Higgs boson couplings to quarks and leptons at the ATLAS experiment

International Conference on Kaon Physics 2019

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On behalf of the ATLAS Collaboration

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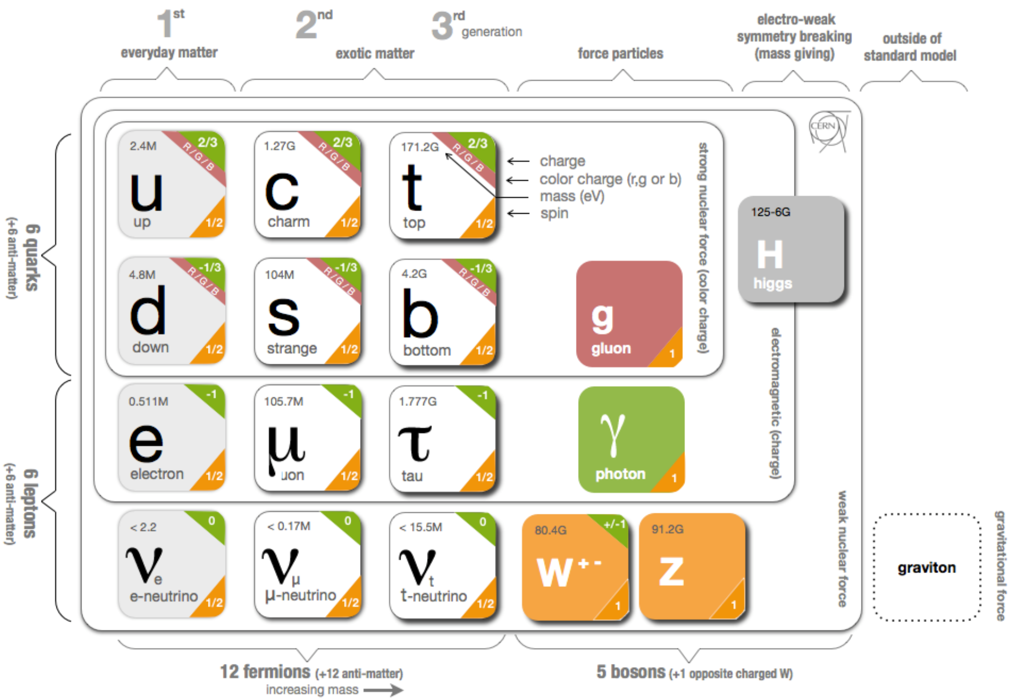
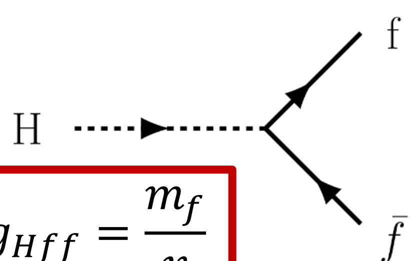
The Higgs boson in the SM

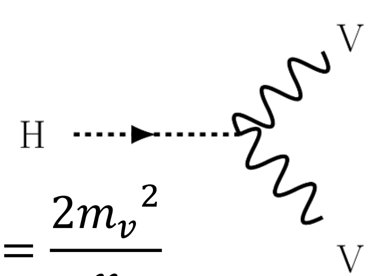


- Following the Higgs Boson with **mass ~ 125 GeV** discovered in 2012, more data have allowed for its properties to be measured.
- The Higgs Boson couplings to other particles are set by their masses, which determine all SM-like Higgs Boson production and decay modes including the Higgs self-coupling.

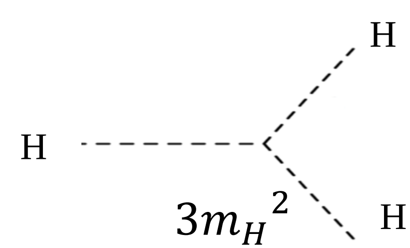
$$\mathcal{L} = -g_{Hff} f \bar{f} H + \delta_V V_\mu V^\mu \left(g_{HVV} H + \frac{g_{HHVV}}{2} H^2 \right) + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{6} H^4$$



