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Higgs Couplings in CMS in Run2

Stephane B Cooperstein for the CMS Collaboration

Abstract

The latest results on Higgs boson couplings using Run-2 data collected by the CMS experiment are presented. These recent developments include the confirmation of what had been the two remaining third generation Yukawa couplings yet to be observed, the top quark and bottom quark couplings. Next, the latest search for the rare Higgs boson decay to a muon-antimuon pair is presented, which should soon give access to the first measurement of a second generation Yukawa coupling. The most stringent limit to date is then shown for the branching fraction of the Higgs boson to undetectable invisible signatures. Finally, the first search for the extremely rare decay of the Higgs boson to quarkonia is shown.

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Higgs couplings in CMS in Run-2

Stephane Cooperstein on behalf of the CMS Collaboration
Department of Physics, Princeton University,
Princeton, NJ 08544-0708

The latest results on Higgs boson couplings using Run-2 data collected by the CMS experiment are presented. These recent developments include the confirmation of what had been the two remaining third generation Yukawa couplings yet to be observed, the top quark and bottom quark couplings. Next, the latest search for the rare Higgs boson decay to a muon-antimuon pair is presented, which should soon give access to the first measurement of a second generation Yukawa coupling. The most stringent limit to date is then shown for the branching fraction of the Higgs boson to undetectable invisible signatures. Finally, the first search for the extremely rare decay of the Higgs boson to quarkonia is shown.

1 Introduction

Enormous progress has been made in measuring the properties of the Higgs boson since its discovery in 2012 [?,?,?], including measurement of the Higgs boson mass to nearly per-mille precision and measurement of the Higgs boson couplings in the bosonic as well as multiple fermionic channels. All measurements so far are consistent with the standard model (SM) expectation within uncertainties. It is, however, just the beginning of an era of precision and rare coupling measurements with the Higgs boson. These measurements will further shed light on whether there are any deviations from the SM in the Higgs sector.

The measurement of Higgs boson couplings to third generation fermions has in particular advanced greatly over the past year. The observation of Higgs boson production in association with a top quark-antiquark pair (ttH), achieved by the CMS Collaboration [?] last spring, established the first direct confirmation of the Yukawa coupling to the top quark [?,?]. The observation of Higgs boson decay to a bottom quark-antiquark pair last summer subsequently confirmed the Yukawa coupling to the bottom quark [?,?]. The third generation Yukawa couplings have thus been directly established, with the observation of Higgs boson decay to tau leptons having been earlier achieved from the combination of ATLAS and CMS Run-1 measurements [?].

The second generation Yukawa couplings will soon be measurable through the very rare decay of the Higgs boson to a muon-antimuon pair, with a branching fraction of 0.022%. The latest result from CMS using 2016 data demonstrates that the measurement of this coupling is nearing experimental reach [?], with an additional more than 100 fb^{-1} of $\sqrt{s} = 13$ TeV data already recorded and a doubling in dataset expected from Run-3 of the LHC.

These measurements of the Higgs boson couplings to SM particles are an important test of the SM description of the Higgs sector. It is however also important to perform complementary direct searches for potential Higgs boson couplings to beyond the SM particles. In particular, the latest direct constraints on the Higgs boson branching fraction to particles which do not leave any trace in the CMS detector (H→invisible) are presented. This result, including the combination with similar Run-1 measurements, yields the most stringent constraint to date on the branching fraction for H→invisible [?]. The result is further interpreted in terms of Higgs-portal models, yielding the most stringent dark matter-nucleon cross section limits to date for low-mass dark matter scenarios.

Finally, a novel search by CMS is presented for Higgs boson decay to quarkonia ($J/\Psi J/\Psi$, $\Upsilon\Upsilon$) in the four-muon final state [?]. An excess in data in this very clean and nearly background-free search would be a clear indication of beyond the SM physics.

2 H→b$\bar{\text{b}}$

With a predicted branching fraction of about 58%, the Higgs boson decay to a bottom quark-antiquark pair is by far the dominant Higgs boson decay mode. Inclusive H→b$\bar{\text{b}}$ searches at hadron colliders are, however, extremely challenging due to the overwhelming production of final states with multiple b jets via strong interactions. The most sensitive H→b$\bar{\text{b}}$ search strategy at the LHC is to consider the production of the Higgs boson in association with a W or Z boson (VH). By requiring the presence of a leptonically W or Z boson in the event, the enormous multiple b-jet backgrounds are highly reduced.

