Unraveling the physics behind modified Higgs couplings: LHC versus a Higgs factory

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Strongly modified $h\gamma\gamma$ and hgg couplings indicate new electroweak and color mediators, respectively, with a light mass and a significant coupling to the Higgs boson. We point out the Higgs boson could have a significant decay width into the mediators. This represents one new class of exotic Higgs decay possibilities: off-shell exotic Higgs decays. We then propose uncovering the hidden new physics through such exotic decays. A great advantage of this strategy is that we can directly probe the couplings between the Higgs boson and the mediators, which is hard to achieve by using other methods. Focusing on the electroweak mediators, we study a simplified model using as an example final states with tau leptons and neutrinos. Because one of the mediators is off shell and its decay products are extremely soft, it is challenging to make a discovery at the Large Hadron Collider. A Higgs factory such as the International Linear Collider, however, could serve as a discovery machine for such exotic Higgs decays even in an early stage.

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I. INTRODUCTION

On July 4, 2012 CERN announced the observation of a Higgs-like boson at the Large Hadron Collider (LHC) with a mass at around 126 GeV [1,2]. Preliminary results based on decay branching ratios indicate a genuine Higgs boson, not an imposter [3], while signal strengths in all observed channels are also consistent with those expected from a Standard Model (SM) Higgs boson, except in the diphoton channel where early data suggest an enhancement over the SM rate of $\mathcal{O}(50\%)$ [4,5]. Both the ATLAS and the CMS collaborations already updated their results on the Higgs-to-diphoton searches using the full data: the ATLAS update indicates a $\sim 2\sigma$ deviation from the SM rate (an enhancement of $\sim 60\%$) [6], while the CMS update indicates relatively small signal rates of 1.11 ± 0.31 based on a cut-based analysis and 0.78 ± 0.27 based on a more sensitive multiple-variable analysis [7].

An enhanced rate in the diphoton channel could arise from modifying any of the following quantities: (1) the production cross section, which at leading order comes from the gluon fusion process, (2) the total width, which is dominated by the partial width of Higgs to $b\bar{b}$ [8,9], and (3) the partial width of Higgs to diphoton [9–12]. Items (1) and (2) alter the signal rate in *all* channels, while (3) only affects the diphoton channel. Current experimental fits (mainly the ATLAS ones) favor a SM Higgs-gluon-gluon (hgg) coupling and an enhanced Higgs-to-diphoton ($h\gamma\gamma$) coupling [6,13], although the statistics is limited and uncertainty quite large.

The $h\gamma\gamma$ and hgg couplings are of special importance. On the experimental side, these couplings enter into the $gg \to h \to \gamma\gamma$ channel, which is the main discovery channel of the Higgs boson at the LHC. On the theoretical side, both couplings are induced only at the loop level and serve as indirect probes of any new particles with a significant coupling to the Higgs [9–12,14]. In particular, new electroweak (EW) (colored) particles coupling to the Higgs would necessarily modify the $h\gamma\gamma$ (hgg) couplings. More importantly, if EW symmetry breaking is natural, new particles with significant couplings to the Higgs must exist to soften the quadratic divergences in the Higgs mass. As a result, there are intricate connections between modifications in the $h\gamma\gamma$ and hgg couplings and the naturalness of TeV scale physics [11,14].

It was shown in Refs. [9–12] that a possible strong enhancement of the $h\gamma\gamma$ coupling indicates new EW states that (i) are light, on the order of 100 GeV [9,10,12], and (ii) couple to the Higgs boson significantly (colored ones are not favored because they tend to modify the hgg coupling in a wrong direction simultaneously, e.g., see [9,15,16], though potentially they can lead to a big modification of multiple Higgs production [17]). Therefore, if the enhancement persists in the future, a top priority will be to devise strategies to search for these light "EW mediators" and to probe their couplings with the Higgs boson. (There are ways to hide these new light states from direct search and precision EW constraints by, for example, assigning a new "parity" to the new particles [11].) A smoking gun signal of EW mediators is a modified rate in Higgs decays into $Z\gamma$ final states [18], which correlates with deviations from the SM width in the diphoton channel [9–12]. Another indirect probe lies in electroweak production of the mediators at the LHC, with search for their decays into SM particles [10,12,19]. The former however

cannot identify the mediators directly while the latter does not involve couplings between the Higgs boson and the mediators.

