Latest LHC results on the Higgs boson

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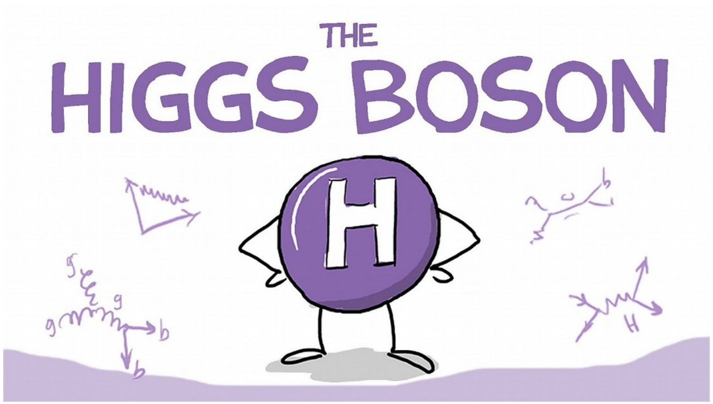
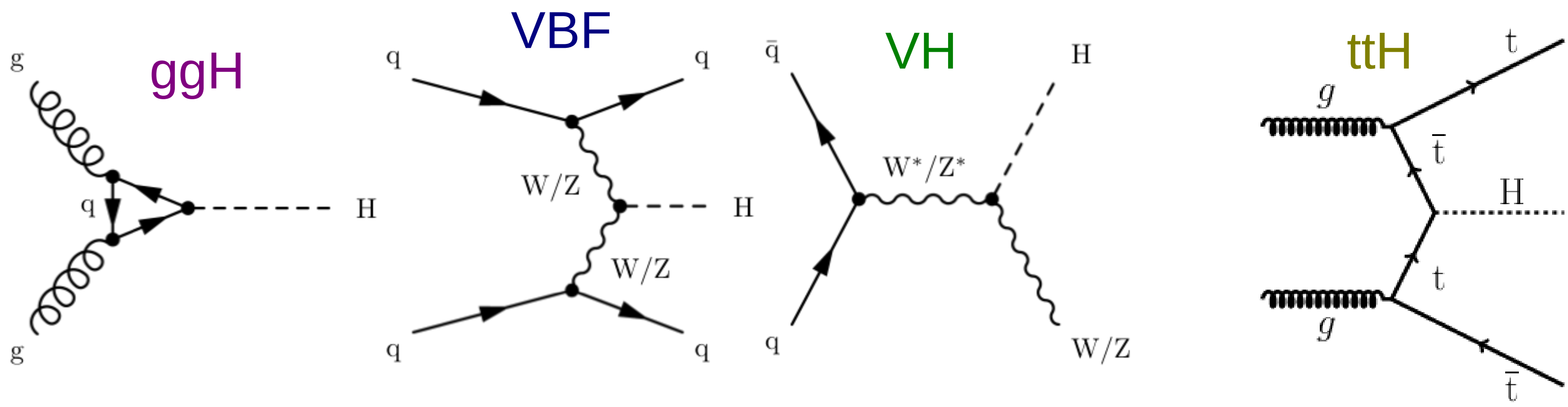
Outline

- Higgs boson discovered 7 years ago (July 4th 2012)
  - m_H = ~125 GeV
  - Precise measurements of its properties are now pursued
  - All seems to be consistent with SM



- **In this talk**:
  - Overview of the SM expectations
  - Current experimental status
  - Recent results from CMS and ATLAS
    - Decay modes, anomalous couplings, differential measurements
      - References at the end
  - Future prospects

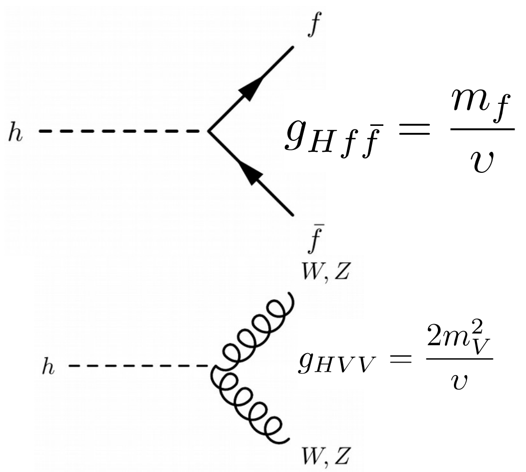
Higgs production at LHC

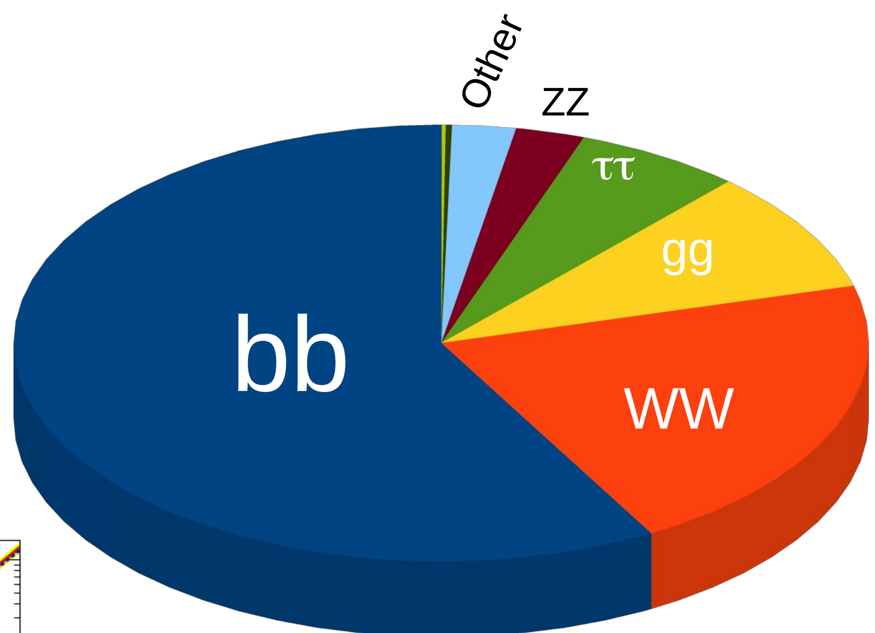


- Total cross section at 13 TeV: **55 pb**
- Production rates:
  - Gluon-gluon Fusion: 88%
  - Vector Boson Fusion: 7%
  - Associate with vector boson: 4%
  - ttH: 1%
- There are experimental advantages of VBF and VH modes: *tagging* events and reducing the backgrounds
  - VBF tag: two jets with m(jj) > 500 GeV and $|\eta(j_1) - \eta(j_2)| > 3.5$
  - Z(ℓℓ)H: two leptons consistent with Z
  - Z(νν)H: transverse missing energy (E_T^{miss})
  - W(ℓν)H: a lepton and E_t^{miss}

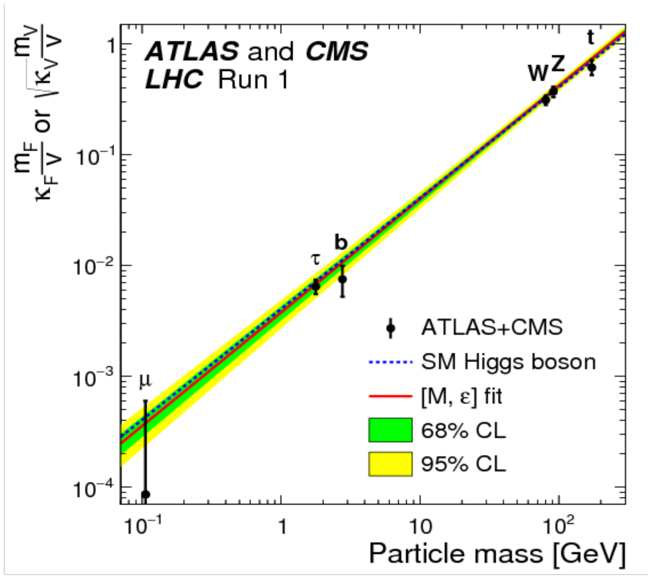
Higgs boson decays

➢ Higgs boson "couples to the mass"

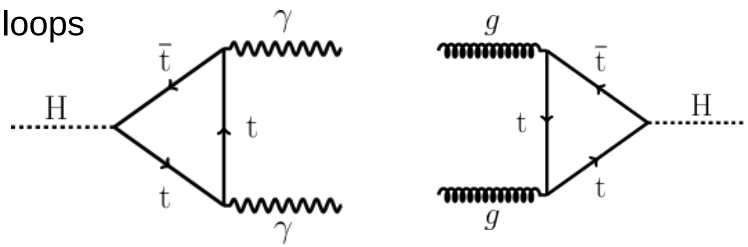




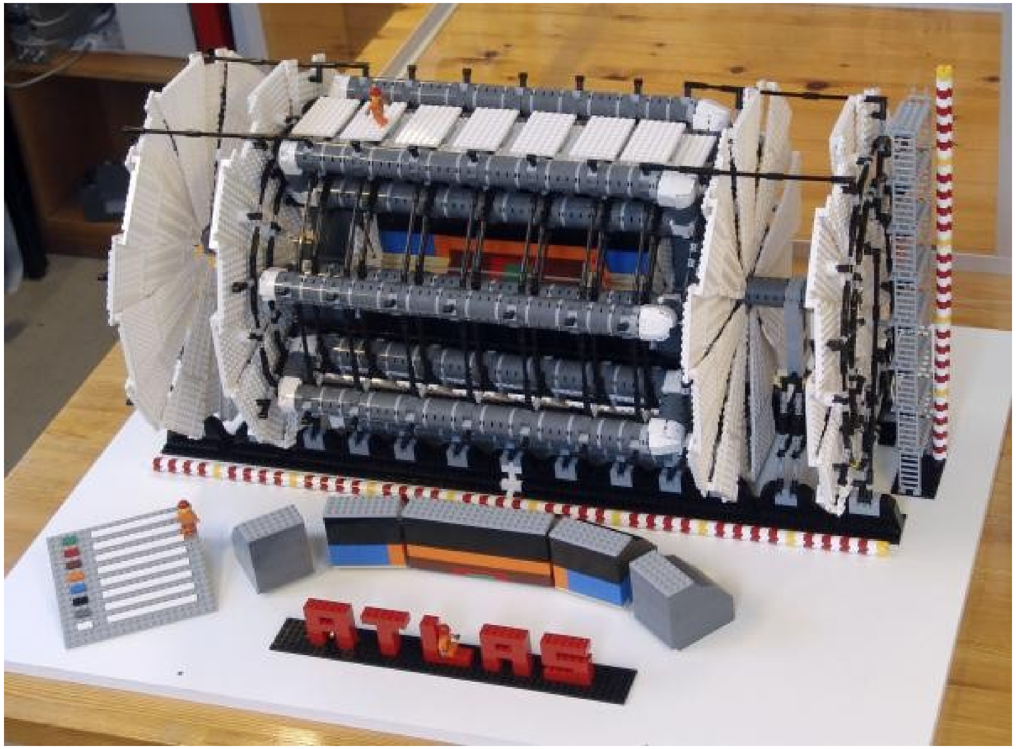
Channel	BR, %
bb	58
WW	21
gg	9
ττ	6.3
ZZ	2.6
cc	2.4
γγ	0.23
Zγ	0.15
μμ	0.02

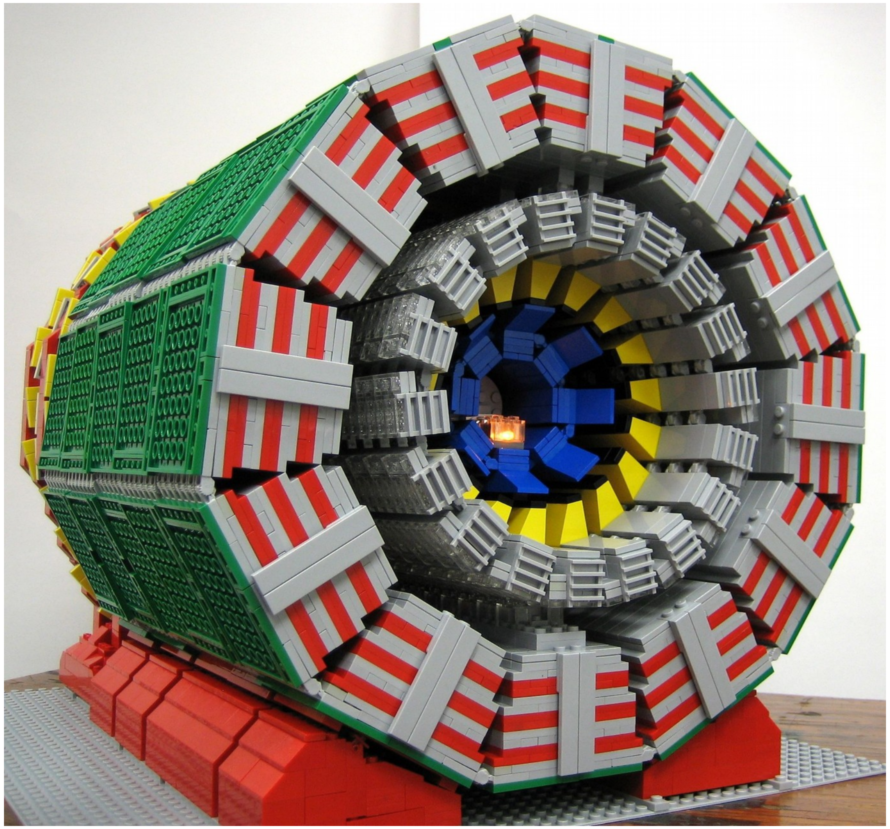


Don't forget the loops



ATLAS and CMS





Year	2011	2012	2016	2017	2018
√s, TeV	7	8	13	13	13
Lumi, 1/fb	**5**	**20**	**40**	**45**	**65**
	Run-1		Run-2		

Current status

Which decays are observed?

