10]. In these models, the couplings of $h$ with the fermions from the third family are

$$- \mathcal{L}_{Y_h} = \frac{m_t}{v} k_U h H + \frac{m_b}{v} k_D h b b + \frac{m_\tau}{v} k_{\tau} h \tau^+ \tau^-,$$

where

$$k_U = \frac{\cos \alpha}{\sin \beta}, \quad k_D = -\frac{\sin \alpha}{\cos \beta}.$$  

The only difference between the Type II and Flipped models lies in the coupling of the charged fermions, given, respectively, by

$$k_\tau = k_D \text{ (Type II)}, \quad k_\tau = k_U \text{ (Flipped)}.$$  

The SM limit is $k_U = k_D = k_\tau = 1$.

We will denote the ratios between the 2HDM and SM rates by

$$\mu_f = \frac{\sigma^{2\text{HDM}}(pp \to h) \Gamma^{2\text{HDM}}[h \to f]}{\sigma^{SM}(pp \to h) \Gamma^{SM}[h \to f] \Gamma^{2\text{HDM}}[h \to \text{all}]/\Gamma^{SM}[h \to \text{all}].}$$

where $\sigma$ is the cross section for Higgs production, $\Gamma[h \to f]$ the decay width into the final state $f$, and $\Gamma[h \to \text{all}]$ is the total Higgs decay width.
B. A naive explanation for the wrong-sign

For simplicity, let us assume that the production of $h$ is due exclusively to the gluon fusion process with intermediate top quark, and that its width is due exclusively to the decay $h \rightarrow \bar{b}b$. Within these assumptions

$$\sqrt{\mu_{VV}} = \pm \frac{k_U}{k_D} \sin (\beta - \alpha),$$

(8)

where the sign (which will be ignored henceforth) is chosen to make the square root positive. Imagine that $\mu_{VV} \sim 1$ because both factors are close to unity. We start by noting that

$$- \frac{k_U}{k_D} = \frac{1}{t_\alpha t_\beta} = \frac{\cos (\beta - \alpha) + \cos (\beta + \alpha)}{\cos (\beta - \alpha) - \cos (\beta + \alpha)},$$

(9)

where $t_\theta$ is the tangent of the angle $\theta$. We find that $|k_U/k_D| \sim 1$ if $\beta - \alpha = \pi/2$, in which case $k_D = +1$ (the right-sign solution), or else if $\beta + \alpha = \pi/2$, in which case $k_D = -1$ (the wrong-sign solution).

Now, we look at the second factor in Eq. (8). We find

$$\frac{\sin (\beta - \alpha)}{\sin (\beta + \alpha)} = \frac{1 - \frac{t_\alpha}{t_\beta}}{1 + \frac{t_\alpha}{t_\beta}} = \frac{1 + \frac{1}{t_\alpha} k_D}{1 - \frac{1}{t_\alpha} k_U}.$$  

(10)

For $|k_U/k_D| \sim 1$, if $t_\beta$ is larger than about 3 (say), then

$$\frac{\sin (\beta - \alpha) \sim \sin (\beta + \alpha) \left[1 + \frac{2}{t_\beta^2} \frac{k_D}{k_U}\right].}$$  

(11)

Thus, the second factor in Eq. (8) is very closely given by $\sin (\beta + \alpha)$ already for moderate values of $t_\beta$. In conclusion, an experimental constraint of $\mu_{VV} \sim 1$ has a solution $\sin (\beta - \alpha) \sim 1$ for all values of $t_\beta$, and it also has a solution $\sin (\beta + \alpha) \sim 1$ for values of $t_\beta \gtrsim 3$. As an illustration, we show in Fig. 1 the constraints on the $\sin \alpha$-$\tan \beta$ plane of a 20% precision measurement of $\mu_{VV}$ around the SM value 1. The left branch corresponds to the right-sign and lies

![Fig. 1: Constraints from $0.8 \leq \mu_{VV} \leq 1.2$ on the $\sin \alpha$-$\tan \beta$ plane.](image)

very close to the line $\sin (\beta - \alpha) = 1$ ($k_D = 1$), while the right branch corresponds to the wrong-sign and lies very close to the line $\sin (\beta + \alpha) = 1$ ($k_D = -1$).

