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Exotic production and decays of the 125 GeV Higgs in the CMS experiment

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The Higgs boson was discovered more than ten years ago by the LHC experiments, CMS and ATLAS. Following the discovery, the experiments have focussed on measuring the Higgs boson properties to ascertain its agreement with the predictions from the Standard Model of particle physics. Recent measurements of the Higgs couplings still allow decays of the Higgs boson to exotic particles. The searches for the exotic production and decay modes of the Higgs boson directly probe the presence of new physics, in contrast to indirect inference drawn from coupling measurements limited by large uncertainty values. This presentation discusses the recent results on these new physics scenarios, utilizing the entire Run 2 data collected by the CMS experiment.

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1. Introduction

The discovery of the Higgs boson by the Large Hadron Collider (LHC) experiments at CERN in 2012 [1–3] provided the experimental validation of the Standard Model (SM) of particle physics. With the data collected until Run 2 of the LHC, various Higgs boson couplings have only been measured with a precision of about 10% for most of the cases. While the precision of the measurements will increase with larger integrated luminosity, the current measurements of the Higgs boson couplings can still include new physics signatures. The current upper bound on the invisible decays of the Higgs boson measured by the CMS experiment is 16% [4]. More importantly, recent measurements of anomalous muon magnetic moment strongly suggest the presence of new physics [5]. These theories can most effectively be tested by direct searches of exotic production and decays of the 125 GeV Higgs boson.

2. Exotic Higgs Boson Decays

2.1 Lepton Flavor Violating Decays

Lepton Flavor Violating (LFV) Higgs boson couplings to leptons and quarks are forbidden in the SM theory. Indirect limits on these couplings have been derived from measurements of muon magnetic moment and $\mu \to e\gamma$ process. Using the full Run 2 data, direct searches of $\mathrm{H} \to \mathrm{e}\tau/\mu\tau$ and $\mathrm{H} \to \mathrm{e}\mu$ final states have been performed. The $\mathrm{H} \to \mathrm{e}\tau/\mu\tau$ final state analysis constrains the SM Higgs branching ratios, $\mathrm{Br}(\mathrm{H} \to \mu\tau)$ and $\mathrm{B}(\mathrm{H} \to \mathrm{e}\tau)$, within the values 0.15 and 0.16 respectively at 95% CL [6]. Observed upper limit on $\mathrm{B}(\mathrm{H} \to \mathrm{e}\mu)$ is determined to be 4.4×10^{-5} at 95% confidence level (CL) [7]. The upper limits as a function of the Higgs boson mass are shown in Fig. 1. An excess of events over background is observed with a 2.8σ local significance at mass near 146 GeV.

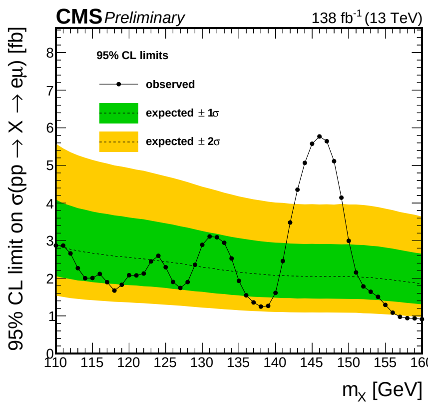

Figure 1: 95% CL upper limit on $\mathrm{B}(\mathrm{H} \to \mathrm{e}\mu)$ as a function of the Higgs boson mass, denoted here as m_X.

2.2 Decays to Pseudoscalars

Higgs decays to pseudoscalar particles (a) arise naturally in the phenomenology of two-Higgs-doublet models, extended with a singlet (2HDM+S) [8, 9], which result in a broad class of new physics signatures that can be experimentally discriminated from SM Higgs boson decays.

The $H \to aa \to 4\gamma$ final state has been examined using both boosted [11] and resolved [12] photon reconstruction techniques. Exploiting the excellent electromagnetic calorimeter performance of the CMS experiment, a single merged photon candidate can be reconstructed for very low mass pseudoscalar particles ($0.1 < m_a < 1.2$ GeV) [10]. In contrast, the resolved final state requires four well-reconstructed and isolated photons, considering a pseudoscalar mass range $15 < m_a < 62$ GeV. The 95% CL upper limits obtained on the $B(H \to aa \to 4\gamma)$ are shown in Fig. 2. Using

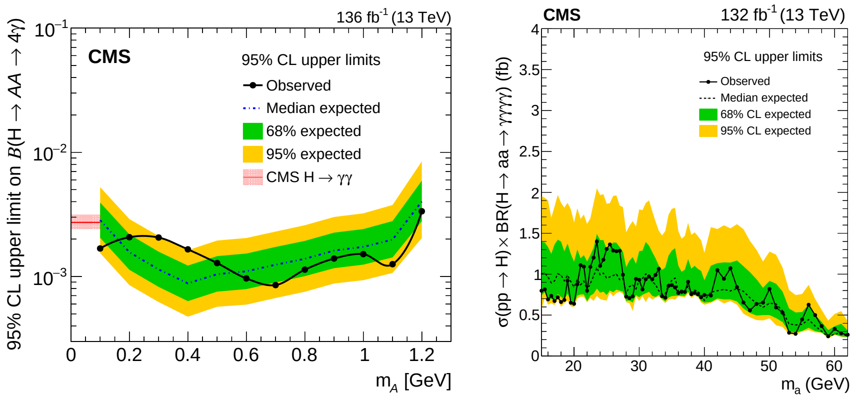

Figure 2: 95% CL upper limits on $B(H \to aa \to 4\gamma)$ as a function of the pseudoscalar mass. The left figure corresponds to the mass range $0.1 < m_a < 1.2$ GeV and the right figure corresponds to $15 < m_a < 62$ GeV.

