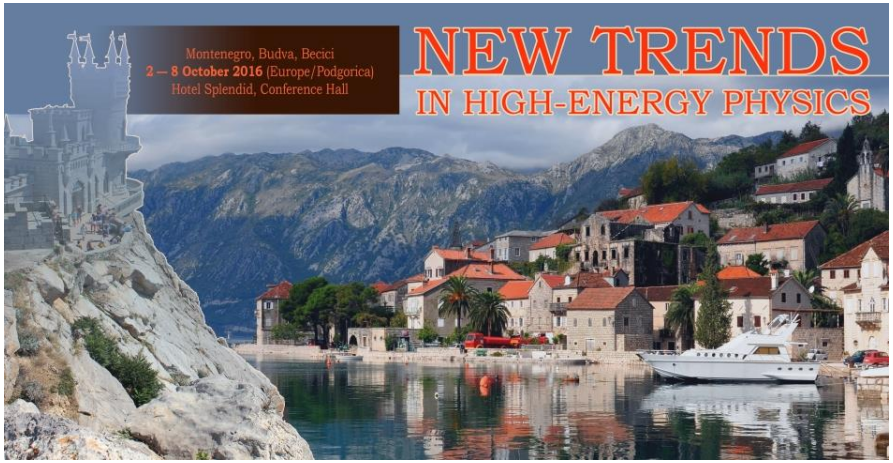
Review of Higgs Results from the ATLAS experiment

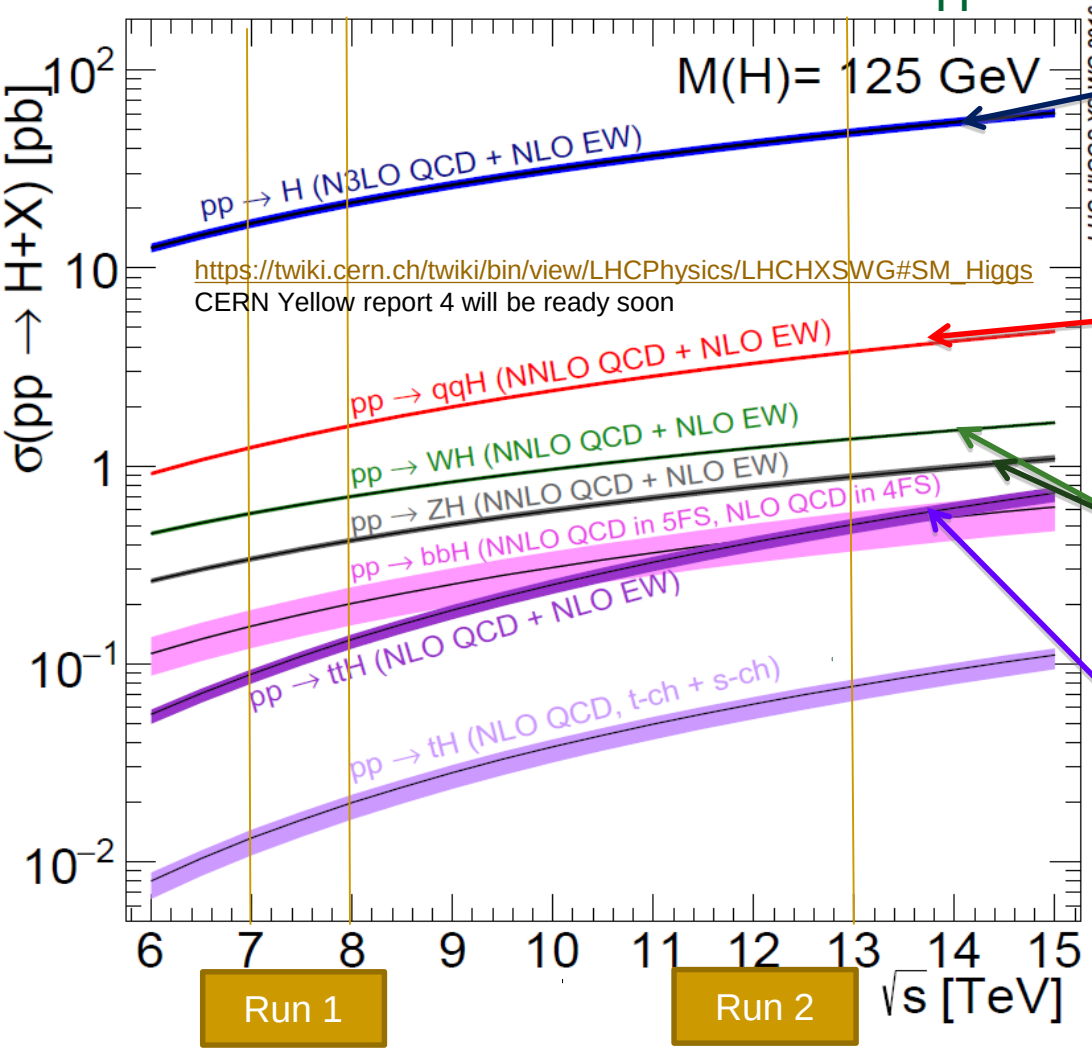


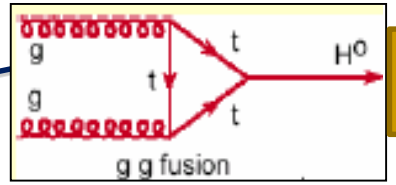
I.I. Tsukerman (ITEP, Moscow, Russia)
for the ATLAS Collaboration,
05.10.2016

Content

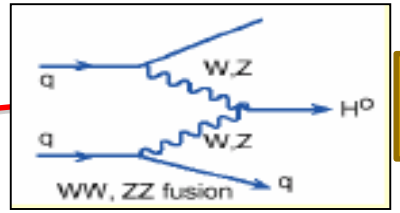
- Standard Model (SM) Higgs boson (H) decay channels
- ATLAS SM H results at 13 TeV LHC
  - H→ZZ→4*l* and H→$\gamma\gamma$ decay modes and their combination
  - (VH, H→bb), ttH and H→$\mu\mu$ production and decay modes
- Search for high-mass H-like resonances at 13 TeV
  - Bosonic H→ZZ, H→WW and H→$\gamma\gamma$ decay modes
  - Exotic H/A→$\tau\tau$ decay mode
- Search for charged Higgs bosons at 13 TeV
- Pair production of Higgs bosons at 13 TeV
- Brief summary of SM H results at 7 and 8 TeV LHC
- Conclusion

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

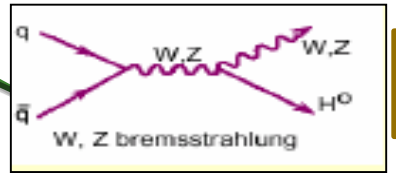




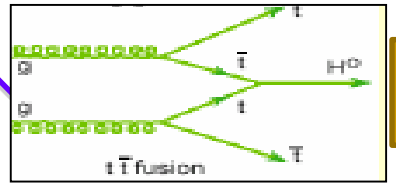
ggF
O(10) pb



VBF
O(1) pb



VH
O(1) pb



ttH
<1 pb

Not considered earlier:
bbH and tH mechanisms

Expected H branching ratios at m_H=125.09 GeV

Numbers are taken from JHEP08 (2016) 045; small update is presented in
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt13TeV

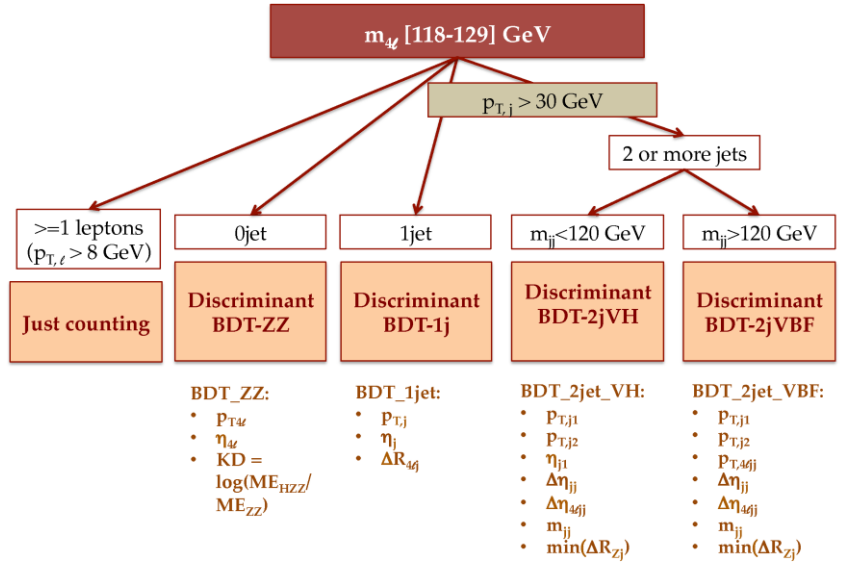
Decay mode	BR, %	Observability in the experiment	Event rates*
H→bb	57.5 ± 1.9	Mainly in VH and ttH production	>10000/15 fb^{-1}
H→WW*	**21.6 ± 0.9**	**Leptonic decays of both W**	**≈7000**/15 fb^{-1}
H→gg	8.56 ± 0.86	no good experimental signature	
H→ττ	**6.30 ± 0.36**	**Mainly in VBF production**	**≈4000**/15 fb^{-1}
H→cc	2.90 ± 0.35	No good experimental signature	
H→ZZ*	**2.67± 0.11**	**Leptonic decays of both Z**	**≈100**/15 fb^{-1}
H→γγ	**0.228 ± 0.011**	**Big continuum background**	**≈2000**/15 fb^{-1}
H→Zγ	0.155 ± 0.014	Leptonic decay of Z	≈100/15 fb^{-1}
H→μμ	0.022 ± 0.001	Big continuum background	≈200/15 fb^{-1}

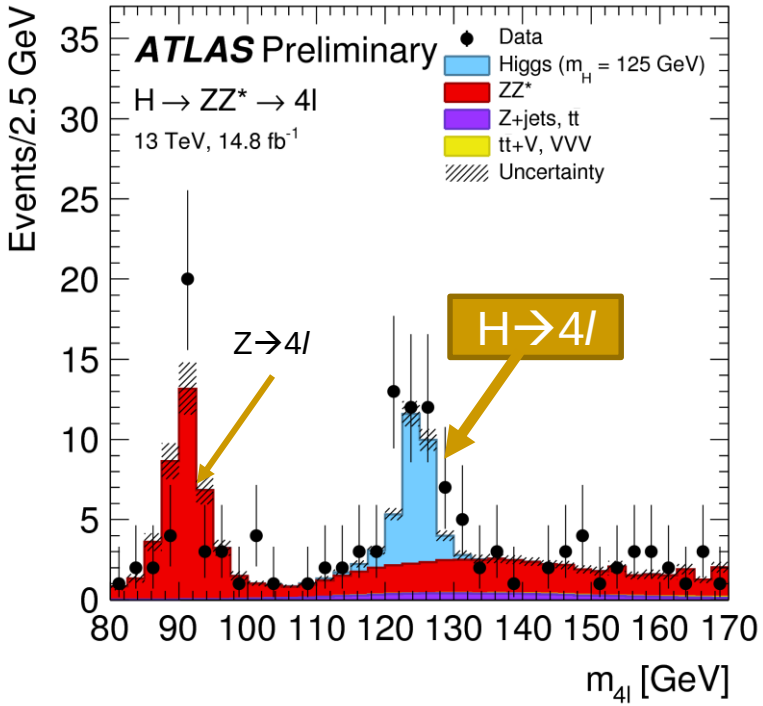
*estimated number of events, collected at 13 TeV pp collisions (for about15 fb^{-1} data sample) assuming 100% detection efficiency

H→ZZ*→4l at 13 TeV

ATLAS-CONF-2016-079

Event categorization to separate different production mechanisms of Higgs boson





Total H cross section measurement

σ_H(meas)=81$^{+18}_{-16}$ pb,

in agreement within 1.6 σ with the SM value σ_H(SM)=55.5$^{+3.8}_{-4.4}$ pb

It is based on fiducial cross section measurement (see backup slide)

44 events observed in 118-129 GeV range

Expected background (BKG): 9.7±0.8 events

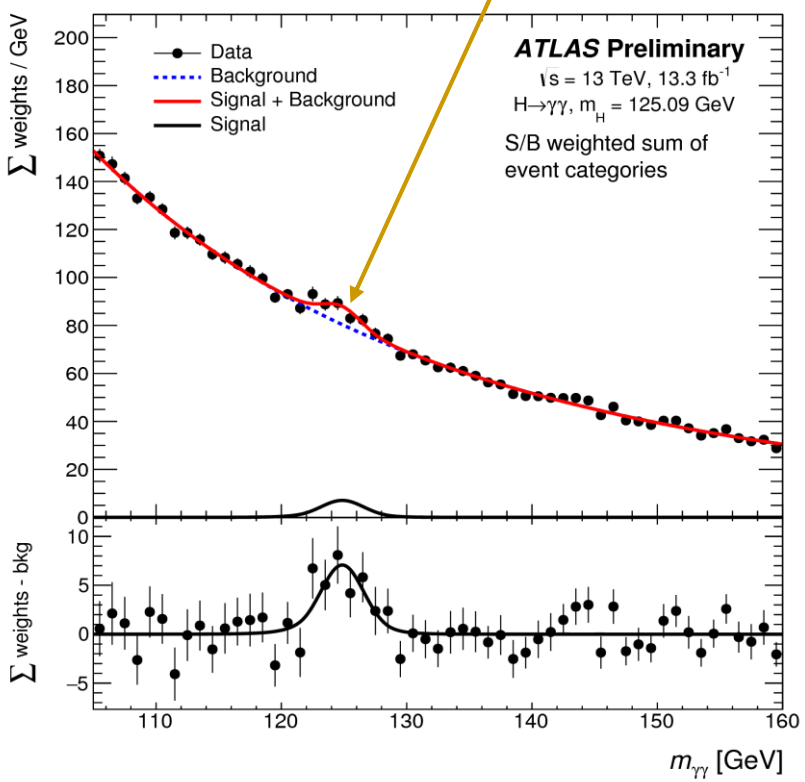
Expected signal at 125 GeV: 22.3 events

SM H is rediscovered at 13TeV LHC, cross sections are measured

H→γγ at 13 TeV

ATLAS-CONF-2016-067

Exclusive categories that are optimized for the best separation of H production processes:
13 categories which correspond to VBF-, ttH- and VH-enriched events; spectrum after weighting



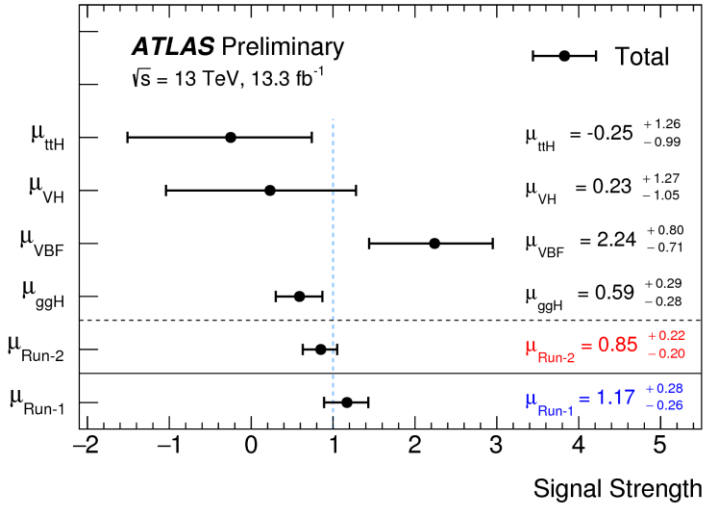
Cross section measurements:

σ_H(fid)=43.2±14.9(stat)±4.9(syst) fb,
in agreement with the SM value

$\sigma_H(SM)=62.8^{+3.4}_{-4.4}$ fb

Fid.vol.: isolated photons with high p_T

Differential cross sections also measured (see backup slide)



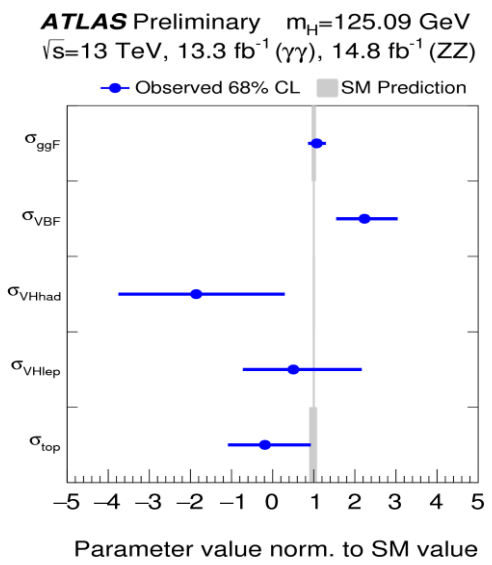
H→γγ is clearly seen at 13 TeV LHC with 4.7σ observed significance

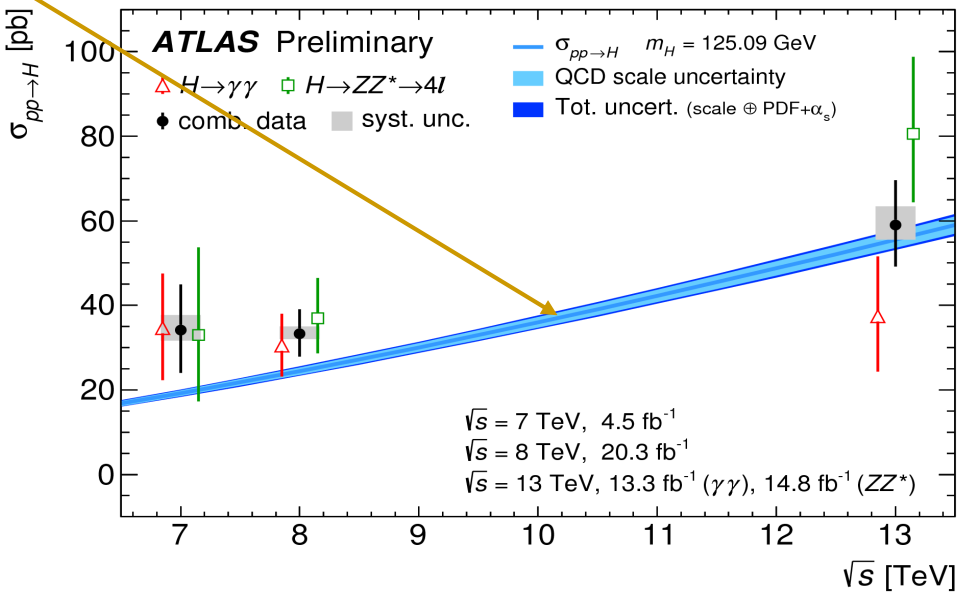
Signal strength agree with SM value,
$\mu=\sigma_{meas}/\sigma_{SM}$=0.85±0.21

Combined $H^0 \rightarrow 4l$, $\gamma\gamma$ at 13 TeV

ATLAS-CONF-2016-081

- H production is seen with local significance 10σ (8.6σ expected)
- Evidence for VBF H production is at about 4σ level (1.9σ expected)
- $\sigma_H \times$ BR are measured for ¦y¦<2.5 for ggF, VBF, VH and ttH (see backup)
- **$\sigma(pp \rightarrow H + X) = 59.0^{+9.7}_{-9.2}$ (stat) $^{+4.4}_{-3.5}$ (syst) pb** is determined from fiducial measurements and combined with older results at 7 and 8 TeV





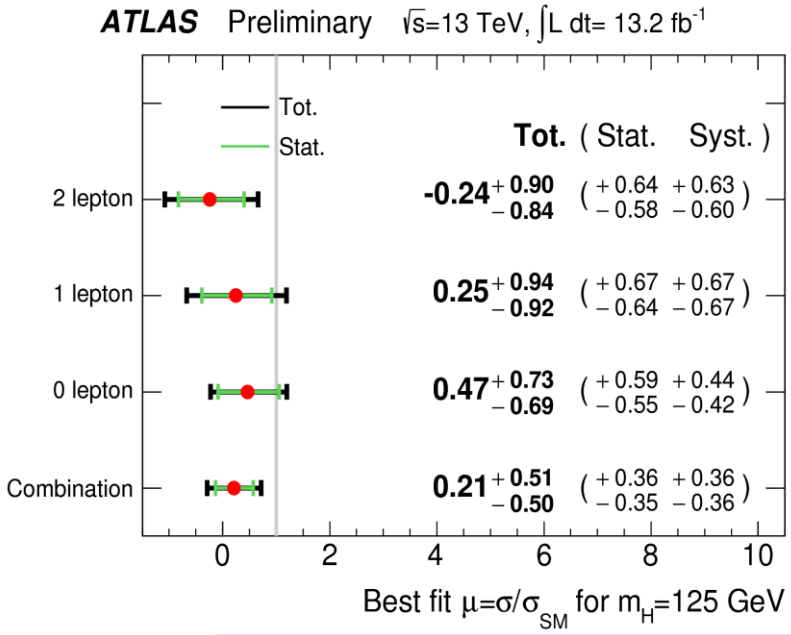
$\mu = \sigma_{meas}/\sigma_{SM} = 1.13 \pm 0.18$

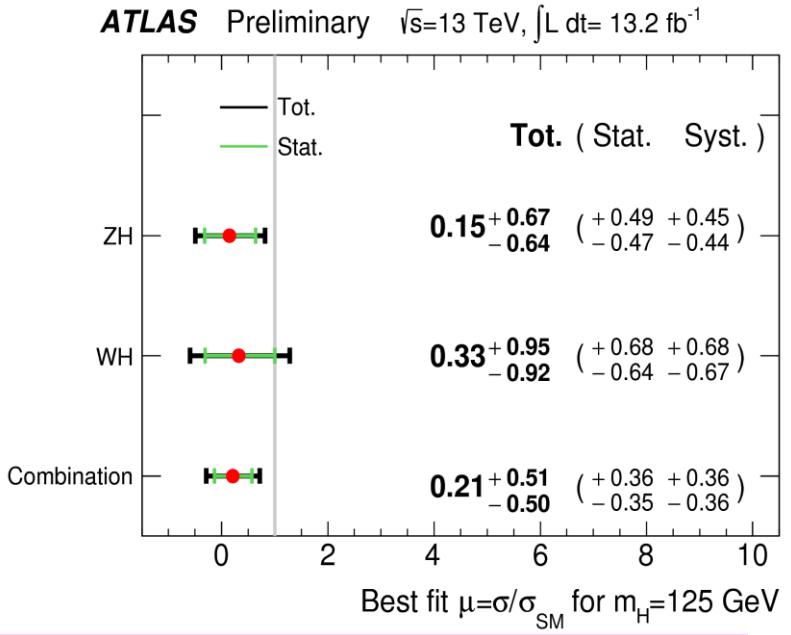
No significant deviation from SM is observed

VH, H→bb at 13 TeV

ATLAS-CONF-2016-091

- 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}
- Dozen of variables in multivariate analysis to discriminate signal from BKG
- Successful validation of the analysis procedure on (W/Z)Z with Z→bb



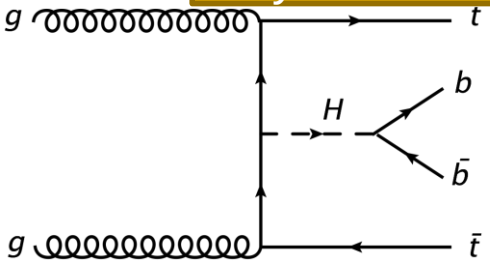


$\mu=\sigma_{meas}/\sigma_{SM}=0.21\pm0.36$ (stat) ±0.36 (syst), corresponds to 0.42σ (1.94σ) observed (expected) sensitivity

ttH, $H^0 \rightarrow bb$, at 13 TeV

ATLAS-CONF-2016-080

Feynman diagrams for ttH, H→bb



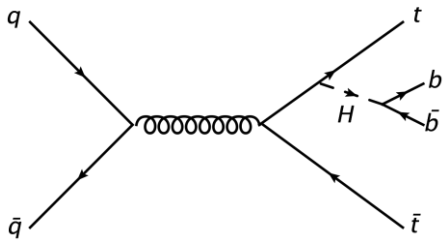
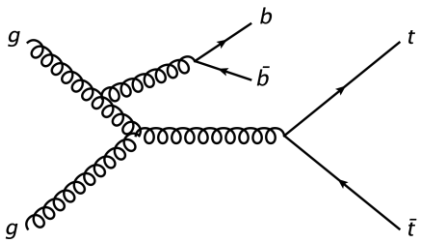
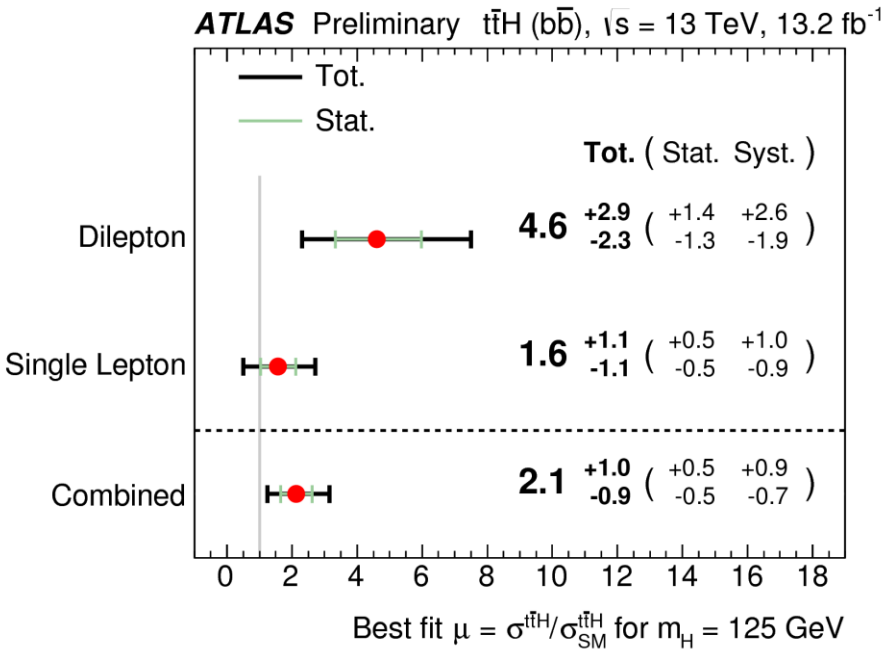


Diagram for main BKG



- Events with at least one top decaying to electron or muon
- Categorization according to jet multiplicity and number of b-jets
- Multivariate technique to discriminate signal from BKG (tt+jets mainly)

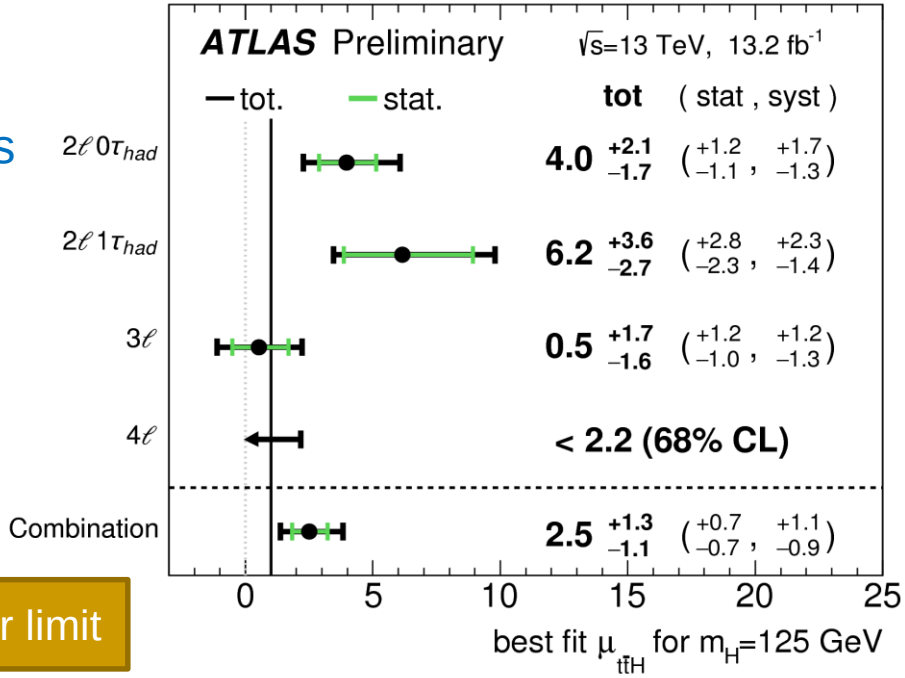


Data are compatible both with BKG-only and SM ttH hypotheses

ttH→multileptons+X at 13 TeV

ATLAS-CONF-2016-058

- Yukawa coupling of H to top can be constrained using pp→ttH+X process
- Final states contain multiple leptons, mostly from H→WW* and H→ττ



Measured signal strength μ and its upper limit

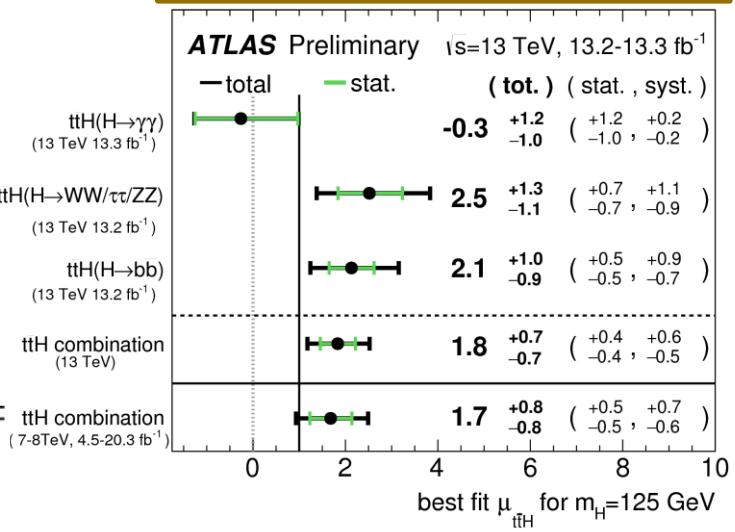
Category	Best fit $\mu_{t\bar{t}H}$	Observed (expected) 95% CL upper limit	Signal-injected 95% CL upper limit
$2\ell 0\tau_{\text{had}}$	$4.0\ ^{+1.2}_{-1.1}\ ^{+1.7}_{-1.3}$	$7.8\ (3.5\ ^{+1.7}_{-1.0})$	4.2
$2\ell 1\tau_{\text{had}}$	$6.2\ ^{+2.8}_{-2.3}\ ^{+2.3}_{-1.4}$	$12.9\ (5.9\ ^{+2.9}_{-1.6})$	6.3
3ℓ	$0.5\ ^{+1.2}_{-1.0}\ ^{+1.2}_{-1.3}$	$3.9\ (3.5\ ^{+1.5}_{-1.0})$	4.3
4ℓ	< 2.2 (68% CL)	$5.2\ (6.6\ ^{+2.9}_{-1.4})$	7.4
Combined	$2.5\ ^{+0.7}_{-0.7}\ ^{+1.1}_{-0.9}$	$4.9\ (2.3\ ^{+1.1}_{-0.6})$	3.1

ttH combined at 13 TeV

ATLAS-CONF-2016-068

Combination of $\gamma\gamma$, multilepton and bb decay channels of Higgs boson in this production mechanism

Measured signal strength



Significance in individual modes and in combination

Channel	Significance	
	Observed $[\sigma]$	Expected $[\sigma]$
$t\bar{t}H,\ H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

ATLAS-CONF-2016-067

ATLAS-CONF-2016-058

ATLAS-CONF-2016-080

$\mu=\sigma_{meas}/\sigma_{SM}=1.8\pm0.7$, 2.8σ (1.8σ) observed (expected) significance.

