Measurement of cross sections and couplings of the Higgs boson in fermionic production and decay modes with the ATLAS detector

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on behalf of the ATLAS collaboration

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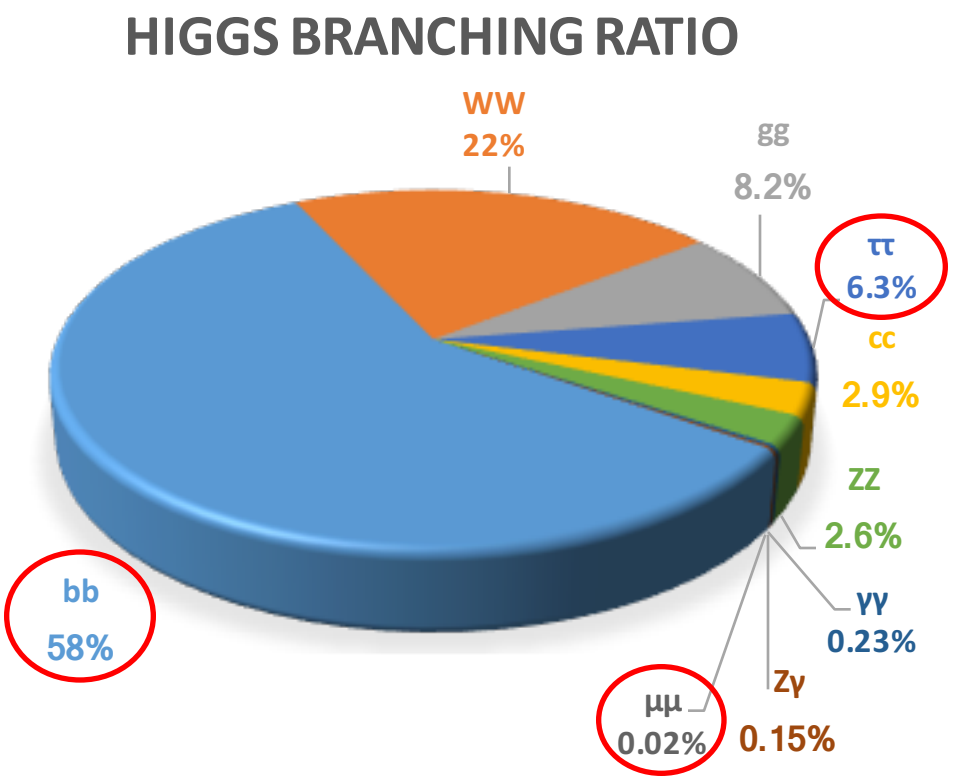
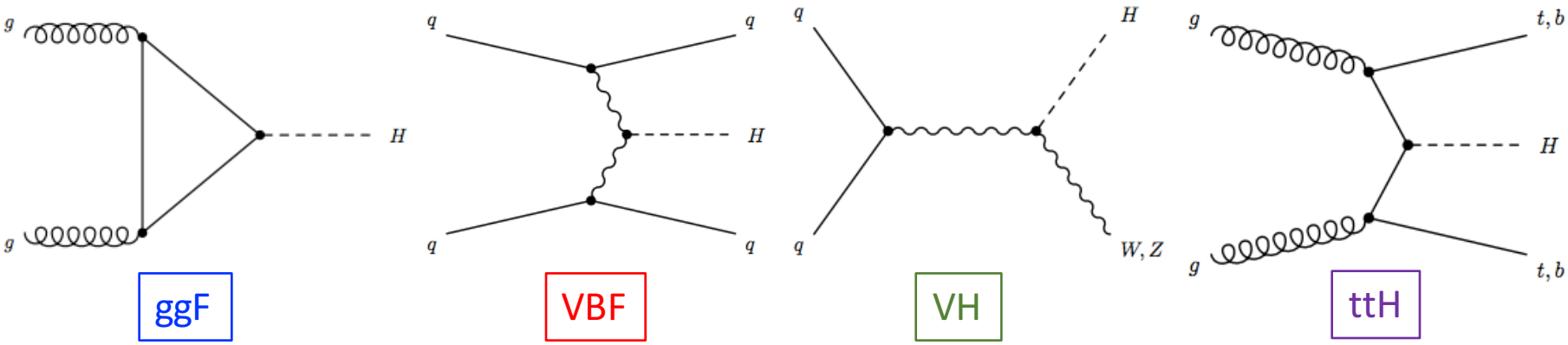
Higgs decay modes

- **The Higgs boson was first discovered in bosonic decay channels.**
- **Studying the coupling in fermionic channels is challenging but essential:**
  - Direct measurement of Yukawa couplings.
  - Test mass-coupling relation predicted by Standard Model.
  - Any deviation might be hint for new physics.

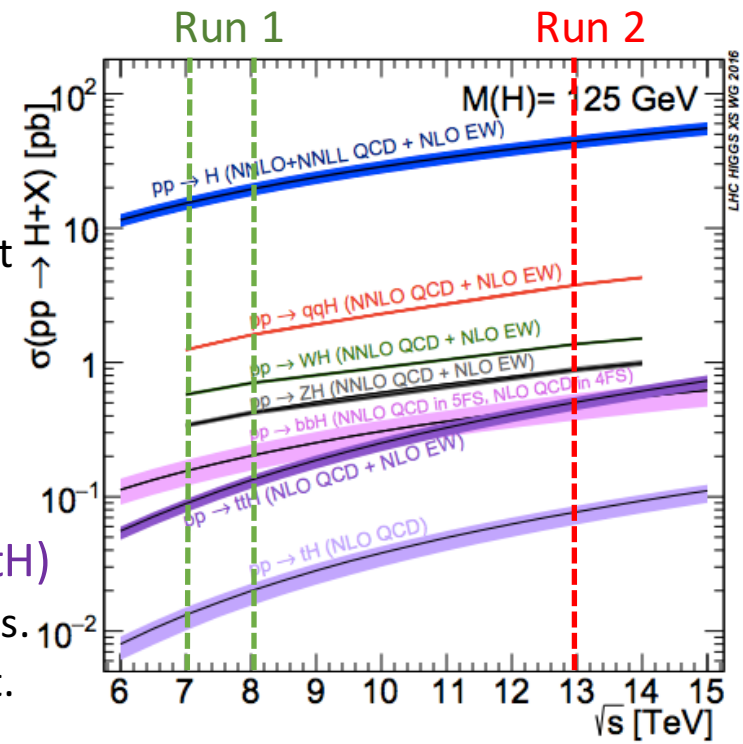
- **This talk will focus on the following fermionic decay channels:**
  - H→bb
  - H→ττ
  - H→μμ



Higgs production modes



- Gluon fusion (ggF)
  - Largest production rate.
- Vector boson fusion (VBF)
  - 2 VBF jets, low hadronic activities in between (except the region where the Higgs decays).
- Associated production with a vector boson (VH)
  - Leptonic decays from W/Z helps in triggering and background suppression.
- Associated production with a pair of top quarks (ttH)
  - Unique channel to study Higgs coupling to top quarks.
  - ➢See Asma Hadef's talk on ttH coupling measurement.



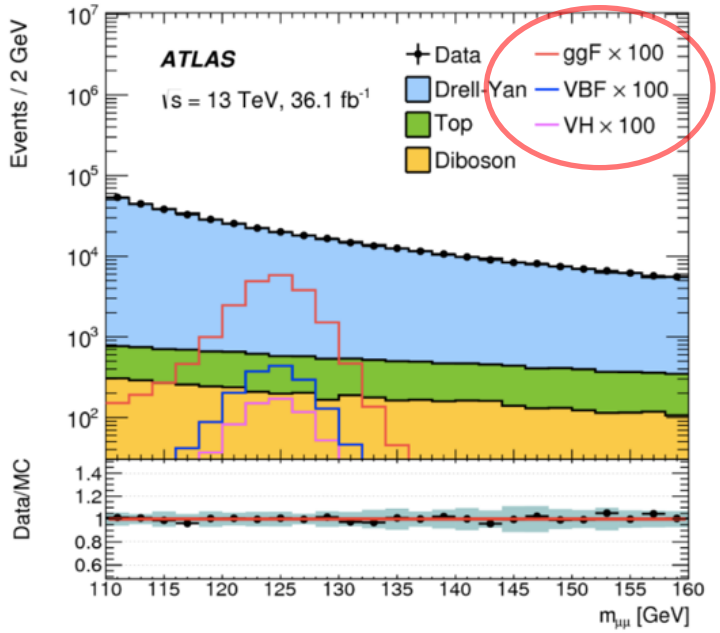
H→Leptons – latest public results

Decay Channels	Dataset		
	7 TeV	8 TeV	13 TeV
H→ττ [JHEP 04 (2015) 117] https://arxiv.org/abs/1501.04943	4.5 fb^{-1}	20.3 fb^{-1}	
H→ττ [PRD 93, 092005 (2016)] https://arxiv.org/abs/1511.08352		20.3 fb^{-1}	
H→μμ [PRL 119 (2017) 051802] https://arxiv.org/abs/1705.04582			36.1 fb^{-1}

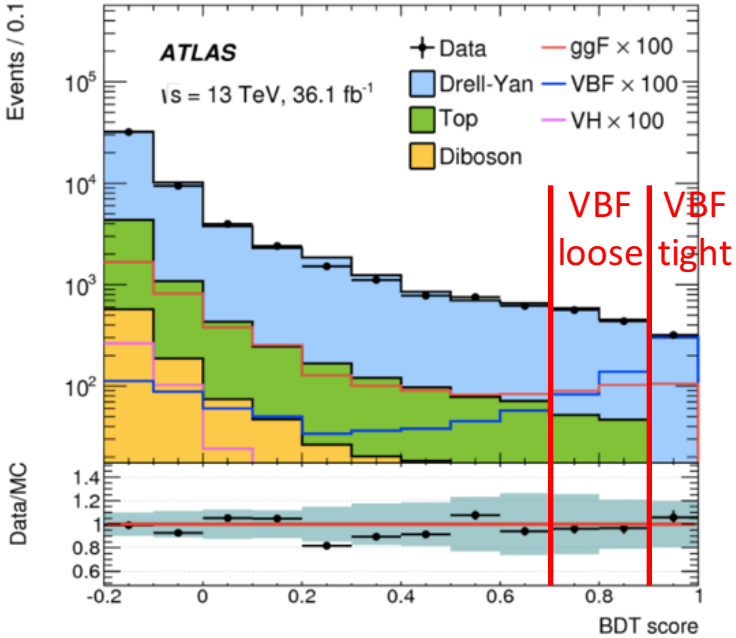
H→μμ

36.1 fb^{-1}, 13 TeV

- Clean signature but very low S/B ratio.
- Use a boost decision tree (BDT) to categorize events and select VBF like events.
- Signal extracted by fitting the $m_{\mu\mu}$ spectra in all categories simultaneously.



