Tests des Standardmodells der Teilchenphysik

Spezialfach Kern-Teilchen-Astrophysik

Tests of the Standard Model of Particles

Spring Semester 2018

Lecture 3

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Overview

Searches of the Higgs boson in fermionic decays

$H \to \tau\tau$

$H \to b\bar{b}$

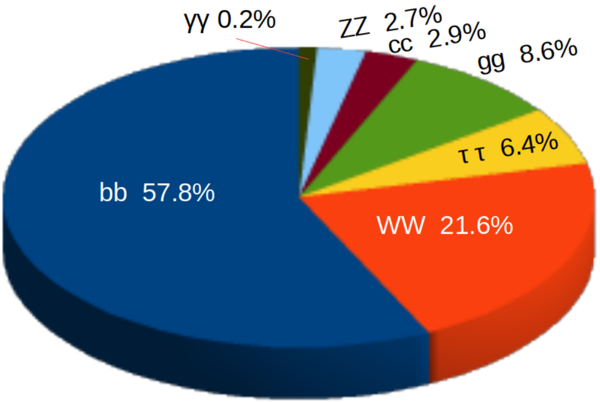
Combined LHC results - tests of the Higgs boson properties

Searching for the Higgs boson in fermionic decays

The Higgs boson interacts with all the massive elementary particles of the SM, including massive fermions: leptons and quarks.

For a Higgs mass of 125 GeV the SM predicts that the most common decay is into a bottomantibottom quark pair, which happens 57.8% of the time.

The second most common fermion decay at that mass is a tau-antitau pair, which happens only about 6.4% of the time.



Higgs discovery and measurements of its properties rely predominantly on studies of the bosonic decay modes: $H \to \gamma\gamma$, $H \to ZZ^*$ and $H \to WW^*$.

To establish the mass generation mechanism for fermions as implemented in the SM, it is of prime importance to demonstrate the direct coupling of the Higgs boson to fermions and the proportionality of its strength to mass.

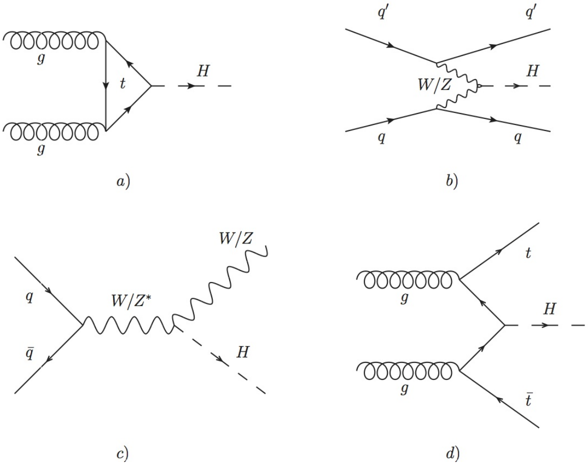
The most promising candidate decay modes are the decays into tau leptons, $H \to \tau\tau$, and bottom quarks (b-quarks), $H \to b\bar{b}$.

Due to the high background, the search for decays to $b\bar{b}$ is restricted to Higgs bosons produced in modes which have a more distinct signature but a lower cross-section, such as Higgs production with an associated vector boson.

The smaller rate of these processes in the presence of still large background makes their detection challenging.

More favorable signal-to-background conditions are expected for $H \to \tau\tau$ decays.

Production modes - reminder

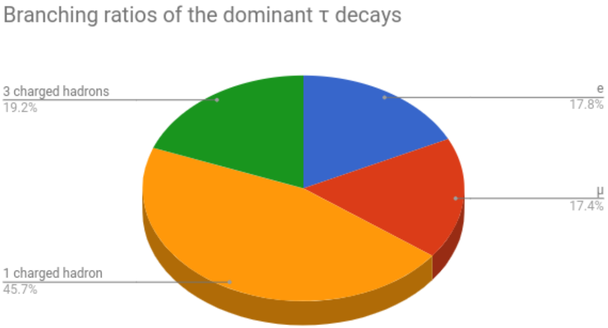


Diagrams of the main production mechanisms in pp collisions at LHC: a) gluon-gluon fusion (ggH), b) vector boson fusion (VBF), c) vector boson association (VH), d) $t\bar{t}$ association ($t\bar{t}H$)

$H \to \tau\tau$

Three distinct final states based on the decay mode of the tau leptons:

- lepton-lepton: both taus decay leptonically (BR=10.3%)
- lepton-hadron: one leptonic and one hadronic decay (BR=42.2%)
- hadron-hadron: both taus decay hadronically (BR=45.5%)



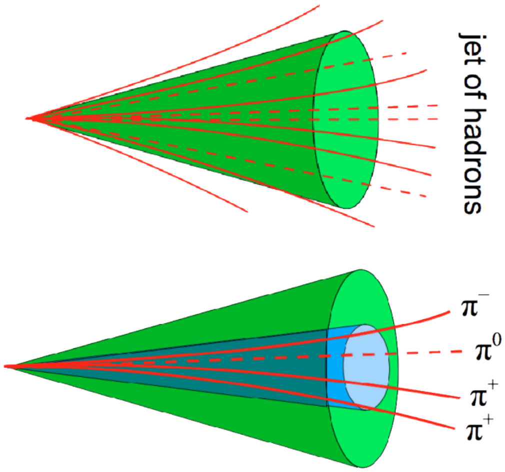


Figure 1: **Top:** decay of a QCD jet. **Bottom:** hadronic tau decay.

Identification of hadronic taus:

- visible decay products of hadronic decay are collimated in a narrow cone
- Exploit tracking and energy shower discriminant variables to distinguish taus from jets and electrons
- Use sophisticated machine learning techniques to select real taus and reject fake taus

Reconstruction of hadronic taus:

- hadronic jets with cone $\Delta R = 0.4$
- 1 or 3 charged tracks in inner cone $\Delta R < 0.2$ ("prongs")

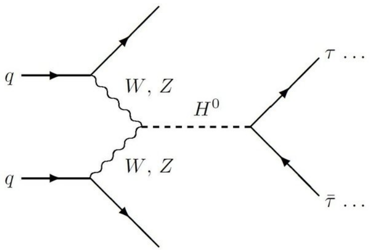


Figure 2: Vector boson fusion channel (VBF).

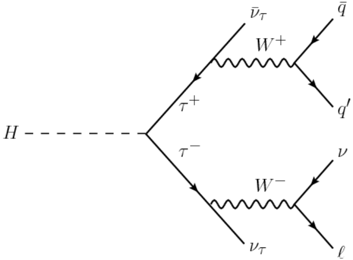


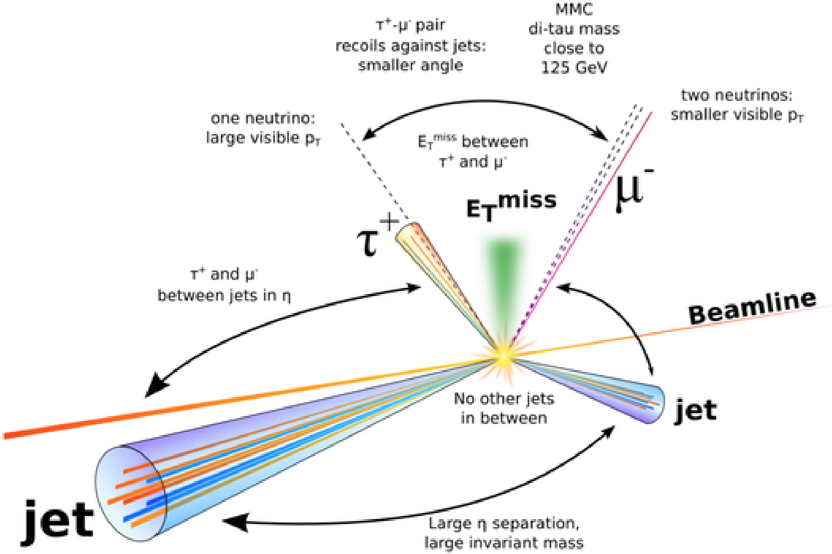
Figure 3: Leptonic and hadronic decay of a tau-pair stemming from the Higgs decay.

