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New physics in resonant production of Higgs boson pairs

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We advocate a search for an extended scalar sector at the LHC via hh production, where h is the 125 GeV Higgs boson. A resonance feature in the hh invariant mass is a smoking gun of an s -channel heavy Higgs resonance, H . With one h decaying to two photons and the other decaying to b -quarks, the resonant signal may be discoverable above the hh continuum background for $M_H < 1$ TeV. The product of the scalar and top Yukawa couplings can be measured to better than 10 – 20% accuracy, and its sign can be inferred from the hh lineshape via interference effects.

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Introduction. The discovery of the 125 GeV Higgs boson at the LHC marks the successful completion of the long quest to validate the spontaneous breaking of the Standard Model (SM) gauge symmetry. The discovery intensifies the search for new physics at the TeV scale using this Higgs particle as a probe. The Higgs branching fractions have been measured in many channels, with the best determinations in $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$, $h \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$, and (to a lesser extent) in $h \rightarrow b\bar{b}, \tau^+\tau^-$ [1, 2]. The h couplings to $t\bar{t}$ and gg have been inferred from the cross sections and the total Higgs width has been bounded above the SM prediction [1–9],

Although all evidence to date is consistent with the SM Higgs sector, new LHC data will be acquired soon at 13 TeV center-of-mass energy. We use the full design energy of $\sqrt{s} = 14$ TeV for our simulations, but the results should be very similar for 13 TeV. The precision of Higgs coupling measurements may reach a level at which the presence of new physics contributions is evident, and an International Linear Collider could provide still greater precision [9–12]. However, new physics may be difficult to detect in single Higgs production, for example in the decoupling limit of an extended scalar sector. Indeed, analyses have been done with LHC8 data [13, 14]. Whether or not this occurs, the measurement of the M_{hh} distribution in double Higgs production at LHC14 and its model independent interpretation could give an important new way to determine whether just the SM Higgs is the whole story. This is the aim of this study.

Double Higgs production is potentially discoverable in several final states, of which the most promising is $hh \rightarrow b\bar{b}\gamma\gamma$, allowing a measurement of λ^{hhh} to $O(50\%)$ from the moderate $M_{b\bar{b}\gamma\gamma}$ region [15, 16]. The presence of $\gamma\gamma$ allows severe rejection of background, but with an attendant high cost to the signal rate. The branching fraction of $hh \rightarrow b\bar{b}\gamma\gamma$ is only 0.28% in the SM, and thus the identification of the SM signal above the continuum background is challenging. Other final states such as $b\bar{b}\tau^+\tau^-$ and $b\bar{b}W^+W^-$ may be looked upon for discovering resonant production of hh , but may be more

challenging [17–20]. Therefore, we decide to concentrate the $b\bar{b}\gamma\gamma$ channel for our analysis as it is relatively clean.

The small SM hh cross section provides an opportunity to search for new physics in this channel, and a number of beyond the SM scenarios lead to enhancements in the continuum or resonant production of Higgs pairs [21–28]. In particular, an s -channel resonance of a heavy Higgs boson, H , can dramatically improve the opportunity for a new physics discovery at the LHC. Measurements of the scalar mass and couplings can lead to a deeper understanding of the scalar sector with implications, for instance, in vacuum (meta)stability [29].

Higgs Pair Production. The Higgs pair is dominantly produced through two classes of amplitudes [30–32]: (i) the triangle diagram in which an s -channel $J^{CP} = 0^+$ particle mediates the gluon-gluon transition to two Higgs bosons and (ii) the box diagram in which the annihilation of two gluons through a loop produces the Higgs boson pair, as shown in Fig. (1). These amplitudes with generic internal/external Higgs bosons (and generic heavy quarks) were first computed in [33], to which we refer readers interested in the details.