In this article we propose searching for the new physics behind the modified $h\gamma\gamma$ coupling via one new class of exotic Higgs decays. If the mediators decay to light particles, an on-shell Higgs can decay to the mediators, at least one of which is off shell, much like Higgs decays to off-shell W/Z bosons. The partial width of this exotic Higgs decay depends on the available modes and phase space for the subsequent mediator decays, which can only be computed in a specific model. However, it could be significant, especially in the parameter region giving rise to a strongly modified $h\gamma\gamma$ coupling where the mediators are light and couple to the Higgs significantly. A similar strategy can be applied for studying the hgg coupling, if a strong modification is indicated by the LHC measurements in the near future.

To illustrate this strategy, we will work in a simplified model with an EW scalar mediator, ϕ, assuming for example that it mainly decays into tau and tau neutrino. One implementation of this is the Minimal-Supersymmetric-Standard-Model with a gauged-$U(1)_{\rm PQ}$ extension [12], where the diphoton width can be enhanced either by EW vectorlike fermions which are required for the $U(1)_{\rm PQ}$ anomaly cancellation or by their superpartners. These charged mediators can decay to SM particles and (or) their superpartners and hence avoid overproduction in the early Universe. We will see that, given a Higgs mass $\sim$126 GeV, one of the mediators is very off shell and it is difficult to search for such decays at the LHC, although with some optimistic assumptions it might be feasible. We then turn to a Higgs factory such as the International Linear Collider (ILC) with $\sqrt{s} = 250$ GeV and show that the discovery potential is fairly promising. Therefore the Higgs factory can be not only a precision machine, but also a discovery machine for the truth behind the strongly modified $h\gamma\gamma$ or hgg couplings.

II. EXOTIC DECAY WIDTH

The partial decay width of $h \to \phi\phi$ depends on three physical parameters: the mass of the scalar mediator, m_ϕ, its total width, Γ_ϕ, and its coupling with the Higgs, c_ϕ, which is defined as in $c_\phi v h \phi\phi^\dagger$ with $v \approx 246$ GeV being the Higgs vacuum expectation value. As a comparison, the change in the $h\gamma\gamma$ coupling depends on two physical parameters: m_ϕ and c_ϕ [11].

Extending the calculations in [20], it is easy to find the partial decay width of $h \to \phi\phi$

$$\Gamma_{h\to\phi\phi} = \int_0^{u_1} dm_+^2 \int_0^{u_2} dm_-^2 \frac{d\Gamma_{h\to\phi\phi}}{dm_+^2\, dm_-^2}, \tag{1}$$

where $m_\pm$ is the invariant mass of $\phi_\pm$, $u_1 = m_h^2$, $u_2 = (m_h - m_+)^2$, and

$$\frac{d\Gamma_{h\to\phi\phi}}{dm_+^2\, dm_-^2} = \frac{c_\phi^2 v^2}{16\pi m_h^3}\sqrt{m_h^2-(m_+ + m_-)^2}\sqrt{m_h^2-(m_+ - m_-)^2}P_+P_-. \tag{2}$$

$P_\pm$ are the propagators of $\phi^\pm$:

$$P_\pm = \frac{m_\pm \Gamma_\pm}{\pi}\frac{1}{(m_\pm^2 - m_\phi^2)^2 + m_\pm^2\Gamma_\pm^2}. \tag{3}$$

