Measurement of the properties of the SM-like Higgs boson in ATLAS and CMS

CHARGED 2018

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On behalf of the ATLAS and CMS Collaborations

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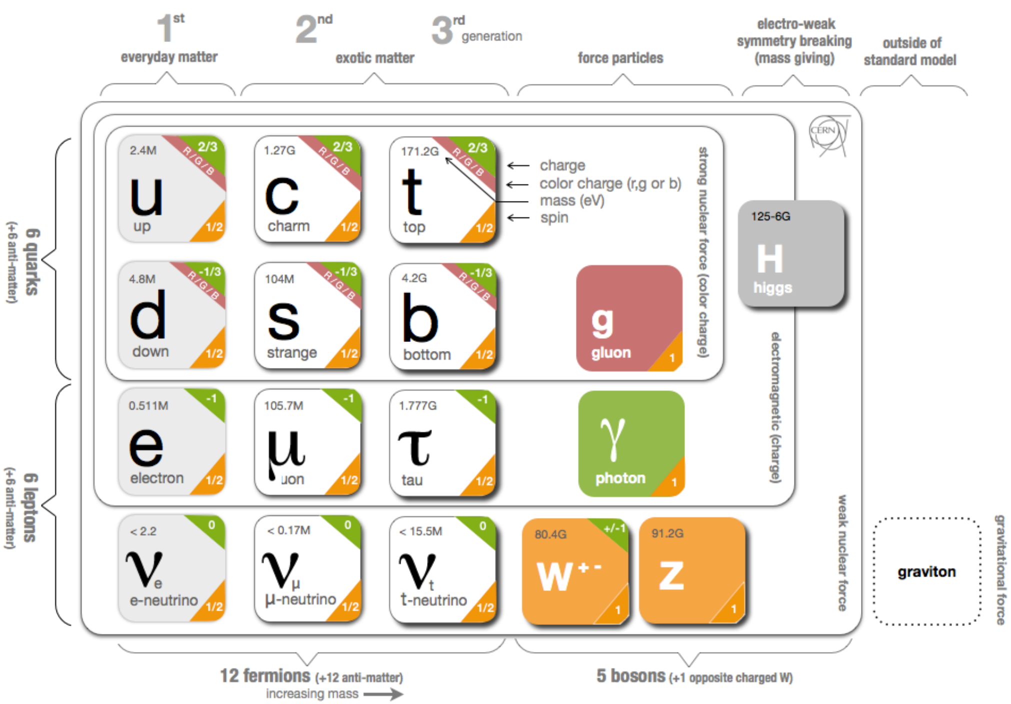
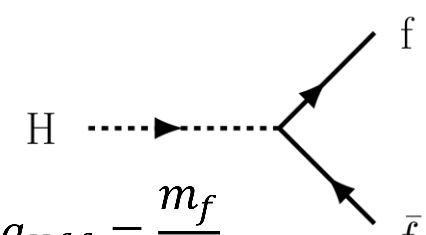
The Higgs boson in the SM

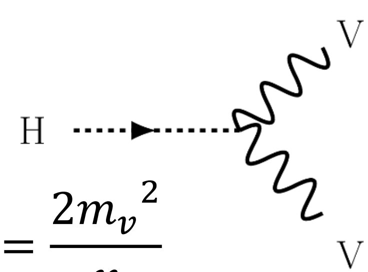


- Following the Higgs Boson with **mass ~ 125 GeV** discovered in 2012, more data have allowed for its properties to measured.
- The Higgs Boson couplings to other particles are set by their masses, which determine all SM-like Higgs Boson production and decay modes including the Higgs self-coupling.

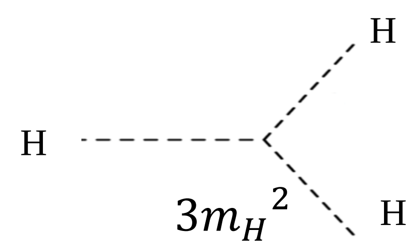
$$\mathcal{L} = -g_{Hff} f\bar{f}H + \delta_V V_\mu V^\mu \left(g_{HVV} H + \frac{g_{HHVV}}{2} H^2 \right) + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{6} H^4$$



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

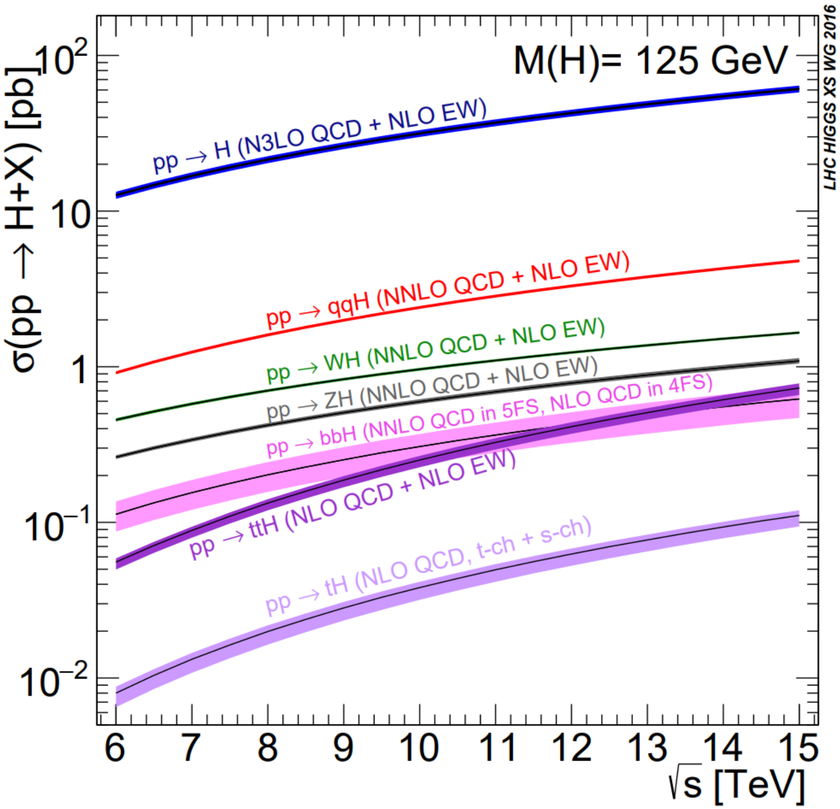


$$g_{HVV} = \frac{2{m_v}^2}{v}$$



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

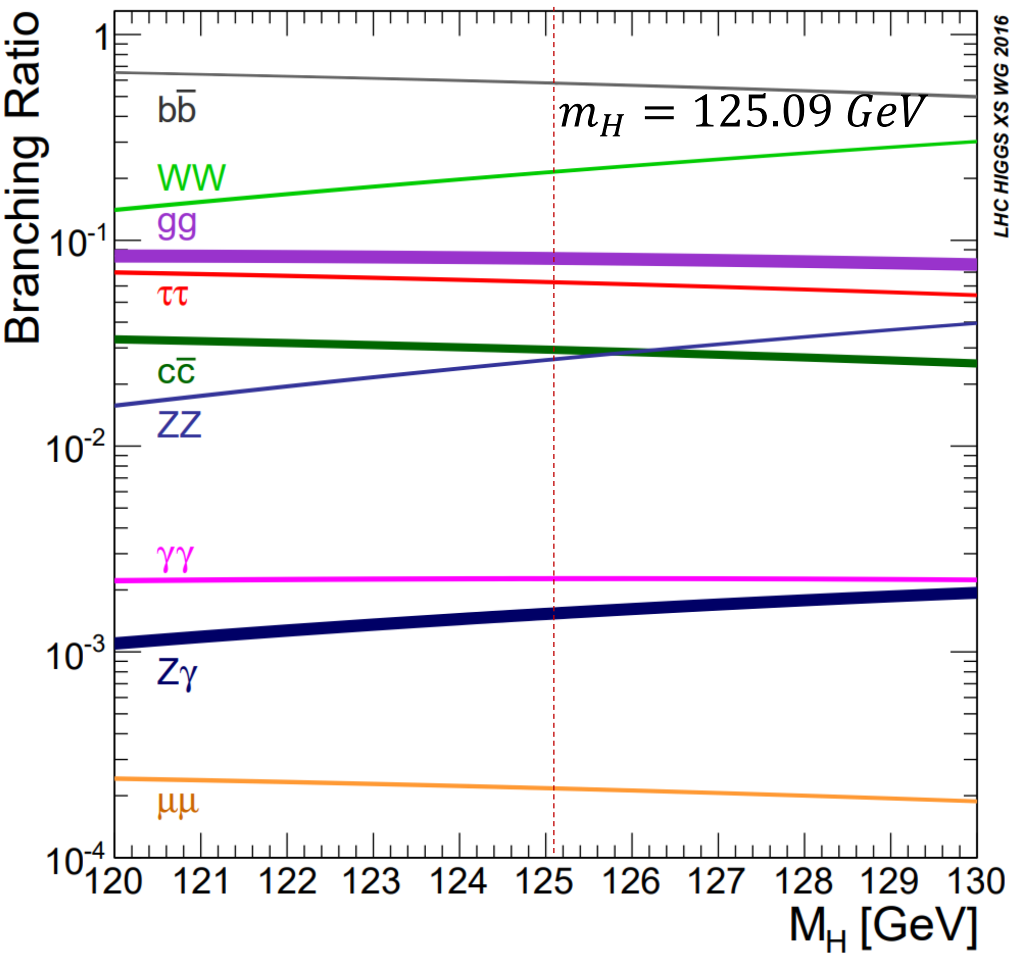
SM Higgs Production at LHC



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

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

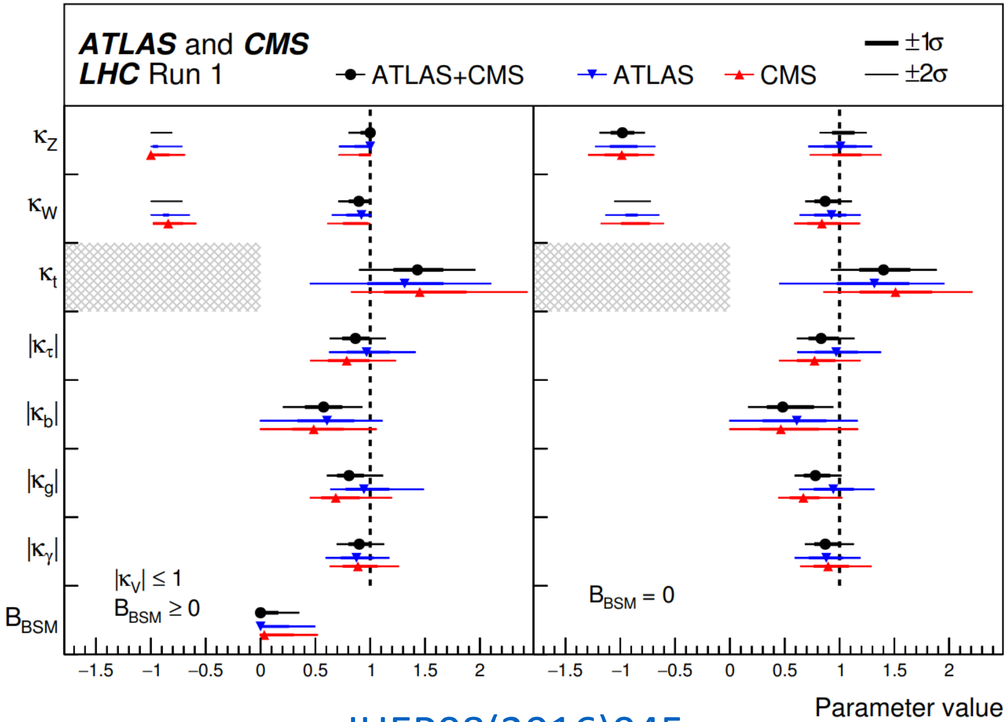
- H→ZZ*→4l (l=e,μ) and H→γγ: low BR but clean signature. The excellent mass resolution is crucial for the Higgs boson mass measurement.
- H→WW*: high BR but low mass resolution.
- H→bb and H→ττ : high BR, low S/B and low mass resolution at LHC.

Outline

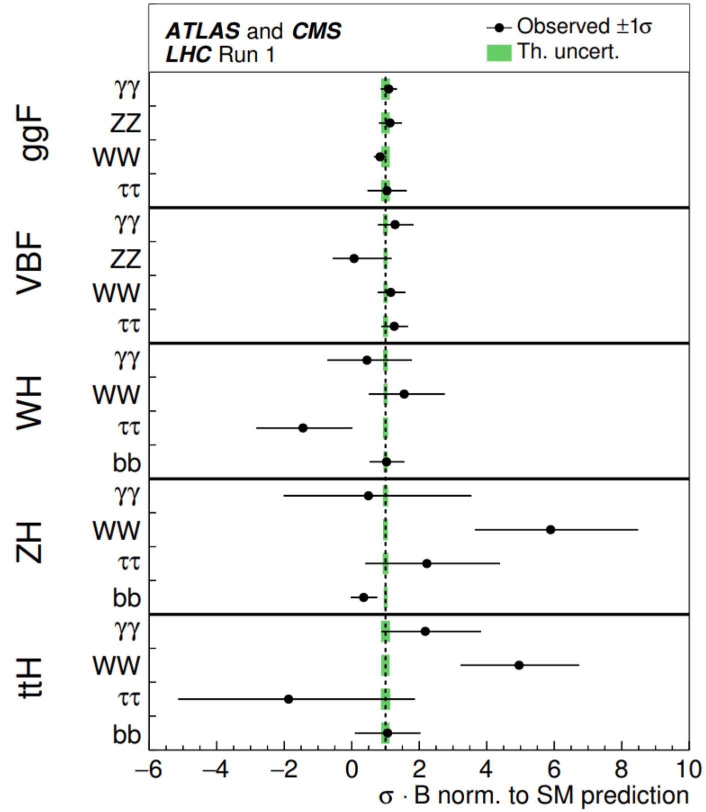
- LHC Run-1 Legacy
- Property measurement results:
  - Mass and width
  - Differential cross sections
  - Production, decay and coupling
  - Di-Higgs production and Higgs self-coupling
- Summary

Caveat: To fits the time allocated, only a selective set of results will be shown.

LHC Run 1 Legacy

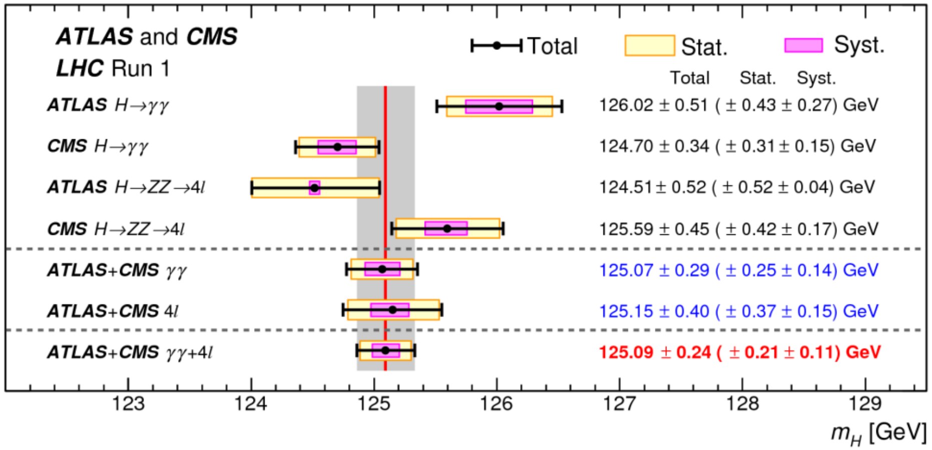


JHEP08(2016)045

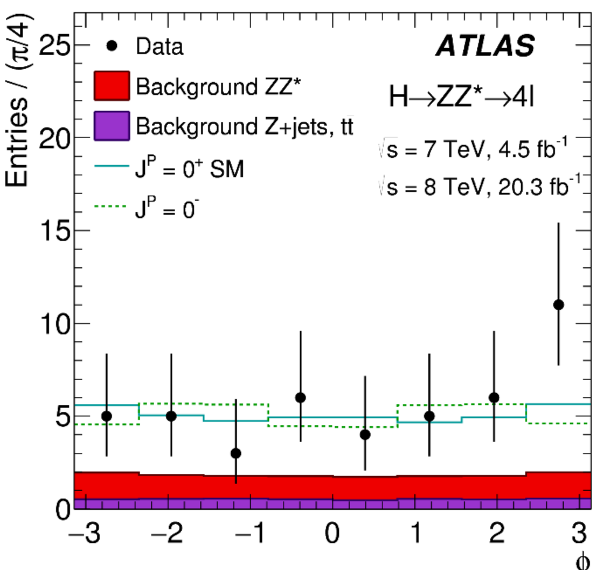


- **Gluon fusion** and **Vector boson fusion** production modes are **observed** in Run-1.
- ***H→ZZ*, H→γγ, H→WW*** and ***H→ττ*** decay modes are **observed** in Run-1.
- Higgs boson couplings measured with ~10% - 30% precision.
- The 95% CL upper limit for **BR(BSM)** is **0.34**.