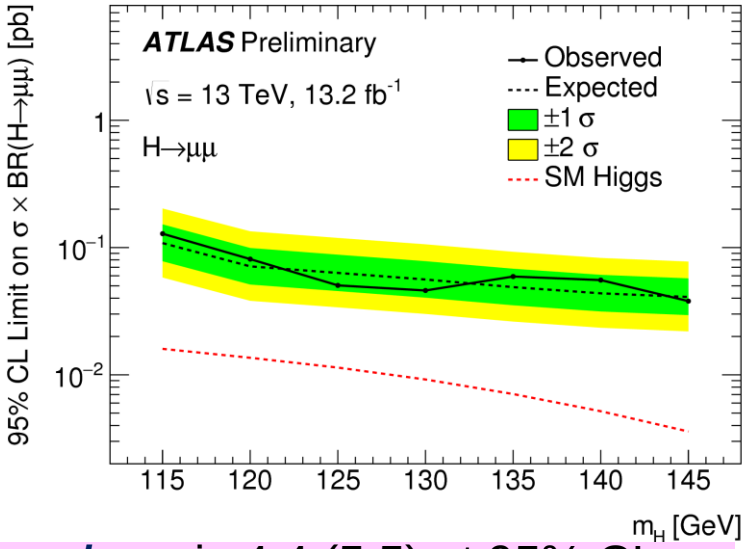
H→μμ at 13 TeV

ATLAS-CONF-2016-041

- Clean signature to measure H coupling to second-generation fermions
- Event categorization to increase signal sensitivity: seven categories with different S/B ratios based on muon η, $p_T^{\mu\mu}$, and VBF di-jet signature
- Multivariate analysis with many kinematic variables

Event rates within 120GeV< $m_{\mu\mu}$<130 GeV

	Signal[125]	Z+jets	Top	Di-boson	Total background	S/$\sqrt{B}$	Data
Central, low $p_T^{\mu\mu}$	4.0	3404	6	10	3419	0.07	3552
Non-central, low $p_T^{\mu\mu}$	10.8	13184	23	45	13252	0.09	14262
Central, medium $p_T^{\mu\mu}$	9.0	2872	49	31	2952	0.17	2883
Non-central, medium $p_T^{\mu\mu}$	23.9	10255	177	157	10590	0.23	11269
Central, high $p_T^{\mu\mu}$	6.6	1128	106	27	1261	0.19	1272
Non-central, high $p_T^{\mu\mu}$	15.4	3939	334	106	4379	0.23	4264
VBF	2.5	78	7	1	85	0.28	117



Observed (expected) upper limit on $\mu=\sigma_{meas}/\sigma_{SM}$ is 4.4 (5.5) at 95% CL
It is reduced down to 3.5 (4.3) for combined Run1 and Run2 data

Non-SM Higgs bosons

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

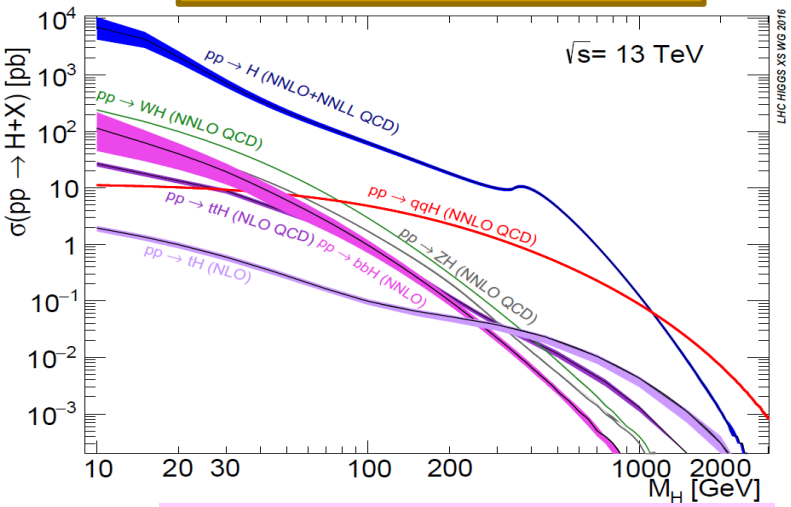
  Great success of the SM, however it does not explain many things.

- Many extensions of the SM proposed by theorists were rejected after this discovery, but some of them are OK.

The simplest "toy" model is Narrow Width Approximation (NWA) where additional high-mass Higgs boson (H) behaves as SM Higgs boson h, except the width is fixed to be equal to the h(125) width.

Very easy to produce MC samples, no interference with background processes

σ_H in NWA vs its mass



At very high m_H VBF mechanism becomes dominant for NWA H!

Another option is additional Higgs doublet:

- 5 Higgs bosons

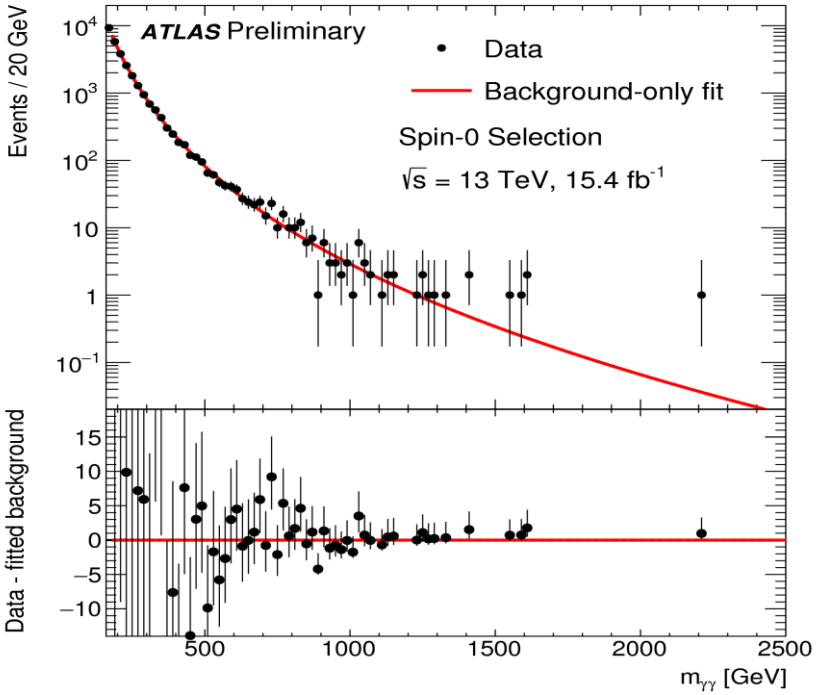
CP-even Higgses (*) CP-odd Higgs (*) Charged (*)

* assuming CP conservation

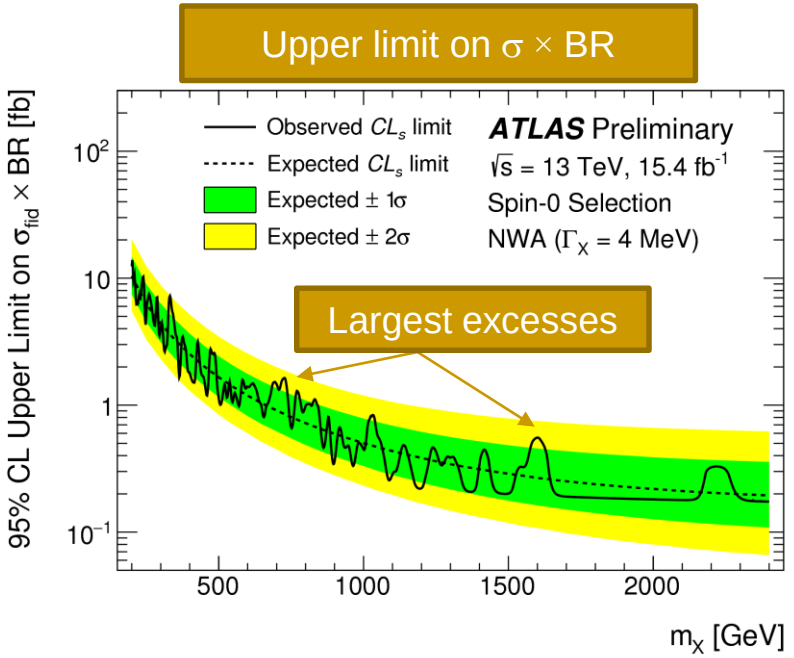
High-mass H→γγ at 13 TeV

ATLAS-CONF-2016-059

- Excess near 750 GeV seen in γγ 2015 data (3.2 fb^{-1}) both by ATLAS and CMS
- In ATLAS, deviation from the SM was at 3.4σ level at m_H=730 GeV
- New analysis uses five times larger data sample, mostly taken in 2016
- Search mass range is 200-2500 GeV



35891 events with hard γ selected



Data consistent with SM hypothesis
Global significance of excesses <1σ

High-mass H→WW→lνlν at 13 TeV

ATLAS-CONF-2016-074

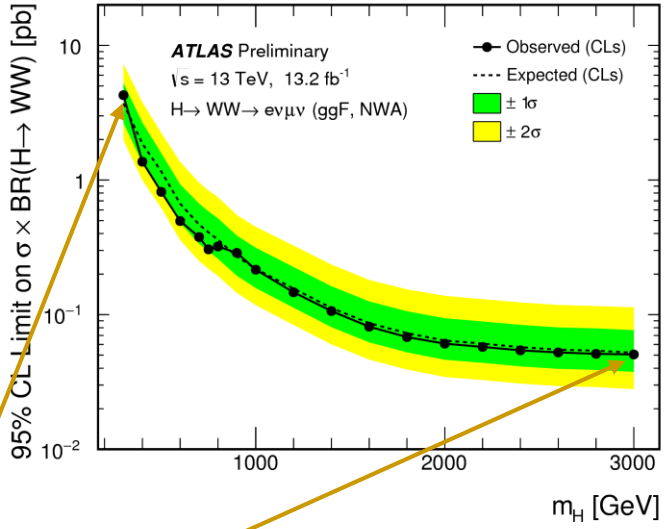
- Search mass range: 300-3000 GeV
- Selection criteria optimized for high-mass Higgs boson searches; multivariate analysis
- ggF- and two VBF-enriched categories
- Only WW→eνμν decay channel used

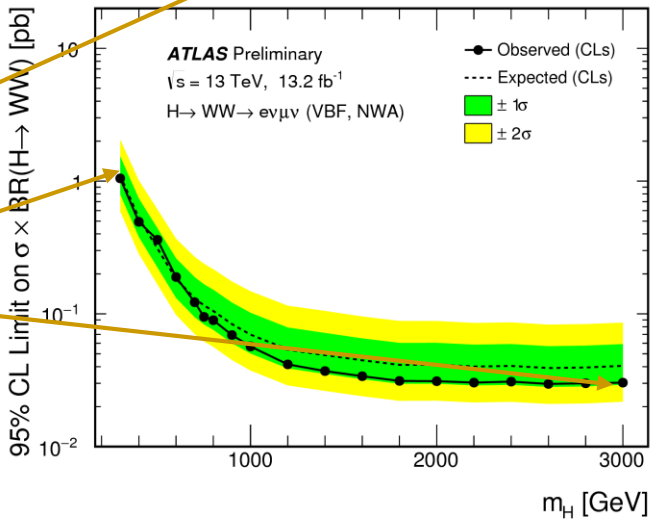
Observed 95% CL exclusion for
$\sigma_H \times BR(H \to WW)$ using NWA approach:

<4.3 pb at m_H=300 GeV for ggF production
<51 fb at m_H=3000 GeV for ggF production

<1.1 pb at m_H=300 GeV for VBF production
<30 fb at m_H=3000 GeV for VBF production

No significant excess above background is found in the search mass range





High-mass H→ZZ→4*l* at 13 TeV

ATLAS-CONF-2016-079

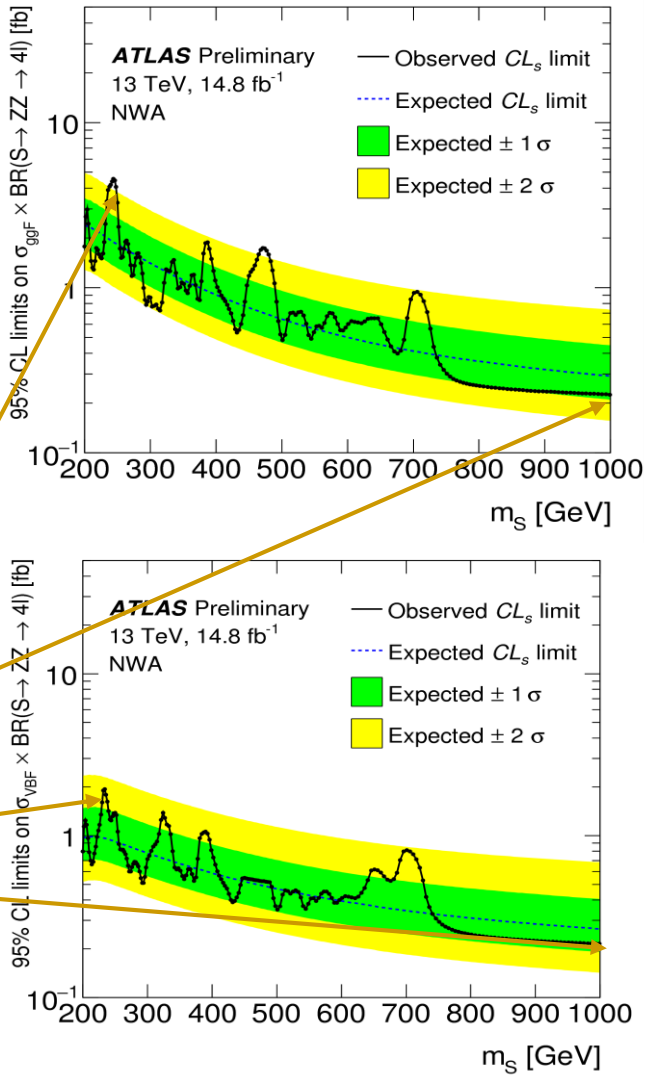
- Search mass range: 200-1000 GeV
- Selection criteria optimized for high-mass Higgs boson searches; multivariate analysis
- ggF- and VBF-enriched categories