Note here $m_\pm$ is the invariant mass of the possibly off-shell ϕ, and $\Gamma_\pm$ is the total width of ϕ at the corresponding $m_\pm$, which is model independent. For illustration, we consider a simplified model, assuming $\phi \to \tau + \nu_\tau$ predominantly. This was suggested in [12]. Then the partial width $\Gamma_\pm$ is

$$\Gamma_\pm = \frac{c_{\phi\nu_\tau\tau}^2 m_\pm}{16\pi}, \tag{4}$$

where $c_{\phi\nu_\tau\tau}$ is the $\phi\nu_\tau\tau$ coupling in the mass eigenbasis. In this analysis, we assume $c_{\phi\nu_\tau\tau} = 0.6$, comparable with the EW coupling. For $m_\phi \sim 100$ GeV, the on-shell decay width is then

$$\Gamma_\phi \sim 0.7 \text{ GeV}. \tag{5}$$

The contours of $\Gamma_{h\to\phi\phi}/\Gamma^{\rm SM}_{h\to\tau\bar\tau}$ and $\Gamma_{h\to\gamma\gamma}/\Gamma^{\rm SM}_{h\to\gamma\gamma}$ are shown in Fig. 1. These contours indicate a strong positive correlation between $\Gamma_{h\to\phi\phi}$ and $\Gamma_{h\to\gamma\gamma}$. We see the partial width of $h \to \phi\phi$ could be sizable in the parameter region where the diphoton width is enhanced significantly. For the benchmark (blue star) with $m_h = 126$ GeV, $m_\phi = 92$ GeV (as a comparison, the current LEP bounds on the stau mass vary between 80 and 90 GeV under the assumption that the stau slepton decays into a tau lepton and a neutralino only, with the neutralino being massless [21]) and $c_\phi = 1$, an enhancement of $\sim$60% for the Higgs-to-diphoton decay width (indicated by the ATLAS full-data analyses [6], with

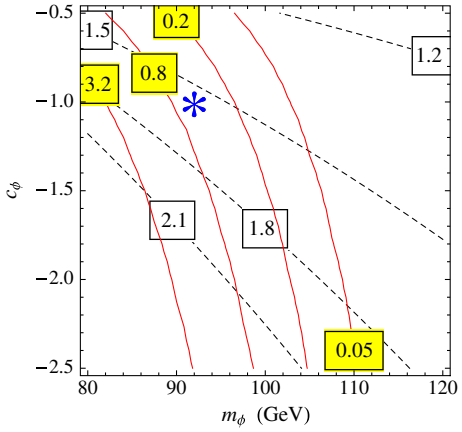

FIG. 1 (color online). Contours for $\Gamma_{h\to\phi\phi}/\Gamma^{\rm SM}_{h\to\tau\bar\tau}$ (red, solid) and $\Gamma_{h\to\gamma\gamma}/\Gamma^{\rm SM}_{h\to\gamma\gamma}$ (black, dashed).

a SM Higgs production cross section assumed) leads to a partial decay width $\Gamma_{h\to\phi\phi} \sim 0.5 \times \Gamma^{\rm SM}_{h\to\tau\bar{\tau}}$. Recall $\mathrm{BR}_{\rm SM}(h \to \tau\bar{\tau}) \approx 6.4\%$ for a 126 GeV SM Higgs, so such an exotic decay mode potentially can lead to significant implications for colliders. A cautionary remark is that the exotic partial width becomes very small if both mediators in the decay are only allowed to be off shell (i.e., if $m_\phi > m_h$), in which case our method may not be applicable. But, such a scenario usually requires a larger fine-tuning to escape theoretical and experimental constraints, given similar modification strength for the $h\gamma\gamma$ coupling.

III. LHC STUDY

We first consider the discovery potential at the LHC. Since each mediator decays into τ plus ν_τ, the signature is $2\tau + \not{p}_{\rm T}$, which is very similar to the SM $h \to \tau\tau$ decay. In this work we only consider the vector-boson fusion (VBF) production of the Higgs, which has the best signal-to-background ratio in the SM $h \to \tau\bar{\tau}$ search [22]. In particular, we use the dileptonic channel $2\tau_l + \not{p}_{\rm T}$ to illustrate the LHC sensitivity (with $l = e, \mu$). It is well known that the VBF selection cuts have contaminations from the gluon fusion channel, which we include in our simulations.

