Measurements of the Higgs boson properties at the ATLAS experiment

SEBASTIAN OLIVARES ON BEHALF OF THE ATLAS COLLABORATION

PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

1ST MEDITERRANEAN CONFERENCE ON HIGGS PHYSICS, TANGIER, MOROCCO

Outline

- Introduction to the properties of the Higgs boson

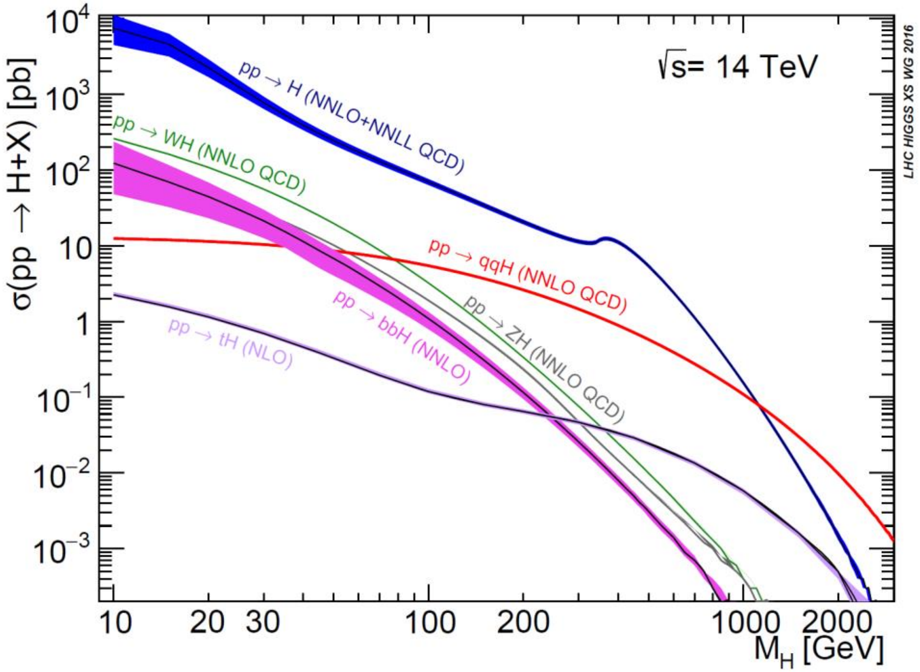
- Measurement of the properties at the ATLAS detector:
  - Mass
  - Spin and parity quantum numbers
  - Couplings
  - Fiducial cross-sections
  - Total decay width

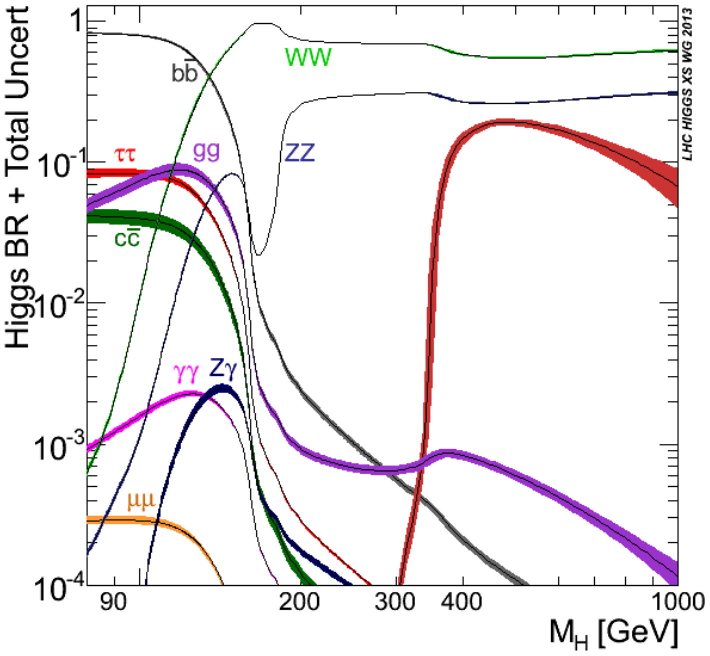
- Conclusion

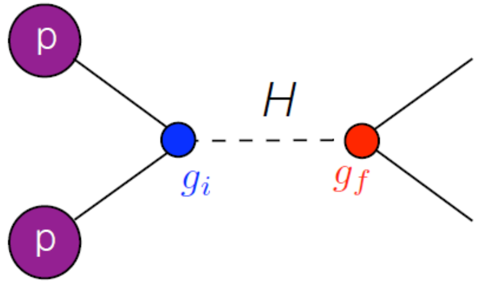
Standard model before Higgs discovery

- The Standard Model (SM) it's a extremely successful theory that has **19 free parameters** (considering massless neutrinos)

- The **Higgs boson is related to most of them**
  - **masses of the elementary particles** (including the Higgs boson) and their **couplings** to the Higgs boson
  - **Higgs vacuum expectation value (VEV)**



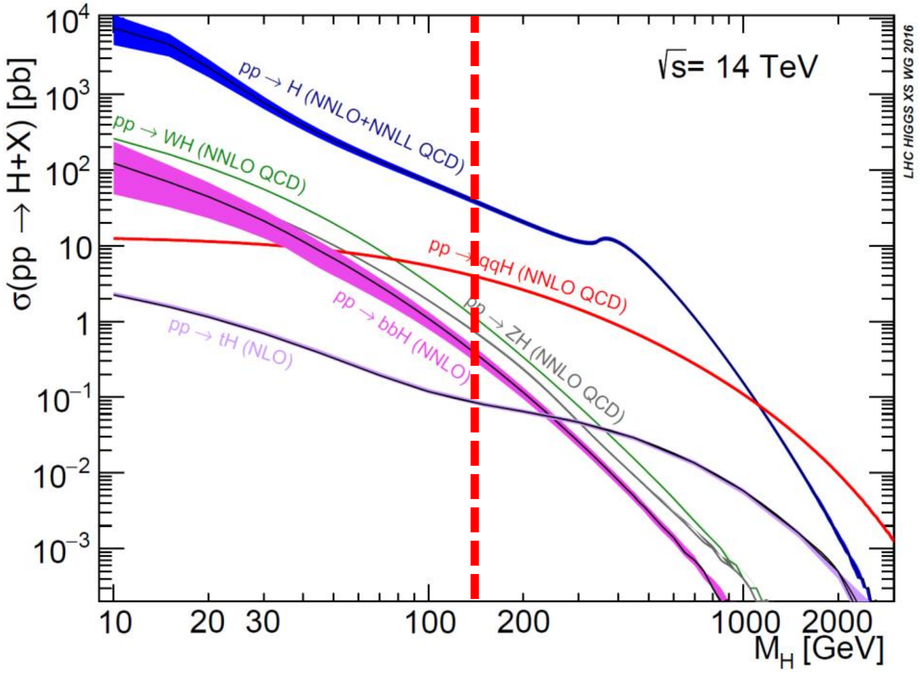


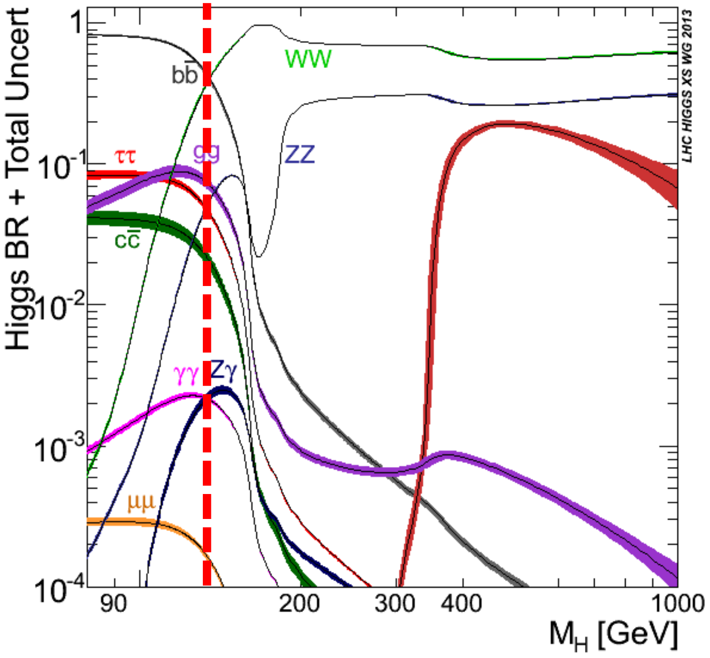


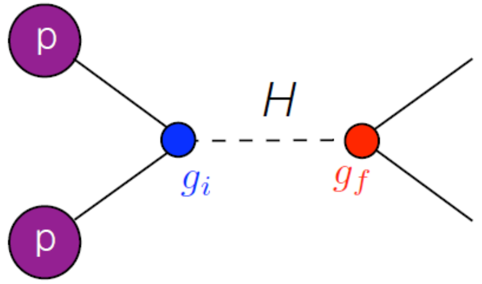
$$g_{Hff} = \frac{m_f}{v} \qquad g_{HVV} = \frac{2m_V^2}{v}$$

Standard model after Higgs discovery

- But roughly all the parameters are **correlated**; so each time a particle was discovered more **than one parameter were fixed**
- The last elementary particle discovered, in 2012 by the ATLAS and CMS collaborations, was the Higgs boson, **but it's the one predicted by the SM?**







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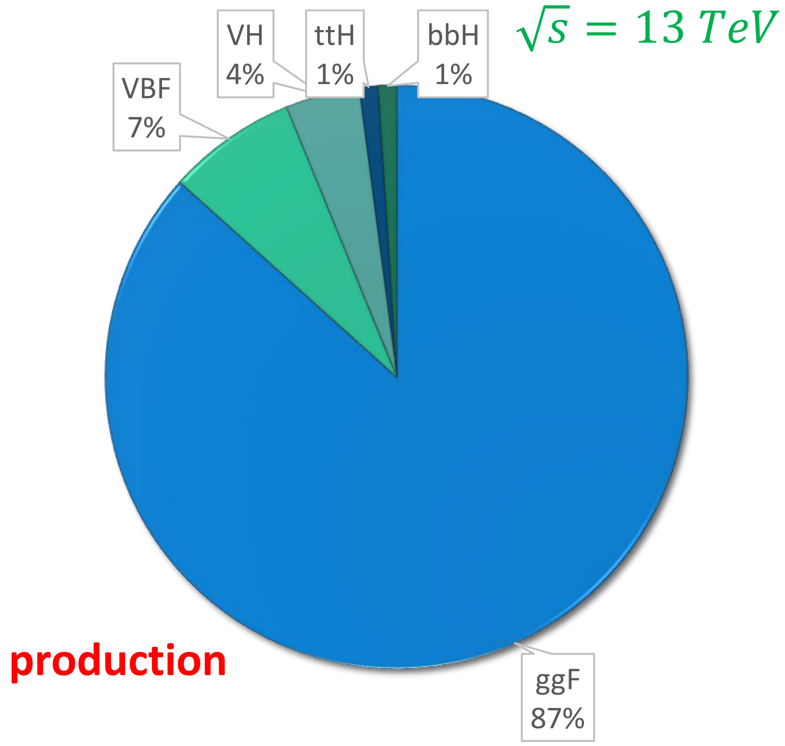