The most recent VH, H→b$\bar{\text{b}}$ result from CMS uses 41.3 fb^{-1} of $\sqrt{s} = 13$ TeV data collected in 2017 [?]. This analysis includes several important improvements with respect to previous VH, H→b$\bar{\text{b}}$ searches. The latest machine learning technology (deep neural networks) have been integrated to perform b-jet identification, estimate the b-jet energy, and to differentiate the signal among various large backgrounds. In addition, a kinematic fit is now performed in the Z→ $\ell\ell$ channel which takes advantage of the inherent lack of missing energy in the event from neutrinos under the signal hypothesis to better constrain the Higgs boson candidate mass.

This result has been combined with previous VH, H→b$\bar{\text{b}}$ searches using 2016 and Run-1 data. Figure **??** (left) visualizes the combined result, with events grouped based on the predicted signal-to-background ratio. In addition, a complementary analysis is performed by extracting the H→b$\bar{\text{b}}$ signal from a direct fit of the Higgs boson candidate invariant mass rather than the output of a multivariate discriminant. Figure **??** (right) shows the resulting combined Higgs boson candidate mass distrbiution with nonresonant backgrounds subtracted.

H→b$\bar{\text{b}}$ searches performed by CMS in the less sensitive primary Higgs boson production modes (gluon fusion, ttH, and vector boson fusion) are additionally included in the combination, yielding an excess in the data incompatible with the SM background-only hypothesis with an observed (expected) significance of 5.6σ (5.5σ). The measured signal strength relative to the SM prediction for the Higgs boson with mass $m_H = 125.09$ GeV is $\mu = \frac{\sigma}{\sigma_{SM}} = 1.04 \pm 0.20$. This constitutes the observation of Higgs boson decay to bottom quarks and therefore direct confirmation of the Yukawa coupling to the bottom quark.

3 H→ $\mu^+\mu^-$

The Higgs boson decay to a muon-antimuon pair provides a very well reconstructed experimental signature, but is statistically limited with the currently available datasets and subject to a large $Z/\gamma^* \to \ell\ell$ background. A boosted decision tree (BDT) is trained to select the kinematic regions with the highest signal to background ratio based on event-level and kinematic observables. A

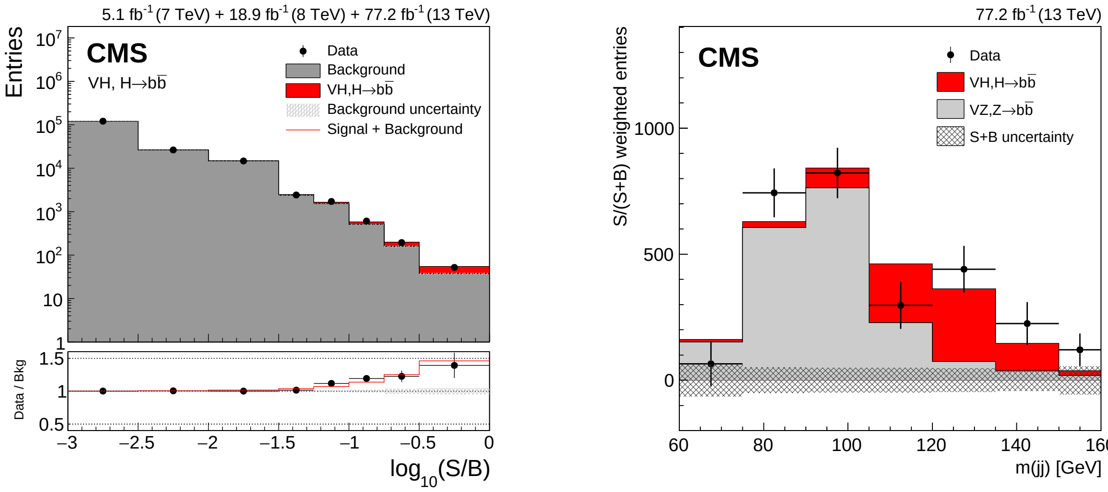

Figure 1 – Left: combination of VH, H→bb̄ searches with events merged into a single distribution based on the expected signal to background ratio. Right: Higgs boson candidate invariant mass distribution with nonresonant backgrounds subtracted for the combination of 2016 and 2017 data [?].