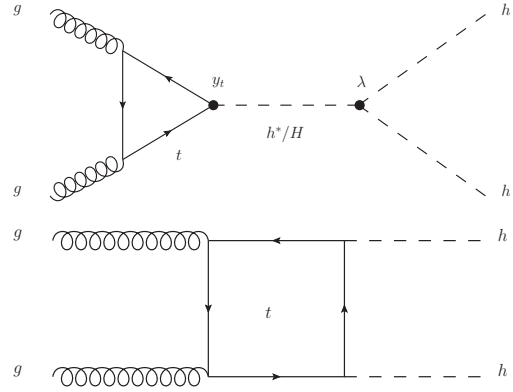


FIG. 1: Representative processes that contribute to Higgs boson pair production. The final state requires a 0^+ resonance.

The differential cross section at the parton level is

$$\frac{d\hat{\sigma}_{gg \rightarrow hh}}{d\hat{t}} = K \frac{G_F^2 \alpha_s^2}{256(2\pi)^3} \times \left[\left| (C_\Delta F_\Delta + C_\square F_\square) \right|^2 + \left| C_\square G_\square \right|^2 \right], \quad (1)$$

in which the C 's are coupling form factors, the F 's and G 's are gauge invariant form factors arising from orthogonal gluonic tensor structures, and the NLO+NNLL K-factor is $K = 2.27$ at 14 TeV [34–41]. Resonant production can shift the overall K-factor, as $\sigma_{NLO+NNLL}/\sigma_{LO}$ can be $\sqrt{\hat{s}}$ dependent. However, since the K-factor has not been calculated for the resonant process, we adopt the SM value under the reasonable assumption that any change in its value due to the H resonance is small.

The s -channel diagram in Fig. 1 contains the h and H exchanges, where H is the heavy resonance that must be a 0^+ state. Note that the particle(s) that couple to the SM doublet Φ need not carry quantum numbers, and can couple to quarks via mixing. We denote the coupling of the H to the hh pair as

$$\mathcal{L} \supset -\lambda^{hhH} H \Phi^\dagger \Phi. \quad (2)$$

The SM tri-scalar coupling has the form $\lambda_{SM}^{hhh} = 3M_h^2/v$. The coupling combination $\lambda^{hhH} y_t^H$, where y_t^H is the t -quark Yukawa coupling to H , is the prefactor in the s -channel H amplitude. We do not impose constraints from unitarity or vacuum stability on λ^{hhH} and y_t^H , as these constraints are highly model-dependent, and we wish to remain as general as possible here. The hh cross section is shown in Fig. 2 for LHC14. The enhancement from the resonance is typically over 100 fb, well above the SM value of $\sigma_{pp \rightarrow hh}^{SM} = 43$ fb [36]. For a sufficiently heavy H , the λ^{hhh} uncertainty is approximated to be the SM uncertainty [16]; there is a strong dependence of the coupling uncertainty at low M_{hh} , where the SM signal is strong.

Measuring the hh lineshape. In the $b\bar{b}\gamma\gamma$ channel, the dominant irreducible background is the continuum $pp \rightarrow b\bar{b}\gamma\gamma$ process. We also include the additional processes listed in [16] and adopt their tagging efficiencies, mis-tag rates, threshold requirements and momentum smearing. We use MadGraph to simulate the resonant production of $hh \rightarrow b\bar{b}\gamma\gamma$ and as minimal cuts, require two b -tags, two γ tags and $|M_{bb} - m_h| < 20$ GeV and $|M_{\gamma\gamma} - m_h| < 10$ GeV. Additional details on the simulation and acceptance criteria are given in [42].