$$g_{Hff} = \frac{m_f}{v}$$

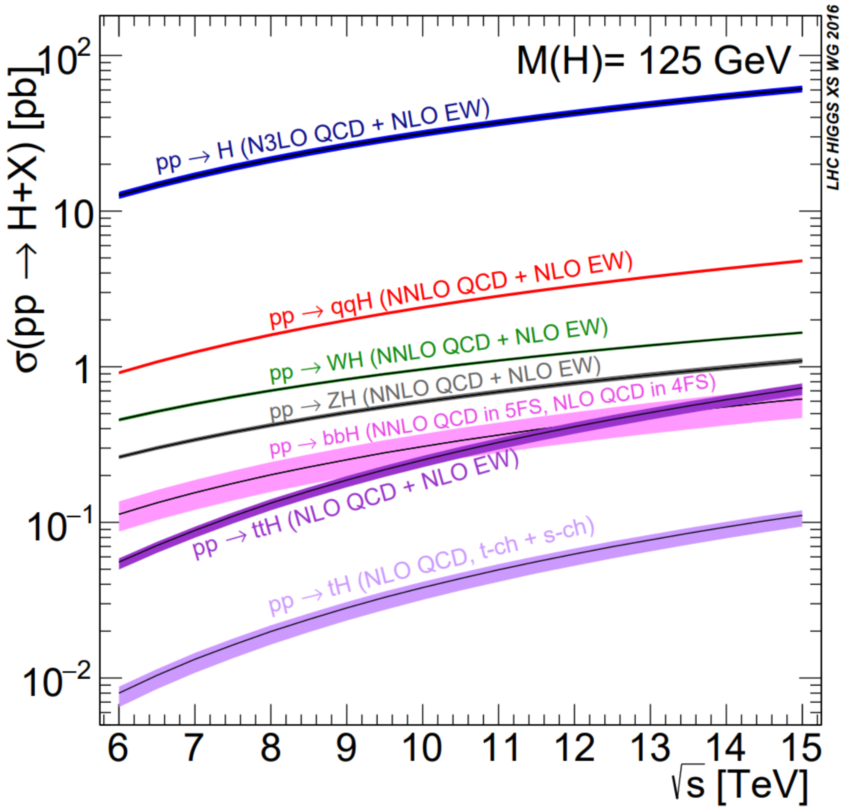


$$g_{HVV} = \frac{2 m_v{}^2}{v}$$



$$g_{HHH} = \frac{3 m_H{}^2}{v}$$

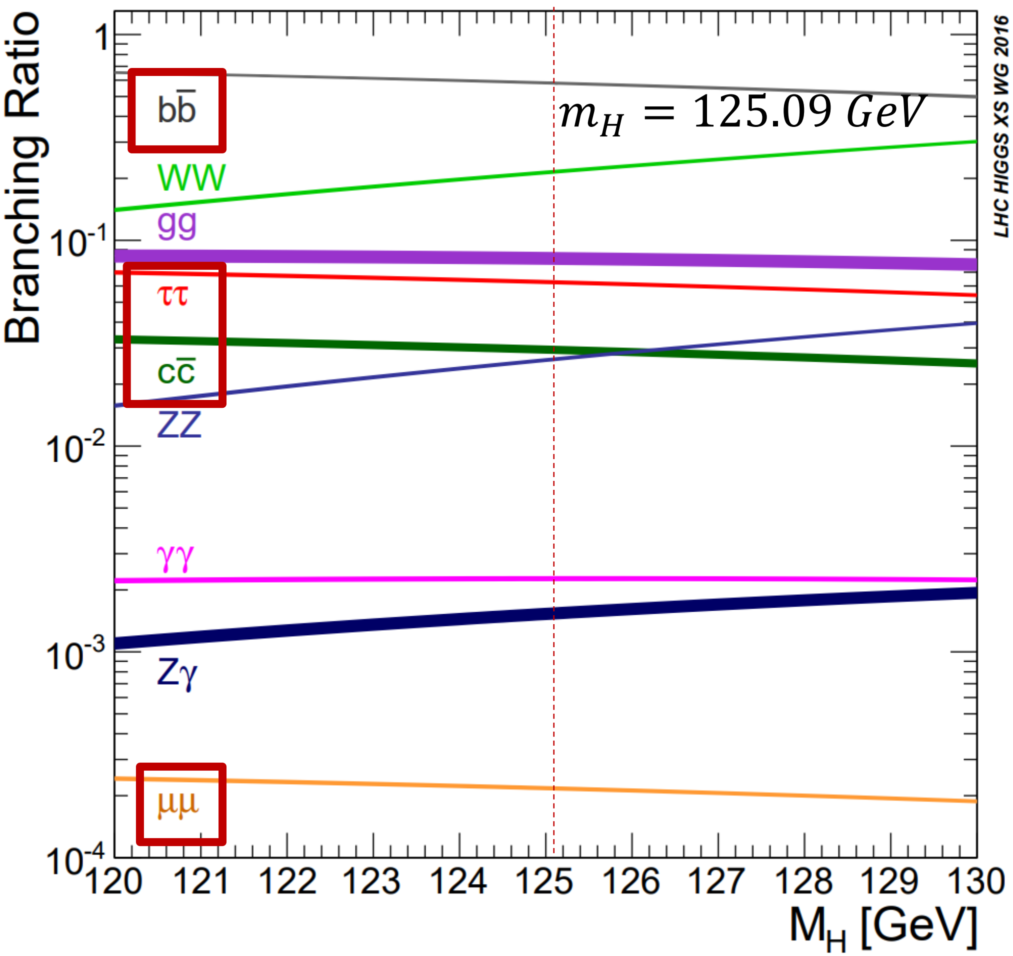
SM Higgs Production at LHC



XS in pb	13 TeV	8 TeV	σ13/σ8
ggF	48.52	21.39	**2.3**
VBF	3.78	1.60	2.4
WH	1.37	0.70	2.0
ZH	0.88	0.42	2.1
bbH	0.49	0.20	**2.4**
ttH	0.51	0.13	**3.8**
tH	0.09	0.02	**3.9**

- There is **an increase** in production cross sections from increased center-of-mass energy.
- ***ttH*** provides direct measurement of Yukawa coupling, but with a small production rate.
- **ggF** provides indirect measurement of couplings to quarks at LHC via virtual loops.

SM Higgs Decay BR



Decay channel	Branching Ratio[%]
H→bb	**58.09**
*H→WW**	21.52
H→gg	8.18
H→ττ	**6.26**
H→cc	**2.88**
*H→ZZ**	2.64
H→γγ	0.23
H→Zγ	0.15
H→μμ	**0.022**

- **H→bb** and **H→ττ** : high BR, low S/B and low mass resolution at LHC, providing direct measurement of the Yukawa coupling.
- *H→γγ* can also provide indirect measurement of couplings to quarks via virtual loops.

Outline

- Higgs fermion coupling physics results from ATLAS:
  - Decay to quarks:
    - $H \rightarrow bb$
    - $H \rightarrow cc$
    - $H \rightarrow J/\Psi\gamma$, $\Upsilon(nS)\gamma$, $\Phi\gamma$ and $\rho\gamma$
  - to leptons:
    - $H \rightarrow \tau\tau$
    - $H \rightarrow \mu\mu$
    - $H \rightarrow ee$
  - *ttH* production
  - Yukawa coupling from the combination results
- Summary

Caveat: Only a selective set of results will be shown.

H→bb

- *H→bb* takes the largest BR~58% → drives total width
- This decay is studied by ATLAS in all of the major Higgs production modes.
- In the **most sensitive *VH, H→bb*** analysis, 3 channels (0-, 1- and 2 charged leptons from the vector boson) developed in ATLAS.
- Analyses are now dominated by systematic uncertainties for ***VH, H→bb*** → Improvement on systematics needed.
- **VBF, *H→bb*** consists of the inclusive VBF analysis, and the analysis of VBF with an associated photon.

80fb^{-1}

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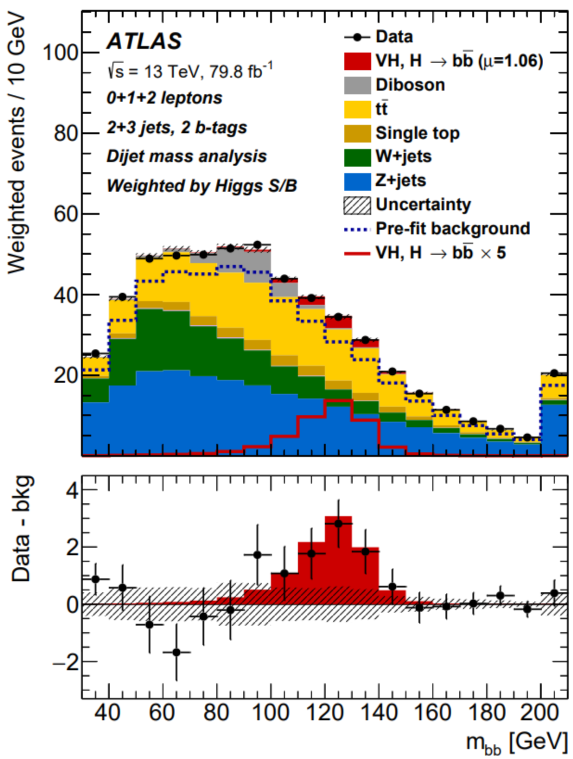
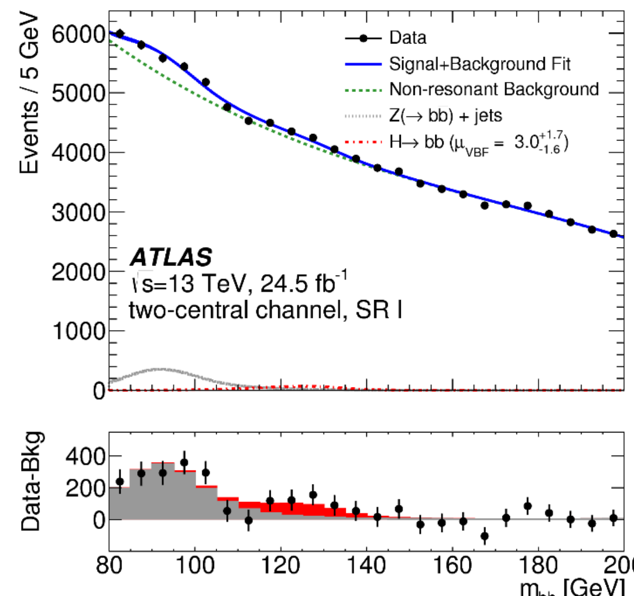


