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# Partially (in)visible Higgs decays at the LHC

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ABSTRACT

Both ATLAS and CMS have reported a discovery of a Standard Model-like Higgs boson $H$ of mass around 125 GeV. Consistency with the Standard Model implies the non-observation of non-SM-like decay modes of the newly discovered particle. Sensitivity to such decay modes, especially when they involve partially invisible final states is currently beyond scrutiny of the LHC. We systematically study such decay channels in the form of $H \to AA \to \text{jets} + \text{missing energy}$, with $A$ a light scalar or pseudo-scalar, and analyze to what extent these exotic branching fractions can be constrained by direct measurements at the LHC. While the analysis is challenging, constraints as good as $\text{BR} \lesssim 10\%$ can be obtained.



## 1. Introduction

Recent results obtained at the Large Hadron Collider by the ATLAS and CMS experiments [1,2] have revealed the existence of a light Higgs candidate [3] with a mass of $\sim 125$ GeV. The observation of this new particle combines evidence in the $H \to \gamma\gamma$, $H \to ZZ$ and $H \to W^+W^-$ channels. Given the yet small collected luminosity, the properties of this newly discovered resonance are still subject to large statistical uncertainties [4]. Analyses targeting *e.g.* spin and $\mathcal{CP}$ [5,6] of the new particle and a more precise extraction of its couplings to known matter will be addressed with a larger data sample.

The current observations leave open a plurality of phenomenological possibilities of Higgs sector-modifications [7,8]. Especially the extraction of the resonance's couplings is influenced by non-standard decays [9–13] since it is based on a fit to combinations of various production $p$ and decay modes $d$. These are functions of the partial and total decay widths and *all* couplings $\{g_i\}$:

$$\sigma_p \times \text{BR}_d \sim \frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}} \sim g_p^2 g_d^2 \Big/ \left( \sum_{\text{modes}} g_i^2 \right). \quad (1)$$

The total width $\Gamma_{\text{tot}}$ in current fits is typically approximated by including a freely flowing invisible partial width [14] to the list of decay modes or by imposing the constraint $\Gamma_{\text{invis}} \sim g_{\text{invis}}^2 = 0$.

Extracting such an invisible[1] or partially visible branching ratio is an experimentally ambitious task. The decay of the Higgs via a light scalar or pseudo-scalar $A$ can be buried in a large hadronic background, experimental systematics can limit the sensitivity to such decays, and non-SM phenomenology can easily be missed. The signature $H \to AA$ occurs in many extensions of the SM, *e.g.*, the next-to-minimal supersymmetric Standard Model [15], Higgs-portal models [16], and whenever an approximate symmetry of the Higgs potential is explicitly broken by a small term in the potential, giving a light pseudo-Nambu–Goldstone boson (see [17] for a clear discussion). However the signature can be missed by standard searches, depending on how $A$ itself decays, and new dedicated strategies need to be devised. Obviously, an observation of such a novel decay channel $H \to AA$ would directly imply physics beyond the Standard Model.

Subjet methods (pioneered in Ref. [18]) have proven particularly successful in getting a handle on such a modified phenomenology. In particular, subjet analyses applied to the decay chains $H \to 2A \to 4X$ have unravelled potential sensitivity to these non-standard decays if the (pseudo)scalar $A$ is light $\mathcal{O}(10\text{–}20\ \text{GeV})$. A decay of the Higgs to $AA$ is well motivated on general grounds; one can keep a reasonably open mind with regards to how the $AA$ subsequently decay. $H \to AA \to 4g$ is considered in [19], $H \to AA \to 4\tau$ in [20], $H \to 2A \to 2\tau 2\mu$ in [17] and $H \to 2A \to 4c$ in [21]. Higgs decays into resonances with masses close to hadronic bound states have been studied in Refs. [10,22]. Sensitivity to the signatures discussed in Refs. [10,17, 19–22] follows from fundamentally distinct QCD and electroweak

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[1] Note that from Eq. (1) "invisible" also means fully visible in a non-standard search channel.

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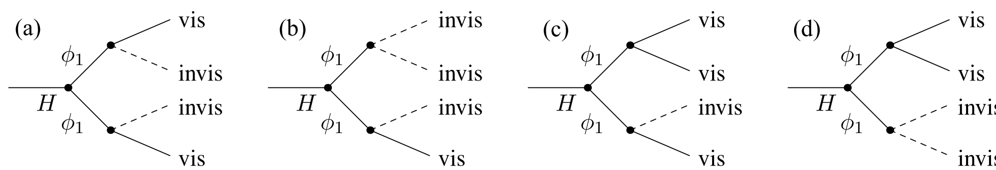


**Fig. 1.** Higgs decay topologies in the simplified models that we study for the purpose of this Letter. "vis" is a placeholder for $u\bar{u}$, $d\bar{d}$ flavor quark pairs that give rise to visible hadronic energy.

properties, highlighting the diverse power that jet substructure-based approaches offer.

There is one major difference in the analysis of purely hadronic final states compared to electroweak final states. Quite often the latter involve a significant amount of missing energy, which is aligned with the direction of the fat jet that is input to grooming and/or tagging algorithms [23]. Normally such an event topology is avoided to minimize systematic uncertainties. In, *e.g.*, searches for supersymmetry in the jets + missing energy channel [24] one requires a missing energy vector $\not{E}_T$ well isolated from a number of hard jets, to reduce systematics. Decays $H \to AA$ with $m_H/m_A \gg 2$, on the other hand, naturally involve non-isolation of $\not{E}_T$, which might even be not too large depending on the decay of $A$. In the phase space region where we can separate signal from background a SUSY-inspired search strategy based on a strong $\not{E}_T$ isolation becomes impossible.

