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CMS CR -2014/042

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

14 April 2014 (v3, 28 April 2014)

Search for a Higgs to Fermions with the CMS detector at the LHC

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Abstract

The discovery of a new boson at the LHC in 2012 has lead to an exciting time in high energy particle physics. The first observations were in decays to $\gamma\gamma$, WW, and ZZ and came with tests of spin parity and measurements of the new bosons mass. An important remaining question is the coupling of this boson to fermions. In this paper the current CMS results for Higgs boson decays to $\tau\tau$, $\mu\mu$ and $\mathrm{b\bar{b}}$ will be presented. These searches show an observed significance of 3.2 σ to $\tau\tau$, 2.1 σ to $\mathrm{b\bar{b}}$ and no significant excess to $\mu\mu$. The combination of the $\tau\tau$ and $\mathrm{b\bar{b}}$ results in a combined observed significance of 3.8 σ which gives strong evidence for the direct coupling of the 125 GeV Higgs boson to down-type fermions.

Presented at *LaThuile 2014 XXVIIIth Rencontres de Physique de la Vallee dAoste*

Search for a Higgs to Fermions with the CMS detector at the LHC

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Summary. — The discovery of a new boson at the LHC in 2012 has lead to an exciting time in high energy particle physics. The first observations were in decays to $\gamma\gamma$, WW, and ZZ and came with tests of spin parity and measurements of the new bosons mass. An important remaining question is the coupling of this boson to fermions. In this paper the current CMS results for Higgs boson decays to $\tau\tau$, $\mu\mu$ and $b\bar{b}$ will be presented. These searches show an observed significance of 3.2 σ to $\tau\tau$, 2.1 σ to $b\bar{b}$ and no significant excess to $\mu\mu$. The combination of the $\tau\tau$ and $b\bar{b}$ results in a combined observed significance of 3.8 σ which gives strong evidence for the direct coupling of the 125 GeV Higgs boson to down-type fermions.

PACS 14.80.Bn – . . . .

1. – Introduction

One of the defining goals of the LHC physics program was to discover the mechanism of electroweak symmetry breaking, which explains the mass of the W and Z bosons when compared to the massless photon. In the standard model (SM) this is done via the Higgs Mechanism, which predicts an additional boson. In 2012 a new boson was discovered at the LHC [1, 2] in decays to $\gamma\gamma$, WW, and ZZ with a mass near 125 GeV that had properties like those predicted from a SM Higgs boson.

An important remaining question is whether this new boson also couples to fermions, in particular to down-type fermions. Determination of couplings to down-type fermions requires measuring their direct decays from the Higgs boson. In this paper searches for Higgs decays to $\mu\mu$, $b\bar{b}$ and $\tau\tau$ will be discussed followed by a combination of the $b\bar{b}$ and $\tau\tau$ searches.

2. – Higgs to $\mu\mu$

In the SM decays of the Higgs boson to $\mu\mu$ are a very rare process with branching fractions on the order of 2.2×10^{-4} at $m_H = 125$ GeV. The CMS $\mu\mu$ analysis [3] is done with a total luminosity of 5.0fb^{-1} at 7 TeV and 19.7fb^{-1} at 8 TeV. The analysis is split into categories based on the number of reconstructed jets in the event, the transverse momentum of the $\mu\mu$ system and the psuedorapidity of the reconstructed muons.

The search is done looking for a resonant peak in the $\mu\mu$ mass spectrum coming from the combination of the Drell-Yan, $t\bar{t}$ and di-boson pair production backgrounds. A fit is done to the $M_{\mu\mu}$ distribution, Fig. 1, from the data. The signal is modeled with a double Gaussian function and the background is parameterized with a polynomial and an exponential term. The analysis shows no significant excess so an observed (expected) limit, Fig. 1, is set at $7.4(5.1^{+2.3}_{-1.5})$ times the SM expectation at 95% confidence for $m_{\mathrm{H}} = 125$ GeV.

