Higgs status

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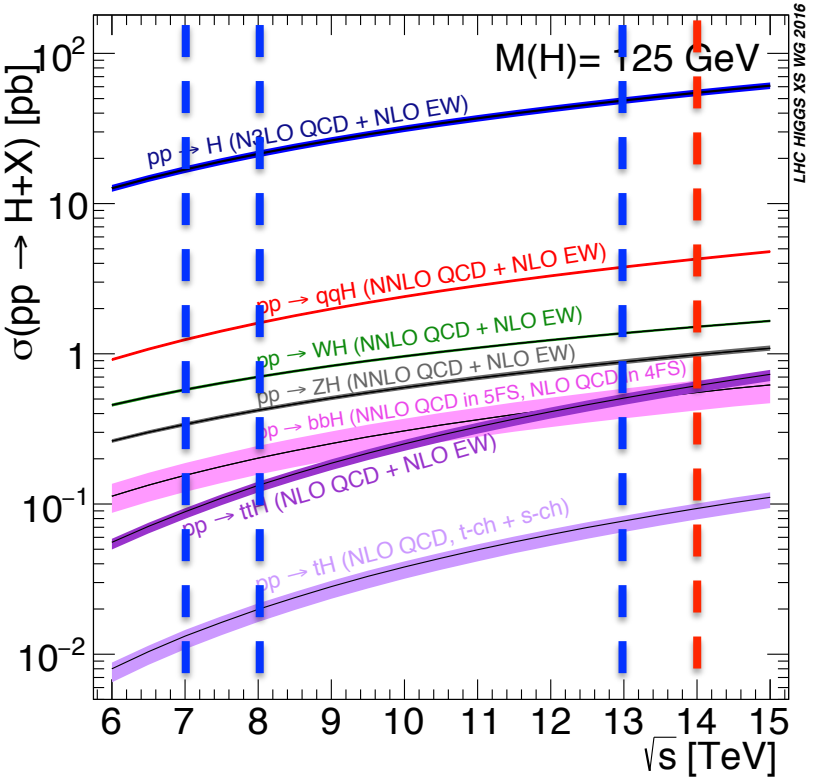
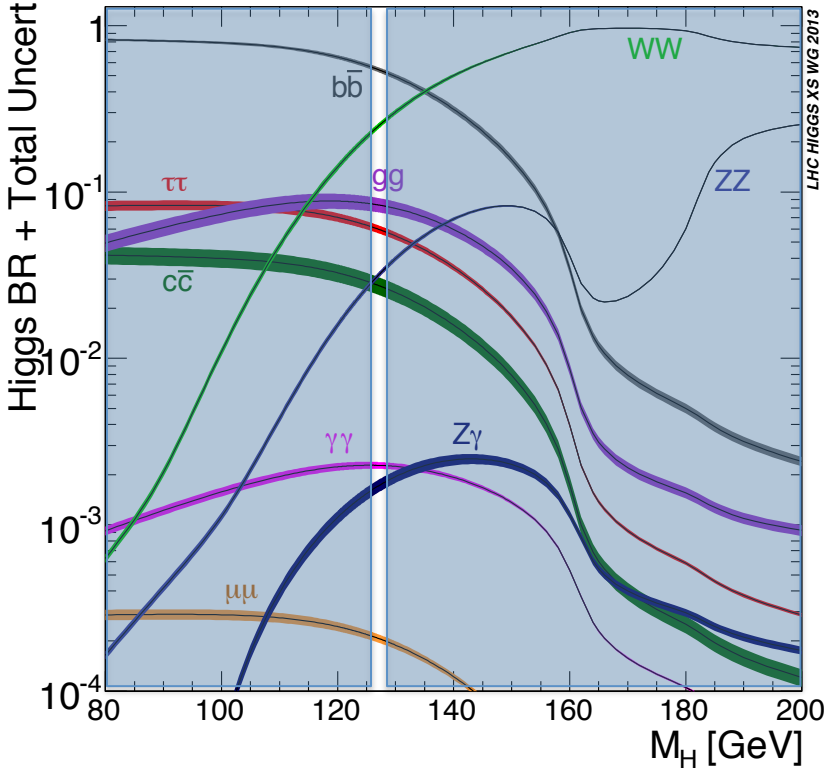
The Hong Kong University of Science and Technology
and HKUST Institute for Advanced Study

on behalf of the ATLAS and CMS Collaborations

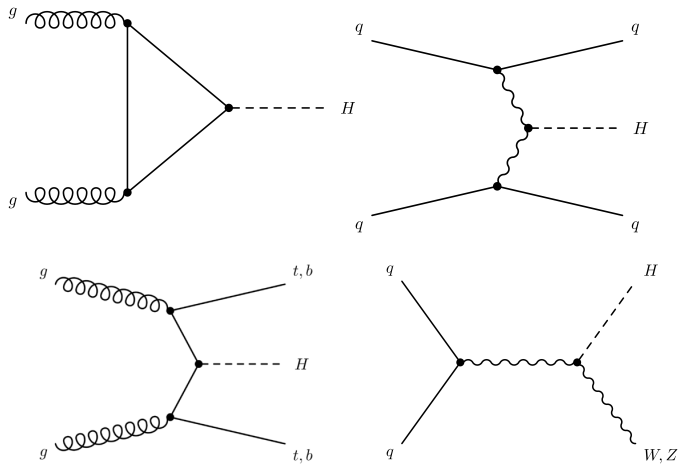
Standard Model Higgs boson at the LHC





At m_H = 125.09 GeV
and √s = 13 TeV

ggF	48 pb
VBF	3.8 pb
W(Z)H	1.34 (0.9) pb
ttH	0.5 pb



arXiv:1610.07922 [hep-ph] *https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG*

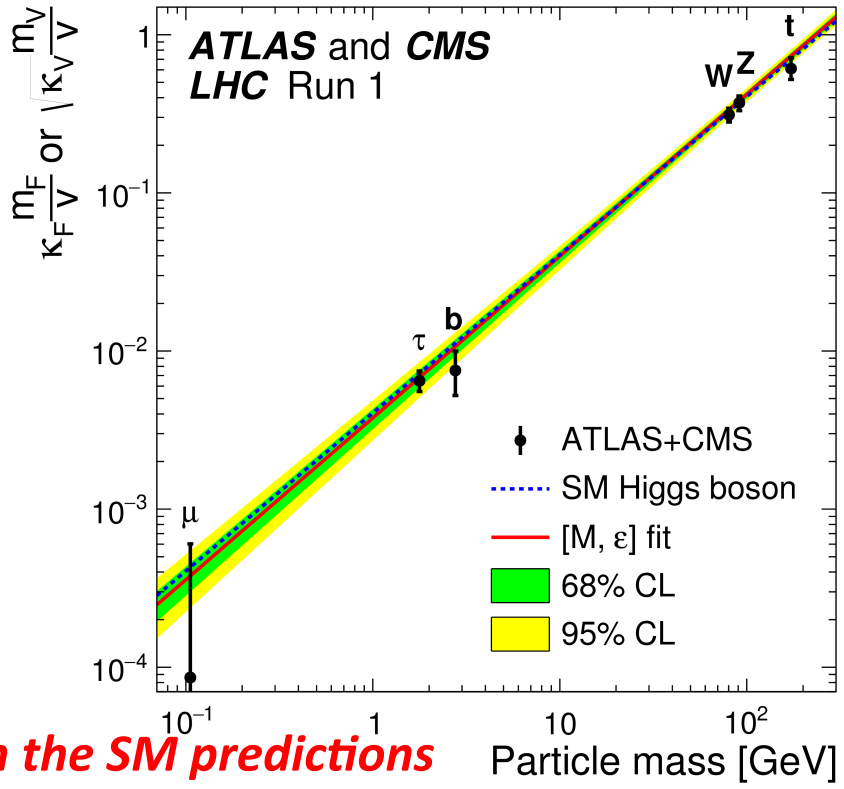
Legacy of the LHC Run-1

- Discovery of a new neutral scalar boson, first in di-boson, then in di-fermion decays.

- Observations:
  - H→γγ, H→ZZ$^{(*)}$→4l, H→WW→lνlν and H→ττ decays.
  - Gluon-fusion and VBF production.
  - Evidence for VH and ttH processes.

- Individual and combined ATLAS and CMS measurements in Run-1 include:
  - Mass and width
  - Couplings scale factors
  - Spin, parity, tensor structure of couplings and CP-mixing.

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

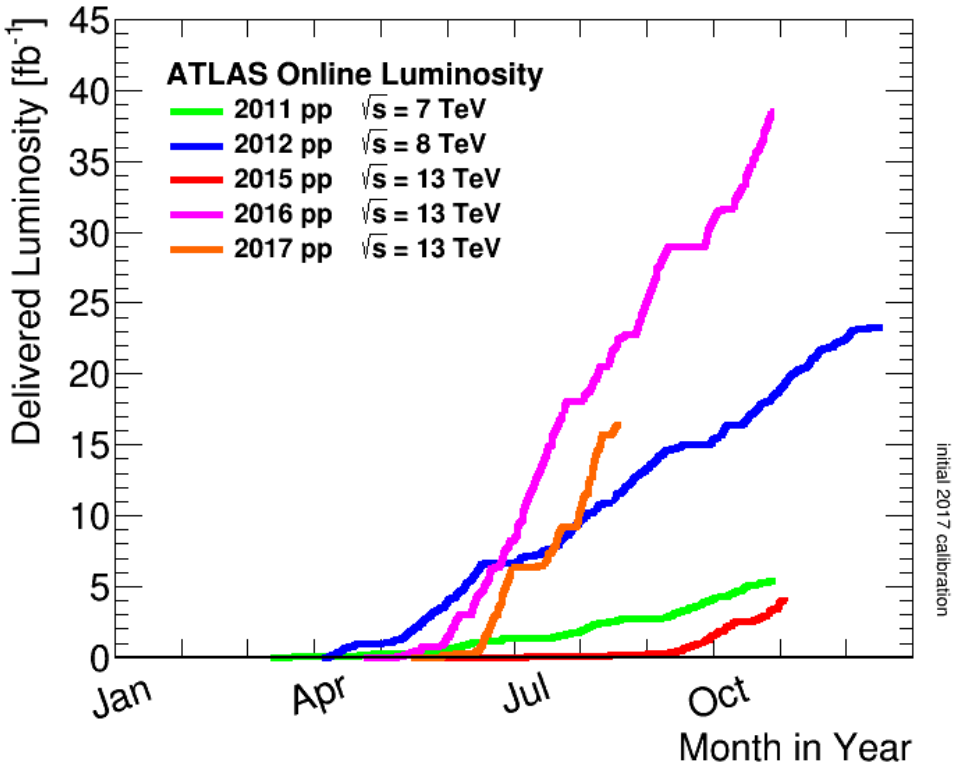


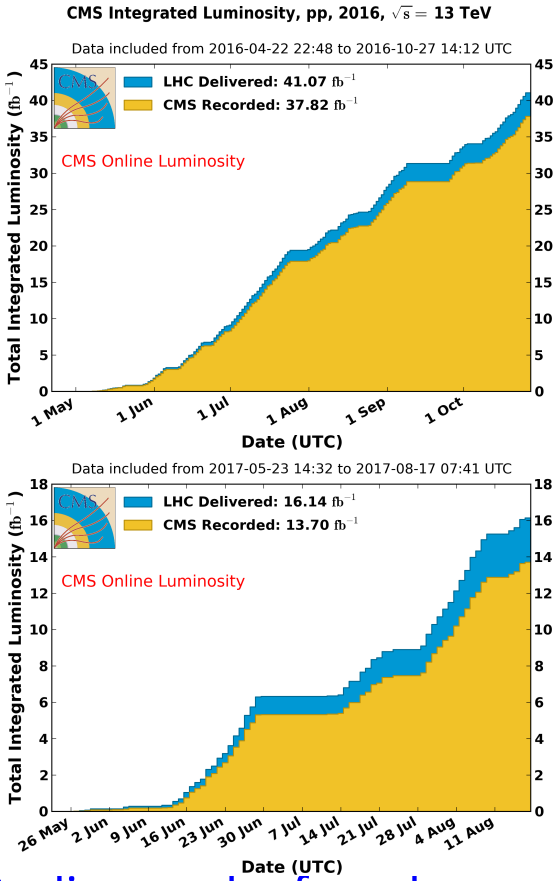
Initial compatibility with the SM predictions

JHEP 08 (2016) 045

ATLAS and CMS in Run-2

- Both experiments had very successful data taking campaign during 2016 and 2017.

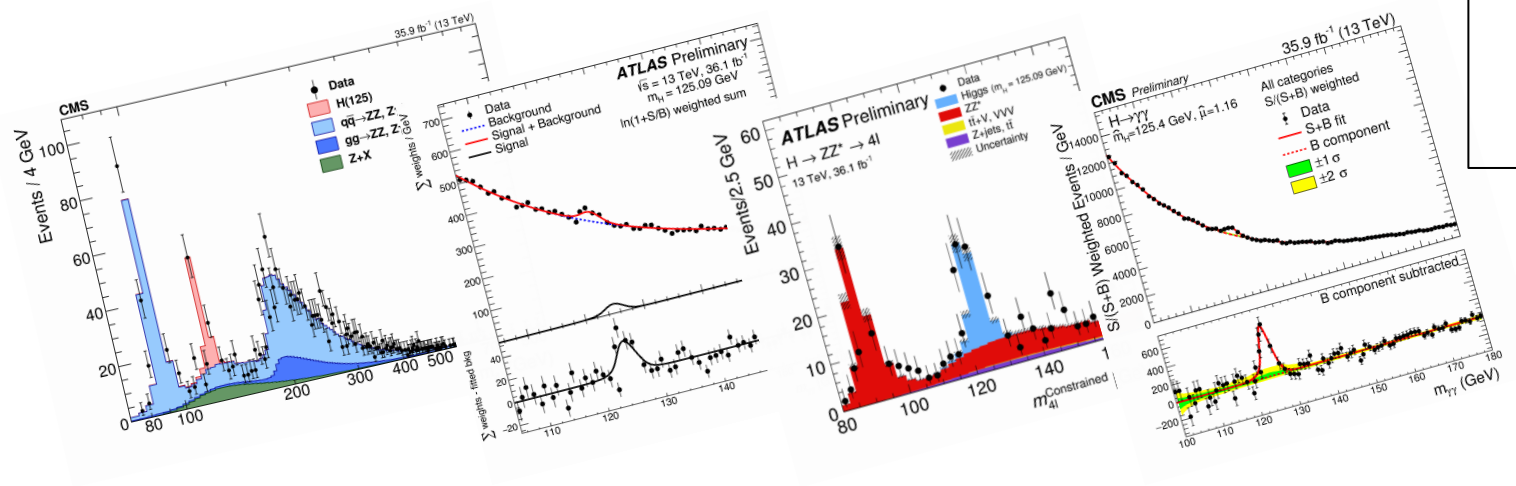


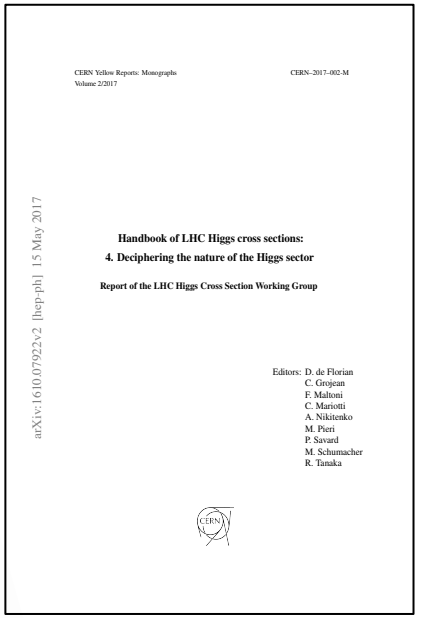


- All results shown today, together with other latest studies can be found:
  - ATLAS: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults*
  - CMS: *http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html*

ATLAS and CMS in Run-2

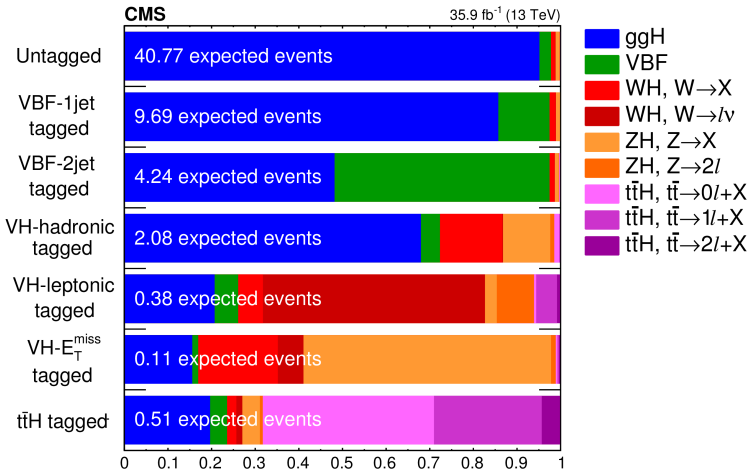
- Updates of many analyses up to 36.1 fb^{-1} collected at $\sqrt{s}$=13TeV in 2015 and 2016. Re-observation of signal. Main focus:
  - Observation of production and decay modes not visible or having limited evidence in Run-1.
  - Precision measurements of properties: couplings, tensor structure, fiducial and differential cross sections. Possibility of measuring cross-sections in exclusive bins of phase-space: Simplified Template (ST) cross-sections. Strategy outlined in the LHC XS WG Yellow Report 4: arXiv:1610.07922v2





Couplings and rates

Couplings and rates in H→ZZ(*)→4l (CMS)



Analysis in event categories enriched in different production mechanisms.