Topological signature of the "VBF category":

- forward-backward jet pair, each jet moves in opposite pseudorapidity detector hemishperes $\rightarrow$ large $\Delta\eta$ gap spanned by the edge jets

$$m_{jj} = \sqrt{m_1^2 + m_2^2 + 2\left(E_T^{(1)} E_T^{(2)} \cosh y - \boldsymbol{p}_T^{(1)} \cdot \boldsymbol{p}_T^{(2)}\right)} \quad \text{with} \quad y \simeq \eta \quad \text{for} \quad p \gg m \qquad (1)$$

- due to quark color conservation (t-channel), little jet activity is expected i nthe central region
- E_T^{miss} in the event


MMC
di-tau mass
close to
125 GeV
τ+-μ- pair
recoils against jets:
smaller angle
two neutrinos:
smaller visible pT
one neutrino:
large visible pT
ET miss between
τ+ and μ-
ETmiss
μ-
τ+
τ+ and μ-
between jets in η
Beamline
jet
No other jets
in between
Large η separation,
large invariant mass
jet

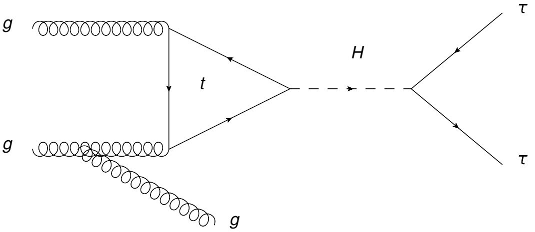


Figure 4: Gluon-gluon fusion channel (ggH).

The "boosted category" contains events where the reconstructed Higgs boson candidate has a large transverse momentum.

It is dominated by events produced via gluon fusion with additional jets from gluon radiation.

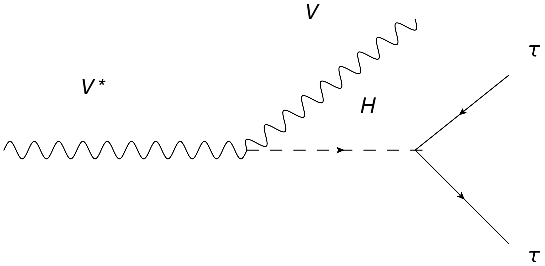
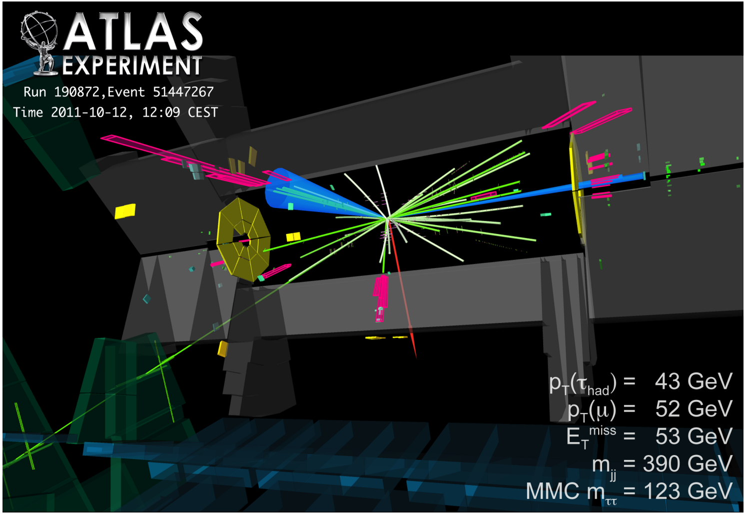


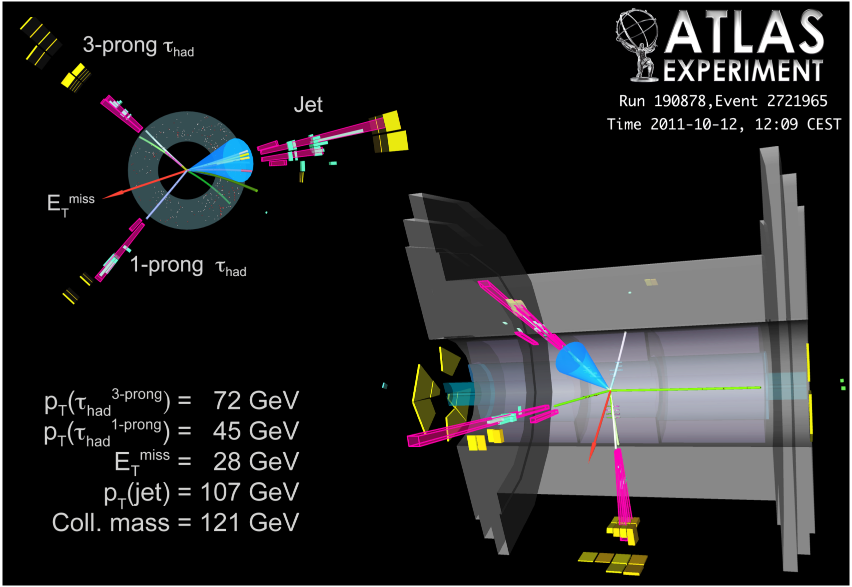
Figure 5: Associated production (VH) with $V = W$ or Z.

The "VH category" exploits events with a $H \to \tau\tau$ and $V \to \ell\ell$ decays. It has the smallest production cross-section but quite a distinct signature.

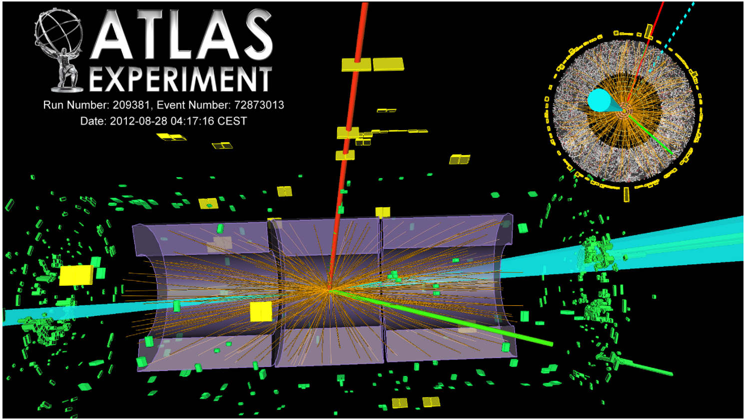
ATLAS search at $\sqrt{s} = 7,\, 8$ TeV:



Event display of a $H \to \tau\tau \to \tau_\mu \tau_{\mathrm{had}}$ + 2 forward jets in a VBF event candidate.

