Evidence for Higgs boson production in decays to two b-quarks using the ATLAS detector

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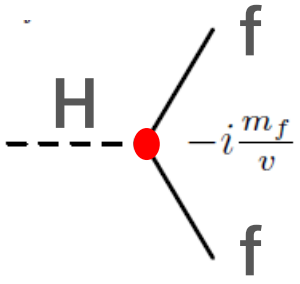
On behalf of the ATLAS collaboration

ICHEP 2018, Seoul, Korea 2018 July 5th

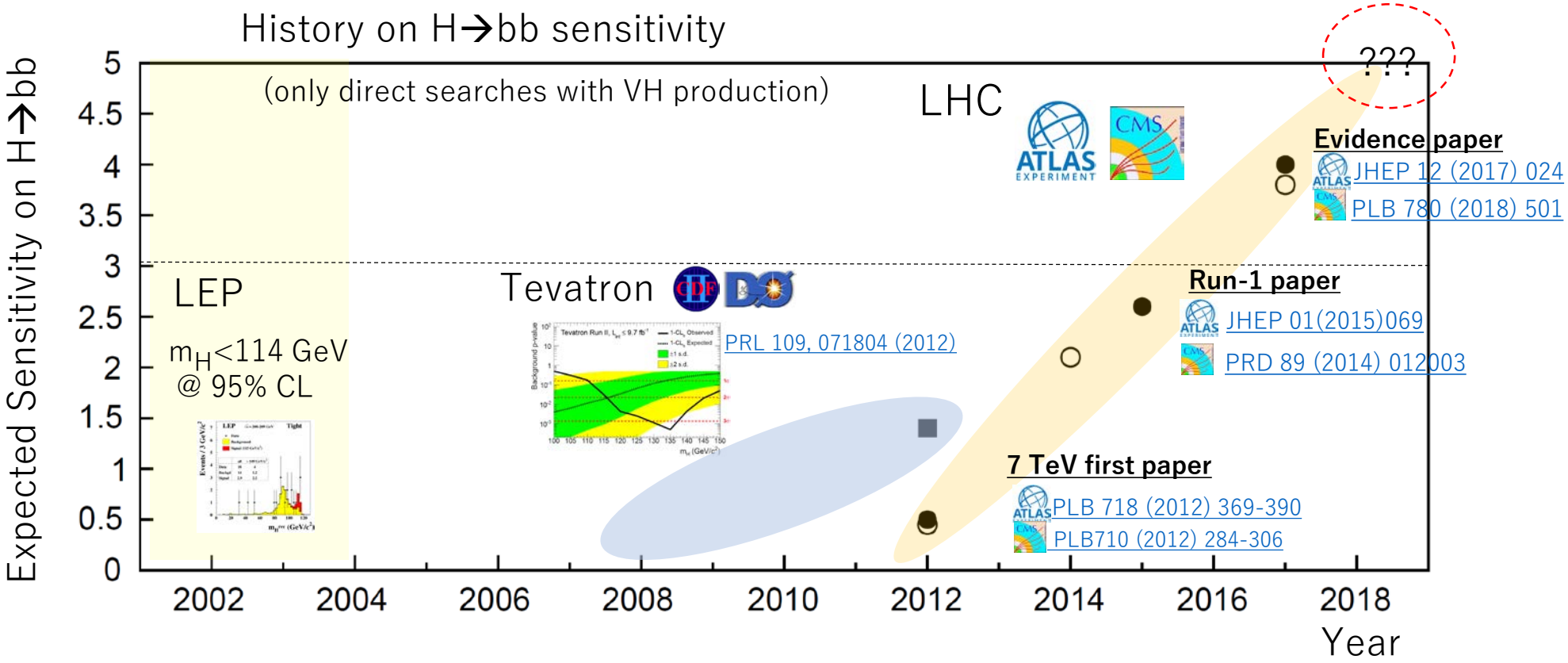
Road to discovery of H→bb

- Higgs mechanism: EWSB and Yukawa coupling.
- H→bb was one of key channels for Higgs search.
- Started in LEP era, developed in Tevatron, then LHC.

