Unburied Higgs boson: Jet substructure techniques for searching for Higgs' decay into gluons

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Unburied Higgs

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Many models of physics beyond the Standard Model yield exotic Higgs decays. Some of these, particularly those in which the Higgs decays to light quarks or gluons, can be very difficult to discover experimentally. Here we introduce a new set of jet substructure techniques designed to search for such a Higgs when its dominant decay is into gluons via light, uncolored resonances. We study this scenario in both $V + h$ and $t\bar{t} + h$ production channels, and find both channels lead to discovery at the LHC with $\gtrsim 5\sigma$ at $\mathcal{L} \sim 100$ fb^{-1}.

I. INTRODUCTION

Discovering the Higgs boson is one of the main physics goals of the LHC program. While collider search strategies have been well developed for the Standard Model (SM) Higgs, the presence of new light degrees of freedom can dramatically alter Higgs phenomenology. For instance, in a class of models with an extended Higgs sector, the Higgs can decay via the cascade $h \to 2a \to 4X$, where a is an on-shell pseudoscalar and X is a SM state to which the pseudoscalar decays. When this decay dominates, the branching fractions into the standard discovery channels such as $h \to \gamma\gamma, \tau\tau, b\bar{b}$ are very suppressed, and new LHC strategies have to be developed to discover the Higgs. Previous studies have considered the pseudoscalar decaying into $2b$, 2τ, 2μ, and 2γ [1]. A more challenging case is when the pseudoscalar decays into light hadronic final states, as is predicted in the "buried Higgs" model [2] where the dominant decay is $h \to 2a \to 4$ gluons. A further motivation to consider this particular decay is that it is less constrained by existing LEP analyses and may allow a the Higgs mass well below 115 GeV [3].

Here we will introduce powerful new jet substructure techniques which enable the LHC to discover a Higgs whose dominant decay is to QCD-like jets via a light uncolored resonance. Specifically, we will consider the decay $h \to 2a \to 4g$ where $m_h \sim 80$ GeV–120 GeV and a is a pseudoscalar with $m_a \lesssim 10$ GeV. At first sight discovering this Higgs using its dominant decay mode seems hopeless because the dominant Higgs production channels are swamped by overwhelming QCD backgrounds. To make progress, we follow the strategy pioneered by Ref. [4] and consider the Higgs in a *boosted* regime. By going to this extreme kinematical limit we are able to substantially reduce the background to our signal. However, the backgrounds are still considerable, and whereas Ref. [4] made use of b-tagging to push the boosted Higgs into the discovery region, here the situation is more challenging.

Fortunately, these exotic Higgs decays have three features which can distinguish them from QCD backgrounds: (1) the small pseudo-scalar mass m_a furnishes an additional light scale, (2) the Higgs decay is symmetric, as both a's have equal mass, and (3) both the Higgs and the a's are uncolored. We will find that the key to success lies in employing jet substructure tools sensitive to these characteristics. We will use these tools to devise a set of cuts that allows us to obtain more than $\sim 5\sigma$ signal significance at the LHC with $\sqrt{s} = 14$ TeV and $\mathcal{L} \sim 100$ fb^{-1}.

This paper is organized as follows. Sec. II discusses a model illustrating the type of exotic Higgs decay we wish to investigate. In Sec. III, we will introduce jet substructure tools designed to find this Higgs, which we will then employ in Sec. IV to study the Higgs in the $V + h$ and $t\bar{t} + h$ production channels. Sec. V contains our conclusions.

II. ILLUSTRATIVE MODEL

Higgs decays into light jets occur in well-motivated theoretical frameworks. In the presence of a light pseudoscalar particle a with cubic couplings to the Higgs, the Higgs can undergo the cascade decay $h \to 2a \to 4$ partons. This cascade was shown to be the generic decay mode in a class of models where the Higgs is a supersymmetric Goldstone boson [2], and is also possible in extensions of the MSSM with an additional singlet superfield [5].

