Associated Higgs plus vector boson test of a fermiophobic Higgs boson

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Production in association with an electroweak vector boson V is a distinctive mode of production for a Higgs boson H without tree-level couplings to fermions, known as a fermiophobic Higgs boson. We focus on HV associated production with H decay into a pair of photons, and V into a pair of jets, with the goal of distinguishing a fermiophobic Higgs boson from the standard model Higgs boson. Performing a simulation of the signal and pertinent QCD backgrounds, and using the same event selection cuts employed by the LHC ATLAS Collaboration, we argue that existing LHC data at 7 TeV with 4.9 fb^{-1} of integrated luminosity may distinguish a fermiophobic Higgs boson from a standard model Higgs boson near 125 GeV at about 1.9 standard deviation signal significance (1.9σ) per experiment. At 8 TeV we show that associated production could yield 2.8σ significance per experiment with 10 fb^{-1} of data.

PACS numbers: 11.15.Ex, 14.80.Ec, 14.80.Bn

I. INTRODUCTION

Evidence in the past year from experiments at the CERN Large Hadron Collider (LHC) [1, 2] and the Fermilab Tevatron [3] encourages a strong sense of anticipation that the long-sought neutral Higgs boson is on the verge of discovery with mass in the vicinity of 125 GeV. As more data are analyzed, and the LHC energy is increased from 7 TeV to 8 TeV, experimental investigations will naturally turn toward determination of the properties of the observed mass enhancement — particularly, the branching fractions into pairs of gauge bosons, standard model fermions, and possibly other states.

The original formulation of electroweak symmetry breaking (EWSB) focused on couplings of the Higgs boson to massive gauge bosons [4]. Tree-level Yukawa couplings between fermions and Higgs bosons came later in the current version of the "standard model" (SM) in which the Higgs boson serves as the agent for generation of fermion masses as well as gauge boson masses. Proposals have also been made of Higgs doublets [5] or triplets [6] in which the Higgs boson is explicitly "fermiophobic," namely, without tree-level couplings to fermions.

In this paper, we emphasize a measurement that offers the possibility to test a broad class of models where Higgs boson couplings to fermions, if they exist, are small enough that they do not effect the branching fractions to gauge bosons. We focus on HV associated production where H decays into a pair of photons, $H \rightarrow \gamma\gamma$, and $V = W$, Z decays into a pair of jets, $V \rightarrow jj$. We investigate whether the peak observed near 125 GeV in the diphoton $\gamma\gamma$ invariant mass spectrum [7, 8] in the 7 TeV LHC data provides support for a suppressed fermion coupling hypothesis. We show that this process offers excellent prospects for distinguishing a fermiophobic Higgs boson from a standard model Higgs boson.

The phenomenology of a fermiophobic Higgs boson is very different from the SM case. Since the coupling to top quarks $Ht\bar{t}$ is suppressed, a fermiophobic Higgs boson is not produced through the dominant SM production channel, the gluon-gluon fusion process $gg \rightarrow H$, where the interaction occurs through a top-quark loop. Rather, production of a fermiophobic Higgs boson occurs in association with an electroweak gauge boson $pp \rightarrow HVX$ where $V = W$, Z, or through vector boson fusion (VBF), $VV \rightarrow H$. Between these two modes, the relative cross section favors VBF, but HV associated production offers the opportunity to observe a final state in which there are two potentially prominent resonances in coincidence, the Higgs boson peak in $H \rightarrow \gamma\gamma$ along with the V peak in the dijet mass distribution $V \rightarrow jj$. The favorable branching fraction for $V \rightarrow jj$ guides our choice of this decay channel rather than the leptonic decays $W \rightarrow \ell\nu$ or $Z \rightarrow \ell^+\ell^-$.