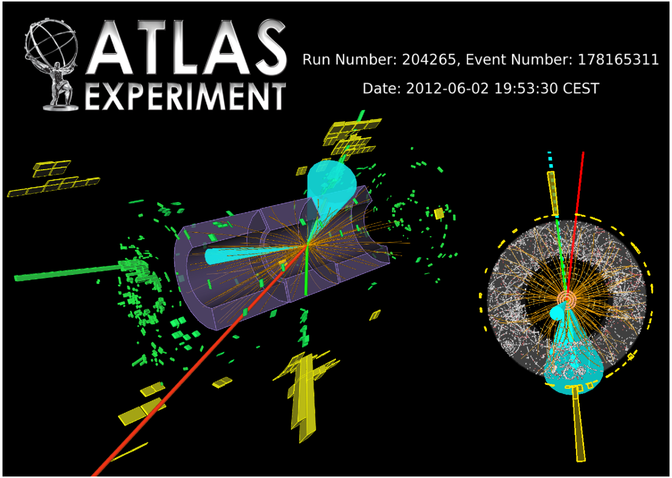


Event display of a $H \to \tau\tau \to \tau_{\text{had}}\tau_{\text{had}} + 1$ high-p_T jet.



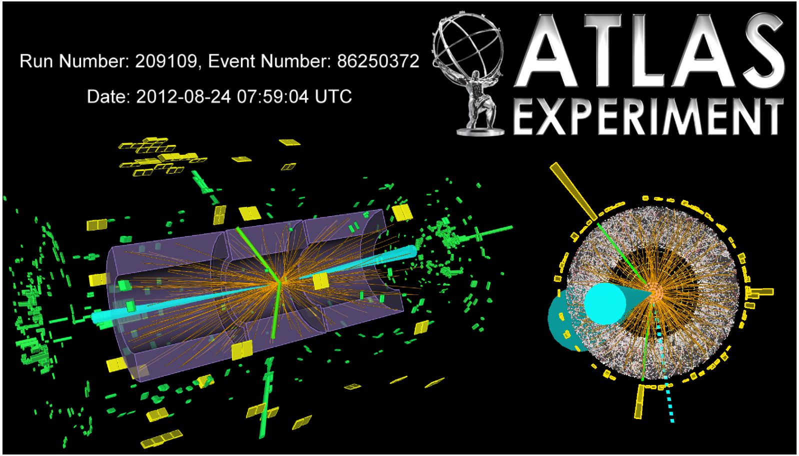
Display of an event selected by the $H \to \tau\tau \to \tau_\ell\tau_\ell$ $(\ell = e,\ \mu)$ analysis in the VBF category, where one τ decays to an electron and the other to a muon.

The electron is indicated by a green track and the muon indicated by a red track. The dashed line represents the direction of the E_T^{miss} vector, and there are two VBF jets marked with turquoise cones. The muon p_T is 20 GeV, the electron p_T is 17 GeV, $E_T^{\text{miss}} = 43$ GeV, $m_{\text{jj}} = 1610$ GeV and $m_{\tau\tau} = 126$ GeV.

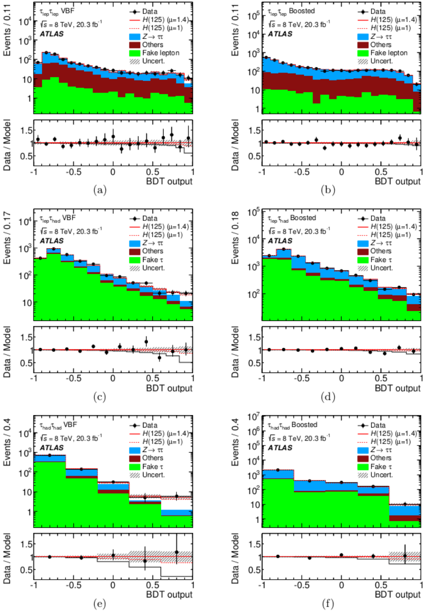


Display of an event selected by the $H \to \tau\tau \to \tau_\ell \tau_{\text{had}}$ ($\ell = e, \mu$) analysis in the VBF category, where one μ decays to a muon.

The hadronically decaying τ lepton (1 prong decay) is indicated by a green track and the muon is indicated by a red track. The dashed line represents the direction of the $E_T$miss vector, and there are two VBF jets marked with turquoise cones. The muon p_T is 63 GeV, the τ_{had} candidate pT is 96 GeV, $E_T\text{miss} = 119$ GeV, $m_{\text{jj}} = 625$ GeV and $m_{\tau\tau} = 129$ GeV.



Display of an event selected by the $H \to \tau\tau \to \tau_{\text{had}}\tau_{\text{had}}$ analysis in the VBF category. The τ_{had} candidates are indicated by green tracks. The dashed line represents the direction of the $E_T$miss vector, and there are two VBF jets marked with turquoise cones. The transverse momenta of theτ_{had} candidates are 56 GeV and 49 GeV, $E_T\text{miss} = 26$ GeV, $m_{jj} = 408$ GeV GeV and $m_{\tau\tau} = 131$ GeV.



Train Boosted Decision Trees (BDT) to teach the machine how to distinguish signal from background events, separately for each channel (lep-lep, lep-had, had-had) and category (VBF, ggH)

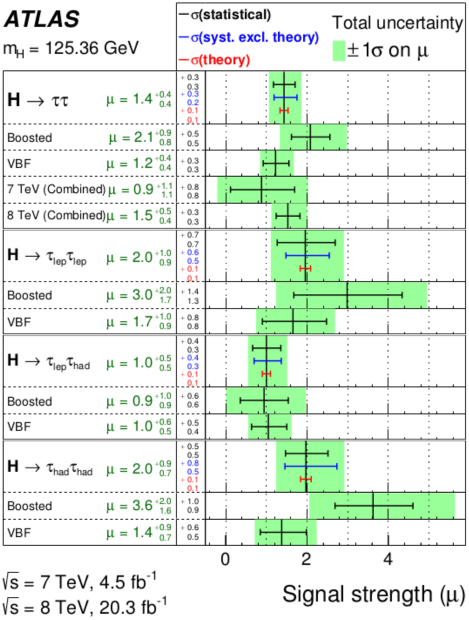
Apply the BDT training on data and simulation, and distribute the result.

Excess of events is seen in bins with high BDT scores, i.e. where the signal-like events lie.

Ref.: JHEP 04 (2015) 117, ATLAS collaboration.

The best-fit value for the signal strength $\mu = \sigma\ \sigma_{\mathsf{SM}}$ in the individual channels and their combination for the full ATLAS datasets at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

The signal strength obtained from the combined $H \to \tau\tau$ analysis is ~ 1.4.

