Observation of Higgs boson decay to b-quarks at ATLAS and CMS experiments

Victor Kim

Outline

- Motivation

- Width of Higgs boson decay to b-quarks in SM

- Status of Higgs boson decay to b-quarks before Summer 2018

- ATLAS & CMS: analysis with 2017 data

- ATLAS & CMS: combination with previous data

- Conclusions

based on
- ATLAS and CMS papers submitted in Aug. 24, 2018
- ATLAS and CMS presentations in Aug. 28, 2018 @LPCC CERN

Motivation

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

In the SM, the Higgs mechanism provides masses to bosons and fermions

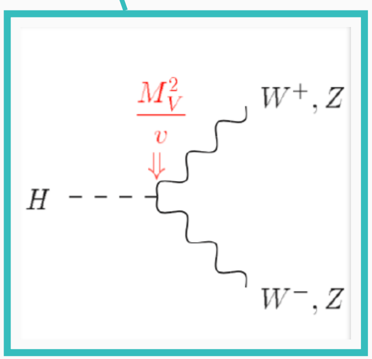
- Higgs boson discovery in 2012 opens a whole new sector of the Lagrangian
- Yukawa couplings not required by EWSB

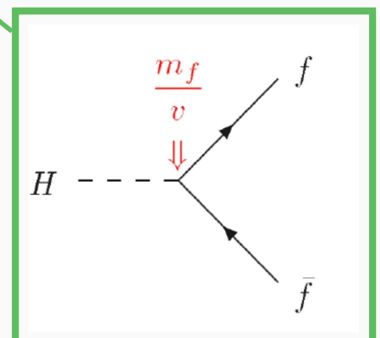
  $\Rightarrow$ ad-hoc solution to generate fermion masses

Main questions to answer

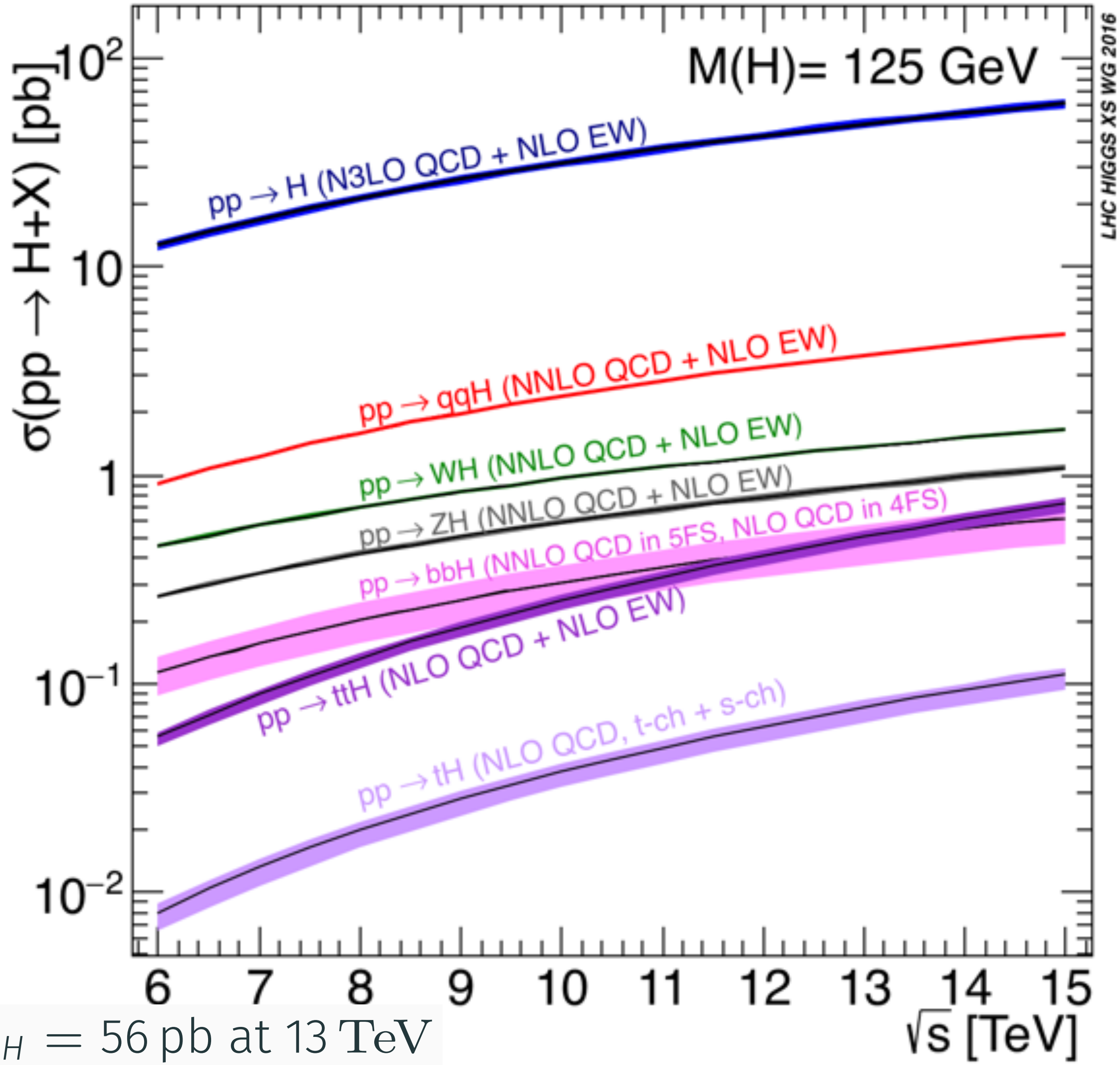
- Is the SM structure of the Lagrangian correct ?
- Are the values of the couplings as predicted in the SM ?

$\Rightarrow$ Broad programme at the LHC



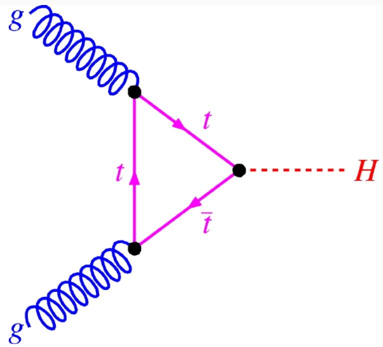


SM Higgs boson production @LHC



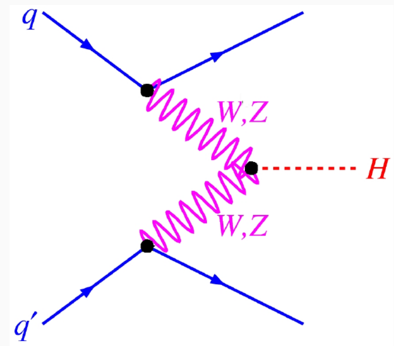
Total cross-section $\sigma_H = 56\,\text{pb}$ at 13 TeV

SM Higgs boson production @LHC: 4 main modes



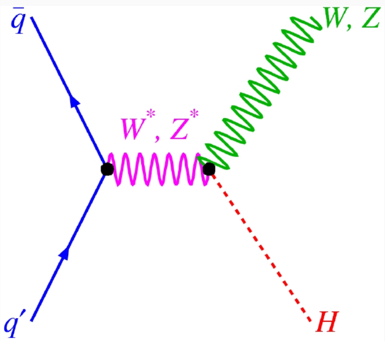
Gluon fusion (ggF)

- Dominant mode (88% of the total)



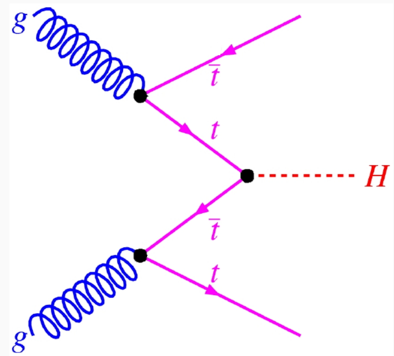
Vector boson fusion (VBF)

- 7% of the total



$VH = WH/ZH$

- 3% of the total



$t\bar{t}H$

- 1% of the total

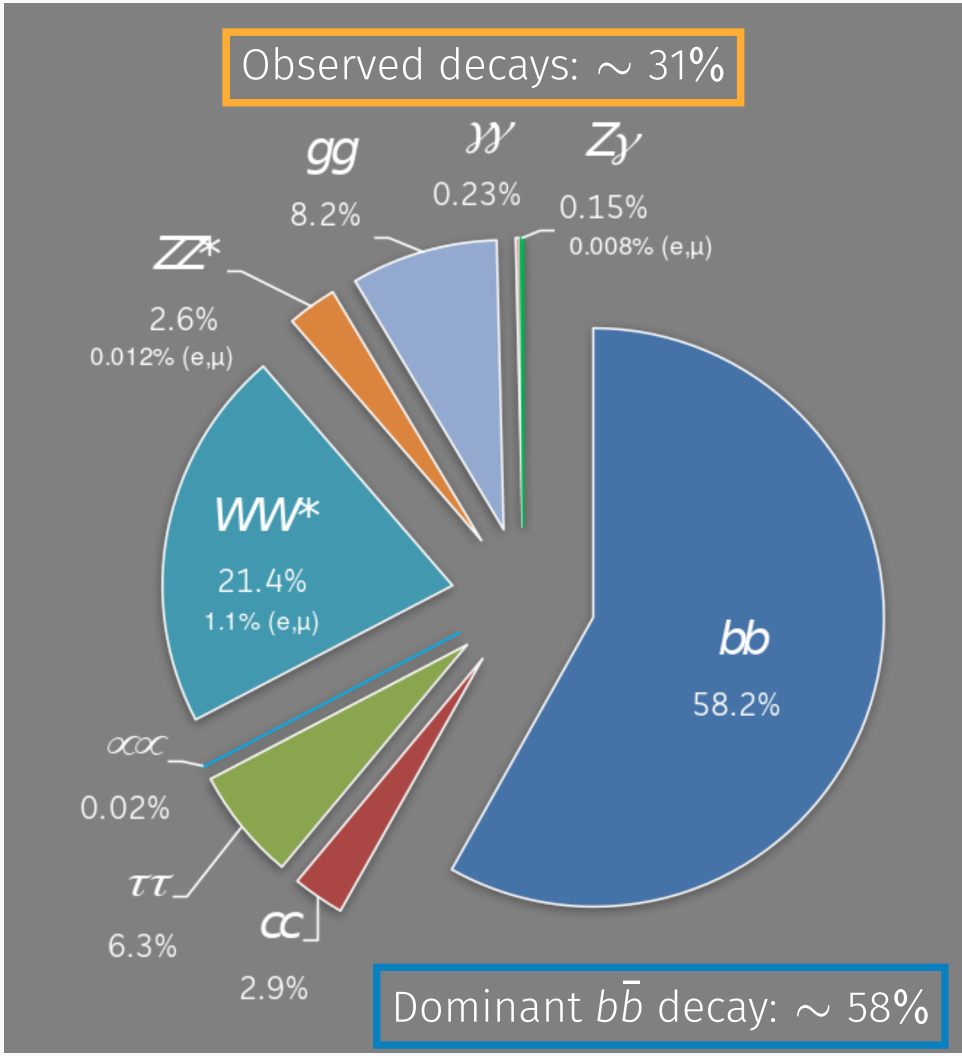
Higgs boson branching ratios

The Higgs boson couples to mass

$\Rightarrow$ Many decay modes accessible at the LHC

$\Rightarrow$ $b\bar{b}$ largest BR $\sim$ 58%

$\Rightarrow$ Coupling to $\gamma\gamma$ or gg through loops



$H \to b\bar{b}$ and Higgs boson couplings

- Total width not directly measurable at the LHC

  $\Rightarrow$ Only coupling ratios truly model-independent

- Hypothesis of SM structure of the loops and no BSM decays

  $\Rightarrow$ $b\bar{b}$ largest BR: drives total width, thus measurements of absolute couplings

