Searching for Higgs Decays to as Many as 8 Leptons

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We propose a search for Higgs decays with as many as 8 leptons in the final state. This signal can arise in a simple model with a hidden vector (A_d) that gets mass via a hidden scalar (h_d) vacuum expectation value. The 125 GeV Higgs boson can then decay $H \to h_d h_d \to 4A_d \to 8f$, where f are standard model fermions. We recast current searches and show that a branching ratio (BR) of $H \to h_d h_d$ as large as 10% is allowed. We also describe a dedicated search that could place bounds on $\mathrm{BR}(H \to h_d h_d)$ as low as 10^{-5} using only 36 fb^{-1} of data, with significant improvements coming from greater integrated luminosity.

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Introduction.—The discovery of the Higgs boson [1,2] completes the standard model (SM), but it also opens up a new avenue to look for deviations from the SM. In this Letter, we present an as yet unattempted measurement that could be done to probe physics beyond the SM.

The Higgs square operator $H^\dagger H$ is the only gauge invariant scalar operator of dimension lower than four in the SM. Therefore, it is natural to expect that, if there is another sector that talks to the SM, its scalars could couple to the SM via this "Higgs portal" operator [3]. In this Letter, we posit a very simple hidden sector: a new U(1) gauge boson that acquires mass via a hidden sector Higgs mechanism, and the hidden Higgs boson has a renormalizable coupling to the SM via the Higgs portal. The new gauge boson generically couples to the SM through the "vector portal" [4], and the phenomenology of a hidden Abelian gauge group was first studied in [5].

The model with Higgs and vector portal couplings was studied in the ultralight regime in [6,7]. It was studied for general Higgs phenomenology in [8], and it has been most thoroughly studied in the context of Higgs decays to 4 leptons [9–14]. With this model, however, there is a large region of parameter space where decays to more than 4 leptons are possible. If we take the hidden scalar to be lighter than half the Higgs mass, and the hidden photon to be lighter than half the hidden scalar mass, then the SM Higgs boson could decay via

$$H \to h_d h_d \to A_d A_d A_d A_d \to 8f, \qquad (1)$$

where H is the SM Higgs boson at 125 GeV, h_d and A_d are the hidden sector scalar and vector, respectively, and f are SM fermions. The first decay occurs through the Higgs portal operator and current limits allow its branching ratio to be as large as $\mathcal{O}(10\%)$. The second decay is the dominant decay of the hidden sector Higgs boson if kinematically allowed because of the minimality of the hidden sector. If there were other hidden sector fields, then this branching ratio could be reduced, but it is naturally large as long as the hidden gauge coupling is reasonably large.

The decay of the hidden photon goes via the vector portal coupling even if it is extremely small. The Higgs portal coupling does not mediate hidden vector decays at tree level. If the hidden vector is parametrically lighter than the Z, then it dominantly couples to the electromagnetic current, thus giving each hidden photon a significant branching ratio to SM leptons. This branching ratio can be extracted from the R ratio of e^+e^- scattering to hadrons relative to that to muons [13]. This can in turn be extracted from data at low masses [13] and from three-loop QCD calculation of R at higher masses [15].

Higgs decays to lepton jets [16] can also arise from this model [17] (see also [18] for Higgs decays to lepton jets in a different model), and the work of [17] studies Higgs decays to leptons where the mass of the A_d is $\sim$1 GeV, so that the final state lepton pairs are very collimated and may be treated as a single detector object. In this Letter, we consider the general case as long as the decays in Eq. (1) are kinematically allowed and explore the phenomenology of this scenario. We find that current constraints on this process are dominated by the CMS multilepton searches [19] and are quite weak. We also show that there are searches that are very low background and could be performed with current and future data, which would explore significant regions of parameter space.