$m_{\mu\mu}$ in inclusive signal region



- Event categorization (8 categories):
  - njet≥2, high BDT score events:
    - VBF tight, VBF loose.
  - Remaining events enter ggF categories.
  - Split based on $p_T^{\mu\mu}$ and η_μ:
    - Low, medium and high $p_T^{\mu\mu}$ categories.
    - Central, non-central categories.

PRL 119 (2017) 051802

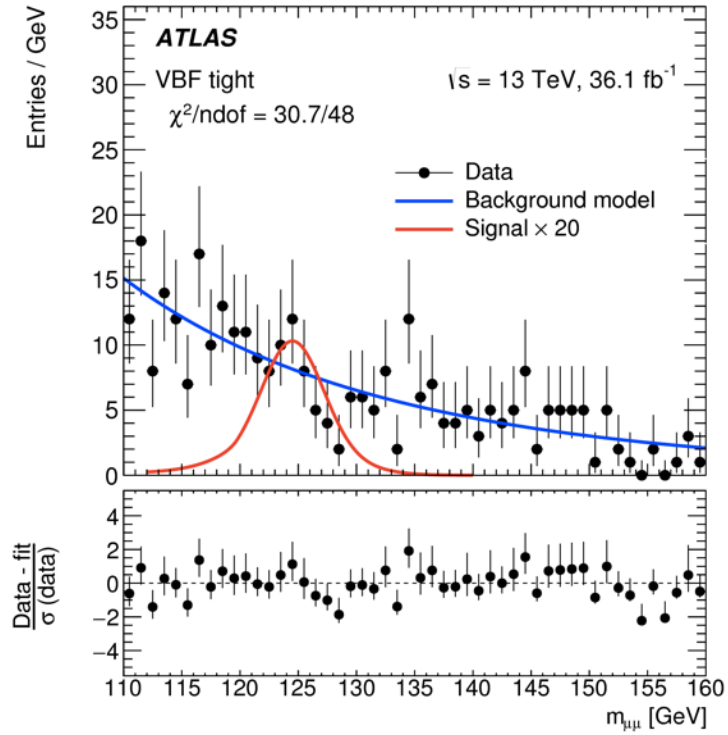
H→μμ – Results

36.1 fb^{-1}, 13 TeV

- No significant excess observed in data.
  - Analysis limited by data statistics.

- **Run 2 results:**
  - Observed upper limit: 3.0 x SM.
  - Expected upper limit: 3.1 x SM.
  - Signal strength μ=-0.1±1.5.

- **Combined with Run 1 (7 and 8 TeV data):**
  - Observed upper limit: 2.8 x SM.
  - Expected upper limit: 2.9 x SM.
  - Signal strength μ=-0.1±1.4.



$m_{\mu\mu}$ in VBF tight category

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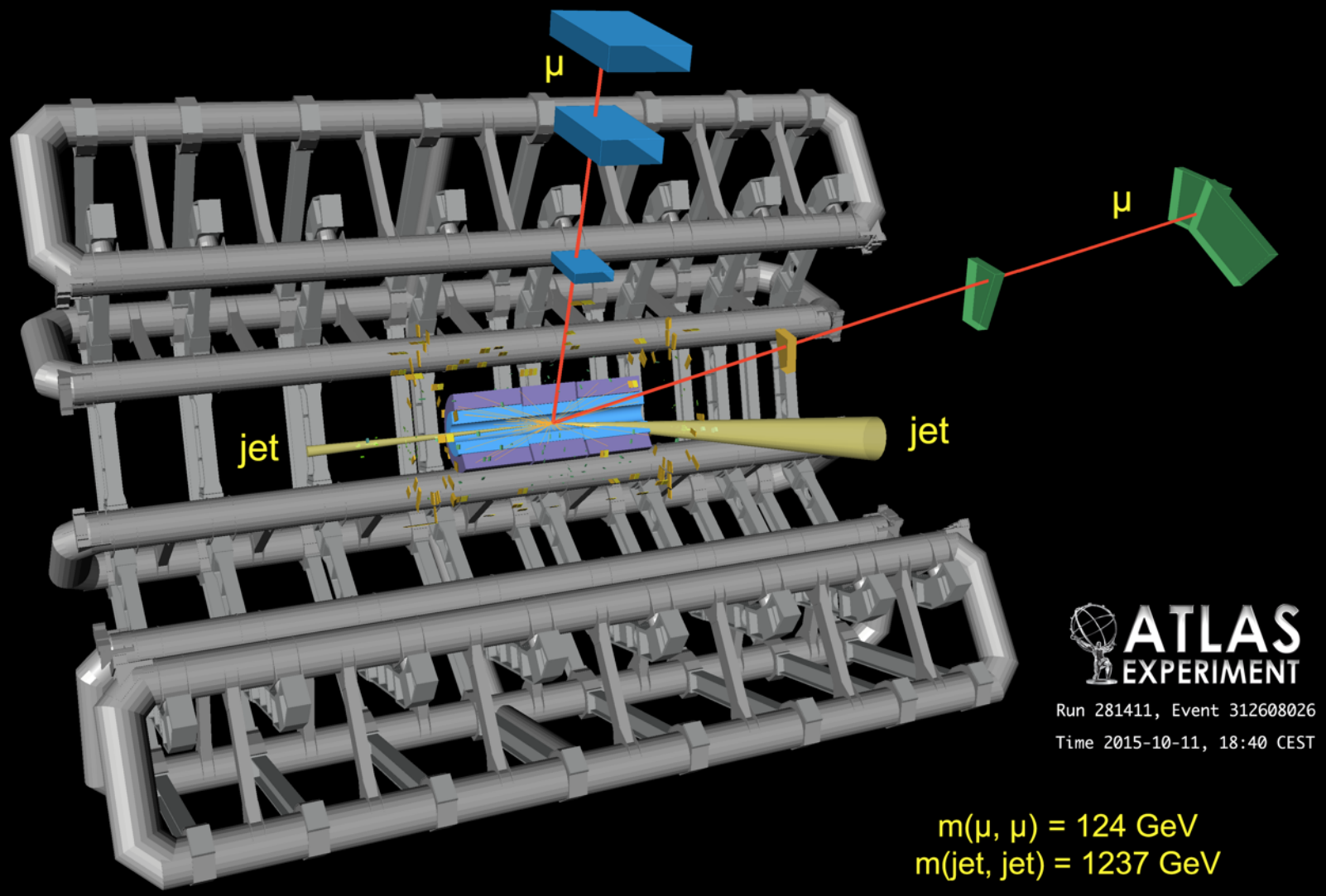
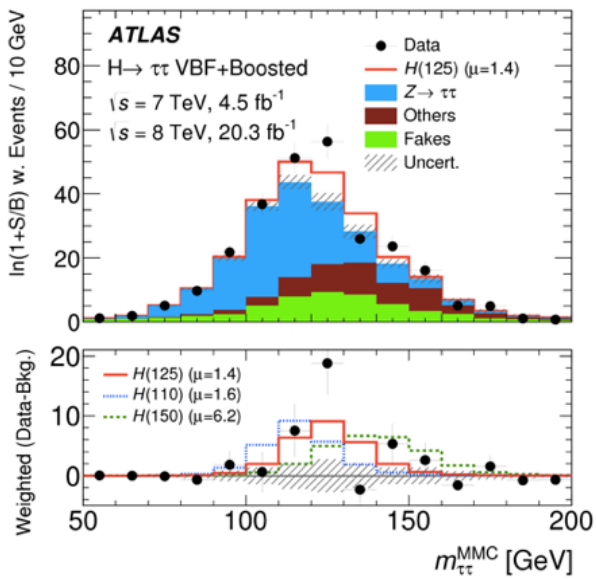
VBF H→μμ candidate recorded in 2015