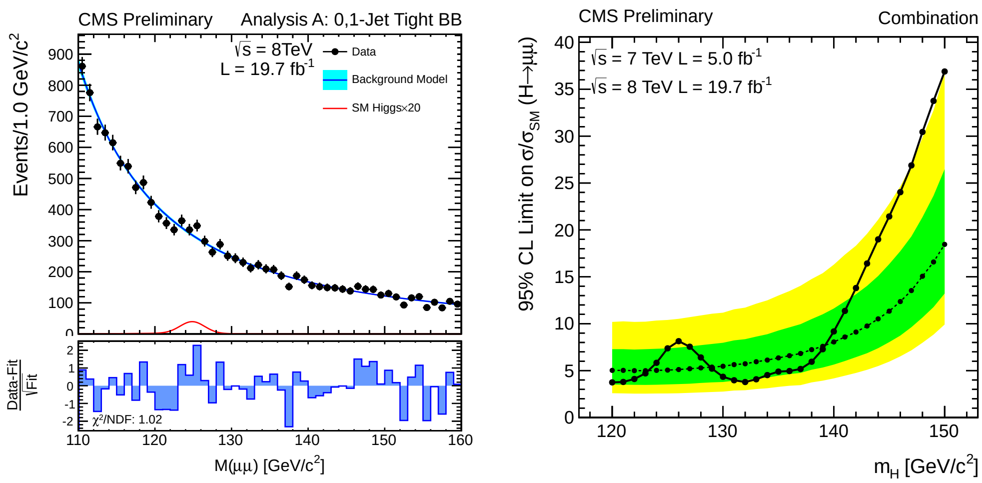

Fig. 1. – The dimuon invariant mass at $\sqrt{s} = 8$ TeV along with the fit used to estimate the background for the 0,1 Jet category with tight selection and both muons in the barrel region (Left). Expected and observed 95% CL Limit on $\sigma/\sigma_{\mathrm{SM}}$ as a function of m_{H} (Right).

3. – Higgs to $b\bar{b}$

A SM Higgs boson of $m_{\mathrm{H}} = 125$ GeV has a large branching fraction to $b\bar{b}$. Along with this large production rate also comes a large background from multi-jet events, therefore CMS searches [4] for $H \to b\bar{b}$ focus on Higgs boson production in association with a $W^{\pm}/Z$ boson. The CMS $b\bar{b}$ analysis is done with a total luminosity of 5.1fb^{-1} at 7 TeV and 18.9fb^{-1} at 8 TeV. The associated production analysis is done in a total of six topologies with a Z decaying to an electron pair, muon pair, a pair of neutrinos or a W decaying to an electron, muon or tau. A search for $H \to b\bar{b}$ with Vector Boson Fusion (VBF) production is also performed by CMS [5].

The associated production analysis utilizes a Boosted Decision Tree (BDT) to discriminate the Higgs boson signal from the backgrounds. The BDT includes event kinematics, b-jet tagging discriminators, and various system angles. The events are then categorized based on the transverse momentum of the vector boson. The analysis has a broad excess that is consistent with a Higgs boson of $m_{\mathrm{H}} = 125$ GeV. The excess has a significance of 2.1 standard deviations at $m_{\mathrm{H}} = 125$ GeV with a best fit $\mu = \sigma/\sigma_{\mathrm{SM}} = 1.0 \pm 0.5$.

