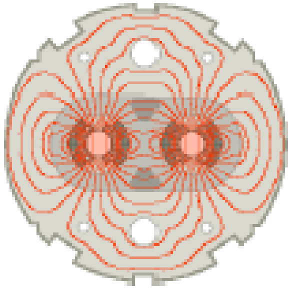
Measurements of the Higgs boson by ATLAS and CMS

ITEP

LHC



I.I. Tsukerman for the ATLAS and CMS Collaborations,

NRC KI "ITEP" Moscow

4th Int. Conference on Particle Physics and Astrophysics,

Moscow, Russia, MEPhI, October 2018

Content

- Introduction: LHC, ATLAS and CMS experiments

- The SM-like Higgs boson h: measurements and searches
  - expected production cross sections and branching ratios for SM h
  - measurements of bosonic decay modes: $ZZ^* \rightarrow 4l$, $\gamma\gamma$, $WW^* \rightarrow l\nu l\nu$
  - measurements of fermionic decay modes: $\tau\tau$ and Vh, $h \rightarrow bb$
  - measurement of tth production
  - searches for non-resonant hh-production

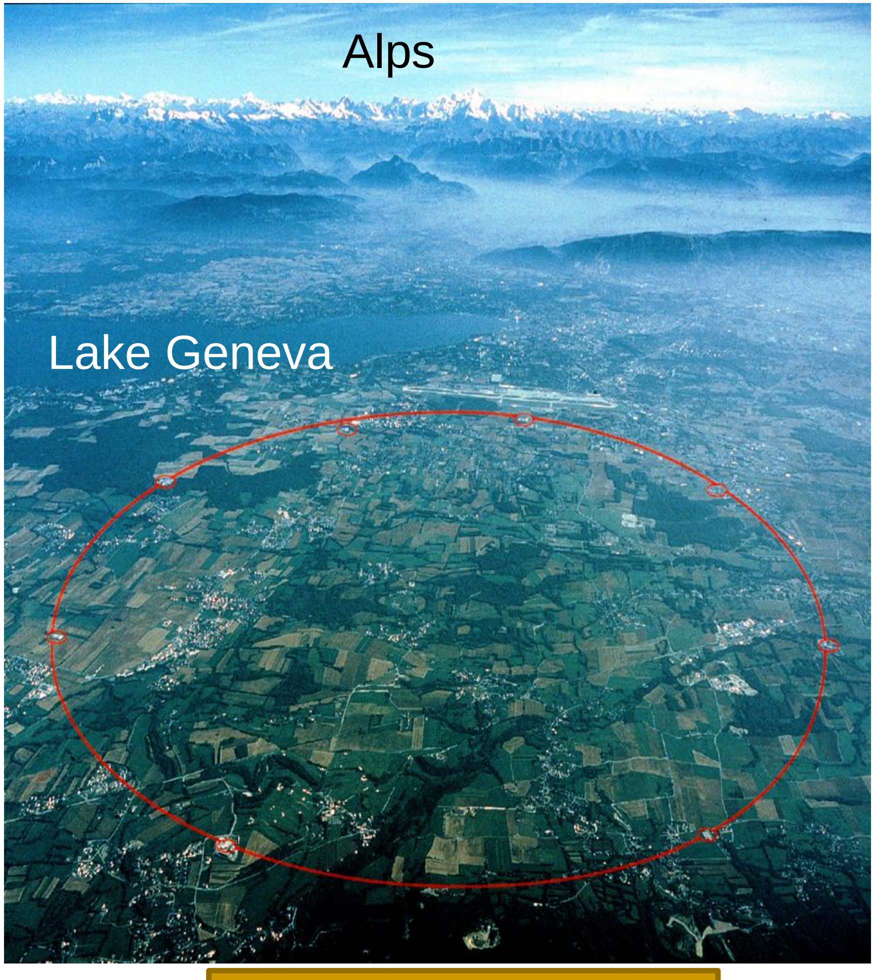
- Searches for beyond SM (BSM) Higgs boson (H)
  - searches for BSM double Higgs boson production
  - charged BSM Higgs boson searches
  - searches for MSSM A/H boson

- Conclusion

The Large Hadron Collider (LHC) (JINST 3 (2008) S08001)

- LHC operated with proton-proton (pp)-collisions at $\sqrt{s}$ = 7 TeV in 2010-2011 and at 8 TeV in 2012.
  50 ns between collisions, 1380 bunches
- After shutdown in 2013-2014 it resumed operation at 13 TeV (25 ns bunch spacing, 2556 bunches)
- Multi-purpose experiments: **ATLAS and CMS**
  Another big experiments: LHCb, ALICE
- Delivered data:
  2011: 5.5 fb^{-1} per ATLAS and CMS
  2012: 23 fb^{-1} 2015: 4 fb^{-1}
  2016: 40 fb^{-1} 2017: 50 fb^{-1} 2018: 60 fb^{-1}

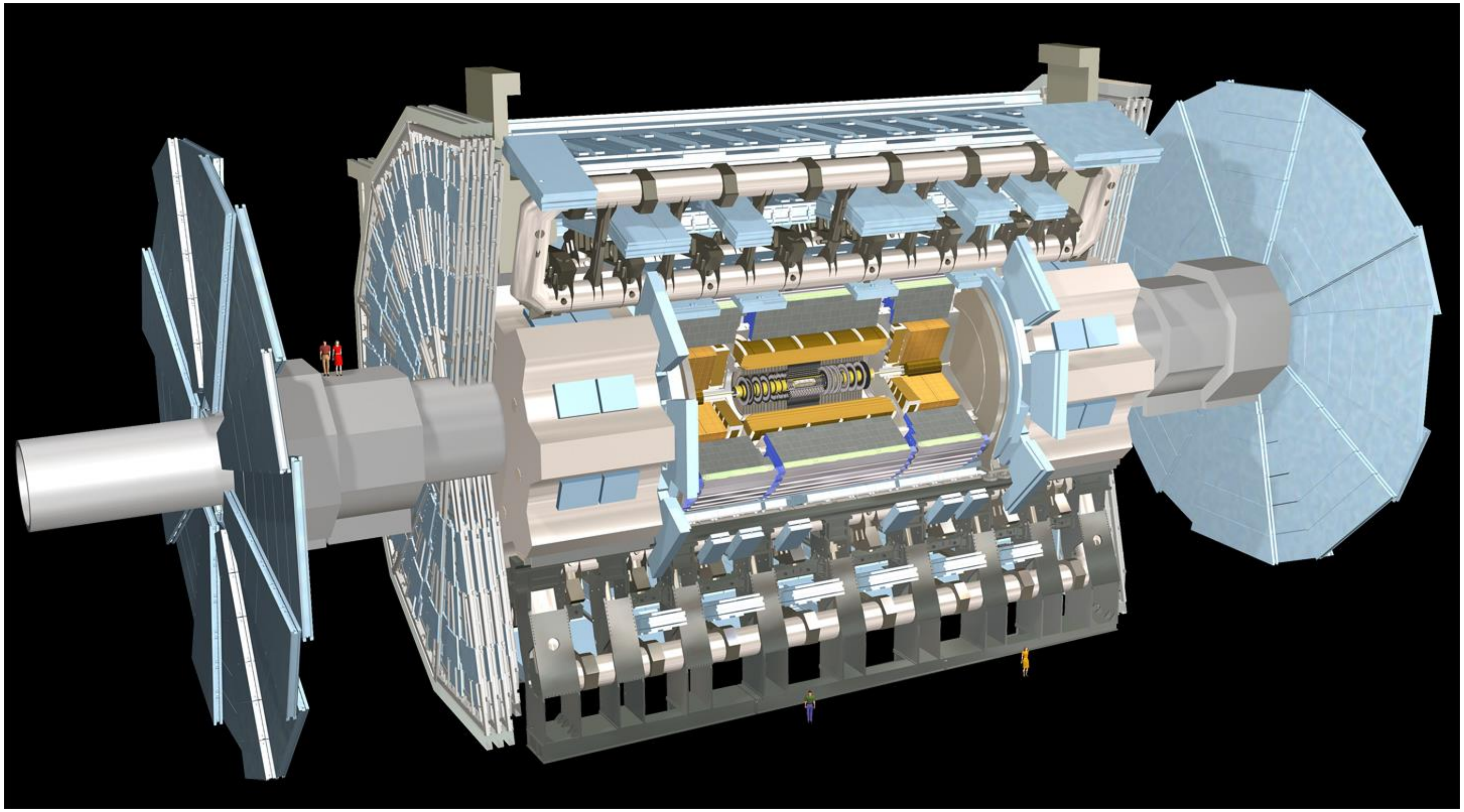
Luminosity of 2×10^{34} $cm^{-2}s^{-1}$ is reached in 2017 and 2018 which exceeds the design value by a factor of two



LHC, top view

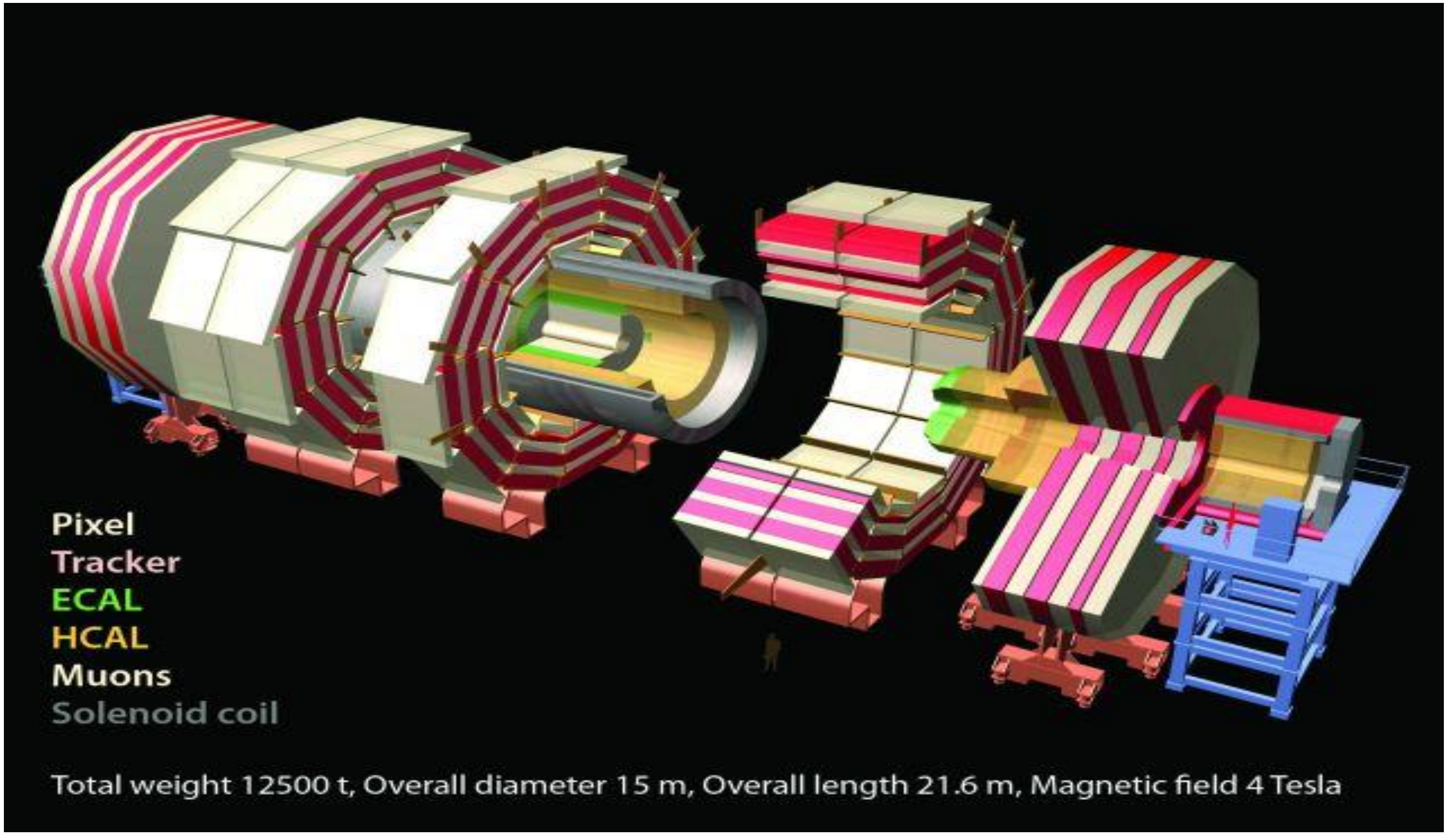
LHC operated and operates perfectly!

The ATLAS experiment (JINST 3 (2008) S08003)



>3,000 physicists from 182 institutions representing 38 countries
Main goals: Higgs boson and other SM studies, searches for new physics

The CMS experiment (JINST 3 (2008) S08004)



>3,000 physicists from about 200 institutions in 42 countries
Main goals: Higgs boson and other SM studies, searches for new physics

Higgs boson in the Standard Model (SM)

- Higgs boson (h) provides fundamental particles with masses
- Higgs boson mass is the only free parameter in the theory.
  From theoretical considerations (perturbative unitarity): $m_h < 1$ TeV
- h is expected to have **vacuum quantum numbers**, i.e. $J^P = 0^+$

What we knew about h boson about ten years ago?

- $m_h > 114.4$ GeV at 95% CL, smaller masses excluded at higher level

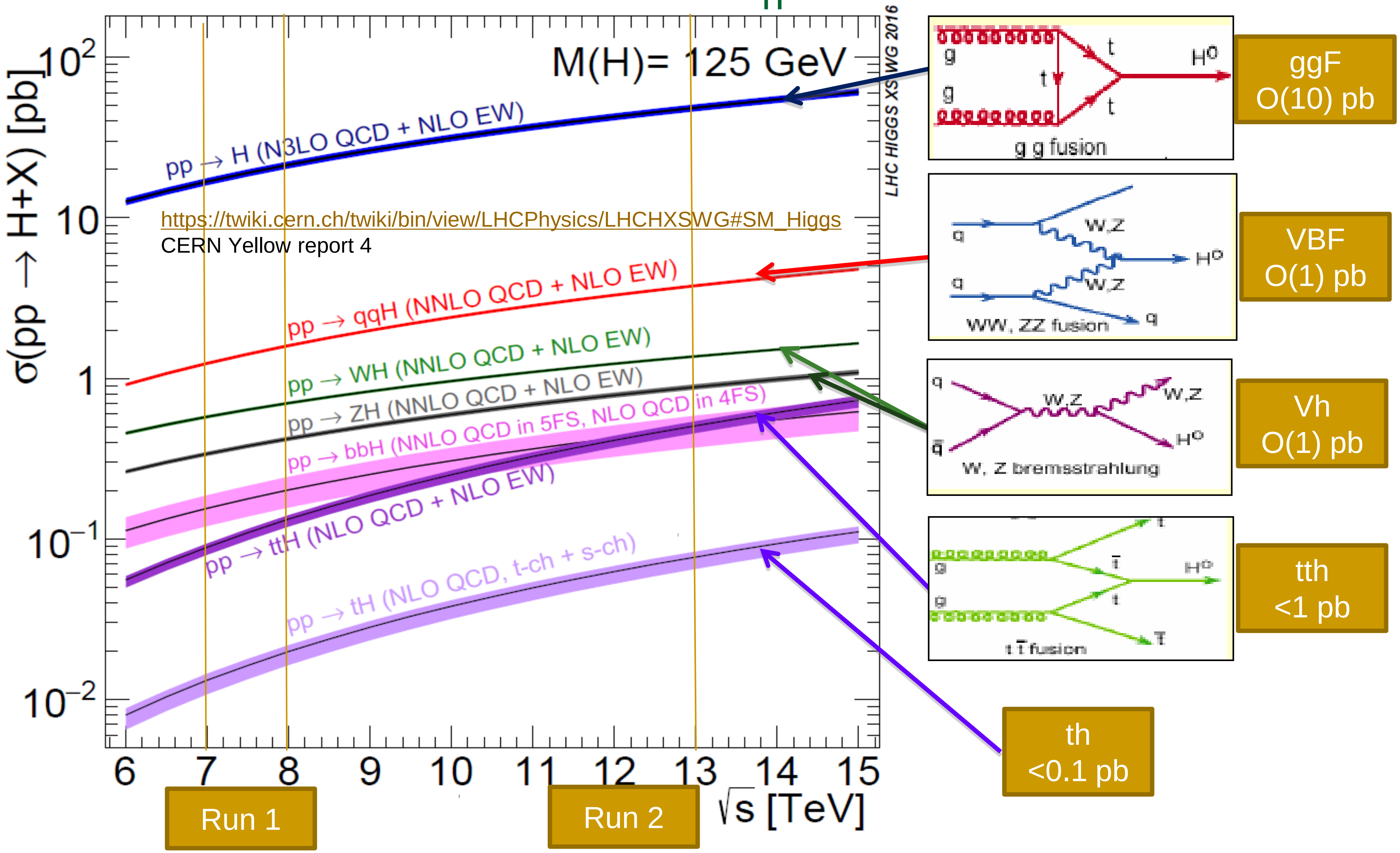
Combined results from four LEP experiments, PL B565 (2003) 61

- $m_h < 152$ GeV at 95% CL, predicted value: $m_h = 94^{+29}_{-24}$ GeV

from theoretical analysis of EW precision data, http://lepewwg.web.cern.ch

- Discovered by both ATLAS and CMS experiments, $m_h \approx 125$ GeV
  ATLAS: PL B716 (2012) 1, CMS: PL B716 (2012) 30; seminar at CERN 04.07.2012
  Note. FNAL CDF + D0 experiments found $\approx 3\sigma$ evidence for h boson

Expected SM Higgs boson production cross sections at LHC vs √s at m_h=125 GeV



Expected h branching ratios at m_h=125.09 GeV

Numbers for the BR are taken from
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV

Decay mode	BR, %	Observability in the experiment	Event rates*
h→bb	**57.5 ± 1.9**	**Mainly in Vh and tth production**	**>24000/36 fb^{-1}**
h→WW*	**21.6 ± 0.9**	**Leptonic decays of both W**	**≈17000**/36 fb^{-1}
h→gg	8.56 ± 0.86	no good experimental signature	
h→ττ	**6.30 ± 0.36**	**Mainly in VBF production**	**≈10000**/36 fb^{-1}
h→cc	2.90 ± 0.35	Very big continuum background	
h→ZZ*	**2.67± 0.11**	**Leptonic decays of both Z**	**≈250**/36 fb^{-1}
h→γγ	**0.228 ± 0.011**	**Excellent photon resolution**	**≈5000**/36 fb^{-1}
h→Zγ	0.155 ± 0.014	Leptonic decay of Z	≈250/36 fb^{-1}
h→μμ	0.022 ± 0.001	Excellent muon resolution	≈500/36 fb^{-1}

*estimated number of events, collected at 13 TeV pp collisions (for 36 fb^{-1} data sample taken in 2015-16) assuming 100% detection efficiency

h→ZZ*→4*l* invariant mass spectra at 13 TeV

ATLAS: ATLAS-CONF-2018-018

195 events observed with m_{4l} 115-130 GeV

Expected background: 59±4 events

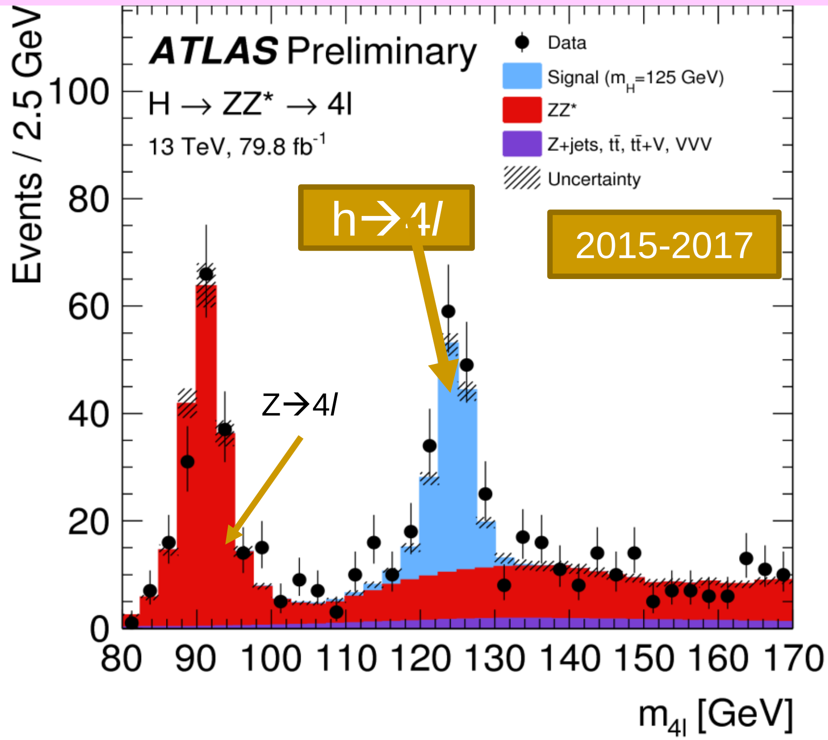
Expected signal at 125 GeV: 112±5 events