H→ττ

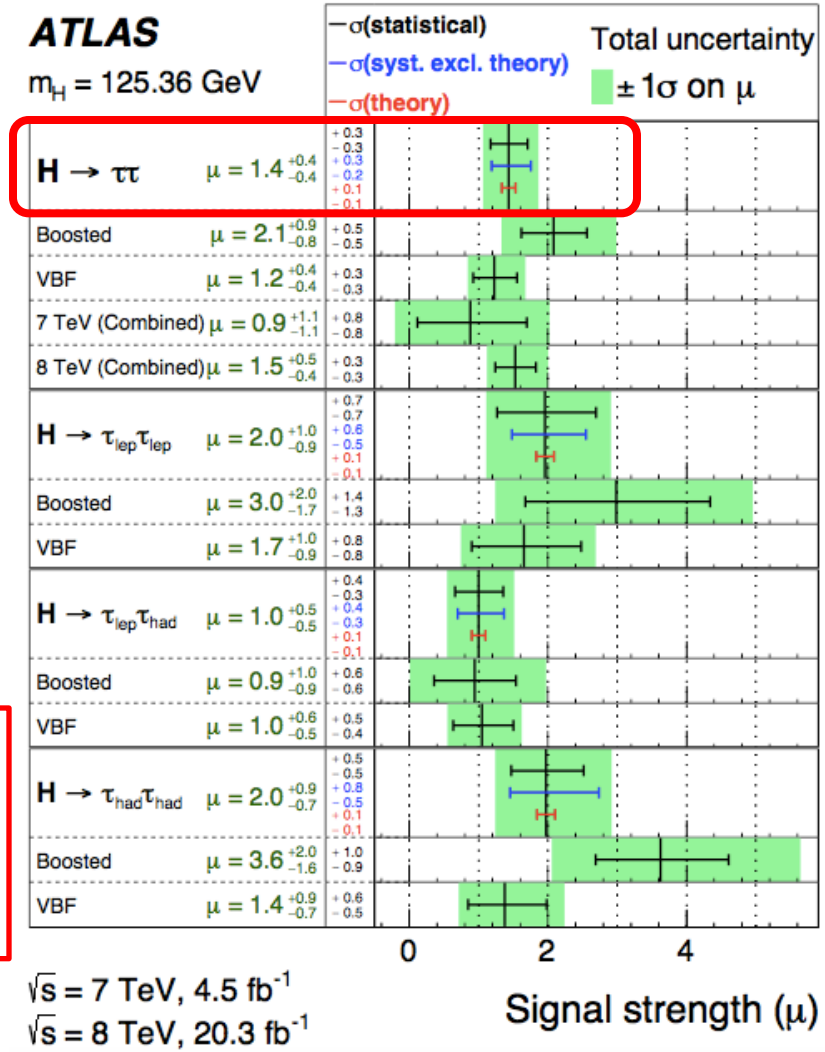
4.5 fb^{-1}, 7 TeV + 20.3 fb^{-1}, 8 TeV

- 3 channels, based on τ decays.
  - $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$.
- 2 categories: VBF and boosted.
  - Targeting VBF, ggF+j events.
  - VH events are also considered as signal.
- Di-tau invariant mass reconstructed using Missing Mass Calculator (MMC) method.
- BDT output as final discriminant to extract signal.



JHEP 04 (2015) 117

Significance:
Observed: **4.5σ**
Expected: 3.4σ
Evidence for H→ττ



Combination with CMS Run 1 data:
5.5σ observed (exp. 5.0σ) JHEP 08 (2016) 045

H→ττ

- Evidence for Higgs Yukawa coupling to τ.
- Overall signal strength:

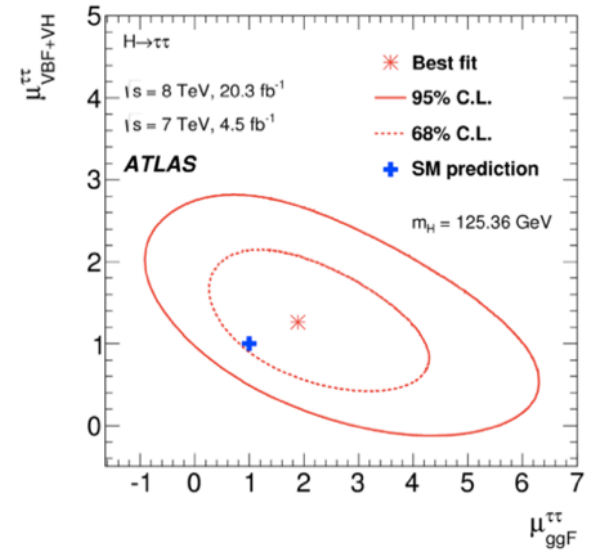
$$\mu = 1.43\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.32}_{-0.25}(\text{syst.})\ \pm 0.09(\text{theory syst.})$$

- Signal strengths of different production processes (**ggF** and **VBF+VH**) are determined:

$$\mu^{\tau\tau}_{ggF} = 2.0\ \pm 0.8(\text{stat.})\ ^{+1.2}_{-0.8}(\text{syst.})\ \pm 0.3(\text{theory syst.})$$

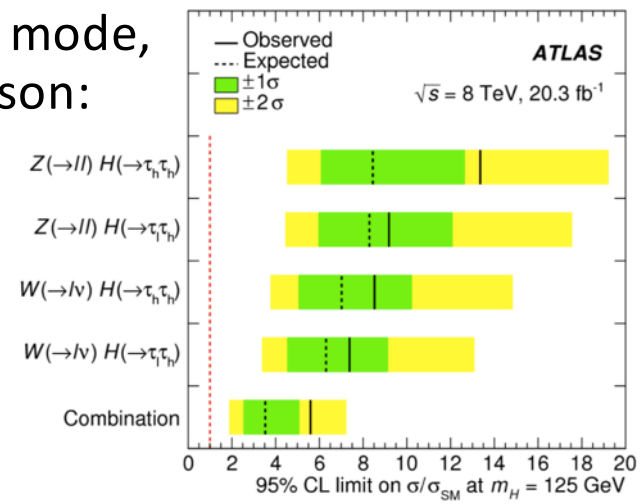
$$\mu^{\tau\tau}_{\text{VBF}+VH} = 1.24\ ^{+0.49}_{-0.45}(\text{stat.})\ ^{+0.31}_{-0.29}(\text{syst.})\ \pm 0.08(\text{theory syst.})$$

JHEP 04 (2015) 117



- A similar analysis targeting the **VH** production mode, exploiting the leptonic decays of the vector boson:
  - Signal extracted by fitting reconstructed Higgs candidate mass distributions.
  - Data agree with the background expectation
  - Upper limit: 5.6 x SM (exp. 3.5 x SM)
  - Signal strength μ=2.3±1.6

PRD 93, 092005 (2016)



H→bb – latest public results

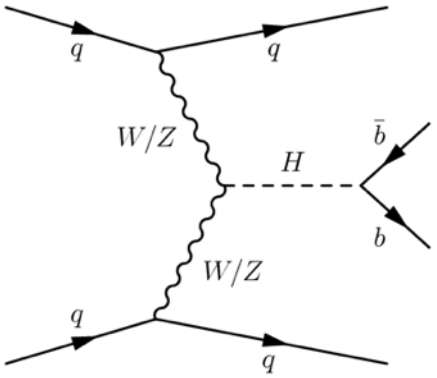
Production Modes	Dataset	
	8 TeV	13 TeV
ggH, H→bb	Overwhelming multi-jet background	
VBF H, H→bb [JHEP 11 (2016) 112] https://arxiv.org/abs/1606.02181	20.2 fb^{-1}	
VBF H+γ, H→bb [ATLAS-CONF-2016-063] https://cds.cern.ch/record/2206201		12.6 fb^{-1}
VH, H→bb [arXiv:1708.03299] (submitted to JHEP) https://arxiv.org/abs/1708.03299		36.1 fb^{-1}
ttH, H→bb [ATLAS-CONF-2016-080] https://cds.cern.ch/record/2206255		13.2 fb^{-1}

See Asma Hadef's talk:
ttH Coupling Measurement with the ATLAS Detector at the LHC

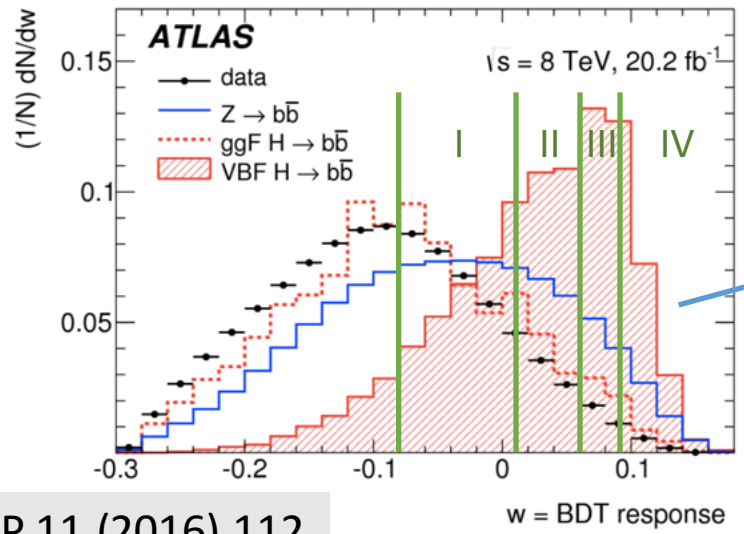
VBF H, H→bb

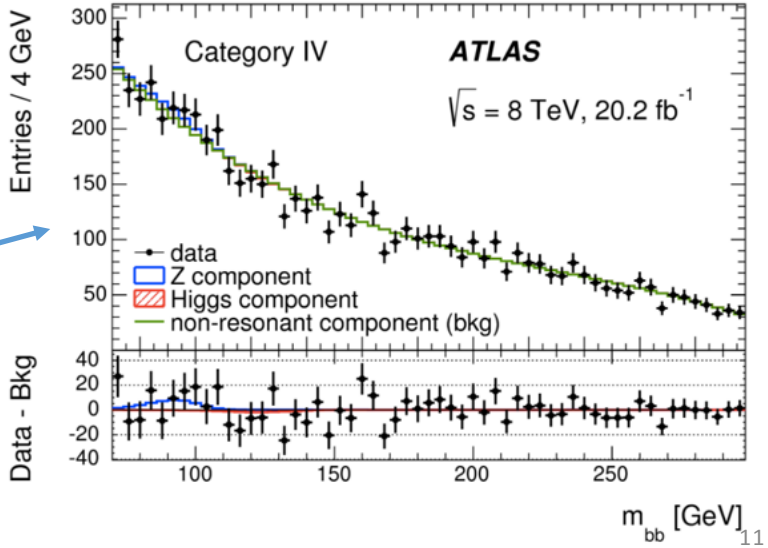
20.2 fb^{-1}, 8 TeV

- Search for H->bb in VBF production mode.
- Event topology:
  - Two central b-jets from Higgs decay.
  - Two forward VBF jets close to the beam line.
- BDT to separate signal from multi-jet background using VBF topology, categorize events into 4 signal categories.
- Final discriminant: invariant mass of the signal b-jets from Higgs decay m_{bb}.
- Limited by statistics in data sideband used to determine the background.



