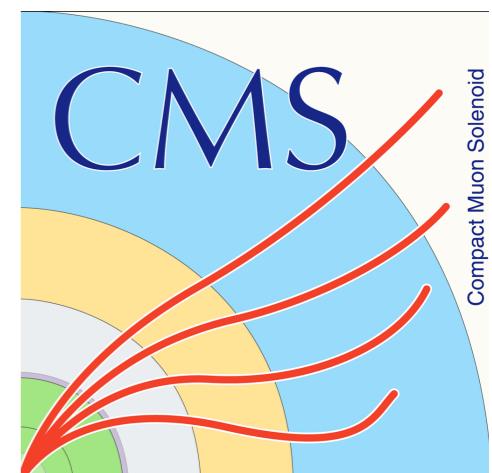




Higgs physics at the LHC

Rebeca Gonzalez Suarez
on behalf of the ATLAS and CMS experiments



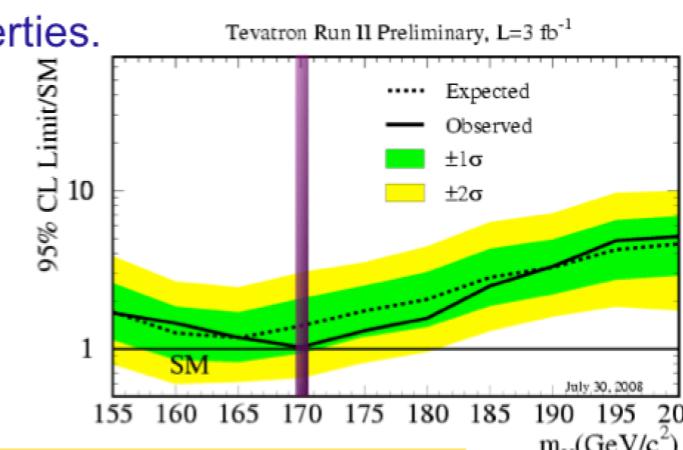
8 years ago

- August 2008, **ICHEP, Philadelphia:**
 - Higgs searches at the Tevatron were entering a new phase



Conclusions

- The Higgs boson search is in its most exciting era ever
 - The Tevatron experiments have achieved sensitivity to the SM Higgs boson production cross section
 - In addition there is strong sensitivity to beyond the SM Higgs
 - With the advent of the LHC we will have the potential to observe the SM Higgs boson and study it's properties.
- We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV
 - Expect large exclusion, or evidence, with full Tevatron data set and improvements



SM Higgs Excluded: $m_H = 170 \text{ GeV}$

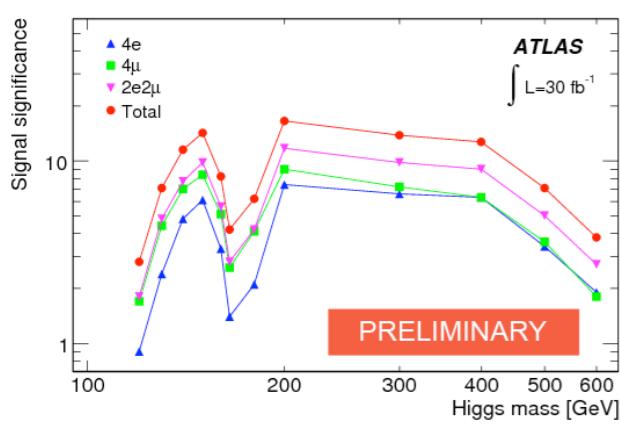
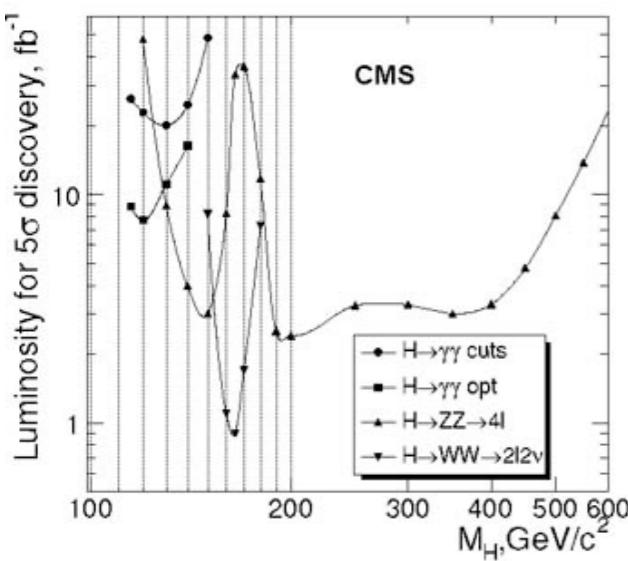
M. Herndon, ICHEP 2008

25

- And the LHC was just about to start colliding...

Fast track Higgs discovery

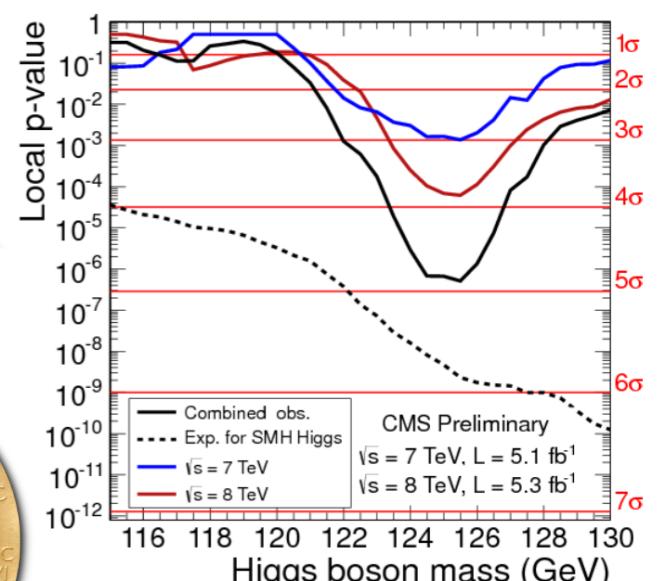
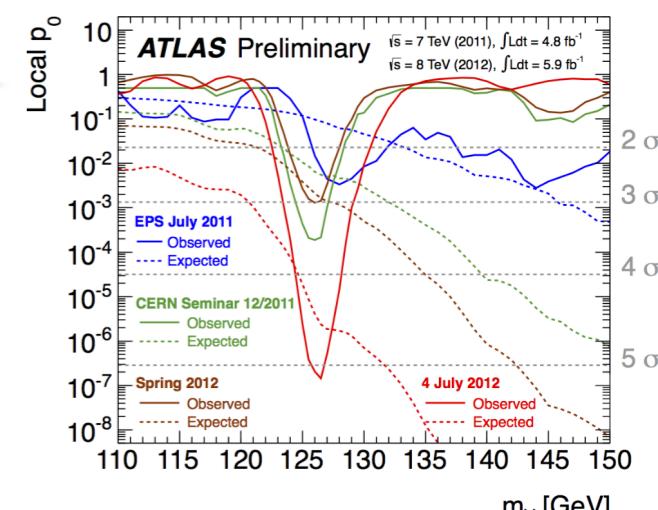
What ATLAS and CMS presented at ICHEP08



ATLAS: [arXiv:1207.7214](https://arxiv.org/abs/1207.7214)
CMS: [arXiv:1207.7235](https://arxiv.org/abs/1207.7235)

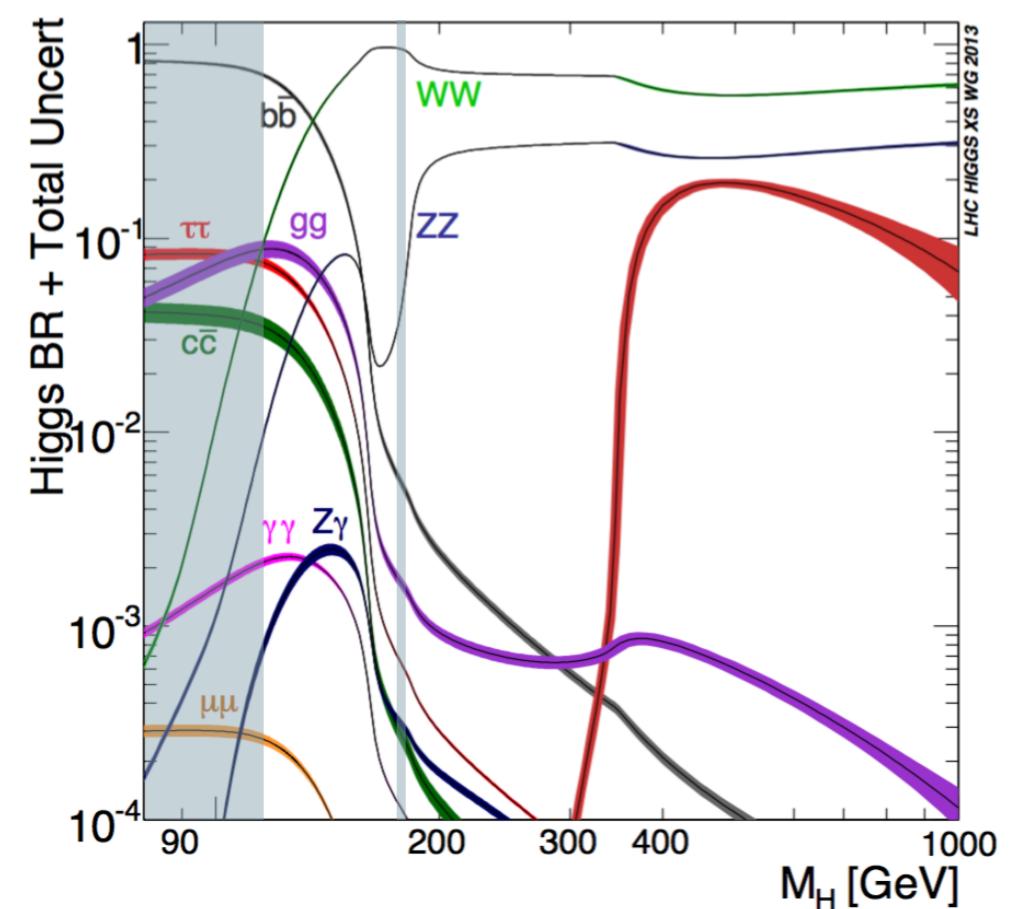
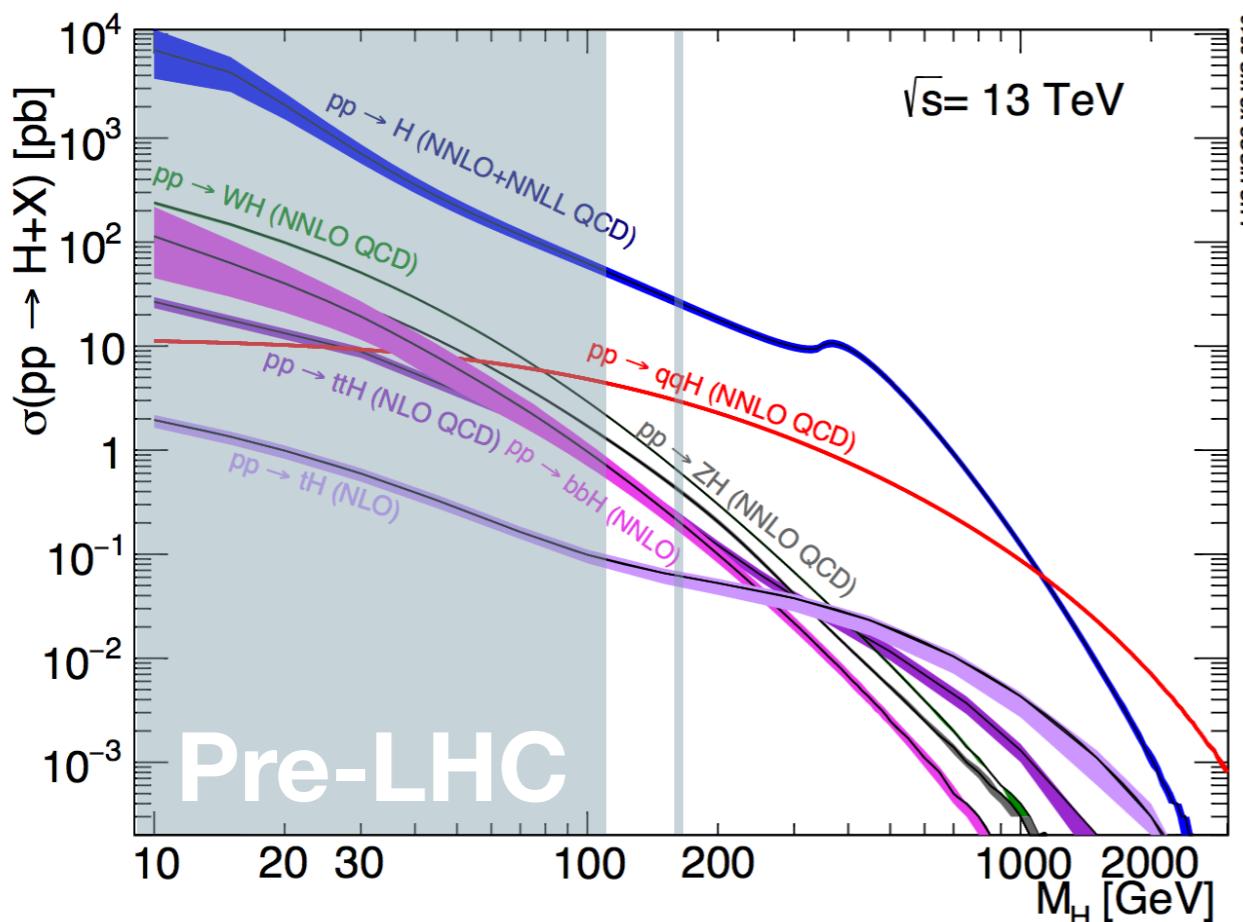


What ATLAS and CMS presented in 2012!



Higgs searches at the LHC

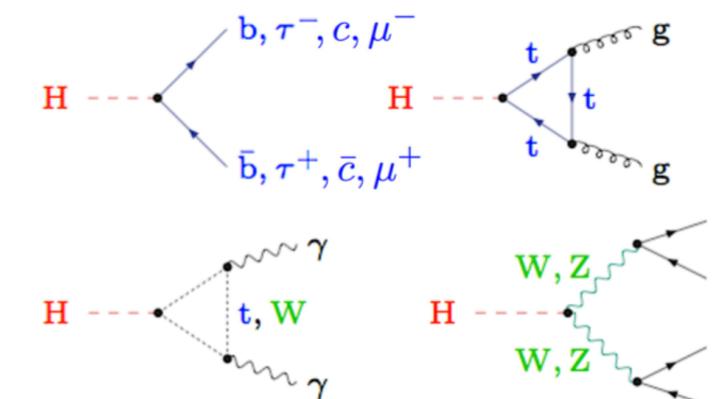
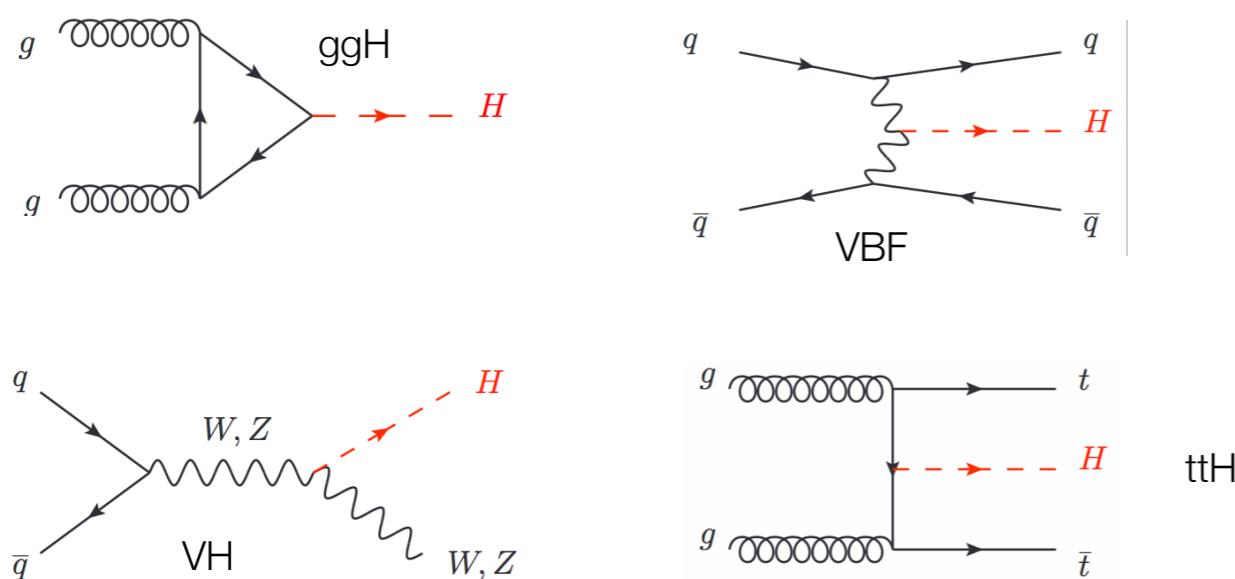
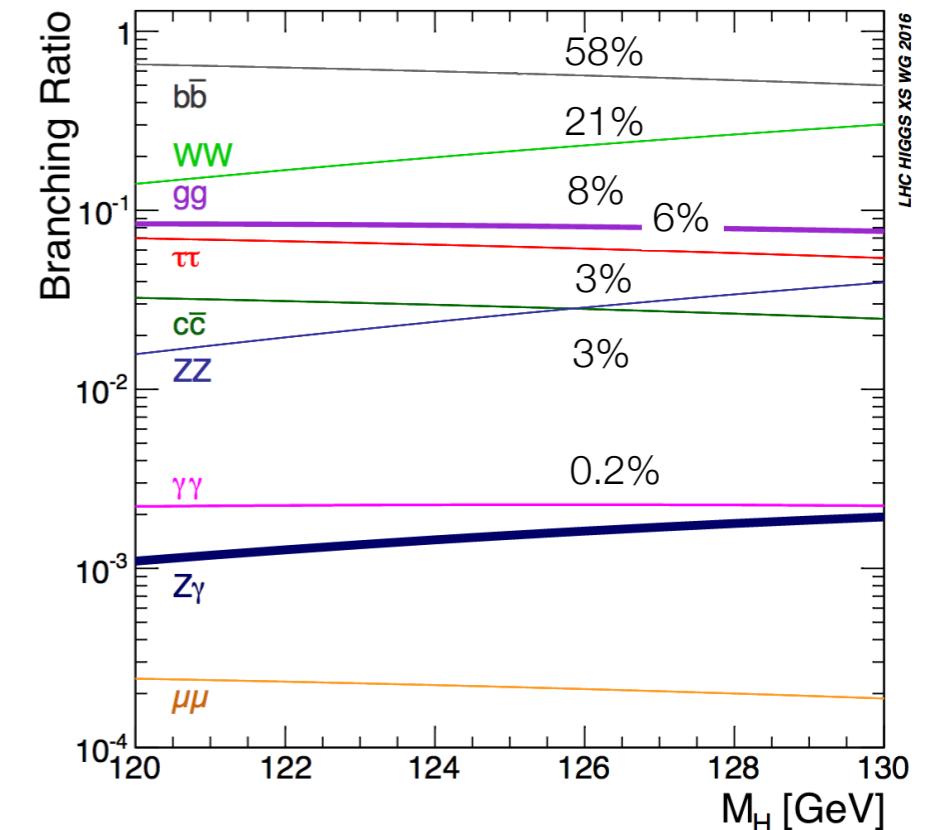
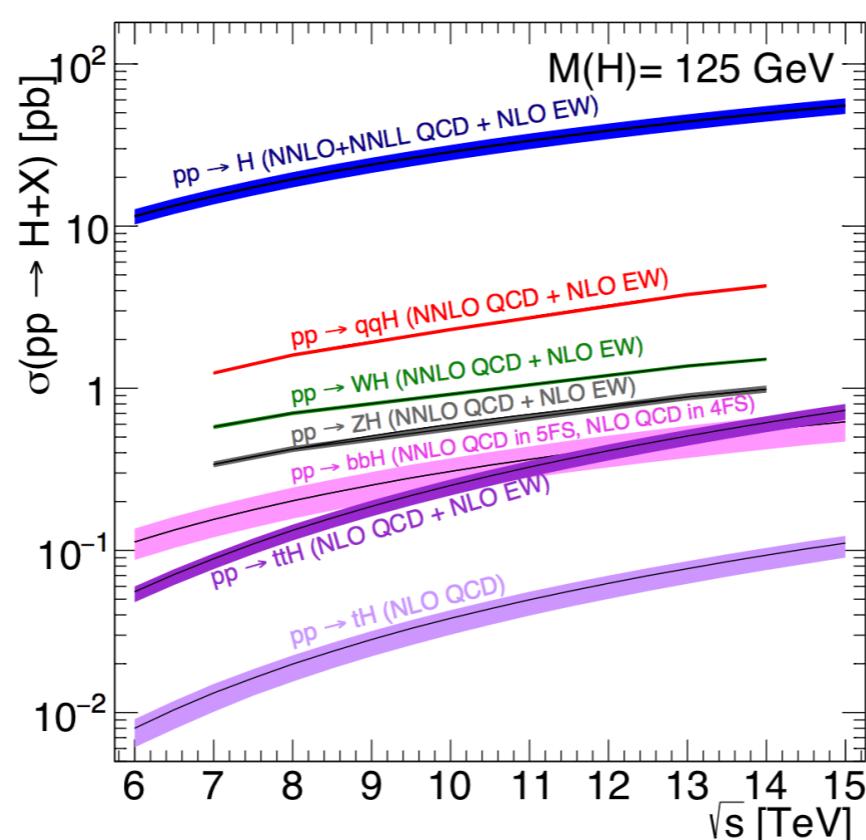
- When the LHC started colliding → Higgs sector still mostly unexplored
- Experimental signatures are defined by the **production** and **decay** of the Higgs boson
 - At the LHC, **gluon fusion** production dominates over almost the full mass spectra
 - Higgs decays are much more dependent on the Higgs mass