Channel	BR, %	Observed ?	Data set
bb	58	✓	☆ Run 1 + 2016 + 2017
WW	21	✓	Run 1 + 2016
gg	9	✗	-
ττ	6.3	✓	Run 1 + 2016
ZZ	2.6	✓	☆ Run 1 + Run 2
cc	2.4	✗	☆ 2016
γγ	0.23	✓	Run 1 + 2016
Zγ	0.15	✗	Run 1, 2016
μμ	0.02	✗	☆ Run 1, 2016
Invisible	~0	✗	☆ Run 1, 2016
rare	~0	✗	Run 1, 2016

☆ - covered in this talk

While H → gg is hopeless, here there is some hope...

Full Run-2 for differential and ttH

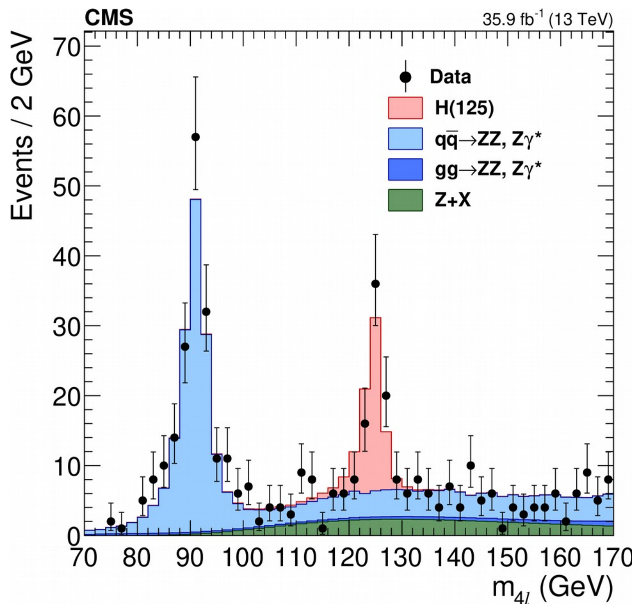
~6xSM

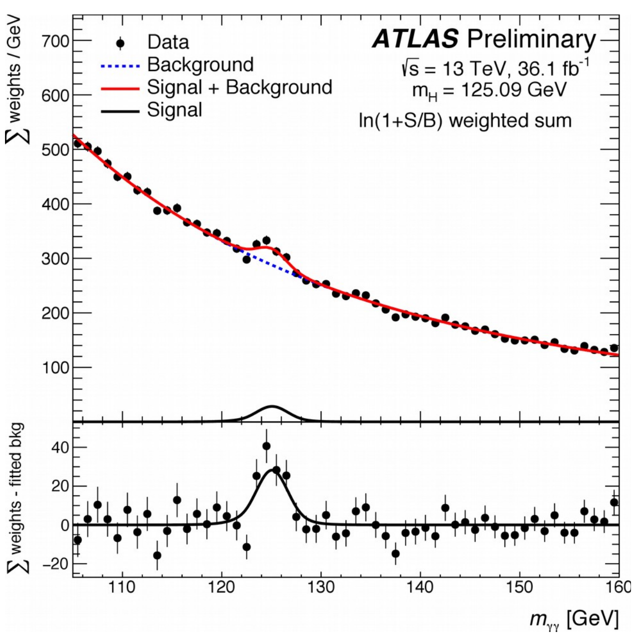
~2xSM

Not yet seen, but we are close!

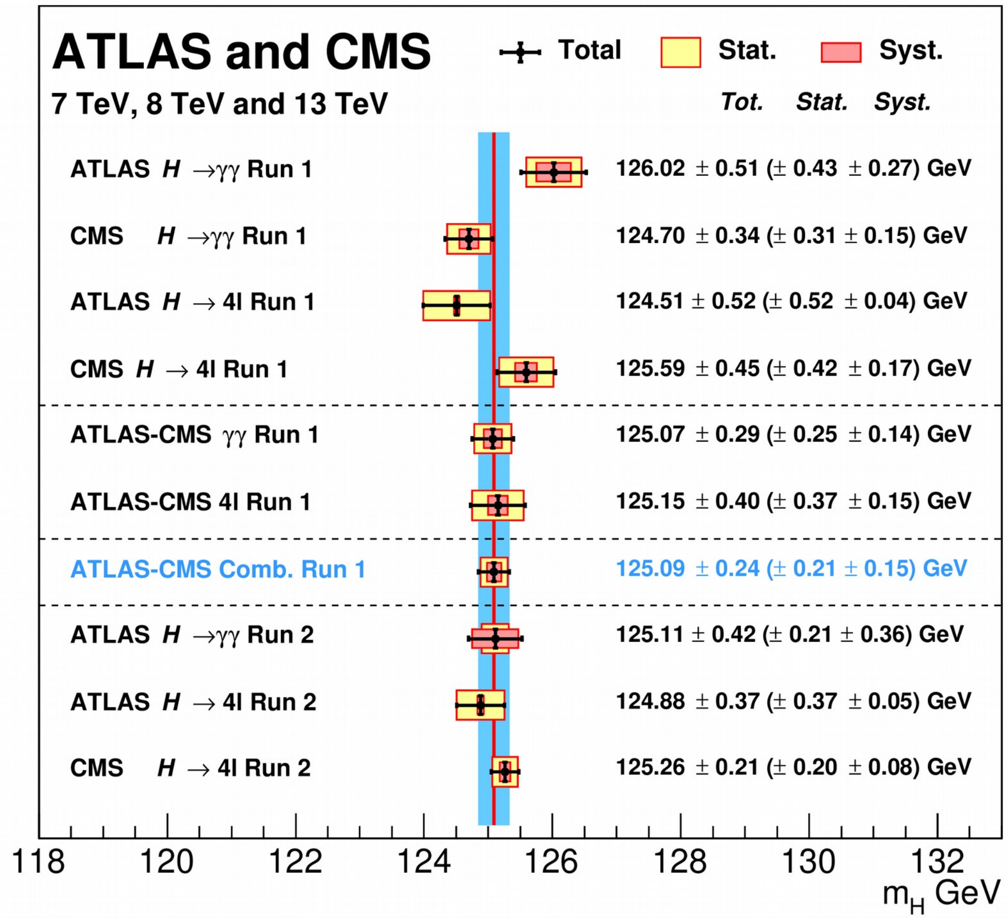
In SM, only H→ZZ→4ν

What’s the mass again?

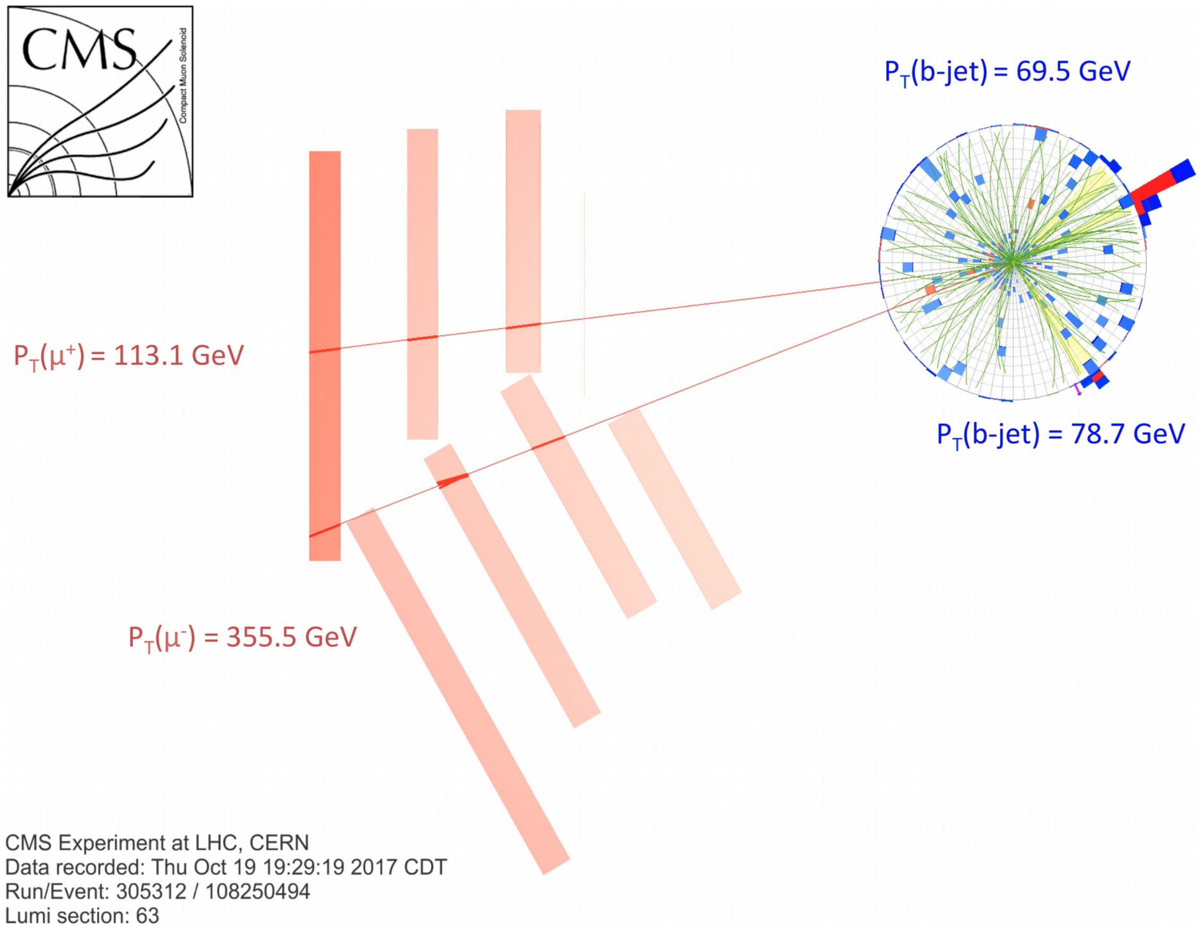




- Mass of the Higgs boson is a fundamental parameter of nature
  - Its measurement is improving



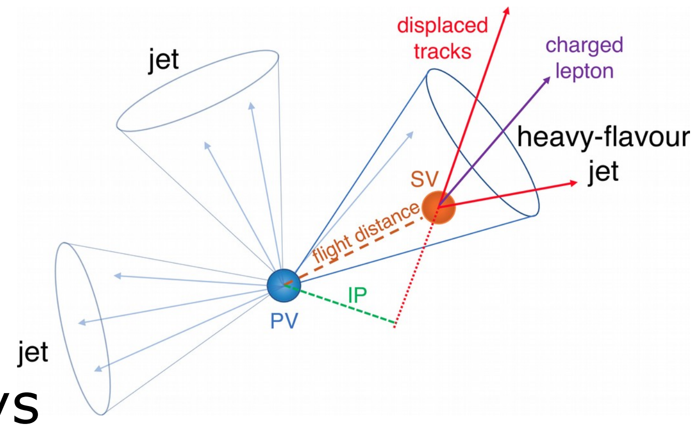
$H \to bb$


CMS
Compact Muon Solenoid
P_T(b-jet) = 69.5 GeV
$P_T(\mu^+)$ = 113.1 GeV
P_T(b-jet) = 78.7 GeV
$P_T(\mu^-)$ = 355.5 GeV
CMS Experiment at LHC, CERN
Data recorded: Thu Oct 19 19:29:19 2017 CDT
Run/Event: 305312 / 108250494
Lumi section: 63

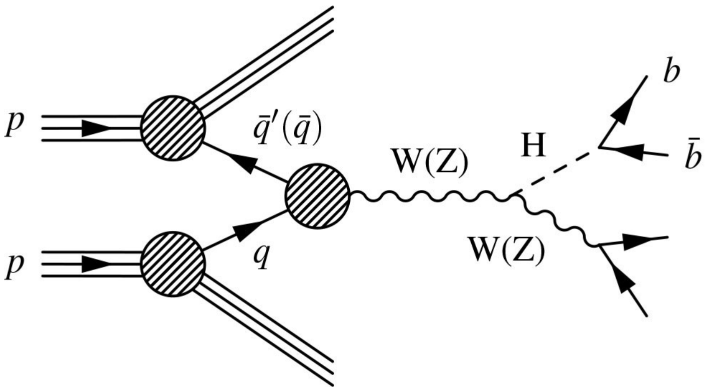
H → bb in VH production

$BR_{SM}(H \rightarrow bb) = 58\%$

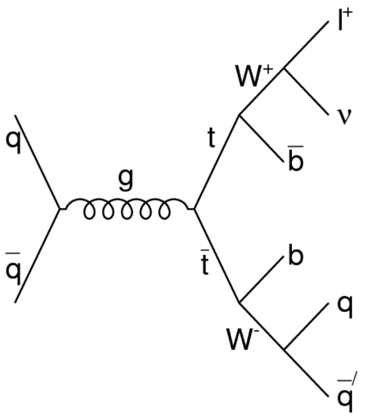
- H → bb is important
  - Largest decay branching fraction
  - Drives the uncertainty on the total Higgs boson width
- But difficult
  - Jets are not the cleanest objects to reconstruct
  - In ggH channel – large backgrounds from QCD processes
- **VH production is key**
  - W/Z leptonic decays are easy to identify
    - Providing trigger and offline selection
    - Eliminating QCD background
  - V and H are back-to-back and boosted
    - Helps to reduce backgrounds further
- **B-tagger is a second key**
  - Secondary verteces from B-hadron decays
  - Help from machine learning used