95% C.L. upper limit:
Observed 4.4 x SM
Expected 5.4 x SM



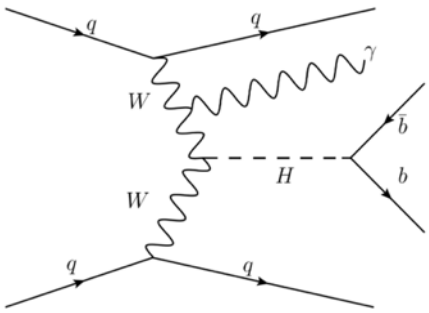


JHEP 11 (2016) 112

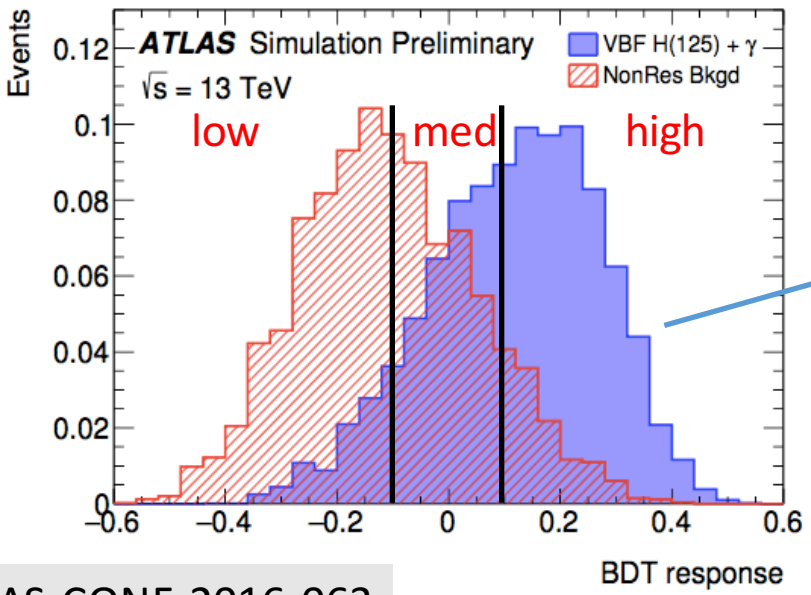
VBF H+γ, H→bb

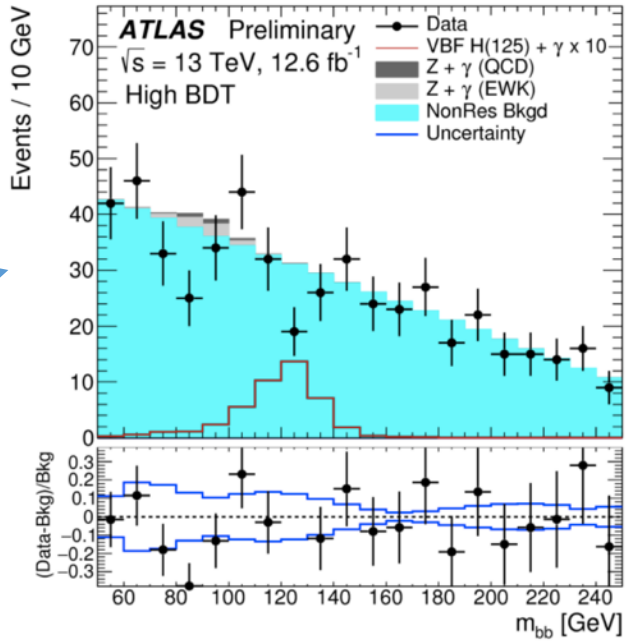
12.6 fb^{-1}, 13 TeV

- ❑Search for VBF H->bb with an additional photon:
  - ✓Extra handler for triggering.
  - ✓Suppression of multi-jet background.
- ❑Dedicated VBF+γ trigger to access low m_{bb} sideband.
- ❑BDT to separate signal from multi-jet background.
  - ❑Fit m_{bb} in 3 BDT regions.
- ❑Only a subset of 2015+16 data are used.
  - ❑Limited by data statistics.
  - ❑We are updating the analysis with full dataset.



95% C.L. Upper limit:
Observed: 4.0 x SM
Expected: 6.0 x SM



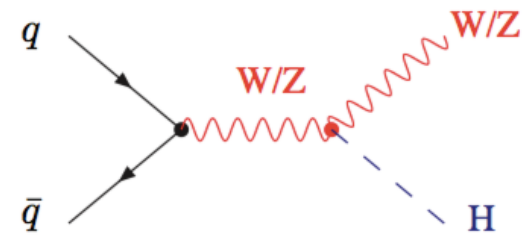


ATLAS-CONF-2016-063

VH, H→bb

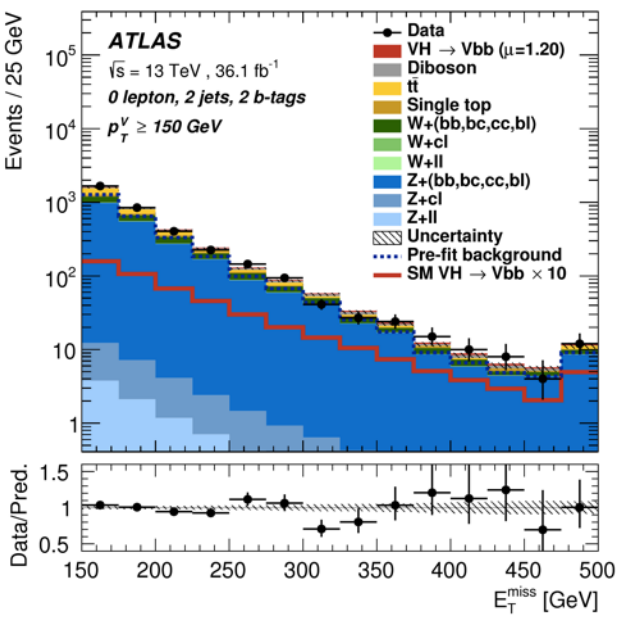
36.1 fb^{-1}, 13 TeV

- Most sensitive production mode for H->bb.
- Explore 3 channels, denoted by number of charged leptons.