The LHC ATLAS and CMS collaborations consider the fermiophobic possibility in two recent papers [9, 10]. In the $pp \rightarrow \gamma\gamma + jj + X$ channel, CMS requires the transverse energy of the two jets to be larger than 30 and 20 GeV, with large pseudorapidity separation between the jets, $(|\eta_{j_1} - \eta_{j_2}| > 3.5)$, and dijet invariant mass larger than 350 GeV. These cuts are designed for the VBF production process. In the HV channel, they concentrate on the leptonic decay modes of the vector bosons. While the background is smaller, the signal is suppressed by the small branching fraction to leptons. ATLAS uses the inclusive diphoton channel $pp \rightarrow \gamma\gamma + X$. In the diphoton mass region near 125 GeV, they see some evidence for an increase in the signal to background ratio at large values of the transverse momentum of the diphoton pair. This increase is qualitatively consistent with the expectation of a harder Higgs boson p_T spectrum from VBF and associated production, compared to the SM gluon fusion mechanism. On the other hand, the

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ratio of the Higgs signal to QCD background in the $\gamma\gamma$ channel also improves with p_T of the Higgs boson in the SM [11], so the p_T spectrum alone is not a good discriminator. The fermiophobic possibility must be reconciled also with a Tevatron collider enhancement in the $b\bar{b}$ mass spectrum [3] in the general vicinity of 125 GeV, implying a possible coupling of the Higgs boson to fermions. However, these results have yet to be corroborated by LHC data and could be interpreted in a model in which effective Yukawa couplings are radiatively induced [12].

The emphasis in this paper is placed on the investigation the fermiophobic option in associated production, with V decay to a pair of jets. We compute the expected signal rates from associated production and VBF, and the backgrounds from $pp \to \gamma\gamma jj + X$ in perturbative quantum chromodynamics. Adopting event selections similar to those used by the LHC collaborations, we show that the current 4.9 fb^{-1} might contain $\sim$1.9 standard deviation (1.9σ) evidence for a fermiophobic Higgs boson in the $pp \to HVX$ channel. We argue that clear evidence (2.8σ) of a fermiophobic Higgs boson could be obtained by study of the $pp \to HVX$ channel at 8 TeV with 10 fb^{-1} of integrated luminosity. We urge concentrated experimental effort on Higgs plus vector boson associated production.

II. PRODUCTION AND DECAY OF A FERMIOPHOBIC HIGGS BOSON

Fermiophobic Higgs bosons are produced predominantly via HV ($V = W$, Z) associated production or vector boson fusion (VBF). Associated production will produce hard jets if $V \to jj$ (Fig. 1a), with the invariant mass of the dijet system M_{jj} showing a resonance structure in the electroweak gauge boson mass region ($M_V \sim$80–91 GeV). Vector boson fusion is characterized by two hard forward jets (Fig. 1b), and it contributes a long tail to the dijet invariant mass distribution, with few events in the M_V mass region. In contrast, additional jets from production of a SM Higgs boson are mostly from soft initial state radiation (ISR) off the gluon-gluon fusion initial state. We exploit these different event topologies to distinguish a fermiophobic Higgs boson from a standard model Higgs boson.
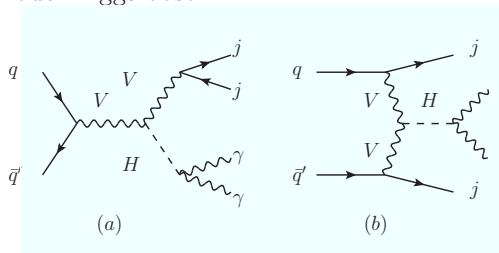

FIG. 1: Feynman diagrams for (a) HW/HZ associated production with H decay to diphotons and W/Z decay to dijets; and (b) vector boson fusion (VBF) production of H+dijets.

The contribution to diphoton production from a fermiophobic Higgs is surprisingly large. While the cross section for fermiophobic Higgs production is suppressed compared to the SM by an order of magnitude, the branching fraction for $H \to \gamma\gamma$ is correspondingly increased. The net result is that the production cross section for $pp \to H + X \to \gamma\gamma + X$ for a fermiophobic Higgs boson is predicted to be nearly identical to that of a SM Higgs boson [12].

In order to compare directly with data, we begin with a Higgs to diphoton signal analysis by the ATLAS Collaboration [7, 13]. ATLAS sees an excess of events when compared to either the fermiophobic or SM Higgs models of a factor of $2.0^{+0.84}_{-0.7}$ [13]. Since we wish to distinguish a fermiophobic Higgs signal from a SM Higgs signal, we focus on predicting the *fraction* of the ATLAS $H \to \gamma\gamma$ data sample that should contain a dijet invariant mass peak M_{jj} near the W and Z masses. Hence, we normalize the total number of events in our signal predictions by this experimental factor of 2.