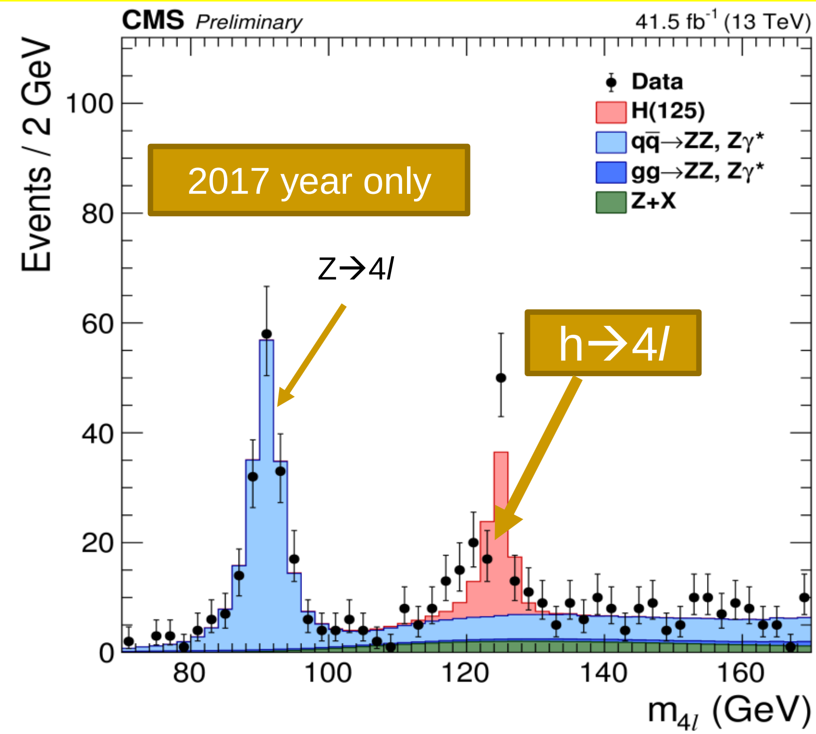
CMS: CMS-PAS-HIG-2018-001

126 events observed with m_{4l} 117-130 GeV

Expected background: 39±3 events

Expected signal at 125.1 GeV: 69±6 events





Very clear maximum around 125 GeV is seen by both experiments

h→4l fiducial cross section and signal strength

ATLAS: ATLAS-CONF-2018-018

2015-2017 years:

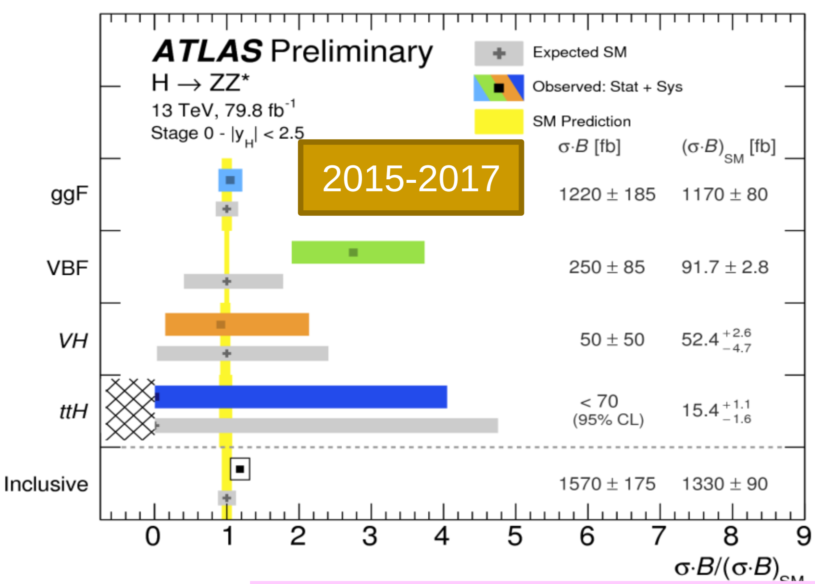
$\sigma_{meas} / \sigma_{SM} = \mu = 1.19^{+0.16}_{-0.15}$ at 125 GeV

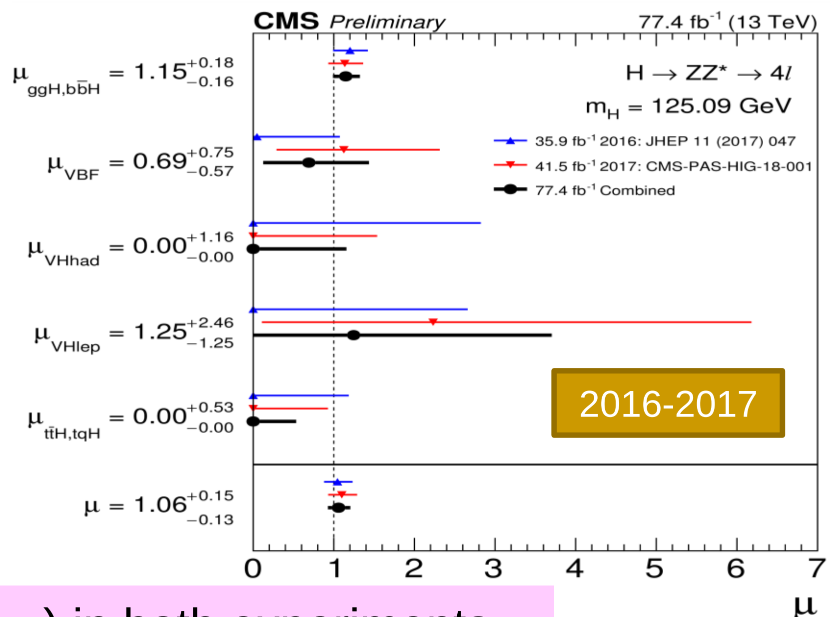
Measured fid. cross section: 4.0 ±0.5 fb
Expected fid. cross section: 3.35 ±0.15 fb

CMS: CMS-PAS-HIG-2018-001

$\mu = 1.06^{+0.15}_{-0.13}$ at 125.1 GeV (2016-2017)

2015-16 data only, JHEP 1711 (2017) 047:
Measured fid. cross section: 2.9 ±0.6 fb
Expected fid. cross section: 2.76 ±0.14 fb





h→4l significance is O(10 σ) in both experiments
No significant deviation from the SM is observed

h→ γγ invariant mass at 13 TeV

- **ATLAS:** ATLAS-CONF-2018-028
- **CMS:** arXiv:1804.02716

Many categories; 733K events selected

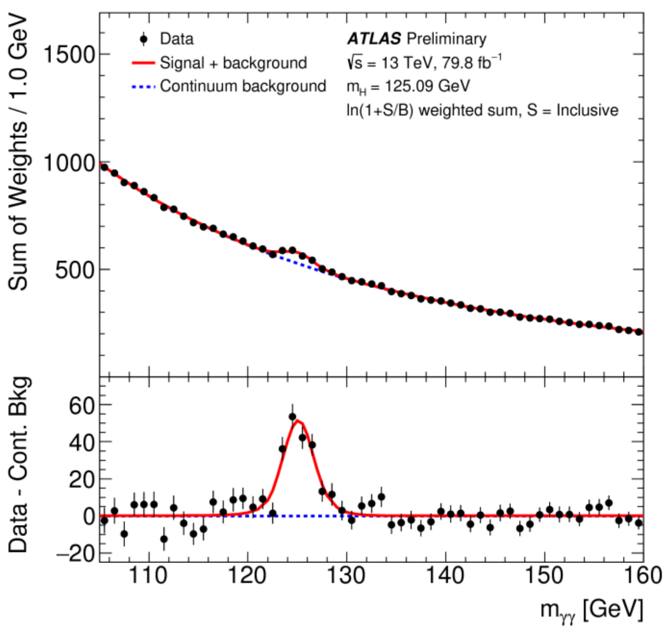
Average signal/background ratio ≈0.02

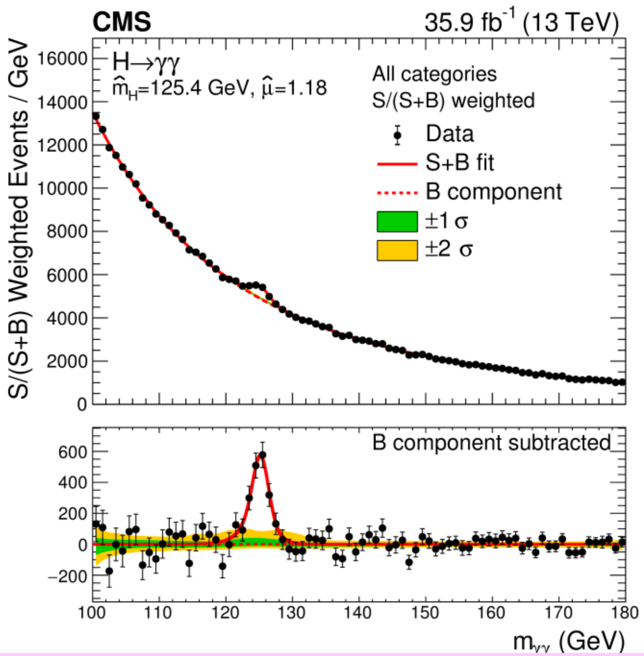
$M_{\gamma\gamma}$ resolution is ≈1.9 GeV at 125 GeV

Many categories

Expected: ≈1800 h→γγ events near 125 GeV

$M_{\gamma\gamma}$ resolution is about 1.7 GeV at 125 GeV





Clear excess around 125 GeV is seen by both experiments

h→ γγ signal strength at 13 TeV

ATLAS: ATLAS-CONF-2018-028

μ=1.06±0.13 at 125.09 GeV

Measured fid. cross section: 60.4 ±8.5 fb

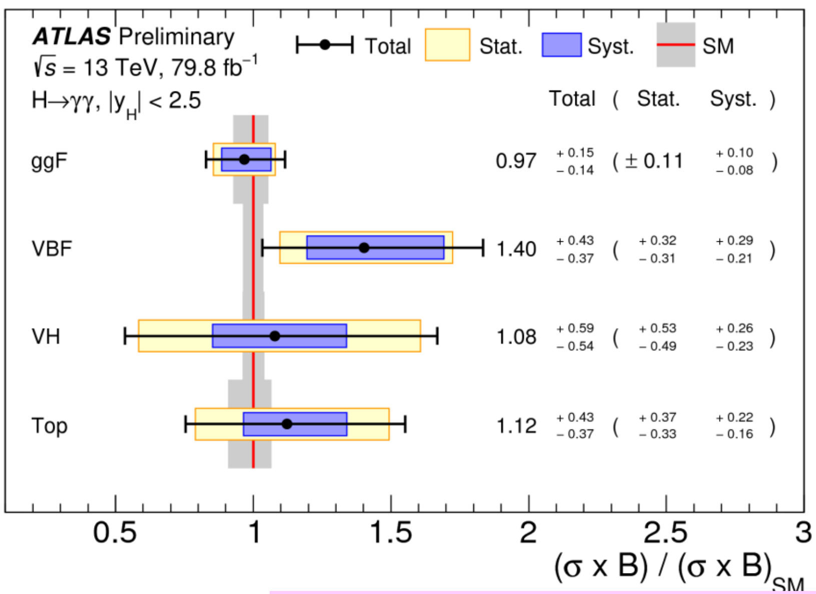
Expected fid. cross section: 63.5 ±3.3 fb

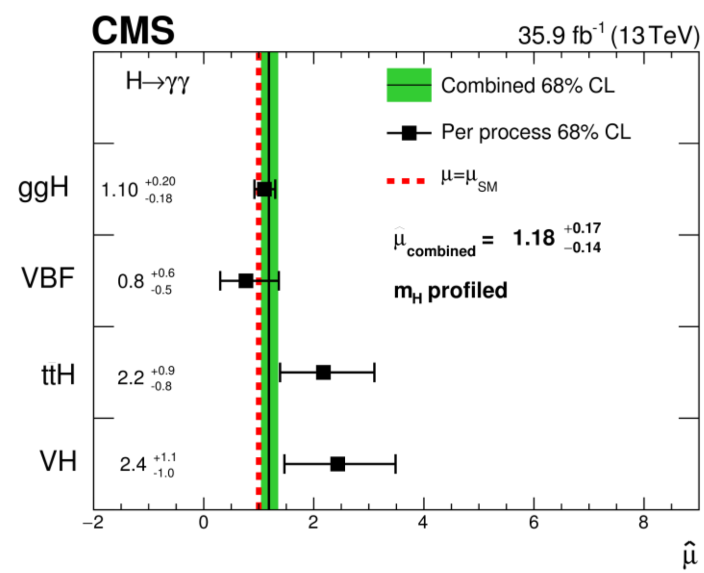
CMS: arXiv:1804.02716, 1807.03825

$\mu=1.18^{+0.17}_{-0.14}$ at 125.09 GeV

Measured fid. cross section: 84 ±13 fb

Expected fid. cross section: 73 ±4 fb





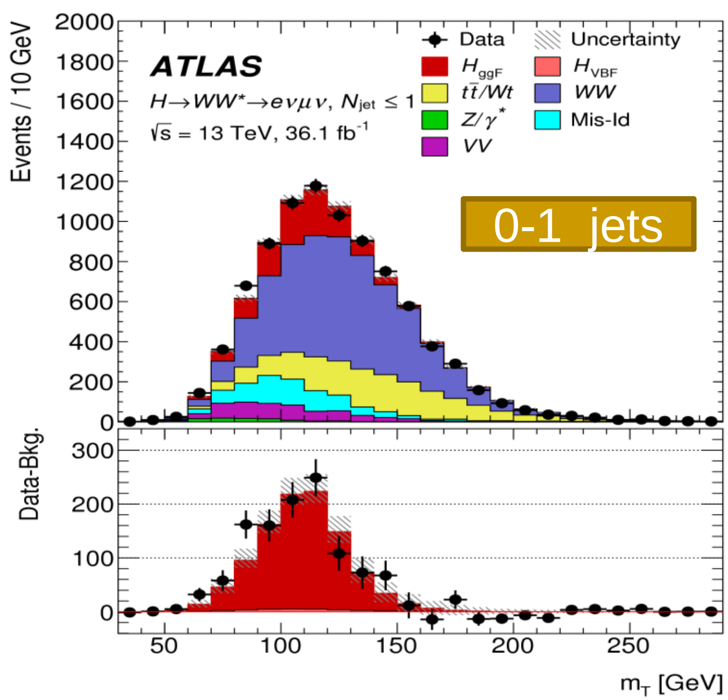
h→γγ significance exceeds 5 σ in both experiments
No significant deviation from the SM is observed

$h \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ transverse mass at 13 TeV

- Only transverse mass m_T can be reconstructed
- Categories: 0 jets: mainly ggF, 1 jets: ggF+VBF, 2 jets: mainly VBF

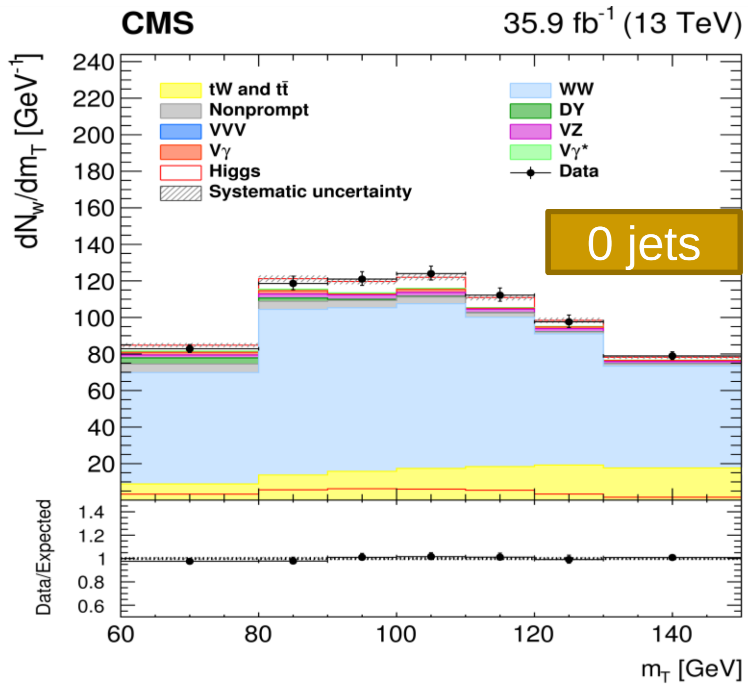
ATLAS: arXiv:1808.09054

Vh channel not yet included
Same flavours not included



CMS: arXiv:1806.05246

Vh channel included
Same flavours included



Big and wide bump around 100-120 GeV is seen by both experiments

h→ WW$^{(*)}$→$l\nu l\nu$ signal strength at 13 TeV

ATLAS: arXiv:1808.09054

Observed significance: 6.3 σ
Expected significance: 5.2 σ

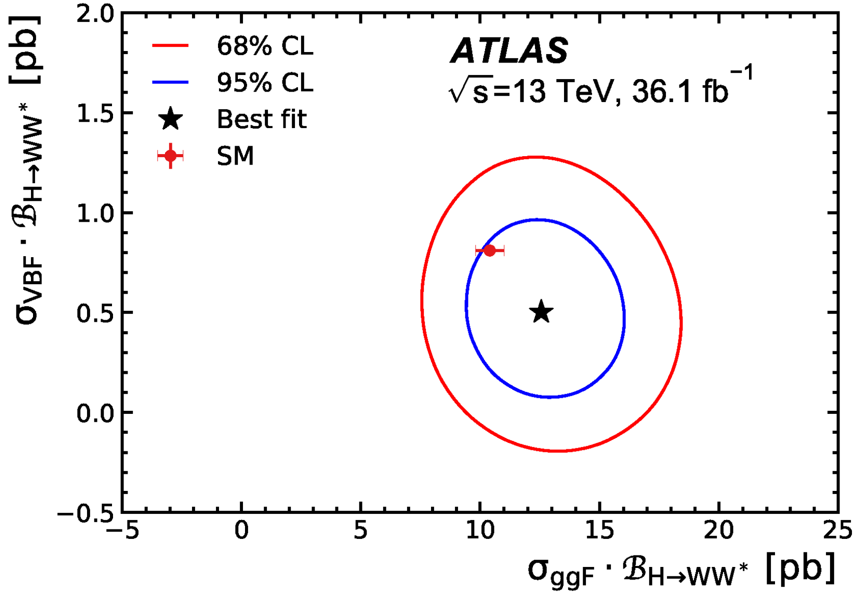
$\mu_{ggF}=1.21^{+0.22}_{-0.21}$, $\mu_{VBF}=0.62^{+0.37}_{-0.36}$