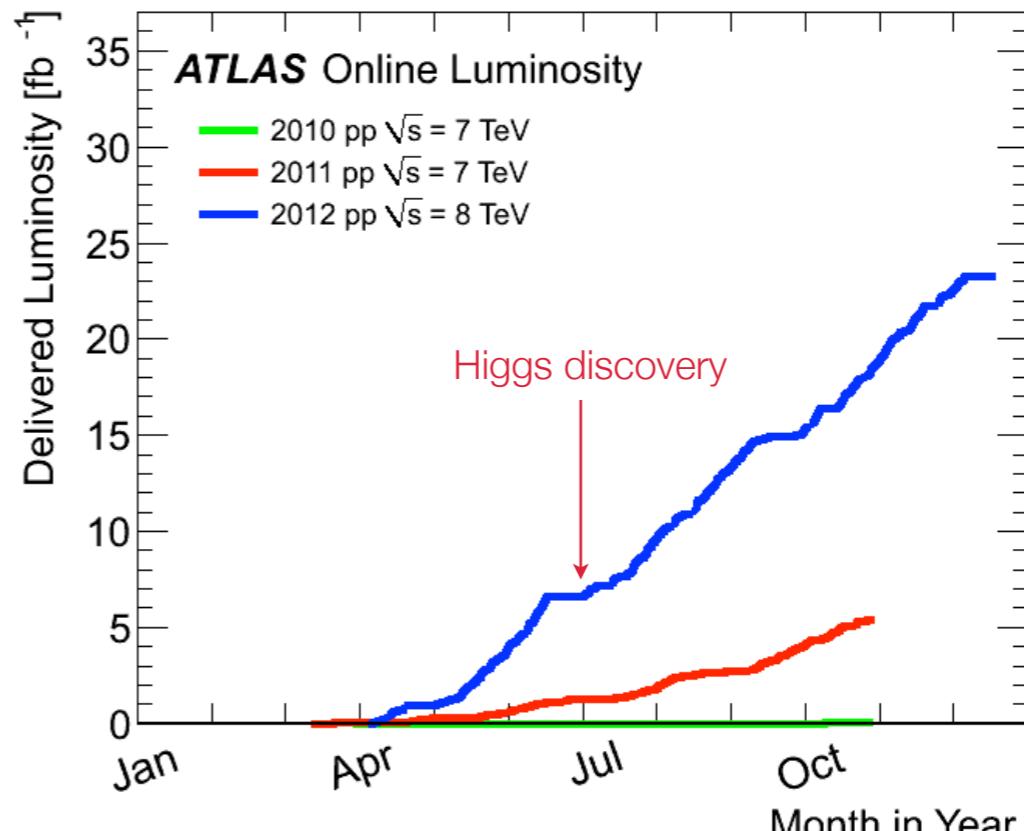
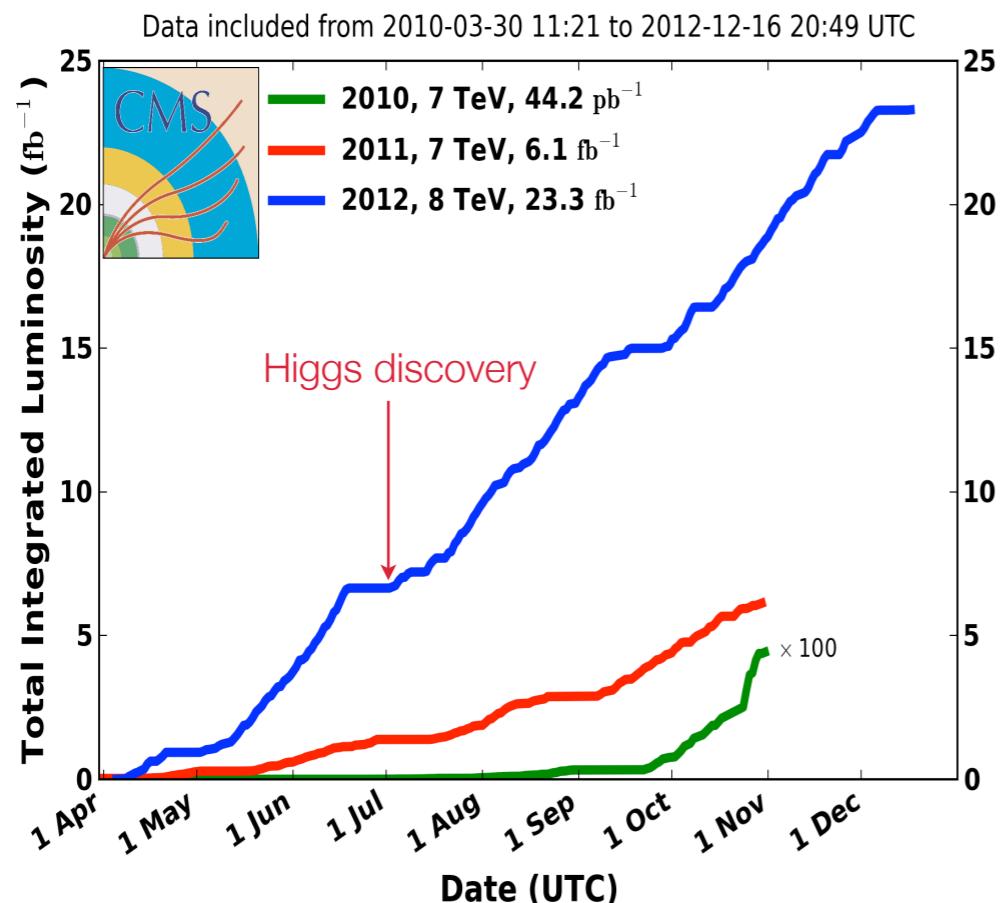
A 125 GeV Higgs boson

- Knowing where to look: **$m_H = 125 \text{ GeV}$** → everything is easier

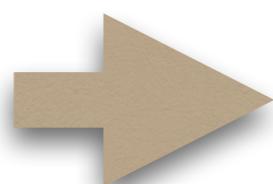
	cross section [pb]		
	7TeV	8TeV	13TeV
ggH	15.31	19.47	44.14
VBF	1.24	1.60	3.78
WH	0.58	0.70	1.37
ZH	0.34	0.42	0.88
VH	0.92	1.12	2.26
ttH	0.09	0.13	0.51
bbH	0.16	0.20	0.49
tH	0.01	0.02	0.08
HH	0.02	0.01	0.04



LHC Run-1



Three years of running
 $\sim 5\text{fb}^{-1}$ of pp collisions at 7TeV
 $\sim 20\text{fb}^{-1}$ at 8TeV

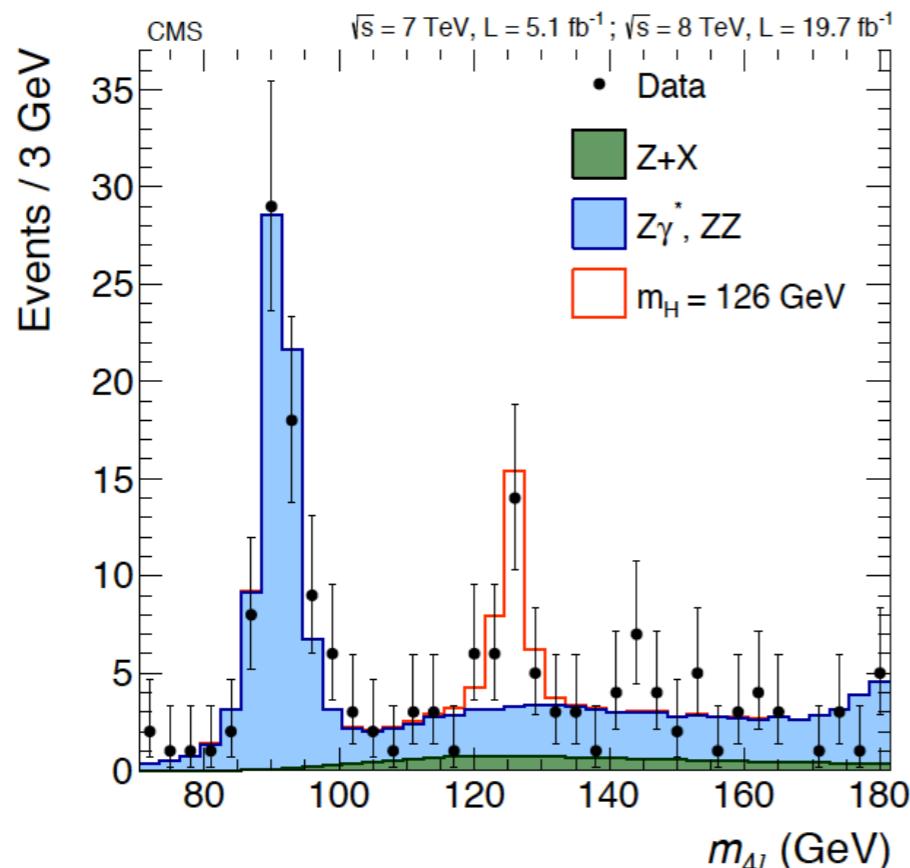


$> 500\text{k}$ Higgs bosons per experiment
 $\sim 1 \text{ million of Higgs events}$
What did we do with them?

The Run-1 Legacy: **SM** Higgs analyses

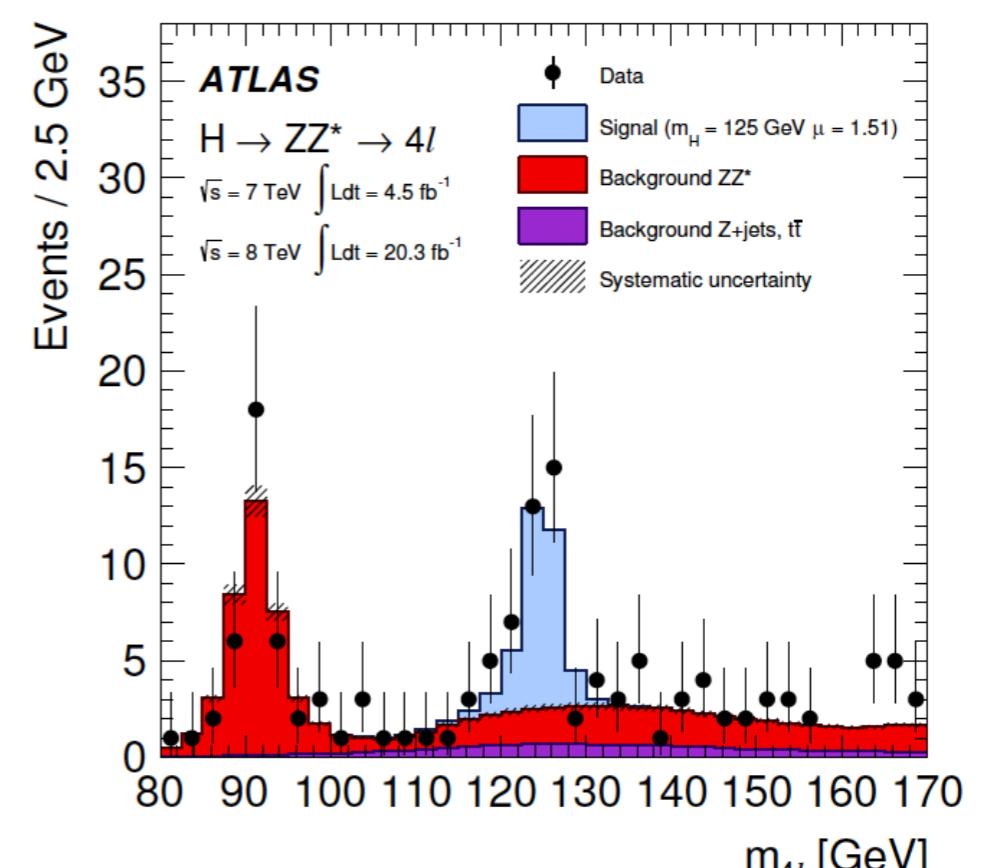
H \rightarrow ZZ \rightarrow 4l

- Already before data considered “the golden channel” (\rightarrow it is)
 - 4 lepton (4e, 4 μ , 2e2 μ) decay: extremely clean signature
 - Mass peak
 - High S/B
- Inclusive, fiducial, and differential cross sections measured
- Properties: Mass, width, spin, parity



CMS: arXiv:1312.5353 **6.8 σ** (6.7)

$\mu (\sigma/\sigma_{SM}) = 0.93 + 0.26 - 0.23 \text{ (stat.)} + 0.13 - 0.09 \text{ (syst.)}$



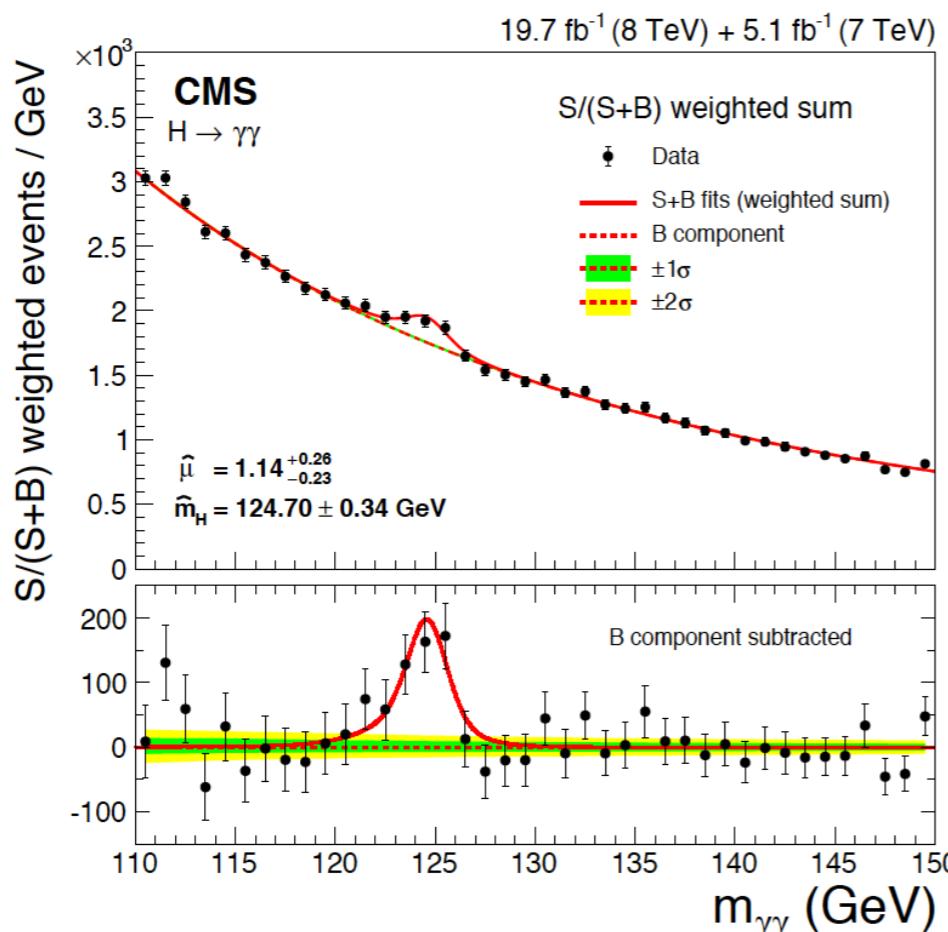
ATLAS: arXiv:1408.5191 **8.1 σ** (6.2)

$\mu (\sigma/\sigma_{SM}) = 1.44 + 0.40 - 0.33$

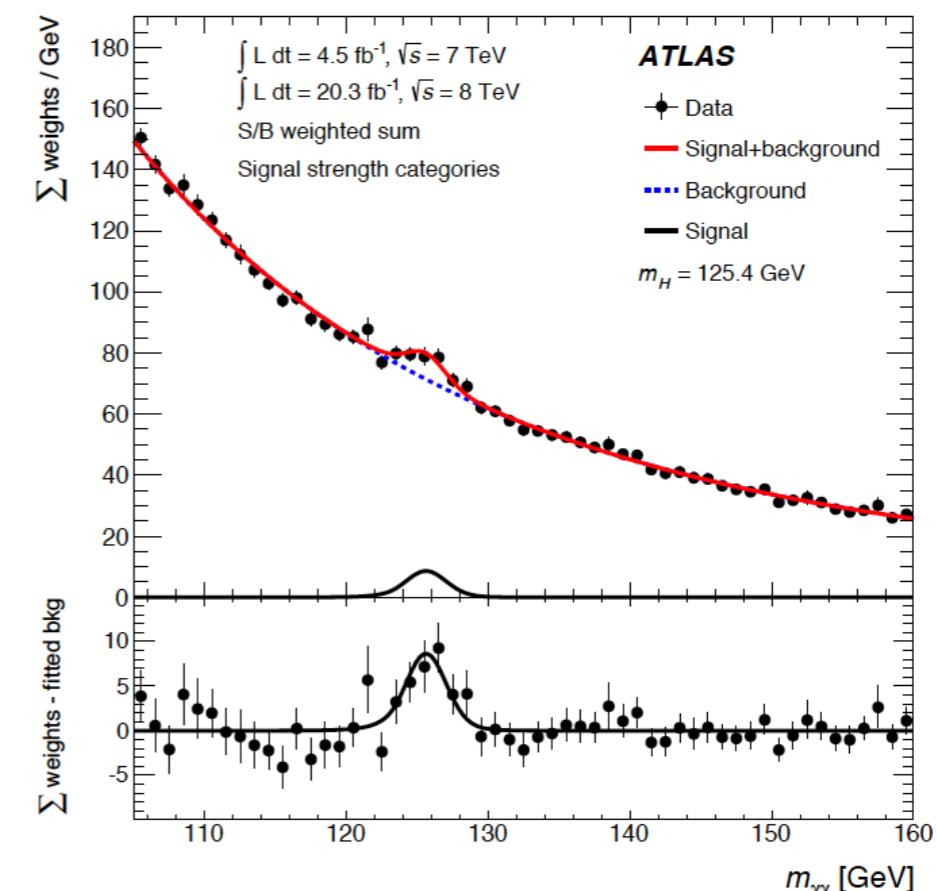
Fiducial and Differential: arXiv:1408.3226 arXiv:1512.08377

H \rightarrow $\gamma\gamma$

- Second highest signal significance at the LHC
 - Despite small branching fraction and large di-photon continuum background
- Clean final-state topology
 - mass reconstruction with high precision
- Inclusive and fiducial cross sections, differential distributions



CMS: arXiv:1407.0558 **5.7 σ** (5.2)
 $\mu = 1.14^{+0.26}_{-0.23}$

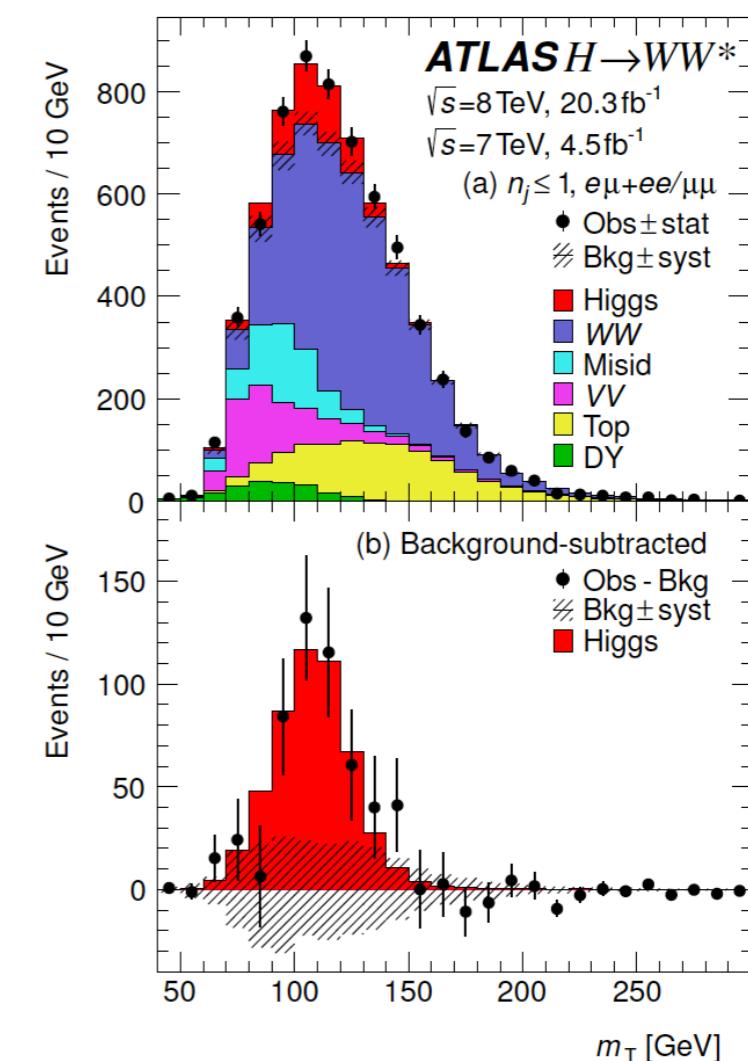
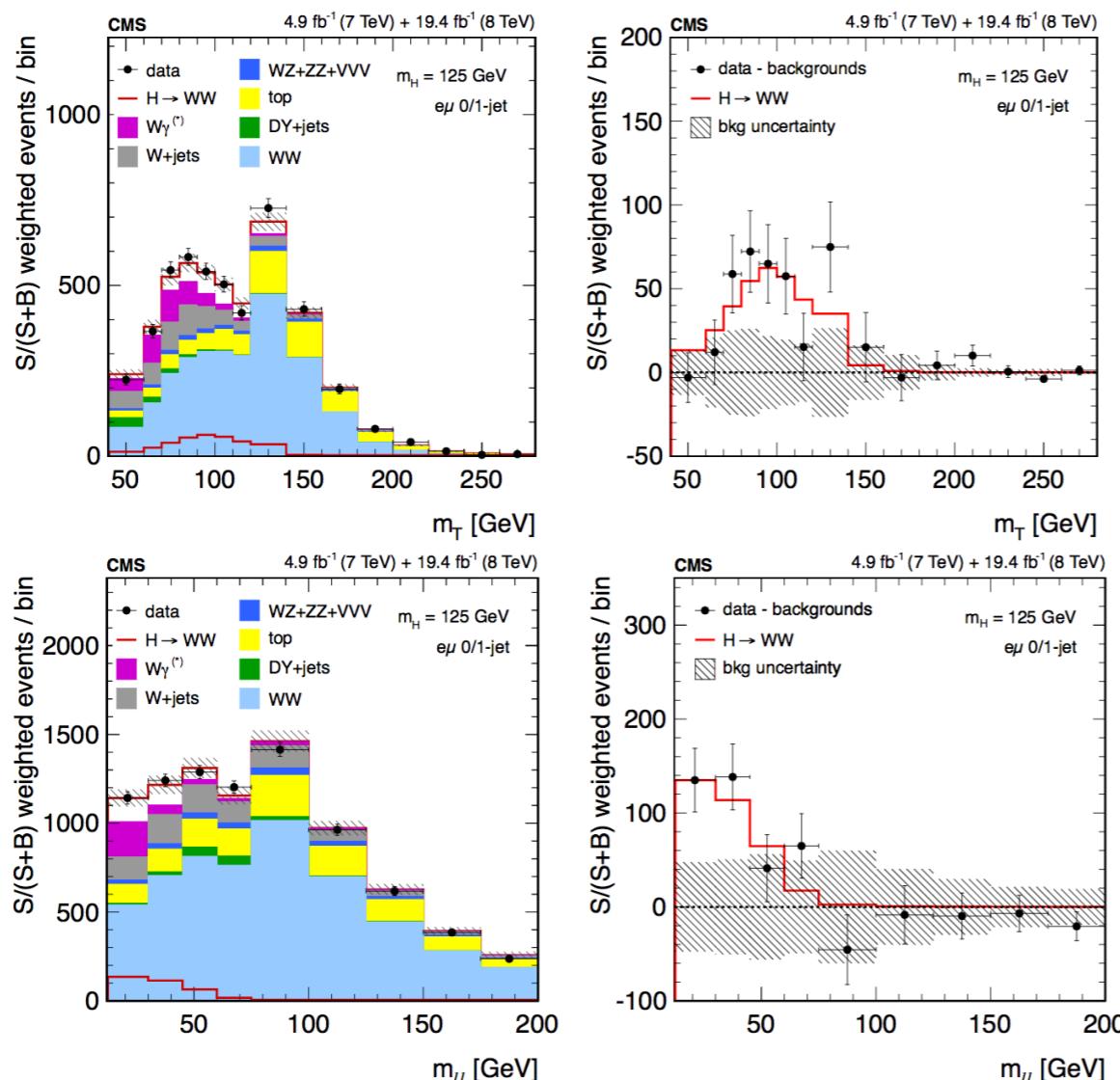


ATLAS: arXiv:1408.7084 **5.2 σ** (4.6)
 $\mu = 1.17 \pm 0.27$

Fiducial and Differential: arXiv:1407.4222 arXiv:1508.07819

H \rightarrow WW \rightarrow 2l2v

- Balanced channel
- Second highest decay rate at 125GeV (21%), clear signature with two opposite sign leptons
- However: neutrinos in the final state \rightarrow No full system reconstruction, no mass peak
- Background contribution: WW, tt, DY, fake leptons