VH, H→bb

$25\ \text{fb}^{-1}$

Phys. Rev. D 98 (2018) 052003

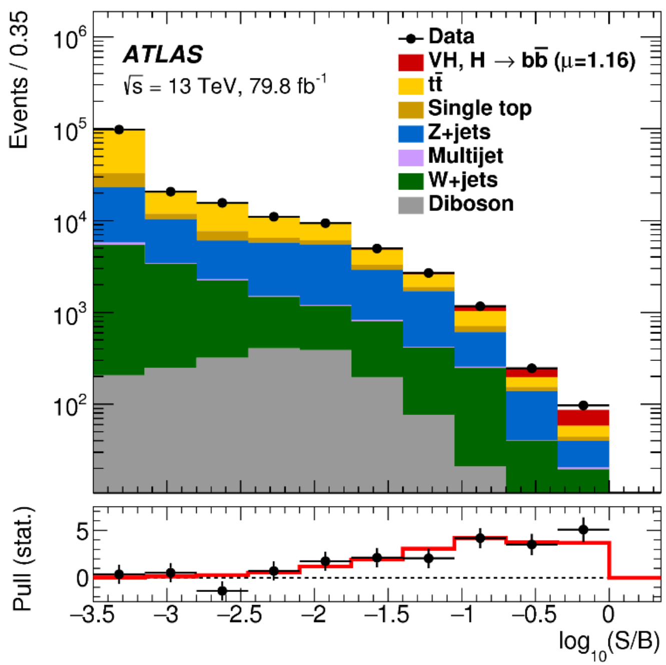


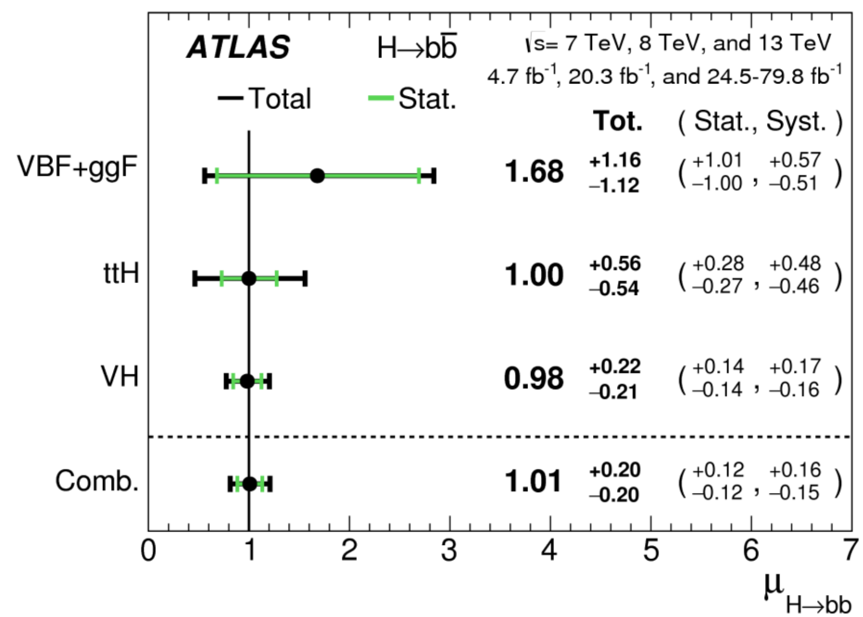
VBF, H→bb

$H \rightarrow bb$

- Run-1 *VH(bb)* ATLAS+CMS combined significance **2.6σ(3.7σ exp.)** JHEP 08 (2016) 045
- Run-2 **36** fb^{-1} ATLAS only evidence of *VH(bb)*: **3.5σ(3.0σ exp.)** JHEP 12 (2017) 024

H→bb **observation with 80** fb^{-1}**!** Phys. Lett. B 786 (2018) 59

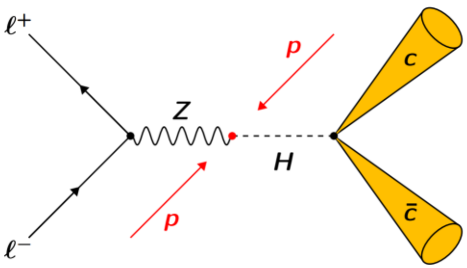


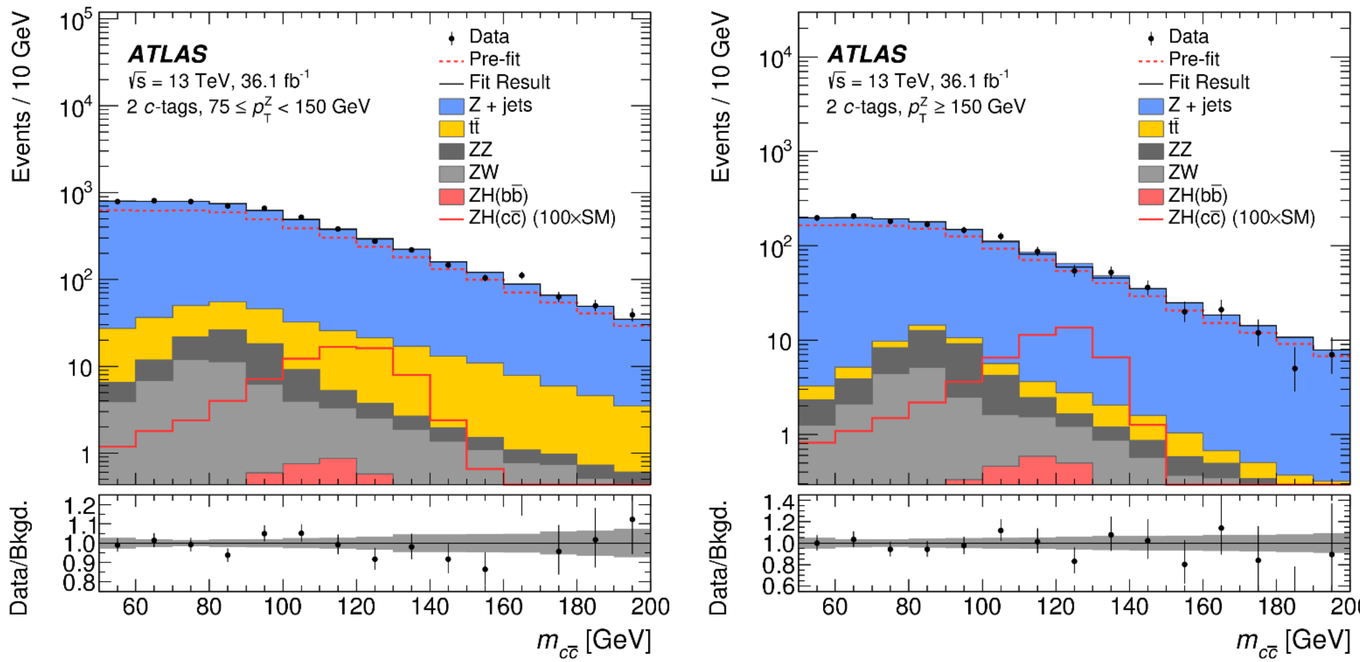


- *VH(bb)* Run 1+2 combined significance **4.9σ(5.1σ exp.)**
- *H(bb)* Run 1+2 combined significance **5.4σ(5.5σ exp.)**

H→cc

- ***H→cc*** constitutes the largest part of the SM prediction for the Higgs decay width which we have no experimental evidence.
- **Inclusive direct** search for ***ZH→llcc*** performed.
- Charm-tagging algorithms developed to separate *c*-jets from light flavor and *b*-jets, giving *c*-jets efficiency of around 40%, and rejection factors of 4.0 and 20 for *b*-jets and *l*-jets.





