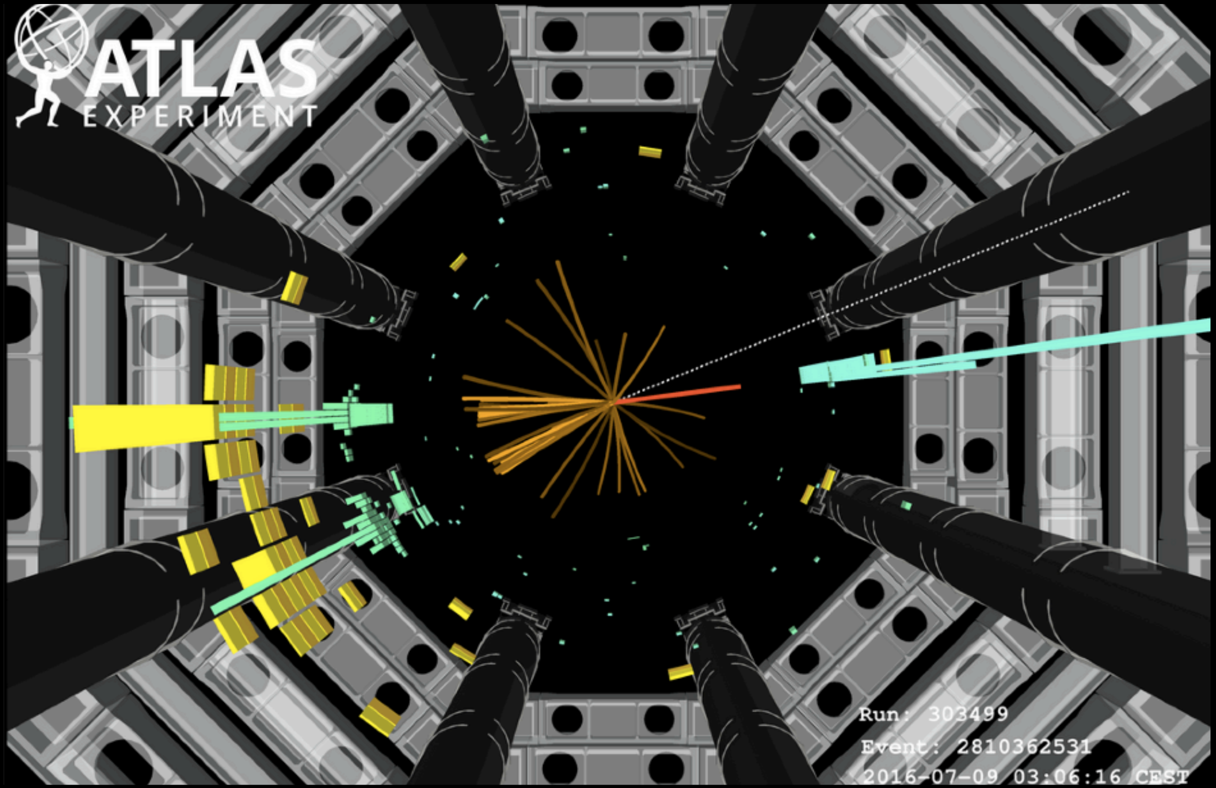
H→bb and beyond

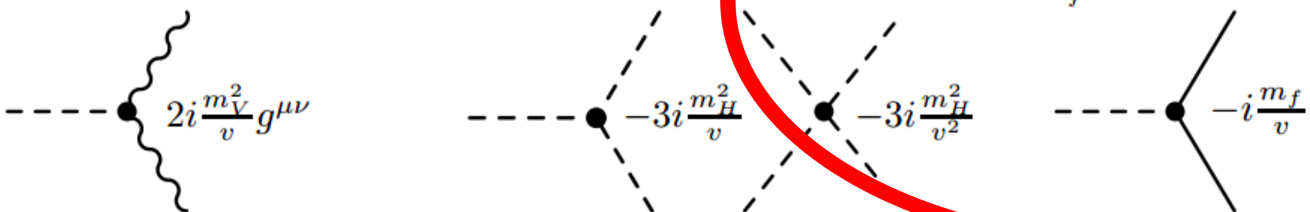


Patricia Conde Muíño
(IST & LIP)

Higgs couplings to quarks

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons	Higgs self-couplings	Couplings to fermions
$\left[m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$	$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$	$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$

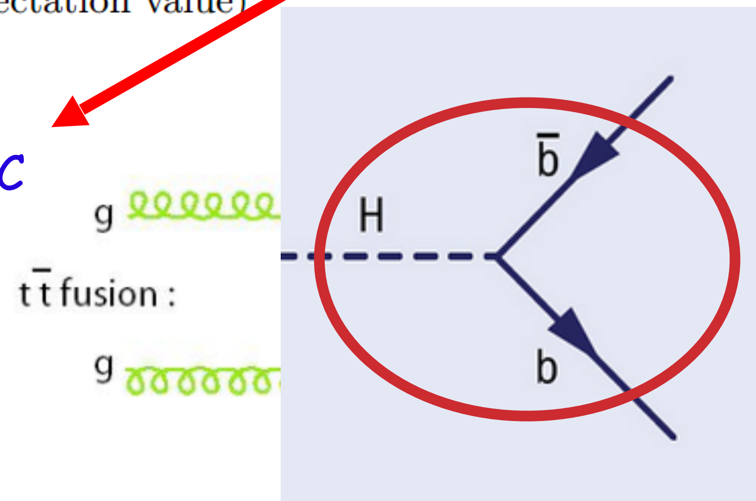


$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \quad (v = \text{vacuum expectation value})$$

★ Fermion couplings:

➢ Only few of them accessible at the LHC

- ➢ t, b, c?
- ➢ Leptons: τ, μ?

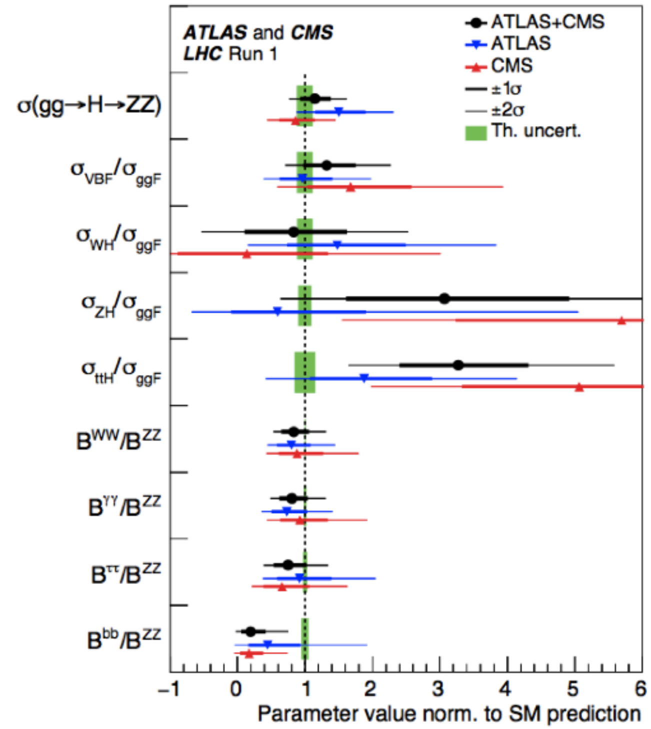


Motivation: why H→bb?

