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Search for Higgs boson rare decays at CMS

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Recent results on searches for rare decays of the Higgs boson, obtained using 35.9 fb^{-1} of proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the CMS detector, are presented. This report includes searches for the Higgs boson decaying into invisible particles, muon pairs, $J/\psi\gamma$ and $Z\gamma$ final states. No significant deviations from the standard model predictions have been observed and upper limits are placed on the corresponding decay branching fractions.

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1. Introduction

Direct searches for rare decays of the Higgs boson allow for important test of the robustness of the SM predictions. This report presents the most recent results from the CMS Collaboration [1] on searches for rare decays of the Higgs boson, based on 35.9 fb^{-1} of 13 TeV data.

2. Searches for invisible decays of the Higgs boson

In the SM, the Higgs boson decays to invisible particles only through $\mathrm{H} \to \mathrm{ZZ} \to 4\nu$ with a branching fraction ($\mathscr{B}$) of about 0.1%. Deviations from the SM expectation would represent a clear indication of BSM physics in the Higgs sector. To increase the sensitivity to invisible decays of the Higgs boson ($\mathrm{H_{inv}}$), all the dominant Higgs production modes are explored: gluon fusion (ggH) [2], VH where a boosted W or Z boson decays either leptonically [3] or hadronically [2], and vector boson fusion (VBF) [4]. The common feature of all these searches is the requirement that the invisible particles should recoil with high transverse momentum (p_{T}) against a visible system, resulting in an event with a large p_{T} imbalance ($p_{\mathrm{T}}^{\mathrm{miss}}$). In the VBF channel the recoiling system is characterized by two jets that exhibit a large pseudorapidity gap ($\Delta\eta_{\mathrm{jj}}$) and form a large invariant mass (m_{jj}). While earlier searches probing the VBF $\mathrm{H_{inv}}$ final state were based on counting experiments, the presented analysis exploits the distinctive kinematic features of the VBF topology by extracting the signal from a fit to the shape of the m_{jj} distribution. This strategy has been optimized to provide an improved sensitivity, resulting in the most sensitive VBF $\mathrm{H_{inv}}$ search reported to date. The main expected backgrounds originate from $\mathrm{Z}(\nu\nu)$+jets and $\mathrm{W}(\ell\nu)$+jets processes. The $\mathrm{Z}(\nu\nu)$+jets background is estimated from data using $\mathrm{Z}/\gamma^{*}(\ell\ell)$+jets events, while the $\mathrm{W}(\ell\nu)$+jets background is constrained using single-lepton control regions (CRs). The $p_{\mathrm{T}}^{\mathrm{miss}}$ in all the CRs is calculated by excluding the identified leptons. It corresponds to the p_{T} of the hadronic recoil system, which resembles the $p_{\mathrm{T}}^{\mathrm{miss}}$ expected for the V+jets backgrounds in the signal region (SR). Data are found to be in agreement with the estimated backgrounds. Figure 1 (left) shows the observed and expected m_{jj} distributions in the SR, where the background prediction is obtained by fitting the data under the background-only hypothesis. The observed (expected) 95% CL upper limit on $\mathscr{B}(\mathrm{H} \to \mathrm{inv})$ is measured to be 28 (21)%. The result from the VBF analysis is combined with those from the ggH and the VH channels. The combination yields to an observed (expected) 95% CL upper limit of $\mathscr{B}(\mathrm{H} \to \mathrm{inv}) < 24$ (18)% [4], as shown Fig. 1 (right).

3. Search for the Higgs boson decaying into two muons

The search for Higgs boson decays to muons is of particular importance because it represents the golden channel able to probe Higgs boson couplings to fermions of the second generation. The main challenge is represented by the small expected signal over background ratio. In fact, for $m_{\mathrm{H}} = 125$ GeV, the predicted $\mathscr{B}$ into muons is 2.17×10^{-4}, which corresponds to few hundred signal events expected in 35.9 fb^{-1} of 13 TeV data. In this final state, the signal would appear as a tiny peak, whose width is driven by the $O(\mathrm{GeV})$ muon p_{T} resolution, over a smoothly falling mass spectrum ($m_{\mu\mu}$) from SM backgrounds, primarily Z/γ^{*}, diboson and leptonic $\mathrm{t\bar{t}}$ decays. In the presented $\mathrm{H} \to \mu\mu$ search [5], to enhance the sensitivity to the Higgs boson signal, events

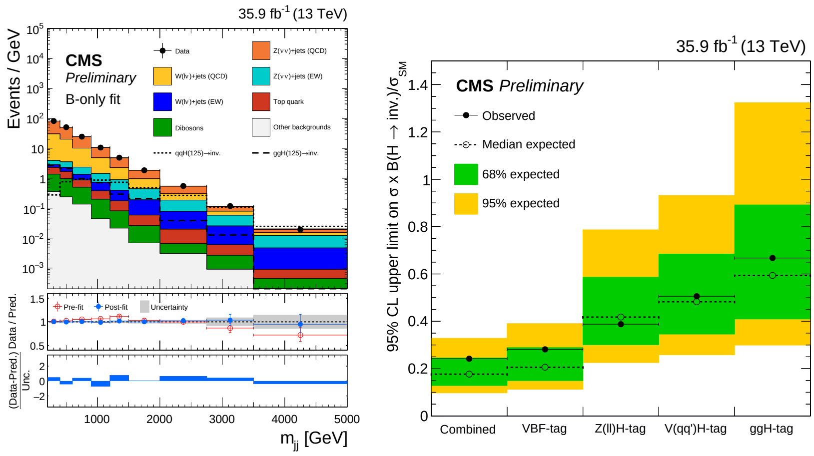

Figure 1: On the left, the observed $m_{\rm jj}$ distribution in the SR of the VBF search compared to the post-fit backgrounds from SM processes [4]. On the right, observed and expected 95% CL upper limits on $\mathscr{B}(\mathrm{H} \to \mathrm{inv})$ for both individual channels targeting VBF [4], $\mathrm{Z}(\ell\ell)\mathrm{H}$ [3], $\mathrm{V}(qq)\mathrm{H}$ [2] and ggH [2] production mode, as well as their combination assuming an SM Higgs boson with $m_{\mathrm{H}} = 125$ GeV.