We note that, because both factors in Eq. (8) get closer to one in the right-sign and wrong-sign limits, a moderate precision in $\mu_{VV}$ implies a very precise line in the $\sin \alpha$-$\tan \beta$ plane [11]. As shown in detail in section IIB of [11], for $\tan \beta = 10$ and a precision of 20% in $\mu_{VV}$, $\sin^2 (\beta - \alpha)$ is determined to better than 0.5% in the wrong-sign branch.
III. THE $h \rightarrow \Upsilon \gamma$ DECAY IN 2HDM

A. Decay rate

The $h \rightarrow \Upsilon \gamma$ decay rate may be written as

$$\Gamma[h \rightarrow \Upsilon \gamma] = \frac{1}{8\pi} \frac{m_h^2 - m_\Upsilon^2}{m_h^2} |A_{\text{direct}} + A_{\text{indirect}}|^2. \quad (12)$$

The direct diagram is shown in Fig. 2(b) and arises from the direct $hbb$ coupling ($k_D$). The indirect diagram is shown in Fig. 2(a) and arises from the effective $h\gamma\gamma$ with a virtual photon morphing into an $\Upsilon$.

![Feynman diagrams](image)

**FIG. 2:** Feynman diagrams contributing to the $h \rightarrow \Upsilon \gamma$ process. The diagrams originate from two different couplings: (a) loop induced $h\gamma\gamma$ (indirect) coupling; (b) $hbb$ Yukawa (direct) coupling.

We adapt the calculations of Ref. [12] to the 2HDM, and write

$$A_{\text{direct}} = -\frac{2}{\sqrt{3}} e k_D \left( \sqrt{2} G_F \frac{m_\Upsilon}{m_h} \right)^{1/2} \frac{m_h^2 - m_\Upsilon^2}{m_h^2 - m_\Upsilon^2/2 - 2m_b^2} \phi_0(\Upsilon),$$

$$A_{\text{indirect}} = \frac{e g_{\Upsilon \gamma}}{m_\Upsilon^2} \left( \sqrt{2} G_F \right)^{1/2} \frac{\alpha}{\pi} \frac{X}{\sqrt{m_h}}.$$

(13)

where $G_F$ is Fermi’s constant, $e$ is the positron charge, $k_D$ is given in Eq. (5), $m_\Upsilon$ and $m_b$ are the $\Upsilon$ and $b$-quark masses, $\alpha$ is the fine-structure constant, $\phi_0^2(\Upsilon) \sim 0.512$ GeV$^3$ is the wave function of $\Upsilon$ at the origin, and

$$g_{\Upsilon \gamma} = \frac{2}{\sqrt{3}} \sqrt{m_\Upsilon} \phi_0(\Upsilon), \quad (14)$$

whose magnitude can be determined from

$$\Gamma[\Upsilon \rightarrow \ell^+ \ell^-] = \frac{4\pi \alpha^2(m_\Upsilon)}{3m_\Upsilon^4} g_{\Upsilon \gamma}^2. \quad (15)$$

Our expressions in Eqs. (13) bear three differences with respect to Eqs. (14a)-(14b) of Ref. [12]. First, we have included explicitly in $A_{\text{direct}}$ the factor $\eta = 0.689$ mentioned at the end of section IIA of [12], due to the full NLO corrections [12, 13]. Second, we have corrected in $A_{\text{indirect}}$ a $\sqrt{2}$ misprint. Finally, we have defined $X = -X/4$, where $X$ is the function arising from the calculation of the effective $h\gamma\gamma$ coupling at one-loop in the 2HDM, which can be found in appendix B of Ref. [14].

As shown in [12], the direct and indirect contributions interfere destructively in an almost complete manner in the SM, and $h \rightarrow \Upsilon \gamma$ cannot be detected. This is also the case in the right-sign solution of the 2HDM. In contrast, the wrong-sign solution has a constructive interference, raising the prospects for detection. This is what we turn to next.

---

1 We are grateful to G. Bodwin for clarifications on this point. We agree with their Eq. (12), but have a $\sqrt{2}$ difference with respect to their Eq. (14b).
B. The importance of $h \rightarrow \Upsilon \gamma$ for the wrong-sign scenario

As mentioned, the experimental measurement of $\mu_{VV}$ means that the $hVV$ and $ht\bar{t}$ couplings lie close to their SM values. As a result, $h \rightarrow \gamma\gamma$ in the 2HDM is still dominated by the $W$ loop, with a small destructive interference correction from the top loop. There are two novelties in the 2HDM. First, the alteration of $k_D$. The bottom loop contribution is negligible in the SM. It can indeed change sign in the 2HDM, but, since $\mu_{VV}$ places $|k_D| \sim 1$, it cannot have a strong impact. Second, there is a charged Higgs loop. This decouples with the mass of the charged Higgs, but it can still give a contribution of up to ten percent for values of the charged Higgs mass around 600 GeV. Such effects are inevitable in the wrong-sign scenario $[9]$. One concludes that only precise measurements of the $h \rightarrow \gamma\gamma$ decay can yield a signal for the wrong-sign solution of the 2HDM $[9,11]$; the only method presented thus far.

