Deciphering the CP nature of the 750 GeV resonance

M. Chala\textsuperscript{a}, C. Grojean\textsuperscript{a,b}, M. Riembau\textsuperscript{a,c} and T. Vantalon\textsuperscript{a,c}

\textsuperscript{a} DESY, Notkestrasse 85, D-22607 Hamburg, Germany
\textsuperscript{b} on leave from ICREA, E-08010 Barcelona, Spain
\textsuperscript{c} IFAE, Barcelona Institute of Science and Technology (BIST) Campus UAB, E-08193 Bellaterra, Spain
mikael.chala@desy.de, christophe.grojean@desy.de, marc.riembau@desy.de, tvantalon@ifae.es

The recently observed excess in diphoton events at around 750 GeV can be satisfactorily described in terms of a new spin-0 real singlet with effective interactions to the gauge bosons. In this letter we first review the current constraints on this setup. We further explore the production in association with a gauge boson. We show the potential of this channel to unravel current flat directions in the allowed parameter space. We then study the potential of two different asymmetries for disentangling the CP nature of such a singlet in both gluon fusion and vector-boson fusion. For this matter, we perform an estimation of the efficiency for selecting signal and background events in eight different decay modes, namely $4\ell$, $2\ell 2\gamma$, $2\ell E_T$, $2\gamma 2\ell$, $4\ell 2\gamma$, $2\ell 2\gamma 2\ell$, $4\ell 2\ell$ and $4\ell \ell E_T$. We emphasize that the very different couplings of this new singlet to the Standard Model particles as well as the larger mass provide a distinctive phenomenology with respect to Higgs searches. We finally show that a large region of the parameter space region could be tested within the current LHC run, the dominant channel being $2\gamma 2\ell$.

I. INTRODUCTION

The first bunch of data in proton-proton collisions at $\sqrt{s} = 13$ TeV were successfully delivered by the LHC during last year. Surprisingly, the first analyses on these data with as few as $\sim 3 \text{ fb}^{-1}$ have revealed unexpected results. Indeed, the ATLAS\textsuperscript{[1]} and CMS\textsuperscript{[2]} experiments have pointed out an excess in diphoton events with an invariant mass of around 750 GeV; the local significance ranging from 2 to around 3$\sigma$. The reported excess survived further scrutiny\textsuperscript{[3]} and appears as the best hint in decades for physics beyond the Standard Model (SM) at colliders. This fact explains the excitement of the particle physics community, which has translated into a plethora of papers in less than three months\textsuperscript{[4]}.

This diphoton excess can be easily interpreted in terms of a spin-0 real singlet (although explanations in terms of spin-1 and spin-2 particles have also deserved some attention). Both production and decay are hence to be mediated by heavier states whose effects\textsuperscript{1} can be encoded in a small set of effective operators. Throughout this letter we adopt this approach and we explore the potential of the next run of data to unravel the CP nature of this candidate, namely whether it is a scalar or a pseudo-scalar. We start considering a generic parameterization in section II and discussing the current constraints. Production via gluon fusion (GF) and vector-boson fusion (VBF) turn out to be sizable in a large region of the parameter space. However, they are shown to give flat directions that can be only disentangled if new production mechanisms are considered. In this respect, we explore the potential of producing the singlet resonance in association with a Standard Model (SM) gauge boson in section III. The rest of the article is structured as follows. In sections IV and V we introduce two asymmetries in GF and VBF events. They are intended to differentiate the two CP hypothesis. The advantage of this approach relies on the fact that most systematic uncertainties cancel out. Statistical uncertainties are on the other hand properly taken into account. We perform simulations to estimate the efficiency for selecting signal and background events in both categories in eight different decay modes: $4\ell$, $2\ell 2\ell$, $2\ell E_T$, $2\gamma 2\ell$, $4\ell 2\gamma$, $2\ell 2\gamma 2\ell$, $4\ell 2\ell$ and $4\ell \ell E_T$. We show that after all cuts, sizable efficiencies are obtained for most signals while still keeping backgrounds under control. Despite that we do not attempt to optimize these cuts, all together the 8 channels can probe a wide region of the available parameter space within the current run of the LHC, as explained in section VI. We conclude in section VII.

\[1\] The model proposed in [2] is an exception where the diphoton excess originates from a solitary new degree of freedom without the need for any additional electrically charged particles, nor new strong dynamics. Alternative non-resonant models with long decay chains have also been proposed to explain the 750 GeV diphoton excess. In this letter, we limit ourselves to the simplest interpretation with a single resonance whose couplings to gluons and photons are mediated by additional heavier states charged under QCD and QED.

