The Compact Muon Solenoid Experiment
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Beyond Standard Model Higgs Boson Physics at the CMS Experiment

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Abstract

Searches for Beyond Standard Model (BSM) Higgs bosons at the CMS experiment are presented. The analyses are based on proton-proton collision data recorded by the CMS experiment at the LHC at CERN at 7 TeV and 8 TeV centre-of-mass energies in the years 2011 and 2012 respectively, corresponding to an integrated luminosity of up to 25 fb^{-1} . No evidence for additional Higgs bosons other than the 125 GeV standard model-like Higgs boson are found, and stringent exclusion limits are derived in different BSM scenarios.

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Abstract Searches for Beyond Standard Model (BSM) Higgs bosons at the CMS experiment are presented. The analyses are based on proton-proton collision data recorded by the CMS experiment at the LHC at CERN at 7 TeV and 8 TeV centre-of-mass energies in the years 2011 and 2012 respectively, corresponding to an integrated luminosity of up to 25 fb^{-1} . No evidence for additional Higgs bosons other than the 125 GeV standard model-like Higgs boson are found, and stringent exclusion limits are derived in different BSM scenarios.

1 Introduction

The discovery of a Higgs boson with a mass of around 125 GeV by the ATLAS and CMS collaborations [1, 2] was a great success for elementary particle physics. However, it remains to be seen whether the observed state, which is compatible with the standard model (SM) Higgs boson, is the only Higgs boson in the spectrum, or if there are additional Higgs bosons. Moreover, the discovery of the SM Higgs boson still would not explain quadratically divergent self-energy corrections at high energies, the so-called hierarchy problem, and would also leave further questions such as the origin of dark matter unanswered. The SM is therefore most likely incomplete. Analyses of the Higgs boson couplings based on the available experimental data at CMS, which have been determined with 15-20% accuracy, can only set a limit on the Higgs boson branching ratio to beyond standard model (BSM) particles. Fixing all tree-level couplings to the SM (for W, Z, τ , bottom and top) and introducing effective couplings for loop induced processes (for gluon and photon) leaves room for BSM Higgs decays with branching fraction $\text{BR}_{\text{BSM}} < 32\%$ at 95% confidence level (CL) [3, 4]. There are several theoretical models with an extended Higgs sector. Among the most popular and generic ones are the so-called 2 Higgs Doublet

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Models (2HDM) [5]. Having two complex scalar SU(2) doublets, they are an effective extension of the SM. In total, five different Higgs bosons are predicted: two CP even and one CP odd electrically neutral Higgs bosons, denoted by h , H , and A , respectively, and two charged Higgs bosons, $H^\pm$. The parameters used to describe a 2HDM are the Higgs boson masses, and the ratios of their vacuum expectation values, $\tan\beta$. There are several classes of 2HDMs, the most relevant ones are the so-called type I, where one SU(2) doublet gives masses to all leptons and quarks and the other doublet essentially decouples from fermions, and the so-called type II, where one doublet gives mass to up-type fermions and the down-type fermions receive mass from the other doublet. Another intriguing theoretical model is supersymmetry (SUSY), which brings along super-partners of the SM particles. The minimal supersymmetric standard model (MSSM), whose Higgs sector is equivalent to the one of a constrained 2HDM of type II and the next-to MSSM (NMSSM) with one additional singlet are among experimentally best tested models, because they have less independent parameters and are more predictive. Avenues to BSM Higgs boson physics can also be exploited from invisible decays of Higgs boson interpreted in dark matter models and lepton flavour violating Higgs boson decays.

2 BSM Higgs Boson Searches

The CMS experiment [6] has covered a broad range of scenarios to test BSM physics in the Higgs sector. The analysis review presented here would focus on MSSM neutral Higgs boson and charged Higgs boson searches, lepton flavour violating Higgs boson decays and invisible Higgs boson decays sensitive to dark matter searches.