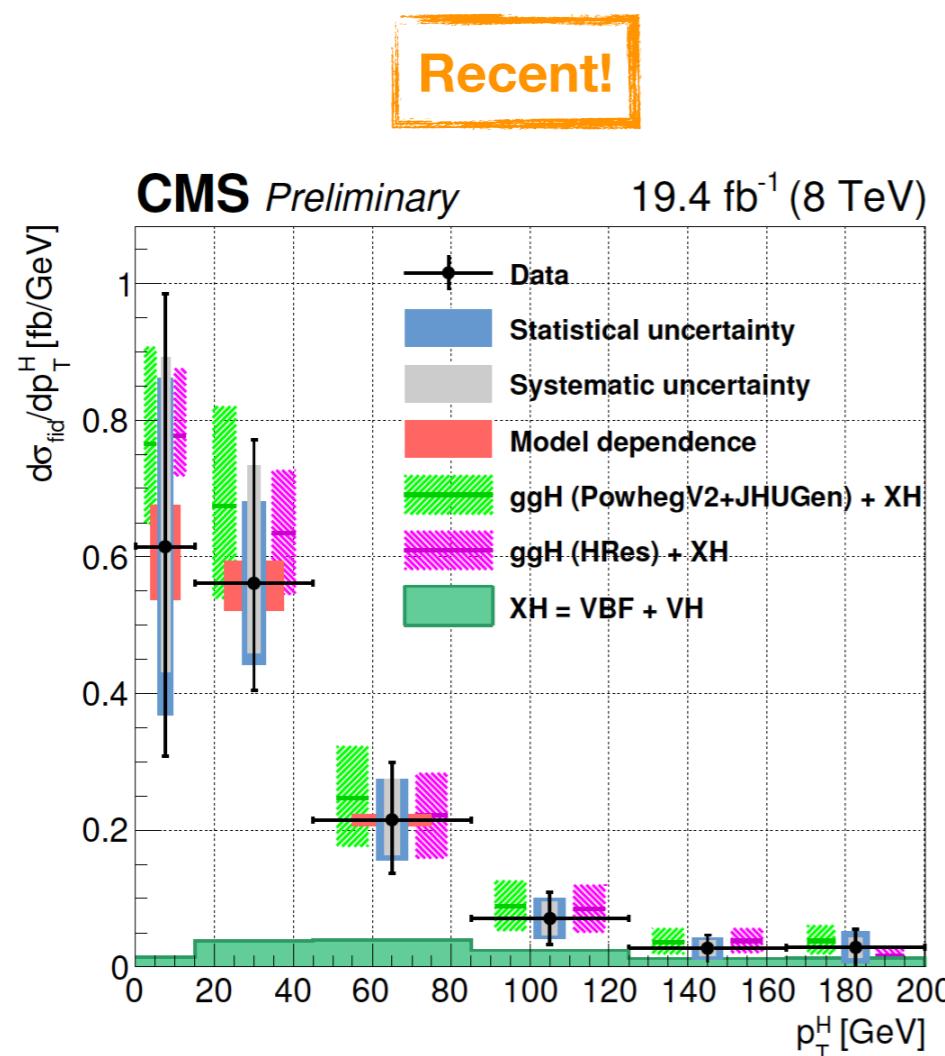


CMS: arXiv:1312.1129 **4.3 σ** (5.8) $\mu = 0.72 \pm 0.20 - 0.18$

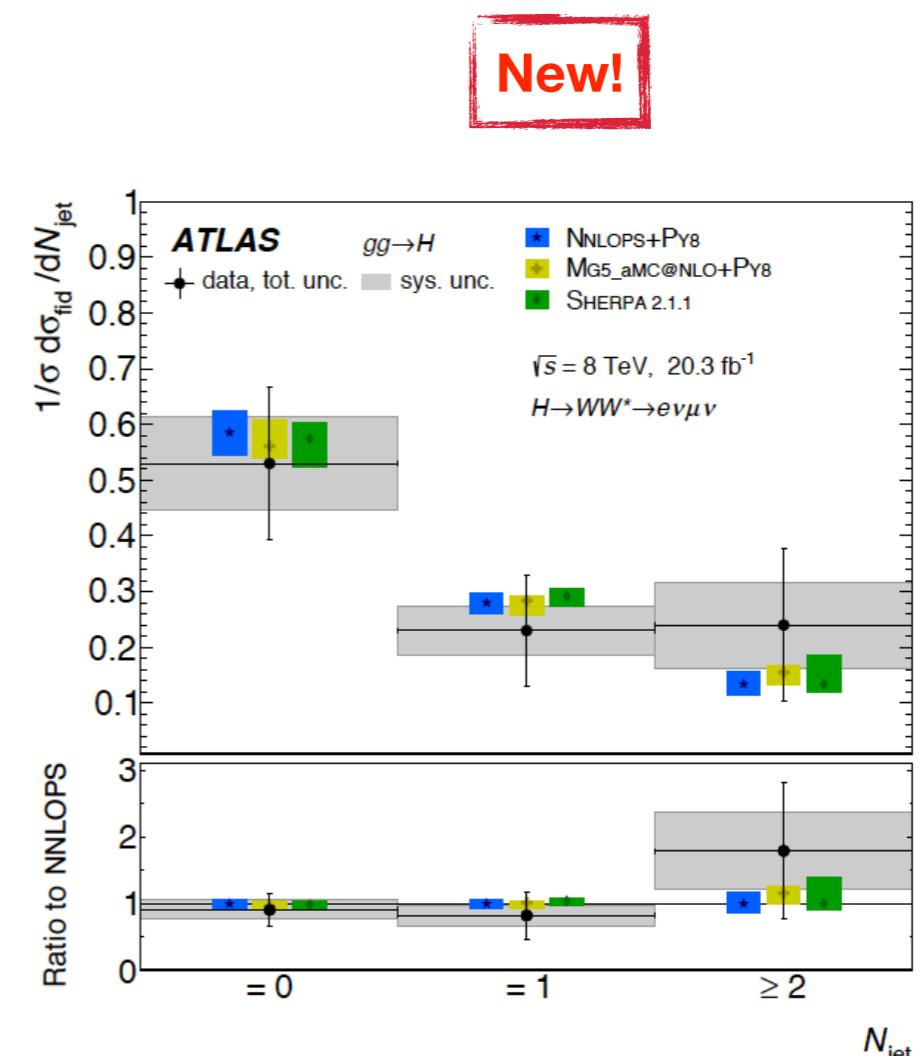
ATLAS: arXiv:1412.2641 **6.1 σ** (5.8)
 $\mu = 1.09 \pm 0.16 - 0.15 \text{ (stat)} \pm 0.17 - 0.14 \text{ (syst)}$
arXiv:1506.06641 VH

H \rightarrow WW \rightarrow 2l2v

- Latest results in this channel from both ATLAS and CMS focus on differential distributions



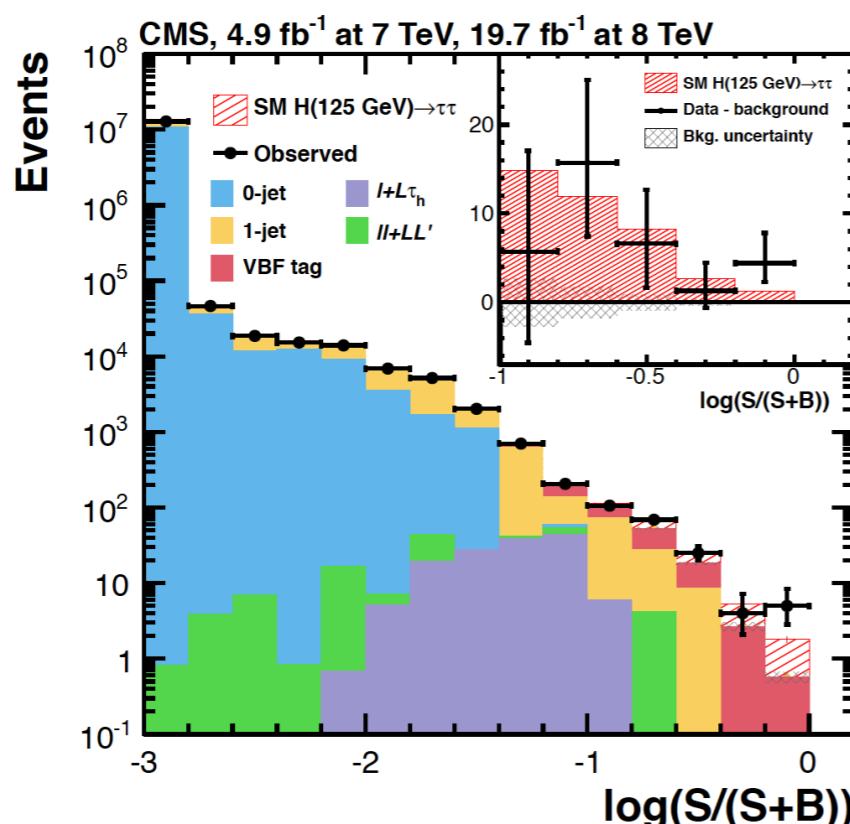
CMS: [HIG-15-010](#)
p_T Higgs, differential distributions
8TeV



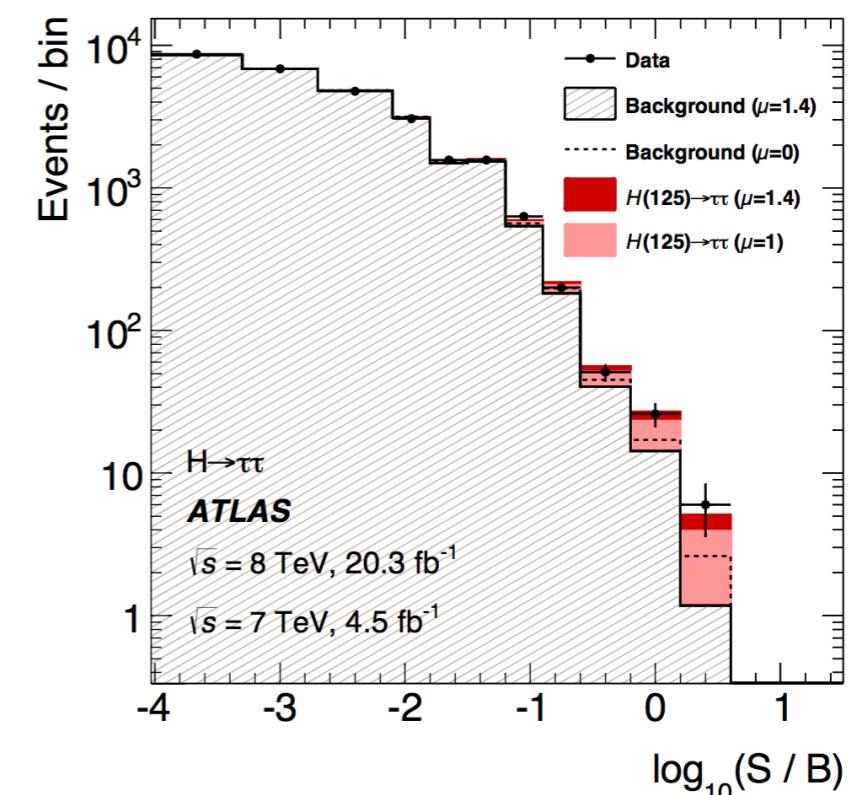
ATLAS: [arXiv:1604.02997](#)
Fiducial and differential cross sections
8TeV

H \rightarrow $\tau\tau$

- Most sensitive **fermion decay**
- **Low Branching Fraction**, complex final state
 - Accessible via VBF
- Different categories and τ decays ($\tau_{\text{lep}}, \tau_{\text{had}}$)



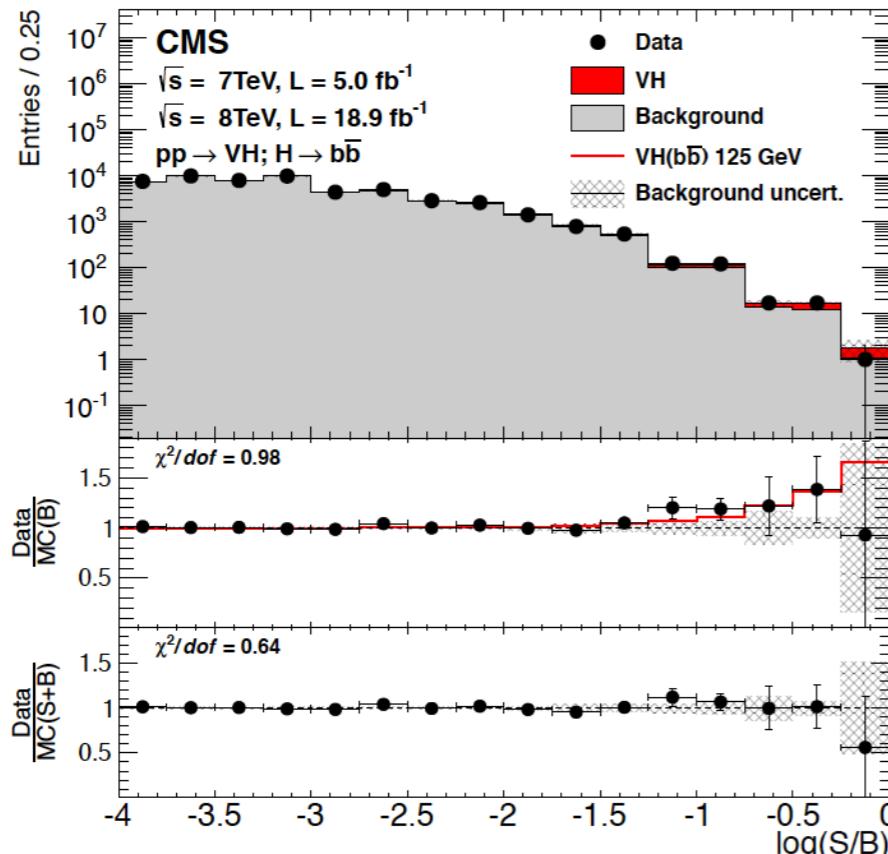
CMS: [arXiv:1401.5041](https://arxiv.org/abs/1401.5041) **3.2 σ** (3.7)
 $\mu = 0.78 \pm 0.27$



ATLAS: [arXiv:1501.04943](https://arxiv.org/abs/1501.04943) **4.5 σ** (3.4)
 $\mu = 1.43 +0.43 -0.37$
[arXiv:1511.08352](https://arxiv.org/abs/1511.08352) VH

H \rightarrow bb

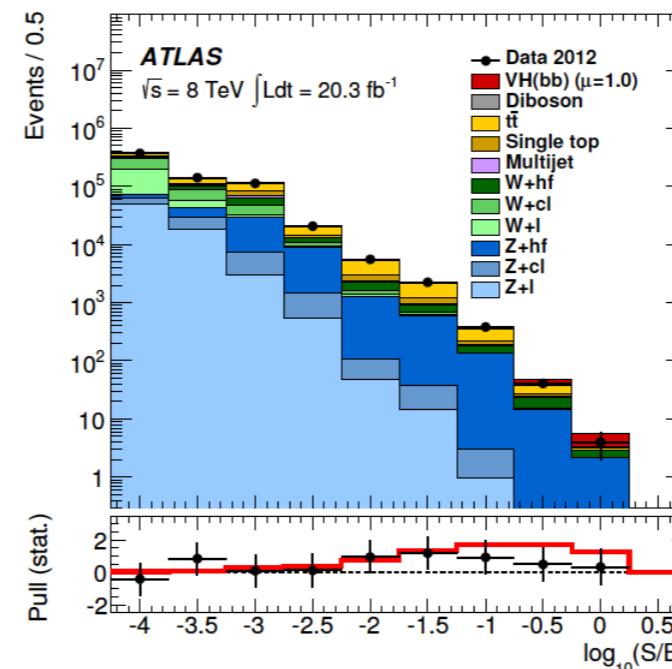
- Highest BR of all at 125 (almost 60%)
 - Still really difficult \rightarrow ggH overwhelmed by background
- Needs associated production to get a handle



CMS: arXiv:1310.3687 **2.1 σ** (2.1)

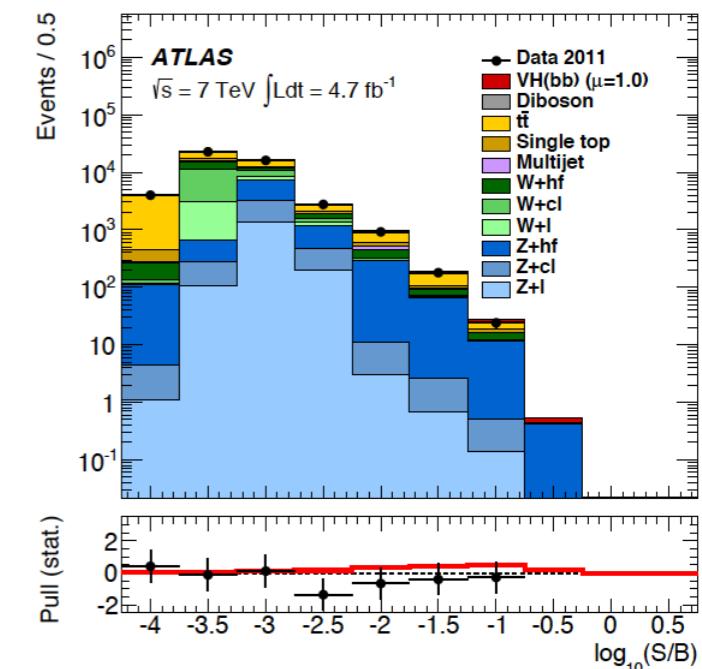
$$\mu = 1.0 \pm 0.5$$

H \rightarrow bb in VH



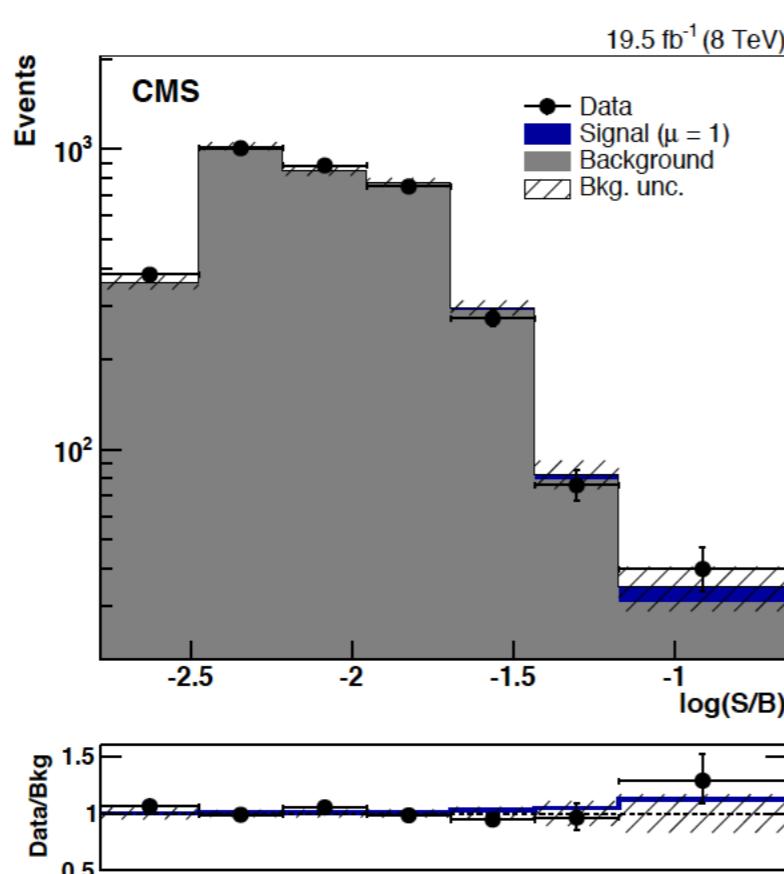
ATLAS: arXiv:1409.6212 **1.4 σ** (2.6)
 $\mu = 0.52 \pm 0.32(\text{stat.}) \pm 0.24(\text{syst.})$
H \rightarrow bb in VH

Another important associated production for H \rightarrow bb: ttH

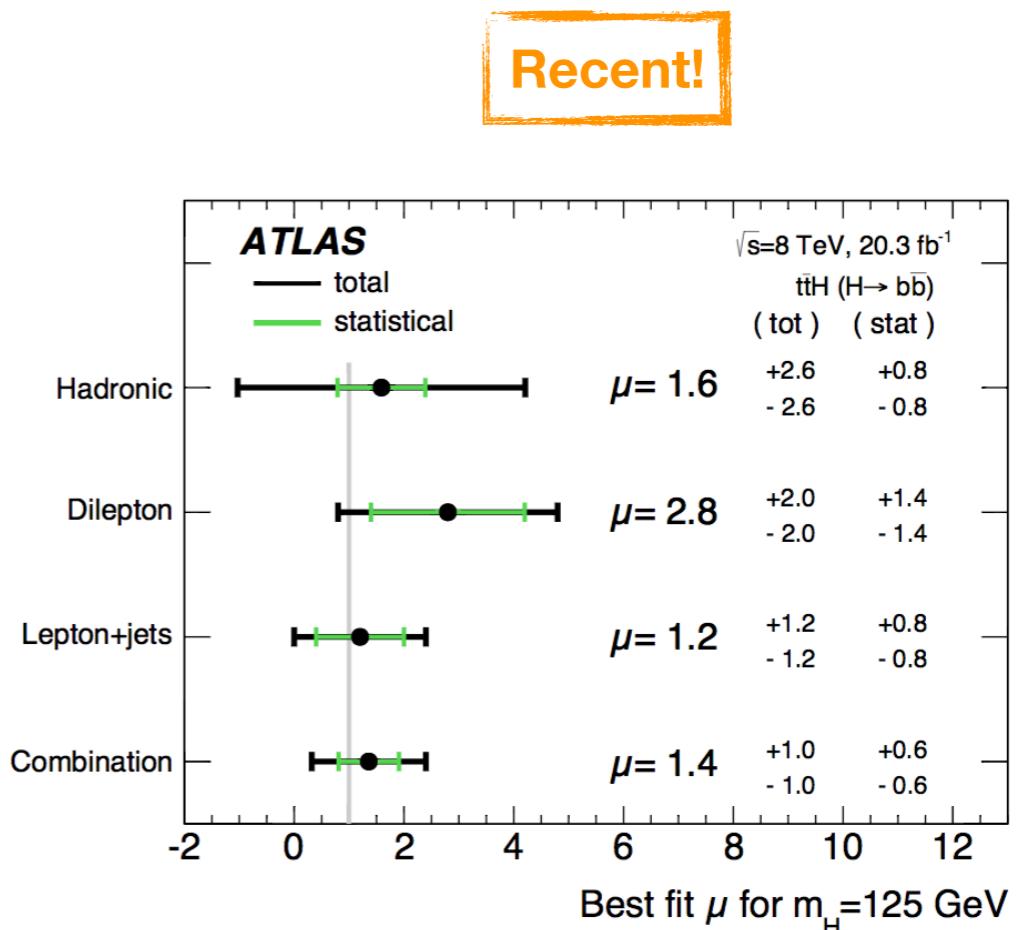


ttH, H \rightarrow bb

- Low production rate
- Two top quarks \rightarrow rich and very characteristic signatures
- ttH, H \rightarrow bb: Matrix Element methods



CMS: [arXiv:1502.02485](https://arxiv.org/abs/1502.02485) ME
[arXiv:1303.0763](https://arxiv.org/abs/1303.0763)

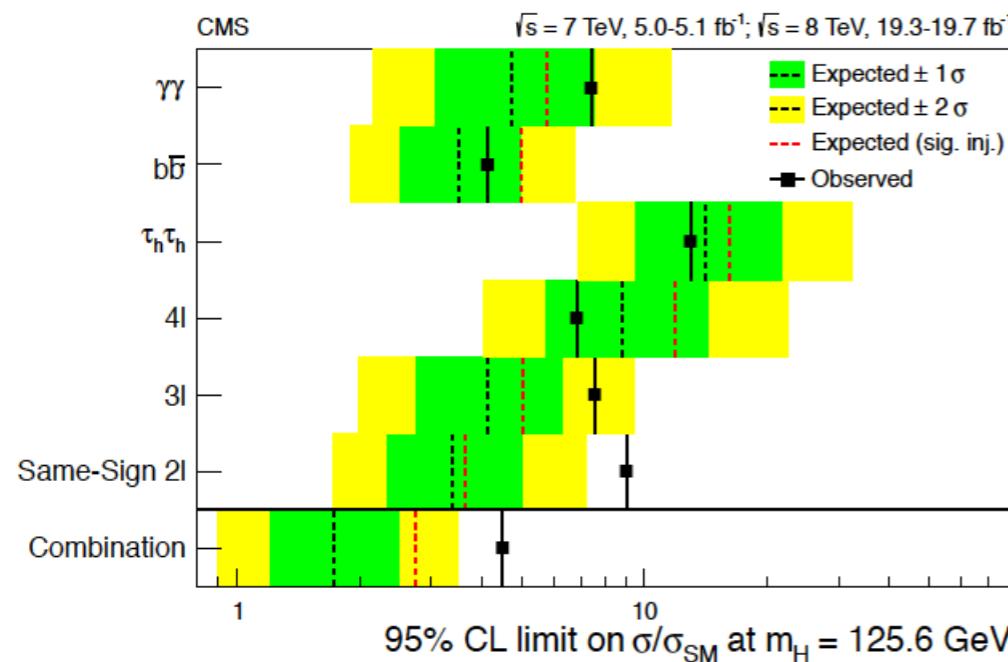


ATLAS: [arXiv:1604.03812](https://arxiv.org/abs/1604.03812)
[arXiv:1503.05066](https://arxiv.org/abs/1503.05066)
ME included in NN

