

# EVIDENCE FOR THE $H \rightarrow bb$ DECAY IN $VH$ PRODUCTION AT ATLAS

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LLR Seminar, 6/11/17

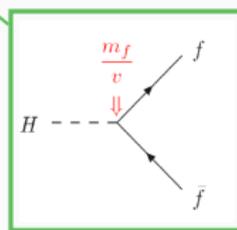
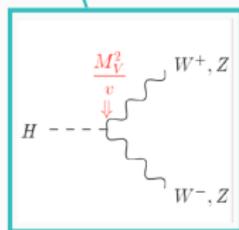


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c.$$

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

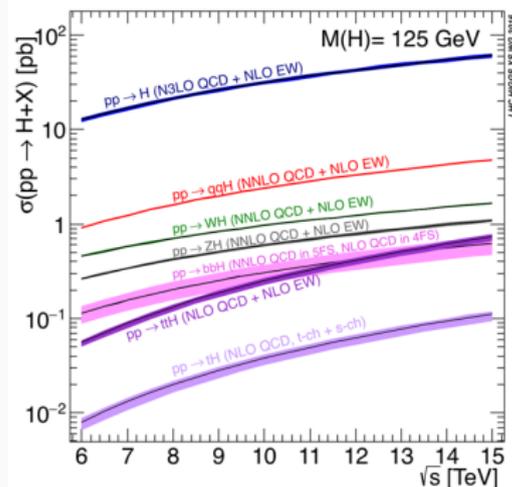
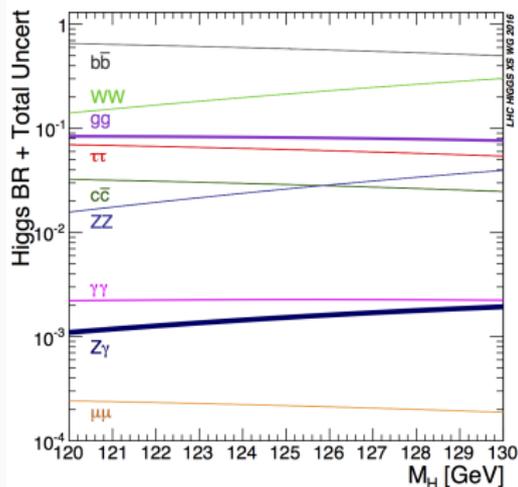
$$+ \left( \frac{1}{2} D_\mu \phi \right)^2 - V(\phi)$$

- In the SM, the Higgs mechanism provides masses to bosons and fermions
- Higgs discovery in 2012
  - ⇒ exploration of a whole new sector in the lagrangian !
- Obviously a major goal of the LHC programme



In the SM, all predictions fixed once Higgs mass is known

- Mass known at 2 per-mille level !  $m_H = 125.09 \pm 0.24$  GeV
- Very rich phenomenology at 125 GeV

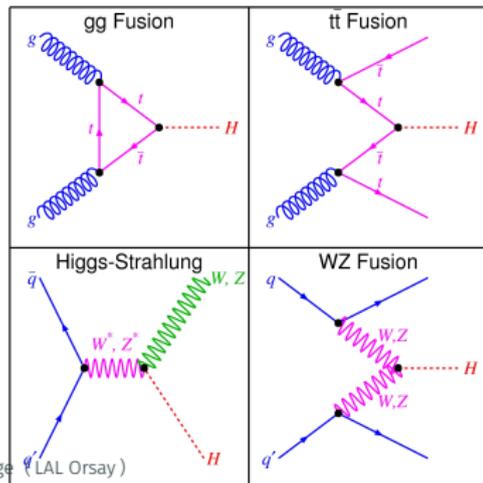
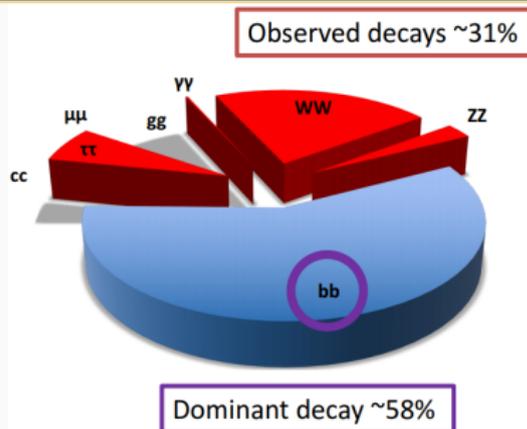


## Consequence

- Any deviation in couplings, spin/CP properties, differential distributions
- Would be a sign of new physics

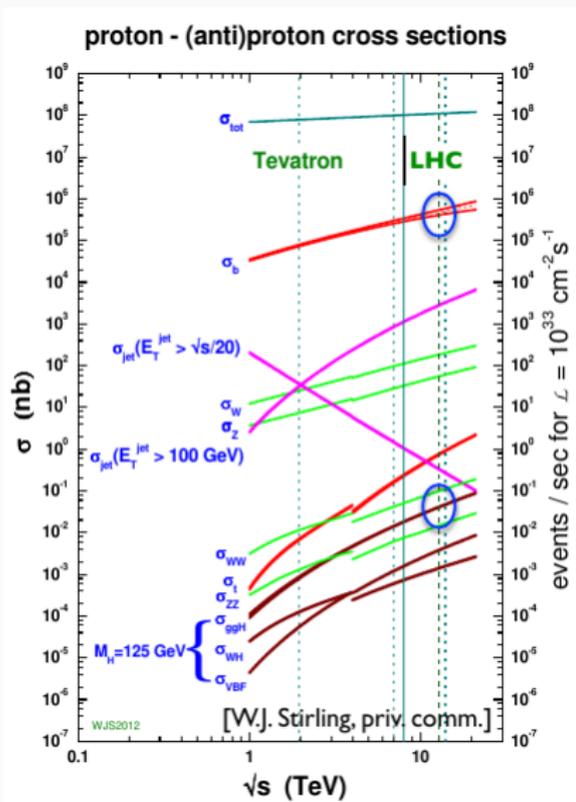
## $H \rightarrow bb$

- Important search on its own (coupling to  $b$  quark)
- Largest BR:  $\sim 58\%$
- Drives the total width, thus measurements of absolute couplings
- Limits the amount of BSM decays allowed

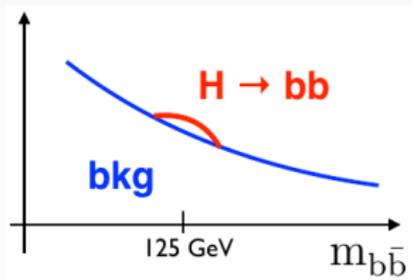


## Where to look

- ggF** Need to go to highly boosted regime (recent CMS analysis)
- VBF** Analysis à la  $H\gamma\gamma$ . Also exploits VBF+ $\gamma$  topology
- VH** Most sensitive channel
- ttH** Also important because of  $ttH$  production (direct coupling to top quark)



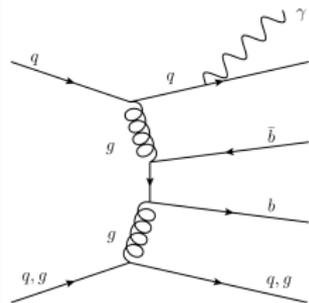
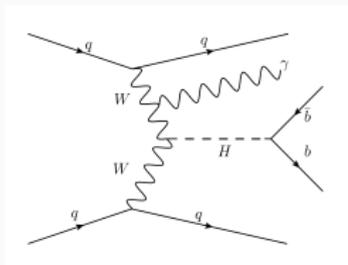
Very large production of  $b$ -jets at the LHC



- Inclusive production (2  $b$ -jets in final state) overwhelmed by bkg's by many orders of magnitude
- Signatures of associated productions help reducing the bkg's
- But although S/B can be much better, it's never very large

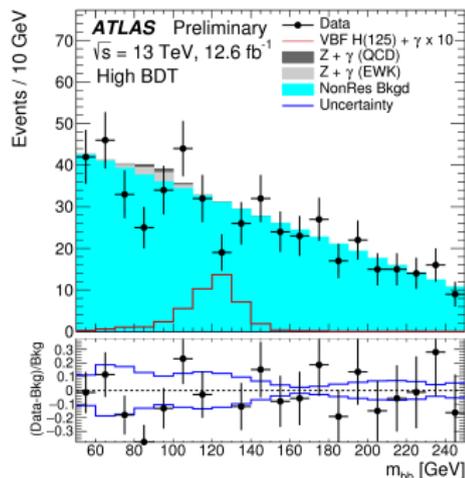
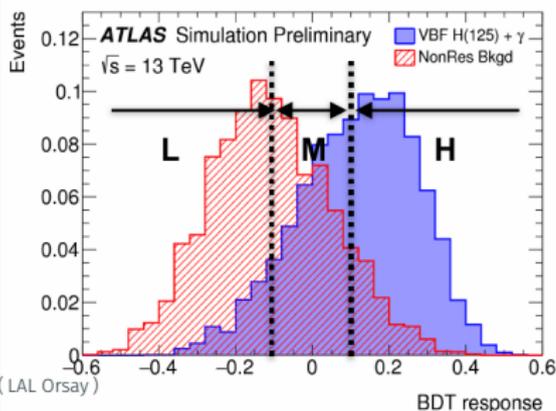
## VBF+ $\gamma$ channel

