PROCEEDINGS OF SCIENCE

Studying the Higgs-charm Yukawa coupling with the CMS detector

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The Yukawa coupling between the Higgs boson and charm quark is a fundamental quantity of the Standard Model of particle physics. Here, a number of analyses using the CMS detector are presented which aim to measure this quantity. All analyses use the full Run-2 dataset of the CMS detector, corresponding to an integrated luminosity of 138 fb^{-1}. The respective analyses report bounds on the signal strength modifier κ_c of this Yukawa coupling.

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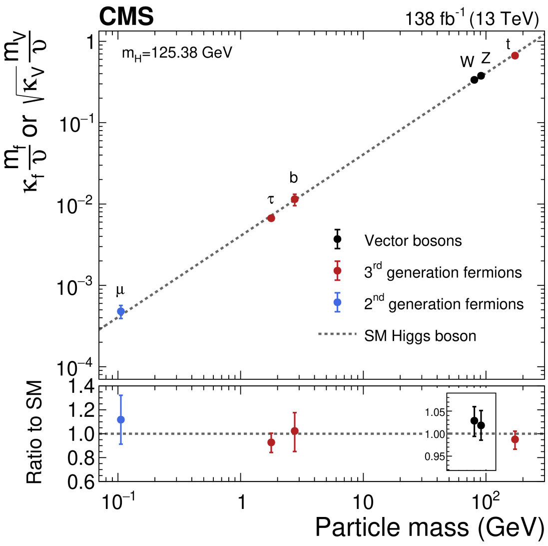

Figure 1: The measured coupling modifiers of the coupling between the Higgs boson and fermions as well as heavy gauge bosons as functions of fermion or gauge boson mass, where v is the vacuum expectation value of the Higgs field. [4]

1. Introduction

The Higgs boson discovery in 2012 [1][2][3] by the CMS and ATLAS collaborations marked a significant milestone in the understanding of the electroweak sector of the Standard Model (SM) of particle physics. Since this discovery, there has been a continuous effort to measure the properties of the Higgs boson [4] and to determine whether these are consistent with the theoretical predictions of the SM. A significant subset of these properties are the couplings between the Higgs boson and other massive fermions and bosons, which in the SM are responsible for giving these particles their mass. As can be seen in Figure 1, a number of these couplings been measured and indeed align with the values expected from the SM. However, the measurement of the so-called Yukawa couplings of several of the lighter fermions still remain an open challenge as these couplings decrease in strength with smaller fermion masses.

The next lightest fermion candidate for such a measurement is the charm quark. Consequentially, the study of the Yukawa-coupling between the Higgs boson and the charm quark is of significant interest [5]. Typically, this can be parametrised using a signal strength modifier κ_c, denoting the measured signal strength in terms of the SM signal strength. In this context, a number of analyses targetting this quantity using the CMS detector [6] are presented. All of these analyses use the data collected between 2016 – 2018 at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}.

2. Charm quark associated Higgs boson production

This analysis [7] targets processes in which a Higgs boson is produced alongside a charm quark (henceforth referred to as the cH process) and the Higgs boson decays to a pair of photons.

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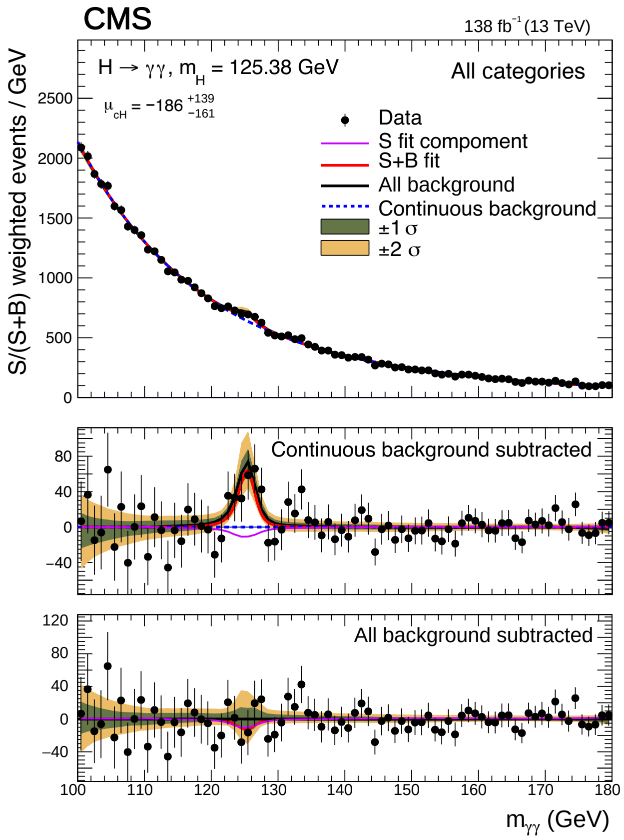