$$\frac{g_f}{\sqrt{2}} = \frac{m_f}{v}$$



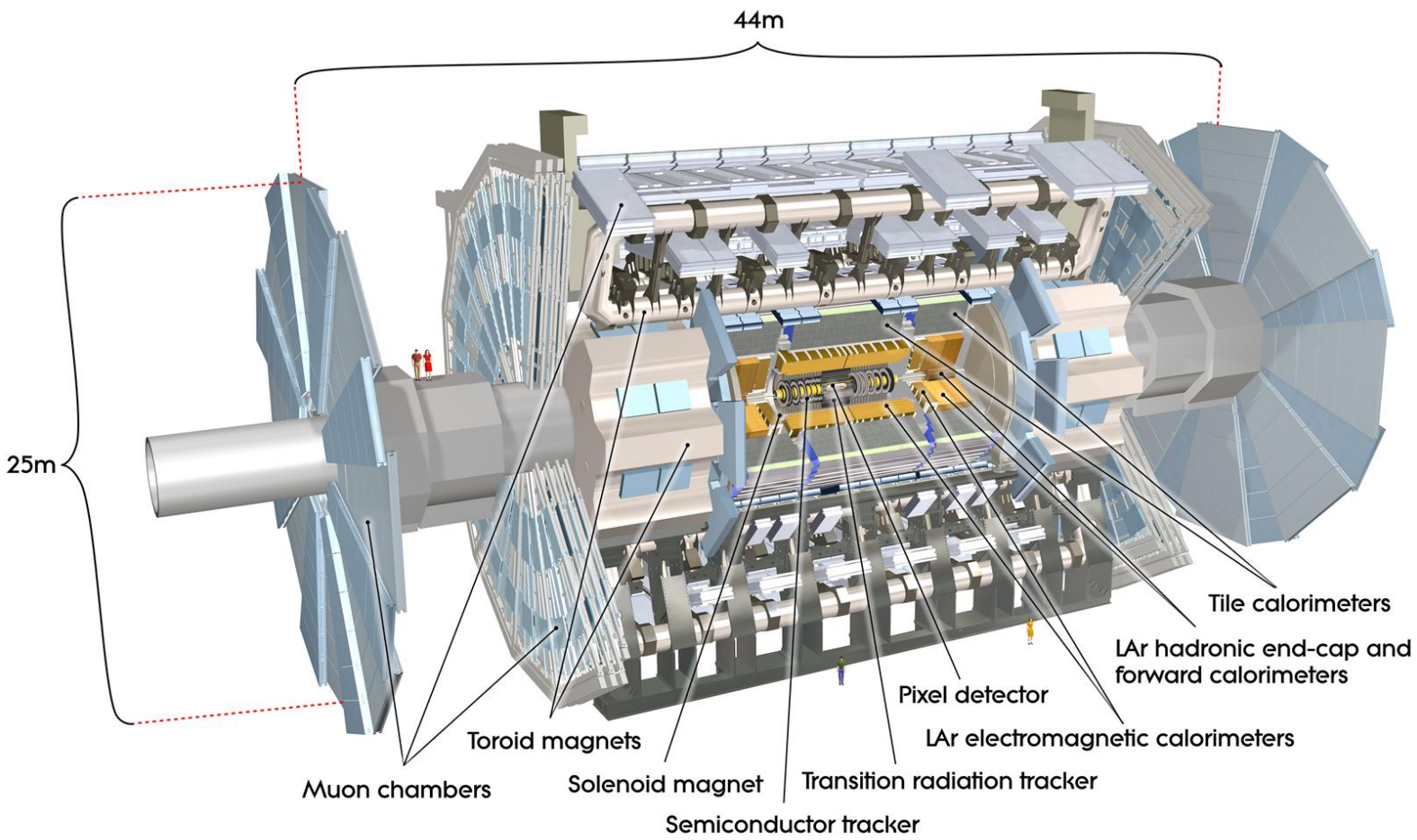
History on H→bb sensitivity

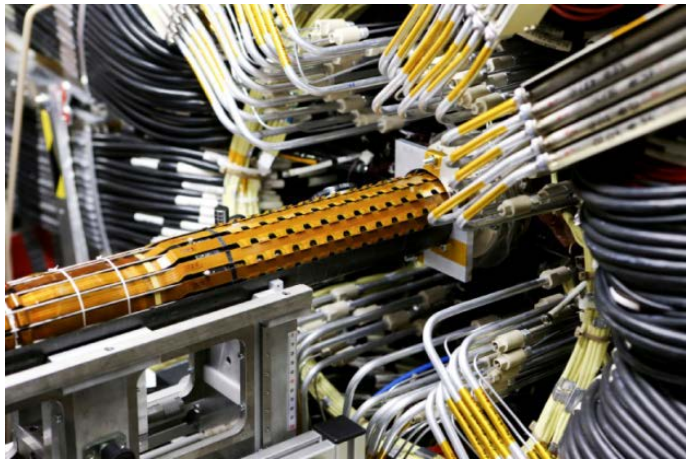


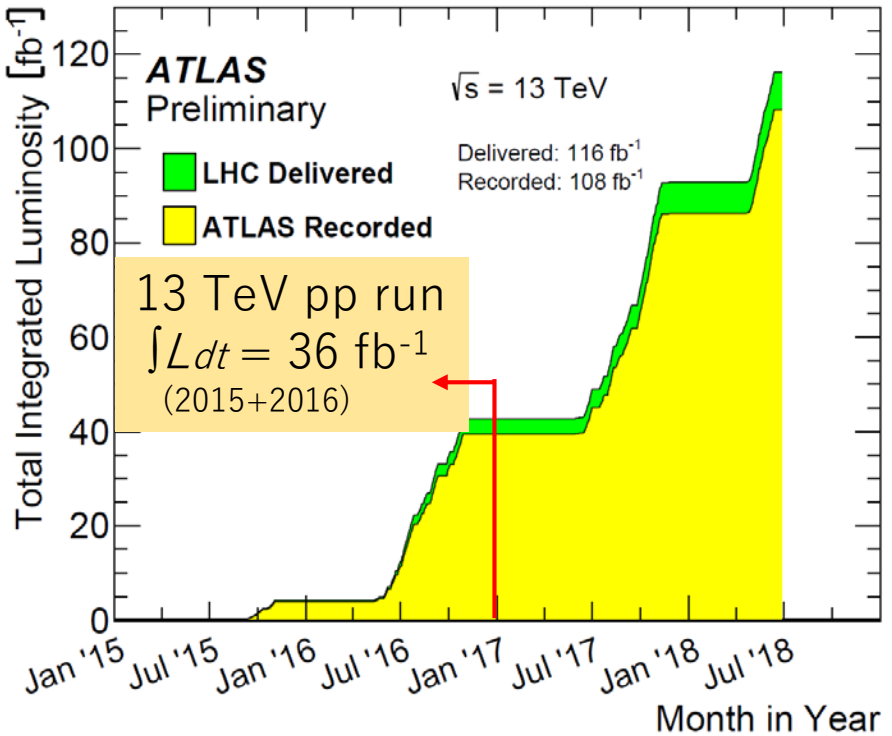
H→fermion BR at m_H = 125 GeV

Decay	Br
bb	58 %
ττ	6.3 %
cc	2.9 %
μμ	0.022 %

ATLAS detector







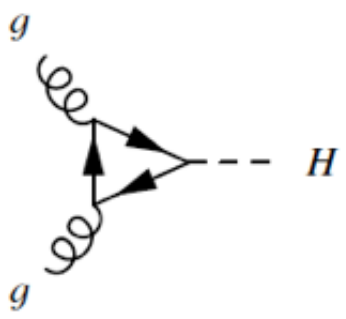
- General purpose detector
- Excellent vertex detector for b-tagging.

H→bb searches with VH, VBF and ttH

- H→bb is hadronic final state
  → need a clear signature for trigger at hadron collider

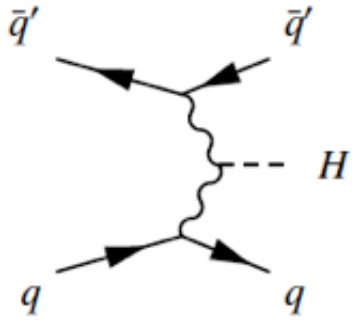
Xsec @ 13 TeV

ggF: σ = 43.9 pb



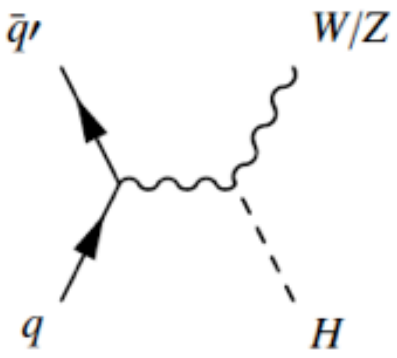
Largest production
Tough to use due to huge multi-jet background
(CMS uses boosted channel.)

VBF: σ = 3.7 pb



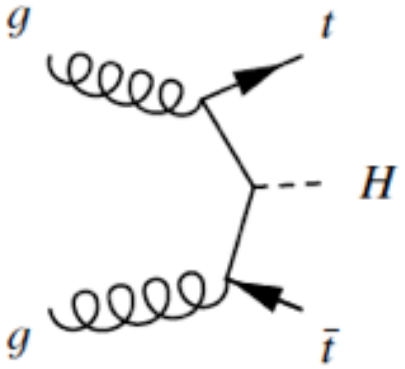
Signature of Forward jets
→ can be triggered.
Photon associated VBF signature enhances sensitivity!
→ see next page.