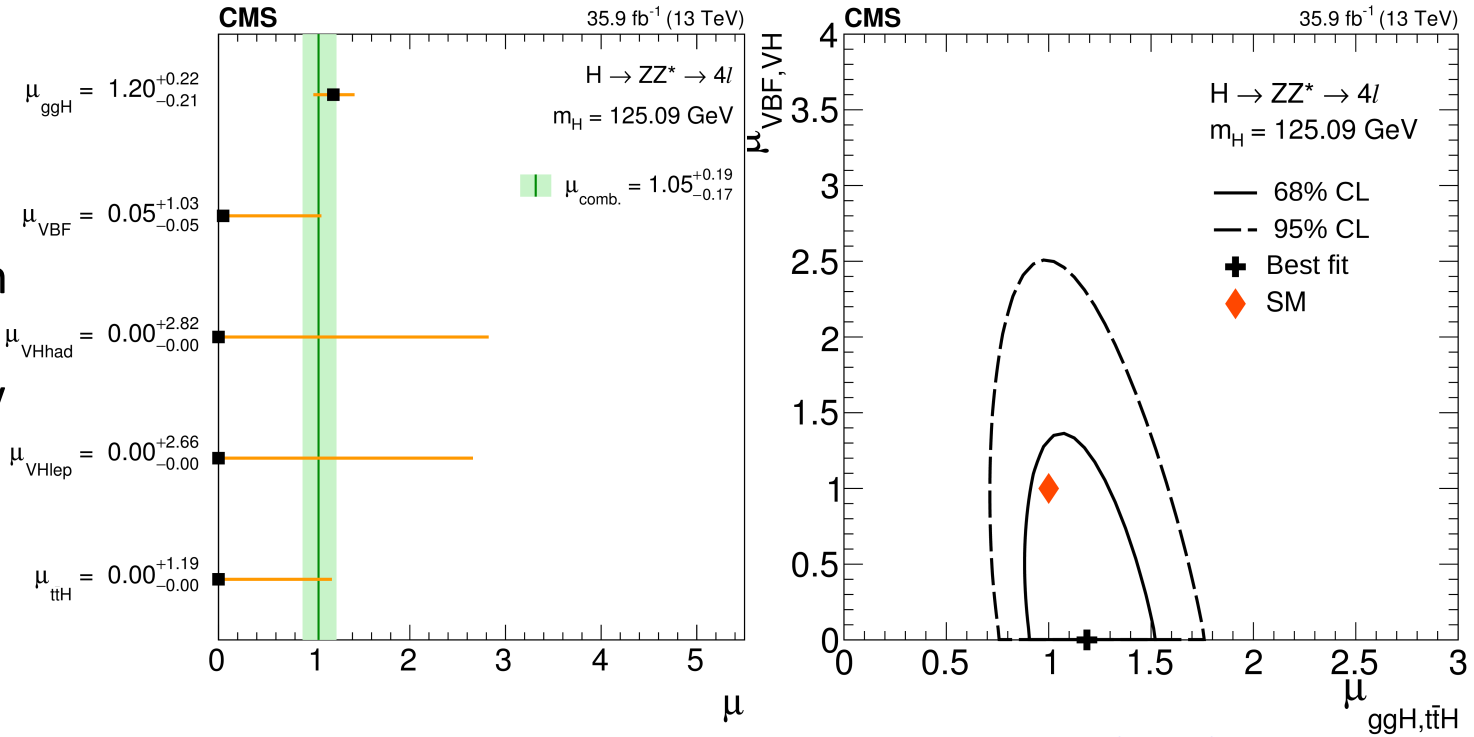
ME-based discriminant to exploit fully production and decay kinematics. m_{4l} vs ME discriminant fit.

$$\mu = 1.05^{+0.15}_{-0.14}(stat.)^{+0.11}_{-0.09}(syst.)$$

Observed (Expected) events in the signal region

118 <m_H< 130 GeV

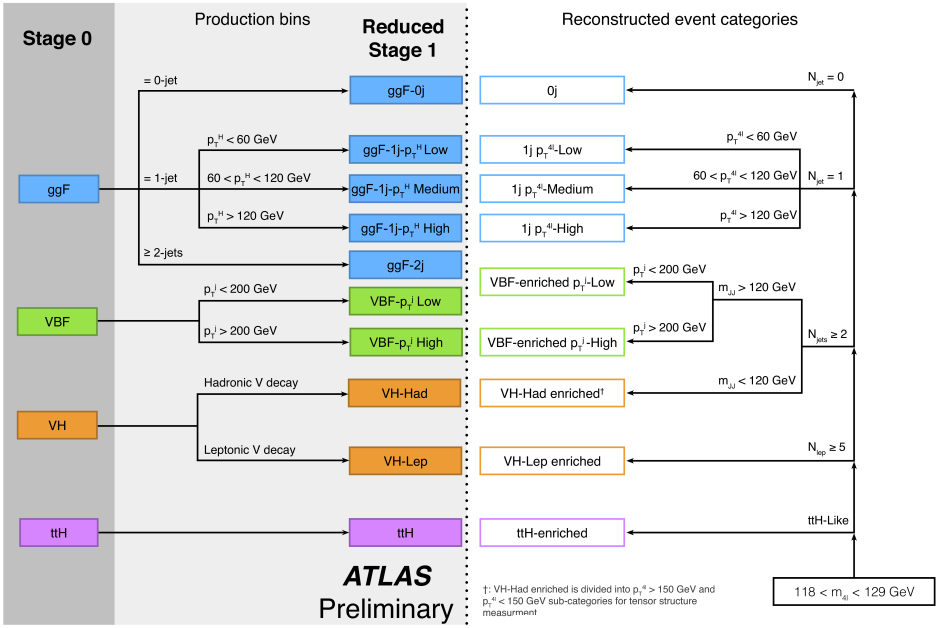
1479 (1417^{+89}_{-94})



pp → H + X SM cross section at up to N3LO QCD (YR4)

arXiv:1706.09936 [hep-ex]

Couplings and rates in H→ZZ(*)→4l (ATLAS)



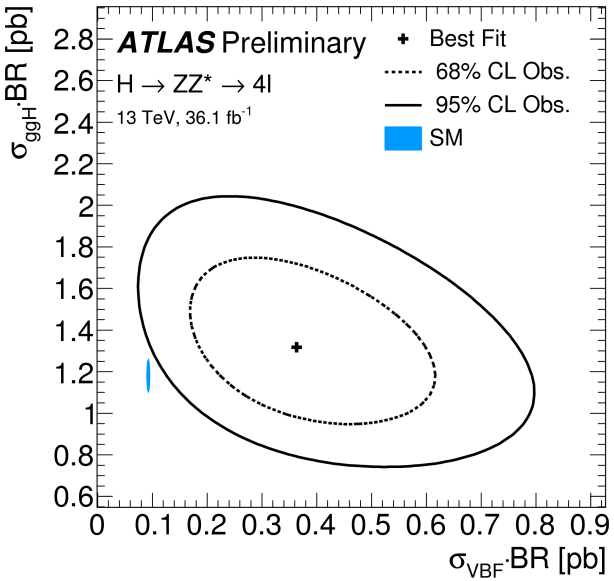
Analysis in two stages.

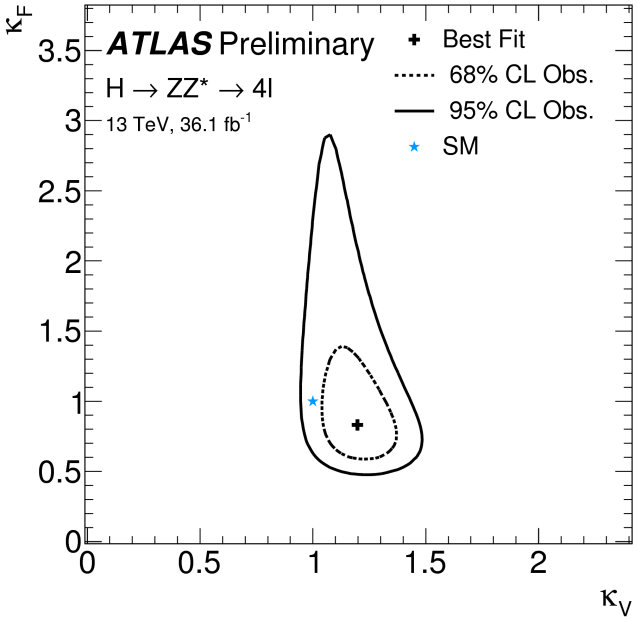
Stage 0: defining event categories to enrich different production mechanisms.

Reduced stage 1: defining categories similar to ST cross sections, merging under-populated bins.

$$\mu = 1.28^{+0.18}_{-0.17}(stat.)^{+0.08}_{-0.06}(syst.)^{+0.08}_{-0.06}(th.)$$

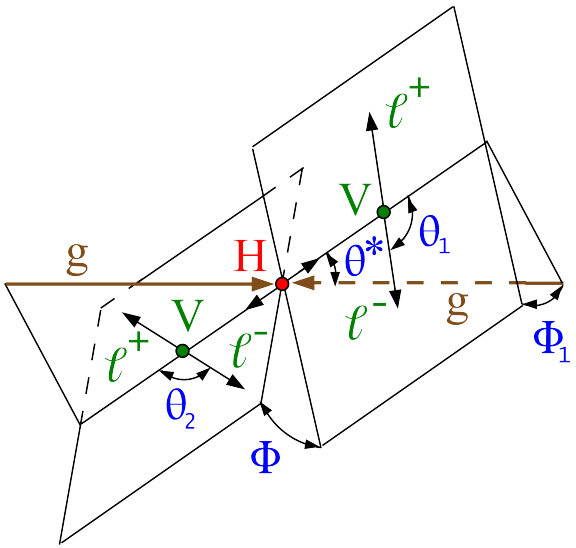
Slight excess of events in 2-jet (VBF) category





ATLAS-CONF-2017-043

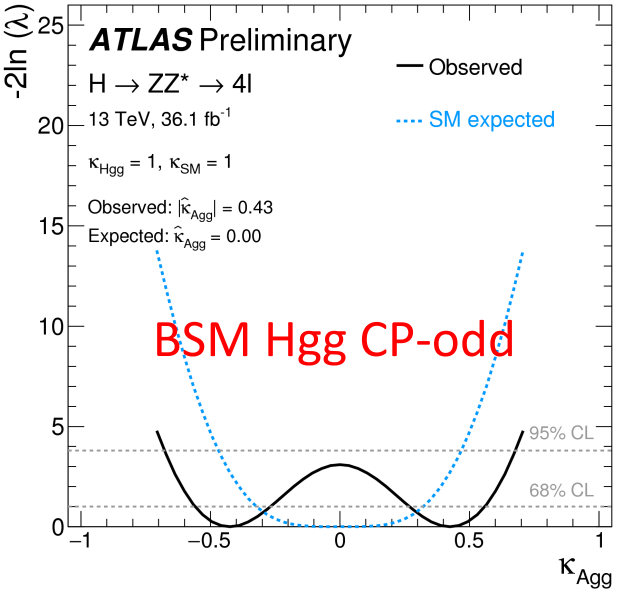
Anomalous couplings in H→ZZ(*)→4l

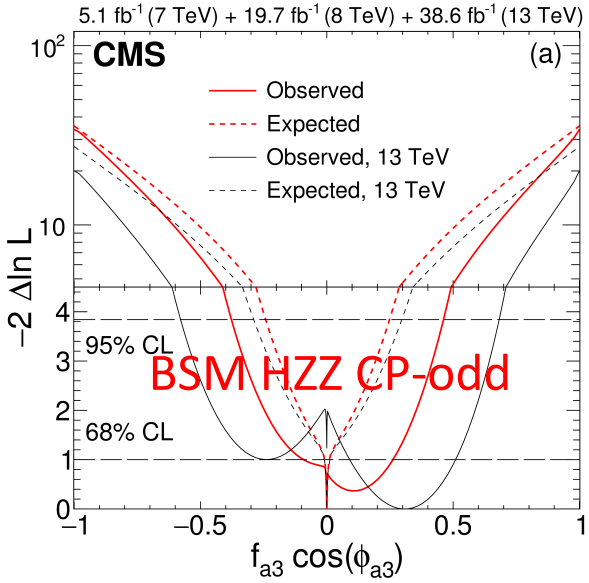


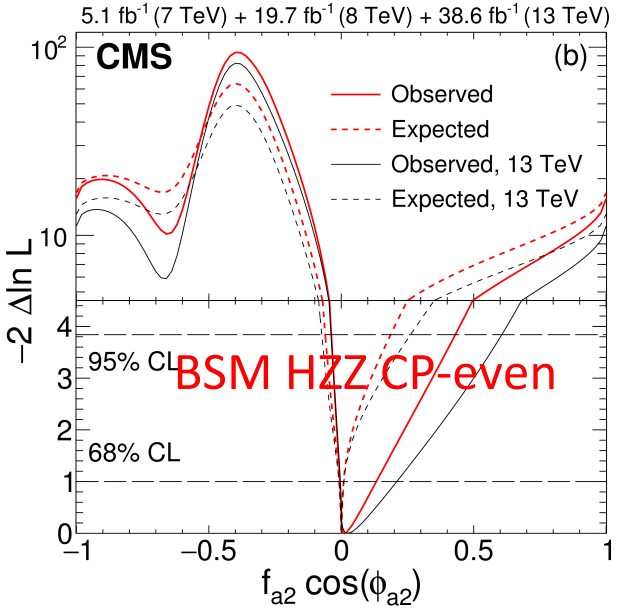
CMS: analysis of the FS kinematics of the H→4l decay.

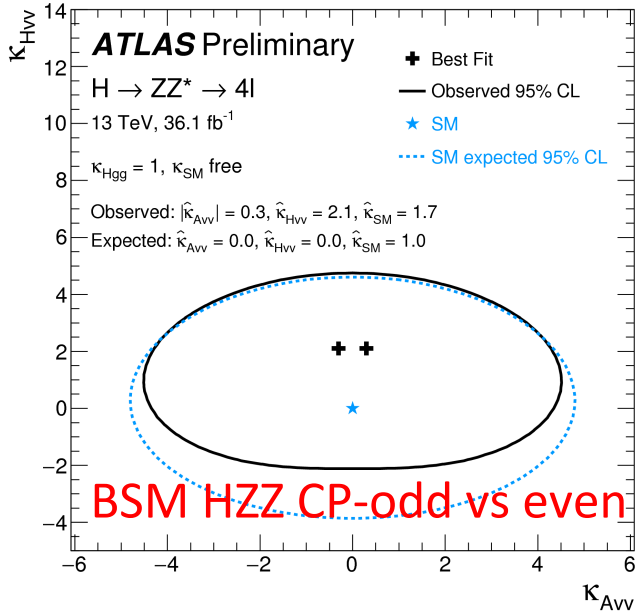
ATLAS: interpretation of event rates in analysis categories.

Overall fully compatible with the SM. Upper limits on BSM contributions



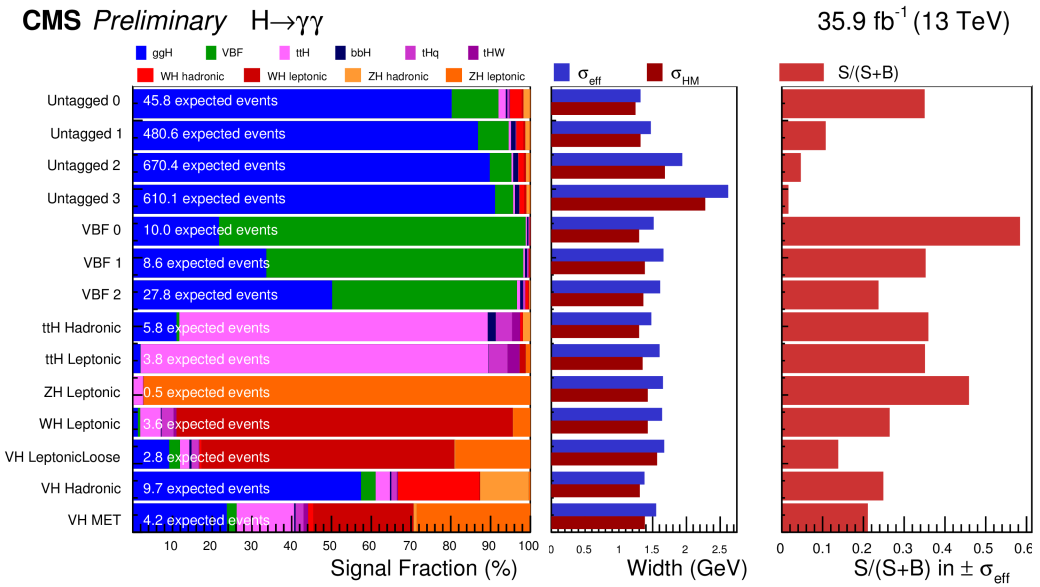


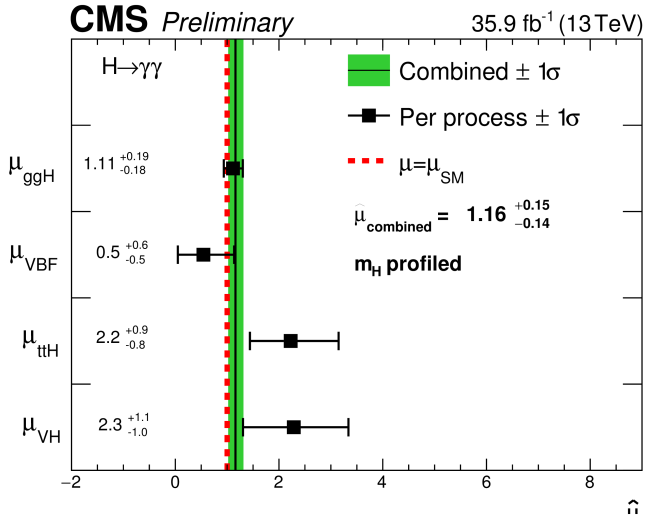


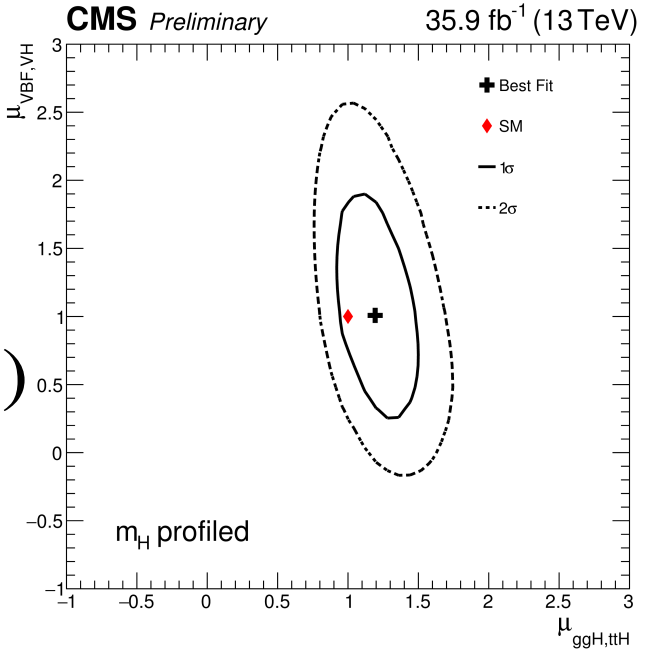


Couplings and rates in H→γγ (CMS)

14 event categories, depending on the production mechanism and di-photon kinematics.







Combined signal strength:

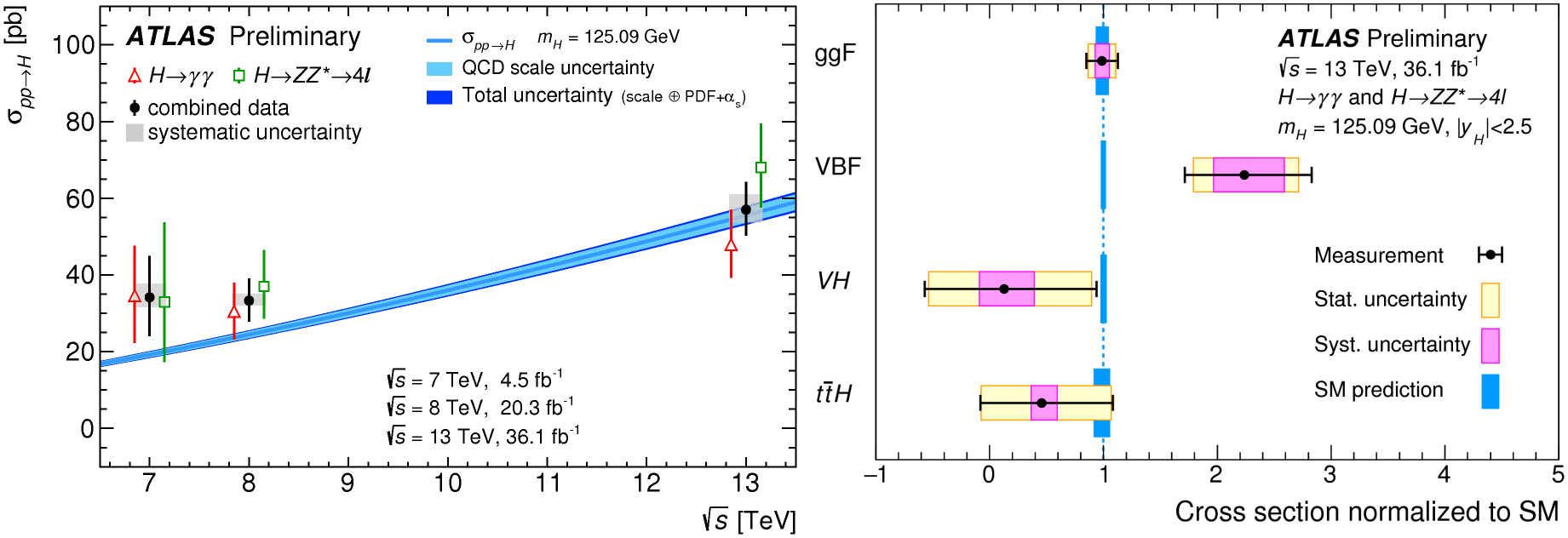
$$\mu = 1.16^{+0.11}_{-0.09}(stat.)^{+0.08}_{-0.10}(syst.)^{+0.06}_{-0.05}(theo.)$$

Significance Observed(Expected):
VBF 1.1σ(1.9σ) ttH 3.3σ (1.5σ)
VH 2.4σ (1.2 σ)

CMS PAS HIG-16-040

Couplings in H→γγ and H→ZZ$^{(*)}$→4l (ATLAS)

Combined total and by production mechanism cross section measurements.