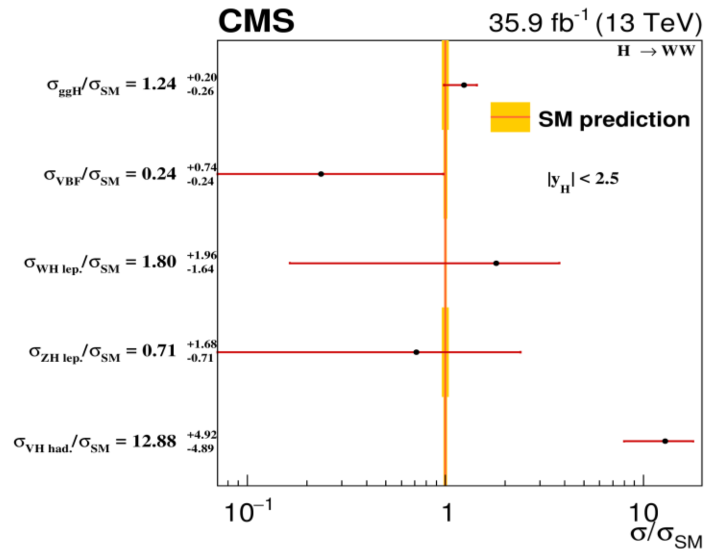
CMS: arXiv:1806.05246

$\mu=1.28^{+0.18}_{-0.17}$ at 125.1 GeV

Observed significance: 9.1 σ
Expected significance: 7.1 σ
Fiducial cross sections measured

$\mu_{ggF}=1.38^{+0.21}_{-0.24}$, $\mu_{VBF}=0.29^{+0.66}_{-0.29}$



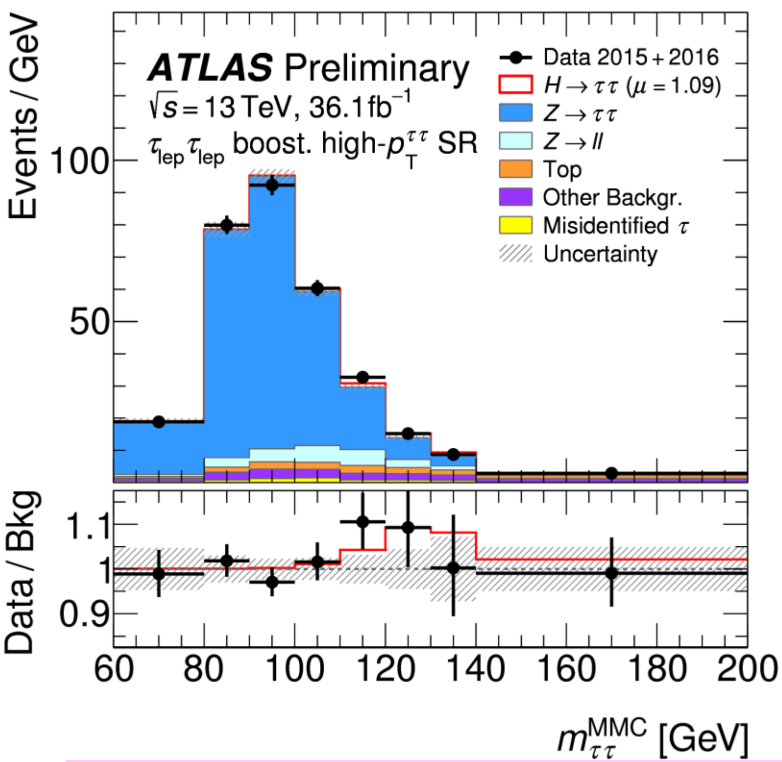


h→WW* significance exceeds 5 σ in each experiment
No significant deviation from the SM is observed

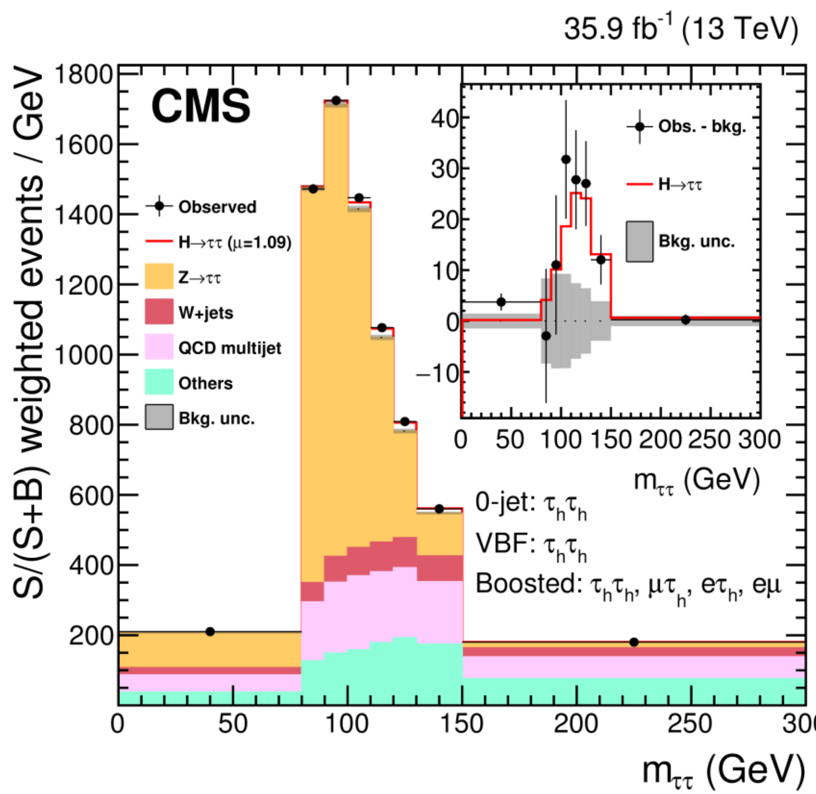
h→ $\tau\tau$ invariant mass at 13 TeV

- Many event categories to improve signal significance
- Signature: two reconstructed taus in *ll*, *l*h and *hh* decay modes
- Major role of VBF and "boosted h→$\tau\tau$" categories

ATLAS: ATLAS-CONF-2018-021



CMS: PL B779 (2018) 283



Big and wide bump around 125 GeV is seen by both experiments

h→ $\tau\tau$ signal strength at 13 TeV

ATLAS: ATLAS-CONF-2018-021

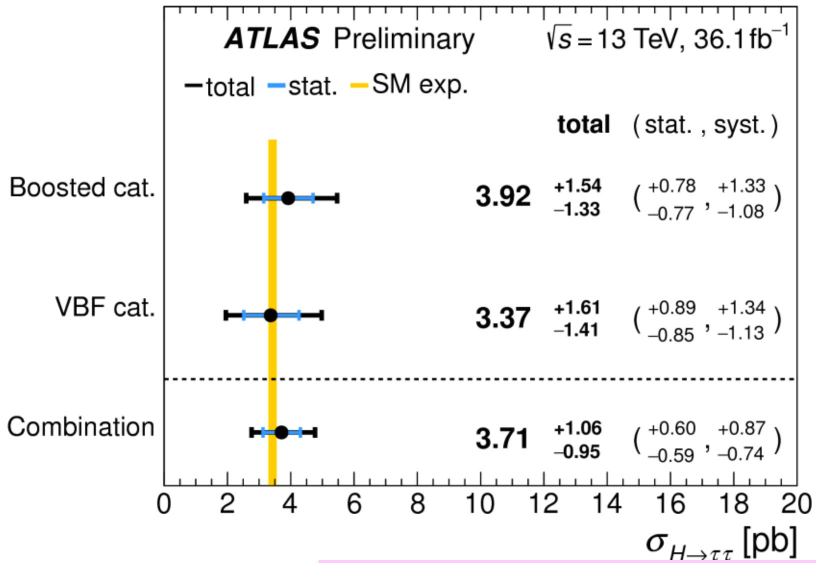
$\mu=1.09^{+0.36}_{-0.30}$ at 125.1 GeV

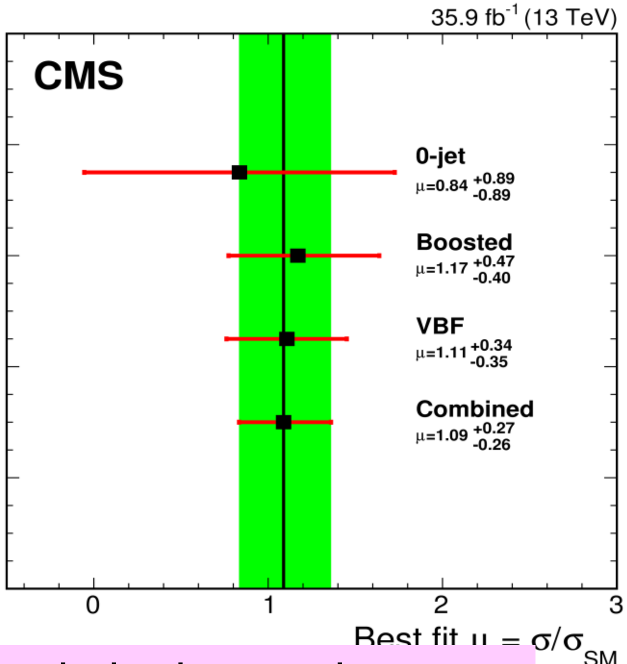
Observed significance: 4.4 σ, 6.4σ with Run1
Expected significance: 4.1 σ, 5.4σ with Run1

CMS: PL B779 (2018) 283

$\mu=1.09\pm0.26$ at 125 GeV

Observed significance: 4.9 σ, 5.9σ with Run1
Expected significance: 4.7 σ, 5.9σ with Run1



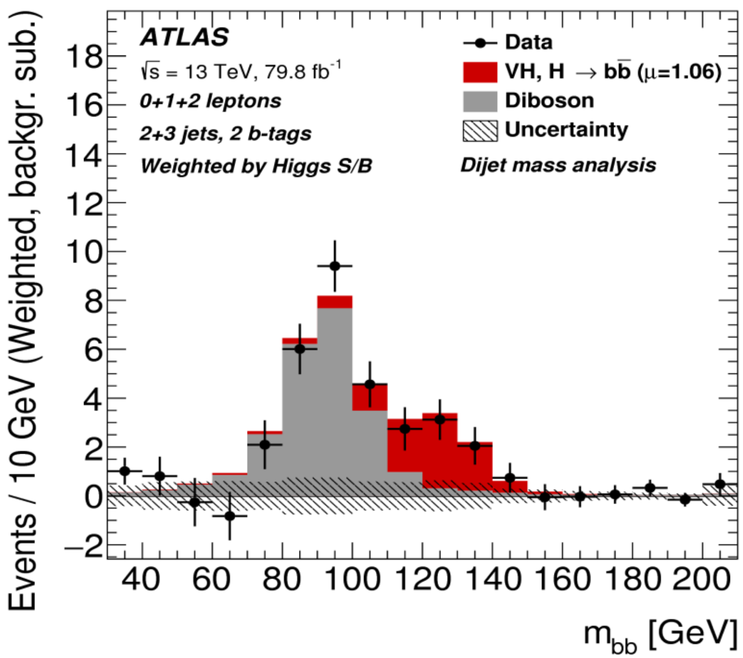


h→$\tau\tau$ significance exceeds 5 σ in both experiments
No significant deviation from the SM is observed

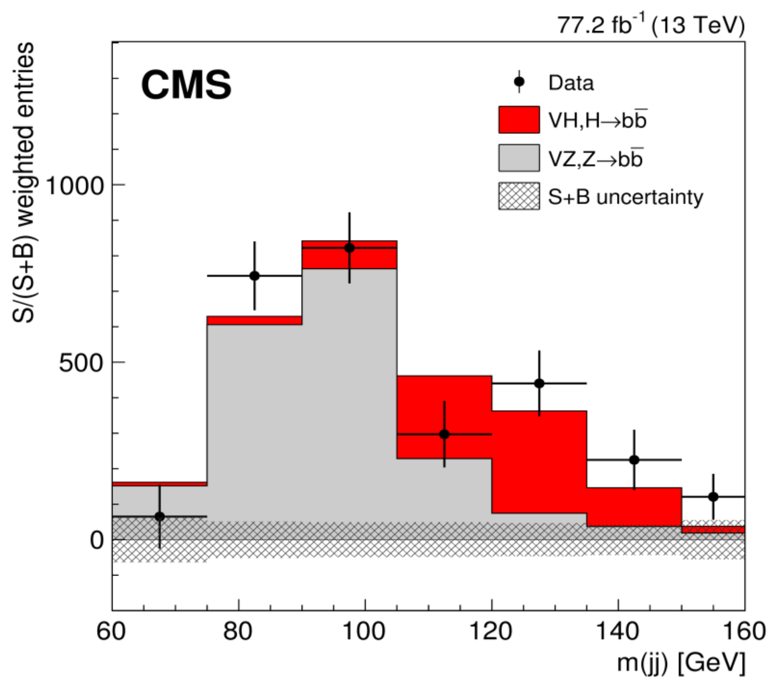
(W+Z)h, h→bb invariant mass at 13 TeV

- Separate final states with 0 (Z→νν), 1 (W→*l*ν) and 2 (Z→*ll*) leptons
- Signatures: two b-jets and tight lepton(s) or large E_T^{miss}
- Many variables in multivariate analysis to separate signal from background
- Successful validation of the analysis procedure on (W/Z)Z with Z→bb

ATLAS: PL B786 (2018) 59



CMS: arXiv:1808.08242, PRL accepted



Wide bump around 125 GeV is seen by both experiments

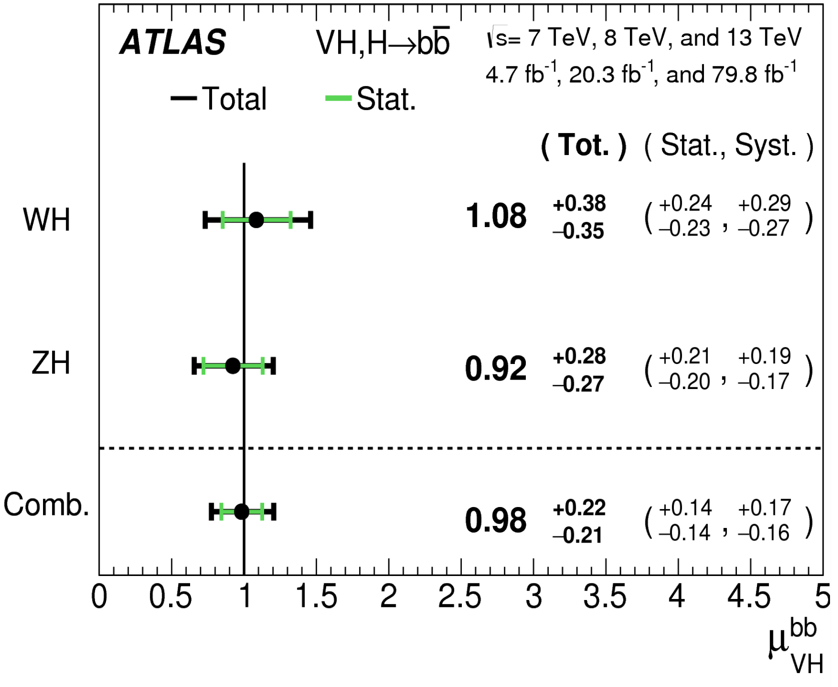
(W+Z)h, h→bb signal strength at 13 TeV

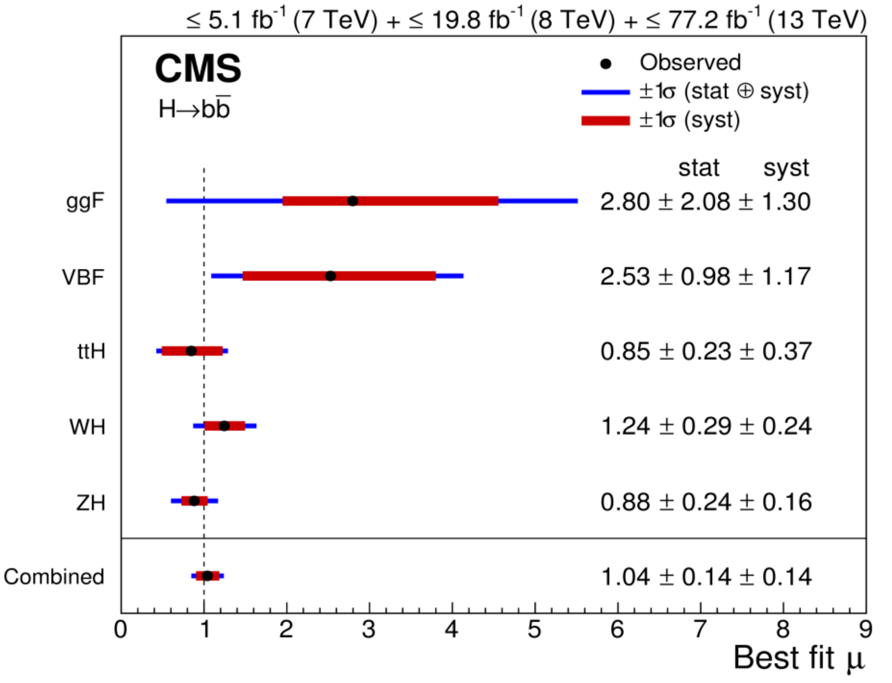
ATLAS: PL B786 (2018) 59

μ= 1.01 ±0.20 at 125 GeV for VH only
Obs. significance: 4.9 σ, 5.4 σ with Run1
Exp. significance: 4.4 σ, 5.5 σ with Run1

CMS: arXiv:1808.08242, PRL accepted

μ=1.04±0.20 at 125 GeV including non-Vh
Obs. signif.: 4.8 σ, 5.6 σ including non-Vh
Exp. signif.: 4.9 σ , 5.5 σ including non-Vh





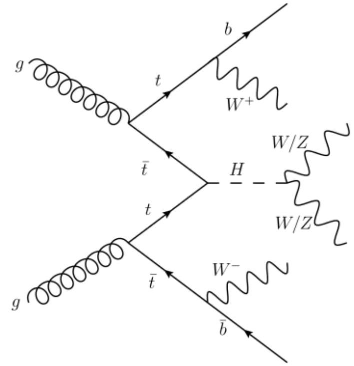
h→bb significance exceeds 5 σ in both experiments
No significant deviation from the SM is observed

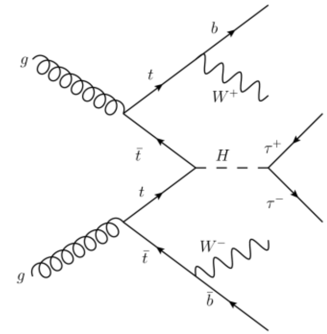
Observation of tth production

tth, h→VV

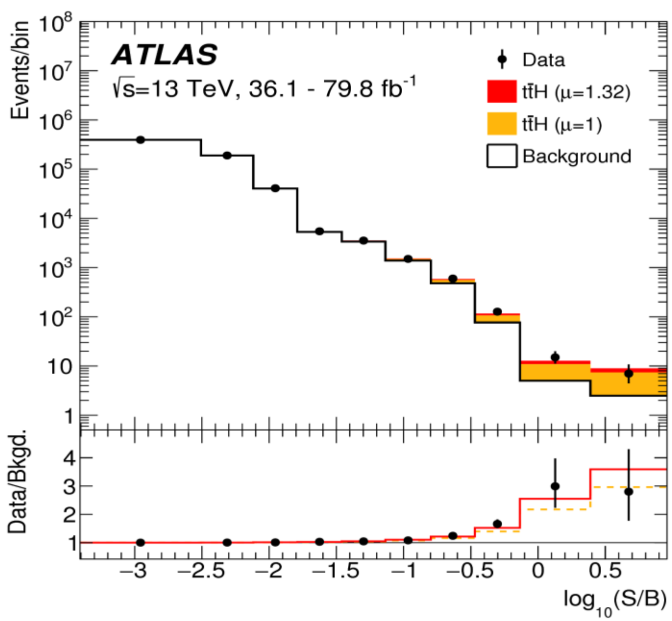
tth, h→ττ

- Yukawa coupling of h to top can be directly constrained using pp→tth+X process
- Final states with h→ZZ*, WW*, ττ (multi-leptons), bb, γγ