- Rare production ( $\alpha_{QED}$  compared to VBF)
- Great at triggering and suppressing background
- Even more than you think: destructive interference



## First analysis for ICHEP 2016

- ATLAS-CONF-2016-063 with partial 13 TeV data ( $12.6 \text{ fb}^{-1}$ )
- BDT to create 3 categories, then fit  $m_{b\bar{b}}$  in each of them
- $Zb\bar{b}$  as first signal to look for



Result	$H(\rightarrow b\bar{b}) + \gamma jj$	$Z(\rightarrow b\bar{b}) + \gamma jj$
Expected significance	0.4	1.3
Expected $p$ -value	0.4	0.1
Observed $p$ -value	0.9	0.4
Expected limit	6.0 $^{+2.3}_{-1.7}$	1.8 $^{+0.7}_{-0.5}$
Observed limit	4.0	2.0
Observed signal strength $\mu$	-3.9 $^{+2.8}_{-2.7}$	0.3 $\pm 0.8$

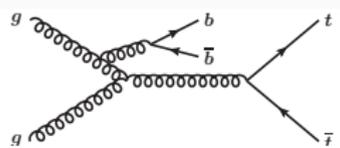
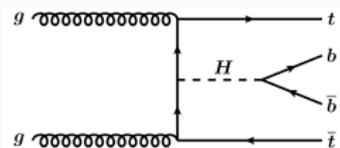
## Results

- Still rather low sensitivity
- Hugely dominated by data stat. Will be great for high lumi.
- Then large signal modelling uncertainties

Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across $\eta$	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

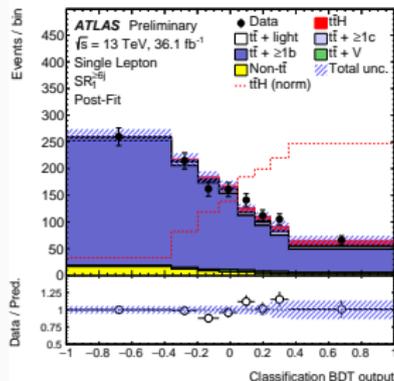
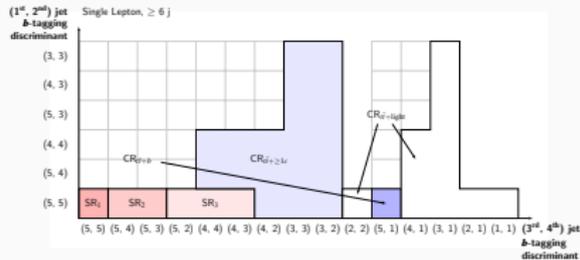
## $t\bar{t}H(bb)$ channel

- Lower production (but not much lower) than  $VH(bb)$
- Very busy topologies
- Combinatorics



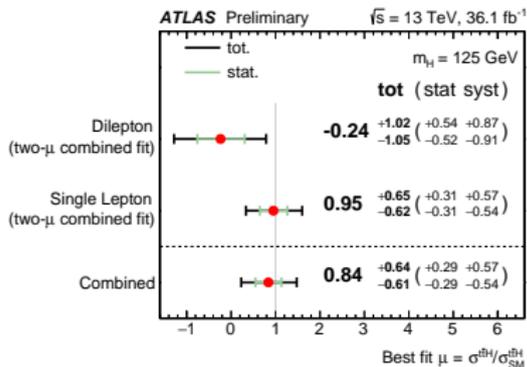
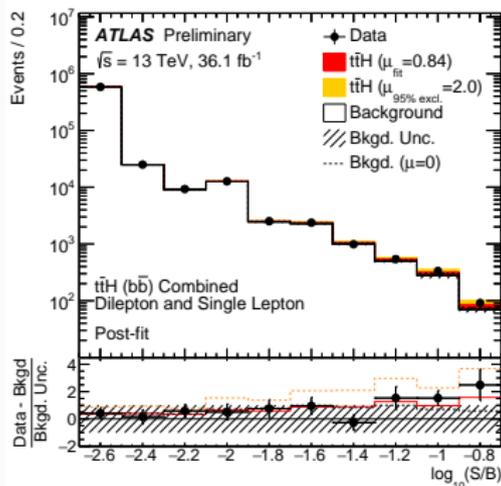
## Recent analysis with 2016 data: CONF-2017-076

- Semi-leptonic (dominant) and dileptonic  $t\bar{t}$  decays
- Many jets and  $b$ -jets in final state
- Use ML techniques to resolve the combinatorics, then to discriminate signal from backgrounds
- MEM and likelihood discriminants used as inputs to the BDTs
- Use of  $b$ -tagging distribution also very important
- Simultaneous fit of 18 SR and 20 CR



## Results

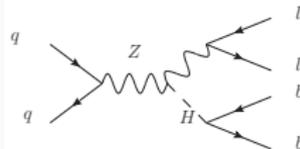
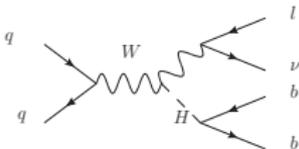
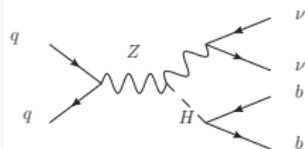
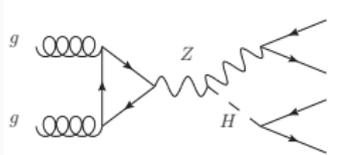
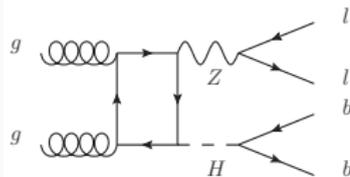
- Compatible results between the single- and di-lepton channels
- Sensitivity  $1.4\sigma$  ( $1.6\sigma$  exp)
  - Corresponds to a limit of  $2.0 \times SM$
- Extreme sensitivity to  $t\bar{t} + b\bar{b}$  modelling
- Also quite sensitive to  $b$ -tagging and jet energy scale



Uncertainty source	$\Delta\mu$
$t\bar{t} + \geq 1b$ modelling	+0.46 -0.46
Background model statistics	+0.29 -0.31
$b$ -tagging efficiency and mis-tag rates	+0.16 -0.16
Jet energy scale and resolution	+0.14 -0.14
$t\bar{t}H$ modelling	+0.22 -0.05
$t\bar{t} + \geq 1c$ modelling	+0.09 -0.11
JVT, pileup modelling	+0.03 -0.05
Other background modelling	+0.08 -0.08
$t\bar{t}$ + light modelling	+0.06 -0.03
Luminosity	+0.03 -0.02
Light lepton ( $e, \mu$ ) id., isolation, trigger	+0.03 -0.04
<b>Total systematic uncertainty</b>	<b>+0.57 -0.54</b>
$t\bar{t} + \geq 1b$ normalisation	+0.09 -0.10
$t\bar{t} + \geq 1c$ normalisation	+0.02 -0.03
Intrinsic statistical uncertainty	+0.21 -0.20
<b>Total statistical uncertainty</b>	<b>+0.29 -0.29</b>
<b>Total uncertainty</b>	<b>+0.64 -0.61</b>

## Processes

- $ZH$  and  $WH$ 
  - Leptonic decays for bkg rejection and trigger
  - 3 channels: 0, 1, 2 (charged) leptons
- $ZH$  has  $gg$  induced diagrams
  - 10% of cross-section
  - $p_T$  spectrum peaking around 140 GeV

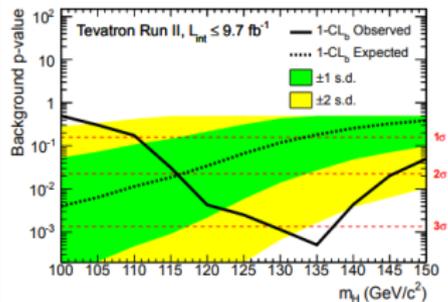


## Previous results

Tevatron legacy:  $3.1\sigma$  global,  $2.8\sigma$  at 125 GeV (1.5 exp.)

