Interference between the Standard Model Higgs boson and the Beyond Standard Model and its dependence on the kinetic variable

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The experimentally observed coupling scale factor for the SM particles (k) being > 1 ($BR_{new} = 0.43$), a new Higgs scalar is introduced for unitarity at very high energy. The new Higgs scalar cannot be constrained by the measurement of on-shell and off-shell cross section for masses < 350 GeV. The interference technique which depends on the relative sign of the couplings of the interfering particles is the best method for constraining Higgs width and predicting the new physics particles beyond the energy scale of present day LHC. Here, we study the interference between the Higgs decay channel $b\bar{b}$ initiated by the gluon fusion.

Keywords: Standard Model of Particle Physics, Higgs boson, Decay width, Interference

I. INTRODUCTION

The Standard Model of particle physics (SM) which provides the remarkable description of the properties of elementary particles possess two main classes of particles: bosons and fermions and a SU(3)×SU(2)×U(1) gauge group, where the fermions have three generations of quarks and leptons[1]. All the SM particles interact via three fundamental forces: the electromagnetic, the weak, and the strong interaction, with the first two being unified in the electroweak force. [2]. It is confirmed after the discovery of Higgs boson in 2012 [3] at Large Hadron Collider, CERN. The precise measurements of its properties such as mass, width, CP properties, production cross section, couplings to other particles has opened a new era of research in particle physics as small deviations in the measurements may manifest the beyond Standard Model physics (BSM) scenario.

The observation of a Higgs boson [4] with a mass of around 125 GeV by the ATLAS and CMS collaborations is consistent with the expectation of the SM, but future test of the properties of this particle, such as decay width and the structure of its couplings to the known SM particles are needed to determine its nature. The Higgs couplings at LHC are measured primarily in form of signal strength [5] i.e. the rate of Higgs production and decay in particular final states.

On the Higgs resonance, the couplings can be parameterized by a collection of multiplicative factor k_i that modify the corresponding SM couplings. The on-resonance rate in a particular decay channel can then be expressed in the narrow-width approximation as

$$Rate_{ij} = \sigma_i \frac{\Gamma_j}{\Gamma_{tot}} = k_i^2 \sigma_i^{SM} \frac{k_j^2 \Gamma_j^{SM}}{\sum_k k_k^2 \Gamma_k^{SM} + \Gamma_{new}} \quad (1)$$

where σ_i is the Higgs production cross section in production mode [6] i, Γ_j is the Higgs decay partial width into final state j, Γ_{tot} is the total width [7] of the Higgs boson, the corresponding quantities in the SM are denoted with a superscript and Γ_{new} represents the partial width of the Higgs bososn into new non-SM final states.

Rate measurements in all accessible production and decay channels are combined in a fit to extract the coupling factor k_i [8] as shown in FIG. 1.[9], e.g. a scenario in which all the coupling modification factors have a common value $k_i \equiv k > 1$ and there is a new, unobserved contribution to the Higgs total width $\Gamma_{new} > 0$. In this case, the Higgs production and decay rates measurable at the LHC are given by

$$Rate_{ij} = \frac{k^4 \sigma_i^{SM} \Gamma_j^{SM}}{\sum_k k_k^2 \Gamma_k^{SM} + \Gamma_{new}} \quad (2)$$

All the measured Higgs production and decay rates will be equal to their SM values if

$$k^2 = \frac{1}{1 - BR_{new}} \quad (3)$$

where

$$BR_{new} = \frac{\Gamma_{new}}{\Gamma_{tot}} = \frac{\Gamma_{new}}{k^2 \Gamma_{tot}^{SM} + \Gamma_{new}} \quad (4)$$

Two novel techniques have been proposed since the Higgs boson discovery that offer direct sensitivity

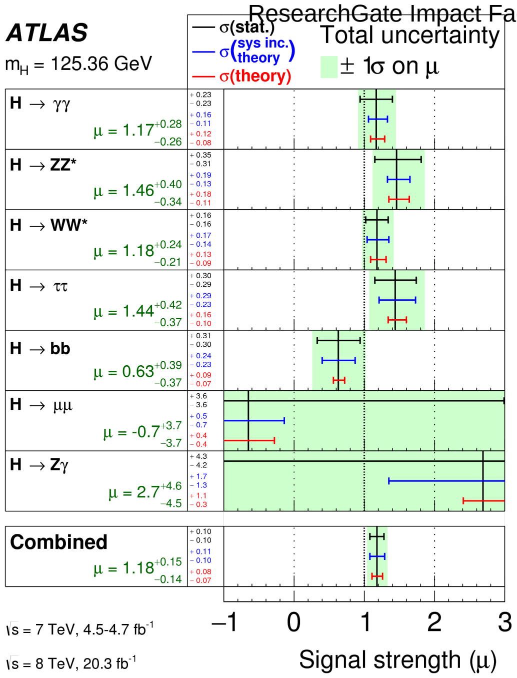

FIG. 1. The observed signal strengths and uncertainties for different Higgs boson decay channels and their combination for $m_h = 125.36$ GeV
Source: ATLAS Open Data

