Accumulating Evidence for the Associate Production of a Neutral Scalar with Mass around 151 GeV

Andreas Crivellin, Yaquan Fang, Oliver Fischer, Abhaya Kumar, Mukesh Kumar, Elias Malwa, Bruce Mellado, Ntsoko Rapheeha, Xifeng Ruan, and Qiyu Sha

1 Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland
2 Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
3 CERN Theory Division, CH-1211 Geneva 23, Switzerland
4 Institute of High Energy Physics, 10B, Yuquan Road, Shijing District, Beijing, China, 100049
5 University of Chinese Academy of Sciences (CAS), 19A Yuquan Road, Shijing District, Beijing, China, 100049
6 Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, UK
7 School of Physics and Institute for Collider Particle Physics, University of the Witwatersrand, Johannesburg, Wits 2050, South Africa.
8 iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa.

In recent years, hints for “multi-lepton anomalies” have been accumulated by the analysis of Large Hadron Collider (LHC) data, pointing towards the existence of beyond the Standard Model (SM) Higgs bosons: a new scalar particle $S$ with a mass $m_S$ in the range between 130 GeV and 160 GeV, produced from the decay of a heavier new scalar particle, $H$. Motivated by this observation, we perform a search for the signatures of $S$ within this mass region, which has been studied by CMS and ATLAS as a by-product of the SM Higgs searches in the side-bands of the kinematic regions. Combining the $\gamma\gamma$ and $Z\gamma$ channels, with associated leptons, di-jets, bottom quarks and missing energy, we obtain a local (global) significance of $5.1 \sigma$ ($4.8 \sigma$) for a mass of $m_S = 151.5$ GeV and provide the preferred ranges for the corresponding (fiducial) cross sections. This is a strong indication for a scalar resonance $S$ decaying into photons, and, to a lesser extent to $Z\gamma$, in association with missing energy, jets or leptons. Hints for the decays into, or production in association with, bottom quarks are statistically less significant. In order to test this hypothesis, we propose a search for $H \rightarrow \gamma\gamma b\bar{b}, \tau^+\tau^- b\bar{b}$ in asymmetric configurations that has not yet been performed by ATLAS and CMS.

I. INTRODUCTION

The discovery of the Brout-Englert-Higgs boson ($h$) [1–4] at the LHC by ATLAS [5] and CMS [6] has opened a new chapter in particle physics. Measurements so far indicate that this 125 GeV boson has properties compatible with those predicted by the SM [7, 8]. However, this does not exclude the existence of additional scalar bosons as long as their possible mixing with the SM Higgs is sufficiently small, such that the properties of the latter remain to a good approximation unchanged.

In fact, in recent years the so-called “multi-lepton anomalies” emerged as deviations from the SM predictions in several analyses of multi-lepton final states from ATLAS and CMS, as observed in Refs. [9–12]. These hints for New Physics (NP) are statistically most compelling in non-resonant di-leptons (both opposite and same sign) final states as well as in the three-lepton channel (with and without the presence of $b$-tagged jets). These signatures can be explained by the decay of a neutral scalar $H$ into a lighter one $S$ and the SM Higgs [13], i.e. $H \rightarrow Sh, SS$, as realized e.g. within the 2HDM$+$ model (also called N2HDM) [14–18].

The explanation of the multi-lepton anomalies in the 2HDM$+$ framework requires the mass of $S$ to be between 130 GeV and 160 GeV [9]. Fortunately, this mass range is covered in the side bands of CMS and ATLAS searches for the SM Higgs. Therefore, the published analyses of di-photon, $Z\gamma$ and $b\bar{b}$ resonances [25–32] can be used to search for a signal of $S$. For the search of di-photon resonances both inclusive distributions, as well as analyses including the associate production of leptons, ($b$-) jets and missing transverse energy ($E_{T,\text{miss}}$) are available. Importantly, it is possible to combine the information from these channels without specifying an explicit model.
model, such that the only assumption is a scalar particle \( S \) with an associate production mechanism.

In this article we present a combined fit of the different channels, briefly discuss the implications of the different signals for the properties of \( S \), and suggest a new search for \( S \) via the search for asymmetric \( \gamma\gamma b\bar{b}, \tau^+\tau^- b\bar{b} \) signals.