Here we advocate that $h \rightarrow \Upsilon \gamma$ is a good candidate to determine the sign of $k_D$. This occurs precisely because the cancellation is almost complete in the SM. A change in the sign of $k_D$ means that the interference becomes constructive, thus increasing by orders of magnitude the $h \rightarrow \Upsilon \gamma$ decay rate. This can be used to constrain the wrong-sign solution in the 2HDM.

We have performed a full simulation of the real 2HDM, including theoretical constraints from bounded from below potential $[15]$, perturbative unitarity $[16,18]$, oblique radiative parameters $[19,21]$, and we keep $m_{H^\pm} > 480$ GeV to respect B-physics constraints. We include all production mechanisms $[22,24]$ and take $\mu_{VV}, \mu_{\gamma\gamma},$ and $\mu_{\tau\tau}$ to lie within 20% of the SM, in close accordance with the latest LHC constraints $[25]$.

The results of our simulation in the type II model are shown in Fig. 3. The red/dark-grey points pass all theoretical constraints. The blue/black (green/light-grey) points pass those and also $\mu_{VV}, \mu_{\gamma\gamma},$ and $\mu_{\tau\tau}$ at 20% (10%). The situation for the flipped model is very similar, with only very slight differences in the allowed regions, due to the different dependence on $\mu_{\tau\tau}$.

There are several features of note. After theoretical constraints, the simulation allows for a very large range of $k_D$. Contrary to what one might naively expect, having a large $k_D$ does not improve much the $h \rightarrow \Upsilon \gamma$ branching ratio. The point is that, although a large $k_D$ does indeed increase the direct amplitude, in accordance with Eq. (13), in the 2HDM the width of $h$ is dominated by $h \rightarrow b\bar{b}$, which also increases with $k_D$. Once one introduces the experimental constraints, the values for $k_D$ get restricted to right-sign ($k_D \sim 1$) and wrong-sign ($k_D \sim -1$) regions. As explained in Sec. [11B] this is mostly due to $\mu_{VV}$ and simple trigonometry $[11]$. Finally, one sees that, due to the same destructive interference at play in the SM, the right-sign solution leads to a minute $h \rightarrow \Upsilon \gamma$ branching ratio around $10^{-8}$. In contrast, the wrong-sign solution leads to constructive interference and a $h \rightarrow \Upsilon \gamma$ branching ratio larger by two orders of magnitude.

The possible experimental reach is best seen in Fig. 3(b), where we show a simulation of $\sigma(pp \rightarrow h) \times BR(h \rightarrow \Upsilon \gamma)$ at 13 TeV. For the wrong-sign, we find a value around 0.06 fb. The current run II data lies around 15 fb$^{-1}$ total integrated luminosity $[24]$ and will ultimately achieve around 100 fb$^{-1}$, meaning that a measurement is becoming possible. This 0.06 fb estimate arises from the precise values taken for $g_Y$ and the scale chosen for $\alpha$ in the various steps of the calculation. A detailed discussion, including relativistic corrections, can be found in $[19]$. Our result presents a lower limit on the number of events, meaning that detection prospects are likely to be superior. Of course, an even better determination is possible at the High-Luminosity LHC, allowing for the detection or completely ruling
out of the wrong-sign solution. We have made a simulation at 14 TeV and obtain the expected increase of about 15% from 0.06 fb into around 0.07 fb, in both Type II and Flipped.

IV. CONCLUSIONS

The decay $h \rightarrow \Upsilon \gamma$ is very small in the SM, due to a cancellation between the direct and indirect diagrams. In contrast, in theories with a negative $hbb$ coupling, the interference becomes constructive and the rate is increased by orders of magnitude. We have studied this effect on the wrong-sign solution of the Type II and flipped 2HDM. We make detailed predictions for the number of events consistent with current bounds on the 2HDM and prove that searches for $h \rightarrow \Upsilon \gamma$ constitute a viable and clean method to constrain the wrong-sign solution, especially at a high luminosity facility.

Acknowledgments

We are grateful to G. Bodwin for discussions and to R. Santos for carefully reading the manuscript. This work is supported in part by the Portuguese Fundação para a Ciência e Tecnologia (FCT) under contract UID/FIS/00777/2013.