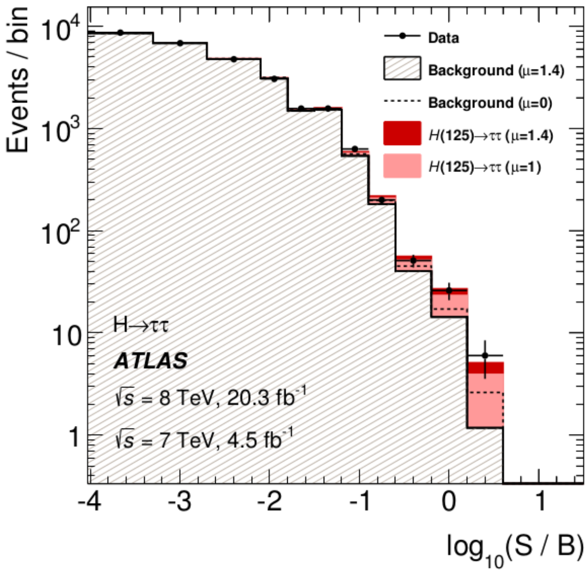


Event yields as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from the BDT output bin of each event, assuming a signal strength $\mu = \sigma\ \sigma_{\mathsf{SM}} = 1.4$ (best fit).

Events in all categories are included.

The predicted background is obtained from the global fit.

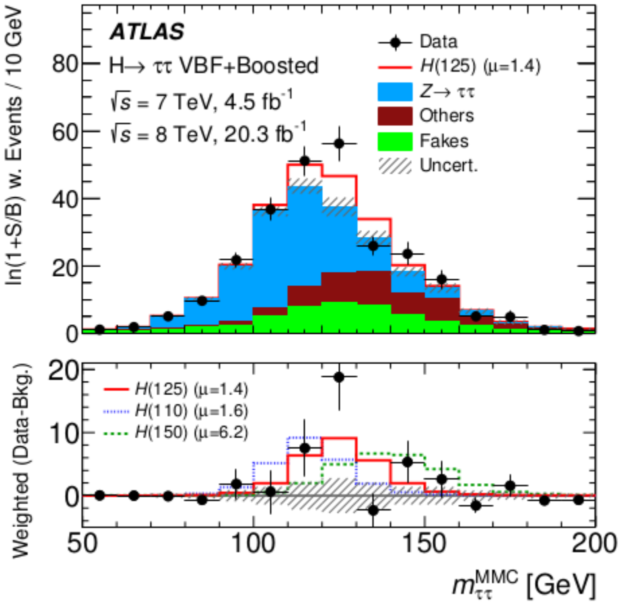
Clear excess of $H \to \tau\tau$ events is seen.



To visualise the compatibility of this excess of events above background predictions with the SM Higgs boson at $m_H = 125$ GeV, a weighted distribution of events as a function of the $m_{\tau\tau}$ is shown.

The events are weighted by a factor of $\ln(1 + S/B)$, which enhances the events compatible with the signal hypothesis.

The excess of events in this mass distribution is consistent with the expectation for a Standard Model Higgs boson with $m_H = 125$ GeV with significance 4.5σ (observed) and 3.3σ (expected) $\rightarrow$ evidence!



CMS analysis at $\sqrt{s} = 7\ 8\ \mathrm{TeV}$:

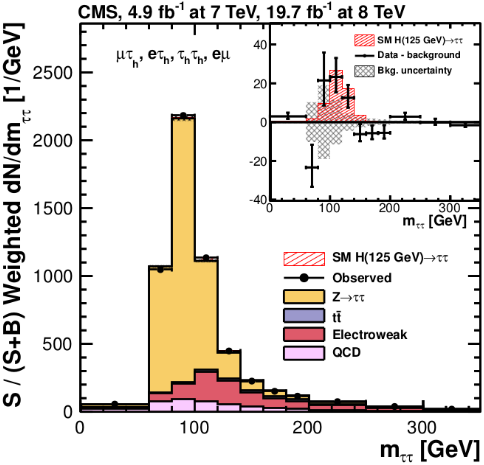
- Cut-based analysis targeting VBF and ggH production modes
- Define search regions based on jet multiplicity:
  - 0-jet: targets Higgs boson events produced via gluon fusion
  - 1-jet: targets Higgs boson events produced via VBF
  - 2-jet: contains all the events that do not enter one of the previous categories
- The invariant mass of the visible tau decays, m_{vis}, and using the $E_T \mathrm{miss}$ information, $m_{\tau\tau}$, are the main discriminants
- The $m_{\tau\tau}$ distributions are combined for the $\tau_\ell\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_e\tau_\mu$ channels

The normalization of the predicted background distributions corresponds to the result of the global fit.

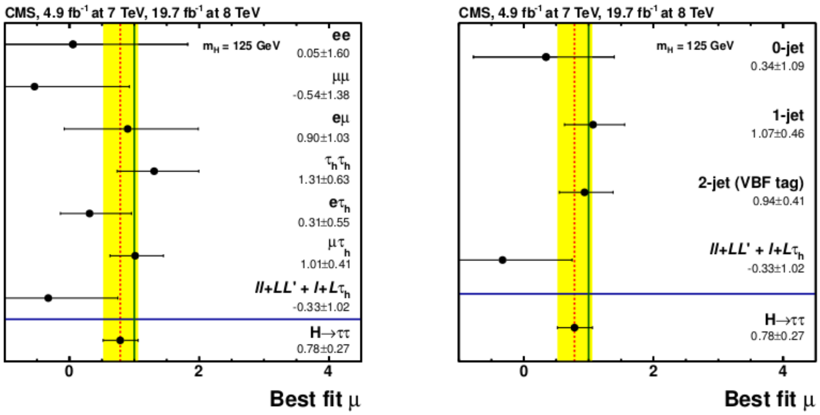
The signal distribution, on the other hand, is normalized to the SM prediction ($\mu = 1$).

The distributions obtained in each category of each channel are weighted by the ratio between the expected signal and signal-plus-background yields in the category, obtained in the central $m_{\tau\tau}$ interval containing 68% of the signal events.

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 $m_H = 125$ GeV.



Ref.: J. High Energy Phys. 05 (2014) 104, CMS collaboration.

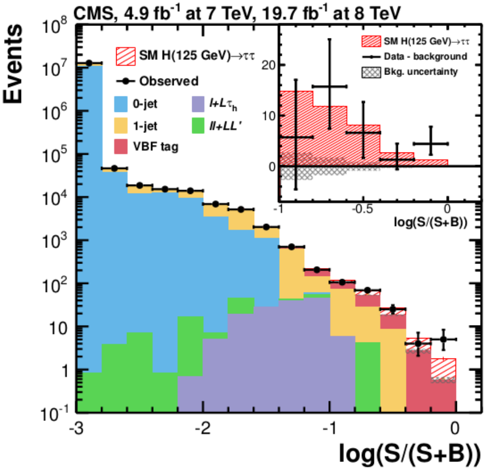


Best-fit signal strength values, for independent channels (left) and categories (right), for $m_H = 125$ GeV.
The combined value in both plots corresponds to $\hat{\mu} = 0.78 \pm 0.27$, obtained in the global fit combining all categories of all channels. The dashed line corresponds to the best-fit μ value.