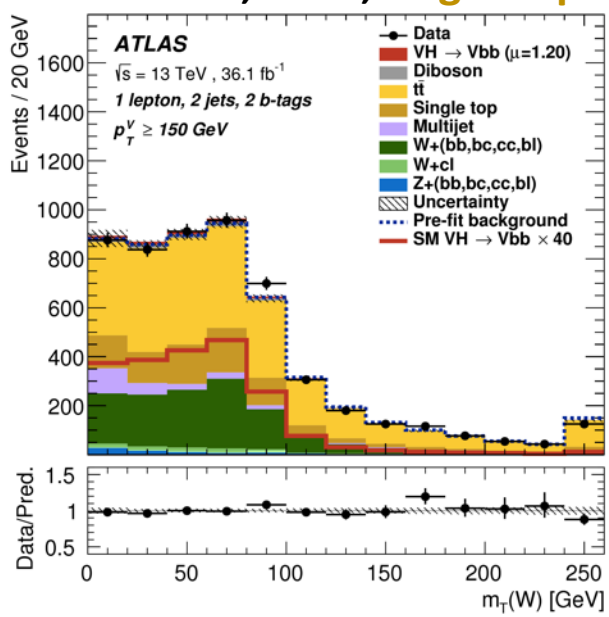
0-lepton ZH→ννbb

Z+hf, W+hf, ttbar



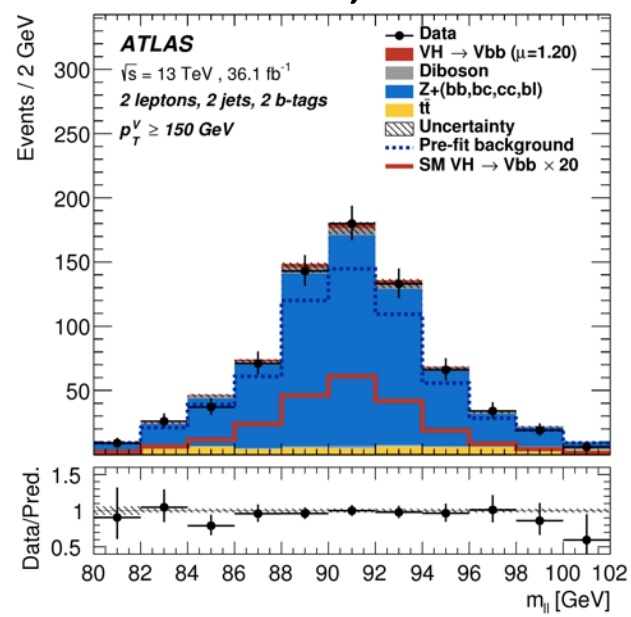
1-lepton WH→lνbb

W+hf, ttbar, single-top



2-lepton ZH→llbb

Z+hf, ttbar



arXiv:1708.03299

36.1 fb^{-1}, 13 TeV

VH, H→bb – Analysis strategy

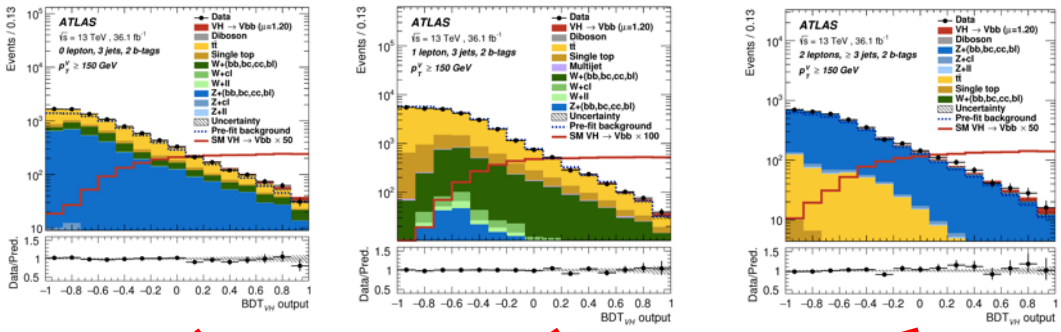
- Search for H→bb in 0/1/2-lepton channels:
  - Exactly 2 or 3 jets (≥3 jets for 2-lepton channel)
  - Exactly 2 b-tagged.
  - Focus on events with high vector boson transverse momentum (p_T^V).
- Events further categorized according to p_T^V and jet multiplicity:
  - 8 signal regions and 6 control regions.
- BDT as discriminant in signal regions
  - Dedicated BDT in each signal region.
- m_{bb} or yield as discriminant in control regions.

Channel	SR/CR	Categories			
		75 GeV < p_T^V < 150 GeV		p_T^V > 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

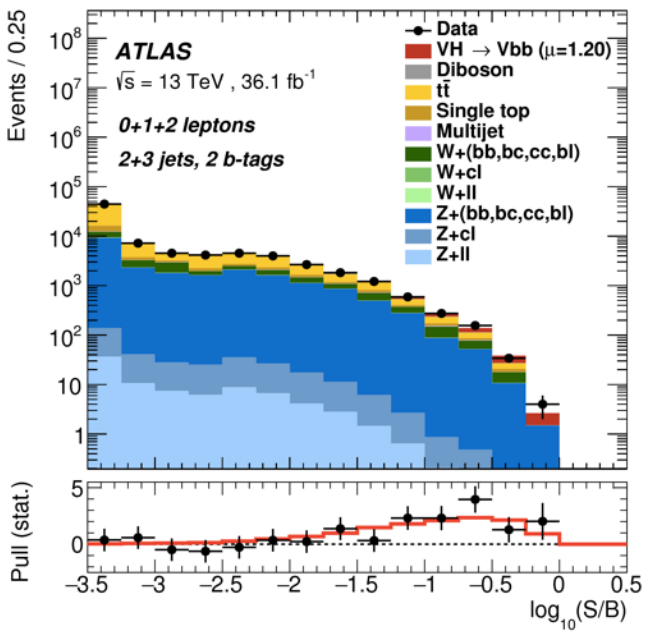
arXiv:1708.03299

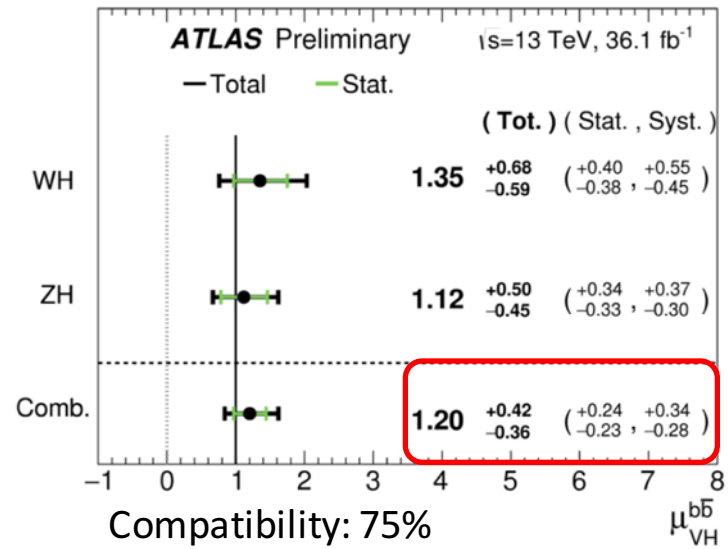
36.1 fb-1, 13 TeV

VH, H→bb – Run 2 results (BDT analysis)



BDT$_{VH}$





Compatibility: 75%

Significance:

Observed **3.5σ**

Expected 3.0σ

Evidence of H->bb

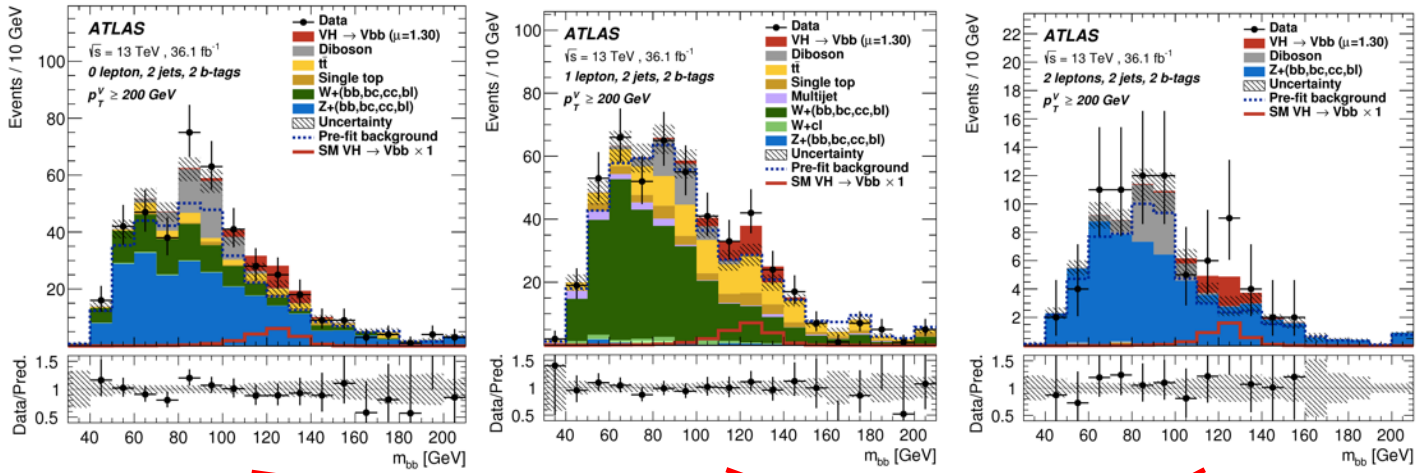
- Compatibility:
  - 3 lepton channels: 10%
  - WH vs ZH: 75%
- Dominant uncertainties:
  - Signal modeling
  - Monte Carlo statistics
  - b-tagging uncertainties

arXiv:1708.03299

VH, H→bb – dijet mass analysis

36.1 fb^{-1}, 13 TeV

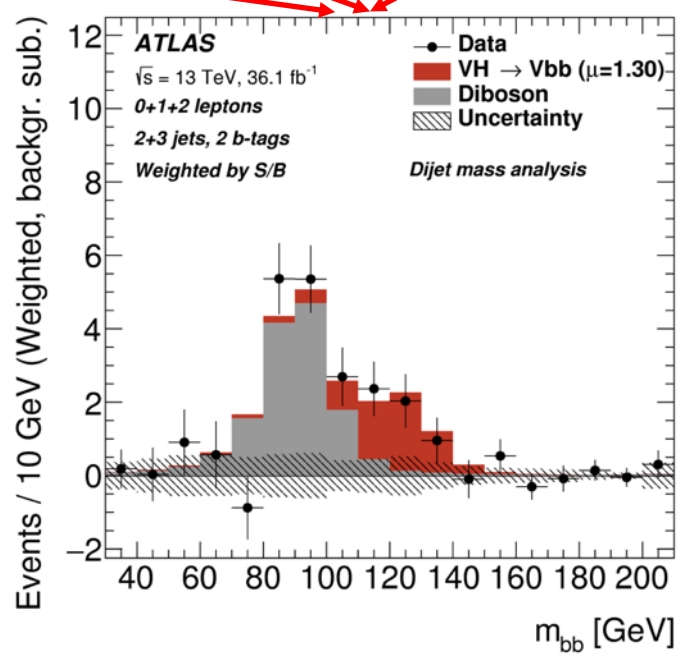
- Use m_{bb} as discriminant with additional cuts.