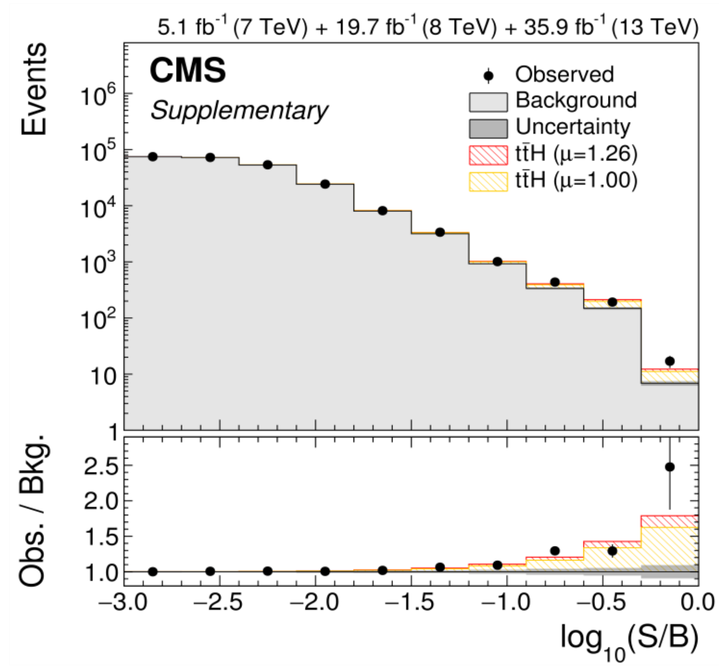




ATLAS: PL B784 (2018) 173



CMS: PRL120 (2018) 231801



Observation of tth production at 13 TeV

ATLAS: PL B784 (2018) 173

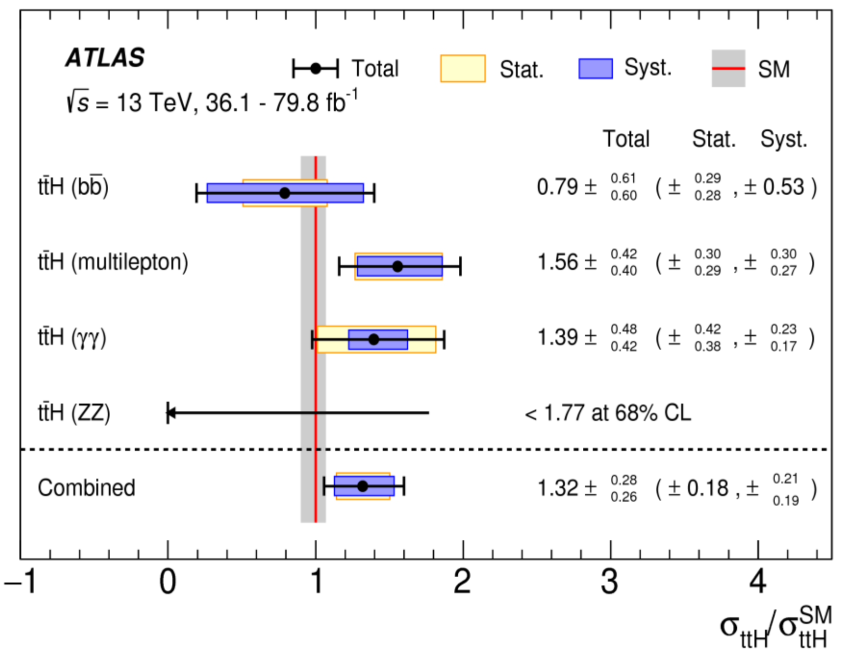
$\mu=1.32^{+0.28}_{-0.26}$ at 125.1 GeV

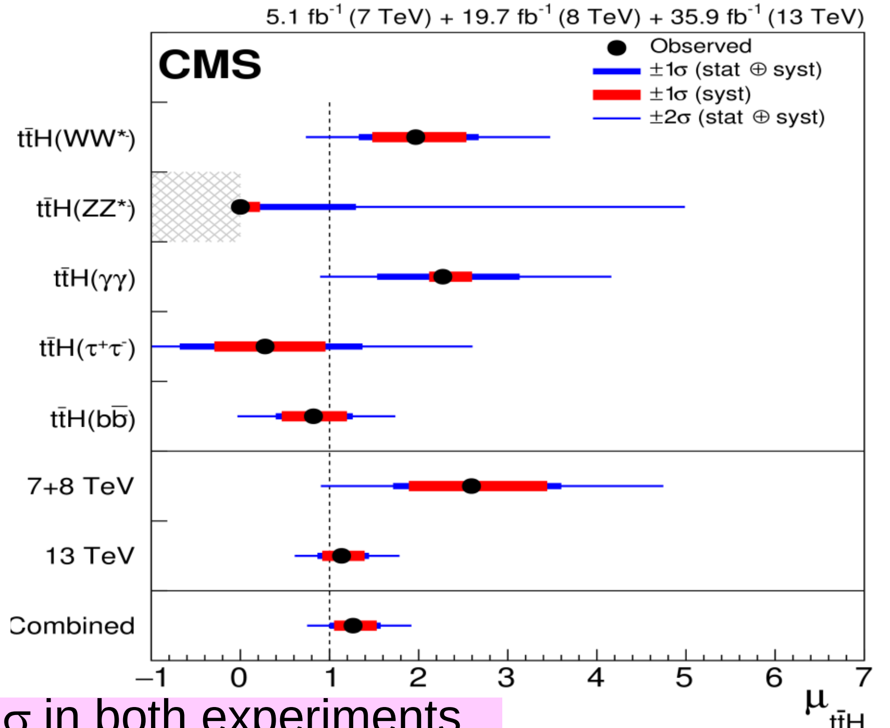
Obs. significance: 5.8 σ, 6.3 σ with Run1
Exp. significance: 4.9 σ, 5.1 σ with Run1

CMS: PRL120 (2018) 231801

$\mu=1.26^{+0.31}_{-0.26}$ at 125.1 GeV

Observed significance: 5.2 σ
Expected significance: 4.2 σ





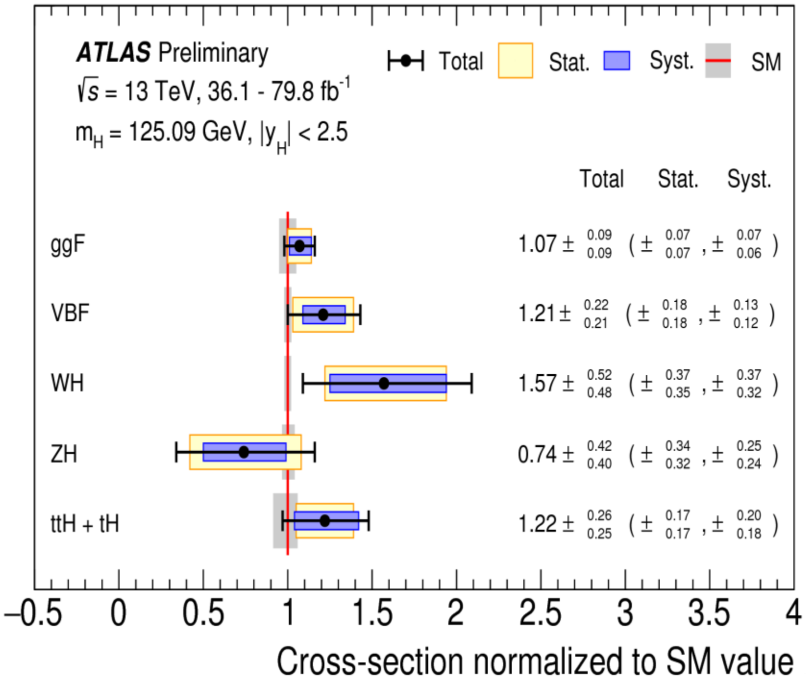
tth significance exceeds 5 σ in both experiments
No significant deviation from the SM is observed

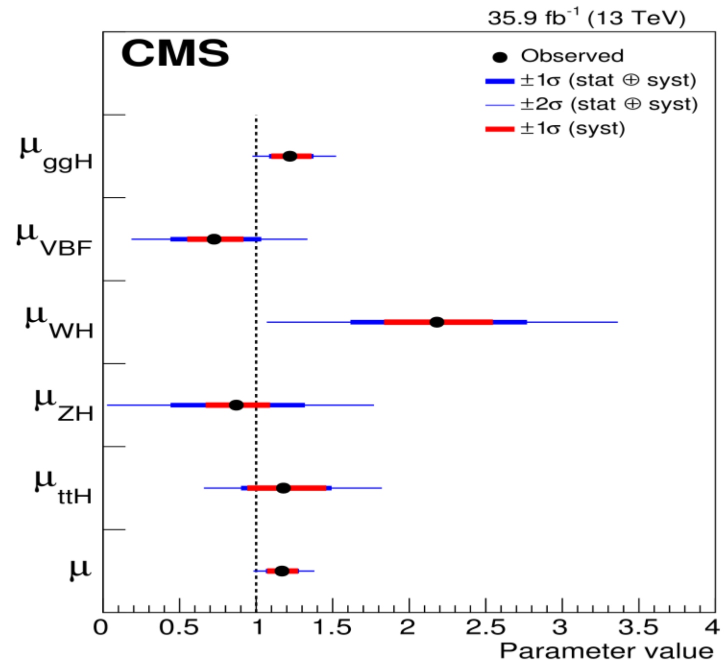
Higgs boson combination at 13 TeV: production

ATLAS: CONF-2018-031 July 2018 **CMS:** HIG-17-031 September 2018

$\mu = 1.13^{+0.09}_{-0.08}$ at 125.09 GeV

$\mu = 1.17^{+0.10}_{-0.10}$ at 125.09 GeV



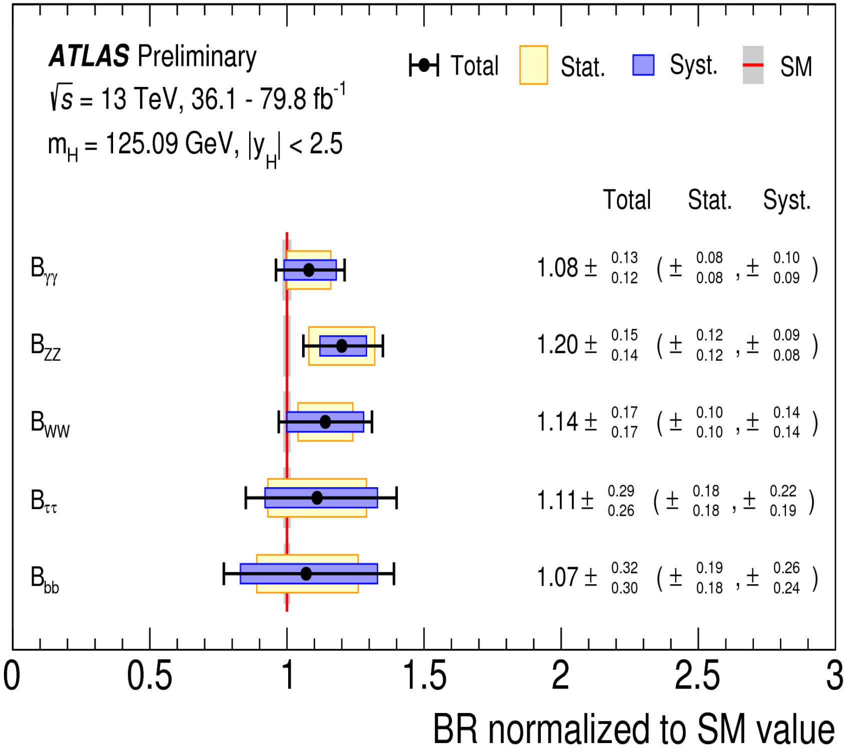


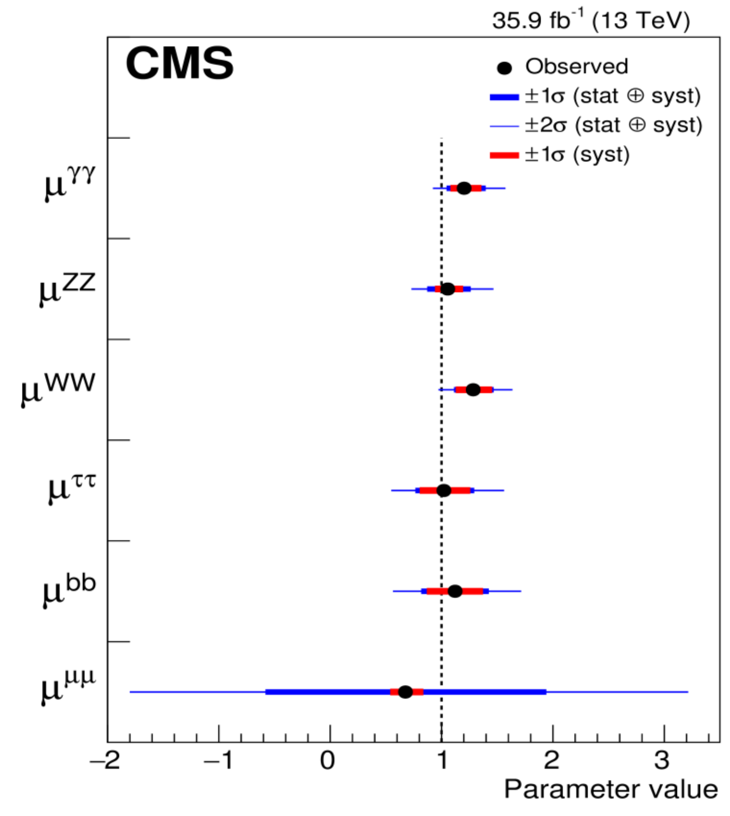
All four main production modes are observed by each experiment
No significant deviation from the SM is found assuming SM branching ratios

Higgs boson combination at 13 TeV: decays

ATLAS: CONF-2018-031 July 2018 **CMS:** HIG-17-031 September 2018

For bb, only 36 fb^{-1} result included





All five main decay modes are observed by each experiment
No significant deviation from the SM is found assuming SM production modes

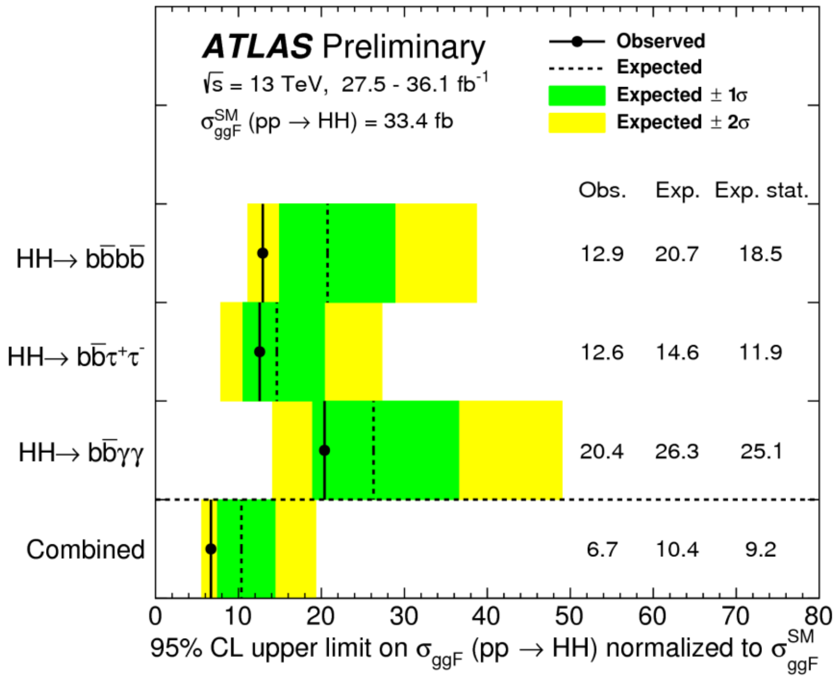
Limits on non-resonant hh production at 13 TeV

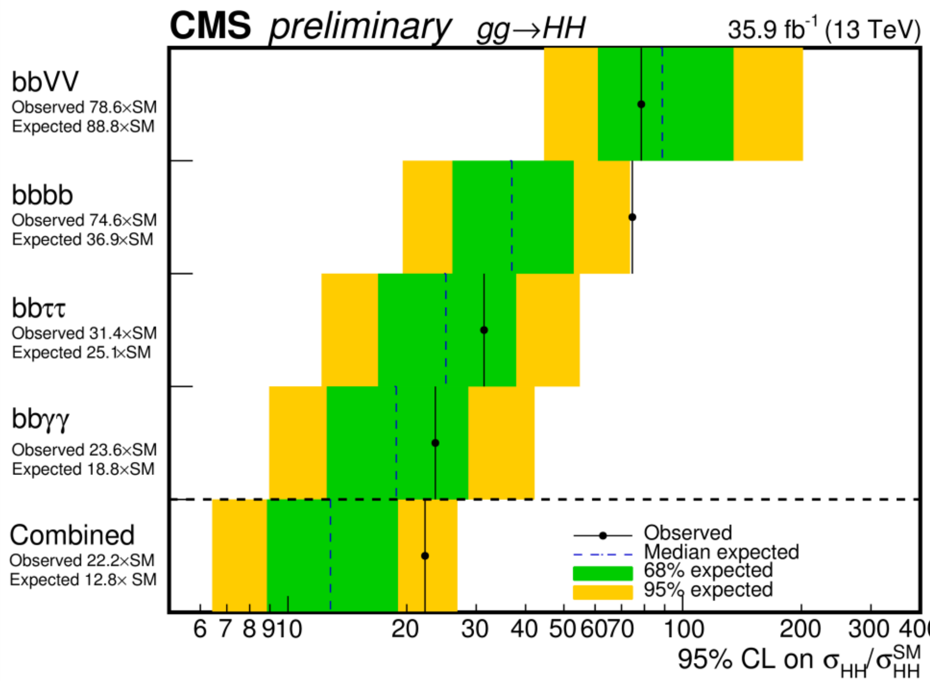
ATLAS: ATLAS-CONF-2018-043

Three decay combinations of two h-bosons are joined to put a limit on non-resonant hh-production

CMS: PAS-HIG-17-030

Four decay combinations of two h-bosons are joined to put a limit on non-resonant hh-production





Aiming for observation of the SM hh-production with 3000 fb^{-1}

Non-SM Higgs bosons

- SM-like Higgs boson (h) with m_h=125 GeV was discovered six years ago

  Great success of the SM, however it does not explain many things.
- Many extensions of the SM proposed by theorists were rejected after this discovery, but some of them have not been excluded.