LHC Run 1 Legacy



Phys. Rev. Lett. 114, 191803



EPJC. C75(2015) 476

- The Run-1 Higgs boson mass is measured from a combination of the four results in the H→ZZ*→4l (l=e,μ) and H→γγ channels for ATLAS and CMS.
- **~ 0.2%** precision reached by Run-1 Higgs boson mass measurement.
- As for spin/parity, both CMS and ATLAS results show SM ($J^p = 0^+$) is highly favored against pure alternative. (Exclude tested hypotheses with CL > 99.9%)
- Studies of width, differential distributions didn't show deviation with SM prediction.

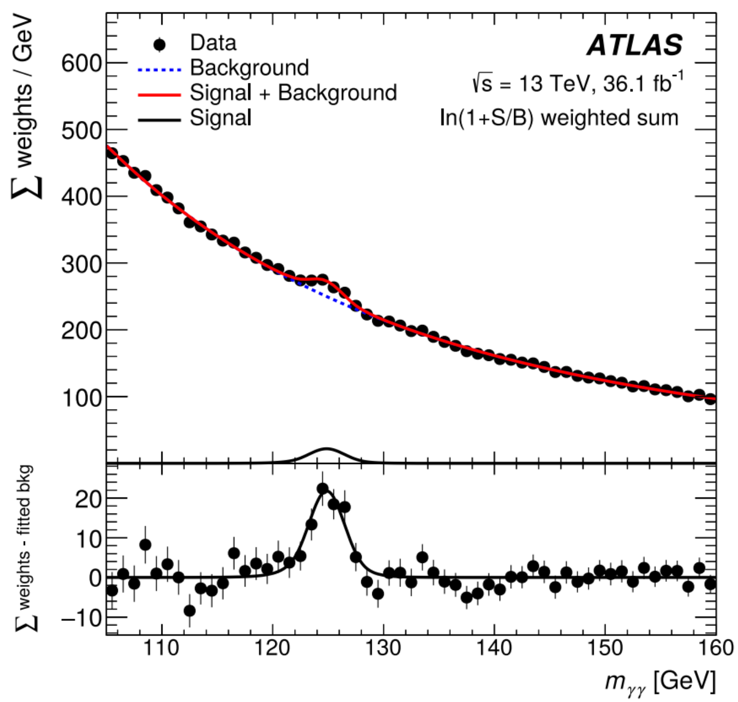
LHC Run-2 13 TeV:

Mass and Width of Higgs Boson

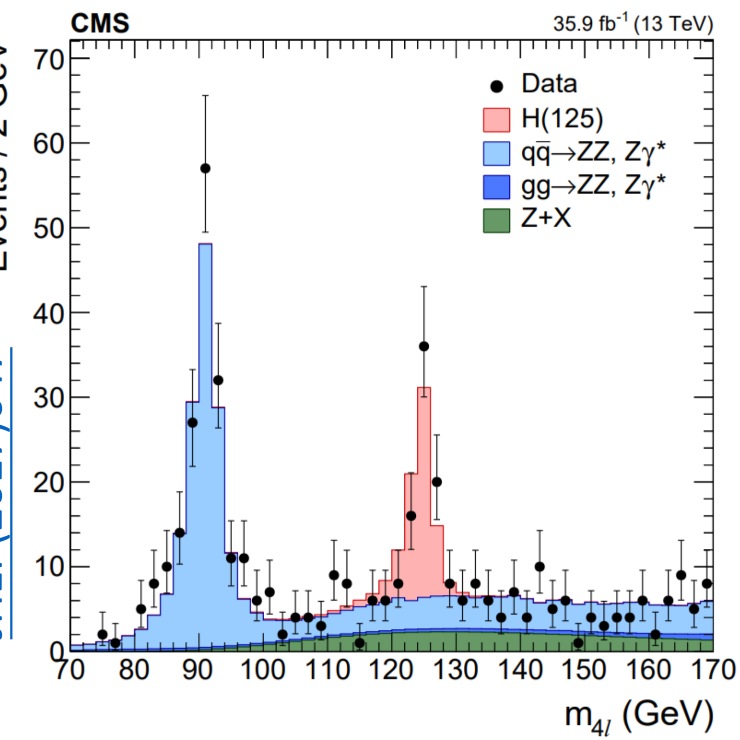
Mass Measurement

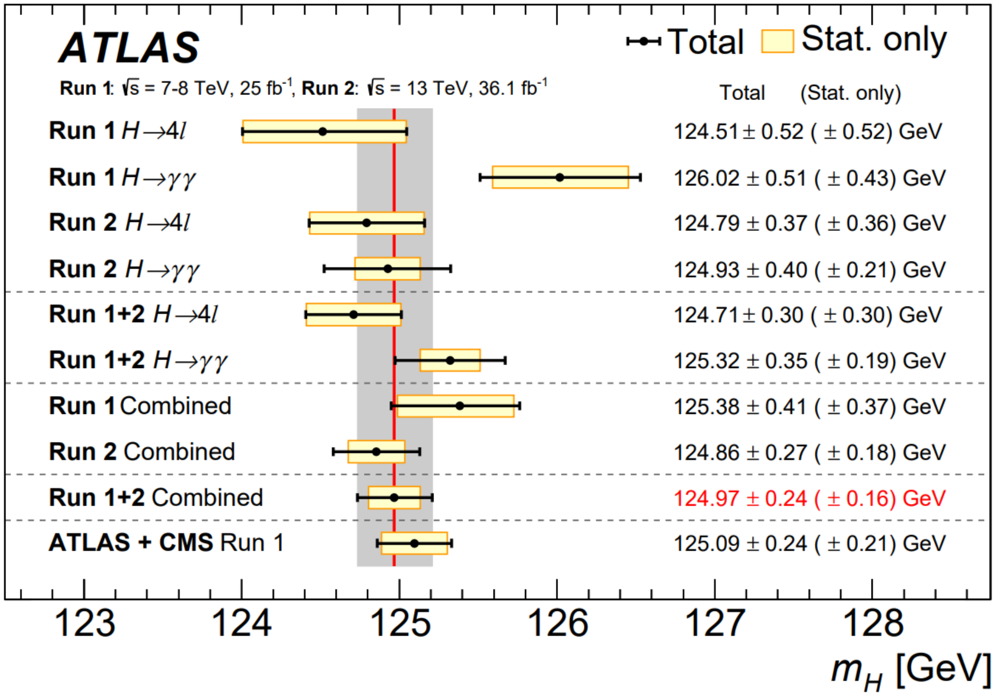
- Mass measurement is performed based on H→ZZ*→4l(l=e,μ) and H→γγ analysis channels.
- To achieve the optimal calibration of photon/lepton, detailed performance studies have been performed.

Phys. Lett. B 784(2018)345



JHEP(2017)047





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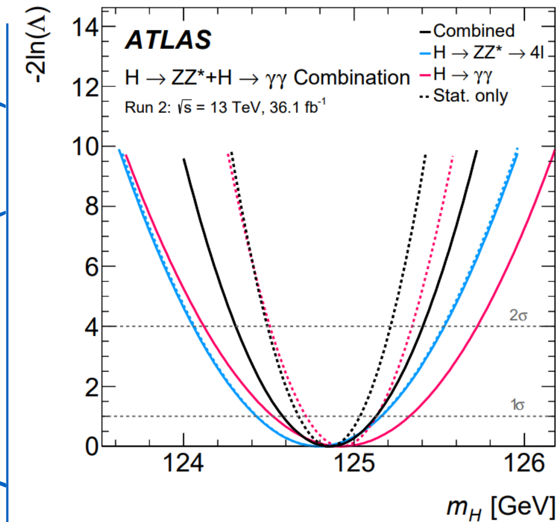
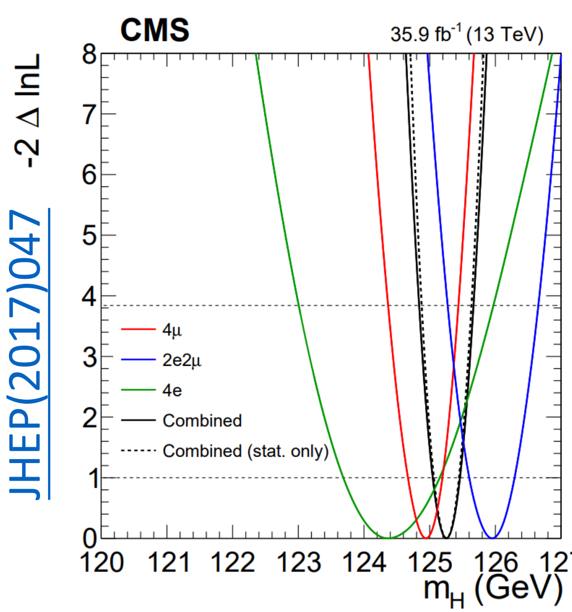


Measured m_H:

- ATLAS+CMS Run 1 combined: $125.09 \pm 0.24\ GeV$
- ATLAS Run 2 combined: $124.86 \pm 0.27\ GeV$
- ATLAS Run 1+2 combined: $124.97 \pm 0.24\ GeV = 124.97 \pm 0.19(\text{stat}) \pm 0.13(\text{syst}) GeV$
- CMS Run 2 $H \rightarrow ZZ^* \rightarrow 4l$: $125.26 \pm 0.21\ \text{GeV} = 125.26 \pm 0.20(\text{stat}) \pm 0.08(\text{syst}) GeV$

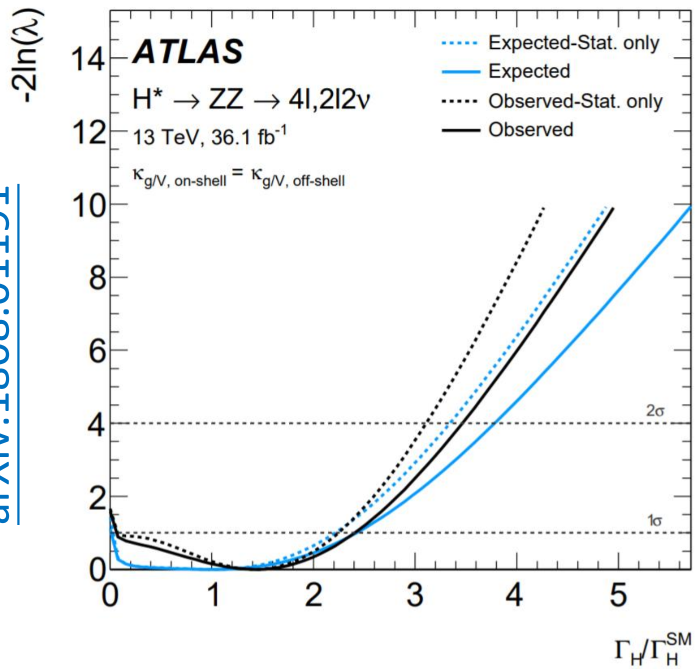
JHEP(2017)047



Width Measurement

- It is difficult to directly measure Higgs boson width (~4 MeV predicted by SM).
- The best direct limit is Γ_H<1.10 GeV @ 95% CL from CMS *H→ZZ* →4l*
- Indirect limit can be set from measuring the on- and off-shell signal strength in high-mass tails:

arXiv:1808.01191



$$\sigma_{\mathrm{off-shell}} \propto \kappa^2_{g,\mathrm{off-shell}} \cdot \kappa^2_{Z,\mathrm{off-shell}}$$

$$\sigma_{\mathrm{on-shell}} \propto \frac{\kappa^2_{g,\mathrm{on-shell}} \cdot \kappa^2_{Z,\mathrm{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

$$\mu_{\mathrm{off-shell}} = \frac{\sigma_{\mathrm{off-shell}}}{\sigma_{\mathrm{off-shell,SM}}} < 3.8 \text{ @ 95\% CL}$$

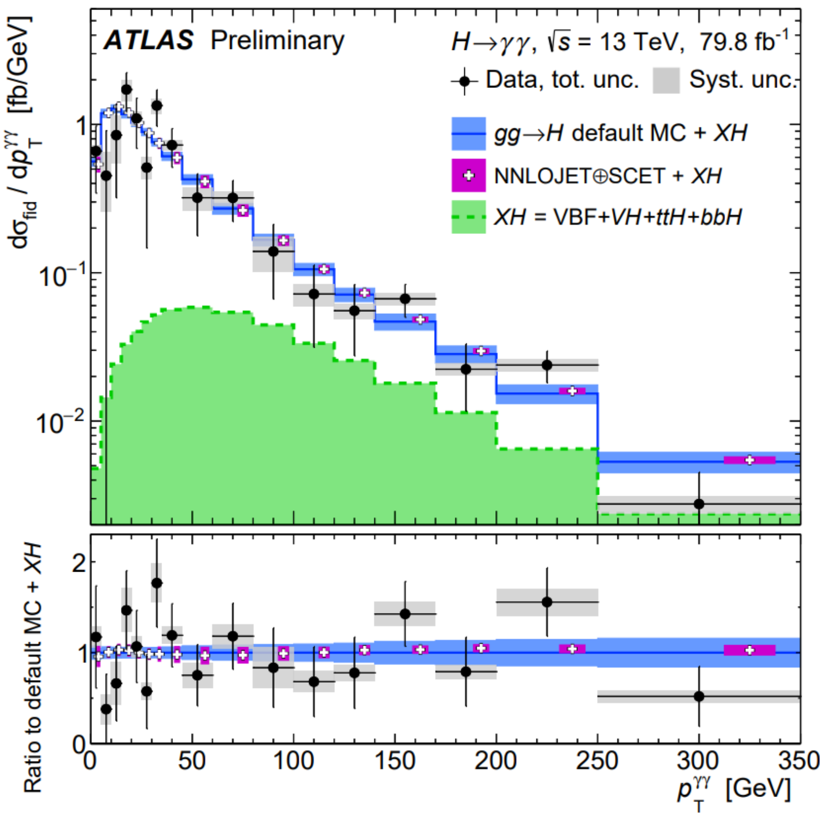
- ATLAS Run-1 result: Γ_H<22.7 MeV @ 95% CL (33.0 MeV exp.)
- The latest ATLAS Run-2 combining *H(*)→ZZ(*) →4l* and *H*→ZZ →2l2v* : Γ_H<14.4 MeV @ 95% CL (15.2 MeV exp.)

