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Evidence for Higgs Boson decay to a pair of muons at CMS

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Summary. — The CMS collaboration recently presented their results on the first-ever evidence of Higgs decay to a pair of muons with 137 fb^{-1} of data at $\sqrt{s} = 13$ TeV (THE CMS COLLABORATION, *JHEP*, **01** (2021) 148). The analysis targeted four different production modes, the gluon fusion (ggH) , the vector boson fusion (VBF), the Higgs-strahlung process (VH) and the production in association with a pair of top quarks (ttH). Each of these categories had developed it's own dedicated boosted decision tree (BDT) or a deep neural-network (DNN) to efficiently separate the signal from the major background processes. The VBF category used a template-based fit to the DNN score whereas the remaining categories performed data-driven fits to the dimuon mass spectrum. A combined fit from all these categories sees a slight excess in the data corresponding to 3.0 standard deviations at $M_H = 125.38$ GeV (the most precise measurement of the Higgs boson mass to date (THE CMS COLLABORATION, *Phys. Lett. B*, **805** (2020) 135425)).

1. – Introduction

The Higgs field is responsible for the Standard Model (SM) gauge bosons acquiring a mass through Electro-Weak Symmetry Breaking (EWSB). It is also responsible for the fermion masses through Yukawa couplings. The Higgs couplings to the third generation fermions and the gauge bosons have already been well measured at the LHC. The next natural step is to measure the Higgs coupling to the second generation fermions, such as muons.

The SM predicts $B(H \to \mu\mu) \sim 2.15{*}10^{-4}$ with a Higgs mass at 125.38 GeV. Although this decay channel has a very good mass resolution (1.5 - 3 GeV), it's largely dominated by the Drell-Yan production of $Z \to \mu\mu$ and the electroweak production of a Z boson, along with smaller contributions from $t\bar{t}$, single top, diboson and triboson processes.

The CMS detector [1] at CERN has exceptional muon reconstruction capabilities because of its inner tracker layers, the 3.8T magnetic field provided by the solenoid and the outer gas filled muon chambers. The muon p_T resolution varies from 1% at 50GeV to 10% at 1TeV. Since the p_T of the muons coming from the $H \to \mu\mu$ decay peak primarily around 50-60 GeV, this CMS analysis benefits heavily from the excellent muon momentum resolution.

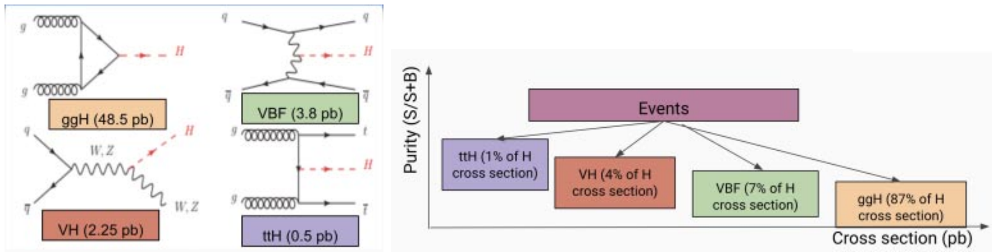

Fig. 1. – Left: Feynman diagrams and cross sections ($\sqrt{s} = 13$ TeV) for different Higgs production mechanisms. Right: Illustrative signal purity *vs.* cross section for different Higgs production mechanisms.

2. – Search strategy

The Higgs Boson production happens through four major mechanisms, the gluon fusion (ggH) , the vector boson fusion (VBF), the Higgs-strahlung process (VH) and the production in association with a pair of top quarks (ttH) (fig. 1). The ttH process has the smallest cross section but offers the cleanest signature (S/S+B) in our detector, whereas the ggH process, which has the highest cross section, gets subdued against other backgrounds with similar final states (fig. 1). The basic goal of this analysis is to separately look at each of these production mechanisms, identifying important characteristics specific to each process and performing a classic bump hunt analysis in the dimuon mass spectrum (fig. 2).

We identify events containing a pair of muons (p_T >20 GeV, $|\eta| < 2.4$) that are oppositely charged and are well isolated. We additionally require the invariant mass of the muon pair ($M_{\mu\mu}$) to be ϵ [110,150] GeV. We then perform the following broad classification of events into separate categories:

- **ttH** This is an exclusive category defined by the presence of b-jets in the events and is further subdivided into leptonic (additional leptons from the top quark decay) and hadronic (additional jets from the top quark decay) channels.