II. METHODOLOGY

As outlined in the introduction, we use CMS and ATLAS analyses of SM Higgs decays which cover (implicitly) also the search for other Higgs-like resonances from a scalar \( S \) in the side bands. In fact, depending on the specific channel, searches can cover scalar masses \((m_S)\) up to 180 GeV. However, since some searches only reach 160 GeV, we will use the region between 140 GeV (in order to avoid overlap with SM Higgs signals) and 155 GeV as the use of a side-band fit further reduces the range within one can search for a resonance. Importantly, this happens to be the mass range motivated by the multi-lepton anomalies.

Let us summarize the CMS and ATLAS searches used in our analysis:

\[ S(Z(\ell^+\ell^-)\gamma) + \ell: \] \( m_S \) is reconstructed from the invariant mass of the \( Z\gamma \) pair and \( S \) is assumed to be produced in association with one additional lepton (other than the leptons originating from the decays of the \( Z \)). This data is extracted from Fig. 5 in Ref. [31].

\[ S(\gamma\gamma) + E_{\text{miss}}^T: \] In these channels \( m_S \) is reconstructed from the invariant mass of \( \gamma\gamma \) and \( S \) is produced in association with \( E_{\text{miss}}^T \). The data is taken from Fig. 6 in Ref. [29] and Fig. 3 in Ref. [30].

\[ S(b\bar{b}) + E_{\text{miss}}^T: \] \( m_S \) is reconstructed from the invariant mass of \( b\bar{b} \) and \( S \) is produced in association with \( E_{\text{miss}}^T \). The data is taken from Fig. 14 (a) in Ref. [32].

\[ S(\gamma\gamma) + b: \] \( m_S \) decays to two photons and is produced in association with \( b \) quarks (which, in the 2HDM+S model, could originate from \( S \) but also from \( h \) if \( H \to Sh \) is non-negligible). The data is obtained from Fig. 2 (top-right) and Fig. 2 in Ref. [27].

\[ S(\gamma\gamma) + V(W, Z): \] \( S \) decays to two photons and is produced in association with a \( W \) or a \( Z \) boson. The corresponding data is given in Fig. 15 bottom-left in Ref. [24] and Fig. 9 (c) and (d) in Ref. [26].

\[ S(\gamma\gamma) \text{ inclusive}: \] Here \( m_S \) is reconstructed from the invariant mass of the photon pair while the search is quasi-inclusive, however, vector boson fusion, \( W \) and \( Z \) as well as top quark associated production are excluded. Note that there is no veto on missing energy, but that this channel covers only a very tiny phase space of the quasi-inclusive final state. (see Fig. 15 top-left in Ref. [24] and Fig. 9 (a) in Ref. [26]).

For each category discussed above, we model the background via a function:

\[
f(m; b, \{a\}) = (1 - m)^a_0 + a_1 \log(m),
\]

where \(a_{0,1}\) and \(b\) are free parameters (different for each category) and \(m\) is the invariant mass of the distribution, e.g. the di-photon mass. This corresponds to the background-only hypothesis and the goodness of the corresponding fit results in the \(p\)-value of the SM.

In order to search for a signal in each category, we add to the background the function in Eq. (1) a double-sided-crystal-ball function:

\[
N = \begin{cases} 
e^{-t^2/2} & \text{if } -\alpha_{\text{Low}} \leq t \leq \alpha_{\text{High}} \\ e^{-0.5n_5_{\text{Low}}} - e^{-0.5n_5_{\text{High}}} & \text{if } t < -\alpha_{\text{Low}} \\ \frac{n_{\text{High}}}{n_{\text{Low}}}(e^{\alpha_{\text{High}} - \alpha_{\text{Low}} - t} - e^{-0.5n_5_{\text{High}}}) & \text{if } t > \alpha_{\text{High}}. \\ \end{cases}
\]