Three fermiophobic Higgs signal processes should contribute to the ATLAS diphoton mass peak: HW, HZ, and VBF. In order to determine the proportion of each signal process we calculate the acceptance of each process at next-to-leading-order (NLO) in QCD. We generate weighted signal events using MCFM [14], where we substitute photons for b quarks in the final state, and use HDECAY [15] to correct for the branching fraction for $H \to \gamma\gamma$. We impose ATLAS inspired [7] acceptance cuts on the two photons in the final state:

- Photon candidates are ordered in transverse energy E_T, and the leading (subleading) candidate is required to have $E_T > 40$ GeV (25 GeV);

- Both photons must satisfy pseudorapidity cuts of $1.52 < |\eta_\gamma| < 2.37$ or $|\eta_\gamma| < 1.37$;

- Both photons must be isolated with at most 5 GeV of energy deposited in a cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ around the candidate, where ϕ is the azimuthal angle, after the photon energy is removed.

We determine the number of events that should appear in each production channel after ATLAS photon acceptance cuts by applying a photon reconstruction and identification efficiency. This efficiency is 65% for $E_T = 25$ GeV and 95% for $E_T = 80$ GeV. We do a linear extrapolation of photon efficiencies for other values of photon E_T, and assume that it is 100% for a photon with $E_T > 90$ GeV. We use the ATLAS isolation cut acceptance of 87% for a 120 GeV Higgs boson [7]. As a cross check, we calculate the diphoton acceptance for the gluon-gluon fusion channel using the same method and find a cut acceptance of 34.9%, in very good agreement with the 35% given by ATLAS [7].

The numbers of events predicted in 4.9 fb^{-1} at 7 TeV from the HW, HZ, and VBF channels before and after ATLAS acceptance cuts (scaled by the factor of 2 above) are shown in Table I. Vector boson fusion supplies the

largest fraction of the Higgs diphoton events. However, since the distinguishing feature is a W or Z dijet mass peak in the HV final state of interest to us, our additional cuts are optimized to select the HW and HZ processes.

TABLE I: Numbers of signal and background events after cuts expected in 4.9 fb^{-1} of data at 7 TeV. ATLAS γ cuts in the second line include photon acceptances, efficiencies, and isolation.

Channel	HW	HZ	VBF	Bkgd.
Incl. $H \to \gamma\gamma + X$	$86.4^{+36.3}_{-30.2}$	$47.6^{+20.0}_{-16.7}$	$188.6^{+79.2}_{-66.0}$	—
ATLAS γ cuts	$36.4^{+15.3}_{-12.7}$	$20.0^{+8.4}_{-7.0}$	$84.0^{+35.3}_{-29.4}$	22349
$|M_{\gamma\gamma} - 125| < 3.8$ GeV	$29.1^{+12.2}_{-10.2}$	$16.3^{+6.8}_{-5.7}$	$68.6^{+28.8}_{-24.0}$	2859
≥ 2 jet acceptance	$14.8^{+6.2}_{-5.2}$	$9.1^{+3.8}_{-3.2}$	$50.9^{+21.4}_{-17.8}$	575
$\Delta\phi_{jj} < 2.8$	$13.3^{+5.6}_{-4.7}$	$8.0^{+3.4}_{-2.8}$	$43.6^{+18.3}_{-15.3}$	447
$\Delta R_{jj} < 3.0$	$12.4^{+5.2}_{-4.4}$	$7.5^{+3.1}_{-2.6}$	$10.1^{+4.3}_{-3.6}$	329
$|\eta_{jj} - \eta_{\gamma\gamma}| < 1.0$	$8.4^{+3.5}_{-2.9}$	$5.0^{+2.1}_{-1.8}$	$4.8^{+2.0}_{-1.7}$	130
$|M_{jj} - 75| < 25$ GeV	$6.7^{+2.8}_{-2.3}$	$3.8^{+1.6}_{-1.3}$	$1.6^{+0.7}_{-0.5}$	42.4