Differential cross sections measurement

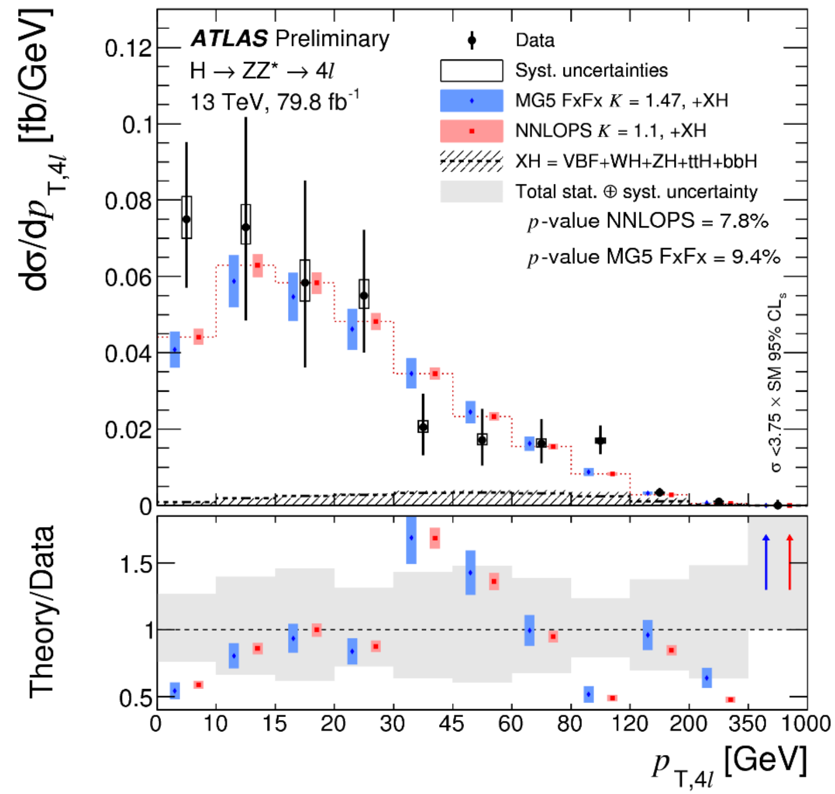
Differential cross sections

- Differential cross sections measurement probe the kinematic properties of the Higgs boson, which is **sensitive to new physics**.
- **Minimal model dependence**. Measurements are corrected for detector effects. Results are reported **at the particle level**.

ATLAS-CONF-2018-028



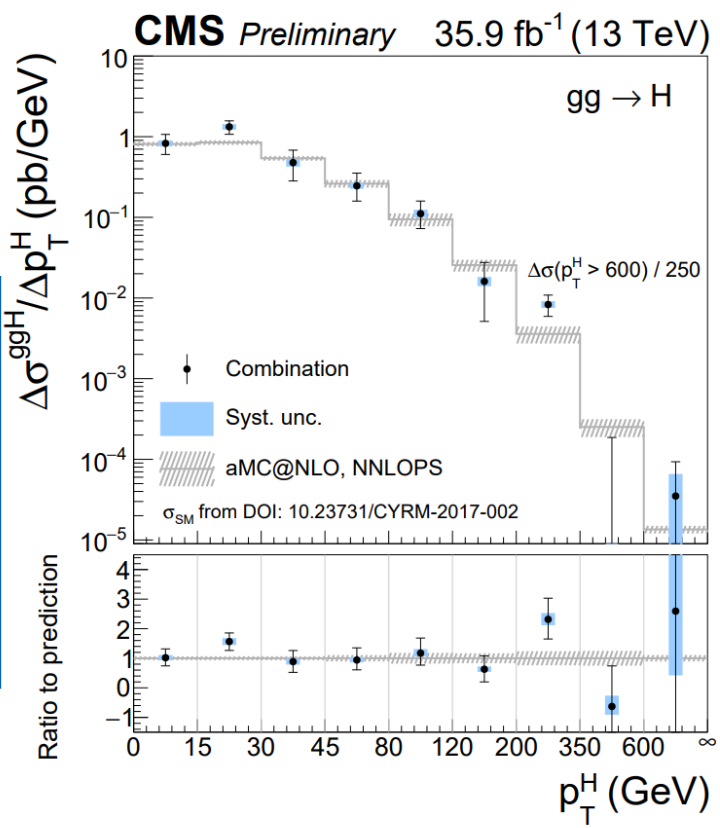
ATLAS-CONF-2018-018



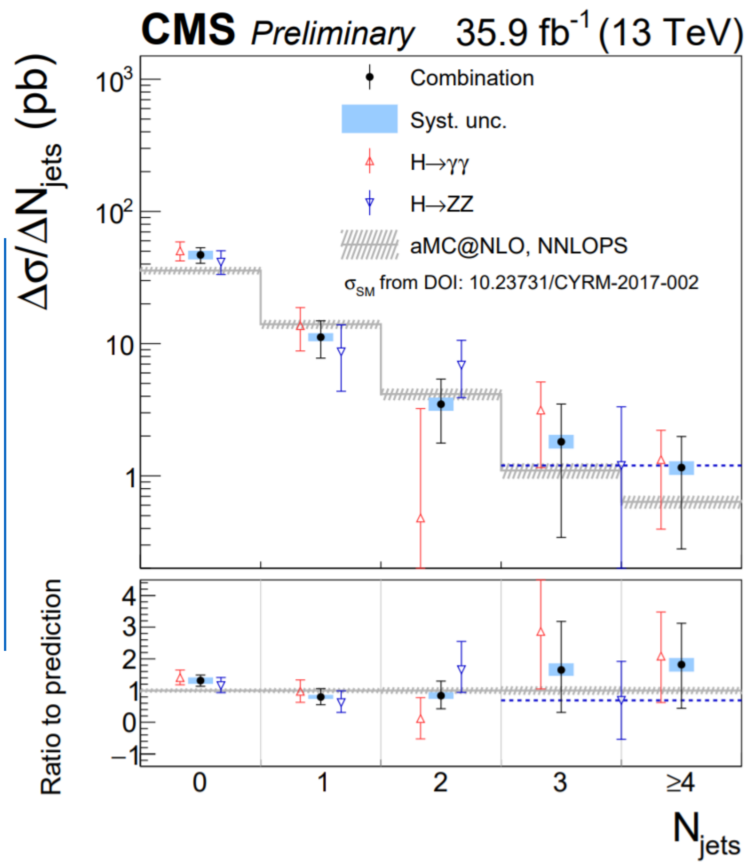
- 79.8/fb *H→γγ* and *H→ZZ* →4l* result from ATLAS. 35.9/fb *H→γγ*, *H→ZZ** and *H→bb* from CMS.

Differential Cross sections

CMS-PAS-HIG-17-028



CMS-PAS-HIG-17-028



- Various differential measurements probed.
- **Unprecedented precision reached**.
- In general, results are all **compatible with SM prediction**.

Higgs coupling: production and decay modes

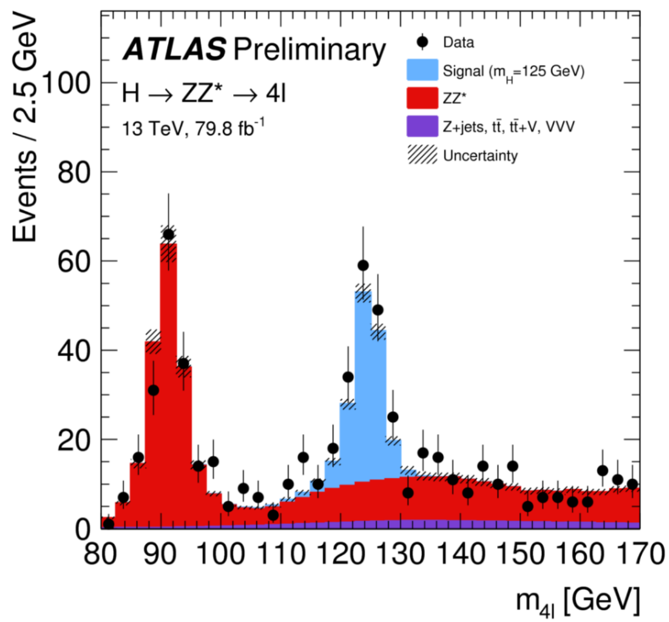
ATLAS EXPERIMENT

CMS

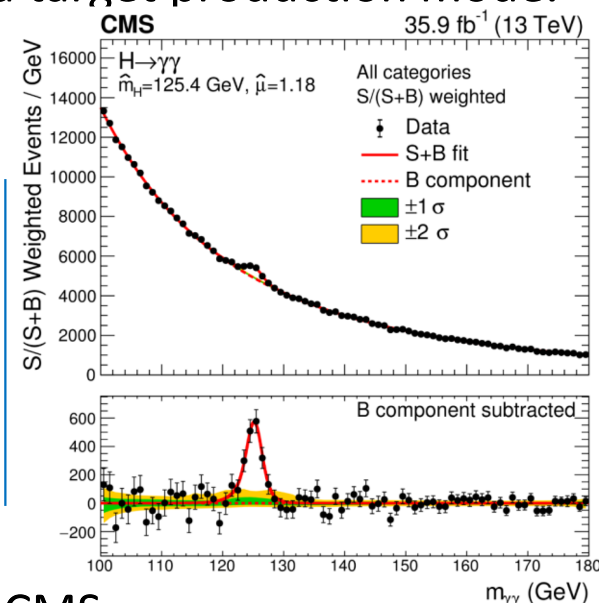
$H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$

- **Clean signature** and **excellent invariant mass resolution**.
- Disentangle different production modes of the signal.
- Analysis measures production rates and properties by splitting dataset into independent "categories" enhanced in a target production mode.

ATLAS-CONF-2018-018



CMS-HIG-16-040



ATLAS:

$$H \to \gamma\gamma,\ \mu = 1.06^{+0.14}_{-0.12}(80/\mathrm{fb})$$
$$1.06^{+0.08}_{-0.08}(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{exp.})^{+0.07}_{-0.06}(\mathrm{th.})$$

$$H \to ZZ* \to 4l,\ \mu = 1.19^{+0.16}_{-0.15}(80/\mathrm{fb})$$
$$1.19^{+0.12}_{-0.12}(\mathrm{stat.})^{+0.06}_{-0.06}(\mathrm{exp.})^{+0.08}_{-0.07}(\mathrm{th.})$$

CMS:

$$H \to \gamma\gamma, \mu = 1.18^{+0.17}_{-0.14}(36/\mathrm{fb})$$
$$1.18^{+0.12}_{-0.11}(\mathrm{stat.})^{+0.09}_{-0.07}(\mathrm{exp.})^{+0.07}_{-0.06}(\mathrm{th.})$$

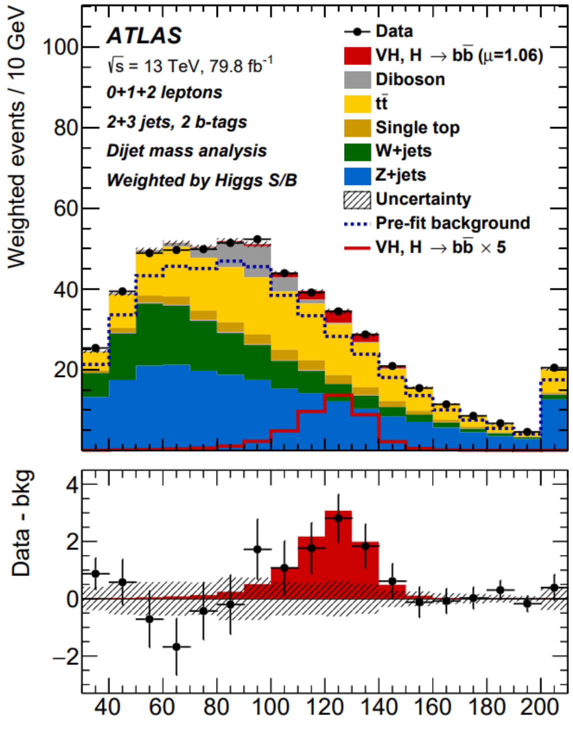
$$H \to ZZ* \to 4l, \mu = 1.05^{+0.19}_{-0.17}(36/\mathrm{fb})$$
$$1.05^{+0.15}_{-0.14}(\mathrm{stat.})^{+0.11}_{-0.09}(\mathrm{syst.})$$

H→bb

- *H→bb* takes the largest BR~58% → drives total width, constrains BSM BR allowed.
- In the **most sensitive *VH, H→bb*** analysis, both ATLAS and CMS have 3 channels (0-, 1-, 2 charged leptons from the vector boson)
- Using MVA to increase S/B in the signal region. Control regions to validate background and derive the normalizations. **Shapes from MC**.
- Analyses are now dominated by systematic uncertainties → Adding new data is not enough.