- If BSM particles allowed in loops and decays

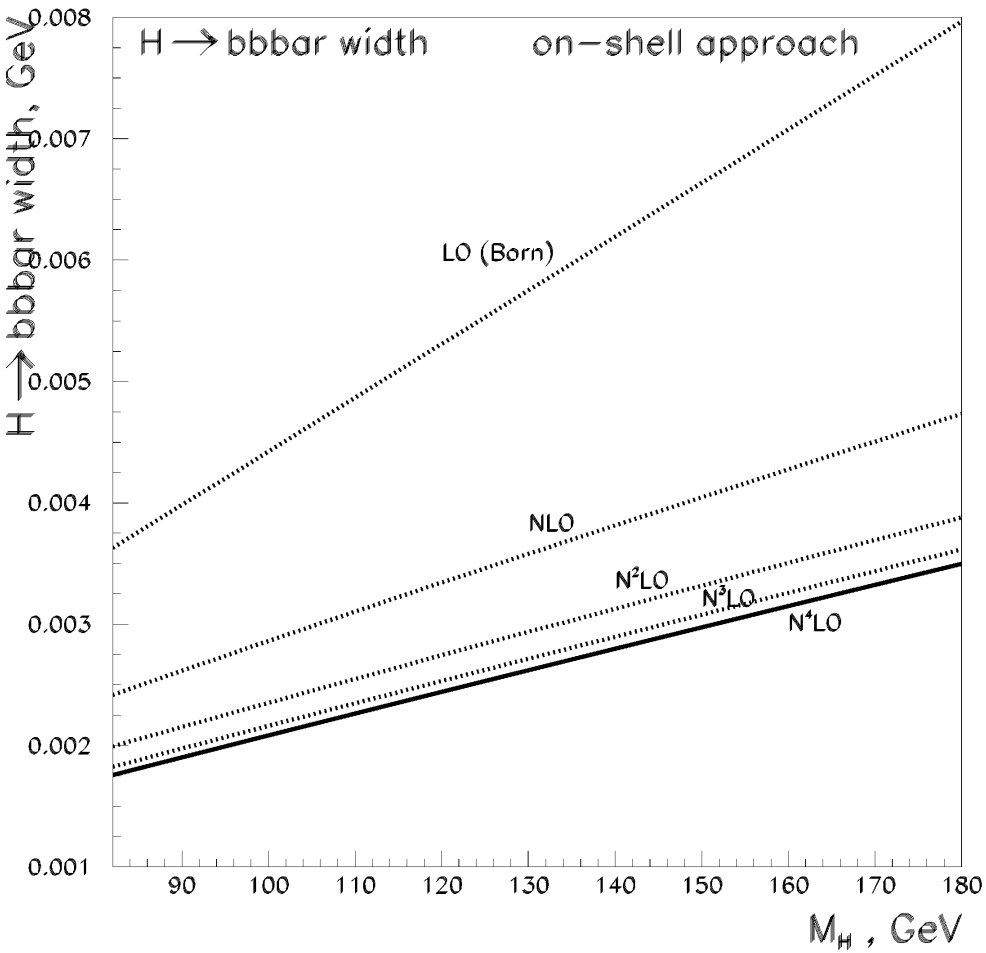
  $\Rightarrow$ Measuring $H \to b\bar{b}$ limits BSM branching fraction allowed

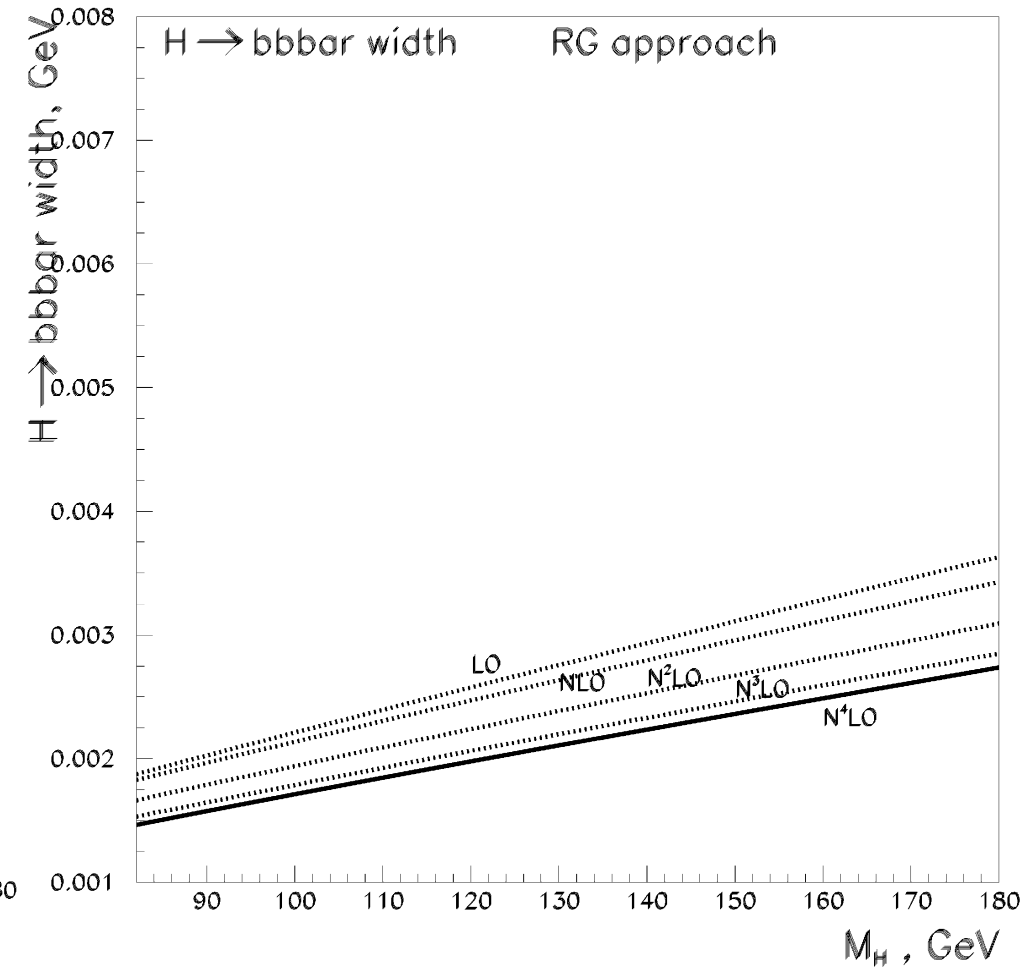
Higgs boson width to b-quarks upto N^4LO

P. Baikov, K. Chetyrkin, J. Kuhn (2006)
A. Kataev, V. K. (2008)

$$\Gamma_{H\bar{b}b} = \Gamma_0^b \frac{\overline{m}_b^2(M_H)}{m_b^2}\left[1 + \sum_{i\geq 1} \Delta\Gamma_i\, a_s^i(M_H)\right]$$

$$\Gamma_0^b = 3\sqrt{2}/8\pi G_F M_H\, m_b^2$$





H->bb searches @LEP

Physics Letters B 565 (2003) 61–75

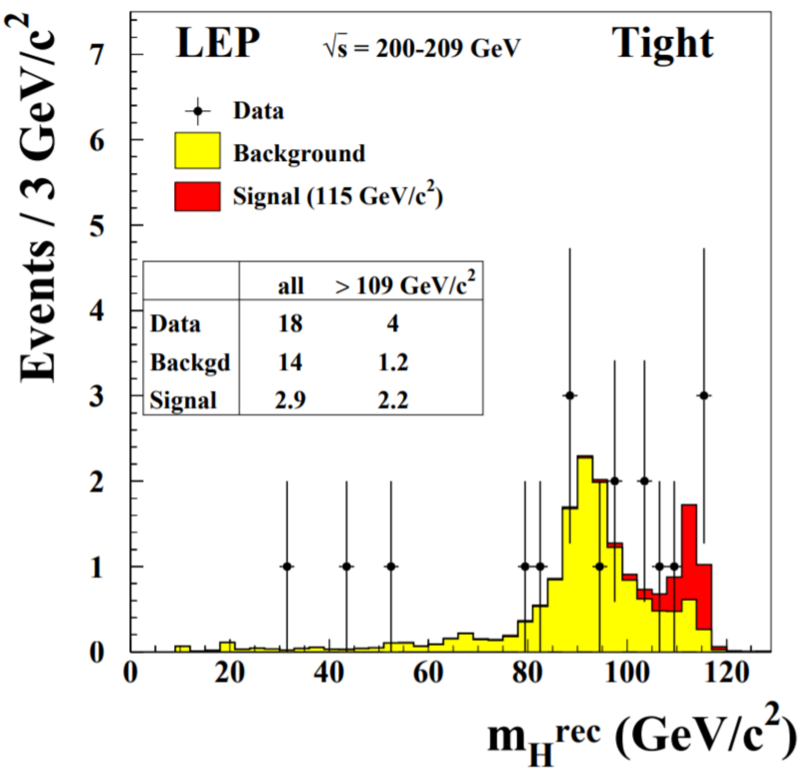
ELSEVIER

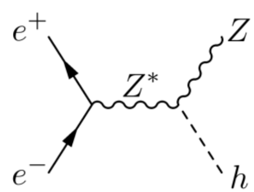
Search for the Standard Model Higgs boson at LEP

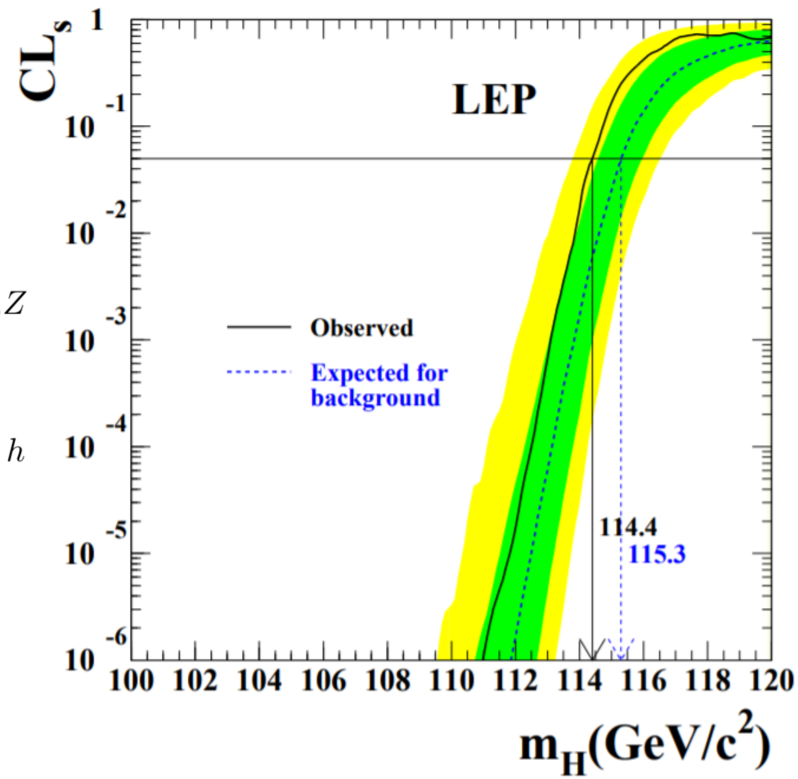
ALEPH Collaboration [1] DELPHI Collaboration [2] L3 Collaboration [3] OPAL Collaboration [4]
The LEP Working Group for Higgs Boson Searches [5]

PHYSICS LETTERS B

m_H > 114.4 GeV @ 95%CL



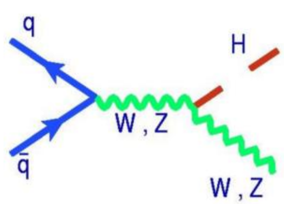


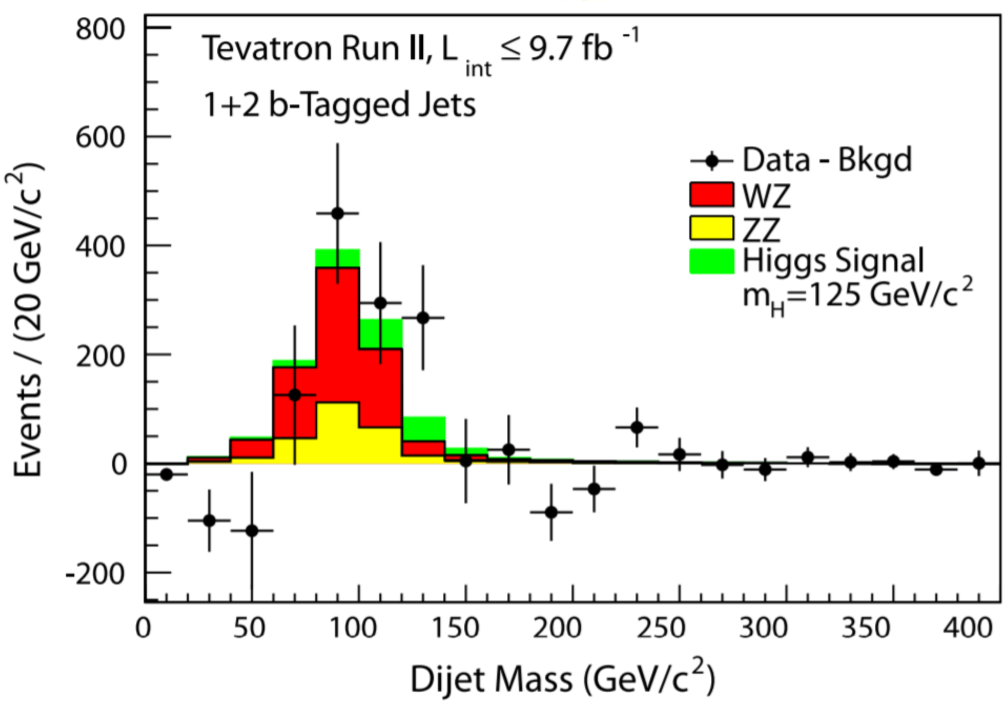


PRL 109, 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

(*CDF Collaboration)
(†D0 Collaboration)