- Higgs boson observed & measured mainly in bosonic channels (gg, WW, ZZ)
  - Compatible with SM
- H→bb: largest BR in the SM (~58%)
  - Constrain total width and measure absolute coupling
  - Probe the Higgs couplings to quarks
- Evidence of fermionic decays in Run 1:
  - H→: 5.5σ (expected 5σ)
  - H→bb: 2.6σ (expected 3.7σ)
- Run 1 signal strength for H→bb:

$$\mu_{bb}^{CMS+ATLAS} = 0.70^{+0.29}_{-0.27}$$

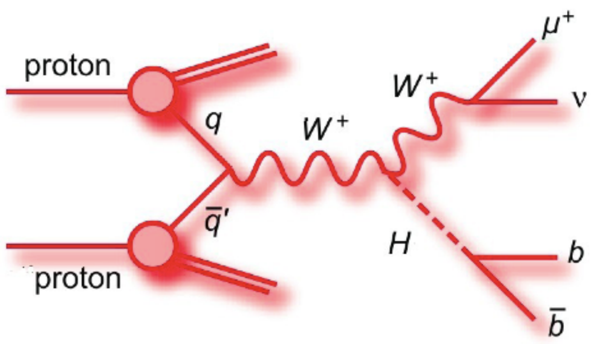
ATLAS+CMS Run 1
Coupling combination

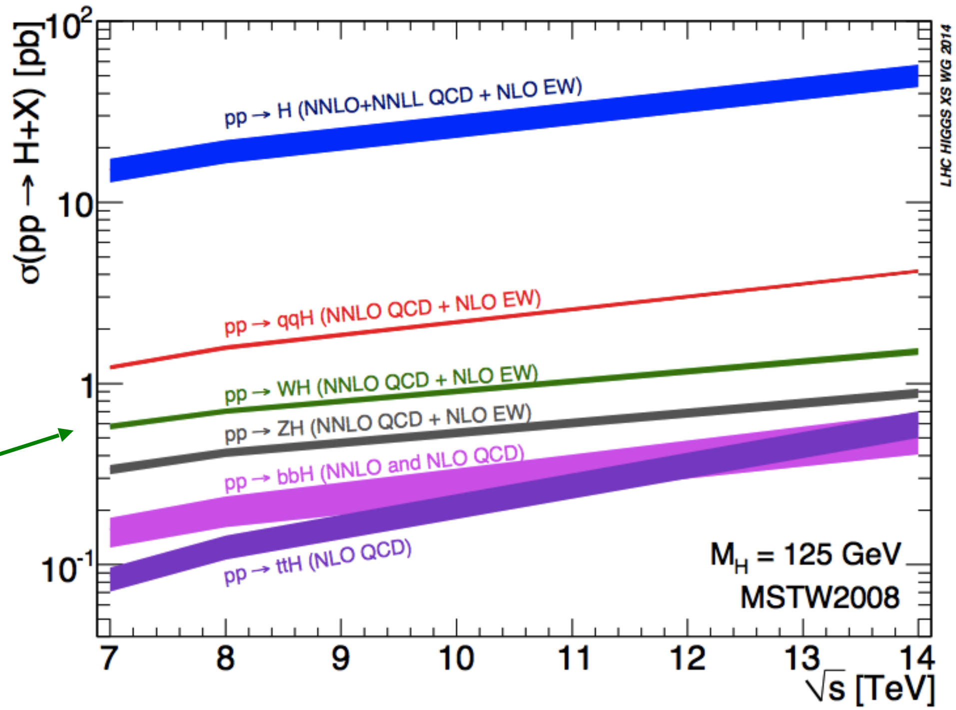


How?

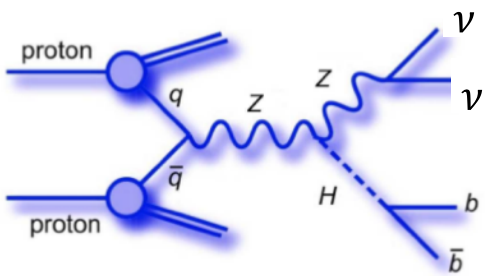
- Huge background from SM b-quark pair production
  - Need clear signatures
- Explore non-dominant production modes
  - Associated production with W or Z (VH search)

    WH: σ = 1.373 pb
    ZH: σ = 0.884 pb
  - ttH production
  - Vector boson fusion

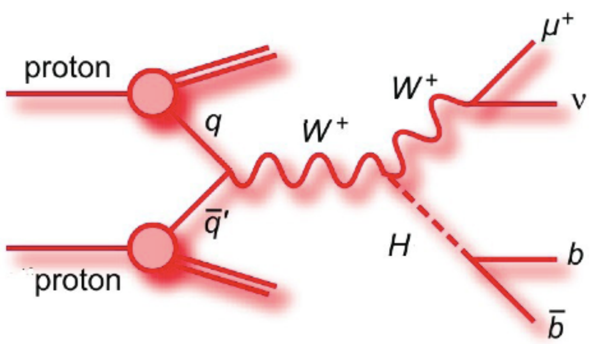




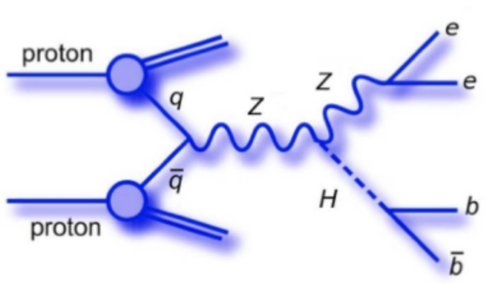
VH searches: 3 channels



- **0-lepton:**
  - E_T^{miss} > 150 GeV



- **1-lepton:**
  - e/μ, p_T>25 GeV
  - Tight isolation
  - Missing E_T >30 GeV (e chn)
  - p_T^V > 150 GeV



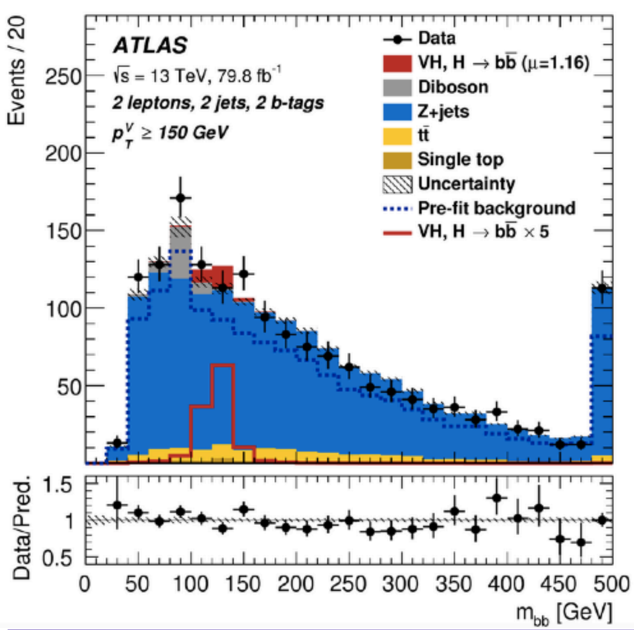
- **2-leptons:**
  - Isolated ee, μμ
  - p_T^1>25 GeV, p_T^2>7 GeV
  - p_T^V > 75 GeV
  - $m_{\ell\ell}$ compatible with m_Z

- **Two jets**
  - anti-kT with R=0.4
  - P_T^{j1}>45 GeV
  - p_T^{j2}>20 GeV
- **B-tagging**
  - Eff: 70%, light jet mistag rate: 0.3%, charm mistag rate: 8%
- **Analysis categories:**
  - 2/3 jets (0/1lepton)
  - 2/≥3jets (2lept.)
  - p_T^V bins
    - 75-150, > 150 GeV (2lepton)
    - >150 GeV (0/1lepton)

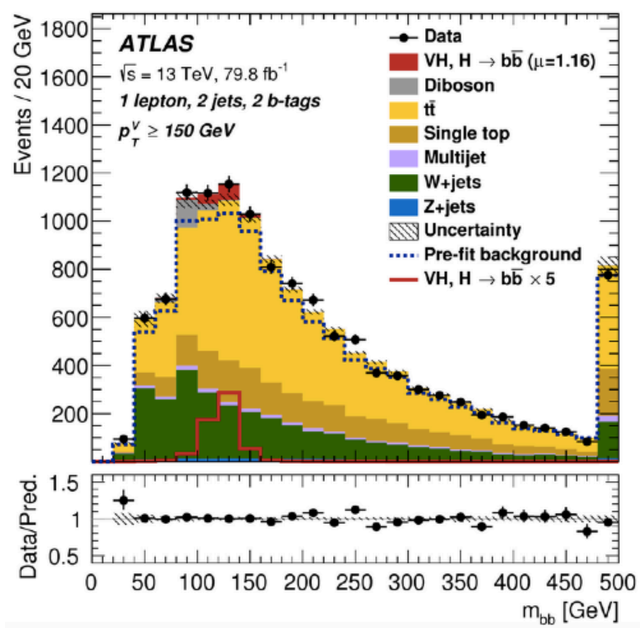
Main backgrounds

- Dominant backgrounds dependent on channel
  - Z+bjets dominates in 0, 2 lepton channels
  - Top quark and W+jets in 1 lepton channel
  - Multi-jet important in 1 lepton channel