A simple model.—We consider the following hidden sector Lagrangian added to the SM:

$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + |D_\mu h_d|^2 - V(h_d^\dagger h_d), \qquad (2)$$

where h_d is the hidden (or dark) sector Higgs boson, and $F_{\mu\nu}$ is the field strength tensor for the hidden U(1) gauge boson A_d. The h_d has unit charge under the hidden U(1). $V(h_d^\dagger h_d)$ is the usual wine bottle potential with negative mass squared term, so that h_d gets a vacuum expectation value (VEV) even in the absence of portal operators. We also add a portal Lagrangian,

$$\mathcal{L}_{\text{portal}} = \frac{\epsilon}{2\cos\theta_w}F^{\mu\nu}B_{\mu\nu} + \lambda h_d^\dagger h_d H^\dagger H, \qquad (3)$$

where H is the SM Higgs boson and $B_{\mu\nu}$ is the field strength for SM hypercharge. Current limits on this model require both λ and ϵ to be small, as we will see in detail below, so we work to first order in both. Detailed formulas for the mixings and couplings in this model can be found, for example, in [9,13,17]. Here we state the results for the processes of interest in our study.

Both the SM Higgs boson and the hidden Higgs boson get VEVs in the absence of the portal coupling,

$$\langle h_d \rangle \approx \frac{v_d}{\sqrt{2}} \qquad \langle H \rangle \approx \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \qquad (4)$$

with $v \approx 246$ GeV. The Higgs portal coupling shifts the VEVs by $\mathcal{O}(\lambda)$, and it induces mixing between the SM and hidden Higgs bosons, which in turn allows the SM Higgs boson to decay to two hidden vectors. If kinematically allowed, the tree-level width for this decay is given by

$$\Gamma(H \to A_d A_d) = \frac{\lambda^2}{32\pi}\frac{v^2}{m_H}\left(1 - \frac{m_{h_d}^2}{m_H^2}\right)^{-2} \times \sqrt{1 - \frac{4m_{A_d}^2}{m_H^2}}\left(1 - \frac{4m_{A_d}^2}{m_H^2} + \frac{12m_{A_d}^4}{m_H^4}\right). \qquad (5)$$

The decay of the Higgs boson to two hidden Higgs bosons is mediated by the Higgs portal coupling with a Higgs VEV insertion

$$\Gamma(H \to h_d h_d) = \frac{\lambda^2 v^2}{32\pi m_H}\sqrt{1 - \frac{4m_{h_d}^2}{m_H^2}}. \qquad (6)$$

Therefore, the branching ratio to hidden scalars is typically comparable to that to hidden vectors.

This model can also give Higgs decay to Z and A_d, which would go through the vector portal. Constraints require $\epsilon \lesssim 10^{-3}$ (see below), and this decay is further suppressed by m_A^2/m_Z^2, so it is negligible in the parameter space of interest. The Z can also decay as $Z \to A_d h_d$, which was studied in detail in [20]. While the LHC is not presently sensitive to this decay in this model, it may become sensitive in the future.

The branching ratio (BR) of the SM-like Higgs decay to hidden scalars is given by

$$\mathrm{BR}(H \to h_d h_d) \approx \frac{\Gamma(H \to h_d h_d)}{\Gamma_H^{\text{SM}}} \approx 0.1\% \left(\frac{\lambda}{10^{-3}}\right)^2, \qquad (7)$$

where the first approximation is that the hidden sector does not significantly contribute to the total width, and the second is assuming that the hidden scalar mass is well below half of the Higgs mass.

With this minimal hidden sector, the only decay of the hidden Higgs boson that is not suppressed by small couplings is that to two hidden vectors as long as it is kinematically allowed. So in that regime,

$$\mathrm{BR}(h_d \to A_d A_d) \approx 100\%, \qquad m_{h_d} > 2m_{A_d}. \qquad (8)$$

One could expand the hidden sector to include, for example, a dark matter candidate [21]. This could change some of the phenomenology, but we leave more complicated models to future work.