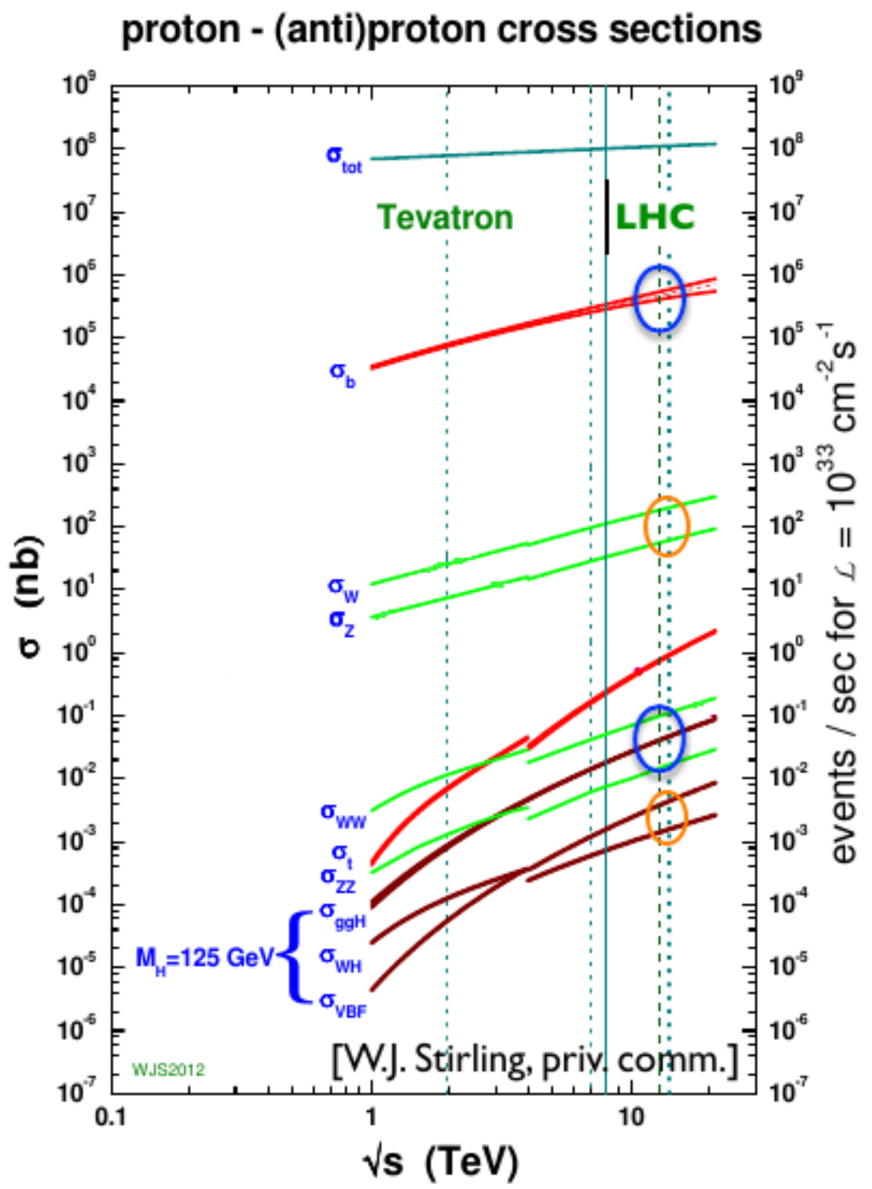
Significance

2.8σ observed @ 125 GeV

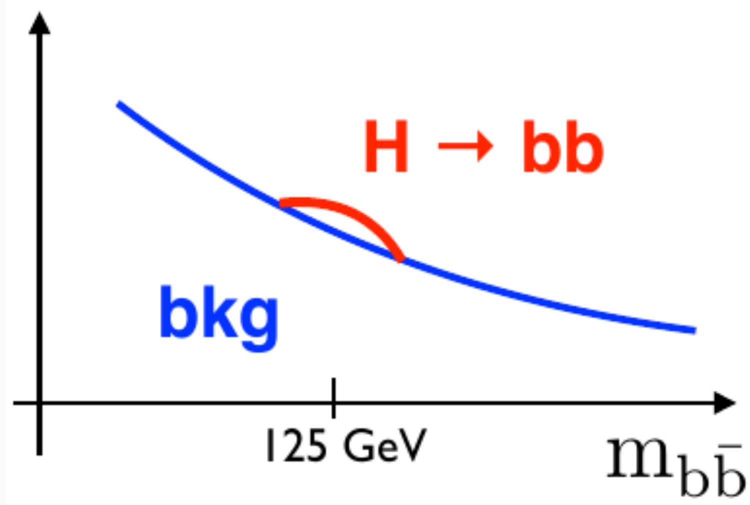
(1.5σ expected)

3.1σ in full mass range

Searches for H->bb @LHC: challenges



Very large multi-*b*-jets production cross-section at the LHC

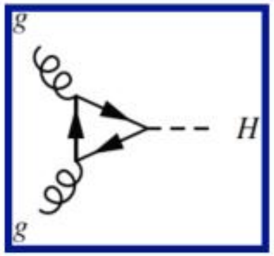


- Inclusive Higgs boson production (2 *b*-jets in final state) overwhelmed by bkgs by many orders of magnitude

Use associated productions to reduce bkgs

ggF Only possible in boosted regime
VBF Inclusive search + exclusive VBF+γ search
VH Most sensitive channel
ttH Also important for top Yukawa coupling

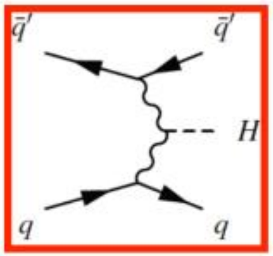
Higgs boson production modes for H->bb search



Gluon Fusion (87%)

Overwhelming (**10^7 larger**) background of b-quark production due to strong interactions

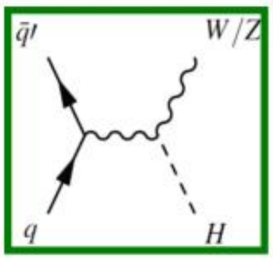
CMS: PRL 120 (2018) 071802



Vector-Boson Fusion (7%)

Very large background but a very distinctive topology
ISR photon to enhance S/B

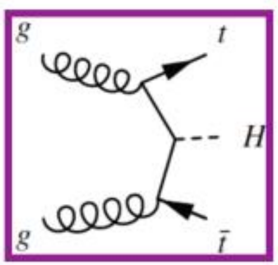
ATLAS: arXiv:1807.08639 submitted to PRD
ATLAS: JHEP 11 (2016) 112
CMS: HIG-16-003
CMS: PRD 92 (2015) 032008



Higgs-strahlung (4%)

leptons, E_T^{mis} to trigger and high p_T V suppress backgrounds

Most sensitive



Top Fusion ttH (1%)

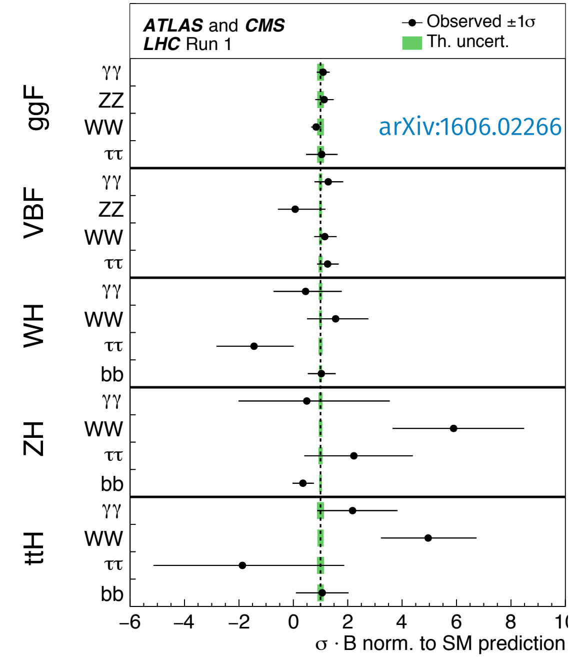
dominant background is $t\bar{t}$ + jets

ATLAS: JHEP 05 (2016) 160
ATLAS: PRD 97, 072016 (2018)
CMS: JHEP 09 (2014) 087
CMS: arXiv:1804.03682 submitted to JHEP
CMS: JHEP 06 (2018) 101

Higgs boson couplings before Summer 2018

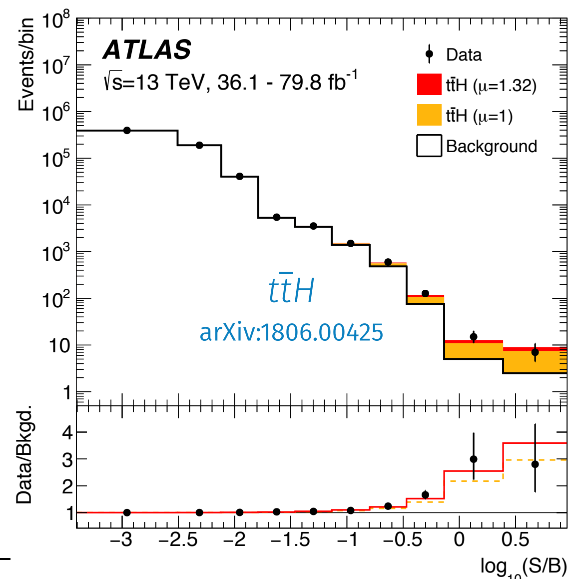
Run-1 Legacy

- ggF and VBF production modes observed
- Observation of decays in vector bosons (γ, Z, W)
- Observation of Yukawa couplings to τ leptons



Run-2 Achievements

- Many measurements much better than Run-1 accuracy
- Direct observation of top Yukawa coupling
- Single-experiment observation of VBF and $t\bar{t}H$ production modes and of τ decays.
- Evidence for $b\bar{b}$ decays



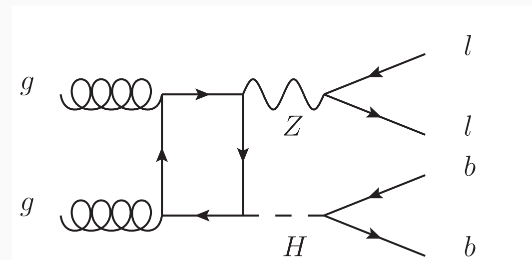
Summary

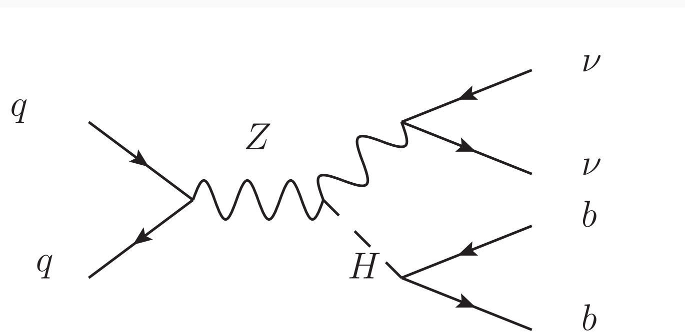
- All measurements in agreement with SM so far
- Observations of VH production and of $b\bar{b}$ decays still missing
- Yukawa couplings to second generation fermions not yet in reach

Processes

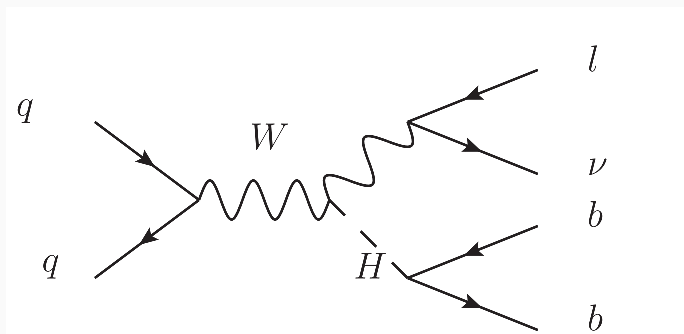
- ZH and WH production
  - Leptonic decays of Z/W for bkg rejection and trigger
  - 3 channels: 0, 1, 2 electrons or muons
- $H \to b\bar{b}$ decays
  - 2 high-p_T b-jets
- Possibly additional jets