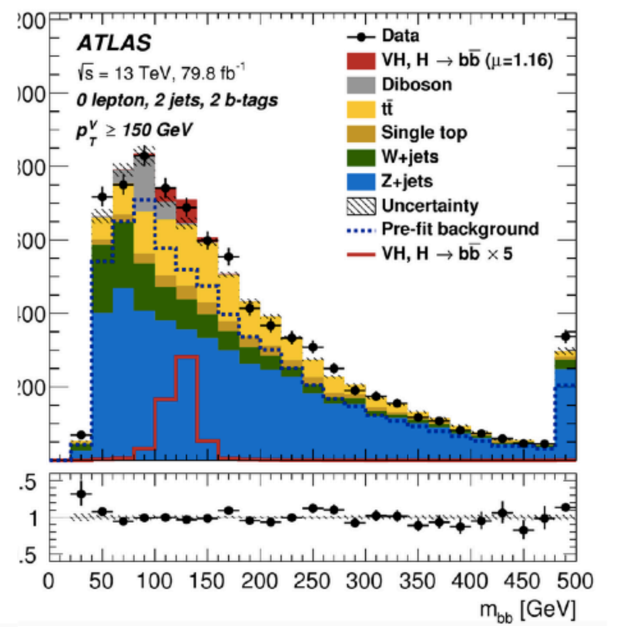
0 lepton



1 lepton



2 leptons



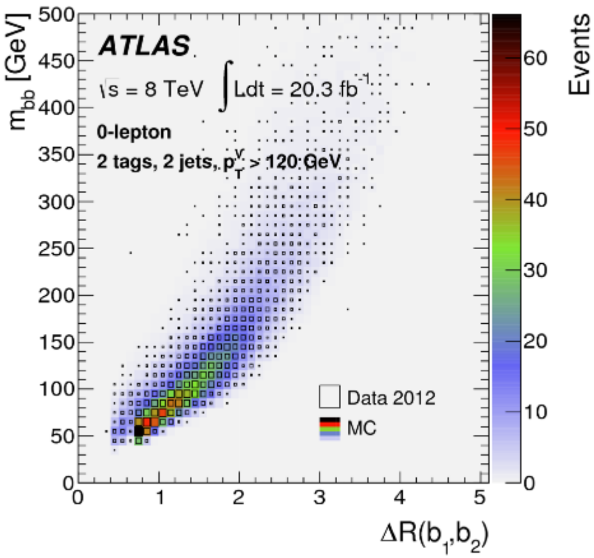
Multi-variate analysis

- Boosted decision tree (BDT)

  Combine many different variables

  Trained in 8 categories: 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)

- Most discrimination from m_{bb} and $\Delta R(b_1,b_2)$

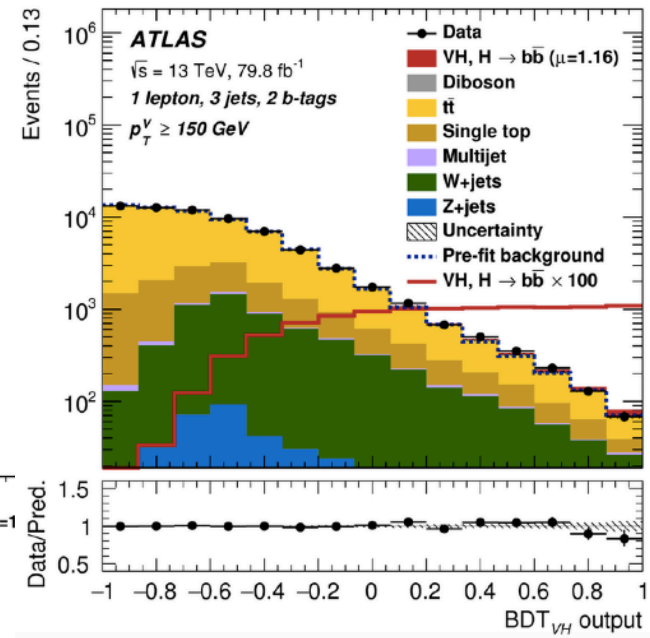


Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$E_T^{miss}/\sqrt{S_T}$			×
m_{top}		×	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		×	
		Only in 3-jet events	
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

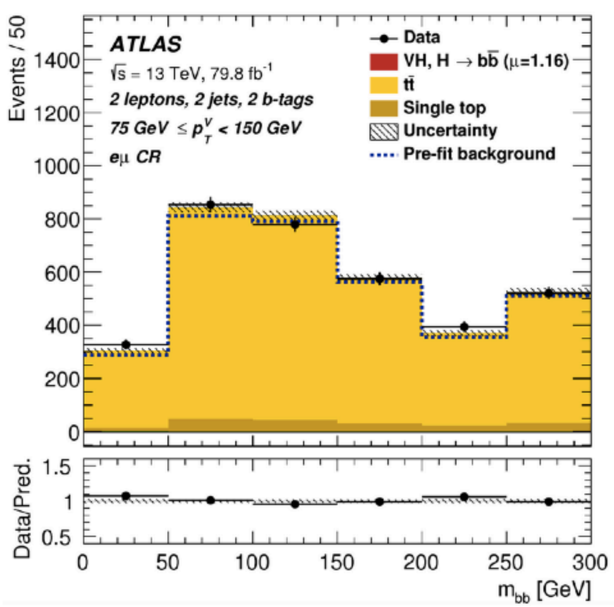
- New in run 2: m_{Top}, $|\Delta Y(V,H)|$ → +7% in sensitivity

Combined fit

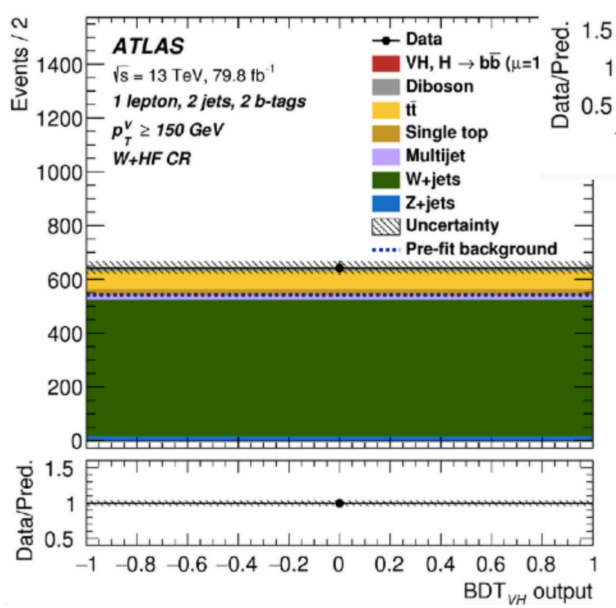
- Signal strength from profiled likelihood fit
  - Take into account all event categories
- Use BDT discriminant as input
- Control regions to constrain the backgrounds



Eμ control region



W+HF control region

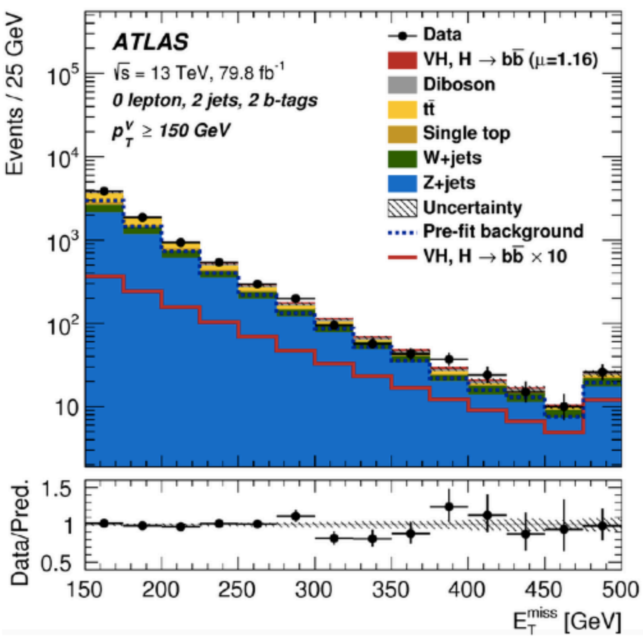


Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
$W+$HF 2-jet	1.19 ± 0.12
$W+$HF 3-jet	1.05 ± 0.12
$Z+$HF 2-jet	1.37 ± 0.11
$Z+$HF 3-jet	1.09 ± 0.09