II. PARAMETERIZATION AND CURRENT CONSTRAINTS

This letter aims mainly to provide a guideline for future efforts on the analysis of the parity properties of a resonance $S$ with mass $M \sim 750$ GeV. We assume $S$ to be a spin-0 SM gauge singlet. Besides, the production cross section into diphotons mediated by $S$ is assumed to be 8 fb. The question of the spin and parity properties of $S$ is made legitimate by the unexpected character of the excess and thus by the absence of any particular theoreti-
cal prejudice towards one hypothesis. Actually we do not focus on any particular model nor we attempt to address the effective-field theory of \( S \) in full generality. In fact, the relevant Lagrangian for our phenomenological study can be parameterized as [6]

\[
\mathcal{L} = \frac{1}{2M} S \left( g_3^2 c_{gg} G^2 + g_2^2 c_{WW} W^2 + g_2^2 c_{BB} B^2 \right) + g_3^2 c_{gg} G^2 + g_2^2 c_{WW} W^2 + g_2^2 c_{BB} B^2 .
\]

Here, \( g_3, g_2 \) and \( g_1 \) stand for the SM \( SU(3), SU(2) \) and \( U(1) \) gauge couplings, respectively. \( G, W \) and \( B \) are the corresponding field-strength tensors. For a generic \( F, \tilde{F} \) is defined as \( F_{\mu\nu} = \frac{i}{2} \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta} \). The tilded (non-tilded) coefficients are zero if \( S \) is a scalar (pseudo-scalar). We disregard further couplings to the SM fermions and the Higgs doublet since they do not introduce any qualitative change in our analysis. Actually the latter has anyway to be small to pass the constraints from Higgs measurements [7] and \( ZZ \) resonant searches [8]. The decay width of \( S \) into the different decay modes provided by the interactions above can be easily computed for \( M \gg m_{W,Z} \), with \( m_{W/Z} \) the mass of the \( W^\pm (Z) \) boson. In this limit, the decay widths to the different pairs of gauge bosons are given by

\[
\begin{align*}
\Gamma_{gg} &= 8\pi\alpha_3^2 M \left( \frac{1}{2} c_{gg}^2 + \frac{1}{2} c_{gg}^2 \right), \\
\Gamma_{\gamma\gamma} &= \pi\alpha_3^2 M \left( c_{\gamma\gamma}^2 + c_{\gamma\gamma}^2 \right), \\
\Gamma_{Z\gamma} &= 2\pi\alpha_3^2 M \left[ \left( c_{BB} t_W - \frac{c_{WW}}{t_W} \right)^2 + \left( c_{BB} t_W - \frac{c_{WW}}{t_W} \right)^2 \right],
\end{align*}
\]

where \( c_{gg} = c_{BB} + c_{WW}, t_W \) and \( s_W \) the tangent and sine of the Weinberg angle, \( \alpha_3 \) the fine-structure constant and \( \alpha_3 = g_3^2/(4\pi) \). The photon field-strength coefficient is thus given by \( 4\pi\alpha_3 c_{\gamma\gamma}/2M \). The cross section for the single production of \( S \) and the subsequent decay into two photons at a center of mass energy \( \sqrt{s} \) reads

\[
\sigma_{\gamma\gamma}(s) = \frac{1}{8 M^2} \left( C_{gg} \Gamma_{gg} + C_{\gamma\gamma} \Gamma_{\gamma\gamma} \right) \Gamma_{\gamma\gamma},
\]