- ZH has additional gg induced diagrams

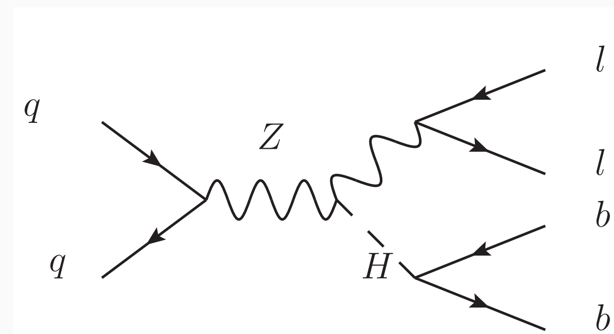




0-lepton



1-lepton

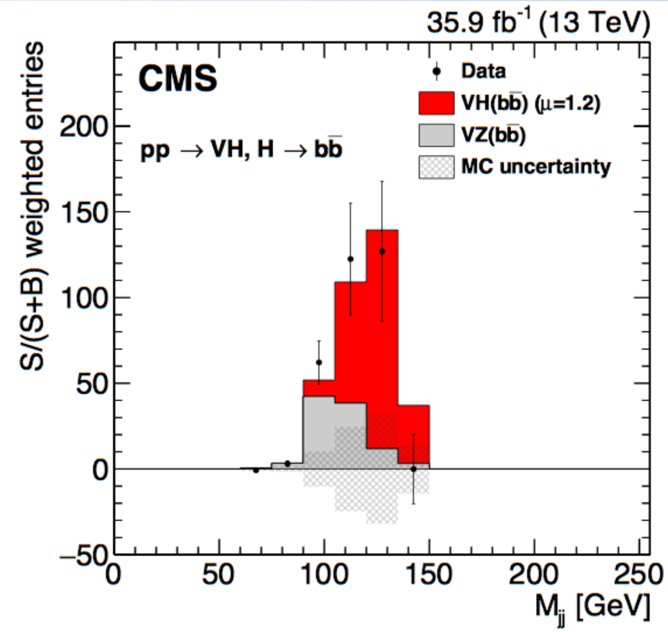


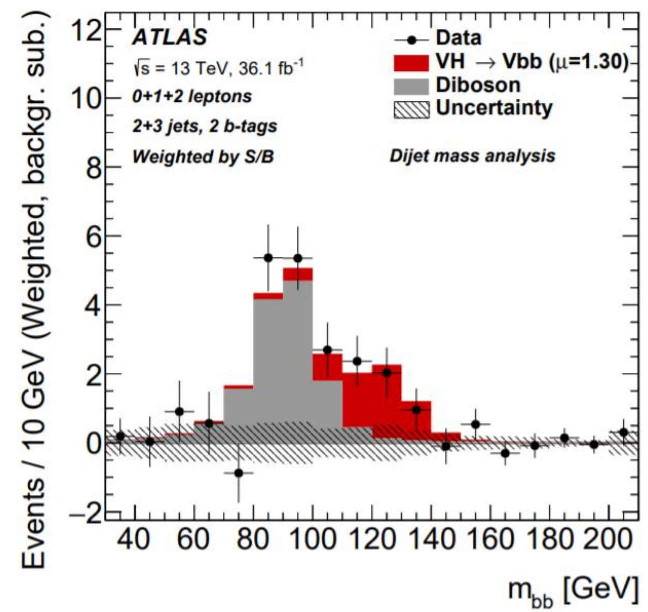
2-leptons

- **VH(bb) evidence at LHC established with 2016 data by both ATLAS and CMS**
  - Detectors clearly demonstrated ability to deal with very high pile-up for such complex analysis
- **Signal strength uncertainty ~40%**

	signal strength	significance (exp)	significance (obs)
ATLAS Run 1 [1]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run 1 [2]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run 1 [3]	$0.79^{+0.29}_{-0.27}$	3.7σ	2.6σ
ATLAS 2015+2016 [4]	$1.20^{+0.42}_{-0.36}$	3.0σ	**3.5σ**
CMS 2016 [5]	$1.19^{+0.40}_{-0.38}$	2.8σ	**3.3σ**

[1] JHEP 01 (2015) 069
[2] JHEP 08 (2016) 045
[3] JHEP 08 (2016) 045
[4] JHEP 12 (2017) 024
[5] PLB 780 (2018) 501





New H->bb analysis: key elements

- increased datasets

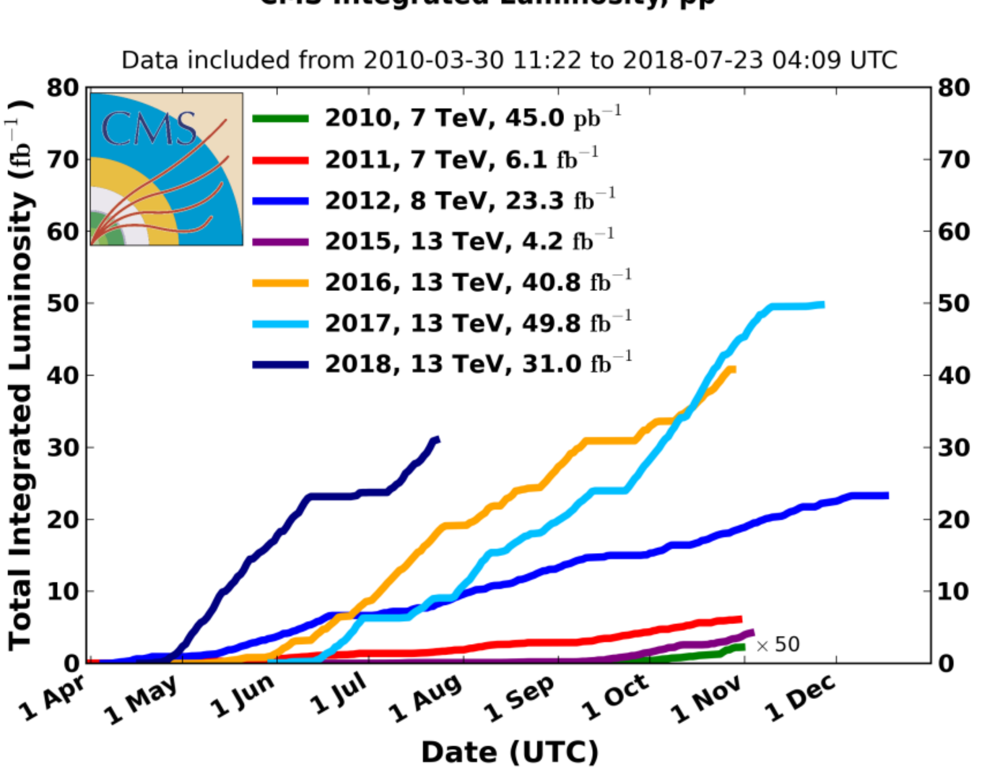
- improved b-tagging

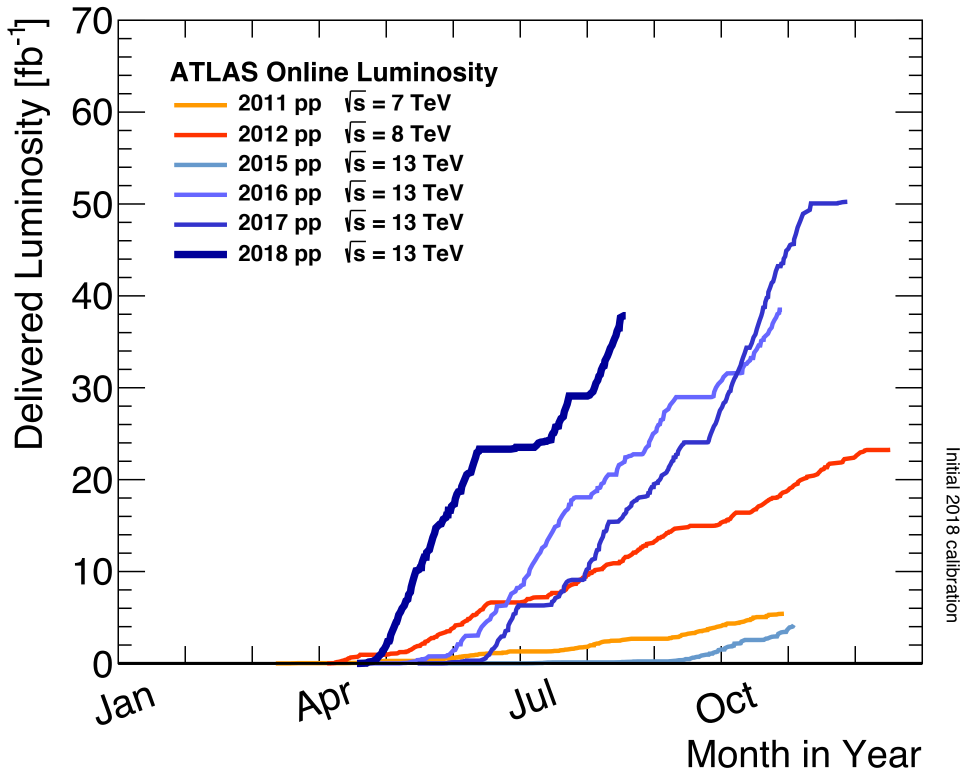
- improved dijet invariant mass resolution m_{bb}

- high pT-kinematics

Data: stunning LHC performance

- After successful Run 1, **LHC has produced >3 years of 13 TeV data with stunning performance**
- Expected integrated luminosity **>150 fb^{-1} by the end of 2018**
- **DESIGN peak luminosity exceeded by a factor of 2**
  - Average pileup ~38 in 2017 and 2018
- Incredible machine availability, **>50% of time in stable operation**





b-tagging: ATLAS

b-tagging

- Depends critically on the excellent operation of the tracker
- Performance in Run 2 relying on
  - New IBL detector installed in LS1 (2013-2014)
  - Tracking optimized for high-PU and high-p_{T} environments
  - Better ML algorithms

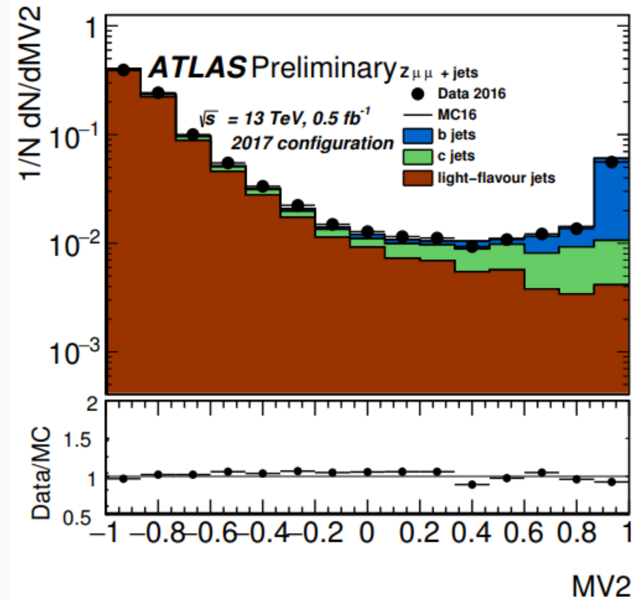
Run 2 performance

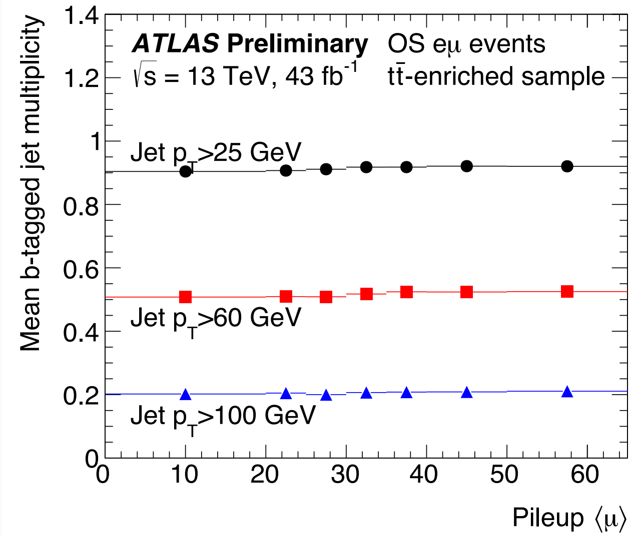
- Rejection of light / *c* jets 300 / 8 at 70% *b*-jets efficiency
- Well modelled in simulation
- Good performance even at high pile-up