$H \to bb$ in VH production

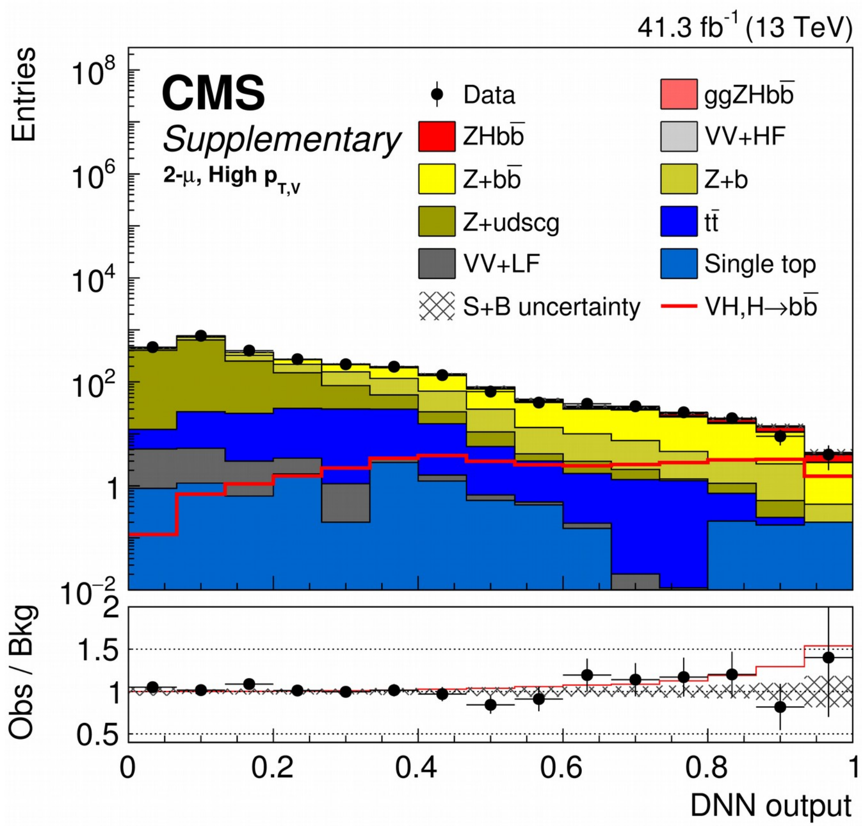


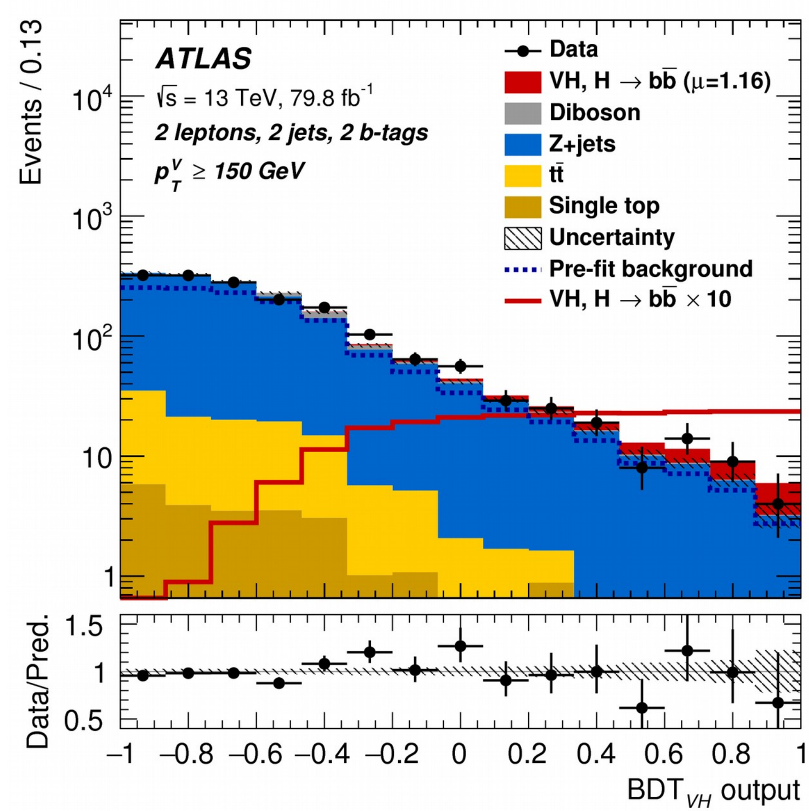
- Main backgrounds:
  - Z+2jets, W+2jets
  - tt and single-t



- 3 channels: with 2, 1 or 0 leptons (+2 b-tagged jets)
  - Z(ℓℓ)H(bb), W(ℓν)H(bb) or Z(νν)H(bb) decays
  - Select events with $p_T(Z/W/E_T^{miss})$ > 150 (170) GeV
    - In 2-lep channel, also ~50 < $p_T(Z)$ < 150 GeV
  - Select two jets with high b-tagging score
  - Constrain the backgrounds: use control regions (by reversing some selections)
  - Train BDT (DNN) discriminator: separate signal and background processes
    - Fit the data to Signal + Background predictions

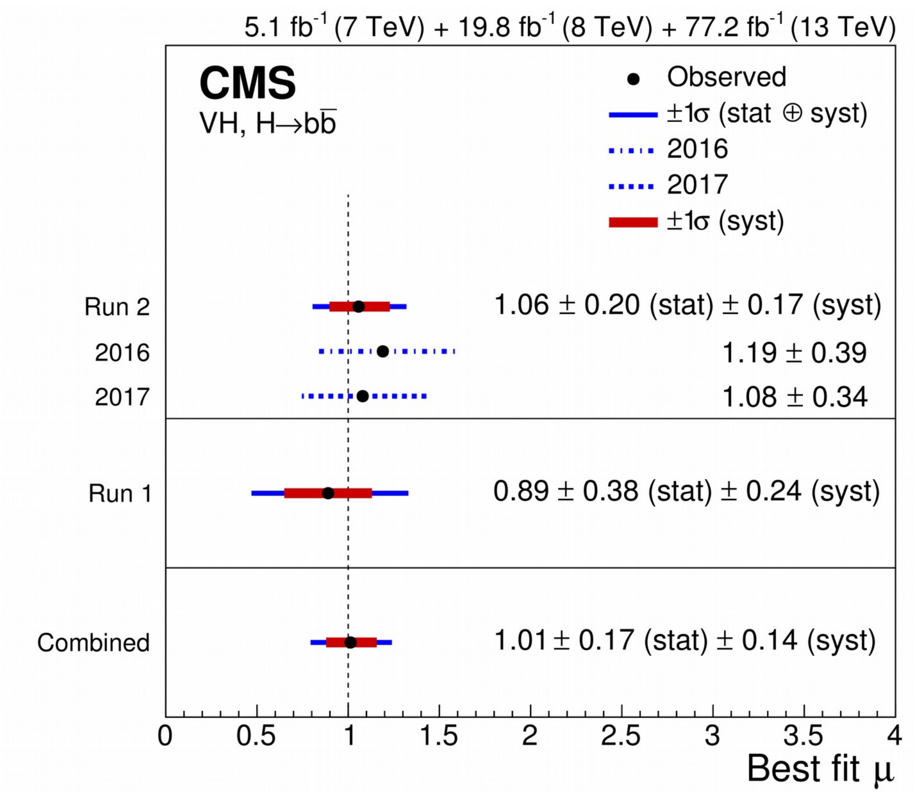
DNN (BDT) output

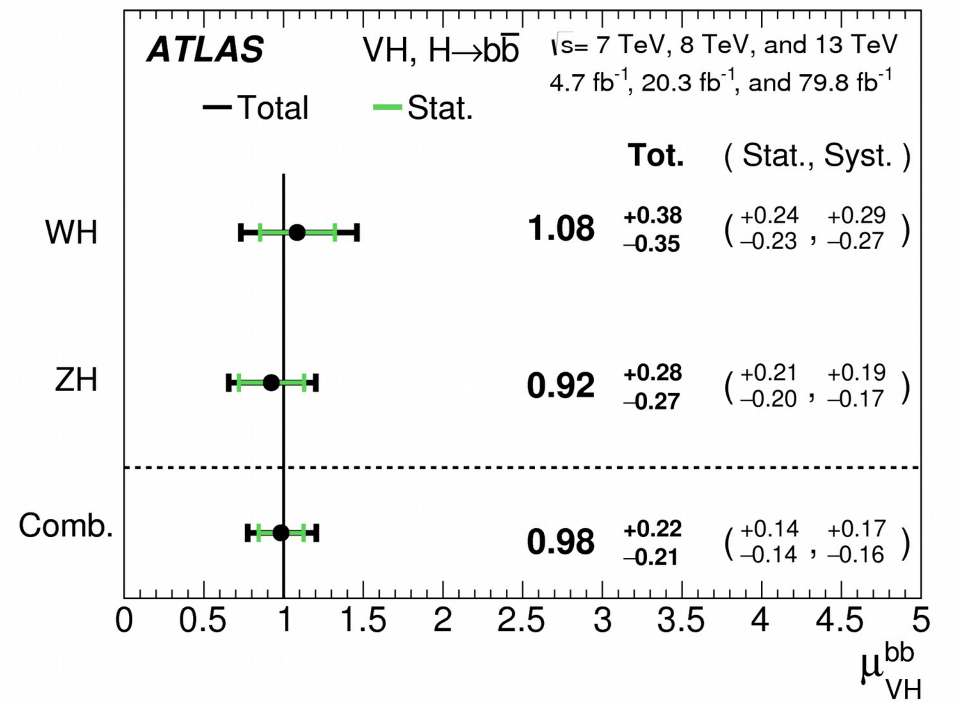




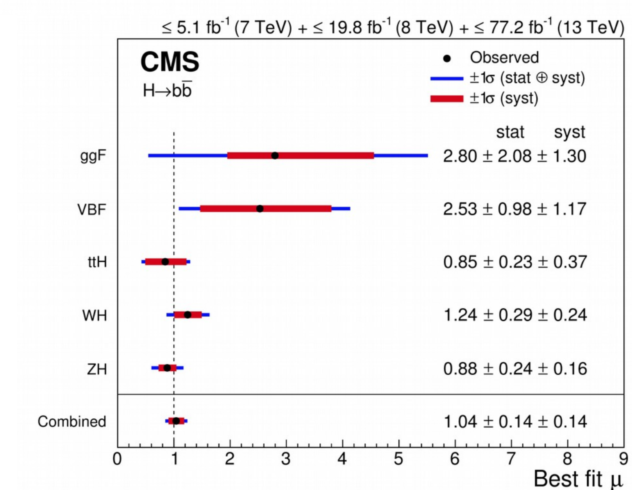
- 2-lepton channel, with high $p_T(Z)$
- Most significant is the most right bin