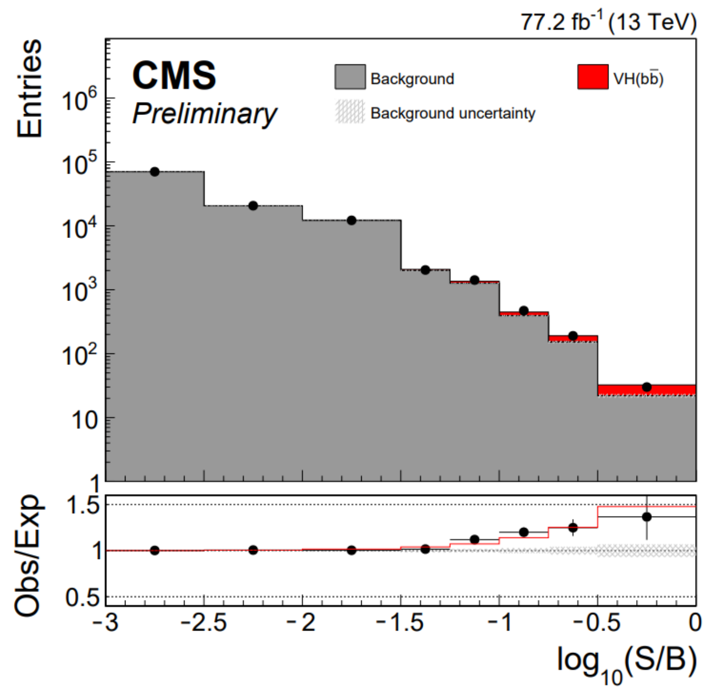
~80/fb

HIGG-2018-04



Mass spectrum of bb

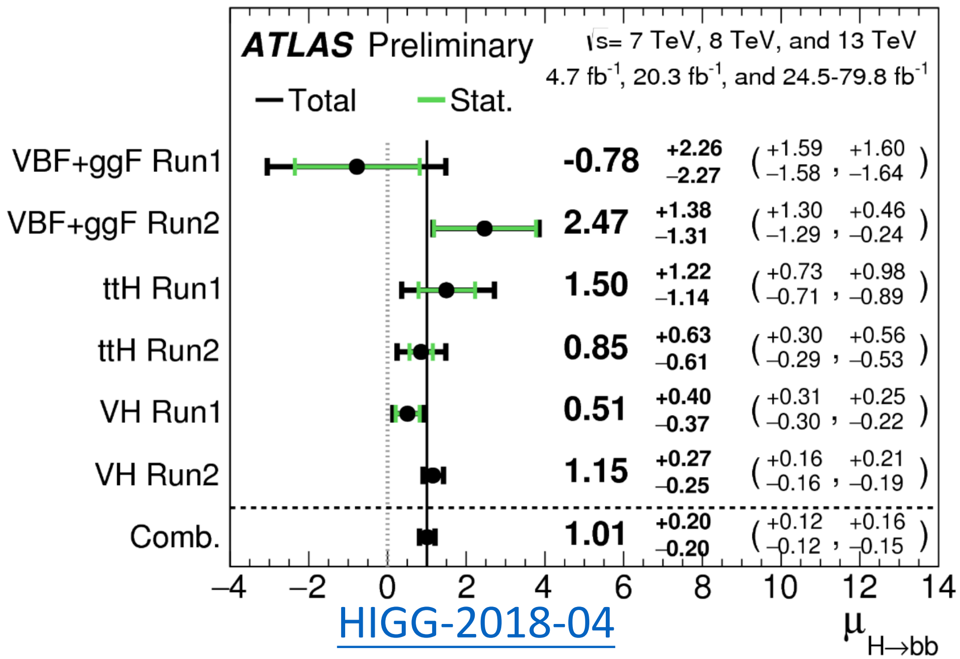
CMS-PAS-HIG-18-016



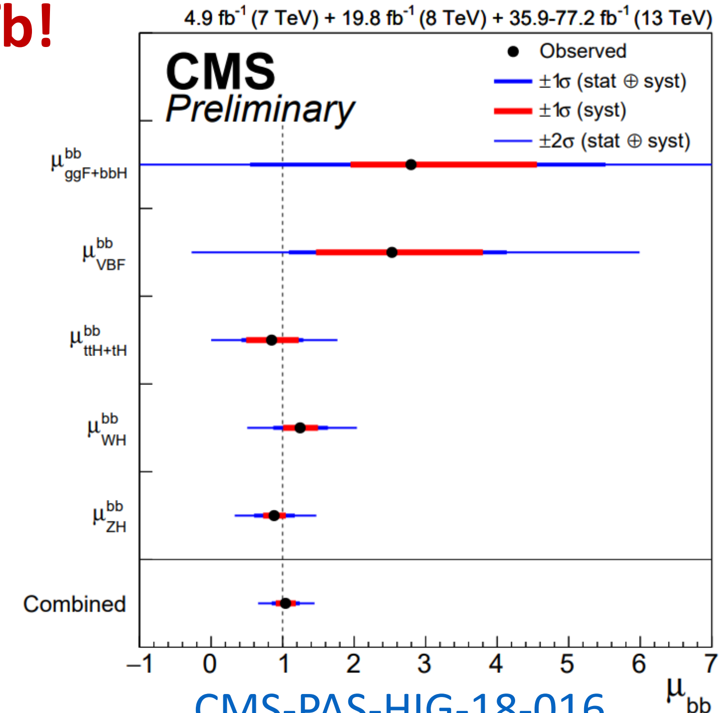
H→bb

- Run-1 *VH(bb)* ATLAS+CMS combined significance **2.6σ(3.7σ exp.)**
- Run-2 **36/fb** evidence of *VH(bb)*: **3.5σ(3.0σ exp.)** from ATLAS and **3.3σ(2.8σ exp.)** from CMS.

***H→bb* observation with 80/fb!**



HIGG-2018-04



CMS-PAS-HIG-18-016

ATLAS:

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

CMS:

- *VH(bb)* Run 1+2 combined significance **4.9σ(4.8σ exp.)**
- *H(bb)* Run 1+2 combined significance **5.5σ(5.6σ exp.)**

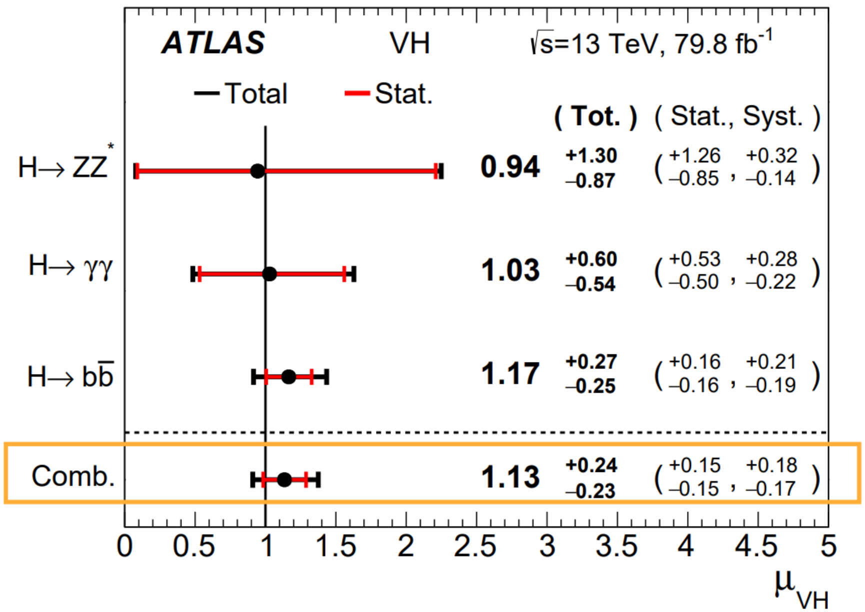
H→bb measurements assume SM production cross sections.

VH production mode

- VH takes ~ 3% of the total Higgs boson production on LHC.
- Only targets leptonic decay mode for bb channel. ZZ and yy also have regions for hadronic categories.

VH production mode observed after VH combination!

- ATLAS combine Run-2 analyses in bb, *γγ* and 4l final states.
- Results assume SM Higgs boson branching fractions.
- Observation of *VH* production at 5.3σ (4.8σ exp.)
- **Dominant contribution is from bb channel: 4.9σ.**
- 1.1σ and 1.9σ contribution from 4l and *γγ* channel, respectively.

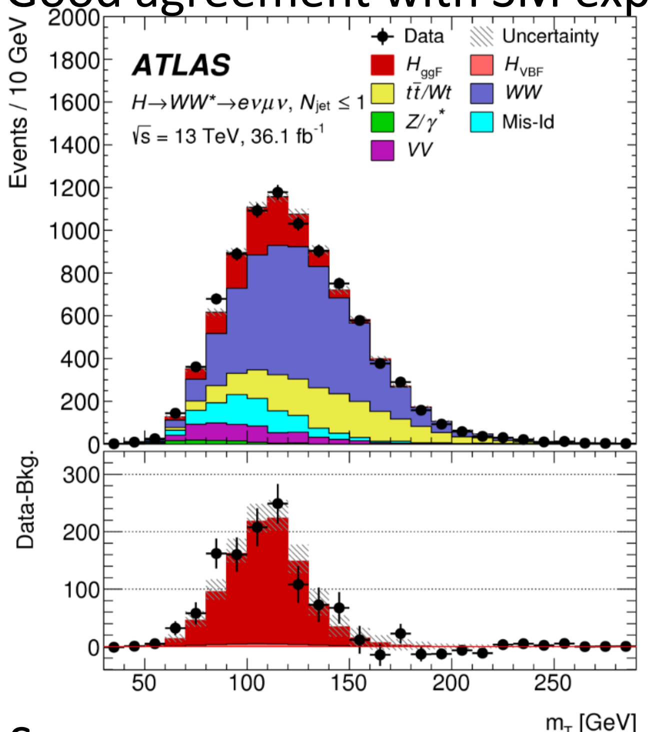


CERN-EP-2018-215

H→WW*

- ATLAS and CMS use various categories targeted for ggH/VBF production. CMS also uses 3l+4l events targeting VH
- Good agreement with SM expectation.

CERN-EP-2018-212



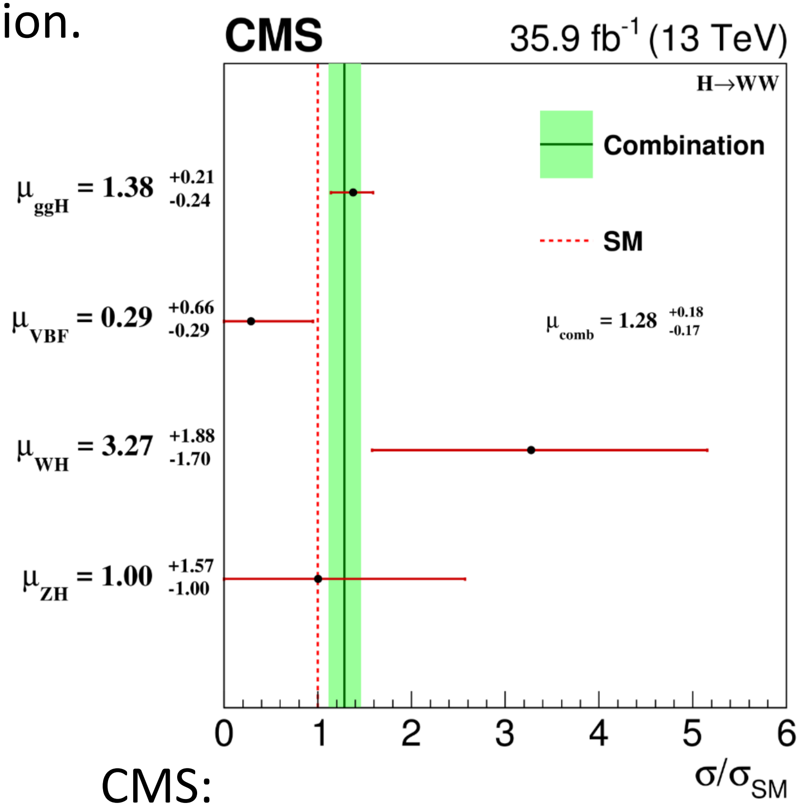
ATLAS:

$H\to WW,\ \mu_{ggF} = 1.21^{+0.22}_{-0.21}$ 6.3σ(5.2σ exp.)

$1.21^{+0.10}_{-0.10}(\text{stat.})^{+0.15}_{-0.15}(\text{exp.})^{+0.13}_{-0.12}(\text{th.})$

$H\to WW,\ \mu_{VBF} = 0.62^{+0.37}_{-0.36}$ 1.9σ(2.7σ exp.)

$0.62^{+0.30}_{-0.28}(\text{stat.})^{+0.16}_{-0.16}(\text{exp.})^{+0.13}_{-0.13}(\text{th.})$



CERN-EP-2018-141

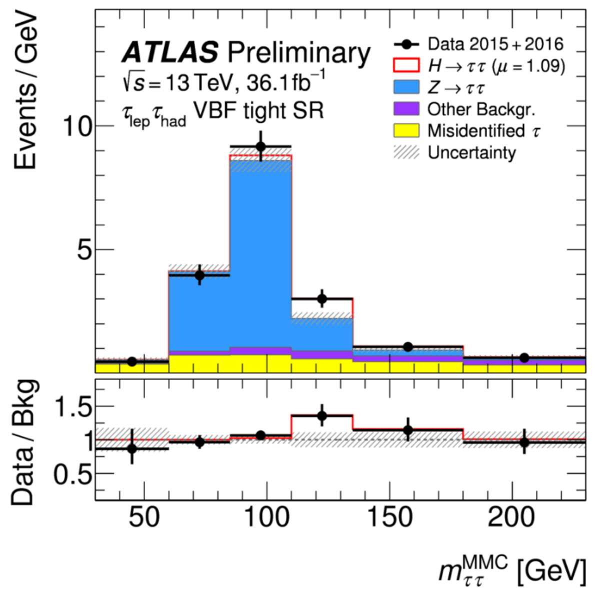
CMS:

$H\to WW,\ \mu = 1.28^{+0.18}_{-0.17}$ 9.1σ(7.1σ exp.)

$1.28^{+0.10}_{-0.10}(\text{stat.})^{+0.11}_{-0.11}(\text{exp.})^{+0.10}_{-0.07}(\text{th.})$

- ATLAS and CMS developed 3 channels targeting all possible di-tau decay modes.
- Both τ leptonic and hadronic decay modes considered.
- **Both experiments observe $H \rightarrow \tau\tau$ with > 5σ.**

ATLAS-CONF-2018-021



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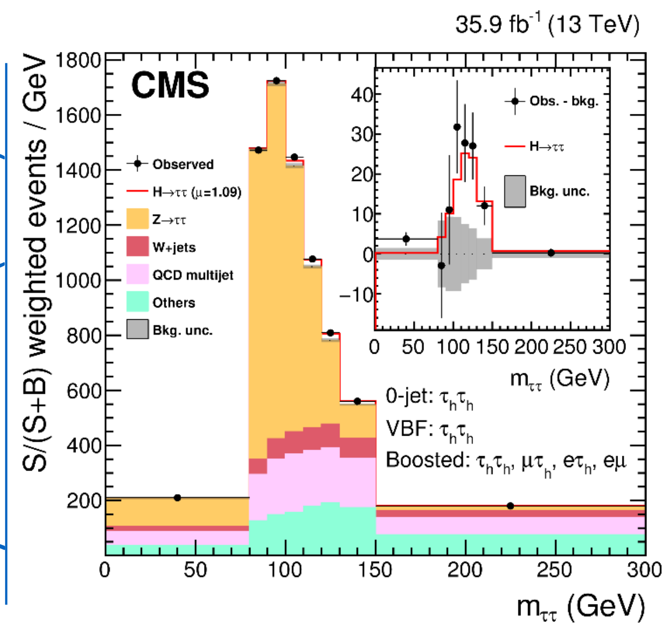


ATLAS:

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

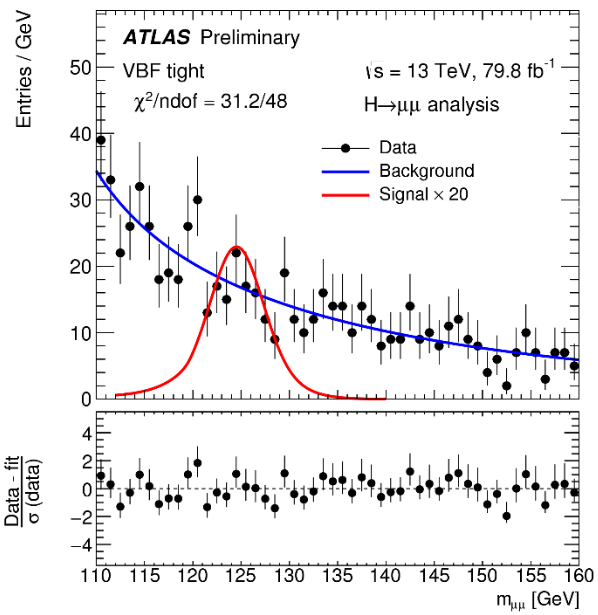
CMS:

Run-2 4.9σ(4.7σ exp.)
Run 1+2 5.9σ(5.9σ exp.)

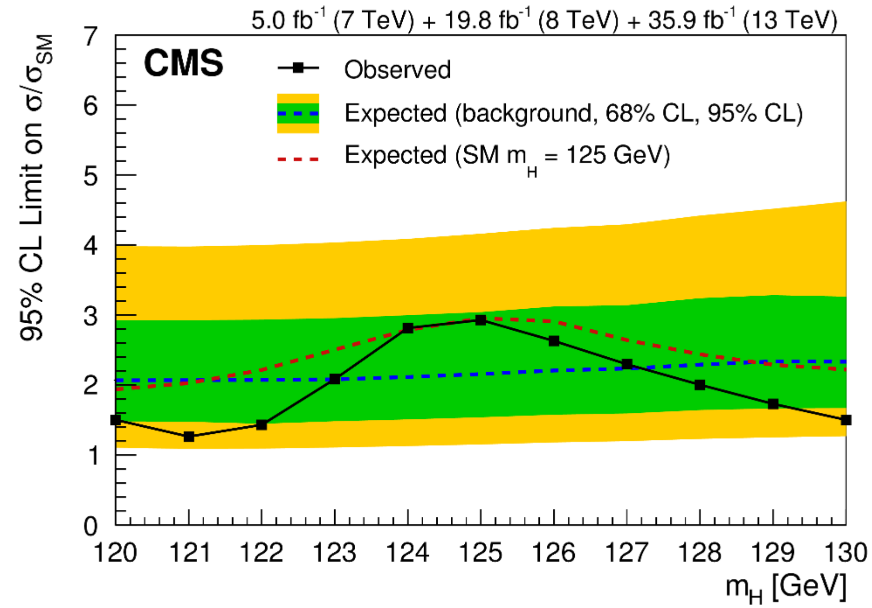
$H \rightarrow \mu\mu$

- Probe 2nd generation fermions coupling. Clean experimental signature with very small BR. Large Drell-Yan background.
- Events categorized by dimuon pT, and BDT that enhances VBF contribution.
- Fitting strategy: extract a signal peak from a continuum falling background, which is similar to the *H→γγ* analysis.