Total pp → H + X cross sections compared to SM predictions at up to N3LO QCD (with POWHEG NNLOPS acceptance corr.)

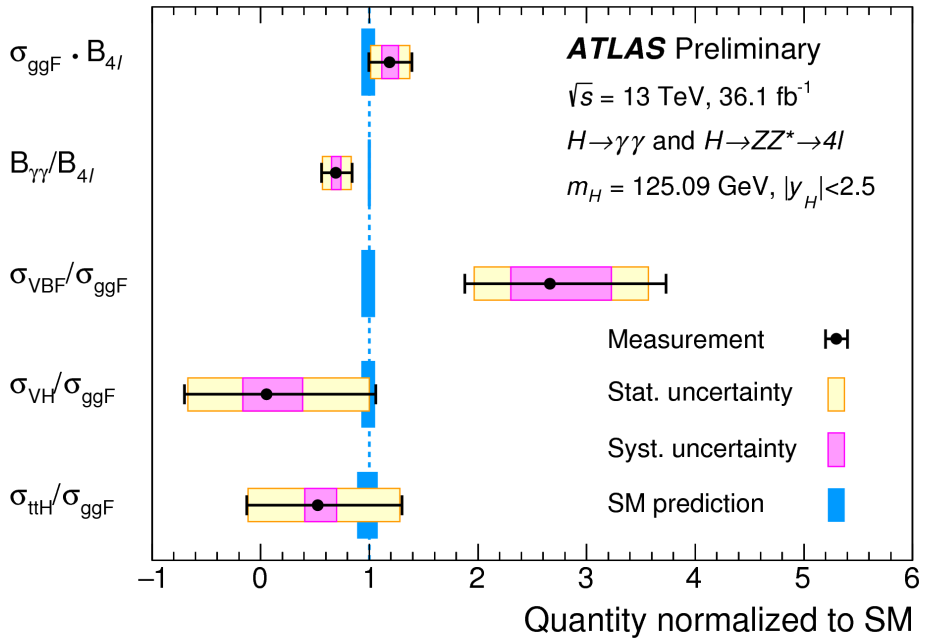
Cross sections for ggF, VBF, VH, and ttH are normalized to the SM predictions assumption of SM branching fractions. Overall good agreement except for the VBF.

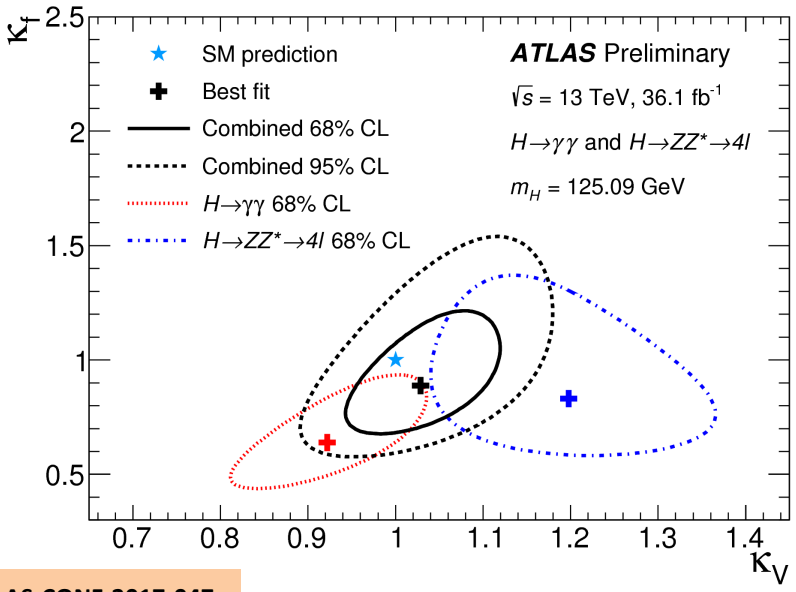
ATLAS-CONF-2017-047

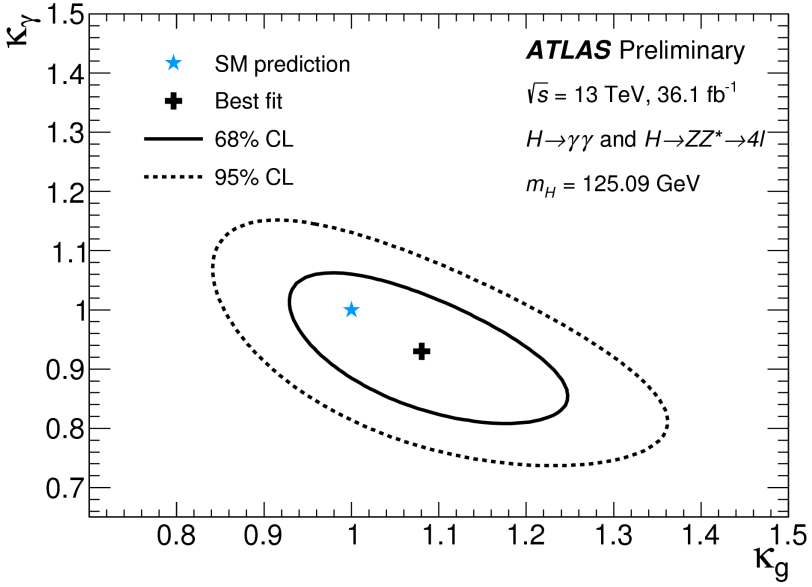
Couplings in H→γγ and H→ZZ(*)→4l (ATLAS)

Combined measurements of cross section and BR ratios per production/decay mode and comparison to the SM expectation.
Slight excess in 2-jet events due to 4l.

5-dimensional compatibility: p^{SM} = 3%.





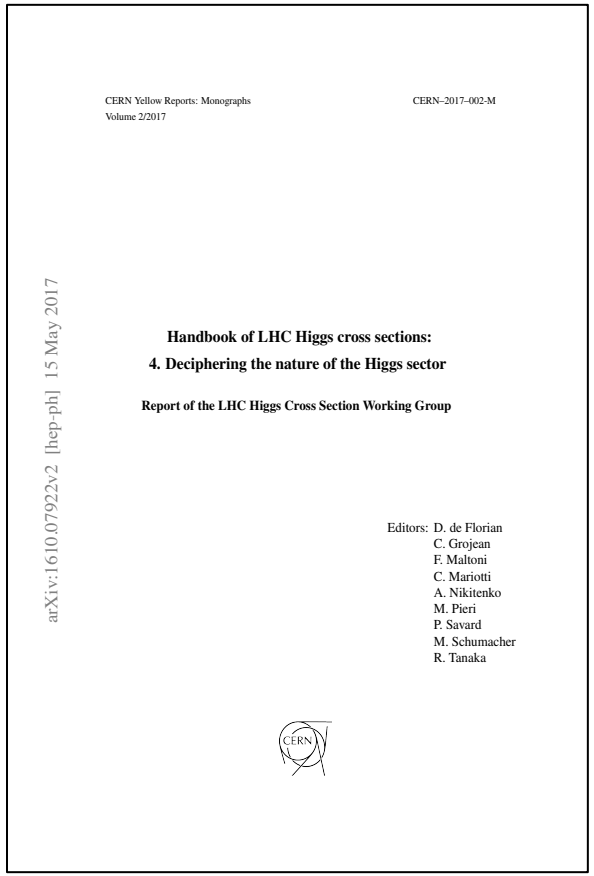


ATLAS-CONF-2017-047

Simplified template cross-sections

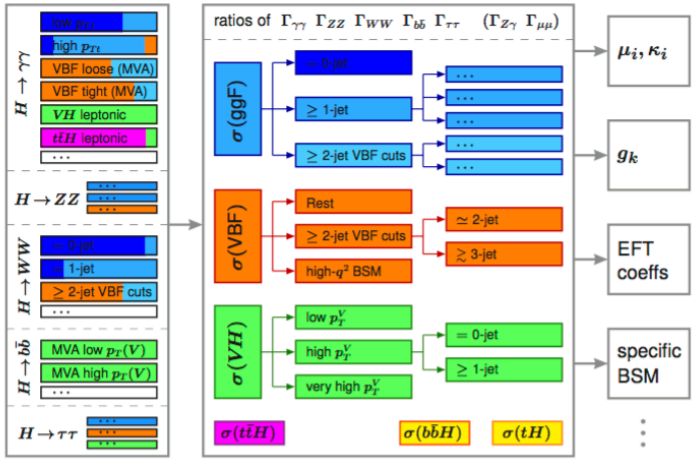
- Coupling measurements framework proposed by the LHC Higgs Cross section working group (YR4) for the LHC Run-2.
  - Extends and complements scaling coefficients framework implemented for the Run-1.
  - Agreed by ATLAS and CMS Higgs groups and by the theory community.

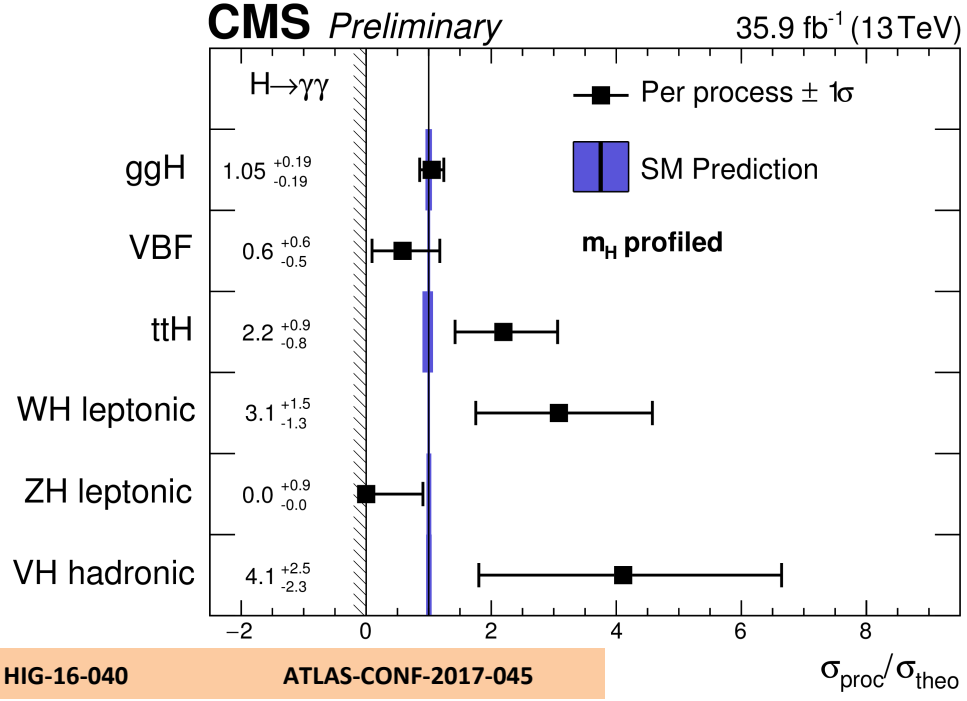
- Common approach to all Higgs decay channels, allowing easy combination.
  - Measurement of CS in exclusive regions of phase space.
  - CS measurements per production mode.
  - Measurements in exclusive regions of phase space –"STXS bins".

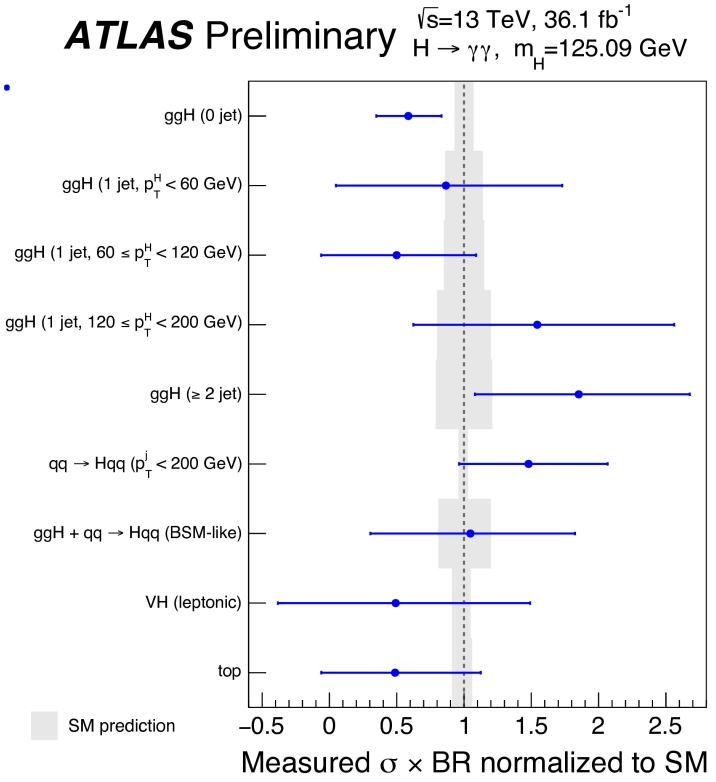


H→γγ ST cross sections

- The STXS bins are selected such as to:
  - Minimize dependence on theoretical uncertainties.
  - Maximize experimental sensitivity.
  - Isolate possible BSM effects.
- Theoretical uncertainties on overall signal cross sections have no impact except for the cases when they cause migration between categories.



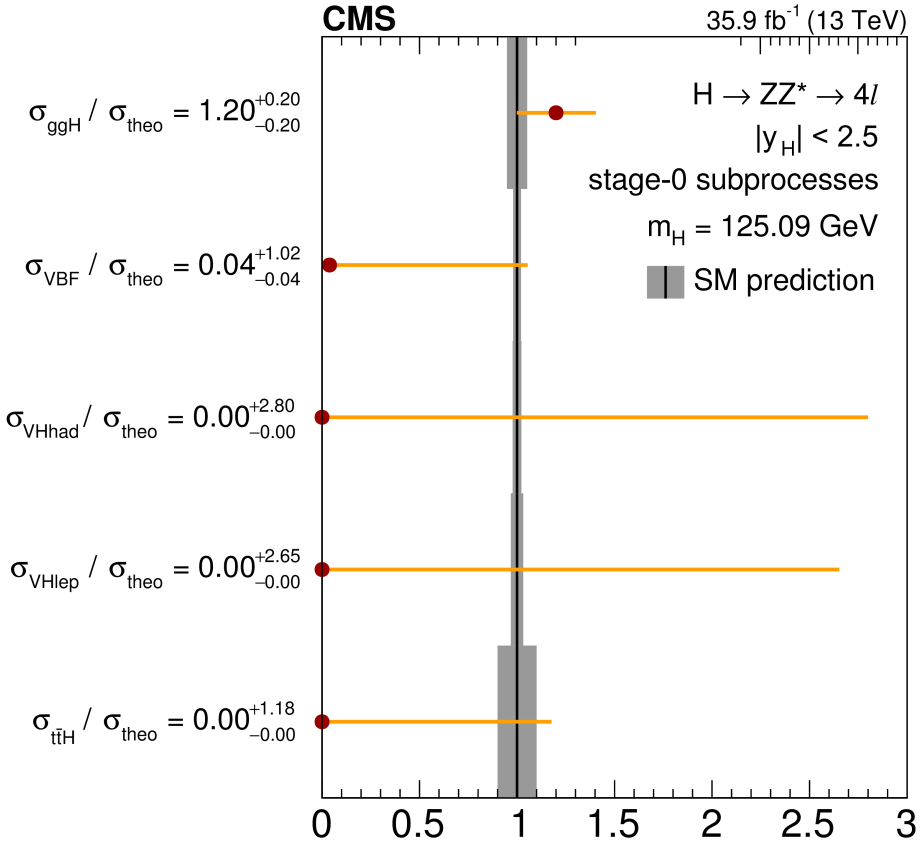


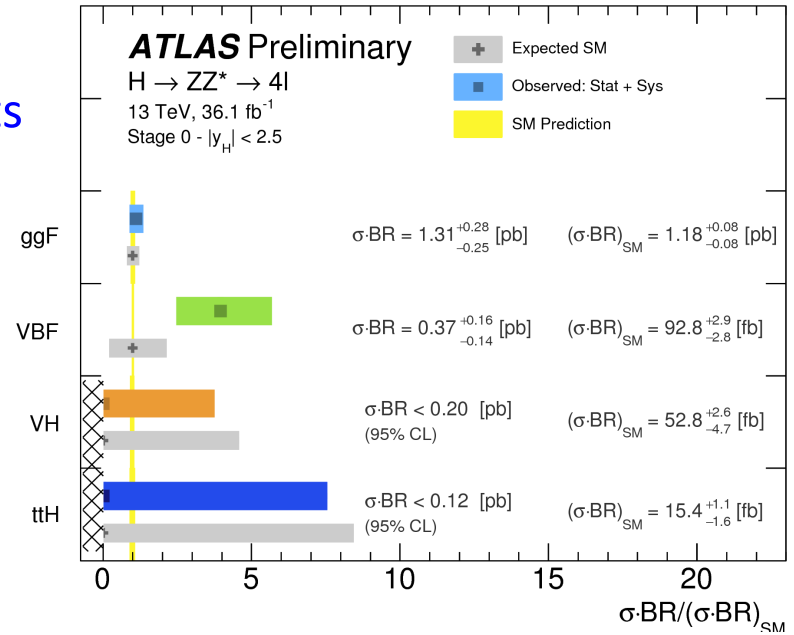


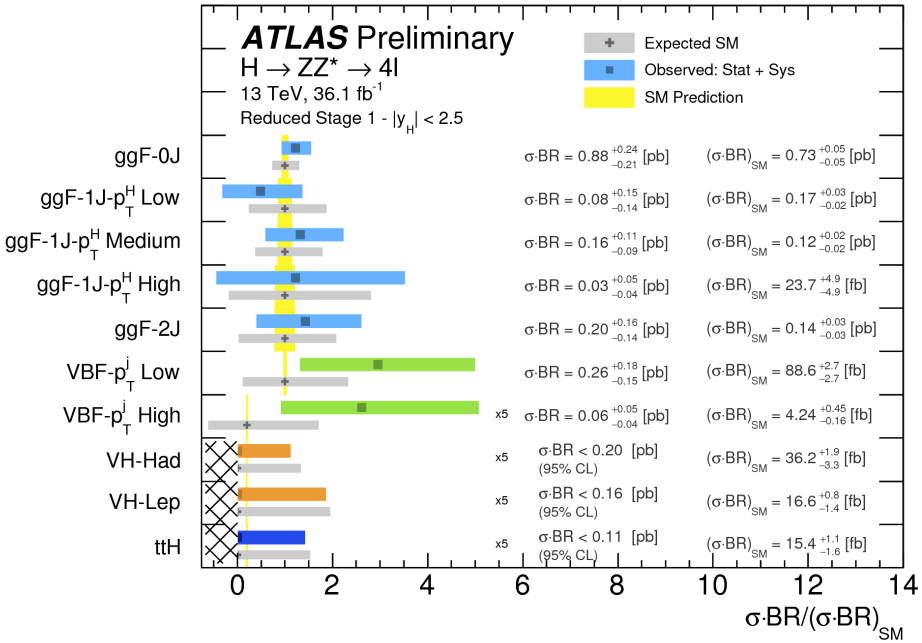
CMS PAS HIG-16-040 ATLAS-CONF-2017-045

H→ZZ(*)→4l ST cross sections

- Stage-0 and reduced Stage-1 measurements in bins with enough statistics.
- Normalized to the SM expectations.