- BSM models with additional Higgs bosons

  - Electroweak singlet (EWS) models which includes extra heavy scalar higgs boson

  - Another models include additional Higgs doublet (2HDM):

  - 5 Higgs bosons

CP-even Higgses (*) CP-odd Higgs (*) Charged (*)

* assuming CP conservation

Parameters: Higgs boson masses, ratio of VEV for two doublets (tan β), mixing angle between H and h (α), potential parameter mixing the two doublets ($m_{12}{}^2$)

Minimal supersymmetric models (MSSM) are subset of 2HDM

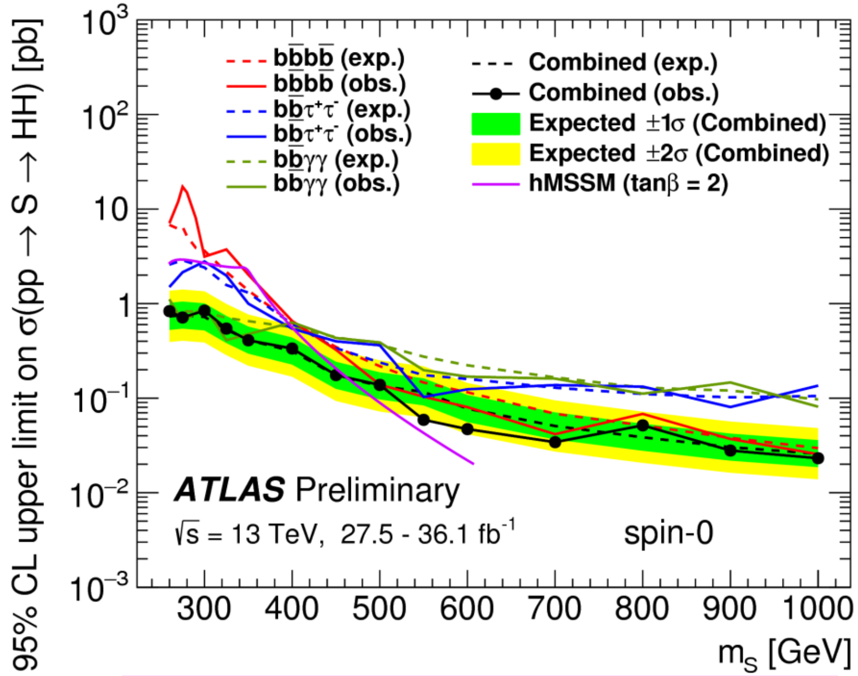
Limits on H→hh production at 13 TeV

ATLAS: ATLAS-CONF-2018-043

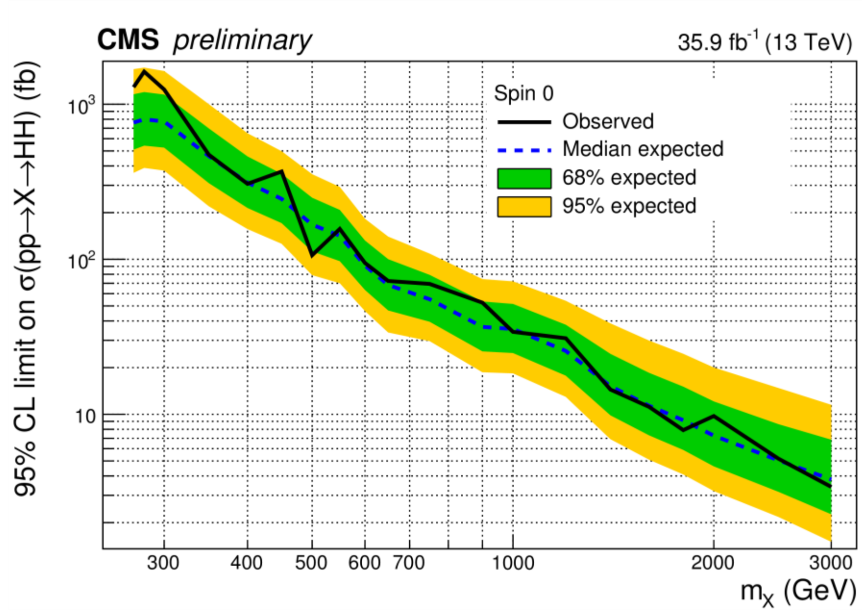
- Similar combinations of hh-decays are used to search for H→hh resonance
- HMSSM for interpretation of results

CMS: PAS-HIG-17-030

- Similar combinations of hh-decays are used to search for H→hh resonance



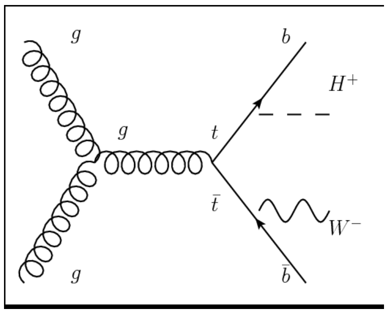
95% CL limits vary from 1pb at 300 GeV to 20 fb at 1 TeV



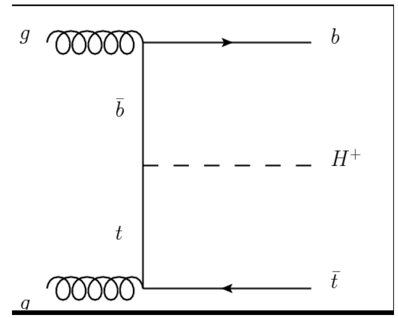
95% CL limits vary from O(1 pb) at 300 GeV to 3.5 fb at 3 TeV

Charged Higgs boson searches

- $H^{\pm}$ in MSSM. Relation between m_{top} and $M_{H^{\pm}}$ dictates both production mode and decay channels

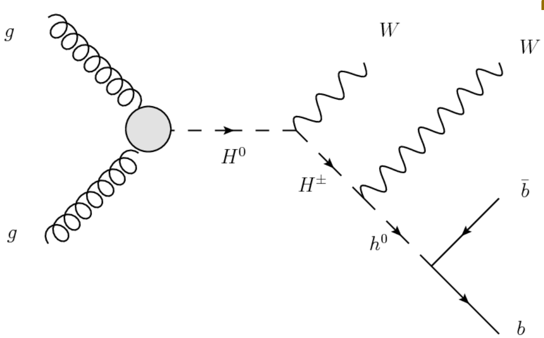


Low mass $H^{\pm}$:
$H^{\pm}bWb$ final state
$H^{\pm} \rightarrow cs$ at $\tan\beta < 1$
$H^{\pm} \rightarrow \tau\nu_{\tau}$ at $\tan\beta > 1$



High mass $H^{\pm}$:
$tH^{\pm}$ final state
$H^{\pm} \rightarrow \tau\nu_{\tau}$ is OK

- Charged Higgs boson in 2HDM cascade

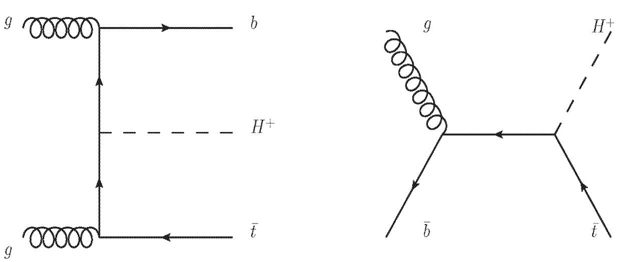


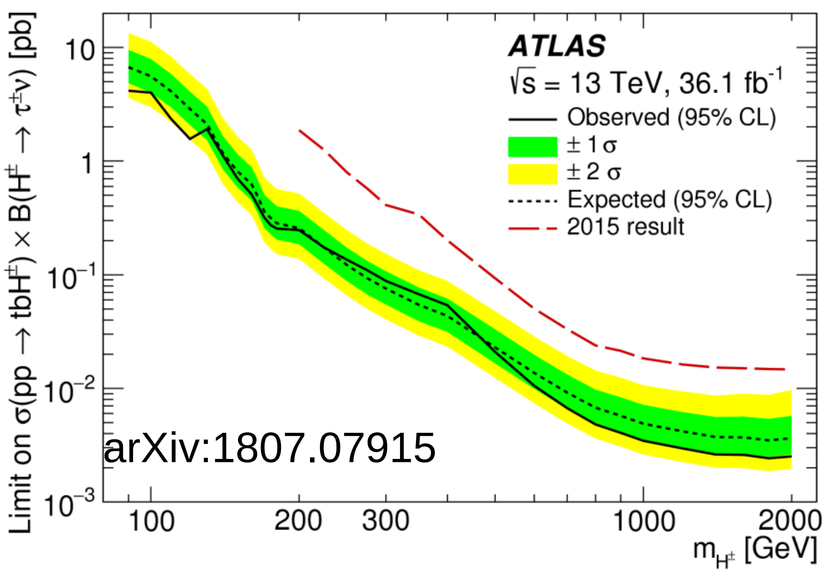
- A^0 is assumed to be too heavy
- h^0 is 125 GeV Higgs boson
- Final state is $WWb\bar{b}$ as for $t\bar{t}$-background

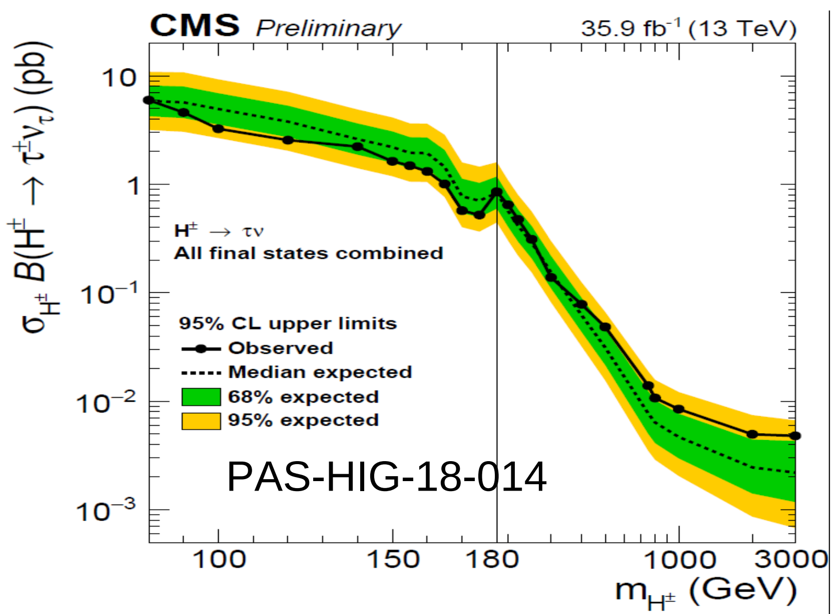
$H^+ \to \tau\nu$ at 13 TeV

- Search mass range: 90-2000 GeV for ATLAS, 80-3000 GeV for CMS, production mode $pp \to tbH^+$ ($m_H > m_{top}$)
- Final states with one τ-lepton and $W \to$ hadrons
- Interpretation in hMSSM benchmark scenario

Diagrams for tbH+ production





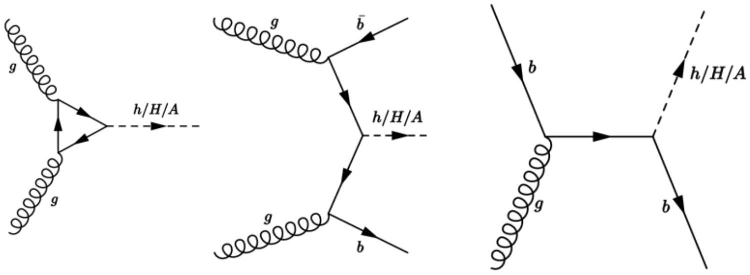


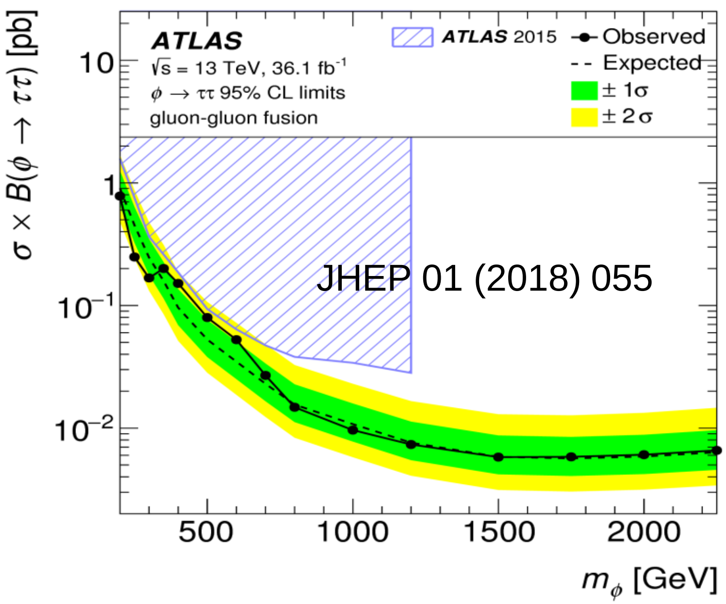
Limits on $\sigma(pp \to tbH^+) \times BR(H^+ \to \tau\nu)$: 4.2 (0.0025) pb at 90 (2000) GeV

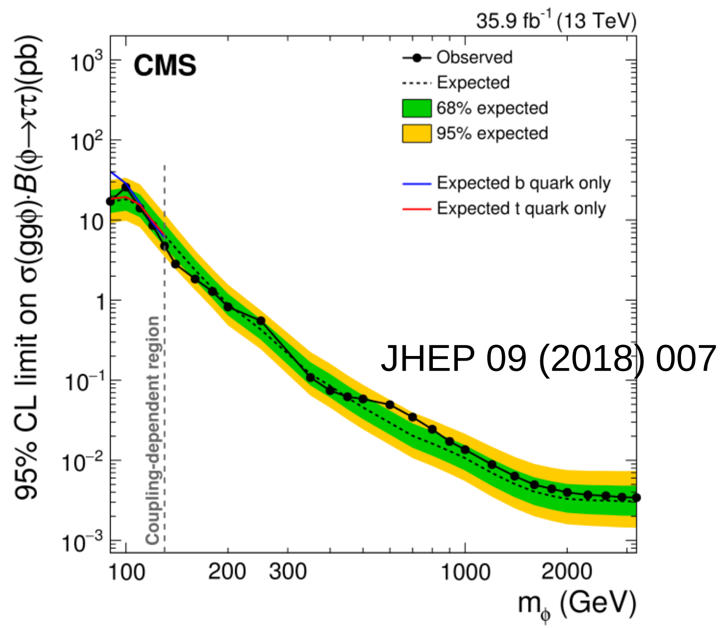
Limits on $\sigma(pp \to tbH^+) \times BR(H^+ \to \tau\nu)$: 6 (0.005) pb at 80 (3000) GeV

A/H^0→ττ at 13 TeV

- Search mass range: 200-2250 GeV
- Production via gluon fusion or b-associated
- hh and *l*h final states of two taus
- Interpretation in MSSM benchmark scenarios







Limits on **σ × BR(H/A→ττ)** for ggF:
780 (5.8) fb at 200 (2250) GeV

Limits on **σ × BR(H/A→ττ)** for bbH/A:
700 (3.7) fb at 200 (2250) GeV

Limits on **σ × BR(H/A→ττ)** for ggF:
18 pb (3.5 fb) at 90 (3200) GeV

Limits on **σ × BR(H/A→ττ)** for bbH/A:
15 pb (2.5) fb at 90 (3200) GeV

Conclusion

With 7-13 TeV LHC data, the ATLAS and CMS collaborations observed four main production mechanisms and five main decays of the Higgs boson. Their cross sections / branching ratios were measured. They all agree with the SM predictions.

With the same datasets, ATLAS and CMS measured some differential cross sections for the SM-like Higgs boson and compared them with the most recent theoretical calculations.

ATLAS and CMS also performed searches for non-standard Higgs bosons in many final states. Nothing was found yet. Strict limits on production cross sections of new scalars were put.

ATLAS and CMS continues to improve existing measurements and to search for deviations from the SM with new 13 TeV data and, in the future, will use 14 TeV data.

Backup slides

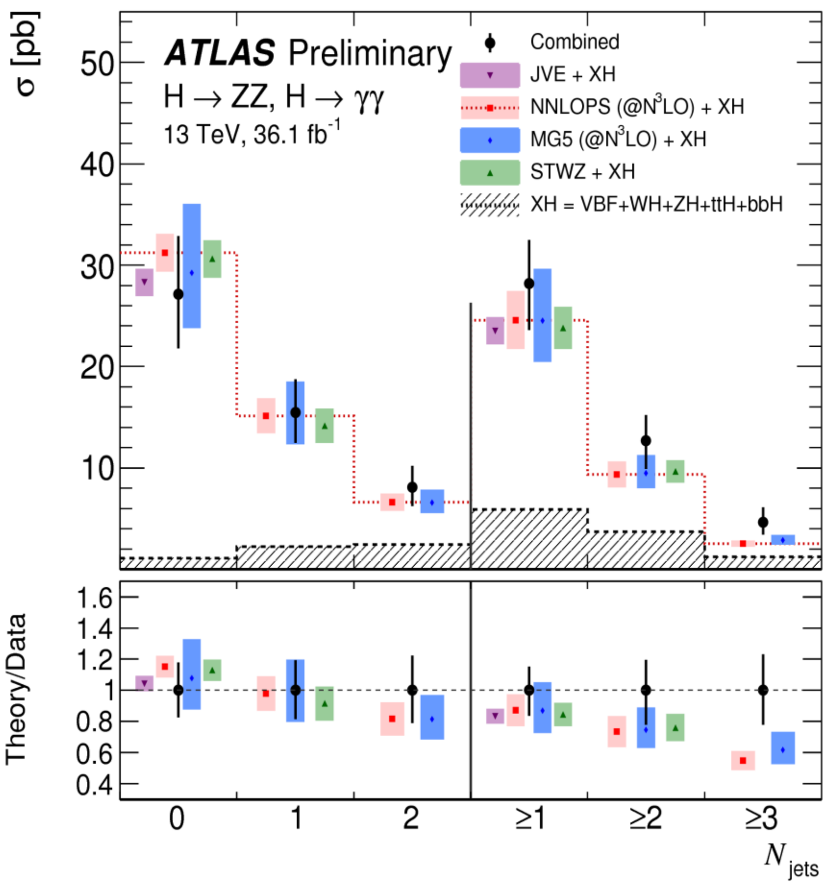
- Combined h differential cross sections at 13 TeV
- Searches for h/H→invisible at 13 TeV
- Brief summary of h results at 7 and 8 TeV
- Perspectives of h/H searches and measurements at HL-LHC
- Off-shell h→4l at 13 TeV in CMS
- Measurement of Higgs boson mass at 13 TeV
- Simplified template h cross sections in ATLAS at 13 TeV
- Low mass spin-0 diphoton resonances at 13 TeV
- Searches for H^+→tb at 13 TeV in ATLAS
- Fiducial volume definitions for h→4l and $\gamma\gamma$ cross sections
- H→$\gamma\gamma$ and H→Zγ exclusion at 13 TeV
- FCNC t→hc(u) in ATLAS and th-production in CMS

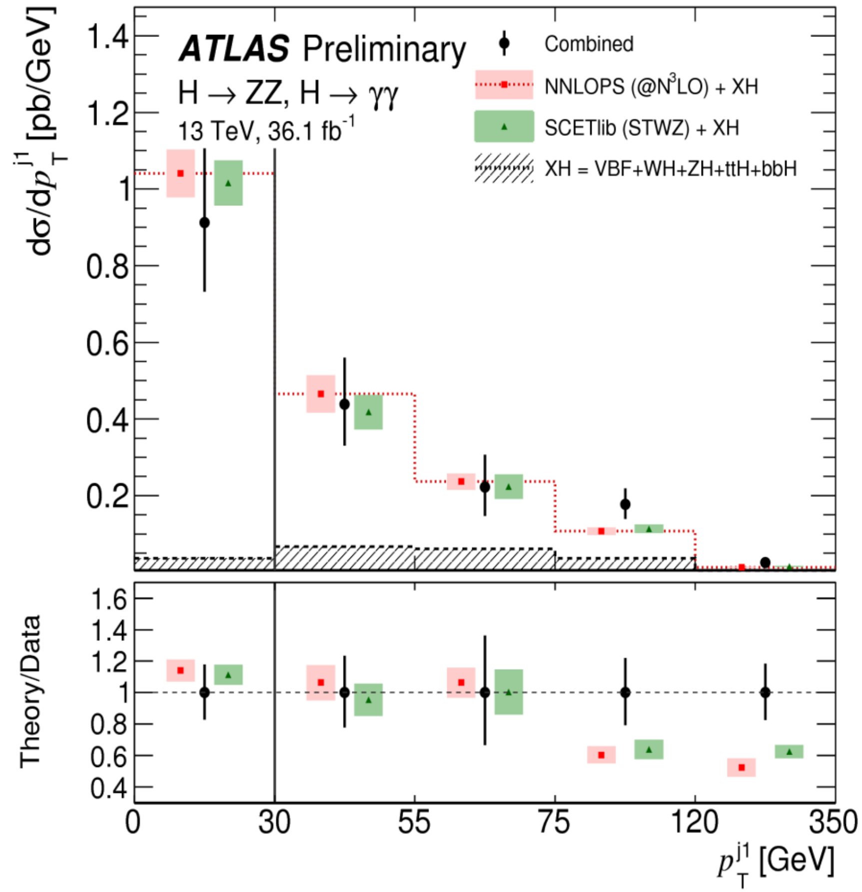
ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS public results: http://cms-results.web.cern.ch/cms-results/public-results/publications/