the entire Run 2 luminosity, a search for the Higgs decays to pseudoscalar particles, which further decay to pairs of b quarks and muons or tau leptons, has been performed within the mass range $12 < m_a < 60$ GeV [13]. The results of the two final state searches, $\mu\mu$bb and $\tau\tau$bb, are used to determine upper limits on the branching fraction $B(H \to aa \to \ell\ell bb)$ with ℓ being a muon or a tau lepton. The 95% CL upper limits obtained on the $B(H \to aa \to \ell\ell bb)$ are shown in Fig. 3.

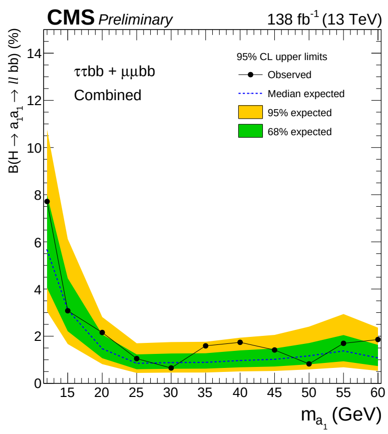

Figure 3: 95% CL upper limit on $B(H \to aa \to \ell\ell bb)$ as a function of the pseudoscalar mass.

2.3 Decays to Axion-like Particles and Invisible Decays

Axion-like Particles or ALPs are predicted in extended SM theories addressing strong CP problems. The first search of ALPs at the LHC has been performed recently using the $H \to Za$

production mode, where the pseudoscalar ALP mass varies within the range $1 < m_a < 30$ GeV [14]. Left plot of Fig. 4 shows the 95% CL upper limits obtained on the production cross section $\sigma(H \to Za \to \ell\ell\gamma\gamma)$ as a function of m_a. Several BSM theories predict enhanced Higgs to invisible decay or H $\to$ inv., for example, in scenarios where the Higgs can decay to a pair of dark matter particles. In a recent search, H $\to$ inv. process is explored in the fully hadronic final states in the $t\bar{t}H$ and VH production modes, using the full Run 2 data [15]. Combining the results with previously studied channels, the upper limit on the B(H $\to$ inv.) is determined to be 0.15 at 95% CL, which is the most stringent to date, illustrated in the right plot of Fig. 4.

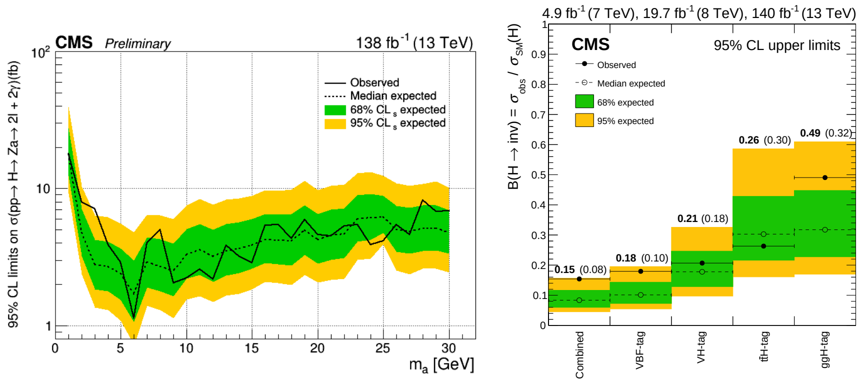

Figure 4: Left: 95% CL upper limit on $\sigma(H \to Za \to \ell\ell\gamma\gamma)$ as a function of the pseudoscalar mass. Right: 95% CL upper limit on B(H $\to$ inv.), obtained for different production modes of the Higgs boson.

3. Exotic Higgs Boson Production

Traditional searches of dark matter particles at the LHC involve weakly interacting massive particles (WIMPs) recoiling against visible SM particles. A mono-Higgs event results from the Higgs being radiated by a dark matter particle or Higgs interaction with a dark matter particle via a mediator. Thus, final states with missing transverse momentum or p_T^{miss} are investigated considering two main models: Z′-2HDM and baryonic Z′. Several Higgs boson decay modes are considered in the analysis using partial Run 2 data: $b\bar{b}$, $\tau\tau$, $\gamma\gamma$, WW and ZZ [16]. No significant deviations from the SM prediction is observed for both models considered in the analysis.

4. Conclusion

Since the start of the LHC, experiments have been exploring exotic Higgs final states. Recently, advanced algorithms involving machine learning techniques have improved the search strategies. Compared to previous analyses using partial Run 2 statistics, the updated results show significant improvement beyond what is expected from increasing the integrated luminosity alone. Stringent upper limits are placed on the explored phase spaces of mono-Higgs production, invisible and LFV decays of the Higgs boson. However, several channels in the H $\to$ aa decay have not yet been studied due to limitations in statistics and particle reconstruction techniques. The incoming data from Run 3, will extend our reach to these final states and strengthen our understanding of the nature of the Higgs boson.

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