to the product of the Higgs boson production and decay couplings in selected channels, and hence, via the corresponding signal strength, to the Higgs total width. The first makes the use of the tiny shift in the reconstructed Higgs resonance position in the $gg \to h \to \gamma\gamma$ invariant mass spectrum caused by interference between the signal and continumm background. This method is not sensitive and able to constrain $\Gamma_{tot} < 15\Gamma_{tot}^{SM}$. The second uses the contribution of off-shell $gg \to h \to ZZ^*$ production to the total $gg \to h \to ZZ^*$ rate above the ZZ^* production threshold.

The CMS and ATLAS experiments [10] have set constraints of $\Gamma_{tot}^{SM} < 13$ MeV at 95% confidence level (CL) on the Higgs boson total decay width using the off-shell production method, which relies on the relative measurement of off-shell and on-shell production. The precision on Γ_{tot}^{SM} from on-shell measurement of the width of the resonance peak alone is approximately 1 GeV, which is significantly worse than the results from the off-shell methods.

$$\Gamma_{tot} < 3.17\Gamma_{tot}^{SM} \implies k < 1.33 \implies BR_{new} = 0.43 \tag{5}$$

Since $BR_{new} > 0$, this clearly shows the motivations for Beyond standard model of physics (Calculation using the CMS ATLAS 2019 published results). Since, $k > 1$, the Higgs couplings to the SM particles are enhanced. The longitudinal mode of scattering amplitude are no longer unitarized. We consider the situation in which a single additional (undiscovered) neutral Higgs boson H completes the unitarization of longitudinal mode of scattering amplitude. FIG. 1 shows the plot of observed signal strength and uncertanties for the different SM decay channels using ATLAS Run1 datasets and the fitted value is $\mu = 1.18$.

II. TWO-HIGGS DOUBLET MODEL & INTERFERENCE

The two-Higgs-Doublet Model (2HDM)[11] is the simplest extension of the standard model with one extra scalar doublet. Since this model contains two complex doublets of scalar fields, ϕ_1 and ϕ_2, there are eight degrees of freedom that will be used to give masses to the gauge boson. After symmetry breaking, three Goldstone bosons provide the longitudinal modes of the bosons $W^{\pm}$ and Z, that become massive and thus there remain five physical Higgs bosons : three neutral ones h_1 , h_2 , h_3 and two charged ones $H^{\pm}$.

Interference generically refers to the cross-term (in the probability of a given process) between two different contributions to the transition amplitude. It is typical of wave and quantum mechanics. In particle physics, the amplitude is essentially given by a matrix element $\mathcal{M} = \sum_i \mathcal{M}_i$ which corresponds, in perturbation theory, to a sum of individual Feynman diagrams. The interference is then the sum of

$$\mathcal{M}^2 = \sum_i \mid \mathcal{M}_i \mid^2 + \sum_{i<j} 2Re\left(\mathcal{M}_i^* \mathcal{M}_j\right) \tag{6}$$

while the first terms are the "diagonal", or "pure", contributions.

The relative size of the interference in a particular process (i.e. considering a single "entry" of the "matix" $\mathcal{M}$) only depends on the relative size (and phase) of the different $\mathcal{M}_i$. What determines the presence or absence of interference, as well as its size and sign, can be - somewhat arbitrary- separated into two categories.

The details regarding the nature and sign of the interference are given in the reference [12]. The process under consideration is the production of a pair of particles **a** and **b** by the process **X** and **Y** at the LHC[13]. The gluon initiated higgs production is a loop process, here in the Figure 2 and the in the calculation, the equivalent vertex is considered.

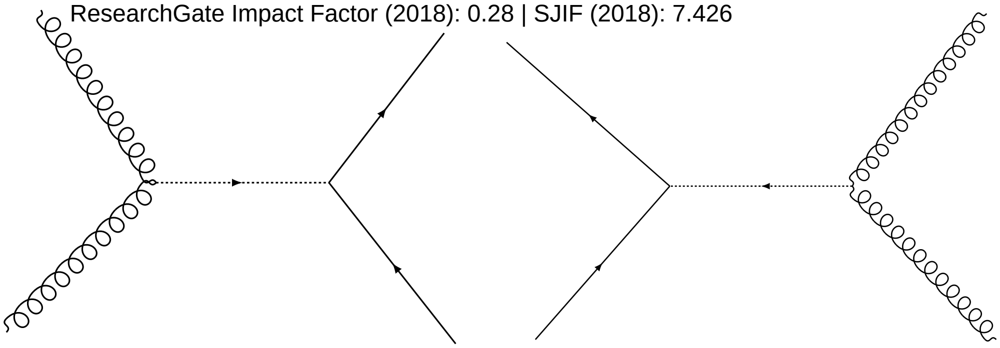

FIG. 2. Feynman Diagram for the interfernce for the gluon initiated h → $b\bar{b}$ decay