Observed 95% CL exclusion for
$\sigma_H \times BR(H\rightarrow 4l)$ using NWA approach:

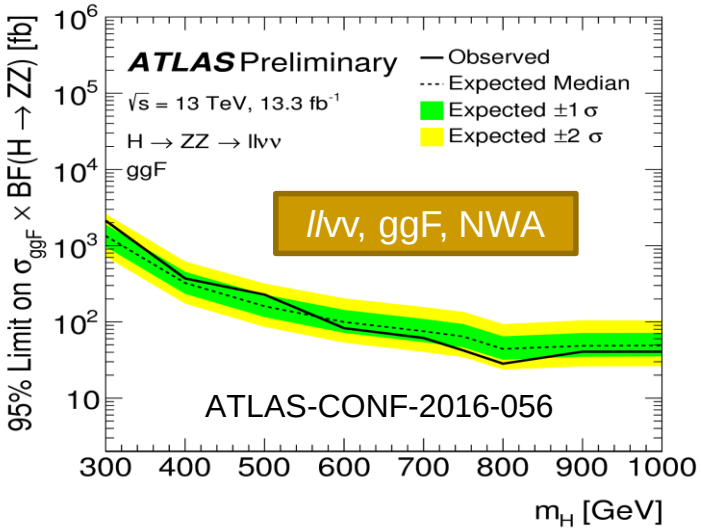
<4.6 fb at m_H=244 GeV for ggF production
<0.22 fb at m_H=1000 GeV for ggF production

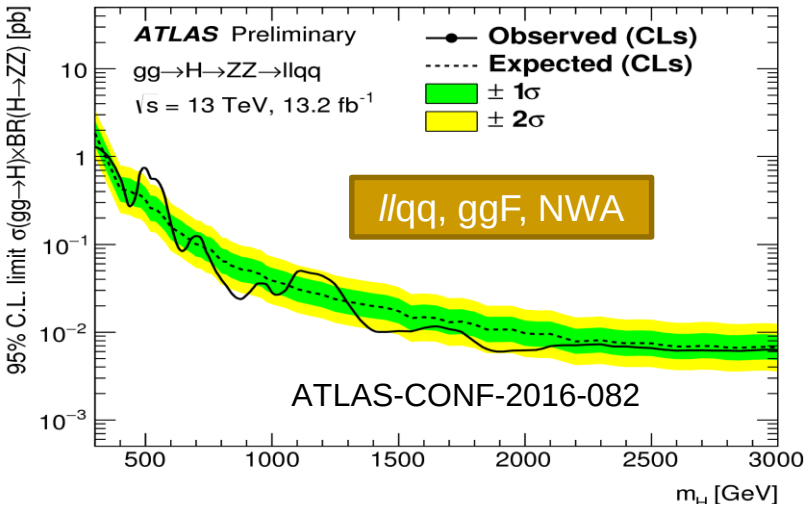
<1.9 fb at m_H=234 GeV for VBF production
<0.2 fb at m_H=1000 GeV for VBF production

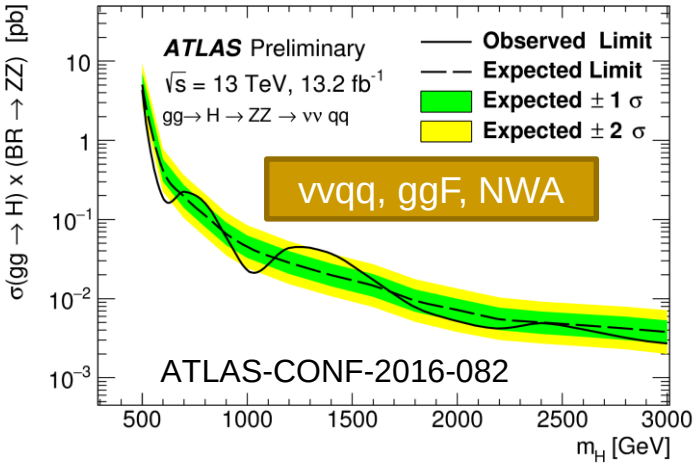
No significant excess above background is found in the search mass range

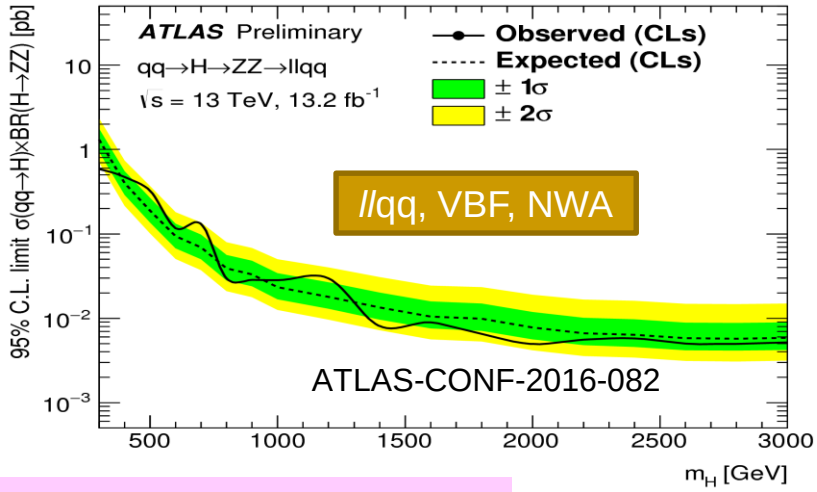


High-mass H→ZZ→(*ll*νν,*ll*qq,ννqq) at 13 TeV









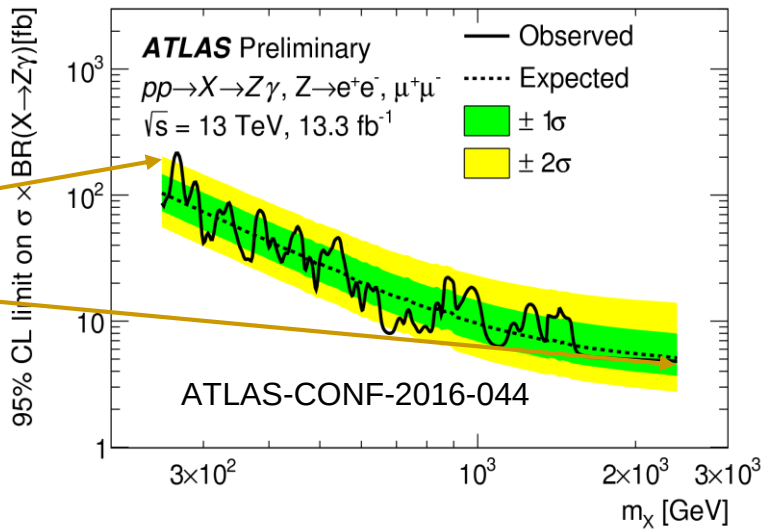
No significant deviation from SM is observed

High-mass H→Zγ and H→WW→lνqq at 13 TeV

Observed 95% CL exclusion for
$\sigma_H \times BR(H \to Z\gamma)$ using NWA approach:

<215 fb at m_H=270 GeV
<5 fb at m_H=2400 GeV

No significant excess above BKG is found in the range 250-2400 GeV

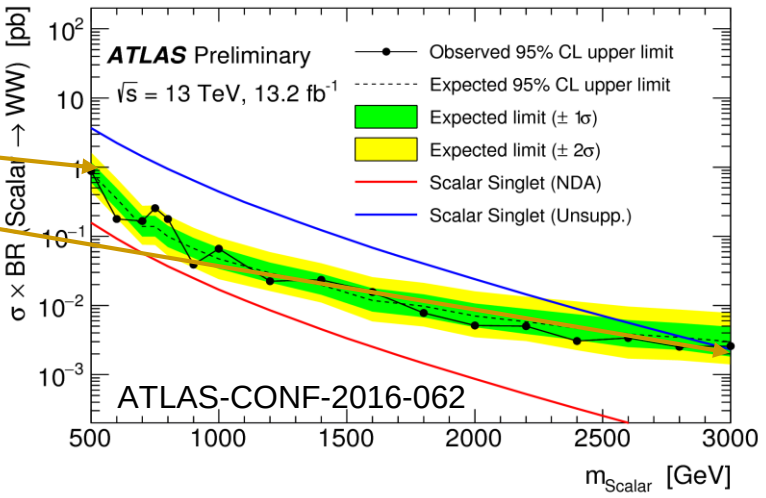


Observed 95% CL exclusion in ggF for
$\sigma_H \times BR(H \to WW)$ using NWA approach:

<1 pb at m_H=500 GeV
<2.5 fb at m_H=3000 GeV

Other models also considered, limits put

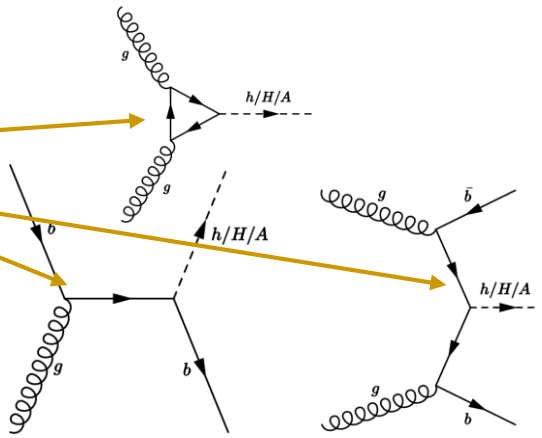
No significant excess above BKG is found in the range 500-3000 GeV

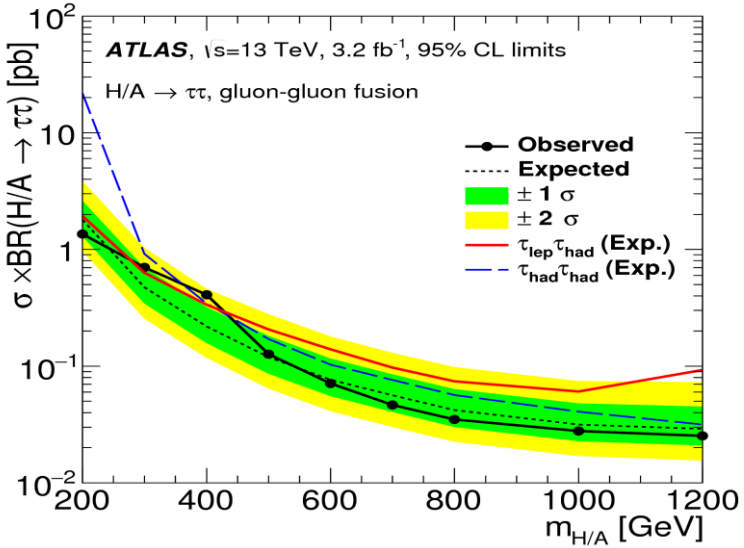


$A/H^0 \rightarrow \tau\tau$ at 13 TeV in ATLAS

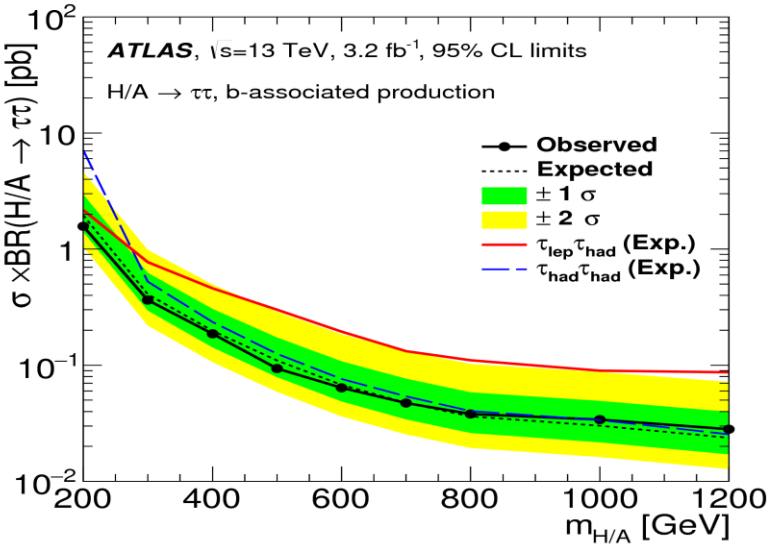
ATLAS-CONF-2016-085

- Search mass range: 200-1200 GeV
- Production via gluon fusion or b-associated
- hh and /h final states of two taus
- Interpretation in MSSM benchmark scenarios





Limits on $\sigma \times BR(H/A \rightarrow \tau\tau)$ for ggF: 1.3 (0.025) pb at 200 (1200) GeV



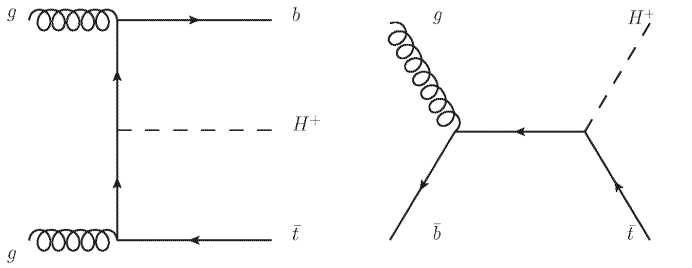
Limits on $\sigma \times BR(H/A \rightarrow \tau\tau)$ for bH/A: 1.5 (0.03) pb at 200 (1200) GeV

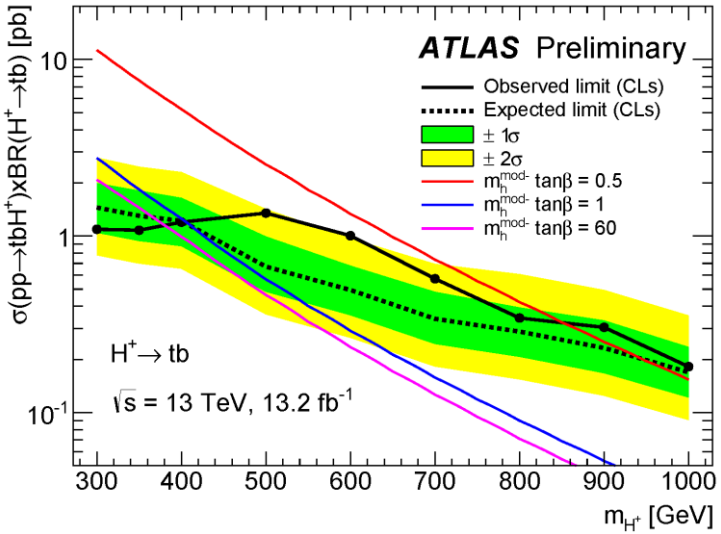
$H^+ \rightarrow tb$ at 13 TeV in ATLAS

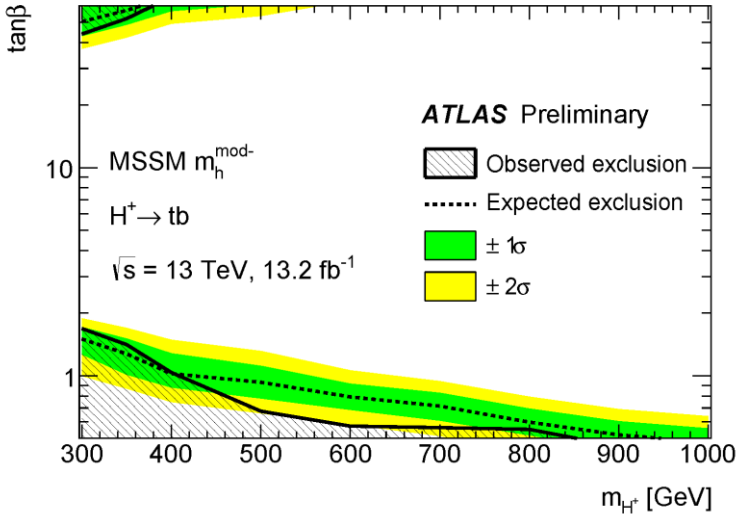
ATLAS-CONF-2016-089

- 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 **$\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow tb)$**: 1.09 (0.18) pb at 300 (1000) GeV

