Measurements of the Higgs boson properties at the ATLAS experiment

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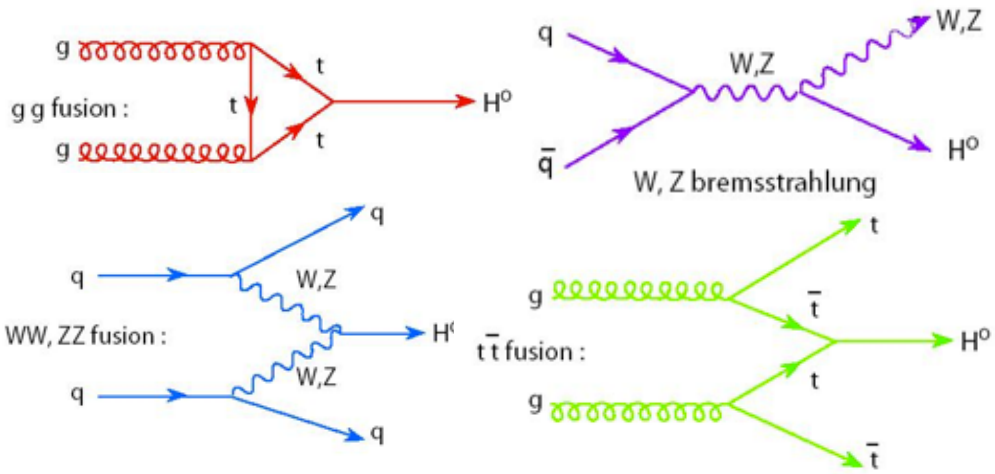
In this presentation:

- **Introduction**
  - Higgs @ LHC
    - Run1 discovery of the Higgs with $m_H \sim 125$ GeV, $J^{PC} = 0^{++}$ consistent with the SM expectations within uncertainties
- **Run2: Higgs boson property measurements**
  - Mass and Higgs Width
  - Cross section per production mode, and Differential XS measurements in most sensitive channels
  - Run2 observations: Hbb-bar, Hττ, VH, ttH
  - Summary and perspectives
- **Conclusions**

Production and decay modes

The Higgs production at LHC can occur through the following mechanisms:



ggF: is the dominant production mode, $\sigma^{ggF}/\sigma^{TOT}$ = 87% @ 13 TeV.

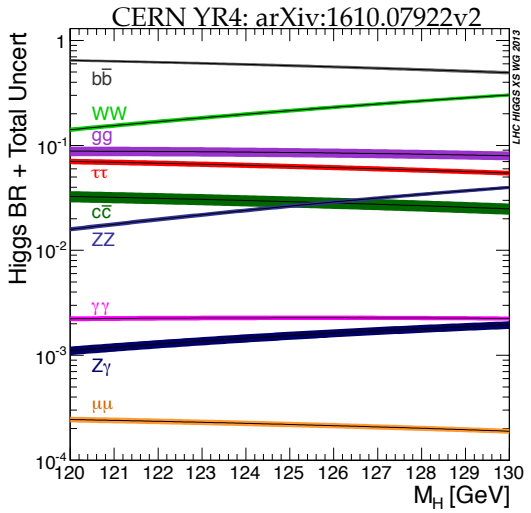
VBF: whose signature is characterized by H+2jet forward, $\sigma^{VBF}/\sigma^{TOT}$ = 7% @ 13 TeV.

VH: whose signature is composed by a H associated to a W or a Z boson, σ^{VH}/σ^{TOT} = 4% @ 13 TeV.

ttH-bbH: in which the H is associated to tt-bar / bb-bar pairs, $\sigma^{ttH+bbH}/\sigma^{TOT}$ = 2% @ 13 TeV.

Decay channels:

- H->ZZ*->4l: pure channel by very low statistics ($BR_{H->ZZ*->4l} \sim 2 \cdot 10^{-4}$)
- H->γγ : simple final state but low BR and large background
- H->WW*->lνlν: good sensitivity but low mass resolution
- H->bb-bar: huge bkg, best accesible via VH production
- H->ττ: very large bkg, best accesible via VBF and boosted H production
- H->Zγ & H->μμ: low BR



Analyses in RunI have been optimized for the discovery

- Observed boson compatible, within the uncertainties, with the Higgs predicted by the SM -> deviations are small

Measurements of:

- **Fiducial Cross Sections and Differential Cross Sections** in variables sensitive to the quantum numbers of the Higgs boson (spin, CP), production modes, proton PDFs and perturbative QCD effects

Interpretations in terms of:

- **Signal strenght**: defined as the ratio of the XS • BR with respect to the SM (more model dependent): $\mu = (\sigma\, BR)_{obs}/(\sigma\, BR)_{SM}$
- **Coupling modifiers (k_j)**: parametrizing production and decay, coupling modifiers as multiplicative factors, narrow width approximation

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H} \qquad \text{where} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}} \;, \quad \kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}}$$

-> k_j=1 refers to the Standard Model case (SM)