$\Rightarrow$ Use only events with 2 good *b*-tags

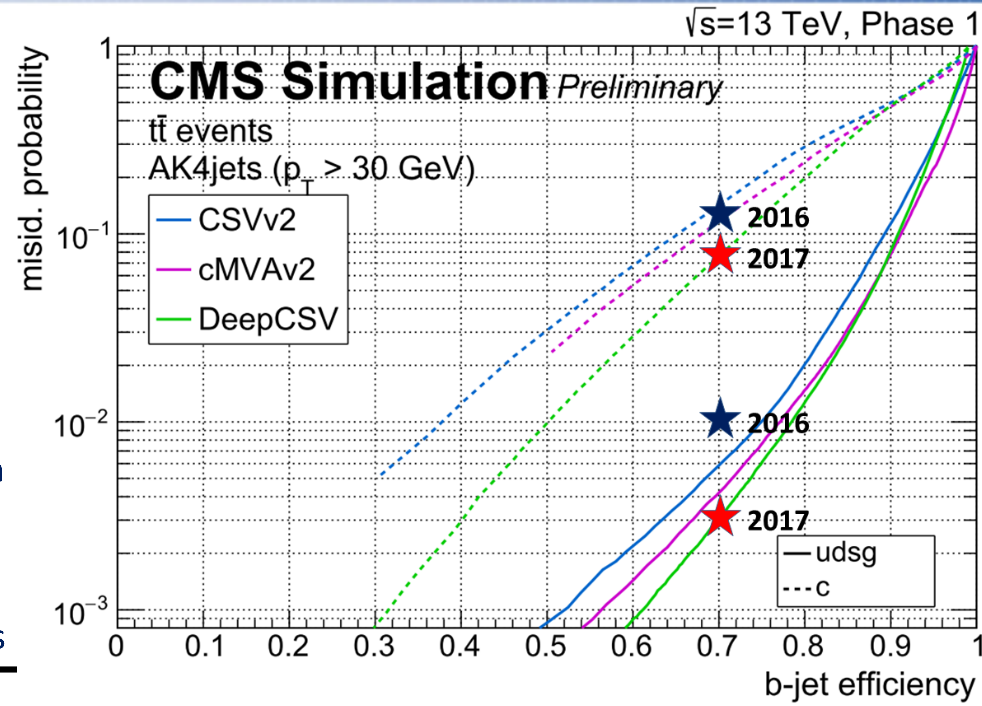
b-tagging discriminant

b-tagging discriminant





b-tagging: CMS

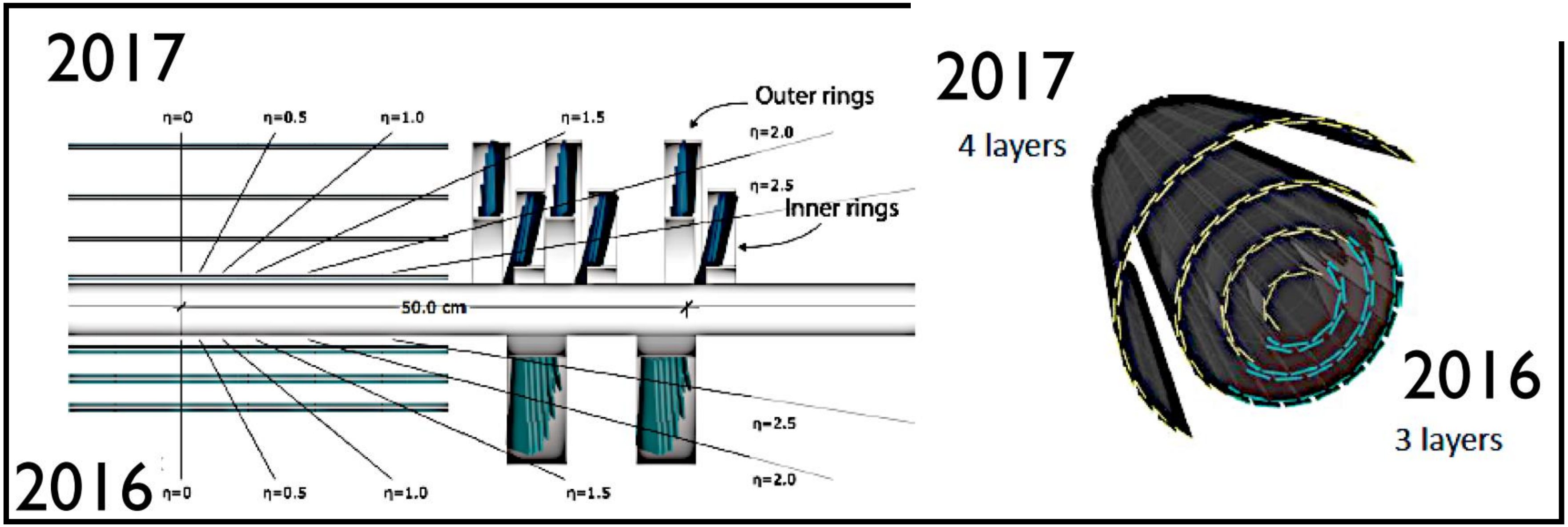


Continuous effort to improve b-tagging at CMS

- **New pixel detector** (4 layers)
- **DNN algorithm (DeepCSV) with additional per-track information**
- **Contamination from q/g < 1% for efficiency ~70%**

MC corrections derived on data with $t\bar{t}$ events

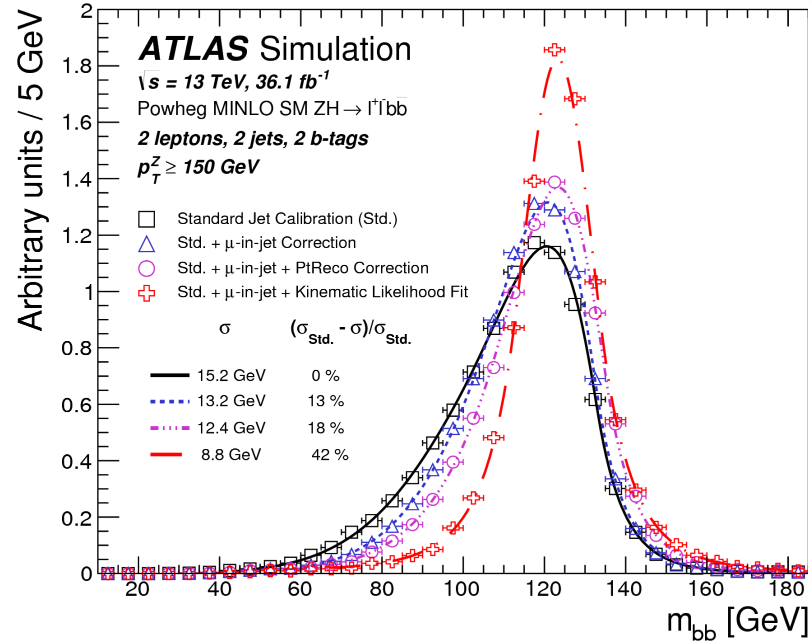
Good agreement between data and MC verified in all analysis regions



Mass resolution improvements

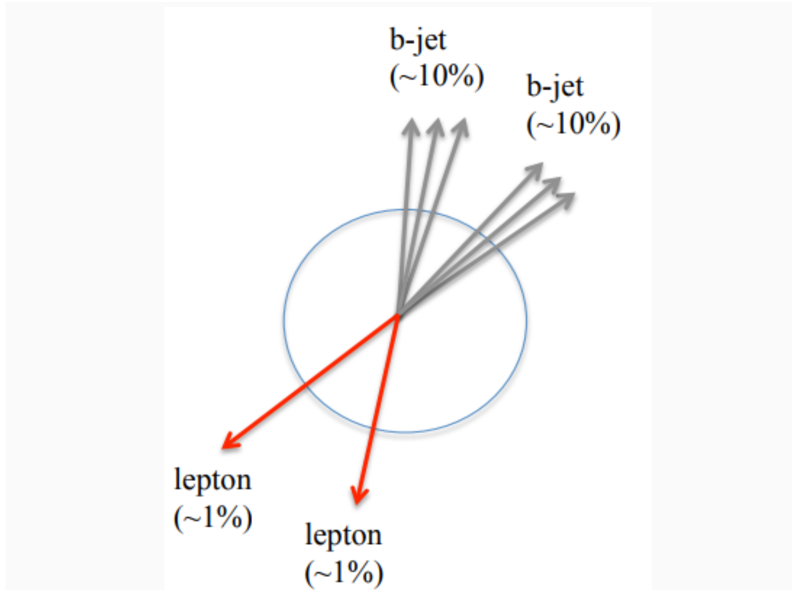
Higgs boson candidate from a pair of *b*-jets

- Add muons in the vicinity (semi-lep. decays)
- Simple average jet p_T correction
  - Accounts for neutrinos, and interplay of resolution and p_T spectrum effects.
- Mass resolution improvement: $\sim$ 18%



Kinematic Fit in 2-lepton channel

- Final state fully reconstructed
- High resolution on leptons
- Constrain jet kinematics better:
  $\sum \vec{p_T}(\ell) = -\vec{p_T}(bb)$ modulo soft radiation
- Mass resolution improvement: $\sim$ 40%



Diboson WZ, ZZ

- Similar to VH
- Lower mass, larger cross-section
- Softer $p_T(V)$ spectrum
- Sherpa 2.2.1

Z+hf, W+hf

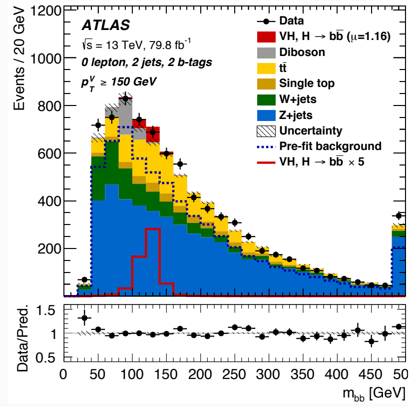
- Same final state as VH
- non-peaking
- Sherpa 2.2.1

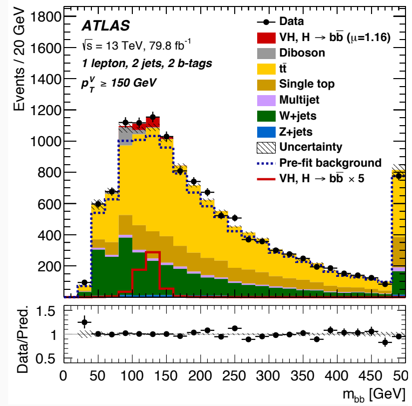
$t\bar{t}$, single-top

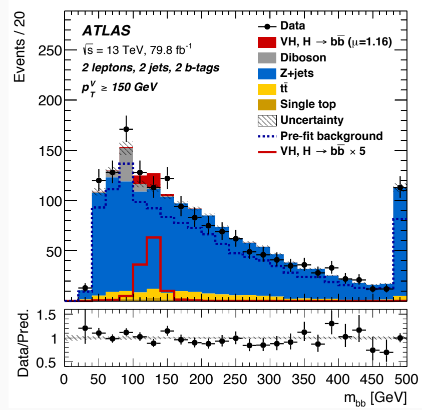
- 2 lepton: same final state as signal
- 0 and 1 leptons: additional jets and/or leptons, not reconstructed
- Powheg+Pythia

Multijet

- Very large cross-section and high rejection factors
- Negligible in 0- and 2-lepton
- Small and data-driven in 1-lepton



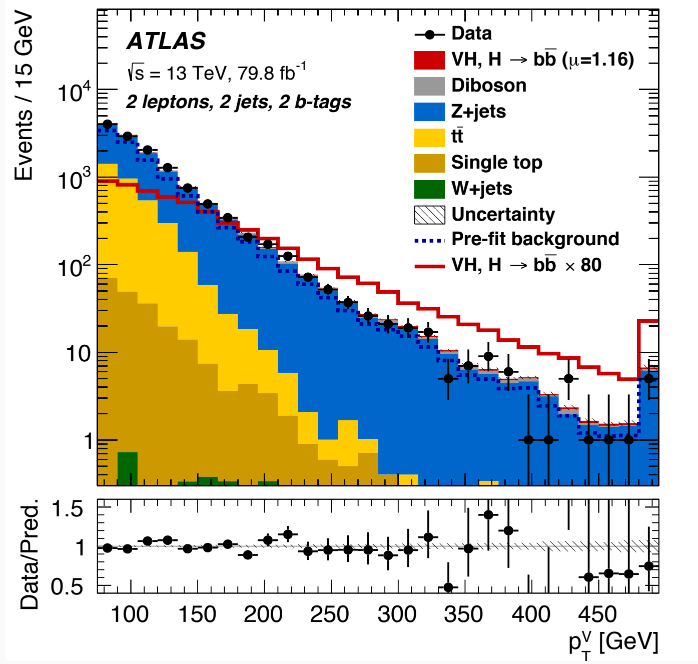




Consequences

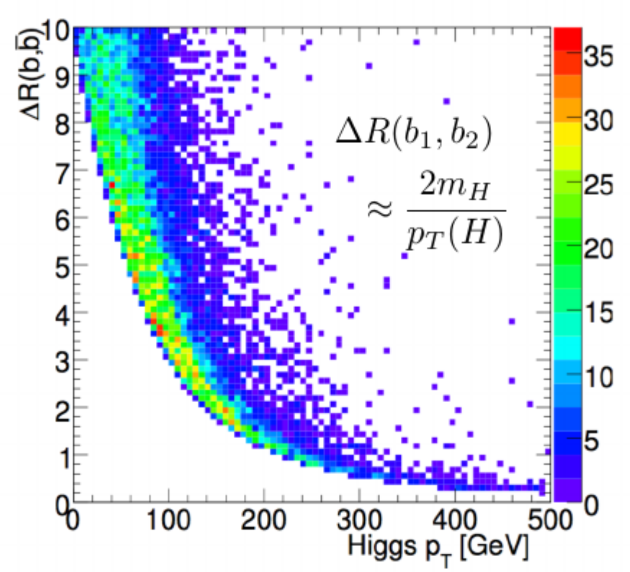
- Diboson process: validation of the analysis
- m_{bb}, $\Delta R(b, b)$ very powerful variables
- S/B depends on number of jets in the event

High-pT kinematics



Improving S/B

- Harder p_T^V spectrum for signal than bkgs
  - Going to high-p_T improves S/B
- Used for event classification: $75 < p_T^V < 150$ GeV, $p_T^V > 150$ GeV
- Added as input variable in MVA analysis
- Need large bkg MC statistics in tails of distributions !



