On-shell interference effects in Higgs boson final states

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Top quark loops in Higgs production via gluon fusion at large invariant final state masses can induce important interference effects in searches for additional Higgs bosons as predicted in, e.g., Higgs portal scenarios and the minimal supersymmetric Standard Model when the heavy scalar is broad or the final state resolution is poor. Currently, the limit setting as performed by both ATLAS and CMS is based on injecting a heavy Higgs-like signal neglecting interference effects. In this paper, we perform a study of such "on-shell" interference effects in $pp \to ZZ$ and find that they lead to a $\lesssim \mathcal{O}(30\%)$ width scheme-dependent modification of the signal strength. Including the continuum contributions to obtain, e.g., the full $pp \to ZZ \to 4\ell$ final state, this modification is reduced to the 10% level in the considered intermediate mass range.

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I. INTRODUCTION

The discovery of the Higgs boson [1–3] with signal strengths in good agreement with the Standard Model (SM) expectation marks the end of the endeavor to complete the SM particle spectrum. The Higgs mechanism, i.e., the nonlinear realization of gauge invariance with a nontrivial vacuum configuration, is the only known theoretically consistent quantum field theory (QFT) framework that allows to include gauge boson masses in non-Abelian field theories. Furthermore, as formulated in the minimal setup of the SM, fermion masses can be included through nontrivial and chirality-breaking interactions with this vacuum.

While the semiclassical limit as expressed in the tree-level Lagrangian captures all these effects at face value, the implications beyond leading order are less obvious. Unitarity, or equivalently electroweak renormalizability, shapes the phenomenology of the physical Higgs boson by directly linking the fermion and gauge boson sectors [4]. Hence, modifying the couplings of the Higgs to fermions or gauge bosons in a nonconsistent way typically introduces theoretical shortcomings, which can be resolved by understanding the SM as a low-energy effective field theory (EFT) [5–15].

In non-EFT extensions of the SM, the currently allowed range of Higgs couplings can be mapped onto a prediction of additional resonances that contribute to the restoration of high scale unitarity through compensating a deviation of the observed Higgs couplings from the SM. A minimal framework that has been adopted by the experiments to look for such states is the so-called Higgs portal scenario [16], which provides a well-defined setting to model and interpret searches for additional SM-like Higgs resonances [17], and, at the same time, interfaces the SM with known BSM effects [18–21].

One of the most promising processes to search for such an additional heavy state is Higgs production via gluon fusion with subsequent decay to leptons $pp \to ZZ \to 4\ell$ (a first complete analysis was presented in [22]) or semi-leptonic ZZ decays [23], depending on the mass of the heavy Higgs-like state. The $pp \to ZZ$ channels have gained a lot of interest recently in the context of "off-shell" Higgs measurements [24–28] (see also [29]), in particular as probe of new physics [22,30–35]. Due to an a priori large light Higgs contribution at large invariant final state masses [24], setting limits by injecting a signal hypothesis without including interference effects can in principle lead to a quantitatively wrong exclusion in the absence of an excess.

In Monte Carlo programs that underpin this limit setting procedure, we typically employ a Breit-Wigner propagator

$$\Delta_h(p^2, m_h^2, \Gamma_h) = \frac{i}{p^2 - m_h^2 + i m_h \Gamma_h} \tag{1}$$

to ensure a correct behavior at low Higgs boson virtualities (this means, in particular, a nondiverging cross section). However, the Breit-Wigner distribution cannot be motivated from first-principle quantum field theory and typically is tantamount to unitarity violation [36–38].

That said, the structure of Eq. (1) is reminiscent of a Dyson resummation of the imaginary part of the Higgs

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self-energy $\Sigma_H(p^2)$ for timelike momenta, which is related to its total decay width via

$$\mathrm{Im}\{\Sigma_H(p^2)\} \sim \frac{p^2\Gamma_h}{m_h} \tag{2}$$

(see Ref. [39] for an analysis in a gauge-invariant QFT context). It should be stressed that this relation can only serve as a scaling argument for the Higgs boson; for details see, e.g., [38]. In any case, the Breit-Wigner distribution, especially for spacelike momenta, is an *ad hoc* substitution, $\Gamma_h \to \Gamma_h m_h^2/p^2$.