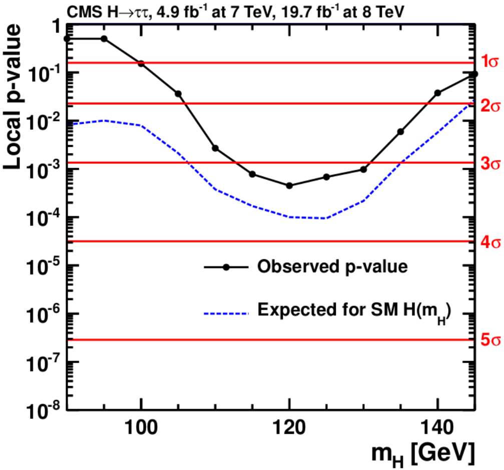
Combined observed and predicted distributions of the decimal logarithm $\log(S/(S+B))$ in each bin of the final reconstructed di-tau mass or discriminator distributions obtained in all event categories and decay channels, with $S/(S+B)$ denoting the ratio of the predicted signal and signal-plus-background event yields in each bin.

The normalization of the predicted background distributions corresponds to the result of the global fit.

The signal distribution, on the other hand, is normalized to the SM prediction ($\mu = 1$).

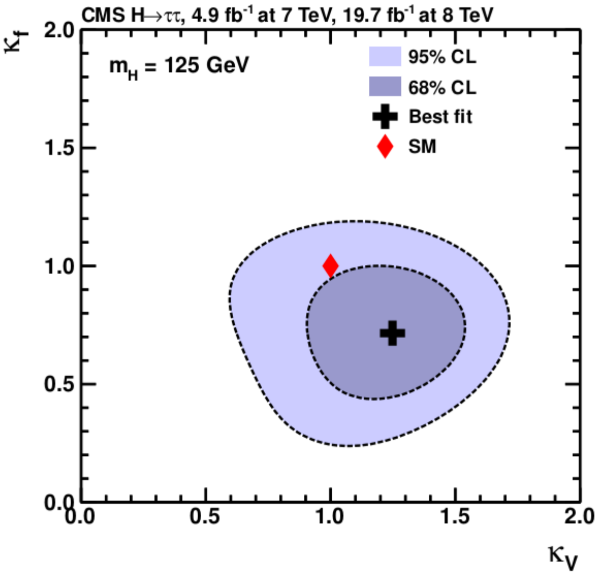


The inset shows the corresponding difference between the observed data and expected background distributions, together with the signal distribution for a SM Higgs boson at $m_H = 125\ \mathrm{GeV} \rightarrow$ evidence for the coupling between the τ lepton and the 125 GeV Higgs boson!



An excess of events over the background-only hypothesis is observed with a local significance in excess of 3 standard deviations for Higgs boson mass hypotheses between $m_H = 115$ and 130 GeV, and equal to 3.2 standard deviations at $m_H = 125$ GeV, to be compared to an expected significance of 3.7 standard deviations.

Local p-value and significance in number of standard deviations as a function of the SM Higgs boson mass hypothesis for the combination of all decay channels.

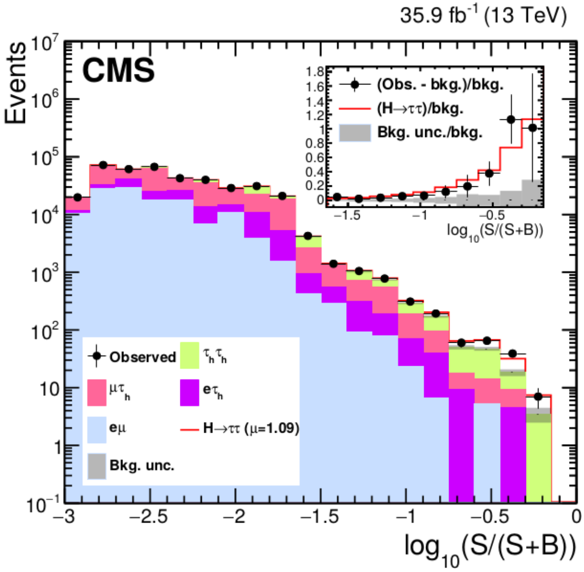


A likelihood scan in the two-dimensional (κ_V, k_f) parameter space for $m_H = 125$ GeV.

The κ_V and κ_f parameters quantify the ratio between the measured and the SM value for the coupling of the Higgs boson to vector bosons and fermions, respectively.

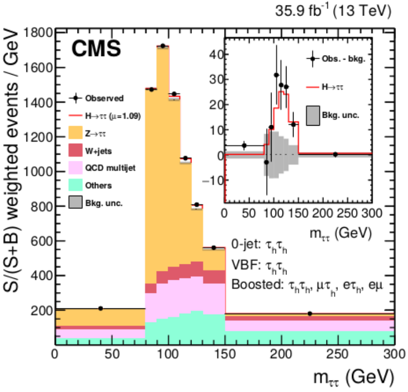
The observed likelihood contour is consistent with the SM expectation of $\kappa_V = 1$, $k_f = 1$.

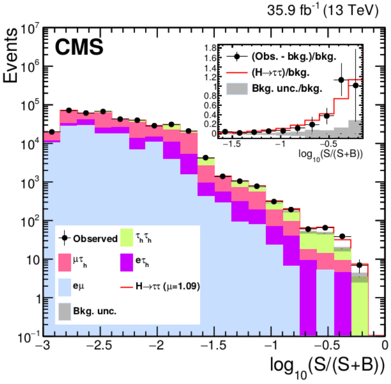
CMS search at $\sqrt{s} = 13$ TeV:



Grouping events in the signal region by their decimal logarithm of the ratio of the signal (S) to signal-plus-background (S + B) in each bin, an excess of observed events with respect to the SM background expectation is clearly visible in the most sensitive bins of the analysis.

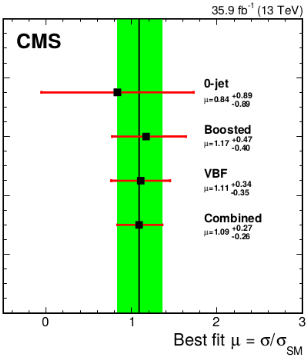
Ref.: Phys. Lett. B 779 (2018) 283, CMS Collaboration

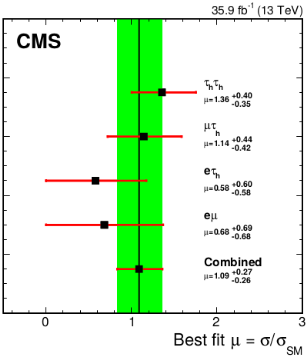




▷ Combined observed and predicted $m_{\tau\tau}$ distributions. ▷ Every mass distribution for a constant range of the second dimension of the signal distributions has been summed with a weight of $S/(S+B)$ to increase the contribution of the most sensitive distributions.

