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Higgs physics at CMS

Andre Georg Holzner for the CMS Collaboration

Abstract

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Abstract This article reviews recent measurements of the properties of the standard model (SM) Higgs boson using data recorded with the CMS detector at the LHC: its mass, width and couplings to other SM particles. We also summarise highlights from searches for new physical phenomena in the Higgs sector as they are proposed in many extensions of the SM: flavour violating and invisible decay modes, resonances decaying into Higgs bosons and searches for additional Higgs bosons.

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1 Introduction

With the discovery of a Higgs boson like particle with mass 125 GeV at the Large Hadron Collider (LHC) in 2012, the focus has shifted from searching for the Higgs boson to the precise measurement of the new particle's properties. One of the obvious questions is now whether this new particle, in addition to being responsible for electroweak symmetry breaking, is also linked to currently unsolved puzzles such as the existence of dark matter. Moreover, the Higgs boson mass in the standard model (SM) suffers from large radiative corrections which can be many orders of magnitude larger than the mass itself. Several extensions to the SM have been proposed to solve this problem, many of which introduce additional Higgs bosons.

In this report, we summarise recent results related to SM Higgs boson measurements and searches for beyond SM phenomena in the Higgs sector using data recorded with the CMS detector at LHC.

Section 2 discusses the measurements of the properties of the newly discovered particle: mass, width and couplings to other SM particles. Section 3 describes searches for lepton flavour and invisible decays of the Higgs boson. Searches for resonances decaying in a pair of SM Higgs bosons are covered in Section 4 and

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searches for additional Higgs bosons are discussed in section 5. Finally, Section 6 concludes this article.

2 Higgs Boson properties

The first step after the Higgs boson was observed was to measure its properties in order verify whether they are compatible with those of the SM Higgs boson or whether this is a different particle.

2.1 Mass and Width

The precise determination of the Higgs boson mass is not only important to check the consistency of the SM in conjunction with top quark and W boson masses and therefore constrain beyond the SM physics but also lays the foundation for the measurement of any other property whose predicted value depends on the mass.

The measurement of the Higgs boson mass relies on the two high resolution (but small branching ratio) channels $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\ell'$ (with $\ell = \mathrm{e}$ or μ) and $\mathrm{H} \to \gamma\gamma$. The mass was measured by the ATLAS and CMS experiments in LHC run I to be [1]:

$$125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (scale)} \pm 0.02 \text{ (other)} \pm 0.01 \text{ (theory) GeV},$$

which corresponds to a precision of 0.2%. While the largest part of the uncertainty is still statistical, the energy scale uncertainties are the dominant source of systematic uncertainty and may be reduced with the larger samples expected to be recorded during LHC run II.

A Higgs boson width larger than the value predicted by the SM would be an indication of invisible or undetected decays. The width in the SM (4 MeV) is three orders of magnitude smaller than the experimental resolution of the best channels (four leptons, two photons). Nevertheless, it is possible to constrain the width from the off-shell boson mass distribution. Using the $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\ell'$ and $2\ell 2\nu$ analyses, an upper limit of 4.2 times the SM width is set at 95% confidence level (CL) [2].

2.2 Couplings to Other SM Particles

Given that the Higgs boson mass is known, the SM predicts the couplings of the Higgs boson to other particles. These couplings are measured using a fit to the signal strengths observed in the analyses targeting specific combinations of production mechanisms and decay modes. A coupling modifier κ (the ratio of the observed coupling to the value predicted by the SM) is fitted for each type of coupling of the Higgs boson to other particles. All probed couplings are consistent with the SM values $\kappa = 1$, as shown Fig. 1 left [3]. Drawing the Yukawa and reduced boson couplings ($\sqrt{\kappa_\mathrm{V}} \cdot m_\mathrm{V}/\nu$ where ν is the vacuum expectation value) versus the particle masses (Fig. 1 right), it becomes clear that the couplings scale as function of the masses as predicted by the SM.

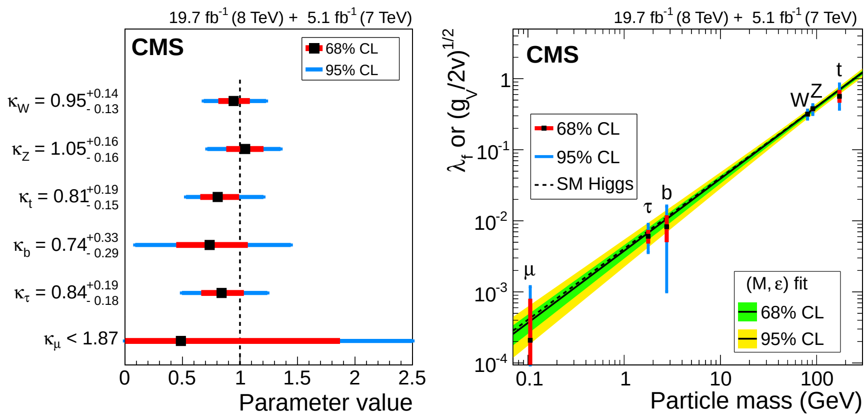

Fig. 1 Measured coupling modifier factors κ for the Higgs boson couplings to other particles (left) and comparison of the scaling of the coupling of the observed boson to fermions and gauge bosons versus particle mass (right). The coupling modifiers (and thus the scaling of the couplings with mass) are consistent with the prediction from the SM.