- Right plot: Dijet mass after subtracting all backgrounds except diboson.
- Clear excess of data on the right of Z→bb peak:
  - Observed significance 3.5σ.
  - Expected significance 2.8σ.

$$\mu = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst})$$

- An important validation of VH BDT analysis.

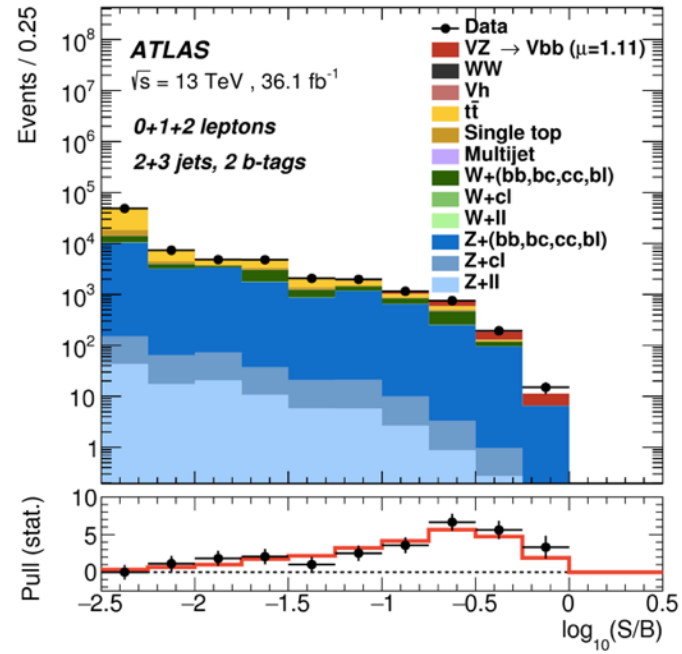


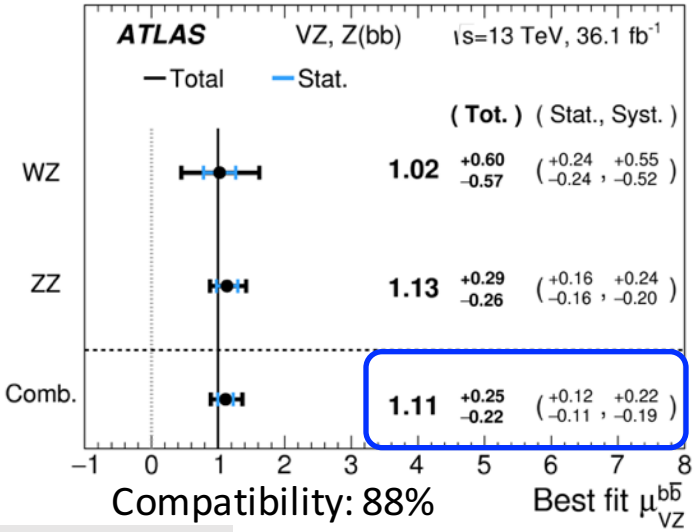
arXiv:1708.03299

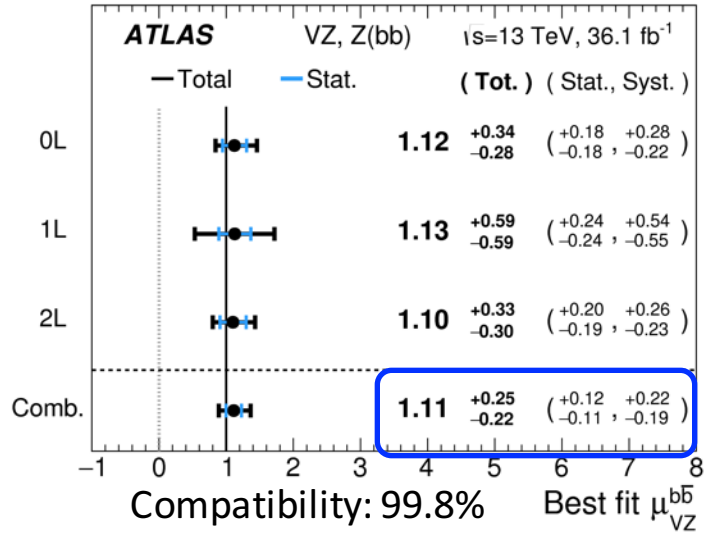
VZ, Z→bb validation

36.1 fb^{-1}, 13 TeV

- Diboson analysis targeting **VZ(bb)**, which has a signature very similar to VH(bb).
  - Validate the modeling of background and the associated uncertainties in the VH(bb) BDT analysis.
- **5.8σ** observation of **VZ, Z->bb**.
- 5.3σ expected.
- In good agreement with SM expectation.