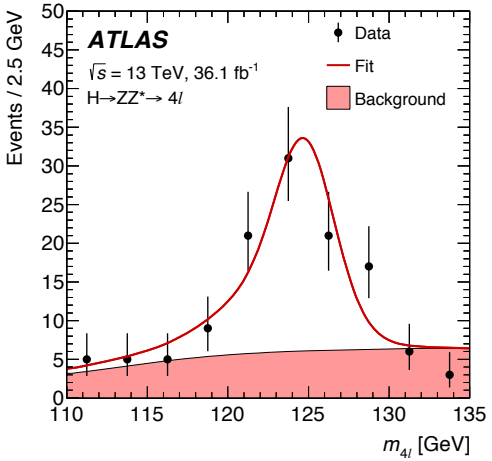
Higgs mass and off-shell couplings

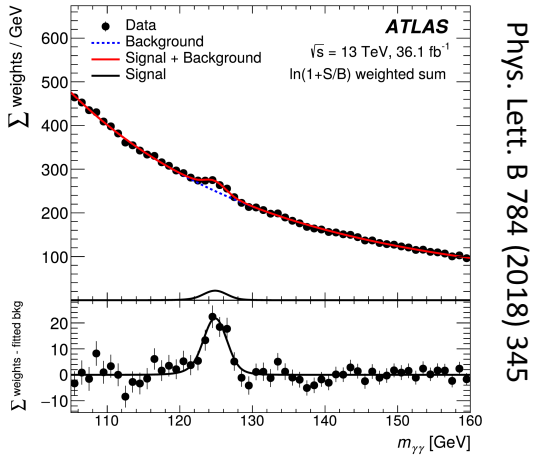
HZZ* and Hγγ are the most sensitive channels

- high p_T isoltated leptons from Z decay
- 2 well isolated photons in mass range

Resolution on mass 1-2%

Low BR but clean signature





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$m_{ZZ^*} = 124.79 \pm 0.37$ GeV

$m_{\gamma\gamma} = 124.93 \pm 0.40$ GeV

Run1+2 ATLAS Comb. $m_H = 124.97 \pm 0.24$ GeV

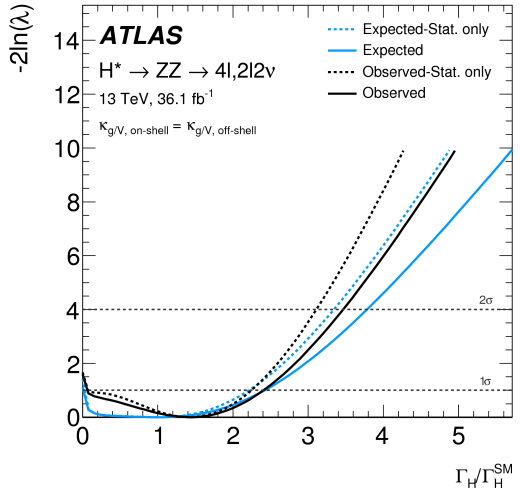
Higgs width (no direct measurement dominated by detector resolution)

$\sigma_{off\text{-}shell} \sim k^2_{g,off\text{-}shell}\, k^2_{Z,off\text{-}shell}$

$\sigma_{on\text{-}shell} \sim k^2_{g,on\text{-}shell}\, k^2_{Z,on\text{-}shell} / (\Gamma_H / \Gamma_H^{SM})$

Measurements from HZZ improved expected limits by a factor 2 wrt Run1

$\Gamma_H < 3.8\ (3.4)\ \Gamma_H^{SM}$ @ 95% CL



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Differential Cross Sections from γγ and 4l

- Fiducial phase space (to minimize the model dependency)
- Corrected for detection efficiency and resolution effects
- Variables sensitive to the H boson properties have been chosen

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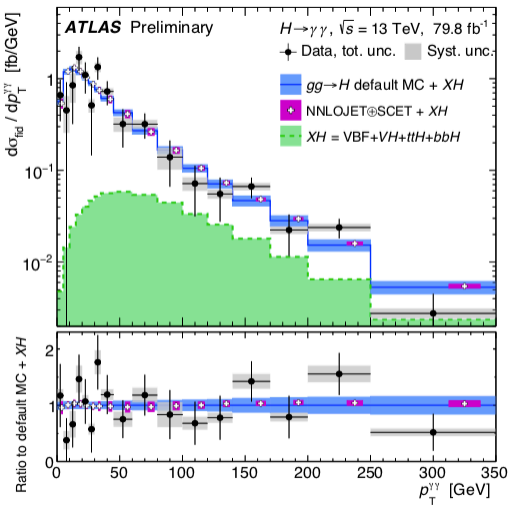

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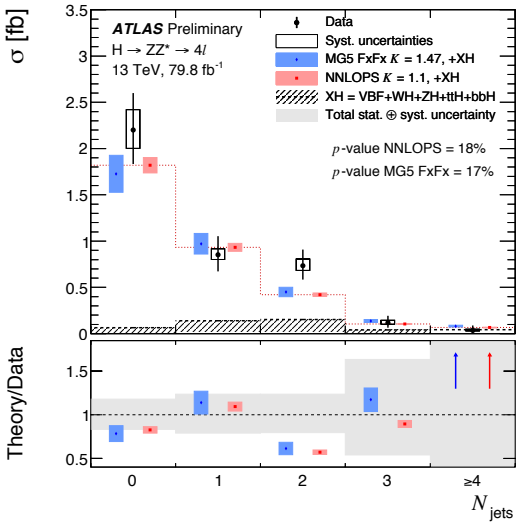


(p_T^H to probe perturbative QCD and the relative rates in production modes, Njets sensitive to the relative rate in production modes and radiative corrections)