The ttH production is interesting on its own

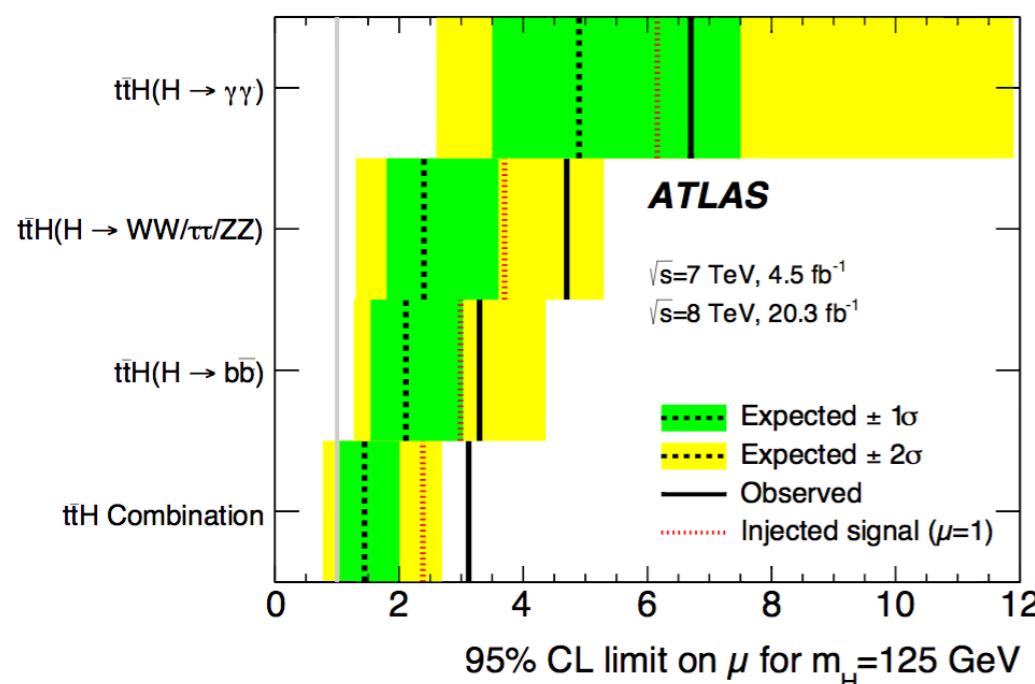
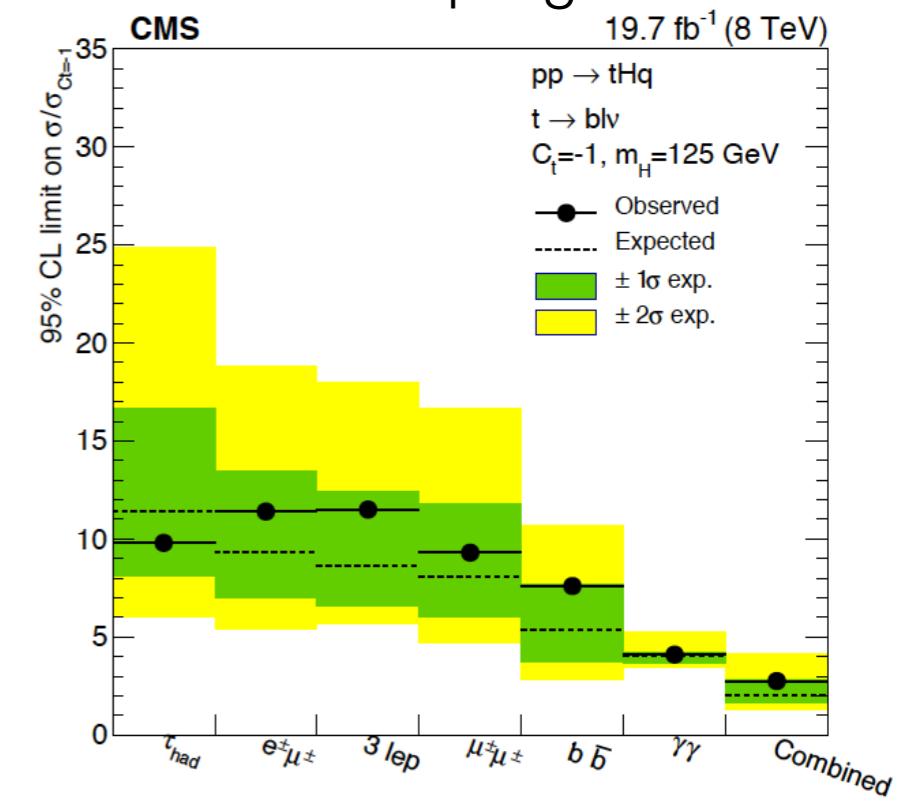
ttH and tH

- Direct assessment of the Top-Higgs Yukawa coupling, important parameter to test the SM
 - Indirect: ggH production, $H \rightarrow \gamma\gamma$
 - ttH production studied in many channels: $H \rightarrow bb/\gamma\gamma/WW/ZZ/\tau\tau$



CMS:
[arXiv:1408.1682](https://arxiv.org/abs/1408.1682)
 Run-1 combination
2 σ excess over SM

Rare alternative production:
 single top plus Higgs (tH) \rightarrow
 Sensitive to the sign of the
 coupling



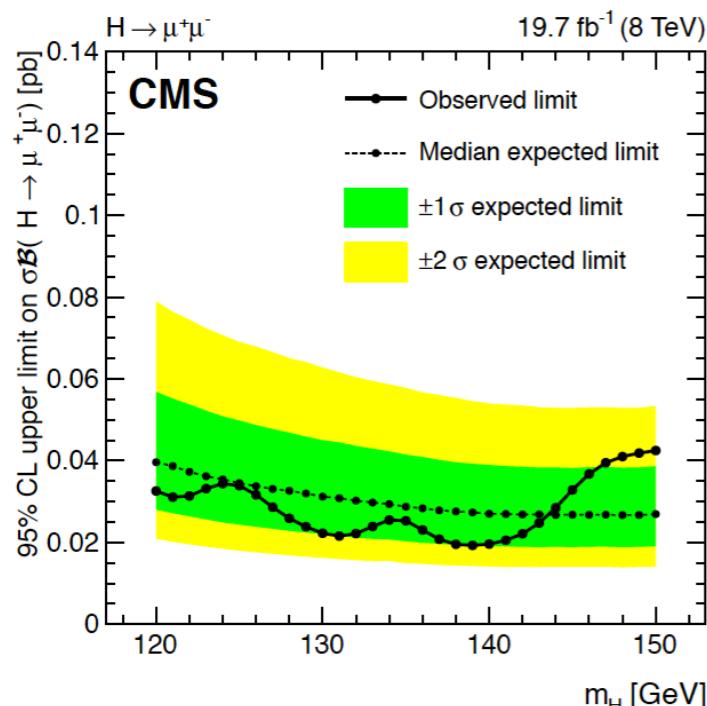
Recent!

ATLAS:
[arXiv:1604.03812](https://arxiv.org/abs/1604.03812)
 ttH Run-1 combination

CMS: [arXiv:1509.08159](https://arxiv.org/abs/1509.08159)
 tH combination
 $H \rightarrow bb/\gamma\gamma/WW/ZZ/\tau\tau$

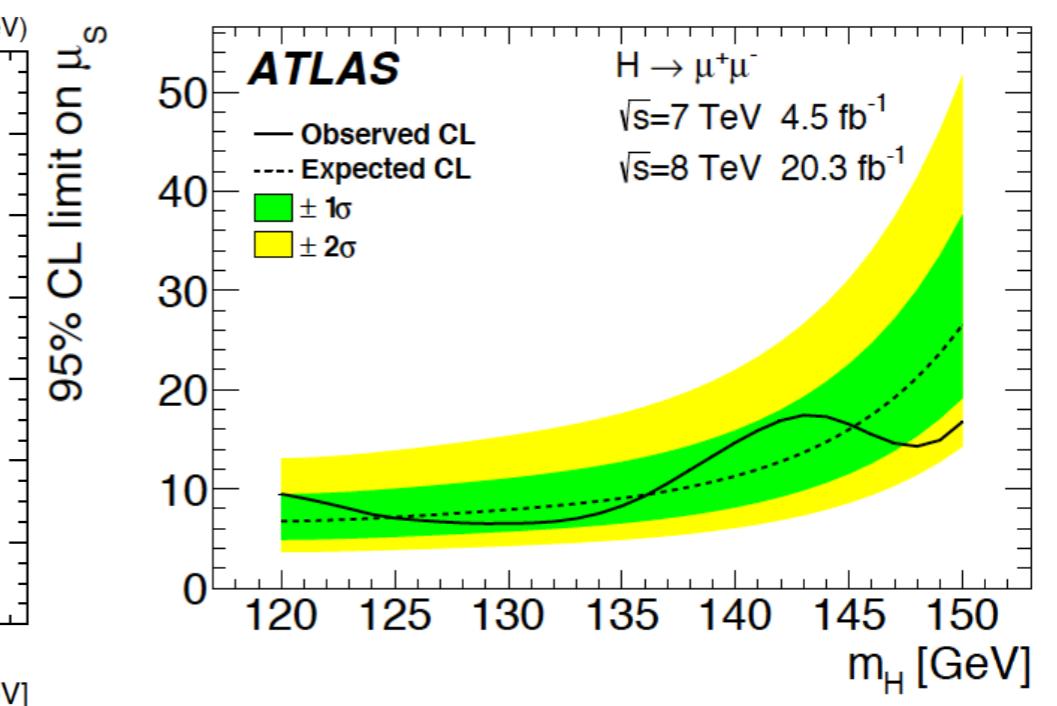
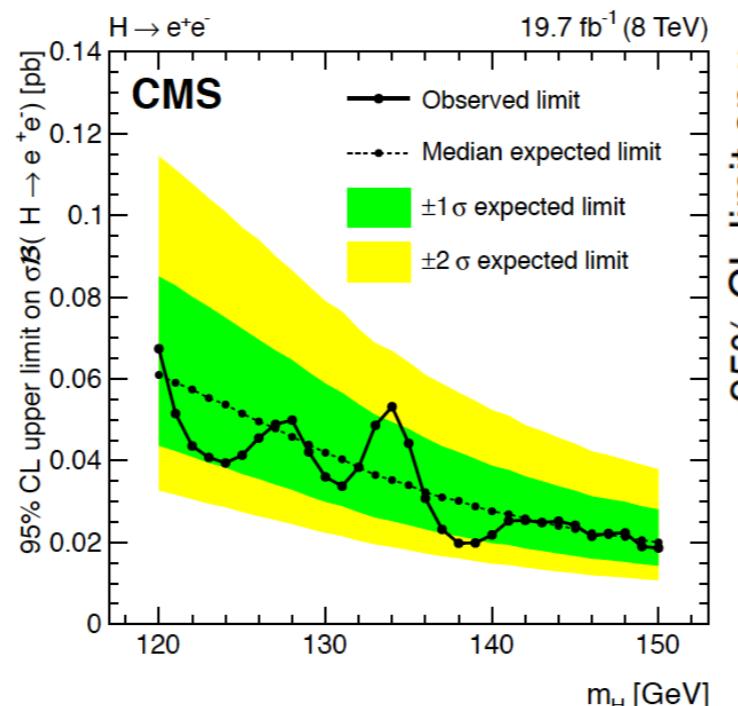
$H \rightarrow \mu\mu/ee$

- Setting limits on branching fraction
 - which in the SM is very small (< 0.1%)
- Data confirms that the leptonic couplings of the Higgs are not flavor-universal



CMS: [arXiv:1410.6679](https://arxiv.org/abs/1410.6679)

$H \rightarrow ee/\mu\mu$



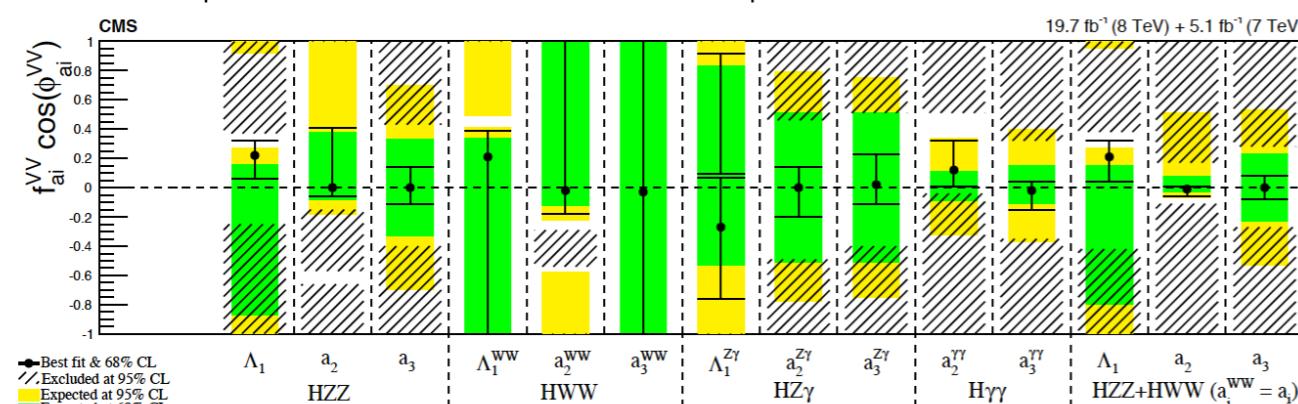
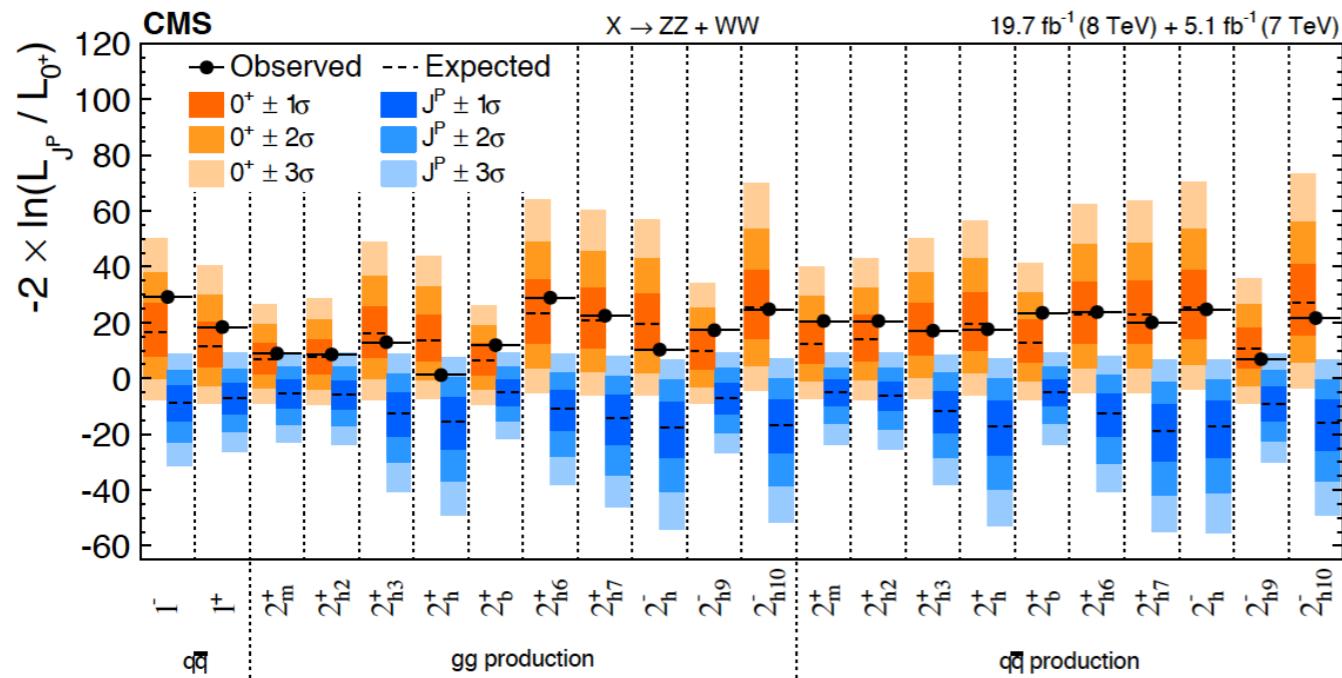
ATLAS: [arXiv:1406.7663](https://arxiv.org/abs/1406.7663)

$H \rightarrow \mu\mu$

Properties: spin, parity

- Several decays: WW/ZZ/Z γ / $\gamma\gamma$
 - Exotic spin** hypothesis and anomalous **HW couplings** in spin 0
- New ATLAS result testing CP invariance in VBF production

ATLAS: arXiv:1506.05669
HIGG-2013-17

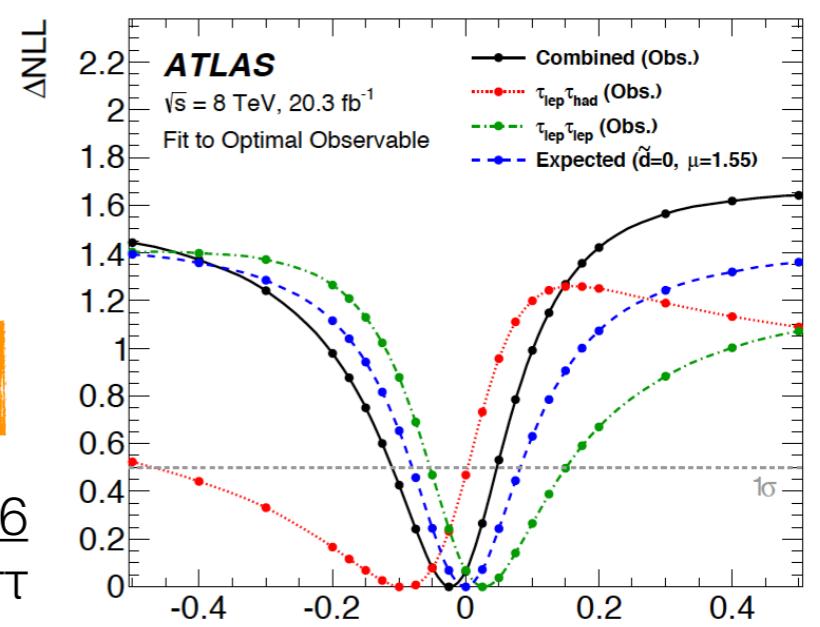
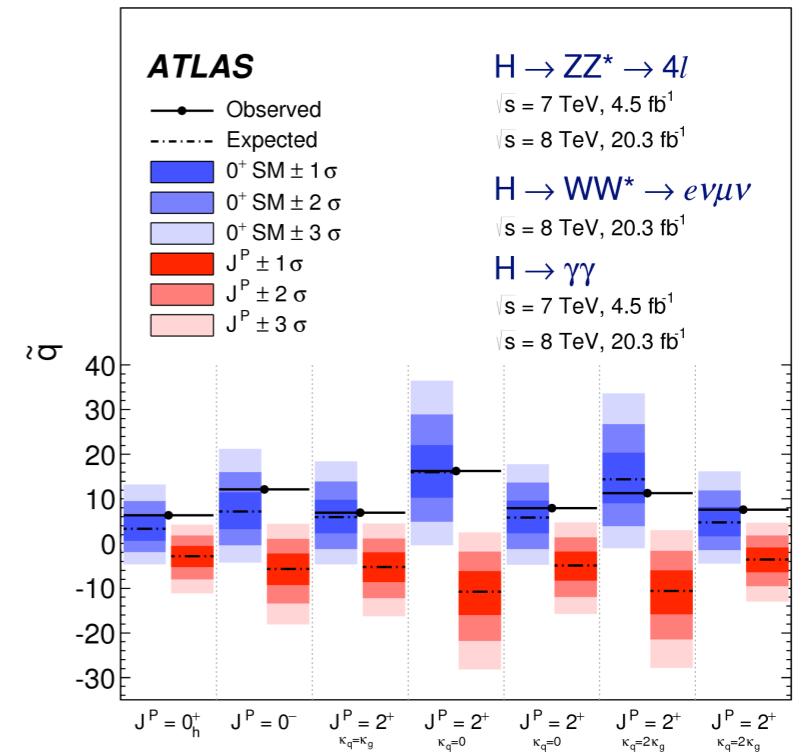


CMS: arXiv:1411.3441

$J^{CP} = 0^{++}$ favored

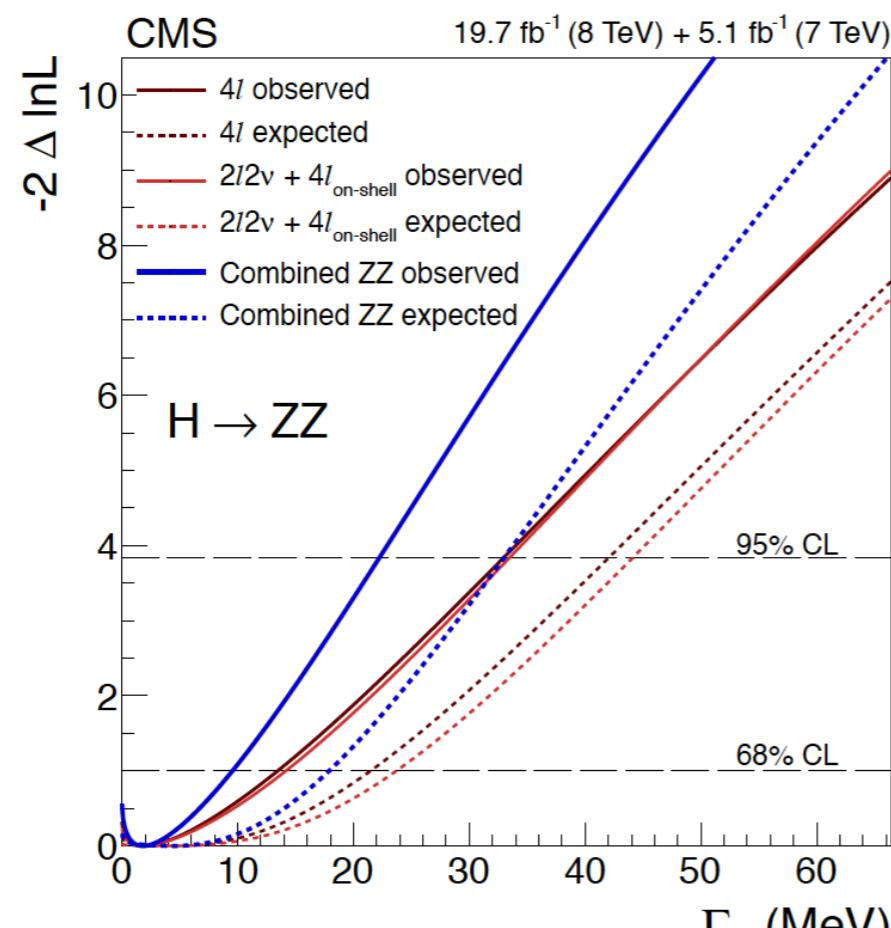
Recent!