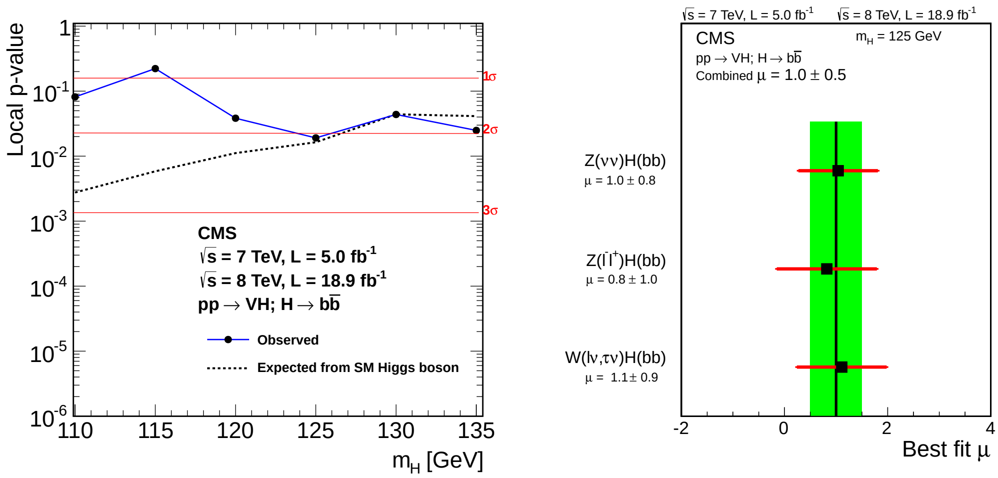

Fig. 2. – Local p-values and corresponding significance (measured in standard deviations) for the background-only hypothesis to account for the observed excess of events in the data for the $b\bar{b}$ VH analysis. (Left). The best-fit value of the production cross section for a 125 GeV Higgs boson relative to the standard model cross section, i.e., signal strength μ, for partial combinations of channels and for all channels combined (band) (Right).

4. – Higgs to $\tau\tau$

Searches for a Higgs boson decaying to a pair of taus are very important for probing the properties of a SM Higgs boson. The SM predicts a branching ratio to taus of approximately 6% for a 125 GeV Higgs boson. Due to smaller backgrounds and better resolution then $b\bar{b}$ searches, $\tau\tau$ searches offer the highest potential sensitivity for measuring direct coupling to fermions. The CMS search [6] is sensitive to gluon gluon fusion (ggF), vector boson fusion (VBF) along with associated Higgs (VH) production modes. Also the search is done in all six possible $\tau\tau$ decay channels: $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$, and $\tau_e\tau_e$ along with dedicated search channels for the VH modes. The CMS $\tau\tau$ analysis is done with a total luminosity of 4.9fb^{-1} at 7 TeV and 19.7fb^{-1} at 8 TeV.

The main $\tau\tau$ search is done in categories, Fig. 3, split by the number of jets, transverse momentum of the τ legs and the transverse momentum of the $\tau\tau$ system ($p_T^{\tau\tau}$), Fig. 4. Of particular interest are high sensitivity categories such as 1 jet categories with $p_T^{\tau\tau} >$ 100 GeV focusing on boosted ggF events and 2 jet categories requiring high M_{jj}, $\Delta\eta_{jj}$ and $p_T^{\tau\tau}$ that targets VBF production, Fig. 5. The categories are then combined in a maximum likelihood fit of the $\tau\tau$ system mass to search for the presence of a SM Higgs signal.

Important backgrounds in the $\tau\tau$ search include irreducible Drell Yan to $\tau\tau$ and reducible backgrounds W plus jets, QCD multi jet, $t\bar{t}$. Drell Yan to $\tau\tau$ is estimated using a data embedding technique which starts with real $\mu\mu$ events and replaces the muons with Monte Carlo taus. This technique gives jets, missing energy, pileup and underlying event from the original data which reduces systematic uncertainties. The rest of the important reducible backgrounds are measured using data driven techniques including fake rates and sidebands.