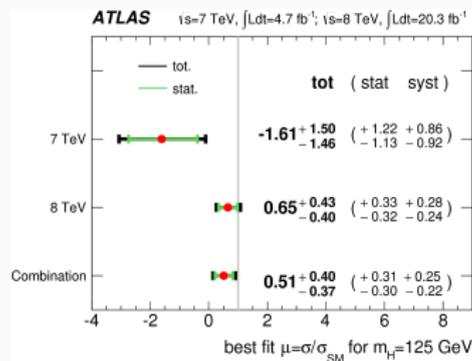
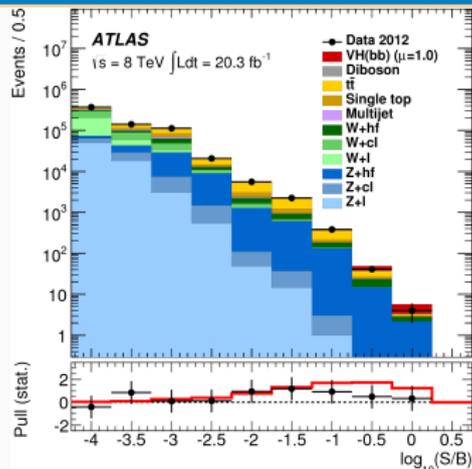
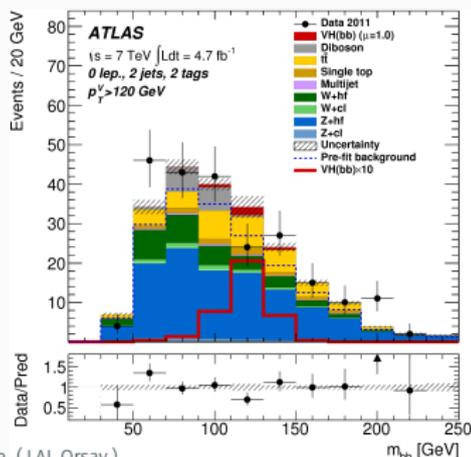
ATLAS and CMS Run 1:  $1.4\sigma$  (2.6) /  $2.1\sigma$  (2.5)

LHC combination:  $2.6\sigma$  (3.7)



## Final Run 1 analysis

- Result of major undertaking
- Highly optimized analysis, to squeeze as much sensitivity as possible ( $2.6\sigma$  exp)
- Introduction of BDTs, use of pseudo-continuous tagging
- Price: high complexity. 38 regions in MVA analysis, 92 regions in  $m_{bb}$  analysis (and almost 600 bins fitted)

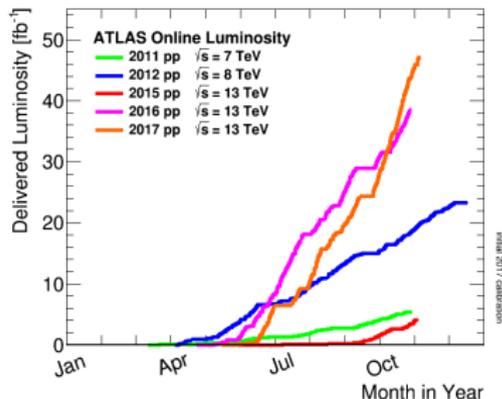


## Machine and Physics

- Run 1:  $\sim 5 + 20 \text{ fb}^{-1}$  @ 7 and 8 TeV / Run 2:  $36 \text{ fb}^{-1}$ 
  - But higher pileup
- $\sqrt{s} = 13 \text{ TeV}$ : higher cross-section  $\sim \times 2$
- Backgrounds increase as well:  $Z/W+\text{jets} \times 1.7$ , but  $t\bar{t} \times 3.3$

## First Run 2 result

- ICHEP 2016: [ATLAS-CONF-2016-091](#)
- Dataset  $13.6 \text{ fb}^{-1}$ : analysis = proof-of-concept for Run 2
- Simplify ! Keep BDTs, but remove difficult regions, and simplify use of  $b$ -tagging
- Expected sensitivity  $1.9\sigma$



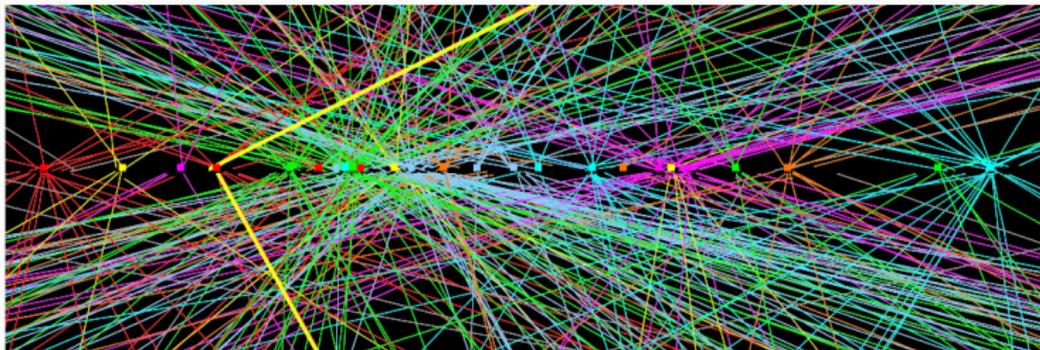
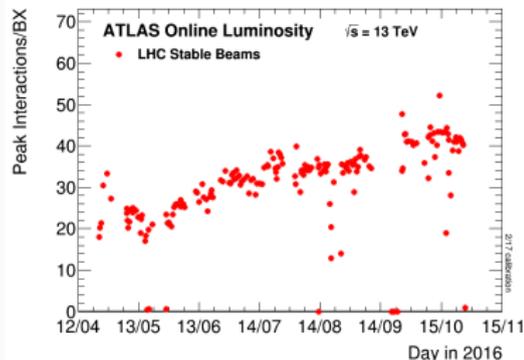
From  $13.6$  to  $36 \text{ fb}^{-1}$

General philosophy: Keep the analysis simple

- No major changes
  - Important improvements, but limited in scope.
  - Major item: background modelling and systematics
- $\Rightarrow$  more solid analysis, larger integrated lumi: key to  $3\sigma$  ?

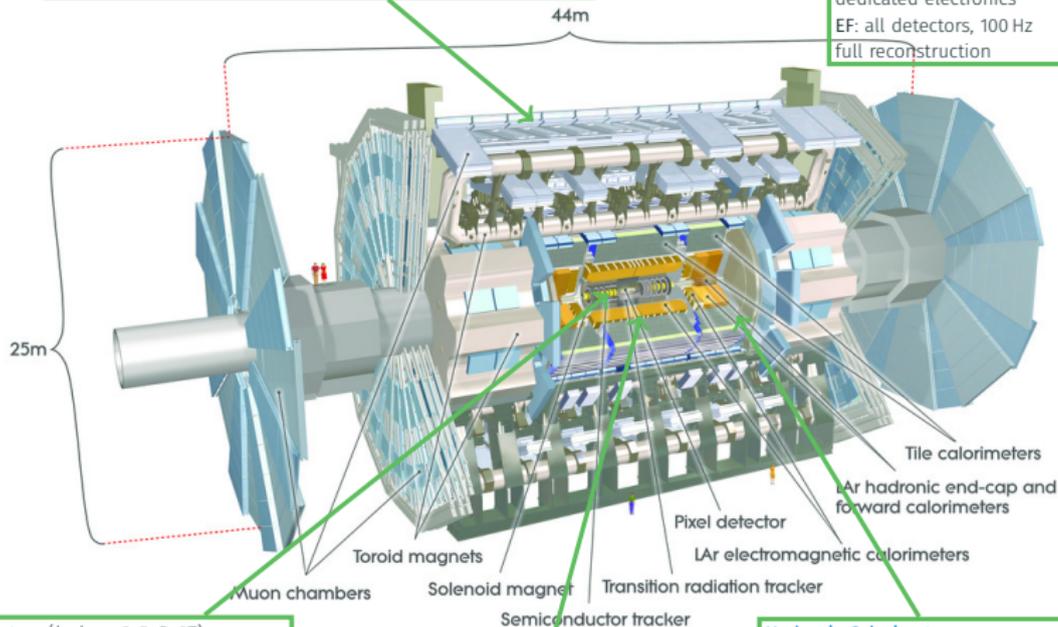
## Harsh conditions !

- Up to  $\sim 40$  PU interactions per event (routinely up to 60 in 2017...)
- Lot of work on reconstruction algorithms in ATLAS to reduce their PU dependence
- Especially jet reconstruction and  $b$ -tagging



**Muon Spectrometer:** ( $|\eta| < 2.7$ )  
 Air toroid with drift chambers,  
 Provides  $\mu$  trigger and momentum measurement,  
 Resolution  $< 10\%$  up to  $p \sim 1$  TeV.

**Trigger System:**  
 3 levels  
 L1: calo and muons, 100 kHz  
 dedicated electronics  
 EF: all detectors, 100 Hz  
 full reconstruction



**Inner Detector:** ( $|\eta| < 2.5, B=2T$ )

Si Pixels, SCT, TRT  
 Precision tracking,  
 Vertex reconstruction,  
 $e/\pi$  separation  
 $\sigma/p_T \sim 3.8 \cdot 10^{-4} p_T \oplus 0.015$

**EM Calorimeter:** ( $|\eta| < 3.2$ )

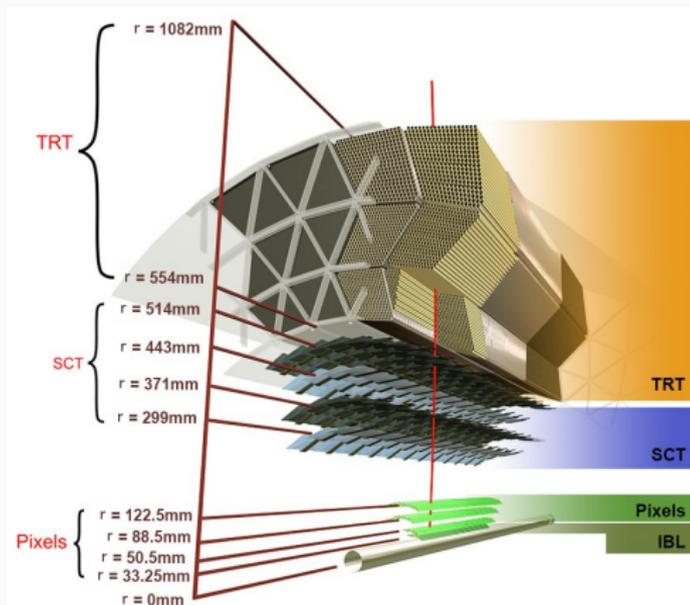
Pb-LAr, accordion structure  
 Provides trigger on  $e/\gamma$ ,  
 Identification and measurement  
 $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

**Hadronic Calorimeter:**

Scint/Fe tiles in barrel ( $|\eta| < 1.7$ )  
 W/Cu-LAr in endcaps ( $|\eta| < 4.9$ )  
 Provides jet trigger and energy measurement,  
 $\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$   
 Hermetic coverage for MET

## ATLAS Inner detector

- Made of 3 sub-detectors: Silicon Pixel, Silicon Strip and TRT
- New innermost layer IBL installed during LS1
  - Comes with a smaller, thinner beam pipe:  $R = 3.3$  cm
  - Smaller pixel size ( $50 \times 250 \mu\text{m}$ )
  - More radiation hard
- $b$ -tagging in general and  $H(bb)$  in particular one of the main motivations for the upgrade !

