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Exotic Higgs decays at the LHC

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Many interesting extensions to the Standard Model predict nonstandard decays of the 125 GeV Higgs boson. The ATLAS and CMS experiments at the LHC have searched for processes including decays of the Higgs boson to long-lived, weakly interacting particles, decays of the Higgs boson to dark photons, decays of the Higgs boson to pairs of new (pseudo)scalars, and lepton-flavor violating decays of the Higgs boson. This note will summarize the state of these analyses using data taken through the end of 2016.

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1. Introduction

Since the discovery of the Higgs boson in 2012, all measurements of its properties have agreed very well with the expectations of the Standard Model (SM). But there are still open questions for which the Higgs boson could play a major role in the answers, including questions of fine-tuning in the SM, the nature of dark matter, and the origin of the observed matter-antimatter asymmetry. Many models which address these questions predict nonstandard "exotic" decays of the observed 125 GeV Higgs boson [1]. "Exotic" here is not the same as "rare;" in fact, detailed analyses of the couplings of the Higgs boson using Run 1 data imply that the branching fraction of the SM Higgs boson to non-SM particles can be as much as 0.34 (95% CL) [2], so there is still plenty of room for beyond-SM physics in the decays of the Higgs boson.

This note summarizes four classes of searches: invisible decays of the Higgs boson; Higgs boson decays to a dark-sector photon; decays of the Higgs boson to (pseudo)scalars; and lepton-flavor-violating decays of the Higgs boson. These analyses use approximately 36 fb^{-1} of $\sqrt{s} =$ 13 TeV Run 2 data collected through 2016 by the ATLAS and CMS experiments [3, 4] at the LHC.

2. Invisible decays of the Higgs boson

Many extensions to the SM predict decays of the SM Higgs boson into weakly-interacting massive particles (WIMPs), which can be invisible to the detector. As the $H \to 4\nu$ rate in the SM is quite small, this is a promising way to search for new physics.

The Higgs boson could be produced by vector-boson fusion (VBF); in this case, one looks for two jets widely separated in η with large m_{jj}. One can also look for a Higgs boson produced in association with either a Z boson decaying to a pair of leptons or a W/Z boson decaying to a pair of quarks; in the latter case, one can look for both final states with two resolved jets and final states in which the two jets have merged into a single large jet, consistent with W/Z boson decay. This final state will also have sensitivity to the case where a Higgs boson is produced recoiling against a jet. In all cases, one also requires a large $E_{\mathrm{T}}^{\mathrm{miss}}$, ascribed to the invisible Higgs boson decay. Both ATLAS and CMS have carried out searches in these channels [5–8]; selected distributions from these analyses are shown in Figure 1. Limits are extracted by fitting the distributions of either m_{jj} in the VBF case, or $E_{\mathrm{T}}^{\mathrm{miss}}$ otherwise; the CMS analysis with $Z \to \ell\ell$ uses a boosted decision tree (BDT) to extract the limit. The resulting limits on the branching fraction of invisible decays of the Higgs boson $\mathcal{B}_{\text{inv}}$, along with combinations over data taken through 2016, are (at 95% CL with expected limits in parentheses):

Channel	ATLAS $\mathcal{B}_{\text{inv}}$	CMS $\mathcal{B}_{\text{inv}}$
VBF ($H \to \text{inv}$)	< 0.37 (0.28) [8]	< 0.33 (0.25) [5]
$(H \to \text{inv}) + (Z \to \ell\ell)$	< 0.67 (0.39) [8]	< 0.40 (0.42) [6]
$(H \to \text{inv}) + (W/Z \to \text{had})$	< 0.83 (0.58) [8]	< 0.53 (0.40) [7]
Run 1 (25 fb^{-1}, 7+8 TeV)	< 0.25 (0.27) [8]	
Run 1 + 2015 (27.1 fb^{-1}, 7+8+13 TeV)		< 0.24 (0.23) [9]
2015 + 2016 (36.1 fb^{-1})	< 0.38 (0.21) [8]	
2016 (35.9 fb^{-1})		< 0.26 (0.20) [5]
All	< 0.26 (0.17) [8]	< 0.19 (0.15) [5]

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Figure 1 also shows the CMS results interpreted as a limit on nuclear scattering cross section as a function of the WIMP mass, given one of two specific models (comparable ATLAS results are in [8]). Compared to limits from direct-detection experiments, it is seen that the LHC results contribute significantly for small WIMP masses (between 1 and 10 GeV).