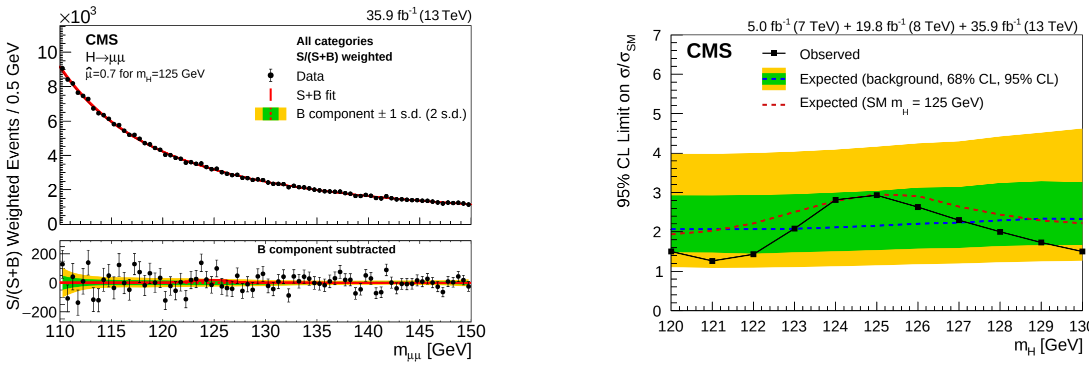

Figure 2 – Left: dimuon invariant mass distribution combined over all categories, with each category assigned a weight based on the signal to signal plus background ratio. Right: 95% confidence level upper limits on the product of the cross section and branching ratio as a function of Higgs boson candidate mass, for the combination of 2016 and Run-1 data [?].

fit is then performed to the dimuon invariant mass spectrum with events categorized based on BDT score and muon η. Figure **??** (left) shows the combined dimuon invariant mass distribution with each category assigned a weight according to the expected signal to signal plus background ratio. This latest result using 2016 data is then combined with similar Run-1 searches and interpreted in terms of 95% confidence level upper limits on the product of the cross section and branching fraction with respect to the SM expectation as a function of m_H (Fig. **??**, right). An excess in the data over the SM background is observed (expected) with a significance of 0.9σ (1.0σ), with a corresponding signal strength of $\mu = 1.0 \pm 1.0(\text{stat.}) \pm 0.1(\text{syst.})$.

This analysis in particular benefits from the excellent muon resolution achieved by the CMS detector. Although more data are needed in order to exclude the background-only hypothesis, with the large 140 fb^{-1} dataset already recorded during Run-2 as well as the similar dataset expected from Run-3 it should be possible to make the first measurements of a second generation Yukawa coupling via H→ $\mu^+\mu^-$.

4 ttH

Direct confirmation of the Yukawa coupling to the top quark was achieved last spring with the observation of ttH production by the CMS Collaboration [?]. This result combined searches for

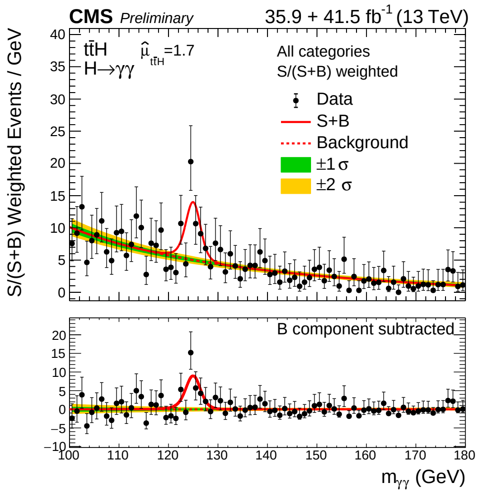

Figure 3 – Diphoton invariant mass distribution combined over all categories for the ttH, H $\rightarrow \gamma\gamma$ analysis on 2017 data combined with the previous measurement on 2016 data. Each category is assigned a weight according to the ratio of the signal to signal plus background expectation [?].

ttH production in multiple channels targeting different Higgs boson decay modes, namely the diphoton, $b\bar{b}$, and multilepton (WW^*, ZZ^*, and $\tau\tau$) decay channels, using the combination of 2016 and Run-1 data. Since the ttH observation, ttH measurements in the multilepton and diphoton channels have been performed on the 2017 data. These latest results not only double the $\sqrt{s}$ = 13 TeV dataset, but also incorporate important improvements in preparation for achieving the best possible precision on measurements with the full Run-2 dataset of more than 140 fb^{-1}.