Post-fit distributions

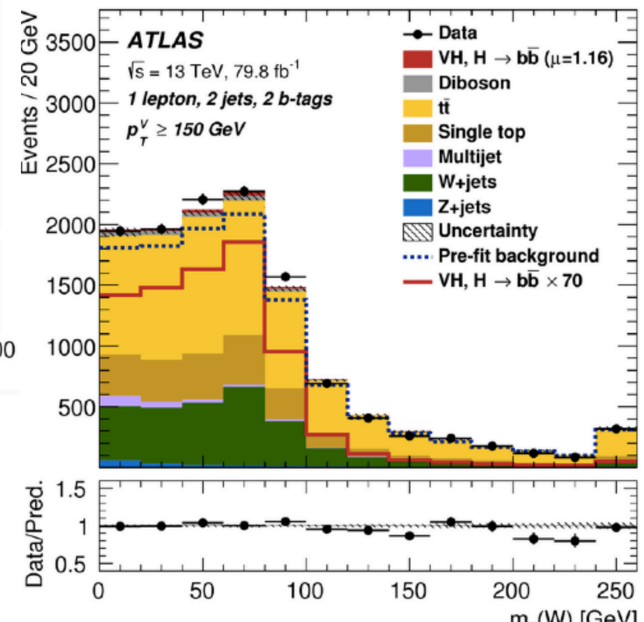
E_T^{miss}

0 lep, 2jets, 2btags



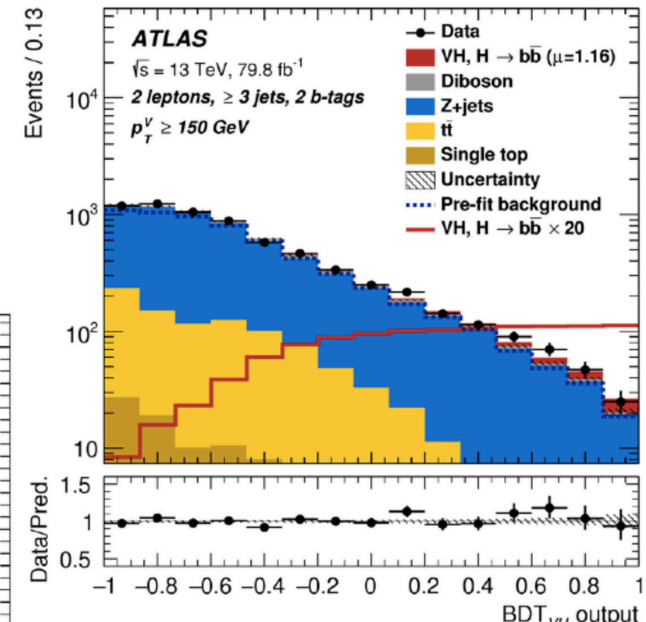
W transverse mass

1 lep., 3jets, 2 btags



2 leptons, 2 tags, 2 jets

BDT discriminant

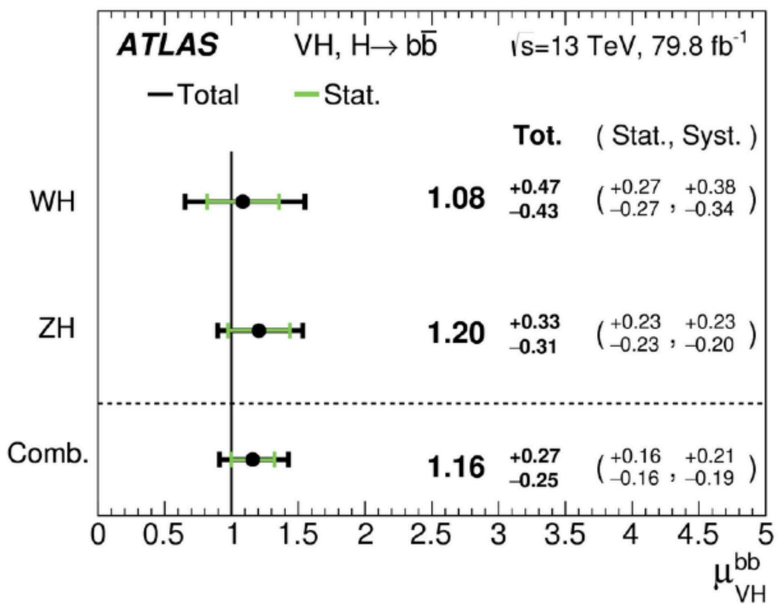


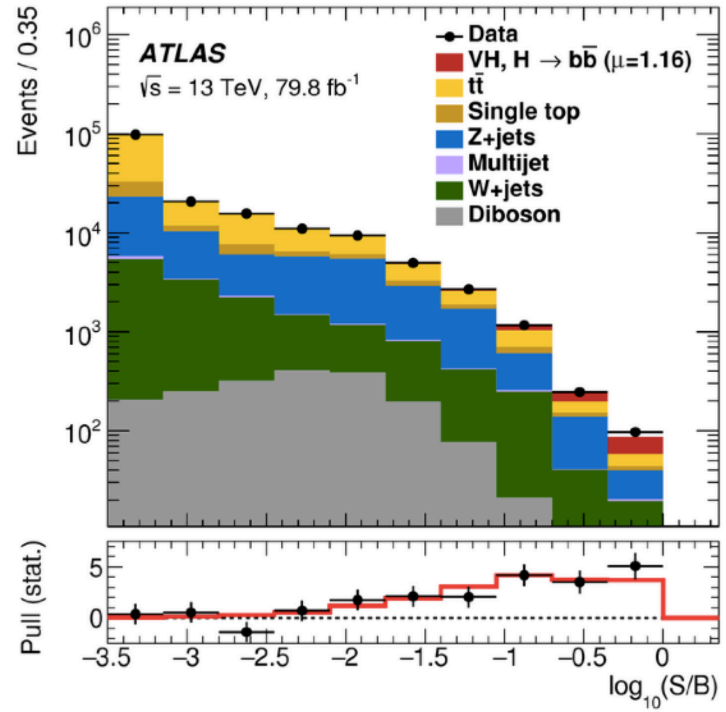
Results for Run 2 with 79 fb^{-1} of data

- 79 fb^{-1} of pp collisions at $\sqrt{s}$= 13 TeV
  - 4.9σ evidence observed (4.3σ expected)
  - systematic uncertainties start to dominate!!

$$\mu_{VH}^{bb} = 1.16^{+0.27}_{-0.25} = 1.16 \pm 0.16(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$$

ATLAS-CONF-2016-091

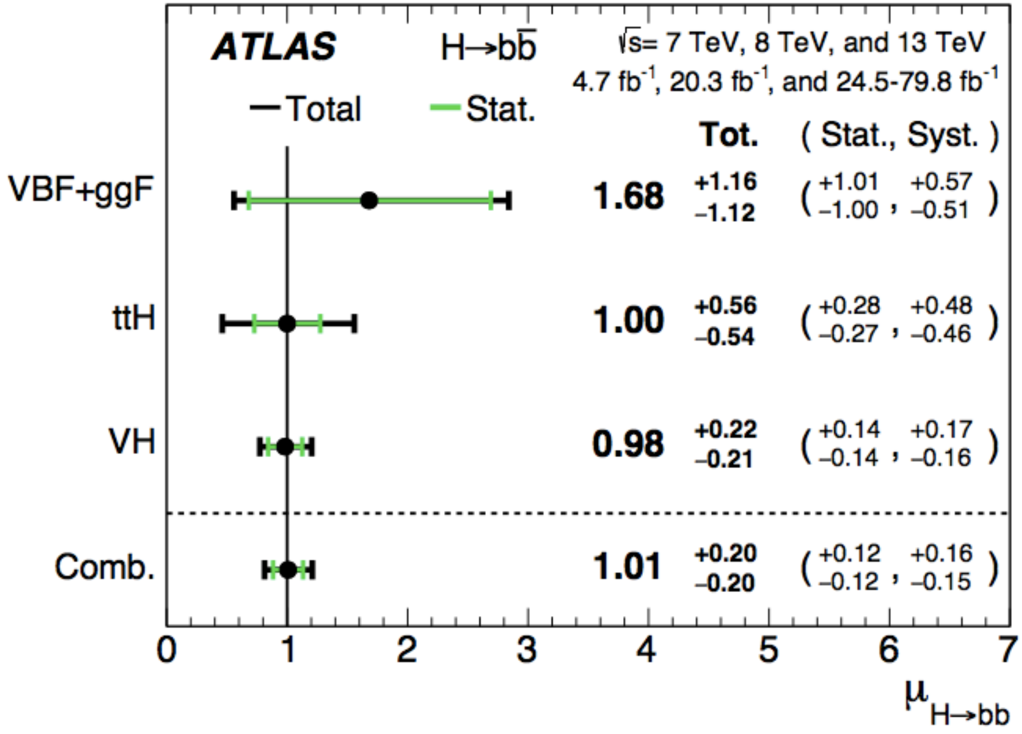




Dominant systematics from b-tagging, background normalization & modelling (W+jets, Z+jets, top)