VH(bb), results

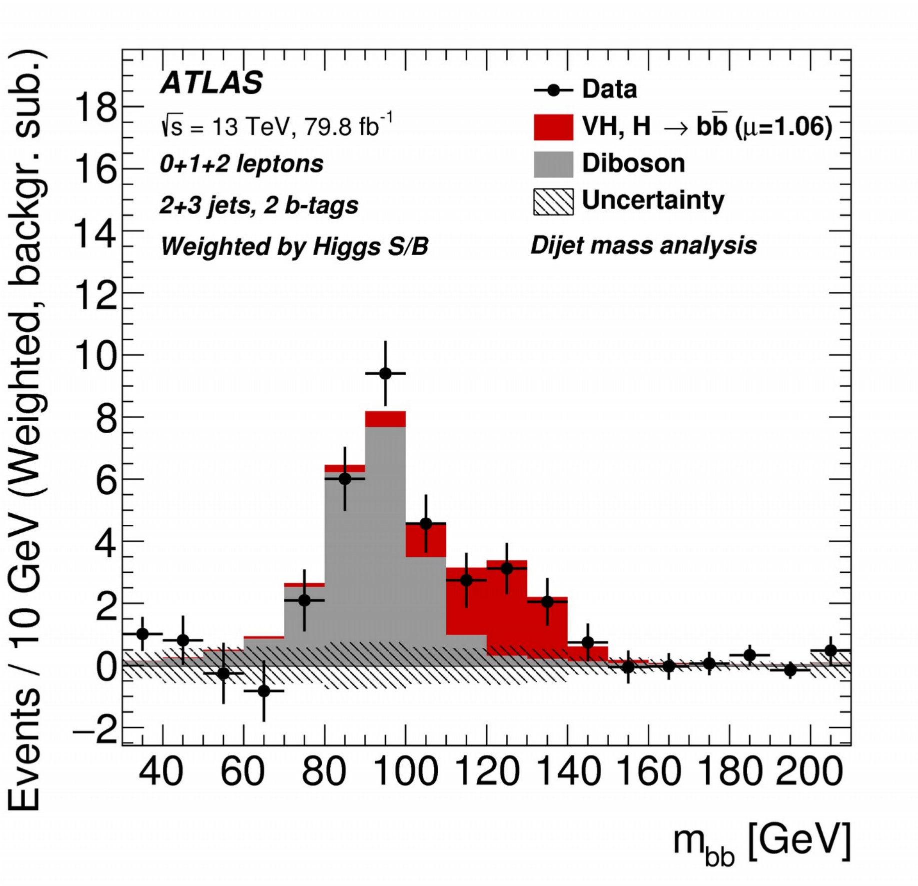


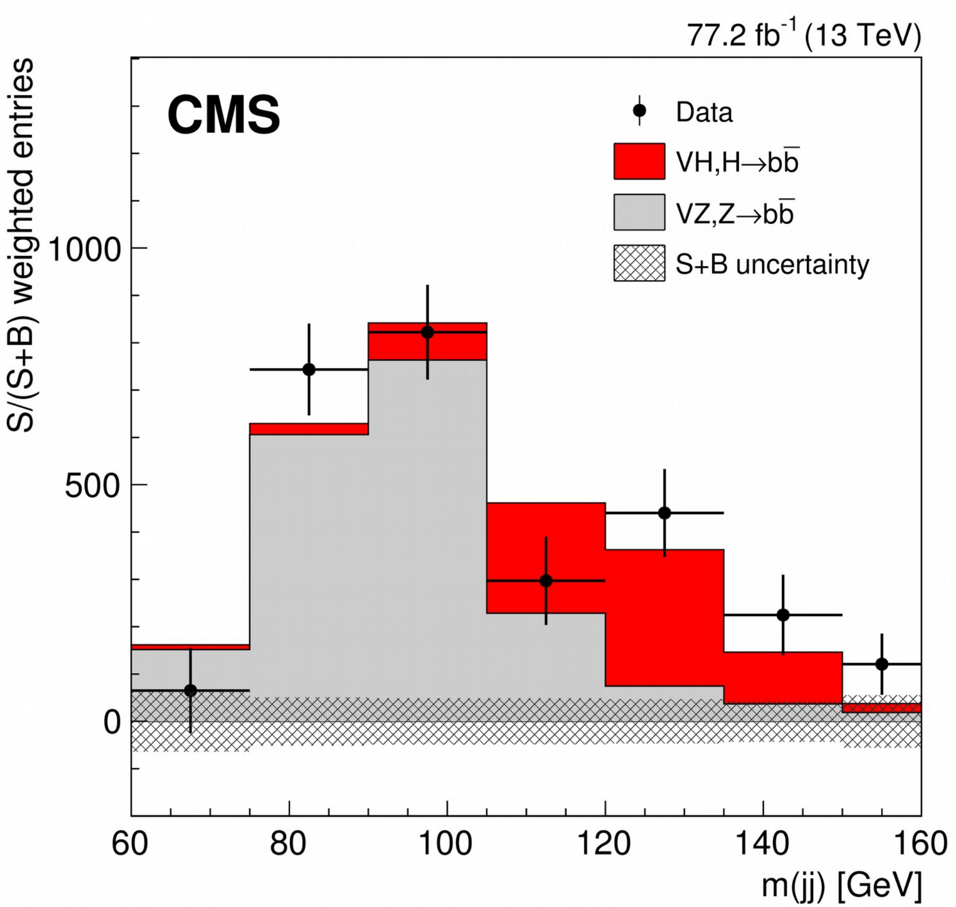


- Further combination with ttH, ggH, VBF processes are done
- Both ATLAS and CMS independently observe the H→bb decay



VH(bb), weighted m_{bb}

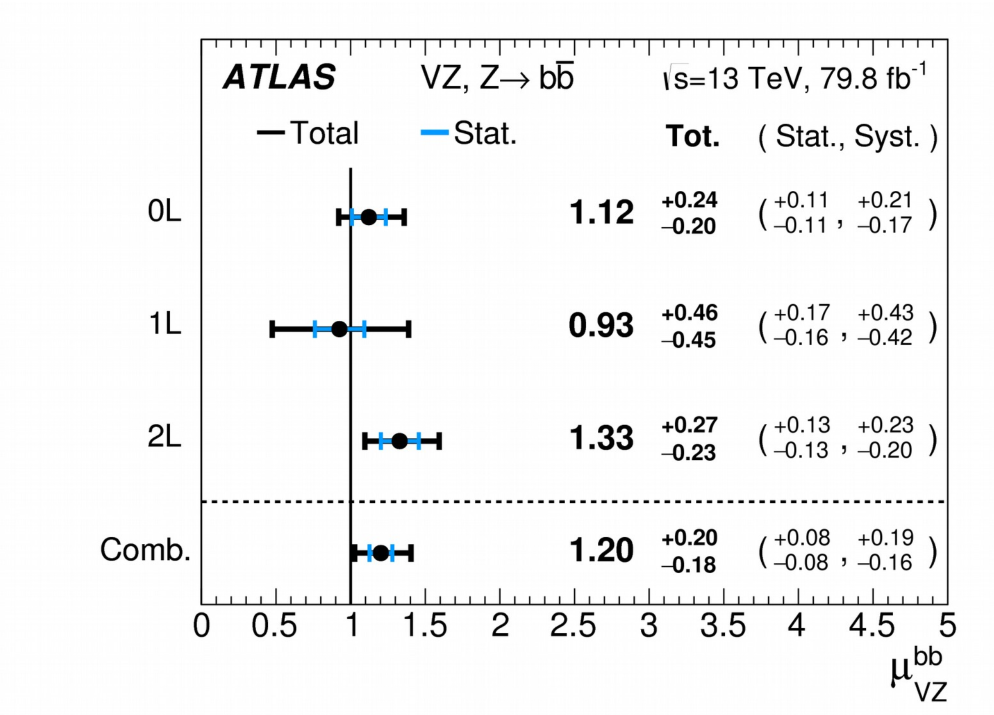


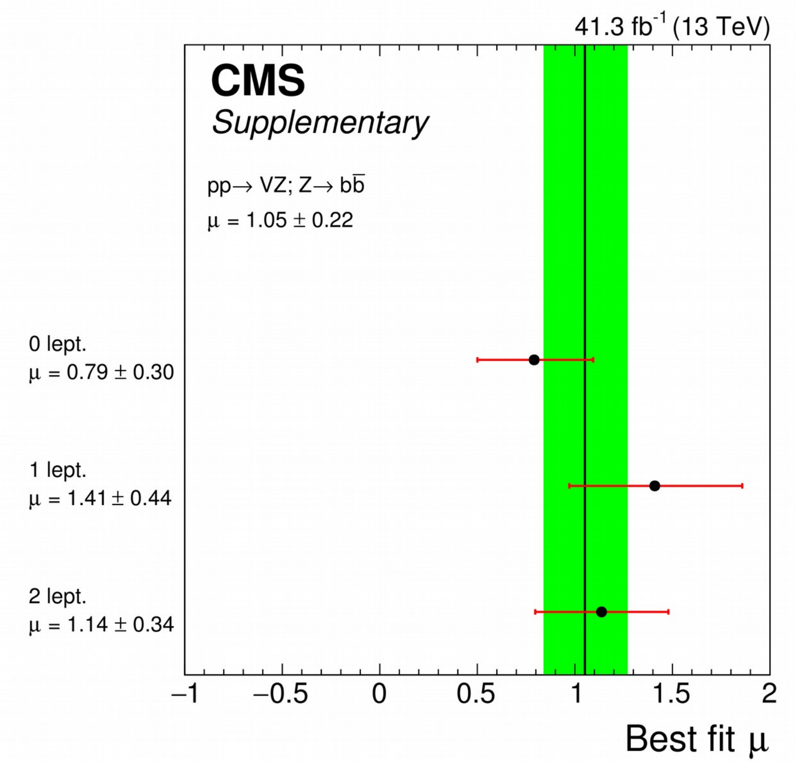


All backgrounds subtracted except di-bosons

VZ(bb) measurement

- A non-Higgs process VZ, with $Z \rightarrow bb$ is a good calibration process to measure.
- As a validation of the experimental techniques (b-tagging, DNN/BDT training) both ATLAS and CMS measure this process.



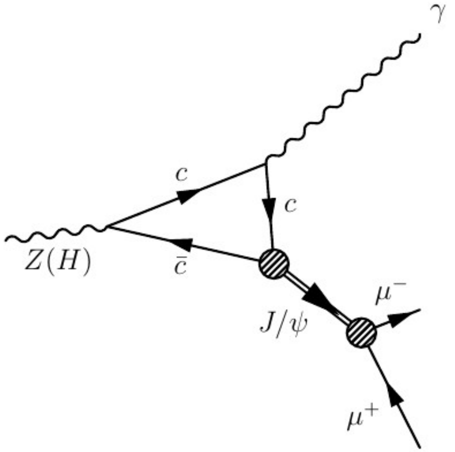


$H \to cc$?

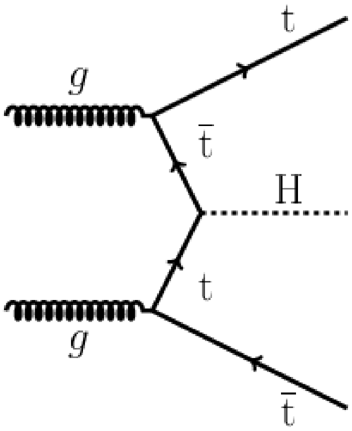
Yes we can .. try

$BR_{SM}(H \rightarrow cc) = 2.4\%$

- Exploiting techniques from V+H(bb) analysis we can use them for V+H(cc) search
  - Charm jet identification is less efficient than for b-jets, limiting the performance
  - When compared to SM prediction: take into account that BR(H → bb) = **20** x BR(H → cc)
  - Result of ATLAS 2016 data:
    - Limit at 110 x SM prediction
      - 2-lepton channel; m_{jj} fit
  - CMS results for H→cc search are coming out soon
  - Other ways to probe Hcc coupling?
    - Try H → J/ψ+γ decay
      - Theory BR = 3 x 10^{-6}
      - CMS limit: 260 x SM
      - ATLAS limit: 120 x SM
    - Differential measurement (see later)