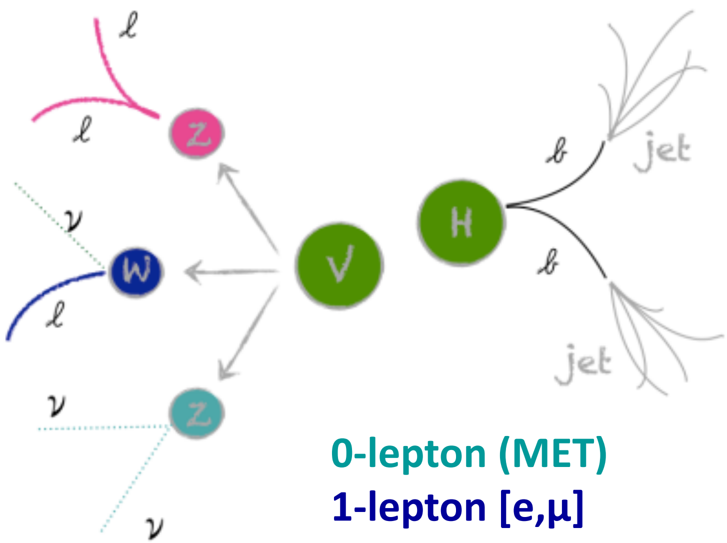
Topology

- $H \to b\bar{b}$ is a simple 2-body decay
- At high p_T, can cut hard on $\Delta R(b, b)$ with very high signal efficiency
- Helps reducing backgrounds significantly
  - Most prominently $t\bar{t}$

VH(bb): analysis strategy - 1

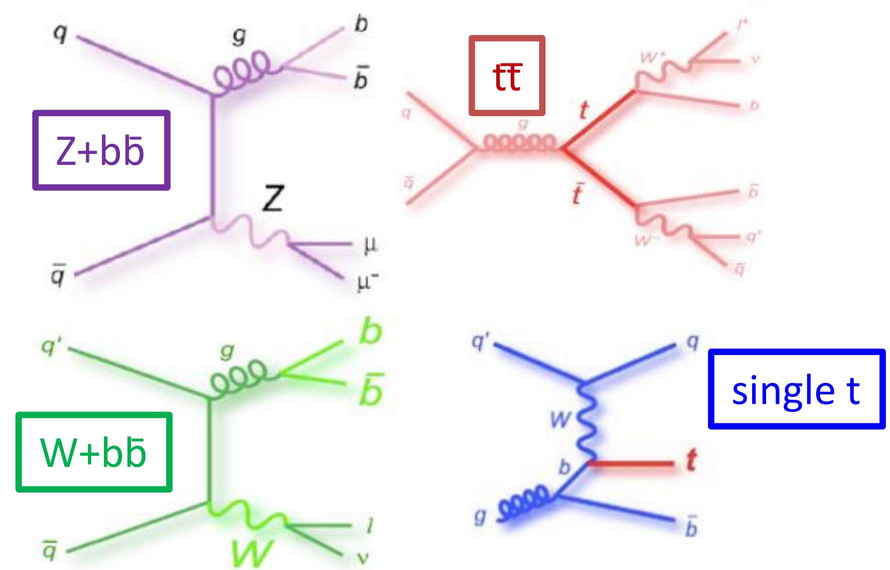
- **Analysis strategy:**
  - **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
    - To target Z(νν)H(bb), W(lν)H(bb)and Z(ll)H(bb) processes
  - **Signal region designed to increase S/B**
    - **Large boost** for vector boson
    - **Multivariate analysis** exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tag)
  - **Control regions** to validate backgrounds and control/constrain normalizations

signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds



normalization from data, shapes from MC

- **Analysis strategy:**
  - **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
    - To target Z(νν)H(bb), W(lν)H(bb)and Z(ll)H(bb) processes
  - **Signal region designed to increase S/B**
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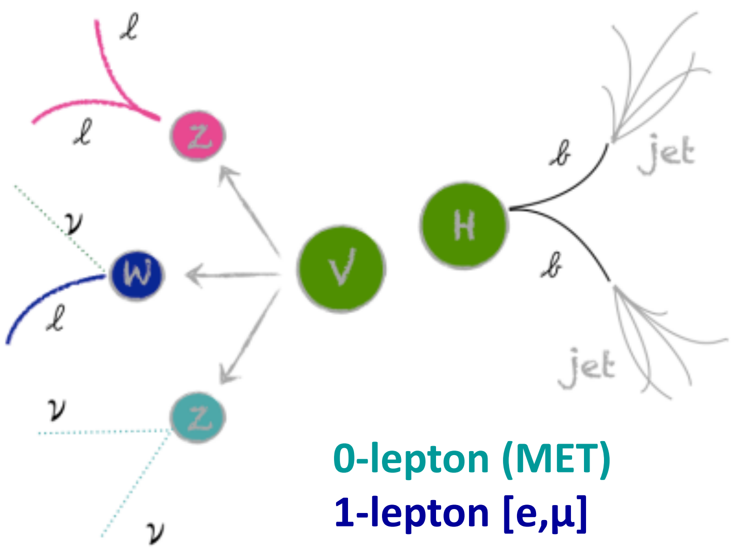
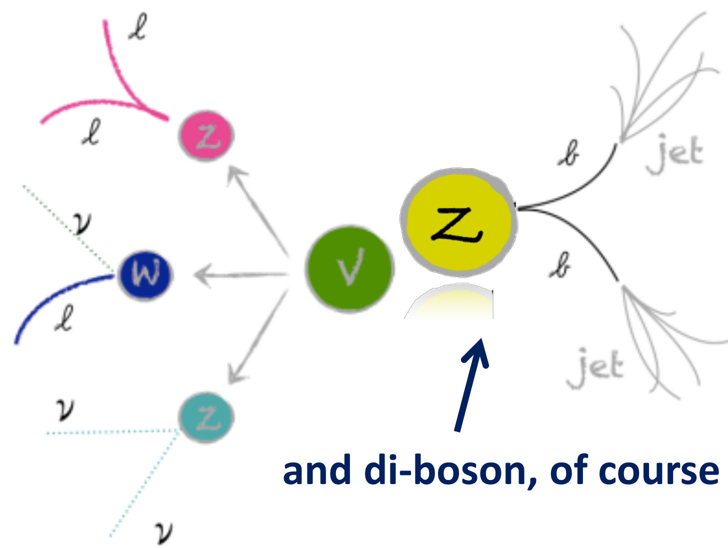
signal



0-lepton (MET)
1-lepton [e,μ]
2-leptons [ee,μμ]

irreducible backgrounds

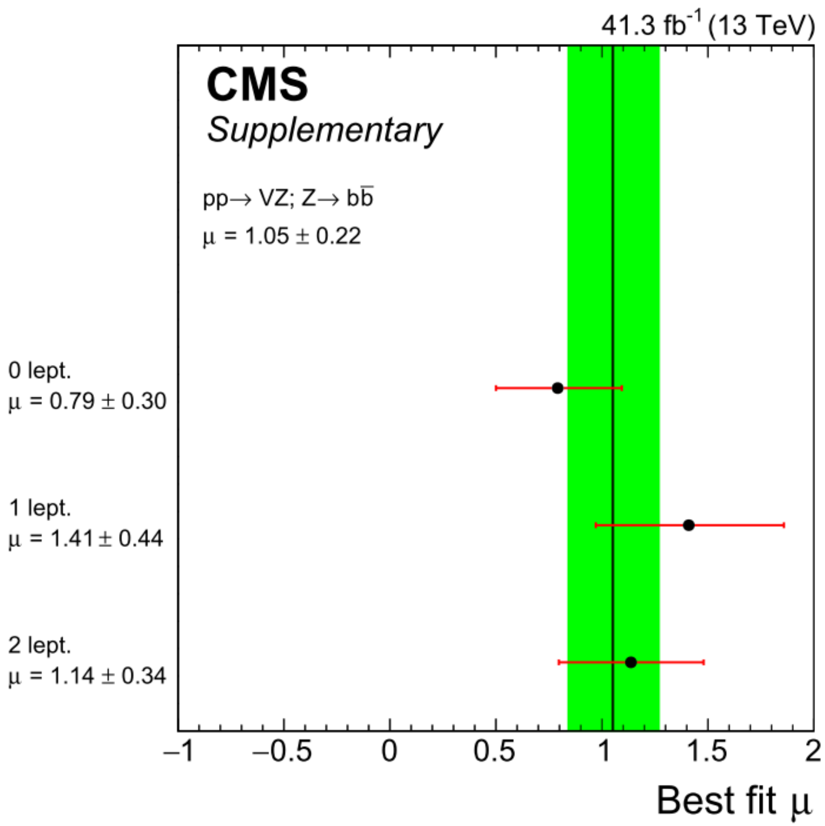


and di-boson, of course

used to validate the analysis strategy

Analysis validation: VZ(bb) @CMS

- **VZ analysis** using Z(bb) standard candle next to H(bb) peak
- **Same "technology" used for VH(bb) fit**
  - Same DNN inputs (but dedicated training), same Control Regions, VH(bb) normalized to SM and left free to float
  - Larger m(bb) window in Signal Region to fully include Z(bb) peak