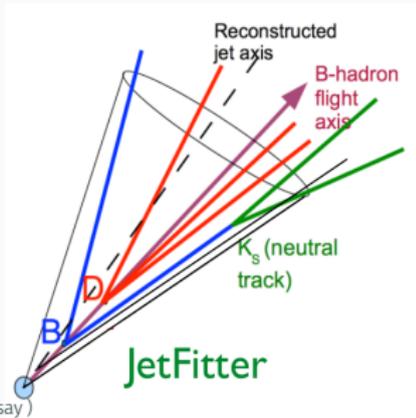


## *b*-tagging

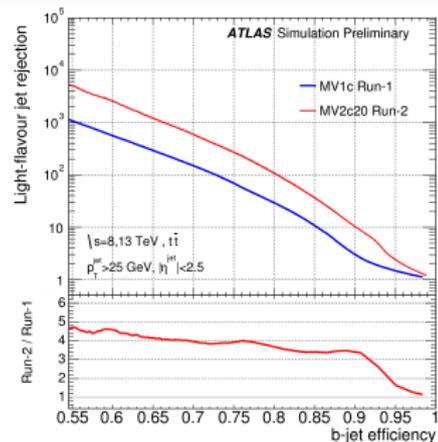
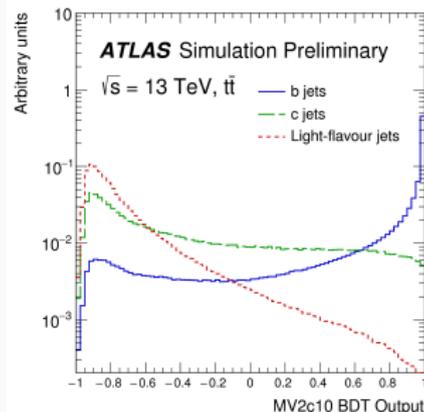
- Algorithms to identify jets from *b* hadrons
- Use track impact parameters, and reconstruction of secondary vertices

## Run 2 performance

- Typical performance: 70%/8.2%/0.3% *b/c*/light efficiency
- Large improvement compared to Run 1, esp. on *c*-jet rejection
  - Tracking optimized for high-PU environments
  - Better algorithms + new IBL
- Makes it easier to use only events with 2 good *b*-tags



N. Morange (LAL Orsay)



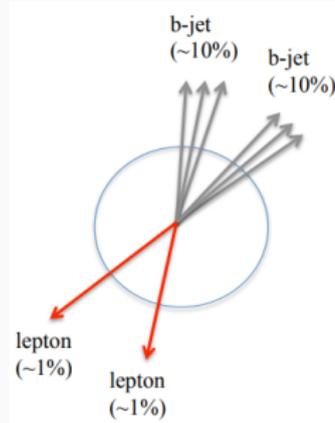
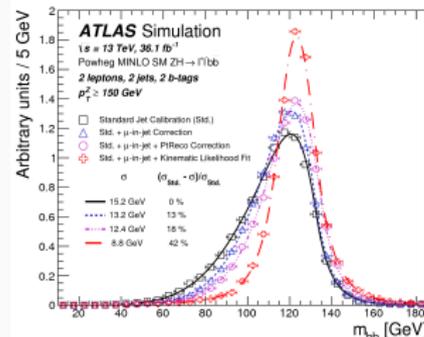
## Mass resolution improvements

We have 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.
- Improvement  $\sim 18\%$

## Kinematic Fit

- 2 leptons: final state fully reconstructed
- High resolution on leptons
- Constrain jet kinematics better:  
 $\sum p_T(\ell) = p_T(bb)$  modulo intrinsic  $k_T$
- Improvement  $\sim 40\%$



## Z+hf, W+hf

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

## Diboson WZ, ZZ

- Peaking at lower mass than the signal
- Larger cross-section
- Softer  $p_T(V)$  spectrum
- Sherpa 2.2.1

## Conclusions

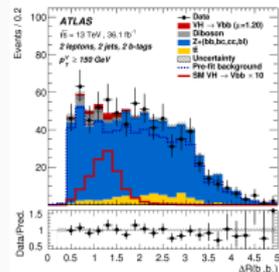
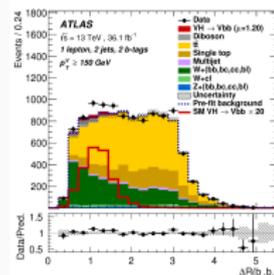
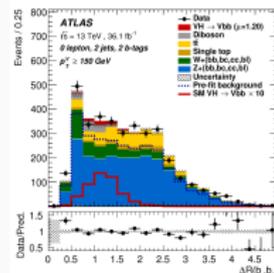
- $m_{bb}$ ,  $\Delta R(b, b)$  very powerful variables
- Better S/B at higher  $p_T(V)$
- S/B depends on number of jets in the event
- Measurement of diboson process excellent validation of the analysis

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

- 2 lepton: same final state as signal
- 0 and 1 leptons: additional jets, and/or missing leptons
- Powheg+Pythia

## Multijet

- Very large cross-section and high rejection factors
- Channel-dependent
- Data-driven

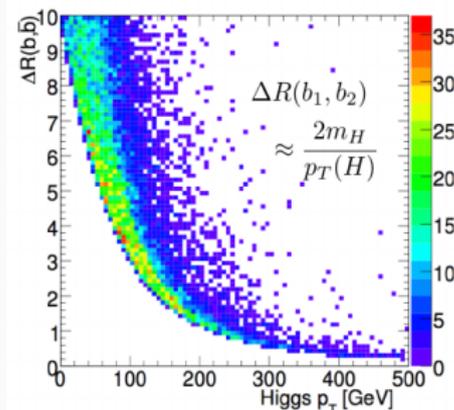
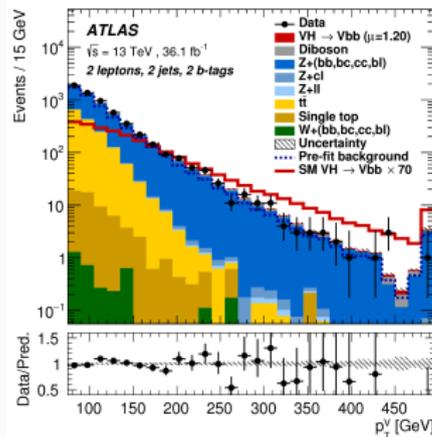


## Improving S/B

- Much harder spectrum for signal than bkg
- Going to high- $p_T$  improves S/B
- Use it for event classification:  
 $75 < p_T(V) < 150 \text{ GeV}, p_T(V) > 150 \text{ GeV}$
- Add it in our MVAs as well
- Need large bkg statistics in tails of distributions !