Run 1 + Run 2 combination

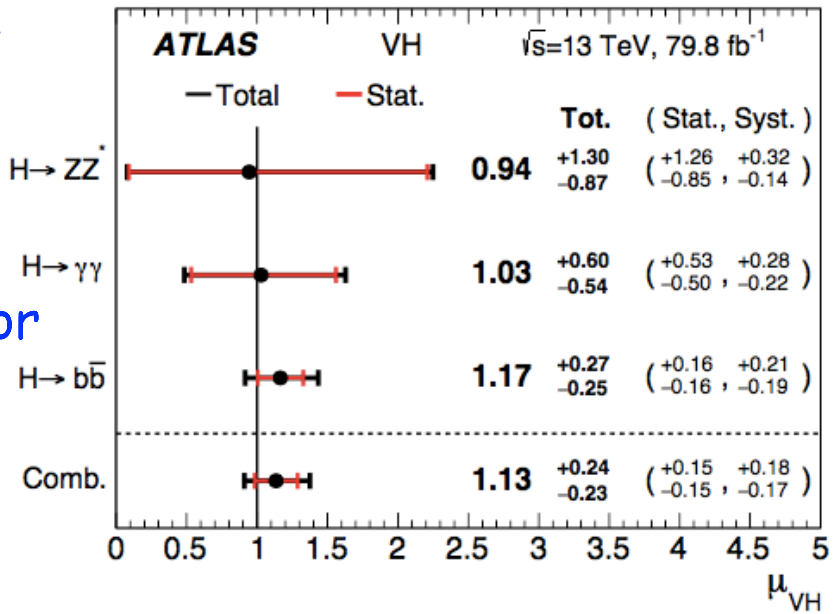
- ★ Includes ttH and vector boson fusion (with H->bb) channels
- ★ 5.4σ observation!! (5.5σ expected)



Observation of VH production

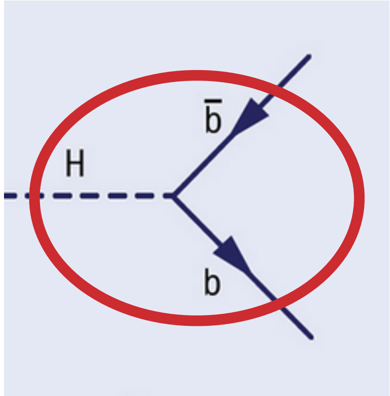
- Combination with two more channels
  - Four leptons (ZZ)
  - γγ
- Direct observation of the Higgs produced in association with vector bosons!
-

Channel	Significance Exp.	Significance Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3



And what now?

Probing the Hbb coupling



★Questions

- ➡ Is it really as the SM predicts?
- ➡ What is the sign of the coupling?
- ➡ Are there anomalous components?

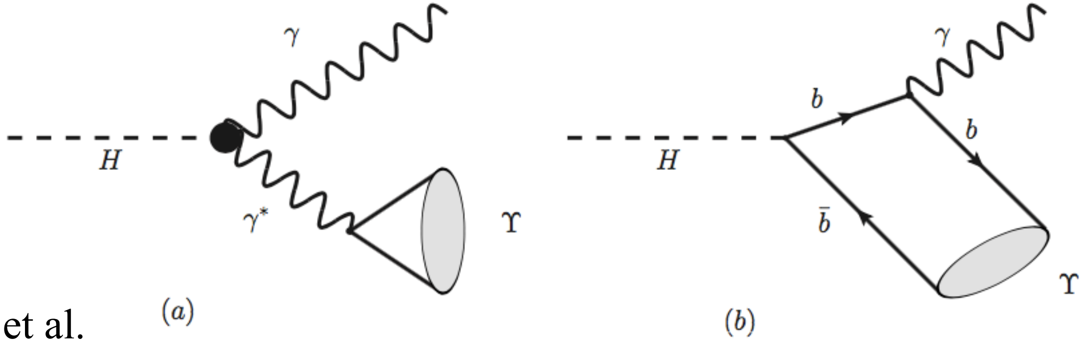
★Probing the sign of the Hbb coupling:

- ➡ Decay $H \to \Upsilon\gamma$

Interference between two difference diagrams results in very low BR

Can be enhanced if the sign of the coupling is the opposite!

Very difficult channel —> will need HL-LHC



T. Modak et al.

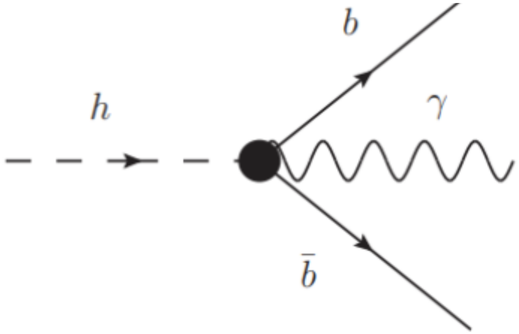
Phys.Rev. D94 (2016) no.7, 075017

Can we probe anomalous couplings in H→bb?

- ★ Look at the hbbγ effective vertex
  - ➡ Can we measure this decay at ATLAS?
- ★ Previous studies
  - ➡ ZH production
  - ➡ Basic selection

    Foton pT, missing ET, $m_{\ell\ell}$, $\Delta\varphi_{\gamma\ell\ell}$, …

$$L_{hb\bar{b}\gamma} = \frac{1}{\Lambda^2} F^{\mu\nu} \bar{b} \sigma_{\mu\nu} (d_1 + i d_2 \gamma_5) b h$$



Dwivedi et al, PhysRevD.96.015035

Process	$\sqrt{s}$ =14 TeV					
	σ (pb)	NEV ($\mathcal{L}$ =1000 fb^{-1})				
		C0	C1	C2	C3	C4
$pp \to Zh, h \to b\bar{b}\gamma$	3.332×10^{-4}	83	70	41	39	29
$pp \to Zh\gamma$	4.765×10^{-5}	17	13	1	1	-
$pp \to t\bar{t}\gamma$	0.03144	5214	586	31	5	4
$pp \to \ell^+\ell^- b\bar{b}\gamma$	0.01373	3149	2507	345	98	54
$pp \to \ell^+\ell^- jj\gamma$	3.589	5355	4523	427	213	107

★ hbbγ coupling can be probed at the LHC at 14 TeV at the 3σ level with an integrated luminosity of ~ 2000 fb^{-1}

Can we probe anomalous couplings in H→bb?

A. Kelly's master thesis

- ★Can we use the photon to trigger and exploit higher cross section in the gluon-gluon fusion mechanism?
- ★Back of the envelope calculation
  - ➡ Using mad graph to generate the signals
  - ➡ Basic cuts in ZH production would lead to S/sqrt(B) ~3

Process	$\sqrt{s} = 14$ TeV			
	σ(pb)	Number of Events (L = 1000 fb^{-1})		
		generator cuts	$P_{T\gamma} \geq 20$ GeV	$P_{T\gamma} \geq 60$ GeV $P_{Tj1} \geq 40$ GeV $P_{Tj2} \geq 20$ GeV
BSM $pp \to h \to b\bar{b}\gamma$	1.8	1.8×10^6	1.6×10^6	2.6×10^5
$pp \to b\bar{b}\gamma$	1.9×10^4	1.9×10^{10}	1.3×10^8	1.7×10^6
$pp \to b\bar{b}j$	$1.5 \times 10^7 \times \frac{1}{5000} = 3 \times 10^3$	3×10^9	7.6×10^8	6.0×10^6
$S/\sqrt{B}$	-	12	54	93