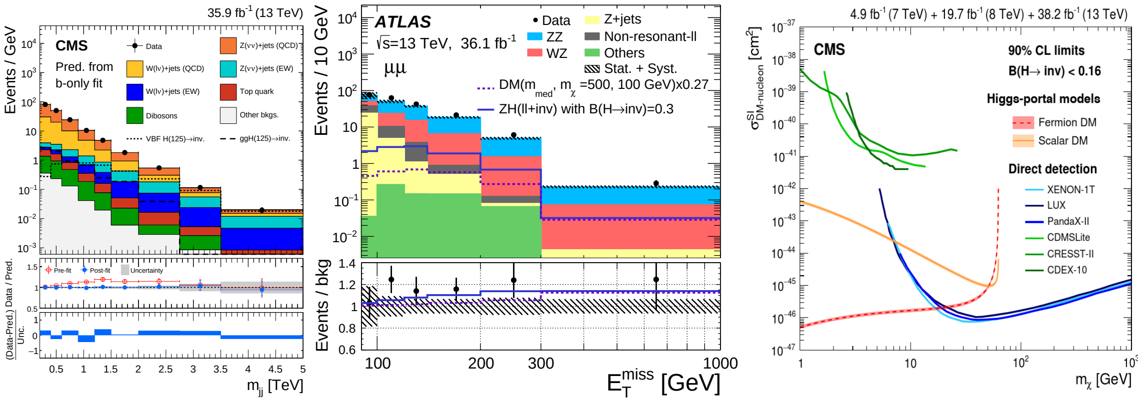

Figure 1: Selected $H \to$ inv search results. Left: m_{jj} distribution from the CMS VBF $H \to$ inv search [5]; Middle: $E_T^{\rm miss}$ distribution from the ATLAS $(H \to \text{inv})(Z \to \ell\ell)$ search in the $\mu\mu$ channel [10]; Right: CMS nuclear scattering cross section limits for specific WIMP models compared to direct-detection limits [5].

3. Higgs boson decays to dark photons

Some dark-matter-inspired extensions to the SM include a $U(1)$ dark gauge symmetry, giving rise to a gauge boson Z_d, or "dark photon" [11]. This dark photon can then mix with the SM Higgs boson with some strength κ, giving rise to a $H \to Z_d Z_d$ decay; or it could mix with the SM gauge bosons with strength ε, giving rise to $H \to ZZ_d$ decays. The Z_d should decay to lepton pairs with a significant branching fraction ($\sim 15\%$); these decays will be prompt for $\varepsilon \gtrsim 10^{-5}$.

ATLAS has searched for these processes in 4ℓ final states [12] consisting of two lepton pairs: $4e$, $2e2\mu$, and 4μ. The overall invariant mass must be consistent with the SM Higgs boson mass. For $H \to Z_d Z_d$, each lepton pair must be inconsistent with both $J/\psi/\Upsilon$ decays and with mispaired Z boson decay, and the two lepton pairs must have similar mass. For the low-mass region $1 < m_{Z_d} < 15$ GeV, only the 4μ final state is considered. Backgrounds are primarily $H \to ZZ^*$ and ZZ^*. In the high (low)-mass region, 6 (0) events are observed with an expected background of 3.9 ± 0.3 (0.4 ± 0.1). For $H \to ZZ_d$, one lepton pair must be consistent with $Z \to \ell\ell$ decay, and one looks for a peak in the invariant mass of the other pair. Here, 102 events are observed, with a background of 86.8 ± 7.5. Selected results are shown in Figure 2.

4. Higgs boson decays to scalars

Models with two Higgs doublets and an additional scalar field (2HDM+S) predict that the SM Higgs boson can decay into a new (pseudo)scalar a [1]. The $a \to bb$ decay would usually dominate, but other decays may be significant depending on the model, such as $a \to \mu\mu$, $\tau\tau$, $\gamma\gamma$, or gg.

ATLAS has searched for such decays in several final states. (The corresponding CMS analyses are covered in [13] and are not repeated here.) First $(V \to \ell\ell/\ell\nu)(H \to aa \to bbbb)$ [14], requiring