In the model of [2] the Higgs boson h has an effective derivative interaction with the pseudoscalar a,

$$\mathcal{L}_{ha^2} \sim \frac{v}{f^2} h(\partial_\mu a)^2 \tag{1}$$

where v is the electroweak scale and f is the global symmetry breaking scale. As long as f is not much larger than the electroweak scale the decay $h \to 2a$ dominates over the standard $h \to b\bar{b}$ mode. The pseudoscalar is not stable because it has Yukawa couplings to the SM fermions, $i\tilde{y}_\psi a\bar{\psi}\gamma_5\psi$. The largest Yukawa coupling is to the 3rd generation quarks, while couplings to leptons and lighter quark generations are suppressed. Thus, for $m_a > 2m_b \sim 10$ GeV the pseudoscalar decays almost exclusively into bottom quarks, resulting in the $h \to 4b$ cascade. For $m_a < 2m_b$ the structure of the pseudoscalar Yukawa couplings means that the decay into two gluons via a loop of 3rd generation quarks dominates over tree level decays to (e.g.) 2τ or $2c$. The net result is a $h \to 4g$ cascade decay occurring with a $0.8 \sim 0.9$ branching fraction. For this decay mode, the Higgs mass is only limited by OPAL's model-independent bound, $m_h < 86$ GeV assuming the Higgs is produced with the SM cross section [3]. For simplicity and clarity of presentation, in this paper we assume a 100% Higgs branching fraction into four gluons.

The production of buried Higgses at the LHC proceeds through similar vertices as in the SM. We shall assume here that the Higgs couples to the electroweak bosons and the top quarks with the same strength as in the SM, although in some models realizing the buried Higgs scenario these couplings may again be slightly modified.

III. JET SUBSTRUCTURE TOOLS

A buried Higgs is difficult to discover because its decay products are difficult to distinguish from ordinary QCD radiation. In the case at hand, because $m_a \ll m_h$, the gluons from each a are very collimated, and so an *unboosted* buried Higgs will be resolved as two jets. This will be very difficult to distinguish from the enormous backgrounds from QCD radiation. The extreme kinematic configuration where the Higgs has a large p_T, and is thus resolved entirely in one jet, is far more difficult for background processes to mimic. In this regime, the two jets from Higgs decay are themselves collimated into a single fat jet with a characteristic substructure. We will consider two such boosted scenarios, $pp \to hW$ (adopting the basic kinematic cuts of Ref. [4]) and $pp \to ht\bar{t}$ with a mildly boosted Higgs.

The first step of our analyses is to cluster our events into relatively large jets and identify a candidate boosted Higgs jet. We then, along the lines of Ref. [4, 6], use a cleaning procedure to remove contamination from pileup and underlying event from the jet and place a cut on its mass. To make further progress we must look to the distinguishing features of the exotic decays.

One characteristic feature of the signal is that the jets from decays of light pseudoscalars a have small invariant masses, of order $m_a \lesssim 10$ GeV. This is clearly independent of the a's p_T, while the invariant mass of a QCD jet grows with p_T: $\sqrt{\langle m_J^2 \rangle} \sim \frac{\bar{C}\alpha_s}{\pi} p_T R$, where $\bar{C} = 3(4/3)$ for gluon (quark) initiated jets [7]. Because we work in the boosted regime where the a's have a large p_T, we expect the bulk of the QCD background subjets to have masses above 10 GeV. Thus, requiring that the average mass of the two hardest subjets be small (throughout we will denote the ith hardest subjet as j_i),

$$\overline{m} \equiv \frac{m(j_1) + m(j_2)}{2} < 10 \text{ GeV},$$

is an efficient way to separate signal from background.