The process under consideration is the production of a pair of particles **a** and **b** by the process **X** and **Y** at the LHC.

$$\begin{aligned} pp &\to X \to a \quad b \\ pp &\to Y \to a \quad b \end{aligned} \tag{7}$$

which is mediated by the particles X and Y. Neglecting the masses of external particles, if the scattering angle is integrated over and no asymmetric acceptance cut is used (i.e. different rapidity cut for particle and anti-particle), parity-odd effects drop out and the only relevant coupling factors appearing in the matrix element squared are

$$\mathcal{M}_X^* \mathcal{M}_Y \propto \left(g_{pa} g_{pb}\right)_X \left(g_{pa} g_{pb}\right)_Y \tag{8}$$

where g_{pa} and g_{pb} are couplings for particles X and Y respectively.
The kinematic dependence is given by the propagator factors

$$\frac{\left(\hat{s} - m_X^2\right)\left(\hat{s} - m_Y^2\right) + \left(m_X \Gamma_X\right)\left(m_Y \Gamma_Y\right)}{\left(\left(\hat{s} - m_X^2\right)^2 + m_X \Gamma_X^2\right)^2 \left(\left(\hat{s} - m_Y^2\right)^2 + m_Y \Gamma_Y^2\right)^2} \tag{9}$$

where $\hat{s}$ is the center-of-mas energy of the partonic process squared; m and Γ are the mass and the width of the resonance.
Whether the interference is constructive or destructive depends on the relative sign of (8) and (9). The propagator factor in interference contributions, as a function of $\hat{s}$, always changes sign when crossing both resonance peaks; in the region of interest, between the resonance, it is negative. If the coupling factor is positive, in particular if the couplings are sequential, the interference is destructive in the intermediate range.

III. RESULTS AND DISCUSSION

The gluon fusion process have larger parton density function (PDFs). In 2HDM, interference contributions by the gluon fusion process is considered for the Higgs decay channel bottom, anti-bottom. The h_2 and A resonances are taken to be as narrow as allowed by the commonly adopted assumtion that only direct decay to SM fermions is allowed. Thus, here the interference is between the two Higgs boson signals i.e. between the $b\bar{b}$ production by SM CP-even Higgs and BSM CP-even Higgs h2 and BSM CP-odd Higgs. The overall interference is generally destructive in the intermediate region depending on the opposite sign in the couplings.

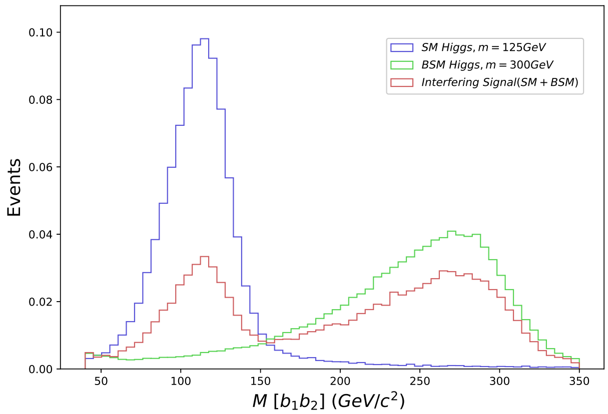

FIG. 3. Invariant mass plot for bottom anti-bottom quarks for Standard model Higgs and Beyond Standard Model CP-even Higgs at 300 (GeV) SM Higgs and the their interfering signal.

The observable considered here is the cross section $\sigma(pp \to b\bar{b})$ for producing the bottom and anti-bottom quarks as shown in TABLE 1. The kinematic variable, invariant mass $M_{b\bar{b}}$ is plotted for the different masses of the additional, undiscovered Higgs boson, m_{h2} = 300 Gev, 400 GeV, 550 GeV, 750 GeV, 1000 GeV and pseudoscalar mass, m_A = 300 GeV.