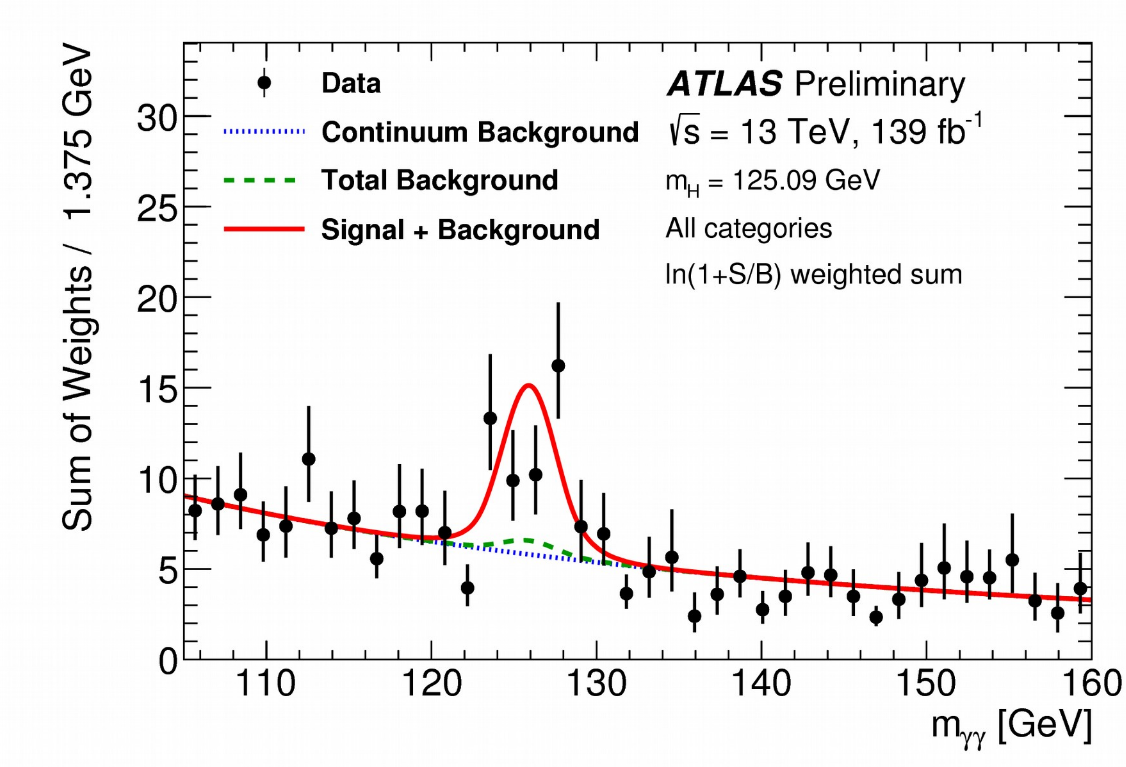
ttH production

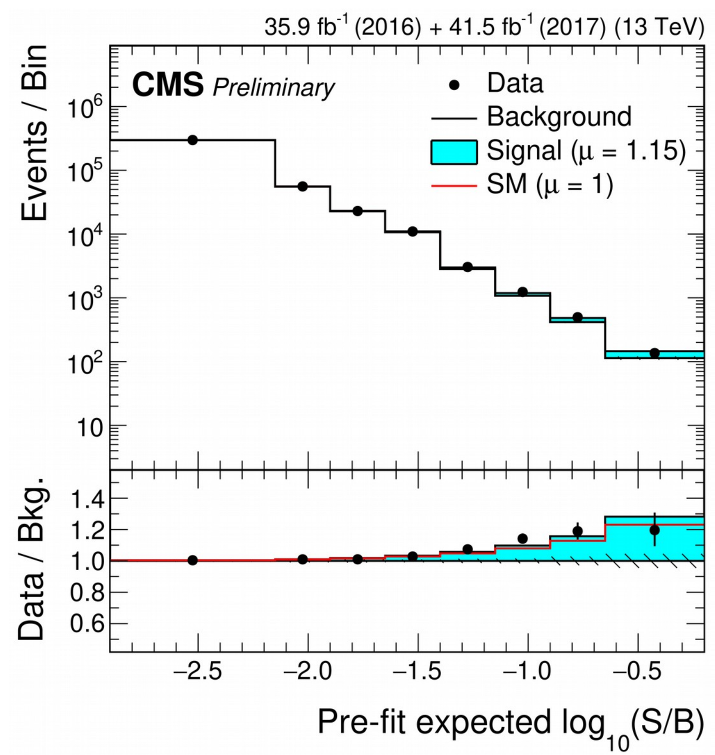


Evidence for ttH

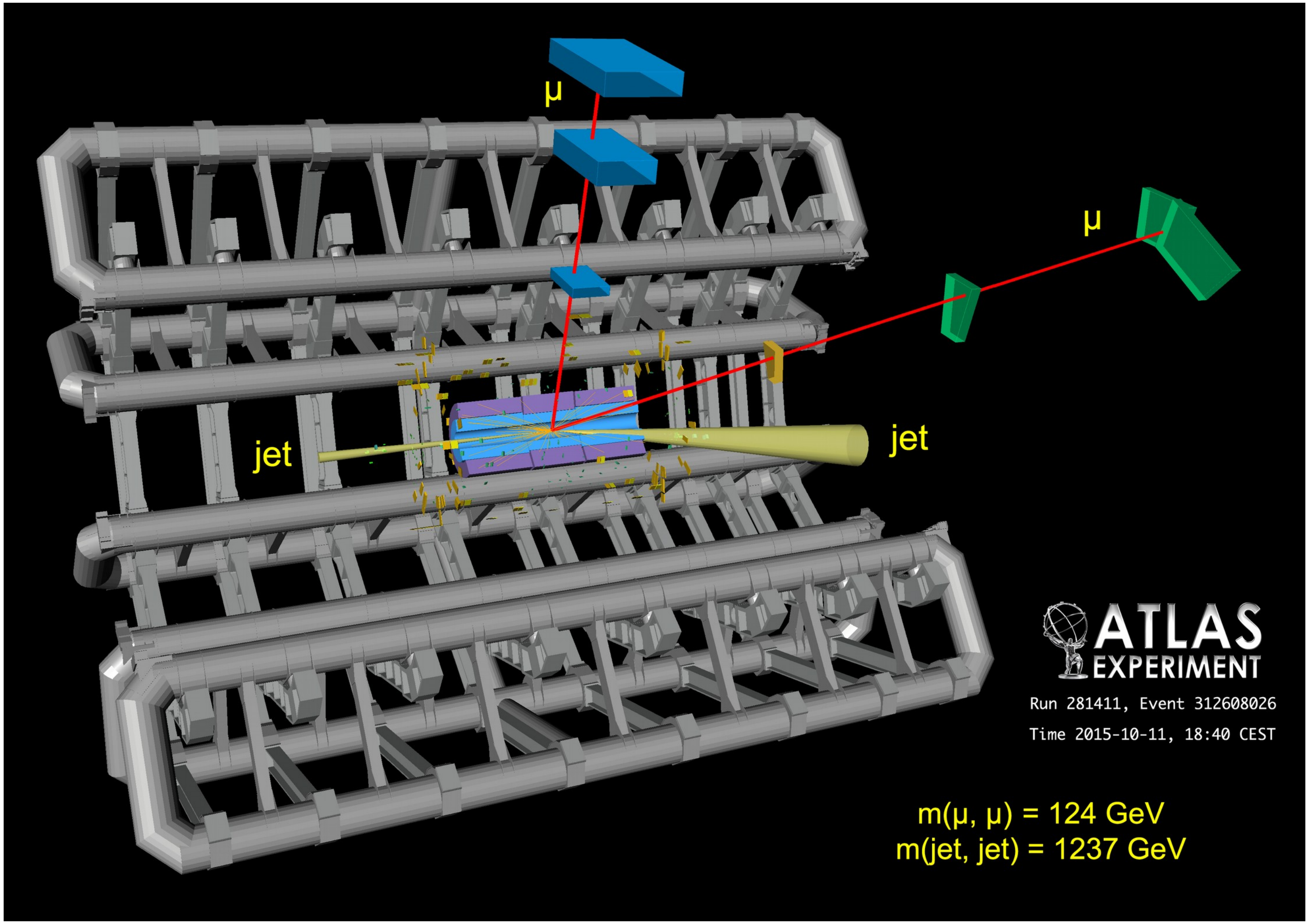
$\sigma(ttH) = 0.01 \times \sigma(tot)$

- Evidence for direct ttH process reported by ATLAS using full Run-2 data in $H \to \gamma\gamma$ decay channel, with $\mu = 1.59^{+0.43}_{-0.39}$
- CMS instead used $H \to bb$ decay in 2016+2017 data set and reports $\mu = 1.49\ ^{+0.21}_{-0.20}(\mathrm{stat})\ ^{+0.39}_{-0.35}\ (\mathrm{syst})$





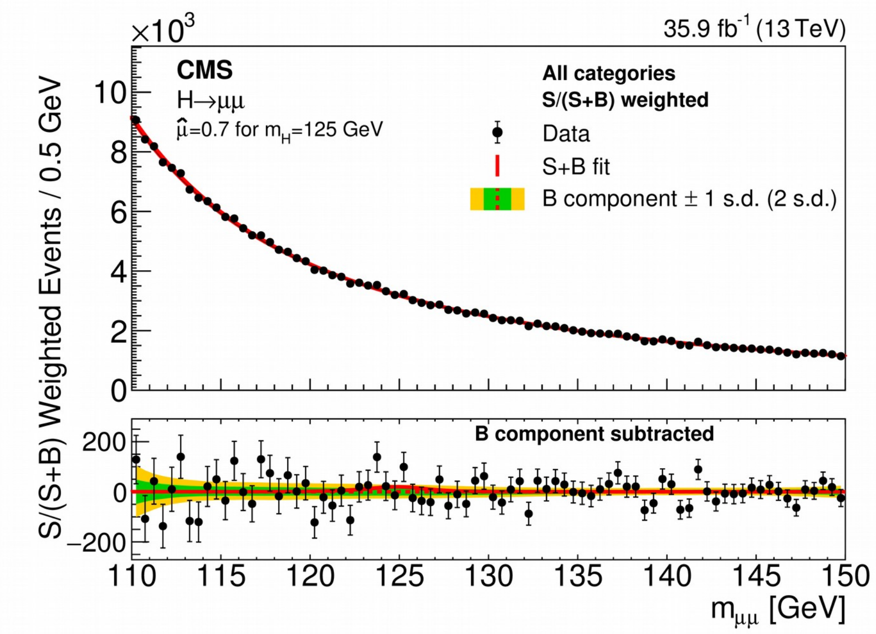
$H \to \mu\mu$

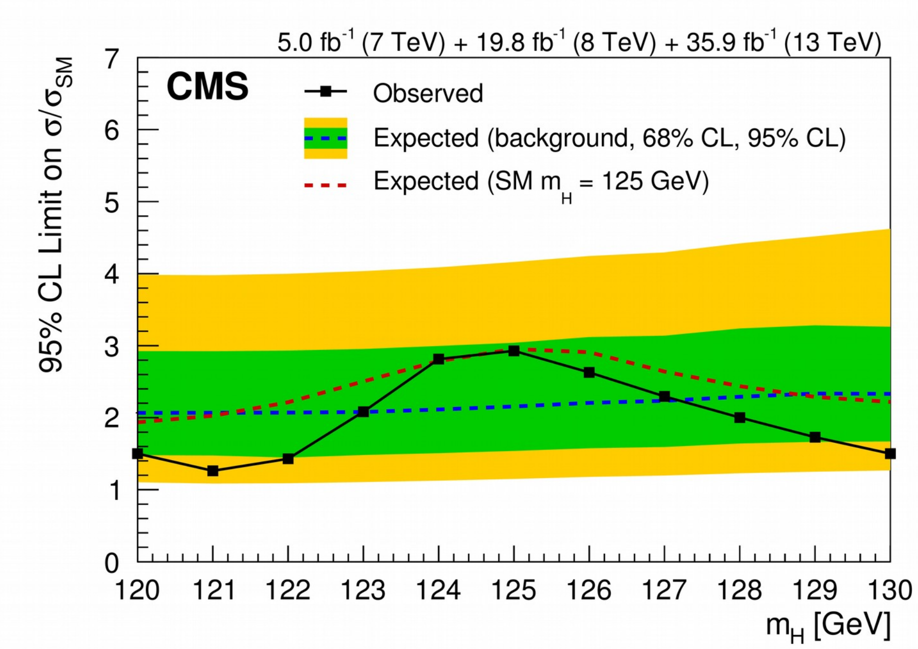

μ
μ
jet
jet
ATLAS
EXPERIMENT
Run 281411, Event 312608026
Time 2015-10-11, 18:40 CEST
m(μ, μ) = 124 GeV
m(jet, jet) = 1237 GeV

$H \rightarrow \mu\mu$

$BR_{SM}(H \rightarrow \mu\mu) = 0.02\%$

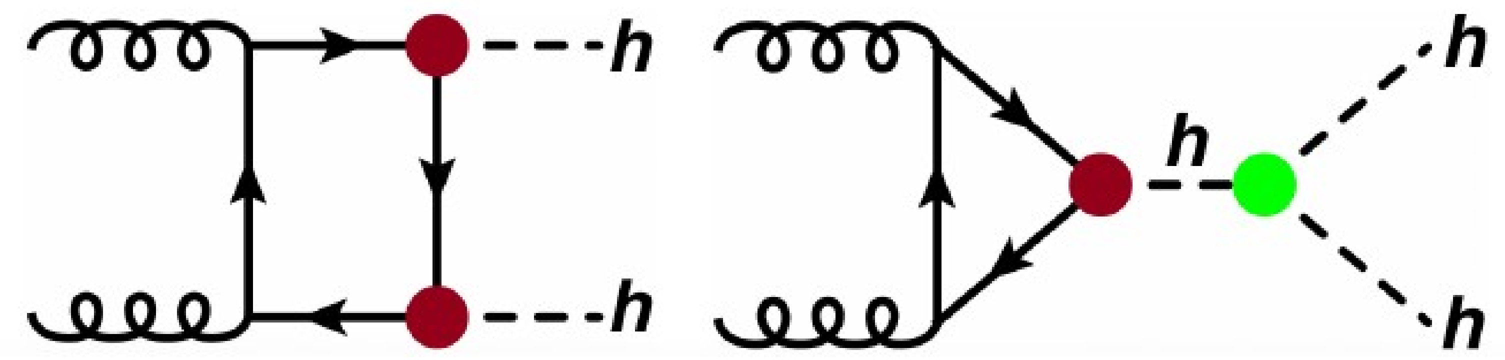
- The $H \rightarrow \mu\mu$ is not observed yet
  - Which is in agreement with SM





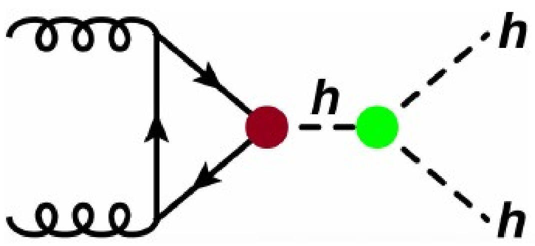
- ATLAS results (same data set, released in 2017):
  - Upper limit 2.8 x SM prediction

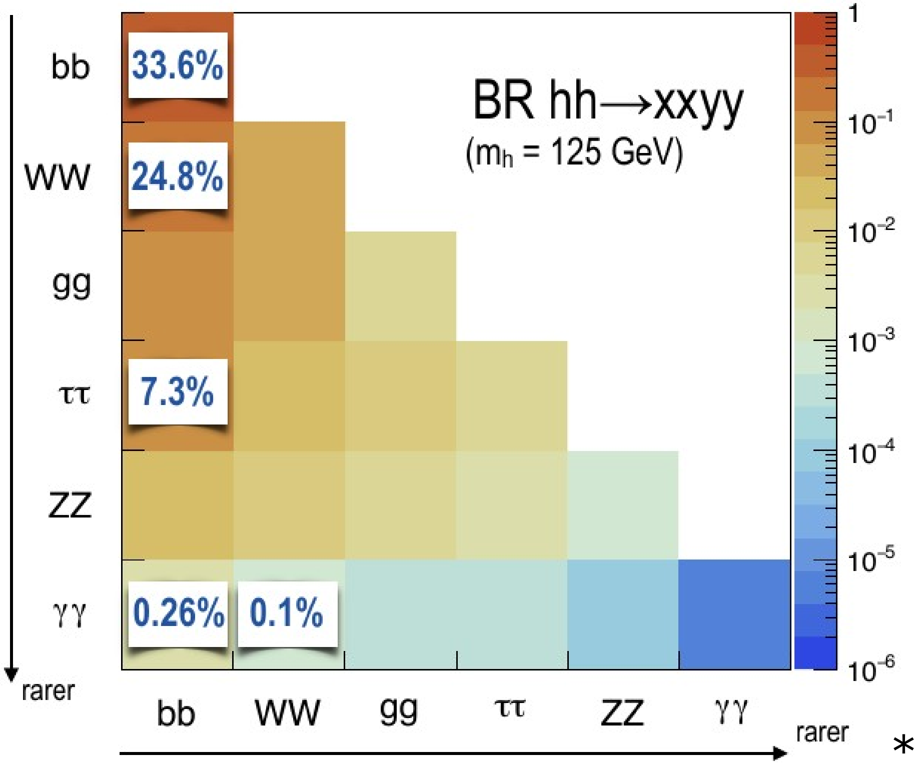
HH



HH production and decays at LHC

- Sensitive to $\mathbf{k}_\lambda$ – the only way to probe the structure of the Higgs potential
- Cross section is tiny: 31 fb (~2000 smaller than single Higgs production)