The dominant component of the diphoton background is identified by ATLAS to be $\gamma\gamma$+n-jet production, with some contamination from electrons and/or jets faking photons. We generate inclusive $\gamma\gamma + \mathrm{n}j$ (n $\leqslant$ 2) QCD backgrounds using MADEVENT [16], add initial- and final-state showering effects using PYTHIA [17], and mimic detector effects using PGS [18]. To avoid double counting, we use MLM matching [19]. After imposing the diphoton cuts and efficiencies and isolation, we rescale the number of events having $100 < m_{\gamma\gamma} < 160$ GeV by a factor 1.41 in order to match the ATLAS measurement of 22349 background diphoton events (22489 total $\gamma\gamma$ events −140 signal events). In addition to these processes, we calculate $W\gamma\gamma$, $W\gamma j$, Wjj, $Z\gamma\gamma$, $Z\gamma j$, Zjj, but find they contribute less than 1 event after acceptance cuts, so we do not consider them further. The total background after ATLAS photon cuts is listed in the last column of Table I.

III. ISOLATING HV ASSOCIATED PRODUCTION

We focus our analysis on isolating the HV ($V = W$, Z) signal by first isolating Higgs bosons plus jets. We identify the narrow Higgs peak by placing an invariant mass cut of $121.2 < M_{\gamma\gamma} < 128.8$ GeV [7] (third line of Table I). We then demand at least 2 jets with $|\eta_j| < 4.5$, with the leading (subleading) jet required to have $E_{Tj} > 40$ (13) GeV. In Table I, we see that after jet acceptance, we predict a 3.1σ significance for H+dijet production, and a signal to background ratio $S/B \sim 1/8$. It is encouraging that we maintain evidence for Higgs production, however, the signal at this point is dominated by vector boson fusion. Kinematically, VBF tends to have very forward jets, with a broad distribution in the invariant mass M_{jj}. The rest of our cuts are concerned

with extracting a relatively pure HW/HZ sample.

The next three cuts in Table I make use of different aspects of the fact that HV is a two-body final state. Because V recoils against H, we expect the dijets from V decay to be boosted near each other in the detector. To enhance this signature we demand $\Delta\phi_{j_1 j_2} < 2.8$, where $\Delta\phi_{j_1 j_2}$ is the azimuthal angle between the leading jet and the subleading jet. We suppress the forward radiation in VBF and the background ISR by placing a cut on $\Delta R_{j_1 j_2} < 3.0$. Finally, we note that the Higgs and W/Z bosons are produced back-to-back in the center of momentum frame, and tend to be boosted to nearly the same rapidity. Hence we place a tight cut on the difference in pseudorapidity between the reconstructed H ($\gamma\gamma$) and V (jj) of $|\eta_{jj} - \eta_{\gamma\gamma}| < 1.0$.

At this point the significance for a fermiophobic Higgs is 1.6σ, with $S/B \sim 1/7$. In order to improve both the significance and purity, we examine the dijet invariant mass distribution M_{jj} in Fig. 2. Here we see the region that includes the W and Z boson masses, 50–100 GeV, shows a significant peak over background (including an assumed background uncertainty of $\sqrt{B}$ events); while above and below the peak, a handful of VBF events remains. Hence we make a final cut to extract the vector boson mass window $50 < M_{jj} < 100$ GeV. This leaves us with 12 signal events over a background of 42.4, a relatively clean $S/B \sim 1/3.5$, and a significance of 1.9σ. Observation of this excess would be a tantalizing hint of the existence of a fermiophobic Higgs boson.
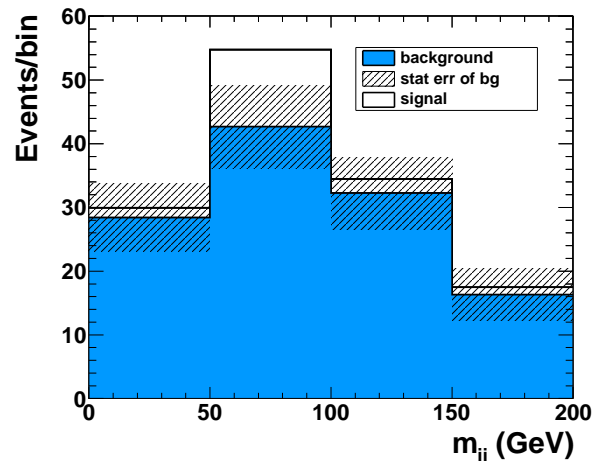