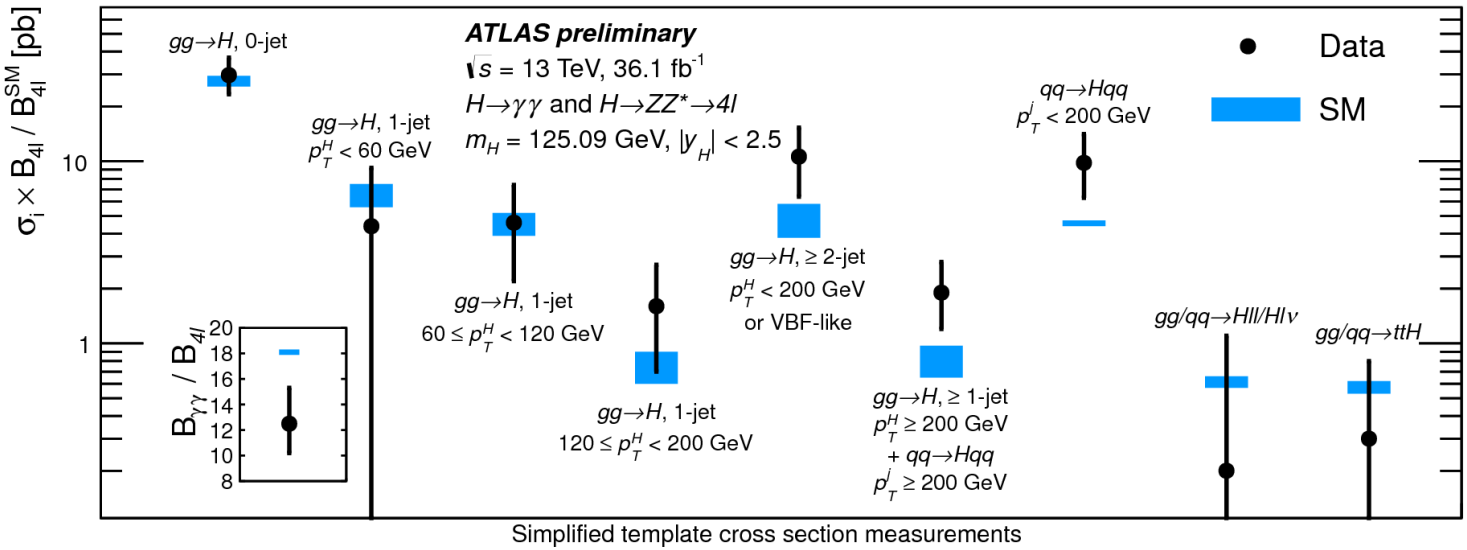




arXiv:1706.09936 [hep-ex] ATLAS-CONF-2017-043

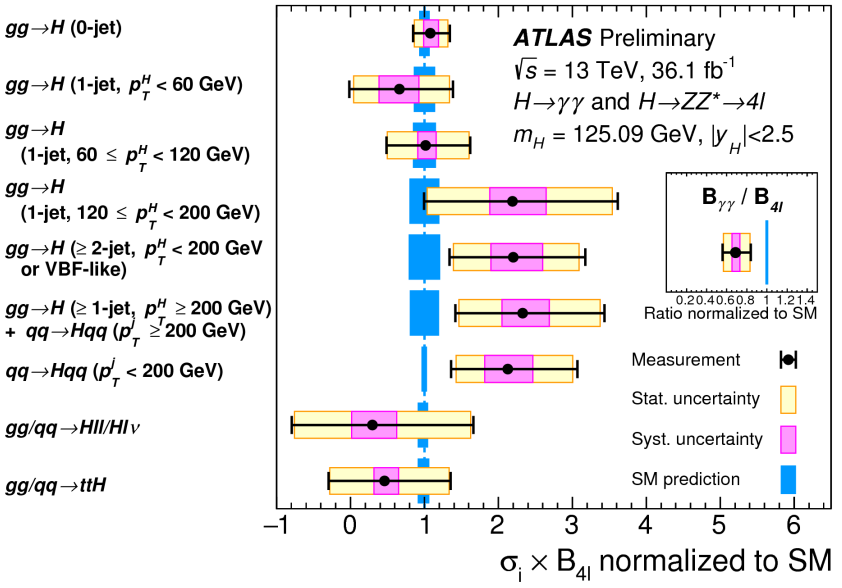
H→γγ and H→ZZ(*)→4l ST cross sections

- ATLAS ST cross sections combination for H→ZZ(*)→4l and H→γγ



Merged STXS Stage-1 regions. Absolute and relative to the SM expectations.

The slight excess in 2-jet category is driven by the H→4l results.

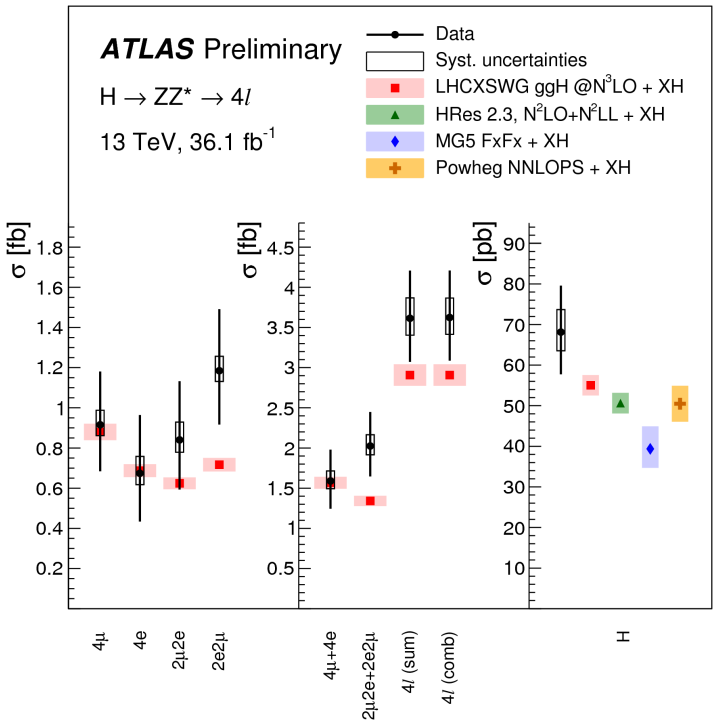


ATLAS-CONF-2017-046

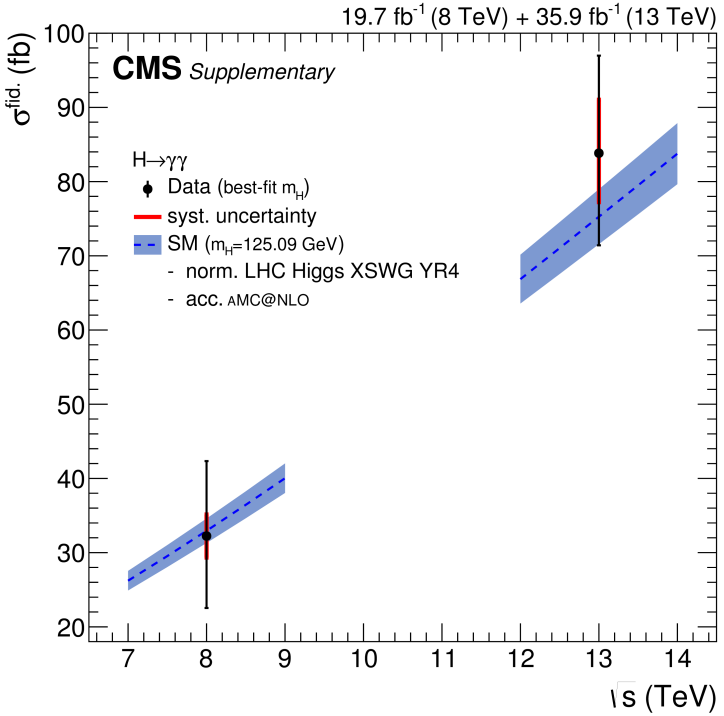
Fiducial and differential cross-sections

H→γγ and H→ZZ(*)→4l inclusive fiducial cross sections

Cross-sections measured in a fiducial phase-space, closely matching the experimental acceptance to avoid model-dependent extrapolations. Corrected for detector inefficiencies and resolution.



Good agreement with N3LO ggF (YR4).



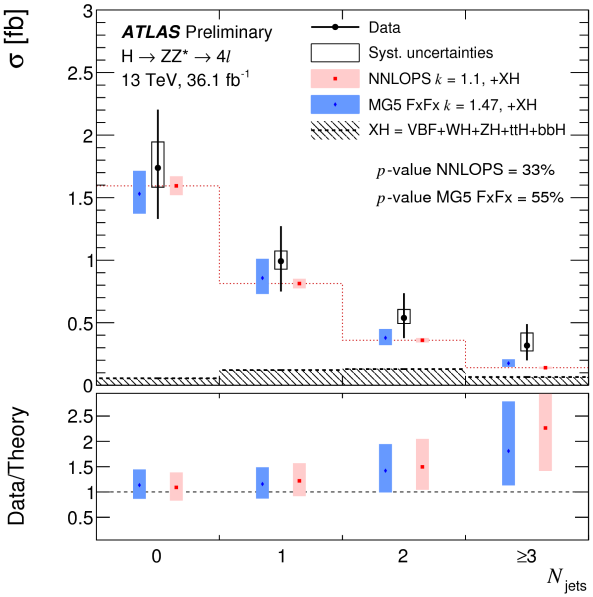
Good agreement with MG_aMC@NLO prediction normalized to the HXSWG YR4 total CS.

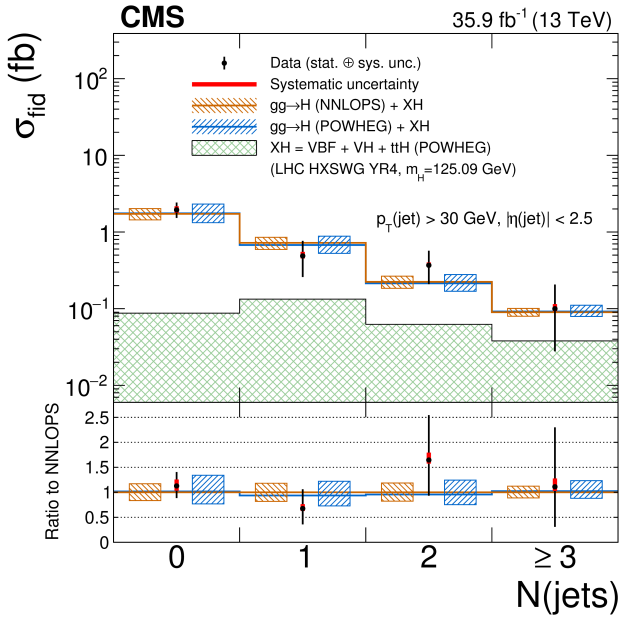
ATLAS-CONF-2017-032 CMS-PAS-HIG-17-015 arXiv:1706.09936 ATLAS-CONF-2017-045

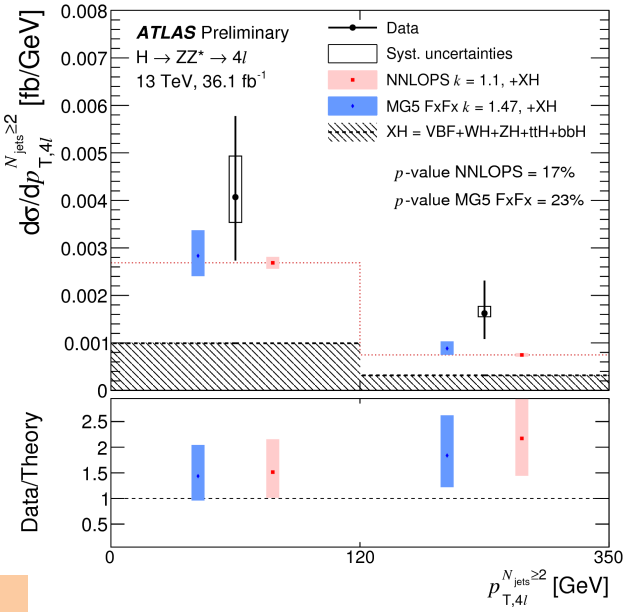
H→ZZ(*)→4l differential fiducial cross sections

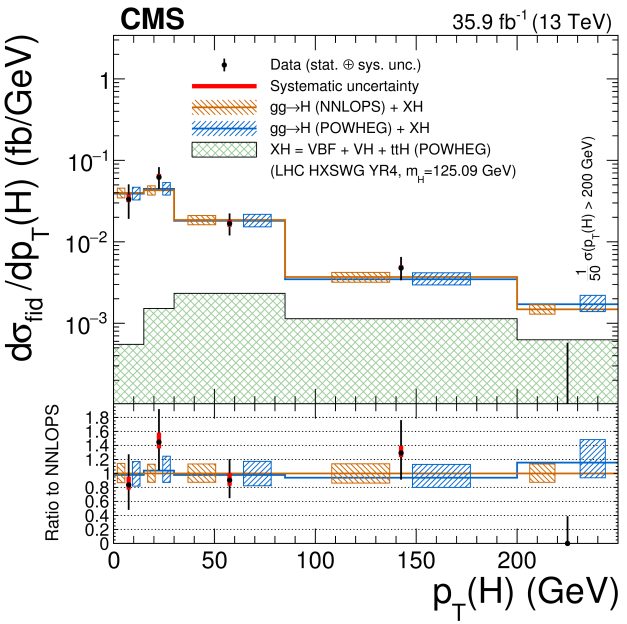
N_{jet}: Probing production modes and gluon emission in H→4l. Overall good agreement; worsens for ATLAS at high multiplicities.

p_T^H: Probing the perturbative QCD calculations for different production modes and searching for new physics by measuring the $p_{T,4l}$ in bins of jet multiplicity.



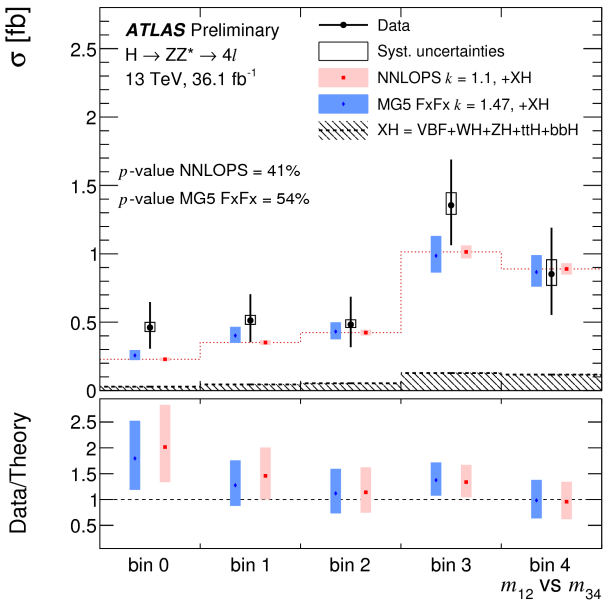






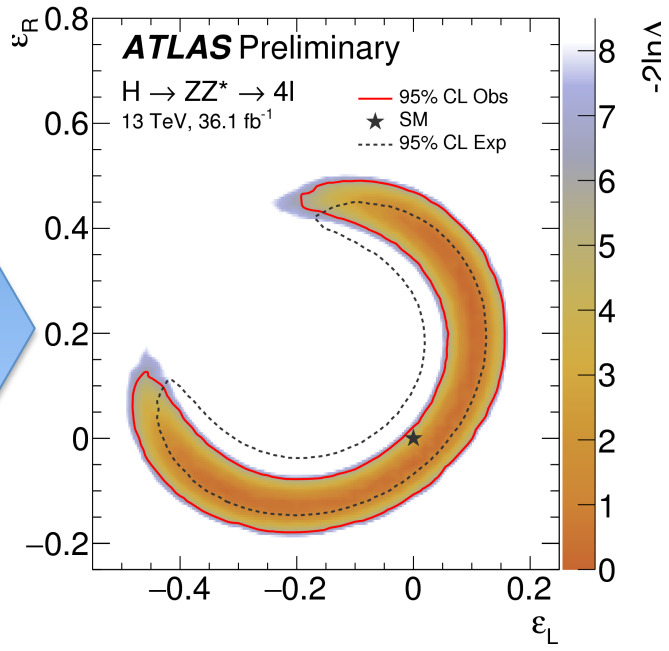
ATLAS-CONF-2017-032 arXiv:1706.09936

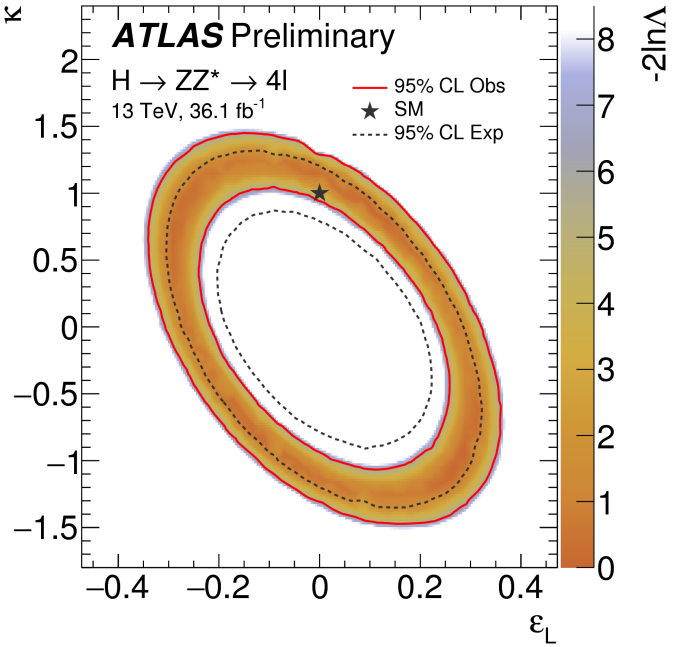
Anomalous couplings interpretation in $H \rightarrow ZZ^{(*)} \rightarrow 4l$



Limits on modified Higgs decays within the framework of pseudo-observables (Eur. Phys. J. C75 (2015) 128).