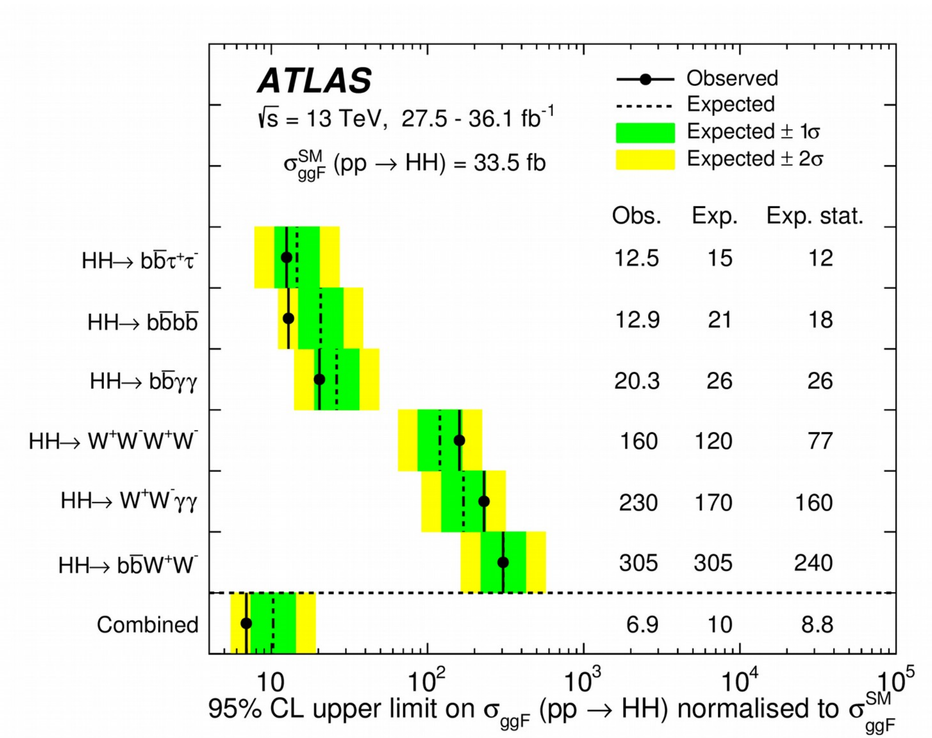


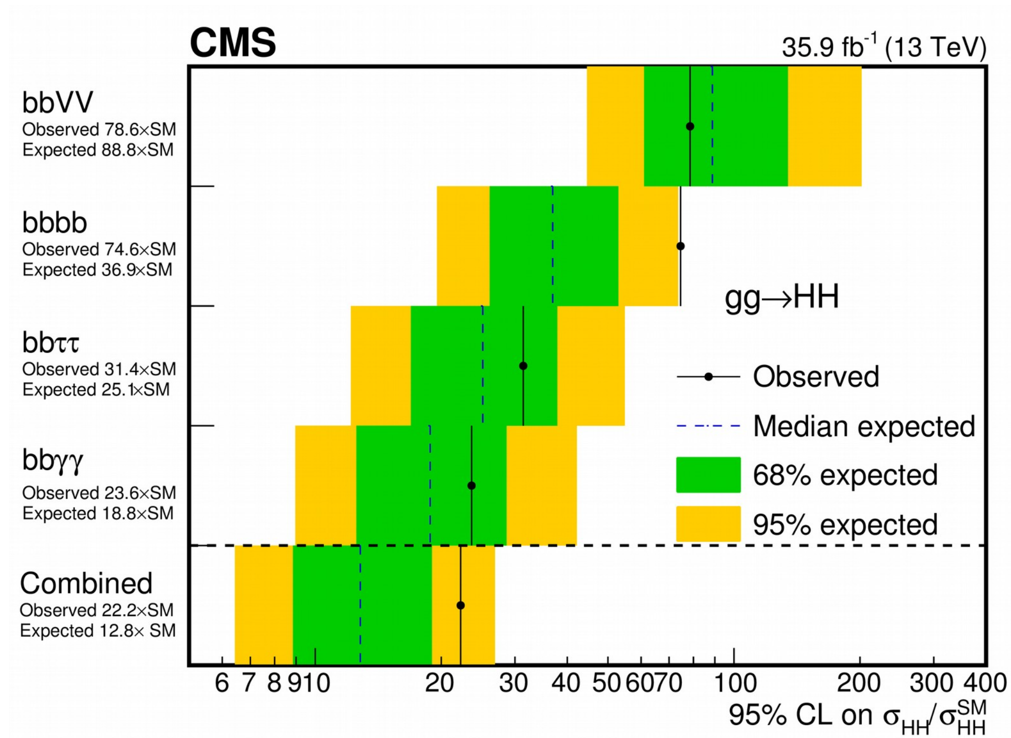


- Combination of decay channels can be studied
- Hot topic of ATLAS and CMS measurements right now

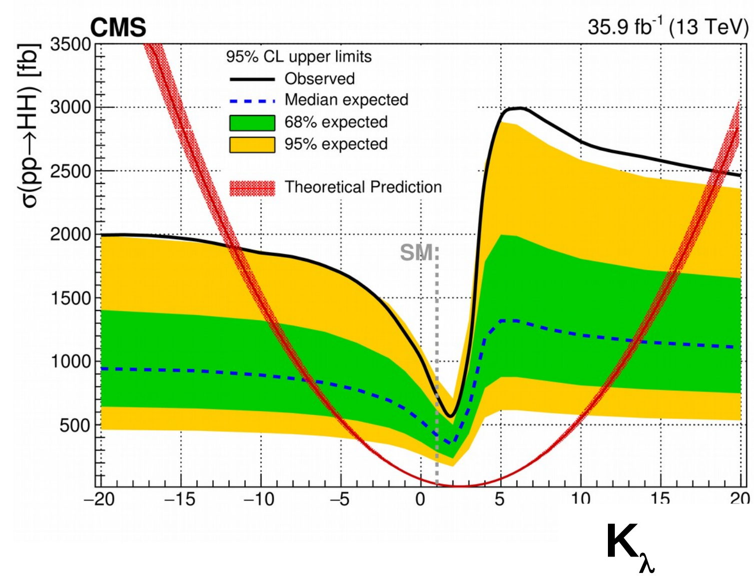
* BR numbers, assuming decay rates as for SM H(125) boson

Summary of HH searches





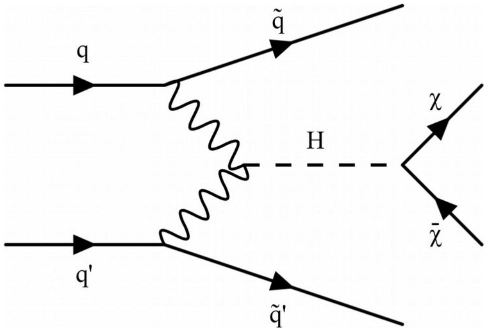
- Sensitivity at ~10xSM
  - Impressive results compared to the expectation of ~10 years ago!
- Constraining the couplings:
  - $-10 < k_\lambda < 15$

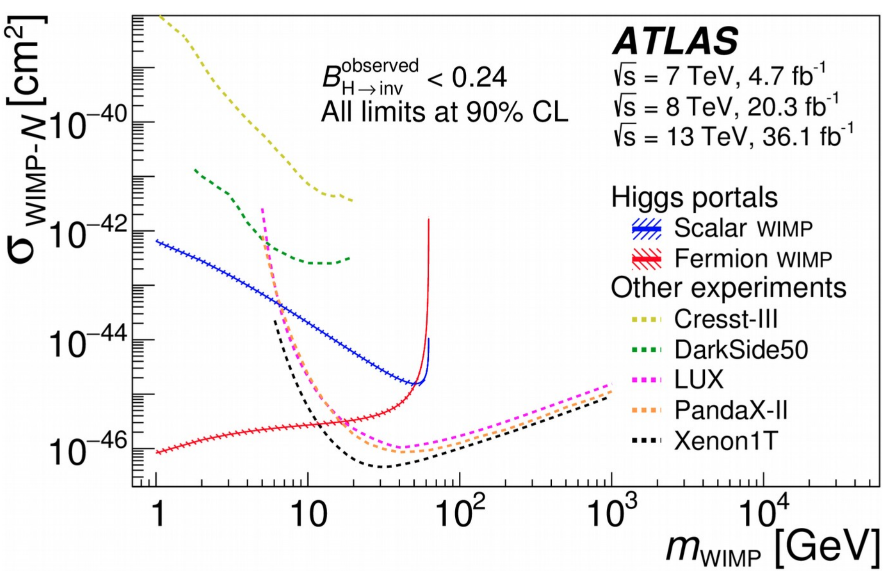


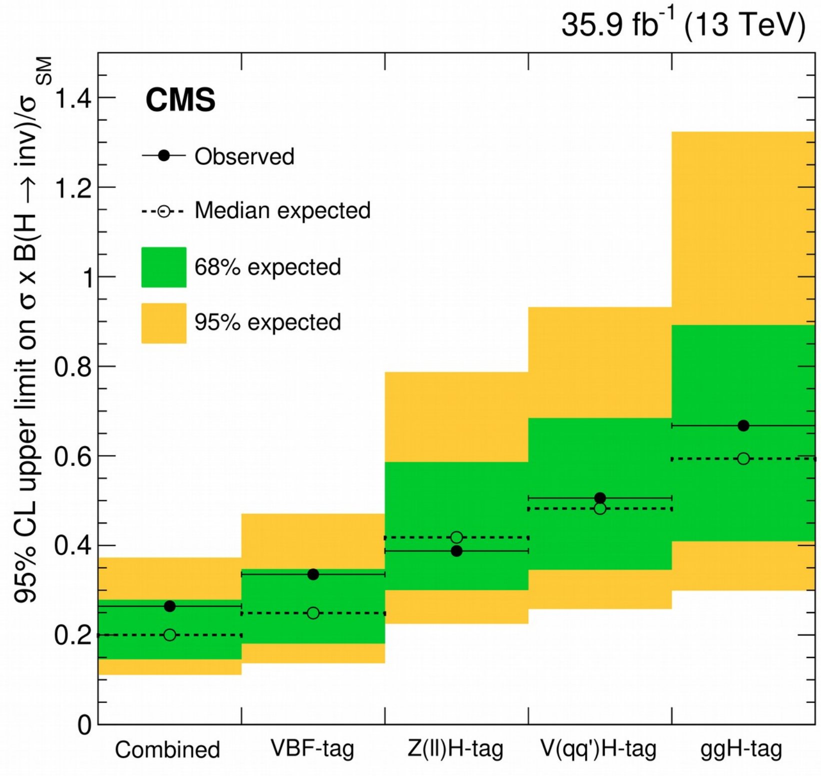
H → invisible

H → invisible

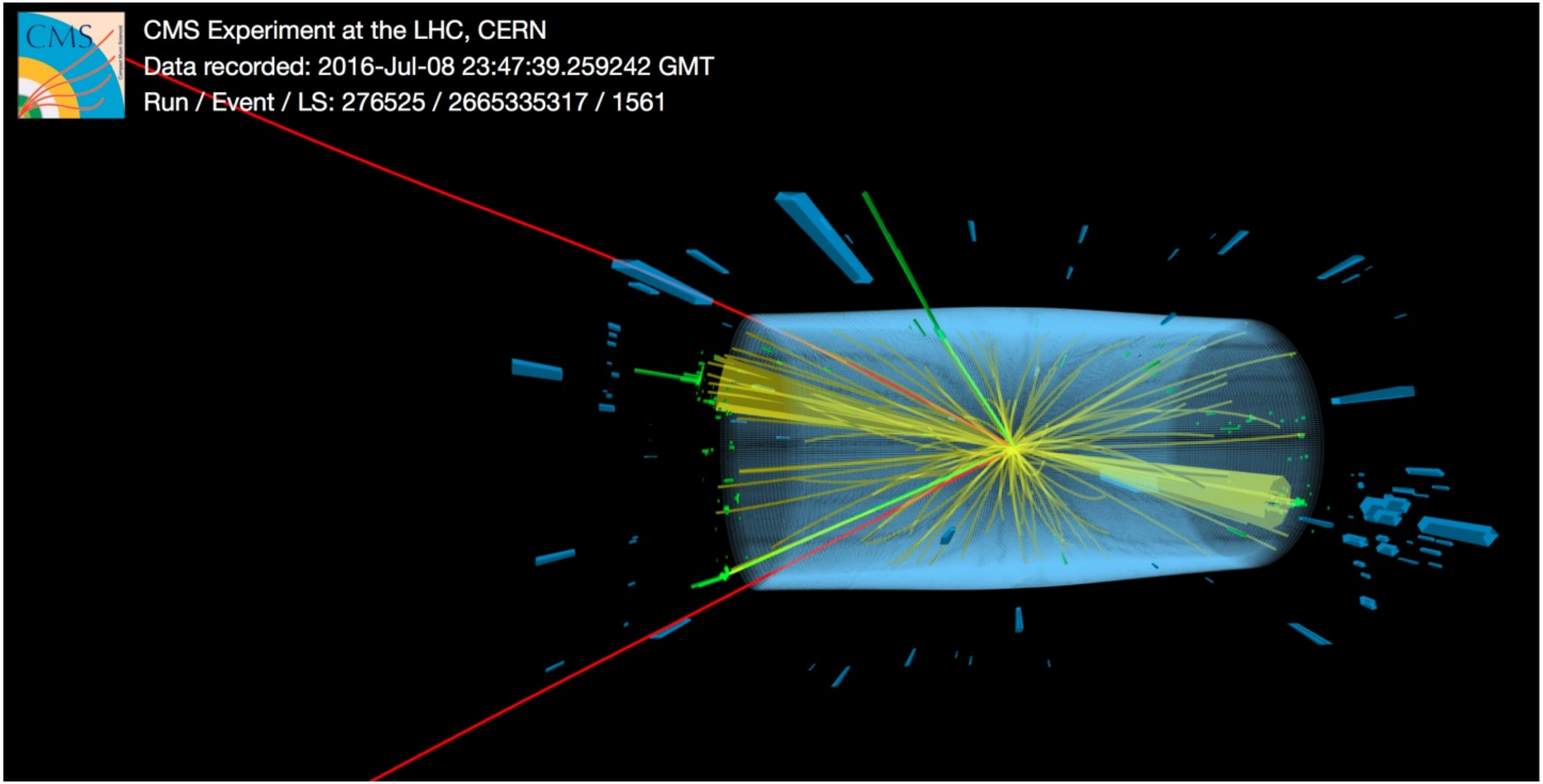
- There must be dark matter
  - What if H decays to it?
    - It's invisible
    - Search for events with large E_T^{miss}
- ATLAS result (Run 1 + 2017):
  - BR(H→inv) < 26%
- CMS result (Run 1 + 2017):
  - BR(H→inv) < 19%