We first study resonant production alone, which serves to determine the response of the detector simulation to an injection of hh states at a given $\sqrt{\hat{s}}$, greatly simplifying the subsequent analysis. The analytic differential distributions are Gaussian smeared according to the resonant shape after event simulation including particle identification and isolation. In the range of masses we consider,

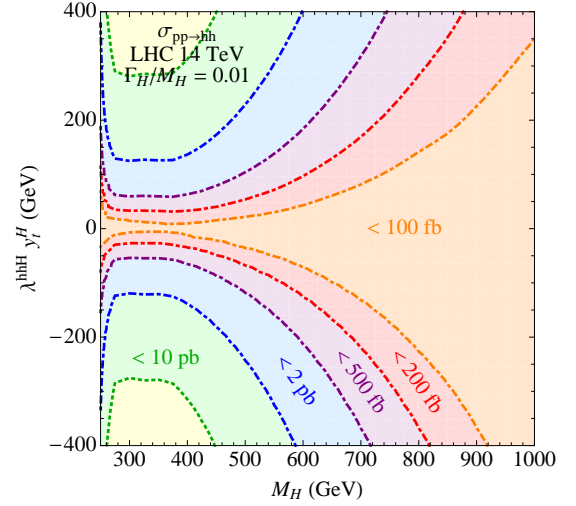


FIG. 2: Higgs pair production cross section at LHC14 with $\Gamma_H/M_H = 1\%$. $\sigma_{pp \rightarrow hh}^{SM} = 43$ fb (with a NLO+NNLL K-factor).

$M_H = 200$ – 1000 GeV, the energy resolution of the reconstructed $b\bar{b}\gamma\gamma$ resonance is found to vary with increasing M_H between 5 – 25 GeV. The acceptance is computed for each resonant mass, which ranges from 6–11%.

To determine how well the $H \rightarrow hh$ resonance signal can be measured at LHC14, we perform a $\Delta\chi^2$ fit of the M_{hh} distribution to the expected SM $pp \rightarrow hh$ distribution that does not contain a resonance. We also include the effect of increased uncertainty via background subtraction by inflating the Poisson uncertainty according to the continuum $b\bar{b}\gamma\gamma$ background distribution, and assume a 100% background normalization uncertainty.

The differential event rate is computed via

$$\frac{d\sigma_{b\bar{b}\gamma\gamma}}{dM_{b\bar{b}\gamma\gamma}} = 2 \text{BF}(h \rightarrow b\bar{b}) \text{BF}(h \rightarrow \gamma\gamma) A(M_{b\bar{b}\gamma\gamma}) \times \int dM' G(M', M_{b\bar{b}\gamma\gamma}) \frac{d\sigma_{gg \rightarrow hh}}{dM'} \int_{(M')^2/s}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau}, \quad (3)$$

where $A(M_{b\bar{b}\gamma\gamma})$ is the signal acceptance with the resonance at $M_H = M_{b\bar{b}\gamma\gamma}$, the Gaussian kernel with energy resolution σ is $G(E', E) = (\sqrt{2\pi}\sigma)^{-1} e^{-\frac{(E' - E)^2}{2\sigma^2}}$, and $d\mathcal{L}_{gg}/d\tau$ is the parton luminosity for gg collisions.

In addition to λ^{hhh} , which we set to its SM value for our simulations, the two parameters that determine the resonant production rate are M_H and $\lambda^{hhH} y_t^H$. The total width of H affects the lineshape; however, it may vary considerably depending on the coupling of H to gauge bosons and λ^{hhH} . Since these couplings do not directly influence the resonant cross section (only the combination $\lambda^{hhH} y_t^H$ is measurable), we can take Γ_H/M_H to be an independent free parameter. In Fig. 3, we show the differential distributions for $M_H = 500$ (800) GeV with