Here \( N \) is a normalization parameter, \( t = (m - m_S)/\sigma_{CB} \) with \( \sigma_{CB} \) the width of the Gaussian part of the function, \(m\) is the invariant mass of the distribution and \( m_S \) the mass of the new resonance we are interested in (which is the same for all channels). \( \alpha_{\text{Low}}(\alpha_{\text{High}}) \) is the point where the Gaussian becomes a power law on the low (high) mass side and we set \( \alpha_{\text{Low}}(\alpha_{\text{High}}) = 1.5 \). \( n_{\text{Low}}(n_{\text{High}}) \) is the exponent of this power law and \( n_{\text{Low}}(n_{\text{High}}) \) is set to 5 (9). The fit results are quite insensitive to the specific choice of \( \alpha_{\text{Low}}(\alpha_{\text{High}}) \) or \( n_{\text{Low}}(n_{\text{High}}) \). As we assume that the physical width of \( S \) is much smaller than the detector resolution of the respective channels, \( \sigma_{CB} \) is thus determined by the detector resolution: \( \sigma_{CB} = 1.5 \) GeV for the di-photon and \( Z\gamma \) channel, and \( \sigma_{CB} = 14 \) GeV for the \( b\bar{b} \) channel.

For any given final state (category), the relative contribution of sub-categories to the total signal strength is taken to be proportional to the observed excess in each spectrum. For some of the spectra, this is obtained by a \( N_S/(N_S + N_B) \) or \( \ln(1 + N_S/N_B) \) re-weighting, where \( N_S \) is the number of SM Higgs events in the sub-category in the original analysis and \( N_B \) is the number of background events under the Higgs boson peak. The spectra are then re-weighted using a constant factor \( N_{h,\text{unweighted}}/N_{h,\text{weighted}} \), where \( N_{h,\text{unweighted}} \) is the number of SM Higgs (125) GeV signal events obtained in the CMS or ATLAS analyses. The simultaneous fit of \( m_S \) using all channels therefore takes into account the different integrated luminosity in each analysis. This is then implemented into the likelihood ratio formalism, relying on the software used as well for the discovery of the SM Higgs boson [7] [8].
III. ANALYSIS AND RESULTS

Table I shows the extracted total cross section for the quasi-inclusive di-photon analysis, the limit on the total $4\ell$ cross section (not included in the signal analysis) and the fiducial cross sections for all other associate production channels.

We define the signal yield as $Y = \epsilon \cdot \sigma_S \cdot L$, where $\sigma_S$ is the total or fiducial cross section, depending on the analysis, the (channel dependent) luminosity $L$ and the efficiency $\epsilon$, which parametrizes analysis-specific selection criteria and the geometric acceptance of the detector. Based on the efficiencies quoted in the different ATLAS and CMS analyses, we assume that the value of $\epsilon$ is on average 59% for the di-photon channel and 24% for the $Z\gamma$ channel. Therefore, $Y$ corresponds to the number of observed signal events in a given channel.

The spectra of the channels in which the excesses are most significant are shown in Fig. 1 and the combination of all channels in Fig. 2, excluding the $b\bar{b}$ channel due to the large resolution. Note that the background curves here do not exactly correspond to the SM hypothesis but rather to Eq. (1) in the combined fit to Eq. (1) and Eq. (2). For improved visualization, each plot combines the spectra from ATLAS and CMS (if available) for the same final states by using a signal over background ($N_S/N_B$) re-weighting, such that $N_S$ is the number of signal at the peak ($\pm 3\text{GeV}$) of the crystal-ball function and $N_B$ are the corresponding background events within this range.

Combining all spectra (being a function of a common mass $m_S$) the local $p$-value that a background-only hypothesis is true is shown in Fig. 3 as a function of $m_S$. The maximal local significance for a resonance is 5.1$\sigma$ at $m_S = 151.5$ GeV, where it varies by 1$\sigma$ when shifting the mass by 1 GeV. Taking into account the look-elsewhere effect due to the mass scan between 140 GeV to 155 GeV, the significance is reduced to 4.8$\sigma$. We observe that the di-photon final states, in particular in channels with associated $E^\text{miss}_T$, contribute most to the excess. Furthermore, while there is a preference for a decay of $S$ to $Z\gamma$ and $b\bar{b}$ the significance for the latter is, with 1.2$\sigma$, quite small. We remark that the limits on the to-