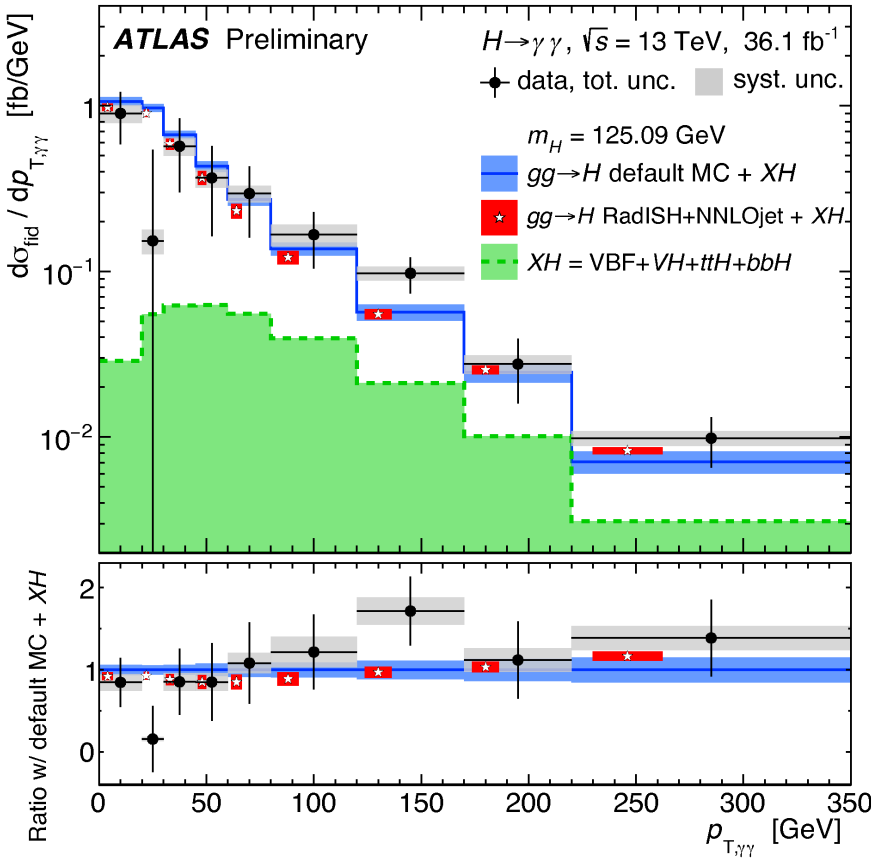
$e_{Zl(left)}$ and $e_{Zl(right)}$ modify the terms responsible for contact interactions between Higgs and left- and right-handed leptons respectively, assuming lepton-flavor universality. k_{HZZ} modifies the Higgs coupling to Z bosons.

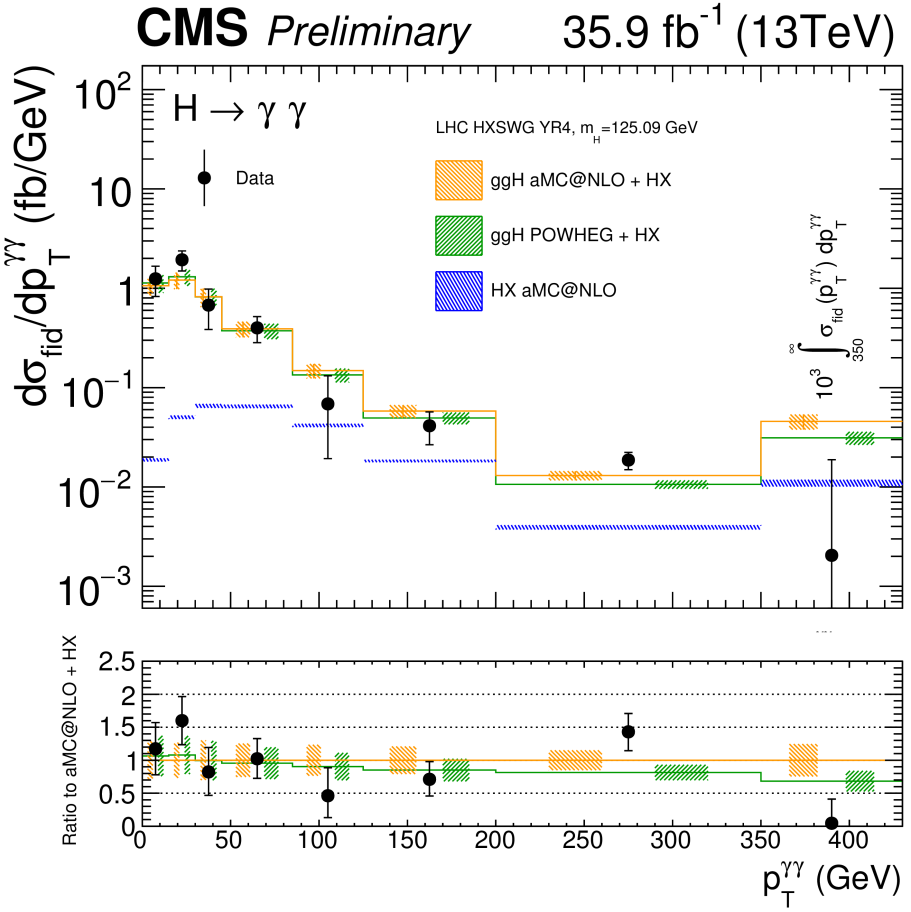




ATLAS-CONF-2017-032

H→γγ differential fiducial cross sections





p_T^H: Broad compatibility with the MC predictions. Getting worse at high p_T^H.

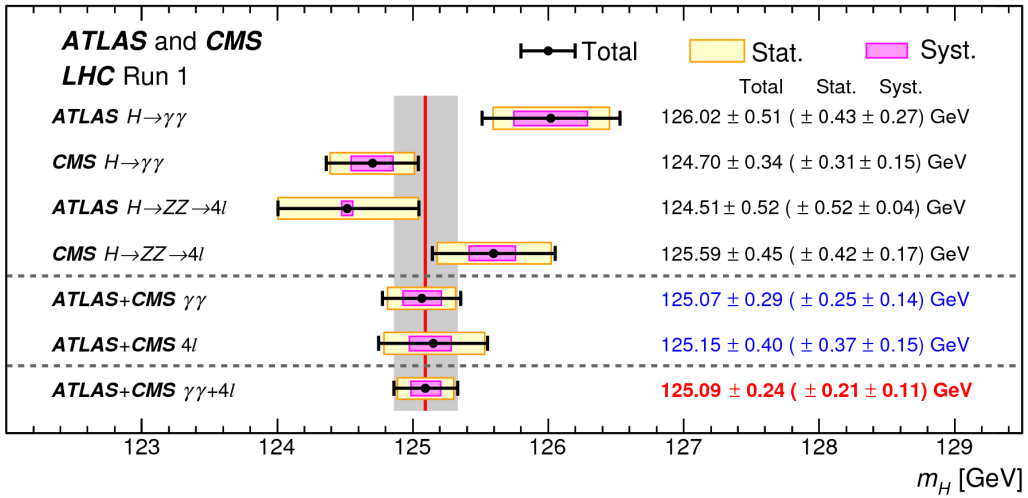
On Higgs properties in di-boson decays, see more in presentation by T. Dai

ATLAS-CONF-2017-032 CMS-PAS-HIG-17-015

Higgs mass and width

Phys. Rev. Lett. 114. 191803 215

Higgs mass and width

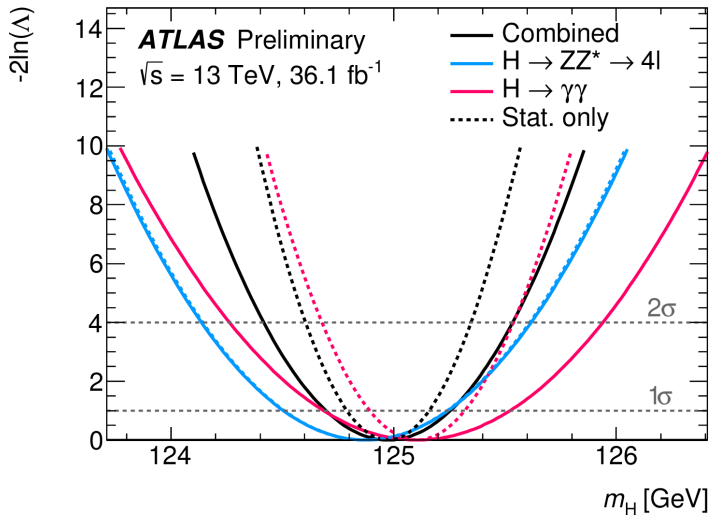


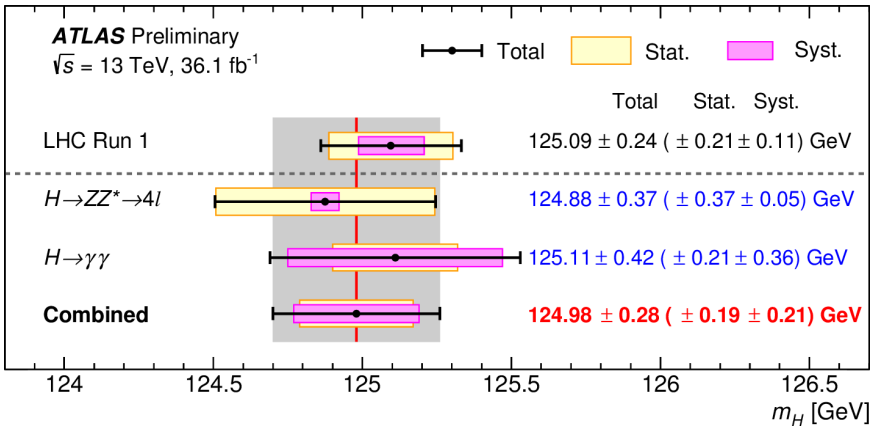
$m_H^{RUN-1} = 125.09 \pm 0.24$ GeV
$= 125.09 \pm 0.21$ (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV

5 fb^{-1} at √s=7 TeV and 20 fb^{-1} at √s=8 TeV for both experiments.
Dominated by stat. uncertainties.

Run-2 ATLAS measurement in 4l + γγ with 36.1 fb^{-1} at 13 TeV.

$m_H = 125.98 \pm 0.19$ (stat) ± 0.21 (syst) GeV





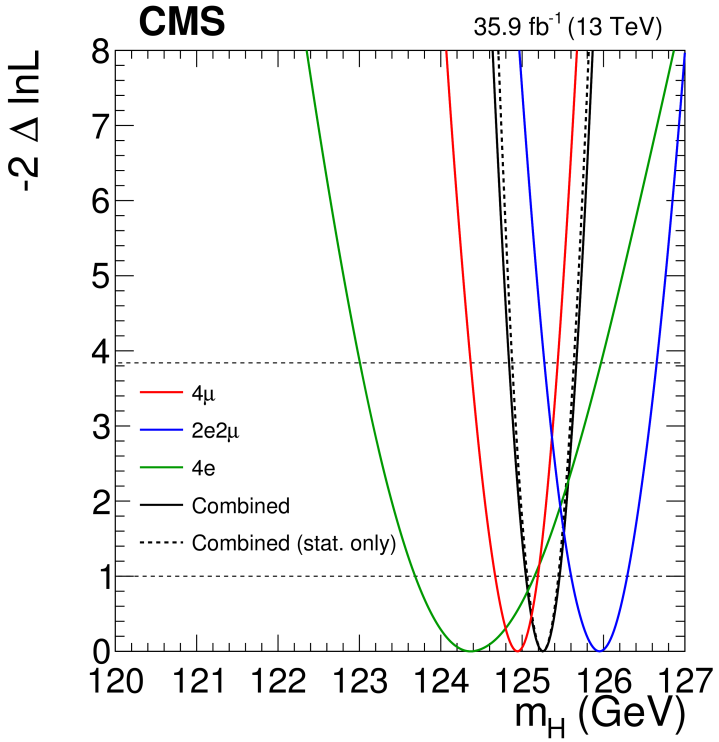
ATLAS-CONF-2017-046

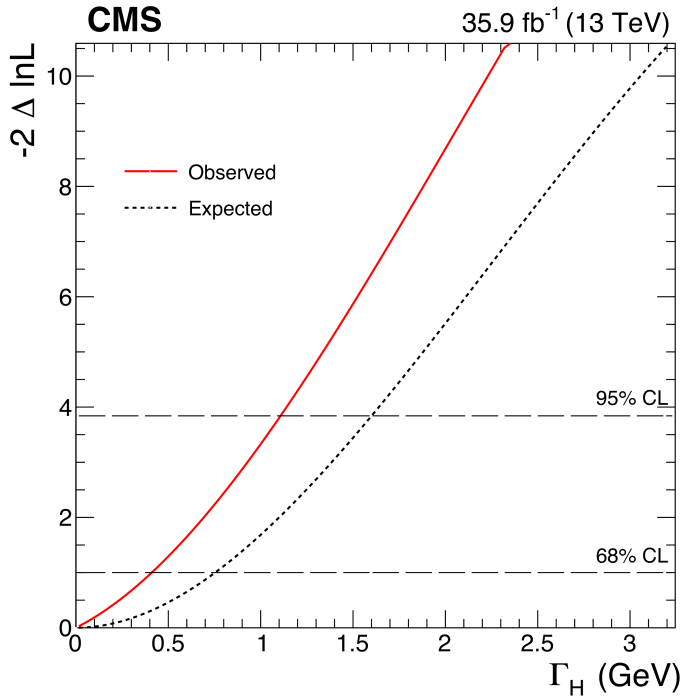
(see dedicated presentation by N. Bruscino)

Higgs mass and width

CMS measurement in H→4l channel with 35.9 fb^{-1} at 13 TeV. Precision exceeding the Run-1 combined ATLAS + CMS 2-channel measurement!

Dominated by the stat. uncertainty. m_H = 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV.





Direct measurement of the Higgs width based on the on-shell Higgs production.

No assumptions on BSM physics. Limited by experimental Higgs mass resolution.

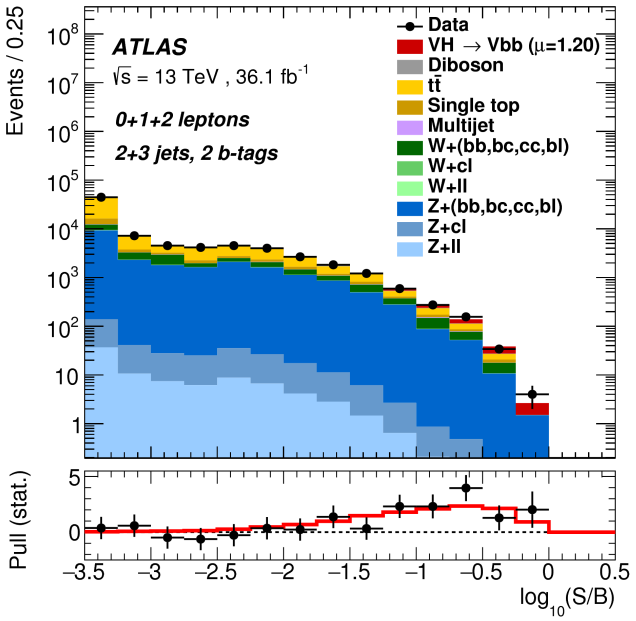
$\Gamma_H < 1.10$ GeV at 95% CL

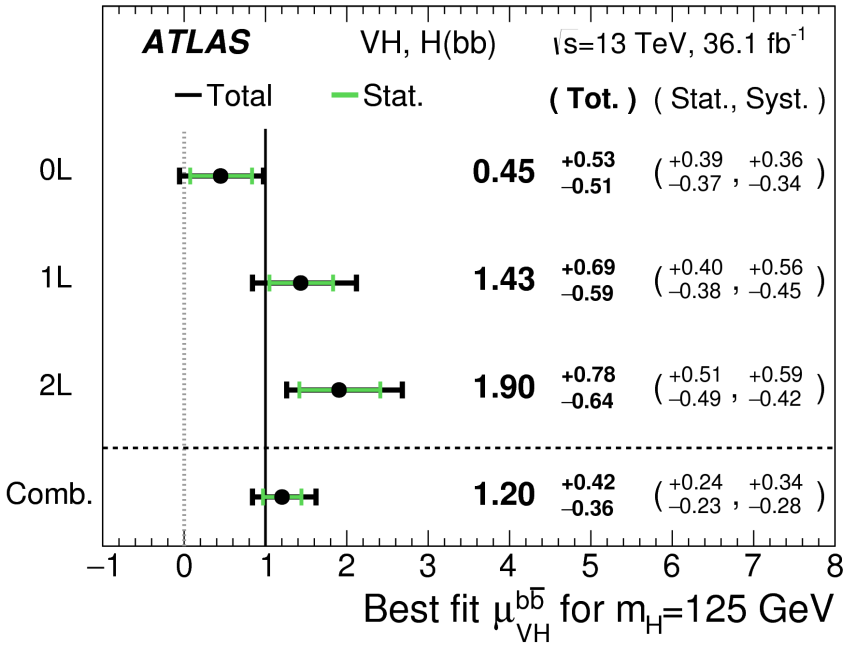
arXiv:1706.09936

Couplings to fermions

Evidence for H→bb (ATLAS)

- Search for W/Z associate production of H→bb using 36 fb^{-1} of data.
  - Cleanest channel. Leptonic decays of e/w bosons allow for easy triggering and rejection of multijet background.
  - ZH→vvbb, WH→lvbb and ZH→llbb final states: 0,1,2 leptons + 2 b-jets.
  - Multivariate analysis, based on event kinematics. Trained to maximize S/B separation in each channel.