with \( \Gamma_S \) stands for the total width. \( C_{gg} \) and \( C_{\gamma\gamma} \) represent instead dimensionless parton luminosities for gluon and photon fusion, respectively. Their values at 8 (13) TeV have been found to be approximately 174 (2137) and 11 (54), respectively [6]. The single production of \( S \) via GF at 13 TeV is thus enhanced with respect to 8 TeV by a factor of \( \sim 5 \), which can be in agreement with the absence of departures from the SM predictions in the first LHC run. This in fact translates into a bound on \( \sigma_{\gamma\gamma}(8 \text{ TeV}) \lesssim 2 \text{ fb} \) [9, 10]. This observation is no longer true for single production via photon fusion. It is only increased by a factor of \( \sim 2.9 \) and therefore in tension with current constraints (see for example [11, 12]). The \( c_{gg} \) coupling is bounded from above (below) to avoid too large (small) a diphoton cross section. In the same vein, experimental searches for resonant \( Z\gamma [13], ZZ [14] \) and \( W^+W^- [15] \) production at 8 TeV set stringent limits on this setup. This information is summarized in Fig. 1. The allowed parameter space in the \( c_{\gamma\gamma} - c_{WW}/c_{BB} \)
plane that can explain the excess while evading the current bounds is presented in this plot. For every point in this plane, $c_{gg}$ has been fixed so that $\sigma^{\gamma\gamma}(13 \text{ TeV}) = 8 \text{ fb}$. The corresponding values are shown in dashed blue lines. Notice also that the bounds coming from direct searches would be much weaker if $\sigma^{\gamma\gamma}(13 \text{ TeV})$ was smaller. The solid green (brown) contour lines stand for the total (additional) width. In the left panel of the figure we assume that $\Gamma_S$ coincides with these contours. In the right panel we fix it instead to the best-fit value reported by the ATLAS Collaboration \cite{1}, $\Gamma_S = 45 \text{ GeV}$, by considering an additional partial width of $S$ into soft (or partially invisible) particles that escape detection.

III. ASSOCIATED PRODUCTION

It can be seen from Fig. 1 that resonance searches for massive gauge bosons are only sensitive to the ratio $c_{WW}/c_{BB}$. Other flat directions are of course also apparent. In fact, even if it was possible to determine $\Gamma_S$ experimentally, we would have to measure all $S$ decay modes to be able to bound each coupling independently. This seems highly unrealistic, first, because $\Gamma_S$ might remain out of the experimental resolution, and second because it would require to also tag decays into gluons and (potentially) invisible particles, a notoriously difficult task in the busy hadronic environment of the LHC. Thus, different strategies should be considered in this respect. One possibility relies on $S$ production in association with a gauge boson (a previous study in this direction has been presented in \cite{16}). The corresponding cross sections are depicted in Fig. 2. These have been computed by using MadGraph v5 \cite{17} (Feynrules v2 \cite{18} has been first used to implement the interactions of Eq. 1). In the region of parameter space compatible with the reported excess, the associated production cross sections can be as large as few tens fb. And even for rare decay modes, (e.g. a branching ratio below $0.001$ for $S \to ZZ \to 4f$), enough events can still be collected with large luminosities. Note also that the corresponding backgrounds are almost negligible (see for example \cite{19} for an experimental study of three photon final states). Thus, in Fig. 3 we elaborate on the idea of resolving flat directions using further production modes. To this end, we consider an hypothetical scenario in which the ratio $c_{WW}/c_{BB}$ has been experimentally established (this measurement can be performed by just observing the ratio of $\gamma\gamma$ events over $ZZ$ or $Z\gamma$ events). Clearly, $c_{\gamma\gamma}$ and $c_{gg}$ cannot just be individually determined by fitting the diphoton excess. This flat direction in the $c_{gg} - c_{\gamma\gamma}$ plane is depicted by the orange band in Fig. 4 for $\Gamma_S = 45 \text{ GeV}$ and $c_{VV}/c_{BB} = 1$. Now in addition if the associated production $SW^\pm \to 2\gamma 2j$ is observed to be, for example, $0.01 \pm 0.005 \text{ fb}$, this relation is broken and $c_{\gamma\gamma}$ can be constrained independently, as shown by the vertical band in the figure.

The discussion above assumes no substantial direct coupling of $S$ to the SM fermions. If such couplings exist, another contribution to the associated production originates when an EW gauge boson is radiated off from one of the initial quarks. However, the cross section is negligible when linked to light quarks under the assumption that the couplings obey a minimal flavor violation structure and are therefore naturally expected to be of the size of the Yukawa couplings. Flavor constraints would be hard to evade otherwise. If large couplings to the light quarks were nonetheless present, relying on some cancellation to pass flavor constraints, then a detailed study of the kinematic would be worth performing in order to discriminate the various contributions to the associated production. We have checked that the associated production cross section via an initial $b$ quark remains smaller than the contributions computed in Fig. 2 in most of the parameter space. Finally, we have checked that the gluon-fusion associated production $S + W^\pm / Z / \gamma$ together with an extra jet is typically subdominant too, except in the region of small $c_{\gamma\gamma} (< 0.1)$ where it can anyway be reduced by an appropriate cut on the gauge boson $p_T$ and by vetoing the extra jet.