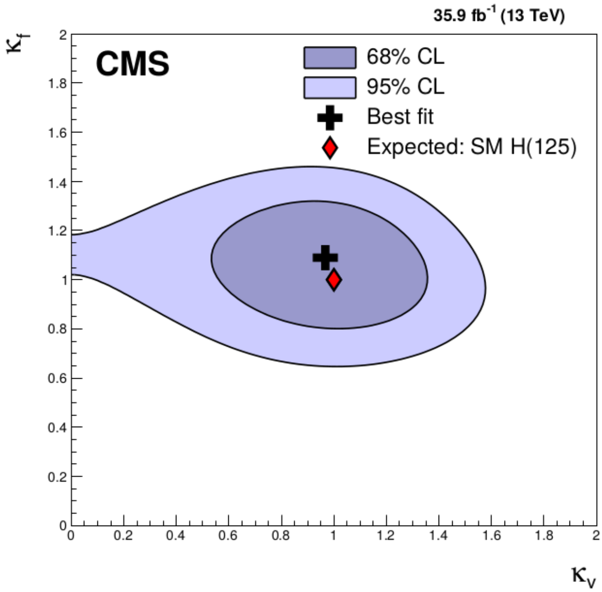
▷ The excess in data is quantified by calculating the corresponding local p-value using a profile likelihood ratio test statistic. ▷The observed significance for a SM Higgs boson with $m_H = 125.09$ GeV is 4.9σ, for an expected significance of 4.7σ.





Best fit signal strength per category (left) and channel (right), for $m_H = 125.09\ \mathrm{GeV}$.

The combination of the measurements at $\sqrt{s} = 7, 8$ and $13\ \mathrm{TeV}$ with the CMS detector leads to the first observation by a single experiment of decays of the Higgs boson to pairs of τ leptons, with a significance of 5.9σ!

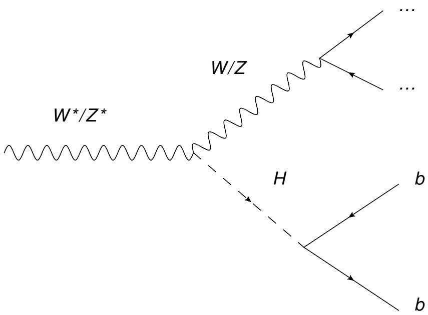


The observed likelihood contour is consistent with the SM expectation of κ_V and κ_f equal to unity.

$H \to b\bar{b}$

The decay of the SM Higgs boson into pairs of b-quarks is expected to have a branching ratio of 58% for $m_H = 125\ \text{GeV}$, the largest among all decay modes.

Accessing $H \to b\bar{b}$ decays is crucial for constraining the overall Higgs boson decay width.

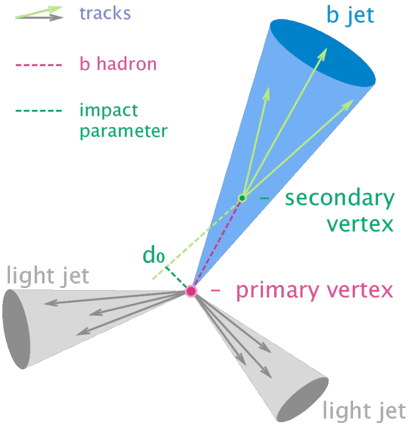


At the LHC, the very large backgrounds arising from multi-jet production make an inclusive search extremely challenging.

The most sensitive production modes for probing $H \to b\bar{b}$ decays are those where the Higgs boson is produced in association with a W or Z boson; their leptonic decay modes lead to clean signatures, while rejecting most of the multi-jet backgrounds.

B-tagging using unique features of b-jets:

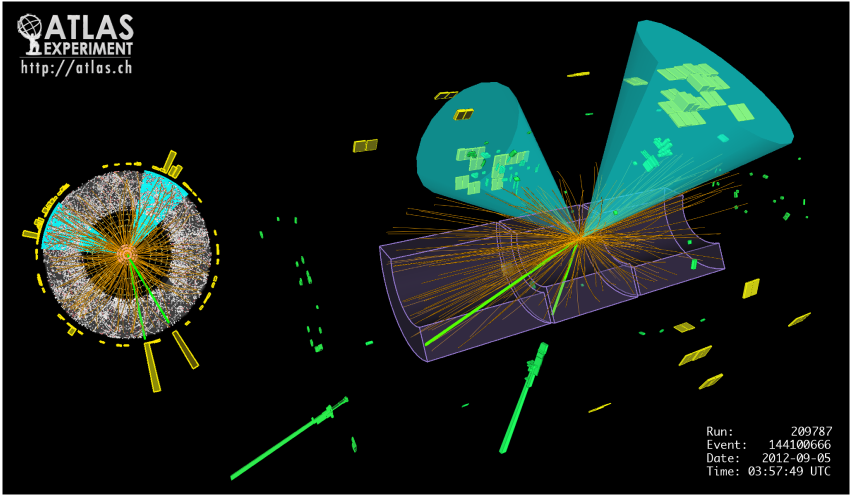
- Hadrons containing bottom quarks have sufficient lifetime that they travel some distance before decaying inside the detector.
- The bottom quark is much more massive (bare mass ~ 4.2 GeV) than anything it decays into: its decay products tend to have higher transverse momentum (momentum perpendicular to the original direction of the bottom quark, and therefore of the b-jet).
- This causes b-jets to be wider, have higher multiplicities (numbers of constituent particles) and invariant masses, and also to contain low-energy leptons with momentum perpendicular to the jet.
- These two features can be measured, and jets that have them are more likely to be b-jets.



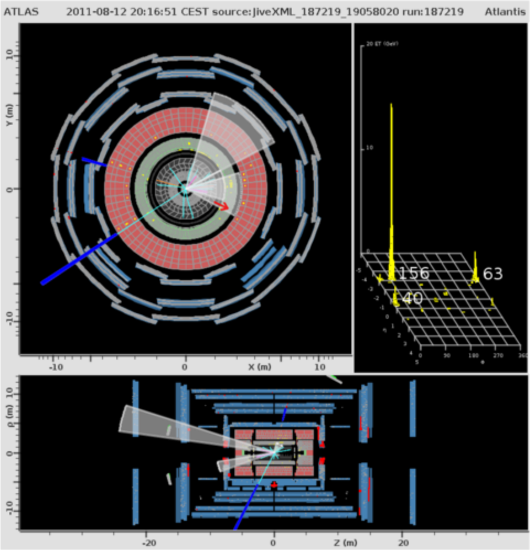
b-quark lifetime: $\sim \times 10^{-12}$ s which can travel $d = \gamma c \tau \simeq 10 \times 3 \times 10^{11} \frac{\text{mm}}{\text{s}} \times 10^{-12}\ \text{s} = 3\ \text{mm}$ assuming $\gamma = E/m_{\text{hadron}} \simeq 50\ \text{GeV}/5\ \text{GeV} = 10$

ATLAS search at $\sqrt{s} = 7,\ 8,\ 13\ \mathrm{TeV}$:

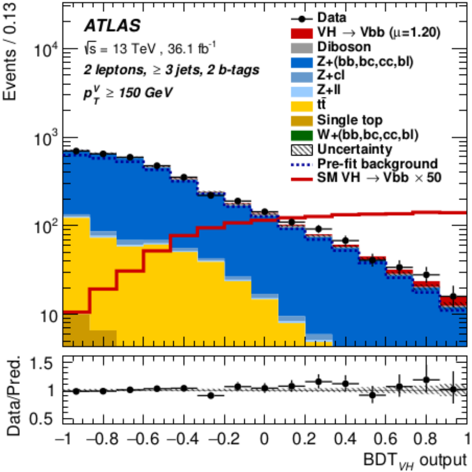
- Three main signatures are explored, $ZH \to \nu\nu b\bar{b}$, $WH \to \ell\nu b\bar{b}$ and $ZH \to \ell\ell b\bar{b}$.
- The respective analysis categories that target these decay modes are referred to as the 0-, 1- and 2-lepton channels, based on the number of selected charged leptons (e or μ).
- A b-tagging algorithm is used to identify the jets consistent with originating from a $H \to b\bar{b}$ decay.
- In order to maximize the sensitivity to the Higgs boson signal, a set of observables encoding information about event kinematics and topology is combined into a multivariate discriminant.
- A binned maximum-likelihood fit, referred to as the global likelihood fit, is applied to data simultaneously across the 3 channels in multiple analysis regions.
- The likelihood fit uses the multivariate discriminant as the main fit observable, in order to extract the signal yield and normalizations of the main backgrounds.
- Multivariate discriminants making use of boosted decision trees (BDTs) are constructed, trained and evaluated in each lepton channel and analysis region separately.