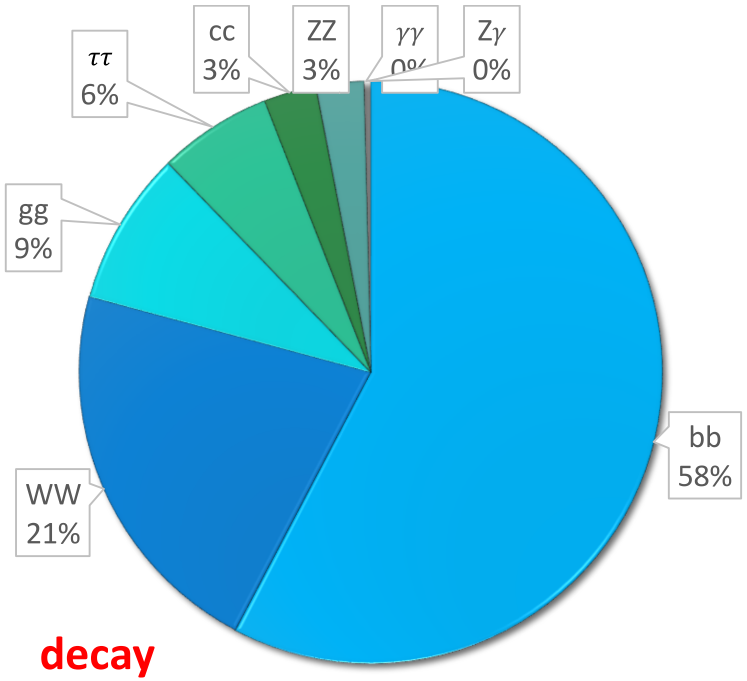

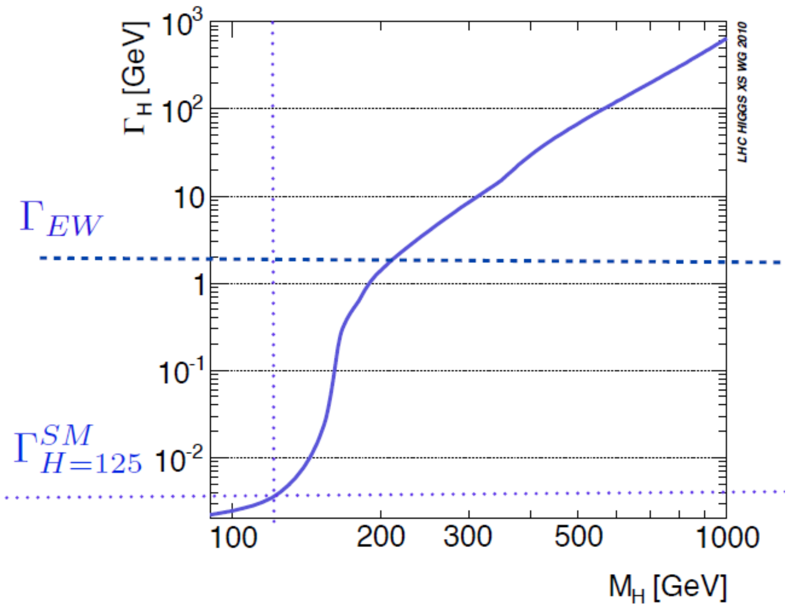

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- But roughly all the parameters are **correlated**; so each time a particle was discovered more than **one parameter were fixed**

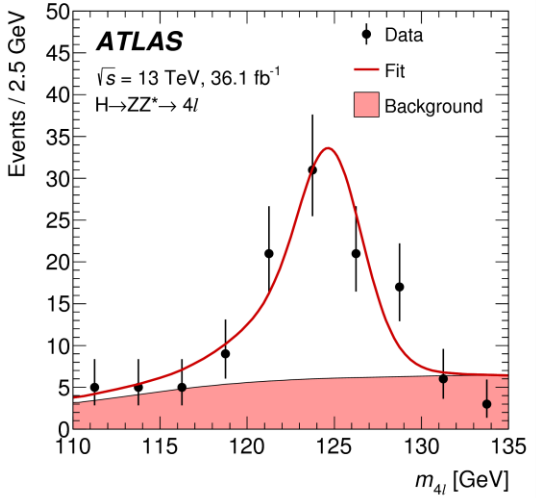
- The last elementary particle discovered was the Higgs boson, **but it's the one predited by the SM?**

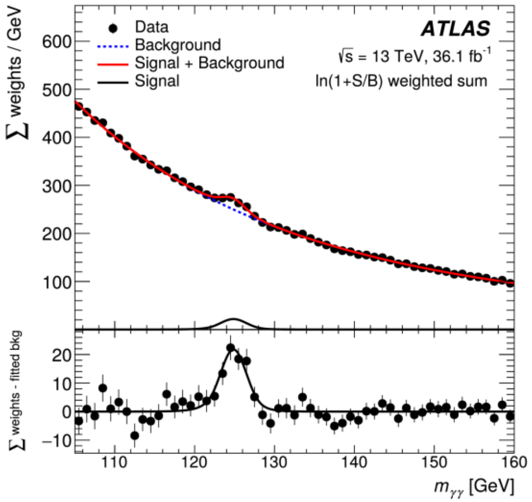
- **We need to study its properties!**
  - Mass
  - Spin and parity quantum numbers
  - Couplings
  - Total decay width

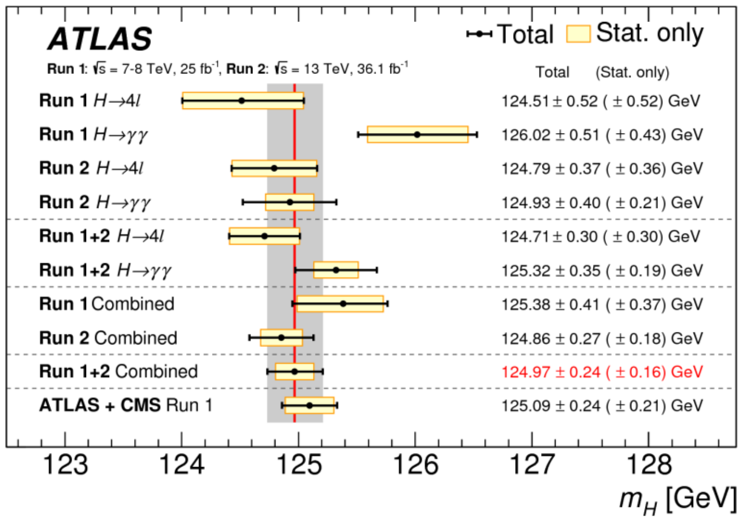
Mass

❖ Phys.Lett. B784 (2018) 345-366

- ATLAS+CMS latest publication 20 fb^{-1} at $\sqrt{s} = 7{,}8\ TeV$ (using $\mathrm{H} \rightarrow ZZ^* \rightarrow 4l$ and $\mathrm{H} \rightarrow \gamma\gamma$): $\mathbf{125.09 \pm 0.21}(\boldsymbol{stat}) \pm \mathbf{0.11}(\boldsymbol{syst})$ **GeV**
- ATLAS Run1+Run2 latest combination 36.1 fb^{-1} at $\sqrt{s} = 13\ TeV$ (using $\mathrm{H} \rightarrow ZZ^* \rightarrow 4l$ and $\mathrm{H} \rightarrow \gamma\gamma$): $\mathbf{124.97 \pm 0.16}(\boldsymbol{stat}) \pm \mathbf{0.13}(\boldsymbol{syst})$ **GeV**
- $\boldsymbol{m_{4l}}$ **modeled as the convolution of a relativistic BW** distribution of 4.1 MeV width and a peak at the central value
- $\boldsymbol{m_{\gamma\gamma}}$ measured from the position of a narrow resonant peak over a large monotonically decreasing background, which is modelled with a **double-sided Crystal ball function**
- The mass is extracted from a simultaneous profile likelihood fit on both channels







Spin/CP

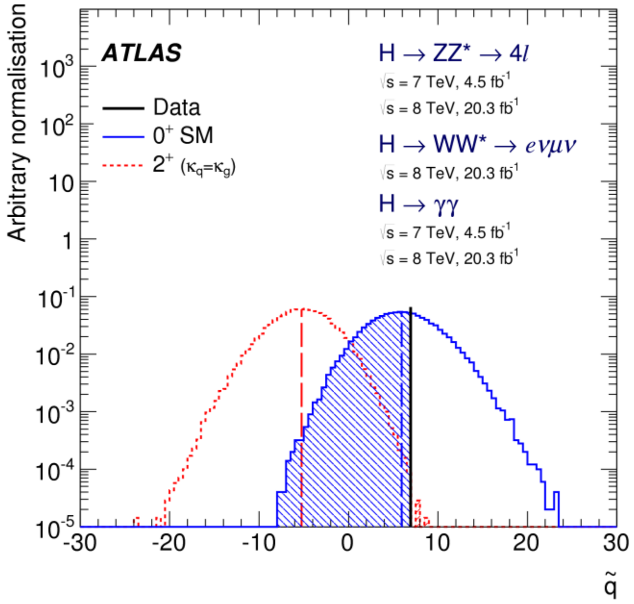
- Eur.Phys.J. C75 (2015) no.10, 476
- Eur.Phys.J. C76 (2016) no.12, 658

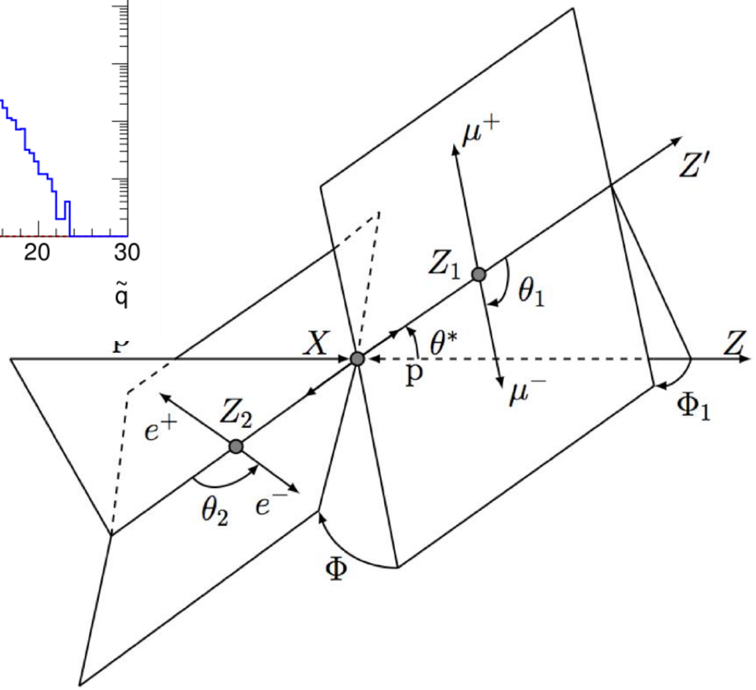
- The Standard Model (SM) Higgs boson hypothesis, corresponding to the quantum numbers $\boldsymbol{J^P = 0^+}$, was tested against several alternative spin scenarios, including non-SM spin-0 and spin-2 models with universal and non-universal couplings to fermions and vector bosons

- ATLAS combined bosonic channels ($\mathrm{H} \to ZZ^* \to 4l$, $\mathrm{H} \to WW^* \to 2l2\nu$ and $\mathrm{H} \to \gamma\gamma$) **excluded all tested alternative hypothesis in favour of the SM Higgs boson at more tan 99.9% confidence level (CL)**

- A first direct test of CP invariance in Higgs boson production via vector-boson fusion (VBF) with the $\mathrm{H} \to \tau^+\tau^-$ decay channel showed no sign of CP violation