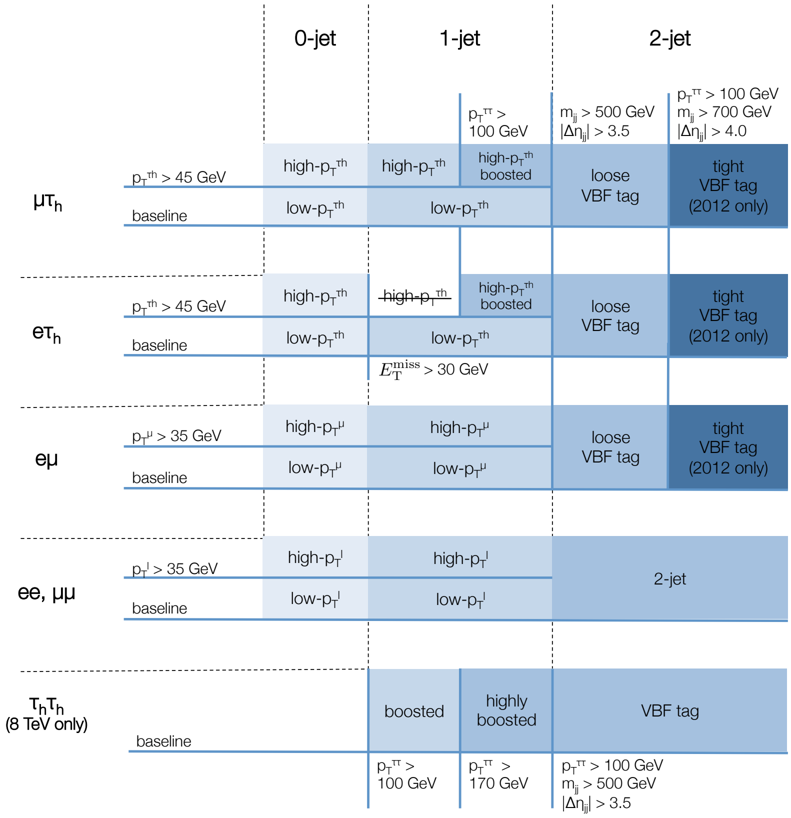

Fig. 3. – Event categories for the non-VH $\tau\tau$ analysis.

The analysis observes an excess of events over the background-only hypothesis with a local significance, Fig. 6, in excess of 3 standard deviations for Higgs boson mass hypotheses between mH = 115 and 130 GeV, and equal to 3.2 (3.7) standard deviations observed (expected) at $m_{\rm H}$ = 125 GeV. The best fit, Fig. 6, of the observed Higgs signal cross section for $m_{\rm H}$ = 125 GeV is 0.78 ± 0.27 times the standard model expectation. This constitutes evidence for a Higgs boson coupling to a pair of taus consistent with the boson observed in the ZZ and $\gamma\gamma$ searches.

5. – $\tau\tau/b\bar{b}$ Combination

In addition to the individual searches for the $b\bar{b}$ and $\tau\tau$ final states CMS has performed a combination [7] of the two searches. This combination results in a combined significance of 3.8 (4.4) standard deviations observed (expected) above the background only hypothesis for $m_{\rm H}$ = 125 GeV. The summary of this result along with the results from the individual channels is available in Table I. This result gives strong evidence for coupling of the 125 GeV Higgs boson to down-type fermions.

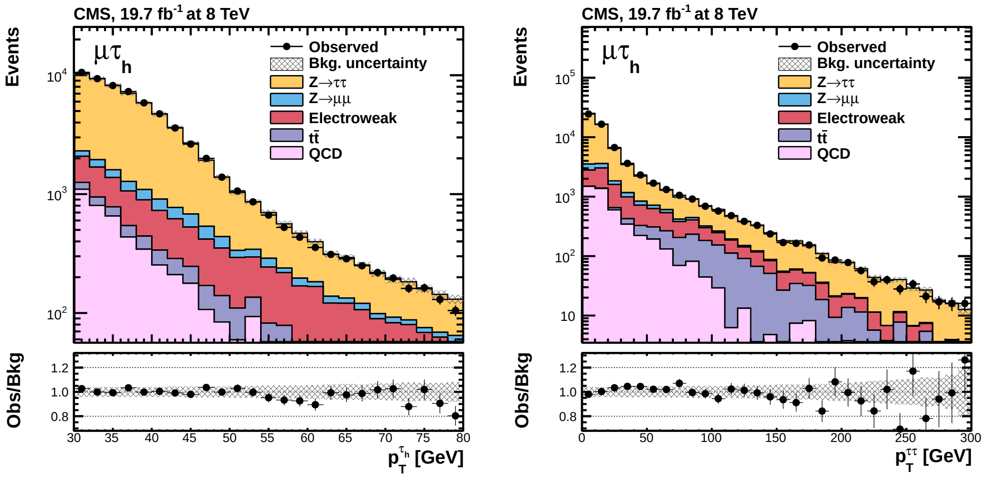

Fig. 4. – Observed and predicted distributions for the $\tau_\mu\tau_\mathrm{h}$ channel after event selection for the transverse momentum of the τ_h leg (Left) and the transverse momentum of the $\tau\tau$ system (right). The yields predicted for the various background contributions correspond to the result of the final fit. The "bkg. uncertainty" band represents the combined statistical and systematic uncertainty in the background yield in each bin.