## Topology

- $H \rightarrow b\bar{b}$  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  $t\bar{t}$



## Z selection

- MET trigger
- MET > 150 GeV
- Veto leptons  $p_T > 7$  GeV

## Higgs candidate

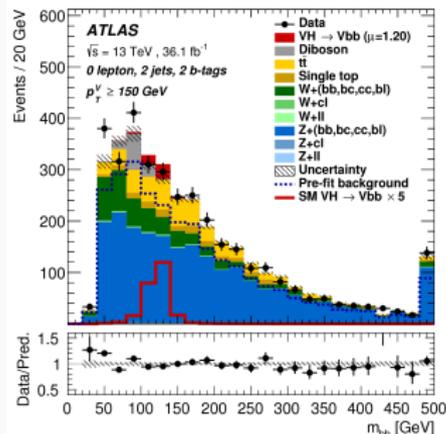
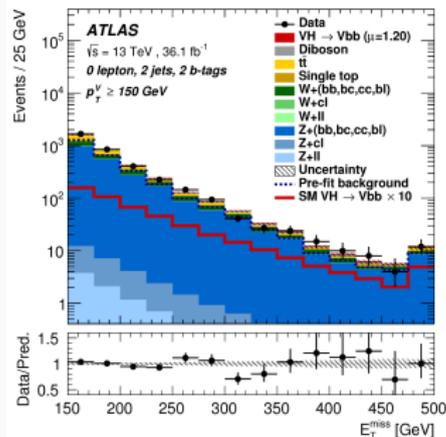
- 2  $b$ -tagged jets. Leading  $p_T > 45$  GeV
- 1 additional jet max

## Anti-QCD

- $\min(\Delta\phi(E_T^{\text{miss}}, \text{jets})) > 20^\circ / 30^\circ$  if 2 / 3 jets
- $\Delta\phi(E_T^{\text{miss}}, bb) > 120^\circ$
- $\Delta\phi(b1, b2) < 140^\circ$
- $\Delta\phi(E_T^{\text{miss}}, E_{T,\text{trk}}^{\text{miss}}) < 09^\circ$

## Signal Acceptance

- ~20% of expected signal events are  $WH(\tau\nu)$
- acceptance for  $ggZH$  70% larger than for  $qqZH$ 
  - Due to harder  $p_T(V)$  spectrum



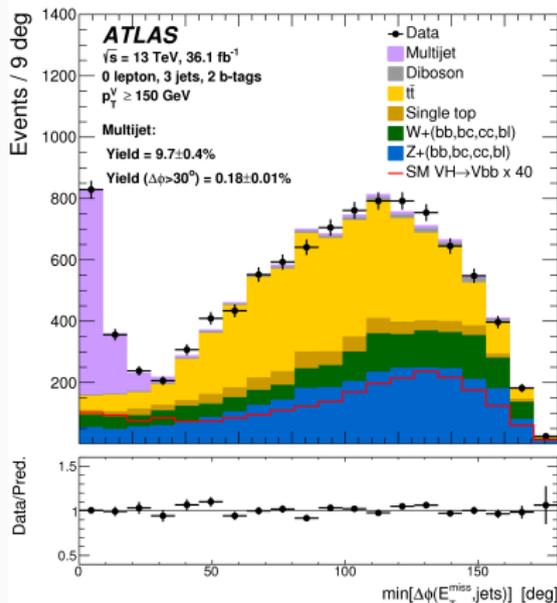
## Multijet events

- Typically arise from jets with large fluctuations in their interaction
- MET aligned with jet
- Cuts on  $\min(\Delta\phi(E_T^{\text{miss}}, \text{jets}))$ ,  $\Delta\phi(E_T^{\text{miss}}, bb)$ ,  $\Delta\phi(b1, b2)$  extremely efficient

⇒ Negligible remaining multijet contribution

## Non-collisional backgrounds

- Usual backgrounds for hadronic final states
- Negligible when requiring 2  $b$ -tags



## W selection

- Single-electron or MET trigger
- Well identified, isolated electron ( $>27$  GeV) or muon ( $>25$  GeV)
- Veto additional leptons  $p_T > 7$  GeV
- $p_T(W) > 150$  GeV

## Higgs candidate

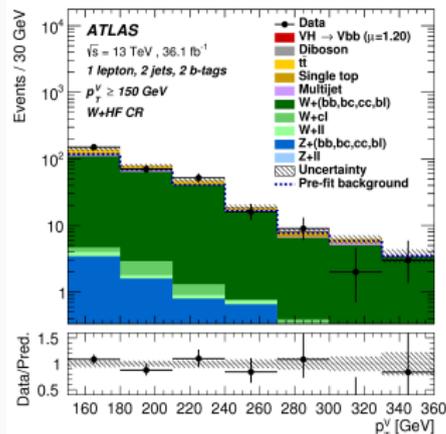
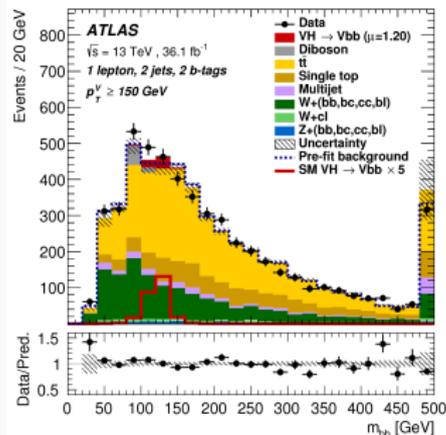
- 2  $b$ -tagged jets. Leading  $p_T > 45$  GeV
- 1 additional jet max

## Anti-QCD

- MET  $> 30$  GeV in electron channel

## W+hf control region

- $m_{bb} < 75$  GeV and  $m_{top} > 225$  GeV
- $>75\%$  pure

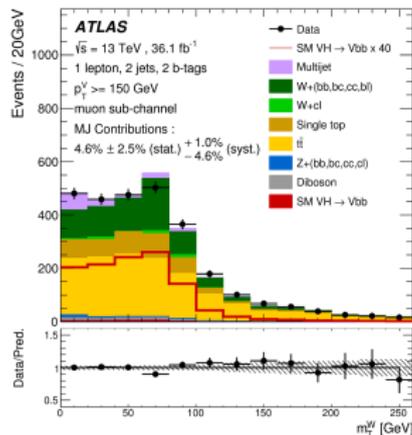
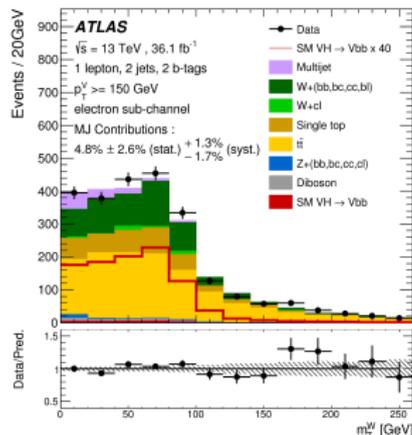


## Multijet events

- From semi-lep decays, or from hadrons (electron channel)
- Reduced by tightening the lepton isolation and ID criteria
- Isolation tuned for the analysis (need tight isolation at high- $p_T$ )

## Multijet estimation

- Separate in electron and muon events
- Templates from inverted isolation
- Corrected for bias in kinematics
- Normalization from fit to  $m_T(W)$



## Z selection

- Single-lepton triggers
- 2 electrons or muons. Leading  $p_T > 27$  GeV, subleading  $p_T > 7$  GeV
- Z mass:  $81 < m_{\ell\ell} < 101$  GeV
- $75 < p_T(Z) < 150$  GeV, or  $p_T(Z) > 150$  GeV

## Higgs candidate

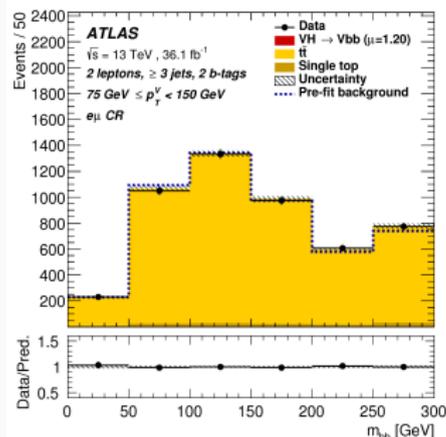
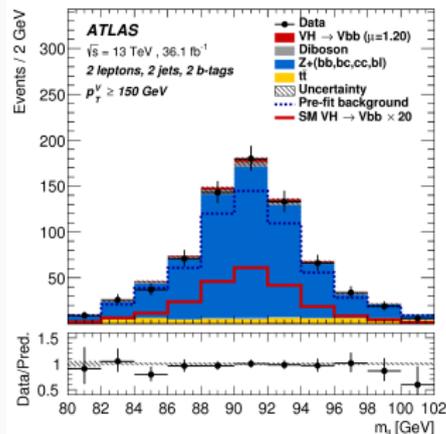
- 2  $b$ -tagged jets. Leading  $p_T > 45$  GeV
- 0, or  $\geq 1$  additional jets

## Top $e\mu$ control region

- Opposite-flavour events
- 99% pure

## Signal Acceptance

- acceptance for  $ggZH$  twice larger than for  $qqZH$ 
  - Due to harder  $p_T(V)$  spectrum

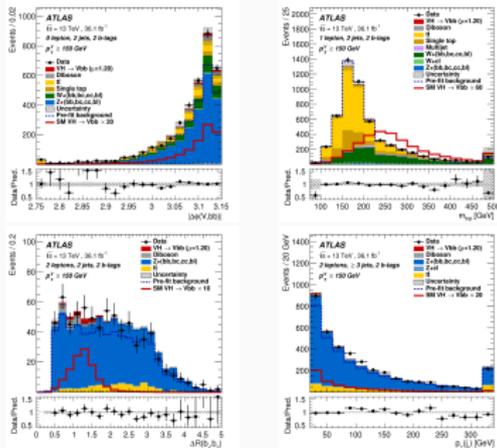


## MVA setup

- Pretty standard BDT analysis
- Input variables and hyper-parameters tuned to yield best sensitivity

## Variables

- Kinematic variables, some specific to 3-jet regions
- $m_{bb}$ ,  $\Delta R(b, b)$  and  $p_T(V)$  most important ones
- Others depend on channel, e.g  $m_{\ell\ell}$  in 2-lepton