FIG. 2: The dijet invariant mass distribution for a fermiophobic Higgs boson signal and background at 7 TeV with 4.9 fb^{-1} of data. Shaded bands show the statistical uncertainty of the background. The second bin covers the vector boson mass region $|M_{jj} - 75 \text{ GeV}| < 25$ GeV.

We contrast our prediction of the dijet invariant mass distribution for a fermiophobic Higgs boson with the distribution one would obtain under our cuts for a standard model Higgs boson. Jets produced along with the SM Higgs boson arise from higher order corrections to the dominant gluon-gluon fusion production mechanism.

Contributions from VBF and associated production are suppressed by the small branching fraction BR($H \to \gamma\gamma$) in the standard model. Using the same cuts described above, we expect 2.5 signal events for the standard model Higgs boson with $|M_{jj} - 75 \text{ GeV}| < 25$ GeV, many fewer than in the fermiophobic Higgs case, and smaller than the uncertainty on the background. The SM situation is illustrated in Fig. 3. We conclude from this comparison, that isolating $HW + HZ$ production is effective at distinguishing a fermiophobic Higgs boson from a standard model Higgs boson.
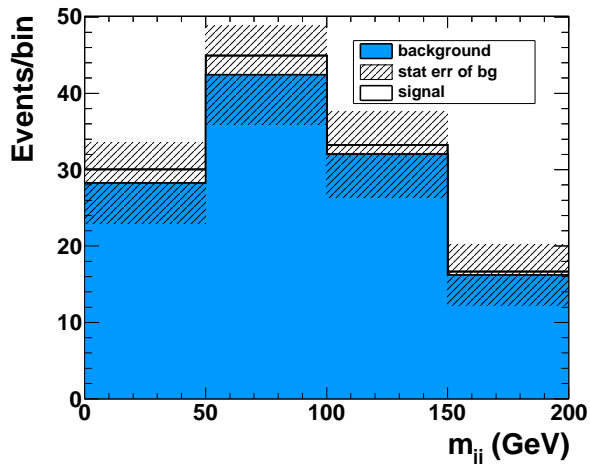

FIG. 3: The dijet invariant mass distribution for a standard model Higgs boson signal and background at 7 TeV with 4.9 fb^{-1} of data. Shaded bands show the statistical uncertainty of the background. The second bin covers the vector boson mass region $|M_{jj} - 75 \text{ GeV}| < 25$ GeV.

We complete our analysis by looking forward to the 8 TeV run of the LHC. In Table II we repeat our analysis for 10 fb^{-1} of data under the assumption that the same factor of 2 event excess will appear in the new data sample. We use the same photon acceptance cuts, efficiencies, and isolation as at 7 TeV. The signal and background cross sections change from 7 to 8 TeV, as does the jet acceptance. With the higher collider energy, the signal jets will be slightly harder and closer in phase space. We make use of these changes to obtain an improvement in the expected signal significance. We increase the transverse energy threshold of the subleading jet to $E_{Tj_2} > 25$ GeV, and we tighten the dijet azimuthal angle cut to $\Delta\phi_{j_1 j_2} < 2.5$. After these cuts we find 4.8σ significance, per experiment, for observation of a Higgs boson plus jets, shown in line 5 of the Table. Both VBF and associated production contribute to this result, with VBF accounting for roughly 2/3 of the signal.

Additional boosts from parton luminosity increase the skew in pseudorapidity between the Higgs and vector bosons; hence, we loosen the Higgs-vector boson pseudorapidity cut to $|\eta_{jj} - \eta_{\gamma\gamma}| < 1.5$. Imposing also the cut $\Delta R_{jj} < 3.0$ to enhance the associated production fraction, we find a slightly reduced purity, $S/B \sim 1/3.9$,

and a significance of $S/\sqrt{B} = 2.8$ for fermiophobic Higgs boson production, shown in the last line of Table II. A clear signal of vector bosons is evident in the dijet mass spectrum (Fig. 4). We expect that the 8 TeV run of the LHC can provide compelling evidence of a fermiophobic Higgs boson.