Strategies to deal with non-SM Higgs decays involving both missing and hadronic energy [25] are, hence, limited. A direct generalization of the standard invisible Higgs decay search in the weak boson fusion channel [11] is not possible. Such an analysis relies on a central jet veto to obtain a sufficiently large signal-over-background ratio $S/B$ to study the jets' azimuthal angle correlation. Applying a central jet veto to central decay $H \to \not{E}_T + \text{hadrons}$ removes the signal that we would like to investigate.

Adapted Higgs + monojet searches [9,13] are challenged by overwhelmingly large dijet and weak boson + jet backgrounds and trigger issues, as soon as missing energy from invisible Higgs decays decreases when turning to a partially visible decay. The latter can at least be partially cured by focussing on the Higgs' $p_T$-distribution's tail. This, however, comes at the price of larger theoretical and experimental uncertainties, which imperatively need to be included to reach a realistic formulation of the branching ratio constraints.

This leaves Higgs-strahlung $pp \to HZ$ as the best-motivated channel to study the situation we have in mind at the LHC. Trigger issues are avoided by reconstructing the leptonic $Z \to e^+e^-$, $\mu^+\mu^-$ decay and no further adjustments to the trigger settings or thresholds are necessary to perform the measurement. Furthermore, the jet energy scale calibration is performed with $Z + \text{jet}$ events, whose distribution is both theoretically and experimentally under good control [26,27]. Data-driven methods can be straightforwardly applied in "ABCD" approaches, when *e.g.* comparing boosted to the un-boosted $Z$ boson kinematics.

## 2. Decay topologies

We employ a simplified-model based approach [28] to investigate the LHC search potential to the $H \to \not{E}_T + \text{hadrons}$ signature. More precisely we study the Higgs decay realizations depicted in Fig. 1. These scenarios (a)–(d) are characterized by different kinematics and different relative contributions of missing and hadronic energy in the final state.

We limit our analysis to the light flavor final states $u, d$; particles with $\sim 10$ GeV masses and a significant coupling to $b$ quarks are not only constrained by upsilon measurements [29], but also give rise to plethora of dedicated phenomenological handles on the final state [22,30,31] that we do not wish to exploit to be as general as possible. Similar arguments hold for the $H \to 4\tau$ decay, which gives rise to sparse but focused hadronic energy deposits [20]. Both these cases (and also $H \to 4g$) are fundamentally different from the topologies of Fig. 1 where "visible" refers to light flavor quarks. The quarks undergo normal showering and hadronization leaving neither the possibility for flavor tags nor for detecting pronged decays from counting charged tracks, as done in the $b$- and $\tau$-flavored decays of $H \to AA$, respectively.

## 3. Elements of the analysis

We implement the decay topologies using FeynRules [32] and use its interface to Sherpa [33,34] to generate events for the mass choices $m_H = 125$ GeV, $m_A = 20$ GeV, $m_{\text{invis}} = 10$ GeV. This choice is not special and the details of eventually extracting the branching ratio are not sensitive to the particular value $m_A$ unless $m_H \ggg m_A$. We will comment on the possibility to extract $m_A$ in Section 4.

We generate background events using Sherpa and include $WW + \text{jet}$, $WZ + \text{jet}$, $ZZ + \text{jet}$, and $t\bar{t} + \text{jets}$ as the main backgrounds to our $pp \to (Z \to \ell^+\ell^-) + \text{jet} + \not{E}_T$ analysis. We normalize our signal and background event samples to the corresponding higher order-corrected cross sections [35–37]. Studying the impact of a mismeasurement of $Z + \text{jets}$ events requires the simulation of a realistic detector environment, and should be addressed by the experiments. However, we may assume on the basis of Refs. [26, 27] that this background can be brought under sufficient control and can be subtracted from the eventual distribution also when the missing energy vector is collinear to the jet. We include a flat shape uncertainty of the background distribution to partly account for the jet energy scale uncertainty in the computation of the expected BR limits in Section 4.

Associated Higgs production with SM-like Higgs decays to $b\bar{b}$ and $\tau\tau$ also comprise backgrounds to our $(Z \to \ell^+\ell^-) + \not{E}_T + \text{jet}$ analysis and we include them consistently throughout.

We reconstruct the events' visible final states using a hybrid ECAL + HCAL implementation which granularizes the final state particles on grids with $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ $(0.1 \times 0.1)$ ECAL (HCAL) as massless cell entries and feed the reconstructed objects to a smearing routine which mimics detector effects as described later on. Doing so, we reconstruct the full three-momenta from the detector geometry with an invariant mass $p^2 = 0$ for each ECAL + HCAL cell, which contains a single or multiple hits.

In the analysis, we first reconstruct isolated stable leptons, by requiring the hadronic energy deposit in the vicinity of the lepton candidate ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \leqslant 0.1$, where $\eta$ and $\phi$ are pseudo-rapidity and azimuthal angle respectively) to be smaller than 10% of the lepton candidate's transverse momentum. We furthermore require exactly two leptons ($p_{T,\ell} > 10$ GeV, $|\eta_\ell| < 2.5$) of identical flavor and opposite charge that recombine the $Z$ mass within $m_Z \pm 10$ GeV (note that this also removes higher-pronged $H \to \tau\tau$ events) and demand $p_{T,Z} = (p_{\ell_1} + p_{\ell_2})_T > 130$ GeV. Subsequently, we cluster Cambridge/Aachen jets with $R = 1.5$ using FastJet [39] and we require at least one such fat jet with $p_T > 100$ GeV. We