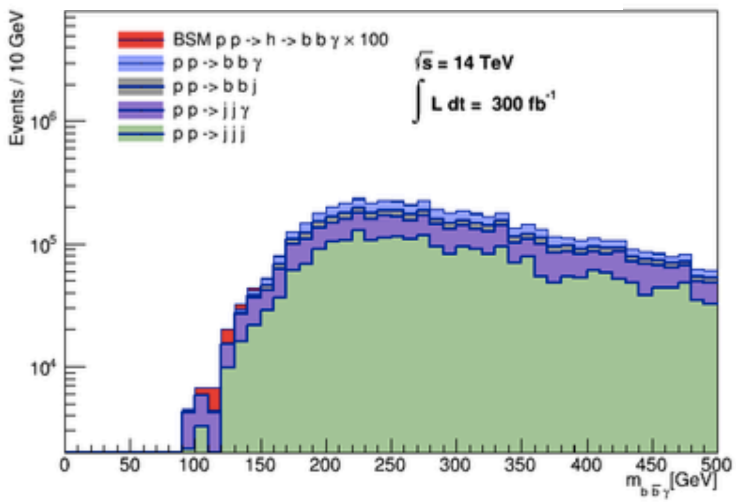
Generator level study H→bbγ

- SM and BSM (d1=6, d2=0) signals produced with madgraph
- Main backgrounds also produced with mad graph
  - bbγ, jjγ, jjj, bbj
- Detector effects simulated with DELPHES
- Optimization of the analysis selection
  - Explored many even shape variables

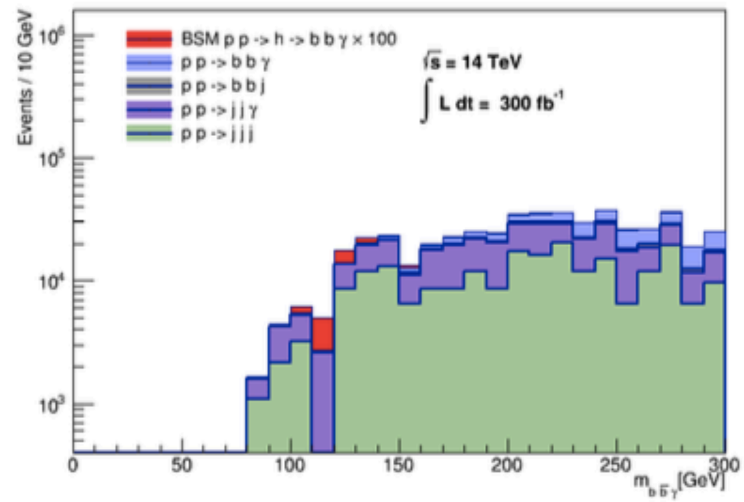
Selection Criteria (Efficiency)	BSM $pp \to h \to b\bar{b}\gamma$	SM $pp \to h \to b\bar{b}\gamma$	$pp \to b\bar{b}\gamma$	$pp \to b\bar{b}j$	$pp \to jj\gamma$	$pp \to jjj$
Generator level Cuts	100 %	100 %	100 %	100 %	100 %	100 %
$P_{T_\gamma} \geq 80$ GeV	8.64 %	9.52 %	14.75 %	24.15 %	16.35 %	25.59 %
$N_{bj} \geq 2$	0.61 %	1.85 %	4.37 %	5.39 %	0.069 %	0.14 %
$\Delta R_{b\gamma} \leq 1.5$	0.43 %	0.48 %	0.85 %	0.28 %	0.012 %	0.017 %
Sphericity ≥ 0.02	0.42 %	0.47 %	0.84 %	0.27 %	0.012 %	0.016 %
100 GeV $\leq m_{b\bar{b}\gamma} \leq$ 135 GeV	0.19 %	0.19 %	0.0023 %	0.0022 %	0.00049 %	0.00068 %

Results for H→bbγ

- The invariant mass of Higgs candidate on log scale without any cuts



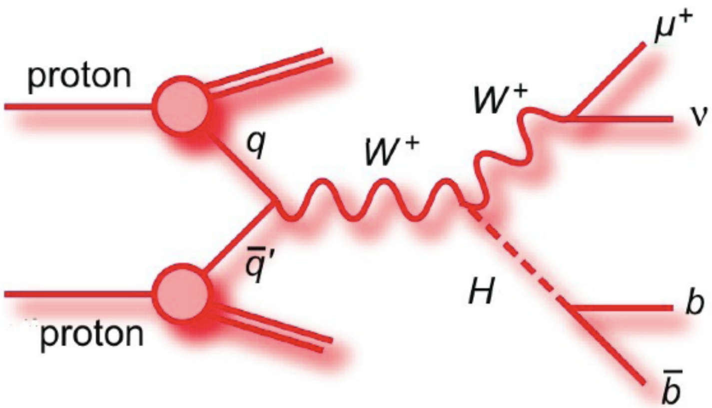
- The invariant mass of Higgs candidate after Sphericity and $\Delta R_{b\gamma}$ cut



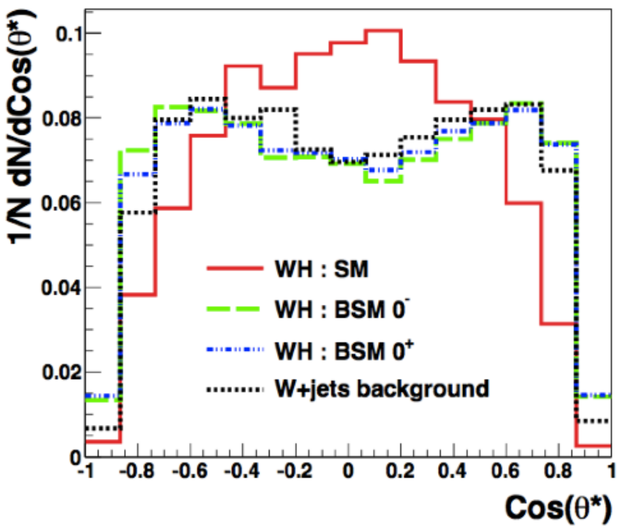
★ This channel could contribute in addition to ZH production, but quite challenging

	Significance $(S/\sqrt{B})$	
Effective Coupling	$\mathcal{L} = 3000\ \text{fb}^{-1}$	$\mathcal{L} = 1000\ \text{fb}^{-1}$
SM coupling	0.0056	0.0033
$d_1 = 5\ d_2 = 5$	1.95	1.13
$d_1 = 6\ d_2 = 0$	1.52	0.88
$d_1 = 6\ d_2 = 0$ (BDT)	2.04	1.18

Probing HWW vertex in WH(bb)



ArXiv:1306.2573v2 (Godbole et al.)



- ★ Angular variables sensitive to anomalous Spin/CP components in the vertices
- ★ Boosted regime enhances the sensitivity!!
- ★ Working on boosted Hbb search in WH production

$$\cos\theta^* = \frac{\vec{p}_{l_1}^{(V)} \cdot \vec{p}_V}{|\vec{p}_{l_1}^{(V)}|\,|\vec{p}_V|},$$

Conclusions

- The Run 2 is bringing a wealth of Higgs properties measurements
- Higgs couplings to quarks have recently being observed by the first time
  - H-> bb decay observation combining 13 TeV (76 fb-1) and 8 and 7 TeV pp collisions data
    - Several channels
  - Observed also the VH associated production mode!
  - Signal strength compatible, in both cases, with SM expectations
- Future:
  - Will require more precise measurements of the coupling vertices

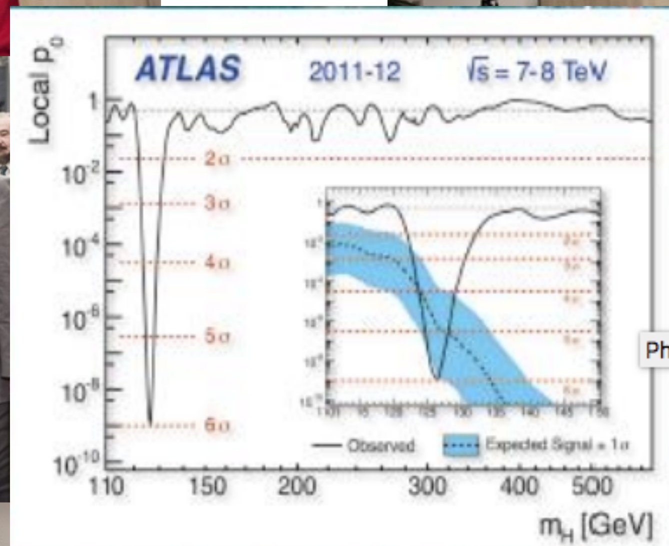
Thank you!