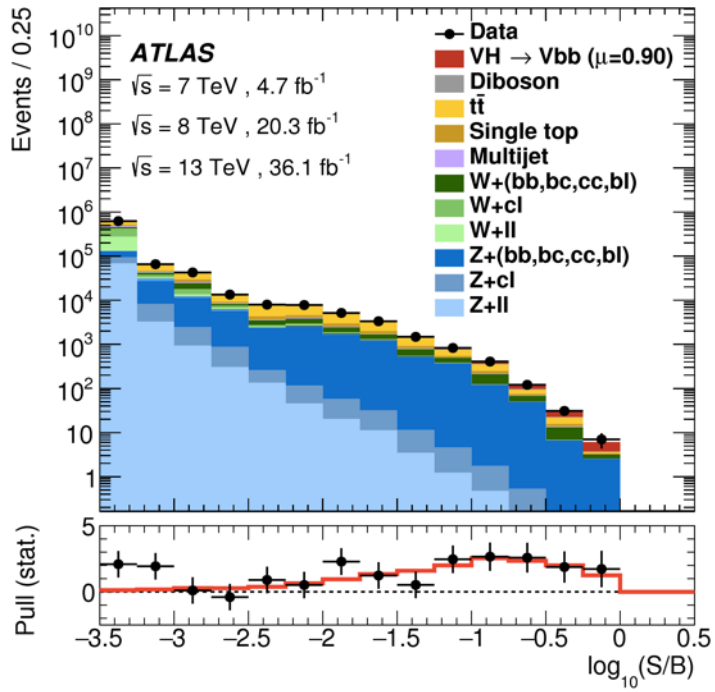


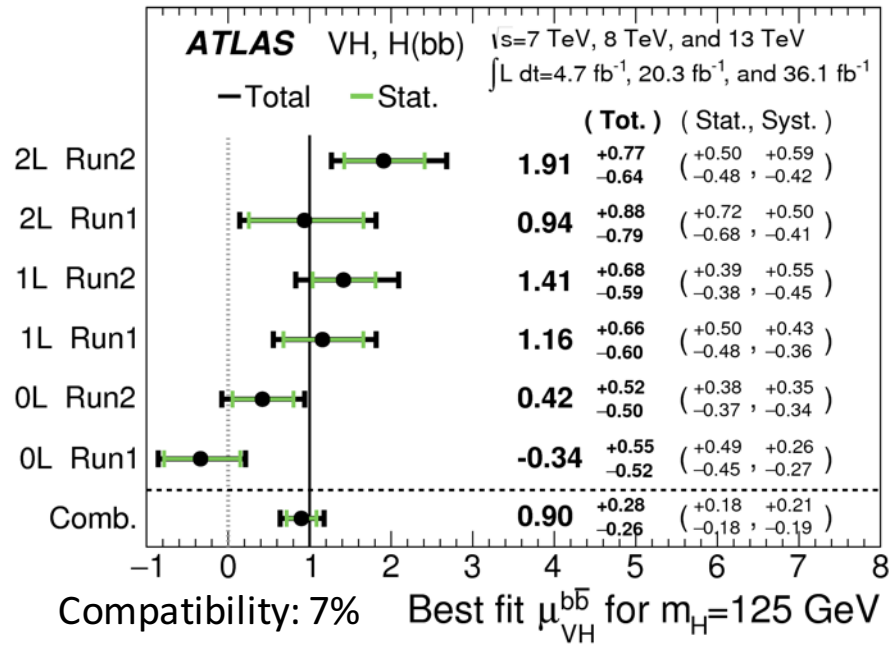




arXiv:1708.03299

VH, H→bb – Run 1 + Run 2 combination



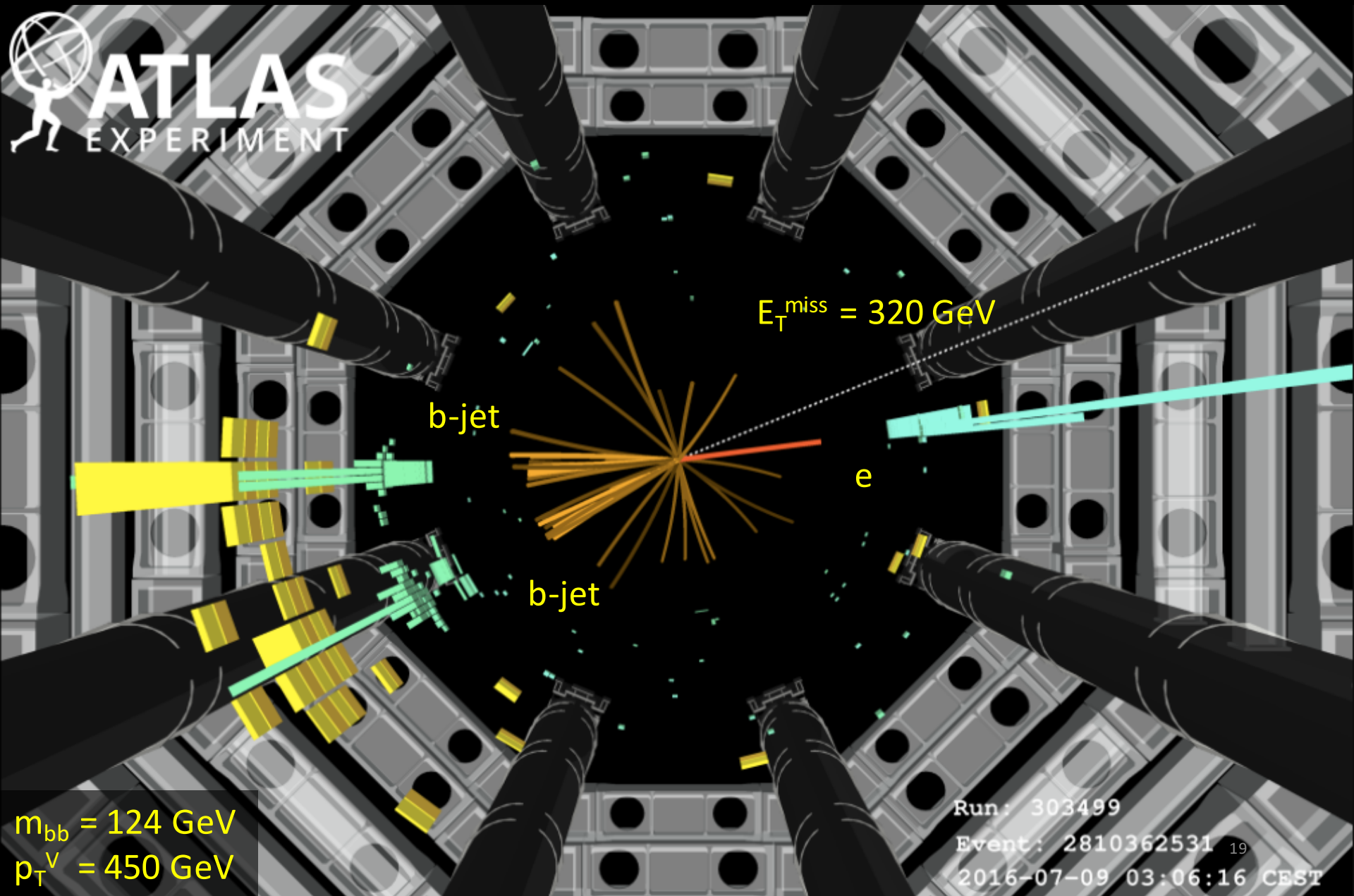


- Combined the Run 2 VH BDT analysis with the corresponding Run 1 analysis.
- Signal modeling and b-jet energy scale uncertainties are correlated for the combined results.
  - Other uncertainty correlations are found to have negligible impact.

Significance
Observed **3.6σ**
Expected 4.0σ
Evidence of H->bb

arXiv:1708.03299

WH→eνbb (1 lepton) candidate recorded in 2016



m_{bb} = 124 GeV
p_T^V = 450 GeV

Summary

- ❑ATLAS is actively exploring the direct coupling of Higgs to fermions.
- ❑**Searches for H→Leptons:**
  - ❑Observation of **H→ττ**:
    - ❑**4.5σ** (exp. 3.4σ) evidence in ATLAS Run 1 data.
    - ❑**5.5σ** (exp. 5.0σ) discovery in combined ATLAS + CMS Run 1 data.
  - ❑Improved limits for **H→μμ** with full 2015+16 data in Run 2.
- ❑**Searches for H→bb:**
  - ❑Study of **VBF** production mode with Run 1 data.
  - ❑Explore new channel **VBF H+γ** in Run 2 data.
  - ❑ **Evidence for H->bb** in **VH** production mode**:**
    - ❑ **3.5σ** observation with full 2015+16 data in Run 2.
    - ❑ **3.6σ** observation in Run 1 + Run 2 combination

- ❑2017 data taking is ongoing.
- ❑Stay tuned for more Run 2 results!

BACKUP

H→μμ – Categorization

36.1 fb^{-1}, 13 TeV

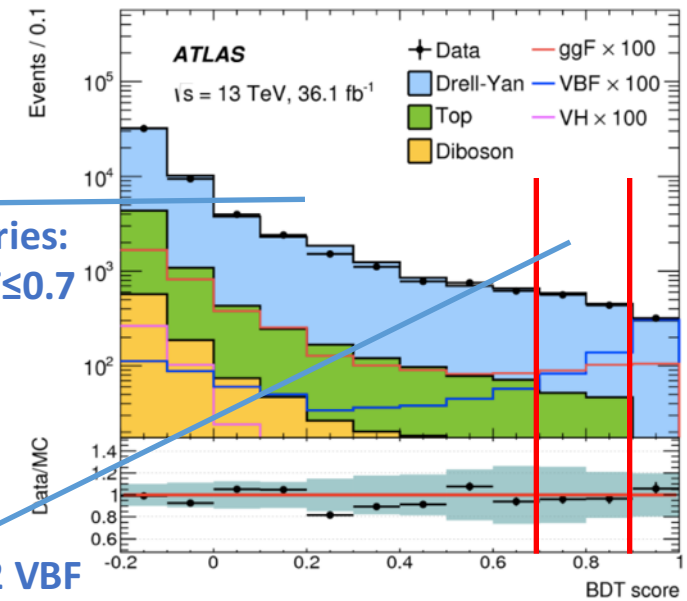
- 8 analysis categories.
  - BDT to select VBF like events:
    - VBF tight, VBF loose.
  - Remaining events enter ggF categories. Split based on $p_T^{\mu\mu}$ and η_μ:
    - Low, medium and high $p_T^{\mu\mu}$ categories.
    - Central, non-central categories.

Central muons $p_T^{\mu\mu} \leq 15$ GeV	Non-central muons $p_T^{\mu\mu} \leq 15$ GeV
Central muons 15 GeV < $p_T^{\mu\mu}$ < 50 GeV	Non-central muons 15 GeV < $p_T^{\mu\mu}$ < 50 GeV
Central muons $p_T^{\mu\mu} \geq 50$ GeV	Non-central muons $p_T^{\mu\mu} \geq 50$ GeV