4.1 Multilepton channel

The ttH multilepton analysis splits events into many categories based on lepton multiplicity, flavor, and charge. In each category a BDT is trained to differentiate signal from background and the BDT distribution is fit to extract the signal. New for the analysis on 2017 data is the inclusion in the signal extraction fit of signal-depleted control regions enhanced in the dominant ttW and ttZ backgrounds. This strategy better constrains the background prediction in the signal region. A new category was also included targeting two electrons or muons in the final state in addition to two hadronically decaying tau leptons. The observed (expected) significance is 1.7σ (2.9σ) with 2017 data alone and 3.2σ (4.0σ) when combined with the previous result on 2016 data [?]. The corresponding signal strength is $\mu = 0.96^{+0.34}_{-0.31}$.

4.2 Diphoton channel

The H $\rightarrow \gamma\gamma$ decay channel yields a very clean experimental signature but is statistically limited due to the small branching fraction as well as the relatively small ttH production cross section ($\sim$ 0.5 pb). The analysis strategy is similar to H$\rightarrow \mu^+\mu^-$, with events categorized based on BDT score and the signal extracted via a simultaneous fit to the diphoton invariant mass in all categories. Many input observables were added to the BDT training for the 2017 analysis and a larger number of categories were introduced in order to maximize sensitivity. Figure **??** shows the diphoton invariant mass distribution combined over all channels for the analysis on 2017 data combined with the previous measurement on 2016 data [?]. The observed (expected) excess in data over the SM backgrounds is 4.1σ (2.7σ), with a signal strength of $\mu = 1.7^{+0.6}_{-0.5}$. The uncertainty on the measurement is dominated by the statistical uncertainty of the data. As the recorded LHC collision datasets largely increase in size over the next years, the diphoton channel will progressively become the dominant channel for measuring ttH production.

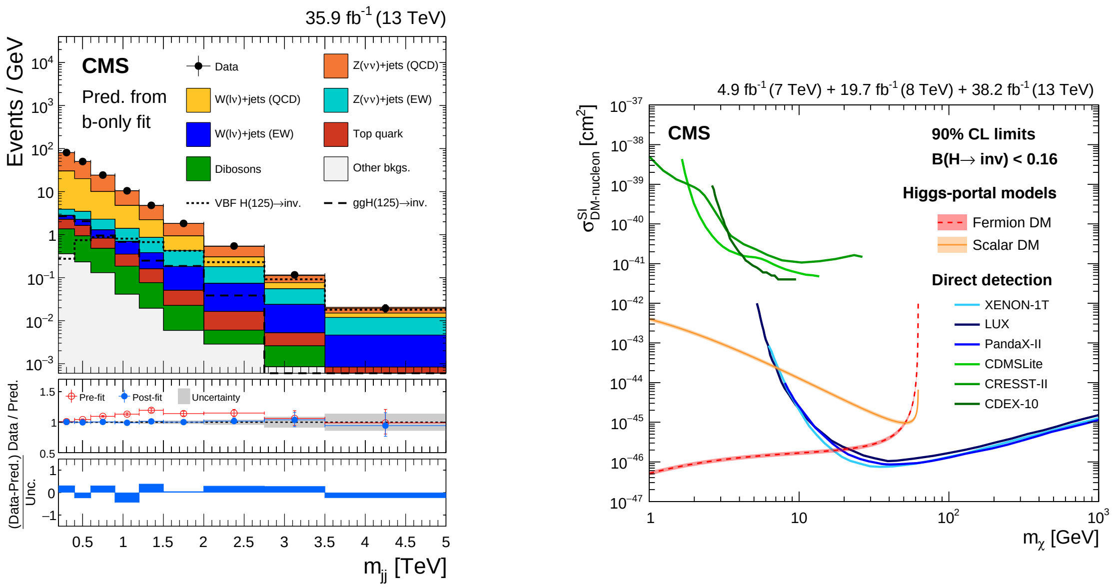

Figure 4 – Left: dijet invariant mass in the vector boson fusion H→invisible search with 2016 data. Right: 90% confidence level upper limits on the dark matter-nucleon scattering amplitude as a function of dark matter candidate mass, from the combination of H→invisible searches in all production modes with 2015, 2016, and Run-1 data [?].