are classified into categories defined by looking at event properties largely uncorrelated with $m_{\mu\mu}$ (hadronic activity, b-tagged jets, kinematic of the dimuon system). These variables are used as input to a boosted decision tree (BDT). Figure 2 (left) shows the BDT output distributions for data and simulated events. Event categories are defined exploiting the BDT score along with the η of the most forward muon, which is used to gauge the $m_{\mu\mu}$ resolution. The number of categories and their boundaries are optimized via an iterative procedure using $\mathrm{S}/\sqrt{\mathrm{B}}$ as figure of merit. In each category, the shape and the normalization of the $m_{\mu\mu}$ distribution for the total background are obtained from a parametric fit to the data using a set of empirical functions, chosen to maximize the expected sensitivity without introducing a bias in the measured signal yield. Figure 2 (right) shows the result of the S+B fits to the data combining all the event categories, weighted by their expected signal-to-background ratio. No significant excess has been observed above the background-only prediction. Upper limits at 95% CL are set on the signal strength modifier, $\mu = (\sigma\mathscr{B})_{\mathrm{obs}}/(\sigma\mathscr{B})_{\mathrm{SM}}$. Finally, this search is combined with an earlier result obtained using Run1 data. The combined observed (expected) 95% CL upper limit on μ is found to be 2.92 (2.16) times the SM value.

4. Search for rare Higgs boson decays into Z/γ and $\mathrm{J}/\psi\gamma$

While the $\mathrm{H} \to \mathrm{Z}\gamma$ search probes the same couplings involved in the $\mathrm{H} \to \gamma\gamma$ channel, the $\mathrm{H} \to \mathrm{J}/\psi\gamma$ decay can be used, along with $\mathrm{H} \to \mu\mu$, to probe the Higgs boson couplings to the second generation of fermions. In both cases, the main challenge is represented by the small expected $\mathscr{B}$ from SM predictions: $\mathscr{B}(\mathrm{H} \to \mathrm{Z}\gamma) = 1.5 \times 10^{-3}$ and $\mathscr{B}(\mathrm{H} \to \mathrm{J}/\psi\gamma) = 3 \times 10^{-6}$. The searches for $\mathrm{H} \to \mathrm{Z}\gamma$ [6] and $\mathrm{H} \to \mathrm{J}/\psi\gamma$ [7] look for rare Higgs decays in final states characterized by one prompt photon and a pair of opposite charged leptons ($\ell = \mu, \mathrm{e}$). Leptonically decaying Z boson or J/ψ candidates are required to select the events and to suppress large background contaminations from SM processes. In the $\mathrm{H} \to \mathrm{Z}\gamma$ analysis both muon and electron decays of the

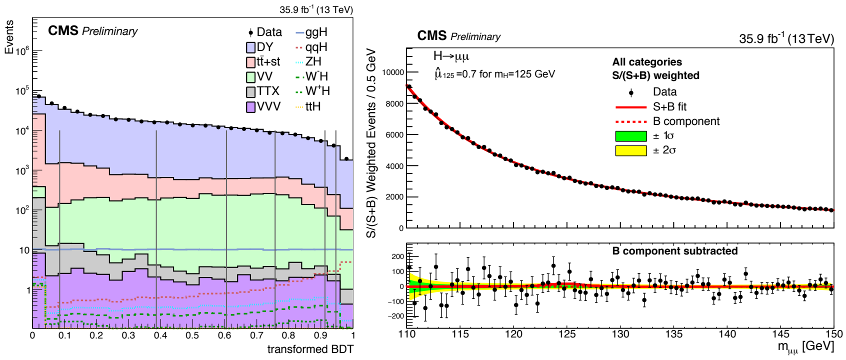

Figure 2: On the left, the BDT output distributions in data and MC simulation [5]. The vertical lines denote the BDT categories used in the analysis. On the right, data and weighted sum of S+B fits to each category. The lower panel shows the difference between the data and the background component of the total fit [5].

Z boson are explored, while in the $\mathrm{H} \to \mathrm{J}/\psi\,\gamma$ search only $\mathrm{J}/\psi \to \mu\mu$ decays are considered. The signal is extracted by fitting the $m_{\ell\ell\gamma}$ spectrum, where it is expected to appear as a narrow peak over a smoothly falling combinatorial background. In the former search, in order to increase the sensitivity, events are first classified into categories targeting to the ggH and VBF modes. Moreover, events in each production category are divided into sub-classes according to the p_{T} resolution of muons, electrons, and photons. In contrast, given the very small amount of $\mathrm{H} \to \mathrm{J}/\psi\,\gamma$ decays expected in 35.9 fb^{-1} of data, events are not classified according to either production modes or mass resolution. No significant excess above the background prediction has been found. The observed (expected) exclusion limit for the $\mathrm{H} \to \mathrm{Z}\gamma \to \ell\ell\gamma$ search is set to be 3.9 (2.0) times the SM expectation, while that obtained for the $\mathrm{H} \to \mathrm{J}/\psi\,\gamma$ branching fraction is 7.6 $(5.2^{+2.4}_{-1.6}) \times 10^{-4}$, which corresponds to 260 (170) times the SM prediction.

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