3 There is also a 2.3$\sigma$ excess (locally) reported by ATLAS in the search for fully hadronic final states originating from $S \rightarrow VV$ [33]. This excess was not included in our fit, since the spectrum was not given in a form usable for our analysis.
H with di-boson signatures, such as yields obtained in the different categories are consistent by more than a factor 2. We observe that the signal tal cross sections should not differ from the fiducial ones within the cuts that were applied in the analysis, the to-

| Channel | Cross. sec. [fb] | Obs. lim. | Exp. lim. |
|---------|-----------------|-----------|-----------|
| $S(\gamma\gamma)$ | $4.1\pm2.6$ | $9.0$ | $5.4$ |
| $S(\gamma\gamma) + E_{miss}^T > 90$ GeV | $0.42\pm0.13$ | $0.65$ | $0.22$ |
| $S(\gamma\gamma) + V \to jj$ | $0.28\pm0.28$ | $0.80$ | $0.57$ |
| $S(\gamma\gamma) + b$-jets | $0.08\pm0.08$ | $0.22$ | $0.16$ |
| $S(\ell\ell) + V \to t\bar{t}$ or $t\ell\ell$ | $1.3\pm0.7$ | $2.8$ | $2.1$ |
| $S[bb] + 150 < E_{miss}^T < 250$ GeV | $0.90\pm0.79$ | $2.2$ | $2.0$ |
| $S(4\ell)$ | $0.10\pm0.13$ | $0.28$ | $0.33$ |

TABLE I: Extracted cross sections in fb for each final state considered here (see main text for details). The observed and expected limits on fiducial cross-section at 95% confidence level are also provided. For the second and the last category total cross sections are quoted while for the associate production channels fiducial ones are given. The $S \to 4\ell$ is not included in the fit but rather given as a constraint.

case, in order to allow for a $E_{miss}^T$ of more than 90 GeV, $m_H > 240$ GeV is required and if $m_H$ were above the TeV scale, the efficiency of the search would be significantly affected (due to overproduced $E_{miss}^T$).

Let us therefore interpret the results in Table II assuming that $S$ is pair produced by the decays of $H$ with a mass around 270 GeV (as suggested by the multi lepton anomalies) via $pp \to H \to SS^*$. We remark that also the process including $H \to Sh^{(*)}$ is possible in principle, but we will ignore it for now. The properties of $S$ can be determined approximately from the relative signal strengths of the considered channels: It should clearly decay to photons, and to a lesser extent to $Z\gamma$, and it should decay into invisible final states in order to produce missing energy. Further hints for $S$ decaying into, or it being produced in association with, bottom quarks are less significant statistically, and therefore only optional.

The individual signal strengths of the here considered channels could imply that the couplings of $S$ to SM articles are induced via the mixing with $h$. In this case $S$ would ‘inherit’ the branching ratios of a would-be Higgs boson with a mass of 151 GeV, and one would expect $\text{Br}[S \to bb] \approx 14\%$, $\text{Br}[S \to \tau\tau] \approx 0.16\%$, $\text{Br}[S \to \gamma\gamma] \approx 1.3 \times 10^{-3}$, $\text{Br}[S \to Z\gamma] \approx 2.2 \times 10^{-3}$, $\text{Br}[S \to WW] \approx 72\%$ and $\text{Br}[S \to ZZ^*] \approx 8.1\%$ [36], with a possible re-scaling due to the additional decay of $S$ into some invisible final state. Taking into account that $\text{Br}[Z \to \mu^+\mu^-] = \text{Br}[Z \to e^+e^-] \approx 3.36\%$, one can estimate that in this case $\text{Br}[S \to 4\ell] \approx 0.3\text{Br}[S \to \gamma\gamma]$ which is in conflict with the limit on $S \to 4\ell$ and thus disfavours the mixing hypothesis. This suggests the possibility that the couplings of $S$ to photons and the $Z$ might be loop-induced, for example by vector-like fermions (see e.g. [37][40]), one of which could be neutral and give rise to the $E_{miss}^T$ signatures. In this case, one would, however, not naturally expect a large $\text{Br}[S \to bb]$.

IV. ASYMMETRIC $\gamma\gamma bb$ SEARCHES

In order to verify or falsify the hypothesis of sizable $S \to bb$ or $H \to Sh$ rates, one could search for $H \to SS \to \gamma\gamma bb$ and $H \to Sh \to \gamma\gamma bb$ final states. These
are very promising signatures as they have the highest sensitivity for di-Higgs searches due to a good balance between the di-photon triggering efficiency, the triggering of the invariant mass spectra.