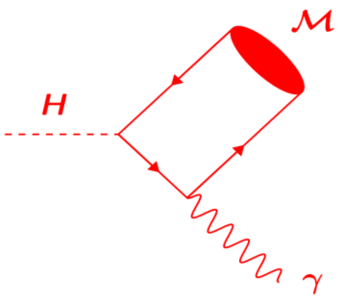
[Phys. Rev. Lett. 120 (2018) 211802]

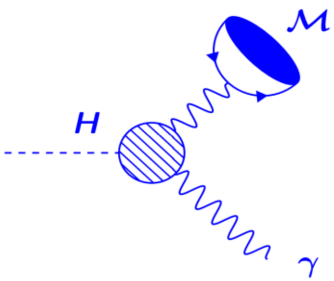
95% CL: σ×B<2.7(3.9 exp.) pb, SM: 26 fb

a factor of about 100 above SM sensitivity from 36.1 fb^{-1} result

$H \rightarrow J/\Psi\gamma$, $Y(nS)\gamma$, $\Phi\gamma$ and $\rho\gamma$

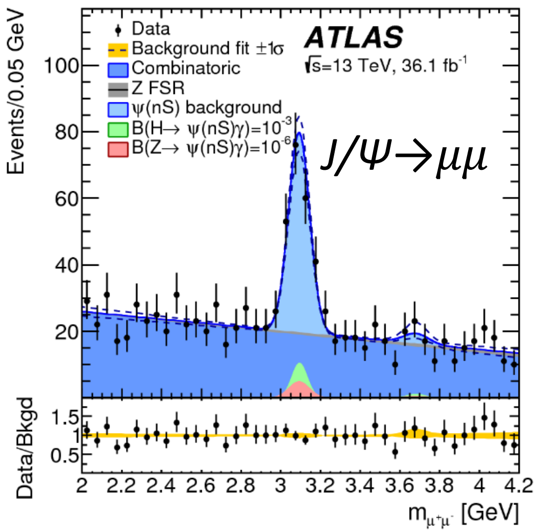
- Final states with J/Ψ, Y(nS)γ, $\Phi\gamma$ and $\rho\gamma$ are explored by ATLAS.
- The SM prediction is O(10^{-6}) Phys. Rev. D 90, 113010 (2014)
- Interference between direct and indirect contributions.
- Direct amplitude provides sensitive to *c, b* and light quark Yukawa couplings, respectively.
- Indirect gives larger contribution to dominate the decay width.

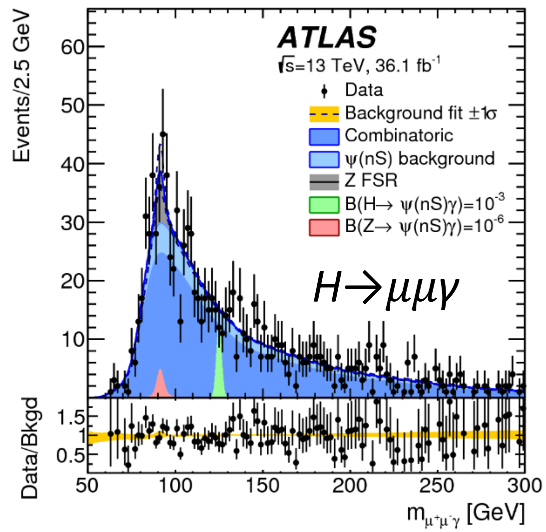


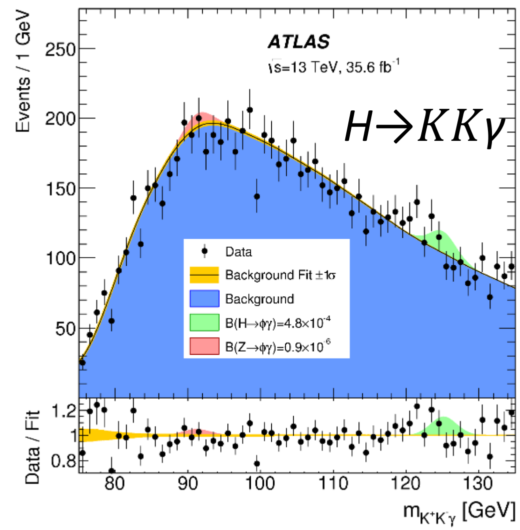


$H\rightarrow J/\Psi\gamma$, $\Upsilon(nS)\gamma$, $\Phi\gamma$ and $\rho\gamma$

- m($\mu\mu$) distributions are used to extract J/Ψ candidates and then m($\mu\mu\gamma$) is used to extract $H\rightarrow J/\Psi\gamma$, as well as the other decay modes.







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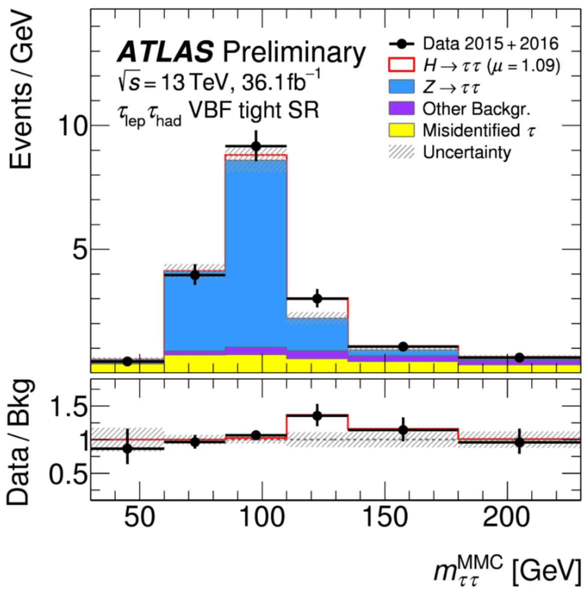
Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H\to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H\to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H\to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H\to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7

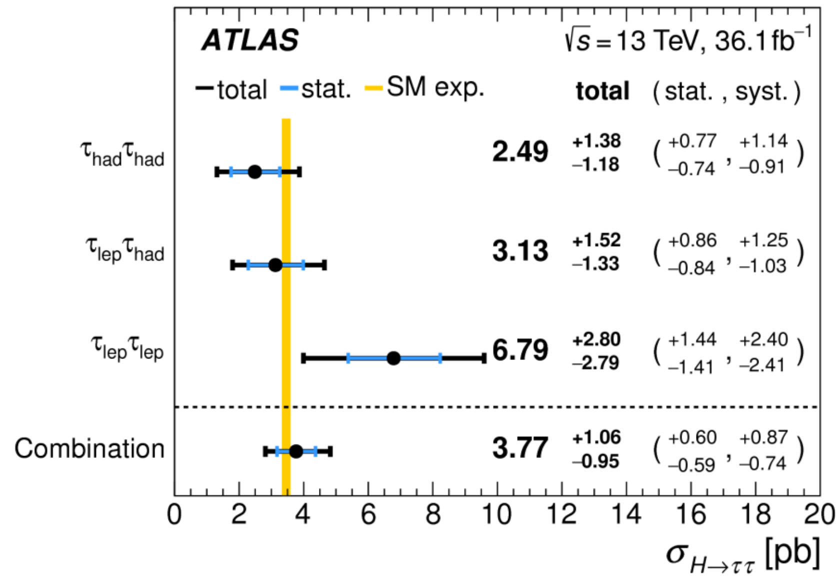
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H\to\phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(H\to\rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8

$H \rightarrow \tau\tau$

- ATLAS covered all possible di-tau decay modes, including *leplep*, *lephad* and *hadhad* channels.
- Large $Z \rightarrow \tau\tau$ background.
- **Observe $H \rightarrow \tau\tau$ with > 5σ** by combining Run-1 (25 fb^{-1})and Run-2(36.1 fb^{-1}).