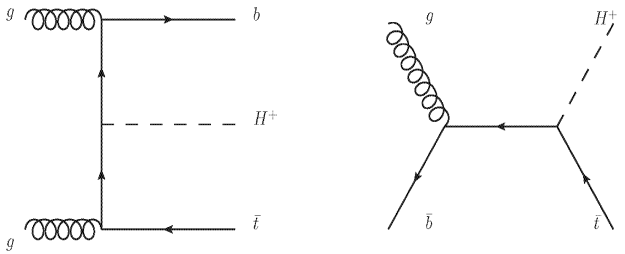
Limits on **tanβ**: some values are excluded mostly for low m_H

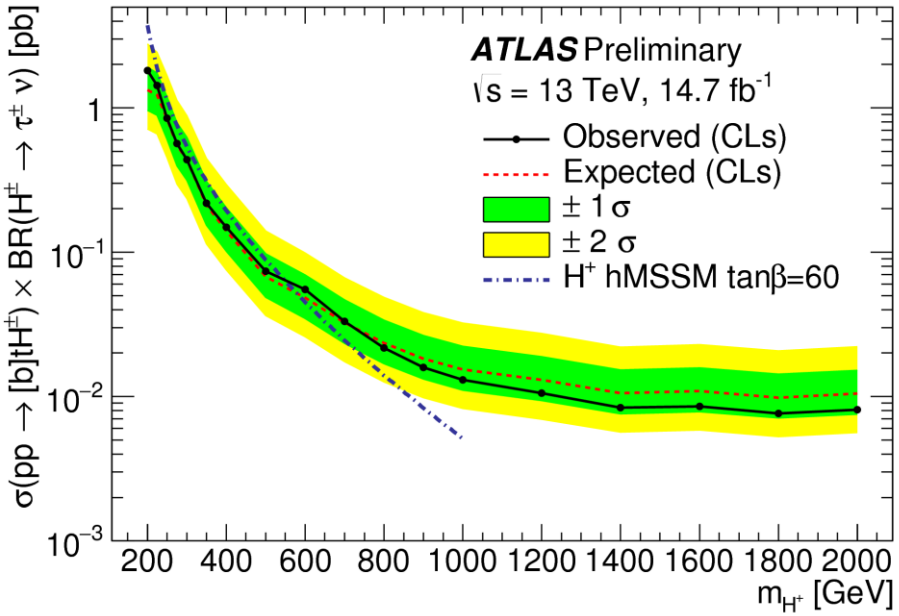
$H^+ \rightarrow \tau\nu$ at 13 TeV in ATLAS

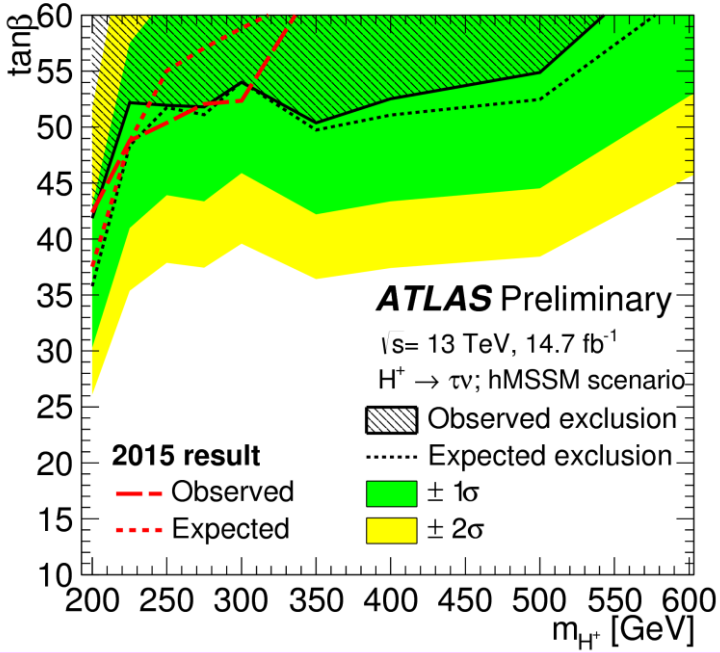
ATLAS-CONF-2016-088

- Search mass range: 200-2000 GeV, production mode $pp \rightarrow tbH^+$ ($m_H > m_{top}$)
- Final states with one τ-lepton and $W \rightarrow$ hadrons
- Interpretation in the one of the hMSSM benchmark scenario

Diagrams for tbH^+ production







Limits on $\sigma(pp \rightarrow tbH^+) \times BR(H^+ \rightarrow \tau\nu)$: 2 (0.008) pb at 200 (2000) GeV

Limits on $\tan\beta$: very large values are excluded mostly for low m_H

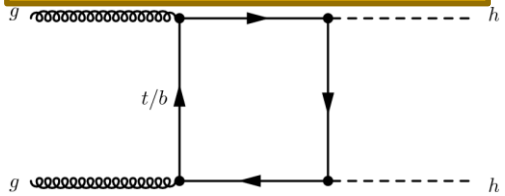
Brief summary of H results at 7-8 TeV

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→γγ mode	$1.17^{+0.28}_{-0.26}$	EPJC76 (2016) 6	5.2σ (discovery)
in H→4*l* mode	$1.46^{+0.40}_{-0.34}$	EPJC76 (2016) 6	8.1σ (discovery)
in H→WW*→lνlν	$1.18^{+0.24}_{-0.21}$	EPJC76 (2016) 6	6.5σ (discovery)
in H→ττ mode	$1.44^{+0.42}_{-0.37}$	EPJC76 (2016) 6	4.5σ (evidence)
in H→bb mode	$0.63^{+0.39}_{-0.37}$	EPJC76 (2016) 6	1.4σ (no evidence)
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	4*l*, *l*ν*l*ν, γγ modes
Width	**<22.7 MeV (95% CL)**	EPJC 75 (2015) 335	Off-shell H→WW/ZZ
BR(H→invisible)	**<0.28 (95% CL)**	JHEP 01 (2016) 172	WIMP searches

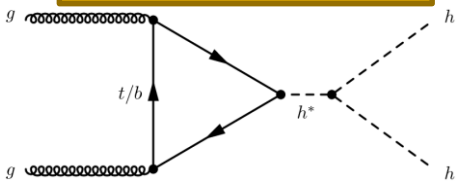
No significant deviation from SM is observed

hh→WWγγ and bbbb at 13 TeV

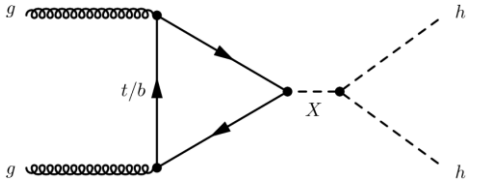
SM H, heavy-quark loop



SM H self-coupling



BSM heavy resonance



SM hh rates are too small for observation, but BSM rates could be much larger

Observed 95% CL exclusion for $\sigma_{gg\to X}$ × **BR(H→hh)**:

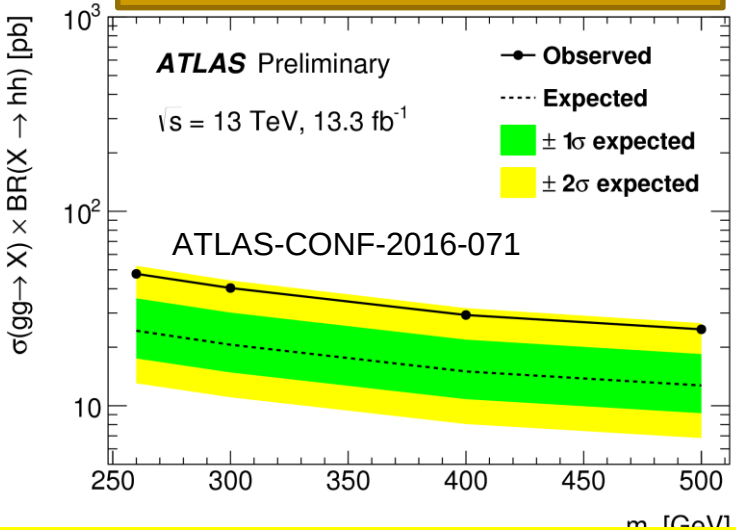
Non-resonant: <25 pb

Resonant: <47.7 fb at m_H=260 GeV

<24.7 pb at m_H=500 GeV

No significant excess above BKG is found in the range 250-500 GeV

hh→γγWW→γγ/vjj final state



Observed 95% CL exclusion for $\sigma_{gg\to H}$ × **BR(H→hh→bbbb)**:

Non-resonant: <330 fb, SM prediction is 11.3 ±1.0 fb

ATLAS-CONF-2016-049

No significant excess above BKG is found in the range 300-3000 GeV

Conclusion

With 7 and 8 TeV LHC data ATLAS measured properties of the Higgs boson such as its couplings, mass, spin and parity.
No deviation from the SM is found.

Using 13-15 fb^{-1} of 13 TeV LHC data, ATLAS obtained preliminary results reconfirming Higgs boson discovery in $4l$ and $\gamma\gamma$ modes.

With the same dataset, ATLAS performed searches for neutral and charge Higgs bosons predicted by some extensions of SM. No evidence for new physics was found yet. Limits on H boson production cross sections in different models were put.

ATLAS continue to study properties of the SM-like H boson improving precision of their measurements and to search for exotic Higgs bosons with new 13-14 TeV data.

Backup slides

• H→ZZ*→4*l* at 13 TeV: details	ATLAS-CONF-2016-079
• H→γγ at 13 TeV: details	ATLAS-CONF-2016-067
• H→ZZ*→4l *and* γγ at 13 TeV: details	ATLAS-CONF-2016-081
• H→γγ high-mass at 13 TeV: details	ATLAS-CONF-2016-059
• H→WW→*l*ν*l*ν high-mass at 13 TeV: details	ATLAS-CONF-2016-074
• Higgs boson mass ATLAS+CMS at 7 and 8 TeV	PRL 114 (2015) 191803
• Higgs boson couplings ATLAS+CMS at 7/8 TeV	JHEP08 (2016) 045
• Higgs boson spin/parity at 8 TeV	EPJC 75 (2015) 476
• Off-shell H→WW and H→ZZ (width) at 8 TeV	EPJC 75 (2015) 335
• H→4*l* and H→γγ diff. cross sections at 8 TeV	PRL 115 (2015) 091801
• VBF H→invisible at 8 TeV	JHEP 01 (2016) 172
• H/Z decays to J/ψγ and Υγ at 8 TeV	PRL 114 (2015) 121801
• Pair production of Higgs bosons at 8 TeV	PRD92 (2015) 092004
• Higgs boson perspectives	a few notes
• VBF+γ H→bb at 13 TeV	ATLAS-CONF-2016-059

Higgs results not covered in these slides

- Most publications/notes issued before 2016
- About ten publications based on first 13 TeV dataset (2015 year data only)
- VBF H→bb at 8 TeV — arXiv:1606.02181, submitted to JHEP
- Lepton-flavour-violating decays of the Higgs — arXiv:1604.07730, submitted to EPJC
- ttH, H→bb at 8 TeV — JHEP05 (2016) 160
- gg→H→WW* cross sections at 8 TeV — JHEP08 (2016) 104
- CP test in VBF H production at 8 TeV — arXiv:1602.04516, submitted to EPJC
- H→tb at 8 TeV — JHEP03 (2016) 127

H→ZZ*→4l at 13 TeV

ATLAS-CONF-2016-079

Cuts for fiducial cross section measurement

Lepton definition	
Muons: $p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$	Electrons: $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading leptons $p_{\mathrm{T}} > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV

Measured fiducial cross sections

Final state	measured σ_{fid} [fb]	$\sigma_{\mathrm{fid,SM}}$ [fb]
4μ	$1.28\ ^{+0.48}_{-0.40}$	$0.93\ ^{+0.06}_{-0.08}$
$4e$	$0.81\ ^{+0.51}_{-0.38}$	$0.73\ ^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\ ^{+0.58}_{-0.46}$	$0.67\ ^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\ ^{+0.49}_{-0.40}$	$0.76\ ^{+0.05}_{-0.06}$

Results agree with SM predictions

Acceptance factors $\mathcal{A}$ [%]					
Decay	Production mode				
Channel	ggF	VBF	WH	ZH	$t\bar{t}H$
4μ	50.9	55.0	43.8	46.5	53.6
$4e$	39.6	43.9	34.4	36.0	44.6
$2\mu 2e$	40.0	42.9	34.0	35.5	42.4
$2e2\mu$	45.9	48.6	38.0	40.4	47.2

These factors are related to fiducial region on the left

Correction factors $\mathcal{C}$ [%]					
Decay	Production mode				
Channel	ggF	VBF	WH	ZH	$t\bar{t}H$
4μ	62.6	64.2	60.8	60.5	41.8
$4e$	42.1	43.2	43.0	42.7	38.7
$2\mu 2e$	46.9	50.9	49.1	48.6	41.7
$2e2\mu$	53.1	54.7	51.8	50.2	36.7

These factors are related to detector efficiency and resolution

H→γγ at 13 TeV

ATLAS-CONF-2016-067

Cuts for fiducial cross section measurement

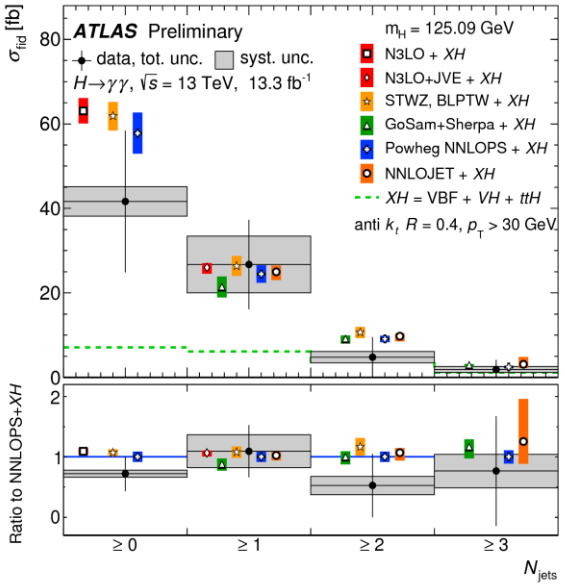
	diphoton baseline	VBF enhanced	single lepton
Photons	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ $p_T^{\gamma_1} > 0.35\, m_{\gamma\gamma}$ and $p_T^{\gamma_2} > 0.25\, m_{\gamma\gamma}$		
Jets	-	$p_T > 30$ GeV , $\lvert y\rvert < 4.4$	-
	-	$m_{jj} > 400$ GeV, $\lvert\Delta y_{jj}\rvert > 2.8$	-
	-	$\lvert\Delta\phi_{\gamma\gamma,jj}\rvert > 2.6$	-
Leptons	-	-	$p_T > 15$ GeV $\lvert\eta\rvert < 2.47$