This simple analysis illustrates the importance of considering the associated production mechanisms. Indeed, the argument does not hold equally well for $S$ production in VBF since it turns out to have a remaining large dependence on $c_{gg}$. The reason is that, contrary to the Higgs case whose couplings to the electroweak gauge bosons appear at the tree level, VBF contamination by gluon initiated processes in the singlet case can be rather large even after tagging on forward jets \cite{20, 21}. Cuts in this respect are provided in section V. Nonetheless, it is worth to point out that measurements in VBF together with the determination of $\Gamma_S$ might shed light on possible $S$ hidden decays \cite{22}.

![Contour lines of the cross sections (in fb) for the associated production channel with an electroweak gauge boson in the plane $c_{\gamma\gamma} - c_{WW}/c_{BB}$. The numbers stand for each group of three contour lines.](image)

On top of it, a last comment concerns the spin-1 alternatives for explaining the diphoton excess. As it has been
pointed out in [24], these scenarios rely on the production of a 750 GeV vector boson that subsequently decays into a photon and a light scalar. The latter further decays into two collimated photons that, at the detector level, appear to be a single one. This kind of setup can not however give rise to sizable amount of three gauge boson events. Particularly with $W^\pm$ in the final state. As a consequence, $S$ production in association with gauge bosons provides a striking signature for disentangling spin-0 and spin-1 models.

The distinctive kinematics of associated production provides different ways to inquire the parity of such a scalar. The polar angle of the radiated vector boson has been highlighted in this respect in the context of Higgs physics (see for example [24, 25], and [26] for related experimental searches at Tevatron). The large Higgs coupling to the longitudinal polarization of the gauge bosons are however instrumental for these studies. The rather small splitting between the Higgs mass and $m_Z$ makes the latter much more appropriate for an early data analysis. We will thus focus on these channels hereafter.

FIG. 3: Regions in the $c_{\gamma\gamma} = c_{gg}$ plane constrained by the diphoton excess for $c_{WW}/c_{BB} = 1$ for $\Gamma_S = 45 \text{ GeV}$. The vertical band stands for the value of $c_{\gamma\gamma}$ determined by measurements of $pp \rightarrow SW^\pm \rightarrow 2\gamma 2j$ (see the text for details). Dijet constraints from 8 TeV data [27, 28] are also shown.

FIG. 4: $\theta^{GF}$ normalized distribution for reconstructed four-lepton signal events for the scalar (solid blue) and the pseudo-scalar (dashed red) cases. The background is shown in dotted green.

### IV. GLUON FUSION

The GF production cross section can be conveniently written as

$$\sigma^{GF} = 123 \times \left( \frac{c_{gg}}{0.01} \right)^2 \text{ fb},$$

as computed at LO using MadGraph. The NN23LO [31] parton-distribution functions (PDFs) have been used. From the computation of the GF production at higher order in the SM, we expect a large K-factor of order $1.7 - 2$ at NLO. This K-factor will anyway drop in the computation of the asymmetry computed below. We do not include it since a consistent treatment would also require a NLO estimation of the various backgrounds, which is beyond the scope of our analysis. Three different decay modes of $S$ are considered in GF, namely $S \rightarrow ZZ$ in both the fully leptonic ($4\ell$) and the semileptonic channels ($2j 2\ell$) as well as $S \rightarrow W^+ W^-$ with semileptonic decay ($2j \ell E_T$). The former has been also recently discussed (although not focusing on the question of the CP property of $S$) in Ref. [32]. In order to tag these events at the experimental level, all events are first required to pass the following set of common cuts. Leptons must have $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$. Jets are instead required to have $p_T > 20 \text{ GeV}$ and $\eta_j < 5$. Same-flavor leptons must be separated by $\Delta R > 0.2$ while different-flavor leptons must fulfill $\Delta R > 0.1$. Besides, all leptons

|          | $4\ell$ | $2j 2\ell$ | $2j \ell E_T$ |
|----------|---------|------------|--------------|
| $\epsilon$ (%) | 42      | 40         | 30           |
| $\sigma_b$ (fb) | 0.04    | 34         | 240          |

TABLE I: Estimated signal efficiencies ($\epsilon$) and background cross sections ($\sigma_b$) for GF events after the cuts described in the text.
must be separated from other jets by $\Delta R > 0.2$, and jets by $\Delta R > 0.4$ among themselves.