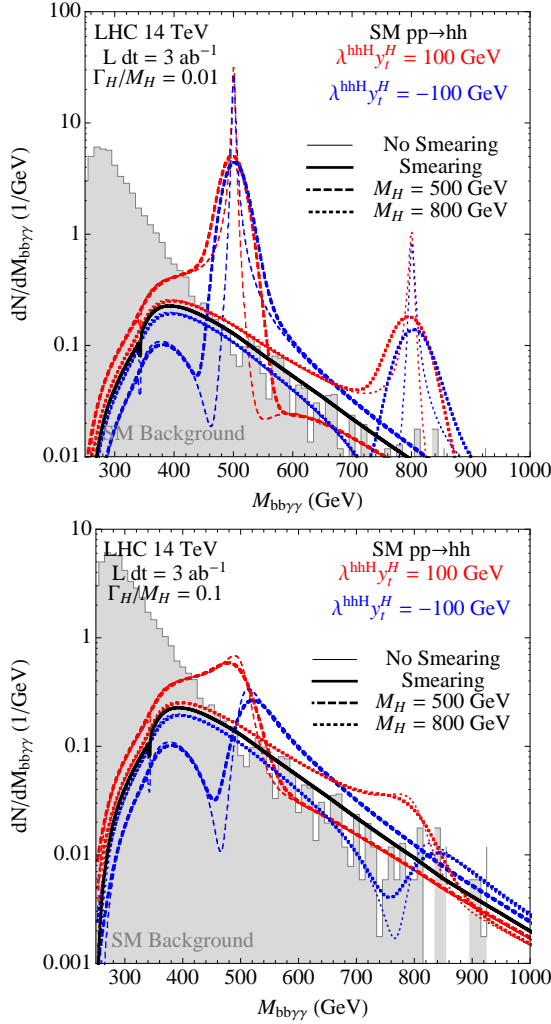


FIG. 3: The $dN/dM_{bb\gamma\gamma}$ distribution for $M_H = 500, 800$ GeV and $\lambda^{hhH} y_t^H = \pm 100$ GeV, for $\Gamma_H/M_H = 1\%$ (top) and $\Gamma_H/M_H = 10\%$ (bottom). The SM $b\bar{b}\gamma\gamma$ continuum background (gray shaded) peaks at low invariant mass while the SM hh continuum is denoted by the black curve. Even with momentum smearing, the sign of $\lambda^{hhH} y_t^H$ can be resolved.

$\Gamma_H/M_H = 1\%$ (10%) for $\lambda^{hhH} y_t^H = \pm 100$ GeV. $\lambda^{hhH} y_t^H$ can vary substantially depending on the underlying theory, but for comparison, 100 GeV is a typical value in the Type-II two Higgs doublet model near the alignment limit for small-to-moderate $\tan\beta \lesssim 1$.

In Fig. 4, we see that with $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$, LHC14 can constrain $|\lambda^{hhH} y_t^H| \gtrsim 100$ (500) GeV over most of the mass range up to 1 TeV for a 1% (10%) total width. The decrease in the reach for low M_H is mainly due to the continuum $b\bar{b}\gamma\gamma$ background at low $M_{b\bar{b}\gamma\gamma}$ and (to a lesser extent) the reduced phase space near threshold.

The sign of $\lambda^{hhH} y_t^H$ can also be determined from the interference of the resonance with the SM hh continuum. This is seen in Fig. 3 where, even with momentum smearing, the interference effect is clearly visible.