VH: σ = 2.3 pb



High pT lepton from W or Z boson.
→ Trigger & suppress multi-jet background.
Main channel for H→bb!

ttH: σ = 0.50 pb



Signature of ttbar pair
→ can be triggered.
- all hadronic
  - lepton(s) w/ H→bb
  - multi-leptons
  - H→γγ
→ Y. Horii's presentation. (7th July afternoon)

H→bb with VBF production

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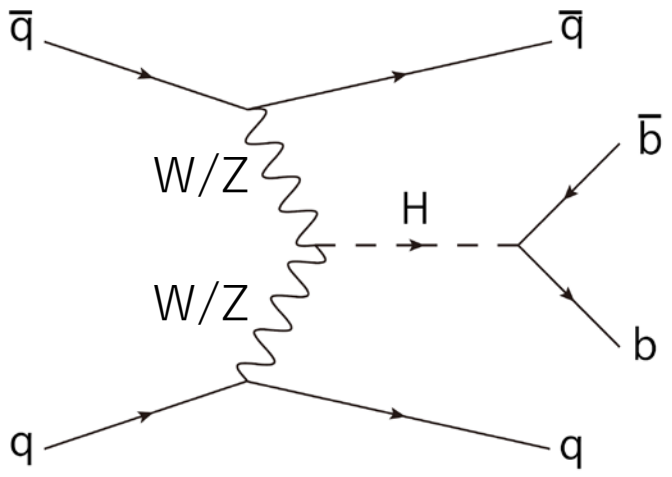

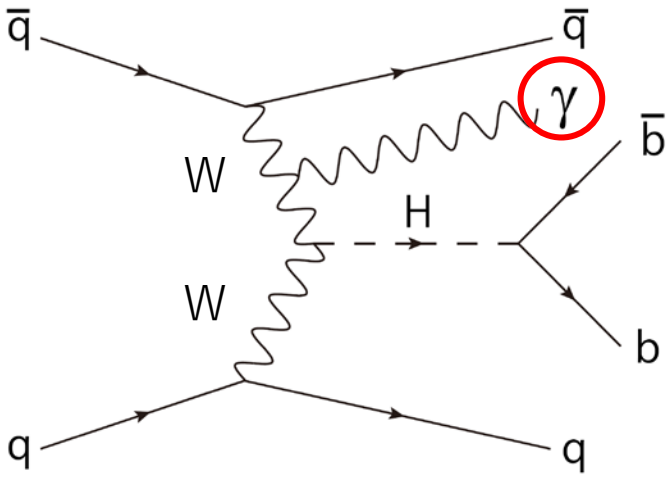

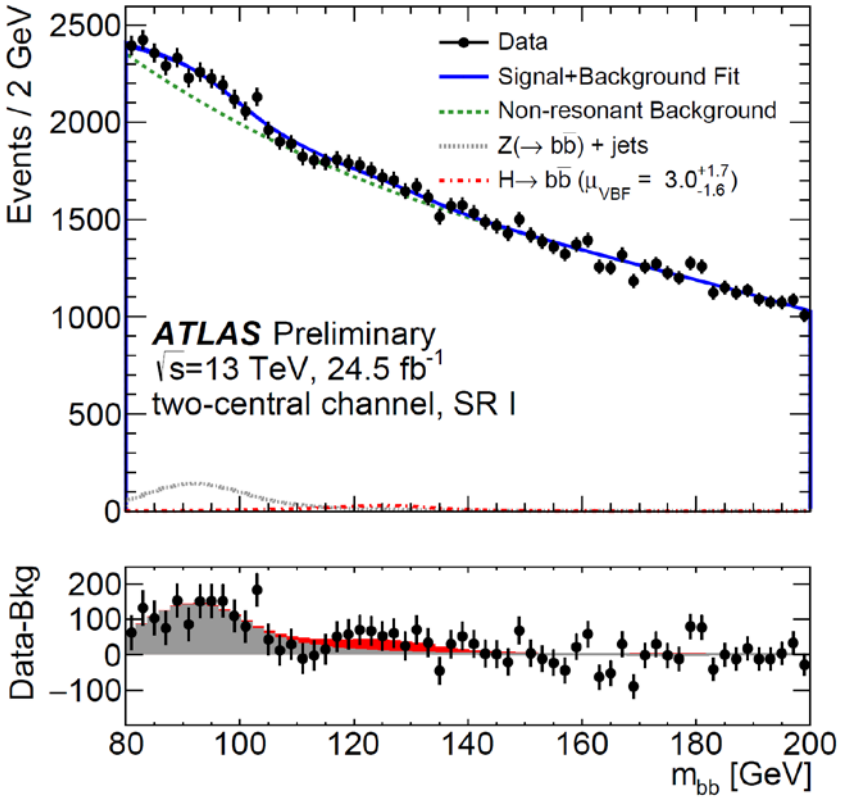

VBF all hadronic:

Two channels to "tag" VBF:

- Two-central
  w/ Forward jet ($3.2 < |\eta| < 4.4$)
- Four-central
  all VBF jets in $|\eta|<2.5$

VBF+photon:

Two forward jet ($3.2 < |h| < 4.4$)
+ **1 high pT photon**

→ good for Trigger

→ suppress gluon initiated BGs.

due to **negative interference** btw **initial** and **final** state radiation.
(this makes also suppress ZZ fusion.
therefore, WW fusion is dominant)

For details: Nucl. Phys. B 781 64-84

- Final discriminant is m_{bb}.
- Background
  - Multi-jet : qqbb(γ) background
  - Z→bb + jets