- **Compatible with CMS results**

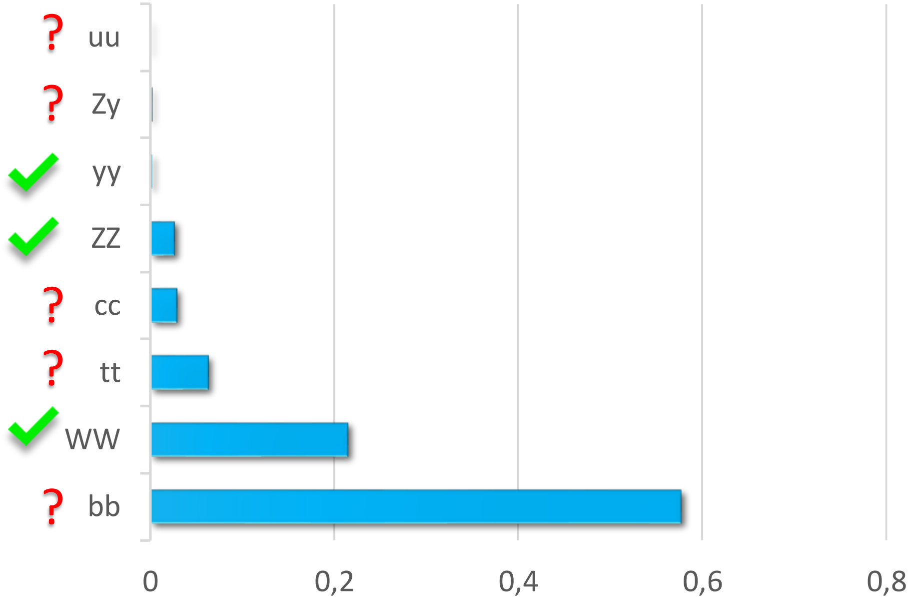




Couplings

- At the LHC experiments, the rates of production and decay modes into a particular final state are parametrised using a parameter called **“signal strength”** (μ), defined as:

$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$



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JHEP 1608 (2016) 045

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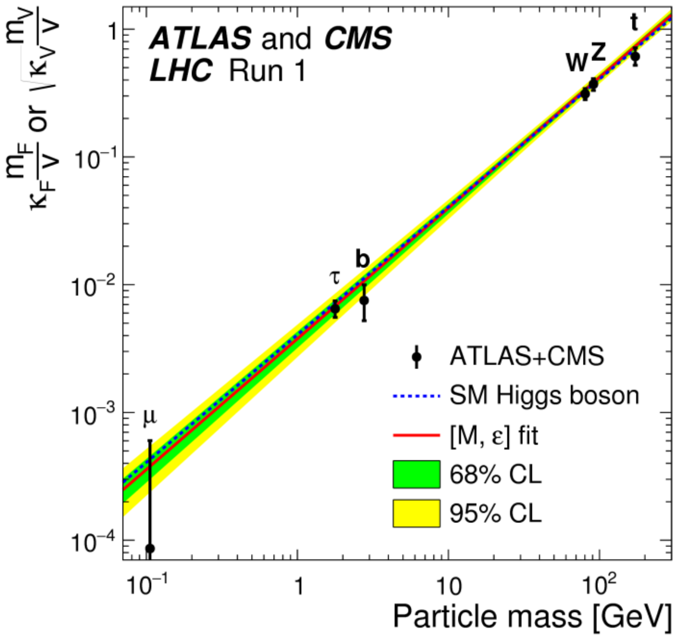
- According to the latest ATLAS and CMS combination, couplings to vector bosons are found to be compatible with those expected from the SM within an approximate 10% uncertainty, while in the case of heavier SM fermions, the uncertainty is of the order of 15-20%. **Beyond Stardard Model (BSM) scenarios are still possible**



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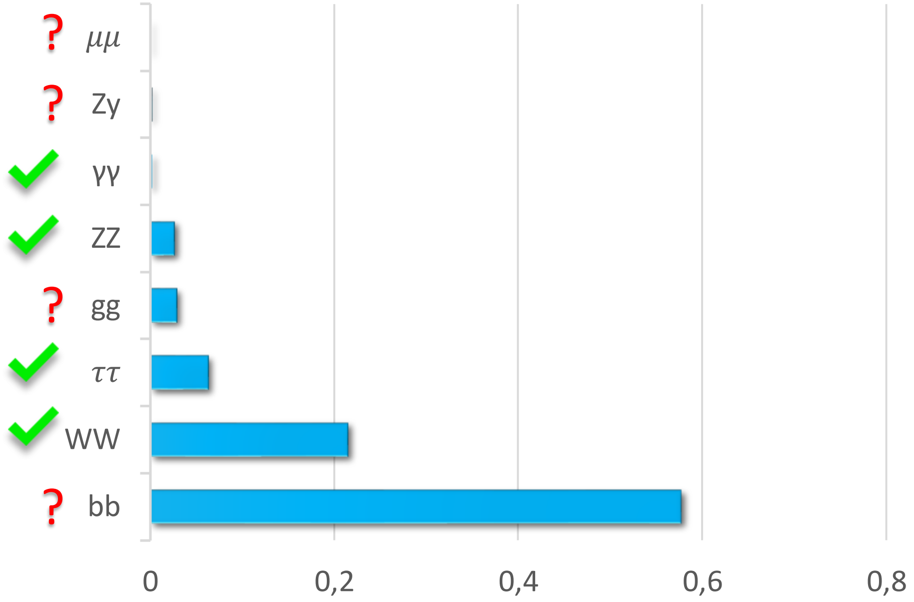

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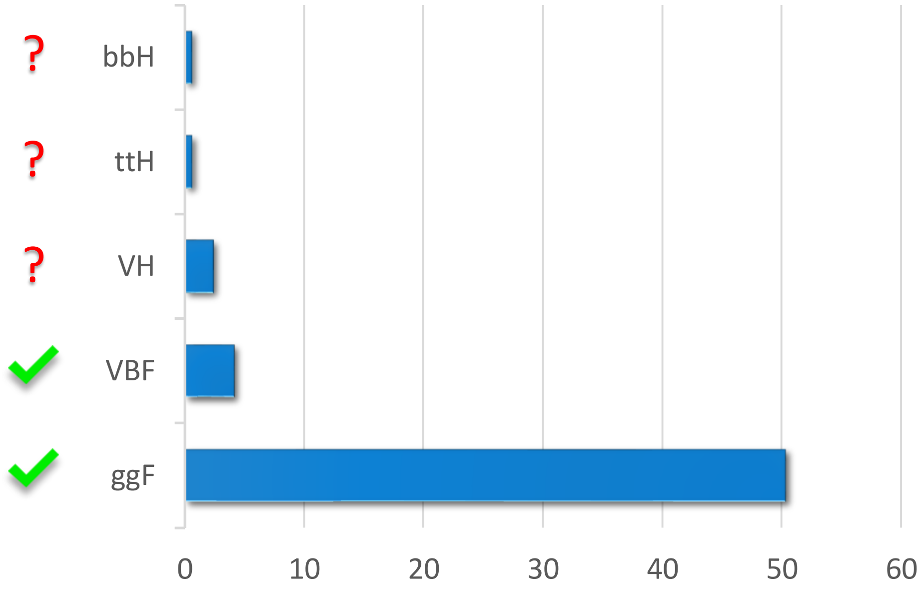


Observation of $H \rightarrow bb$ via VH production

- **Dominant decay of the SM Higgs boson**
- But **large background** from multi-jet production make a ggF search extremely challenging at hadron colliders
- Most sensitive production mode to detect $\boldsymbol{H \rightarrow bb}$ **its via VH**

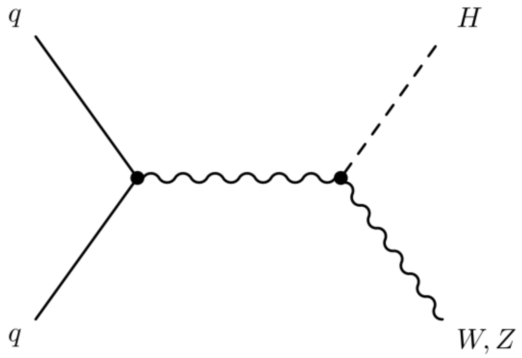
- Background: V+jets, $t\bar{t}$, single-top and di-boson processes
- Using the vector boson decay to 0,1,2 charged leptons
- Multivariate discriminants are used to maximise the sensitivity
- Output distributions are combined in a maximum-likelihood fit

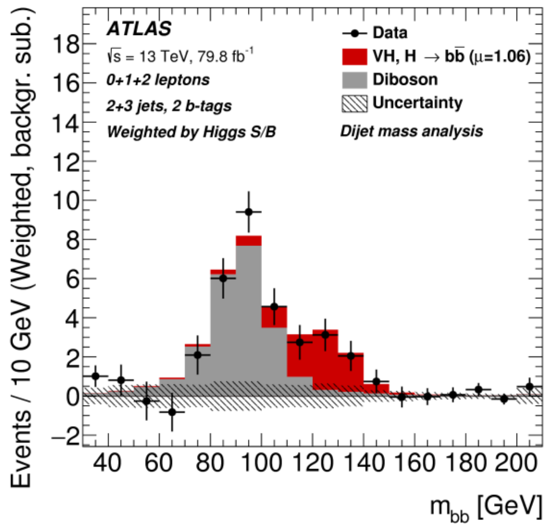
- Data corresponds to an integrated luminosity of 79.8 fb^{-1} at $\sqrt{s} =$ 13 TeV combined with previous analyses
- An **excess over the expected SM background** is observed, with a significance of **5.4 standard deviations**
- **Combined Results consistent with the SM**

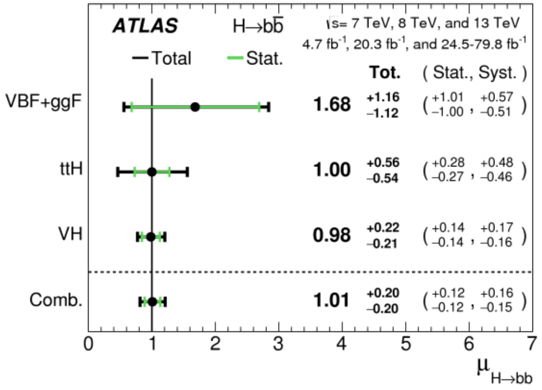
$$\mu_{H\rightarrow bb} = 1.01 \pm 0.12(stat)^{+0.16}_{-0.15}(syst)\ @95\%\ CL$$

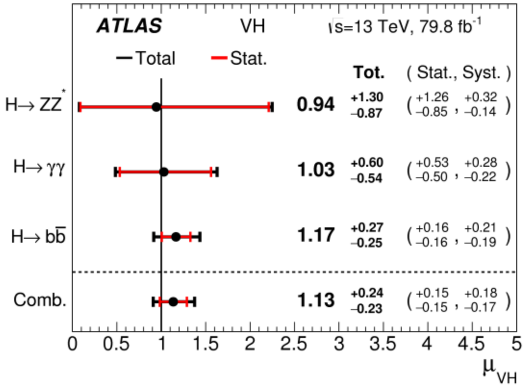
$$\mu_{VH} = 1.13 \pm 0.15(stat)^{+0.18}_{-0.17}(syst)\ @95\%\ CL$$

❖ Phys.Lett. B786 (2018) 59-86









Observation of $t\bar{t}H$ production

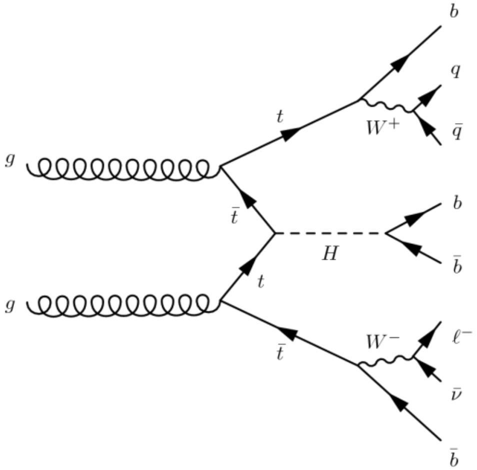
- Particular interest is its coupling to the top quark, the **heaviest particle in the SM**
- The strength of this interaction can be studied through the analysis of top-associated Higgs production ($t\bar{t}H$) events, which provides a **tree-level probe** of the top Yukawa coupling