Figure 2: Invariant diphoton mass distribution $m_{\gamma\gamma}$ of selected events, scaled by S/(S+B) where S (B) is the number of expected signal (background) events. The coloured bands represent different fit components. The middle and lower panels show the $m_{\gamma\gamma}$ distribution with the continuous background and total background contributions subtracted, respectively. [7]

To reconstruct Higgs boson candidates, events with two well-reconstructed photons are selected. Alongside these, events are required to have at least one jet satisfying p_T and η requirements and in which the p_T-leading jet satisfies a c-tagging requirement. Subsequently, events are split into 9 categories per data-taking year using two BDTs designed to separate cH events from the ggH and continuous backgrounds respectively. Both signal and backgrounds are modeled via analytic functions in the $m_{\gamma\gamma}$ variable, which is used as a final discriminator as can be seen in Figure 2. Assuming the absence of signal, observed (expected) upper limits at 95% CL can be placed on κ_c, which are reported at $|\kappa_c| < 38.1$ (72.5). The main uncertainties driving the sensitivity of this result are the statistical uncertainty as well as theoretical uncertainty on modelling the cH and ggH processes.

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3. Inclusive Higgs boson production in 4ℓ final states

This analysis [8] targets inclusive Higgs boson production in four-lepton (ℓ = e, μ) final states. Deviations from the expected production rate can be used to interpret constraints on enhancements on the couplings of the Higgs boson to lighter quarks, including κ_c. To reconstruct the Higgs boson, combinations of leptons (4μ, $4e$, $2\mu 2e$) satisfying a set of criteria (depending on the lepton type) are selected. These events are characterised via a discriminant based on the Higgs boson decay, which is defined as

$$\mathcal{D}_{\text{bkg}}(\Omega) = \frac{\mathcal{P}_{\text{sig}}(\Omega)}{\mathcal{P}_{\text{sig}}(\Omega) + \mathcal{P}_{\text{bkg}}(\Omega)}. \tag{1}$$

Here, $\mathcal{P}_{\text{sig}}$ is defined as the probability for the event to be consistent with the Higgs boson signal and $\mathcal{P}_{\text{bkg}}$ is defined as the probability the event is consistent with the dominant $\text{qq} \rightarrow \text{ZZ/Z}\gamma^* \rightarrow 4\ell$ background. The probabilities $\mathcal{P}$ are calculated using a matrix element method using a set of kinematic variables Ω. Background processes with four final state leptons are estimated via simulation while backgrounds which contain misidentified lepton candidates are estimated from data.

The fit strategy relies on the fact that the $\text{pp} \rightarrow \text{H} \rightarrow 4\ell$ production cross section decreases monotonically with enhanced κ_q, where q can be any light quark (u, d, s, c). Thus any observed excess in the inclusive cross section can be interpreted as enhancements of κ_q. Here, the corresponding quantities for the bottom and top quark κ_b and κ_t are fixed to well-constrained existing measurements, while other κ_q values float in the fit. Using this strategy, an observed (expected) constraint on κ_c of $-4.0(-3.8) < \kappa_c < 3.4(3.2)$ is reported at 95% CL, with no observed excess.

4. Higgs boson decay to a pair of charm quarks in association with a pair of top quarks

This analysis [9] targets events in a Higgs boson decays to $\text{c}\bar{\text{c}}$ and is produced in association with a pair of top quarks (henceforth referred to as $\text{t}\bar{\text{t}}\text{H}$). To target this process, several categories based on the top quark decay are devised. These are the fully hadronic (0L), single-lepton (1L) and dilepton (2L) categories. Each category requires a varying number of jets, which satisfy a set of criteria, as well as a number of leptons depending on the respective category. These objects are fed to a multiclass event classifier, which sorts candidate events into 10 (9) classes in the 0L (1L, 2L) channels:

- two $\text{t}\bar{\text{t}}\text{H}$ classes: $\text{t}\bar{\text{t}}\text{H}(\text{H}{\rightarrow}\text{b}\bar{\text{b}})$, $\text{t}\bar{\text{t}}\text{H}(\text{H}{\rightarrow}\text{c}\bar{\text{c}})$
- two $\text{t}\bar{\text{t}}\text{Z}$ classes: $\text{t}\bar{\text{t}}\text{Z}(\text{Z}{\rightarrow}\text{b}\bar{\text{b}})$, $\text{t}\bar{\text{t}}\text{Z}(\text{Z}{\rightarrow}\text{c}\bar{\text{c}})$
- five $\text{t}\bar{\text{t}}$+jets classes: $\text{t}\bar{\text{t}}$+b, $\text{t}\bar{\text{t}} >1$b, $\text{t}\bar{\text{t}}$+c, $\text{t}\bar{\text{t}} >1$c, $\text{t}\bar{\text{t}}$+light
- (Only in the 0L channel) one QCD multijet class