H→bb with VBF production

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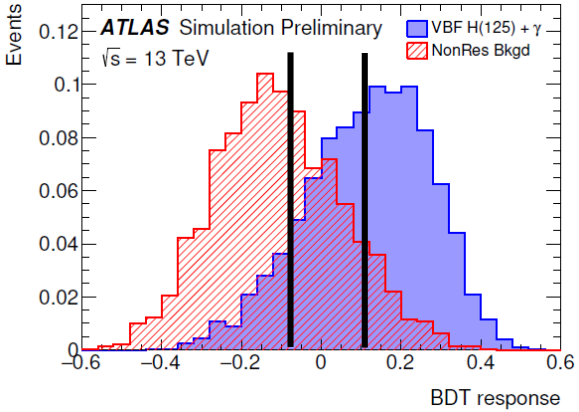
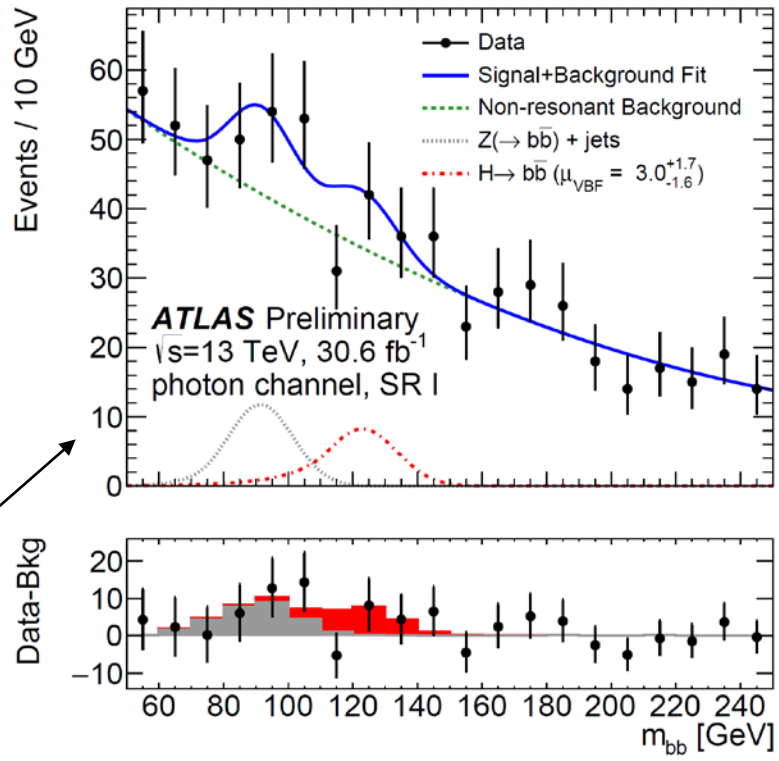
- Both analyses use Boosted Decision Tree to make signal categories.

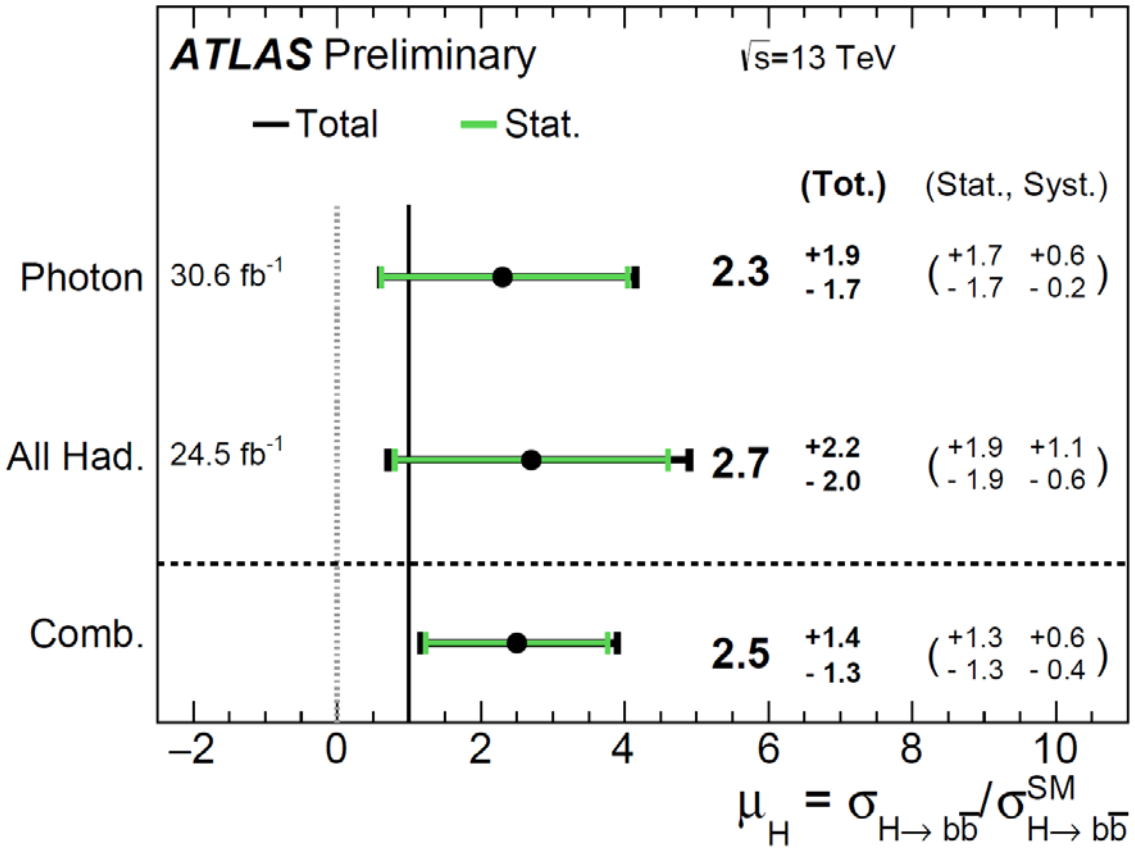
VBF+photon:



Split into three regions
- Low (BDT <-0.1)
- Middle (|BDT|<0.1)
- High (BDT>0.1)



Combined result (all had + VBFγ)