Phys. Rev. D 99, 072001 (2019)

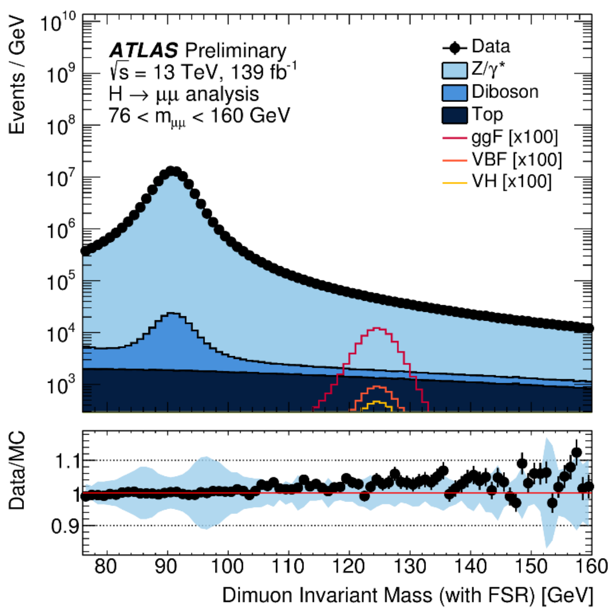


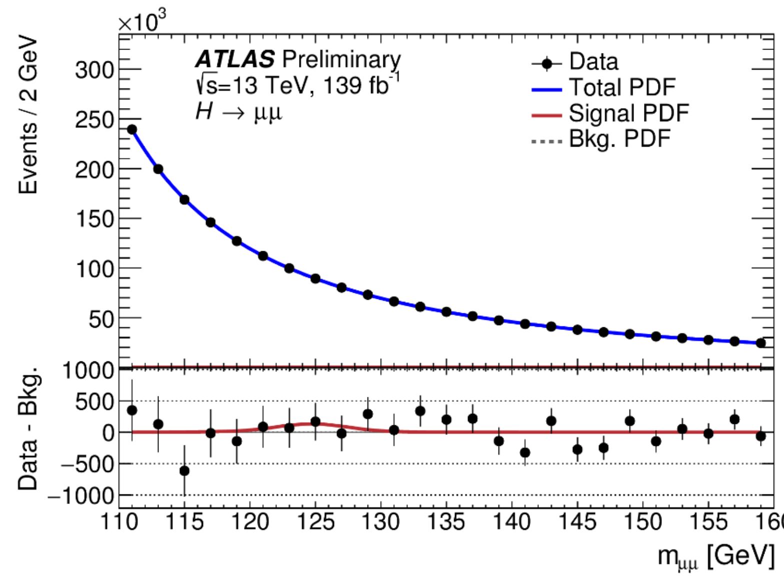


Run-1: 4.5σ(3.4σ exp.)
Run-2: 4.4σ(4.1σ exp.)
Run 1+2: 6.4σ(5.4σ exp.)

- Probe 2nd generation fermions coupling. **Clean experimental signature with very small BR.** Large Drell-Yan background.
- BDTs trained against the background in 0-jet, 1-jet and ≥2-jets categories (ggF and VBF).
- Fit to the $m(\mu\mu)$ in 12 categories simultaneously to extract the signal.

ATLAS-CONF-2019-028





ATLAS (Run2 139 fb^{-1}):

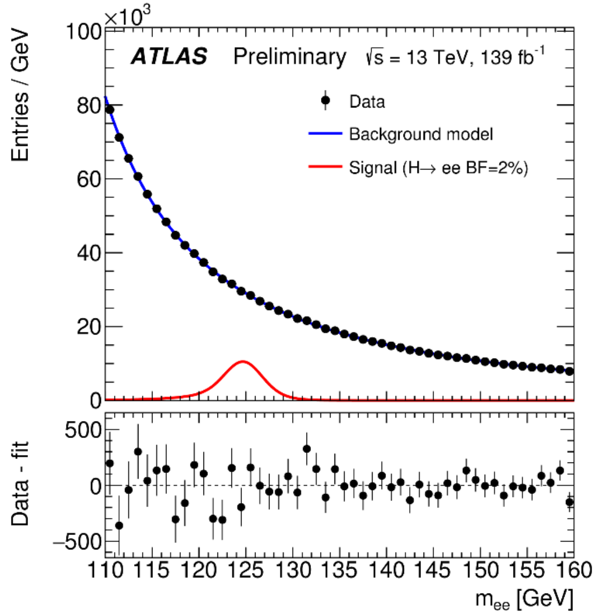
$\mu = 0.5^{+0.7}_{-0.7}$

95% CL: μ<1.3(2.2 exp.)

Significance: 0.8σ (1.5 σ exp.)

$H \rightarrow ee$ and LFV search

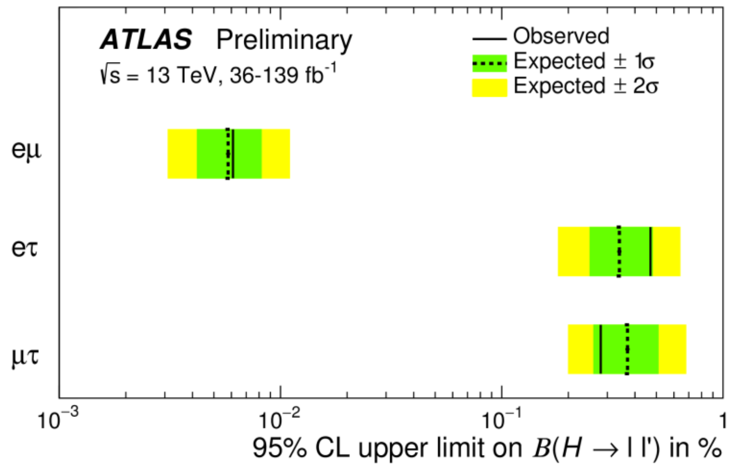
- Search for the 1st generation Yukawa has also been performed by ATLAS.
- As the lightest charged lepton, **the decay of the Higgs boson into a pair of electrons is so extraordinarily rare** ~ 40,000 times less than muons.
- Fitting strategy is similar to the $H \rightarrow \mu\mu$ analysis, to extract a signal peak from a continuum falling background.
- LFV is also searched which may appear in many new-physics theories. More details can be found in Julia's talk.



95% CL: $B(H \rightarrow ee) < 3.6 \times 10^{-4}$

3.5×10^{-4} exp.

SM: 4.9×10^{-9}

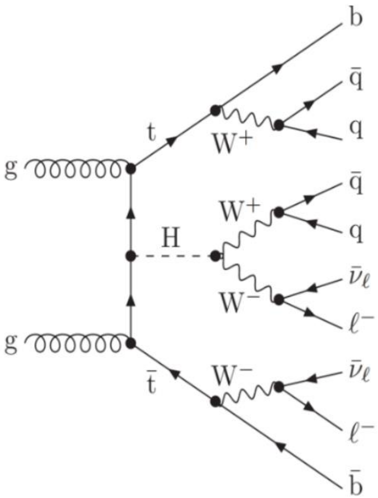


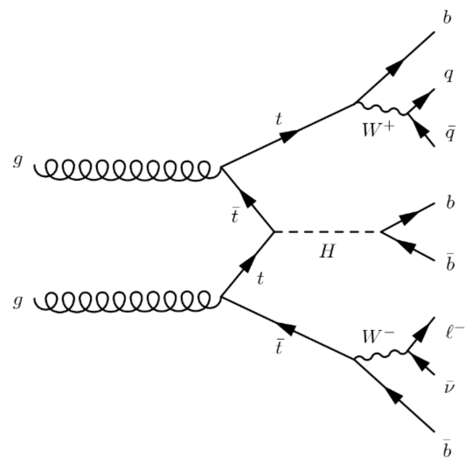
95% CL: $B(H \rightarrow e\mu) < 6.1 \times 10^{-5}$

5.8×10^{-5} exp.

ATLAS-CONF-2019-037

ttH production mode



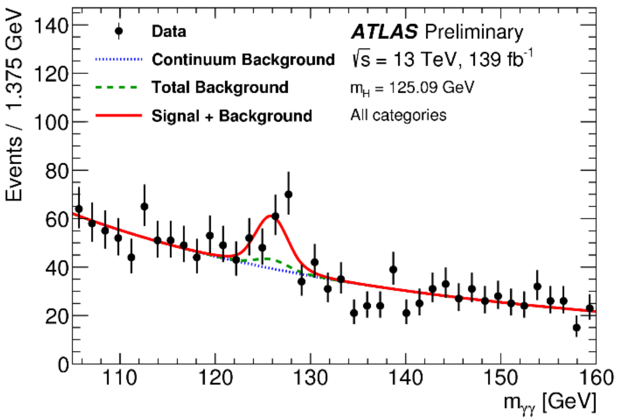


Decay mode	Branching fraction [%]
$H \to bb$	58.1 ± 1.0
$H \to WW$	21.5 ± 0.5
$H \to gg$	8.18 ± 0.59
$H \to \tau\tau$	6.26 ± 0.15
$H \to cc$	2.88 ± 0.14
$H \to ZZ$	2.64 ± 0.06
$H \to \gamma\gamma$	0.227 ± 0.007
$H \to Z\gamma$	0.154 ± 0.011
$H \to \mu\mu$	0.021 ± 0.001

- The coupling strength through a Yukawa coupling is proportional to the mass of the fermion → Largest coupling to top quark
- Deviation of couplings→ sensitive to new physics
- Run-1 ATLAS+CMS combined *ttH* significance 4.4σ(2.0σ exp.)
- Signatures are complex, because both top quarks and H bosons can decay in very different ways. **Multiple decay channels are combined** in order to reach observation.