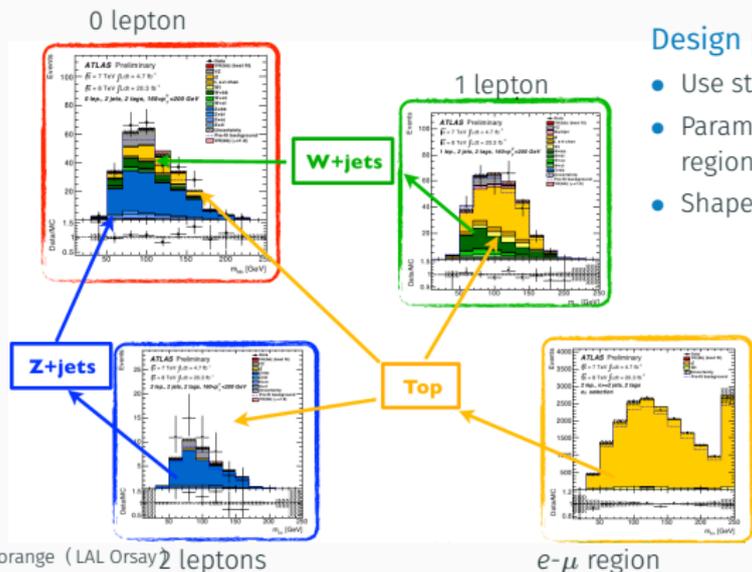
Variable	0-lepton	1-lepton	2-lepton
$p_T^V$	$\equiv E_T^{\text{miss}}$	×	×
$E_T^{\text{miss}}$	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
$m_{bb}$	×	×	×
$\Delta R(\vec{b}_1, \vec{b}_2)$	×	×	×
$ \Delta\eta(\vec{b}_1, \vec{b}_2) $	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$ \Delta\eta(\vec{V}, \vec{bb}) $			×
$m_{\text{eff}}$	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
$m_T^W$		×	
$m_{\ell\ell}$			×
$m_{\text{top}}$		×	
$ \Delta Y(\vec{V}, \vec{bb}) $		×	
	Only in 3-jet events		
$p_T^{\text{jet}_3}$	×	×	×
$m_{bbj}$	×	×	×

## Philosophy

- Large backgrounds with many differences
- Bkg composition varies significantly over a large phase space
- Want to constrain modelling of bkg from data
  - Use as many regions as possible
- Much easier when cuts and phase space are similar among the channels
- Requires delicate understanding of the extrapolation from one region to another

## Design principles

- Use state-of-the-art MC generators
- Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields
- Shape uncertainties on BDTs

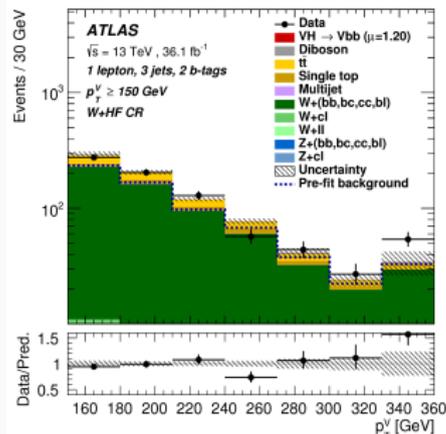
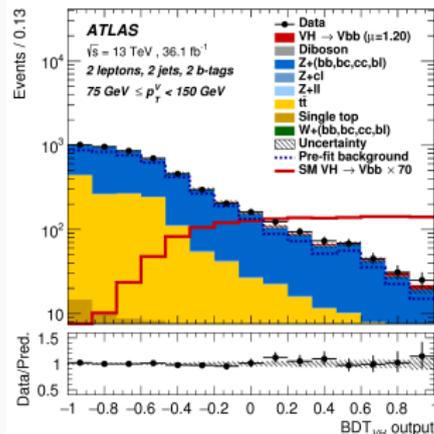


## Principle

- Rely on MEPS@NLO (multi-jet merging at NLO) with up to 2 extra jets
  - 2 lepton low  $p_T(V)$  can constrain  $Z$  normalizations, shapes
  - 1 lepton Whf CR constrains  $W$  norm.
- ⇒ Normalization factors  $\sim 1.25$
- Extrapolations to 0-lepton or 1-lepton SR needed
  - Uncertainties on flavour composition
  - BDT shapes: through  $m_{bb}$  and  $p_T(V)$  variations

$Z + \text{jets}$	
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
$Z + bb$ normalisation	Floating (2-jet, 3-jet)
$Z + bc\text{-to-}Z + bb$ ratio	30 - 40%
$Z + cc\text{-to-}Z + bb$ ratio	13 - 15%
$Z + bl\text{-to-}Z + bb$ ratio	20 - 25%
0-to-2 lepton ratio	7%
$m_{bb}, p_T^V$	S
$W + \text{jets}$	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
$W + bb$ normalisation	Floating (2-jet, 3-jet)
$W + bl\text{-to-}W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc\text{-to-}W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc\text{-to-}W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
$W + HF$ CR to SR ratio	10% (1-lepton)
$m_{bb}, p_T^V$	S

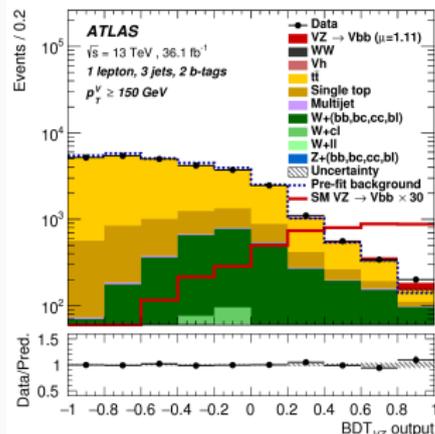
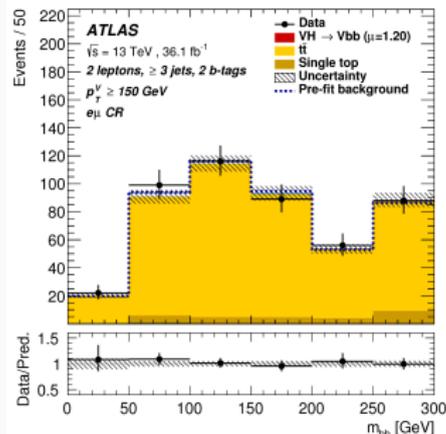
N. Morange (LAL Orsay)



## Principle

- 2 lepton vs 0/1 lepton: different phase space
- 2 lepton  $e\mu$  and 0/1 lepton 3-jet regions very pure
- Normalization factors:  $\sim 0.9$  for 0/1 lepton,  $\sim 1.0$  for 2-lepton
- Uncertainties needed for extrapolation to 0/1 lepton 2-jet regions
- BDT shapes: through  $m_{bb}$  and  $p_T(V)$  variations

$t\bar{t}$ (all are uncorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1 lepton only)
$W$ + HF CR to SR ratio	25%
$m_{bb}, p_T^V$	S
Single top quark	
Cross-section	4.6% ( $s$ -channel), 4.4% ( $t$ -channel), 6.2% ( $Wt$ )
Acceptance 2-jet	17% ( $t$ -channel), 35% ( $Wt$ )
Acceptance 3-jet	20% ( $t$ -channel), 41% ( $Wt$ )
$m_{bb}, p_T^V$	S ( $t$ -channel, $Wt$ )



## Multijet in 1 lepton

- Large shape and norm. effects on the data-driven estimate

## Signal and Diboson

- No constraints from data
- Follow standard recipes for systematics
- Signal: Separate systematics on production (correlated with other channels in future Higgs combinations) from acceptance effects

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations (var.)	10 – 18% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	5.6% (0-lepton), 5.8% (2-lepton)
Acceptance from PS/UE var. for 3 jets	7.3% (0-lepton), 3.1% (2-lepton)
$m_{bb}, p_{T,1}^V$ , from scale var.	S (correlated with WZ uncertainties)
$m_{bb}, p_{T,1}^V$ , from PS/UE var.	S (correlated with WZ uncertainties)
$m_{bb}$ , from matrix-element var.	S (correlated with WZ uncertainties)

WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale var.	13 – 21% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	3.9%
Acceptance from PS/UE var. for 3 jets	11%
$m_{bb}, p_{T,1}^V$ , from scale var.	S (correlated with ZZ uncertainties)
$m_{bb}, p_{T,1}^V$ , from PS/UE var.	S (correlated with ZZ uncertainties)
$m_{bb}$ , from matrix-element var.	S (correlated with ZZ uncertainties)