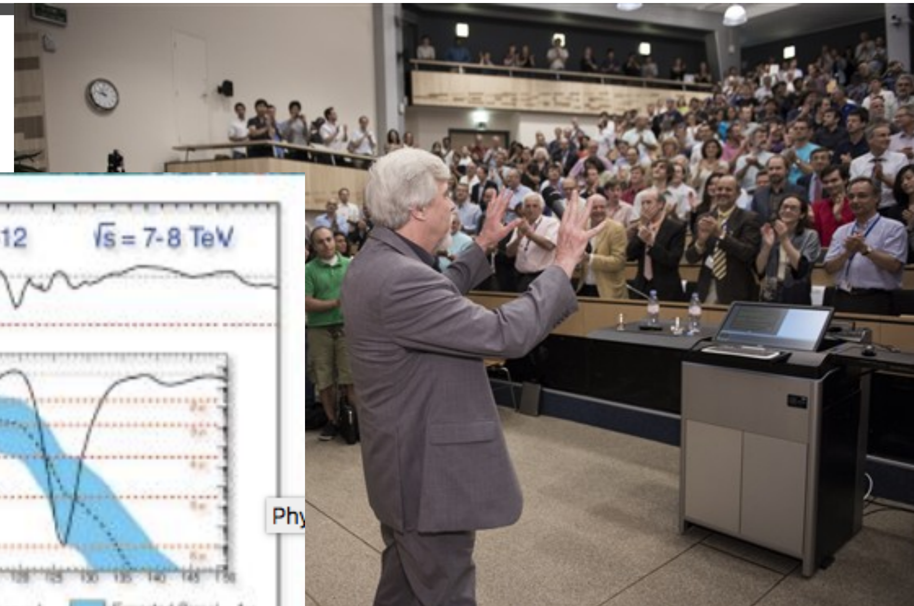
- Acknowledgements

Thanks to the support from CERN/FIS-PAR/0008/2017 , OE, FCT

Backup

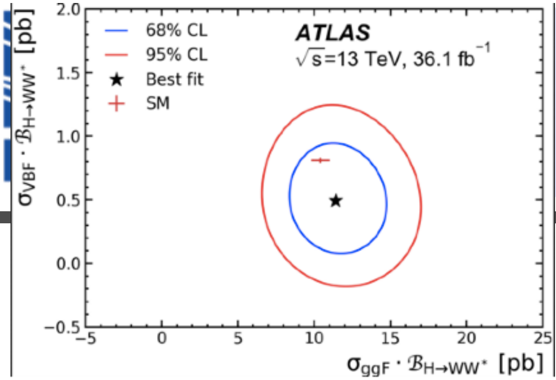
Run 1: Higgs discovery

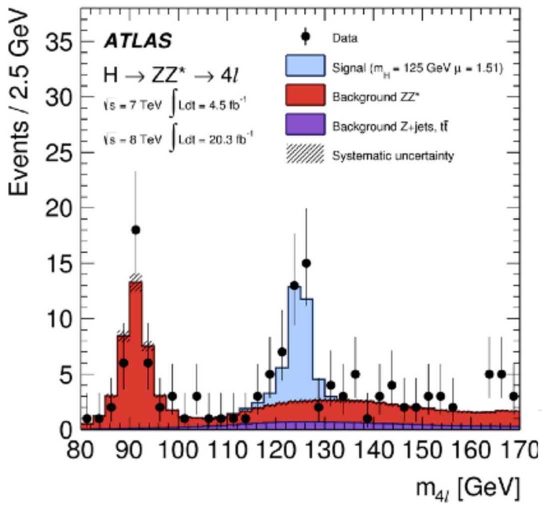


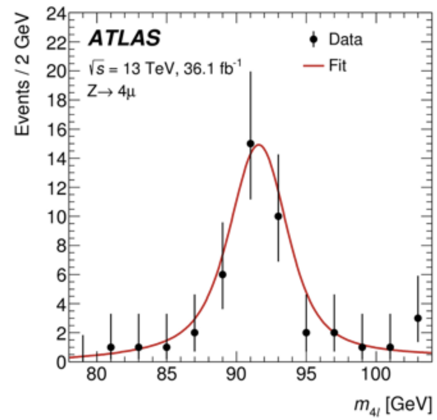


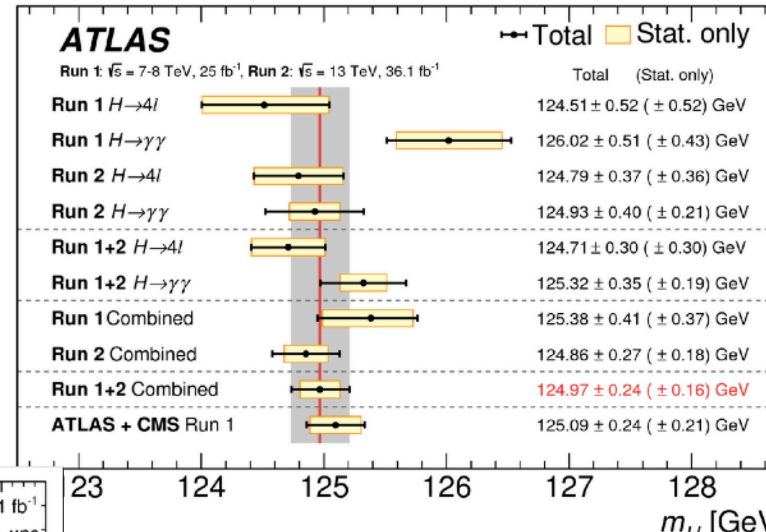
Run 2: measurements!!