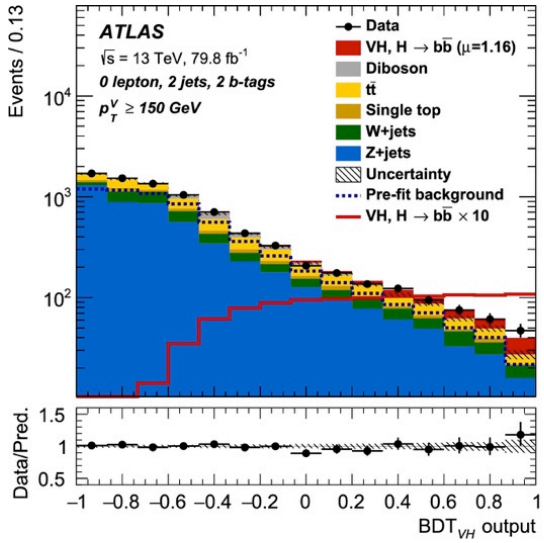
- Results have been compared to several theo. Predictions

	data	SM
$\sigma_{fid}(\gamma\gamma)$	60.4 ± 6.1(stat.) ± 6.0 (exp.) ± 0.3(theo.) fb	63.5 ± 3.3 fb
$\sigma_{fid}(4l)$	4.04 ± 0.41(stat.) ± 0.22 (syst.) fb	3.35 ± 0.15 fb

- Good agreement with SM
- Most measurement statistically limited

Observation of H->bb-bar decays

- **Dominant decay channel for 125 GeV Higgs (BR 58%)**
- **Huge QCD** background suppressed by additional **production mode products**



- **Very important to confirm the Yukawa coupling of the Higgs** to the quark sector
- Previous measurements leave room for BSM physics: **H ->bb-bar drives the uncertainty on the total decay width**

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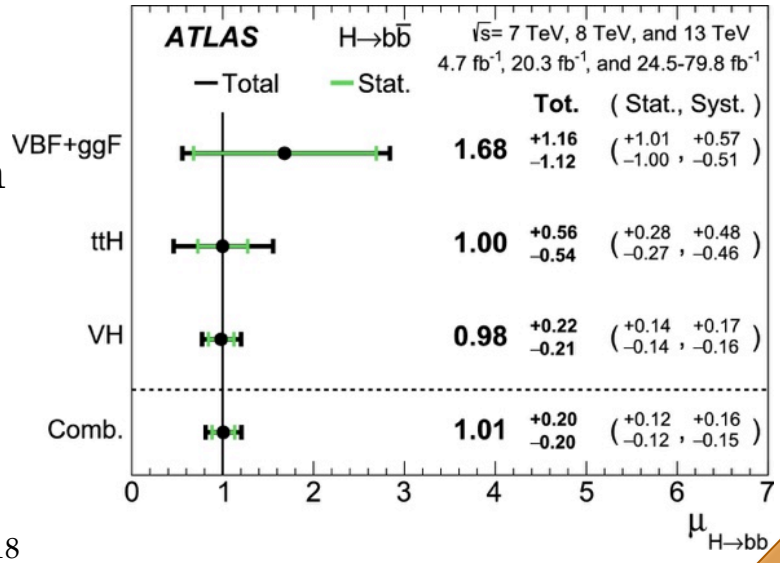
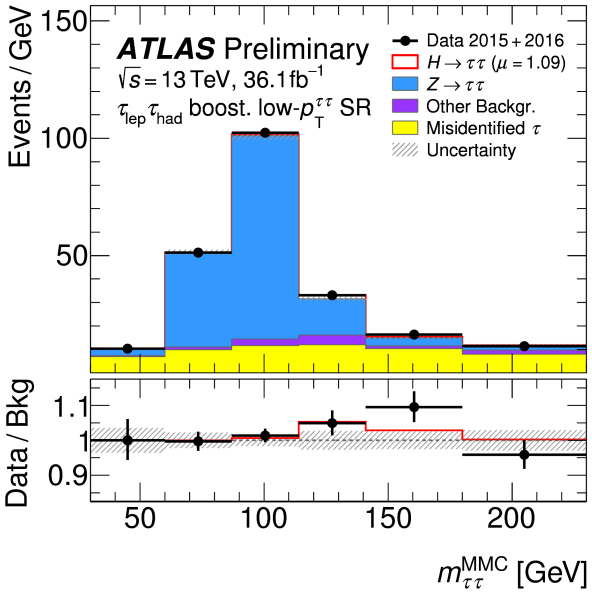
- **MVA used to increase S/B** in the signal region
- Bkg from Control regions, shapes from MC

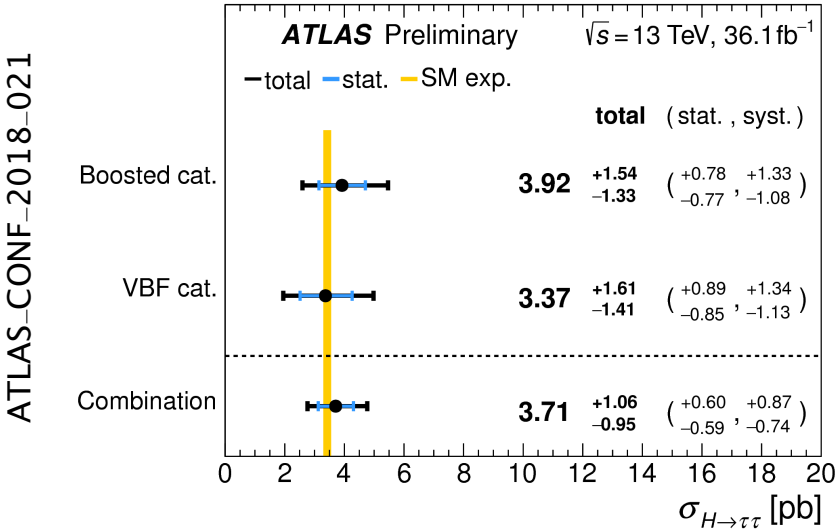


- **Run1+2 results: 5.4 σ observed (5.5 expected)**
- Now dominated by systematic uncertainties