Need more data to observe Hbb with VBF process

Reconstruction of VH

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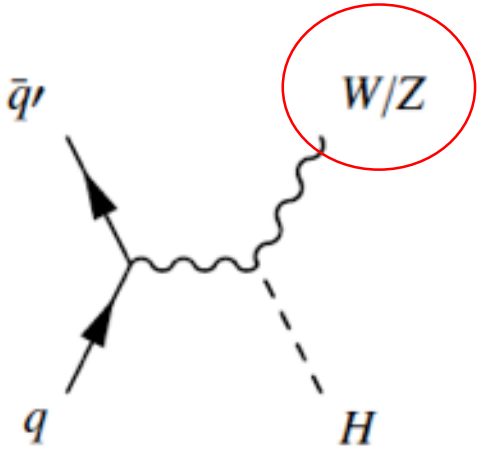
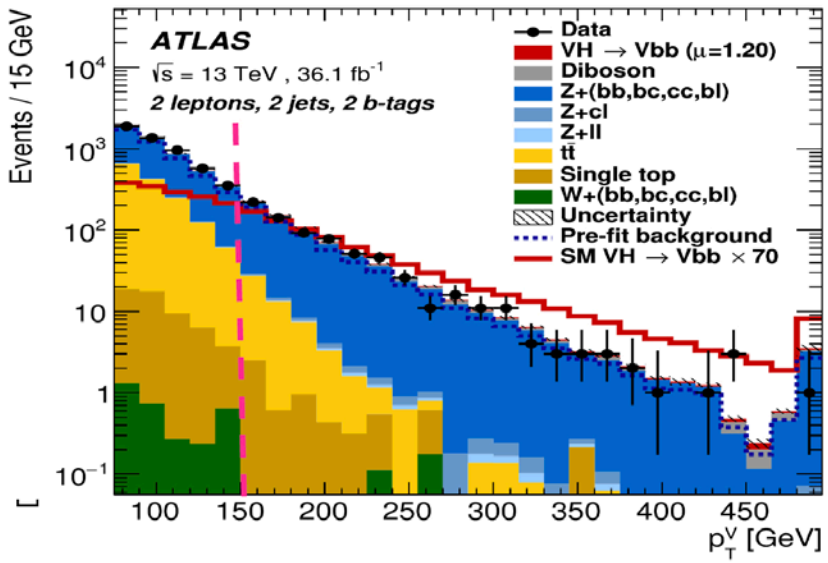
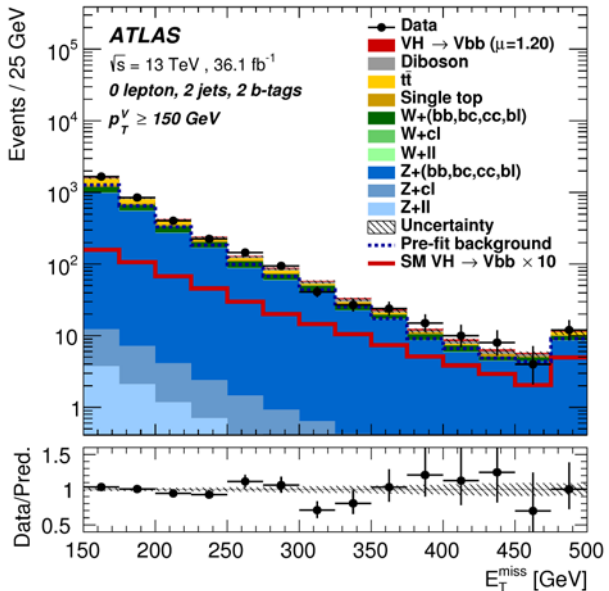
- Reconstruction of W or Z