6. – Summary

This paper presents a short review of the existing searches for Higgs to fermions done by the CMS collaboration. Searches for a Higgs boson decaying to $\mu\mu$, $\mathrm{b\bar{b}}$ and $\tau\tau$ were included. No significant excess in the $\mu\mu$ channel was observed so a limit was set at $7.4(5.1^{+2.3}_{-1.5})$ times the SM expectation at 95% confidence for m_H. In the $\mathrm{b\bar{b}}$ search an excess of 2.1 standard deviations was observed with a best-fit signal strength of $\mu = 1.0 \pm 0.5$. Also in the $\tau\tau$ search an excess is observed with an observed significance of 3.2 standard deviations and a best-fit of $\mu = 0.78 \pm 0.27$ for $m_\mathrm{H} = 125$ GeV. Lastly a combination was performed of the $\mathrm{b\bar{b}}$ and the $\tau\tau$ searches that resulted in a total observed significance of 3.8 standard deviations. This result gives strong evidence for coupling of the 125 GeV Higgs boson to down-type fermions.

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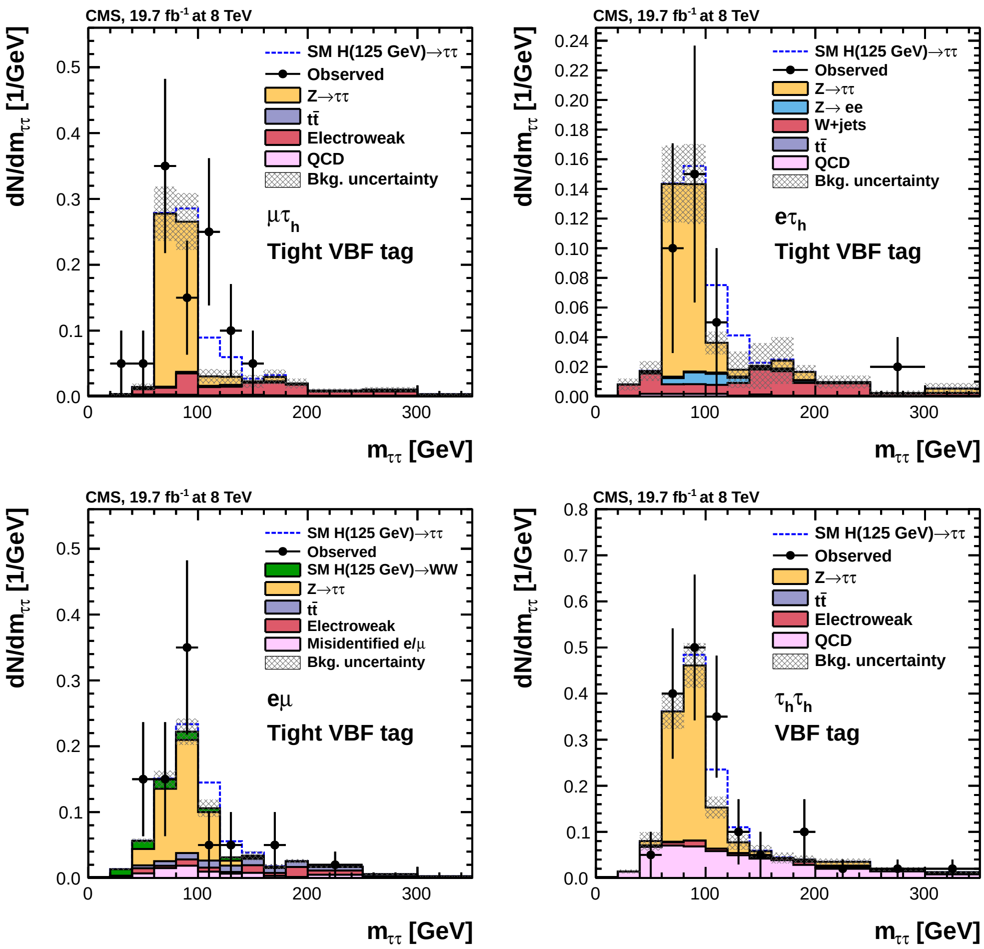

Fig. 5. – Mass distribution for the tight VBF categories in the $H \to \tau\tau$ search after the maximum likelihood fit. $\tau_\mu\tau_{\rm h}$ (Top Left), $\tau_{\rm e}\tau_{\rm h}$ (Top Right), $\tau_{\rm e}\tau_\mu$ (Bottom Left), $\tau_{\rm h}\tau_{\rm h}$ (Bottom Right)

Channel $m_H = 125$ GeV	Significance (σ) Expected	Observed	Best-fit μ
VH $\to$ b$\bar{\rm b}$	2.3	2.1	1.0 $\pm$ 0.5
H $\to \tau\tau$	3.7	3.2	0.78 $\pm$ 0.27
Combined	4.4	3.8	0.83 $\pm$ 0.24