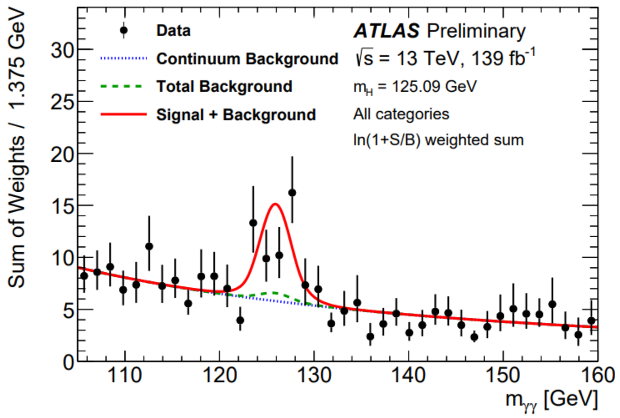
- Channels considered: $b\bar{b}$, WW^*, $\tau^+\tau^-$, $\gamma\gamma$ and ZZ^*
- Output distributions are combined in a maximum-likelihood fit

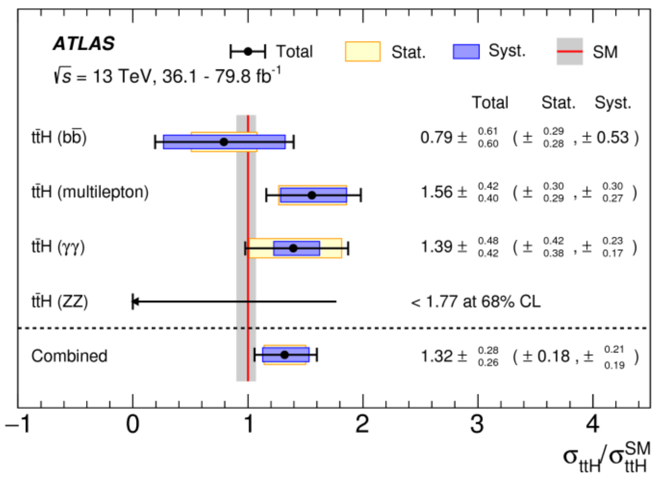
- Data corresponds to an integrated luminosity of 79.8 fb^{-1} at $\sqrt{s} = 13$ TeV combined with previous analyses
- An **excess over the expected SM background is observed**, with a significance of **6.3 standard deviations**
- **Updated result** for the $\mathrm{H} \rightarrow \gamma\gamma$ channel with updated photon identification and jet calibration with **4.9 standard deviation**
- **Results consistent with the SM**

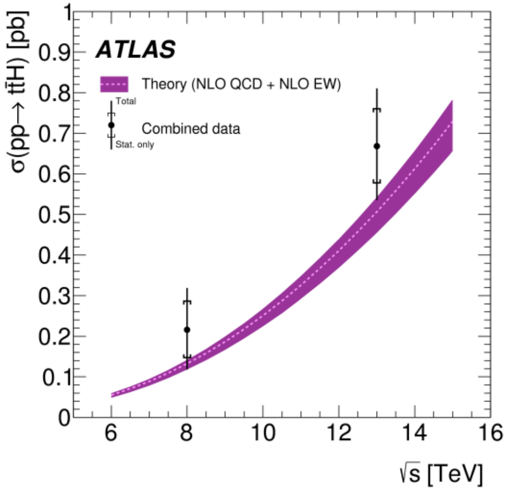
$$\sigma_{ttH}(13\ TeV) = 670 \pm 90(stat)^{+110}_{-100}(syst)\ @95\%\ CL$$

- Phys. Lett. B 784 (2018) 173
- https://cds.cern.ch/record/2665291/files/ATLAS-COM-CONF-2019-004.pdf







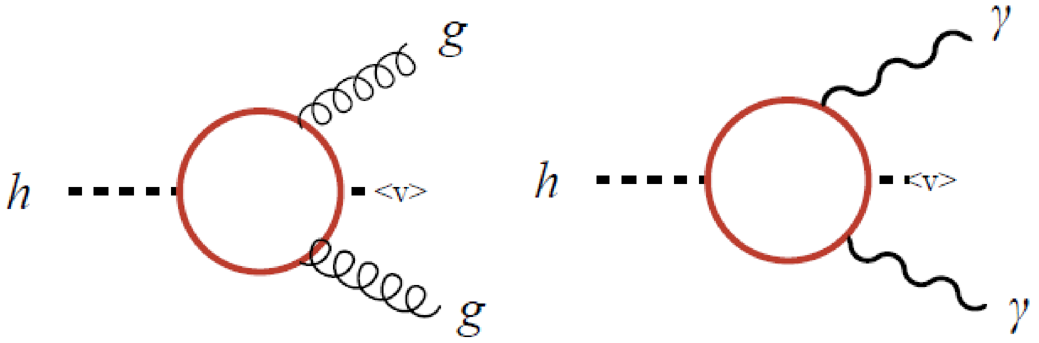


κ framework

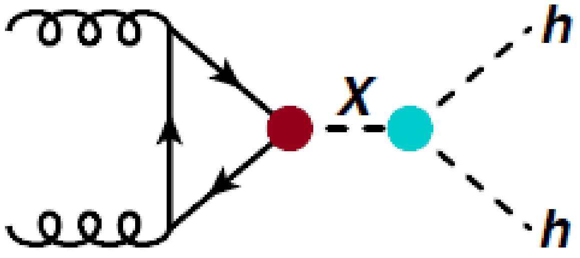
- **We want to probe deviations** (indirect or direct) from the SM rates through coupling strength modifiers in a leading-order tree level motivated framework (κ framework)

$$g_{Hff} = \kappa_f \cdot g_{Hff}^{SM} = \kappa_f \cdot \frac{m_f}{v}$$

$$g_{HVV} = \kappa_V \cdot g_{HVV}^{SM} = \kappa_V \cdot \frac{2m_V^2}{v}$$



Indirect new physics might modify production and/or decay coupling



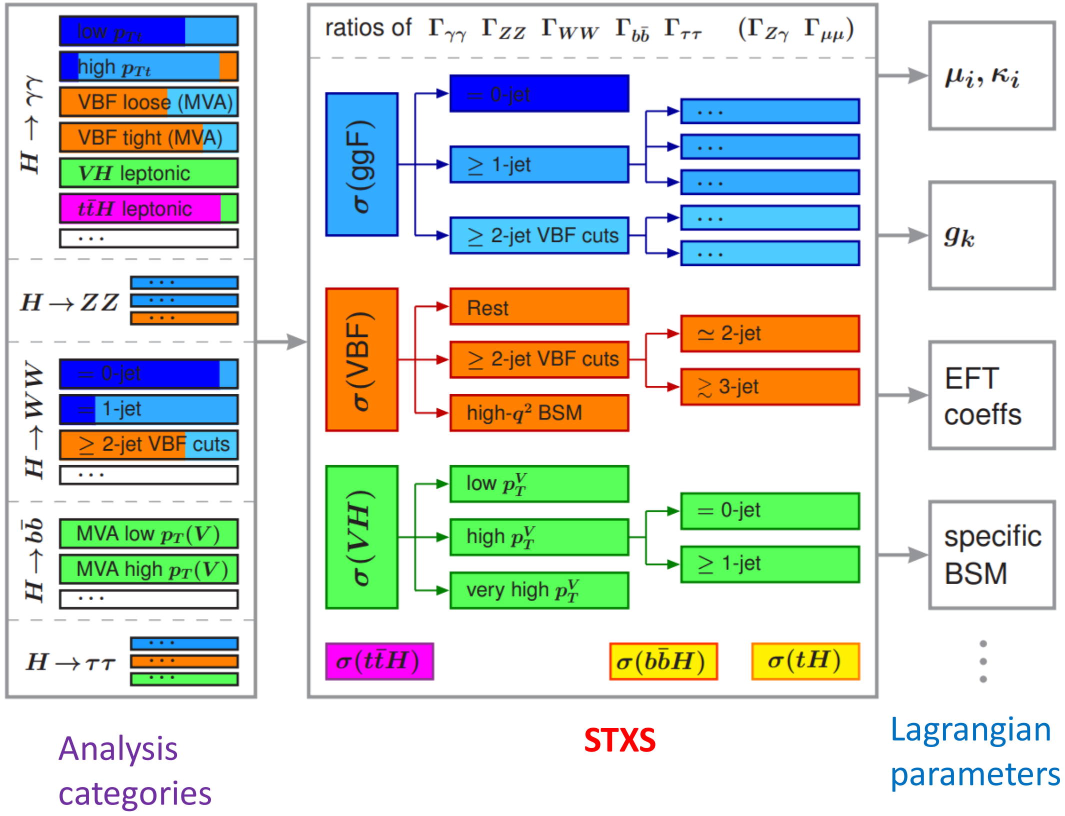
Direct new physics might modify both couplings too

- $g_{Hff}^{SM} = \frac{m_f}{v}$
- $g_{HVV}^{SM} = \frac{2m_V^2}{v}$

Simplified template cross sections

❖ https://cds.cern.ch/record/2669925

- **Simplified Template Cross Sections (STXS)** have been adopted by the LHC experiments as an evolution of the signal strength measurements performed during the first LHC Run
- They provide **more fine-grained measurements** for individual Higgs production modes in various kinematic regions, and **reduce the theoretical uncertainties** that are directly folded into the measurements
- They allow for the use of multivariate analysis techniques and provide a common framework for the combination of measurements in different decay channels and eventually between experiments
- Currently, STXS measurements are available in **all five major Higgs** decay channels, namely $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, $H \to WW^* \to 2\ell 2\nu$, $H \to \tau^+\tau^-$ and $H \to b^+b^-$
- Both individual and combined STXS measurements can then be used as **inputs for subsequent interpretations in BSM**. This can be the determination of overall signal strengths or coupling scale factors, SMEFT coefficients, or tests of specific BSM models



For more details check Katja presentation!

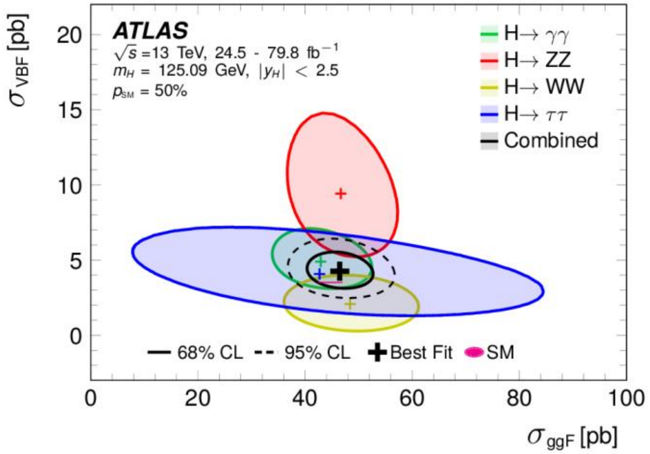
ATLAS coupling combination

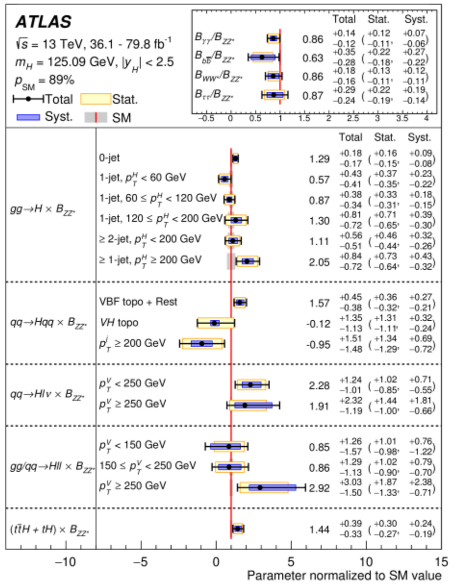
- Decay channels considered: $b\bar{b}, WW^*, \tau^+\tau^-, \gamma\gamma, \mu^+\,\mu^-$ and ZZ^*
- Production channels considered: ggF, VBF, VH, $t\bar{t}H$, tH
- Invisible Higgs decays and off-shell production are included
- Data corresponds to an integrated luminosity of 79.8 fb^{-1} at $\sqrt{s} = 13$ TeV
- All channels (except for $\mu^+\,\mu^-$ and $b\bar{b}$) uses STXS