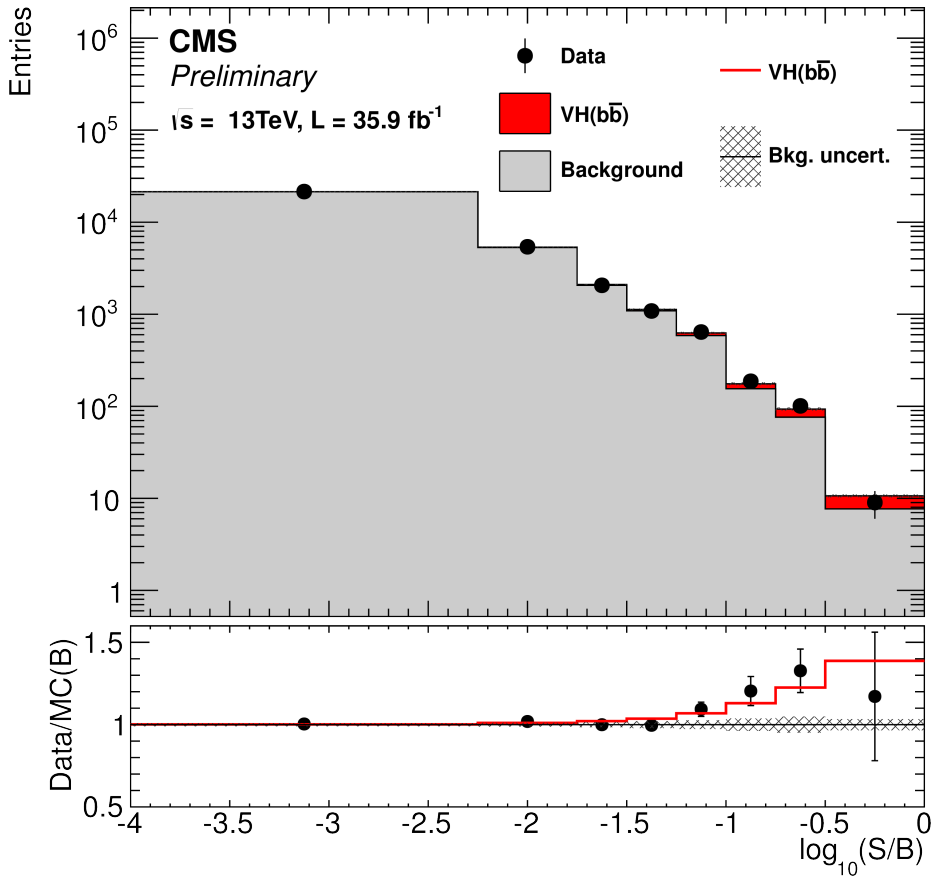


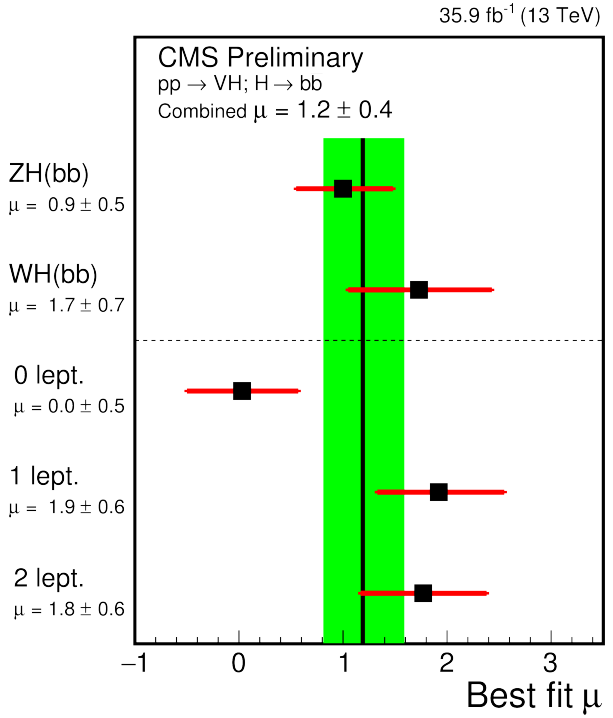
Observed significance: 3.5 st. dev. (exp. 3.0 st. dev). Validated using di-jet mass analysis with consistent result. Z→bb cross-check.

arXiv:1708.03299v2

Evidence for H→bb (CMS)

- Search for W/Z associate production in the 0, 1, 2 – leptons + bb channels.
  - Additional separation in p_T^V channels to increase sensitivity due to boost.
  - Separate multivariate discriminant trained for each signal channel.





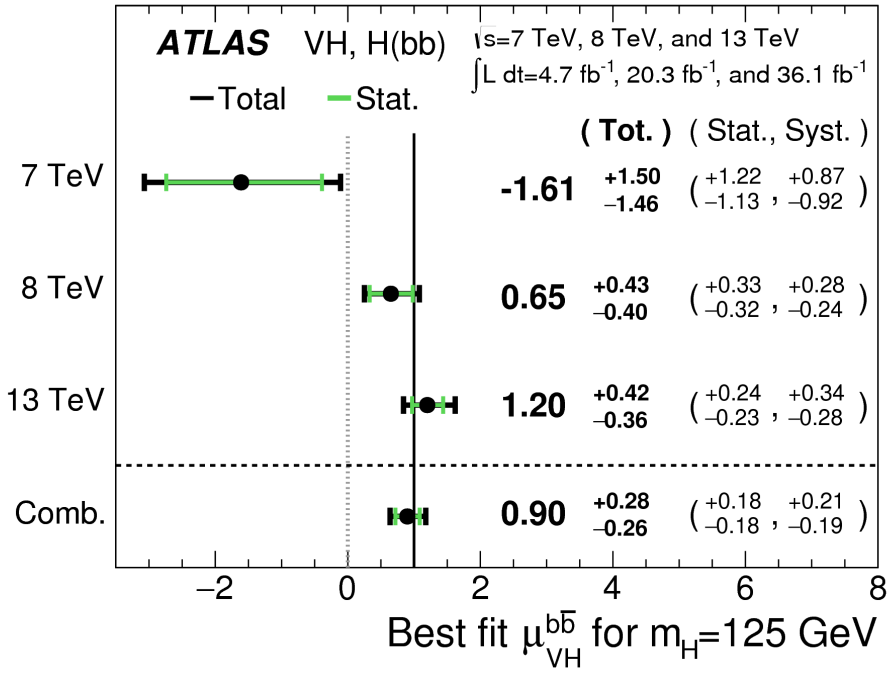
$mH = 125\,\text{GeV}$	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
All channels	2.8	3.3

CMS-PAS-HIG-16-044

Combination with Run-1 VH→bb

- ATLAS: JHEP 01 (2015) 069.
  - Compatibility of signal strength among WH and ZH is 34%. Compatibility between Run-1 and Run-2 measurements – 7%.
  - Total significance: 3.6 (4.0) st. dev.

- CMS: JHEP 08 (2016) 045.
  - Total significance: 3.8 (3.8) st. dev.



mH = 125 GeV	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

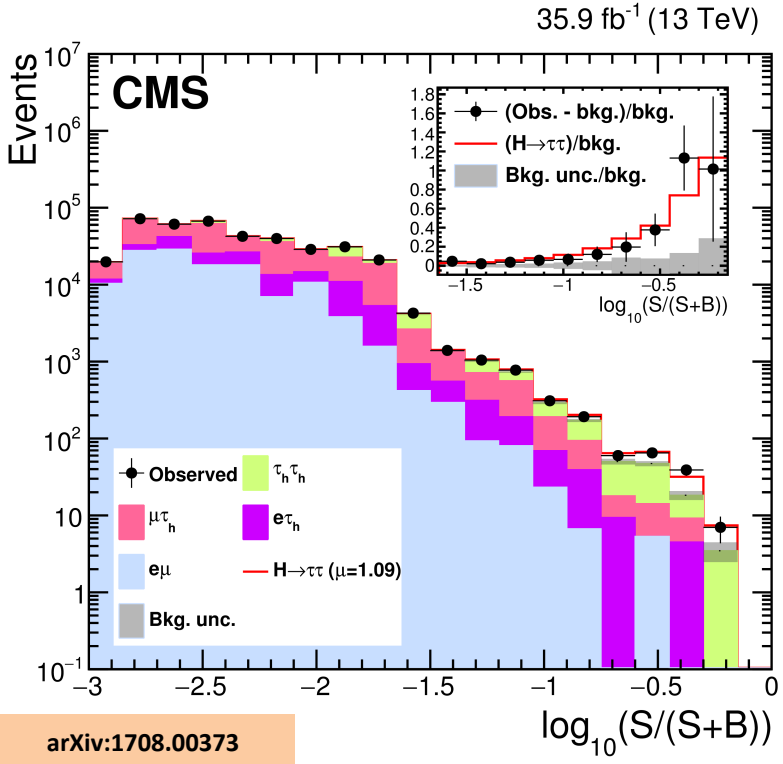
Both experiments observe H→bb process in Run-2 and in Run1+ Run-2 combinations!

arXiv:1708.03299v2 CMS-PAS-HIG-16-044

H→ττ update

- First direct probe of the Yukawa interaction.
  - Established in Run-1 with the combination ATLAS and CMS data.

- Re-visited by CMS with 35.9 fb^{-1}: leptonic and hadronic τ decays. 0-jet, 2-jet (VBF) and "boosted" (all the rest) categories.



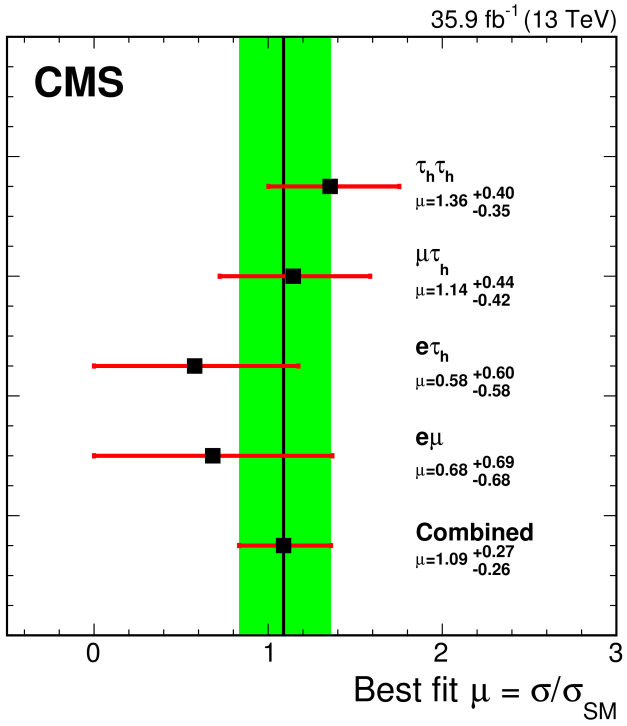
arXiv:1708.00373

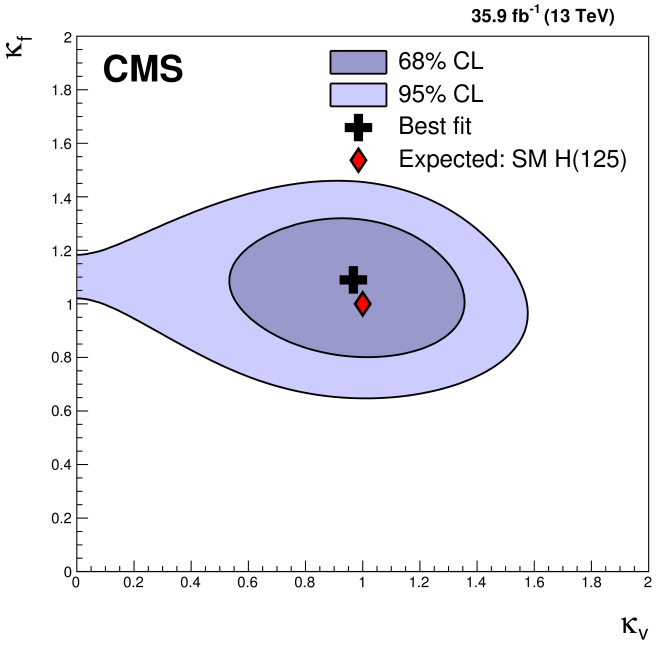
Run-2 only:

4.9 (4.7) st. dev.

Combined with Run-1:

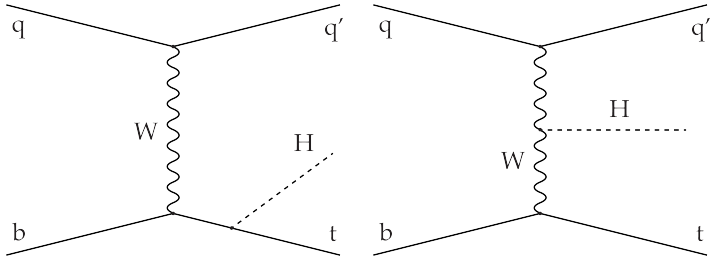
5.9 (5.9) st. dev.



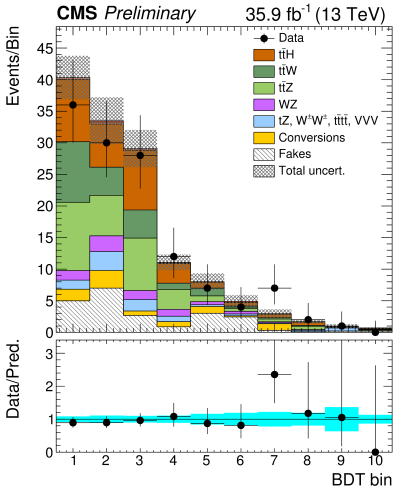


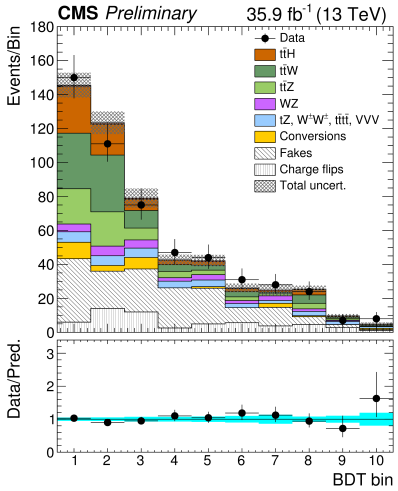
tHq

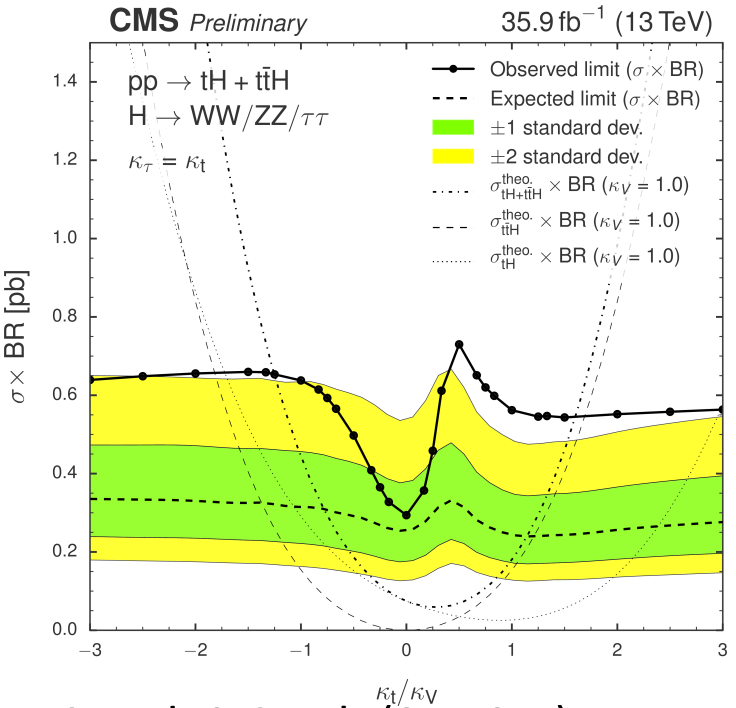
- Direct probe of the top-Yukawa coupling. Sensitive to the relative sign of k_t and k_V due to to the interference of LO diagrams.
  - Very sensitive BSM probe.



- Final states with 2 same sign or 3 leptons: leptonic top decays + Higgs decaying to pairs of W, Z, τ.
  - Separate BDTs trained to extract ll and lll signal from backgrounds: ttV and tt.



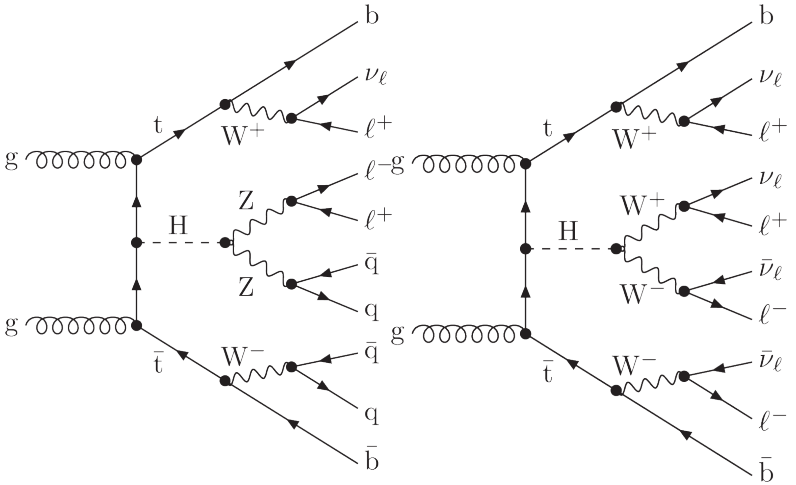




Upper limit on tH+ttH σxBR 0.64 pb for k_t/k_V = -1.0 and 0.65 pb (3.1xSM)
for k_t/k_V = 1.0 $-1.25 \le k_t \le 1.60$ at 95%CL for k_V=1.0

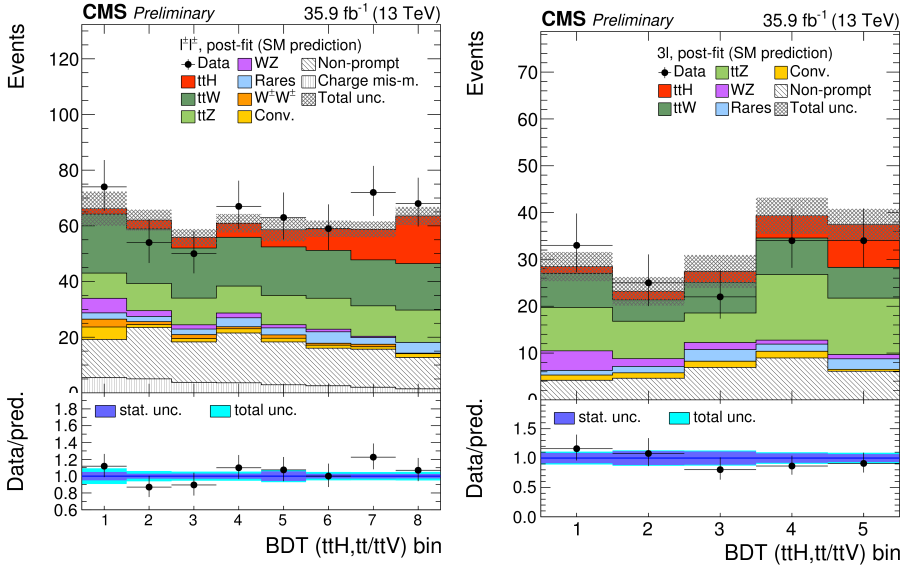
CMS-PAS-HIG-17-005

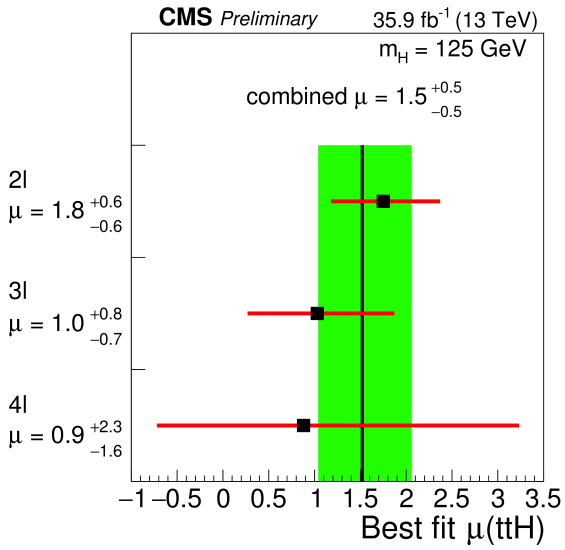
ttH



- The H→ZZ$^{(*)}$→4l and H→γγ analyses by both ATLAS and CMS include ttH production categories. Respective results can be found in corresponding papers.

- Multilepton analysis: targets events with at least one leptonic top and Higgs decaying to pairs of W, Z, τ. Events with 2SS, 3 or 4 leptons and *b*-jets.
  - BDT-based background (ttW and ttZ) suppression in 2l and 3l channels.





For more results on ttHbb see dedicated presentation by W. Luo.