The hidden vector couples to the electromagnetic current with strength ϵe and thus couples democratically to electromagnetic charge. It also couples to the Z current, but that is suppressed by $m_{A_d}^2/m_Z^2$, which is small in the region of parameter space we are interested in. The branching ratio of the hidden vector to leptons (e and μ) was calculated very precisely in [13] and is typically large as long as m_{A_d} is not near a QCD resonance. In this preliminary collider study, we use tree-level branching ratios, keeping in mind that this will not be a suitable approximation near QCD resonances.

From the computations in [13], we can also compute the lifetime of the A_d very precisely, but in the range in which we are interested, it is approximately given by

$$\Gamma \simeq \frac{\epsilon^2 m_{A_d}}{8\pi}, \qquad (9)$$

which translates to a lifetime of

$$c\tau \simeq 5 \times 10^{-8}\ \text{m}\left(\frac{10^{-4}}{\epsilon}\right)^2\left(\frac{10\ \text{GeV}}{m_{A_d}}\right), \qquad (10)$$

so the A_d decays promptly as long as $\epsilon \gtrsim 10^{-6}$, which is the range we will focus on here. If the hidden photon has a macroscopic lifetime, then the current constraints as well as experimental challenges for finding it are quite different, and we leave the small ϵ case with displaced decays to future work.

Current constraints.—We first look at constraints on direct production of the hidden sector fields. If the hidden vector is lighter than the hidden scalar, then dark photon constraints can be straightforwardly applied to this scenario. For $1 \lesssim m_{A_d} \lesssim 10$ GeV, the strongest constraints come from *BABAR* [22] through resonant production of A_d and decay into SM leptons and set a bound on the kinetic mixing parameter ϵ, namely,

$$\epsilon \lesssim \text{few} \times 10^{-4}, \qquad 1 \lesssim m_{A_d} \lesssim 10 \text{ GeV}. \tag{11}$$

Regions close to narrow QCD resonances have much weaker bounds. In this Letter, we therefore do not consider m_{A_d} very close to the mass of the ϕ, J/ψ, and Υ resonances. For larger masses, the leading bounds on ϵ come from LHCb [23] through a dilepton resonance analysis, where the bounds are

$$\epsilon \lesssim 10^{-3}, \qquad 10 \lesssim m_{A_d} \lesssim 40 \text{ GeV}. \tag{12}$$

These bounds apply to prompt decays of the hidden vector, the case we consider here, and we see that there are at least two decades of allowed parameter space where the hidden photon is prompt and not excluded.

In the mass range of interest for the hidden scalar, $10 \lesssim m_{h_d} \lesssim 60$ GeV, the strongest limits on direct production of the h_d via its mixing with the SM Higgs boson come from LEP. The h_d will dominantly decay to two A_d, which then each decay to a pair of SM fermions. Most searches do not look for this particular decay channel, so the bounds are quite weak. The strongest bound comes from the decay mode independent search at OPAL [24], which places a limit on $\sin^2\theta_h$, where θ_h is the mixing angle between the SM-like and hidden Higgs boson. This limit varies from ~ 0.05 at low mass to ~ 0.6 at high mass. In our model,

$$\sin\theta_h \approx \frac{\lambda v v_d}{m_H^2 - m_{h_d}^2}. \tag{13}$$

We can write $m_{A_d} = g_d v_d$ and then use this search to set limits on the scalar portal coupling λ as a function of m_{A_d}, m_{h_d}, and g_d. The limits are inversely proportional to g_d, the hidden gauge coupling, and this search only sets limits for very small values of the hidden gauge coupling, $g_d \lesssim 10^{-2}$. Searches for topologies of the type [25,26]

$$e^+e^- \to H_2 Z \to H_1 H_1 Z \to 4\text{SM} + Z \tag{14}$$

could be sensitive to direct production of h_d if we identify $H_2 = h_d$ and $H_1 = A_d$. These searches, however, do not put any bounds on the scenario, mainly because they require specific final states, and the branching ratio of the A_d to any particular SM state is somewhat small.