Let us illustrate this for $H \rightarrow SS \rightarrow \gamma \gamma b \bar{b}$. Assuming $m_H = 270$ GeV, the dominant branching ratio being $H \rightarrow SS^*$ forces one of the singlet scalars to be off-shell.\(^4\) This type of resonant $\gamma \gamma b \bar{b}$ searches have not been performed by the LHC experiments. Here, two corners of the phase-space are devised to study asymmetric configurations: $m_{\gamma \gamma} \in (145, 155)$ GeV and $m_{SS} \in (70, 120)$ GeV to isolate $H \rightarrow S(\rightarrow \gamma \gamma)S^*(\rightarrow b \bar{b})$; $m_{\gamma \gamma} \in (90, 120)$ GeV and $m_{SS} \in (120, 160)$ GeV to isolate $H \rightarrow S(\rightarrow b \bar{b})S^*(\rightarrow \gamma \gamma)$. In order to predict the resulting signatures, we perform a Monte-Carlo simulation of $pp$ collisions at the LHC. The events corresponding to the signal and SM backgrounds are generated using Madgraph\(^5\) with the NNPDF3.0 parton distribution functions\(^4\). The UFO model files required for the Madgraph analysis have been obtained from FeynRules\(^6\) after a proper implementation of the model. Following this parton level analysis, the parton showering and hadronization are performed using Pythia\(^7\). We use Delphes (v3)\(^8\) for the corresponding detector level simulation after the showering/hadronization. The jet construction at this level has been performed using Fastjet\(^9\) which involves the anti-$K_T$ jet algorithm with radius $R = 0.5$, transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$. Photons are required to have $p_T > 20$ GeV and $|\eta| < 2.5$

Figure 4 shows the expected signal and background yields in $\gamma \gamma b \bar{b}$ final state for one LHC experiment and 500 fb\(^{-1}\) of integrated luminosity. The first configuration displays significantly better signal-to-background rates due to the excellent di-photon invariant mass resolution. Here the benchmark signal cross-section $\sigma(pp \rightarrow H \rightarrow SS^* \rightarrow \gamma \gamma b \bar{b}) = 2$ fb is assumed, which includes the two configurations. The background includes the contribution from $\gamma \gamma$ in association with $\tau$-photons and light quarks. The $b$-jet tagging efficiency for $p_T = 30$ GeV is assumed to be 68%. In this setup a combined significance of over 7$\sigma$ could be achieved per LHC experiment for 500 fb\(^{-1}\) of integrated luminosity, assuming the current best fit to data is confirmed.

Interestingly, as the LEP experiments reported a mild excess (2.3$\sigma$) in the search for a scalar boson ($S'$)\(^9\) using the process $e^+e^- \rightarrow Z(\rightarrow b \bar{b})$ at 98 GeV for the invariant $b \bar{b}$ mass, asymmetric $\gamma \gamma b \bar{b}$ final states could also originate from the decay $H \rightarrow S S'$. This is further supported by the CMS result reporting similar excesses with Run 1 data and 35.9 fb\(^{-1}\) of Run 2 data\(^10\), with a local significance of 2.8$\sigma$ at 95.3 GeV. In this context, $t$ should be noted that searches with asymmetric configurations of $\gamma \gamma b \bar{b}$ are also substantiated.

\section*{V. CONCLUSIONS AND OUTLOOK}

In this article we accumulated evidence for the associate production of new scalar particle $S$ (assumingly via the decay of a heavier boson $H$) with a mass $m_S = 151.5$ GeV by combining the side-band data from CMS and ATLAS searches for the SM Higgs. Including all channels involving photons, $Z$ bosons, $b$-quarks and/or missing energy, we find a global significance of 4.8$\sigma$ (locally 5.1$\sigma$) for a mass range between 130 GeV and 160 GeV.

While the hints that this new scalar is decaying into photons (and to a lesser extent into the $Z \gamma$) are strong, in particular in association with $E_T^{miss}$, decays of $S$ into, or its associate production with, bottom quarks are preferred but still optional. In order to test the decay channel $S \rightarrow b \bar{b}$ we suggest to perform asymmetric searches for the final state $\gamma \gamma b \bar{b}$, $\tau^+ \tau^- b \bar{b}$, which also allows an assessment of the branching ratio $\text{Br}(H \rightarrow S h)$. Furthermore, such signals could be related to the LEP/CMS excess in