6 ggF categories: njet<2 or BDT≤0.7

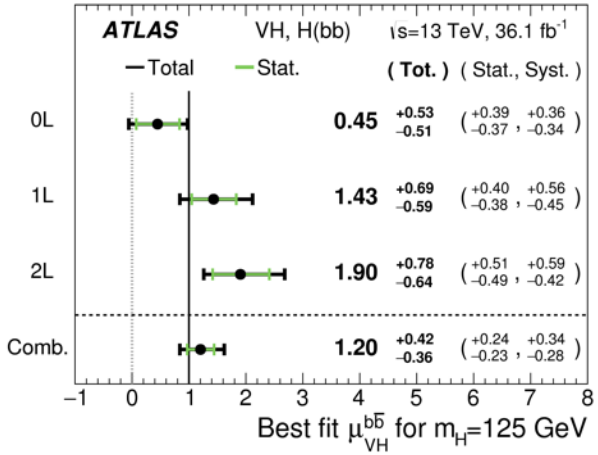
VBF tight BDT≥0.9
VBF loose 0.7<BDT<0.9

2 VBF categories

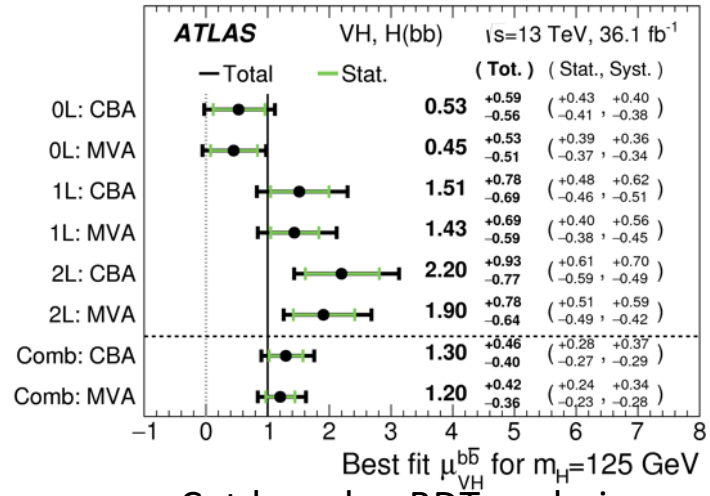


PRL 119 (2017) 051802

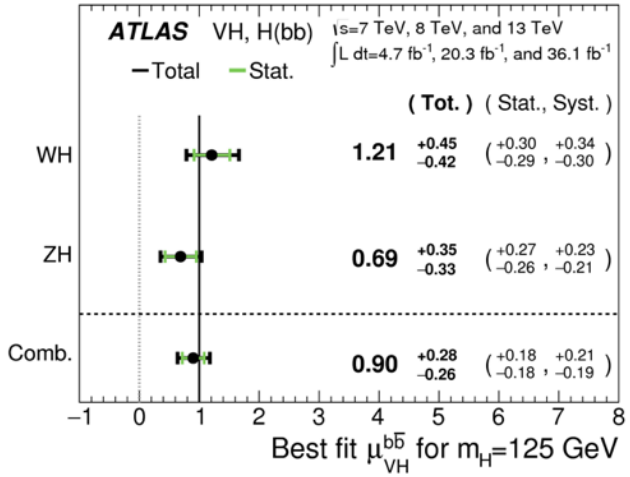
VH, H→bb – Compatibility



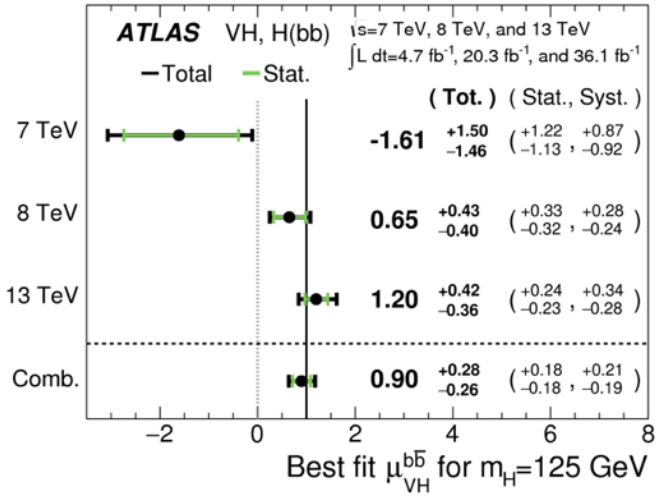
Compatibility: (Run2) 3 channels 10%



Cut-based vs BDT analysis



Compatibility: (Run1+Run2) WH vs ZH 34%



Compatibility: Run1 vs Run2 21%

arXiv:1708.03299

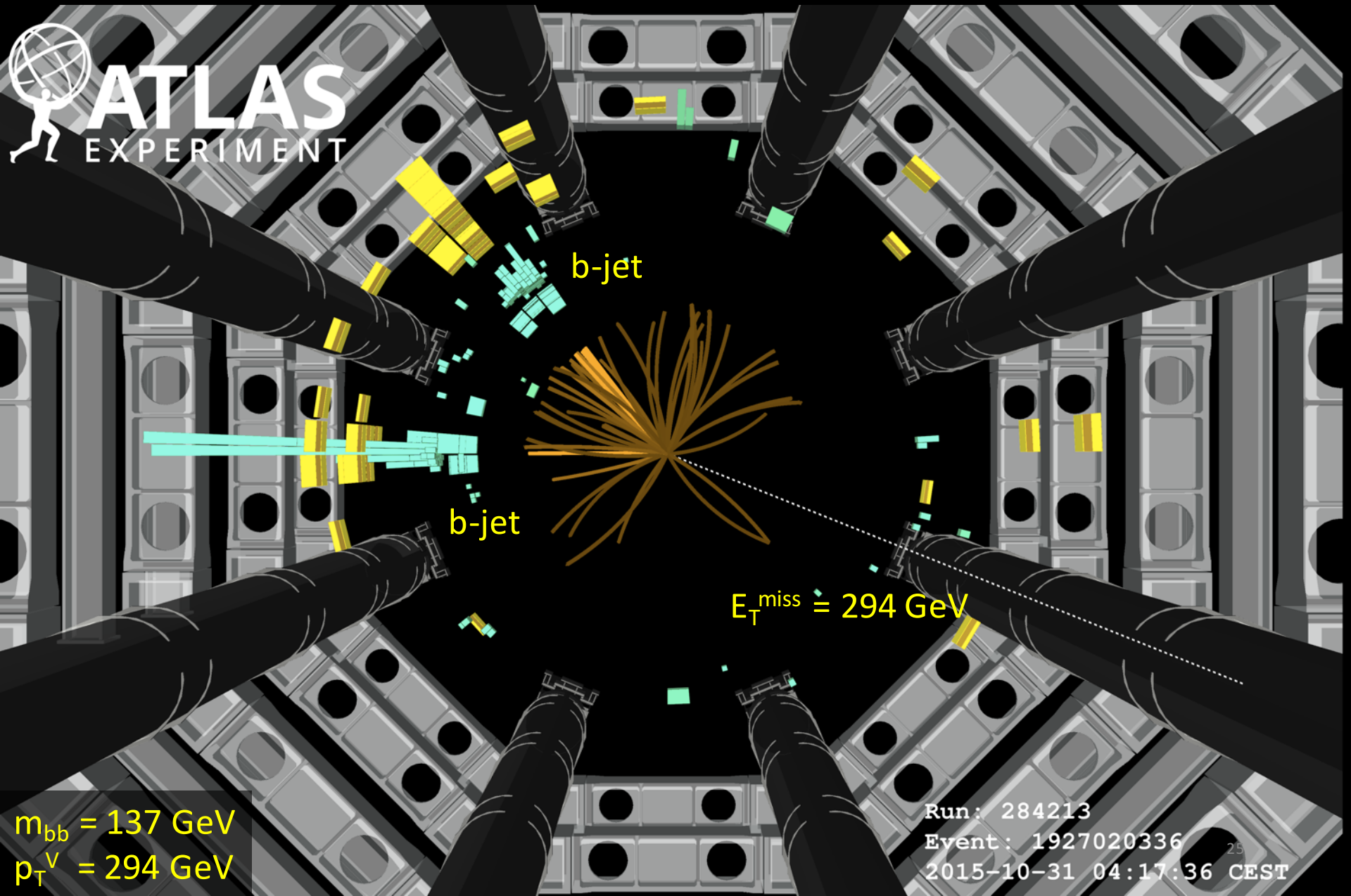
VH, H→bb
Impact of systematics

- Analysis dominated by systematic uncertainties:
  - signal modeling
  - Monte Carlo statistics
  - b-jet tagging uncertainties
  - background modeling

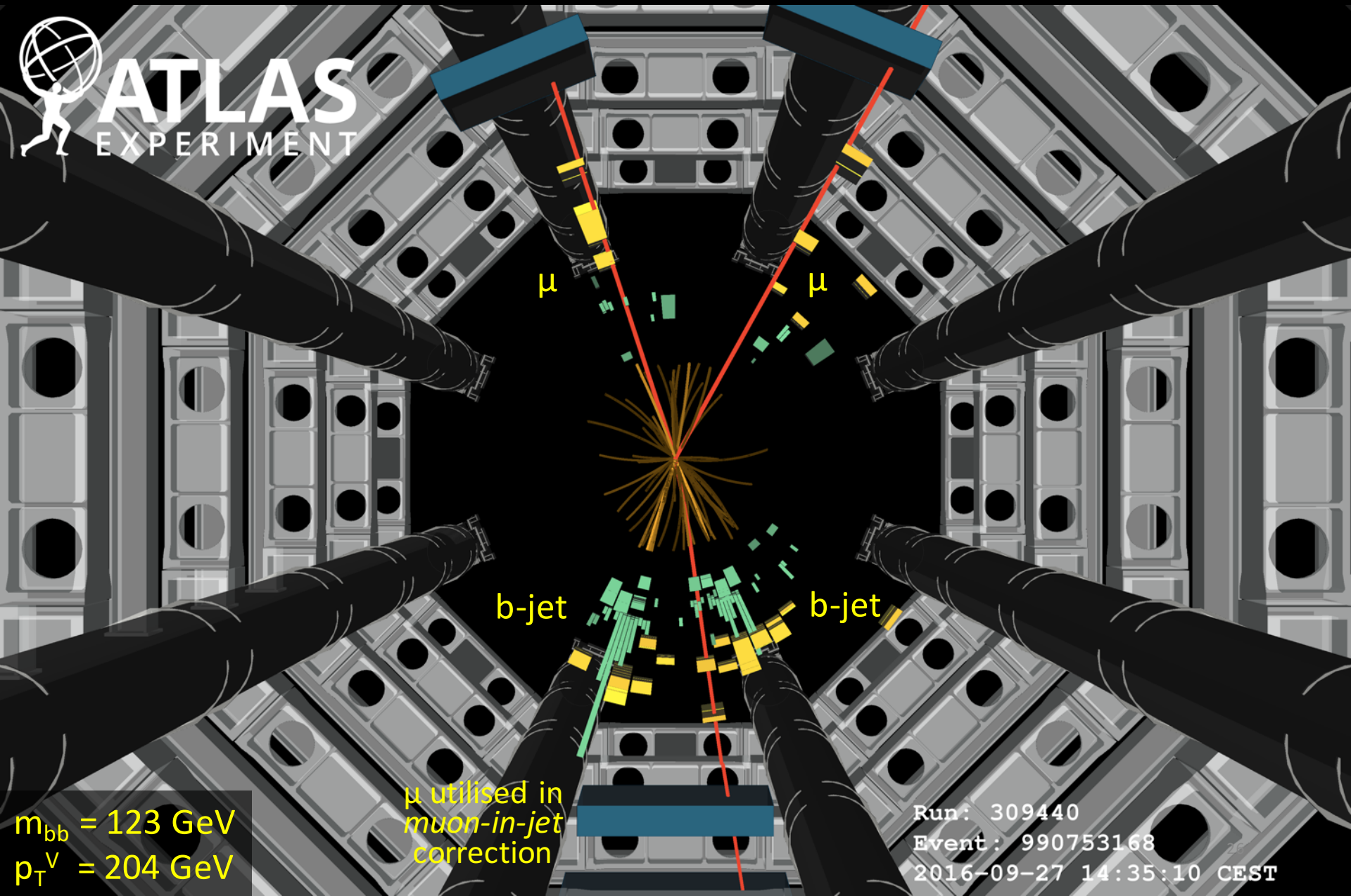
Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z+jets		0.07
W+jets		0.07
$t\bar{t}$		0.07
Single top-quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

arXiv:1708.03299

ZH→ννbb (0-lepton) candidate recorded in 2016



ZH→μμbb (2-lepton) candidate recorded in 2016



m_{bb} = 123 GeV
p_T^V = 204 GeV