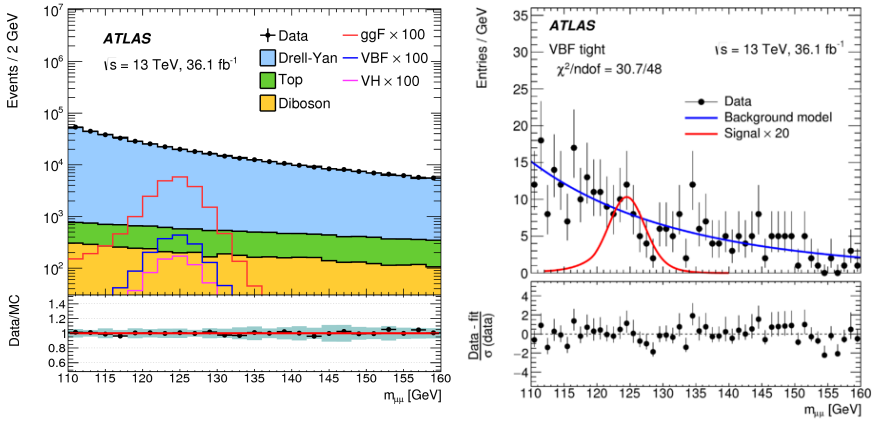
Best fit ttH yield: 1.5±0.5 times the Standard Model prediction. Observed (expected) significance: 3.3 (2.5) st. dev.

CMS-PAS-HIG-17-004

Rare Higgs decay searches

- Searches continue for the rare Higgs decay modes, which - in the SM case – are challenging to observe during the LHC Run-2.

H→μμ

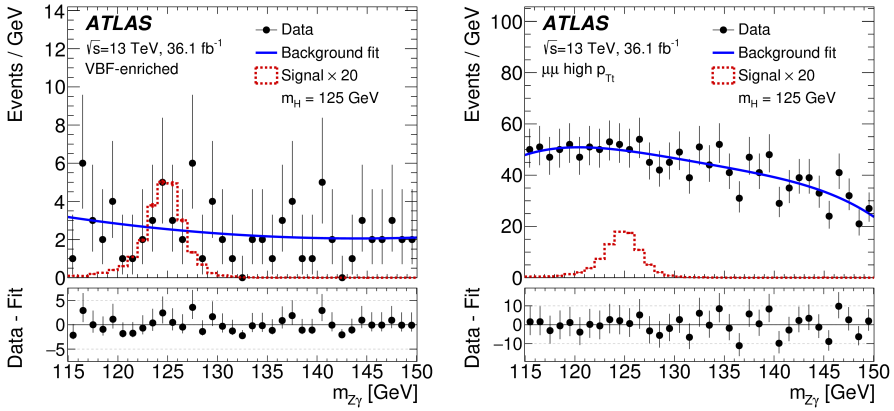


Events with 2 muons, classified using BDT trained on jet kinematics. Two VBF and 6 ggF categories in $p_T^{\mu\mu}$ and $\eta^{\mu\mu}$.

Observed (expected) limit on σxBR is 2.8 (2.9) times the SM value, when combining with Run-1 data.

PRL 119 (2017) 051802 arXiv:1708.00212

H→Zγ



Events with 2 leptons and a photon in the FS. 6 exclusive categories for the SM search: VBF-like, p_T^t of lepton pair, $p_T/m_{ll\gamma}$ of photons.

Observed (expected) limit on σxBR for H(125.09) is 6.6 (5.2) times the SM value.

See also presentations by K. Gregersen and K. Leney

Summary

- ATLAS and CMS are making outstanding progress analyzing the LHC Run-2 data.

- Di-boson decay channels re-visited.
  - Re-observation, measurements of couplings, rates, fiducial and differential cross-sections, tensor structure of couplings, Simplified Template cross sections, mass, width and more….

- Focus on studies of Higgs couplings to fermions.
  - Observation of VH→bb by both experiments.
  - Re-discovery of H→ττ decay by a single experiment.
  - Evidence for ttH Higgs production – next exciting opportunity to study Yukawa couplings.

- No significant deviations from the SM so far. We are entering the precision measurement stage – stay tuned for more results!

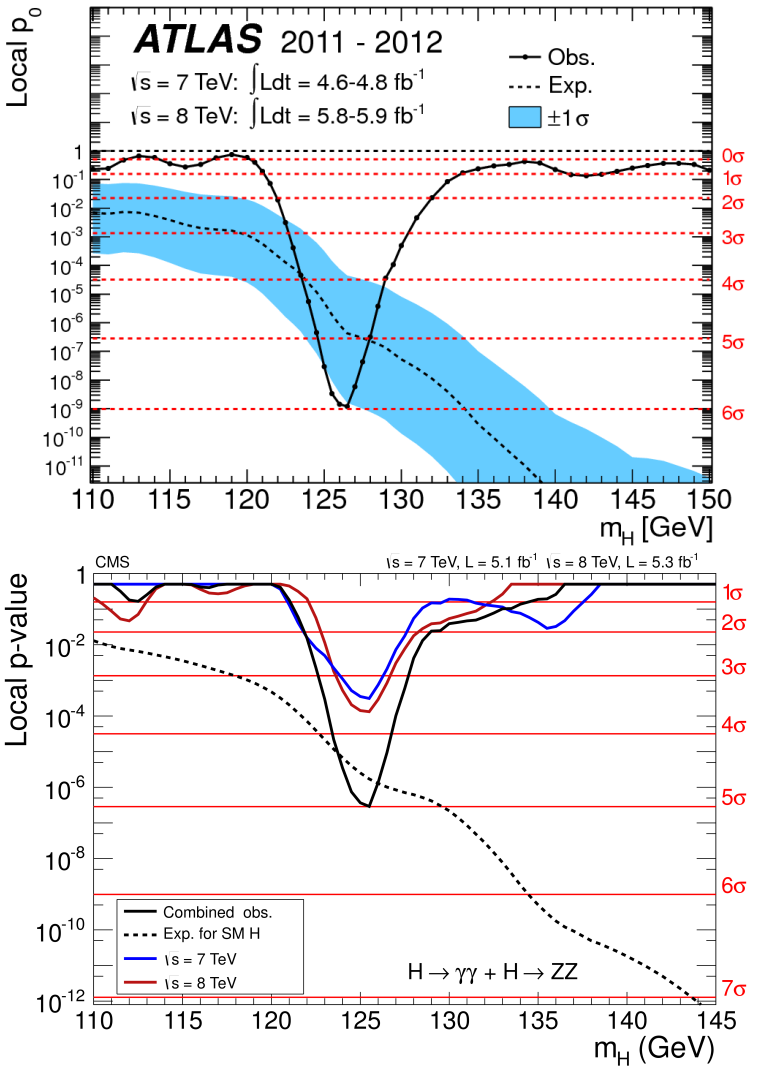
Backup

Legacy of the LHC Run-1

- Discovery of a new neutral scalar boson, first in di-boson, then in di-fermion decays.

- Individual and combined ATLAS and CMS measurements in Run-1 include:
  - Mass
  - Couplings scale factors
  - Higgs width
  - Spin and parity
  - Tensor structure of couplings and CP-mixing

- Establishing initial compatibility with the expectations for the Standard Model Higgs boson.

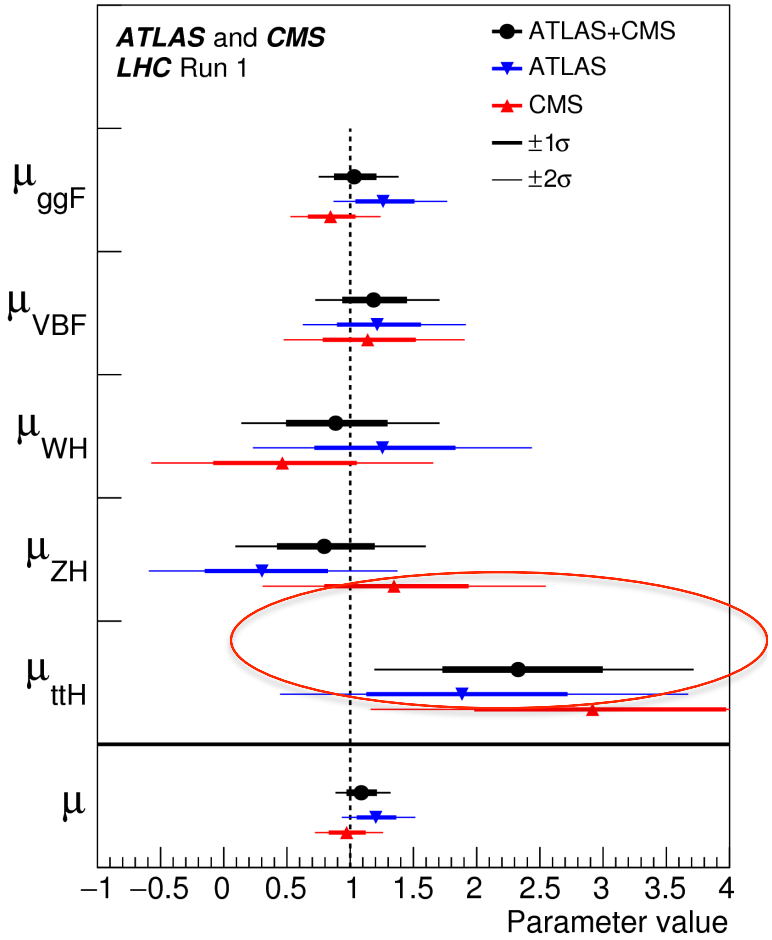


Phys. Lett. B 716, (2012) 1-29, 30

Run-1 legacy

- Observation:
  - H→γγ, H→ZZ$^{(*)}$→4l, H→WW→lvlv and H→ττ decays.
  - Gluon-fusion and VBF production.
- Evidence for VH and ttH processes.

$$\mu = \sigma \cdot BR / (\sigma \cdot BR)_{SM}$$



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

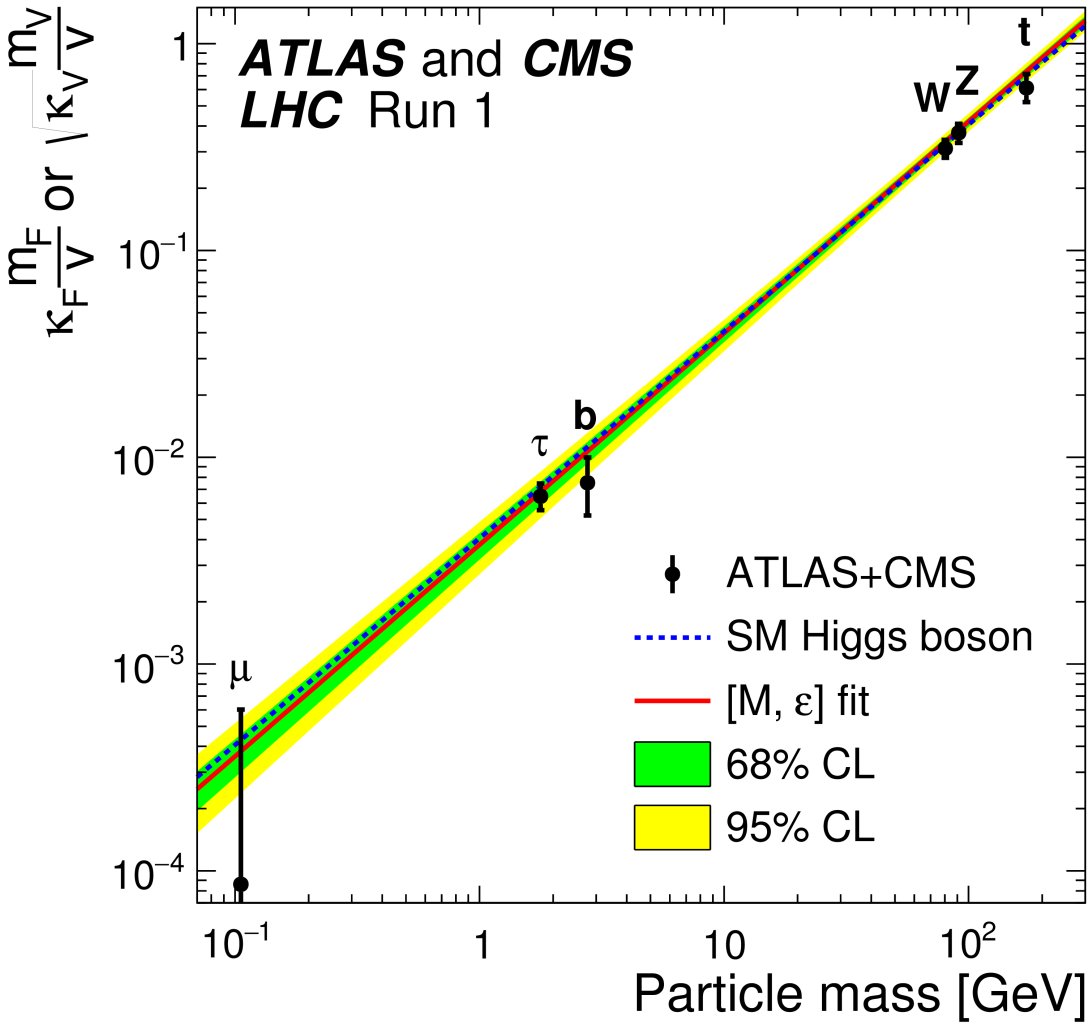
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09 \pm 0.07(stat) \pm 0.04(ex) \pm 0.03(th-bckg)^{+0.07}_{-0.06}(th-sig)$$

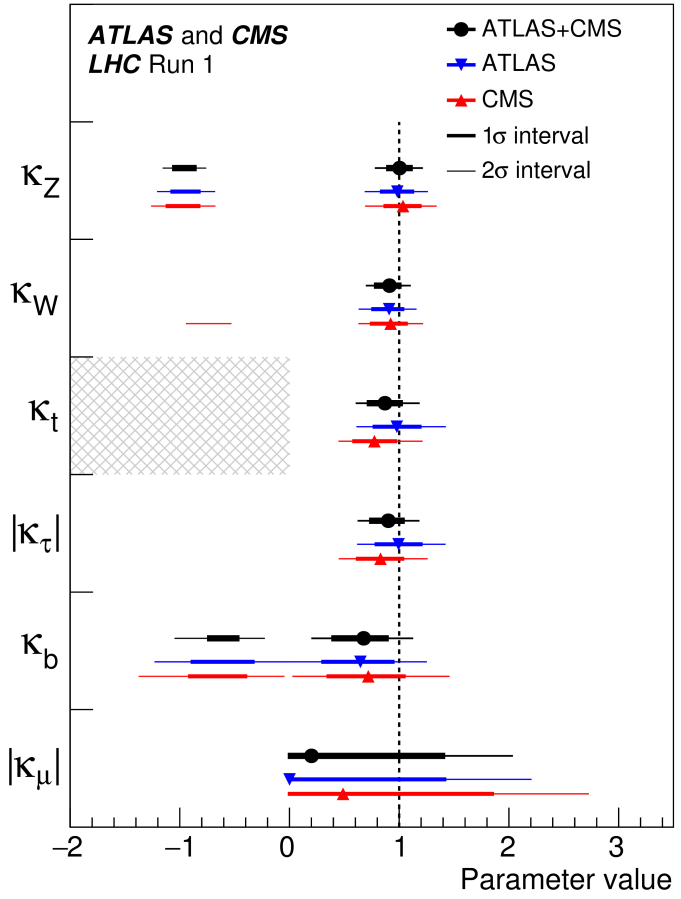
JHEP 08 (2016) 045

Run-1 legacy

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \qquad \kappa_j^2 = \Gamma^j/\Gamma_{SM}^j$$

$$\sigma_i \cdot B^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

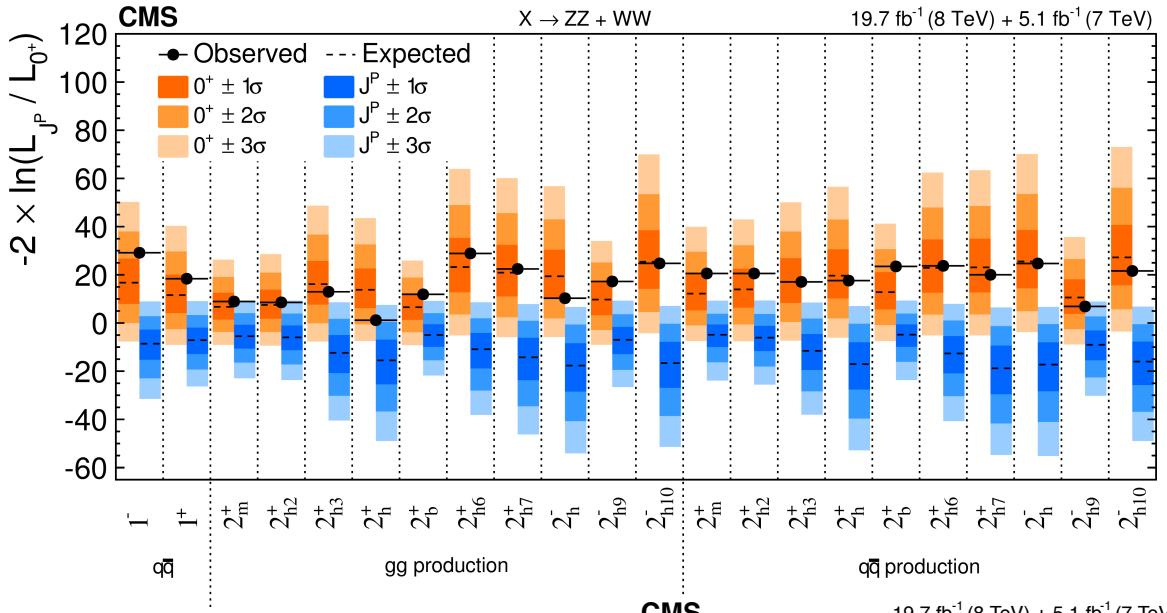




SM Higgs boson

JHEP 08 (2016) 045

Run-1 legacy

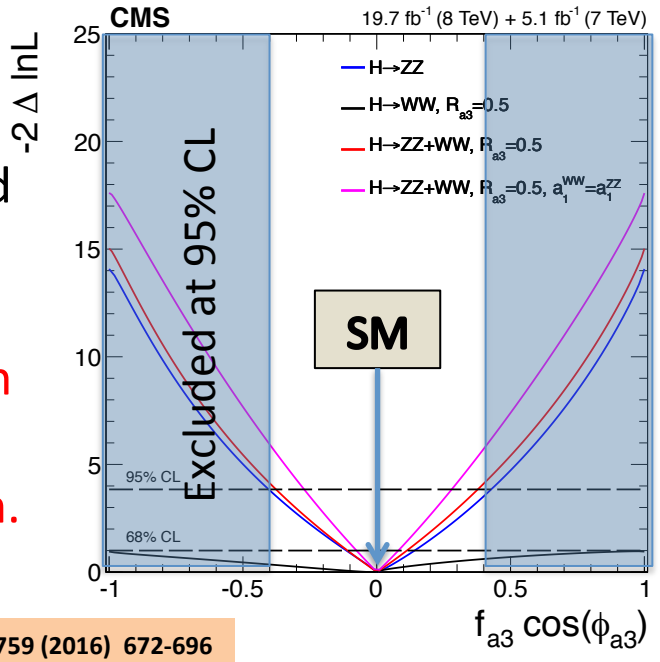


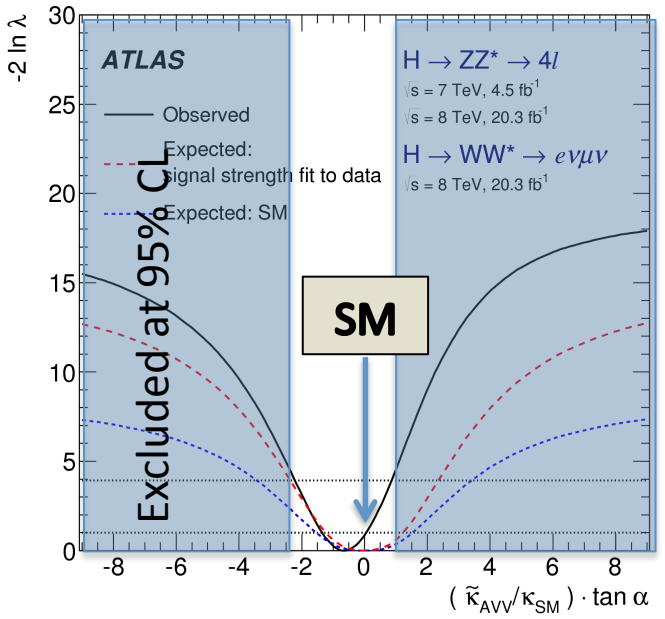
Large campaign to exclude exclude spin 1 and 2 hypotheses. Most non-SM possibilities excluded at >99.9%CL by both experiments.