WW	
Normalisation	25%

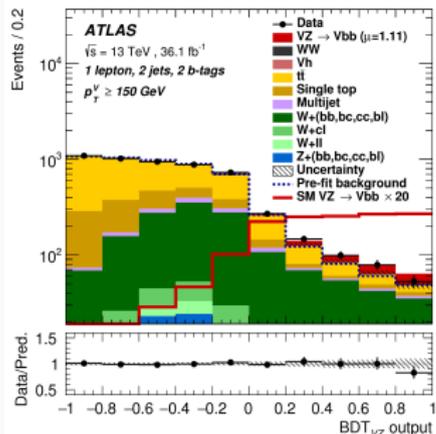
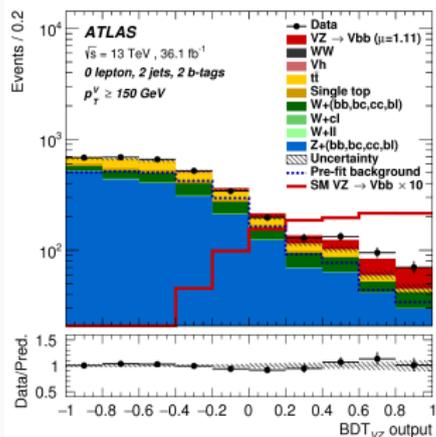
Signal	
Cross-section (scale)	0.7% ( $qq$ ), 27% ( $gg$ )
Cross-section (PDF)	1.9% ( $qq \rightarrow WH$ ), 1.6% ( $qq \rightarrow ZH$ ), 5% ( $gg$ )
Branching ratio	1.7 %
Acceptance from scale variations (var.)	2.5 – 8.8% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	10 – 14% (depending on lepton channel)
Acceptance from PS/UE var. for 3 jets	13%
Acceptance from PDF+ $\alpha_S$ var.	0.5 – 1.3%
$m_{bb}, p_{T,1}^V$ , from scale var.	S
$m_{bb}, p_{T,1}^V$ , from PS/UE var.	S
$m_{bb}, p_{T,1}^V$ , from PDF+ $\alpha_S$ var.	S
$p_{T,1}^V$ from NLO EW correction	S

## A must-have for $VHbb$

- Train the BDTs to look for  $WZ + ZZ$  instead of  $VH$
- Done before looking at  $VH$
- Robust validation of background model and associated uncertainties
- Critical to convince ourselves we are ready to unblind !

## Analysis strategy

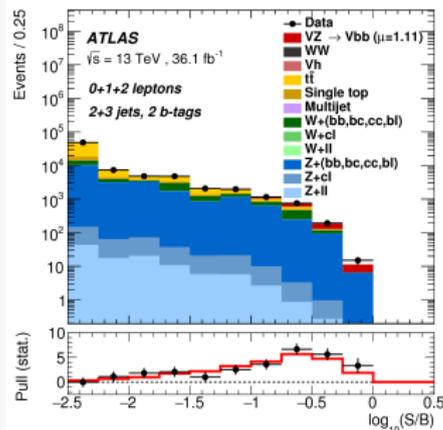
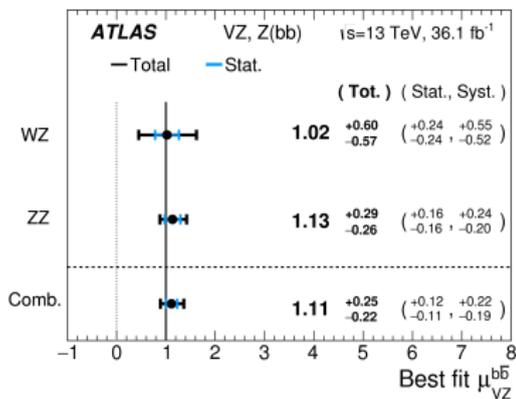
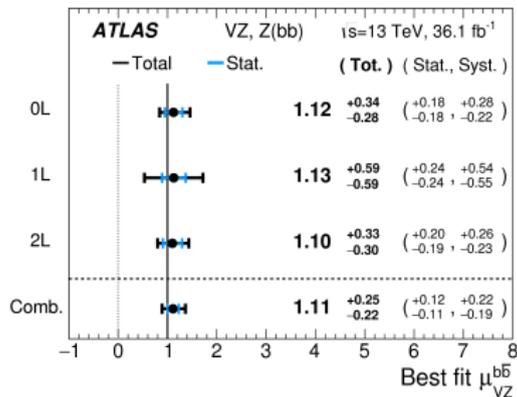
- One main likelihood fit
- BDT in the 8 SR
- $m_{bb}$  in the 4 top  $e\mu$  CR
- Normalization in the 2  $W+hf$  CR
- Systematics parametrized as nuisance parameters



## Results

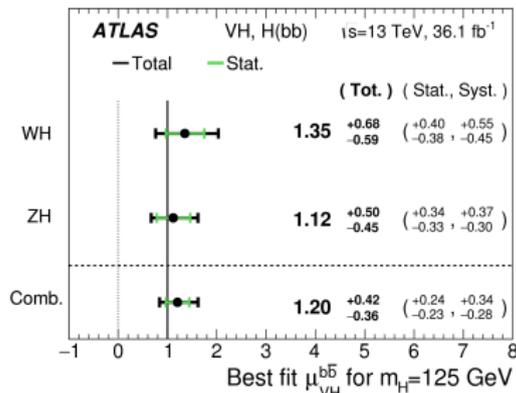
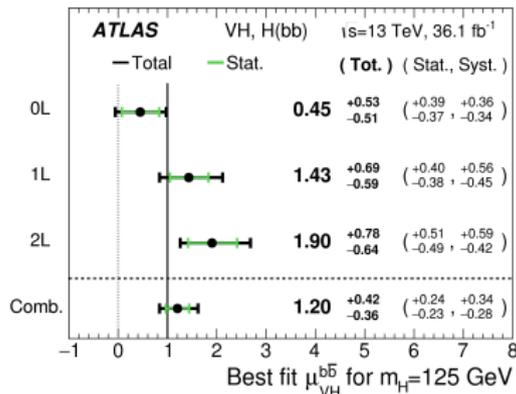
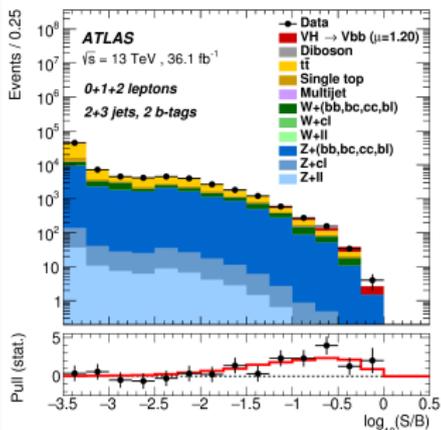
- Clear observation:  $5.8\sigma$  (5.3 exp.)
- Agreement with SM
- Excellent agreement between channels
- Much better sensitivity to ZZ than to WZ: combinatorics ; impact of low  $p_T(V)$  region

⇒ Ready to unblind  $VH$ !



## We have it !

- Evidence for  $bb$  decay at  $3.5\sigma$  (3.0 exp.)
- Dominated by systematics
- Channels compatible at 10% level
- $2.4\sigma$  for  $WH$ ,  $2.6\sigma$  for  $ZH$ :  $VHbb$  most sensitive channel for  $VH$  production
- As cross-sections:
  - $\sigma(WH) \times B(Hbb) = 1.08^{+0.54}_{-0.47}$  pb
  - $\sigma(ZH) \times B(Hbb) = 0.57^{+0.26}_{-0.23}$  pb

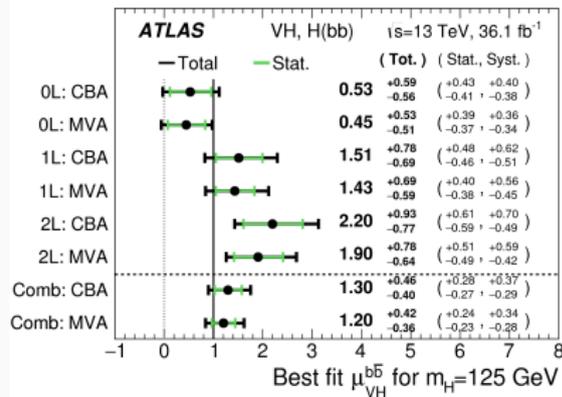
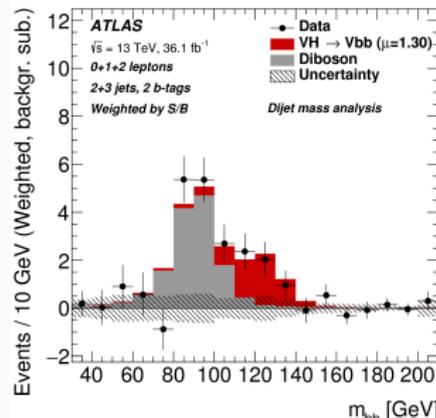
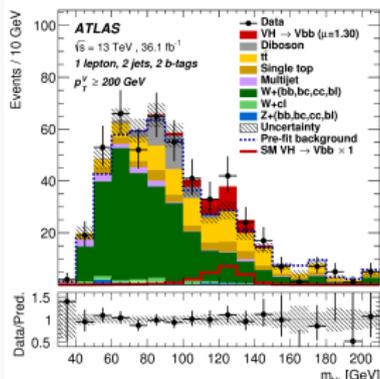


## $m_{bb}$ fit

- Important cross-check to test robustness of result
- Cut  $p_T(V) > 150$  GeV into 150 – 200 and  $> 200$  GeV
- Add simple cuts on:  $\Delta R(b, b)$ ,  $m_T(W)$  (1 lepton),  $E_T^{\text{miss}}$  significance (2 lepton)
- Then fit  $m_{bb}$  !