2.1 MSSM Neutral Higgs Boson Search

The MSSM requires 2 Higgs doublets leading to 5 physical Higgs bosons, h and H are the CP-even scalar ones, A is the CP-odd pseudoscalar boson and H^+ and H^- are the charged ones. At the LHC, the neutral MSSM Higgs bosons, collectively denoted as Φ , are expected to be predominantly produced either in gluon-gluon fusion or in b-quark associated production. CMS has performed a search for $\Phi \rightarrow \tau\tau$ using the full 25 fb^{-1} of the 7 and 8 TeV data considering tau decays into electrons, muons and hadrons with fully leptonic, semi-leptonic and fully hadronic di-tau final states [7]. The good tau reconstruction and identification performance, together with the relatively small SM backgrounds compared to bottom quark decay mode, makes this channel one of the most sensitive to signatures of an extended Higgs sector. Events were collected using a combination of electron, muon and hadronic tau triggers, whose criteria varied during data-taking periods. Events were selected requiring two oppositely charged, isolated leptons and split into two categories of either 0 or at least 1 b-tagged jet to enhance the sensitivity to the two production

modes. The di-tau invariant mass is reconstructed from the leptons and the missing energy in the event using a likelihood technique based on the tau decay phase-space and the missing energy resolution, which results into 15-20% mass resolution. The di-tau invariant mass spectrum shows no evidence for a Higgs boson signal and 95% CL upper bound limits on the Higgs boson production cross-section times the branching fraction to tau pairs have been further interpreted in the MSSM parameter space on the m_A - $\tan\beta$ plane in different MSSM benchmark mixing scenarios. In all cases, as seen in Figure 1, the signal hypothesis is tested against a background plus SM-Higgs hypothesis, taking into account the Higgs boson at 125 GeV.

Fig. 1 Tau pair invariant mass distribution for b-tagged category in $\tau_\mu \tau_h$ final state (left); Exclusion at 95% CL on m_A - $\tan\beta$ plane in the MSSM m_h^{mod+} mixing benchmark scenario (right).

2.2 Charged Higgs Boson Searches

Search for charged Higgs boson is presented in top pair decay for charged Higgs boson mass lighter than the mass difference of the top and bottom quarks and in the $pp \rightarrow \bar{t}bH^+$ and $pp \rightarrow t\bar{b}H^-$ process for charged Higgs boson mass heavier than the mass difference of the top and bottom quarks. The analysis [8] concentrates on the $H^\pm \rightarrow \tau\nu$ decay mode in a fully hadronic final state. The analysed data correspond to an integrated luminosity of 19.7 fb^{-1} in 8 TeV pp collisions. The transverse mass of lepton and missing transverse energy system is exploited for separating the potential signal from expected backgrounds. The observed mass spectrum is in agreement with SM prediction. Model-independent 95% CL upper limits calculated with the modified frequentist CL_s criterion are established in Figure 2 as 1.2-0.16% on $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau\nu)$ for m_{H^+} in the range of 80-160 GeV and 0.38-0.026 pb on $\sigma(pp \rightarrow t(b)H^+) \times B(H^+ \rightarrow \tau\nu)$ for m_{H^+} in the range of 180-600 GeV.

Fig. 2 The expected and observed 95% CL upper limits for light charged Higgs boson (left) and heavy charged Higgs boson (right) in $H^\pm \rightarrow \tau\nu$ decay mode in fully hadronic final state.