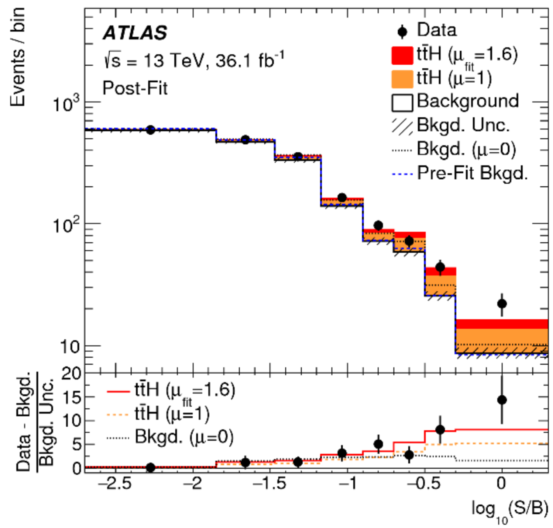
ttH production mode

13 TeV *ttH* results of different decay channels:



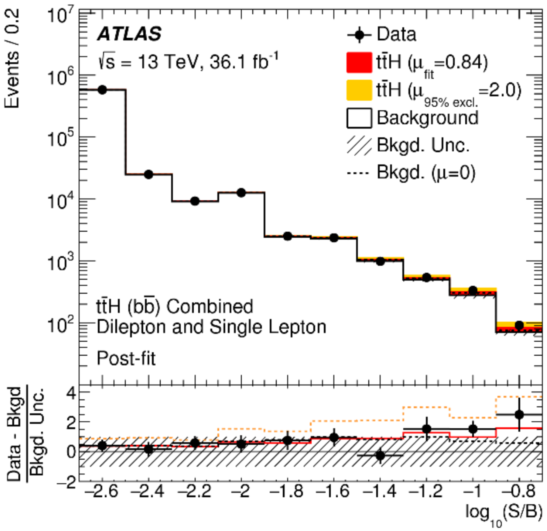
ATLAS-CONF-2019-004

***ttH, H→γγ* (140 fb^{-1}):**
ATLAS 4.9σ (4.2σ exp.)



Phys. Rev. D 97, 072003 (2018)

***ttH*, Multi-lepton (*H→ττ, H→WW**, 36 fb^{-1})**
ATLAS 4.1σ (2.8σ exp.)



Phys. Rev. D 97 (2018) 072016

***ttH, H→bb* (36 fb^{-1})**
ATLAS 1.4σ (1.6σ exp.)

***ttH, H→γγ* (80 fb^{-1}, included in the *ttH* combination)**
ATLAS 4.1σ (3.7σ exp.)
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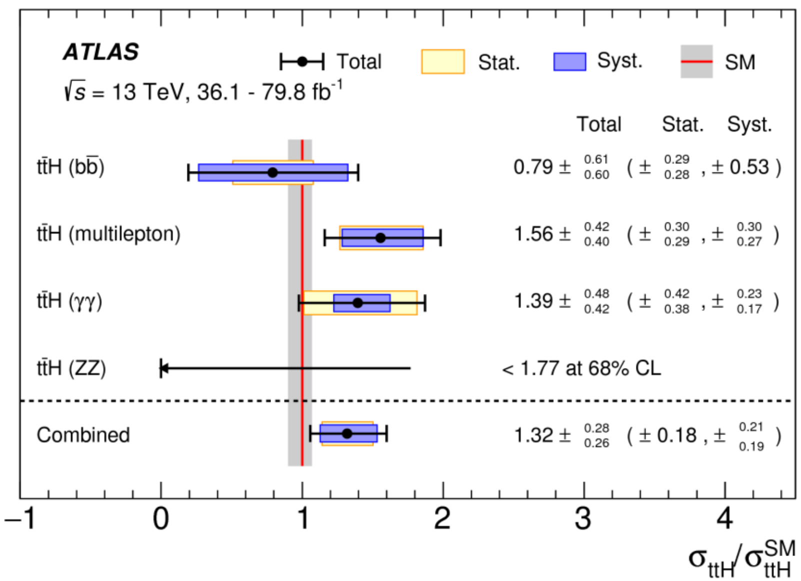
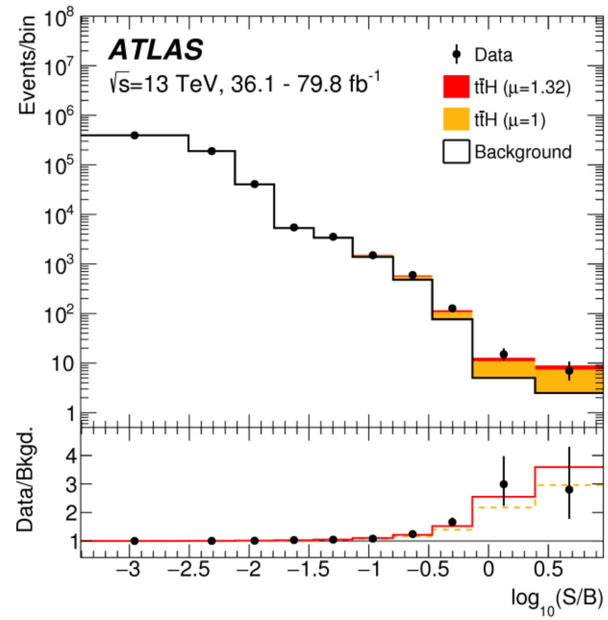
ttH production mode

ttH production mode observed after combination!





[Phys. Lett. B 784 (2018) 173]

ATLAS

Run-2 5.8σ (4.9σ exp.)

Run-1+2 6.3σ (5.1σ exp.)

ttH, H→γγ and *ttH, H→ZZ* limited by statistics, while *ttH, H→bb* dominated by systematic uncertainties. The stat. and syst. uncertainties in *ttH, ML* give equivalent impacts.