## Results

- Evidence at  $3.5\sigma$  ( $2.8\sigma$  exp.)
- Consistent with MVA in all channels



## What limits us on the road to $5\sigma$ ?

**b-tagging** both  $b$  and  $c$  jet tagging corrections

- Will improve with time

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

- Better generators ?
- Understand better differences between generators
- Reduce uncertainties through specific SM measurements
- More data-driven approaches

**Signal modelling** dominated by PS/hadronization

- Needs better understanding of our MCs

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

- Improve on MC filters
- Not easy in all cases, e.g  $t\bar{t}$  phase space in 0/1-lepton
- Improve on MC generation speed

Source of uncertainty		$\sigma_\mu$
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_T^{\text{miss}}$		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		
$Z + \text{jets}$		0.07
$W + \text{jets}$		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

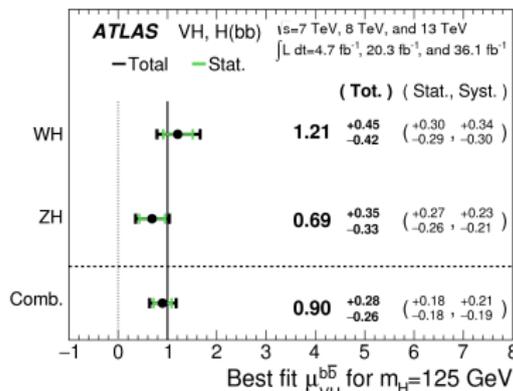
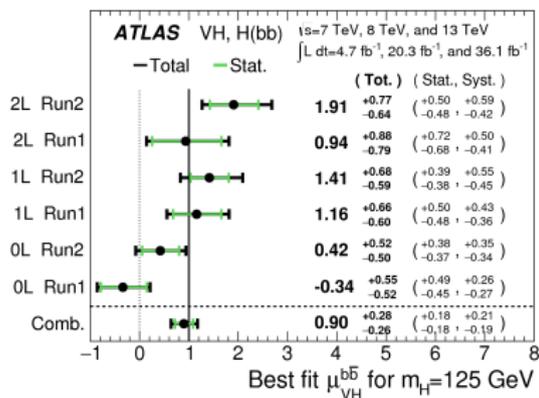
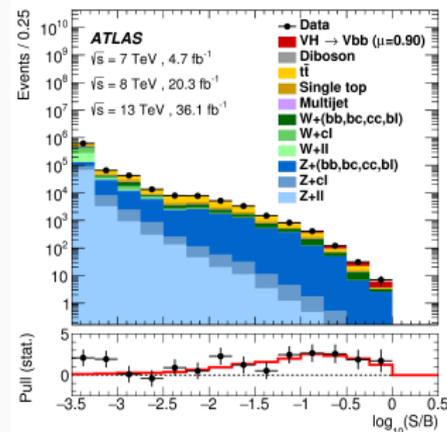
## Combination

### How to correlate systematics ?

- Difficult to be sure in many cases (e.g  $b$ -tagging, when new detector / new algo ?)
- Correlate  $b$ -jet energy scale uncertainty, and Higgs production cross-sections
- Test that other correlations have little impact

## Results

- Evidence at  $3.6\sigma$  (4.0 exp.)
- Compatibility of the 6 measurements: 7%

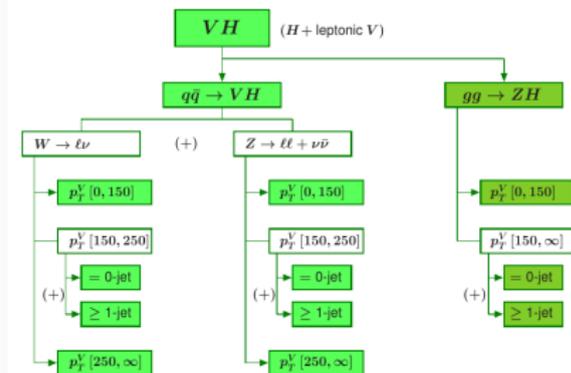
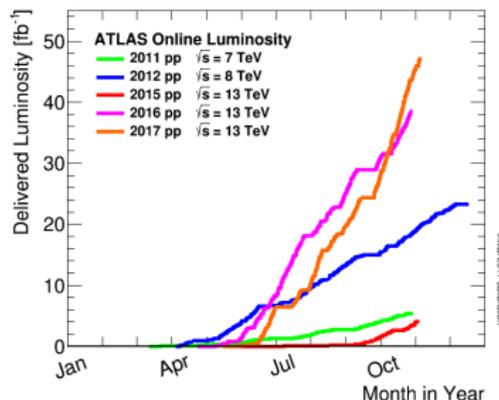


Next step: observation !

- 2017: more stat than 2016 !
- Without systematics, observation would be a no-brainer
- Hard work needed on MC stat generation, background modelling,  $b$ -tagging calibration

Signal Template Cross-sections (?)

- Standardized definition of fiducial regions for Higgs productions
- Fiducial definitions not too far from what can be achieved with differential measurements
- Allows easy combination of Higgs channels and across experiments
- Allows interpretation in EFT bases
- Goal for  $VH(bb)$ :  $p_T(V)$  measurement

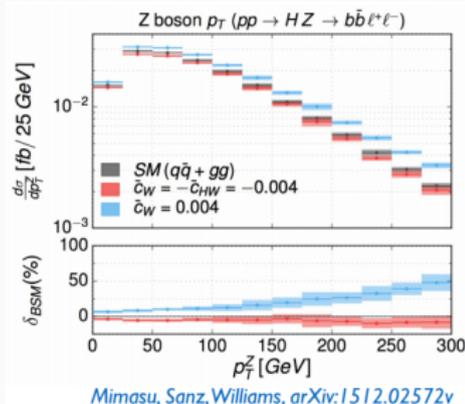
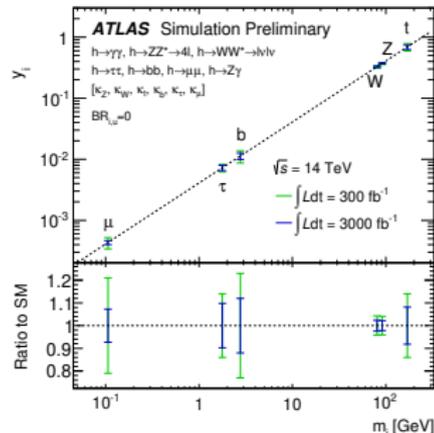
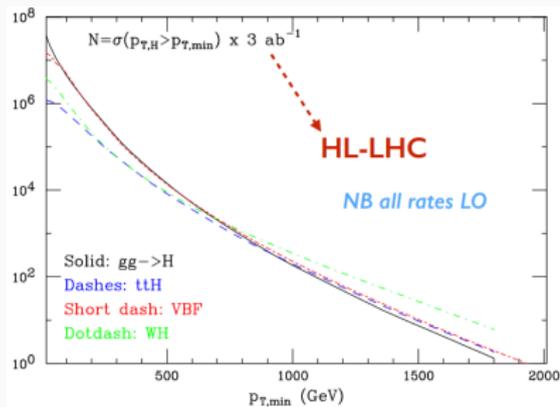


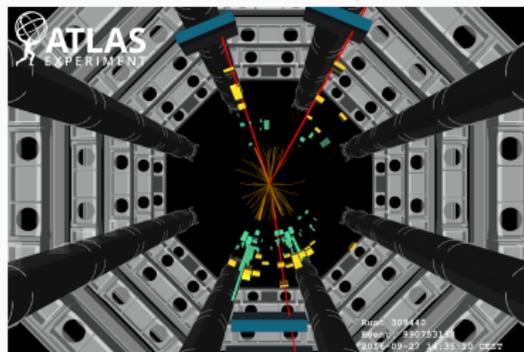
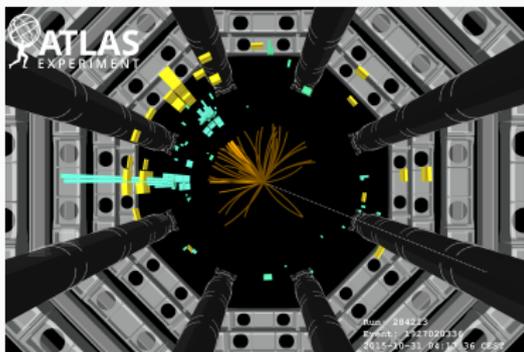
## Couplings

- Projections from ATLAS and CMS
- Coupling to  $b$ -quarks known in the 5–10% range ?
- Very much dependent on the systematics we can achieve

## What for ?

- Deviations from New Physics can be mostly at high- $p_T$
- $VH$  dominates total Higgs x-sec for  $p_T(H) > 800$  GeV !
- Decent statistics expected even in this regime





- Evidence for  $Hbb$  decay at  $3.6\sigma$  in ATLAS
  - [arXiv:1708.03299](https://arxiv.org/abs/1708.03299)
- Similar result by our CMS colleagues
  - [arXiv:1709.07497](https://arxiv.org/abs/1709.07497)
- Interesting to look in all production modes
  - As evidenced by the nice  $VBF+\gamma$  or  $t\bar{t}H(bb)$  results
- Systematically limited in several channels
  - Adding more data will bring diminishing returns
  - Need to reduce systematics
- Next goals: observation and measurements !