The signal events are also distinguished by the symmetry of their decay products: both subjets arise from particles of equal mass. This can be distinguished by a cut on *mass democracy*:

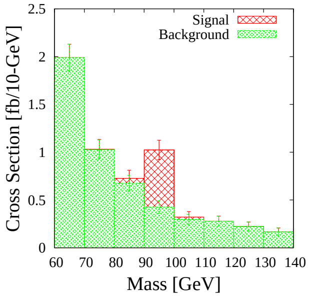
$$\alpha = \min\left[\frac{m(j_1)}{m(j_2)}, \frac{m(j_2)}{m(j_1)}\right] \tag{2}$$

At the parton level $\alpha = 1$ at leading order, while for the background there is no reason for the QCD radiation to produce democratic jets.

Finally, signal and background events differ by their color structure [8]. For signal events color is only seen very late in the Higgs decay process: neither the Higgs nor the a's carry color charge. QCD processes therefore only becomes operative only at the scale ~ 10 GeV after the pseudoscalars decay into gluons. By contrast, the background jets are initiated by hard colored particles, which are color-connected to the rest of the event; moreover, there is more phase space for QCD radiation. Therefore, we expect that the background has more radiation inside the fat jet cone than the signal does. We can quantify this intuition using the flow variable

$$\beta = \frac{p_T(j_3)}{p_T(j_1) + p_T(j_2)}, \tag{3}$$

which is motivated by the fact that the signal is unlikely to yield radiation aside from that constituting the two collimated a's. We therefore expect the typical value of β for background processes to be much larger than for the signal. Before proceeding, we note that β can be sensitive to very soft radiation, depending on the cut one uses. Therefore, we employ β with a threshold: $p_T^{\min}$ and set $\beta = 0$ for $p_T(j_3) < p_T^{\min}$. This particular measure of the color sparseness of the jet amounts to a soft subjet veto inside the catchment area of the fat jet, using a veto threshold determined jet-by-jet. Note however that this veto applies only to the fat jet, and events will typically contain additional radiation beyond that contained in the Higgs candidate fat jet. Other flow variables could be defined to further boost discovery of the buried Higgs. In particular, since signal radiates less, a simple cut on the number of subjets above $p_T^{\min} \sim 1$ GeV falling inside the fat jet cone adds more discriminating power. However we have not included this cut here because QCD predictions for the number of soft jets are not entirely reliable at the present stage. Measuring the number of tracks emanating from the leading subjets could also efficiently separate signal from background [9].



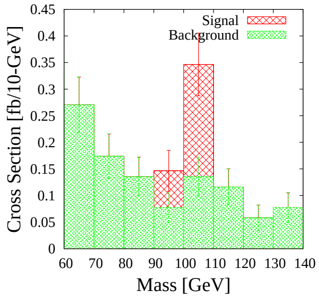


FIG. 1: Reconstructed $m_H = 100$ GeV Higgs mass (left) in the $V+h$ channel, after the cuts of Table I (excluding the cut on m_H); (right) in the $t\bar{t}+h$ channel, after the cuts of Table II (excluding the cut on m_H). The soft radiation threshold for β is taken to be $p_T^{min} = 1$ GeV. Error bars show statistical errors.

TABLE I: Cut efficiencies for a $m_h = 100$ GeV Higgs in the $pp \to hW$ channel using the procedure outlined in Sec. IV A. Significances are shown for $\mathcal{L} = 100\,\text{fb}^{-1}$. At the end of the table we include results obtained using two different values of $p_T^{\min}$ for β. Results shown outside (inside) parentheses are obtained with Pythia (Herwig).

	σ_{sig} (fb)	σ_{bg} (fb)	S/B	$S/\sqrt{B}$
$p_T(j) > 200$ GeV	16	30000	0.00052	0.9
	(16)	(38000)	(0.00050)	(0.9)
subjet mass	12	19000	0.00062	0.9
	(9.0)	(26000)	(0.00035)	(0.6)
Higgs window	7.1	400	0.018	3.6
	(6.0)	(780)	(0.008)	(2.1)
$\alpha > 0.7$	4.1	140	0.030	3.5
	(4.0)	(260)	(0.015)	(2.5)
$\beta < 0.005$,	0.7	0.7	0.90	7.8
$p_T^{\min} = 1$ GeV	(0.4)	(0.4)	(1.0)	(6.3)
$\beta < 0.005$,	2.9	26	0.1	5.7
$p_T^{\min} = 5$ GeV	(2.8)	(24)	(0.1)	(5.7)

IV. ANALYSIS

Here we apply the substructure tools developed above to two processes yielding a boosted Higgs: $pp \to hW$ and $pp \to ht\bar{t}$. Before proceeding with the analysis we describe our Monte Carlo tools and assumptions.