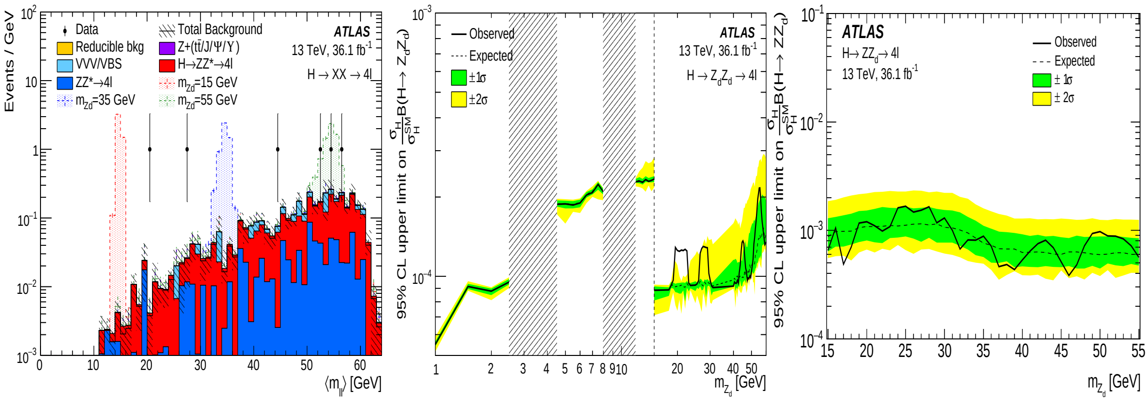

Figure 2: Selected results from the ATLAS dark photon searches [12]. Left: Average invariant mass of the two lepton pairs in the $H \to Z_d Z_d$ search for the high-mass region; Middle: 95% CL limits on $\mathcal{B}(H \to Z_d Z_d)$ as a function of Z_d. The gray strips are regions excluded from the analysis due to large backgrounds from J/ψ and Υ decays; Right: 95% CL limits on $\mathcal{B}(H \to Z Z_d)$ as a function of Z_d.

a reconstructed, leptonically-decaying W or Z boson along with at least three b-tagged jets. Jets are paired to minimize the difference in invariant masses between the pairs, and BDTs are used to discriminate signal from background. Second, $H \to aa \to bb\mu\mu$ [15], significant in some 2HDM models with enhanced lepton couplings. This requires a $\mu^+\mu^-$ pair with $16 < m_{\mu\mu} < 64$ GeV, exactly two b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV, and that the event is kinematically consistent with a decay of the 125 GeV SM Higgs boson. Third, $H \to aa \to \gamma\gamma gg$ [16], significant in models in which decays to fermions are suppressed. The production of the Higgs boson is tagged by the presence of two VBF jets, and again the event must be kinematically consistent with the decay hypothesis. Selected results from these analyses are shown in Figure 3, which also shows limits on $\mathcal{B}(H \to aa)$ from all ATLAS $H \to aa$ searches under the assumption of a specific 2HDM+S model [17], including also results from the $H \to Z_d Z_d$ analysis reinterpreted as $H \to aa$.

5. Lepton-flavor-violating Higgs boson decays

Decays of the Higgs boson into two leptons of differing flavor are forbidden in the SM, but are allowed in some extensions, including supersymmetry, composite Higgs, Randall-Sundrum models, and others (see references in [18]). The decay $H \to e\mu$ is very strongly constrained from searches for $\mu \to e\gamma$ to $\mathcal{B}(H \to e\mu) < \mathcal{O}(10^{-9})$; however, limits on $H \to e\tau$ and $H \to \mu\tau$ from searches for rare τ decays are much larger, $\mathcal{O}(10\%)$ [18].

CMS has searched for the decays $H \to e\tau$ and $H \to \mu\tau$, where the τ lepton decays either hadronically or into a lepton of opposite flavor [18]. This gives four channels: $e\tau_h$, $e\tau_\mu$, $\mu\tau_h$, and $\mu\tau_e$. Each of these is then subdivided into categories based on the jets in the event: 0 jets, 1 jet, 2-jet VBF, and other 2-jet events (ggH). The signal is discriminated using BDTs, and the limit is extracted via a joint fit to the BDT outputs. Backgrounds are primarily $Z \to \tau\tau$, $W+$jets, and QCD with jets misidentified as leptons. Sample results from this analysis are shown in Figure 4. Results, at 95% CL, are $\mathcal{B}(H \to \mu\tau) < 0.25$ (0.25)% and $\mathcal{B}(H \to e\tau) < 0.61$ (0.37)%.