ATLAS: arXiv:1602.04516
CP violation in VBF H \rightarrow $\tau\tau$



Properties: width

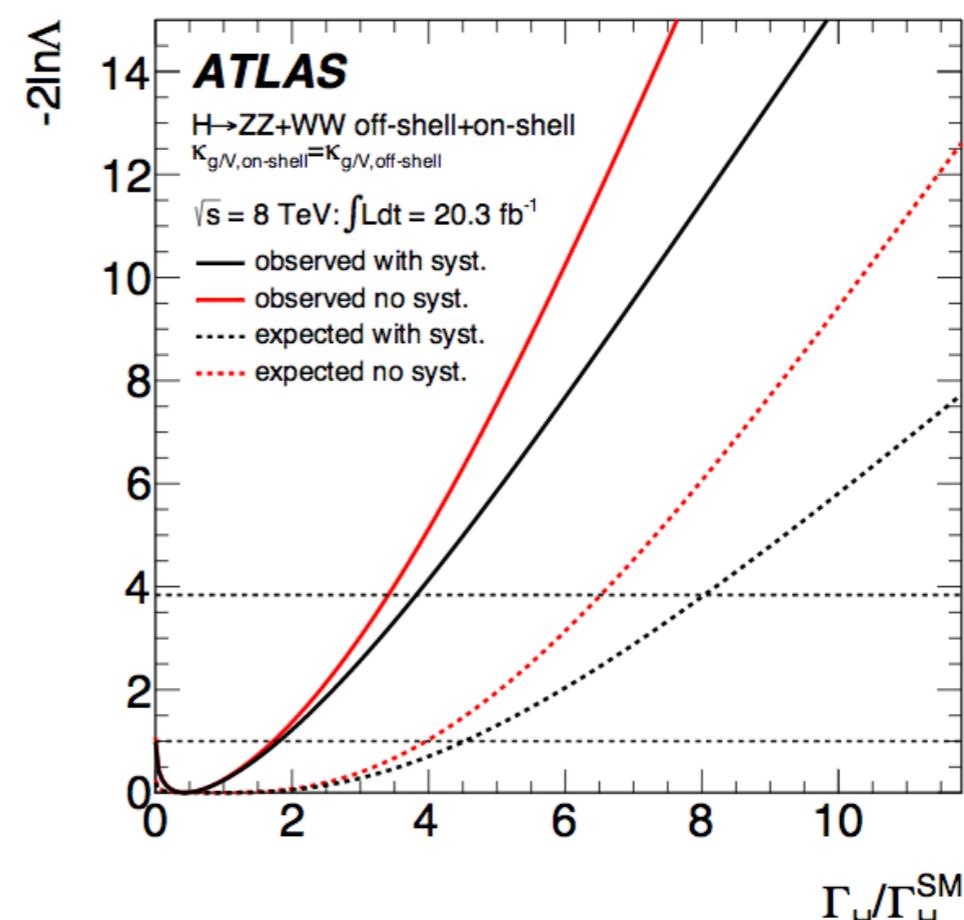
- Direct width measurement at the peak limited by experimental resolution
 - sensitive to values $>> 4$ MeV expected in the SM
 - < 3.4 GeV at 95%CL in $H \rightarrow ZZ \rightarrow 4l$, < 2.4 GeV at 95%CL in $H \rightarrow \gamma\gamma$
- Indirect limits obtained by exploring off-shell production away from resonance peak
 - assumptions are needed to interpret off-shell and on-shell yields in terms of Γ_H



CMS: [arXiv:1405.3455](https://arxiv.org/abs/1405.3455)

$H \rightarrow ZZ$

$\Gamma_H < 22$ MeV at a 95% CL

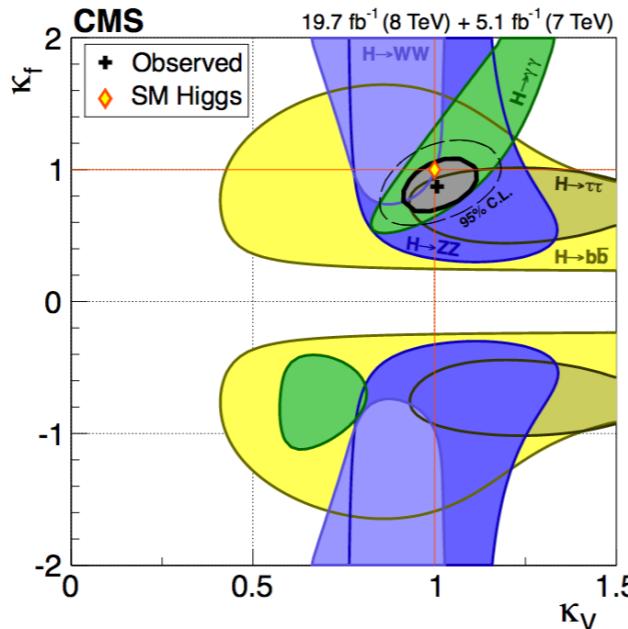
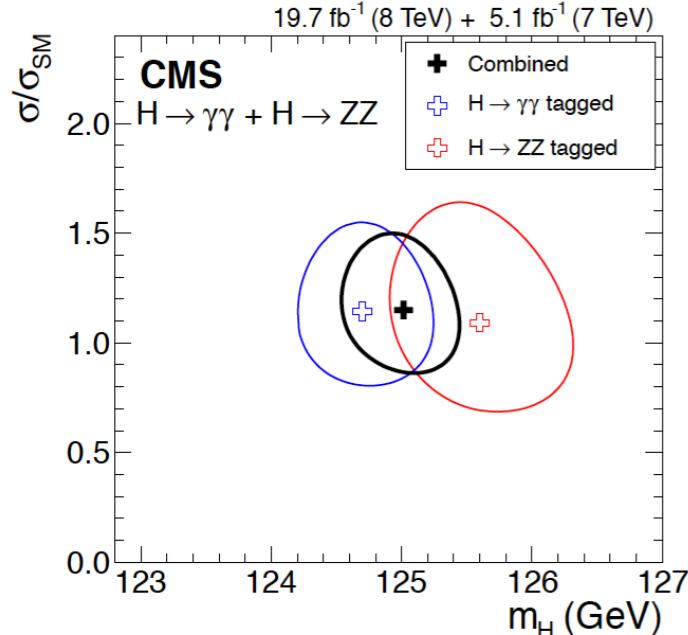


ATLAS: [arXiv:1503.01060](https://arxiv.org/abs/1503.01060)

$H \rightarrow ZZ$ and $H \rightarrow WW$

$\Gamma_H < 22.7$ MeV at a 95% CL

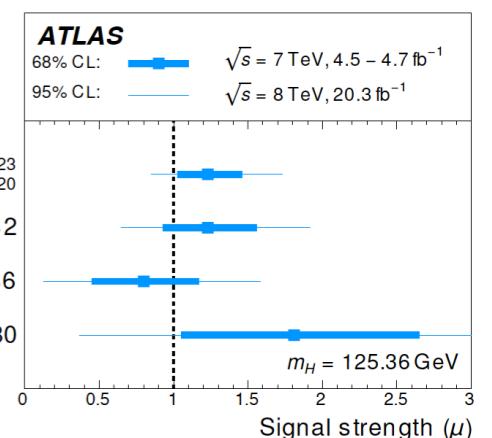
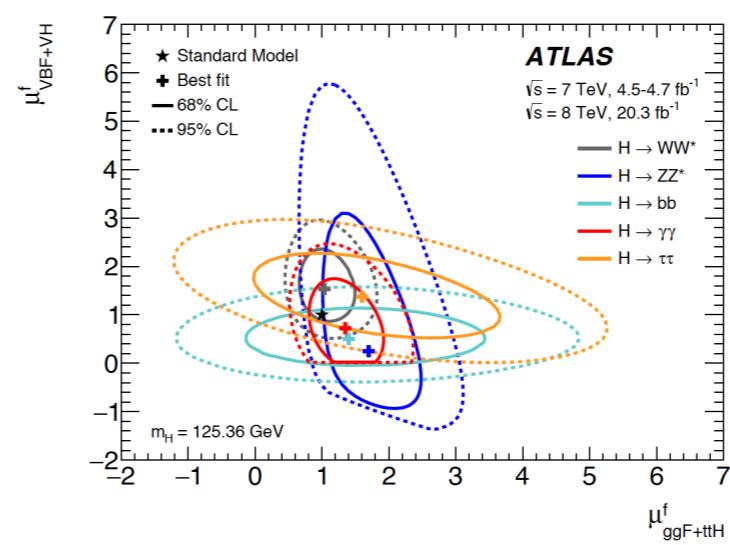
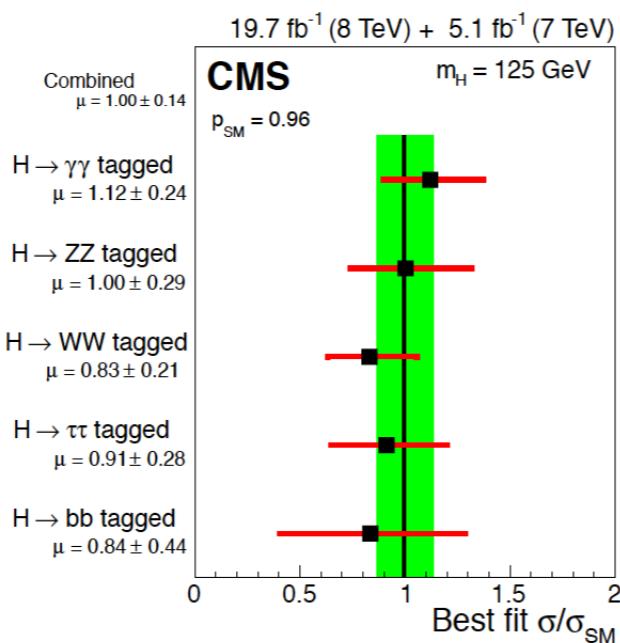
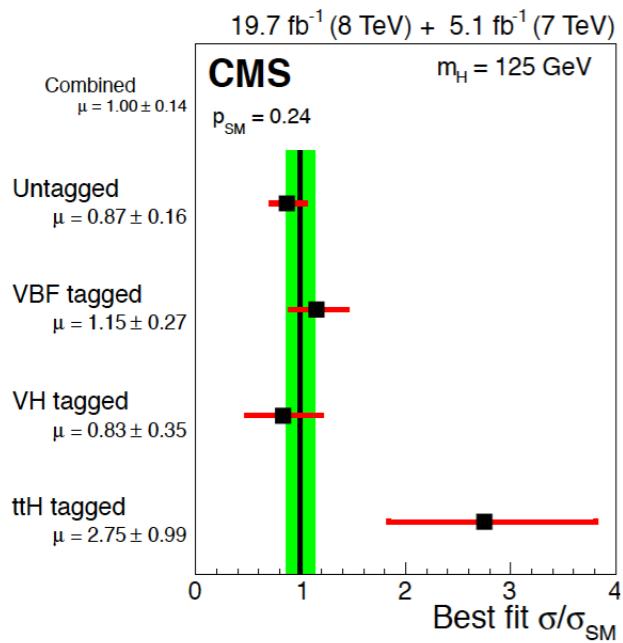
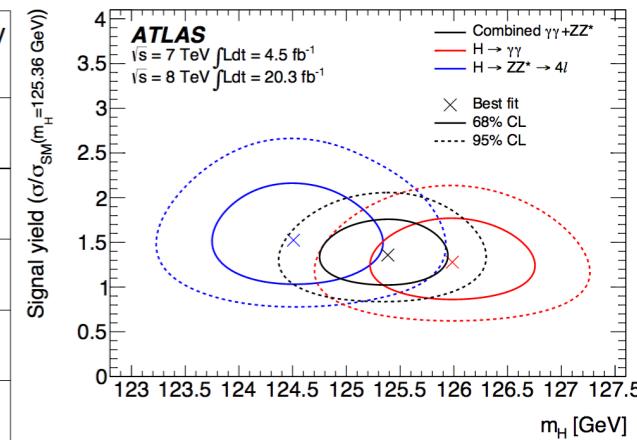
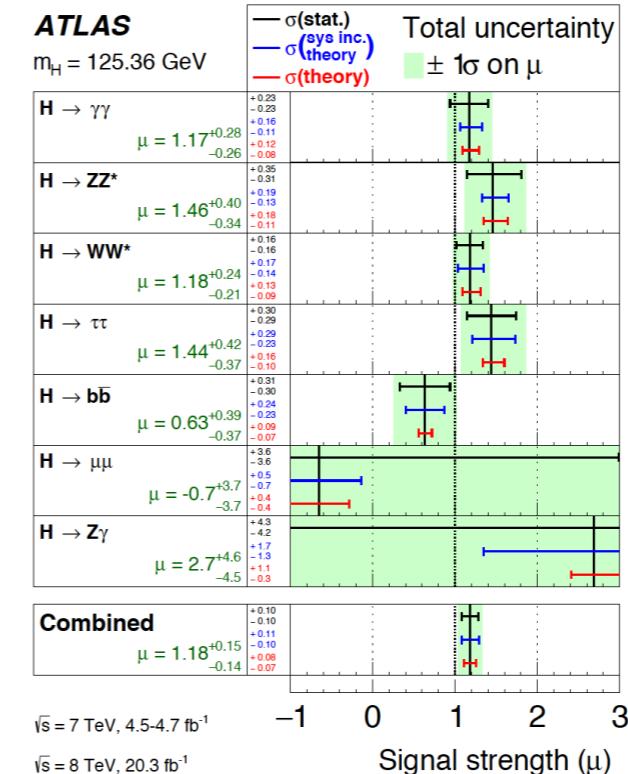
ATLAS and CMS Combinations



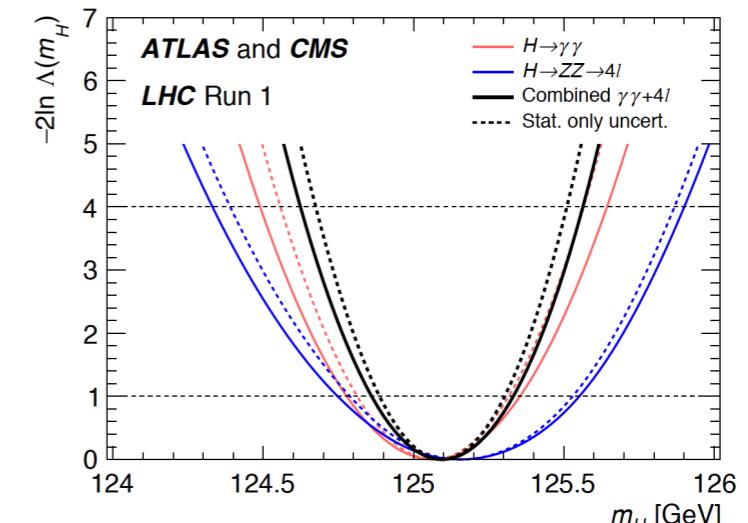
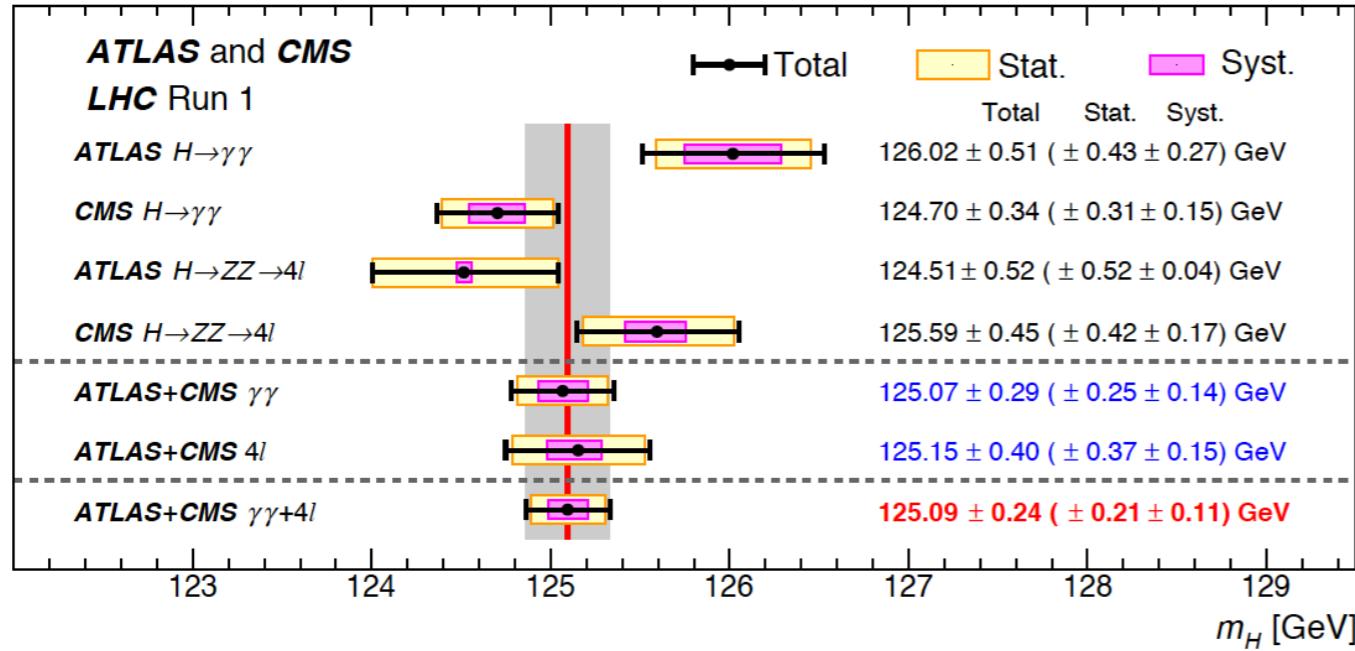
CMS: arXiv:1412.8662

$$m_H = 125.02 \pm 0.26 - 0.27(\text{stat}) \pm 0.14 - 0.15(\text{syst}) \text{ GeV}$$

$$\mu = 1.00 \pm 0.09 \text{ (stat)} \pm 0.08 - 0.07(\text{theo}) \pm 0.07 \text{ (syst)}$$

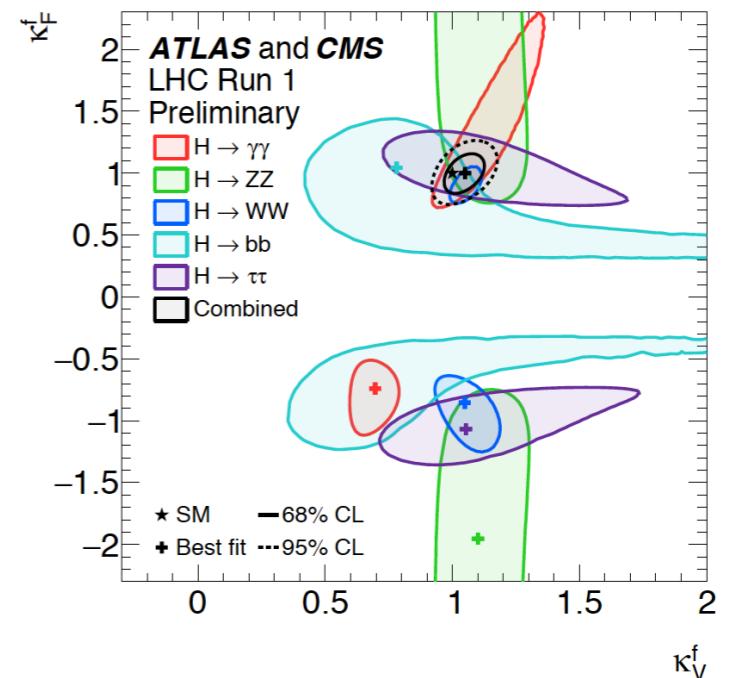
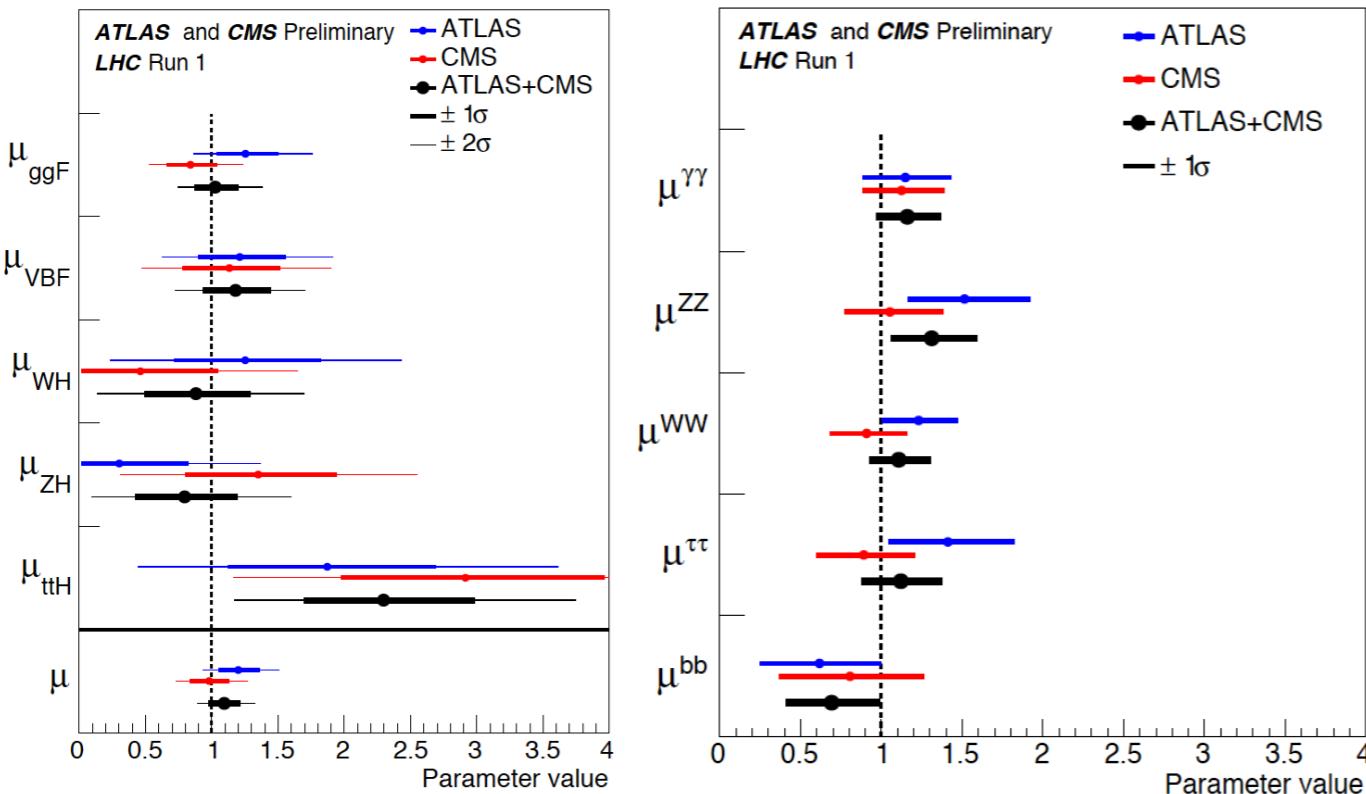


ATLAS “and” CMS combinations



arXiv:1503.07589

$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV



CONF-2015-044/HIG-15-002

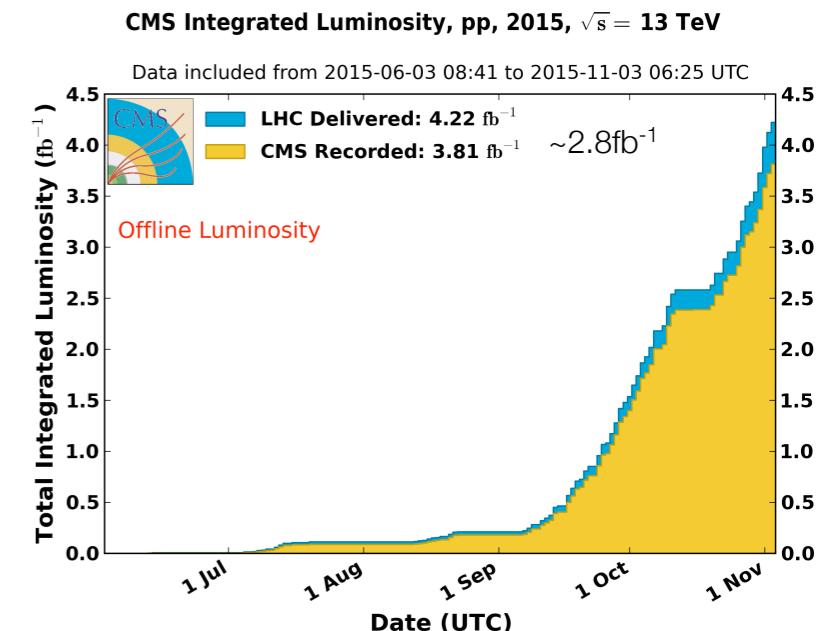
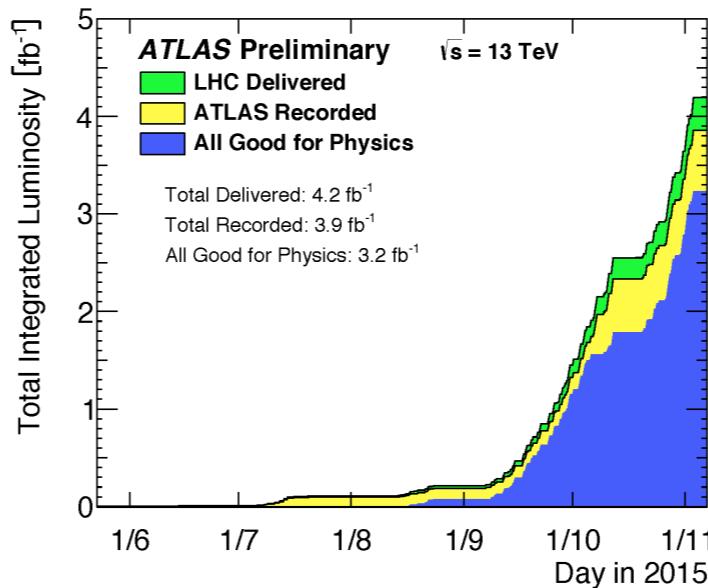
$\mu = 1.09 \pm 0.11$

VBF 5.4σ (4.7) and $H \rightarrow \tau\tau$ 5.5σ (5.0)

From Run-1 to Run-2

LHC Run-2

- LHC Run-2 started last year
 - 4.2fb^{-1} at 13TeV in 2015
 - 2016 data-taking starting now