We generate all signal and background events for $ht\bar{t}$ at tree level using `MadGraph v4` [10] and shower them using `Pythia 6.4.21` [11]. We incorporate underlying event and pile-up using Pythia's "DW" tune and assuming a luminosity per bunch crossing of 0.05 mb^{-1}. We generated signal samples for $m_h = 80, 100, 120$ GeV and $m_a = 8$ GeV. Our $t\bar{t}+$ jets sample is matched out to two jets using the k_T-MLM matching procedure [12] (our $V+$ jets sample requires no matching as it is dominated by $2 \to 2$ processes). We have checked that using the shower-k_T matching scheme only improves the discoverability of the buried Higgs signal. Jet clustering is performed using the anti-k_T algorithm [13] as implemented in `Fastjet 2.3` [14]. When constructing subjets our procedure is to re-cluster the constituents of a jet using anti-k_T with a smaller radius, denoted R_{sub}. Additionally, as a crosscheck, we look at $W+h$ using `HERWIG++` [15].

A. Discovering a buried Higgs in the $V+h$ channel

Here we consider a boosted Higgs recoiling against a vector boson as in Ref. [4]. As the production rate for $pp \to hW$ is larger than $pp \to hZ$, and the branching ratio of W into leptons is much larger than that of Z into leptons, we will restrict ourselves to the process $pp \to hW$ where $W \to l\nu$ for $l = e, \mu$. At the preselection level we require a single isolated lepton with $p_{T,l} > 30$ GeV and missing energy $\not{E}_T > 30$ GeV.

Our events are clustered using jet radii R of 0.8, 1.0, and 1.2 for m_h of 80, 100, and 120 GeV, respectively. The jet radii are determined by a trade-off between having a cone large enough to collect all of the Higgs decay products on the one hand, and having as small a jet area as possible to reduce sensitivity to underlying event and other unassociated soft radiation on the other. This will be particularly important when we come to the soft radiation cut below. To force ourselves into the boosted region we will consider events with a jet of $p_T > 200$ GeV. The typical opening angles for the Higgs decay products are then $\Delta R \sim 2m_h/p_T = 0.8$, 1.0, and 1.2, explaining our choice of cone sizes. The dominant background then is $pp \to W + j$. As one can see in Table I, the initial backgrounds are horrendous. Studying the jet substructure on a smaller angular scale $R_{\text{sub}} = 0.3$ (slightly larger than the typical opening angle for the $a \to gg$ decay, to accommodate a broader range of p_T for the daughter as) begins to improve the situation. Demanding that the average mass of the hardest two $R_{\text{sub}} = 0.3$ subjets lie below 10 GeV and requiring the trimmed [16] mass of the jet (using the trimming parameter $f_{\text{cut}} = 0.03$) lie within $m_h \pm 10$ GeV helps, but it is not sufficient for a Higgs discovery.

However, after cutting on the jet substructure variables $\alpha > 0.7$ and $\beta < 0.005, 0.005,$ and 0.007 for m_h of 80, 100, and 120 GeV, respectively, one finds a prominent signal, discoverable regardless of whether one uses $p_T^{\min} = 1$ GeV or a more conservative 5 GeV. The (trimmed) fat jet mass distribution after these cuts is shown in Fig. 1. The final signal significances for the three Higgs masses we consider are shown in Table III.