Combined h→4*l*, γγ diff. cross sections in ATLAS

ATLAS-CONF-2018-002

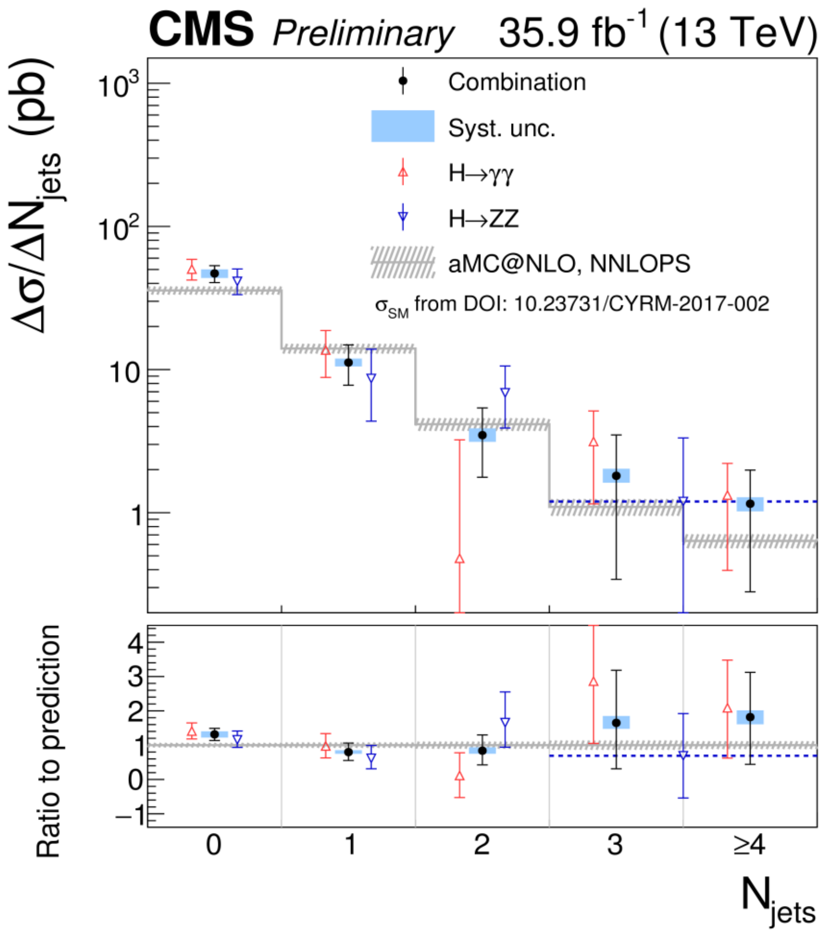


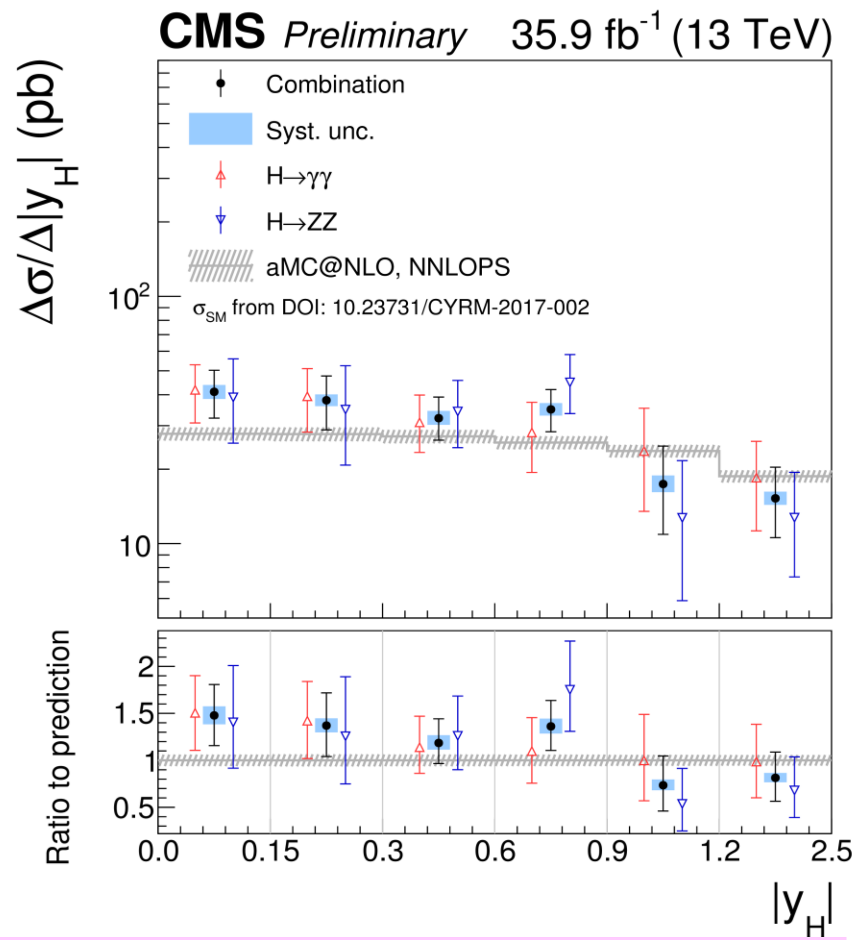


No significant difference with recent theoretical calculations is observed

Combined h→4*l*, γγ, bb diff. cross sections in CMS

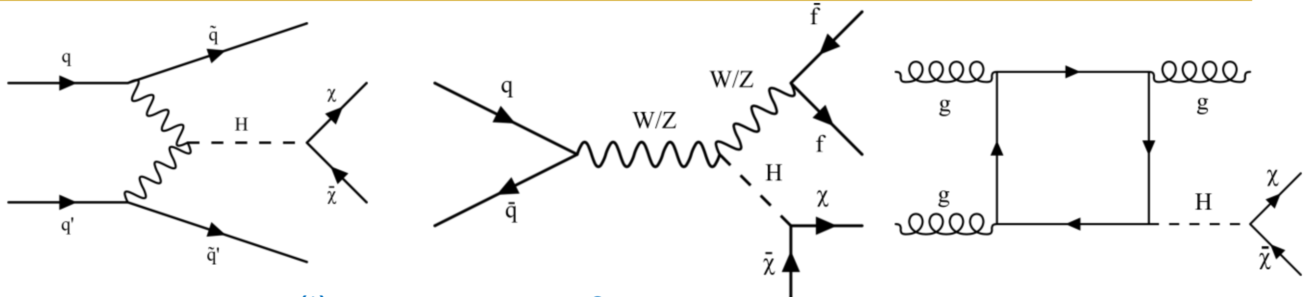
CMS-PAS-HIG-17-028



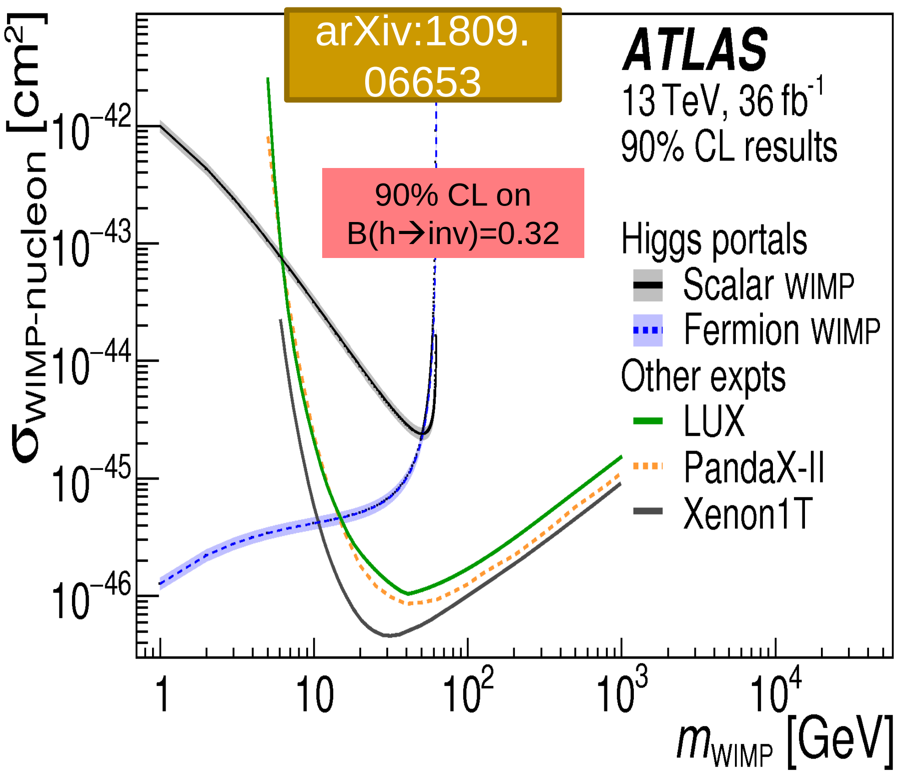


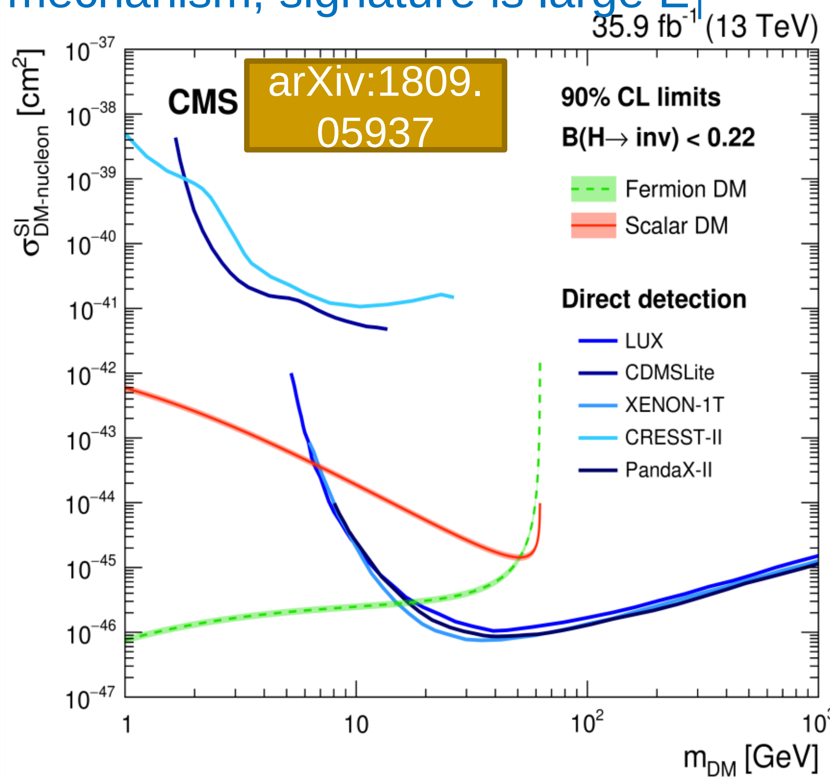
No significant difference with recent theoretical calculations is observed

H→invisible



- In the SM, B(h→inv.)=B(h→ZZ$^{(*)}$→4ν)=O(10^{-3}), but it can be larger in BSM
- Such a decay is a good WIMP and/or Dark Matter candidate
- The best way to search is to use VBF mechanism; signature is large E_T^{miss}





Brief summary of h results at 7-8 TeV

Parameter	Value	Reference	Comment
Mass	**125.36±0.41 GeV**	PR D90 (2014) 052004	125.09±0.24 GeV with CMS
Signal strength vs SM	**1.18±0.15**	EPJC76 (2016) 6	1.09±0.10 with CMS
in $h \rightarrow \gamma\gamma$ mode	$1.17^{+0.28}_{-0.26}$	EPJC76 (2016) 6	5.2σ (discovery)
in $h \rightarrow 4l$ mode	$1.46^{+0.40}_{-0.34}$	EPJC76 (2016) 6	8.1σ (discovery)
in $h \rightarrow WW^{*} \rightarrow l\nu l\nu$	$1.18^{+0.24}_{-0.21}$	EPJC76 (2016) 6	6.5σ (discovery)
in $h \rightarrow \tau\tau$ mode	$1.44^{+0.42}_{-0.37}$	EPJC76 (2016) 6	4.5σ (evidence)
in $h \rightarrow bb$ mode	$0.63^{+0.39}_{-0.37}$	EPJC76 (2016) 6	1.4σ
in ggF production	$1.23^{+0.23}_{-0.20}$	EPJC76 (2016) 6	$1.03^{+0.17}_{-0.15}$ with CMS
in VBF production	1.23±0.32	EPJC76 (2016) 6	$1.18^{+0.25}_{-0.23}$ with CMS
in Vh production	0.80±0.36	EPJC76 (2016) 6	$0.84^{+0.40}_{-0.38}$ with CMS
in tth production	1.81±0.80	EPJC76 (2016) 6	$2.3^{+0.7}_{-0.6}$ with CMS
Spin/parity	**0^{+}**	EPJC 75 (2015) 476	$4l$, $l\nu l\nu$, $\gamma\gamma$ modes
Width	**<22.7 MeV (95% CL)**	EPJC 75 (2015) 335	Off-shell $h \rightarrow WW/ZZ$
BR($h \rightarrow$invisible)	**<0.28 (95% CL)**	JHEP 01 (2016) 172	WIMP searches

No significant deviation from the SM is observed

Higgs boson perspectives at HL-LHC: recent notes

ATLAS:

Vh, $h \rightarrow cc$ PUB-2018-016

$h \rightarrow \mu\mu$ PUB-2018-006

EFT $H \rightarrow 4l$, $\gamma\gamma$ PUB-2017-018

Theory uncertainty PUB-2018-010

$hh \rightarrow bb\gamma\gamma$ PUB-2017-001

$hh \rightarrow bbbb$ PUB-2016-024

tthh PUB-2016-023

VBF $H \rightarrow WW$ PUB-2016-018

…and more results at:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/PUBnotes

CMS:

$h \rightarrow ZZ$, $\gamma\gamma$; BSM $H \rightarrow \tau\tau$, invisible and hh:
CMS-PAS-FTR-16-002 (ECFA 2016)

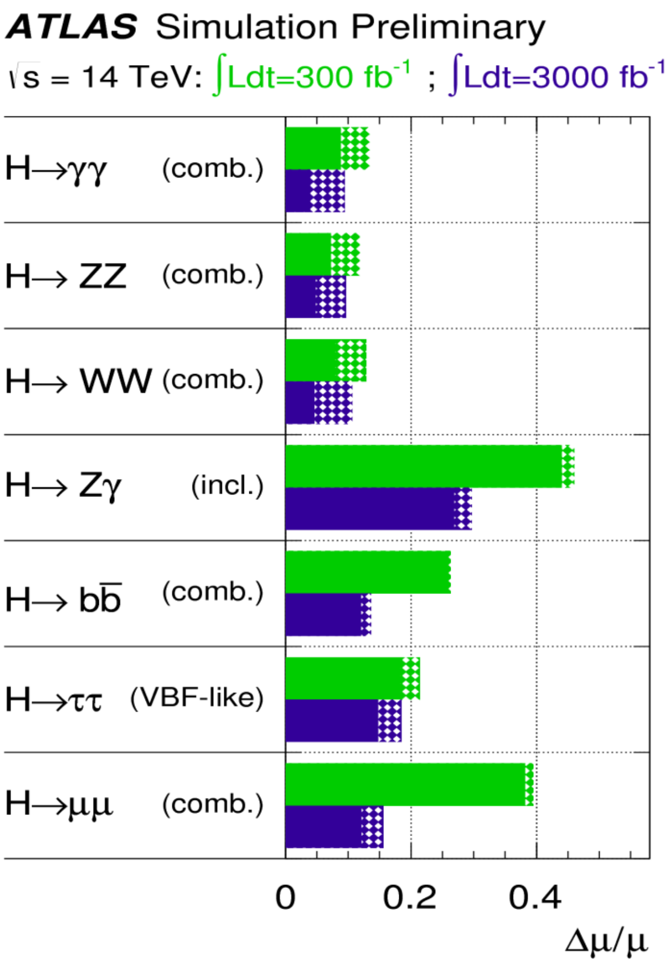
$hh \rightarrow bb\gamma\gamma$, $bb\tau\tau$, bbWW: CMS-PAS-FTR-15-002

…and more results at:

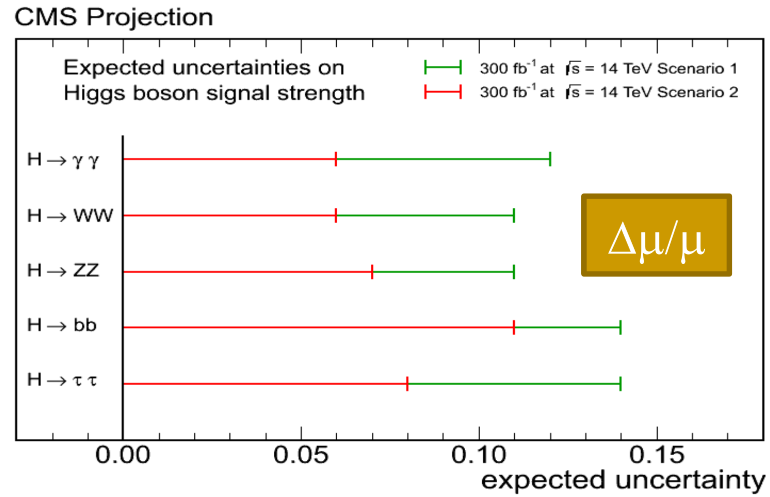
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