\footnote{We notice that in other possible decay channels like $H \rightarrow S h$ and $H \rightarrow hh$ the daughter particles are on-shell, which offers different search strategies in the final states.}
associate $b\bar{b}$ production and point towards a boson $S'$ at $\approx 96$ GeV that could lead to $H \rightarrow S'(S'')$. Our analysis opens up new directions in particle physics. First of all, $S$ could be related to the multi-lepton anomalies. However, due to the absence of a signal in $S \rightarrow ZZ^*$, an alternative mechanism for the lepton production, such as $S \rightarrow NN$, where $N$ has the quantum numbers of a right-handed neutrino, is possible. In such a setup, i.e. the 2HDM+, the quantum numbers of a right-handed neutrino, is possible. Furthermore, in the context of the 96 GeV $S'$ excess searches for $H \rightarrow S'(\rightarrow \gamma\gamma, b\bar{b})S(\rightarrow \text{invisible})$ are interesting.

Acknowledgments

The authors are grateful for support from the South African Department of Science and Innovation through the SA-CERN program and the National Research Foundation for various forms of support. The work of A.C. is supported by a professorship grant of the Swiss National Science Foundation (No. PP00P21_76884).

[1] P. W. Higgs, Phys. Lett. 12, 132 (1964).
[2] F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964).
[3] P. W. Higgs, Phys. Rev. Lett. 13, 508 (1964).
[4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Lett. 13, 585 (1964).
[5] G. Aad et al. (ATLAS), Phys. Lett. B 716, 1 (2012), 1207.7214.
[6] S. Chatrchyan et al. (CMS), Phys. Lett. B 716, 30 (2012), 1207.7235.
[7] S. Chatrchyan et al. (CMS), Phys. Rev. Lett. 110, 081803 (2013), 1212.6639.
[8] G. Aad et al. (ATLAS), Phys. Lett. B 726, 120 (2013), 1307.1432.
[9] S. von Buddenbrock, A. S. Cornell, A. Fadol, M. Kumar, B. Mellado, and X. Ruan, J. Phys. G 45, 115003 (2018), 1711.07874.
[10] S. Buddenbrock, A. S. Cornell, Y. Fang, A. Fadol Mohammed, M. Kumar, B. Mellado, and K. G. Tomiwa, JHEP 10, 157 (2019), 1901.05300.
[11] S. von Buddenbrock, R. Ruiz, and B. Mellado, Phys. Lett. B 811, 135964 (2020), 2009.00392.
[12] Y. Hernandez, M. Kumar, A. S. Cornell, S.-E. Dabbi, Y. Fang, B. Lieberman, R. Mellado, K. Monnakhgotla, X. Ruan, and S. Xin, Eur. Phys. J. C 81, 365 (2021), 1912.06969.
[13] S. von Buddenbrock, N. Chakraborty, A. S. Cornell, D. Kar, M. Kumar, T. Mandal, B. Mellado, B. Mukhopadhyaya, R. G. Reed, and X. Ruan, Eur. Phys. J. C 76, 580 (2016), 1606.01674.
[14] X.-G. He, T. Li, X.-Q. Li, J. Tandean, and H.-C. Tsai, Phys. Rev. D 79, 035021 (2009), 0811.0658.
[15] B. Grzadkowski and P. Osland, Phys. Rev. D 82, 125026 (2010), 0910.4068.
[16] C.-Y. Chen, M. Freid, and M. Sher, Phys. Rev. D 89, 075009 (2014), 1312.3949.
[17] M. Muhlleitner, M. O. P. Sampaio, R. Santos, and J. Wittbrodt, JHEP 03, 094 (2017), 1612.01309.
[18] M. Krause, D. Lopez-Val, M. Muhlleitner, and R. Santos, JHEP 12, 077 (2017), 1708.01578.
[19] M. Aguilar et al. (AMS Collaboration), Phys. Rev. Lett. 122, 041102 (2019), URL https://link.aps.org/doi/10.1103/PhysRevLett.122.041102.
[20] M. Ackermann, M. Ajello, A. Albert, W. B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, R. Bellazzini, E. Bissaldi, et al., The Astrophysical Journal 840, 43 (2017), ISSN 1538-4357, URL http://dx.doi.org/10.3847/1538-4357/aa6cab.