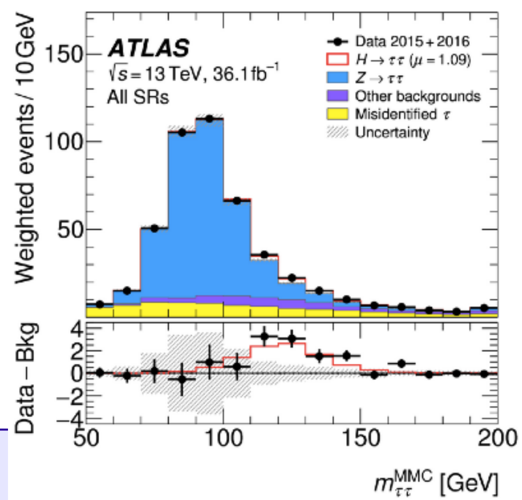
★ Dominated by bosonic channels

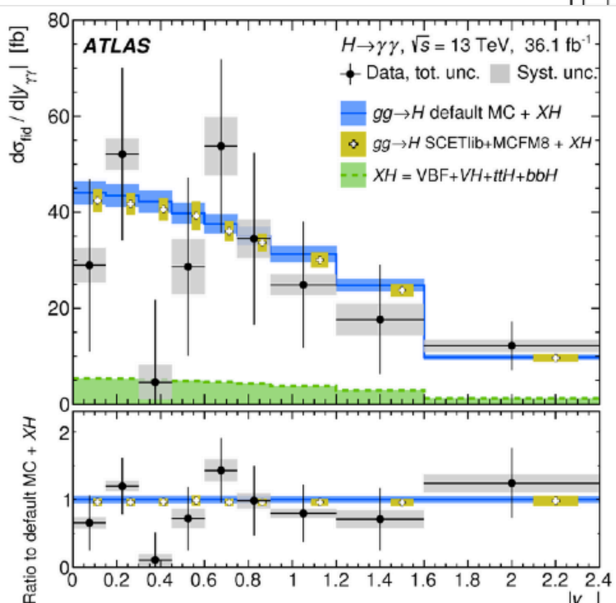


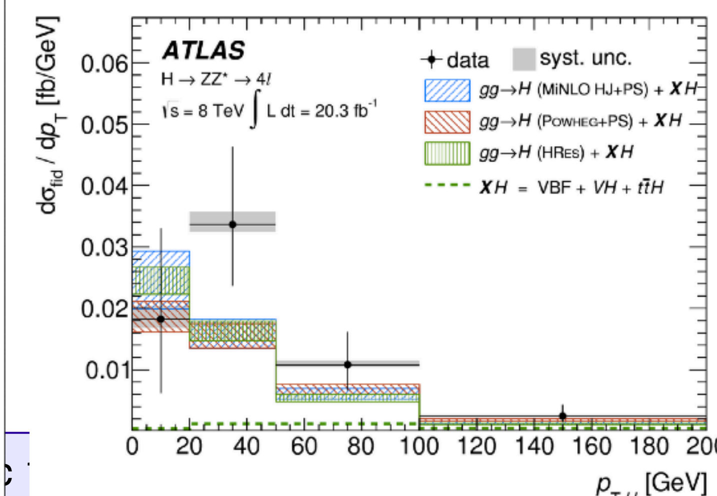






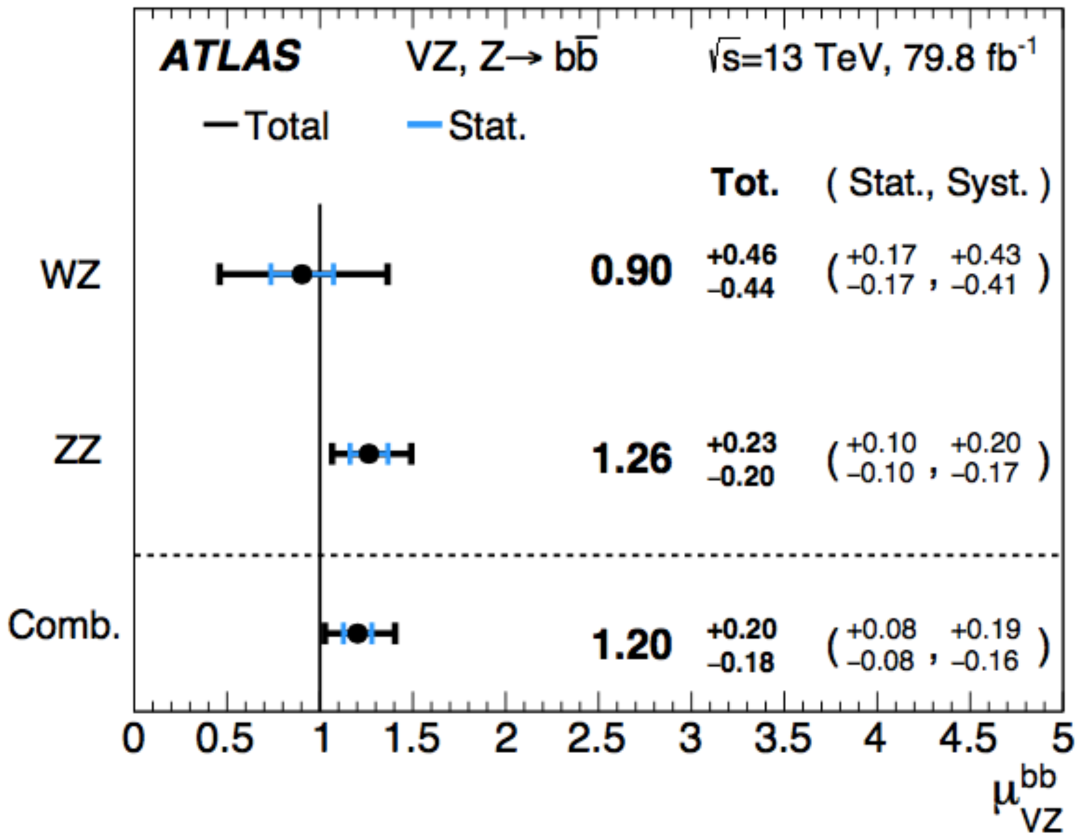


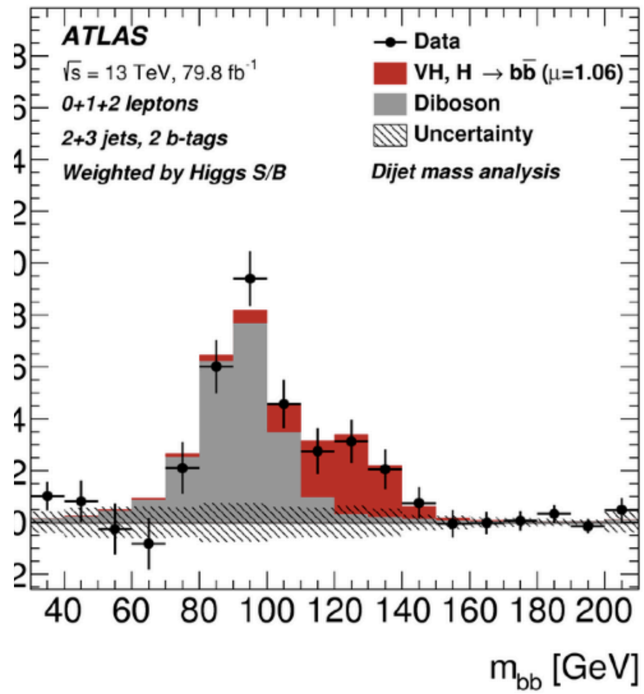




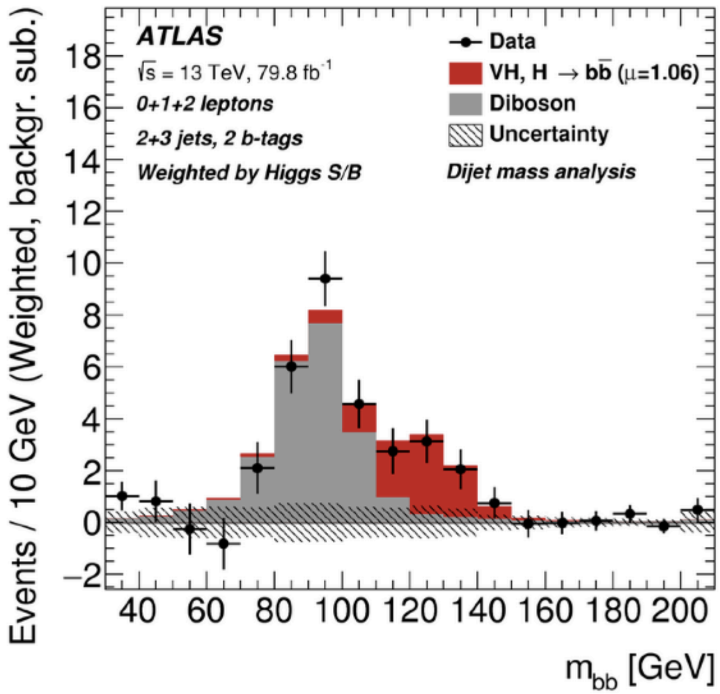
And what about quarks?

VH (Z→bb) analysis





Di-jet mass analysis



- ★ 3.6σ observed
- ★ 3.5σ expected

$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.})$$

Selection

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\|\eta\| < 2.5$ > 30 GeV for $2.5 < \|\eta\| < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^{\circ}$ (2 jets), $> 30^{\circ}$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^{\circ}$	–		–
$\Delta\phi(\vec{b_1}, \vec{b_2})$	$< 140^{\circ}$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^{\circ}$	–		–
p_{T}^{V} regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, $>$ 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Simulation samples

Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH \to \ell\nu b\bar{b}$	POWHEG-BOX v2 [76] + GOSAM [79] + MINLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	PYTHIA 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2 + GOSAM + MINLO	NNPDF3.0NLO$^{(\star)}$	PYTHIA 8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	POWHEG-BOX v2	NNPDF3.0NLO$^{(\star)}$	PYTHIA 8.212	AZNLO	NLO+ NLL [89–93]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	POWHEG-BOX v2 [94]	NNPDF3.0NLO	PYTHIA 8.230	A14 [95]	NNLO+NNLL [96]
s-channel	POWHEG-BOX v2 [97]	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO [98]
t-channel	POWHEG-BOX v2 [97]	NNPDF3.0NLO	PYTHIA 8.230	A14	NLO [99]
Wt	POWHEG-BOX v2 [100]	NNPDF3.0NLO	PYTHIA 8.230	A14	Approximate NNLO [101]
Vector boson + jets					
$W \to \ell\nu$	SHERPA 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	SHERPA 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \to \ell\ell$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
$Z \to \nu\nu$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NNLO
Diboson					
$qq \to WW$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$qq \to WZ$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$qq \to ZZ$	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	Default	NLO
$gg \to VV$	SHERPA 2.2.2	NNPDF3.0NNLO	SHERPA 2.2.2	Default	NLO

Uncertainties in the signal strength

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
$E_{\mathrm{T}}^{\mathrm{miss}}$		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