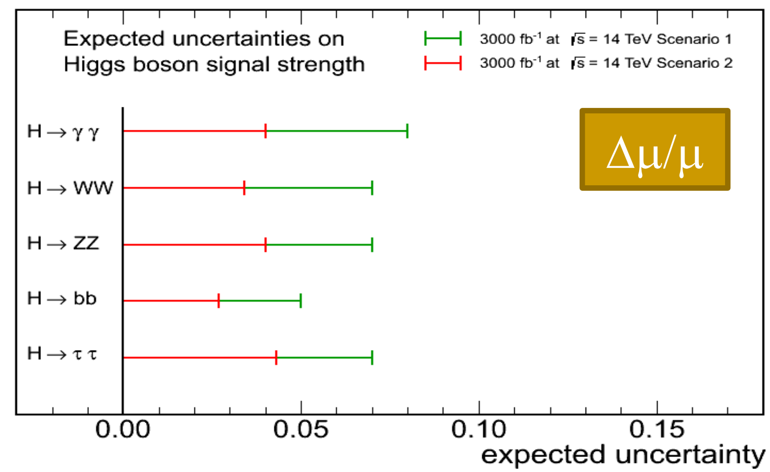
Higgs boson perspectives: ATLAS and CMS

ATLAS-PHYS-PUB-2014-016



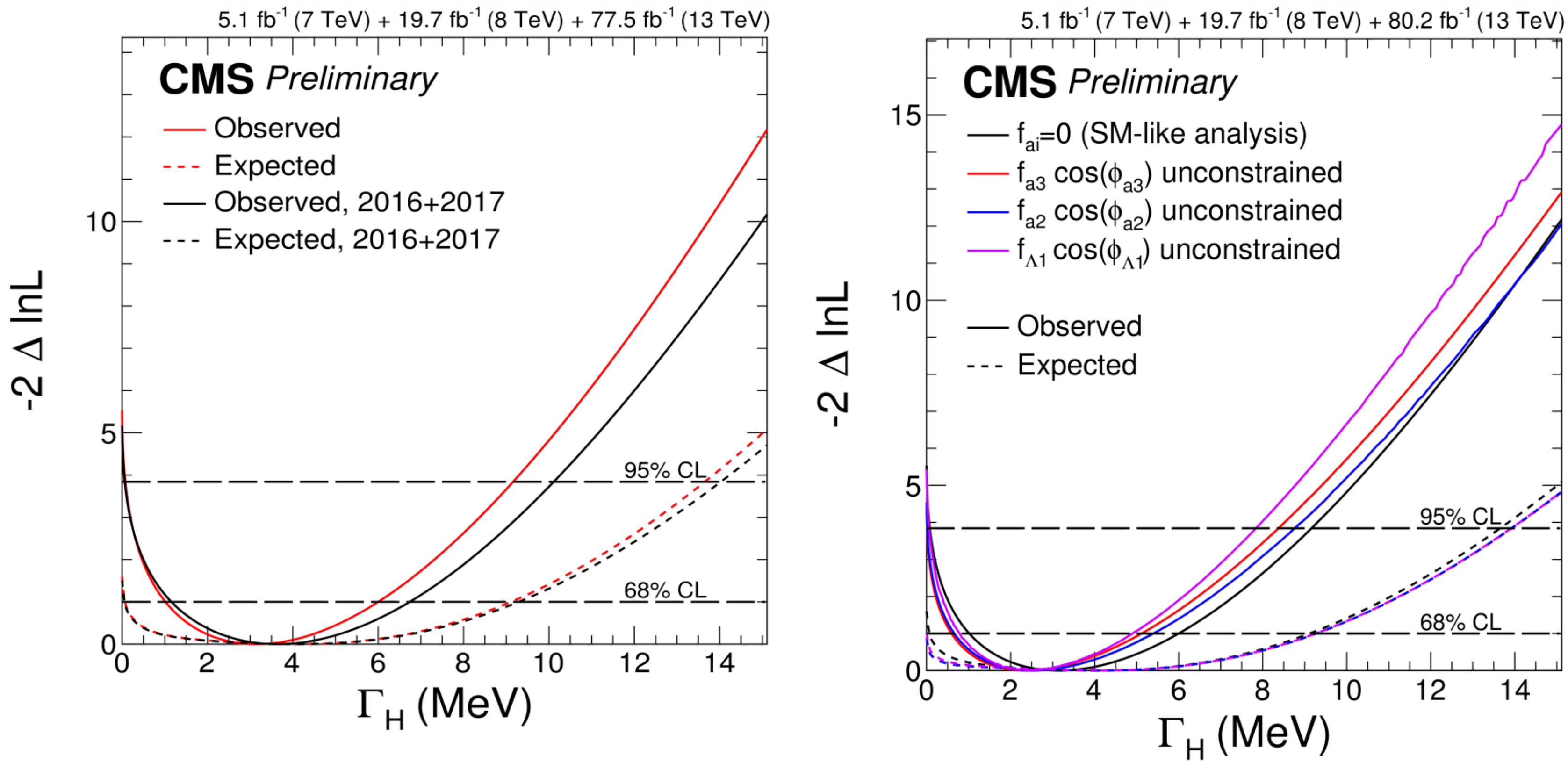
arXiv:1307.7135





Off-shell h→4*l* at 13 TeV in CMS

CMS-PAS-HIG-18-002

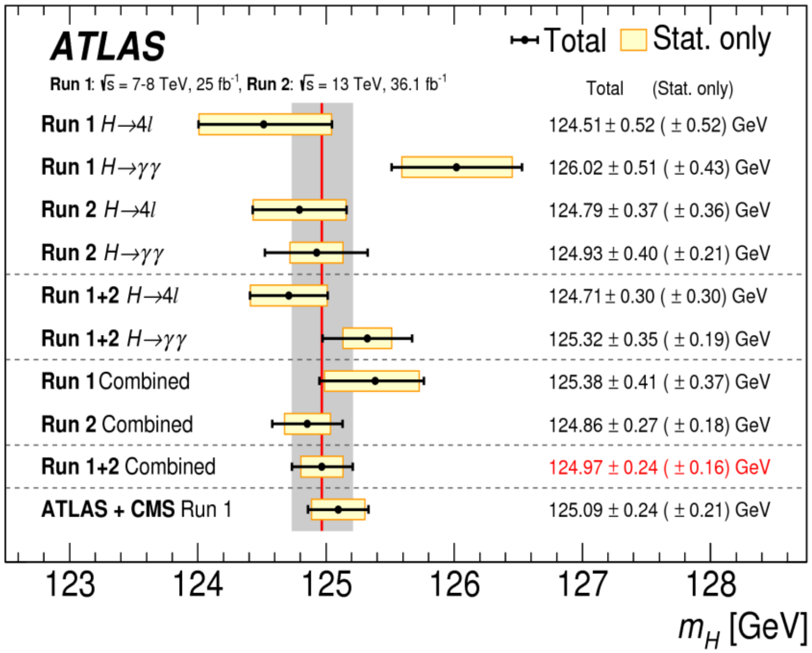


Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

The measured value is compatible with the SM prediction

Higgs boson combination: mass at 13 TeV

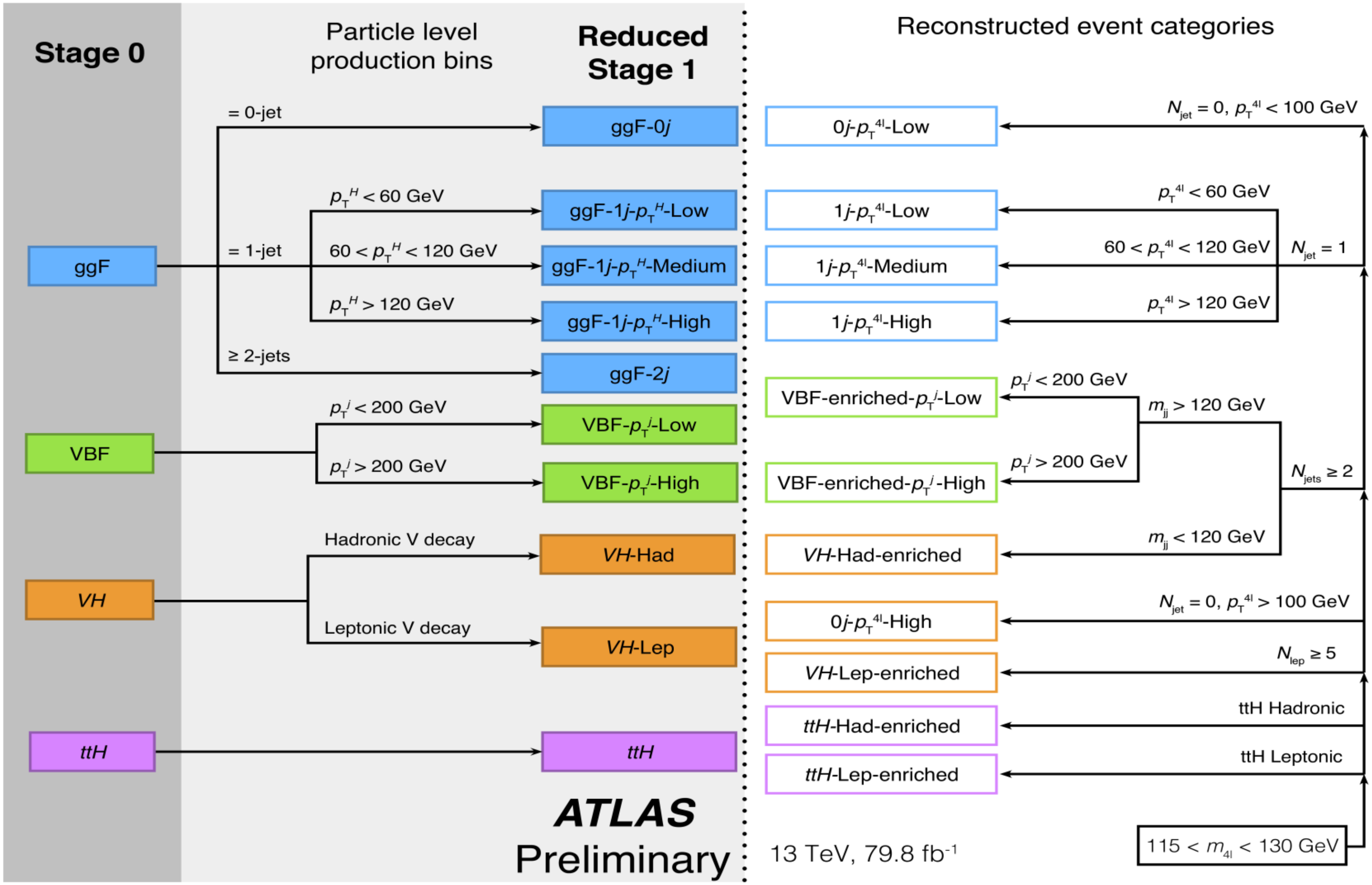
ATLAS: PL B784 (2018) 345



CMS: JHEP 11 (2017) 047

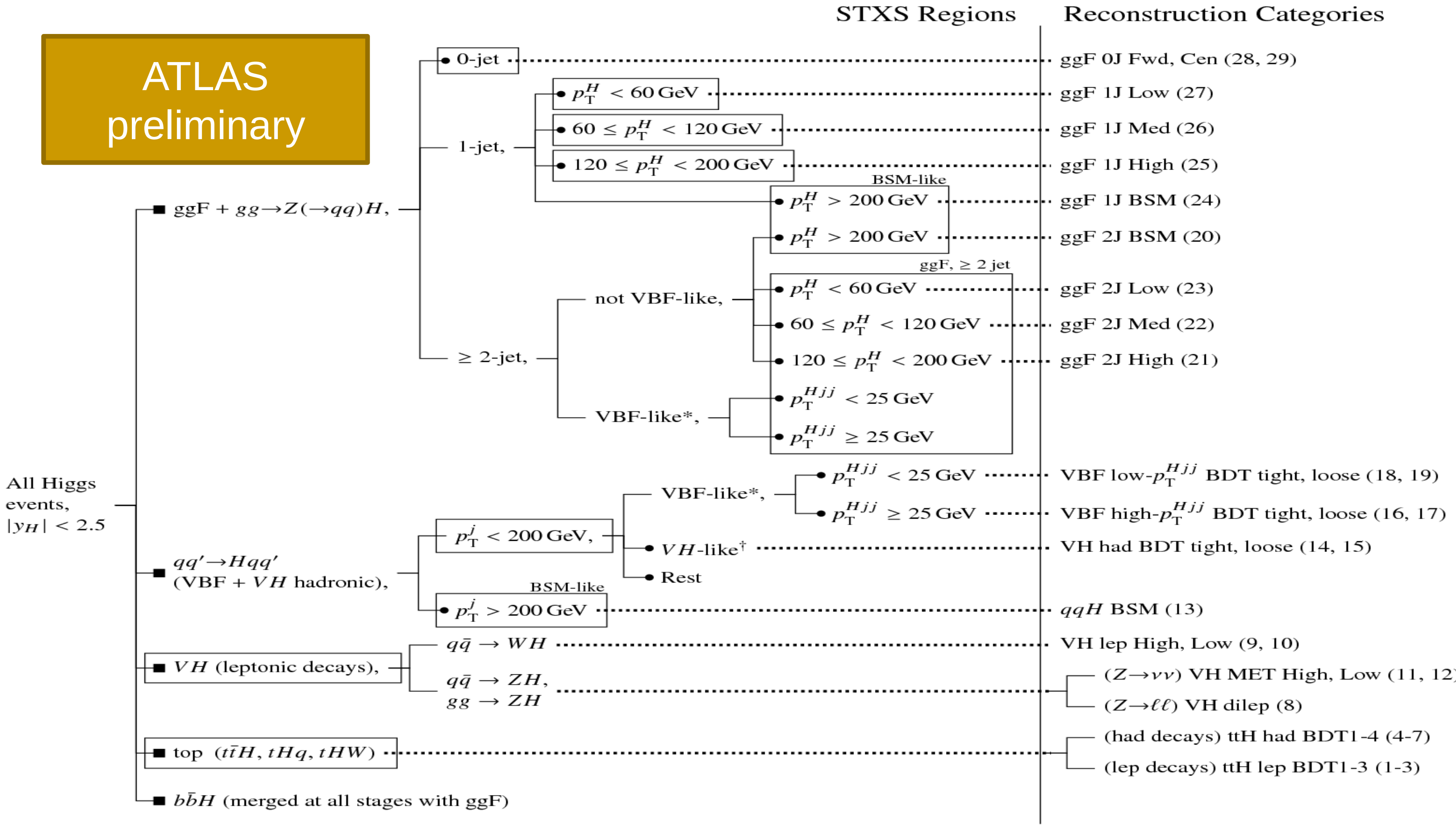
4*l* mass 125.26 ±0.21 GeV

Simplified template x-sections for h→4*l* at 13 TeV



Simplified template x-sections for h→γγ at 13 TeV

ATLAS preliminary

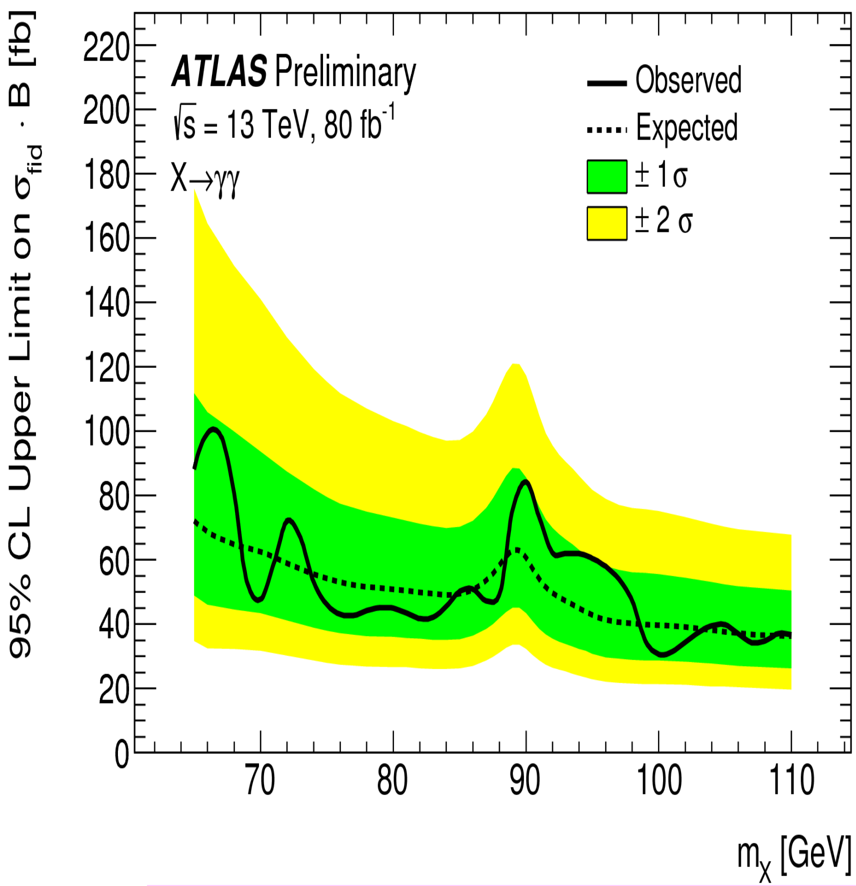


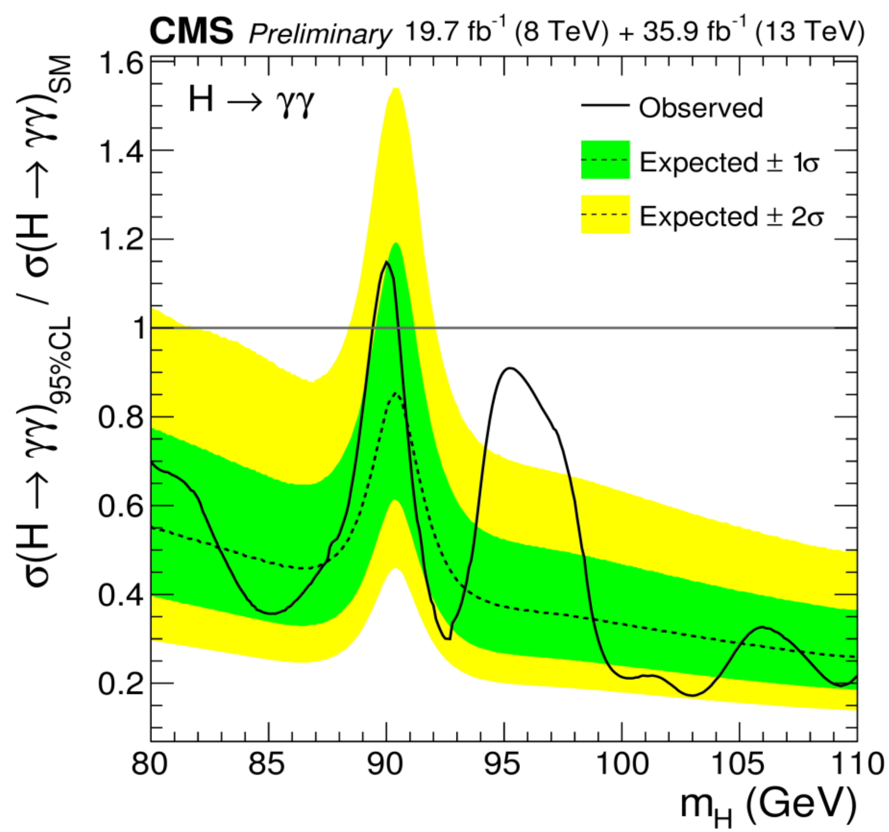
*VBF-like: m_{jj} > 400 GeV, $|\Delta y_{jj}|$ > 2.8

†VH-like: 60 < m_{jj} < 120 GeV

Low mass scalar X→γγ at 13 TeV

- **ATLAS:** ATLAS-CONF-2018-025
- **CMS:** PAS-HIG-17-013



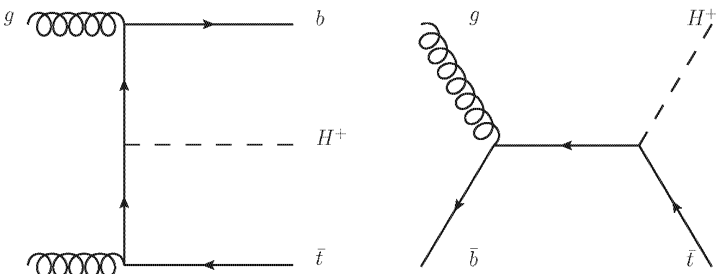


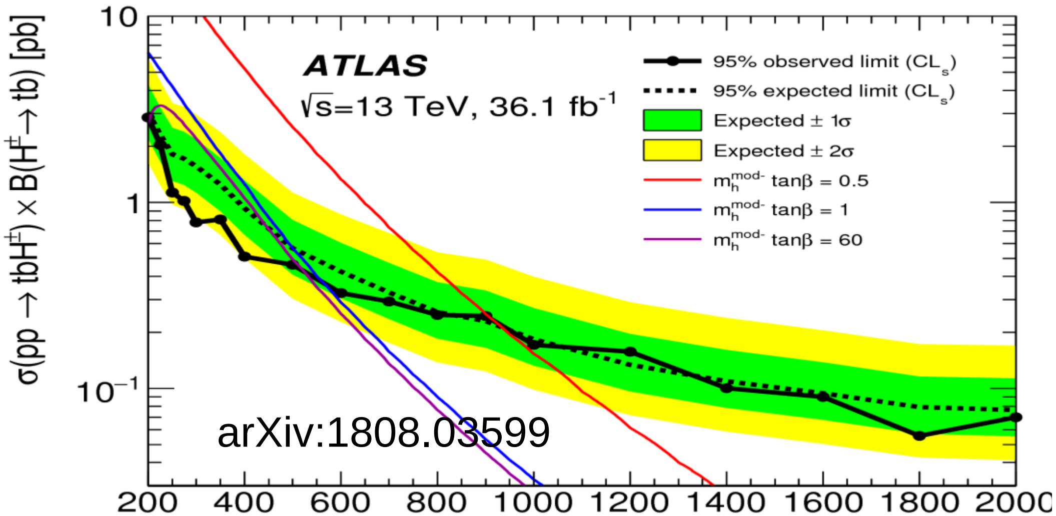
No significant deviation from the SM is observed

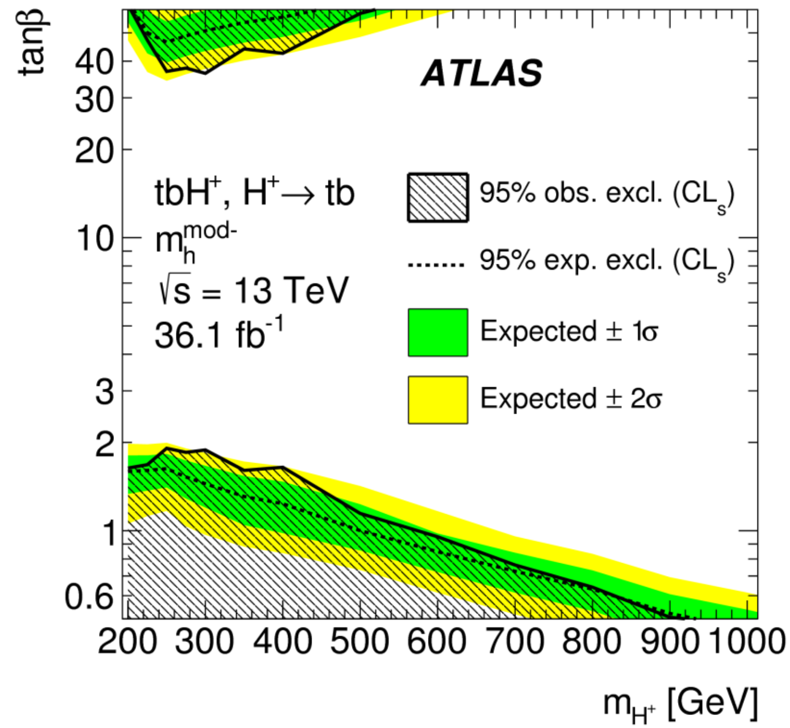
$H^+ \rightarrow tb$ at 13 TeV in ATLAS

- Search mass range: 300-1000 GeV
- Production mode $pp \rightarrow tbH^+$ ($m_H > m_{top}$)
- Multi-jet final states with one lepton from top
- Multivariate analysis, interpretation within benchmark scenarios of MSSM models

Diagrams for tbH^+ production







Limits on $\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow tb)$:
2.9 (0.070) pb at 200 (2000) GeV

Short-term LHC and ATLAS (CMS) perspectives

- 2018: collection of ≈55-60 fb^{-1} of pp collision data at 13 TeV

  Complete ATLAS and CMS data samples will correspond to about 150 fb^{-1}

  A lot of papers is planned based on these ("Run 2") data samples

- 2019-2020: LHC/ATLAS + CMS Upgrade Phase-I

  They should be upgraded to operate at luminosity up to 3×10^{34} cm^{-2} s^{-1}

- 2021-2023: Run 3 at 14 TeV energy aimed to collect 300 fb^{-1}

  More precise measurements of h(125) couplings, and its main decay channels

  Discovery of new physics or set of strict upper limits on cross sections

  Rare b-meson decays, investigation of QGP in PbPb-collisions

- 2024-2026: LHC/experiments Phase-II Upgrade

  High Luminosity (HL)-LHC, the project is under development

  ATLAS and CMS should work at up to 7×10^{34} cm^{-2} s^{-1} luminosities

  For the LHCb experiment Phase-II upgrade will be in 2030.