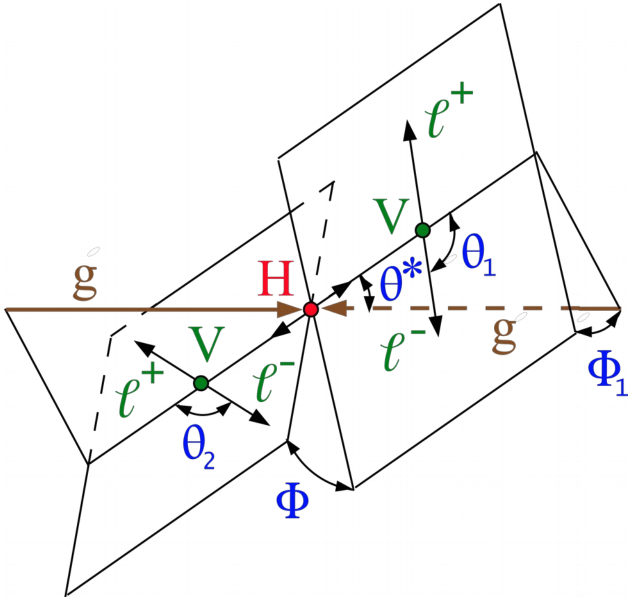
$H \to ZZ \to 4\ell$



Parameterize H → ZZ → 4ℓ

- Scattering amplitude for H → VV

$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} - \frac{\kappa_3^{VV} (q_1 + q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\,\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\,\mu\nu}$$



gg → H → VV → 4ℓ

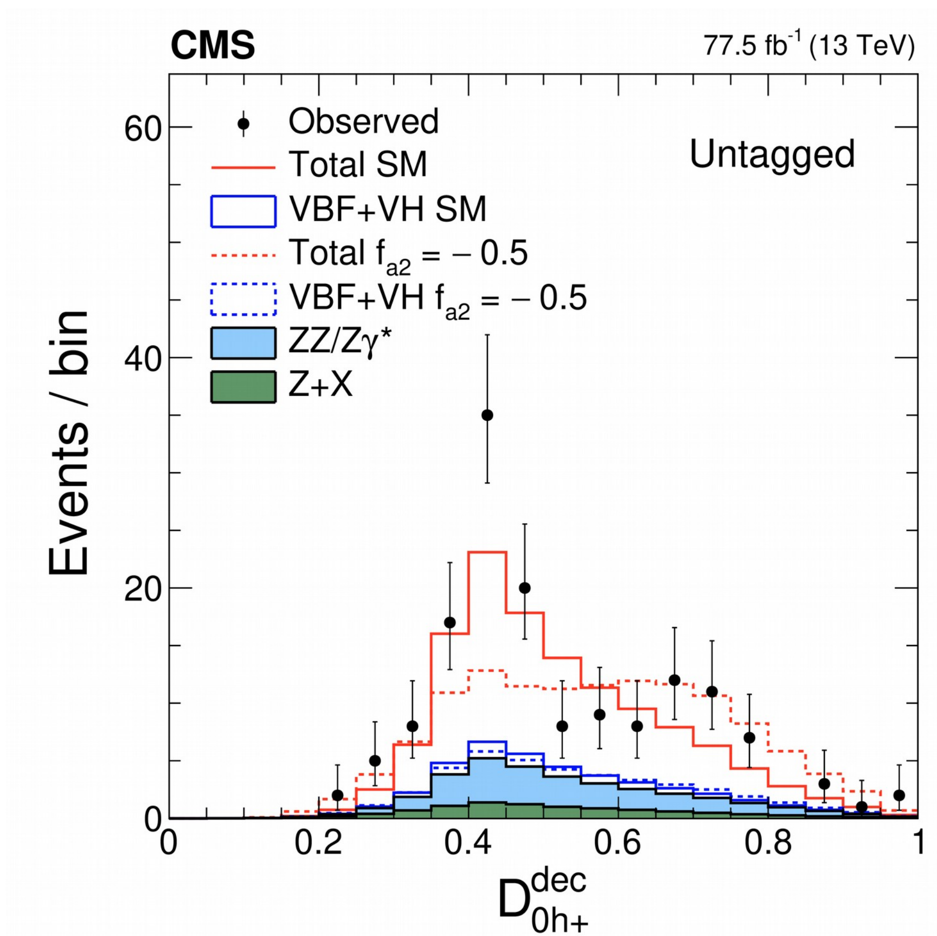
$$\mathbf{\Omega}^{\text{decay}} = \{\theta_1, \theta_2, \Phi, m_1, m_2, m_{4f}\}$$

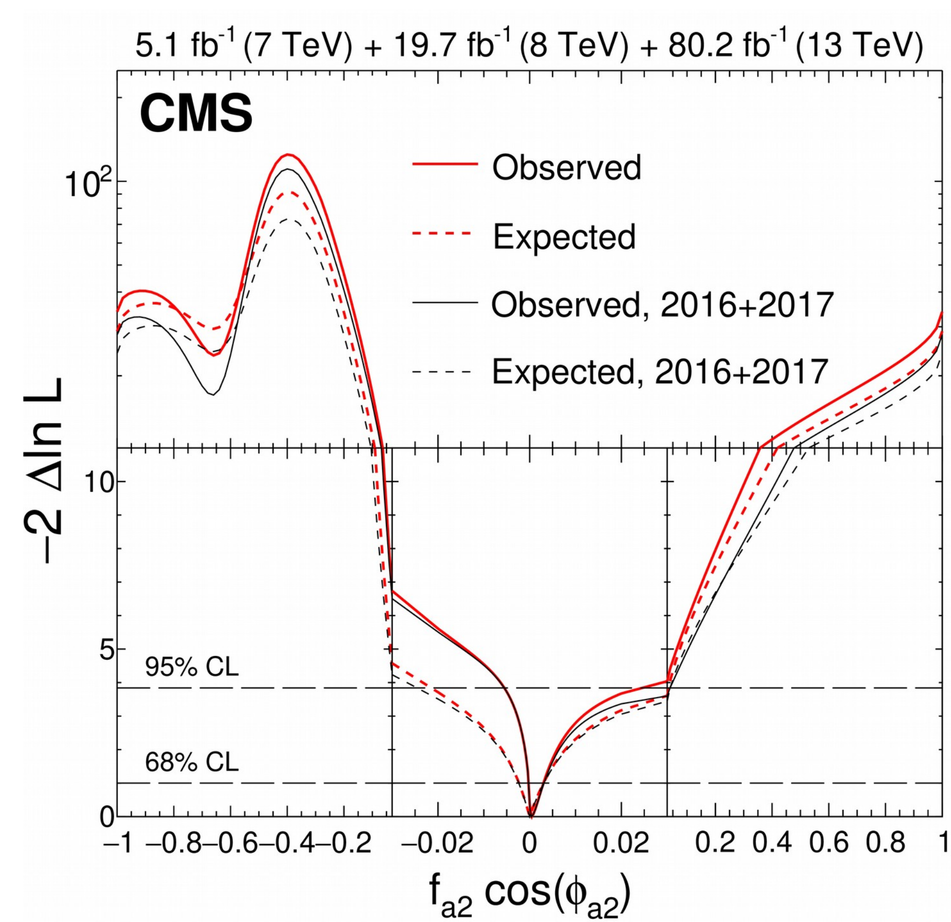
$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})\;\mathcal{P}_{\text{alt}}(\mathbf{\Omega})}},$$

Look at the data

- Various discriminators can be build to constrain non-SM couplings
- Run global ML fit to the data for all Ds and get the results
  - All anomalies are constrained to zeroes