<u>Significance</u>

5.0σ expected

5.2σ observed

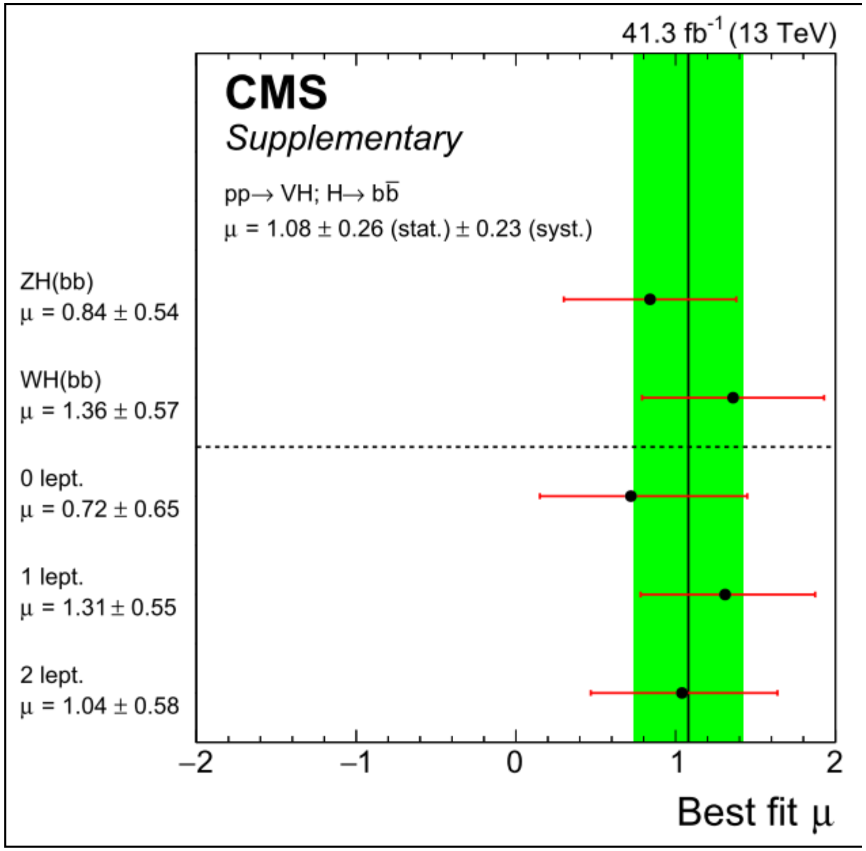
<u>Signal strength</u>

$\mu = 1.05 \pm 0.22$

VH(bb) results with 2017 data @CMS

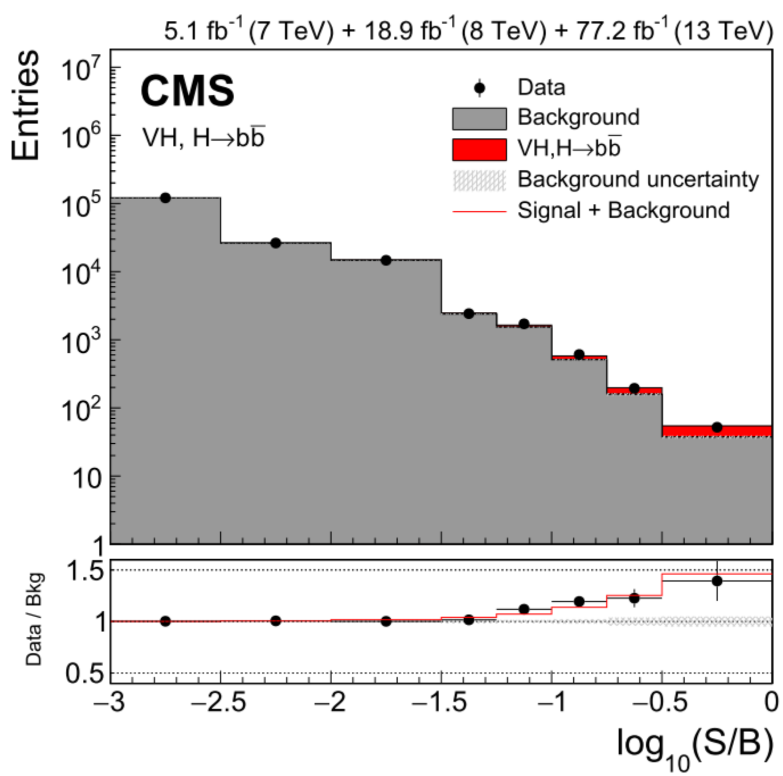
- **Results with 2017 data compatible with SM expectations**
  - **Observed significance 3.3σ, signal strength 1.08 ± 0.34**
  - O(5-10%) increase in analysis sensitivity wrt 2016, depending on channel
  - Remarkable channel compatibility

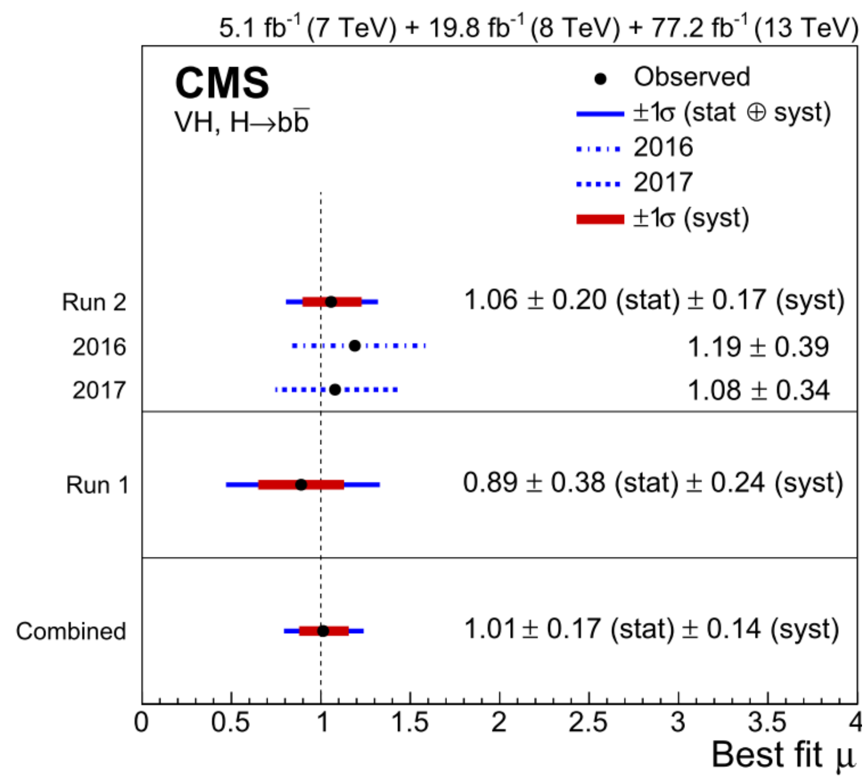
Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
2016	2.8	3.3	1.2 ± 0.4

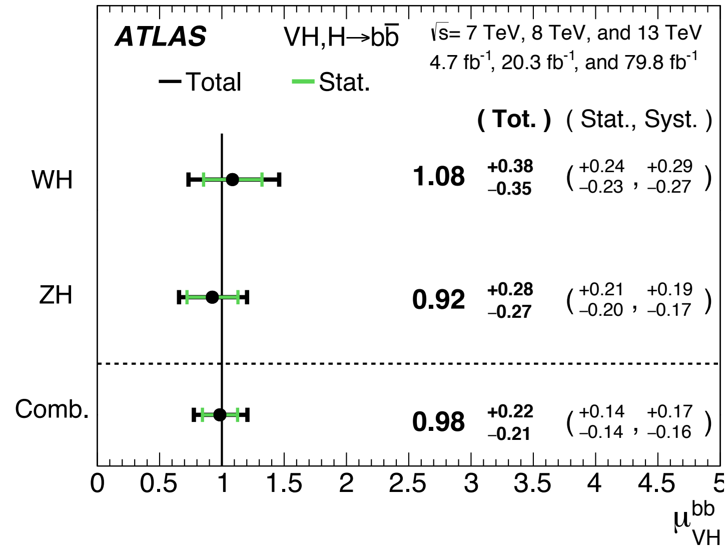


VH(bb): Run 1 + Run 2 combination @CMS

Data set	Significance (σ) Expected	Observed	Signal strength
2017	3.1	3.3	1.08 ± 0.34
Run 2 (2016+2017)	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23







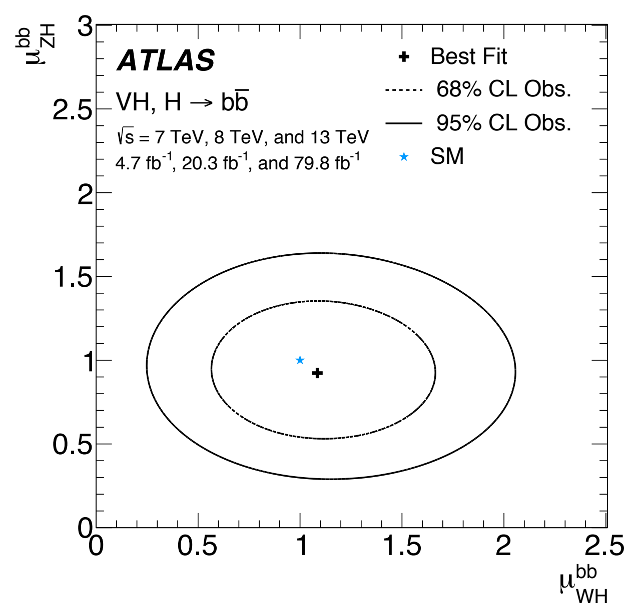
Combination

How to correlate systematic uncertainties ?

- Correlate *b*-jet energy scale uncertainty, and Higgs boson production cross-sections
- Test carefully that other correlations have little impact

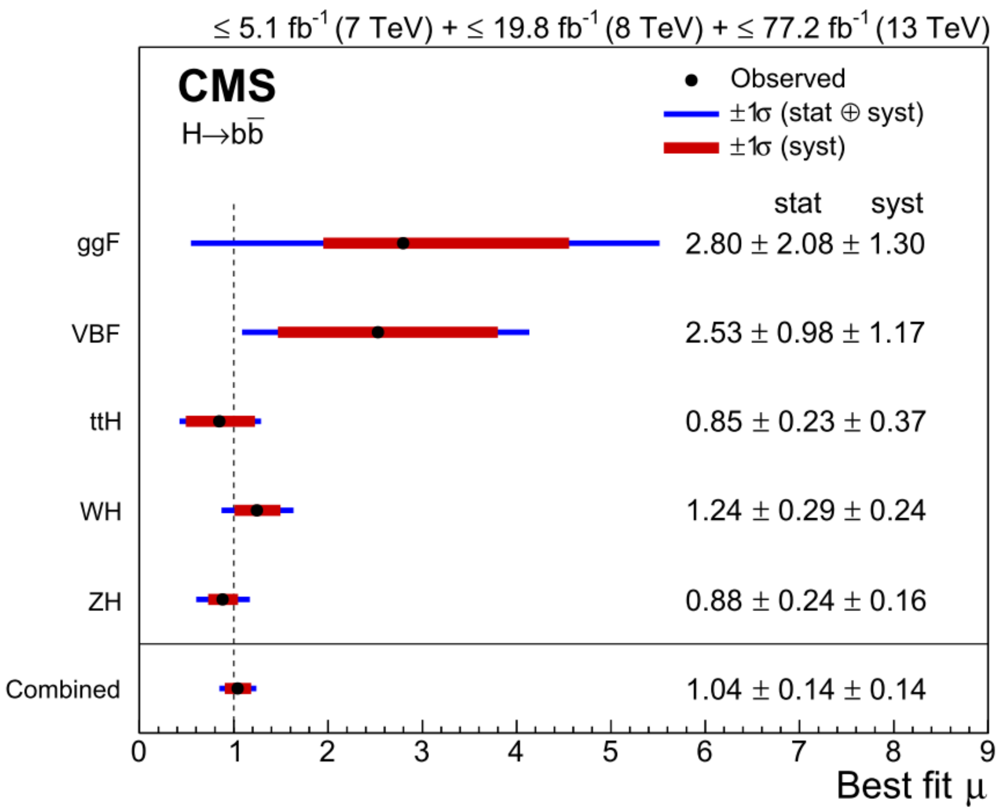
Results

- $VH(bb)$ signal at 4.9σ (5.1σ exp.)
- Signal strength compatible between *WH* and *ZH* modes at 72%



H(bb): production mode combination @CMS

- **Combination of CMS H→bb measurements : VH, boosted ggH, VBF, ttH**
- **Most sources of systematic uncertainty are treated as uncorrelated**
  - Theory uncertainties are correlated between all processes and data sets
- **Measured signal strength is μ = 1.04 ± 0.20**



<u>Significance</u>

5.5σ expected

5.6σ observed

Observation of the H→bb decay by the CMS Collaboration

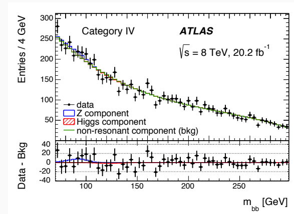
H(bb): production mode combination @ATLAS

$H \to b\bar{b}$ combination

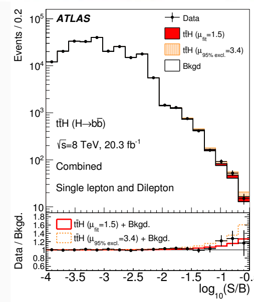
- Combine Run-1 and Run-2 analyses in VH, VBF, $t\bar{t}H$ production modes
  - 2015+2016 Run-2 data for VBF and $t\bar{t}H$
- Uncertainty model from previous Run-1 and Run-2 combinations
- Results assume SM Higgs boson production cross-sections

Results

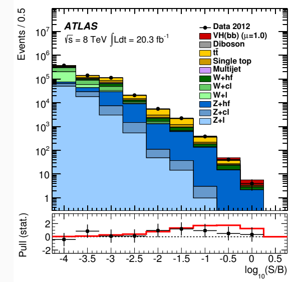
- Observation of $H \to b\bar{b}$ decays at 5.4σ (5.5σ exp.)
- $\mu_{H\to bb} = 1.01 \pm 0.20$
- Contributions of VBF and $t\bar{t}H$ channels 1.5σ and 1.9σ
- Compatibility of the 6 measurements 54%



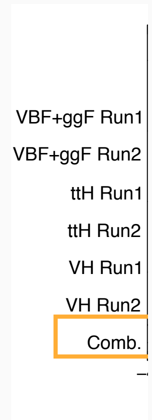
VBF Run-1



$t\bar{t}H$ Run-1



VH Run-1

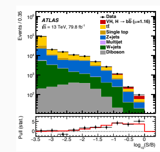


VH combination

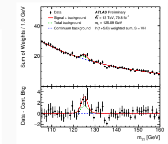
- Combine Run-2 analyses in $b\bar{b}$, $\gamma\gamma$ and 4ℓ decays
  - Updated analyses with 2015-2017 Run-2 data in all channels
- Results assume SM Higgs boson branching fractions