Observation of H->ττ decays

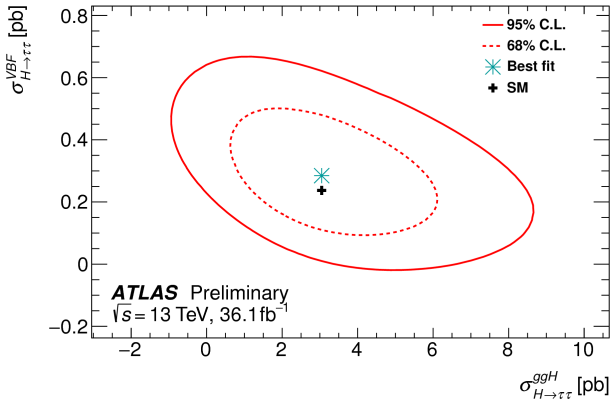
- **Two analysis categories:**
  VBF and boosted (mainly ggF)
- Largest backgrounds from Z + jets and from multijet
- Control regions to constrain Z/γ* -> ττ background
- Fit simulation to data using $m_{\tau\tau}$ distribution
- Run2: observed (expected) significance 4.4 (4.1) σ
- **Combination with Run-1: observed (expected) significance 6.4 (5.4) σ**





$$\sigma^{ggF}_{H\to\tau\tau} = 3.0 \pm 1.0\,(\text{stat.})\,^{+1.6}_{-1.2}\,(\text{syst.})\,\text{pb}$$

$$\sigma^{VBF}_{H\to\tau\tau} = 0.28 \pm 0.09\,(\text{stat.})\,^{+0.11}_{-0.09}\,(\text{syst.})\,\text{pb}$$



Observation of VH production

- **VH takes ~ 4%** of the total Higgs boson production modes at the LHC
- **Observation combining Run2 results:** H->bb-bar , H-> γγ, H->ZZ*
- Assuming SM Higgs boson BR
- **Significance 5.3 σ (4.8 expected) -> Dominant contribution is from bb-bar channel**
- Direct observation of the Higgs boson being produced in association with a vector boson
- Results still statistically dominated

Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

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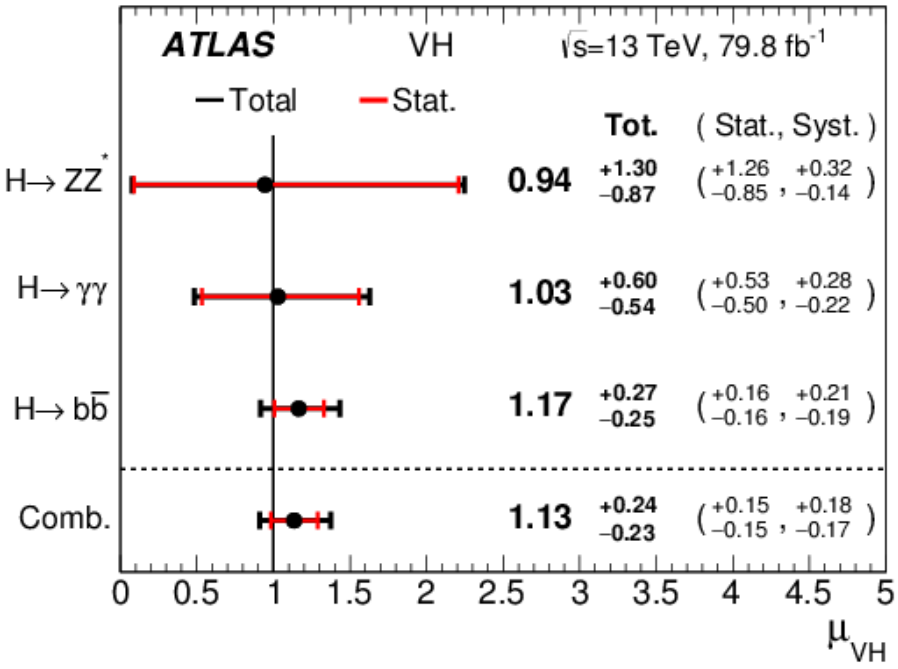
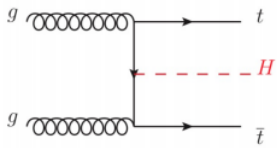
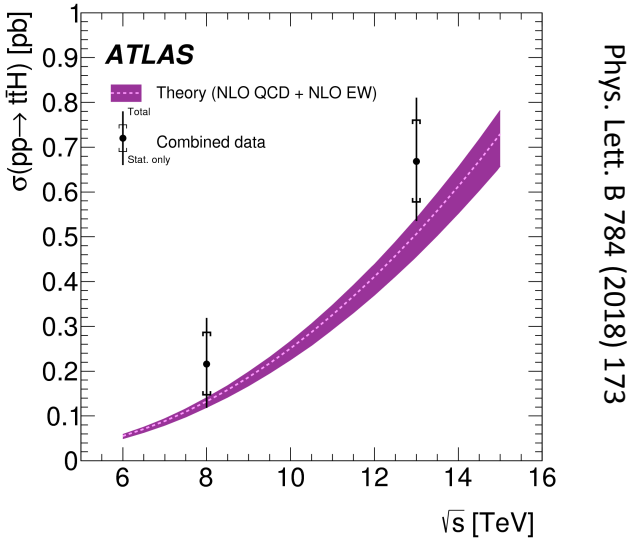