ATLAS-CONF-2018-026



CMS-HIG-17-019



ATLAS (Run2 80/fb):

$H \rightarrow \mu\mu, \mu = 0.1^{+1.0}_{-1.1}$

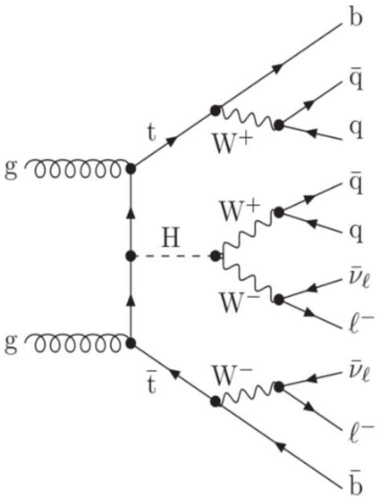
95% CL: μ<2.1(2.0 exp.)

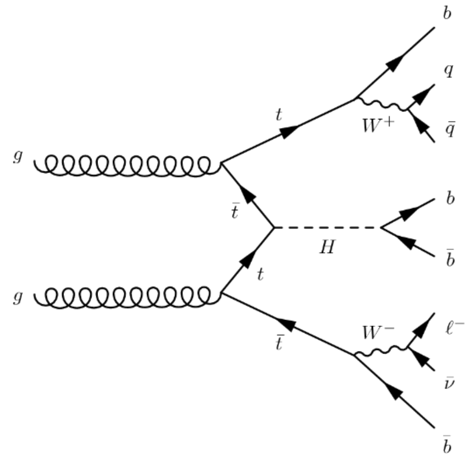
CMS (Run1+Run2 36/fb):

$H \rightarrow \mu\mu, \mu = 0.7^{+1.0}_{-1.0}$

95% CL: μ<2.92(2.16 exp.)

ttH production mode

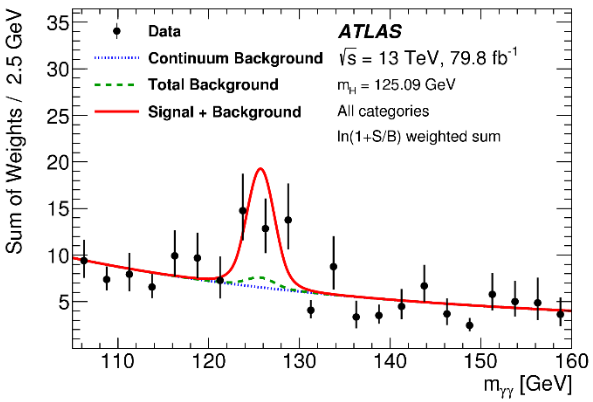


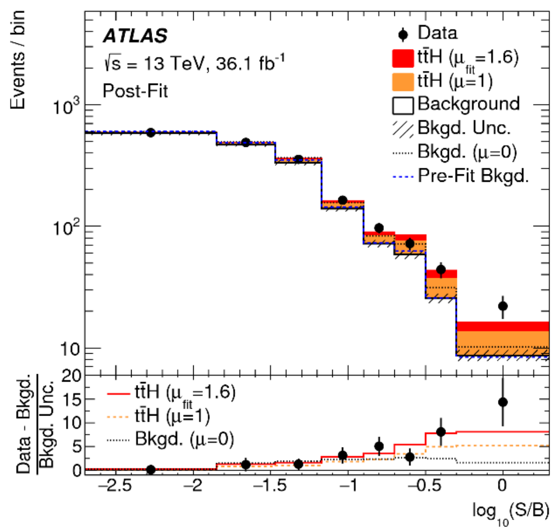


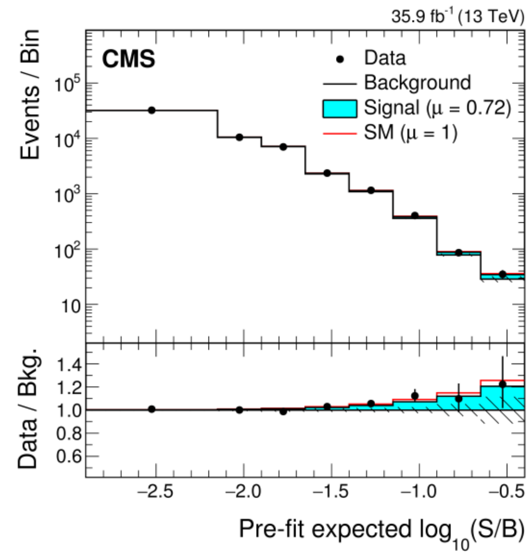
Decay mode	Branching fraction [%]
$H \to bb$	58.1 ± 1.0
$H \to WW$	21.5 ± 0.5
$H \to gg$	8.18 ± 0.59
$H \to \tau\tau$	6.26 ± 0.15
$H \to cc$	2.88 ± 0.14
$H \to ZZ$	2.64 ± 0.06
$H \to \gamma\gamma$	0.227 ± 0.007
$H \to Z\gamma$	0.154 ± 0.011
$H \to \mu\mu$	0.021 ± 0.001

- 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.)
- **Multiple decay channels are combined** in order to reach observation.

13 TeV ttH results of different decay channels:







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

ttH, *H→γγ*

ATLAS 4.1σ (3.7σ exp., 79.8 /fb)

CMS 1.4σ (1.5σ exp., 35.9/fb)

[Phys. Rev. D 97, 072003 (2018)]

ttH, ML(*H→ττ, H→WW, 36/fb)**

ATLAS 4.1σ (2.8σ exp.)

CMS 3.2σ (2.8σ exp.)

[CMS-HIG-17-026]

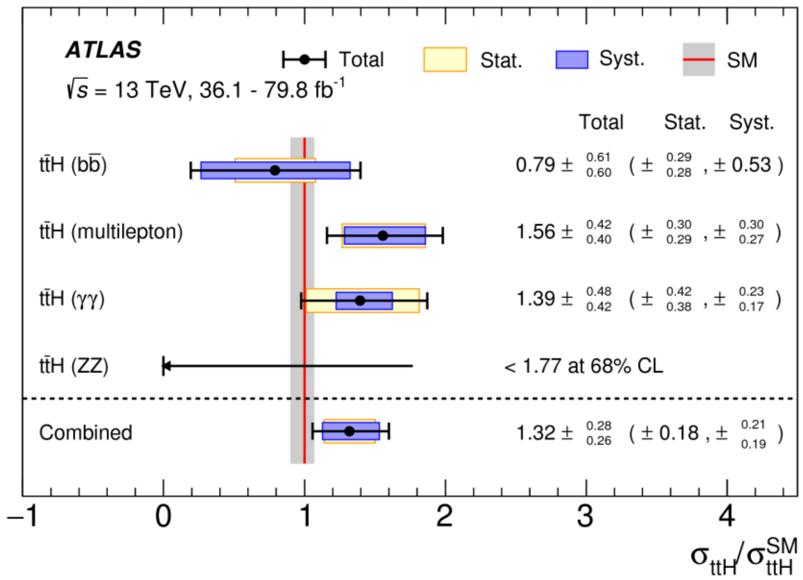
ttH , *H→bb* (36/fb)

ATLAS 1.4σ (1.6σ exp.)

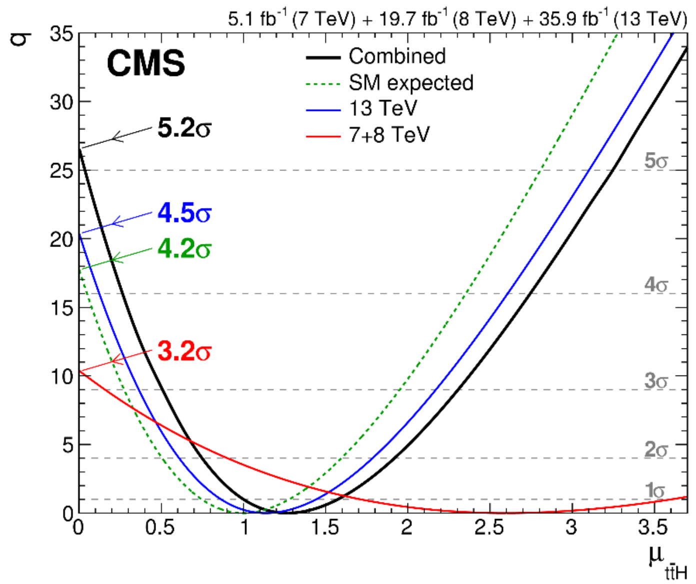
CMS 1.6σ (2.2σ exp.)

ttH production mode

ttH production mode observed after ttH combination!



Phys. Lett. B 784 (2018) 173



Phys. Rev. Lett. 120, 231801 (2018)

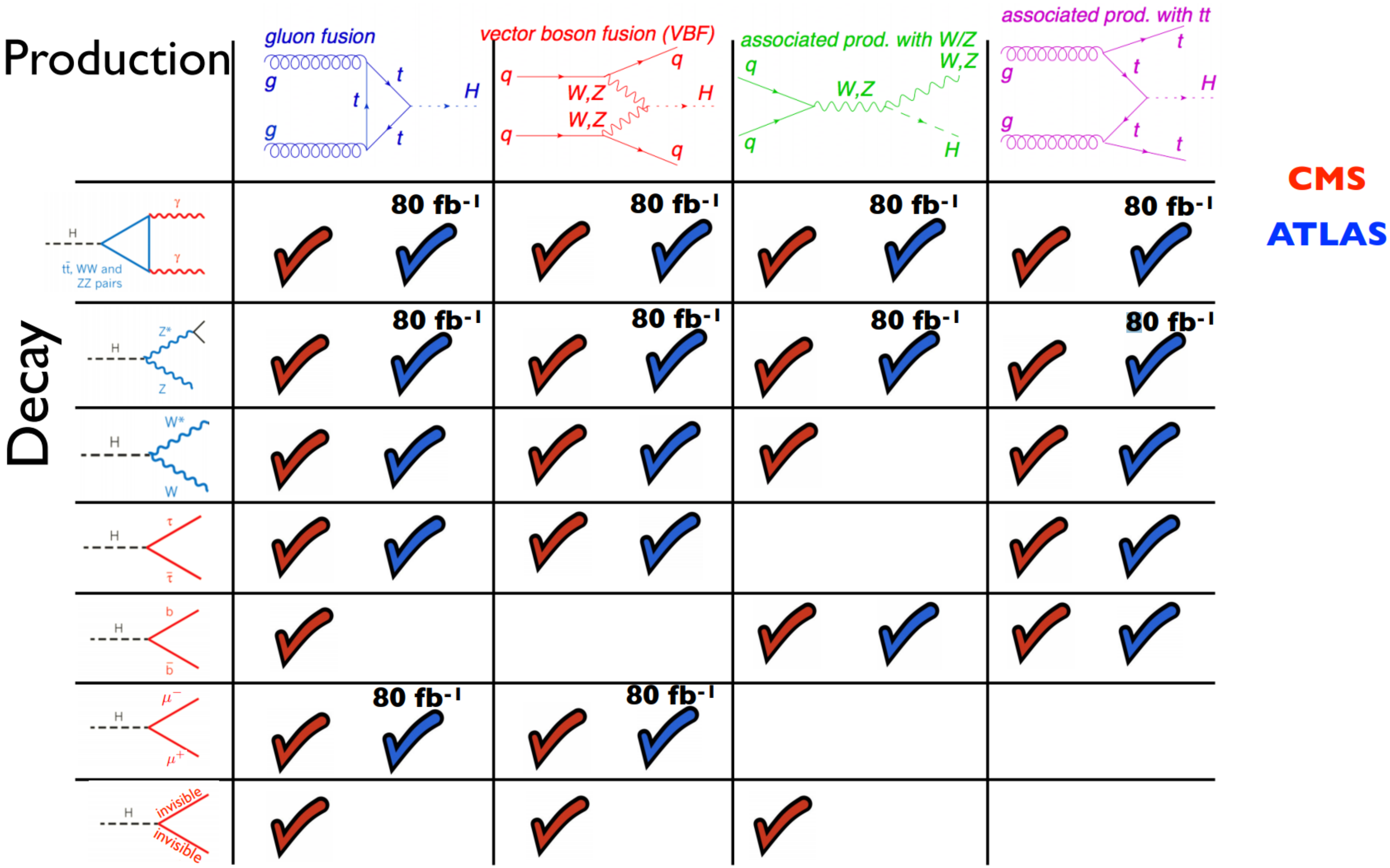
ATLAS
Run-2 5.8σ (4.9σ exp.)
Run-1+2 6.3σ (5.1σ exp.)

CMS
Run-2 4.5σ
Run-1+2 5.2σ (4.2σ exp.)

Higgs coupling:
Combine all Higgs boson measurements

Combination Measurement

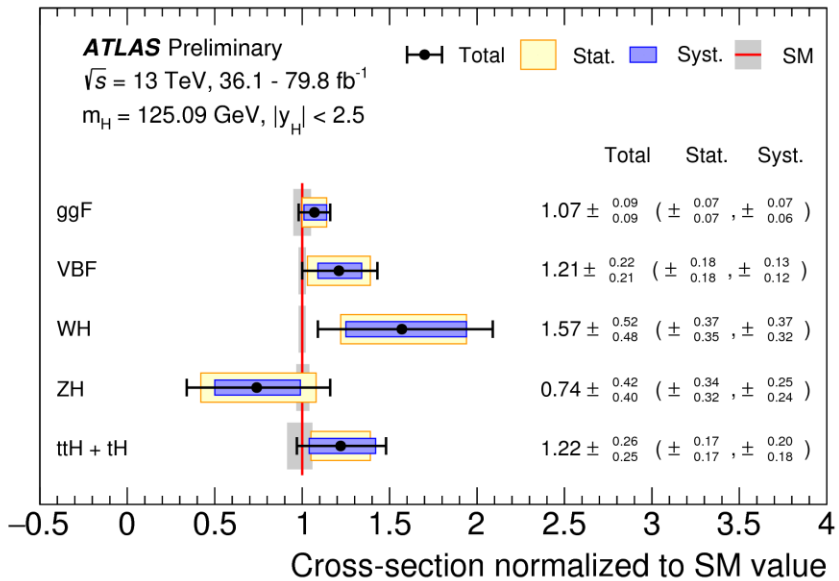
G.Piacquadio's ICHECP talk



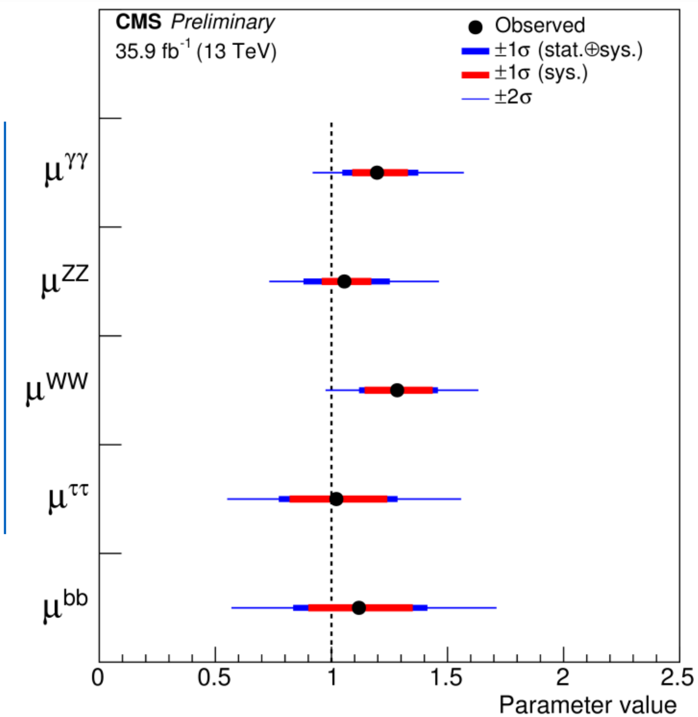
- Combination inputs: CMS has additional ggF *H→bb*, VH *H→WW*, and *H→inv.* channels. ATLAS with *H→ZZ, H→γγ and H→μμ* updated to 80/fb.
- More channels will be covered in the following combination analysis.