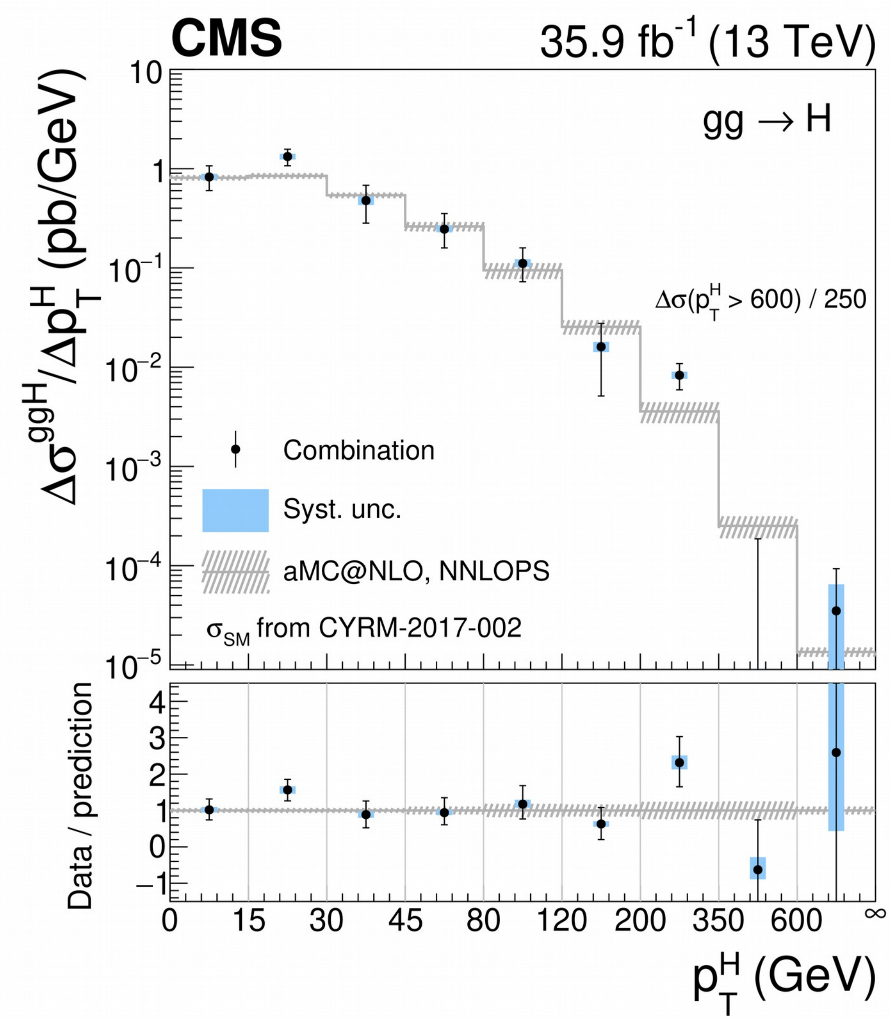


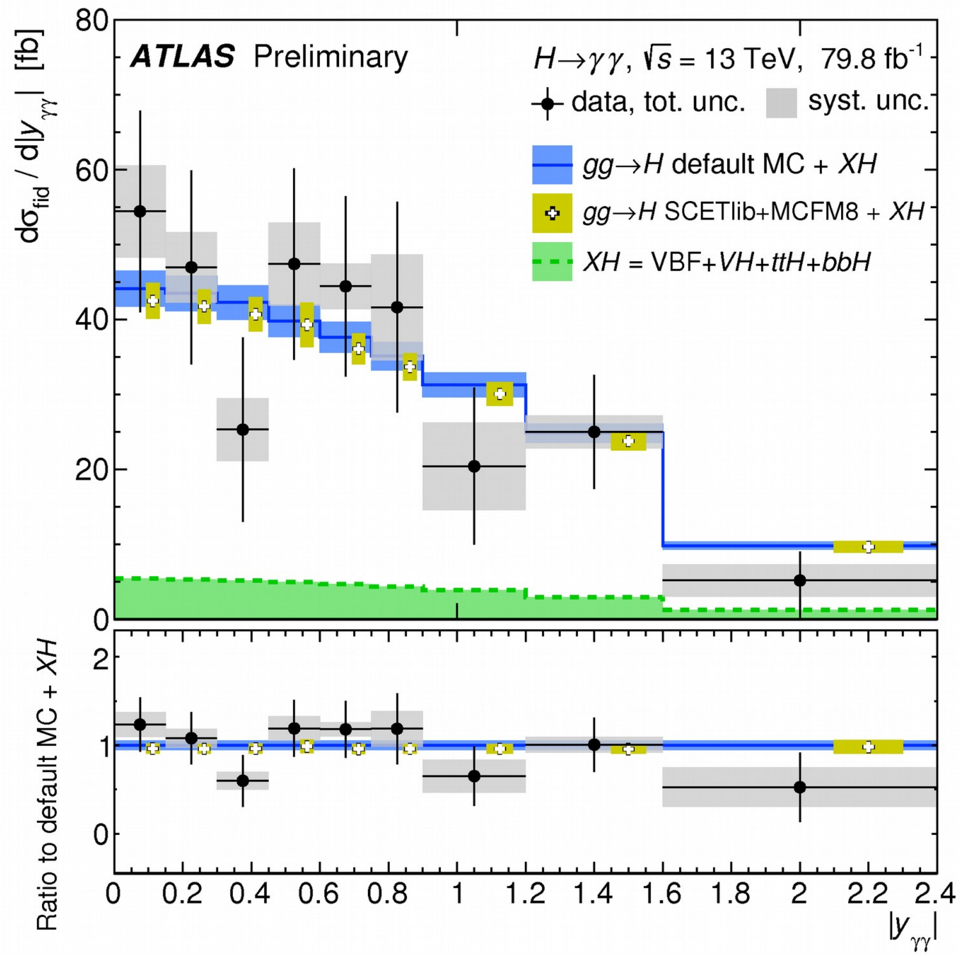


Go differential

Cross section in $p_T(H)$ and y

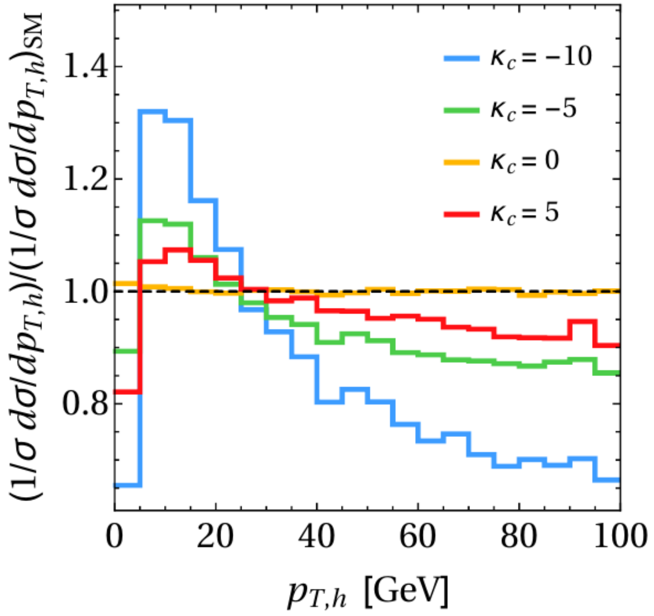
- Measurements of $p_T(H)$ and y(H) from $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$ processes

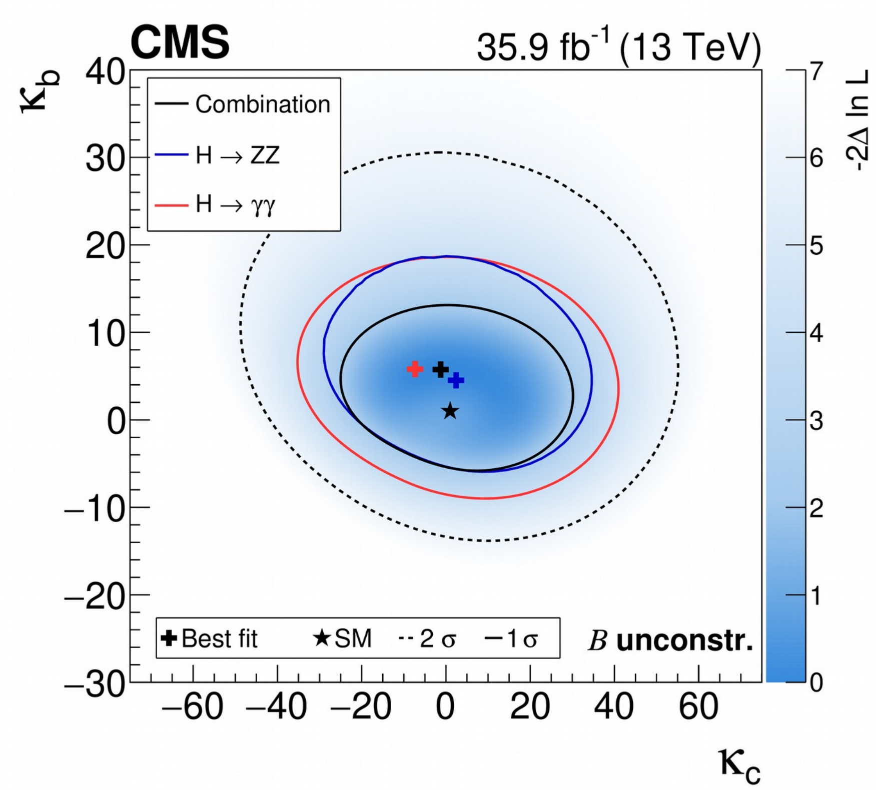




Constrain k_c?

- Differential distributions are sensitive to H couplings
  - Can we constrain k_c from this, for example?
  - Yes, and it could be comparable with direct search



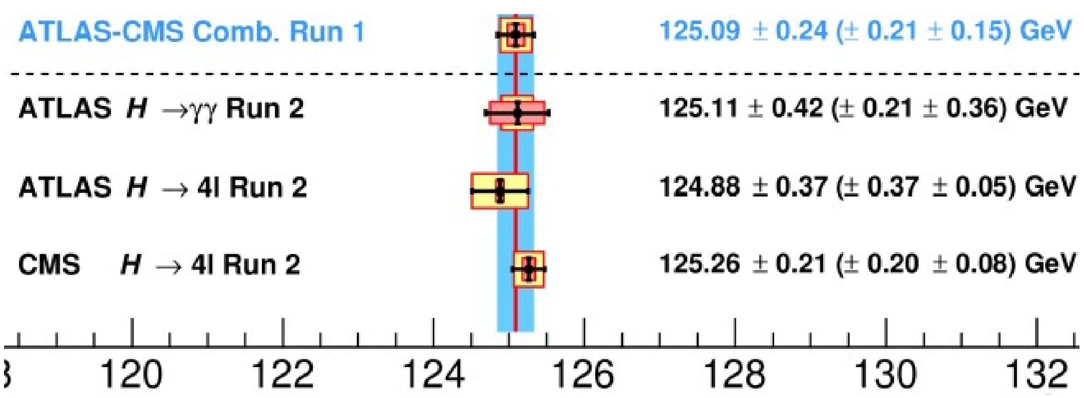


- Other couplings are constrained as well
  - λ_{hhh} is another good example
- Powerful method, but relies on prior theoretical assumptions

Future prospects

With current LHC

- In many channels, still 2017 and 2018 data are to be analyzed
  - More precise m_H measurements in $H \to 4\ell$
  - Better constraints on Hbb, Hcc, HH
- More data are coming in Run 3 (150 /fb expected)
  - Will we observe $H \to \mu\mu$, $H \to Z\gamma$?



- Then: HL-LHC
  - See the amazing LHC Yellow Report

Summary

- The status and recent results on Higgs boson was presented
  - $H \rightarrow bb$ observed at 5 sigma by both CMS and ATLAS
  - Higgs decays to all dominant channels are observed
  - Higgs production via ttH channel is confirmed
  - Limit on HH production is at ~10xSM
  - No statistically significant anomalies are observed so far
    - Standard Model is solid
- More results are coming – stay tuned!

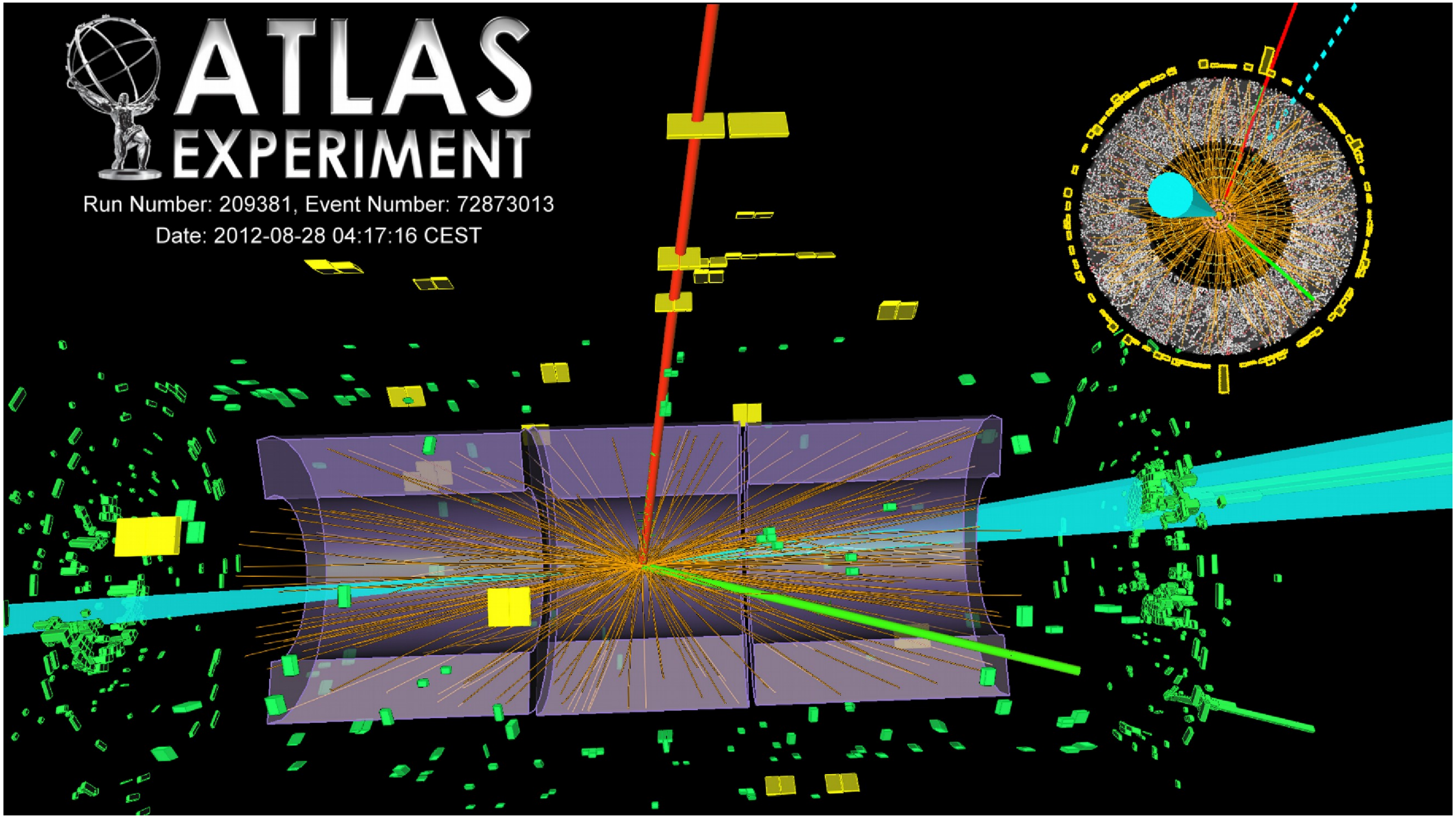
References

H decay channel	ATLAS	CMS
All channels, all Higgs public results:	Click	Click
bb	Phys. Lett. B 786 (2018) 59	Phys. Rev. Lett. 121 (2018) 121801 CMS-HIG-18-030
ττ	Phys. Rev. D 99 (2019) 072001	JHEP 1906 (2019) 093 CMS-HIG-18-032
$ZZ \rightarrow 4l$	Phys. Lett. B 786 (2018) 223 ATLAS-CONF-2018-018	Phys. Rev. D 99 (2019) 112003
cc	Phys. Rev. Lett. 120 (2018) 211802	CMS-HIG-18-031 (not public yet)
γγ	Phys. Lett. B 784 (2018) 345, Phys. Rev. D 98 (2018) 052005 ATLAS-CONF-2018-028 ATLAS-CONF-2019-004	Phys. Lett. B 792 (2019) 369
μμ	Phys. Rev. Lett. 119 (2017) 051802	Phys. Rev. Lett. 122 (2019) 021801
HH	arXiv:1906.02025 ATL-PHYS-PUB-2019-009	Phys. Rev. Lett. 122 (2019) 121803
Invisible	Phys. Rev. Lett. 122, 231801	Phys. Lett. B 793 (2019) 520
rare	Phys. Lett. B 786 (2018) 134	Eur.Phys.J. C79 (2019) 94

The End

Backup

H → ττ


ATLAS
EXPERIMENT
Run Number: 209381, Event Number: 72873013
Date: 2012-08-28 04:17:16 CEST

Status of H → ττ

$BR_{SM}(H \to \tau\tau) = 6.3\%$

- Observation of H → ττ has been reported in a combined result CMS and ATLAS in Run-1
- Recent updates:
  - ATLAS and CMS released results using 2016 data set: the decay is also observed by a single experiment
  - CMS released a dedicated VH analysis, and combined that with previous ggH+VBF