A consistent transition to complex mass poles as indicated in Eq. (2) avoids the theoretical shortcomings [40], and unless we do not artificially split a full scattering amplitude into "signal" and "background" contributions, there are no ambiguities: The renormalized scattering amplitude will be gauge-invariant and unitarity is conserved as a consequence.[1] A proper treatment of heavy Higgs signals in $pp \to ZZ$ scattering has been performed in Ref. [38] in the context of the Standard Model.

In the Higgs portal scenario, $pp \to ZZ$ receives an additional "background" contribution from the off-shell SM Higgs, which can be similar in size, Fig. 1. It is the purpose of this paper to also give a discussion of how important these effects are. In the spirit of Ref. [38], the phenomenological difference of Breit-Wigner propagators vs a theoretically clean definition of signal strengths from complex poles should be included in experimental analyses as an additional source of theoretical uncertainty at the leading-order accuracy that we consider in this work.

This paper is organized as follows: We first quickly review the Higgs portal scenario in Sec. II A to make this work self-consistent before we discuss the light Higgs signal-heavy Higgs signal interference in Sec. IV. Section V is devoted to a discussion of the complete heavy Higgs signal-continuum interference.

II. THE SETUP

A. The Higgs portal scenario

The Higgs portal scenario as introduced in Ref. [16] is an extension of the Higgs sector by another scalar field ϕ,

$$\mathcal{V}_{\mathrm{Higgs}} = \mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \tilde{\mu}_\phi^2|\phi|^2 + \tilde{\lambda}_\phi|\phi|^4 + \eta|\Phi|^2|\phi|^2, \tag{3}$$

where Φ denotes the SM Higgs doublet and ϕ transforms as a singlet under the SM gauge interactions. Minimizing the potential for nontrivial λ_ϕ, we can rewrite Eq. (3) in the standard form,

[1]Practical schemes such as the complex mass scheme [41–44] share this property.

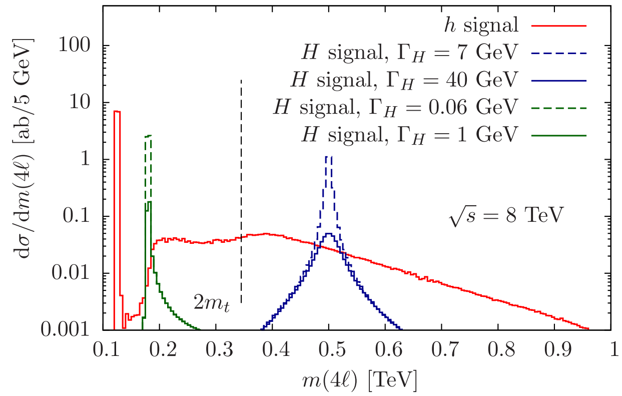

FIG. 1 (color online). The distributions are obtained with a naive Breit-Wigner propagator.

$$\phi = (v_\phi + \tilde{\phi})/\sqrt{2}, \tag{4}$$

$$\Phi = (v_\Phi + \tilde{\Phi})/\sqrt{2}, \tag{5}$$

where $v_{\Phi,\phi}$ are the vacuum expectation values of the corresponding fields, which are functions of the underlying parameters in the Lagrangian (for details see Ref. [17]).

The modifications compared to SM Higgs phenomenology are introduced by a linear mixing between the Φ, ϕ fields that can be diagonalized with a single orthogonal transformation that relates the Lagrangian basis $\{\Phi, \phi\}$ to the mass basis $\{h, H\}$,

$$\begin{pmatrix} \tilde{\Phi} \\ \tilde{\phi} \end{pmatrix}_{\mathcal{L}} = \begin{pmatrix} \cos\chi & -\sin\chi \\ \sin\chi & \cos\chi \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}_{\mathcal{M}}. \tag{6}$$

Equation (6) makes apparent that the bulk of the model's single Higgs phenomenology can be traced back to a single mixing angle, which universally rescales all Higgs couplings. Although parameter choices are possible for which the observed 125 GeV boson is the heavier of the two states, we do not consider this option in the following (for a recent discussion including electroweak precision effects, see Ref. [45]).

In its simplest implementation with only one hidden sector field, the cascade width $H \to hh$ and, hence, the total decay widths are fixed by the SM sector and the extended symmetry breaking potential and provide crucial information to reconstruct the model's parameters in its simplest realization [17,18].