Combination Measurement

ATLAS-CONF-2018-031

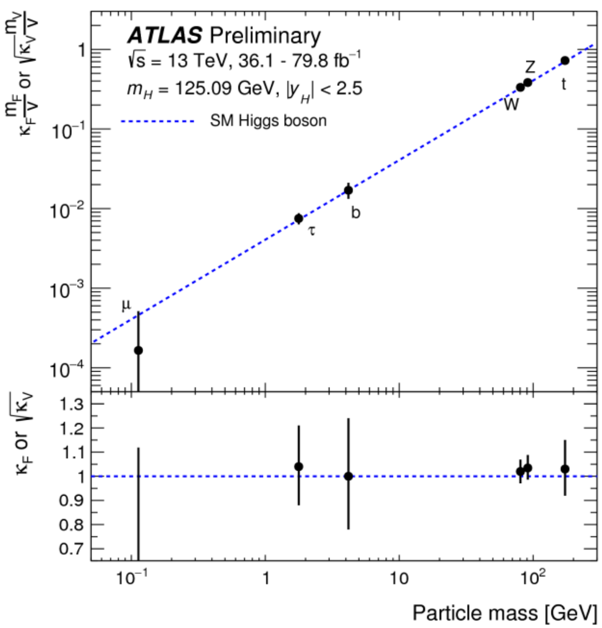


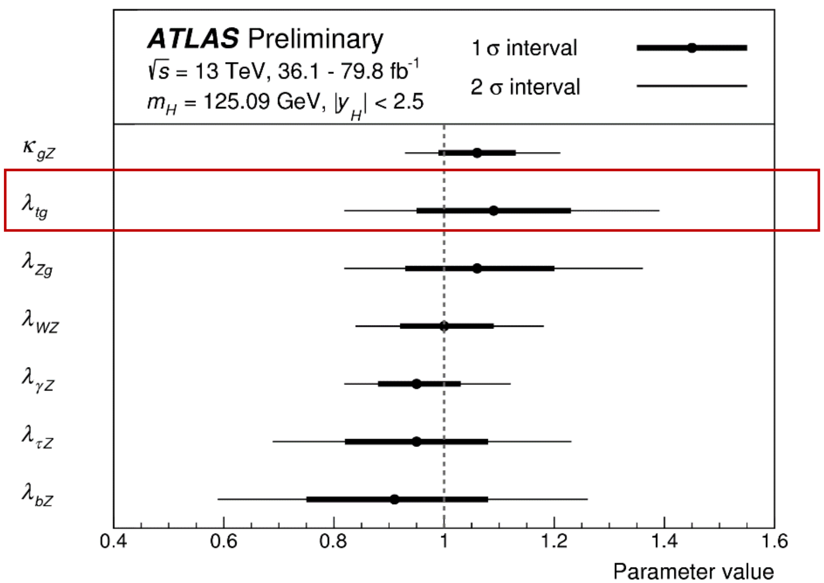
CMS-PAS-HIG-17-031



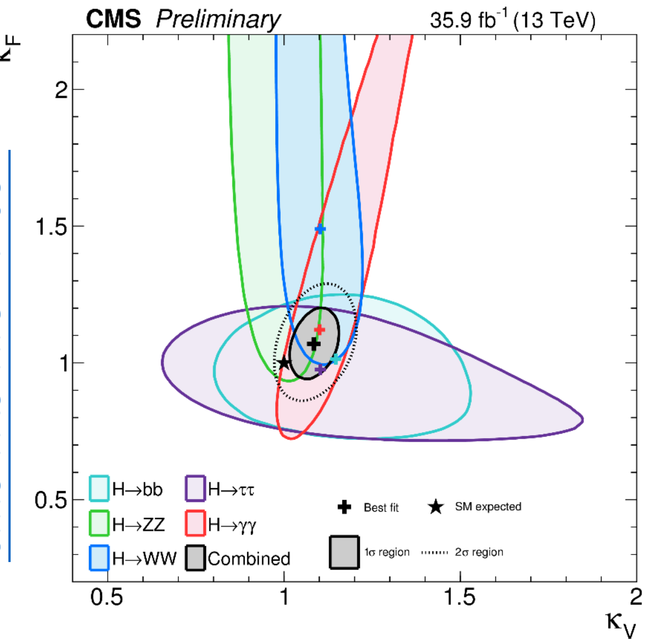
- ATLAS: $\mu = 1.13^{+0.09}_{-0.08} = 1.13^{+0.05}_{-0.05}(\text{stat.})^{+0.05}_{-0.05}(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.})^{+0.03}_{-0.03}(\text{bkg. th.})$
- CMS: $\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}(\text{stat.})^{+0.06}_{-0.05}(\text{sig. th.})^{+0.06}_{-0.05}(\text{other sys.})$
- The overall production rate of the Higgs boson was measured to be in agreement with Standard Model predictions, with an uncertainty of **8%-10%**
- All major production modes have been observed!

ATLAS-CONF-2018-031





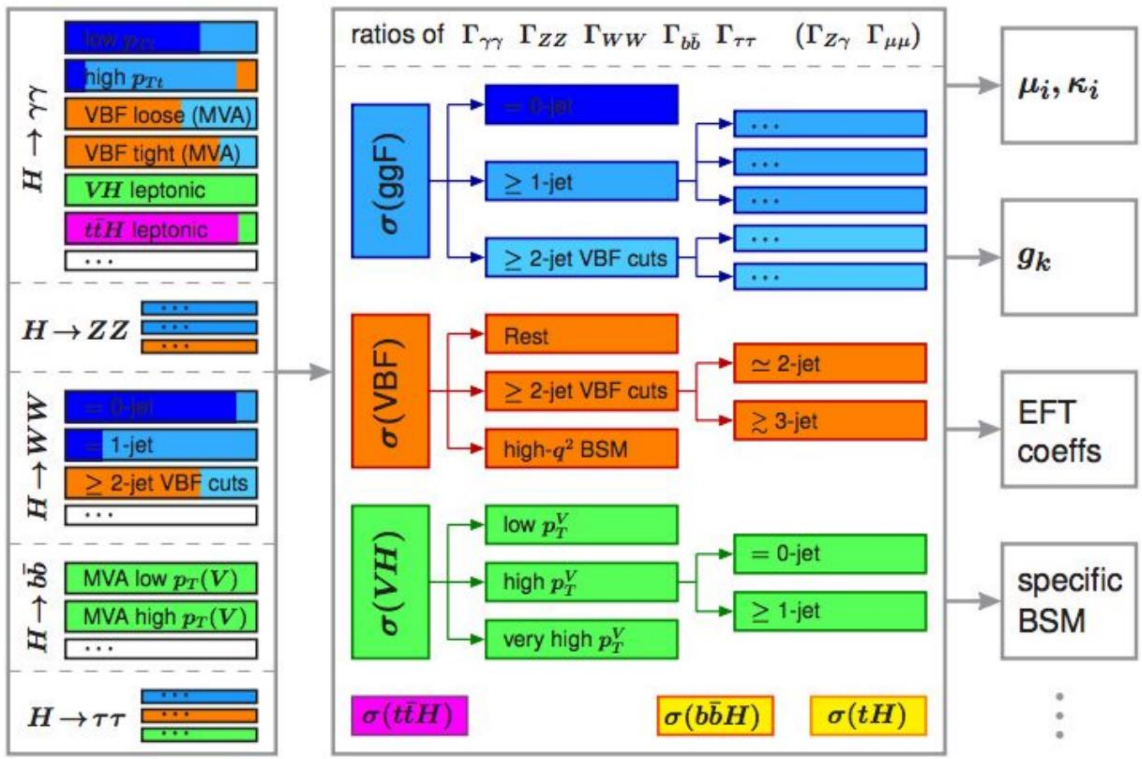
CMS-PAS-HIG-17-031



- Couplings are in an **excellent agreement with the Standard Model** prediction over a range covering 3 orders of magnitude in mass, from the top quark to the much lighter muons.
- The precision is better than Run1 ATLAS+CMS combination.

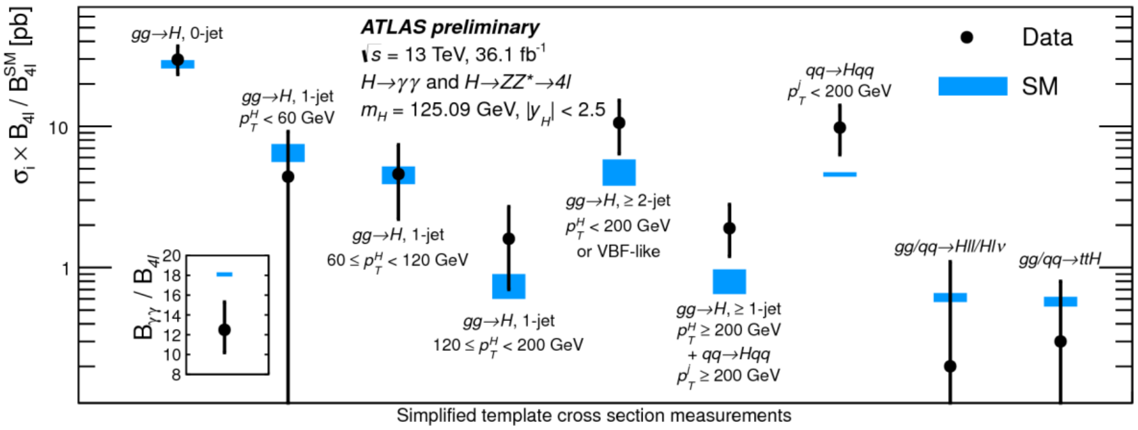
STXS can make Higgs measurements less model dependent than measurements during Run 1

- STXS (Simplified Template Cross Sections) splits Higgs productions into exclusive kinematic regions (Described in YR4 (Section III.2).
- Instead of performing differential measurement in clean channels only, intend for **combination of all decay channels**.
- Minimize the dependence on theoretical uncertainties.



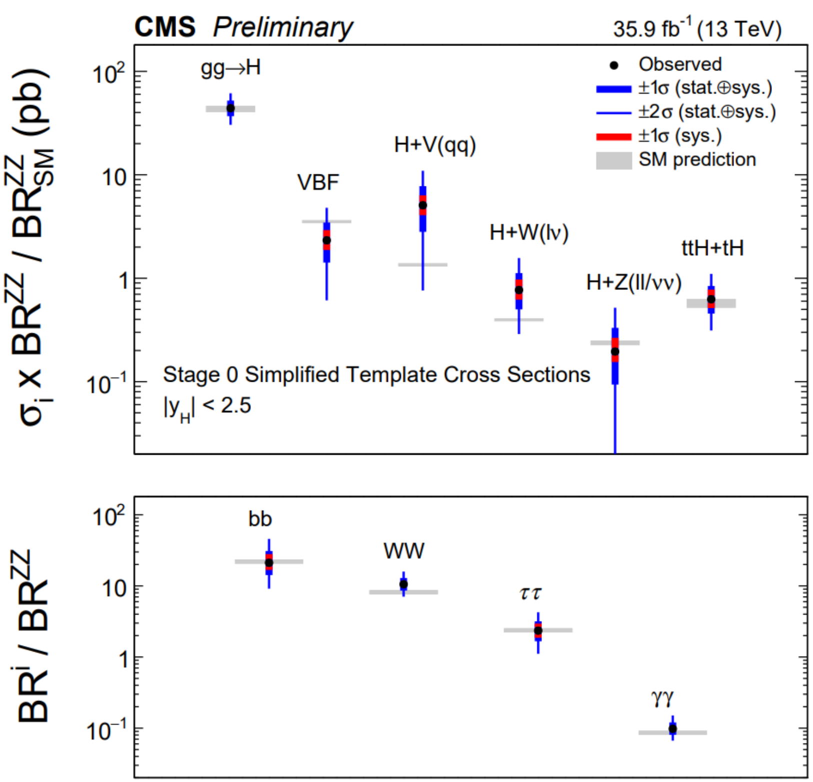
Simplified template cross sections

ATLAS-CONF-2017-047



- ATLAS performed a combination of STXS with a fine granularity measurements for the 36.1/fb ***H→γγ** and* ***H→4l*** channel.
- ggH measurements are in good agreement with the SM.
- Best precisions of ~20% reached

CMS-PAS-HIG-17-031



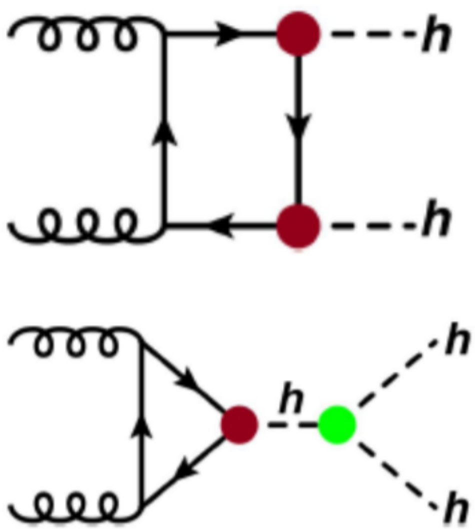
- CMS combined all major decay modes: ***H→γγ, H→ZZ, H→bb, H→WW, H→ττ*** for STXS.
- **Good agreement with SM**. Best precisions of <20% reached