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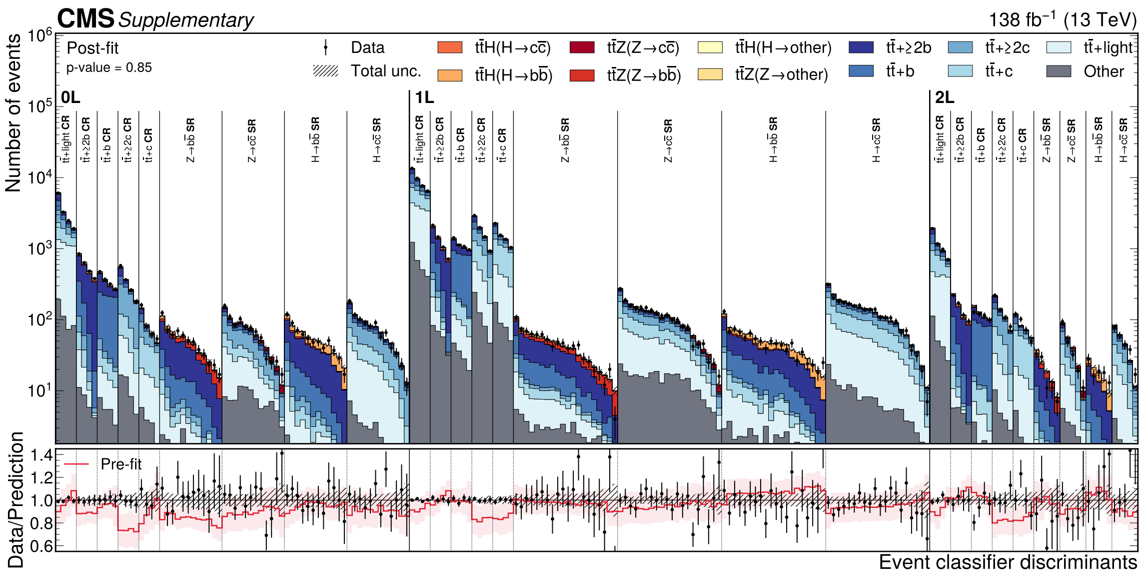

Figure 3: The post-fit distribution of the multiclass event classifier in all 28 classes. The points represent the data, while the coloured histograms represent the predicted background and signal yields. [9]

The inclusion of both $\mathrm{t\bar{t}H(H{\to}c\bar{c})}$ and $\mathrm{t\bar{t}H(H{\to}b\bar{b})}$ classes allows for a simultaneous measurement of κ_c and κ_b, which have similar signatures. Additionally, the inclusion of $\mathrm{t\bar{t}Z}$ classes allows for a measurement of this very similar process, which is used to validate the $\mathrm{t\bar{t}H}$ measurement strategy. Both signal and background processes are estimated using Monte Carlo simulation.

The final fit is performed on the output of the event classifier in the 28 described classes. This can be seen in Figure 3. No excess is found over the background-only hypothesis with respect to the $\mathrm{t\bar{t}H(H{\to}c\bar{c})}$ process. Thus assuming the absence of signal, an observed (expected) upper limit at 95% CL of $\kappa_c > 3.0$ (3.3) is reported. In addition to this, a combination with a previous search in the $\mathrm{VH(H{\to}c\bar{c})}$ channel [10] is performed. For this, an observed (expected) upper limit at 95% CL of $\kappa_c > 3.5$ (2.7) is reported. The main uncertainty sources in this measurement are the statistical uncertainty as well as theoretical uncertainties related to the signal as well as $\mathrm{t\bar{t}}$+jets modelling.

5. Conclusion

The Yukawa coupling between the charm quark and the Higgs boson is an important milestone in determining the properties of the Higgs boson and investigating their consistency with the SM. A typical quantity that characterises this is the signal strength modifier κ_c. The CMS experiment has performed a number of analyses using a variety of analysis strategies to measure this quantity. Due to the absence of an observed signal, the CMS experiment is able to set stringent limits on κ_c using a variety of strategies to analyse the 138 fb^{-1} worth of data from the Run 2 dataset. As the discussed analyses are significantly limited by statistical uncertainty, further improvements are expected from leveraging the LHC Run-3 and High-Luminosity LHC datasets.

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