Higgs boson decays to a pair of gauge bosons are observed with a significance of 6.5 (6.3) standard deviations for Z bosons, 5.6 (5.3) standard deviations for W bosons and 4.7 (5.4) standard deviations for photons where the terms in parentheses denote the expected significances.

The Higgs mechanism was originally introduced to allow for non-zero gauge boson masses, but it is also used to restore gauge invariance of the fermion mass terms in the SM Lagrangian. The evidence for decays to fermions (and therefore Yukawa couplings) is seen with an observed (expected) significance of 3.8 (4.4) standard deviations [4]. The combination of ATLAS and CMS data to determine the Higgs boson couplings was underway at the time of writing.

3 Exotic Higgs boson decays

The measurements described in the previous section hint at the fact that the properties of the boson at 125 GeV are consistent with the SM Higgs boson. Nevertheless, it is important to look for unexpected features such as exotic decays.

3.1 Lepton Flavour Violating Decays

The discovery of neutrino oscillations has shown that lepton flavour is not a universally conserved quantity. Consequently, a natural question to ask is whether direct lepton flavour violation also exists also for charged leptons. Several other experiments have already searched for such decays (see [5] for a review) but the LHC is a unique place to probe whether such effects could come from the Higgs sector.

CMS has searched for Higgs boson decays into all possible pairs of charged leptons, in particular the lepton flavour violating ones (corresponding to off-diagonal elements in the Yukawa coupling matrix) $\mathrm{H} \to \mu^{\pm}\tau^{\mp}$[6], $\mathrm{H} \to \mathrm{e}^{\pm}\tau^{\mp}$ and $\mathrm{H} \to$

$e^{\pm}\mu^{\mp}$ [7] in addition to the lepton flavour conserving channels $H \to \tau^{\pm}\tau^{\mp}$ [8], $H \to \mu^{\pm}\mu^{\mp}$ and $H \to e^{\pm}e^{\mp}$ [9]. With the current data sample, CMS is only sensitive to the SM rate of the $H \to \tau^{\pm}\tau^{\mp}$ channel with $H \to \mu^{\pm}\mu^{\mp}$ becoming accessible in upcoming LHC Runs. No indication of flavour violating decays is found.

3.2 Decays to Invisible Particles

An exotic decay of special interest is the decay of the Higgs boson into invisible particles. An observation of such a decay would be a strong indication of physics beyond the SM with one of the possible interpretations being a decay to dark matter particles.

Searches for invisible Higgs boson decays in the CMS data target the gluon fusion (GF), vector boson fusion (VBF) as well as the associated production channel (WH/ZH). For the gluon fusion production mode, an initial state gluon, leading to a mono-jet signature, is required, as otherwise such events, where the Higgs boson decays invisibly would not be seen in the detector.

The observed (expected) limits on the branching ratio times the ratio of the production cross section and the SM Higgs boson production cross section is 57% (40%) for the VBF analyses, 60% (69%) for the WH/ZH analyses, 67% (71%) for the gluon fusion tagged events and 36% (30%) for the combination [10].

4 Resonances decaying to two Higgs bosons

Several extensions to the SM predict resonances decaying to a pair of Higgs bosons, for example models with spin 0 radions [11] or spin 2 gravitons [12]. CMS has searched for such decays in the $b\bar{b}b\bar{b}$ [13] and $\gamma\gamma b\bar{b}$ [14] final states.

The $b\bar{b}b\bar{b}$ channel is more sensitive than the $\gamma\gamma b\bar{b}$ channel above a mass of about 400 GeV and is used to exclude Kaluza-Klein gravitons with a mass between between 380 and 830 GeV and radions with a decay constant of 1 TeV with a mass in the range 300 to 1000 GeV at 95% CL. A summary of the cross section exclusion for spin 2 resonances is shown in Fig. 2 left.

5 Searches for additional Higgs bosons

Many theories predict the existence of more than one Higgs boson. In particular, supersymmetric theories introduce a second Higgs doublet to avoid gauge anomalies. Two Higgs doublet models (2HDM) in general contain five physical Higgs bosons: a light and heavy scalar h and H, a pseudoscalar A and two charged Higgs bosons H^+ and H^-. This motivates the search for the heavy scalar, the pseudoscalar and the charged Higgs bosons, assuming the light scalar h has the properties of the boson discovered at 125 GeV.