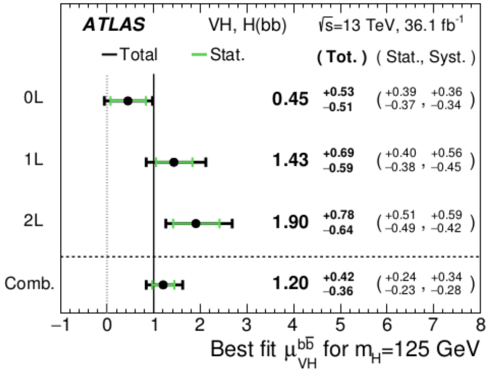
Display of a Higgs boson candidate event with two selected leptons. The two identified b-jets have transverse momenta of 70 GeV and 65 GeV, respectively, with an invariant mass of 122 GeV. The identified electrons have transverse momenta of 63 GeV and 54 GeV, respectively, resulting in a transverse momentum of the Z boson candidate of 115 GeV.



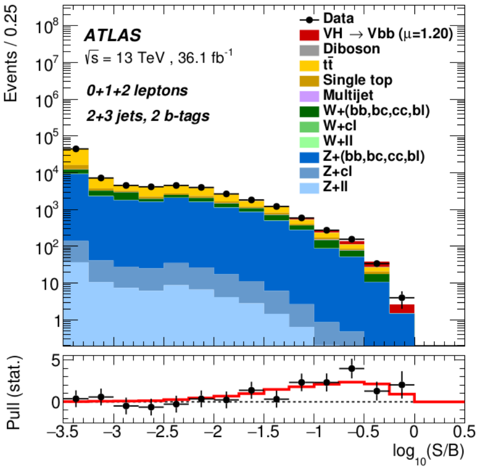
Another $HZ \to \mu\mu b\bar{b}$ event candidate. Ref.: HIGG-2012-08.



The BDT output distribution after the fit for the "$N = 2$ leptons, $N \geq 3$ jets, $N = 2$ b-tagged jets" category.



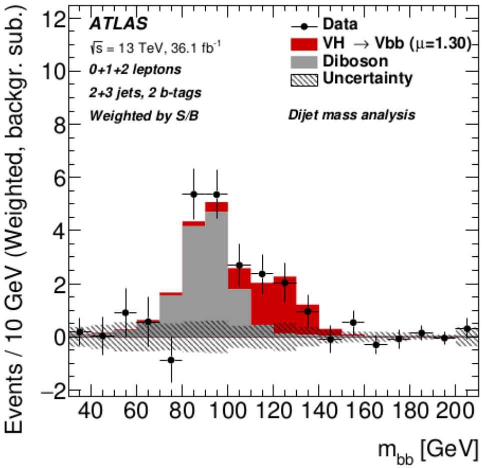
The fitted values of the Higgs boson signal strength parameter μ for $m_H = 125$ GeV for the WH and ZH processes and their combination at $\sqrt{s} = 13$ TeV. Ref.: JHEP 12 (2017) 024, ATLAS Collaboration



Event yields as a function of $\log(S/B)$ for data, background and a Higgs boson signal with $m_H = 125$ GeV.

Final-discriminant bins in all regions are combined into bins of $\log(S/B)$, with the fitted signal being S and the fitted background B.

The Higgs boson signal contribution is shown after rescaling the SM cross-section according to the value of the signal strength parameter extracted from data ($\mu = 1.2$).

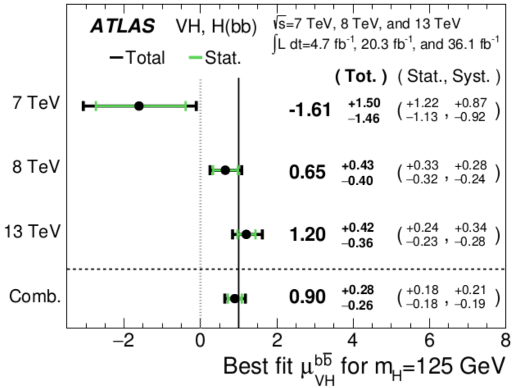


The distribution of m_{bb} in data after subtraction of all backgrounds except for the WZ and ZZ diboson processes.

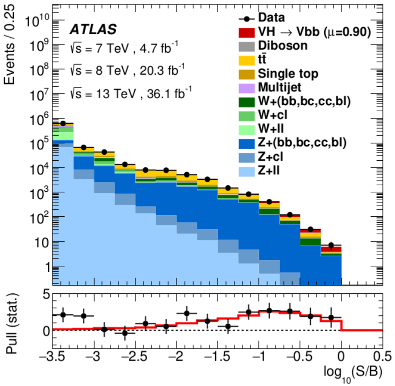
The expected contribution of the associated WH and ZH production of a SM Higgs boson with $m_H = 125\ \mathrm{GeV}$ is shown scaled by the measured combined signal strength ($\mu = 1.3$).

The observed excess has a significance of 3.5 standard deviations, in comparison to an expectation of 2.8 standard deviations.

Combination of all analyses:



The fitted values of the Higgs boson signal strength parameter μ.



Event yields as a function of log(S/B) for data, background and Higgs boson signal with $m_H = 125$ GeV.

The measured signal strength with respect to the SM expectation is found to be $\mu \simeq 0.9$.

An excess over the expected Standard Model background is observed, with a significance of 3.6 standard deviations compared to an expectation of 4.0.

Assuming the Standard Model production strength, the result is consistent with the value of the Yukawa coupling to bottom quarks in the Standard Model.

Evidence for a Standard Model Higgs boson decaying into a $b\bar{b}$ pair and produced in association with a W or Z boson.

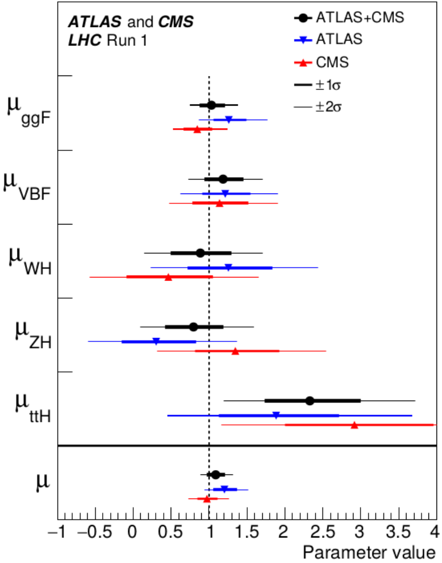
Combined ATLAS & CMS searches at $\sqrt{s} = 7, 8$ TeV

Best fit results for the production signal strengths for the combination of ATLAS and CMS data.