Results

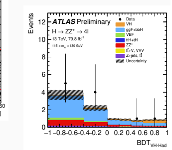
- Observation of VH production at 5.3σ (4.8σ exp.)
- $\mu_{VH} = 1.13 \pm 0.24$
- Contributions of 4ℓ and $\gamma\gamma$ channels 1.1σ and 1.9σ
- Compatibility of the 3 measurements 96%



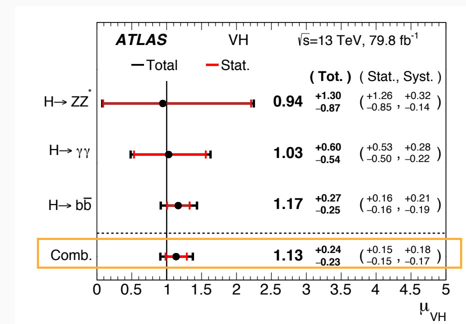
$H \to b\bar{b}$



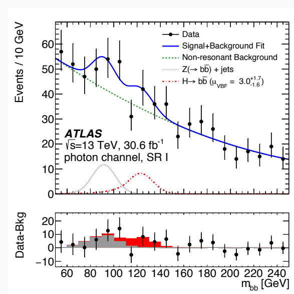
$H \to \gamma\gamma$

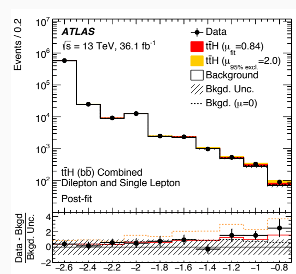


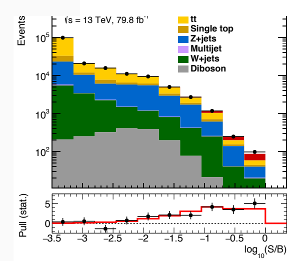
$H \to 4\ell$



VBF Run-2





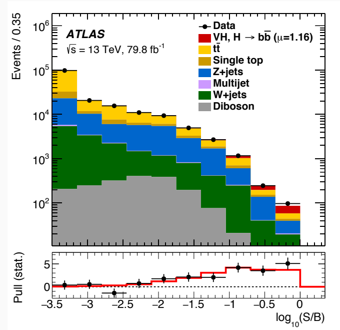


VH combination

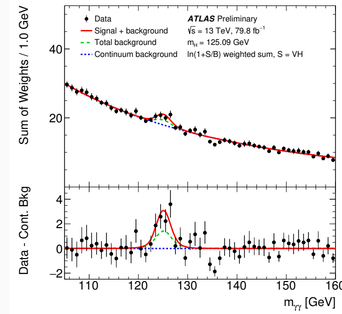
- Combine Run-2 analyses in $b\bar{b}$, $\gamma\gamma$ and 4ℓ decays
  - Updated analyses with 2015-2017 Run-2 data in all channels
- Results assume SM Higgs boson branching fractions

Results

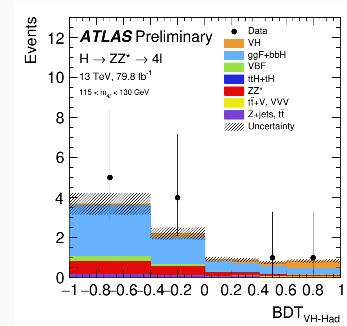
- Observation of *VH* production at 5.3σ (4.8σ exp.)
- $\mu_{VH} = 1.13 \pm 0.24$
- Contributions of 4ℓ and $\gamma\gamma$ channels 1.1σ and 1.9σ
- Compatibility of the 3 measurements 96%



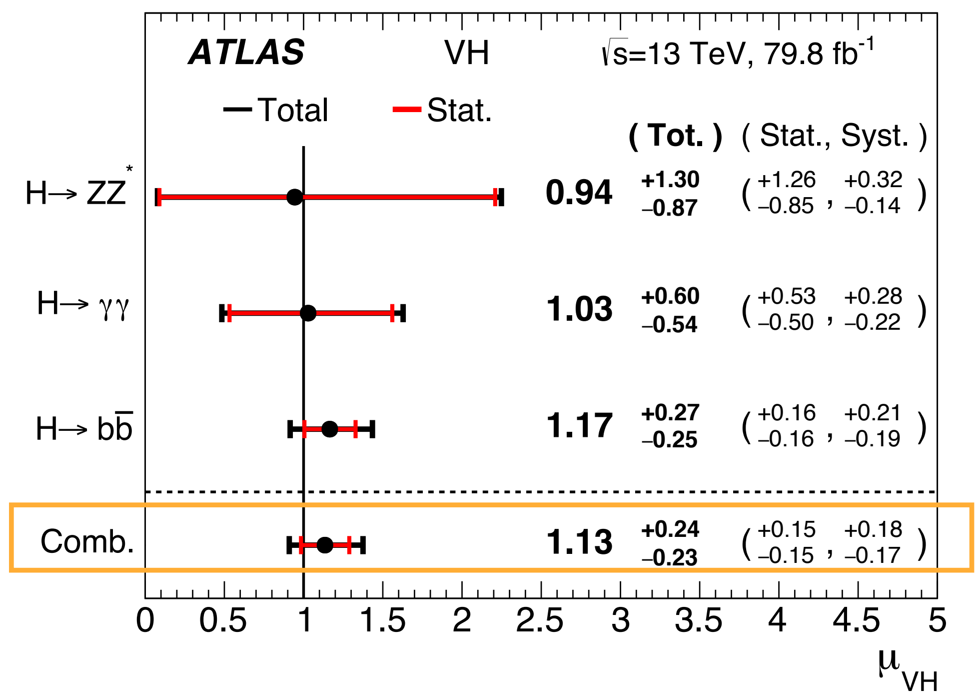
$H \rightarrow b\bar{b}$



$H \rightarrow \gamma\gamma$



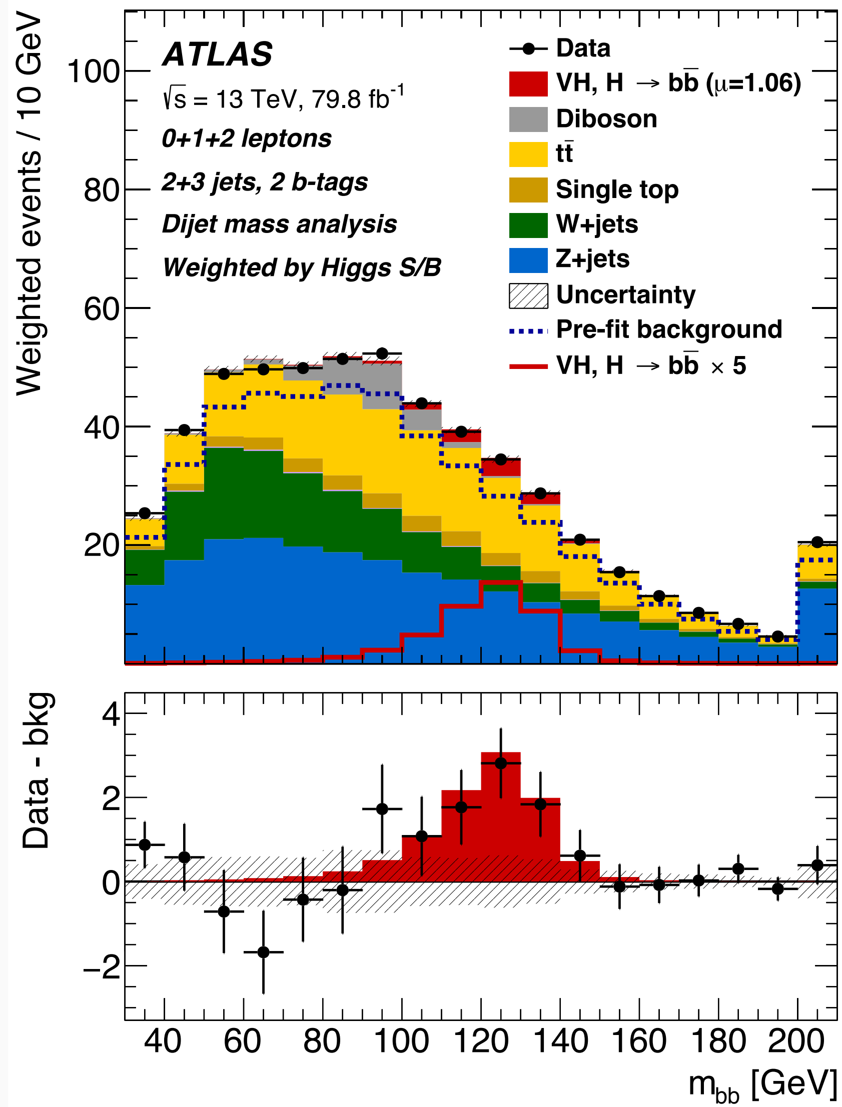
$H \rightarrow 4\ell$



Conclusions: ATLAS

- $VH(bb)$ analysis with 80fb^{-1} of Run-2 data
  - $\mu_{VH}^{bb} = 1.16 \pm 0.26$, with a significance of 4.9σ
  - Cross-checked with the measurement of the $VZ(bb)$ process, and a dijet-mass analysis
- Observation of $H \to b\bar{b}$ decays
  - $\mu_{H\to bb} = 1.01 \pm 0.20$
  - Observation at 5.4σ in combination with $t\bar{t}H$ and VBF production modes
  - 89% of the Higgs boson BR is now observed !
- Observation of VH production

  In combination with $\gamma\gamma$ and 4ℓ analyses
  - $\mu_{VH} = 1.13 \pm 0.24$
  - VH production observed at 5.3σ
  - All main production modes now observed !
- Results submitted to PLB: arXiv:1808.08238
  - Unchanged since their first presentation at ICHEP
  - Additional material: `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2018-04/`

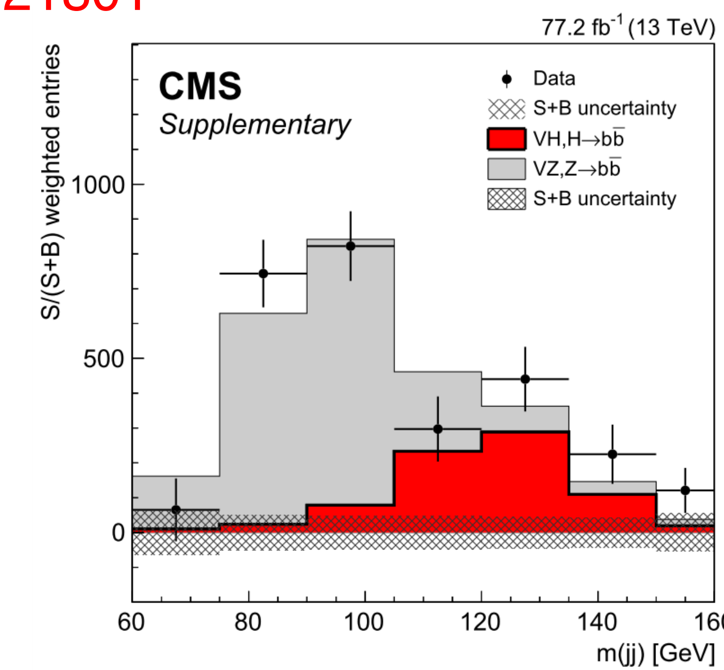


Conclusions: CMS

- **CMS has reached a 5.6σ observation of the H→bb decay, with signal strength μ = 1.04 ± 0.20**
  - Combination of several production channels, dominated by VH(bb)
  - Result contained in **arXiv:1808.08242** and **provisionally accepted for publication in PRL**
    - Thank you to PRL and its referees for their impressive turn-around in reviewing the paper!

Published 17 Sep 2018 in PRL 121 (2018) 121801

- **Standard Model** assumption on **Yukawa coupling to b's confirmed** within the present uncertainty



- This result is the **culmination of H→bb searches** that started at LEP, continued at Tevatron and at the LHC

- Achievement possible only thanks to the **fantastic run of the LHC, and the CMS detector performance**
  - But is only a step towards the ultimate H→bb precision at LHC

Backup Slides

H(bb) systematic uncertainties: impact on measurement @ATLAS

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Analysis dominated by systematic uncertainties

Measured by impact on signal strength (μ)

Many important sources !

b-tagging both b and c jet tagging calibration

- Resp. ∼3% and ∼10% per jet

Background modelling Z+hf, W+hf, $t\bar{t}$

- Mainly shape and extrapolation uncertainties

Signal modelling little impact on significance

- Dominated by systematic uncertainties on the acceptance

MC stats never-ending race between data stat and MC stat

- Use of dedicated MC filters
- Not easy in all cases, e.g $t\bar{t}$ phase space in 0/1-lepton