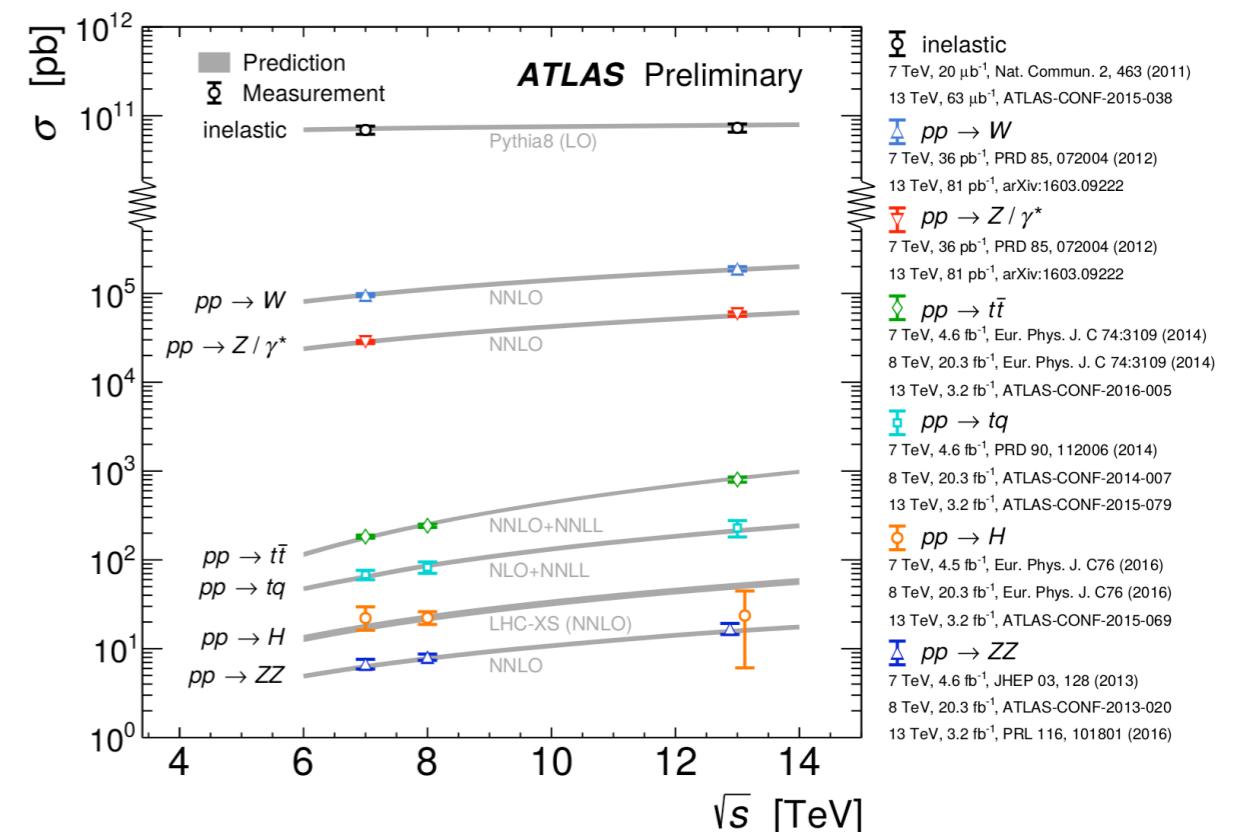


Until the end of 2018 the LHC plans to deliver $\sim 30\text{fb}^{-1}$ of luminosity per year

Process	8/7TeV	13/8TeV
ggH	1.27	2.27
VBF	1.29	2.36
WH	1.22	1.95
ZH	1.24	2.10
VH	1.23	2.01
tth	1.50	3.81
bbH	1.30	2.41
tH	1.51	3.88
HH	0.48	3.39

	13/8TeV
WW	1.98
ZZ	2.03
tt	3.29

Specific Higgs production modes grow more than the backgrounds
ttH, tH, HH much better at 13TeV

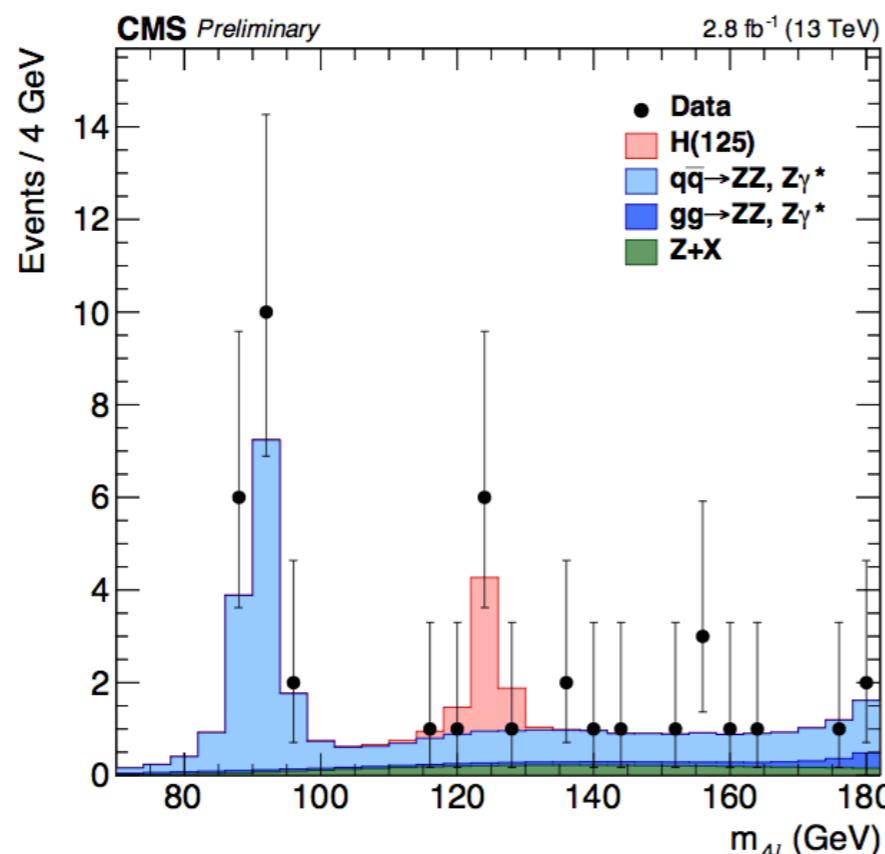


Early 13TeV birds

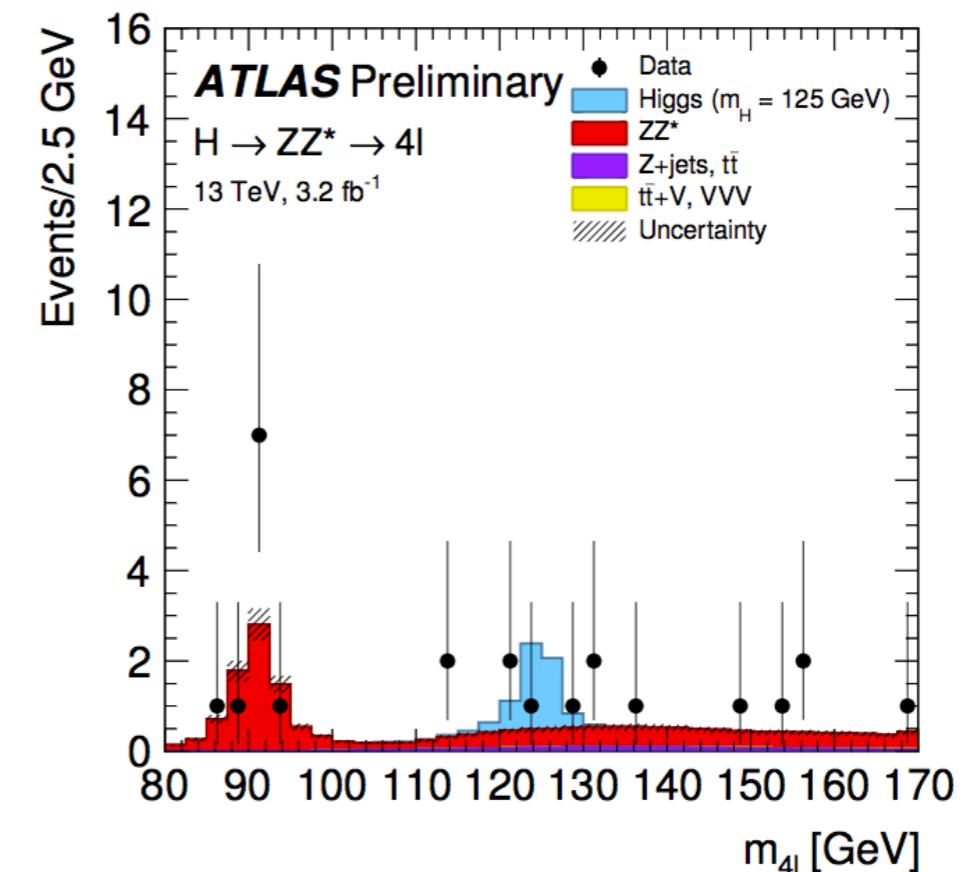
$H \rightarrow ZZ \rightarrow 4l$

Recent!

- The first $H \rightarrow ZZ \rightarrow 4l$ analyses with the full 2015 dataset are public by both ATLAS and CMS
- Sensitivity still low, but peak is already visible

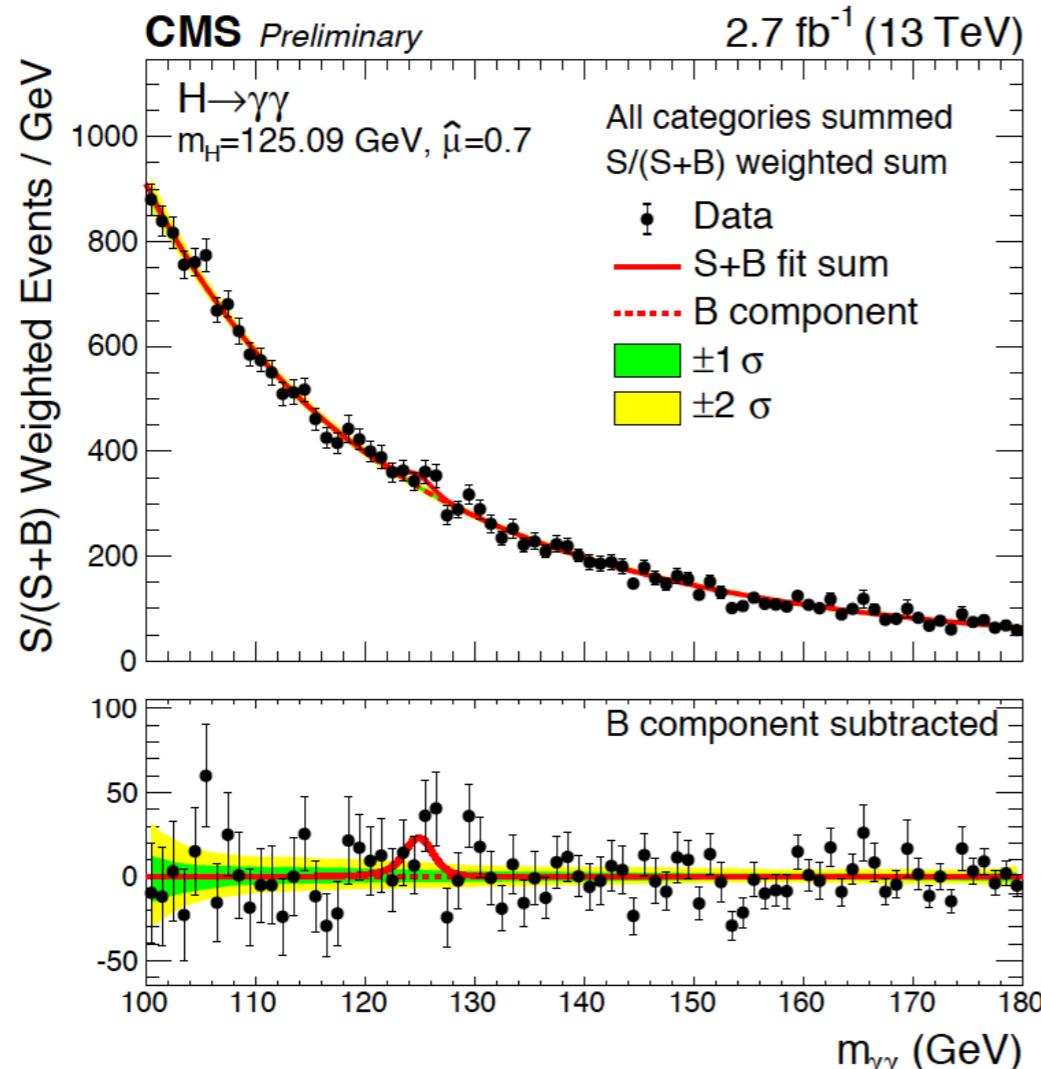


CMS: HIG-15-004 2.8fb^{-1} **2.5σ** (3.4)
 $\mu = 0.82 +0.57 -0.43$

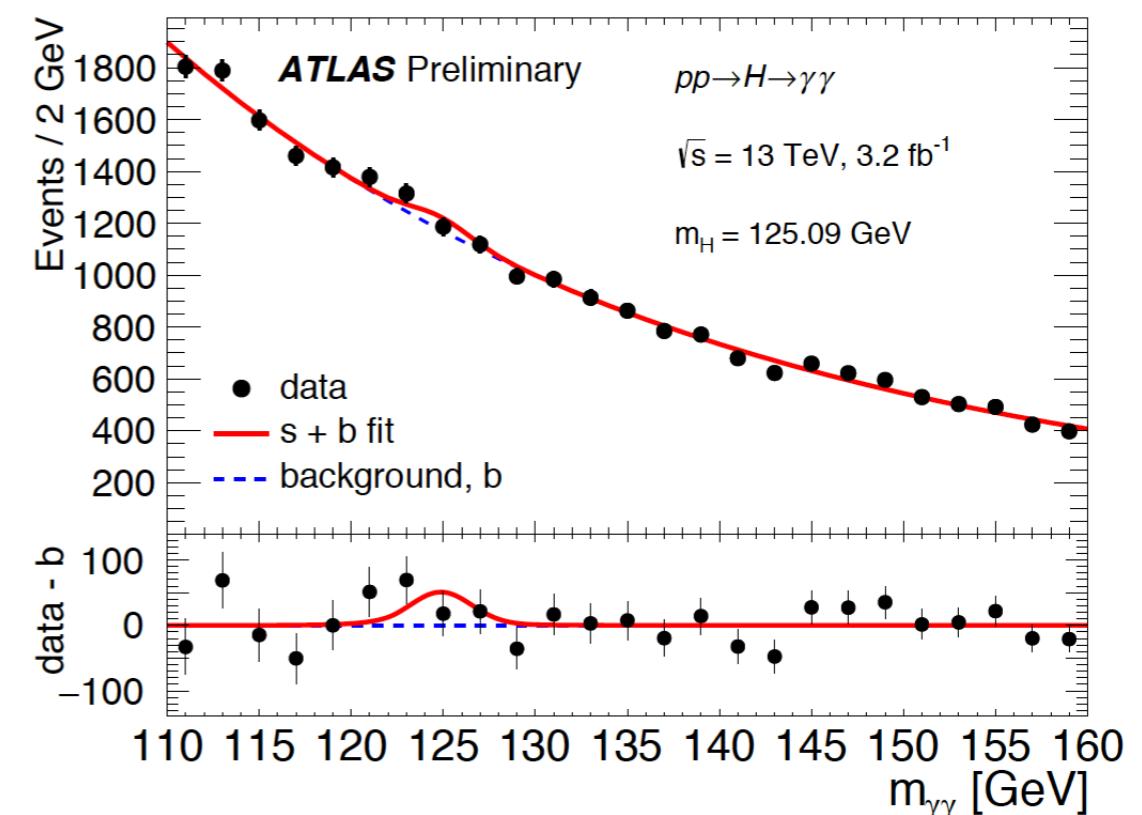


ATLAS: CONF-2015-059 3.2fb^{-1} **1.4σ** (2.8)

- First H \rightarrow $\gamma\gamma$ results also on the path towards rediscovery



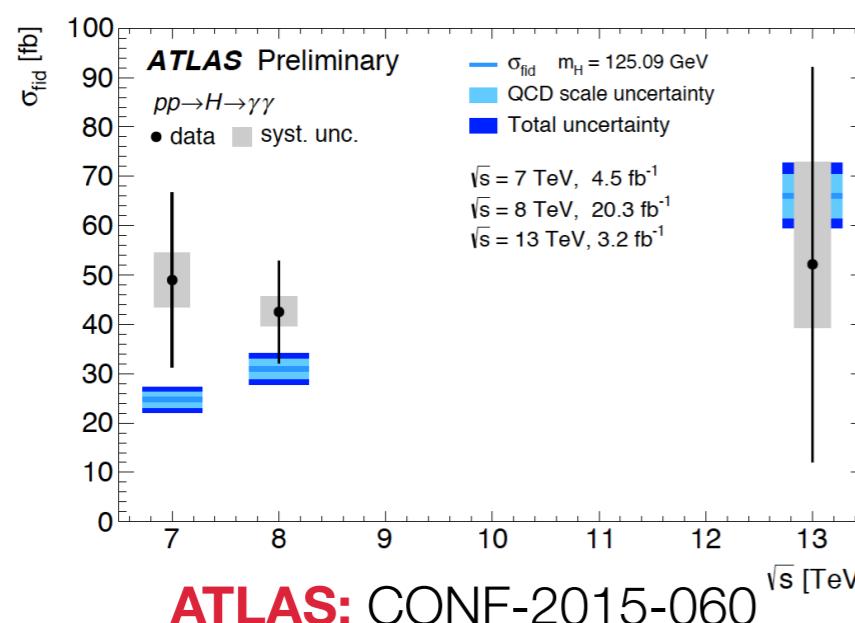
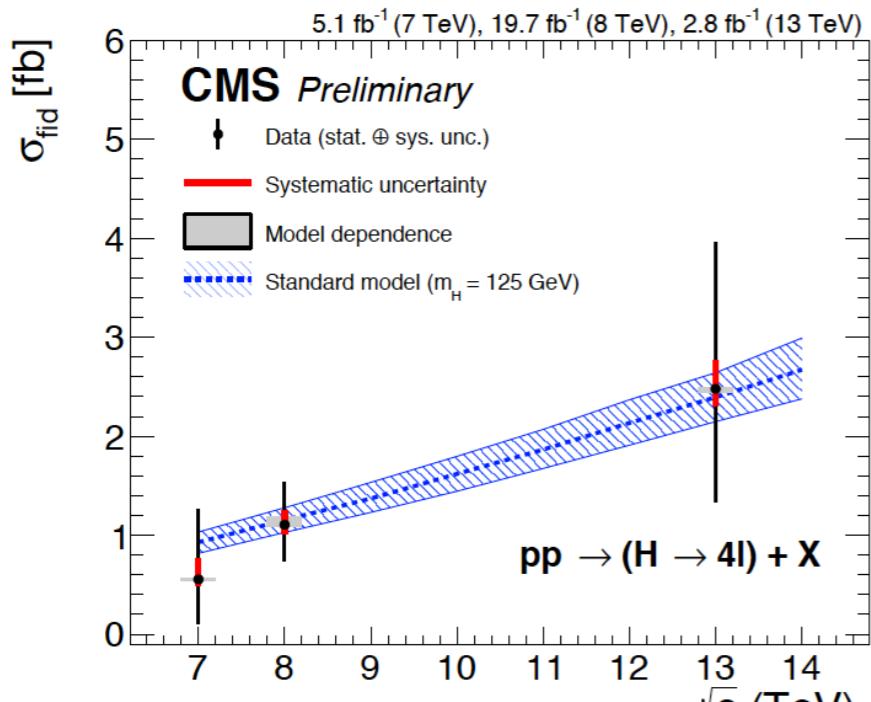
CMS: HIG-15-005 2.7 fb^{-1} **1.7σ (2.7)**
 $\mu = 0.69 +0.47 -0.42$



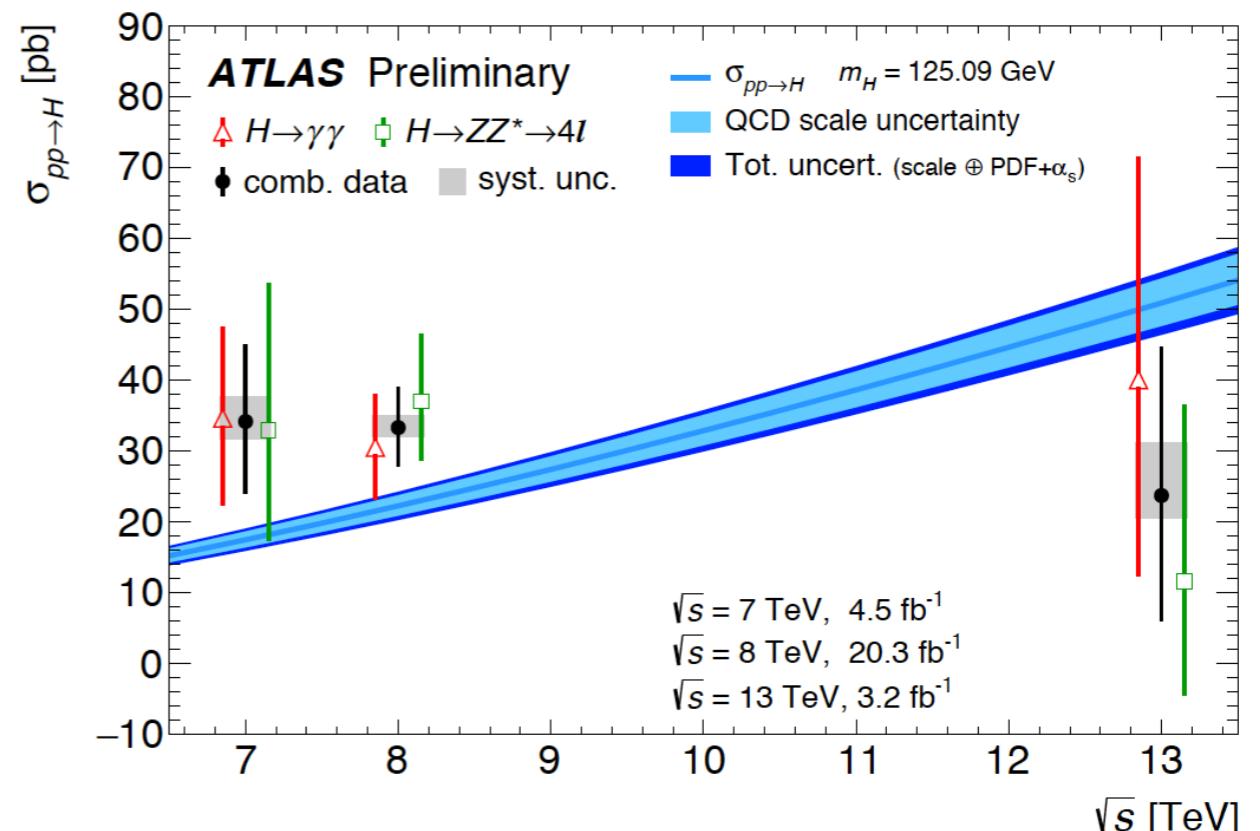
ATLAS: CONF-2015-060 3.2 fb^{-1} **1.5σ (1.9)**

$H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$

- The $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$ results were accompanied by some **additional studies**
 - Fiducial cross sections, high mass $X \rightarrow ZZ$ searches, Dark Matter searches

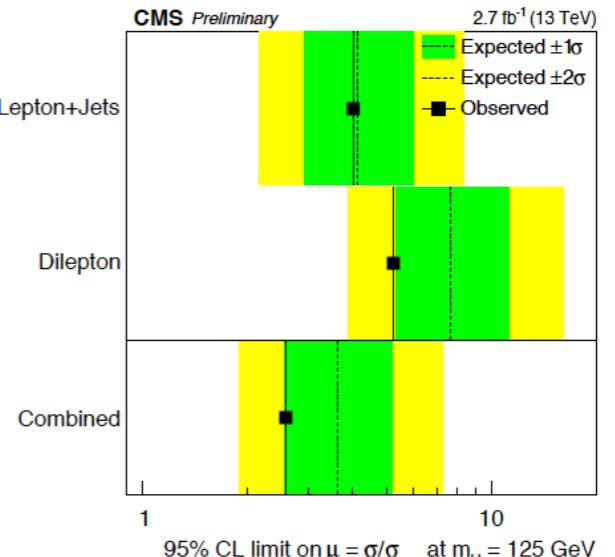
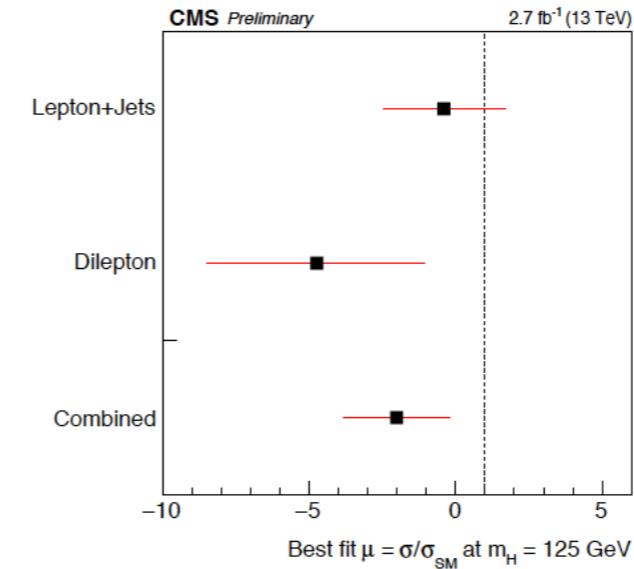
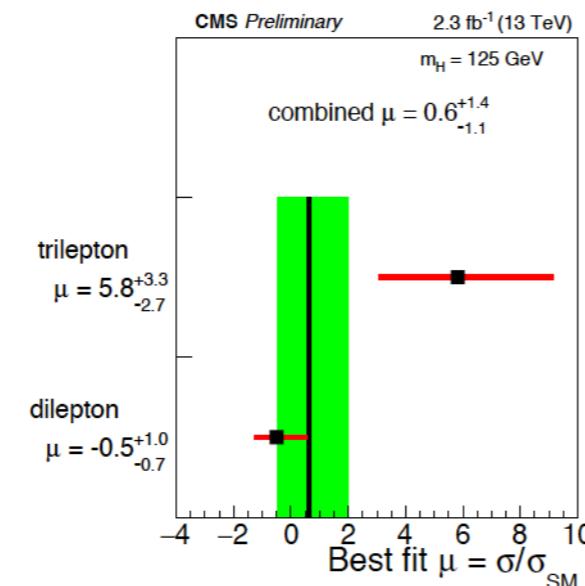
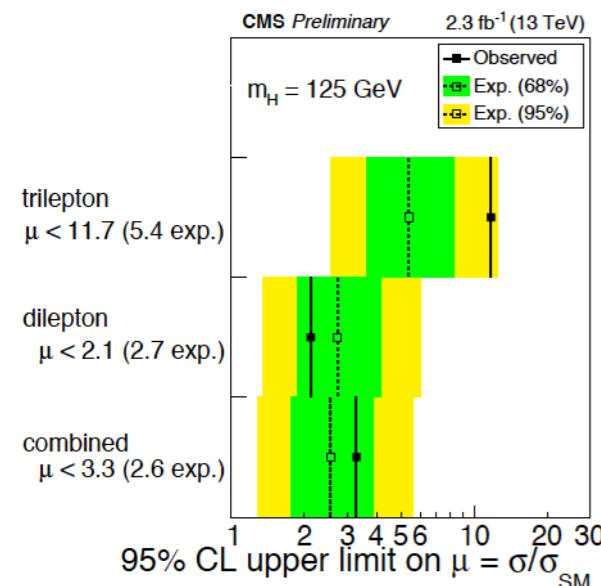