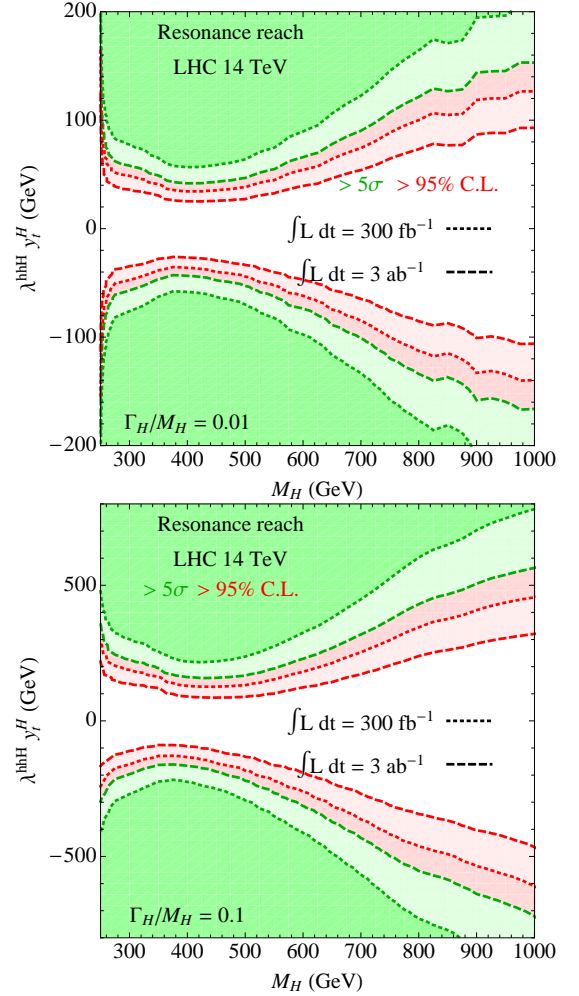


FIG. 4: LHC14 reach of the H resonance in the M_H and coupling plane with $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ for $\Gamma_H/M_H = 1\%$ (top) and $\Gamma_H/M_H = 10\%$ (bottom). The reach is obtained by performing a $\Delta\chi^2$ fit of the simulated resonance to the SM continuum distribution for 1500 model points. The asymmetry in the contours is due to the SM continuum contribution.

For $\lambda^{hhH} y_t^H > 0$, an excess of events occurs below resonance and a deficit above resonance (and vice-versa for $\lambda^{hhH} y_t^H < 0$). This interference also results in an apparent shift of the invariant mass peak to the left (right) for positive (negative) $\lambda^{hhH} y_t^H$, the size of which depends on the total width. In Fig. 5, we show regions over which the sign of $\lambda^{hhH} y_t^H$ can be distinguished via the hh line-shape.

We perform a $\Delta\chi^2$ fit to approximately 1500 points in the $M_H - \lambda^{hhH} y_t^H$ plane for $\Gamma_H/M_H = 0.01(0.1)$, varying M_H , Γ_H , $\lambda^{hhH} y_t^H$, and λ^{hhH} simultaneously and restricting the luminosity to $\mathcal{L} dt = 3 \text{ ab}^{-1}$. We find that M_H can be measured to 0.5% or better and the total width to 20% or better over most of the parameter space. For an intrinsically broader Higgs width with $\Gamma_H/M_H = 0.1$, the fit is degraded for the Higgs mass measurement, but

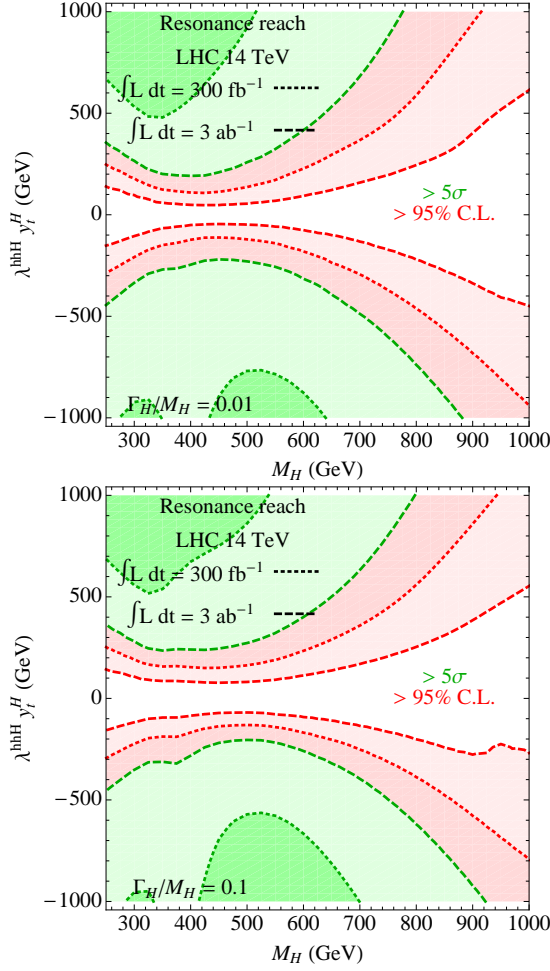


FIG. 5: LHC14 sensitivity to the sign of $\lambda^{hhH} y_t^H$ from the interference between the SM and H resonant diagrams for $\Gamma_H/M_H = 1\%$ (top) and $\Gamma_H/M_H = 10\%$ (bottom).

the fit uncertainty in Γ_H/M_H is not that different.