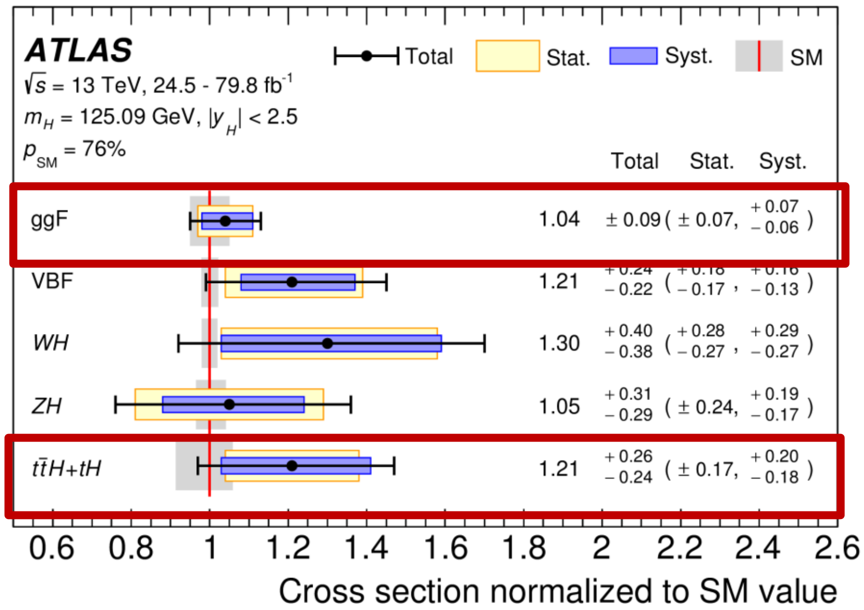
Combined Measurement

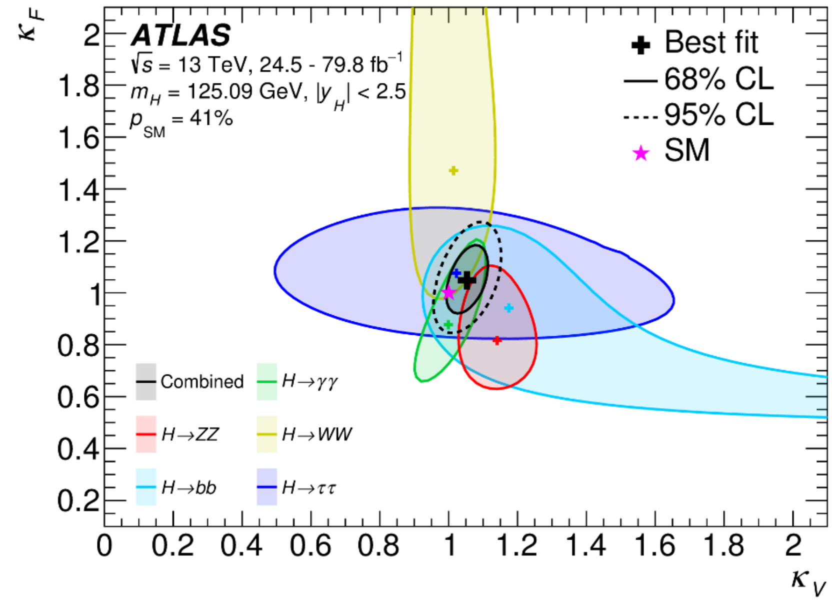
Decay \ Production	gluon fusion	vector boson fusion (VBF)	associated prod. with W/Z	associated prod. with $t\bar{t}$
$H \to \gamma\gamma$ ($t\bar{t}$, WW and ZZ pairs)	80 fb^{-1} ✓	80 fb^{-1} ✓	80 fb^{-1} ✓	80 fb^{-1} ✓
$H \to ZZ^*$	80 fb^{-1} ✓	80 fb^{-1} ✓	80 fb^{-1} ✓	80 fb^{-1} ✓
$H \to WW^*$	36 fb^{-1} ✓	36 fb^{-1} ✓		36 fb^{-1} ✓
$H \to \tau\bar{\tau}$	36 fb^{-1} ✓	36 fb^{-1} ✓		36 fb^{-1} ✓
$H \to b\bar{b}$		25 fb^{-1} ✓	80 fb^{-1} ✓	36 fb^{-1} ✓
$H \to \mu^-\mu^+$	140 fb^{-1} ✓	140 fb^{-1} ✓		
$H \to$ invisible		36 fb^{-1} ✓	36 fb^{-1} ✓	

- Combined measurements of Higgs boson are performed.
- The results of the production cross sections and Higgs coupling modifiers (e.g. κ_F in the "kappa"-framework corresponds to the Higgs Yukawa coupling) are presented.

Combination Measurement

arXiv:1909.02845

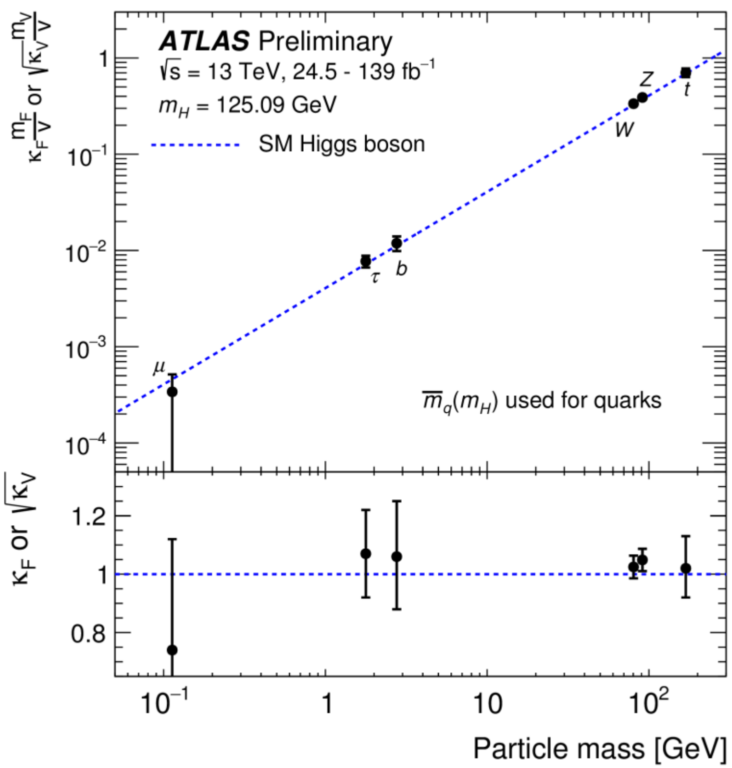


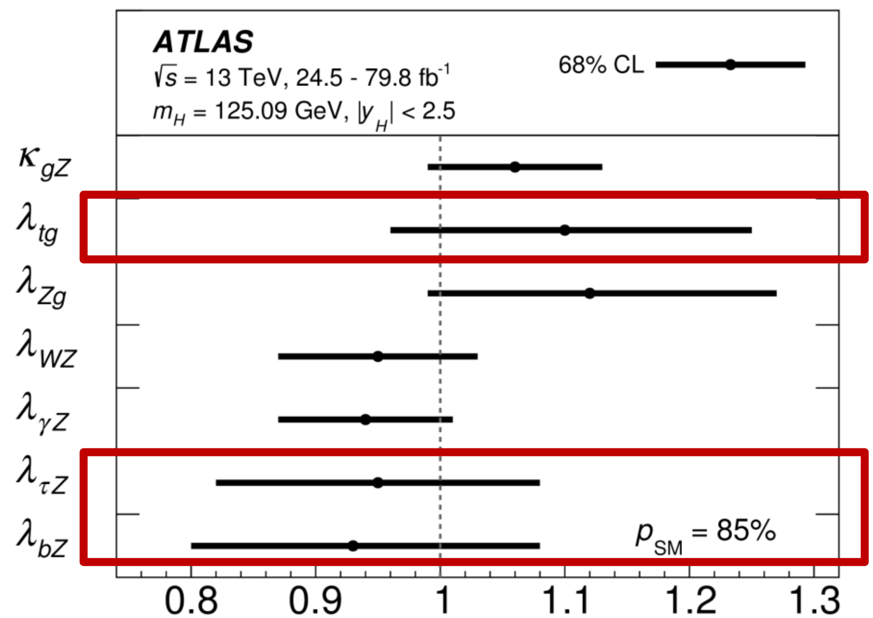


- ATLAS: $\mu = 1.13^{+0.09}_{-0.08} = 1.13^{+0.05}_{-0.05}(\text{stat.})^{+0.05}_{-0.05}(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.})^{+0.03}_{-0.03}(\text{bkg. th.})$
- $\kappa_F = 1.05^{+0.09}_{-0.09}$, $\kappa_V = 1.06^{+0.04}_{-0.04}$
- The overall production rate of the Higgs boson was measured to be in agreement with Standard Model predictions.
- All major production modes have been observed!