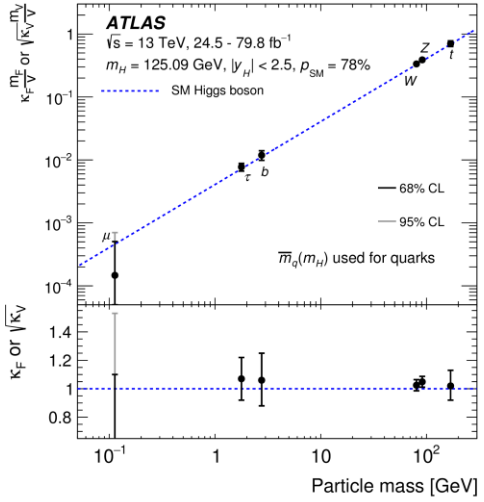
- Observed (expected) significance for **VBF** process of $\boldsymbol{6.5\sigma}$ (5.3σ)
- Observed (expected) significance for **VH** process of $\boldsymbol{5.3\sigma}$ (4.7σ)
- Observed (expected) significance for $\boldsymbol{t\bar{t}H + tH}$ process of $\boldsymbol{5.8\sigma}$ (5.3σ)
- Measurements in kinematic regions defined within the STXS framework are also shown
- **No significant deviations from SM predictions are observed**

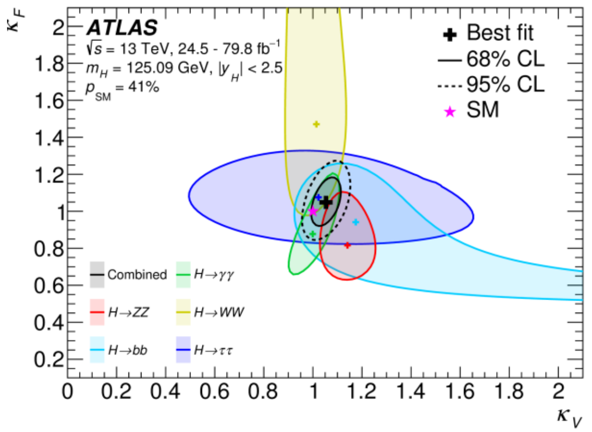
$$\mu_{global} = 1.11^{+0.09}_{-0.08}\ @95\%\ CL$$

❖ CERN-EP-2019-097







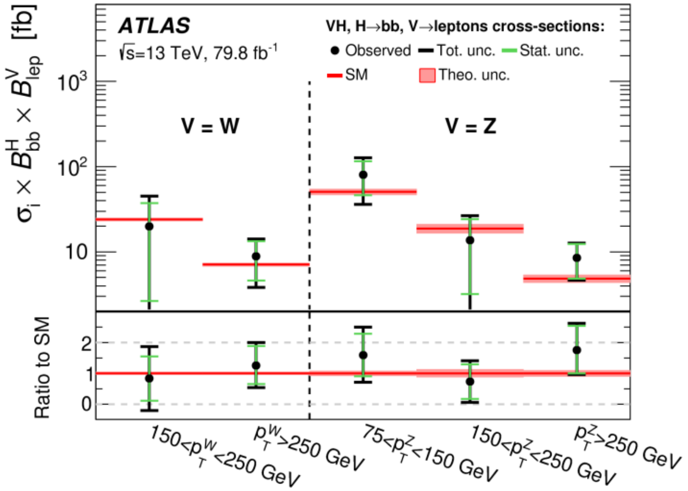


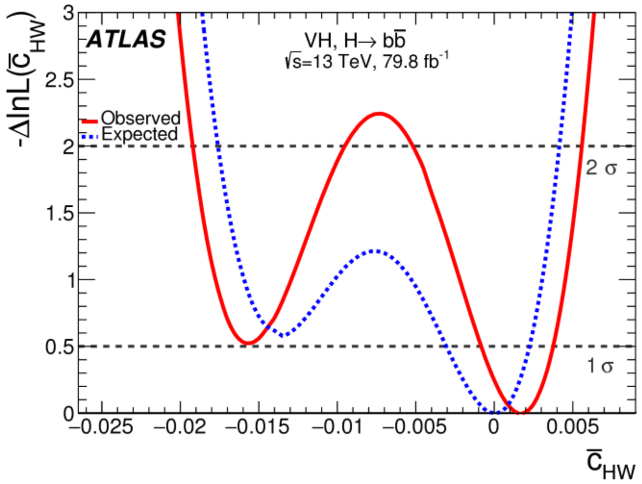
Fiducial cross-section $H \to bb$ via VH production

❖ JHEP 1905 (2019) 141

- Measurements are defined as a function of the vector-boson transverse momentum p_T^V
- The measurements are performed in kinematic fiducial volumes defined in the STXS framework
- Multivariate discriminants are used to maximise the sensitivity

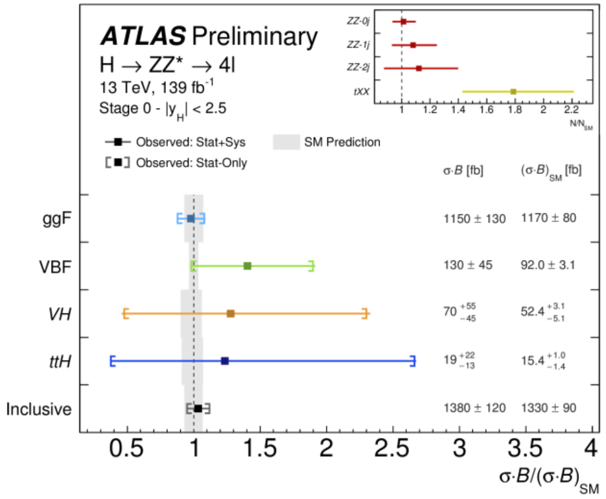
- Measurements are performed for two different choices of the number of p_T^V intervals
- Data corresponds to an integrated luminosity of 79.8 fb^{-1} at $\sqrt{s} = 13$ TeV
- **All measurements are found to be in agreement with the SM** even in high p_T^V (> 250 GeV) regions that are most sensitive to enhancements from potential anomalous interactions between the Higgs boson and the electroweak gauge bosons
- Limits are set on the parameters of an effective Lagrangian (Strongly interacting light Higgs formulation D=6) sensitive to modifications of the Higgs boson couplings to the electroweak gauge bosons



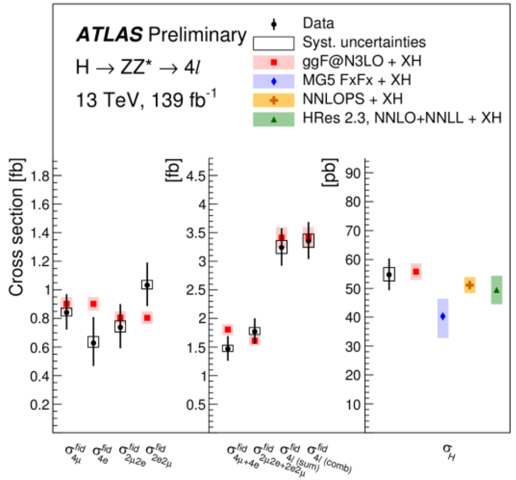


Fiducial and production cross-section $H \rightarrow ZZ^*$

- **Four types of measurements are reported**: inclusive and differential cross sections are measured in the fiducial phase space, cross sections within the Higgs boson rapidity $|y_H|$ = 2.5 of production modes both inclusively and in several exclusive regions
- The measurements are performed in kinematic fiducial volumes defined in the STXS framework
- Production channels considered: ggF, VBF, VH, $t\bar{t}H$, tH
- Neural-Network (NN) discriminants are used to maximise the sensitivity



- Data corresponds to an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV
- Differential cross sections defined in a fiducial region are measured as a function of the transverse momentum p_T^{4l} and the number of jets N_{jets}
- **All measurements are in agreement with the SM prediction** ($\sigma_{fid,SM} = 3.41 \pm 0.18$)



$$\sigma_{fid} = 3.35 \pm 0.30(stat) \pm 0.12(syst)\ fb\ \ @95\%\ CL$$

$$\sigma_{ggF} = 1.15 \pm 0.13\ pb\ \ @95\%\ CL$$
$$\sigma_{VBF} = 0.13 \pm 0.04\ pb\ \ @95\%\ CL$$

❖ http://cdsweb.cern.ch/record/2682107/files/ATLAS-CONF-2019-025.pdf

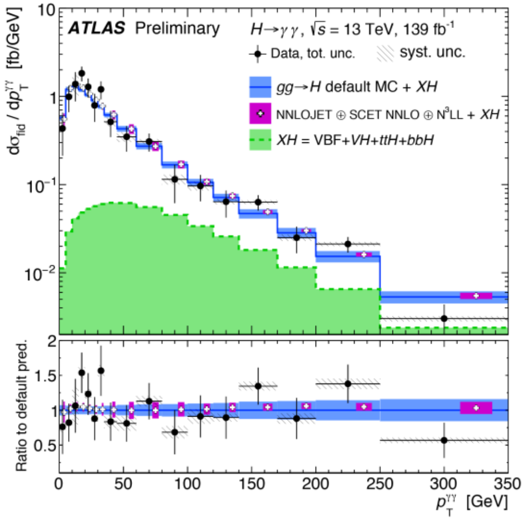
Fiducial cross-section $H \rightarrow \gamma\gamma$

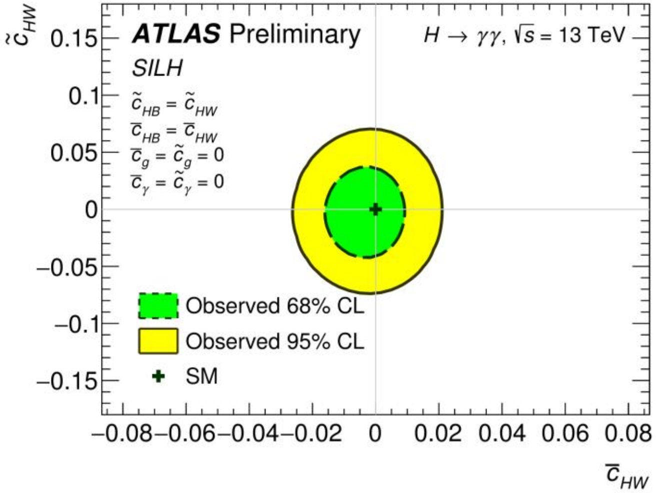
❖ http://cdsweb.cern.ch/record/2682800/files/ATLAS-CONF-2019-029.pdf

- The diphoton cross section is measured in a fiducial region that follows closely the experimental reconstructed signature
- The measurements are performed in kinematic fiducial volumes defined in the STXS framework
- Production channels considered: ggF, VBF, VH, $t\bar{t}H$, tH

- Data corresponds to an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV
- Differential cross sections as a function of different observables sensitive to the Higgs boson production kinematics, the jet kinematics, the CP quantum numbers of the Higgs boson, and the VBF production mechanism are reported and compared to several theoretical predictions.
- **No significant new physics contributions are observed** from the study of two effective field lagrangians (EFT) based on SILH and the Warsaw basis of the SMEFT formalism
- Differential cross-section as a function the p_T of the diphoton system is used to probe the charm Yukawa coupling of the Higgs boson
- **All measurements are in agreement with the SM prediction**

$$\sigma_{fid} = 65.2 \pm 4.5(stat) \pm 5.6(syst)) \pm 0.3(theo)\ fb\ \ @95\%\ CL$$