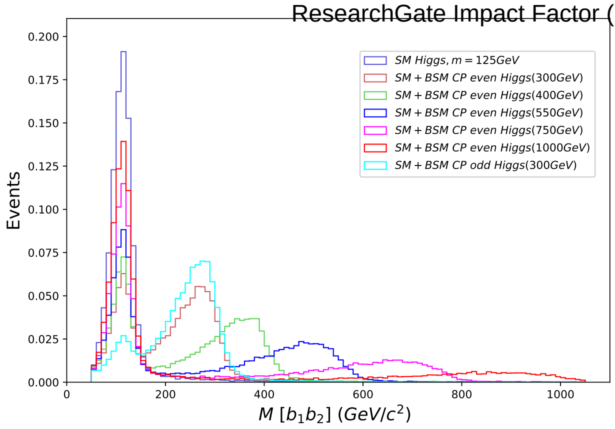

FIG. 4. Invariant mass plot of $b\bar{b}$ for interfering signal

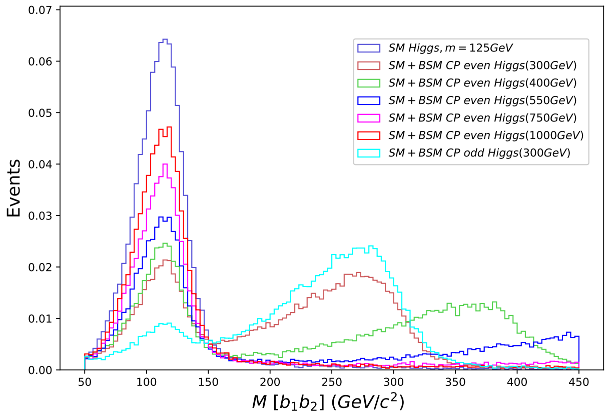

FIG. 5. Invariant mass plot of $b\bar{b}$ for interfering signal in the range 50-450 GeV

$$
\begin{aligned}
h_1 &= hsin(\beta-\alpha) + Hcos(\alpha-\beta) \\
h_2 &= -hcos(\beta-\alpha) + Hsin(\beta-\alpha)
\end{aligned}
\tag{10}
$$

$\tan\beta = \frac{v_2}{v_1}$, α is the mixing angle
if $\beta - \alpha = \frac{\pi}{2}, h_1 = h, h_2 = H$

All the events were generated using MadGraph,the high-energy collision simulations are performed using pythia8.1, the detector simulations using delphes, the analysis of the generated signal were performed using Madanalysis and the values of the input parameters and couplings were calculated using Aanaconda-navigator. The following input parameters were considered for simulation for the different masses of BSM Higgs boson, $tan\beta = 1.732051$, $\sin\alpha = -0.5$, the Higgs boson couplings to gluons, bottom anti-bottom and di-photons were $ggh_1 = ggh_2 = 0.001i$, $h_1 b\bar{b} = -0.0095443i$, $h_2 b\bar{b} = 0.016531i$. The cross-section for the interfering signal was found to be less than the sum of σ_{SM} and σ_{BSM} for $h \to b\bar{b}$

TABLE I. Cross-section for $pp \to h_1 \to b\bar{b}$, $pp \to h_2 \to b\bar{b}$ with $\alpha - \beta = \frac{\pi}{2}$ and $mh_1 = 125$GeV (SM)

2HDM, CP-even Higgs $\to b\bar{b}$		
cross section for SM Higgs $\sigma_{SM} = 8.917$		
BSM Higgs masses	Cross section $\sigma_{BSM}(pb)$	Interfering signal $\sigma_{SM+BSM}(pb)$
300	12.301	21.2172
400	8.5950	17.5113
550	5.3873	14.3036
750	3.1429	12.0592
1000	1.7422	10.6585
2HDM, CP-odd Higgs $\to b\bar{b}$		
300	12.5	2.396

channel which shows the destructive (constructive) interference due to opposite (same) sign of couplings. The invariant mass plot of $b\bar{b}$ quarks shows that due to presence of additional Higgs, the number of events are suppressed considerably. As shown in FIG 5, there is no distinct off-shell for SM Higgs and the additional Higgs mass ≤ 550. From the table, it was found that the interference was nearly the same of the order of $0.007pb$ for the CP-even Higgs and $0.003pb$ for the CP-odd Higgs and it was destructive.

IV. CONCLUSIONS

The nature of the couplings affecting the interference was studied and it was found to be the constructive or destructive based on the relative sign of the couplings. From the invariant mass plot, Figure , it clearly shows that there is no distinct off-shell tail, where the method of constraining the Higgs width based ratio on-shell and off-shell cross-section completely fails for mass of additional, BSM Higgs ≤ 550 GeV. In the reference[14] it has been pointed out that the method of constraining the Higgs width by the method of off-shell and the onshell fails the undiscovered Higgs masses below 350 GeV. With the increase in masses of the heavy Higgs boson, the events for the BSM Higgs is considerably reduced and the luminosity of the Collider should be increased for hunting the heavy Higgs boson masses beyond 750 GeV. The strength of the interference is almost the same between the resonances.

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