LHC constraints arising from decays of the 125 GeV Higgs boson can be set because the mixing of the h_d and H induces decays to $A_d A_d$, which can result in the Higgs decay to 4 leptons [9–14], as shown in Eq. (5). This has been searched for at ATLAS [27,28] and CMS [29], with the strongest bounds coming form the recent 13 TeV ATLAS search [28]. These limits are shown as the dashed red lines in Fig. 1 and are simply the limits shown in Fig. 10 of [28]. There are also searches with τ's and b's in the final state [30,31], but those do not set a nontrivial limit because of significantly larger background than searches with muons or electrons.

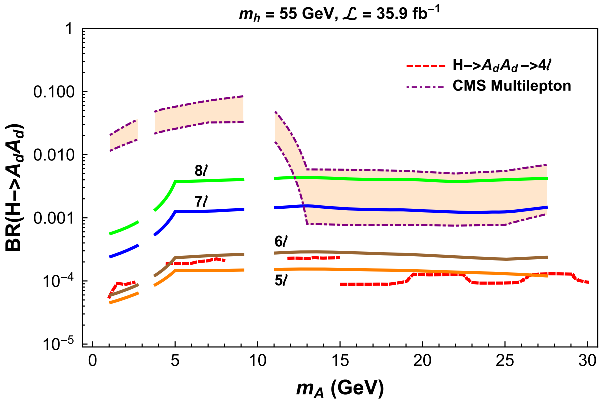

FIG. 1. Current and projected limits on the hidden sector model considered in this Letter. The horizontal axis is the hidden vector mass m_A, and the vertical axis is the branching ratio of the SM-like Higgs boson to two dark vectors. The red dashed curves are limits from the channel $H \to A_d A_d \to 4\ell$ from [28]. The dot-dashed purple curves are recasted limits on $H \to h_d h_d \to 4A_d$ from the CMS multilepton search [19], converted to a limit on $\text{BR}(H \to A_d A_d)$ using Eqs. (5) and (6). The yellow band parametrizes the uncertainty due to lepton efficiency (see text for details). The solid curves are the *projected* limits from the proposed searches with ≥ 5–8 leptons going from bottom to top. Here the mass of the hidden Higgs boson h_d is set to 55 GeV, but the limits are fairly insensitive to that parameter. The projections use an integrated luminosity of 35.9 fb^{-1}. We do not present projections for the hidden photon mass near the ϕ, J/ψ, or Υ resonances.

Finally, we consider the cascade process that can give rise to the decay, $H \to h_d h_d \to 4A_d$. This can be constrained by the CMS multilepton study from [19], whose signal regions are potentially applicable to this topology as they require low-p_T leptons as well as no missing energy. We recast the limit from [19] to set a bound on the model considered here, but we note that, because this is a recast, there are significant uncertainties on our limit. We simulate Higgs production at LHC13 using the model from [13] in MadGraph5_aMC@NLO [32]. Higgs production through gluon fusion is simulated at tree level with an effective gluon-gluon-Higgs vertex, and then the Higgs boson is forced to decay to h_d pairs, which are then allowed to decay inclusively. We shower and hadronize events using PYTHIA 8.2 [33]. While our strategies will focus on leptons, we must shower and hadronize the partons in order to approximate the isolation requirements imposed by experiments. We ignore detector effects in this preliminary study, but we note that these can be important considering the low-p_T thresholds we use and the high-pileup environment of the LHC.

In order to derive the constraints from the CMS search, we must apply lepton identification efficiencies, which are somewhat small for leptons with low p_T. Because [19] only provides the low-p_T lepton tagging efficiencies for the most pessimistic working point, we must use the pessimistic values and obtain a conservative result. The true signal efficiency is almost certainly better than what we find, because [19] states that a looser set of lepton identification criteria are used for searches with 4 leptons, but does not specifically state what these efficiencies are. Therefore, we consider efficiencies of 50% (100%) to set a conservative (aggressive) limit.