To capture the importance of the on-shell interference, however, we choose a different approach to include the particle widths in our simulation by choosing the width of the heavy state as a free parameter. On the one hand, this allows us to scan the impact of the Higgs width on the mentioned interference effects directly. On the other, once we allow for the presence of a hidden sector in the fashion of Eq. (3), there is no a priori reason why the boson widths are fixed to their SM-like values times the characteristic mixing angle supplemented by $H \to hh$. In fact, allowing for more than a single singlet extension as predicted in many UV complete scenarios [18,46] loosens the tight correlation of the Higgs phenomenology of Eq. (6) with the fundamental parameters in the Lagrangian [17]. While we can still interpret the Higgs phenomenology in terms of an (effective) mixing angle due to decreased couplings compared to the SM in this case, the states' widths become less constrained. From this perspective, injecting a heavy Higgs signal whilst keeping its width as a free parameter as performed in recent analyses by the CMS Collaboration [47] is sensitive to a wider class of scenarios and provides a phenomenological bottom up approach to formulate constraints on the presence of extra heavy scalar resonances. The question of the impact of interference effects, which is typically neglected in the limit setting procedure, remains as a crucial systematic uncertainty.

III. WIDTH AND PROPAGATOR

The characteristic structure of Fig. 1 implies a shift of the H pole in comparison to the on-shell mass when inferred from an invariant mass measurement. The quantitative effects have been discussed in Refs. [22,48,49] in detail. In this work we also analyze the impact of the implementation of propagator on this particular feature.

The shape of the four lepton invariant mass distribution is mainly driven by the particular choice of the Breit-Wigner propagator in Eq. (1). Since this choice is *ad hoc*, the phenomenological implications do not have a theoretically well-defined interpretation, especially when the interference with the $gg \to ZZ$ continuum is neglected [38]. This is worsened by the fact that we typically have a high precision for the "signal"[2] that is combined with comparably lower precision for the "background".

There are suggestions to ameliorate this shortcoming by changing the formulation of propagator for the signal contribution [37,38], and we analyze these prescriptions for two parameter choices

$$\cos^2\chi = 0.9 \qquad m_H = 180\ \text{GeV}, \tag{7a}$$

$$\cos^2\chi = 0.9 \qquad m_H = 350\ \text{GeV}. \tag{7b}$$

in addition to the overall impact of interference. These choices are motivated from current signal strength measurements [3] as well as consistency with electroweak precision measurements [50], which prefer a small mixing and a rather light state H. Furthermore, the mass choices coincide with the Z boson and top quark thresholds of the $gg \to h$ subamplitude, which make these mass ranges particularly interesting due to an increase of the continuum (*cf.* Fig. 1).

To reflect finite detector acceptance,[3] we cut on the four lepton invariant mass to isolate the interference effects in this particular on-shell phase space region

$$m(4\ell) = m_H \pm 50\ \text{GeV} \tag{8}$$

and choose three different approaches to include the width in our calculation:

Breit-Wigner (BW) propagator: Most calculations using multipurpose Monte Carlo tools employ a Breit-Wigner propagator; we will use Eq. (1) as a reference.

GPR prescription: A clean separation of signal and background has been proposed in Ref. [38] by Gori, Passarino and Rosco. It is based on splitting the amplitude into a resonant and nonresonant part of the $2 \to 2$ scattering amplitude $pp \to ZZ$,

$$A(s) = S(s) + B(s,t), \tag{9}$$

with the "signal" defined as

$$S = V_{\text{prod}}(s_H)\Delta_H V_{\text{dec}}(s_H). \tag{10}$$

In this equation s_H refers to the complex mass pole of the Higgs boson; i.e., the production and decay parts of the amplitude are evaluated at complex invariant masses, s, t are the familiar Mandelstam variables and the propagator is then given by

$$\Delta_H^{-1}(s) = s - s_H. \tag{11}$$

As argued in Ref. [38], this prescription allows a theoretically robust matching of pseudo-observables between theory and experiment, and we refer the reader to this original publication for details.

Given the leading order nature of our calculation, there is a choice in defining s_H which impacts the final result. We adopt the so-called "bar" convention (in particular to facilitate a comparison with the MS implementation below)

$$s_H = \frac{m_H^2 - i m_H \Gamma_H}{1 + \Gamma_H^2/m_H^2}. \tag{12}$$

An additional comment is necessary here because we will identify m_H and Γ_H with their on-shell parameters. The "goodness" of this identification is given by the ratio Γ_H/m_H: if the width becomes comparable to the mass, the bar scheme will deviate from the on-shell scheme. Since we are working in a tree-level setting, this choice is formally correct but higher order corrections are likely

[2] The higher order QCD corrections to H production directly generalize from the SM.