Combined Measurement

- Couplings are in an excellent agreement with the Standard Model prediction over a range covering 3 orders of magnitude in mass.
- In the Standard Model, the ggF loop is mediated mainly by top quarks. Therefore, possible new physics contributions can be tested by comparing the gluon coupling with the direct measurement of the top quark coupling in Higgs boson production in association with top quarks.





$$\lambda_{tg} = \frac{\kappa_t}{\kappa_g}, \lambda_{\tau Z} = \frac{\kappa_\tau}{\kappa_Z}, \text{etc.}$$

ATLAS Summary plots

ATLAS-CONF-2018-031

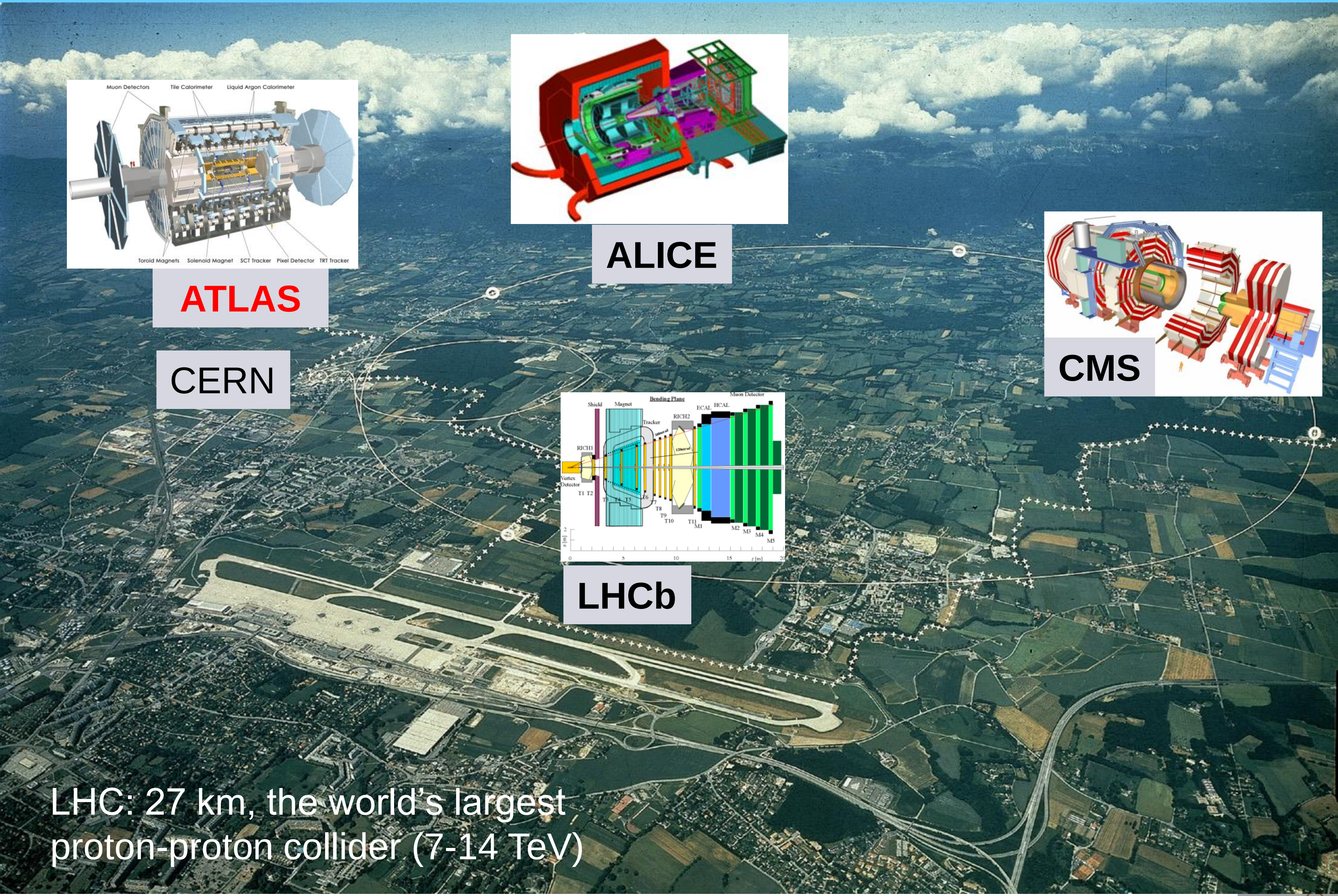
Summary

- A lot of impressive Higgs Yukawa coupling results come from ATLAS Run 1+2
  - All major production modes have been observed.
  - Higgs coupling to **3rd generation fermions** are confirmed, at precision level of **20% for *t* and *b***, and **30% for *τ***, respectively.
  - Improvements made in studying coupling to **2nd generation fermions**, for ***μ*** we are reaching close to SM sensitivity now, while for ***c*** we need much more data .
- No obvious deviation from SM observed so far.
- With all the analysis updated to the full Run-2 dataset and the future HL-LHC, a higher sensitivity to the potential new physics will be reached!

Thanks

Backup

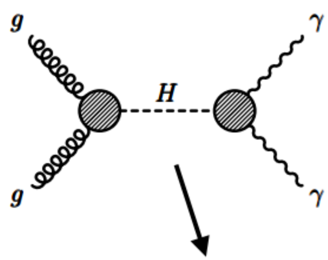
Large Hadron Collider at CERN



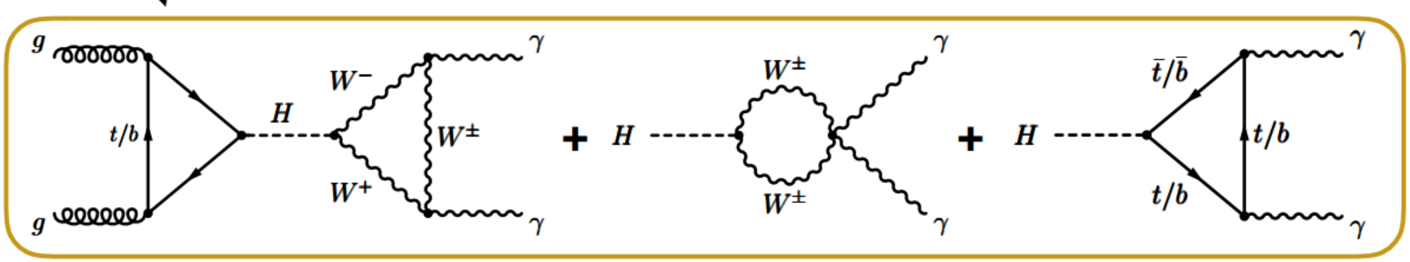
LHC: 27 km, the world's largest
proton-proton collider (7-14 TeV)

“kappa” framework

- Introduce one scale factor κ per SM particle with observable “Higgs coupling” at the LHC: κW, κZ, κt, κb, κτ, κμ, κγ, κg, κH
- Use best available SM calculation for cross sections and BR, to look for deviations from the SM.
- Eg:



$$(\sigma \times \mathbf{BR})(\mathbf{gg} \to \mathbf{H} \to \gamma\gamma) \sim \frac{\kappa_{\mathbf{g}}^{\mathbf{2}}(\kappa_{\mathbf{t}}, \kappa_{\mathbf{b}}, \ldots)\kappa_{\gamma}^{\mathbf{2}}(\kappa_{\mathbf{W}}, \kappa_{\mathbf{t}}, \ldots)}{\kappa_{\mathbf{H}}^{\mathbf{2}}(\kappa_{\mathbf{b}}, \kappa_{\mathbf{W}}, \kappa_{\mathbf{Z}}, \kappa_{\tau}, \kappa_{\mathbf{t}}, \ldots)}$$



- Can handle other production and decay vertices in a similar way (much simpler in most cases)