We find that the signal region H of [19], which requires 4 leptons and fewer than two opposite-sign, same-flavor (OSSF) lepton pairs, is most sensitive to the hidden sector topology we study. Using the CL$_s$ method [34], we estimate a constraint on this scenario at the 95% confidence level, which is shown as the dot-dashed purple line in Fig. 1, with the yellow band showing our uncertainty due to lepton identification efficiencies. All of the constraints in Fig. 1 are shown for $m_{h_d} = 55$ GeV, but the limits are mostly insensitive to the value of this parameter. As discussed above, we use the tree-level branching ratios of the A_d to SM fermions, and we mask our plots when m_{A_d} is near the masses of the ϕ, J/ψ, and Υ. From Fig. 1, we see that the searches for $H \to A_d A_d$ are more sensitive to this model than the CMS multilepton searches, but, as we will show in the next section, a dedicated search could be more sensitive than both.

The CMS multilepton search is sensitive to the process $H \to h_d h_d \to 4A_d$, so we also show the constraints placed on BR$(H \to h_d h_d)$ as a function of m_{h_d} in Fig. 2. This branching ratio is sensitive to m_{A_d} and the limits vary from 10% to 10^{-3} depending on the A_d mass and on whether we use aggressive or conservative parametrization for lepton efficiency.

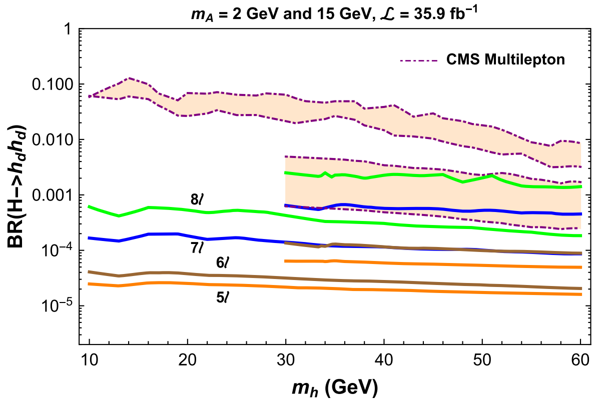

FIG. 2. Current and projected limits on BR$(H \to h_d h_d)$ as a function of the mass of the hidden scalar. Here we show only limits and projections directly on this production mode, and the colors are the same as in Fig. 1. The lines that go all the way across are for $m_{A_d} = 2$ GeV, while those that stop at 30 GeV are for $m_{A_d} = 15$ GeV. Projections are for 35.9 fb^{-1}.

Strategies and projections.—We now comment on potential for improvement with a dedicated analysis. We focus on multilepton final states beyond four leptons because 5^+ lepton final states should have low backgrounds. It is beneficial to use multilepton triggers with low-p_T thresholds. Currently, the 3-lepton triggers seem like a good candidate, given the low-p_T requirements on the leptons. For ATLAS, these are given by [35] (i) three loose e's: $p_T \geq 15, 8, 8$ GeV at L1 [17, 10, 10 at High Level Trigger (HLT)], and (ii) three μ's: $p_T > 6$ GeV (3×6 at HLT). For CMS, a multilepton analysis [36] used three e's: $p_T \geq 15, 8, 5$ GeV.

While these analyses were performed at 8 TeV, the trigger thresholds did not increase significantly in the 13 TeV run [19,37], so we use these thresholds for our estimated projections. For the leptons in addition to those required to pass the trigger, we require $p_T(\mu) > 2$ GeV [38] and $p_T(e) > 5$ GeV [39]. For all electrons (muons), we require $|\eta| < 2.5(2.4)$. We also require that the leptons are isolated using the p_T dependant isolation criteria from [19]. In order to reduce the background, we further require (i) $m_{\mathrm{all}} < 130$ GeV and (ii) $m_{\mathrm{OSSF}} \notin [0, 1.1] \cup [2.7, 3.8] \cup [9.1, 11.1]$ GeV, where m_{all} is the invariant mass of all reconstructed isolated leptons, and its required to be near or below the Higgs mass. This reduces background from processes with top quarks such as $\bar{t}tZ$ to below attobarn (ab) cross sections.