Measured fiducial cross sections

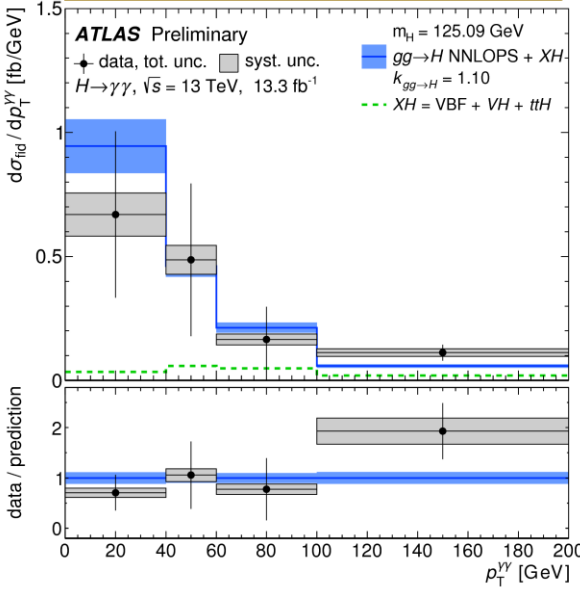
Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8^{+3.4}_{-4.4}$	[N^{3}LO + XH]
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	[NNLOPS + XH]

Results agree with SM predictions

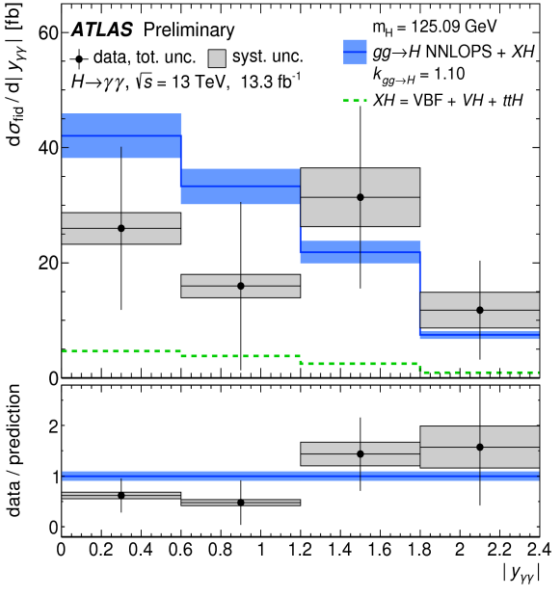
Jet multiplicity



$P_T(\gamma\gamma)$-spectrum



$Y(\gamma\gamma)$-spectrum



Combined $H^0 \to 4l$, $\gamma\gamma$ at 13 TeV

ATLAS-CONF-2016-081

Best fit values of σ×BR for specific channels

		$H \to ZZ^*$	$H \to \gamma\gamma$
ggF	Best fit value (pb)	$1.58^{+0.46}_{-0.39}$	$0.063^{+0.030}_{-0.029}$
	SM prediction (pb)	1.18 ± 0.07	0.101 ± 0.006
VBF	Best fit value (fb)	350^{+260}_{-200}	18^{+6}_{-6}
	SM prediction (fb)	93.0 ± 2.8	8.00 ± 0.29
VHhad	Best fit value (fb)	fixed to SM	$-2.5^{+6.8}_{-5.8}$
	SM prediction (fb)	36.0 ± 1.2	3.09 ± 0.12
VHlep	Best fit value (fb)	fixed to SM	$1.0^{+2.5}_{-1.9}$
	SM prediction (fb)	17.0 ± 0.5	1.46 ± 0.05
top	Best fit value (fb)	fixed to SM	$-0.3^{+1.6}_{-1.2}$
	SM prediction (fb)	15.9 ± 1.5	1.36 ± 0.13

Best fit values of σ_H assuming SM BR

	Best fit value (pb)	SM prediction (pb)
σ_{ggF}	$47.8^{+9.8}_{-9.4}$	44.5 ± 2.3
σ_{VBF}	$7.9^{+2.8}_{-2.4}$	3.52 ± 0.07
σ_{VHhad}	$-2.5^{+2.9}_{-2.6}$	1.36 ± 0.03
σ_{VHlep}	$0.32^{+1.07}_{-0.79}$	0.64 ± 0.02
σ_{top}	$-0.11^{+0.67}_{-0.54}$	0.60 ± 0.06

σ (pp→H +X) measured using $\gamma\gamma$ and $4l$ decays and their combination

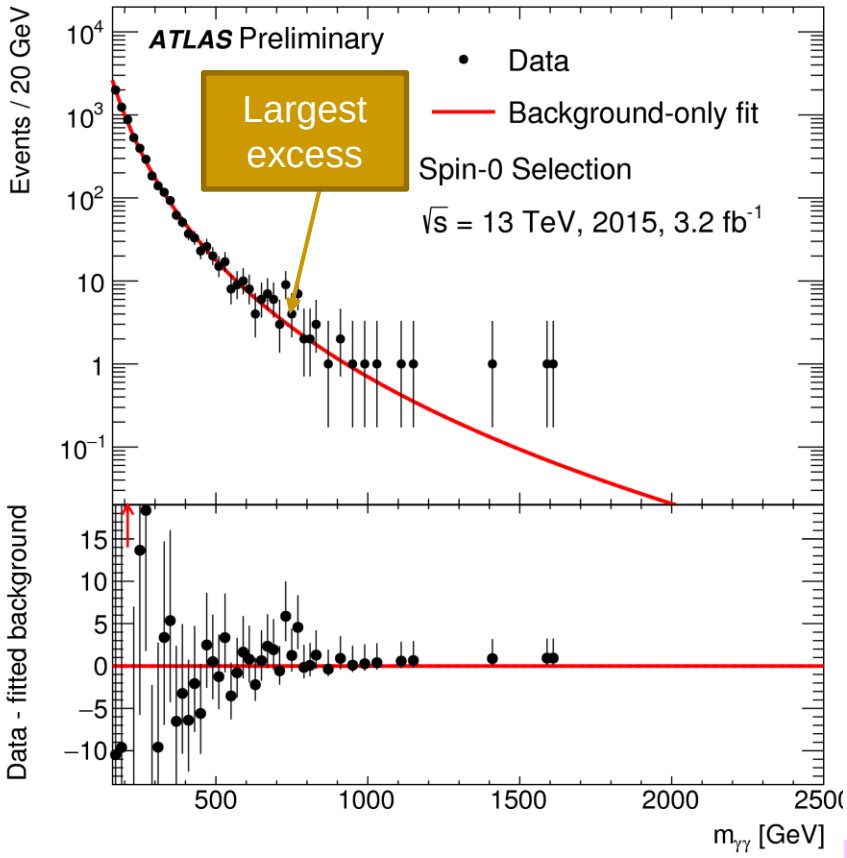
Decay channel	Total cross section ($pp \to H + X$)		
	$\sqrt{s}$ =7 TeV	$\sqrt{s}$ =8 TeV	$\sqrt{s}$ =13 TeV
$H \to \gamma\gamma$	35^{+13}_{-12} pb	$30.5^{+7.5}_{-7.4}$ pb	37^{+14}_{-13} pb
$H \to ZZ^* \to 4\ell$	33^{+21}_{-16} pb	37^{+9}_{-8} pb	81^{+18}_{-16} pb
Combination	34 ± 10 (stat.) $^{+4}_{-2}$ (syst.) pb	$33.3^{+5.5}_{-5.3}$ (stat.) $^{+1.7}_{-1.3}$ (syst.) pb	$59.0^{+9.7}_{-9.2}$ (stat.) $^{+4.4}_{-3.5}$ (syst.) pb
SM predictions [7]	19.2 ± 0.9 pb	24.5 ± 1.1 pb	$55.5^{+2.4}_{-3.4}$ pb

No significant deviation from SM is observed

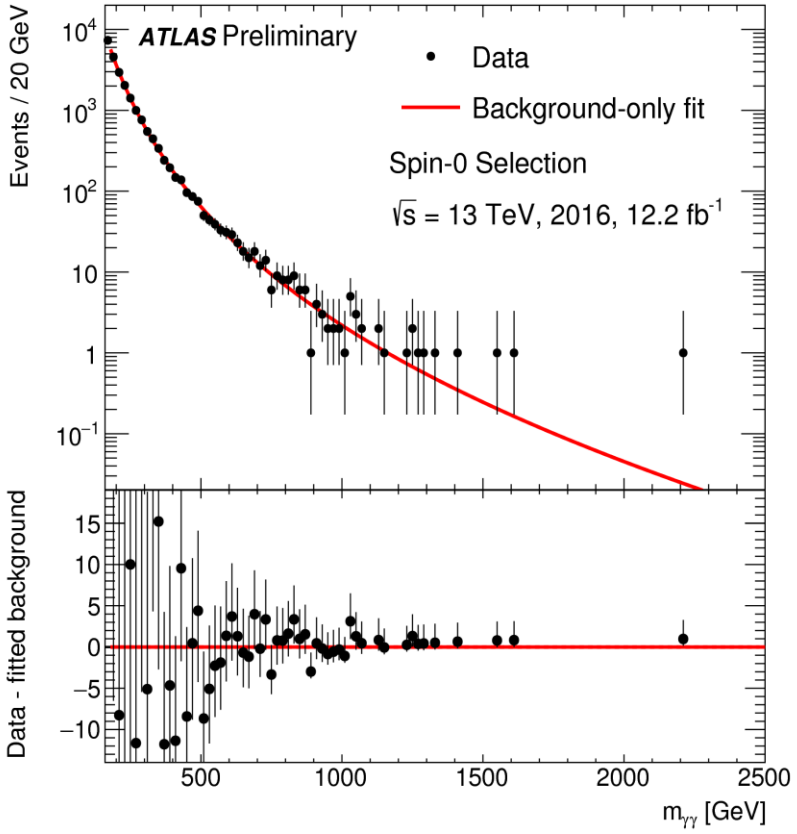
High-mass H→γγ at 13 TeV

ATLAS-CONF-2016-059

$m_{\gamma\gamma}$ in 2015 year data



$m_{\gamma\gamma}$ in 2016 year data



3.4σ local significance at 730 GeV

No significant excesses observed with four times larger statistics

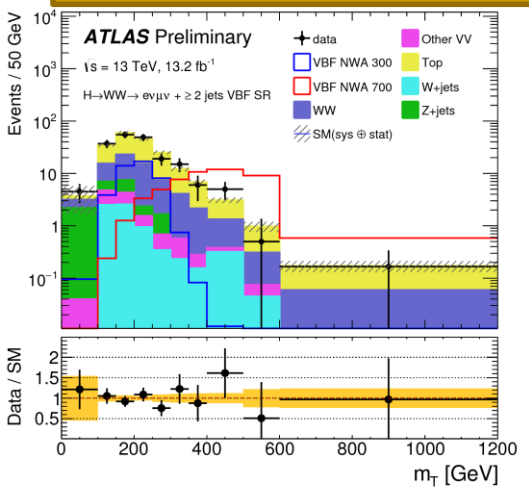
High-mass H→WW→*lνlν* at 13 TeV

ATLAS-CONF-2016-074

Selection criteria for signal regions (SR)

SR_{ggF}	SR_{VBF1J}	SR_{VBF2J}
Preselection cuts: $p_T^{lead} > 25\,GeV$, $p_T^{sublead} > 15\,GeV$, 3rd lepton veto, $m_{\ell\ell} > 10\,GeV$		
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55\,GeV$ $p_T^{lead} > 45\,GeV$ $p_T^{sublead} > 30\,GeV$ $\max(m_T^W) > 50\,GeV$		
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{jet} = 1$ $\lvert\eta_j\rvert > 2.4$ $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{jet} \geq 2$ $m_{jj} > 500\,GeV$ $\lvert\Delta y_{jj}\rvert > 4$

M_T–spectrum for SR VBF2J



LWA=NWA but H width is taken to be “large”; here 5-15% from SM width at given m_H

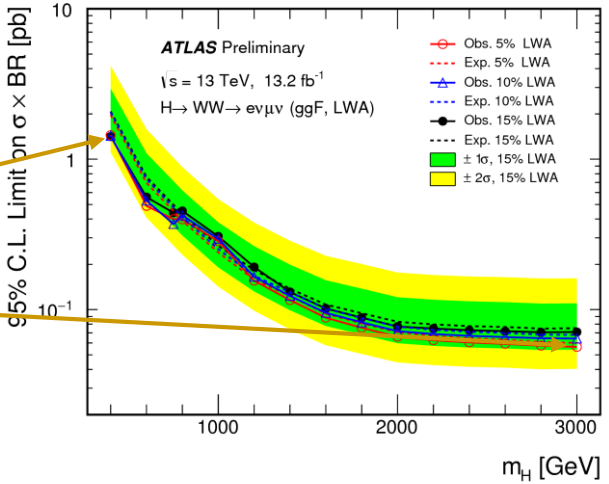
Observed 95% CL exclusion for $\sigma_H \times$ BR(H→WW) in ggF using 15% LWA approach:

<1.4 pb at m_H=400 GeV

<71 fb at m_H=3000 GeV

No significant excess above background is found in the search mass range

Exclusion for ggF using LWA

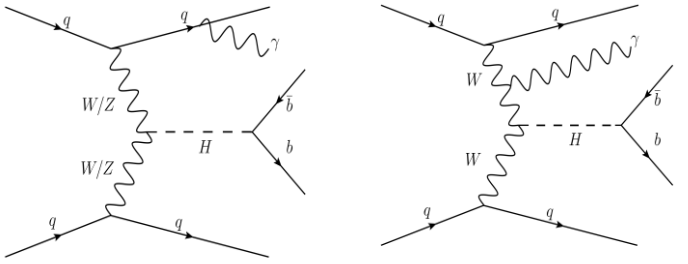


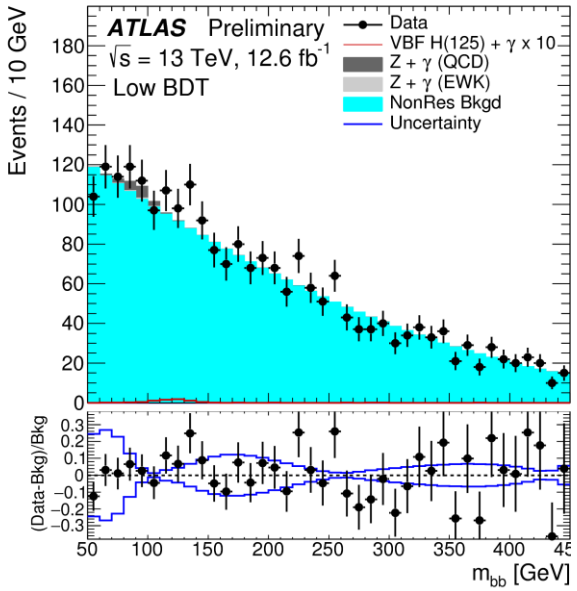
VBF+γ H→bb at 13 TeV

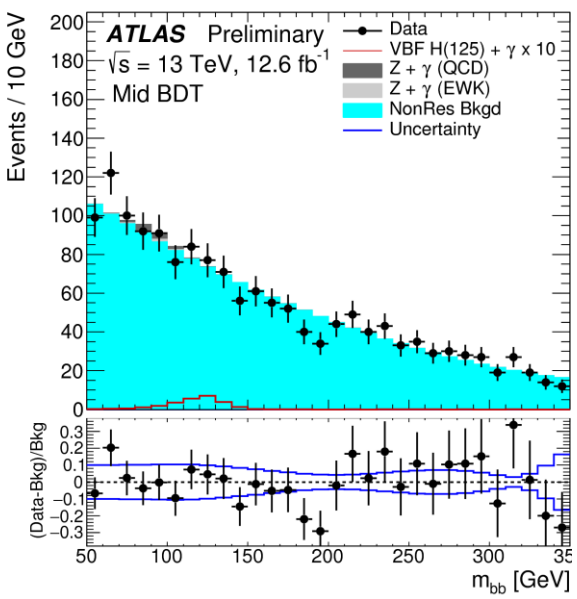
ATLAS-CONF-2016-063

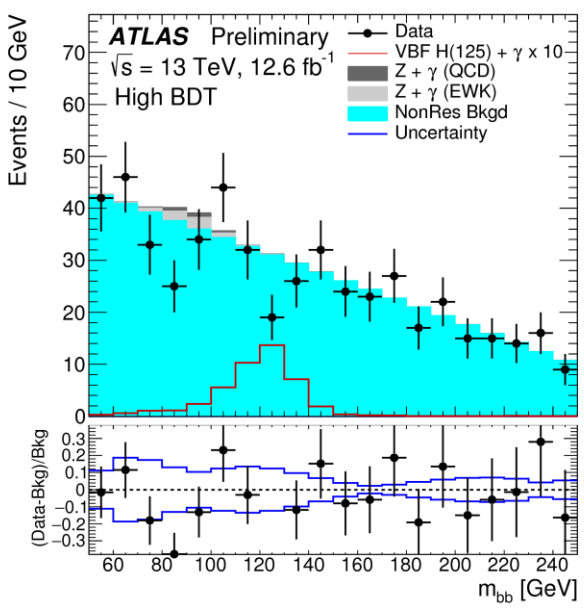
Result	$H(\to b\bar{b}) + \gamma jj$	$Z(\to b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected p-value	0.4	0.1
Observed p-value	0.9	0.4
Expected limit	$6.0\ ^{+2.3}_{-1.7}$	$1.8\ ^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength μ	$-3.9\ ^{+2.8}_{-2.7}$	0.3 ± 0.8

Diagrams for VBF H→bb + γ production



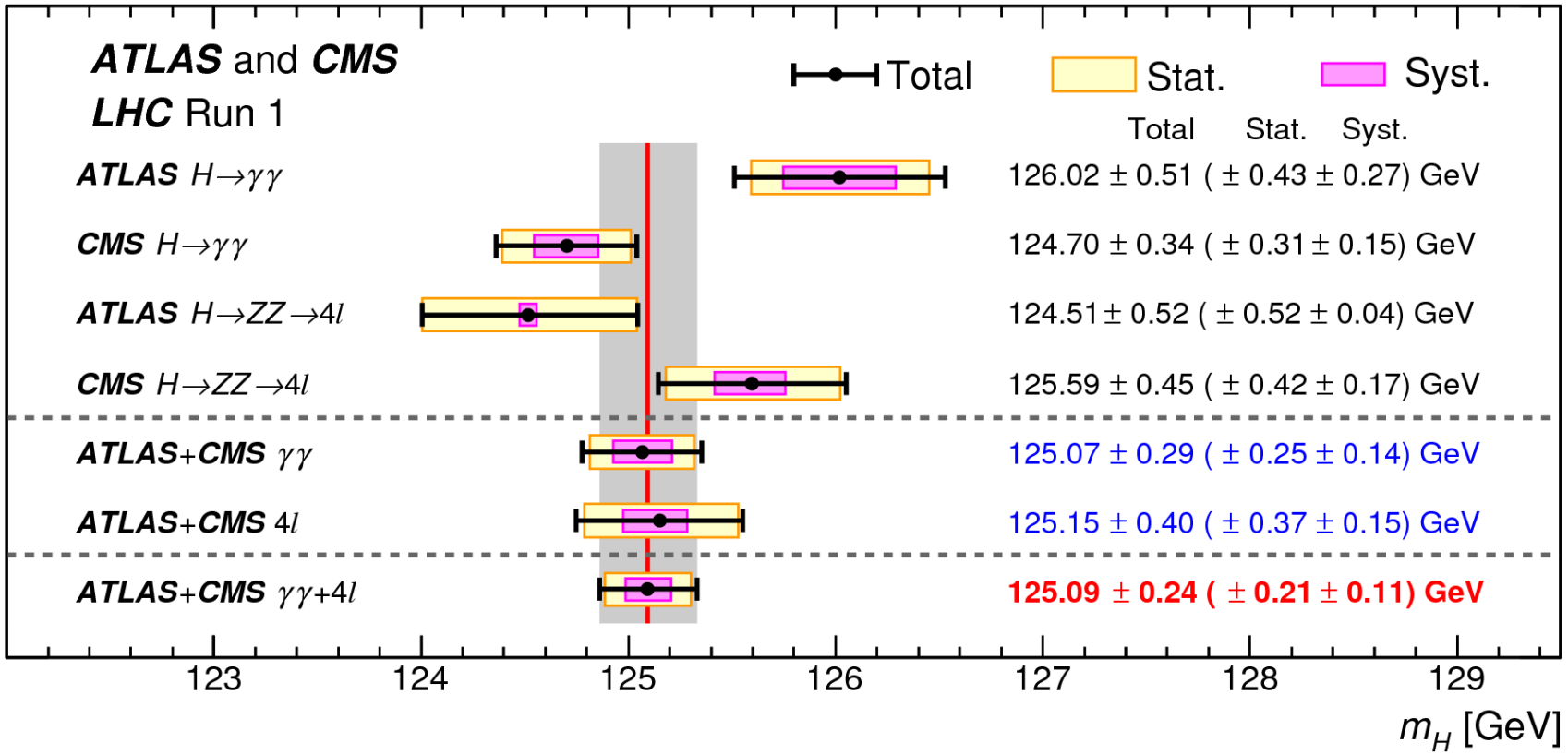






Higgs boson combination: measured mass

ATLAS+CMS: PRL 114 (2015) 191803



m_H=125.09±0.24 GeV, statistical error dominates

Higgs boson combination: measured couplings*

ATLAS+CMS:

JHEP08 (2016) 045

Decay channel	Signal strength ATLAS	Signal strength CMS	Signif. ATLAS	Signif. CMS
H→ γγ	**$1.15^{+0.27}_{-0.25}$**	**$1.12^{+0.25}_{-0.23}$**	**5.0**	**5.6**
H→ ZZ*→ 4*l*	**$1.51^{+0.39}_{-0.34}$**	**$1.05^{+0.32}_{-0.27}$**	**6.6**	**7.0**
H→ WW*	**$1.23^{+0.23}_{-0.21}$**	**$0.91^{+0.24}_{-0.21}$**	**6.8**	**4.8**
H→ ττ	**$1.41^{+0.40}_{-0.35}$**	**$0.89^{+0.31}_{-0.28}$**	**4.4**	**3.4**
H→ bb	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
H→ μμ	-0.7 ±3.6	0.8 ±3.5		

* - at mass 125.09 GeV

- Signal is clearly seen in four channels: ZZ*, WW*, γγ, ττ
- μ=1.09±0.10, statistical error and signal theoretical error dominate

Higgs boson: spin and parity

EPJC 75 (2015) 476

- Channels tested: $H \to ZZ^* \to 4l$, $H \to WW \to e\nu\mu\nu$, $H \to \gamma\gamma$
- Hypotheses tested: 0^+ (main), BSM 0^-, 0_h^+, 2^+ with universal and non-universal couplings to fermions and vector bosons
- Tensor structure of HVV interaction (0^+) also started to be studied

0_h^+ model describes "the interaction of the Higgs boson with the SM vector bosons with higher-dimension operators. Phys. Rev. D **81** (2010) 075022, Phys. Rev. D **86** (2012) 095031

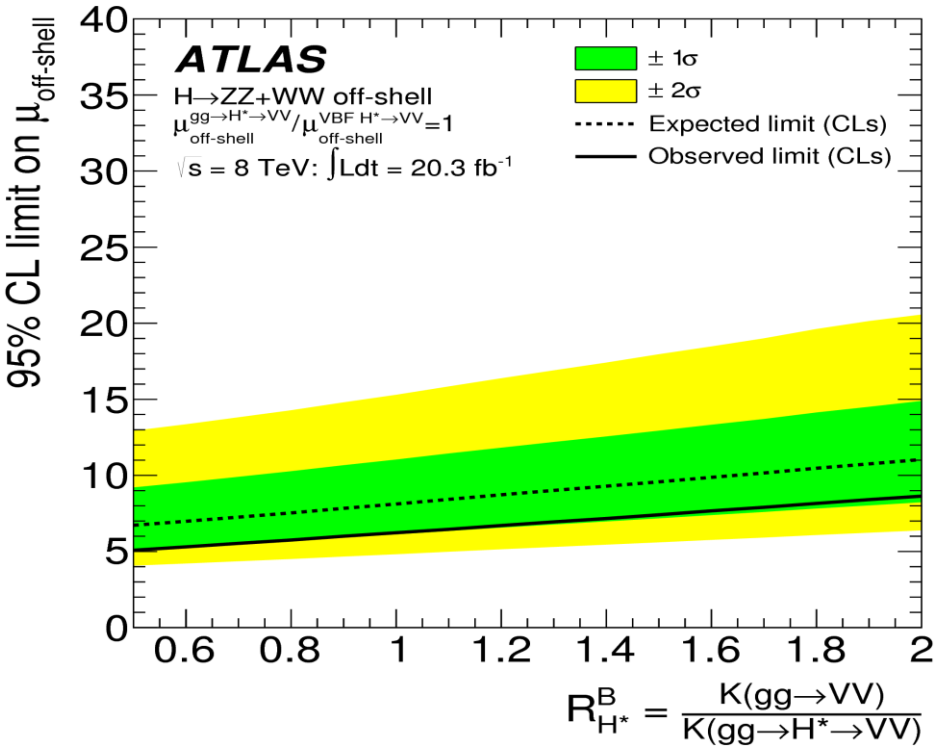
Tested Hypothesis	$p^{\text{alt}}_{\text{exp},\mu=1}$	$p^{\text{alt}}_{\text{exp},\mu=\hat{\mu}}$	$p^{\text{SM}}_{\text{obs}}$	$p^{\text{alt}}_{\text{obs}}$	Obs. CL_s (%)
0_h^+	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
$2^+(\kappa_q = \kappa_g)$	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_{\text{T}} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_{\text{T}} < 125GeV)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\text{T}} < 300GeV)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_{\text{T}} < 125GeV)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

- All alternative to 0^+ hypotheses considered excluded at >99.9% CL
- $1^+/1^-$ hypotheses (forbidden by Landau-Yang theorem for $H \to \gamma\gamma$) excluded earlier
- No deviations from SM are found in the first study of HVV tensor structure

Off-shell H→WW and H→ZZ at 8 TeV

EPJC 75 (2015) 335

- H→ZZ→4*l*, H→ZZ→*ll*νν and H→WW→eνμν modes above $2m_V$ (Z,W) threshold
- 8 TeV data only
- Interference between H signal and gg→VV background
- Varying k-factor for gg→VV background from 0.5 to 2
- 95% CL on off-shell coupling is given

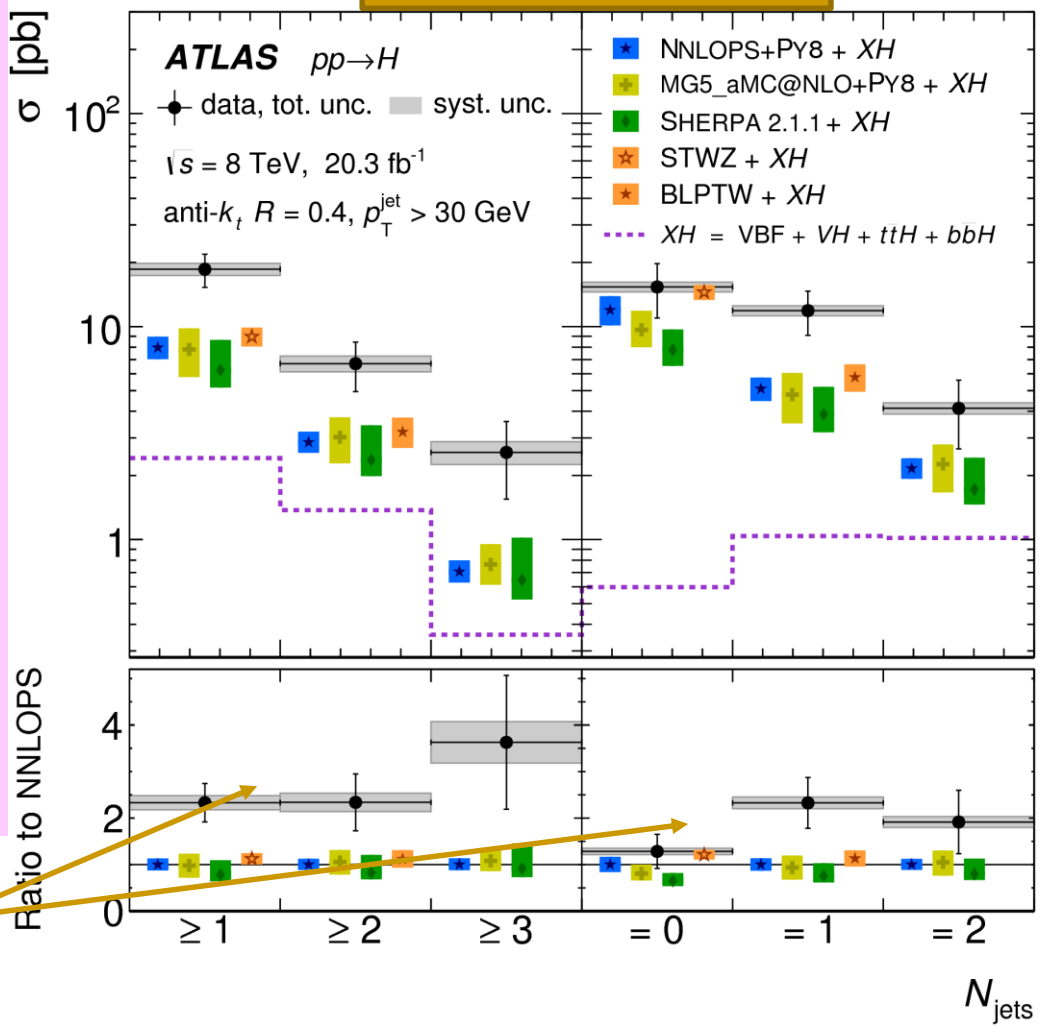


ATLAS: Γ_H <22.7 MeV at 95% CL
CMS: Γ_H <23 MeV at 95% CL, ZZ only, but both 7 and 8 TeV data
SM value: $\Gamma_H \approx 4$ MeV