- **VH(leptonic)** This exclusive category targets the leptonic decays of the W/Z boson in the VH process. This category is further subdivided into a ZH channel with an additional lepton (e/μ) pair with a resonace at the Z boson mass and a WH channel with a single additional lepton (e/μ) and missing energy, with a transverse mass near the W boson mass.

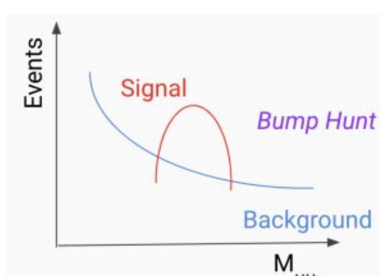

Fig. 2. – An illustrative bump hunt analysis in the dimuon mass spectrum.

- **VBF** The VBF channel is another exclusive category with events having these additional features:
  - Two jets with $p_T > 35\ GeV and > 25\ GeV$.
  - Di-jet mass $(M_{jj}) > 400\ GeV$ and a large angular separation between the two leading jets $(\delta\eta(jj) > 2.5)$.
  - Veto on b-jets to have orthogonality with ttH.
- **ggH** This exclusive category collects all other events which did not fall into any of the previous categories and is mainly dominated by 0/1 jet events.

2˙1. *The ttH, VH and ggH categories.* – We trained independent boosted decision trees (BDTs) for each category against the specific major background targeting the characteristic kinematic properties of that channel. The continuous output score of the BDT is then binned into different boundaries by maximizing the S/B. Individual parametric fits to $M_{\mu\mu}$ are then performed in each of those bins.The background is modelled with a discrete likelihood profile of physics inspired and empirical functions. The signal peak is modelled with a Gaussian function with power-law tails on both sides.

2˙2. *The VBF category.* – The VBF category is the most sensitive channel for this analysis and is further subdivided into two orthogonal analysis regions defined as follows:

- *Signal Region (SR)*: $115 < M_{\mu\mu} < 135\ GeV$
- *SideBand (SB)*: $110 < M_{\mu\mu} < 115\ GeV$ or $135 < m_{\mu\mu} < 150\ GeV$ (assuming M_H =125.0 GeV)

A deep neural network (DNN) was trained for the VBF category in the SR. A template based fit to the DNN score output was performed in both the SB and SR.

3. – Results

A combined fit from all the categories sees an excess in the data at 3.0 standard deviations (2.5 expected). This is the first evidence for a second generation Yukawa coupling to the Higgs boson and is thus exciting. When one looks at the signal strength, which is defined as

$$\mu = \frac{[\sigma * B(H \to \mu\mu)]_{obs}}{[\sigma * B(H \to \mu\mu)]_{SM}}, \tag{1}$$

the global fit value is given by

$$\mu = 1.19^{+0.41}_{-0.39}(stat)^{+0.17}_{-0.16}(syst) \tag{2}$$

A p-value *vs.* a dimuon mass scan was also performed, to understand the most sensitive mass region for this decay channel. This scan was done in the 120-130 GeV mass region, in steps of 100 MeV in 125-126 GeV and in steps of 500 MeV elsewhere. The signal rate was interpolated smoothly for different mass points $[\sigma * B(H \to \mu\mu)]$. For