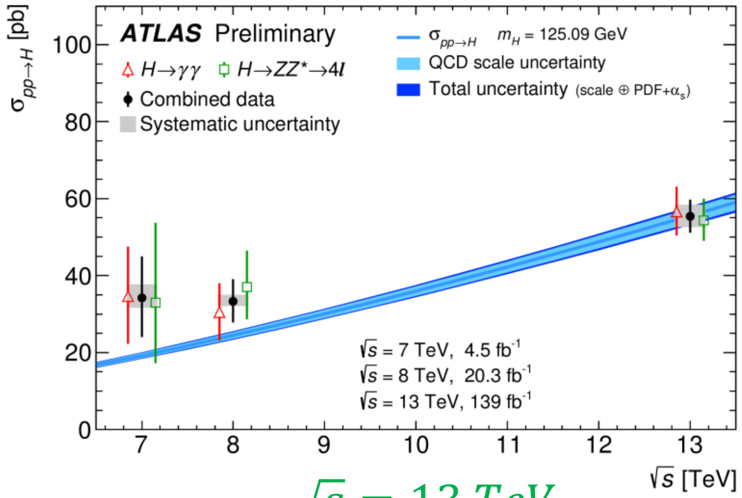


Cross-section $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ combination

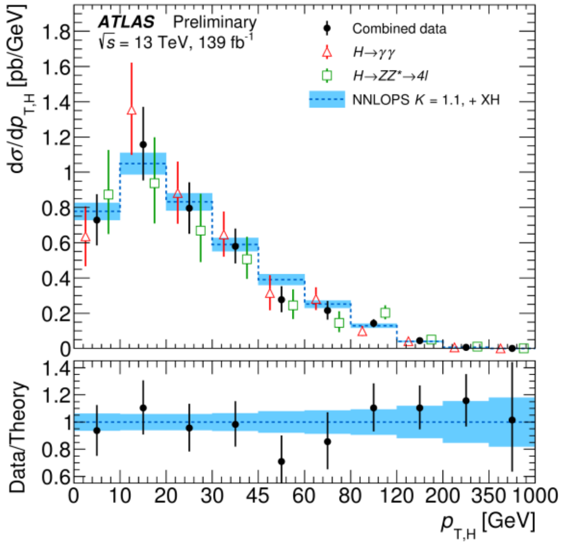
- Combined measurements of the total and differential cross sections of Higgs boson production on the named channels
- Corrections are applied to these yields accounting for luminosity, detector effects, fiducial acceptances, and branching fractions

- Production channels considered: ggF, VBF, VH, $t\bar{t}H$, tH, $b\bar{b}H$
- Data corresponds to an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV
- **Combined measurements are compatible with the SM predictions**
- Differential cross sections are calculated as a function of $p_{T,H}$ for the individual channels and their combination, **being compatible with the SM predictions and between each other**

$$\sigma = 55.4^{+4.3}_{-4.2}\ pb\ \ @95\%\ CL$$



$\sqrt{s} = 13\ TeV$



❖ http://cdsweb.cern.ch/record/2682844/files/ATLAS-CONF-2019-032.pdf

Search for $H \to \mu\mu$ (+ $H \to ee$)

- Searching for **leptonic final states** probes the structure of the Yukawa sector of the SM
- **SM B($H \to ee$) its far below LHC sensitivity** (SM BF: 5×10^{-9}), but SM B($H \to \mu\mu$) has great chances (SM BF: 2.2×10^{-4})

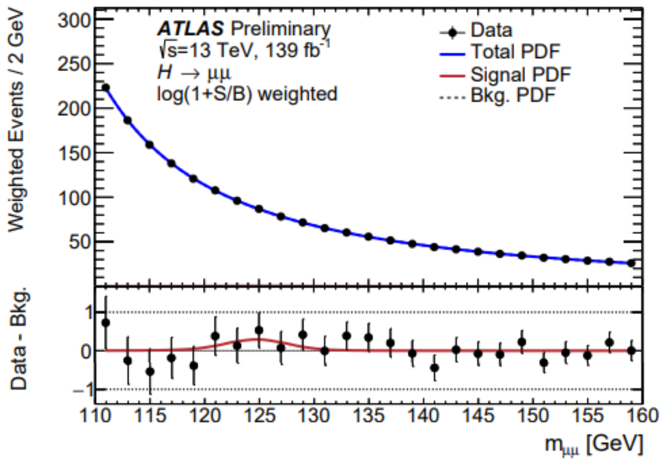
- Analysis selects events with two opposite-charge muons and classifies them into eight mutually exclusive categories
- Two categories are defined using a multivariate discriminant to provide good sensitivity to the vector-boson fusion (VBF) process. Events failing the VBF selection are sorted into ggF categories
- Dominant background Drell-Yan $Z/\gamma^* \to \mu\mu$

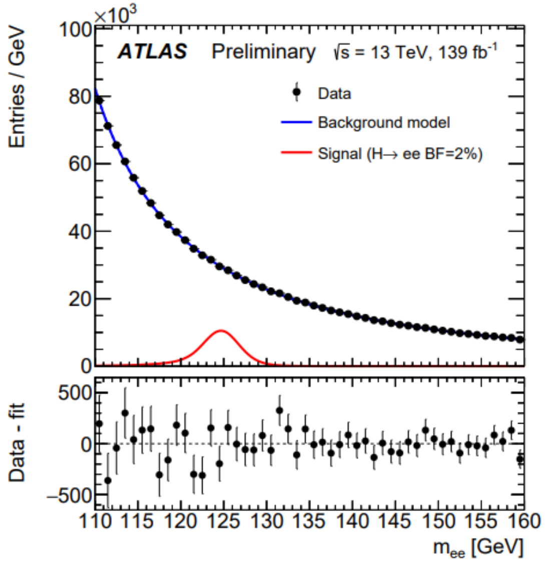
- Data corresponds to an integrated luminosity of 139 fb^{-1} at $\sqrt{s} = 13$ TeV
- Fit uses the range $m_{\mu\mu}$= [120,130] GeV
- **No significant excess over the expected SM background is observed**
- Upper limit calculated (compatible with the SM)

$$B(H \to \mu\mu) < 3.8 \cdot 10^{-4} \;\; @95\% \; CL$$

$$B(H \to ee) < 3.5 \cdot 10^{-4} \;\; @95\% \; CL$$

- https://cds.cern.ch/record/2682155/files/ATLAS-CONF-2019-028.pdf
- https://cds.cern.ch/record/2685338/files/ATLAS-CONF-2019-039.pdf





Search for $H \rightarrow cc$ via ZH production

- Measurements of the **Yukawa coupling of the Higgs boson to quarks in generations other than the third are difficult at hadron colliders**, due to small branching fractions, large backgrounds, and challenges in jet flavor identification
- An alternative approach is introduced to investigate the $H \rightarrow cc$ coupling by requiring the reconstruction of the invariant mass of the Z boson from 2 leptons and the di-jet requiring at least one c-quark

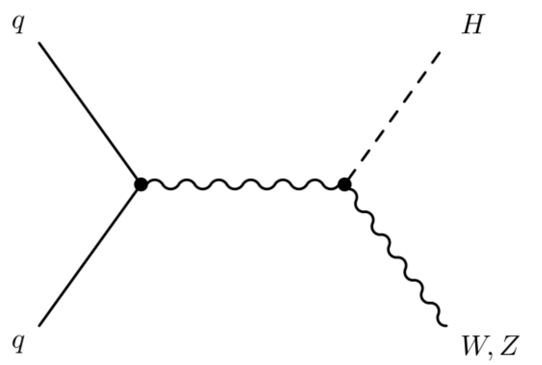
- Main backgrounds: Z+jets, $t\bar{t}$, ZV

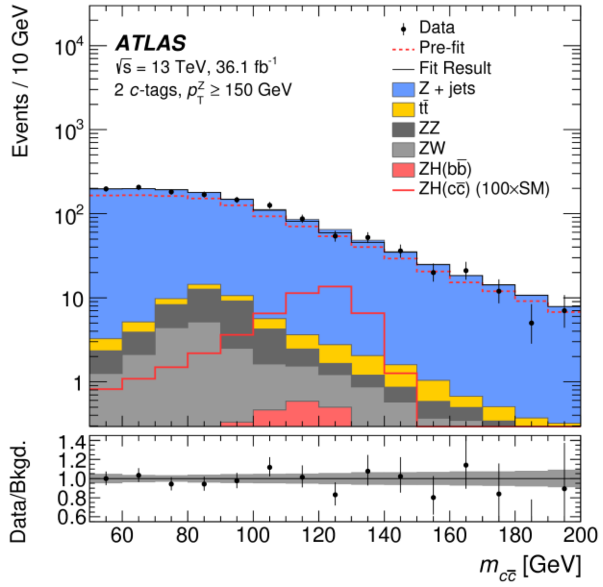
- Data corresponds to an integrated luminosity of 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV
- No **excess over the expected SM background is observed**
- **Upper limit ~100 times higher than SM hypothesis** (previous analysis reached an upper limit of ~500 times higher than the SM hypothesis)

$$\sigma_{ZH} \times B(H \rightarrow cc) < 2.7\ pb\ @95\%\ CL$$

$$\mu_{H\rightarrow cc} < 110\ @95\%\ CL$$

❖ Phys. Rev. Lett. 120 (2018) 211802





For more details check Xin presentation!

Invisible Higgs boson decays

- Numerous models predict detectable production rates of such **Dark Matter (DM)** particles at the Large Hadron Collider (LHC)
- In a wide class of those models, the Higgs boson acts as a portal between a dark sector and the SM sector, either through **Yukawa-type couplings to fermionic dark matter**, or other mechanisms
- Higgs boson decays to DM particles can only be indirectly inferred through **missing transverse momentum** (MET) due to DM particles escaping detection, and are therefore termed "invisible"

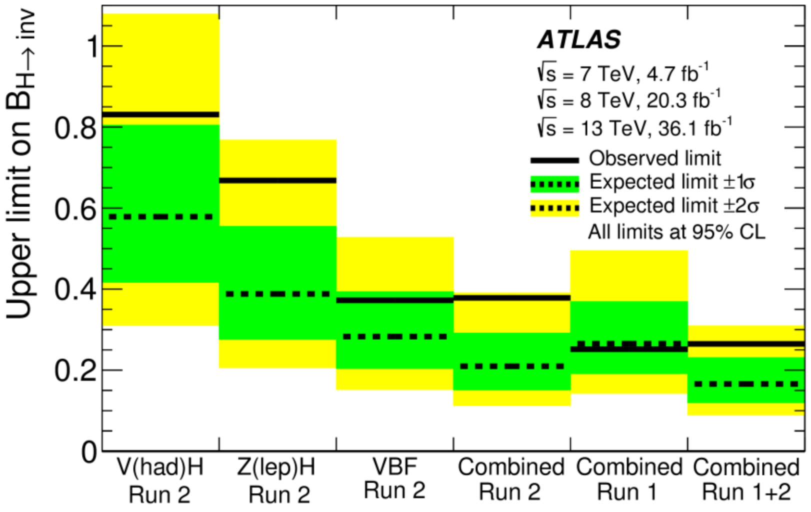
- Production channels considered: VBF and $VH(\mathrm{Z}_{lep}H$ and $\mathrm{V}_{had}H)$
- Output distributions are combined in a maximum-likelihood fit