[3] We perform an analysis in the fully leptonic final states but our findings are directly relevant for the boosted semihadronic analysis [23].

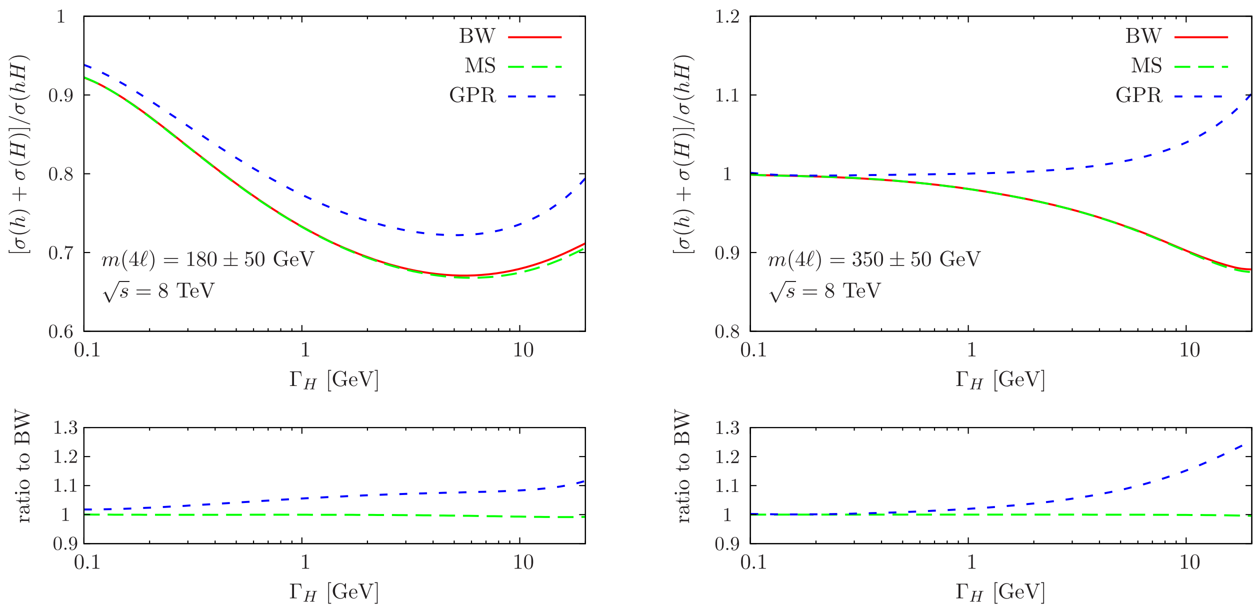

FIG. 2 (color online). Signal-signal ($h + H$) interference as a function of the total heavy Higgs decay width for the two parameter choices detailed in the text.

to quantitatively change our results when Γ_H/m_H becomes large. In the following, we limit ourselves to parameters $\Gamma_H/m_H \lesssim 0.25$.

MS prescription: Seymour showed in [37] that a simple modification of the propagator using a running width

$$\frac{1}{s-m_i^2} \to \left(1 + i\frac{\Gamma_i}{m_i}\right)\left(s - m_i^2 + i\frac{\Gamma_H}{m_i}s\right)^{-1} \qquad (13)$$

serves to reflect all relevant electroweak contributions in the high energy limit. In fact, this prescription is similar to the GPR implementation: Rewriting the propagator $s - s_H$ of Eq. (11) using the definition of Eq. (11) lets Eq. (13) emerge in the bar scheme. Note, however, that the substitution of Eq. (13) does not imply an analytical continuation of production and decay subamplitudes to complex masses.

Since we consider the fully leptonic final state (we neglecting QED contributions), it should be noted that the Z boson decay suffers from similar shortcomings as discussed above [36]. We have explicitly checked the phenomenological impact of the analytic continuation in the complex mass scheme and find a completely negligible effect on the $pp \to 4\ell$ phenomenology and employ a naive Breit-Wigner distribution for this part of the amplitude throughout to allow for a consistent Higgs-specific comparison.

IV. SIGNAL-SIGNAL INTERFERENCE

Let us first turn to "signal-signal" interference, i.e., the interference between the two Higgs bosons [22,48,49], of which the light SM state $m_h = 125$ GeV acts as background. It should be noted that such an analysis without including the $gg \to ZZ$ continuum is incomplete [30,38], although in practical analyses as performed by ATLAS and CMS such a discrimination is implicit.