In the simulation, the events are generated for the $\sqrt{s} =$ 14 TeV LHC with MadGraph5 [23] and are showered with PYTHIA 6 [24]. Here the contributions from underlying events and pileup are also turned on, with the pileup cross section taken to be 0.25 mb. Jet clustering is done in FastJet [25] using the anti-k_t algorithm with a cone size of $R = 0.5$. Lepton isolation requires the net $p_{\rm T}$ of particles in a cone of size $R = 0.3$ to be less than 10% of the lepton's $p_{\rm T}$. The cross sections of the processes with no Higgs involved are obtained from PYTHIA, scaled by the appropriate k factor [26–29], while the cross sections of the other ones are simply scaled from the SM predictions by comparing with the SM $h \to \tau\bar{\tau}$ width. The selection cuts are summarized in Table I.

Figure 2 shows the normalized $p_{\rm T}$ distributions of the two final-state leptons for the signal and the backgrounds. We see that the second hardest lepton for the signal has an extremely soft $p_{\rm T}$ distribution peaked at below 5 GeV, because the off-shell ϕ carries very little invariant mass.

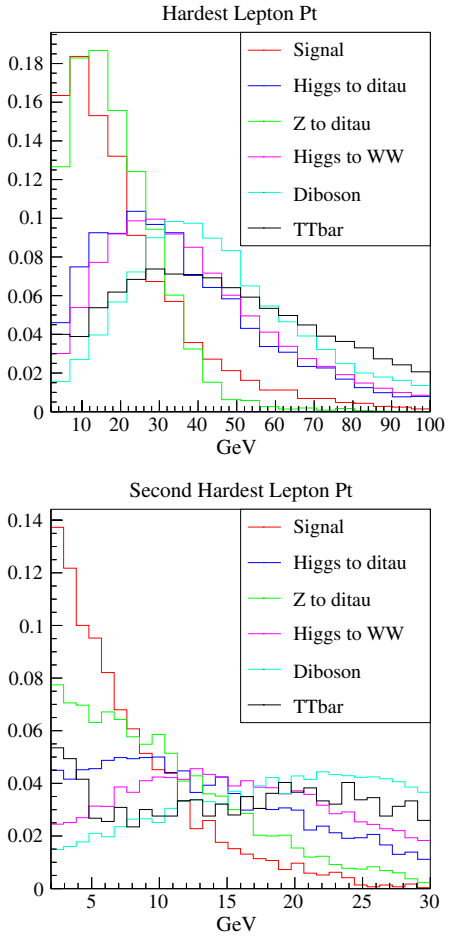

FIG. 2 (color online). Normalized distributions of lepton $p_{\rm T}$.

The feature exemplifies the challenge of making this discovery at the LHC, as the standard dilepton selection cut in Table I eliminates most of the signal. One might consider forgoing the soft lepton and making a single lepton selection. However, in this case the signal is completely overwhelmed by the $W + j$ background, which is suppressed by dilepton selection and thus not included in our simulation. In the end, this analysis shares similar background with the SM $h \to \tau_l\tau_l$ search, which mainly includes $t\bar{t}$, diboson, and $(Z \to \tau\bar{\tau}) + 2j$ [22]. [On the other hand, the

TABLE I. Cuts for the LHC analysis.

Cut 1	Two jets with $p_{\rm T} > 20$ GeV each, $m_{jj} > 650$ GeV, $\lvert\Delta\eta\rvert > 3.5$, and $\eta_1\eta_2 < 0$. Total jet $H_T > 80$ GeV, and no additional jets with $p_{\rm T} > 30$ GeV between forward jets.
Cut 2	Two opposite-sign leptons, harder with 10 GeV $< p_{\rm T} <$ 20 GeV, softer with 10 GeV $< p_{\rm T} <$ 15 GeV $\lvert\eta\rvert < 2.3$ for electrons; $\lvert\eta\rvert < 2.1$ for muons.
Cut 3	Invariant lepton mass $m_{ll} < 20$ GeV, $\not{p}_{\rm T} > 40$ GeV

TABLE II. Cut flows in the LHC analysis. Events produced are for 100 fb^{-1} of data. Gluon fusion contamination is included in the VBF selection. Production cross sections are after preselection cuts which are different for different processes.