[1] G. Aad et al. [ATLAS Collaboration], Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716, 1 (2012) [arXiv:1207.7214 [hep-ex]].
[2] S. Chatrchyan et al. [CMS Collaboration], Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716, 30 (2012) [arXiv:1207.7235 [hep-ex]].
[3] J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, First Glimpses at Higgs’ face, JHEP 1212, 045 (2012) doi:10.1007/JHEP12(2012)045 [arXiv:1207.1717 [hep-ph]].
[4] A. Falkowski, F. Riva and A. Urbano, Higgs at last, JHEP 1311, 111 (2013) doi:10.1007/JHEP11(2013)111 [arXiv:1303.1812 [hep-ph]].
[5] G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors, Phys. Rev. D 88, 075008 (2013) doi:10.1103/PhysRevD.88.075008 [arXiv:1306.2941 [hep-ph]].
[6] J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, *The Higgs Hunter’s Guide* (Westview Press, Boulder, CO, 2000).
[7] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, Phys. Rept. 516, 1 (2012) [arXiv:1106.0034 [hep-ph]].
[8] A. Celis, V. Illisie and A. Pich, Towards a general analysis of LHC data within two-Higgs-doublet models, JHEP 1312, 095 (2013) doi:10.1007/JHEP12(2013)095 [arXiv:1310.7941 [hep-ph]].
[9] P. M. Ferreira, J. F. Gunion, H. E. Haber and R. Santos, Probing wrong-sign Yukawa couplings at the LHC and a future linear collider, Phys. Rev. D 89, no. 11, 115003 (2014) doi:10.1103/PhysRevD.89.115003 [arXiv:1403.4736 [hep-ph]].
[10] P. M. Ferreira, R. Guedes, M. O. P. Sampaio and R. Santos, Wrong sign and symmetric limits and non-decoupling in 2HDMs, JHEP 1412, 067 (2014) doi:10.1007/JHEP12(2014)067 [arXiv:1409.6723 [hep-ph]].
[11] D. Fontes, J. C. Romão and J. P. Silva, A reappraisal of the wrong-sign $hbb$ coupling and the study of $h \rightarrow Z\gamma$, Phys. Rev. D 90, no. 1, 015021 (2014) doi:10.1103/PhysRevD.90.015021 [arXiv:1406.6080 [hep-ph]].
[12] G. T. Bodwin, F. Petriello, S. Stoynev and M. Velasco, Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling, Phys. Rev. D 88, no. 5, 053003 (2013) doi:10.1103/PhysRevD.88.053003 [arXiv:1306.5770 [hep-ph]].
[13] G. T. Bodwin, H. S. Chung, J. H. Ee, J. Lee and F. Petriello, Relativistic corrections to Higgs boson decays to quarkonia, Phys. Rev. D 90, no. 11, 113010 (2014) doi:10.1103/PhysRevD.90.113010 [arXiv:1407.6695 [hep-ph]].
[14] D. Fontes, J. C. Romão and J. P. Silva, $h \rightarrow Z\gamma$ in the complex two Higgs doublet model, JHEP 1412, 043 (2014) doi:10.1007/JHEP12(2014)043 [arXiv:1408.2534 [hep-ph]].
[15] N. G. Deshpande and E. Ma, Pattern of Symmetry Breaking with Two Higgs Doublets, Phys. Rev. D 18, 2574 (1978). doi:10.1103/PhysRevD.18.2574.
[16] S. Kanemura, T. Kubota and E. Takasugi, Lee-Quigg-Thacker bounds for Higgs boson masses in a two doublet model, Phys. Lett. B 313, 155 (1993) doi:10.1016/0370-2693(93)91205-2 [hep-ph/9303263].
[17] A. G. Akerooyd, A. Arhrib and E. M. Naimi, Note on tree level unitarity in the general two Higgs doublet model, Phys. Lett. B 490, 119 (2000) doi:10.1016/S0370-2693(00)00962-X [hep-ph/0006035].
[18] I. F. Ginzburg and I. P. Ivanov, Tree level unitarity constraints in the 2HDM with CP violation, [hep-ph/0312374].
[20] W. Grimus, L. Lavoura, O. M. Ogreid and P. Osland, The Oblique parameters in multi-Higgs-doublet models, Nucl. Phys. B 801, 81 (2008) doi:10.1016/j.nuclphysb.2008.04.019.

[21] M. Bank et al., The Electroweak Fit of the Standard Model after the Discovery of a New Boson at the LHC, Eur. Phys. J. C 72, 2205 (2012) doi:10.1140/epjc/s10052-012-2205-9 [arXiv:1209.2716 [hep-ph]].

[22] M. Spira, HIGLU: A program for the calculation of the total Higgs production cross-section at hadron colliders via gluon fusion including QCD corrections, hep-ph/9510347.

[23] R. V. Harlander, S. Liebler and H. Mantler, SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM, Comput. Phys. Commun. 184, 1605 (2013) doi:10.1016/j.cpc.2013.02.006 [arXiv:1212.3249 [hep-ph]].

[24] LHC Higgs cross section WG picture gallery webpage, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures.

[25] G. Aad et al. [ATLAS and CMS Collaborations], Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, arXiv:1606.02266 [hep-ex].

[26] https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#Run_2_Annual_Charts_of_Luminosit