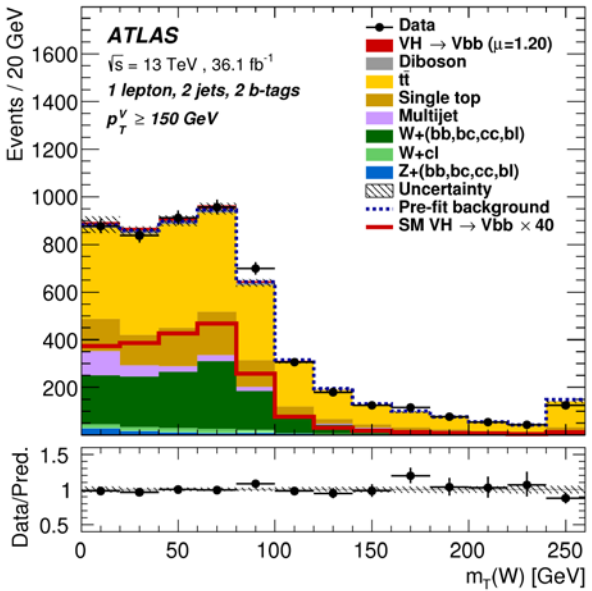


S/B is enhanced as function of $p_T(V)$

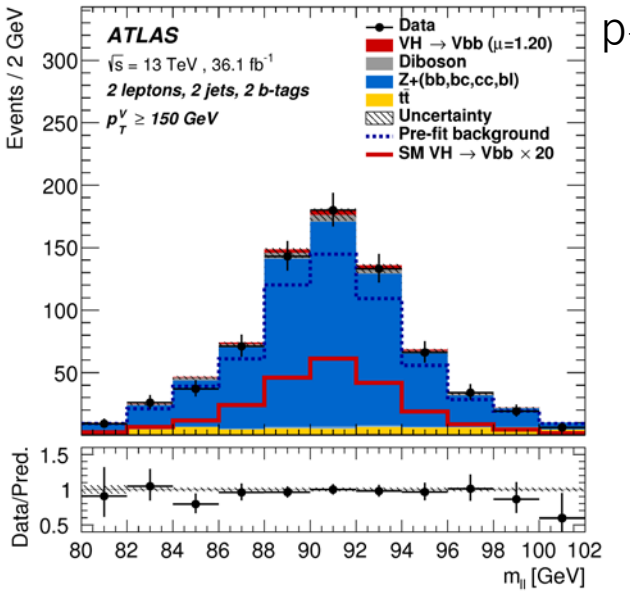
0-lepton: Z→νν: E_T^{Miss} > 150 GeV



1-lepton: W→lν: $p_T(W)$> 150 GeV



2-lepton: Z→ll 75 < $p_T(Z)$<150 GeV, $p_T(Z)$< 150 GeV



H→bb reconstruction

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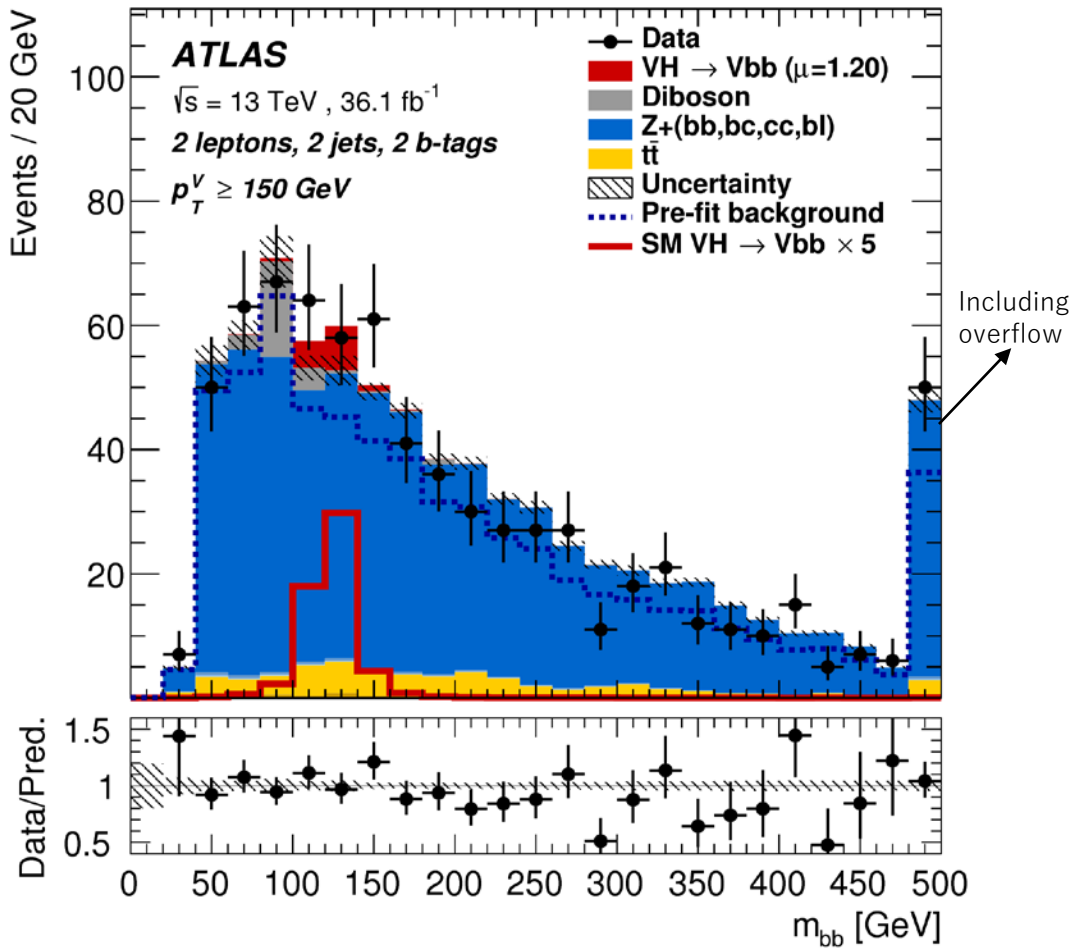
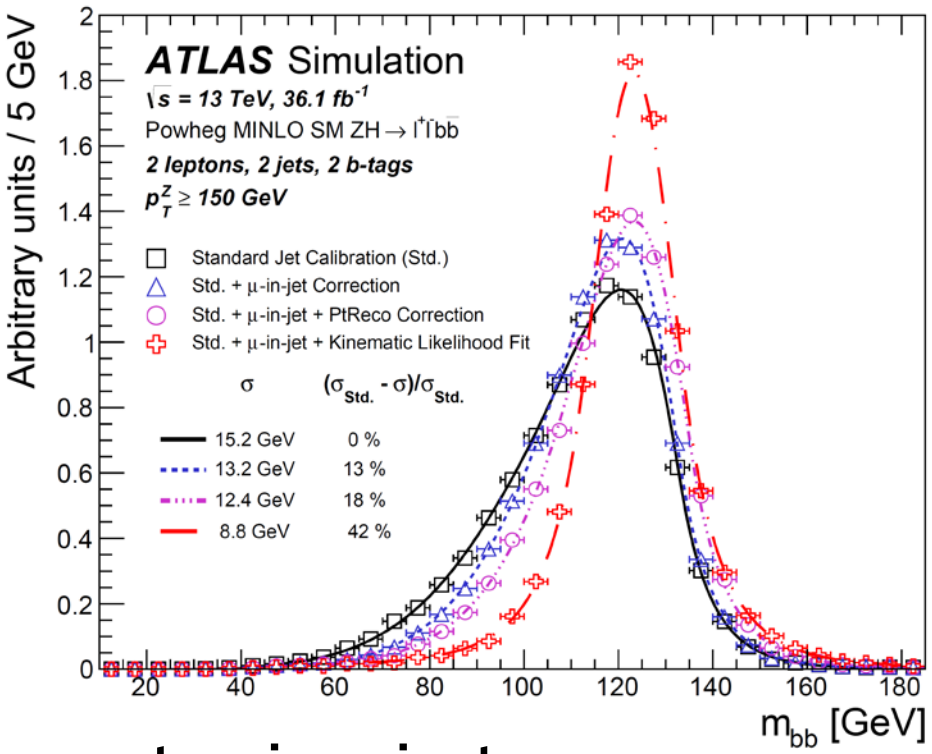
- b-tagging
  - 2 b-tag (MV2c10) with 70% b-jet eff.
    c-jet eff.: 1/12, light jet eff.: 1/380