2.3 Lepton Flavour Violating Higgs Decay

While lepton-flavour violating (LFV) Higgs boson decays are not allowed in SM, they can occur naturally in various BSM models such as composite-Higgs and Randall-Sundrum models. CMS has performed the first direct search for LFV decays $H \rightarrow \mu\tau$ of the 125 GeV Higgs boson in the $\mu\tau_e$ and $\mu\tau_h$ final states using 8 TeV pp collision data [9]. Events were collected triggering and selecting isolated muons and electrons with opposite charge, and divided into jet-multiplicity categories to enhance the sensitivity to different production modes. Since the muon stems promptly from the Higgs boson decay and tends to have larger transverse momentum than in SM Higgs boson to tau pair decay, the Higgs boson candidate mass is reconstructed from the muon, the visible tau decay products and the missing energy. A slight excess of signal events with a significance of 2.5σ is observed. The local p-value of this excess at $m_H = 126$ GeV is 0.007. Interpreted as a limit, this results in a constraint of $B(H \rightarrow \mu\tau) < 1.57\%$ at 95% CL, shown in Figure 3. The best fit branching fraction is $B(H \rightarrow \mu\tau) = (0.89^{+0.40}_{-0.37})\%$. The limit is subsequently used to constrain the flavour violating $Y_{\mu\tau}$ Yukawa coupling to below 3.6×10^{-3} . The sensitivity of the search is an order of magnitude better than the existing indirect limits.

2.4 Higgs Boson in Invisible Decay Mode

A Higgs boson decaying with a significant probability into final states consisting entirely of invisible particles might be measurable if produced in association with other detectable particles. CMS searched this signature [10] for new physics in the Higgs boson associated production with a Z boson, decaying into leptons or bottom quarks, and in vector boson fusion (VBF), with two high momentum forward jets

Fig. 3 Upper limits by category for the LFV $H \rightarrow \mu\tau$ decays (left); Constraints on the flavour violating Yukawa coupling (right).

separated by a large rapidity gap. While the $Z \rightarrow \ell\ell$ ($\ell = e, \mu$) and VBF searches rely on categorisation and cut-based analyses, the $Z \rightarrow b\bar{b}$ uses a multivariate discriminator and an energy regression to the momenta of the two jets to further discriminate the backgrounds and increase the sensitivity. Invisible decays would manifest as an excess of events with high missing energy in the detector. The CMS analysis combines the ZH and VBF channels based on the missing energy and dijet mass distributions, respectively. No significant excess of events over the SM backgrounds have been found, and exclusion limits are interpreted in the Higgs portal model of dark matter (DM), assuming DM couples to the Higgs sector. Different scenarios are proposed, depending on the nature of the DM candidate. The observed limit on the

Fig. 4 Expected and observed 95% CL upper limits on production cross section times invisible branching fraction, normalized to the SM Higgs boson VBF production cross section, for VBF and ZH modes combined (left); Upper limits on the spin-independent DM-nucleon cross section in Higgs-portal models, derived for $m_H=125$ GeV and $\text{B}(H \rightarrow \text{invisible}) < 0.51$ at 90% CL, as a function of the DM mass. Limits are shown separately for scalar, vector and fermion DM (right).

branching ratio is $\text{BR}(H \rightarrow \text{invisible}) < 58\%$ (44% expected) for a SM Higgs boson with a mass of 125 GeV. The analysis shows significant improvement in sensitivity with respect to earlier direct searches. Therefore, CMS has additionally performed a dark matter interpretation using the Higgs-portal model as seen in Figure 4. This model proposes a hidden sector with stable dark matter particles, which, if their mass is below $m_H/2$, would contribute to the invisible decay width of the Higgs boson. The analysis is complementary to direct detection of dark matter and Higgs branching ratio limits can be interpreted as upper limits on the dark matter nucleon cross section. The CMS limits are set on the DM nucleon cross section as a function of the dark matter candidate mass in comparison with direct searches.

3 Conclusion

The CMS experiment at the LHC performed several searches beyond the standard model to determine whether the discovered particle at 125 GeV is the SM Higgs boson or part of an extended Higgs sector. Any finding in conflict with the SM Higgs boson expectation would be a hint for new physics. Several results based on LHC Run-I data have been reviewed. No striking signatures of new phenomena have been observed, and stringent constraints on parameter space of BSM theories have been set. With the upcoming LHC Run-II at a higher centre-of-mass energy, the reach of these analyses will be further extended.

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