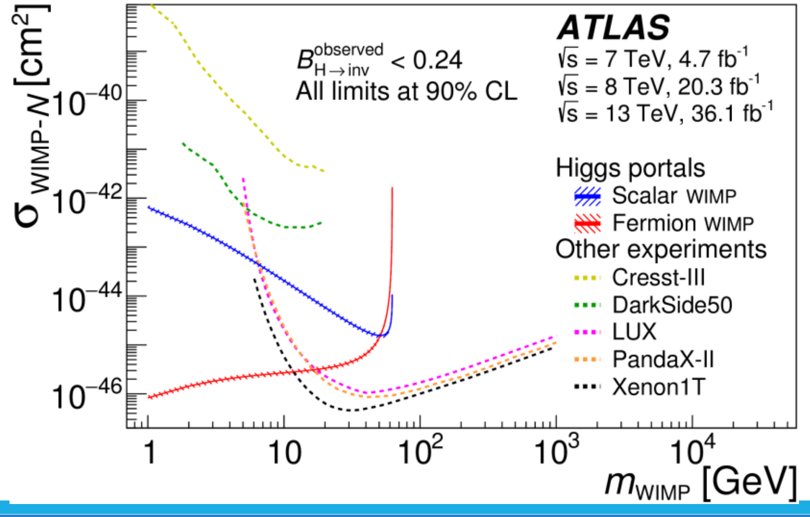
- Data corresponds to an integrated luminosity of 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV combined with previous analyses
- Under the assumption that the Higgs (effective model) decays to a pair of scalar or fermion weakly interactive massive particle (WIMP) using a nuclear interaction

$$\boldsymbol{B(H \to inv) < 0.26 \ @95\%CL}$$

$$\boldsymbol{\sigma_{WIMP-N}(scalar) > 2 \times 10^{-45} cm^2 \ @90\%CL}$$
$$\boldsymbol{\sigma_{WIMP-N}(fermion) > 10^{-46} cm^2 \ @90\%CL}$$

❖ Phys.Rev.Lett. 122 (2019) no.23, 231801





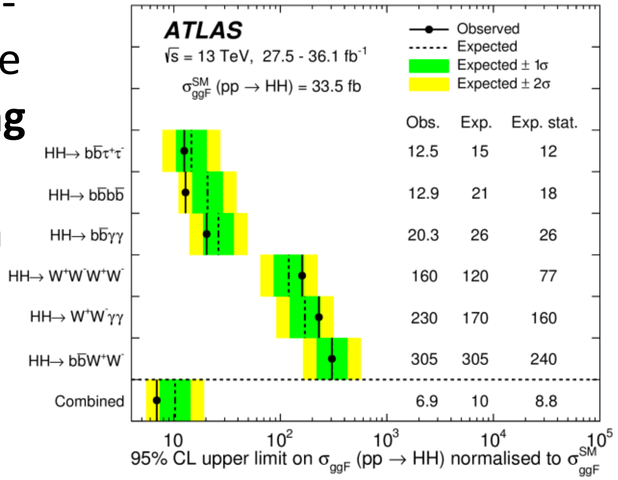
For more details check Kathryn presentation!

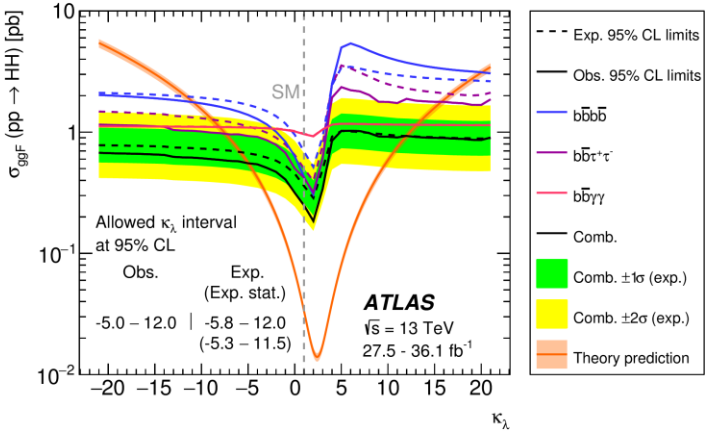
di-Higgs production (self-coupling)

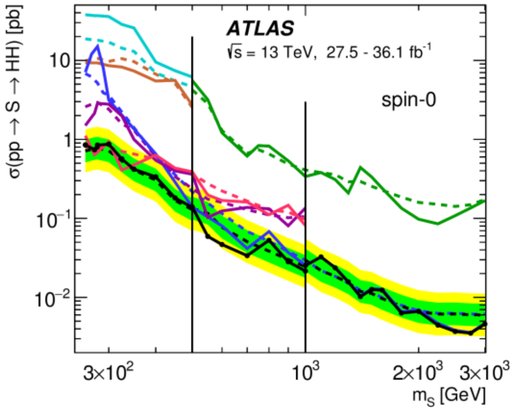
❖ CERN-EP-2019-099

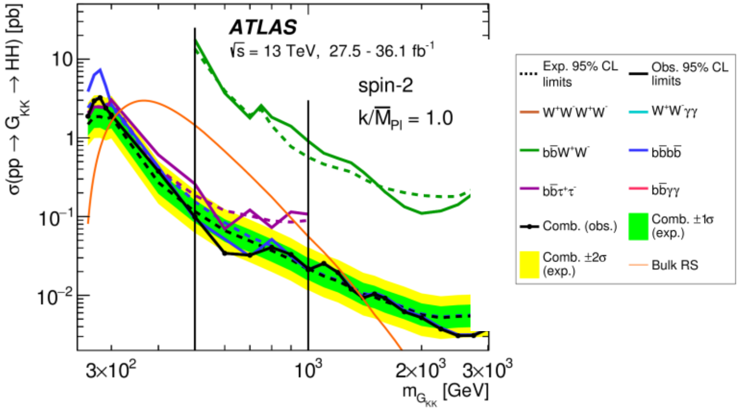
- Measurements of the strengths of the Higgs boson self-interactions and their comparison to SM predictions are necessary to verify the **electroweak symmetry breaking mechanism of the SM**
- But the SM di-Higgs cross-section is **much smaller** than those from single SM Higgs production
- Combination of: $b\bar{b}b\bar{b}$, $b\bar{b}W^+W^-$, $b\bar{b}\tau^+\tau^-$, $W^+W^-W^+W^-$, $b\bar{b}\gamma\gamma$ and $W^+W^-\gamma\gamma$
- Data corresponds to an integrated luminosity of 36.1 fb^{-1}
- **No statistically significant excess of events above the SM predictions is found**
- For the SM hypothesis, the observed 95% CL upper limit on the ggF cross-section is $\mathbf{6.9 \times \mathit{SM}}$ **prediction**, with its coupling defined $\mathbf{-5.0 < \kappa_\lambda < 12.0}$ at 95% CL
- Since the combination there were 2 new results

❖ https://cds.cern.ch/record/2682801 ❖ https://arxiv.org/abs/1908.06765









Higgs off-shell coupling (width)

- The SM Higgs boson has an **extremely narrow total width** (~ 4 MeV) because its main decay channel (b-quark) has a small mass compared to the EW scale

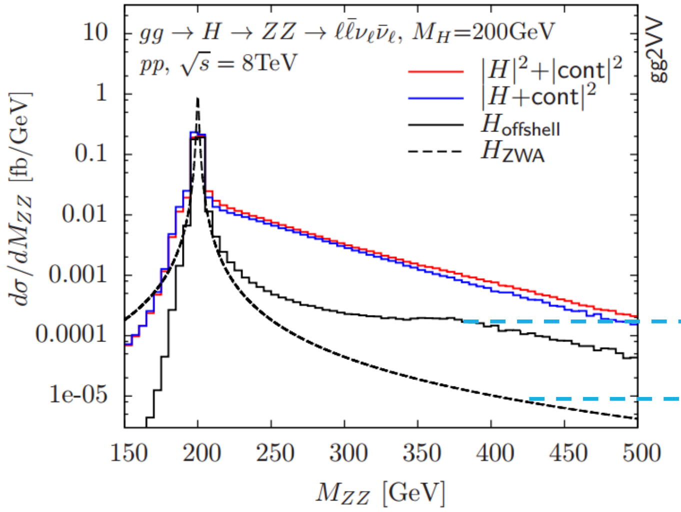
$$\Gamma_H \sim \left(\frac{m_b^2}{m_{EW}^2}\right)\Gamma_{EW}$$

- The **direct method** to measure the Higgs width is by taking the error of the invariant mass shape fitted by a BW curve, but there is not enough experimental resolution at the LHC (~GeV)

$$\Delta t \times \Delta m \sim \frac{h}{2\pi} \longrightarrow \frac{h/2\pi}{\Gamma} \times \Delta m \sim \frac{h}{2\pi} \longrightarrow \Delta m \sim \Gamma$$

- A novel method to constraint the total width by using the $H \rightarrow VV$ **off-shell events** (~20% of the total events), and assuming the same off- and on-shell coupling

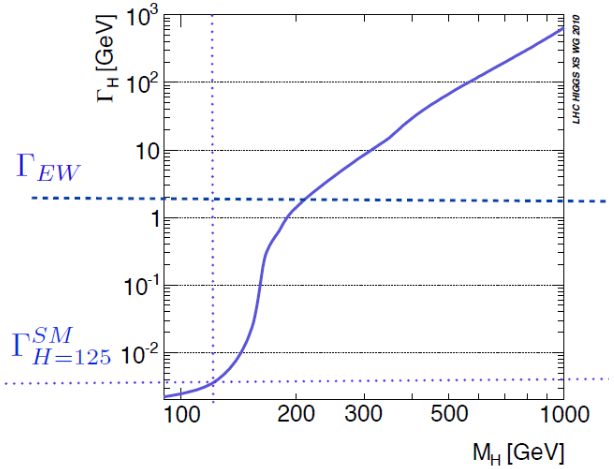
$$\sigma_{on} \sim \frac{\kappa_{gg\rightarrow H}^2 \cdot \kappa_{H\rightarrow VV}^2}{\Gamma_H^2} \qquad \sigma_{off} \sim \kappa_{gg\rightarrow H}^2 \cdot \kappa_{H\rightarrow VV}^2 \longrightarrow \Gamma_H \sim \frac{\sigma_{off}}{\sigma_{on}}$$



Higgs signal shape

BW

Particle	Width[MeV]	Lifetime[s]
t	$\sim 1,300$	$\sim 5 \times 10^{-25}$
W	$\sim 2,000$	$\sim 3 \times 10^{-25}$
Z	$\sim 2,500$	$\sim 2.6 \times 10^{-25}$
h	4.21 ± 0.16	$\sim 1.65 \times 10^{-22}$
b	4.4×10^{-10}	$\sim 1.5 \times 10^{-12}$



Higgs off-shell coupling (width)

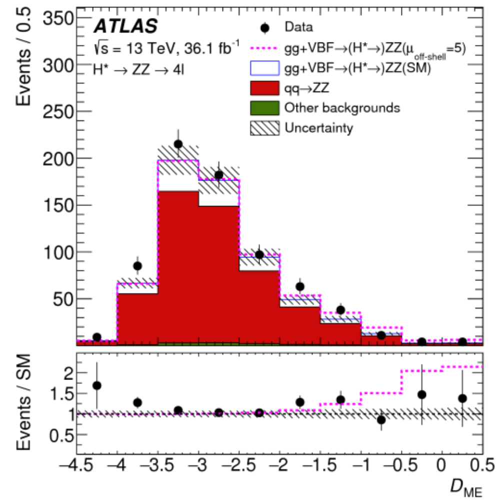
- Off-shell production can provide **sensitivity for new physics** that alters the interaction between the Higgs boson an other fundamental particles

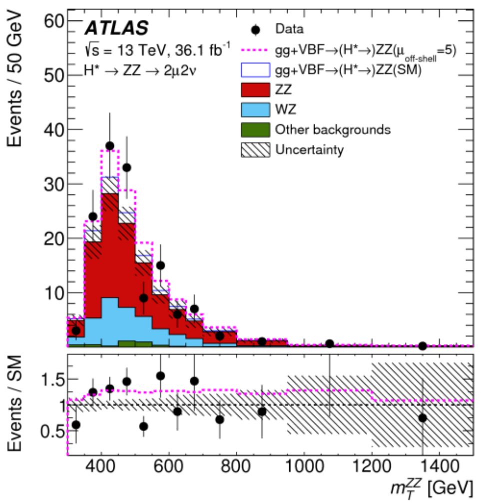
- Analysis region: $220 < m_{4l} < 2000$ GeV
- Decay channels: $ZZ \rightarrow 4l$ and $ZZ \rightarrow 2l2\nu$ (ggF and VBF)