Di-Higgs Production and Higgs self-coupling

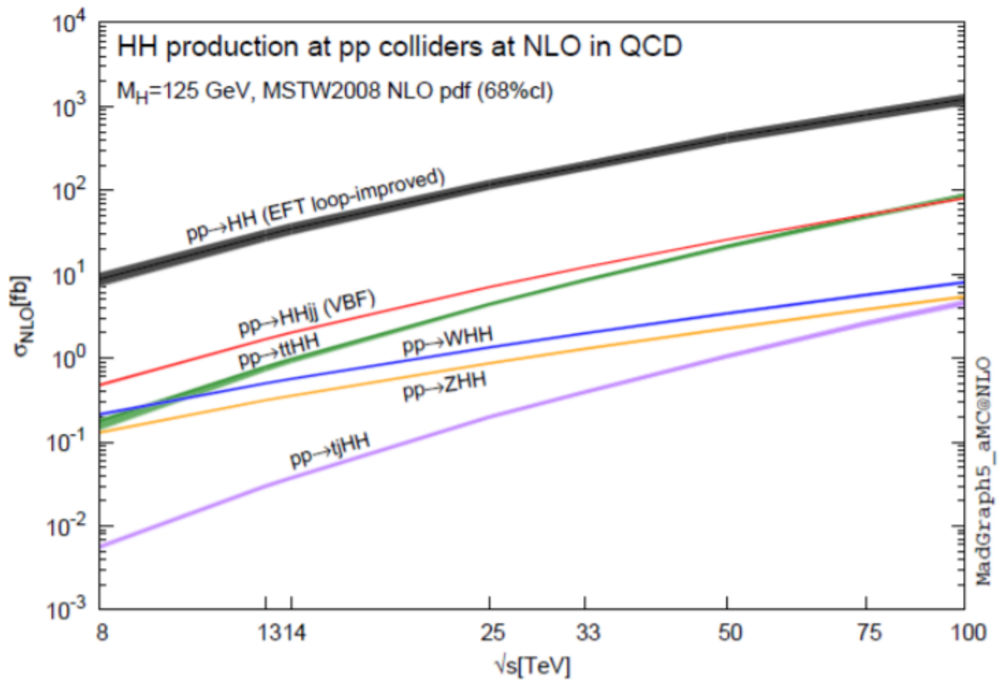
Di-Higgs Production

j. Qian's Higgs Hunting talk

$gg \to HH$ dominates



arXiv: 1401.7340 and LHC Higgs XS group



At $\sqrt{s} = 13$ TeV for $m_H = 125$ GeV

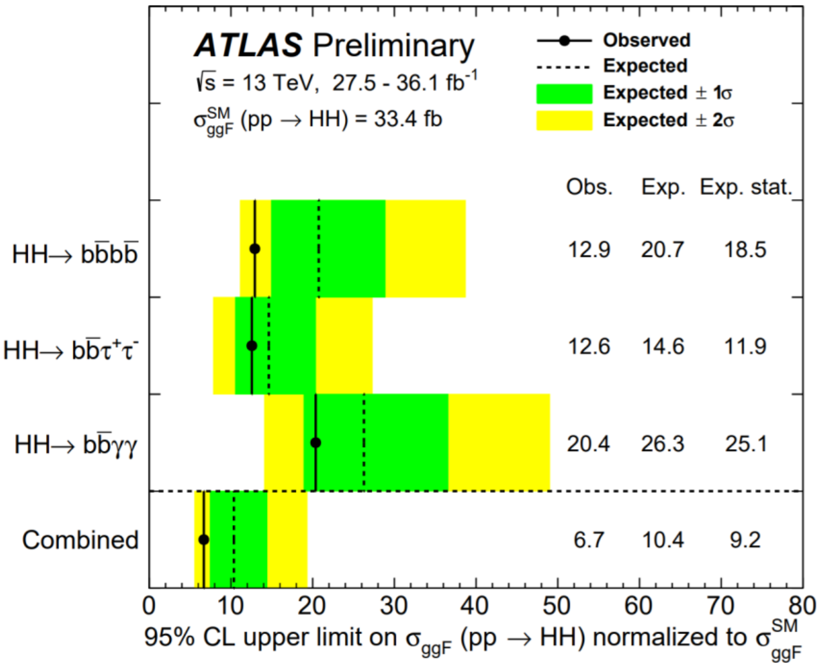
$$\sigma^{SM}_{gg\to HH} = 33.53 \text{ fb} \left[1.0^{+4.3\%}_{-6.0\%}(\text{scale}) \pm 2.3\%(\alpha_S) \pm 2.1\%(\text{PDF}) \pm 5\%(\text{Th.})\right]$$

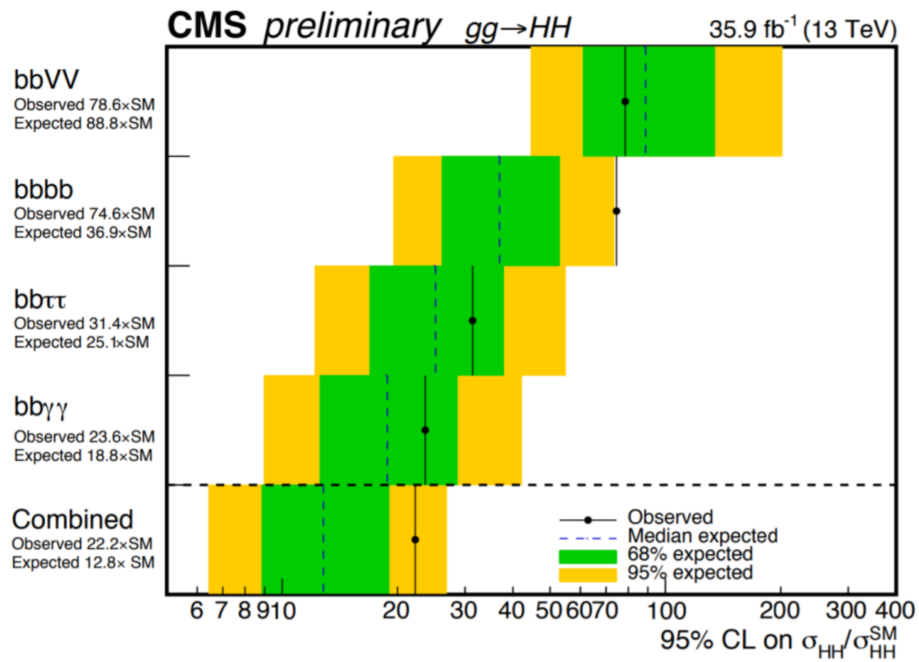
Compared with

$$\sigma^{SM}_{gg\to H} = 48.52 \text{ pb} \left[1.0^{+7.4}_{-7.9}(\text{scale}) \ {}^{+7.1}_{-6.0}(\text{PDF}+\alpha_S)\right]$$

- **~ 1： 1500 difference** → Need to compromise with signal yields (BR) and S/B to select analysis channels
- Higgs self-coupling can be probed by *HH* production at the LHC ($\lambda = \frac{m_H^2}{2v^2} \approx 0.13$ in SM)

Di-Higgs Production





CERN-EP-2018-164

CMS-PAS-HIG-17-030

- Limit from ATLAS HH combination: μ<6.7 (10.4 exp.)
- Limit from CMS HH combination: μ<22 (13 exp.)
- Limit of Higgs self-coupling SF $\kappa_\lambda = \frac{\lambda_H}{\lambda_{H,SM}}$ @95% CL
  - ATLAS: $-5.0 < \kappa_\lambda < 12.1$ ($-5.8 < \kappa_\lambda < 12.0$,exp.)
  - CMS: $-11.8 < \kappa_\lambda < 18.8$ ($-7.1 < \kappa_\lambda < 13.6$,exp.)
- Both CMS and ATLAS results reaches ~x10 SM expected production.
- The next step is to reach SM sensitivity in HL-LHC term!

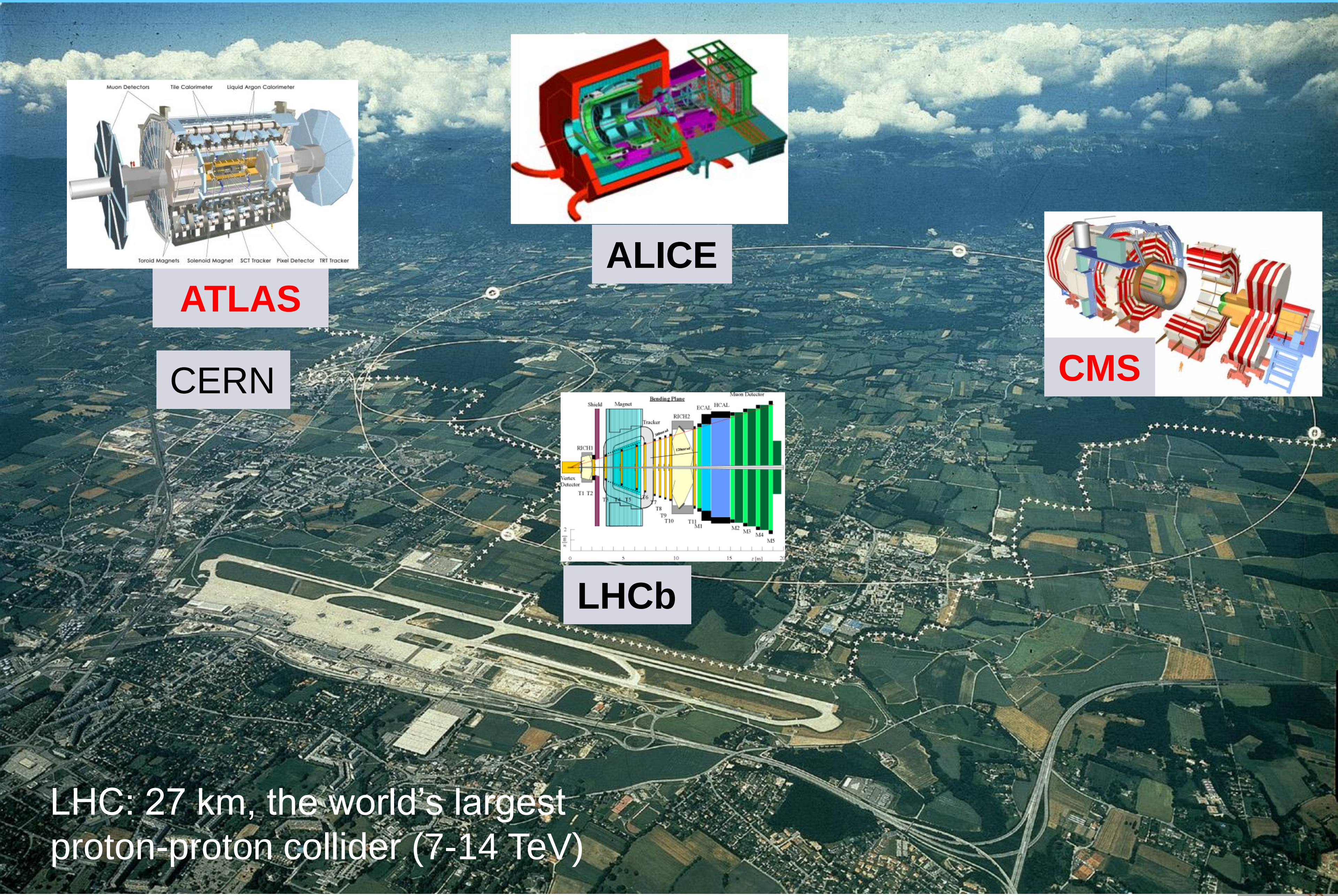
Summary

- A lot of impressive Higgs results come from LHC Run 1+2
  - All major production modes have been observed.
  - Higgs coupling to 3rd generation fermions are confirmed.
  - The mass, width and couplings measurements reach unprecedented precision.
  - Di-Higgs production reaches ~x10 SM expected production.
- No obvious deviation from SM captured so far.
- Waiting for the full Run-2 dataset and the HL-LHC to reach a higher sensitivity to the potential new physics!

Thanks

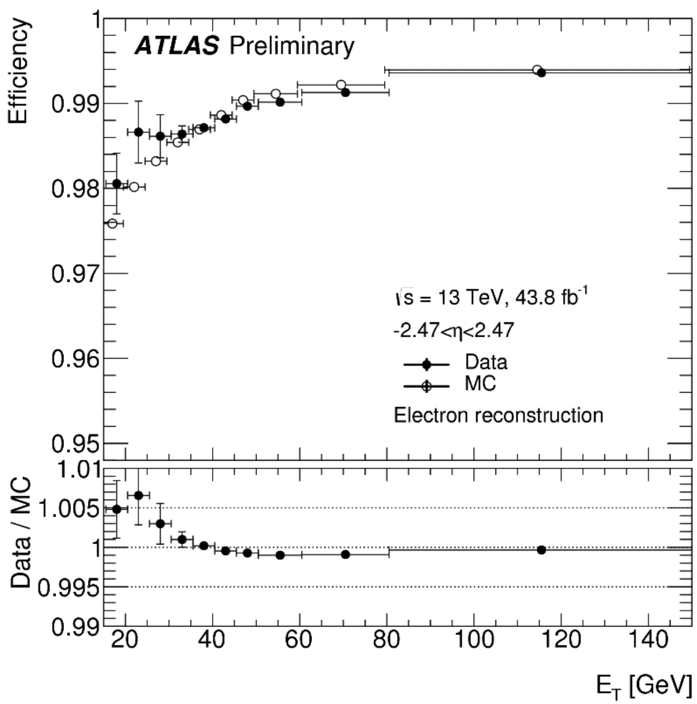
Backup

Large Hadron Collider at CERN

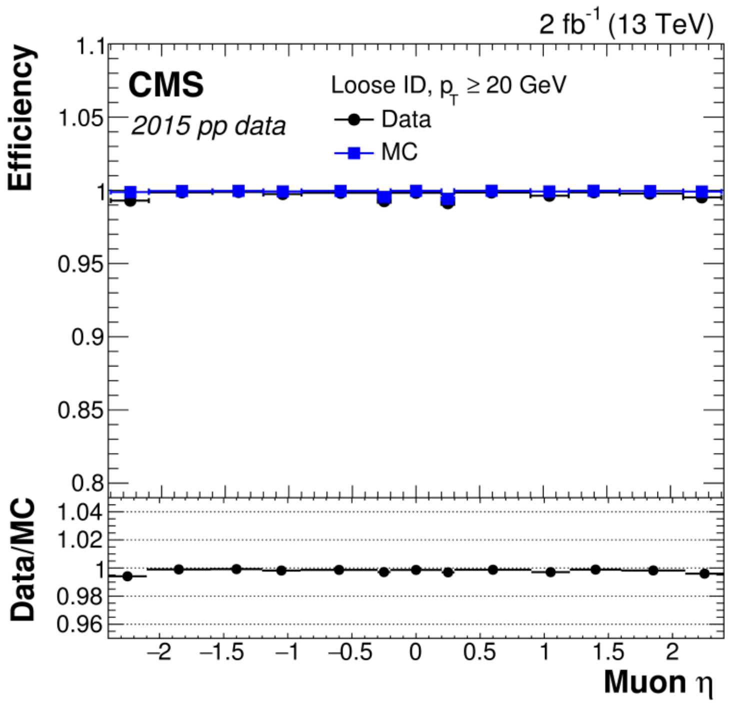


LHC: 27 km, the world's largest proton-proton collider (7-14 TeV)

Detector performance



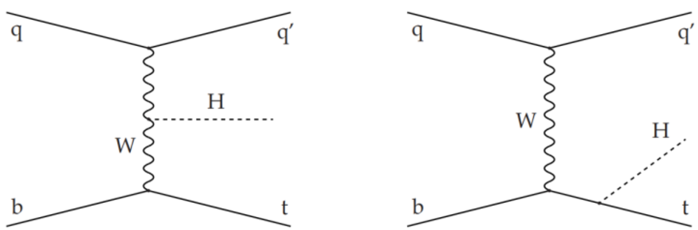
Electron reconstruction efficiencies in Z→ee events as a function of transverse energy ET, integrated over the full pseudo-rapidity range.

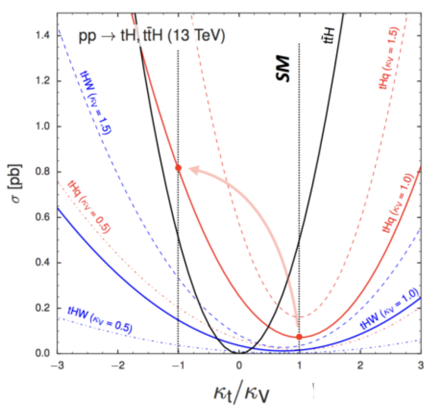


Tag-and-probe efficiency for muon reconstruction and identification in 2015 data (circles), simulation (squares), and the ratio (bottom inset) for loose muons with pT>20 GeV. The statistical uncertainties are smaller than the symbols used to display the measurements.