14 TeV	Signal	$h\to\tau_l\tau_l$	$h\to WW$	$Z\to\tau_l\bar{\tau}_l$	$t\bar{t}$	Diboson
σ (pb)	0.06	0.11	0.27	0.72	8.0	0.17
Cut 1	1539	3041	6393	24757	9377	4421
Cut 2	33	66	74	327	11	13
Cut 3	16	2	16	40	2	4
$S/\sqrt{B}$			$\sim 2\sigma$			

TABLE III. Cuts for the ILC analysis. θ_{l_i} and $\theta_{l_1 l_2}$ are polar angles of the leptons and the reconstructed Z boson $(l_1 + l_2)$ with respect to the beam, respectively. $m_h^{\rm rec}$ is the Higgs recoil mass.

Cut 1	Three leptons l_i $(i = 1, 2, 3)$, with $\lvert\cos\theta_{l_i}\rvert < 0.99$, $E_{l_i} > 3$ GeV, and $E_{l_3} < 20$ GeV. Fourth-lepton (with $\lvert\cos\theta_{l_4}\rvert < 0.99$ and $E_{l_4} > 10$ GeV) veto.
Cut 2	$m_{l_1 l_2} = 91.2 \pm 5$ GeV, $\lvert\cos\theta_{l_1 l_2}\rvert < 0.8$
Cut 3	$\not{p}_T > 70$ GeV
Cut 4	125 GeV $< m_h^{\rm rec} <$ 150 GeV

$(Z \to l^+ l^-) + 2j$ background is removed by the lower cut on $\not{p}_{\rm T}$ and not included.] In addition, the $h \to \tau_l \tau_l$ decay itself is a background for the exotic decay search. In addition to the VBF and dilepton selections, in Table I we further require a maximum value in m_{ll}. For signal events, m_{ll} tends to be small since one of the leptons is soft. An even stronger minimum cut on the missing energy does not help much after the VBF cut, since both the signal and background events left tend to have a relatively large missing energy.

The cut flows for the signal and the backgrounds are summarized in Table II, where a luminosity of 100 fb^{-1} is assumed. We see that the search sensitivity is not too promising, unless new techniques for identifying very soft leptons are developed.

IV. ILC STUDY

Next we demonstrate that a Higgs factory such as the ILC could serve as a discovery machine for the Higgs decay to light EW mediators, even during its early run with $\sqrt{s} = 250$ GeV. To begin with, we assume a beam polarization $(P_{e^-}, P_{e^+}) = (0.8, -0.6)$ for the ILC and focus on the process $(l^\pm = e^\pm, \mu^\pm)$

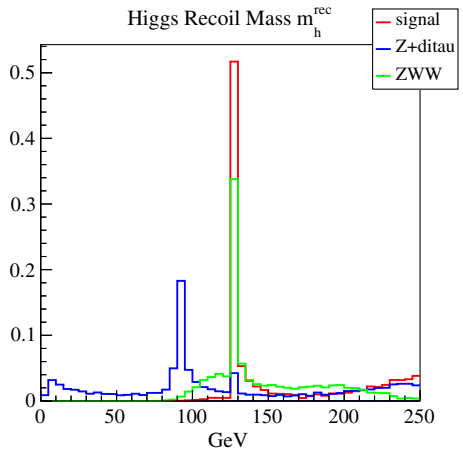

FIG. 3 (color online). Normalized distributions of the Higgs recoil mass.

TABLE IV. Cut flows in the ILC analysis. $S/\sqrt{B}$ is calculated for 40 fb^{-1} of data.

$\sqrt{s} = 250$ GeV	Signal	$Z\tau\bar{\tau}$	ZWW
Xsection (fb)	0.93	27.81	0.02
Events	10 000	10 000	10 000
Cut 1	2420	1854	1404
Cut 2	1272	575	329
Cut 3	821	93	258
Cut 4	820	3	255
$S/\sqrt{B}$		$\sim 5.2\sigma$	

$$e^+ e^- \to Z(h \to \phi\phi \to \tau\bar{\tau}\nu_\tau\bar{\nu}_\tau) \to l^+ l^- l^+ l^- + \not{p}_T. \quad (6)$$

This decay topology provides an extremely clean laboratory, with the main background being $Z + (Z/h \to \tau\bar{\tau})$. Triboson production, ZWW, with all of them decaying leptonically, is subdominant and also included.