- And both channels were also **combined**



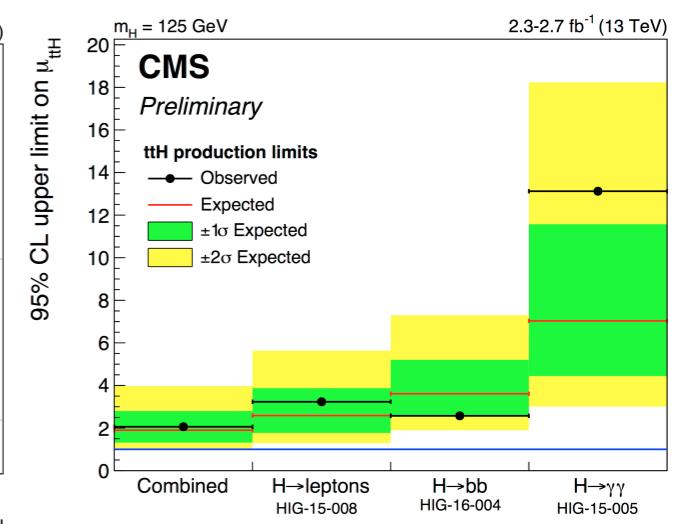
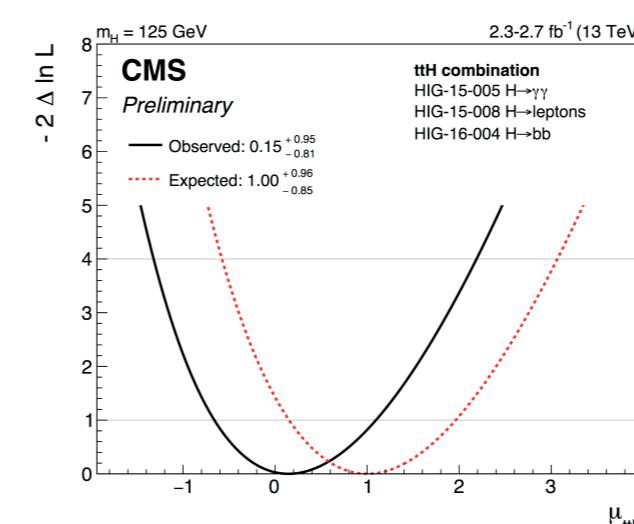
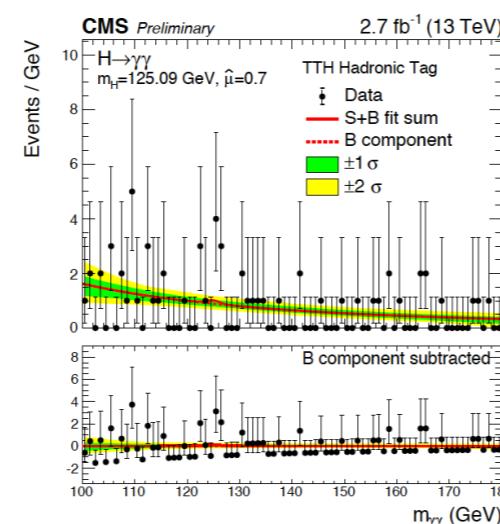
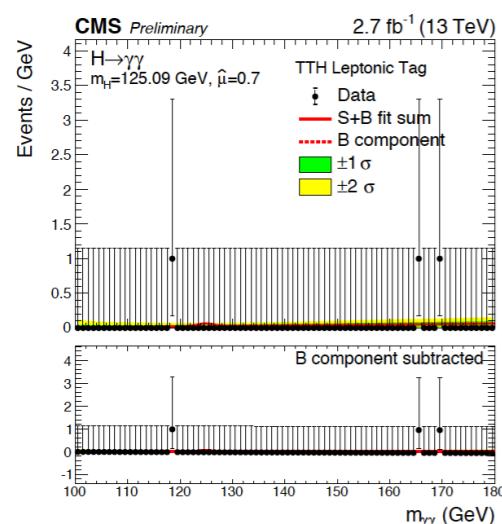
ATLAS: CONF-2015-069
 $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$: total Higgs cross section

- ttH studies performed at 13TeV in $H \rightarrow \gamma\gamma/bb/WW/ZZ/\pi\pi$
- Sensitivity close to the full 8TeV dataset thanks to the increase of the signal cross section
 - Run-1 excess not reproduced



CMS: HIG-15-008 ttH multilepton

CMS: HIG-16-004 ttH, $H \rightarrow bb$



CMS: HIG-15-005 ttH, $H \rightarrow \gamma\gamma$ in the $H\gamma\gamma$ analysis

CMS: ttH Combination Twiki

Beyond (the SM Higgs)

Exotic Higgs(es)

- With the current data → the Higgs boson looks very much SM-like
 - It still could be hiding BSM features
- Two approaches to the characterization of the Higgs as SM (or not)
 1. Precise measurement of its properties
 - Signal strength
 - Mass
 - Width
 - Spin and parity
 - Couplings
 2. Direct searches for BSM phenomena in the Higgs sector
 - Decays
 - Production
 - Heavy resonances decaying to Higgs(es)
 - Search for additional Higgs bosons
 - ...
- **Extensive work in Run-1**, already many results in Run-2, impossible to cover all of them → Focus on the most recent (in no particular order)

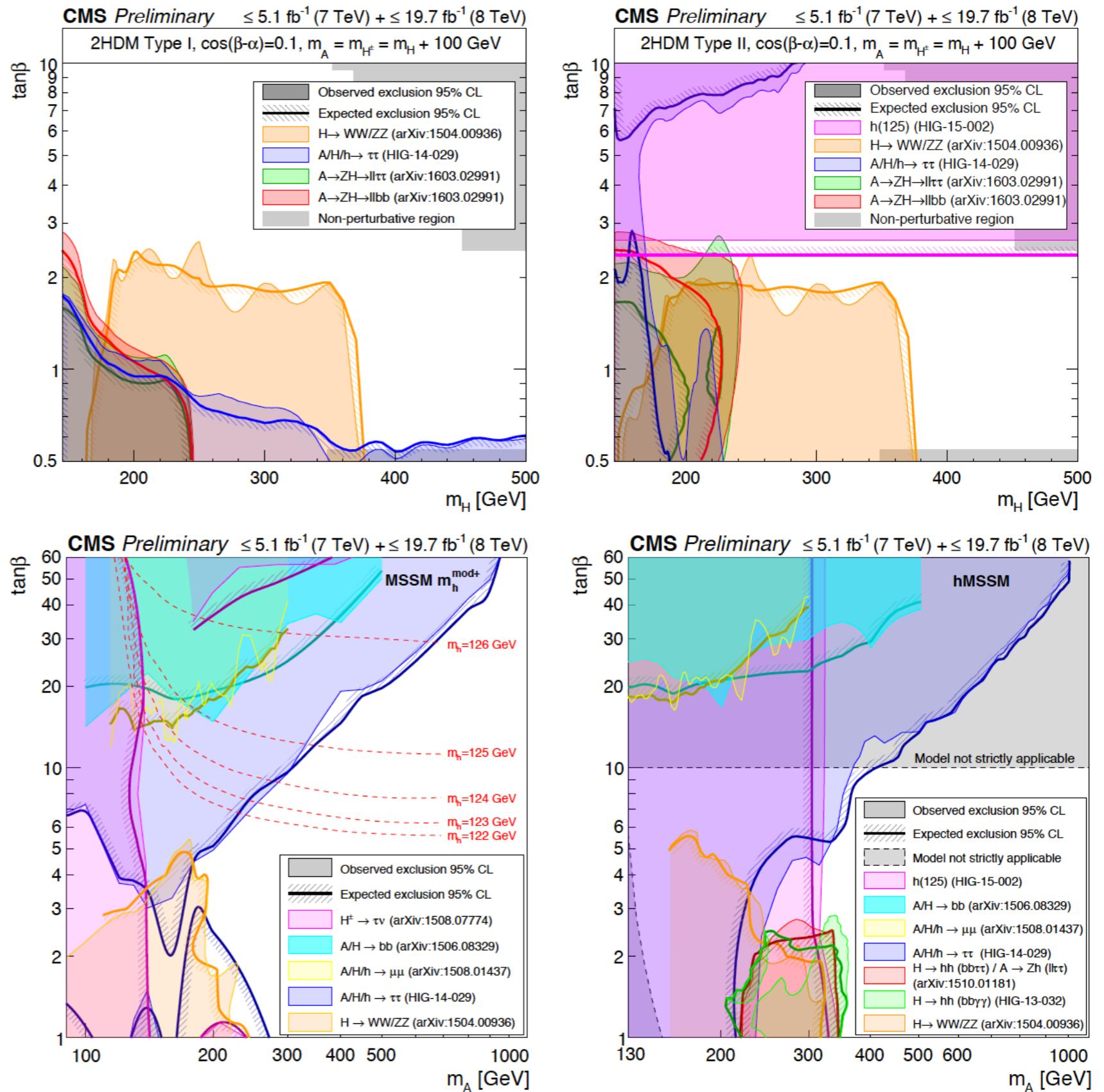
High mass BSM Higgs searches

Recent!

CMS: HIG-16-007

Summary of Run-1
searches for additional
heavy Higgs bosons in:

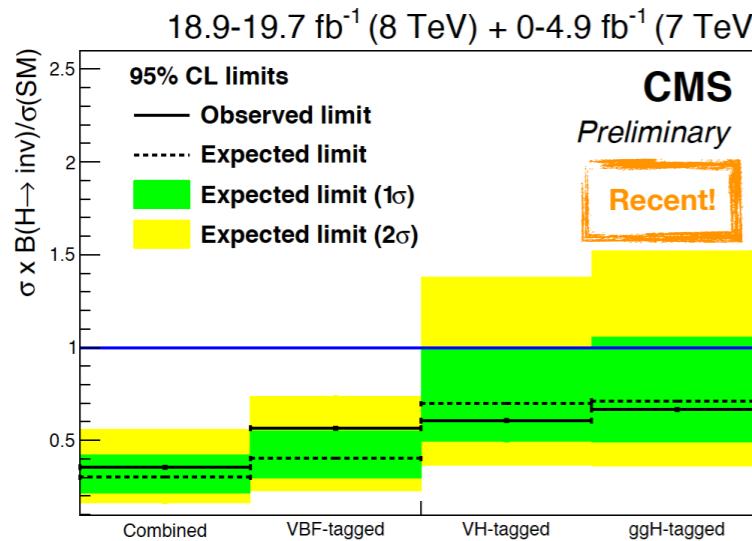
- two benchmark scenarios in two-Higgs doublet models (**2HDM**)
- two benchmark scenarios in the Minimal Supersymmetric (**MSSM**) model



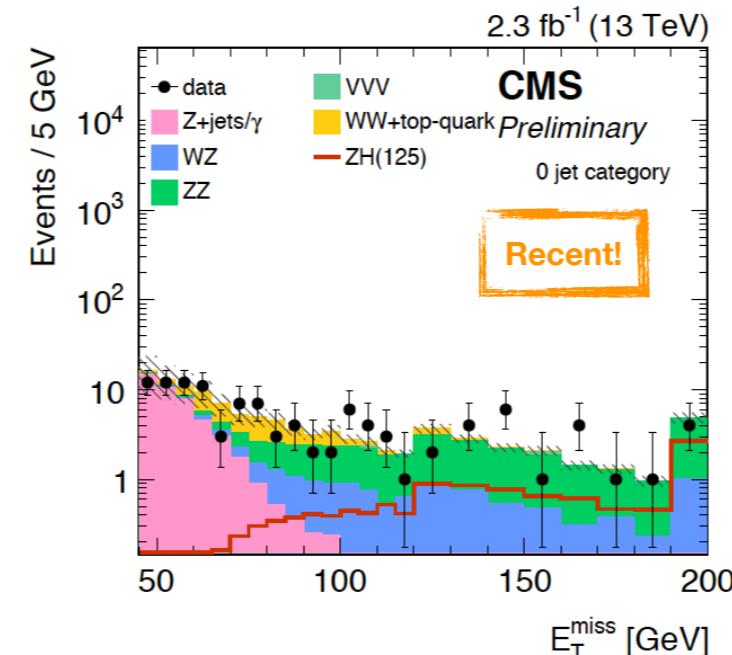
Higgs to invisible/Dark Matter searches

- Invisible Higgs decays appear in several SM extensions (including **Dark Matter**)

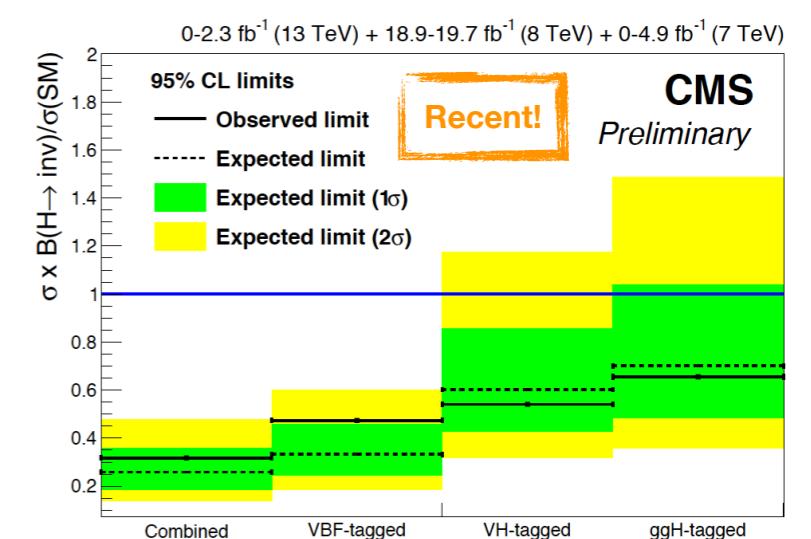
CMS: HIG-15-012 $H \rightarrow \text{inv.}$ Run-1



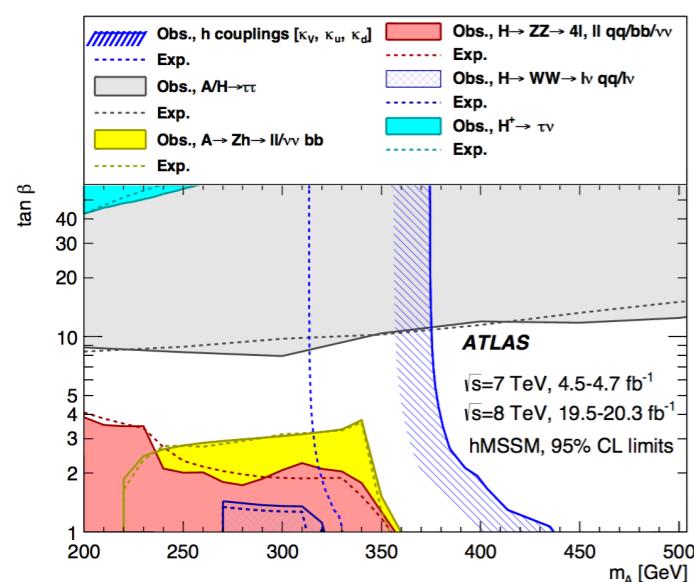
CMS: HIG-16-008
13TeV $ZH \rightarrow 2l + \text{MET}$



CMS: HIG-16-009 VBF 13TeV and combination

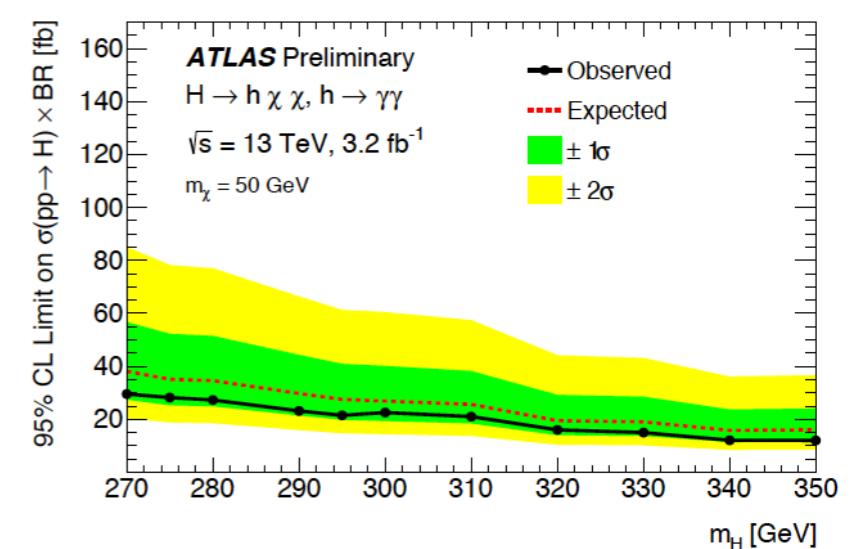


ATLAS: arXiv:1509.00672
Run-1 $H \rightarrow \text{inv.}$



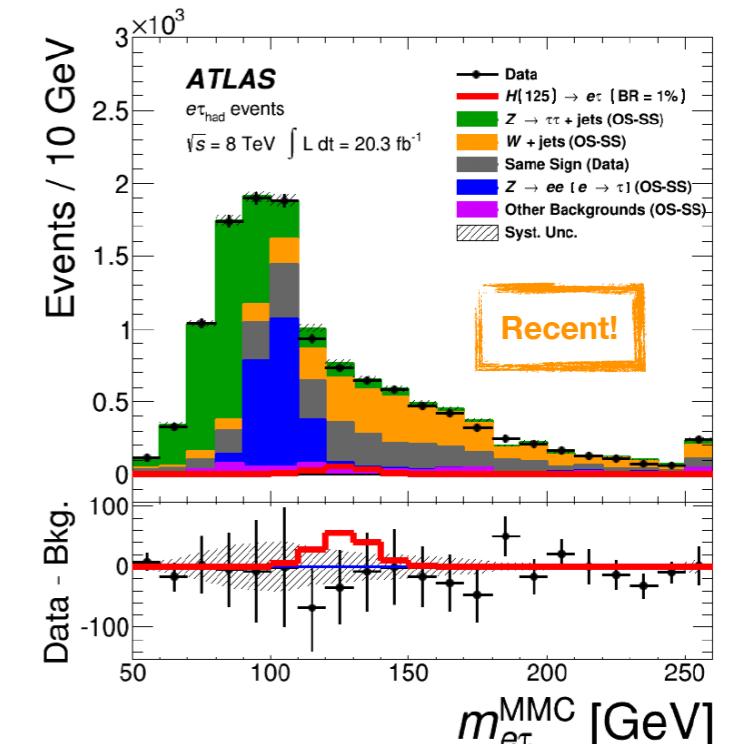
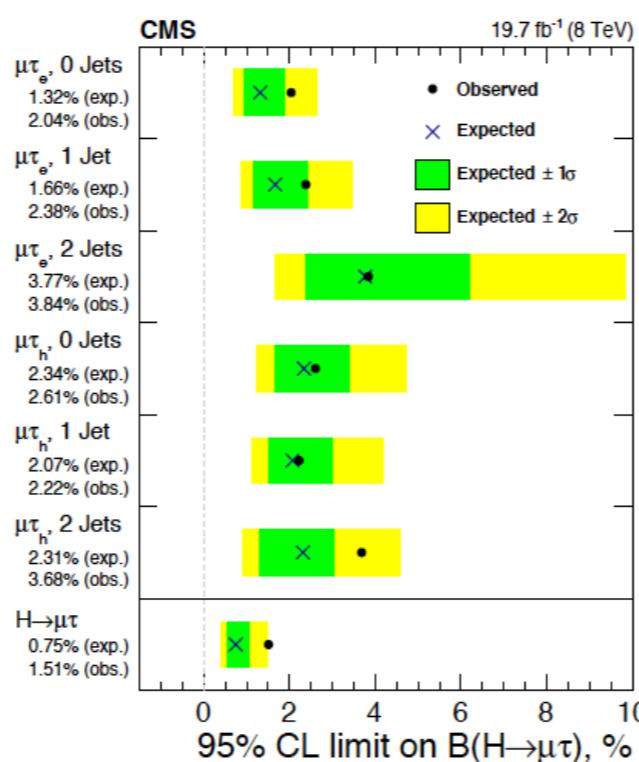
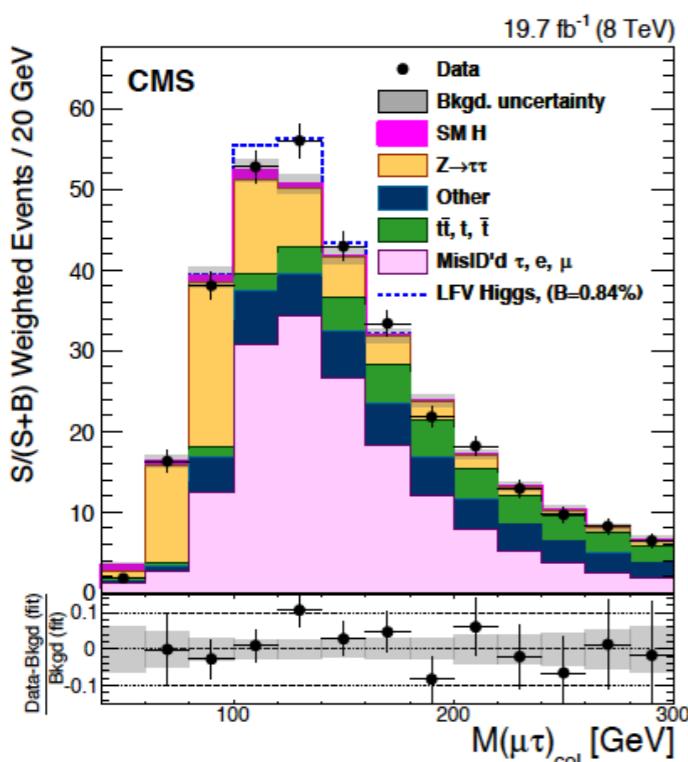
- Searches for Dark Matter produced in association with a Higgs boson, or in Higgs decays

ATLAS: CONF-2016-011
 $\gamma\gamma + \text{MET}$ 13 TeV



LFV Higgs decays

- Lepton-Flavour-Violating (LFV) decays are forbidden in the SM
 - they could appear under certain assumptions and happen naturally in several BSM models: composite Higgs, SUSY...
- Excess of 2.4σ with Run-1 data in CMS, just below 2σ in ATLAS