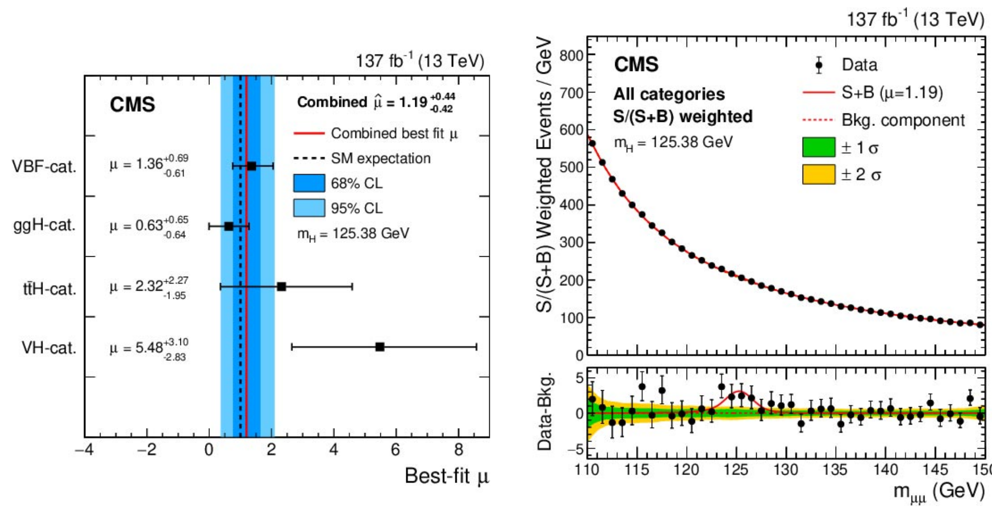

Fig. 3. – Left: Best fit values of the signal strength μ. Right : $M_{\mu\mu}$ mass spectrum for the weighted combination of all event categories.

the ggH, VH and ttH categories, the fit was performed at $M_H = 120$, 125 and 130 GeV in both the data and simulated samples. A smooth interpolation of the fit parameters was done for other mass points. For the VBF category, we evaluated the DNN at different mass points keeping the mass fixed to that value and performed simultaneous fits for both data and simulation at all the mass points. The observed and expected scans are presented in fig. 4. The jitter in the VBF scan is due to the shifting of the data events between DNN bins as the dimuon mass is changed.

The largest systematic uncertainty impacts in this analysis arise from limited statistics in data, the signal and background theory modeling and the main experimental uncertainties include jet energy scale and resolution uncertainties.

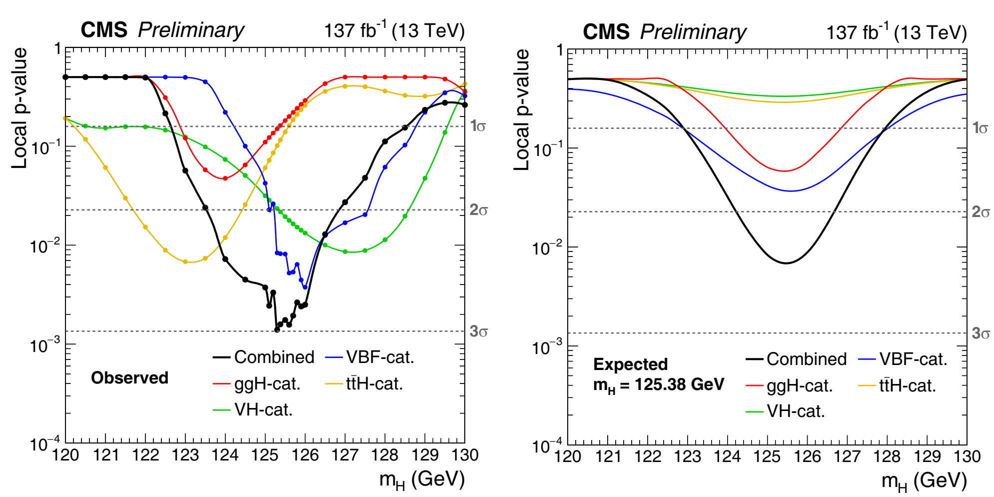

Fig. 4. – p-value *vs.* mass scan: Expected from SM (left) and Observed (right).

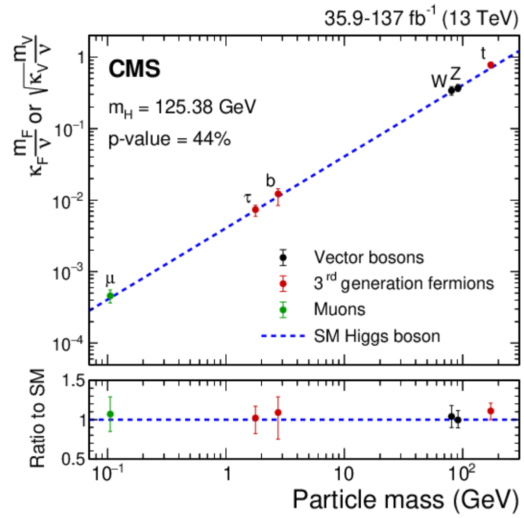

Fig. 5. – The best fit estimates for the reduced coupling modifiers extracted for fermions and weak bosons from the resolved κ-framework compared to their corresponding prediction from the SM. The error bars represent 68% C.L. intervals for the measured parameters.

A combination of results with [2] was performed for measuring κ_μ in the κ framework [3].The best fit value for κ_μ is 1.07 and the corresponding observed 95% C.L. interval is $0.59 < \kappa_\mu < 1.5$.

REFERENCES

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