In Fig. 2 we show the relative deviation $[\sigma(h) + \sigma(H)]/\sigma(hH)$, which is directly sensitive to the discussed interference. It can be seen that in the ZZ threshold region the interference effect can become of the order of 30% and depends crucially on the h signal distribution as can be seen from comparing the two parameter choices in Fig. 2.

The different treatment of the on-shell region in the discussed width schemes induces a $\mathcal{O}(20\%)$ deviation as a function of the H width for light states $m_H \lesssim 350$ GeV. The small relative deviation of the BW and the MS scheme is directly related to selecting a phase space region $s \sim m_H^2$, which induces a modification $\sim\Gamma_H^2/M_H^2$ into the comparison. This ratio is sufficiently small to not have a significant impact of the H on-shell region for the considered parameter range. The main difference of the GPR scheme in comparison to the other schemes is a quantitatively changed behavior for $s \sim m_h$. The larger Γ_H is, the bigger this relative difference, a point already stressed in the SM analysis of [38].

V. SIGNAL-SIGNAL-BACKGROUND INTERFERENCE

A crucial question, given the results of the previous section, concerns how far the overall sensitivity to

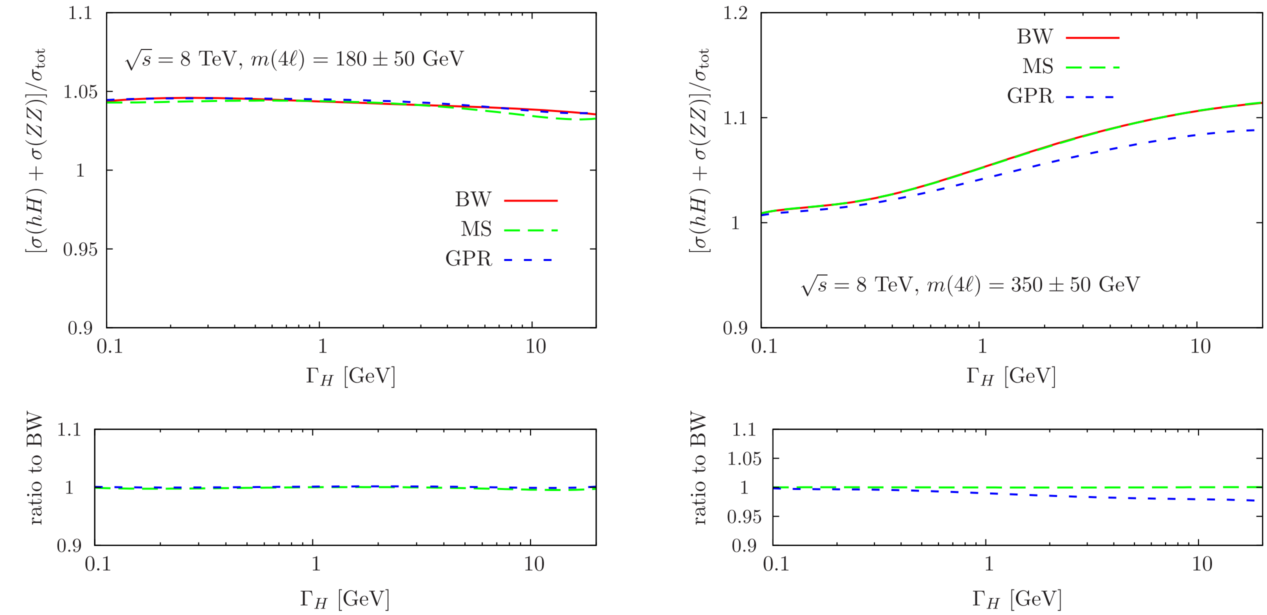

FIG. 3 (color online). $(h + H)$-continuum interference for the discussed prescriptions in the H on-shell region, defined by the selection criteria on the final state invariant mass as shown.