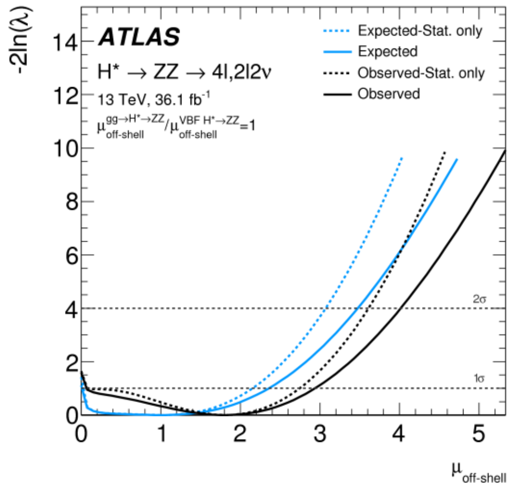
- Data corresponds to an integrated luminosity of 36.1 fb^{-1}
- Largest systematics comes from the uncertainties of the generation gg- and qq-initiated background processes
- A binned maximum likelihood its constructed over the matrix-element discriminator for $ZZ \rightarrow 4l$, and m_T for $ZZ \rightarrow 2l2\nu$

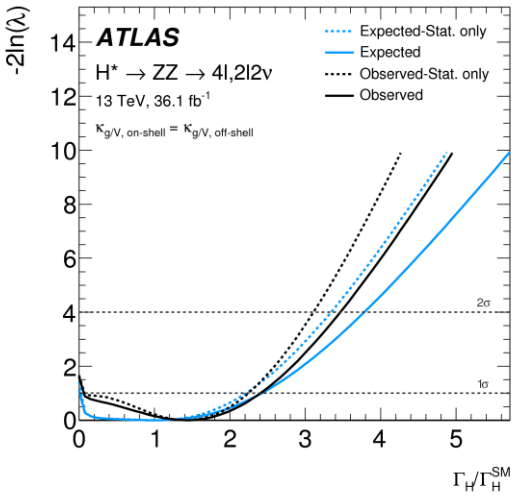
- The observed upper limit of the **off-shell signal strength is 3.8** at 95% CL, while assuming that ratio of both on- and off-shell couplings are the same, the **observed upper limit of the Higgs total width is 14.4 MeV**

❖ Phys.Lett. B786 (2018) 223-244



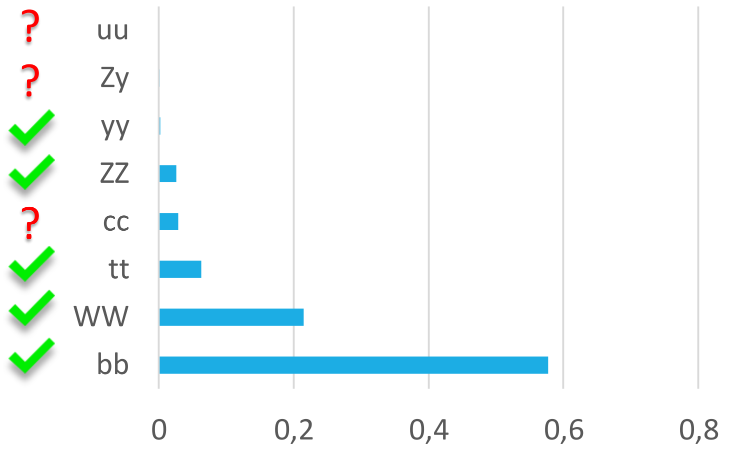


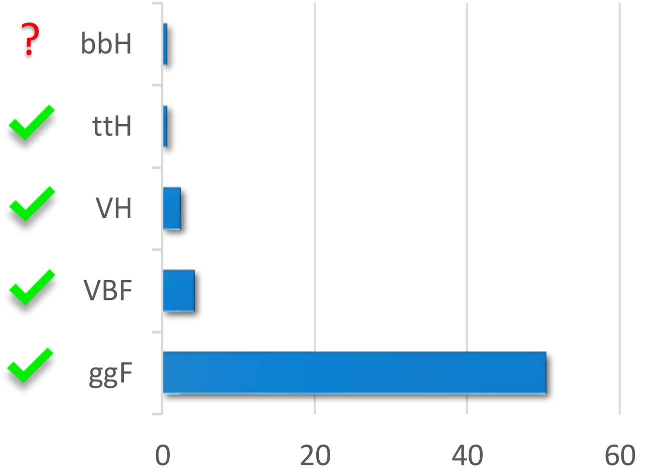




Conclusions

- The observed Higgs boson at the LHC is highly compatible with the SM Higgs boson, but there is still room for BSM candidates
- Most of the production and decay channels has been studied by the ATLAS collaboration, having substantial success in their determination
- One of the greatest challenge for the future of LHC experiments it’s the measurement of the Higgs-self coupling
- We are confident that in the next years we will achieve a proper characterization of the Higgs boson to determine its true nature



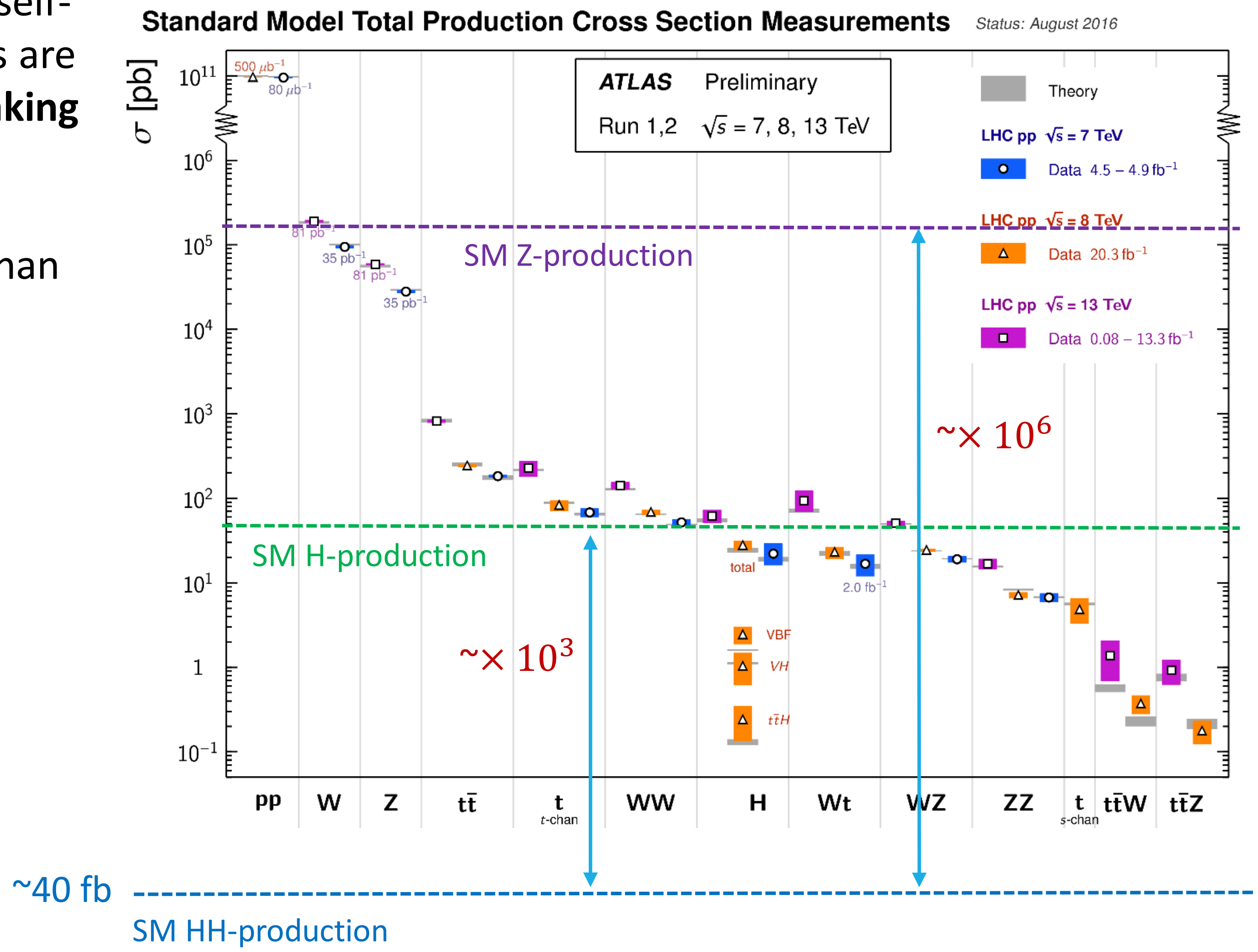


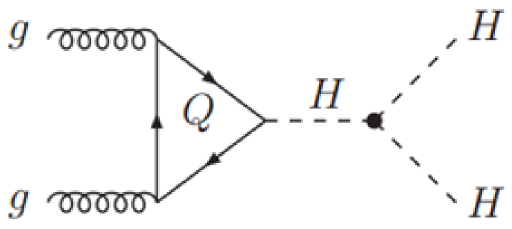
BACKUP

di-Higgs production (self-coupling)

- Measurements of the strengths of the Higgs boson self-interactions and their comparison to SM predictions are necessary to verify the **electroweak symmetry breaking mechanism of the SM**

- But the SM di-Higgs cross-section is **much smaller** than those from single SM Higgs production



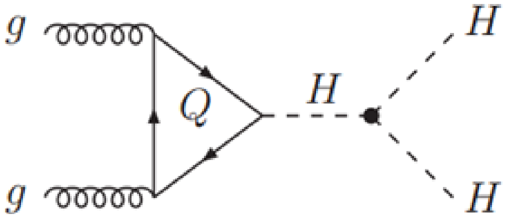


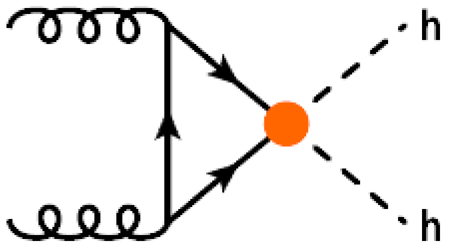
di-Higgs production (self-coupling)

- Measurements of the strengths of the Higgs boson self-interactions and their comparison to SM predictions are necessary to verify the **electroweak (EW) symmetry breaking mechanism of the SM**

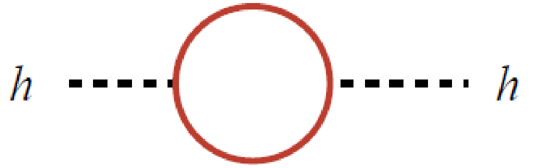
- But the SM di-Higgs cross-section is **much smaller** than those from single SM Higgs production

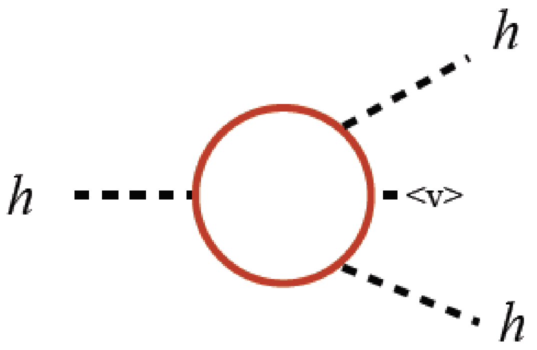
- The existence of an extended scalar sector or the presence of new dynamics at higher scales could modify the Higgs boson self-couplings
  - Non-resonant di-Higgs enhancement
  - Resonant di-Higgs enhancement

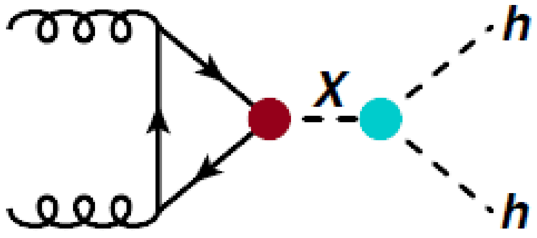




indirect BSM contribution







direct BSM particle