TABLE II: Numbers of signal and background events after cuts expected in 10 fb^{-1} of data at 8 TeV.

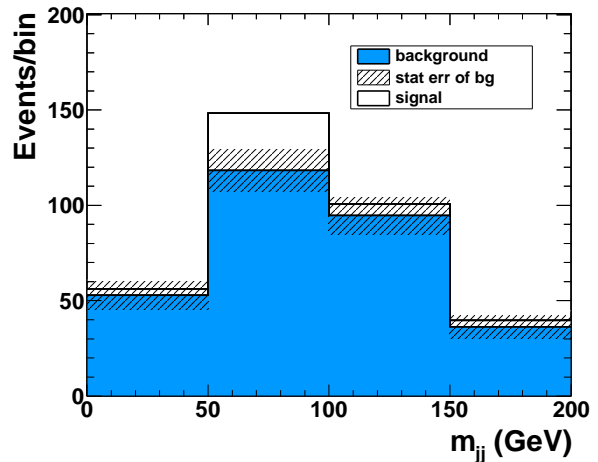| Channel	HW	HZ	VBF	Bkgd.
Incl. $H \to \gamma\gamma + X$	217^{+91}_{-76}	152^{+64}_{-53}	510^{+214}_{-179}	—
ATLAS γ cuts	$86.9^{+36.5}_{-30.4}$	$62.4^{+26.2}_{-21.9}$	$223.5^{+93.9}_{-78.2}$	55599
$|M_{\gamma\gamma} - 125| < 3.8$ GeV	$83.3^{+35.0}_{-29.2}$	$59.8^{+25.1}_{-20.9}$	$199.2^{+83.7}_{-69.7}$	7387
≥ 2 jet acceptance	$28.5^{+12.0}_{-10.0}$	$23.1^{+9.7}_{-8.1}$	$111.0^{+46.6}_{-38.8}$	1126
$\Delta\phi_{jj} < 2.5$	$23.5^{+9.9}_{-8.2}$	$18.3^{+7.7}_{-6.4}$	$80.4^{+33.8}_{-28.1}$	658
$\Delta R_{jj} < 3.0$	$22.5^{+9.5}_{-7.9}$	$17.5^{+7.4}_{-6.1}$	$19.8^{+8.3}_{-6.9}$	539
$|\eta_{jj} - \eta_{\gamma\gamma}| < 1.5$	$19.2^{+8.1}_{-6.7}$	$14.9^{+6.3}_{-5.2}$	$13.3^{+5.6}_{-4.7}$	321
$|M_{jj} - 75| < 25$ GeV	$15.3^{+6.4}_{-5.3}$	$11.2^{+4.7}_{-3.9}$	$3.6^{+1.5}_{-1.3}$	118

FIG. 4: The dijet invariant mass distribution for a fermiophobic Higgs boson signal and background at 8 TeV with 10 fb^{-1} of data. Shaded bands show the statistical uncertainty of the background. The second bin covers the vector boson mass region $|M_{jj} - 75 \text{ GeV}| < 25$ GeV.

IV. CONCLUSIONS

In this paper, we investigate the possibility of using present [7] and future diphoton data from the LHC to distinguish a fermiophobic Higgs boson from a standard model (SM) Higgs boson. Unlike the SM Higgs, nearly 40% of fermiophobic Higgs bosons are produced in association with a W or Z vector boson. Since the largest branching fraction for these vector boson decays is into jets, we focus on $V \to jj$ and devise cut-based analyses that attempt to provide a clean signal and large signifi-

cance. We show that a 1.9σ significance excess could be found in the existing 4.9 fb^{-1} of data at 7 TeV. With the anticipated 10 fb^{-1} to be acquired soon at 8 TeV, we find that 2.8σ evidence should be possible. We expect that these significances could be improved by including additional angular correlations between the diphoton and dijet systems, perhaps in a neural-net based approach, and we encourage the experimental collaborations to expand upon the analysis presented here.

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