H→4*l* and H→γγ differential cross sections at 8 TeV

- Distributions on different kinematical variables (Y_H, p_T^H, N_{jets}, p_T(lead. jet)) were studied
- Total σ obtained
- Comparison with different event generators was performed
- P-values quantifying the compatibility of measured shapes and predictions range from 8% to 88%

PRL 115 (2015) 091801



Example: distribution on jet multiplicities

VBF H→invisible at 8 TeV

arXiv:1508.07869, JHEP01 (2016) 172

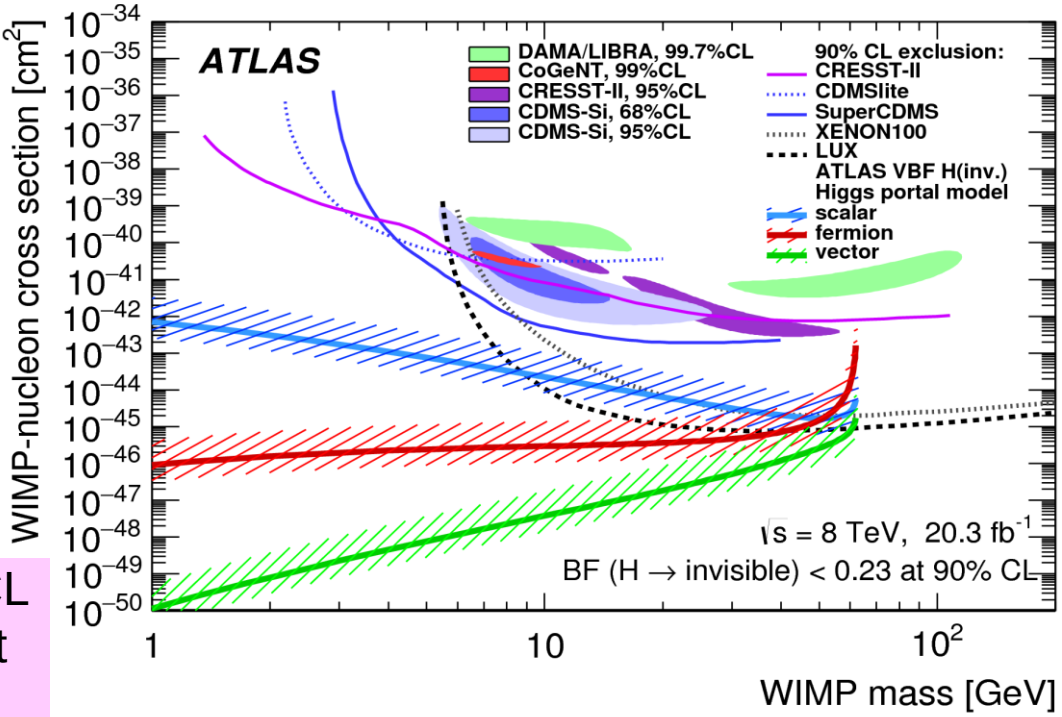
Obtained/expected limits on BR(H→inv.) for VBF mechanism

Results	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ	Observed
SR1	0.35	0.49	0.25	0.67	0.19	0.30
SR2	0.60	0.85	0.43	1.18	0.32	0.83
Combined Results	0.31	0.44	0.23	0.60	0.17	0.28

CMS: limit of 0.58 based on VBF and ZH channels EPJC74 (2014)2980

Signature:

- two very high p_T–jets with large invariant-mass and rapidity separation
- Third jet veto
- very large E_T^{miss}



Obtained limit of 0.28 at 95% CL on BR(H→inv.) is the best limit on this BR achieved so far

Rare H and Z decays to J/ψγ and Υγ at 8 TeV

Quarkonia were reconstructed using their $\mu^+\mu^-$ decays

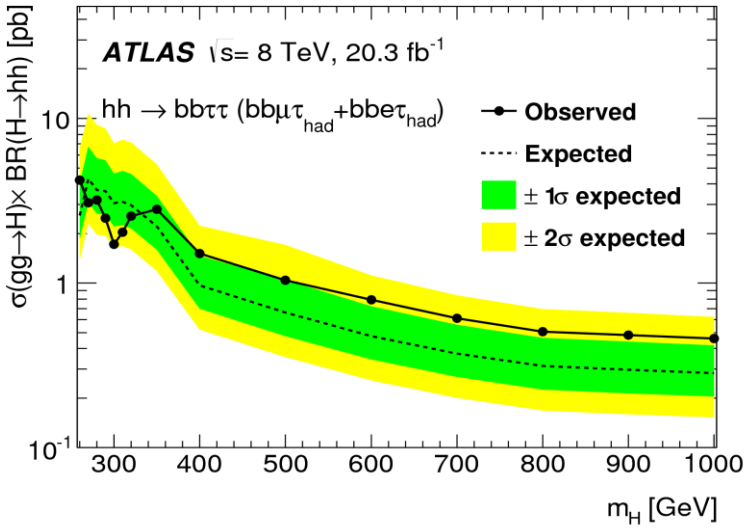
PRL 114 (2015) 121801

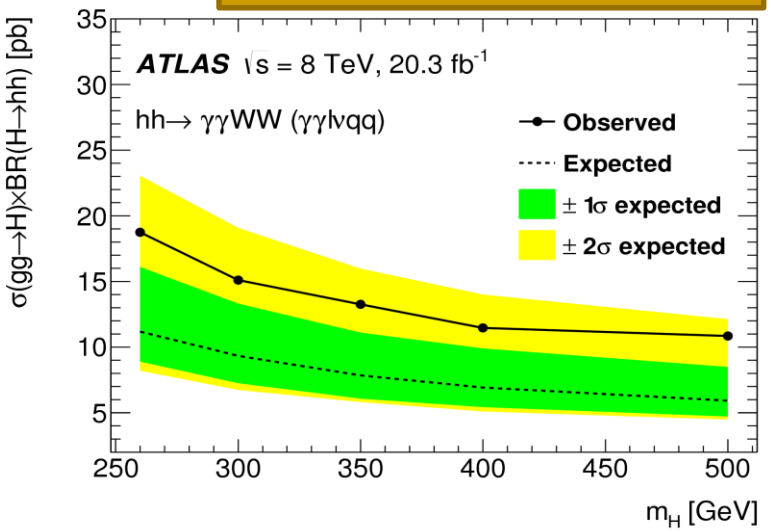
	95% CL_s Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum^n \Upsilon(nS)$
	$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]				
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
	$\mathcal{B}(H \to \mathcal{Q}\gamma)$ [10^{-3}]				
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
	$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]				
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

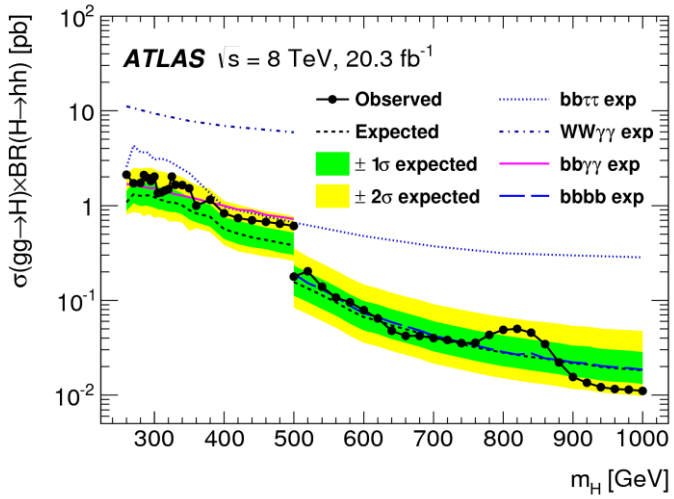
No one from considered rare decays was observed in 8 TeV data

Pair production of Higgs bosons at 8 TeV

PRD92 (2015) 092004



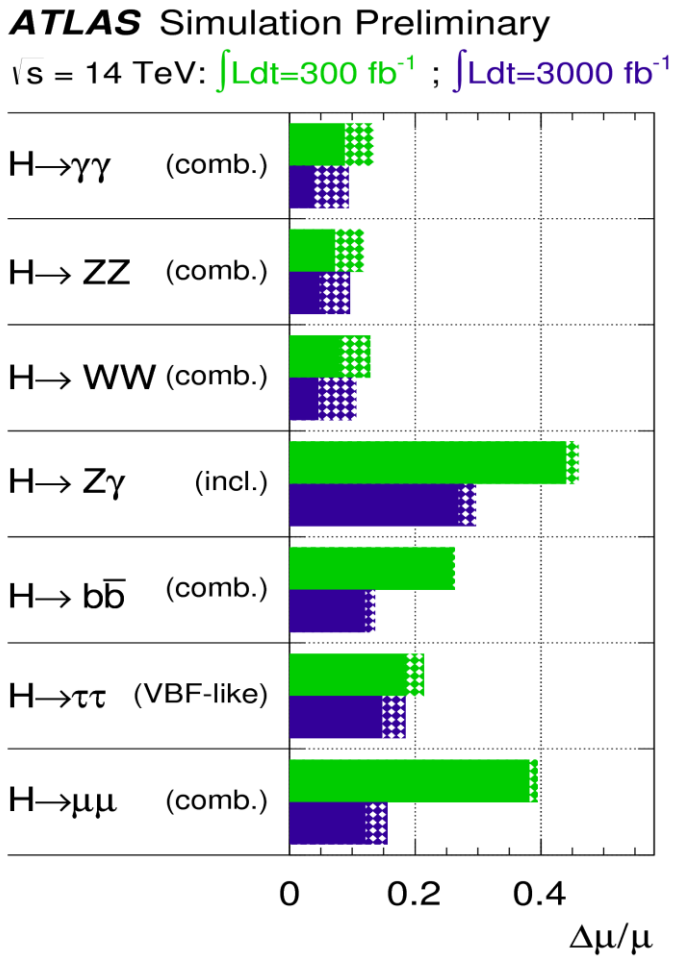




- 0.69 pb limit on non-resonant hh-production, 70 times larger than SM cross section
- 2.1 pb (0.011 pb) limit on H→hh production for m_H = 260 GeV(1000 GeV)
- Interpretations of results in two simplified scenarios of MSSM

Higgs boson perspectives

ATLAS-PHYS-PUB-2014-016



Recent HL-LHC related notes:

VBF H→WW*→evμv	PUB-2016-018
VBF H→ZZ*→4l	PUB-2016-008
H→J/ψγ	PUB-2015-043
HH→bbττ	PUB-2015-046
Off-shell H→ZZ→4l	PUB-2015-024

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): $m_H < 1$ ТэВ
- H is expected to have **vacuum quantum numbers**, i.e. $J^P = 0^+$

What we knew about H boson four years ago?

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

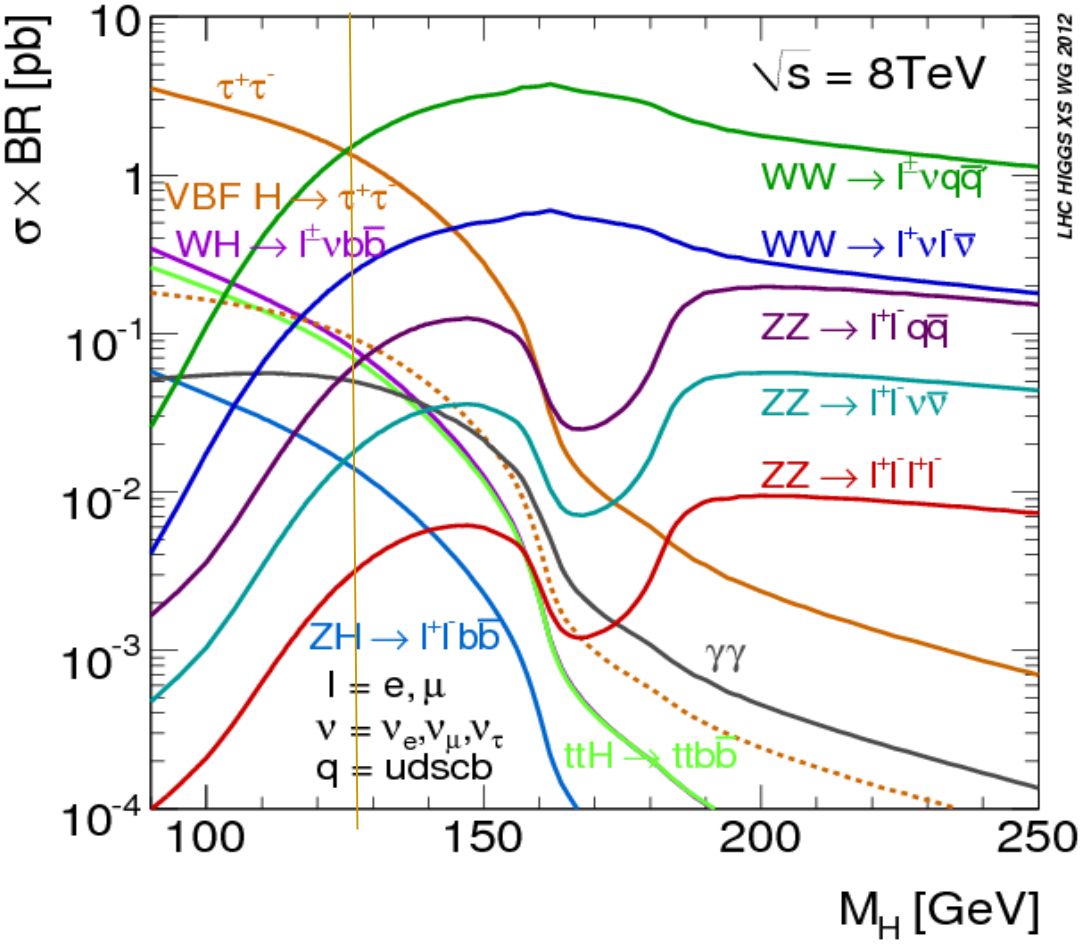
Combined results from four LEP experiments, PL B565 (2003) 61

- $m_H < 152$ 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

σ×BR for SM Higgs boson from theory at 8 TeV



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

m(H)=125 GeV
(measured value):

1.5 pb for ττ and ℓνqq
(very difficult modes)

0.25 pb for WW*→ℓνℓν
(only transverse mass)

0.1 pb for VBF ττ ,
WH→ℓνbb, ZZ*→ℓℓqq, ℓℓνν
(only transverse mass)

0.05 pb for H→γγ
(mass: OK, but S/B<<1)

0.003 pb H→ZZ*→4ℓ
("gold-plate" mode)

0.004 pb H→μμ
(huge Drell-Yan background)