The error bars indicate the 1σ (thick lines) and 2σ (thin lines) intervals.

The measurements of the global signal strength μ are also shown.

Ref.: JHEP08(2016)045, ATLAS/CMS

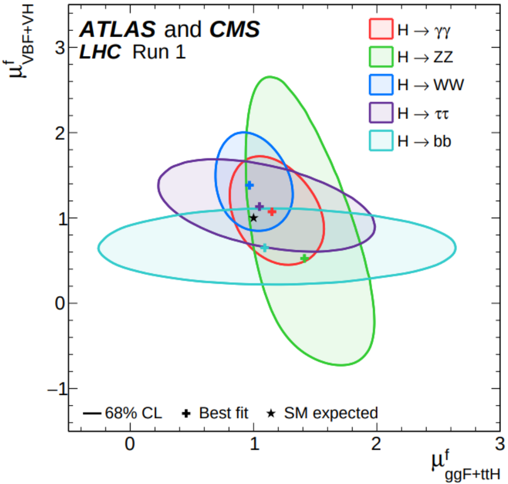


Negative log-likelihood contours at 68% CL in the signal strength plane ($\mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}$) of the VBF and ggH processes, for the combination of ATLAS and CMS.

The result is obtained from a fit of the five decay channels $H \to ZZ$, $H \to WW$, $H \to \gamma\gamma$, $H \to \tau\tau$, and $H \to bb$.

The best fit values obtained for each of the five decay channels are also shown, together with the SM expectation.

Without any additional assumptions about the Higgs boson branching fractions the fit yields: $\mu_V/\mu_F = 1.09^{+0.36}_{-0.28}$, in nice agreement with the SM!



Coupling modifiers - testing the Higgs couplings in the SM:

Coupling modifiers are introduced to interpret the LHC data by introducing specific modifications of the Higgs boson couplings related to Beyond SM physics.

The production and decay of the Higgs boson can be factorized, such that the cross section times branching fraction of an individual channel $\sigma(i \to H \to f)$ contributing to a measured signal yield can be parameterized as:

$$\sigma_i \times \mathrm{BR}^f = \frac{\sigma(\boldsymbol{\kappa}) \times \Gamma^f(\boldsymbol{\kappa})}{\Gamma_H} \tag{2}$$

where

- Γ_H: total width of the Higgs boson
- Γ^f: partial width for Higgs boson decay to the final state f.

A set of coupling modifiers, $\boldsymbol{\kappa}$, is introduced to parameterize possible deviations from the SM predictions of the Higgs boson couplings to SM bosons and fermions.

For a given production process or decay mode, denoted j, a coupling modifier κ_j is defined such that:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{\mathrm{SM}}} \tag{3}$$

All SM cross sections and branching fractions include the best available higher-order QCD and EW corrections.

▷ In SM, all k_j values equal unity.

For example, the coupling modifiers κ_g and κ_γ describe the loop processes for ggH production and $H \to \gamma\gamma$ decay.

Also, the Higgs boson production cross sections and partial decay widths are only sensitive to products of coupling modifiers and not to their absolute sign.

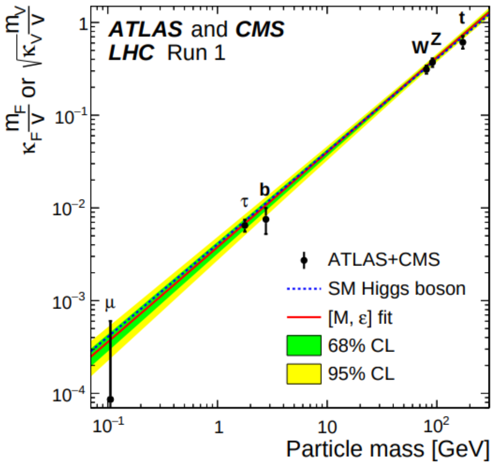
Best fit values as a function of particle mass for the combination of ATLAS and CMS data in the case of the κ parameterization, with parameters defined as

- $\gamma_F \times \frac{m_F}{v}$ for the fermions
- $\sqrt{\kappa_V} \times \frac{m_V}{v}$ for the weak vector bosons

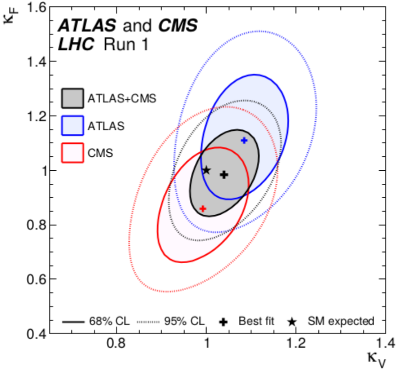
where $v = 246$ GeV is the vacuum expectation value of the Higgs field.

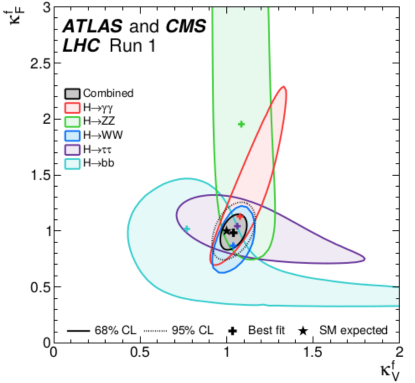
The dashed blue line indicates the predicted dependence on the particle mass in the case of the SM Higgs boson.

The solid red line indicates the best fit result to a phenomenological model with the corresponding 68% and 95% CL bands.



Results of the scan for the global coupling modifiers as well as those obtained separately for each experiment:





Negative log-likelihood contours at 68% and 95% CL in the (κ_F, κ_V) plane for the combination of ATLAS and CMS and for the global fit of all channels. Also shown are the contours obtained for each experiment separately.

Negative log-likelihood contours at 68% CL in the (κ_F^f, κ_V^f) plane for the combination of ATLAS and CMS and for the individual decay channels as well as for their global combination (κ_F, κ_V) assuming that all coupling modifiers are positive.

Synopsis

The observation of the Higgs boson in fermionic decays is fundamental to establish that the observed resonance at $125\ \mathrm{GeV}$ is the SM Higgs boson.

Plethora of stringent tests of the Higgs boson production and decay rates, as well as constraints on its couplings to vector bosons and fermions have been performed and combined by the LHC experiments at $\sqrt{s} = 7$ and $8\ \mathrm{TeV}$.

All results are in agreement with the SM prediction!

The combined signal yield relative to the Standard Model prediction is measured to be $\mu = 1.09 \pm 0.11$.

Appendix

By choosing the z-axis to be the beam direction, then the energy and momentum of a particle can be written as

$$E = m_T \cosh y, \quad p_x, \quad p_y, \quad p_z = m_T \sinh y \tag{4}$$

where m_T, conventionally called "transverse mass" of the particle, is given by

$$m_T^2 = m^2 + p_x^2 + p_y^2 \tag{5}$$

Rapidity y is defined by

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} = \ln \frac{E + p_z}{m_t} = \tanh^{-1} \left(\frac{p_z}{E} \right) \tag{6}$$