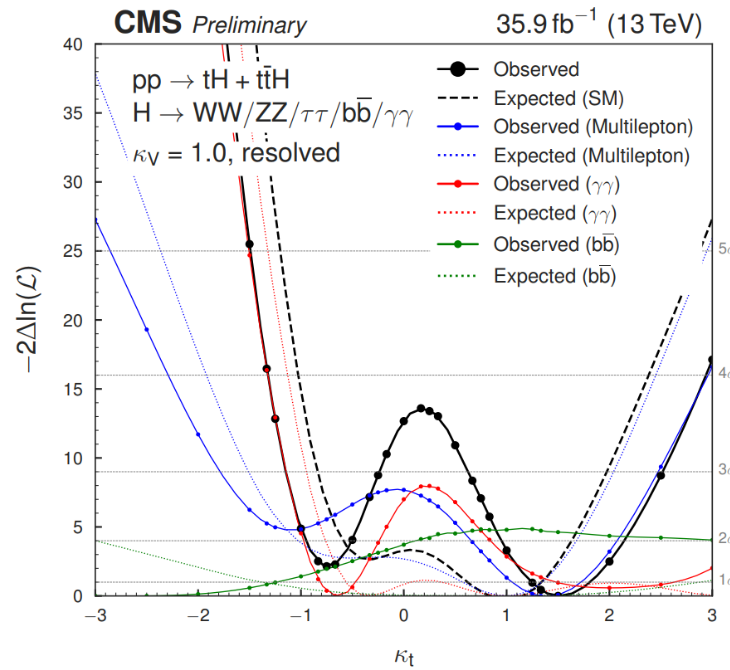
tH production mode

- tH production cross section is small, but **sensitive to the relative sign between κ_t and κ_V** .
- If $\kappa_t/\kappa_V < 0$, tH cross section will be larger than ttH.
- tH production mode can **directly constrain** the sign preference of κ_t/κ_V.



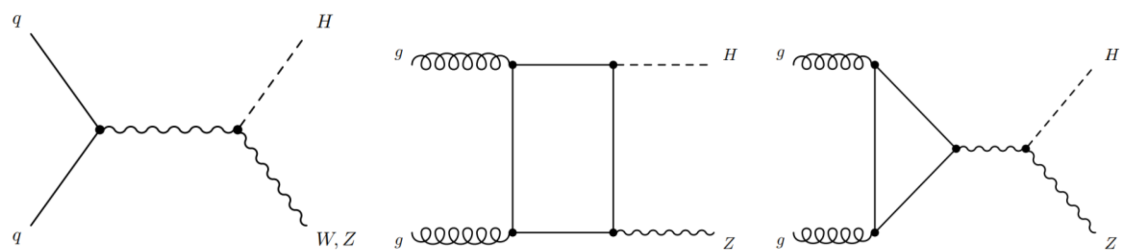


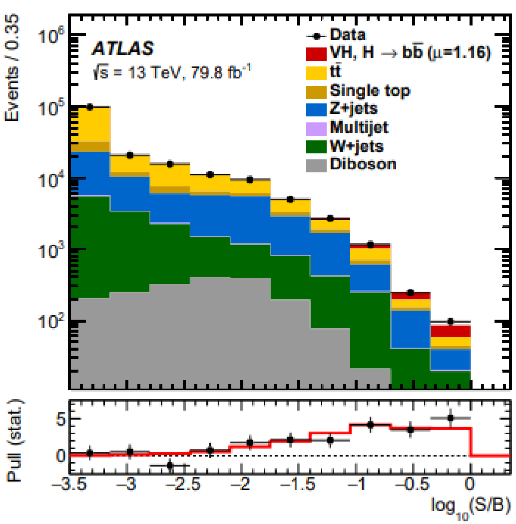
arXiv:1804.02610



- Results from CMS Run-2 36/fb combination of tH ML, tH, *H→bb* and ttH, *H→γγ*
- With the assumption that $\kappa_V = 1$, the negative sign of κ_t/κ_V is excluded at 1.5σ level.

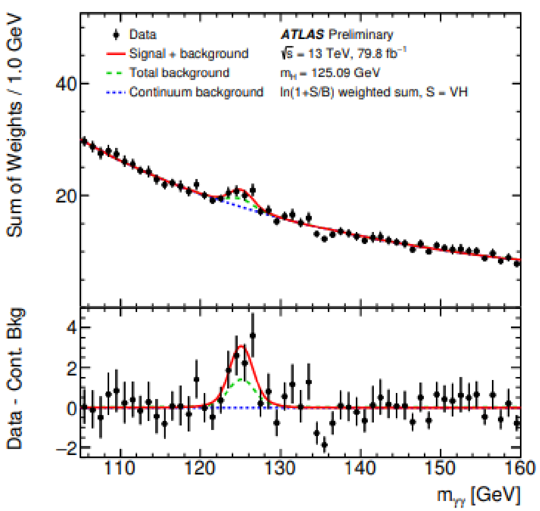
VH production mode





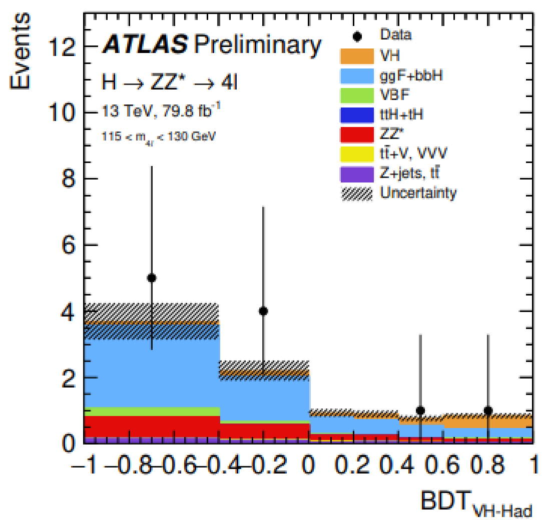
arXiv:1808.08238

H→bb



arXiv:1806.00425

H→γγ

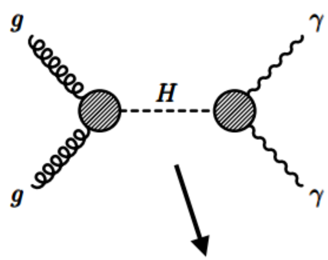


ATLAS-CONF-2018-018

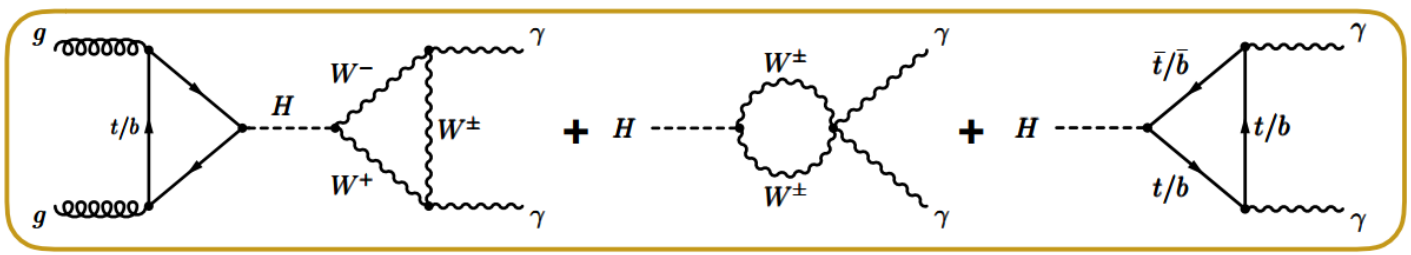
H→ZZ* →4l

"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:



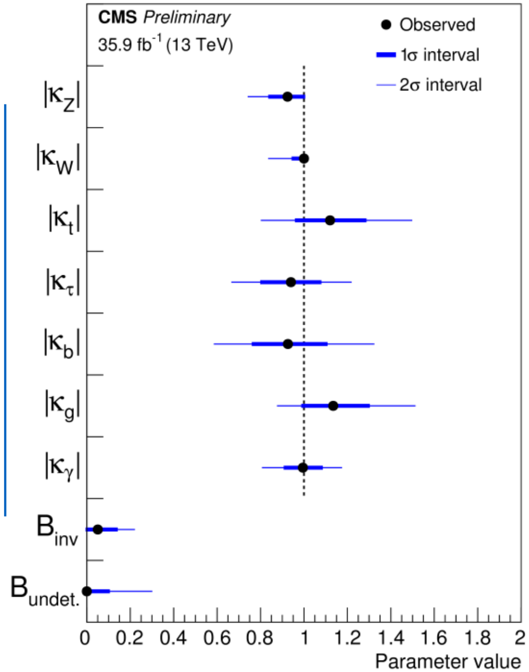
$$(\sigma \times \mathbf{BR})(\mathbf{gg} \to \mathbf{H} \to \gamma\gamma) \sim \frac{\kappa_{\mathbf{g}}^{\mathbf{2}}(\kappa_{\mathbf{t}}, \kappa_{\mathbf{b}}, \ldots)\kappa_{\gamma}^{\mathbf{2}}(\kappa_{\mathbf{W}}, \kappa_{\mathbf{t}}, \ldots)}{\kappa_{\mathbf{H}}^{\mathbf{2}}(\kappa_{\mathbf{b}},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



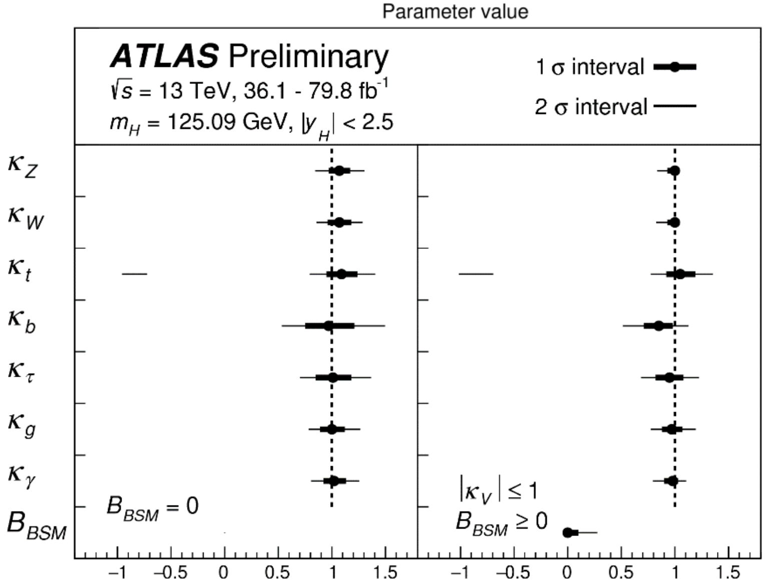
- Can handle other production and decay vertices in a similar way (much simpler in most cases)

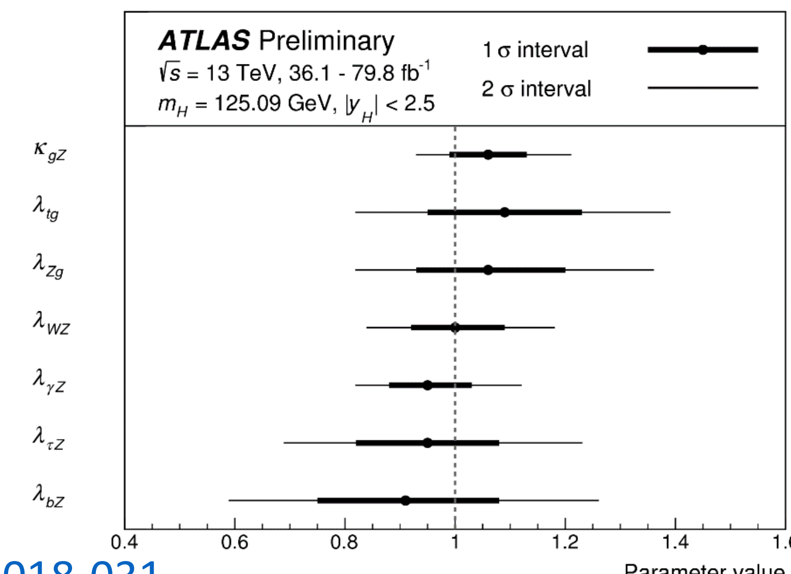
Combination Measurement

CMS-PAS-HIG-17-031



- from Generic kappa model:
  - 95% CL upper limit for B_{BSM} from ATLAS: 0.26
  - 95% CL upper limit for B_{inv} from CMS: 0.22
- Ratio coupling model will reduce the model assumptions and test the possible new physics contributions.
- **Results are in agreement with SM.**

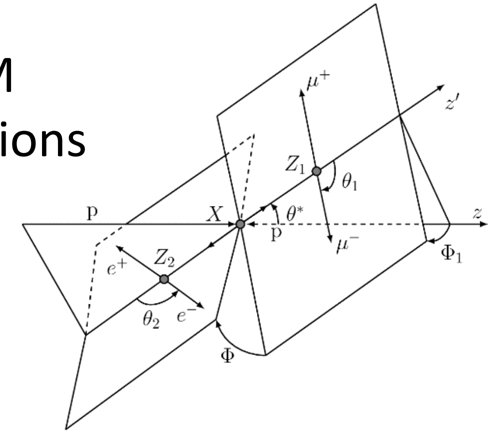




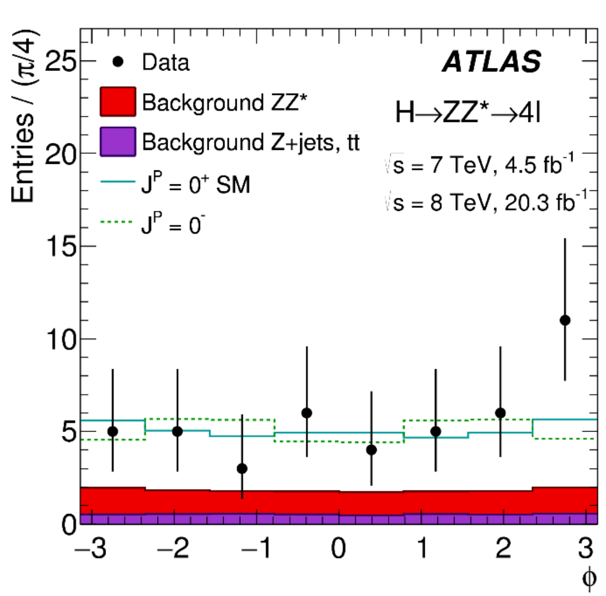
ATLAS-CONF-2018-031

Spin and parity

- Test various alternative spin-parity options against the SM hypothesis $J^p = 0^+$ using angular and kinematic distributions in Higgs decays.
  - H→γγ (sensitivity to 2^+, excludes spin 1).
  - H→ZZ*→4l (sensitivity to all spin/parity).
  - H→WW*→lνlν (sensitivity to spin 1 and 2).
- Both CMS and ATLAS results show SM is highly favored against pure alternative. (Exclude tested hypotheses with CL > 99.9%)

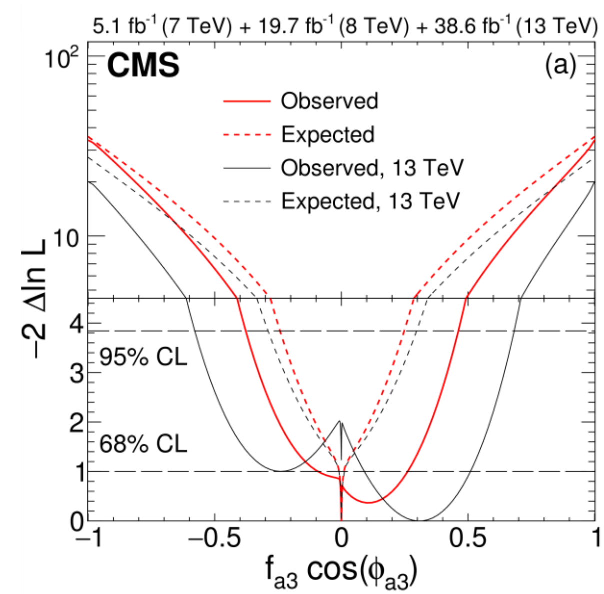


arXiv:1506.05669



ATLAS Run-1

arXiv:1707.00541



CMS Run-2

Significance obs. (exp.)	ATLAS+CMS Run-1	ATLAS(36.1 – 79.8 /fb)
VBF	5.4(4.6)	6.5(5.3)
VH	3.5(4.2)	5.3(4.8)
ttH	4.4(2.0)	5.8(5.3)

- Run 2 *H*→ γγ mass resolution: 1.4-2.1 GeV
- Run 2 *H*→*ZZ** →*4l* mass resolution: 1.6-2.4 GeV