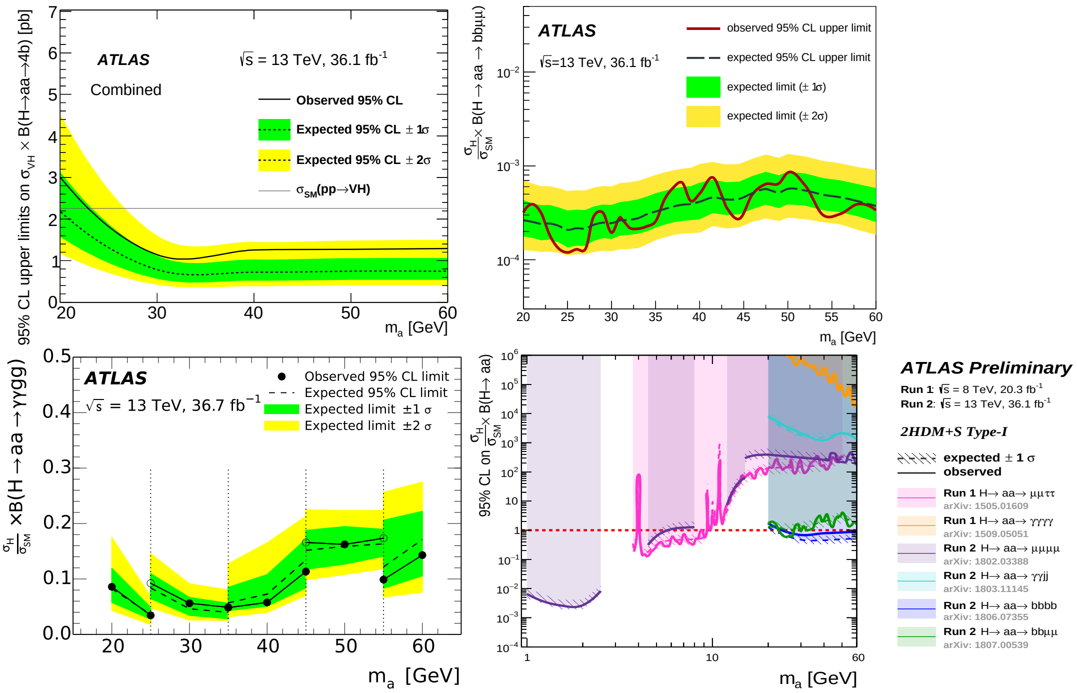

Figure 3: Selected results from the ATLAS searches for Higgs boson decays to new scalars. Top left: 95% CL limit for $\mathcal{B}(H \to aa \to bbbb)$ from VH production [14]; Top right: 95% CL limits on $\mathcal{B}(H \to aa \to bb\mu\mu)$ [15]; Bottom left: 95% CL limit for $\mathcal{B}(H \to aa \to \gamma\gamma gg)$ [16]; Bottom right: 95% CL limits on $H \to aa$ from all ATLAS searches assuming a Type-I 2HDM+S model [17].

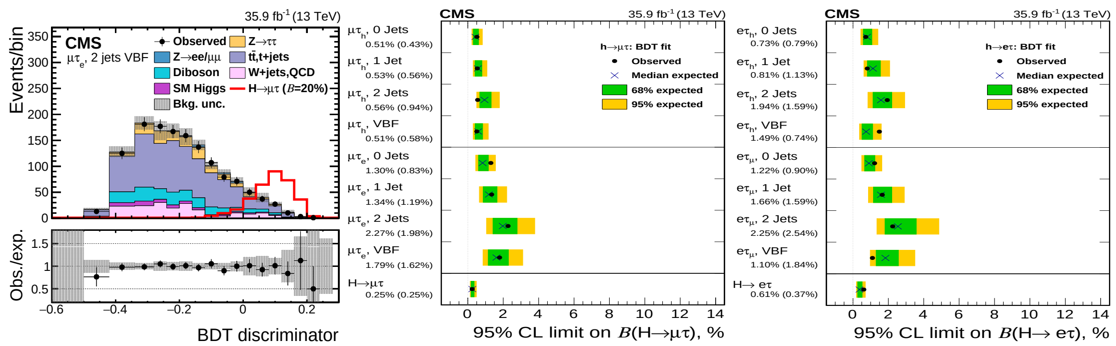

Figure 4: Selected results from the CMS search for lepton-flavor violating decays of the Higgs boson [18]. Left: BDT output for the $\mu\tau_e$ channel with 2 VBF jets; Middle: Limits on $\mathcal{B}(H \to \mu\tau)$ per channel and category; Right: Limits on $\mathcal{B}(H \to e\tau)$ per channel and category.

6. Summary

Nonstandard decays of the SM Higgs boson, predicted by many extensions to the SM, have been searched for by ATLAS and CMS at the LHC. No excesses have been found in data taken through 2016, and limits have been set on branching fractions for the exotic decays $H \to$ invisible, $H \to ZZ_d/Z_dZ_d$, $H \to aa$, and $H \to e\tau/\mu\tau$.

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