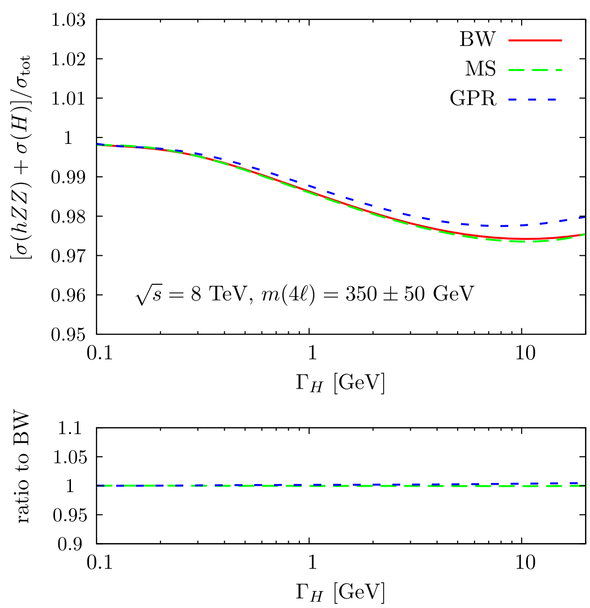

FIG. 4 (color online). $(h +$ continuum$)$-H interference for the discussed prescriptions in the H on-shell region for the heavy state $m_H = 350$ GeV.

interference and the scheme dependence of the previous section translates into a modification of the total cross section when all interference effects are included.

On the one hand, interference of signal and background in $gg \to ZZ$ is known to be a sizable effect at large invariant final state masses [22,24,26], ultimately as a sign of unitarity and gauge invariance of the full scattering amplitude.[4] Hence, when integrating out the off-shell region, interference is non-negligible [25,27,28]. On the other hand, when considering the on-shell region at relatively moderate invariant masses in a consistent electroweak model with only small deformations compared to the SM phenomenology, the individual contribution of the continuum can easily be 2 orders of magnitude above the signal contribution before cancellations in the tail $pp \to ZZ$ above the $t\bar{t}$ threshold become apparent (see Refs. [24,26]). As a consequence, the modifications detailed in the previous section will be significantly diluted if we consider the full final state. This is demonstrated in Figs. 3 and 4, which show the impact of hH-continuum interference and the relative impact of the schemes when we inject an H signal to the h-continuum hypothesis for the $m_H = 350$ GeV choice.[5] The $\sim$30% interference-induced modifications reduce to an overall $\lesssim$10% level with a scheme dependence in the percent range. The former finding is consistent with the results of [49] in support of the earlier claim of [22] that on-shell interference is phenomenologically subleading in high resolution channels at small Γ_H/m_H.

What is the phenomenological lesson to learn and how can experimental results be impacted by our findings? First, our parameter choices are bound to a particular choice of mass scheme, which can only be justified for relatively light

[4]It should be noted that for inconsistent independent rescalings of gauge- and Yukawa-sector Higgs couplings, the Lagrangian becomes ill defined at scales as low as a few hundred GeV [30].

[5]The difference for the $m_h = 180$ GeV spectrum is at the 1% level due to the large continuum contribution.

H masses that we discuss in this paper at the given (leading-order) accuracy. Second, from a practitioner's perspective, the overall impact of the interference effects are tightly related to the treatment of systematic uncertainty treatment in the actual analyses [27,28]. Currently, ATLAS and CMS rely on leading-order precision in modeling the shapes of the $gg \to ZZ$ distribution and the associated systematic uncertainty that feeds into the limit setting are of the order of 25%. Even when we rescale the individual signal and background contributions by total K factors as performed in Refs. [27,28], this uncertainty is considerably bigger than the scheme and interference dependence for our parameter choices. Hence, we can expect that the current results should remain largely unaffected, but for analyses with larger luminosities during run 2, interference effects should be included.

We stress again that for heavy and wide H candidates in the TeV range the situation is qualitatively different. While such parameter choices will automatically imply a tension with observed signal strengths and electroweak precision data as soon as the signal production cross section becomes large in the portal scenario, a thorough inclusion of higher order corrections and a precise definition of pseudo-observables following Ref. [38] is mandatory; a first step in this direction was presented in Ref. [45].

VI. CONCLUSIONS

The search for new resonant contributions in the TeV regime is one of the primary tasks of the LHC during the imminent run 2. Higgs production with subsequent decay to leptons is one of the most promising channels to facilitate a discovery of such a state in the near future, with semihadronic ZZ decays becoming an option for larger m_H values. Depending on the resolution and the width of such an additional particle, additional interference effects and scheme dependencies of this state should be included to consistently model signal strengths and formulate exclusion limits and to correctly interpret a potential discovery.

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