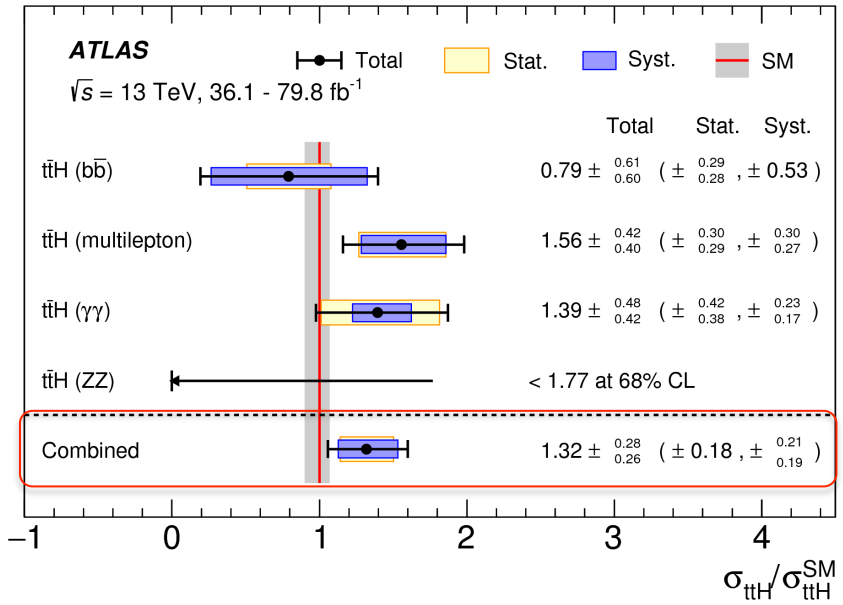
Observation of the ttH production

- **Direct Higgs coupling to top quark, largest Yukawa coupling**





- Deviation of couplings -> sensitive to new physics!
- **Challenging to detect σ_{ttH}~0.5 pb @ 13 TeV**
- Complex final state and huge bkgs
- Combination of results from different decay modes
- Results still stat. dominated



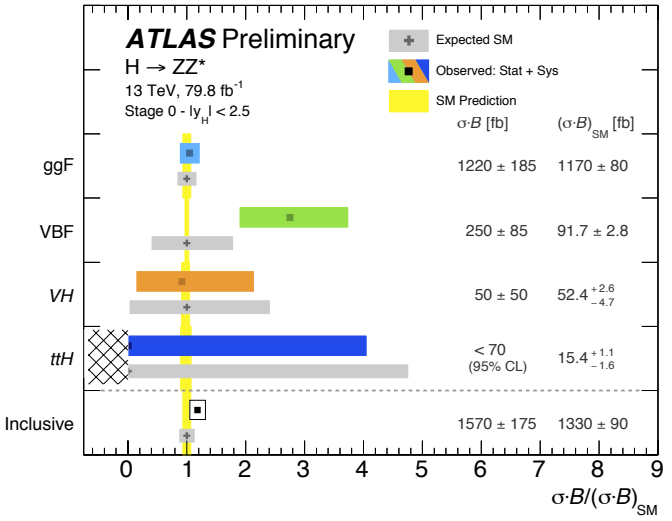
- **Run2 (up to 80 fb-1):**
  5.8 σ (obs.) 4.9 σ (exp.)
  -> driven by γγ and multileptons
- **Run1+2: 6.3 σ (obs.) 5.1 σ (exp.)**

Cross Sections per production mode

Inclusive signal strength compatible with SM expectations within 1 sigma:

$$\mu = 1.13^{+0.09}_{-0.08} = 1.13 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{exp.})\,^{+0.05}_{-0.04}\,(\text{sig. th.}) \pm 0.03\,(\text{bkg. th.})$$

$$\mu = 1.19 \pm 0.12(\text{stat.}) \pm 0.06(\text{exp.})^{+0.08}_{-0.07}(\text{th.}) = 1.19^{+0.16}_{-0.15}$$



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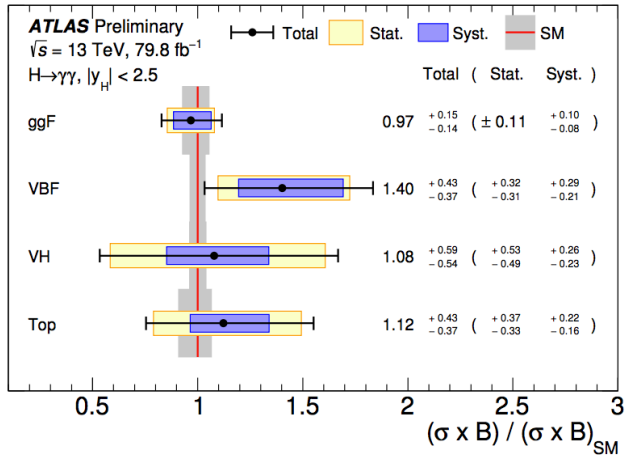
Interesting to investigate XS per prod mode since the measured cross section reflects the strenght of the coupling of the Higgs to SM particles

- Good agreement with SM (some excess in VBF)
- Large evidence of ggF, VBF and (in γγ) ttH
- 4l stat limited
- γγ: syst and stat errors becoming comparable

$$\mu = 1.06\,^{+0.14}_{-0.12} = 1.06 \pm 0.08\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{exp.})\,^{+0.07}_{-0.06}\,(\text{theo.})$$