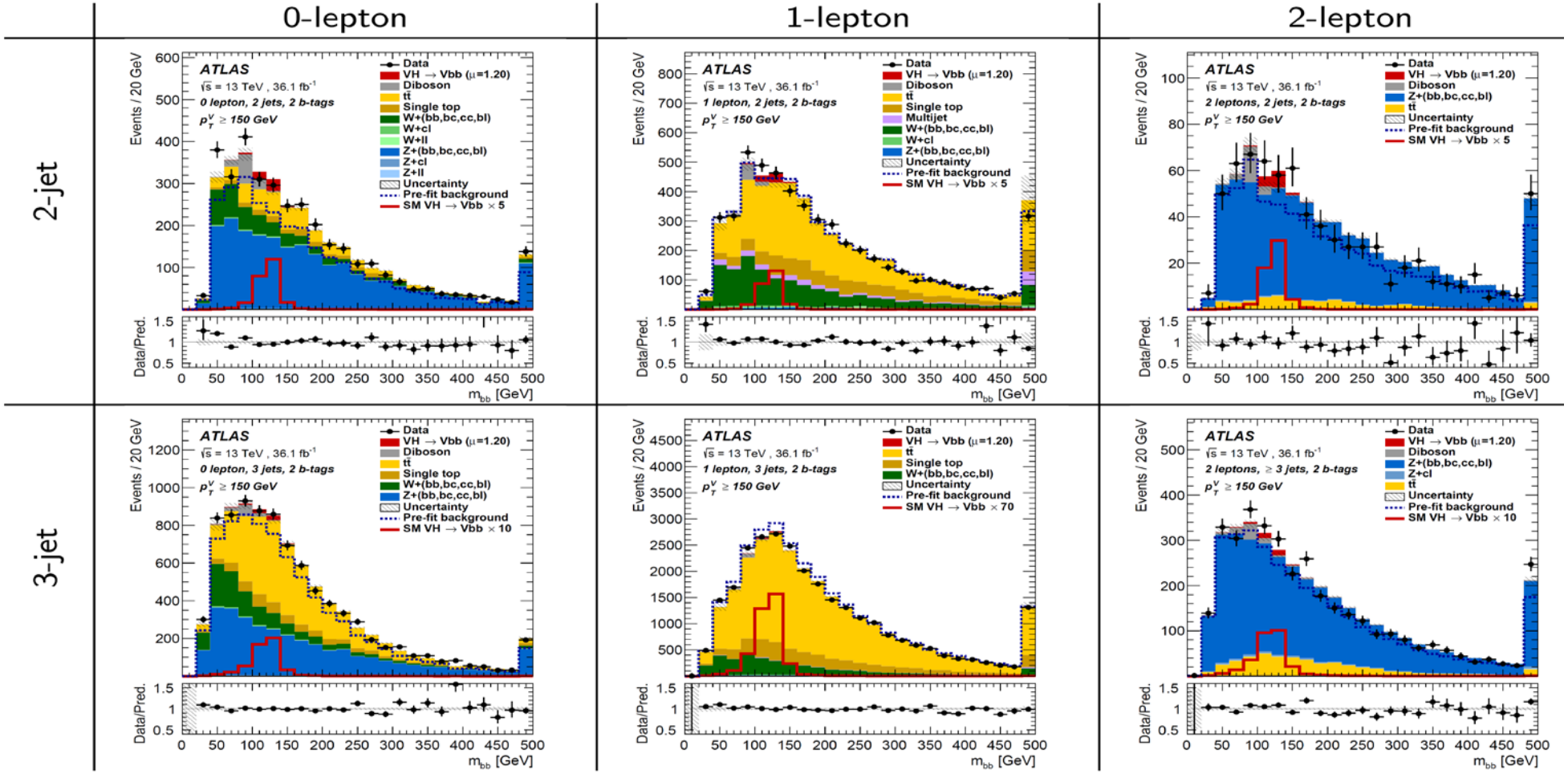
Improvement on invariant mass

- **Muon-in-jet correction** :
  Add momentum of muon inside b-jet.
- **PtReco correction** :
  Apply correction factor accounting for missing neutrino energy and out-of-cone effect based on MC response.
- **Kinematic Fit (2lepton)** :
  Correct b-jet energy by constraint of llbb balance.

Background on VH analyses

- **Z+jets** : 0-lepton and 2-lepton
- **W+jets**: 0-lepton and 1-lepton
- **ttbar**: main background for 1-lepton.
  - Present in 0- and 2-lepton.

Determine simultaneously in the fit.
- Normalization (Z, W, ttbar)
- nuisance parameters (2jet to 3jet SF, systematics)
- H→bb signal strength



Small contributions
- **Single top**
- **multi-jet**
- **diboson**

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Multivariate technique for H→bb

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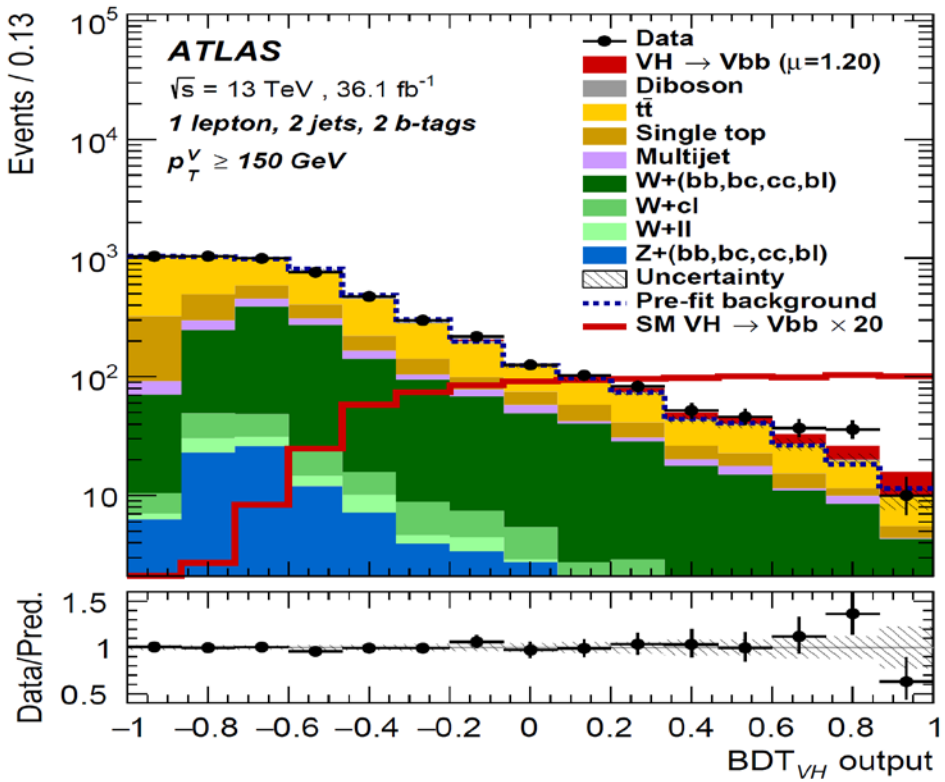
Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$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

- Build final discriminant with Boosted decision tree
- Minimize number of input variable
  - m_{bb}, $\Delta R(b,b)$ and $p_T(V)$ are key variables.
- Training: VH signals vs all Backgrounds.



Lepton categories

0-lepton (E_T^{Miss}>150 GeV)
1-lepton (p_T^W>150 GeV)
2-lepton (75 < p_T^Z < 150 GeV)
(p_T^Z > 150 GeV)

×

Jet categories

2 jets
3 jets (or more*)

*only 2-lepton

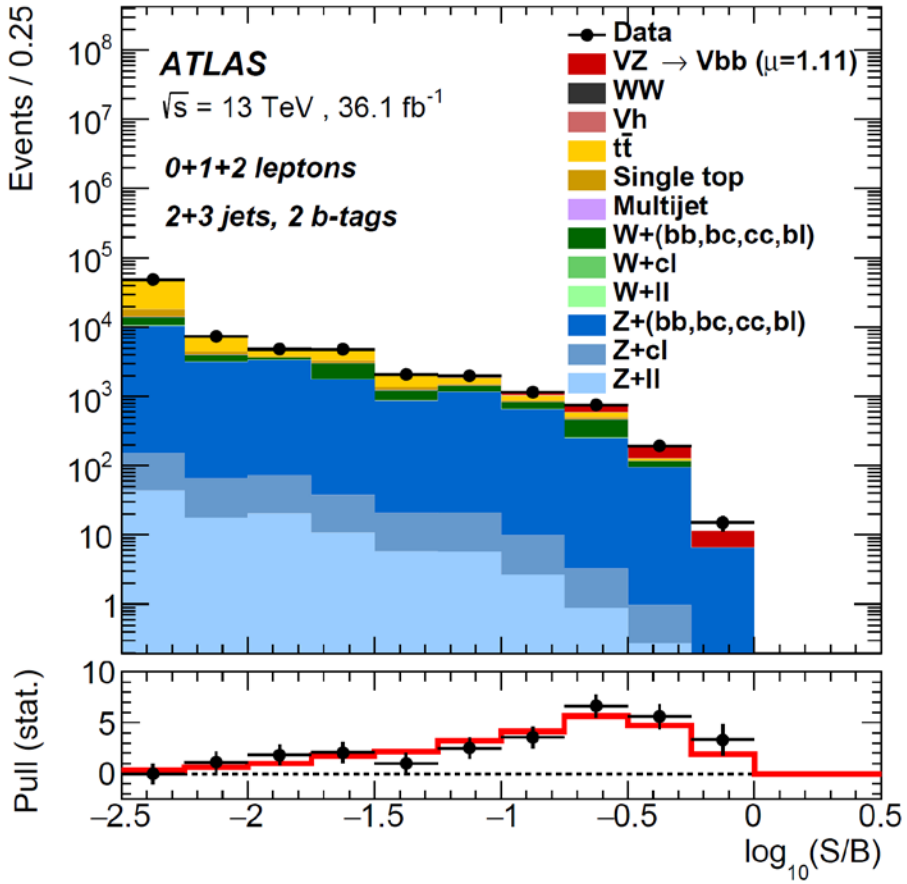
In total
8 signal regions
+ 2 control regions
for final fit.