Spin-0 nature established.

Studies of CP-mixing in di-boson decays using effective amplitude and EFT formalisms.

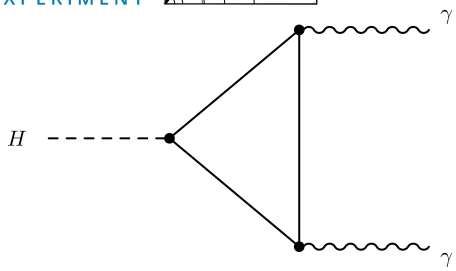
Important: CP-mixing in fermionic sector, common EFT approach.

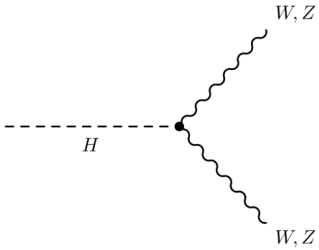


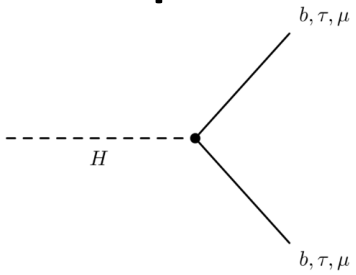


Eur. Phys. J. C75 (2015) 231
Phys. Rev. D 92 (2015) 012004
Phys. Lett. B 759 (2016) 672-696

Backup

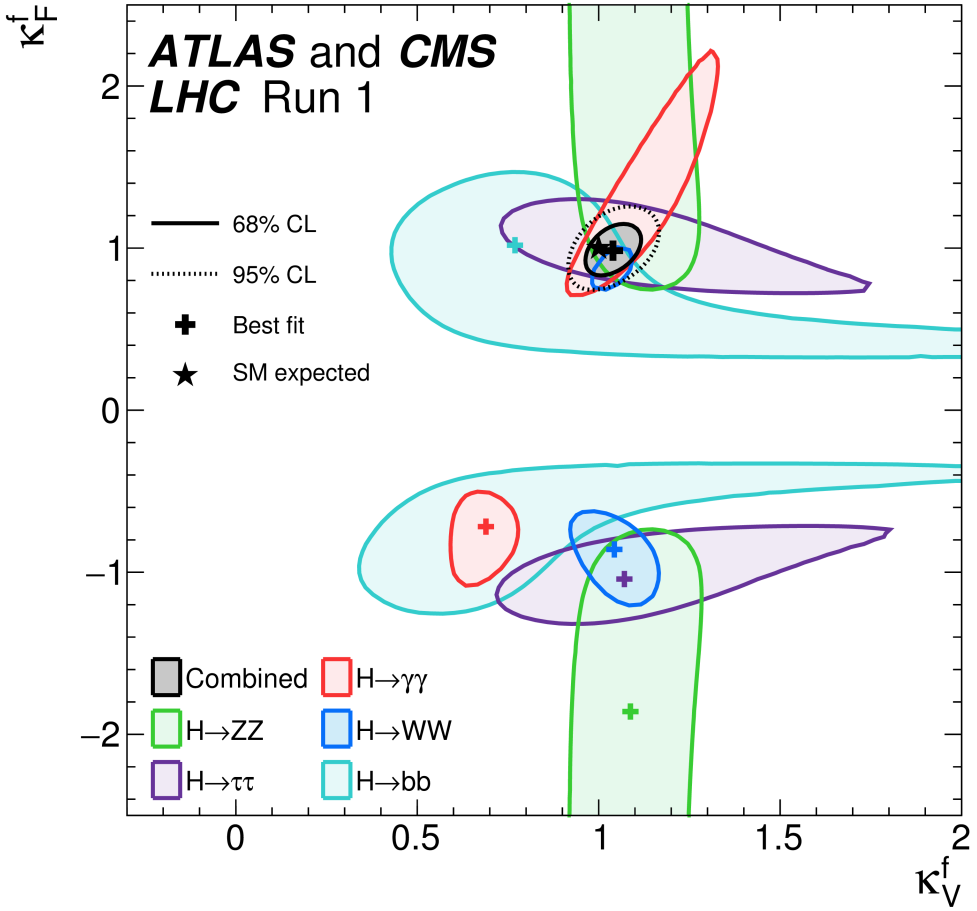




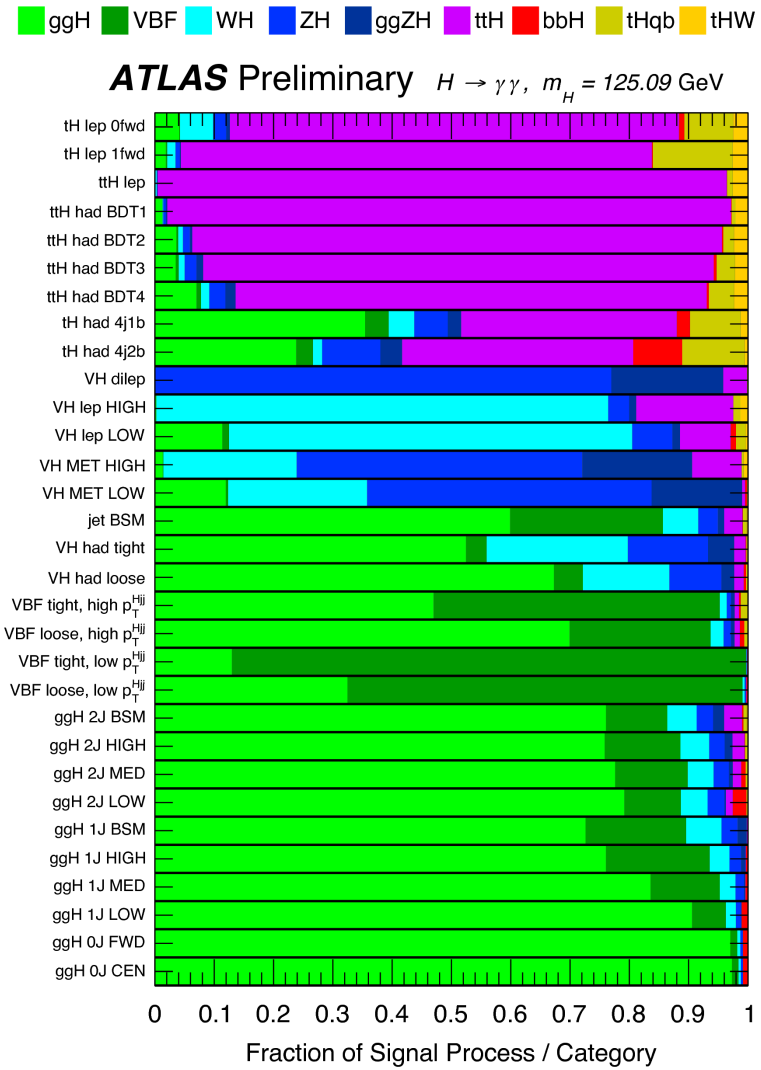


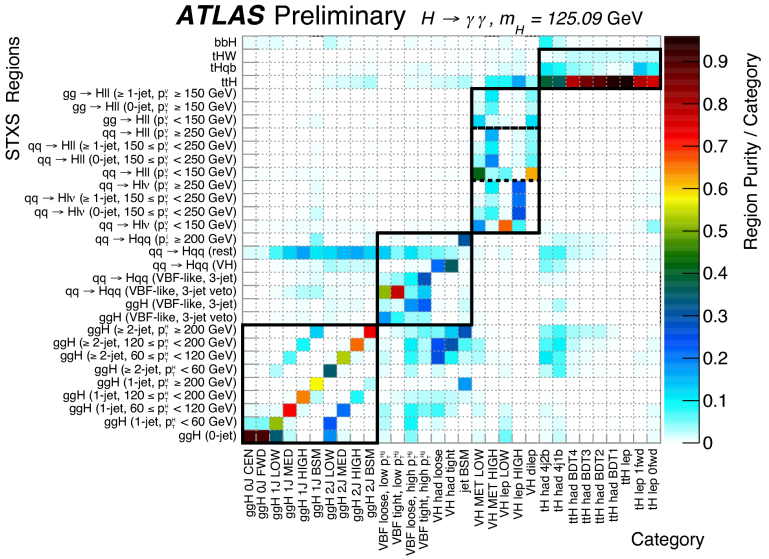
Two-parameters benchmark model with only SM contributions to the total width:

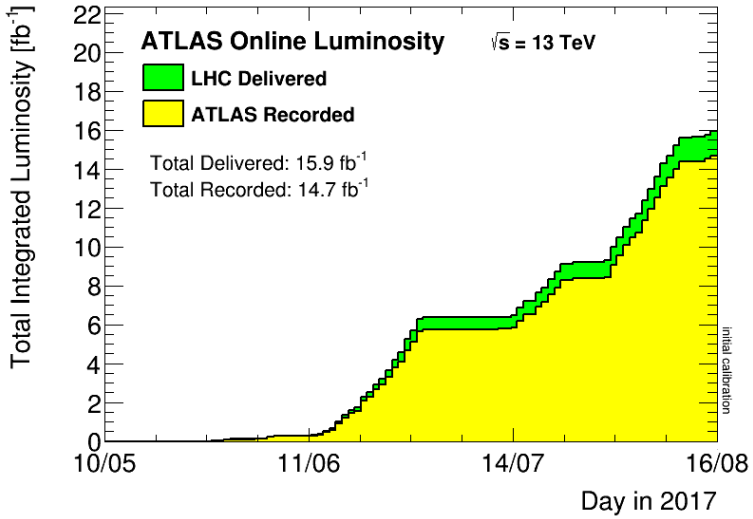
$k_V=k_Z=k_W$; $k_F= k_t=k_b=k_\tau$



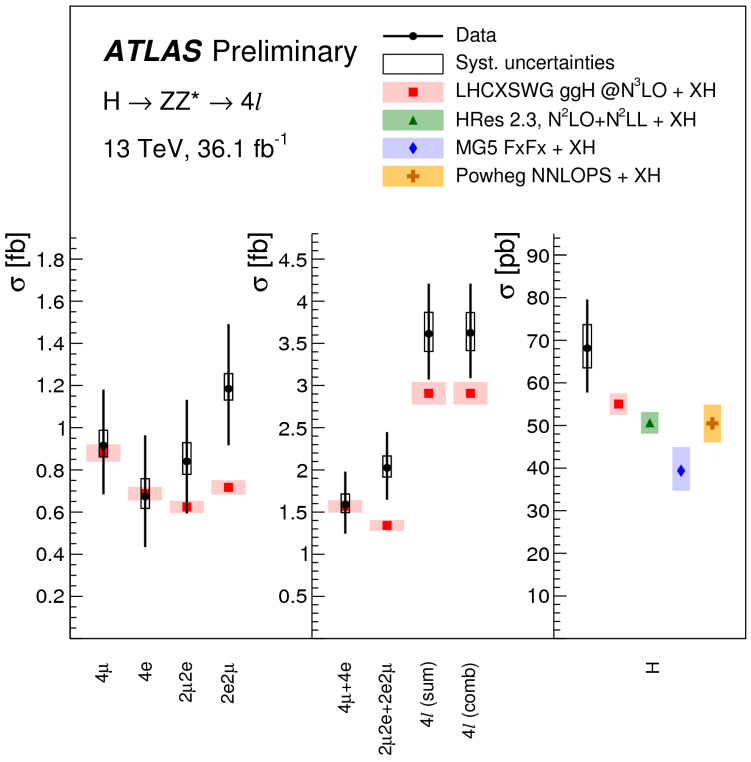
Backup

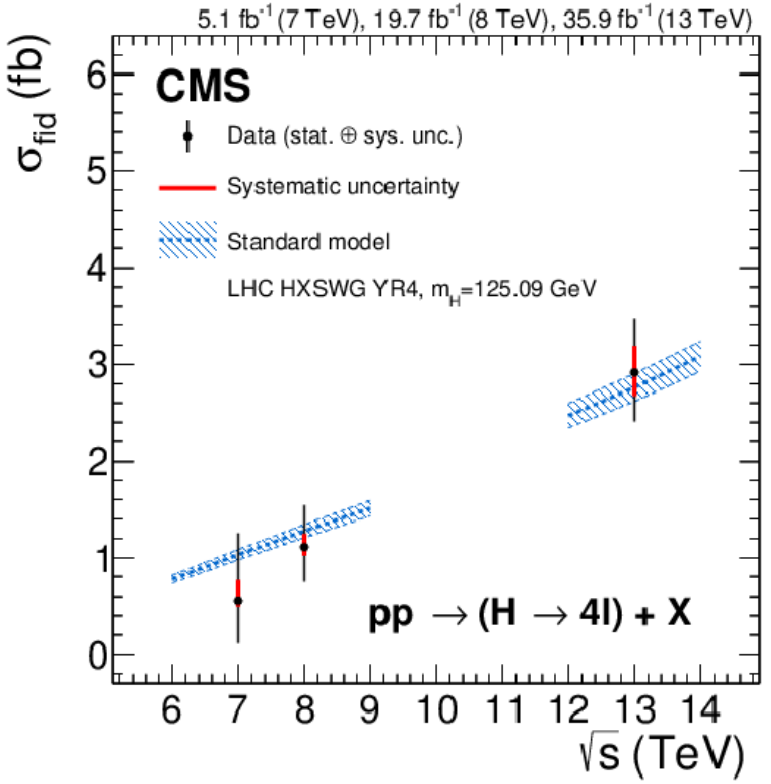

ggH VBF WH ZH ggZH ttH bbH tHqb tHW
ATLAS Preliminary H → γγ, m_H = 125.09 GeV
tH lep 0fwd
tH lep 1fwd
ttH lep
ttH had BDT1
ttH had BDT2
ttH had BDT3
ttH had BDT4
tH had 4j1b
tH had 4j2b
VH dilep
VH lep HIGH
VH lep LOW
VH MET HIGH
VH MET LOW
jet BSM
VH had tight
VH had loose
VBF tight, high p_T^Hjj
VBF loose, high p_T^Hjj
VBF tight, low p_T^Hjj
VBF loose, low p_T^Hjj
ggH 2J BSM
ggH 2J HIGH
ggH 2J MED
ggH 2J LOW
ggH 1J BSM
ggH 1J HIGH
ggH 1J MED
ggH 1J LOW
ggH 0J FWD
ggH 0J CEN
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Fraction of Signal Process / Category


ATLAS Preliminary H → γγ, m_H = 125.09 GeV
STXS Regions
Region Purity / Category
Category

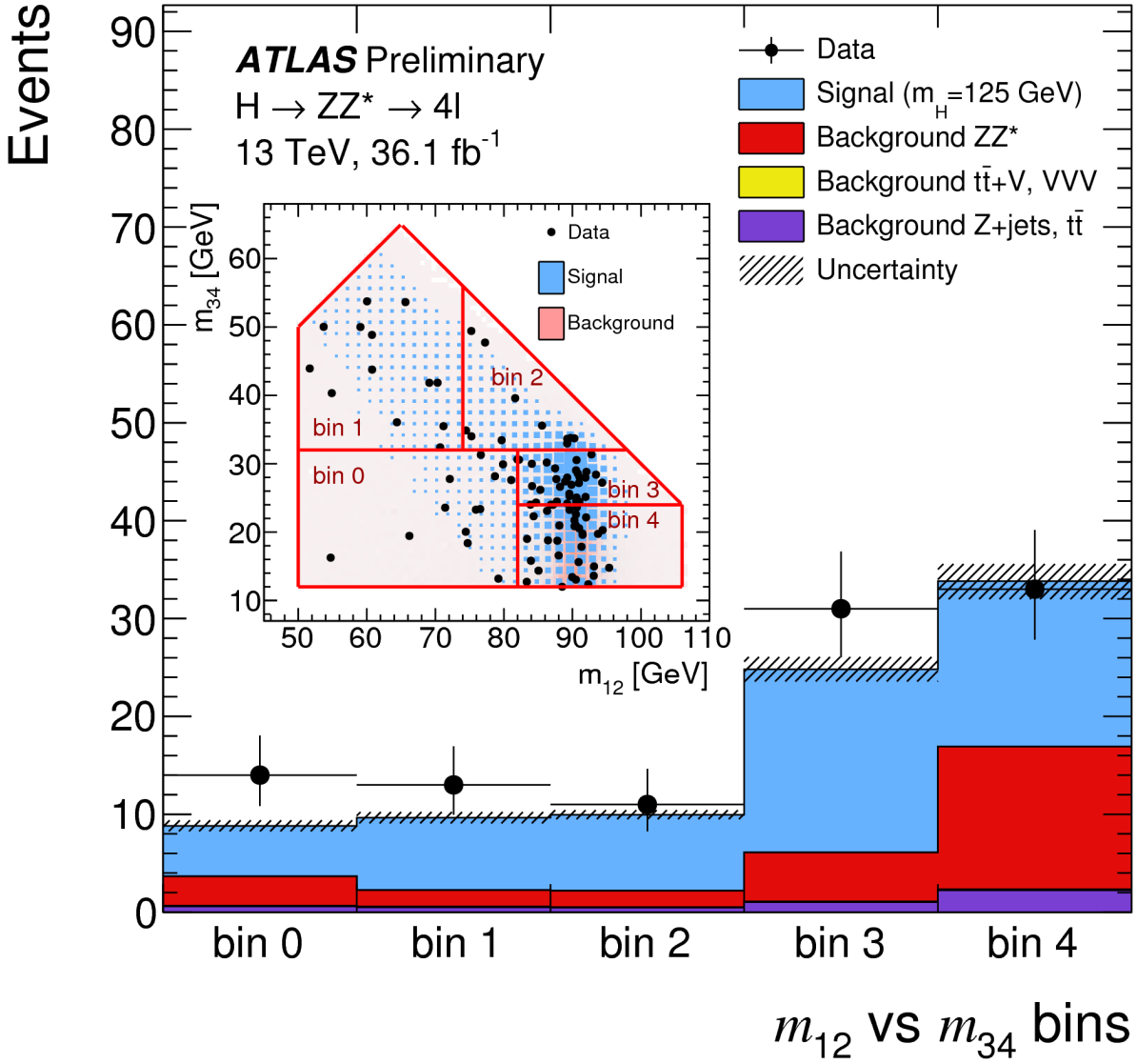

ATLAS Online Luminosity
√s = 13 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 15.9 fb-1
Total Recorded: 14.7 fb-1
Total Integrated Luminosity [fb-1]
10/05
11/06
14/07
16/08
Day in 2017
Initial calibration

H→ZZ(*)→4l inclusive fiducial cross sections





H→γγ inclusive fiducial cross sections



m_{12} vs m_{34} bins