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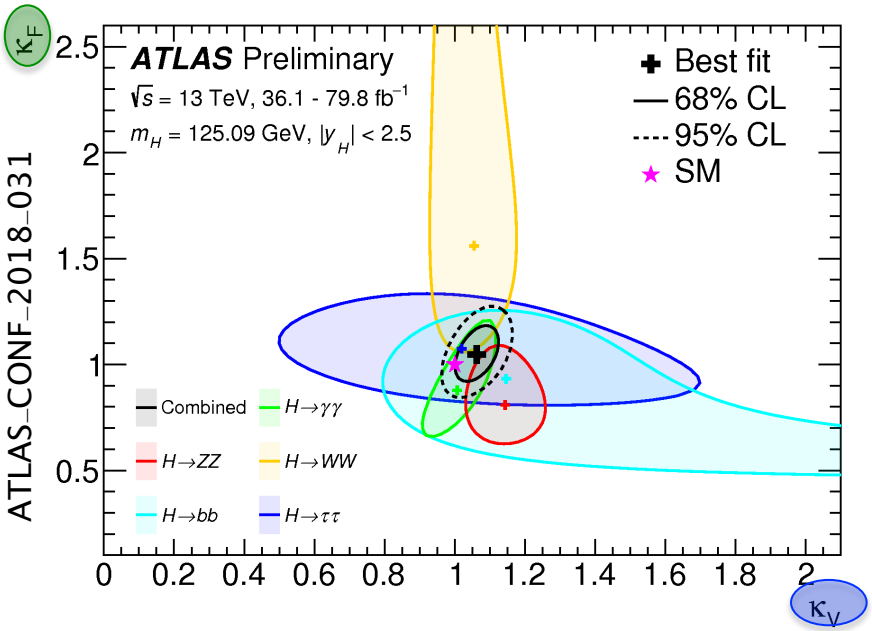
Couplings in kappa framework

The **same results** can be interpreted in terms of **couplings with fermions** or **vector bosons**.

Potential deviations of this couplings from the SM can affect the coupling modifiers (k) :

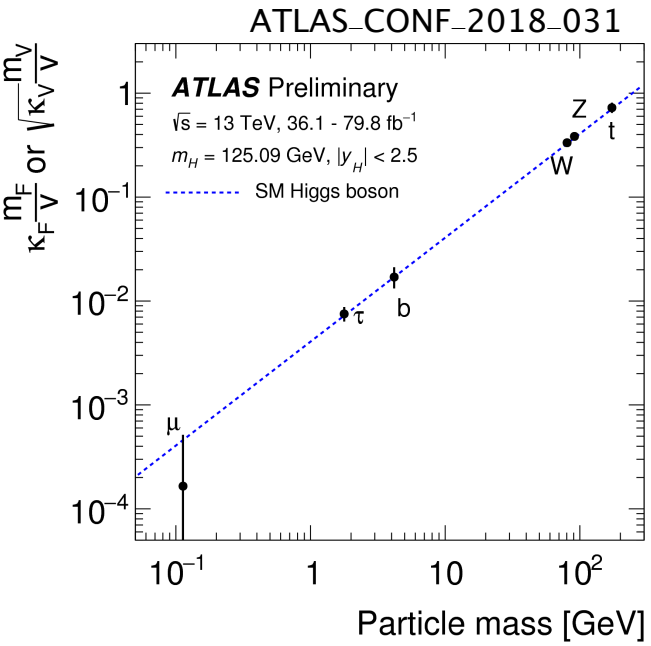
- $\mathbf{k_F}$ for the production/decay mechanisms mediated by fermions
- $\mathbf{k_V}$ for those mediated by vector bosons.



Results obtained with the current statistics does not show significant deviations with respect to the SM

- Higgs mass fixed to $m_H = 125.09$ GeV
- Only the $k_F>0$ and $k_V>0$ quadrant is shown (the H->ZZ*->4l channel is not sensitive to the relative sign of the k but Run1 exclusions from other decay channels)

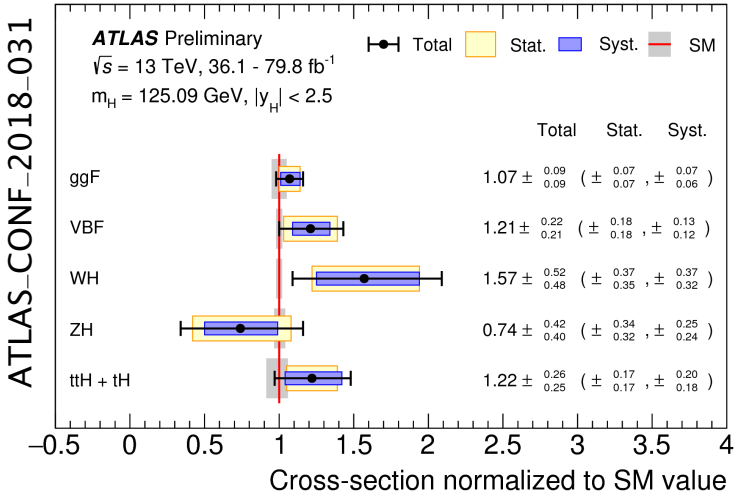
Summary and perspective



The Higgs boson couplings, with current precision, **scale with particle masses as expected from SM predictions**

- No new particles in loop and no BSM Higgs decay considered so far
- Already working on couplings to 2nd generation fermions ->(σ(Hμμ)< 3x SM, σ(Hcc-bar)< 120x SM)

Cross-sections for ggF, VBF, WH, ZH and ttH+tH normalized to their SM predictions, measured with the assumption of SM branching fractions. Measurements still **dominated by statistical errors**.