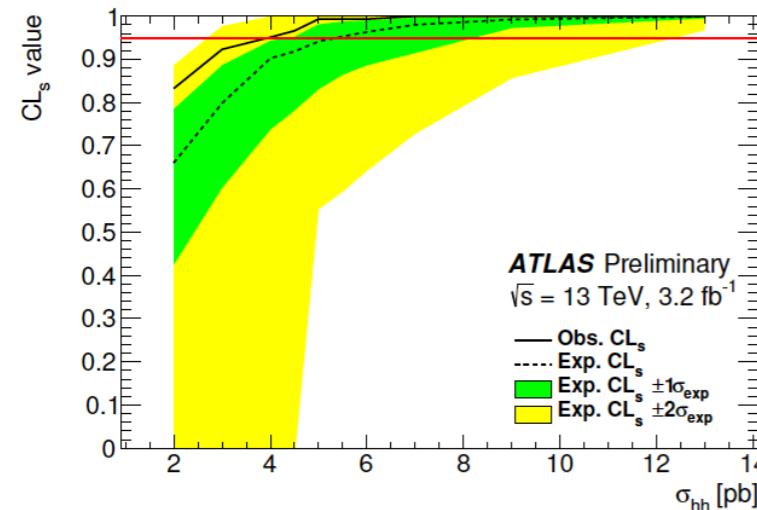
CMS: [arXiv:1502.07400](https://arxiv.org/abs/1502.07400) $H \rightarrow \tau\mu$ (τ_e , τ_{had})
[HIG-14-040](https://cds.cern.ch/record/2142052) $H \rightarrow e\tau/\mu\tau$

ATLAS: [arXiv:1508.03372](https://arxiv.org/abs/1508.03372) $H \rightarrow \tau\mu$ (τ_{had})
[HIGG-2015-09](https://cds.cern.ch/record/2142052) (to be submitted) $H \rightarrow e\tau/\mu\tau$

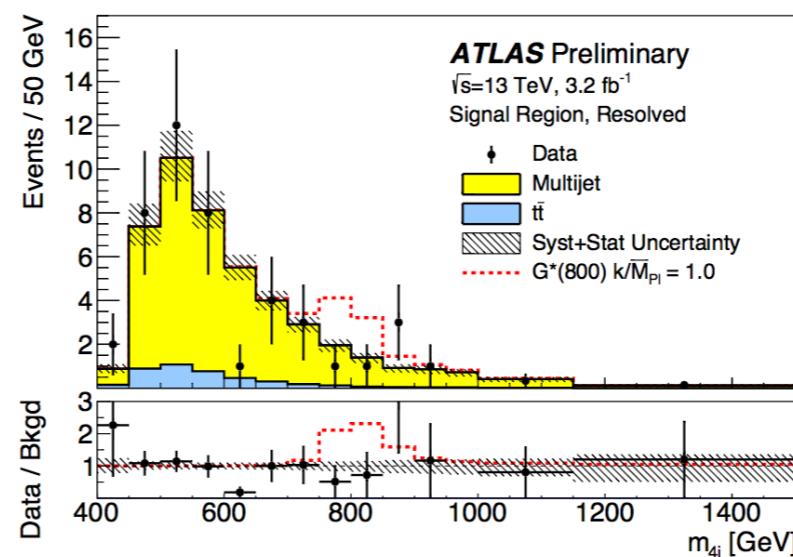
Double Higgs production

- HH production could be **enhanced** by BSM effects or come from the decay of a heavy new particle

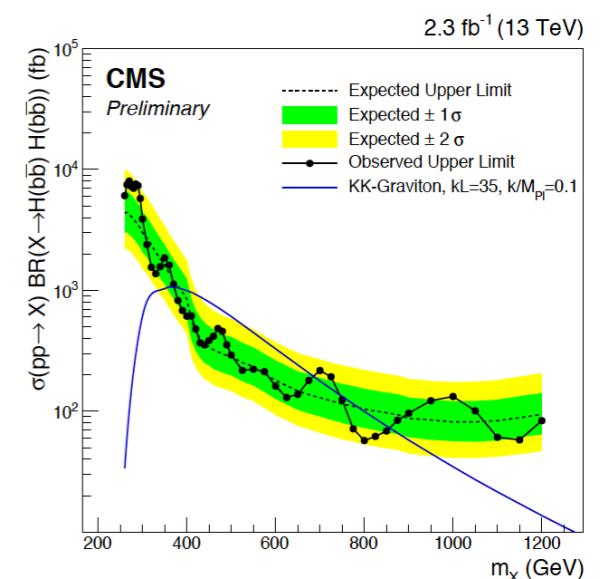
ATLAS: CONF-2016-004
Resonant and non-resonant
 $\text{HH} \rightarrow \text{bb}\gamma\gamma$ 13TeV



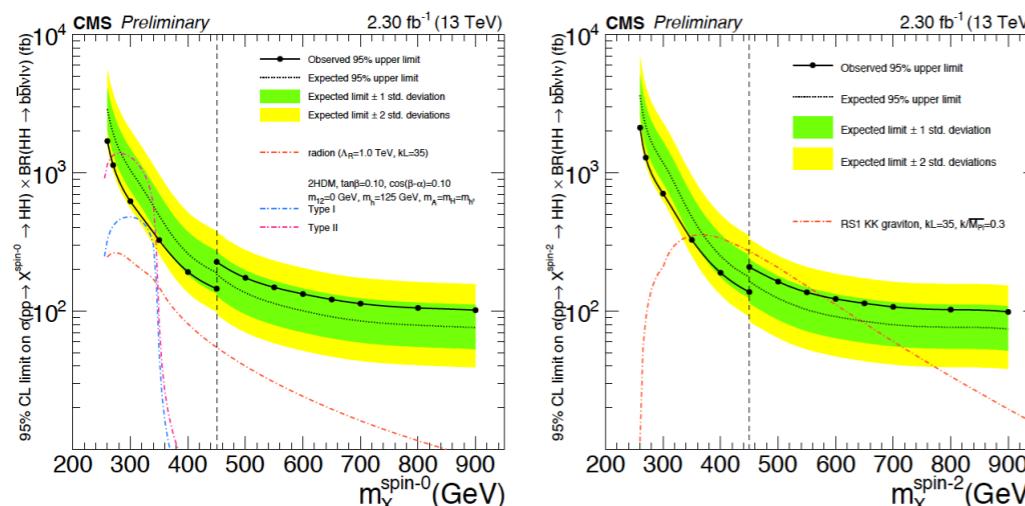
ATLAS: CONF-2016-017
 $\text{HH} \rightarrow \text{bbbb}$ 13TeV



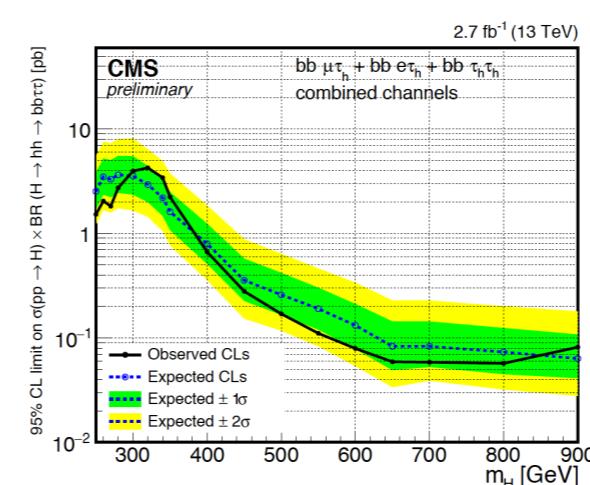
CMS: HIG-16-002
13TeV $\text{HH} \rightarrow \text{bbbb}$



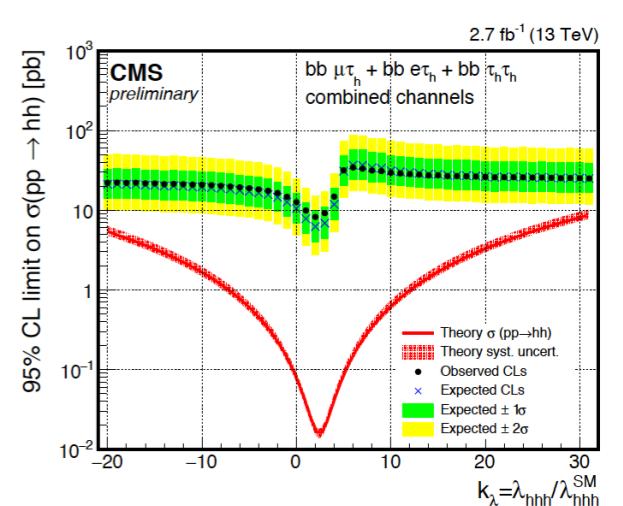
CMS: HIG-16-011
 $\text{HH} \rightarrow \text{WWbb}$ 13TeV



CMS: HIG-16-013
Resonant
 $\text{HH} \rightarrow \text{bb}\tau\tau$ 13 TeV



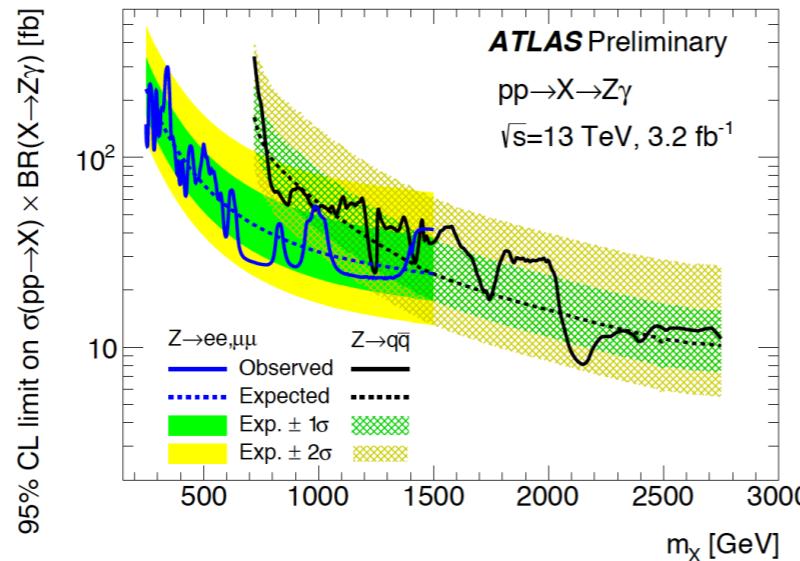
CMS: HIG-16-012
Non-resonant
 $\text{HH} \rightarrow \text{bb}\tau\tau$ 13 TeV



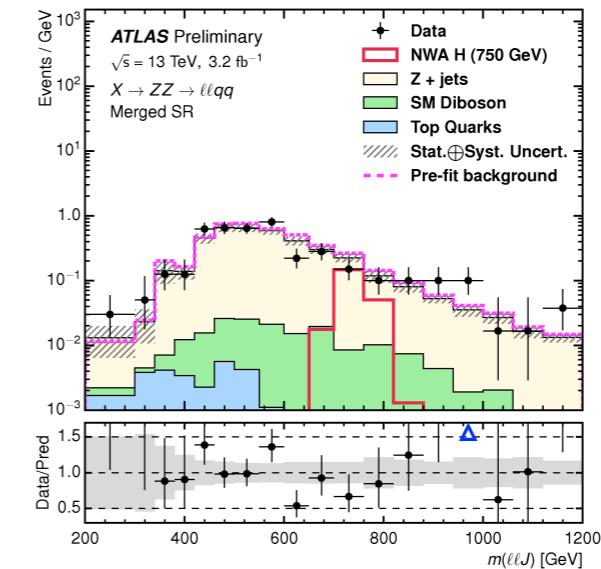
Search for heavy resonances

- Predicted in the **MSSM Extended Higgs sector**, and in many extensions of the SM (extended gauge model, warped extra-dimensions, etc)
- Some high mass searches integrated in SM Higgs analyses

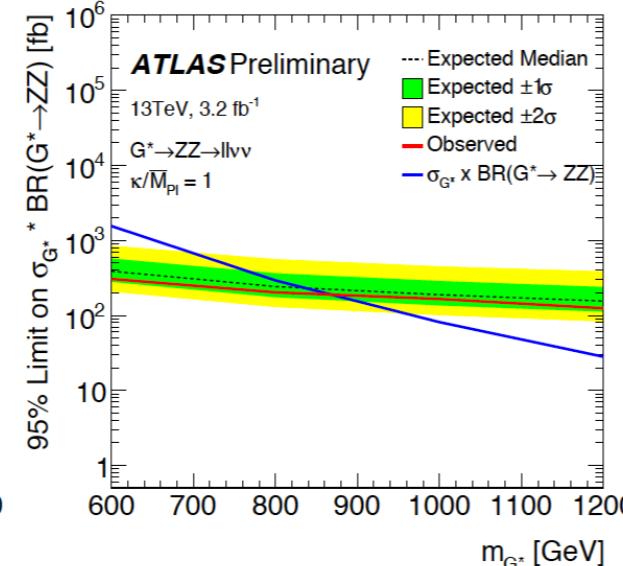
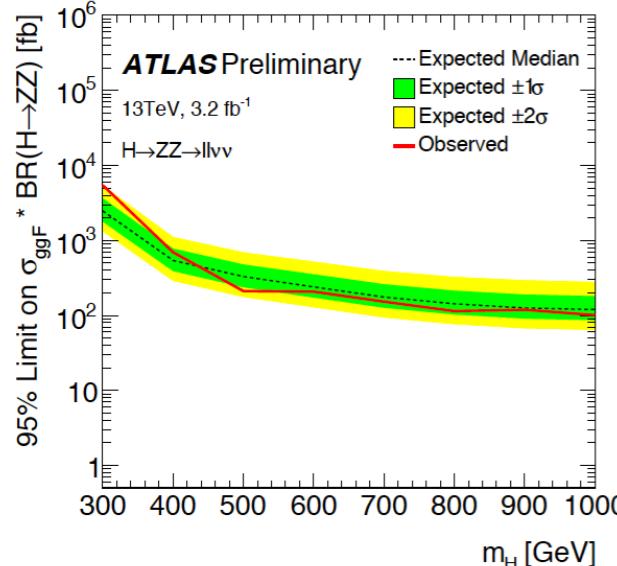
ATLAS: CONF-2016-010
13TeV $X \rightarrow Z\gamma$



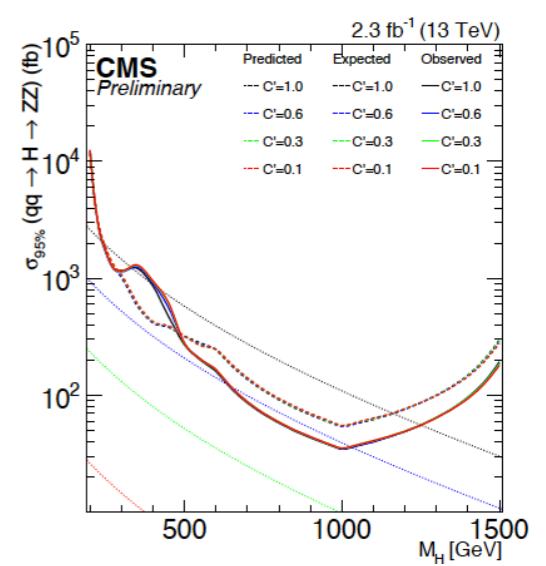
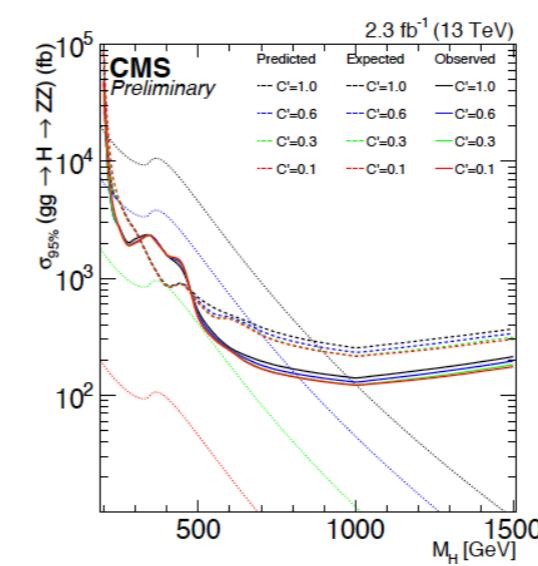
ATLAS: CONF-2016-016
13TeV $X \rightarrow ZZ \rightarrow 2l2q$



ATLAS: CONF-2016-012
13TeV $X \rightarrow ZZ \rightarrow 2l2v$

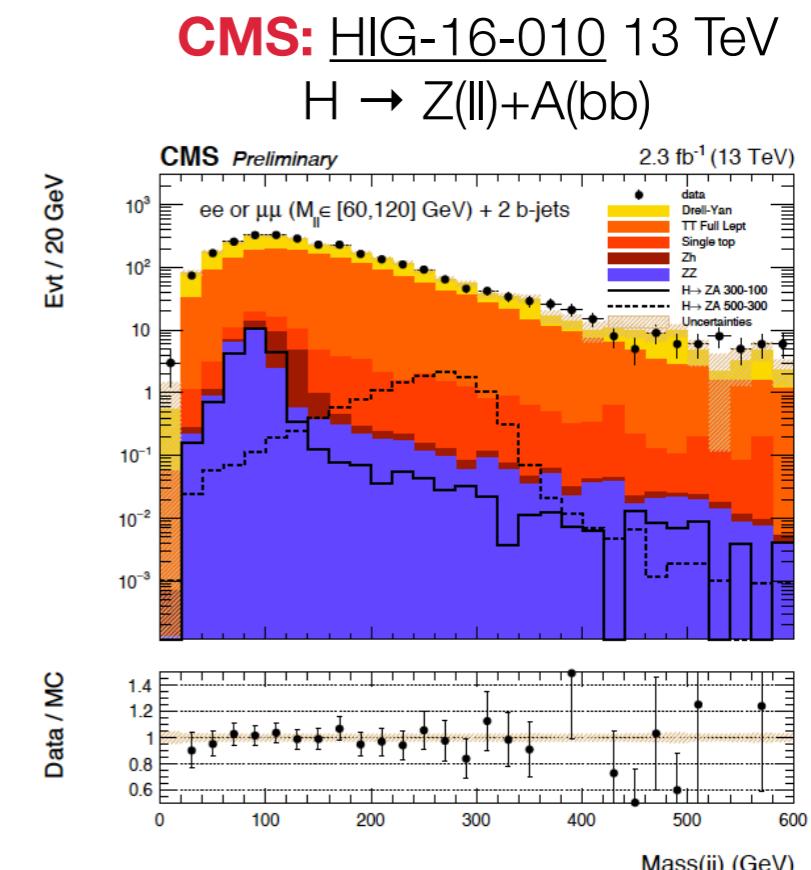
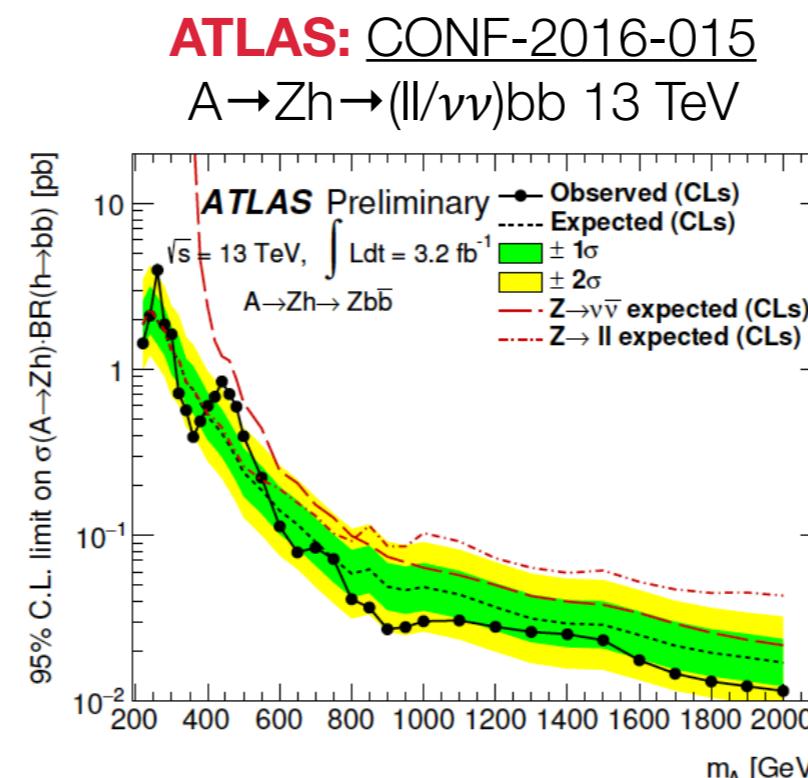
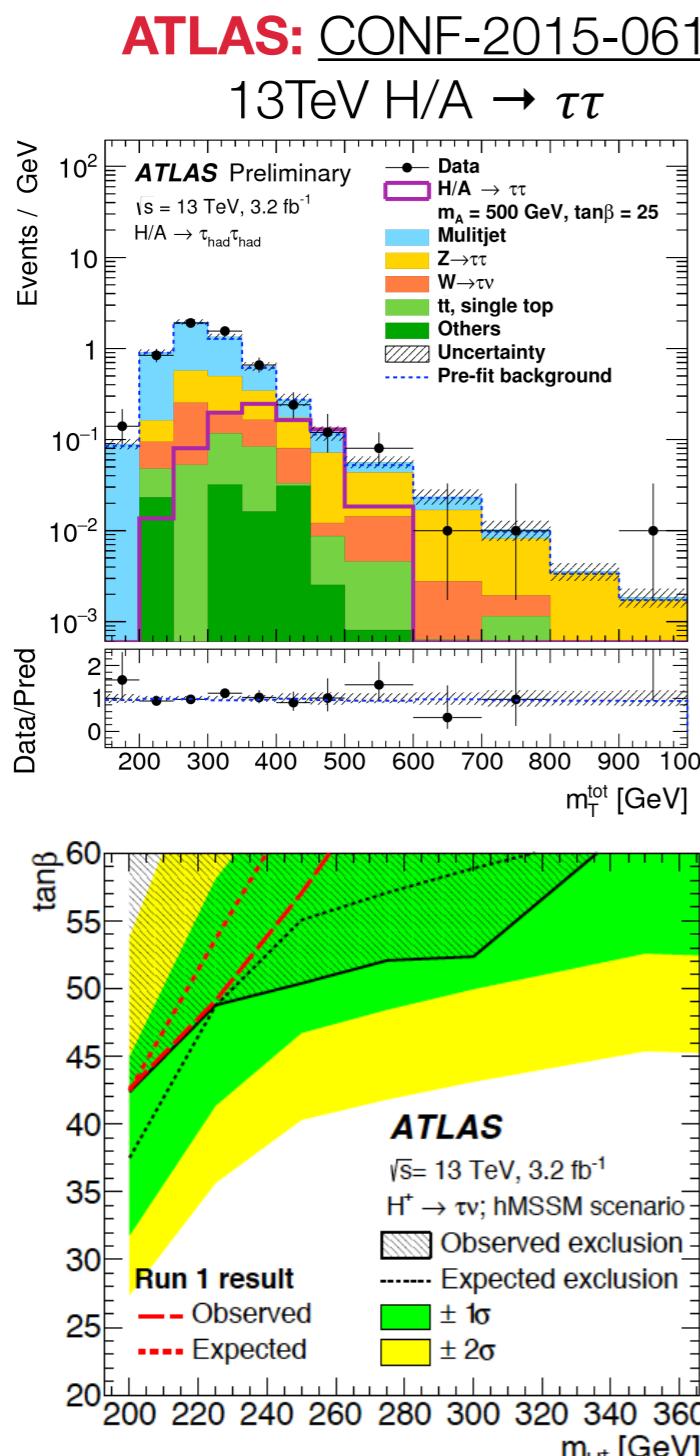


CMS: HIG-16-001
13 TeV $X \rightarrow ZZ \rightarrow 2l2v$



MSSM Higgs searches

- Searches for CP-even (H) and a CP-odd (A) neutral Higgs bosons and charged Higgs (H^\pm) bosons ongoing in many channels



ATLAS: arXiv:1603.09203
13 TeV $H^\pm \rightarrow \tau\nu$

Some of the searches at 13 TeV already performing at the level of the full 8TeV dataset

“No deviations from the SM expectations are observed so far.”

Not so fast!

Tomorrow: ‘**Non-SUSY search for BSM physics at the LHC**’ talk by James Proudfoot, at the *New Physics Searches at the LHC* session will cover the 750GeV $\gamma\gamma$ bump!

Summary

- Higgs searches have been **the flagship of the LHC** during Run-1
 - Clear observation of the process
 - Study of all possible channels
 - Measurement of several properties with good precision

The Higgs boson is very SM-like so far

- **There is still room for new physics** in the Higgs sector:
 - Many exciting searches for new phenomena in place and performing well since Run-1
- On the way to re-discover the Higgs in Run-2, clear goals:
 - Establish as many production/decays modes as possible
 - Measure the Higgs properties with high precision
 - Cover the largest possible phase space in BSM Higgs searches

Run-2 will fully characterize the Higgs boson: Exciting times ahead!