[21] G. Beck, M. Kumar, E. Malwa, B. Mellado, and R. Temo (2021), 2102.10596.
[22] D. Sabatta, A. S. Cornell, A. Goyal, M. Kumar, B. Mellado, and X. Ruan, Chin. Phys. C 44, 063103 (2020), 1909.03969.
[23] B. Abi et al. (Muon g-2), Phys. Rev. Lett. 126, 141801 (2021), 2104.03281.
[24] T. Aoyama et al., Phys. Rept. 887, 1 (2020), 2006.04822.
[25] A. M. Sirunyan et al. (CMS), JHEP 07, 027 (2021), 2103.06956.
[26] (2020).
[27] G. Aad et al. (ATLAS), Phys. Rev. Lett. 125, 061802 (2020), 2004.04545.
[28] A. M. Sirunyan et al. (CMS), Phys. Rev. Lett. 125, 061801 (2020), 2003.10866.
[29] G. Aad et al. (ATLAS) (2021), 2104.13240.
[30] A. M. Sirunyan et al. (CMS), JHEP 09, 046 (2018), 1806.04771.
[31] A. M. Sirunyan et al. (CMS), JHEP 11, 152 (2018), 1806.05996.
[32] ATLAS Collaboration (2020), URL https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-51/.
[33] G. Aad et al. (ATLAS), Phys. Rev. Lett. 126, 121802 (2021), 2010.06548.
[34] ATLAS Collaboration, Eur. Phys. J. C 78, 293 (2018), 1712.06386.
[35] (2019).
[36] J. R. Andersen et al. (LHC Higgs Cross Section Working Group) (2013), 1307.1347.
[37] R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, and R. Torre, JHEP 03, 144 (2016), 1512.04933.
[38] A. Falkowski, O. Slone, and T. Volansky, JHEP 02, 152 (2016), 1512.05777.
[39] R. Benbrik, C.-H. Chen, and T. Nomura, Phys. Rev. D 93, 055034 (2016), 1512.06028.
[40] W. Chao, R. Huo, and J.-H. Yu, Eur. Phys. J. Plus 132, 27 (2017), 1512.05738.
[41] A. M. Sirunyan et al. (CMS), Phys. Lett. B 788, 7 (2019).
[42] M. Aaboud et al. (ATLAS), JHEP 11, 040 (2018), 1807.04873.
[43] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, JHEP 07, 079 (2014), 1405.0301.
[44] R. D. Ball et al. (NNPDF), JHEP 04, 040 (2015), 1410.8849.
[45] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, Comput. Phys. Commun. 185, 2250 (2014), 1310.1921.
[46] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP 05, 026 (2006), hep-ph/0603175.
[47] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi (DELPHES 3), JHEP 02, 057 (2014), 1307.6346.
[48] M. Cacciari, G. P. Salam, and G. Soyez, Eur. Phys. J. C 72, 1896 (2012), 1111.6097.
[49] R. Barate et al. (LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL), Phys. Lett. B 565, 61 (2003), hep-ex/0306033.
[50] A. M. Sirunyan et al. (CMS), Phys. Lett. B 793, 320 (2019), 1811.08459.
[51] A. Crivellin, M. Hoferichter, and P. Schmidt-Wellenburg, Phys. Rev. D 98, 113002 (2018), 1807.11484.
[52] E. J. Chun and T. Mondal, JHEP 11, 077 (2020), 2009.08314.
[53] P. M. Ferreira, B. L. Gonçalves, F. R. Joaquim, and M. Sher (2021), 2104.03367.
[54] M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, and M. Novoa-Brunet, in 55th Rencontres de Moriond on QCD and High Energy Interactions (2021), 2104.08921.
[55] W. Altmannshofer and P. Stangl (2021), 2103.13370.
[56] A. K. Alok, S. Kumbhakar, and S. Uma Sankar (2020), 2001.04395.
[57] T. Hurth, F. Mahmoudi, and S. Neshatpour, Phys. Rev. D 103, 095020 (2021), 2012.12207.
[58] M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, Phys. Rev. D 103, 015030 (2021), 2011.01212.
[59] S.-P. Li, X.-Q. Li, Y.-D. Yang, and X. Zhang, JHEP 09, 149 (2018), 1807.08530.
[60] C. Marzo, L. Marzola, and M. Raidal, Phys. Rev. D 100, 055031 (2019), 1901.08290.
[61] S. Iguro and Y. Omura, JHEP 05, 173 (2018), 1802.01732.
[62] A. Crivellin, D. Müller, and C. Wiegand, JHEP 06, 119 (2019), 1903.10440.