In Fig. 6, we show the 1σ uncertainty of $\lambda^{hhH} y_t^H$, which can be probed to a remarkably sensitive level over most of the parameter space and in some cases to less than 2%. This sensitivity degrades somewhat as the total width is increased, but the uncertainty remains low. For a particular model of Yukawa couplings, the scalar coupling can be accurately deduced. Even better, with an independent measurement of the H coupling to the quark sector, the scalar coupling can be uniquely determined.

Conclusions. We studied resonant pair production of the 125 GeV Higgs h for the final state in which one h decays to $\gamma\gamma$ and the other to $b\bar{b}$. In new physics models with a heavy CP-even Higgs H , the s -channel resonance amplitude of the H interferes with the SM amplitudes. We find that LHC14 sensitivity to the $H \rightarrow hh$ channel is possible if the magnitude of the product of the scalar and top quark Yukawa couplings $\lambda^{hhH} y_t^H$ is $O(100 \text{ GeV})$ or larger (for $M_H \leq 1 \text{ TeV}$) and its sign can be inferred from

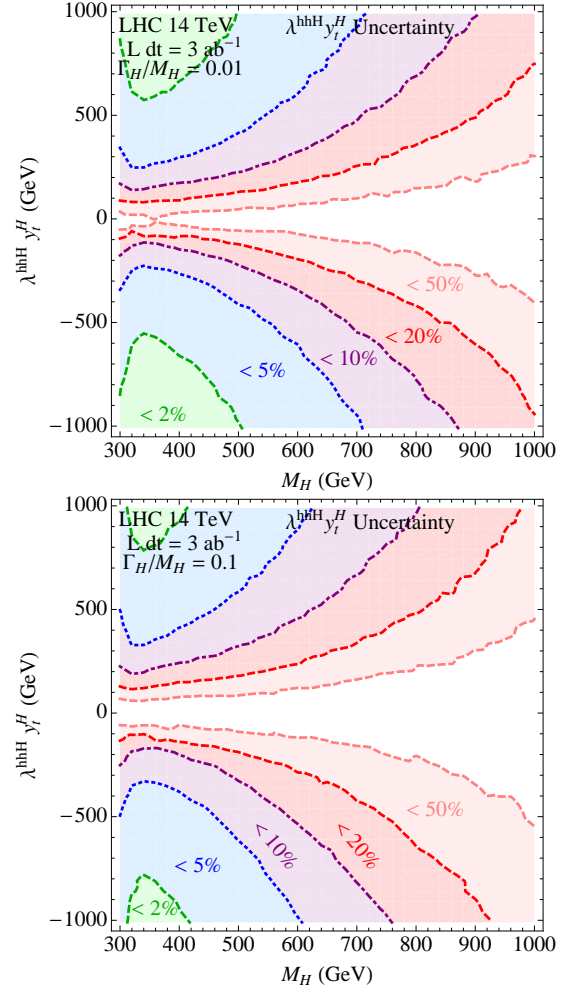


FIG. 6: Fit uncertainties at the 1σ level for $\lambda^{hhH} y_t^H$ for $\Gamma_H/M_H = 0.01$ (top) and 0.1 (bottom) with $\int \mathcal{L} dt = 3 \text{ ab}^{-1}$. For each model point, we perform a $\Delta\chi^2$ fit to the form of Eq. 3, varying M_H , Γ_H , $\lambda^{hhH} y_t^H$, and λ^{hhH} simultaneously.

the hh lineshape via interference effects. $\lambda^{hhH} y_t^H$ can be measured to greater than 10–20% accuracy over a broad range of $M_H \leq 1 \text{ TeV}$. Using the resonant enhancement of hh production, the scalar coupling can be deduced or directly measured, yielding a deeper understanding of the scalar sector with potentially profound implications.

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