m_{OSSF} is the invariant mass of *any* pair of leptons with the opposite signs and the same flavor, and it is required to not be near a QCD resonance which can decay to dileptons and also to not be too low. Given these cuts, the leading background is multiboson production. We simulate in MadGraph5_aMC@NLO $pp \to VV \to 4\ell$, where $V = Z, \gamma$. We then shower and hadronize the events using PYTHIA 8.2 including QED radiation. This procedure yields a cross section for producing 5 (6) leptons to be 18 (0.7) ab. Backgrounds with fake electrons can be estimated from the jet faking electron rate [39] times the rate of events with 4 leptons and should be smaller than real VV background. Fake muons are smaller still.

We can then place a projected limit for $\mathcal{L} = 35.9$ fb^{-1} assuming there will 0.63 (0) expected background events with $\geq n$ leptons with $n = 5$ ($n = 6, 7, 8$). Since all channels have small backgrounds, the ≥ 5 lepton channel will have the best projected limit, but we show all four possible values of n to motivate different possible searches. In particular, an excess in the $n = 8$ lepton bin is particularly interesting as it allows us to potentially fully reconstruct the Higgs invariant mass. We show the projected limit BR$(H \to h_d h_d)$ in Fig. 2. For low mass A_d, a dedicated search along these lines would exceed current limits by about 3 orders of magnitude, while for moderate mass A_d by a factor of a few.

This projected limit assumes a luminosity of 35.9 fb^{-1} at 13 TeV, the same amount of data used in [19] and much less than the total amount of data presently collected. We see that, even with this modest integrated luminosity, branching ratios of $H \to h_d h_d$ as low as $\mathcal{O}(10^{-5})$ can be explored. At higher integrated luminosity, rare background processes will become more important, but we can still expect significant improvements with more data.

We also show the projected bound on $\mathrm{BR}(H \to A_d A_d)$ in Fig. 1 using Eqs. (5) and (6). These bounds are comparable to the recent 13 TeV ATLAS result [28], but we stress that this comparison only applies the minimal model, and relative decay rates of the Higgs boson to vectors vs scalars will be modified in nonminimal models [40].

Summary and conclusions.—Hidden massive photons have recently generated significant interest in the community and spurred significant experimental progress [41]. If such a photon gets mass from a Higgs mechanism, then one naturally expects a Higgs portal coupling between the hidden Higgs boson and the SM Higgs boson. In such a scenario, if the dark vector and scalar are near the weak scale, then the SM-like Higgs boson could easily have a decay

$$H \to h_d h_d \to 4A_d. \tag{15}$$

The A_d could in turn decay to a pair of leptons, allowing for Higgs decays with final state with large numbers of leptons. Such a signature would be spectacular at the LHC and largely background free.

While there are some searches for many leptons, there is no dedicated search for Higgs decay in this channel, and current searches are relatively weak. A dedicated search requiring at least 5 leptons can significantly increase the reach for such a scenario, with Fig. 2 showing a reach with a branching ratio of the SM Higgs boson to two hidden scalars as low as 10^{-5} using the 36 fb^{-1} of data that have already been analyzed. Significant improvements are expected with higher luminosity, especially for $n = 7$, 8 leptons, where the backgrounds should be negligible even at the high-luminosity LHC.

Finally, we note that a genuine experimental study is needed to make precise predictions on the reach. The sensitivity depends on lepton thresholds, the lower the better. At very low thresholds, however, experimental issues such as fakes become significantly more difficult, so we note that, with the low thresholds used in this study, the uncertainties on our projections will be relatively large. Yet given the significant gains possible with a dedicated search and the simplicity of the model presented here, we believe that such a search may be well worth the effort.

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[40] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.121.221803 for a brief discussion of how the branching ratio of the SM-like Higgs boson to hidden scalars can be parametrically enhanced relative to that to hidden vectors in non-minimal models.

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