5 H→invisible

Neutrinos produced in LHC collisions do not interact with the detector material and their presence can only be inferred from a momentum imbalance in the event. Some beyond the SM particles, for example dark matter, may similarly not leave any detectable signature other than the presence of missing energy in the event. The SM predicted branching fraction for the Higgs boson decay to neutrinos is only 0.1%, via H→ZZ→ 4ν. If the Higgs boson interacts with beyond the SM particles, however, the Higgs to invisible branching fraction can be highly enhanced.

The most sensitive search channel for H→invisible at the LHC is via the vector boson production mode, where the presence of two quark jets in the final state with characteristically large dijet invariant mass allows for a crucial supression of large SM backgrounds. A signal region is selected by requiring two jets with intermediate dijet invariant mass and a large missing transverse energy (at least 250 GeV). A fit is then performed of the dijet invariant mass distribution in the signal region, shown in Figure **??** (left). The dominant background contributions from $Z(\nu\nu)$+jets and $W(\ell\nu)$+jets production are constrained by separate control regions enriched in each background.

The absence of a significant excess in the data at large dijet invariant mass values is used to constrain the branching fraction for H→invisible by assuming the SM production cross section. The result is combined with other direct H→invisible searches performed by CMS in the less sensitive gluon fusion and VH production modes on 2015, 2016, and Run-1 data, yielding a 95% confidence level upper limit on the branching fraction for H→invisible of 19% [?]. This constitutes the most stringent limit to date. The result is also interpreted in the context of Higgs-portal models of dark matter interactions, where the Higgs boson serves as a mediator between dark matter and SM particles. The resulting observed upper limits on the dark matter-nucleon scattering cross section are shown in Figure **??** (right) compared with limits from direct detection dark matter experiments. The CMS result yields the most stringent limits for dark matter candidate mass less than 18 (7) GeV under the fermion (scalar) spin hypotheses.

6 H→J/ΨJ/Ψ, ΥΥ

The first search for extremely rare decays of the Higgs boson to quarkonia is presented. The SM predicted branching fractions for H→J/ΨJ/Ψ and H→ ΥΥ are inaccessible at the LHC by many orders of magnitude. Couplings of the Higgs boson to particles beyond the SM or a deviation in the Higgs boson coupling to quarks could however yield large enhancements. The four-muon final state is considered, which benefits from excellent mass resolution and very few events expected from SM backgrounds. An excess of even a few events in data at the Higgs boson mass would be a clear indication of beyond the SM physics. No excess in data is observed, allowing for 95% confidence level upper limits on the branching fraction for H→J/ΨJ/Ψ and H→ ΥΥ to be set at 1.4 x 10^{-3} and 1.8 x 10^{-3}, respectively [?].

7 Summary

The latest measurements from CMS of the Higgs boson couplings using Run-2 data are presented. The direct confirmation of all third generation Yukawa couplings has now been achieved, with the observation of ttH production and the observation of Higgs boson decay to bottom quarks accomplished over this past year. Two of the primary ttH channels have now been performed on the 2017 data, more than doubling the Run-2 dataset used for the ttH observation and incorporating significant analysis improvements.

A promising result on the rare Higgs boson decay to a muon-antimuon pair using 2016 data demonstrates the possibility to measure a second generation Yukawa coupling in the next years. The most stringent limit to date on the branching fraction of the Higgs boson to invisible detector signatures is also presented. Finally, a novel search for Higgs boson decays to quarkonia is shown. With more than 140 fb^{-1} of $\sqrt{s} = 13$ TeV Run-2 data now recorded, significant developments in these measurements are expected in the near future.

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