Finally, as a cross check of the Monte Carlo dependence of our results, we study the case $m_h = 100$ GeV using `HERWIG++` to model showering and hadronization (the same Pythia-generated pileup event sample is used). The signal and background rates obtained using Herwig are shown in parentheses in Table I. The two generators show reasonable agreement on signal efficiencies at a $\sim 20\%$ level. The absolute background rates predicted by Herwig and Pythia agree less well, due in part to the different handling of spin correlations in the W production and decay. The predicted background rates agree to within 50%, roughly comparable to NLO corrections to the cross-section, and in all cases a Higgs mass peak can be clearly observed in 100 fb^{-1}. We conclude that our analysis is a good indicator of the discoverability of the buried Higgs signal.

B. Discovering a buried Higgs in the $t\bar{t}+h$ channel

Here the signal process of interest is the associated production of a Higgs with a $t\bar{t}$ pair, followed by leptonic decays of both top quarks and Higgs decaying as $h \to aa \to 4g$. The final state consists of 2 b-tagged jets, 2 opposite-sign leptons, and (at least) 2 hard jets. The main background is $t\bar{t}+$ jets, with secondary contributions from $Z+b\bar{b}$ and $t\bar{t}Z$. Background processes with jets faking a lepton or a b-jet are subleading. For the signal we use the SM NLO $t\bar{t}H$ cross-section [17]; in particular $\sigma_{tth} \approx 1$ pb for $m_h = 100$ GeV. We use the NLO + NLL calculation of the inclusive $t\bar{t}$ cross-section to normalize the $t\bar{t}+$ jets background [18, 19], $\sigma_{tt} = 908$ pb. The NLO cross-section for $t\bar{t}Z$ is much smaller, $\sigma_{ttZ} = 1.1$ pb [20].

Since the buried Higgs does not produce b-quarks in its decay, the combinatoric problems that contribute to the difficulty of using the $t\bar{t}h$ channel in the SM are significantly ameliorated. In the dileptonic channel, there is in principle no combinatoric background: the decay products of the top quarks can be cleanly separated from the decay products of the Higgs, much as in the $W+h$ channel. We first cluster particles using the anti-k_T algorithm with $R_{sub} = 0.4$. To select for events containing 2 top quarks decaying leptonically we require two opposite-sign isolated leptons and two b-jets satisfying $p_{T,e} > 15$ GeV, $p_{T,\mu} > 10$ GeV, $p_{T,b} > 20$ GeV, $|\eta_{l,b}| < 2.5$. We assume a flat b-tagging efficiency of 0.6. To control the $Z+b\bar{b}$ background we require that same-flavor leptons do not reconstruct a Z, $|m_{\ell\ell} - m_Z| > 10$ GeV. After these cuts the cross-section for $Z+b\bar{b}$ is approximately 10% of the cross-section for dileptonic $t\bar{t}+$ jets. The importance of $Z+b\bar{b}$ drops further relative to $t\bar{t}+$ jets when kinematic cuts are applied, and subsequently we neglect this contribution to the background.

Next, we impose further selection criteria on the remaining untagged jets. We take jets with $p_T > 10$ GeV and further cluster them using the anti-k_T algorithm into fat jets with $R = 1.5$. This large jet radius is necessitated by the relatively moderate p_T cut placed on the Higgs candidates: we are not deep in the boosted regime. We then trim the fat jets by removing the contribution of $R_{sub} = 0.4$ subjets with $p_T < 0.15\, p_{T,fat}$ from the fat jets. This choice of subjet radius reflects the characteristic p_T's of the a's in the $ht\bar{t}$ final state, and in particular will capture a's which pass the subjet p_T cut implemented below. We select events containing at least one fat jet with $p_T > 125$ GeV.