The selection cuts are summarized in Table III. Given that the fourth charged lepton, the one from the off-shell mediator decay, is extremely soft, we use a three-lepton selection and introduce a hard fourth-lepton veto to enhance the signal. In addition, due to a relatively small $\sqrt{s}$, the angular distribution of the Z boson in $e^+ e^- \to Zh$ is flat in $\cos\theta$ [30], while the Z bosons in the $Z\tau\bar{\tau}$ events are more forward because most of the $Z\tau\bar{\tau}$ events are from the di-Z production, which proceeds via t-channel processes. So in Table III we require $\lvert\cos\theta_{l_1 l_2}\rvert < 0.8$ to suppress the $Z\tau\bar{\tau}$ background. Further suppression is achieved by demanding $\not{p}_T > 50$ GeV.

In Fig. 3 we show the normalized distribution of the Higgs recoil mass, $m_h^{\rm rec} \equiv \sqrt{s - 2\sqrt{s}E_{l_1 l_2} + m_{l_1 l_2}^2}$, for both signal and backgrounds, where the peak at the $m_h = 126$ GeV for the signal is difficult to miss. This figure demonstrates the advantage of knowing the center-of-mass energy in a lepton collider such as the ILC: the Higgs mass can be reconstructed precisely even with missing particles in the final state. Our last cut in Table III utilizes $m_h^{\rm rec}$ to cut away the diboson background $Z + (Z \to \tau\bar{\tau})$, which is peaked at m_Z in Fig. 3. It is also interesting to see that both $Z\tau\bar{\tau}$ and ZWW backgrounds receive contributions from $Z + (h \to WW/\tau\bar{\tau})$ processes.

The cut flows for the signal and the backgrounds are summarized in Table IV. For the benchmark that we are considering, the signal cross section is about half of the SM $h \to \tau\bar{\tau}$. We see that a $S/\sqrt{B} \approx 5\sigma$ discovery can be made with about 40 fb^{-1} of data at $\sqrt{s} = 250$ GeV.

V. CONCLUSION

We have shown that light EW mediators contributing to an enhanced Higgs-to-diphoton width could show up in a new class of exotic Higgs decays. We then proposed using such decays to uncover the mediators and explore their couplings to the Higgs boson. Despite a large number of

papers discussing the Higgs decay to diphoton (including collider strategies for further testing), there was no way available to directly probe the couplings between the Higgs boson and any potential loop mediators. We report an initial effort in this direction.

The impact of this work for the future Higgs studies could be even deeper. Exploring new physics directly coupled with the Higgs sector is one of the top priorities of the LHC experiments. In addition to precisely measuring the Higgs coupling with the SM particles, one approach of the same significance but more straightforward is searching for exotic Higgs decays. With no doubt this will be an immediate next step for the Higgs study at colliders, for both theorists and experimentalists. The Higgs decay studied in this article represents one class of new exotic Higgs decay possibilities: off-shell exotic Higgs decays, either into a pair of EW-scale charged scalars or a pair of charged fermions, and it opens a new avenue in this direction.

At colliders, the kinematics of this class of new exotic Higgs decays is special. In general one of the mediators in the exotic Higgs decay is far off shell and its decay products are very soft, which makes it difficult to search for at the LHC, using the standard cuts only. However this might motivate studies of the signals with very soft leptons, e.g., using track information to improve the sensitivity at the LHC. On the other hand, such discoveries can be made with a relatively small amount of data at the ILC with $\sqrt{s} =$ 250 GeV. (One exception could be that a doubly charged scalar works as a mediator. Such a mediator is typically heavy, e.g., see [31]. A more efficient way to probe its coupling with the 125 GeV Higgs could be producing the new mediators at colliders first and then searching for the Higgs boson radiated by the mediators. In this case, the ILC sensitivity might be weak compared with the LHC, due to the limitation of its beam energy scale.) Given the ongoing debate about the possibility of building the ILC, such a contrast is of timely importance. Obviously a detailed comparison between the discovery reaches at the LHC and the ILC, as well as generalizations to other types of mediators and decay final states are warranted.

Systematic studies on these topics are in progress in the context of simplified models and will be reported in [32].

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