Significance obs. (exp.)
Run1
6.5 (5.3)
4.1 (3.7)
5.8 (5.3)

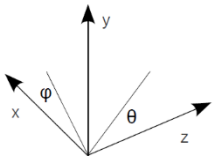
Conclusions

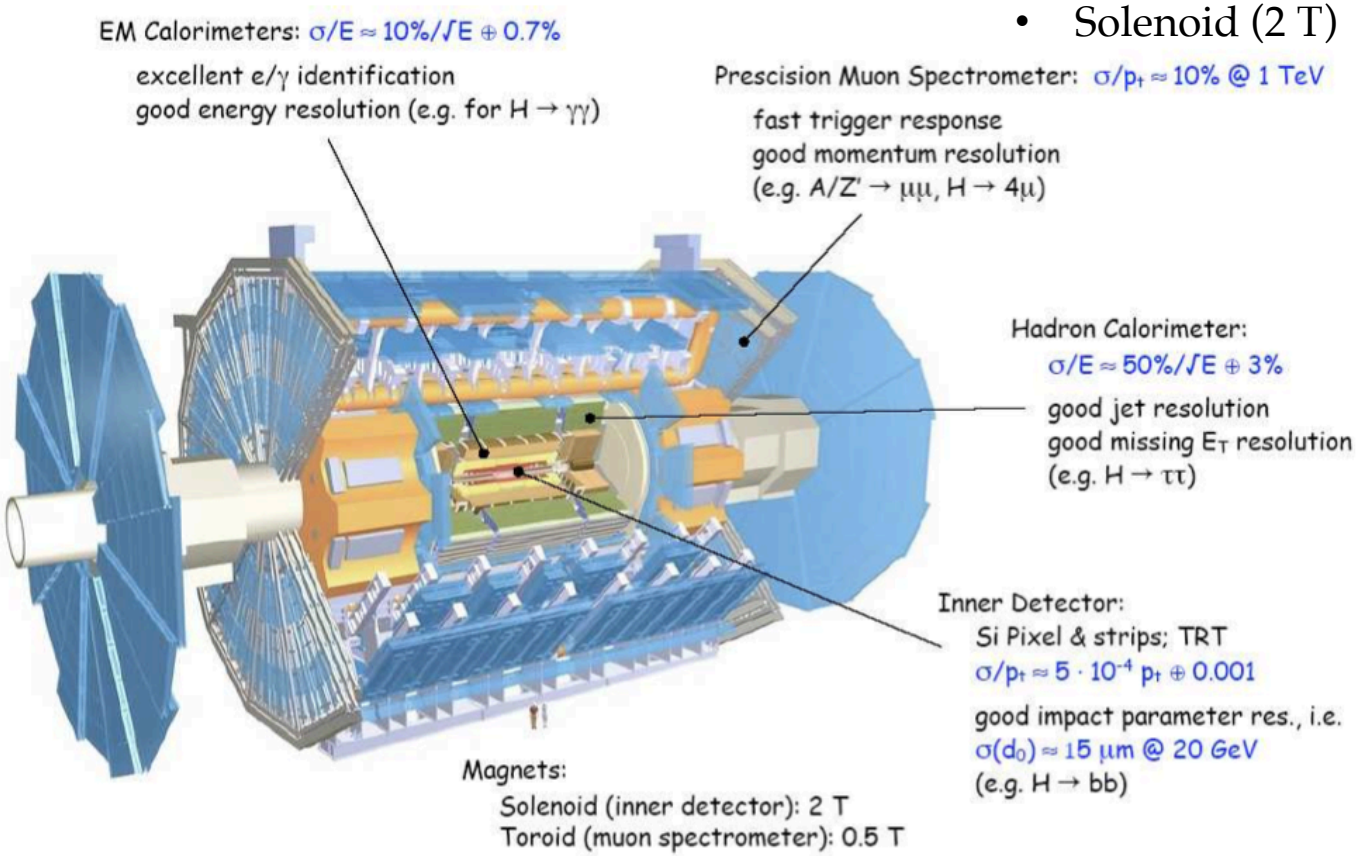
- **LHC has rapidly moved from discovery to exploration**
- With the first 36-80 fb-1 @ 13 TeV:
  - **All main higgs production modes and decay channels directly observed**
  - Direct evidence of **higgs coupling to 3rd generation** SM particles
  - **No significant deviations wrt SM** up to now
- End of Run2: 150fb-1 @ 13 TeV
  - **Statistical improvement** on differential XS measurements and cross sections per production mode
  - **Increasing precision of kinematic property measurements** (sensitive to BSM)
  - **Second generation Yukawa coupling**
  - **CP violation**
  - Search for **LFV higgs decays**
  - **Invisible Higgs decays**

Thanks for your attention!

Backup

A Thoroidal LHC ApparatuS





Inner Detector:

- Silicon trackers (pixel and microstrip)
- Gas trackers (with measurement of the transition radiation, TRT)
- Solenoid (2 T)

Electromagnetic Calorimeter:

- Sampling Pb+LAr

Hadronic Calorimeter:

- Fe+scintillator
- LAr technology

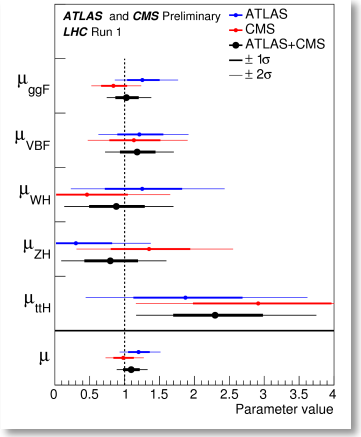
Muon System:

- Superconducting thoroids
- Precision tracking chambers
- Trigger chambers

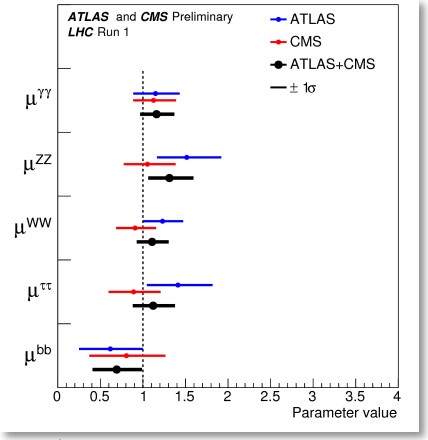
Overview of Run1 results

- Discovery of the Higgs with mass
  m_H= 125.09 ± 0.24 (± 0.21 stat. ± 0.11 syst.) GeV
- Measurements of the **couplings to SM particles consistent with the SM within uncertainties**
- Combined signal strength:
  $\mu = 1.09 \pm 0.07_{stat} \pm 0.04_{exp.syst.} \pm 0.03_{th.bkg}$
  $^{+0.07}_{-0.06}$th.sig
- **Non-SM hyp.** ($J^P_{SM} = 0^+$) **excluded at > 99.9% CL**
- Indirect limits on the width: $\Gamma_H/\Gamma_H^{SM} < 5$ @95% CL

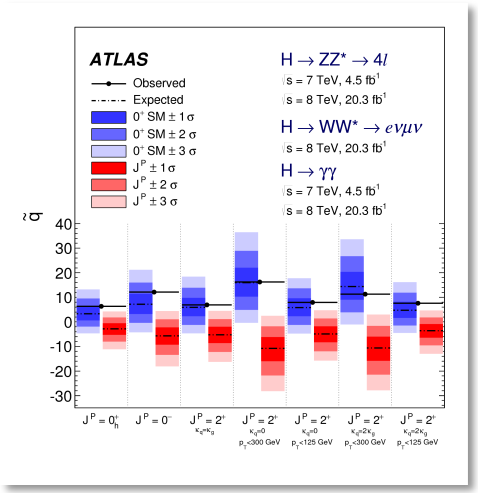
Signal strength: $\mu = (\sigma\ BR)_{obs}/(\sigma\ BR)_{SM}$
(kinematics distributions assumed as from SM)

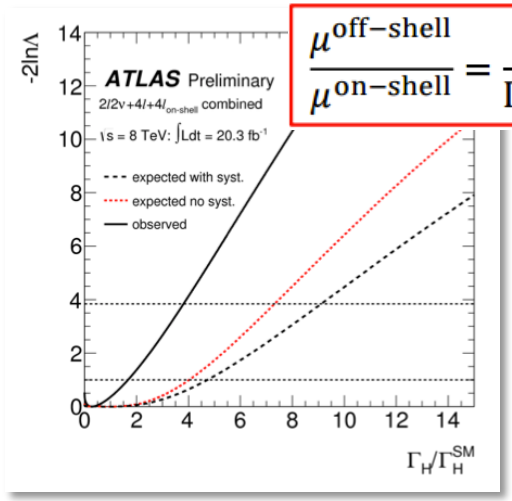


(Assuming BR_{SM})

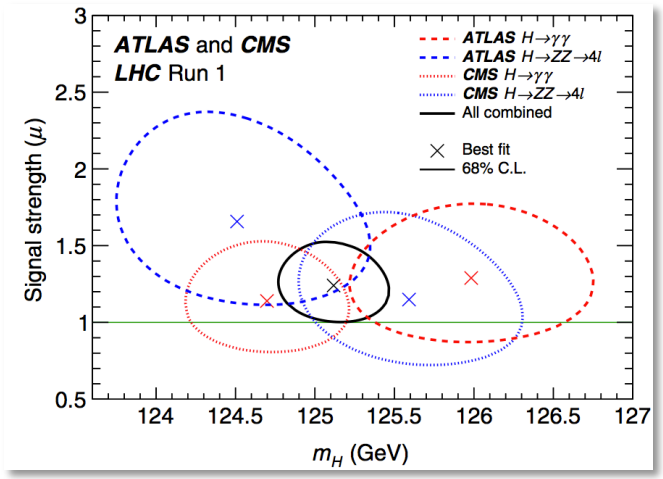


(Assuming XS_{SM} and $XS_{SM(7TeV)}$=$XS_{SM(8TeV)}$)





$$\frac{\mu^{off-shell}}{\mu^{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$



Di higgs production and higgs self coupling

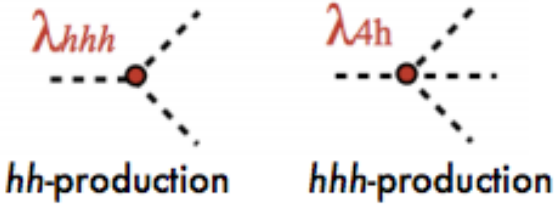
Non-resonant HH production main probe for the Higgs self-coupling

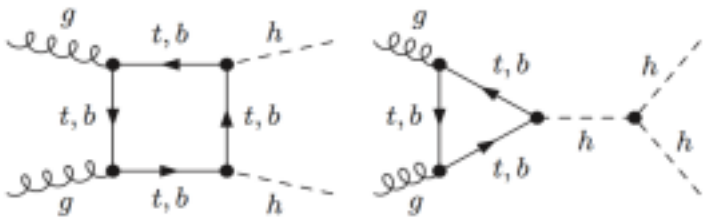
- Tiny cross-section, $\sigma = 33$ fb
- Require full HL-LHC statistics to approach SM sensitivity

Higgs self interaction

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

keystone of the Higgs mechanism and Standard Model, never probed in nature





$\sigma_{HH\ \mathrm{comb}} < 6.7 \times \mathrm{SM}\ (10.4\ \mathrm{exp.})$

μ < @95%	ATLAS
bbbb	<13
bbWW	
bbττ	< 12
bbγγ	< 22
WWγγ	< 230