ATLAS and CMS perspectives for Higgs boson

- Precise measurement of five main decay modes

  10-20% with 300 fb^{-1} , 5-10% with 3000 fb^{-1}

  This precision depends on theory uncertainty to be reached in the future

- Measurement of rare h boson decay modes

  40-50% (15-30%) for $\mu\mu$ and $Z\gamma$ for 300 (3000) fb^{-1}

  Also attempt to observe $h\rightarrow cc$, $h\rightarrow J/\psi\gamma$, $\Upsilon\gamma$ decay modes with 3000 fb^{-1}

- Measurement of the SM hh production (hhh coupling)

  Might be possible only for 3000 fb^{-1} provided many decay combinations of both higgs bosons will be performed

- Discovery / evidence for BSM Higgs boson(s)?

  If not, strict limits on their production cross sections using different production mechanisms and decay modes as much as possible

Long-term LHC plans and FCC-hh

- 2026-2037 – HL-LHC stage

  Full data sample 14 TeV – 3000-4000 fb^{-1}

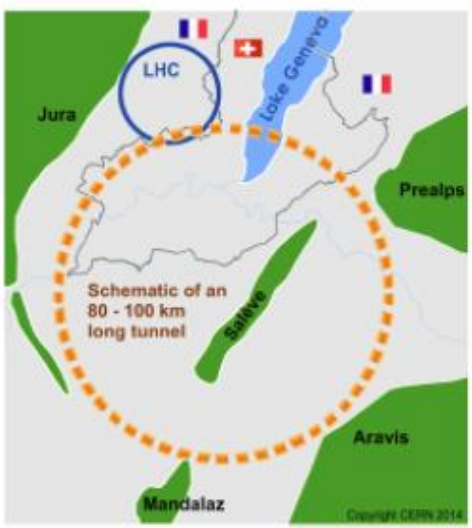
  Precision measurements of h(125) coupling, its rare decays

  Further search of new physics, very rare decays of heavy flavours

- After 2037: new (hadron) supercolliders?

  FCC-hh at CERN (pp: 28-100 TeV) or SppC in China (71 TeV)

  Another options at CERN: FCC-eh, FCC-ee…



Parameter	FCC-hh		SppC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main + 2		2	2 main + 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} cm^{-2}s^{-1}]	5	~25	12	1	5
events/bunch crossing	170	~850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
E-loss/turn synchrotron radiation/beam	5 MeV 3 MW		2 MeV 5.8 MW	7 keV 5.4 kW	7 keV 9.5 kW

Fiducial volume definition for h→4*l*

ATLAS

Leptons and jets	
Leptons:	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets:	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
remove jets with:	$\Delta R(\text{jet}, \ell) < 0.1$
Lepton selection and pairing	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12}):	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34}):	remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements:	50 GeV$< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	115 GeV $< m_{4\ell} <$ 130 GeV
If extra leptons with $p_T > 12$ GeV:	Quadruplet with the largest ME

CMS

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Subleading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7\,(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5\,(2.4)$
Sum p_T of all stable particles within $\Delta R < 0.3$ from lepton	$<0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Invariant mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Invariant mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Invariant mass of any opposite-sign lepton pair	$m_{\ell^+\ell'^-} > 4$ GeV
Invariant mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

Fiducial volume definition for h→γγ

ATLAS

Objects	Definition
Photons	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$, $p_{\mathrm{T}}^{\mathrm{iso},0.2}/p_{\mathrm{T}}^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\|y\| < 4.4$
– Central jets	$\|y\| < 2.5$
– b-jets	$\|y\| < 2.5$, $\Delta R(\mathrm{jet}, b\text{-hadron}) < 0.4$ for b-hadrons with $p_{\mathrm{T}} > 5$ GeV
Leptons, $\ell = e$ or μ	electrons: $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $\|\eta\| < 2.47$ (excluding $1.37 < \|\eta\| < 1.52$)
	muons: $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $\|\eta\| < 2.7$

Fiducial region	Definition
Diphoton fiducial	$N_{\gamma} \geq 2$, $p_{\mathrm{T}}^{\gamma_1} > 0.35 \cdot m_{\gamma\gamma}$, $p_{\mathrm{T}}^{\gamma_2} > 0.25 \cdot m_{\gamma\gamma}$
$N_{b\text{-jets}}$ measurement	Diphoton fiducial, $N_{\mathrm{jets}}^{\mathrm{Cen}} \geq 1$, $N_{\mathrm{leptons}} = 0$

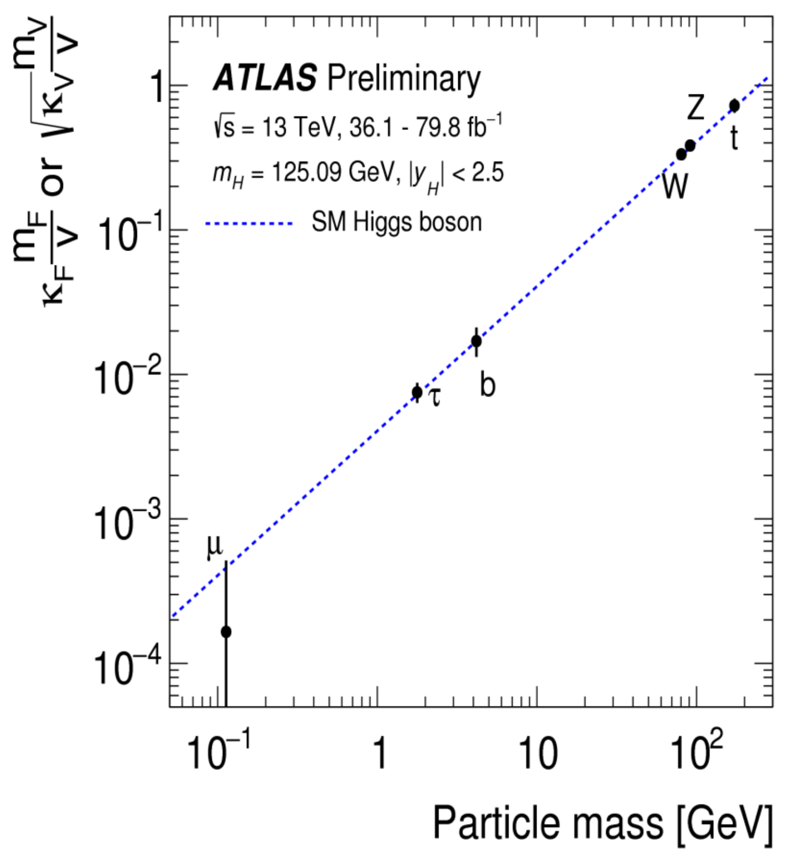
CMS

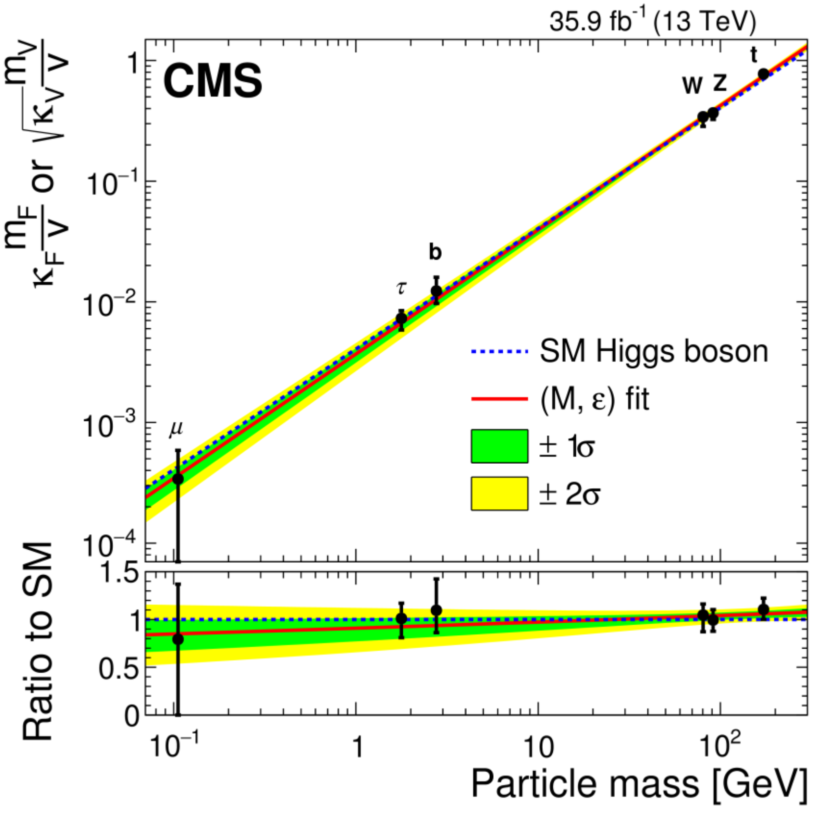
Phase space	Observable	Bin boundaries								
	$p_{\mathrm{T}}^{\gamma\gamma}$ (GeV)	0	15	30	45	80	120	200	350	∞
	N_{jet}	0	1	2	3	4	∞			
Baseline	$\|y^{\gamma\gamma}\|$	0	0.15	0.3	0.6	0.9	2.5			
$p_{\mathrm{T}}^{\gamma_1}/m_{\gamma\gamma} > 1/3$	$\|\cos(\theta^*)\|$	0	0.1	0.25	0.35	0.55	1			
$p_{\mathrm{T}}^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$p_{\mathrm{T}}^{\gamma\gamma}$ (GeV), $N_{\mathrm{jet}} = 0$	0	20	60	∞					
$\|\eta^{\gamma}\| < 2.5$	$p_{\mathrm{T}}^{\gamma\gamma}$ (GeV), $N_{\mathrm{jet}} = 1$	0	60	120	∞					
$\mathrm{Iso}_{\mathrm{gen}}^{\gamma} < 10\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\gamma\gamma}$ (GeV), $N_{\mathrm{jet}} > 1$	0	150	300	∞					
	$N_{\mathrm{jet}}^{\mathrm{b}}$	0	1	2	∞					
	N_{lepton}	0	1	2	∞					
	$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	0	100	200	∞					
1-jet	$p_{\mathrm{T}}^{j_1}$ (GeV)	0	45	70	110	200	∞			
Baseline + $\geq$1 jet	$\|y^{j_1}\|$	0	0.5	1.2	2	2.5				
$p_{\mathrm{T}}^{j} > 30\,\mathrm{GeV}$, $\|\eta^{j}\| < 2.5$	$\|\Delta\phi^{\gamma\gamma,j_1}\|$	0	2.6	2.9	3.03	π				
	$\|\Delta y^{\gamma\gamma,j_1}\|$	0	0.6	1.2	1.9	∞				
	$p_{\mathrm{T}}^{j_2}$ (GeV)	0	45	90	∞					
	$\|y^{j_2}\|$	0	1.2	2.5	4.7					
2-jets	$\|\Delta\phi^{j_1,j_2}\|$	0	0.9	1.8	π					
Baseline + $\geq$2 jets	$\|\Delta\phi^{\gamma\gamma,j_1 j_2}\|$	0	2.9	3.05	π					
$p_{\mathrm{T}}^{j} > 30\,\mathrm{GeV}$, $\|\eta^{j}\| < 4.7$	$\|\overline{\eta}_{j_1 j_2} - \eta_{\gamma\gamma}\|$	0	0.5	1.2	∞					
	$m^{j_1 j_2}$ (GeV)	0	100	150	450	1000	∞			
	$\|\Delta\eta^{j_1,j_2}\|$	0	1.6	4.3	∞					
VBF-enriched	$p_{\mathrm{T}}^{j_2}$ (GeV)	0	45	90	∞					
2-jets + $\|\Delta\eta^{j_1,j_2}\| > 3.5$,	$\|\Delta\phi^{j_1,j_2}\|$	0	0.9	1.8	π					
$m^{j_1 j_2} > 200\,\mathrm{GeV}$	$\|\Delta\phi^{\gamma\gamma,j_1 j_2}\|$	0	2.9	3.05	π					

Higgs boson combination at 13 TeV: couplings

ATLAS: CONF-2018-031 July 2018

CMS: HIG-17-031 September 2018





$h \to \mu\mu$ and $h \to Z\gamma$ exclusion at 13 TeV

Expected $B(h \to \mu\mu) = 2.2 \times 10^{-4}$ only, large DY background

ATLAS: CONF-2018-026, 80 fb^{-1}

At m_H =125 GeV for $\mu\mu$ mode

Observed exclusion: 2.1 σ/σ_{SM}

Expected exclusion: 2.0 σ/σ_{SM}

CMS: arXiv:1807.06325, 36 fb^{-1}

At m_H =125 GeV for $\mu\mu$ mode

Obs. exclusion: 2.95 σ/σ_{SM}, 2.92 with Run 1

Exp. exclusion: 2.45 σ/σ_{SM} ,2.16 with Run 1

Observed $B(H \to \mu\mu) < 0.00064$

Expected $B(h \to Z\gamma \to ee/\mu\mu\gamma) = 5 \times 10^{-5}$ only, sizeable background

ATLAS: JHEP10 (2017)112

At m_H =125 GeV for $Z\gamma$ mode based on 36 fb^{-1}

Observed exclusion: 6.6 σ/σ_{SM}

Expected exclusion: 5.2 σ/σ_{SM}

CMS: arxiv:1806.05996

At m_H =125 GeV for combined $Z(*)\gamma + \gamma^*\gamma$ mode based on 36 fb^{-1}

Observed exclusion: 3.9 σ/σ_{SM}

Expected exclusion: 2.0 σ/σ_{SM}

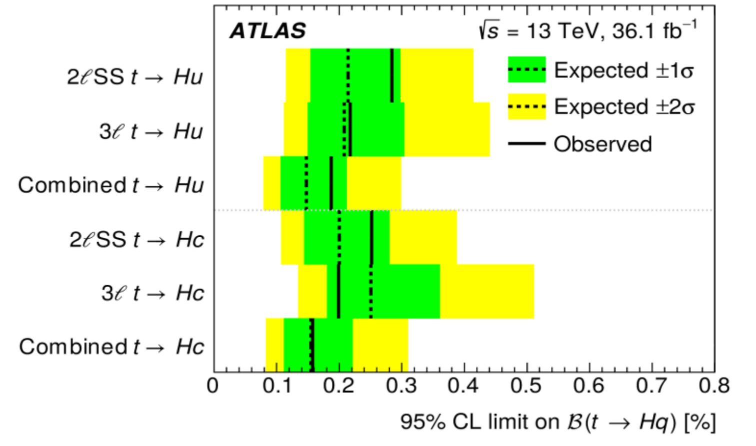
One needs HL-LHC to observe the signal in these modes

FCNC t→hc(u) in ATLAS and th-production in CMS

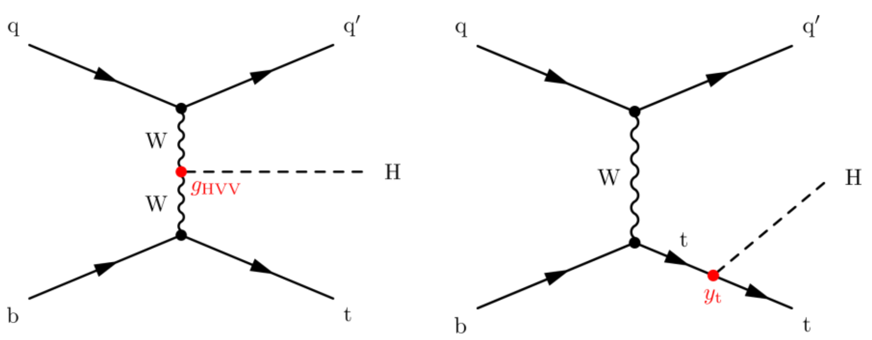
ATLAS: PR D98 (2018) 032002, 36 fb^{-1}

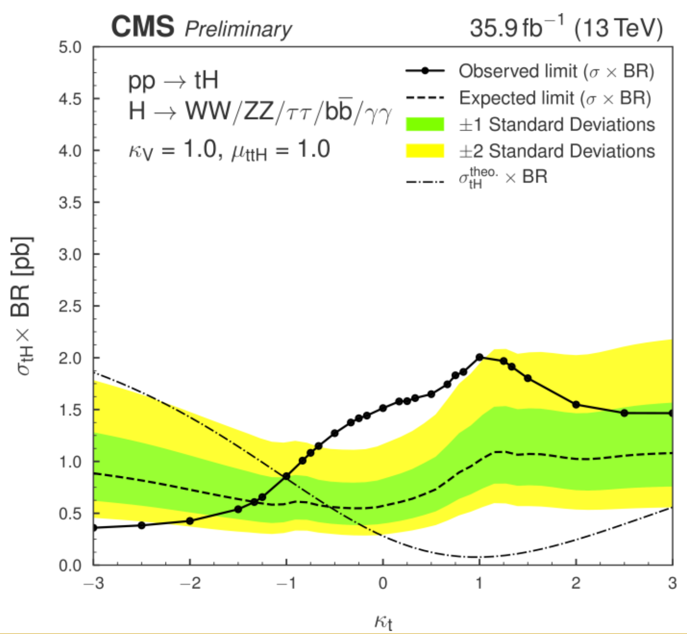
Observed exclusion: B(t→hc)<0.16%
B(t→hu)<0.19%

Expected exclusion: B(t→hc)<0.15%
B(t→hu)<0.15%



CMS: PAS-HIG-18-009, 36 fb^{-1}





Data favour positive value of the modifier of Higgs-top coupling κ_t by 1.5 σ and exclude regions [-0.9 -0.5] and [1.0 - 2.1] at 95% CL

Some models with heavy Higgs bosons

- Most studied are two simple extensions to the SM:
- Electroweak singlet (EWS)
  - New scalar singlet s that mixes with h.
- 2-Higgs-Doublet Model (2HDM)
  - Extra Higgs doublet.
  - Physical particles h, H, A, $H^{\pm}$.
  - Parameters:
    - Masses: m_h, m_H, m_A, $m_{H^{\pm}}$.
    - VEV ratio of the two doublets: $\tan\beta$.
    - Mixing angle between h, H: α.
    - Potential parameter mixing the two doublets: m_{12}^2.
  - Different ways to couple doublets with other particles; most studied:
    - Type-I: All quarks couple to only one doublet.
    - Type-II: Up-type quarks couple to one doublet, down-type quarks to the other.
  - MSSM is a subset of 2HDM.
  - Numerous MSSM benchmark models:
    - hMSSM, $m_h^{\text{mod}+}$, etc.

Denote the 125 GeV resonance as 'h'; H is a heavier resonance.