Then, exactly two opposite-sign lepton pairs are required in the four-lepton channel. The two with invariant mass closest to $m_Z$ are tagged as coming from one $Z$, and the other two from the second one. In the semileptonic $ZZ$ decay exactly two opposite-sign leptons and at least two jets must be present. In the semileptonic $W^+W^-$ decay exactly one lepton and at least two jets and $E_T > 20$ GeV are instead required. The longitudinal momentum of the neutrino can be in this case reconstructed by the $W^\pm$ on-shell condition (see for example [33]). Following Ref. [14], we take the smaller in absolute value among the two possible solutions. There is no further ambiguity in pairing pair of particles with the corresponding massive gauge bosons in any of these channels. We therefore require any reconstructed $Z$ ($W^\pm$) mass to be in a window of $\pm 20$ GeV around $m_Z$ ($m_W$). Besides, each $Z$ and $W^\pm$ is required to have $p_T > 250$ GeV. On top of this, the invariant mass of the four SM tagged particles is required to be in the range $[700,800]$ GeV. Finally, the event must not pass the VBF criteria, to be defined in the next section.

The efficiencies for selecting events in each of these categories are shown in Table I. The estimated cross sections for the SM backgrounds after passing all cuts are also shown. The irreducible backgrounds dominate in all cases. Therefore, only these have been taking into account. In order to compute all these quantities we have generated parton-level events with MadGraph v5 which are subsequently passed through Pythia v6 [34] to account for showering, hadronization and fragmentation effects. The cuts above are finally implemented in MadAnalysis v5 [35],

![FIG. 5: $A_{GF}^S$ distribution for the scalar (solid blue) and the pseudo-scalar (dashed red) cases with 40 observed events after 10$^7$ pseudo experiments. The distance ($d$) between the two central values in terms of the largest $\sigma$ is also shown.](image)

Having reconstructed the momenta of the four decay products, we can define the following asymmetry:

$$A_{GF} = \frac{N(\theta_{GF} > \pi/4) - N(\theta_{GF} < \pi/4)}{N(\theta_{GF} > \pi/4) + N(\theta_{GF} < \pi/4)},$$

(5)

where

$$\theta_{GF} = \begin{cases} \theta & \text{if } \theta < \pi/2 \\ \pi - \theta & \text{if } \theta > \pi/2 \end{cases},$$

(6)

and

$$\theta = \arccos \left( \frac{(p_1 \cdot p_2) \cdot (p_3 \cdot p_4)}{|p_1 \cdot p_2||p_3 \cdot p_4|} \right),$$

(7)

with $p_{1,2}$ and $p_{3,4}$ the three-momenta of the decay products of each massive gauge boson. This observable has been widely used in Higgs physics (see for example [30]). However, the small Higgs mass makes some channels above not suitable for CP studies with this asymmetry, inasmuch as the signal peaks in the region populated by the SM background. For $S$ decays instead, the rather large mass allows us to stay in much more suppressed background regions. Note also that two body $S$ decays could be also considered. As a matter of fact, photon conversion events have been discussed in the Higgs literature [37]. The typical opening angle of the lepton products are however of the order of $m_e/E_\gamma \sim 10^{-6}$, which is well below any present or future experimental sensitivity.

In four-lepton events, the variable defined in Eq. 5 takes the form shown in Fig. 4. No significant departures from this shape are found in other channels. In order to quantify the discrimination power of this asymmetry for a given number $N_{obs}$ of observed events, we perform 10$^7$ pseudo experiments with $N_{obs}$ events each. As a matter of example, the distribution followed by $A_{GF}$ for $N_{obs} = 40$ is shown in Fig. 5. The one (two) sigma statistical uncertainty is defined by the symmetric interval around the center of the distribution containing the 68% (95%) of the total area. For the matter of example, this is also shown in the figure. We further emphasize the discrimination power of this asymmetry by plotting these quantities as a function of the total number of observed events in Fig. 6 for only signal (left panel) and with as much background as signal (right panel). For the latter we assume a flat background distribution. It can be checked that this is a reasonable approximation for all channels (see dotted green line in Fig. 4).