5.1 Additional neutral Higgs bosons

A heavy SM like Higgs boson is searched for decays via a pair of Z bosons ($H \to ZZ \to 2\ell 2\ell', 2\ell 2\nu, 2\ell 2q$), a pair of W bosons ($H \to WW \to \ell\nu\ell\nu, \ell\nu qq$) [15], a pair of photons [16] and $H \to Z\gamma$ [17]. No significant deviation from the background was found in any of these searches in their respective mass ranges (145 - 1000 GeV for the ZZ, WW channels, 150 - 850 GeV for $\gamma\gamma$ and 200 - 500 GeV for $Z\gamma$). The excluded cross section as function of Higgs boson mass is shown in Fig. 2 right.

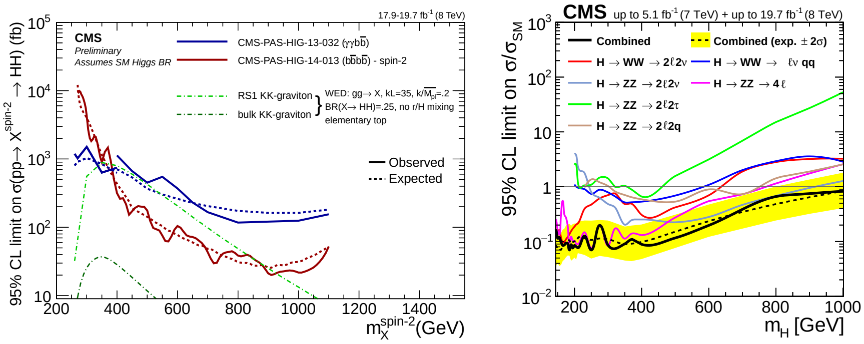

Fig. 2 Upper 95% CL limits on the production cross section for Spin 2 resonances decaying into a pair of Higgs bosons (left) and on the cross section ratio in the search for a heavy SM like Higgs boson (right).

Searches for MSSM like neutral bosons either look for direct decays of the H and A bosons to a pair of taus [18], muons [19] or b quarks [20], or the decay chains $A \to Zh$ with $Z \to \ell^+\ell^-$ and the SM Higgs boson h decaying to $b\bar{b}$ [21] and $H/A \to Z + A/H$ with $Z \to \ell^+\ell^-$ and $A/H \to b\bar{b}$ or $\tau^+\tau^-$ [22]. None of the searches finds signs of a significant deviation from the background and the data are used to put limits on the production cross section times branching ratio in a model independent way and to constraint several MSSM benchmark scenarios.

5.2 Charged Higgs bosons

If the charged Higgs boson is light ($m_{H^\pm} < m_{top} - m_b$), the dominant source of charged Higgs bosons is expected to be the decays of top quarks in $t\bar{t}$ events. Otherwise, the main production mechanism is the direct production involving bottom- or top-quark fusion diagrams. The searches concentrate on the following decay modes: $H^+ \to \tau + \nu_\tau$, $H^+ \to c\bar{s}$ and $H^+ \to t\bar{b}$ (charge conjugates are implicitly included in this section).

No evidence for such a signal is found and constraints are put on several MSSM benchmark models [23]. Model independent 95% CL upper limits are placed on $\mathcal{B}(t \to H^+b) \times \mathcal{B}(H^+ \to \tau^+\nu_\tau) < 1.2 - 0.15\%$ in the range $80 \leq m_{H^+} \leq 160$ GeV and $\sigma(pp \to \bar{t}(b)H^+) \times \mathcal{B}(H^+ \to \tau^+\nu_\tau) < 0.38 - 0.025$ pb for $180 \leq m_{H^+} \leq 600$ GeV.

6 Summary and Outlook

The discovery of a Higgs boson at the LHC has opened up a rich physics program. Precise measurements of the properties of this new particle and comparison to prediction from theory has become an important task. Its discovery also motivates the search for physics phenomena beyond the SM which couple to the Higgs boson.

We summarised measurements of mass, width and couplings of the Higgs boson, presented searches for exotic decays, reviewed searches for resonances decaying into a pair of Higgs bosons and highlighted searches for additional Higgs bosons in 2HDMs.

No significant deviations from the predictions from the SM are observed in any of the measurements or searches. One property of the Higgs boson which still awaits experimental confirmation is its self-coupling. This can be probed using events where a pair of Higgs bosons is produced. Due to the small cross section of this process (about 40 fb [24]) and large backgrounds, the observation of this coupling needs to wait most likely for the High Luminosity LHC data unless new physics phenomena increase the cross section.

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