TABLE I. – *Significance and best-fit* μ *value for the* b$\bar{\rm b}$ *and* $\tau\tau$ *channels and their combination*

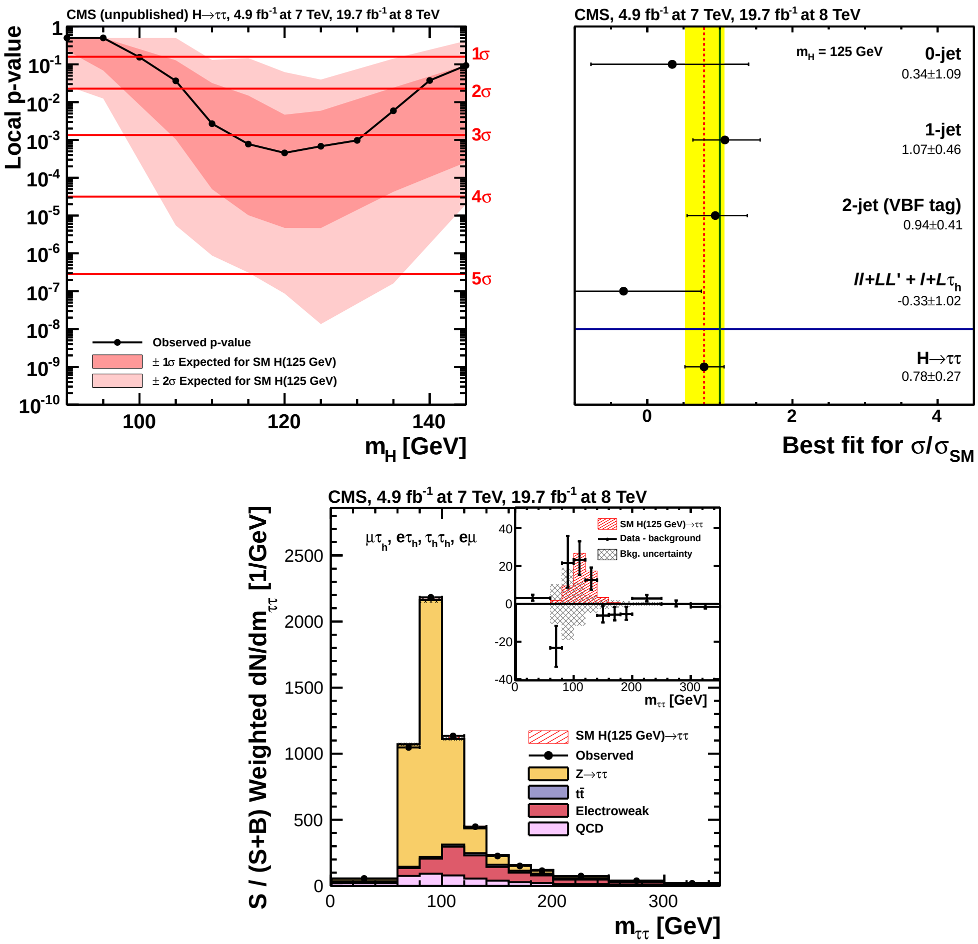

Fig. 6. – (Top Left) Local p-value and significance in number of standard deviations as a function of the SM Higgs boson mass for the combination of all decay channels. The observation (solid line) is compared to the red bands which correspond to 1 and 2 standard deviations from the expectation. (Top Right)Best-fit signal strength values, for independent categories for $m_{\mathrm{H}} = 125$ GeV. The combined value for the $\tau\tau$ analysis in both plots corresponds to $\mu = 0.78 \pm 0.27$. The dashed line corresponds to the best-fit μ value. (Bottom) The combined mass distribution for the $\tau_\mu\tau_{\mathrm{h}}$, $\tau_{\mathrm{e}}\tau_{\mathrm{h}}$, $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$, $\tau_{\mathrm{e}}\tau_\mu$ channels. The distributions obtained in each category of each channel are weighted by the ratio between the expected signal and signal-plus-background yields in each category. The inset shows the corresponding difference between the observed data and expected background distributions, together with the signal distribution for a SM Higgs boson at $m_{\mathrm{H}} = 125$ GeV.