V. VECTOR-BOSON FUSION

The LO cross section for producing $S$ in association with two jets with $p_T$ larger than 10 GeV, separated by at least $\Delta R > 0.1$ and with dijet invariant mass above 400 GeV, can be approximately written as

$$\sigma_{VBF} = 45 \left( \frac{c_{gg}}{0.01} \right)^2 + 1.2 \frac{c_{\gamma\gamma}^2}{(1+r)^2} + 17 \frac{c_{\gamma\gamma}^2}{(1+r)^2} + 43 \frac{c_{\gamma\gamma}^2 r^2}{(1+r)^2} \text{ fb},$$

(8)
with \( r \equiv c_{WW}/c_{BB} \). The coefficients above have been again computed using MadGraph with the NN23LO1 PDFs. The interference between gluon-initiated diagrams (proportional to \( c_{gg} \)) and VBF diagrams is negligible and hence not shown in this equation. Hereafter we denote by \( S^{QCD} \) and \( S^{EW} \) the production computed using each channel alone. \( S^{QCD} \) in the plane \( c_{\gamma\gamma} = c_{WW}/c_{BB} \) can be easily estimated using this equation in light of the \( c_{gg} \) values provided in Fig. 1. Instead \( S^{EW} \) is plotted in Fig. 7.

VBF events can be tagged at the experimental level in five different decay modes of \( S \). These comprise the three possibilities described in the previous section with two additional forward jets, namely \( 4\ell \gamma \), \( 4\ell 2\ell \) and \( 4\ell \ell \bar{E}_{T} \), as well as the decay into \( \gamma\gamma \) and \( \ell\ell\ell\ell \). Events are first selected by imposing the same common cuts as in GF, while photons should be separated from any other tagged particle by \( \Delta R > 0.2 \). When more than two jets are present, forward-jet candidates are selected to be those two jets with invariant mass \( m_{j_1j_2} \), less similar to \( m_Z \) (or \( m_W \)) among the four leading jets. They are subsequently required to fulfill the VBF criteria. This is defined by \( m_{j_1j_2} > 500 \) GeV, \( \eta_{j_1}\eta_{j_2} < 0 \), \( |\Delta\eta_{j_1j_2}| > 3 \) and \( \Delta R_{j_1j_2} > 0.4 \). These cuts are motivated by previous searches for heavy Higgs bosons [5]. Any reconstructed \( Z \)


The discrimination power of this angle is apparent from the plot. In order to quantify it for a given number $N_{\text{obs}}$ of observed events we proceed as in the previous section. The distribution followed by $\mathcal{A}_{\text{VBF}}$ for $N_{\text{obs}} = 40$ and $S_{\text{QCD}} = S_{\text{EW}}$ is shown in Fig. 9. We plot the one and two sigma statistical intervals as a function of the total number of observed events in Fig. 10 for only signal (left panel) and with as much background as signal (right panel). It turns out that less than 40 (60) events are necessary to start disentangling the CP properties of $S$ if there is no background (if there is as much background as signal). Despite this result being apparently much better than the one obtained in GF (see Fig. 6), in practice VBF is much suppressed (see Eq. 4 and Fig. 7) and they are hence complementary.

VI. RESULTS

For each point in the parameter space region and for each of the eight event categories $i$ defined for GF and VBF, we compute $\mathcal{A}_{\text{GF}}$ and $\mathcal{A}_{\text{VBF}}$ by estimating the number of signal and background events. For a fixed luminosity, the latter can be derived from Tables I and II. The number of signal events in each case can be in turn computed as

$$N_{\text{signal}} = \sum_i \sigma \times \text{BR} (S \to i) \times \epsilon_i,$$