The hardest fat jet is our Higgs candidate, and we apply to it similar kinematic and substructure cuts as in the $W+h$ channel. We demand that the candidate jet contains at least 2 $R_{sub} = 0.4$ subjets with $p_T > 40$ GeV with the average mass of the hardest two subjets below 10 GeV. Once again, at this stage bump-hunting for a fat jet in the $m_h \pm 10$ GeV mass window is not enough for a discovery, and we need to cut on the jet substructure. Requiring $\alpha > 0.7$ and $\beta < 0.03$ for $p_{T,min} = 1$ GeV brings us well above the discovery level for $m_h \lesssim 100$. The cut flow for $m_h = 100$ GeV is shown in table II, and the invariant mass distribution of the fat jet mass after all cuts is shown in fig.1. For $m_h = 120$ GeV we need slightly harder kinematic cuts, $p_T(j) > 155$ GeV, $p_T(j_2) > 50$ GeV, $\beta < 0.06$ to lift the significance above the discovery level. The final significance for all Higgs masses is given in table III.

	σ_{sig} (fb)	σ_{bg} (fb)	S/B	$S/\sqrt{B}$
preselection	8.1	6700	0.001	1.0
$p_T(j) > 125$ GeV	3.1	750	0.004	1.1
$p_T(j_2) > 40$ GeV, $\overline{m} < 10$ GeV	0.58	22	0.03	1.2
$m(j) = m_h \pm 10$ GeV	0.45	3.9	0.1	2.3
$\alpha > 0.7$	0.40	2.0	0.2	2.9
$\beta < 0.03$, $p_T^{min} = 1$ GeV	0.28	0.21	1.3	6.1
$\beta < 0.03$, $p_T^{min} = 5$ GeV	0.29	0.25	1.1	5.7

TABLE II: Cut efficiencies for a $m_h = 100$ GeV Higgs in the $t\bar{t}h$ channel using the procedure outlined in Sec. IV B. Significances are shown for $\mathcal{L} = 100\,\text{fb}^{-1}$.

TABLE III: Final signal significance ($S/\sqrt{B}$) and signal-to-background at $\mathcal{L} = 100$ fb^{-1} for three different Higgs masses in the $pp \to hW$ and $pp \to ht\bar{t}$ channels. The numbers in parenthesis are the significance using $p_T^{\min} = 5$ GeV for the β cut, while those outside the parenthesis are for $p_T^{\min} = 1$ GeV.

		$m_h = 80$ GeV	$m_h = 100$ GeV	$m_h = 120$ GeV
$pp \to hW$	$S/\sqrt{B}$	6.6 (4.8)	7.8 (5.7)	7.0 (6.9)
	S/B	0.34 (0.067)	0.90 (0.11)	0.80 (0.24)
$pp \to ht\bar{t}$	$S/\sqrt{B}$	6.1 (5.9)	6.1 (5.7)	7.1 (7.1)
	S/B	1.1 (0.97)	1.3 (1.1)	2.5 (2.5)

V. CONCLUSIONS

Here we have introduced a set of jet substructure techniques designed to discover a Higgs undergoing challenging exotic decays. Remarkably, we found that these tools are sufficient to discover a Higgs whose dominant decay is to four gluons in both $W+h$ and $t\bar{t}+h$ channels after $\mathcal{L} \sim 100$ fb^{-1}. While the systematic errors in both the background cross sections and the color flow cuts will need to be carefully studied, the comfortable values of S/B which we are able to obtain should ensure that discovery is possible. One further lesson is that the $t\bar{t}+h$ channel can be relatively more useful for a non-standard

Higgs than it is in the SM. We believe that similar techniques can be applied to boost the LHC discovery potential for a wider class of models where a light Higgs boson undergoes complex decays, e.g. $h \to 4b$ or $h \to 4\tau$.

These techniques demonstrate the potential for the LHC to probe qualitatively new scenarios of physics beyond the SM as new jet substructure tools are developed. One important point of our analysis is that a lot of discriminating power is contained in soft (a few GeV) QCD radiation. Further progress in detector sensitivity to soft radiation, as well as a better theoretical control over QCD predictions at the low invariant mass region of the spectrum could lead to further improvement in the discovery potential of non-standard Higgs bosons, or indeed to other non-standard new physics.

Note added: When this work was finished Ref. [21] appeared in which the same Higgs decay is studied with similar conclusions for the LHC discovery potential.

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