where $\epsilon_i$ stands for the corresponding experimental efficiency as provided in Tables I and II too. We assume these efficiencies to be independent of the coefficients of the operators in Eq. 4. We have checked that this is the case in almost the whole parameter space, small variations arising only in the VBF $2\gamma 2j$ channel for $c_{\gamma W} \ll c_{\gamma \gamma}$. At any rate, this region is dominated by $S_{\text{QCD}}$ and therefore not sensitive to these variations. The regions where the CP-odd hypothesis can be excluded at the 2$\sigma$ level in favor of the CP-even using these asymmetries separately are shown in Fig. 11. These regions are defined by requiring the mean value of $\mathcal{A}$ in the odd case to be separated by at least 2$\sigma$ from the mean value of $\mathcal{A}$ in the even case. For the matter of example, this separation ($d$) is also shown in Figs. 6 and 9. In the left panel no extra sources for $\Gamma_S$ are considered. In the right panel $\Gamma_S = 45$ GeV instead. The main channels are depicted for a luminosity of 300 fb$^{-1}$.

The separation between the two hypothesis exceeds 1.5$\sigma$ throughout the parameter space. It is important to mention that small variations on the efficiency and cross section of the $2\gamma 2j$ channel can make the corresponding region to look notably different for a fixed luminosity. In that respect, an optimisation of the different cuts can help covering larger regions of the parameter space. At any rate, even with the basic cuts used in our analysis, luminosities slightly larger than 300 fb$^{-1}$ will be sufficient to test at the 2$\sigma$ confidence level the whole parameter space compatible with 8 TeV constraints and 13 TeV data.
FIG. 10: One (dark) and two (light) sigma statistical intervals for $A^\text{VBF}$ as a function of the total number of observed events for only signal (left panel) and as much background as signal (right panel) for the scalar (solid blue) and pseudo-scalar (dashed red) cases. $S_{\text{QCD}} = S_{\text{EW}}$ has been assumed in both panels. The distance ($d$) between the two central values in terms of the largest $\sigma$ is shown in the lower panels.

FIG. 11: Parameter space regions for which the CP odd and even hypothesis can be disentangled at the 2$\sigma$ level with 300 fb$^{-1}$. The region where the CP nature can be determined by the different channels is given by the area above the corresponding line. The grey striped regions are excluded (see Fig. 1). In the left panel we assume no extra contributions to $\Gamma_S$, while in the right panel we fix $\Gamma_S = 45$ GeV. The light area enclosed by the dashed lines stands for the 1.7$\sigma$ region.

The area excluded by searches at 8 TeV (see Fig. 1) has been superimposed. Note that this area would be much smaller if the required diphoton cross section at 13 TeV was smaller than the 8 fb that we are using throughout this letter. With 30 fb$^{-1}$ only a small portion of the available parameter space can be tested.

It can be shown that GF and VBF channels are complementary, the former being mostly sensitive to the upper region with even small $c_{\gamma\gamma}$. It is also worth emphasizing the role played by semileptonic $W^+W^-$ decays. This is in contrast with Higgs physics, for which considering these final states is not even possible, inasmuch as the signal peaks in the region populated by the huge $W^{\pm}j$ jets background. At any rate, the dominant channel is given by $S \rightarrow \gamma\gamma$ in VBF. Indeed, the fact that gluon-initiated processes can also contaminate the EW VBF selection makes this channel sensitive even to regions of small EW couplings, which require large $c_{gg}$.

VII. CONCLUSIONS

The recently observed diphoton excess around 750 GeV is triggering a lot of attention. One of the most widely studied explanations relies on a spin-0 real singlet with effective interactions to the SM gauge bosons. In this letter we have thus adopted this setup and discussed the LHC reach for unraveling the CP properties of such a resonance. First, we reviewed the current constraints and commented on the possibility of avoiding flat directions (e.g., resolving the individual couplings to photons and gluons) by considering the associated production with a gauge boson. We have then studied the LHC potential for unraveling the CP nature of such a scalar. Two different asymmetries have been covered in this regard. These are to be constructed out of events produced in gluon and vector-boson fusion respectively. We have shown that
events in these categories can be efficiently tagged at the experimental level while keeping backgrounds under control. We have emphasized that as few as ~ 50 events are needed to separate the CP even and odd hypotheses. This number of events can be reached in different regions of the parameter space depending of the stage of the next LHC run. In particular, for a long run all the parameter space region is expected to be probed, relying mainly on the VBF $2\gamma$ $2j$ channel.

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