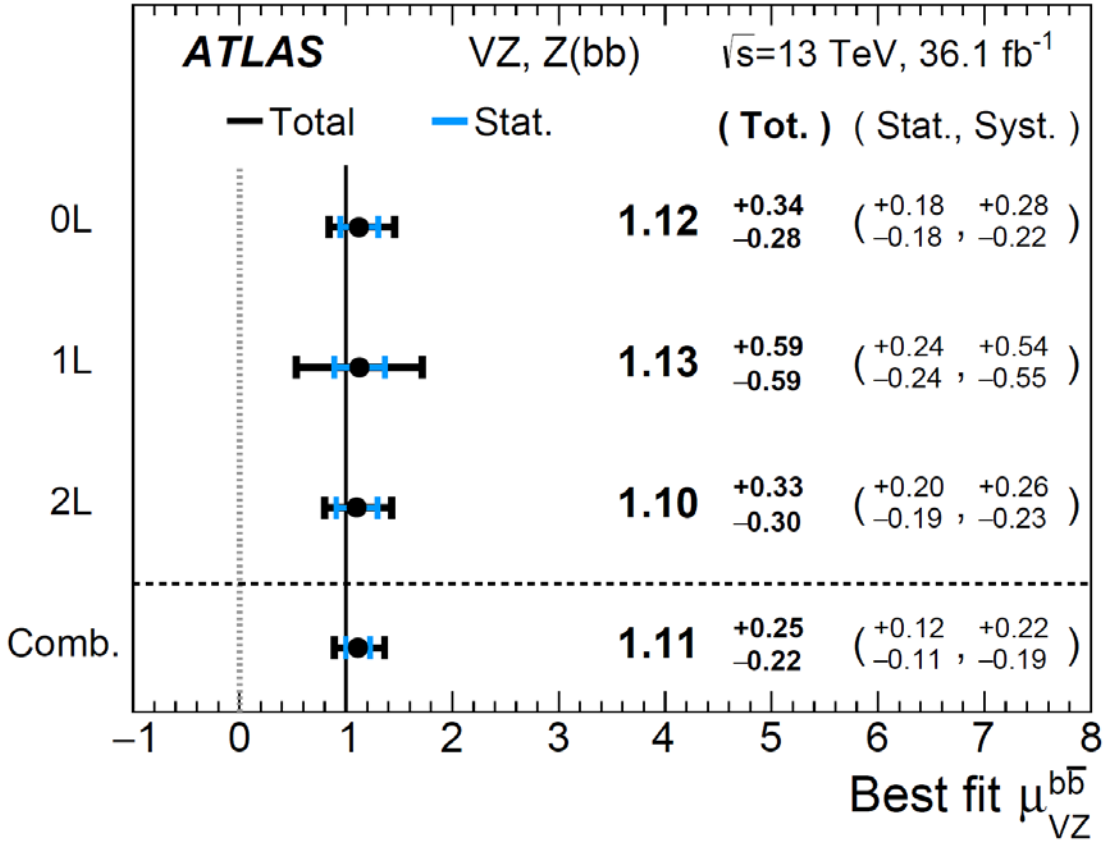
Cross check with Diboson

$$\mu = \frac{(\sigma \cdot BR)_{meas}}{(\sigma \cdot BR)_{SM}}$$

- In order to verify the whole analysis procedure
- Performed measurement of VZ, Z→bb.
  - Same BDT scheme, systematic assignment, and fit procedure.

$$\mu_{VZ}^{b\bar{b}} = 1.11^{+0.25}_{-0.22} \text{ (Obs. } 5.8\,\sigma)$$





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Effect of systematic uncertainties

- Error on $\mu = \frac{(\sigma \cdot BR)_{meas}}{(\sigma \cdot BR)_{SM}}$ for VH, H→bb

Source of uncertainty	σ_μ
Total	0.39
Statistical	0.24
Systematic	0.31

Systematic error is larger than the statistics error.

Experimental uncertainties		
Jets		0.03
E_T^{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

On the experimental side, uncertainty on b-jet efficiency is the dominant systematic.

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

Modeling side:
Signal systematic is the largest source:
- parton shower
- QCD scale change acceptances

Background MC Statistics!
→ can be improved
not so easy task to generate O(Billion) events…

Evidence for H→bb

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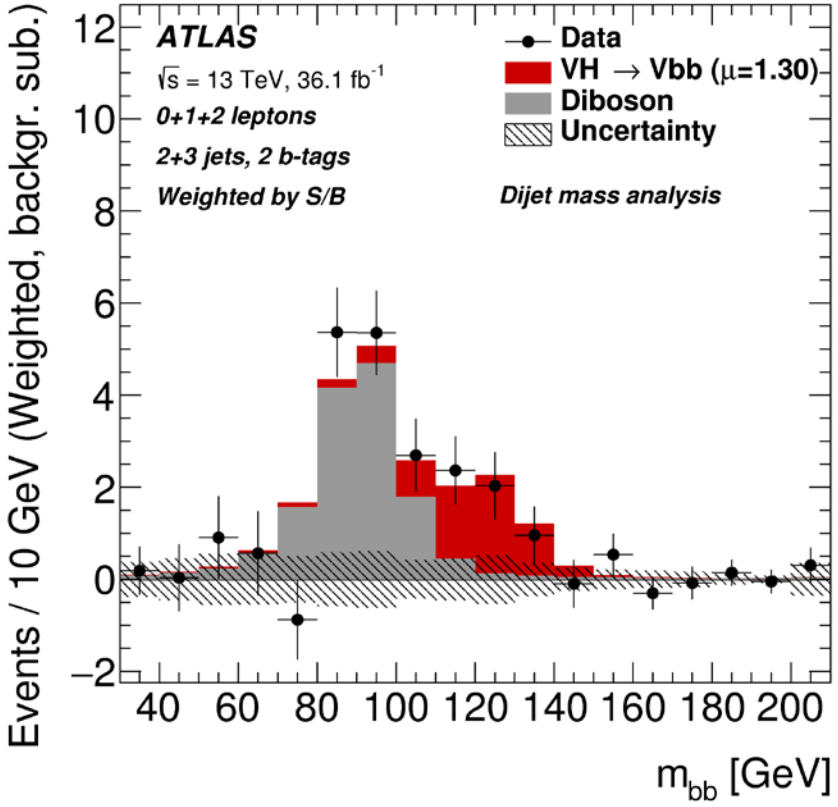
Dijet-mass analysis (cross check)

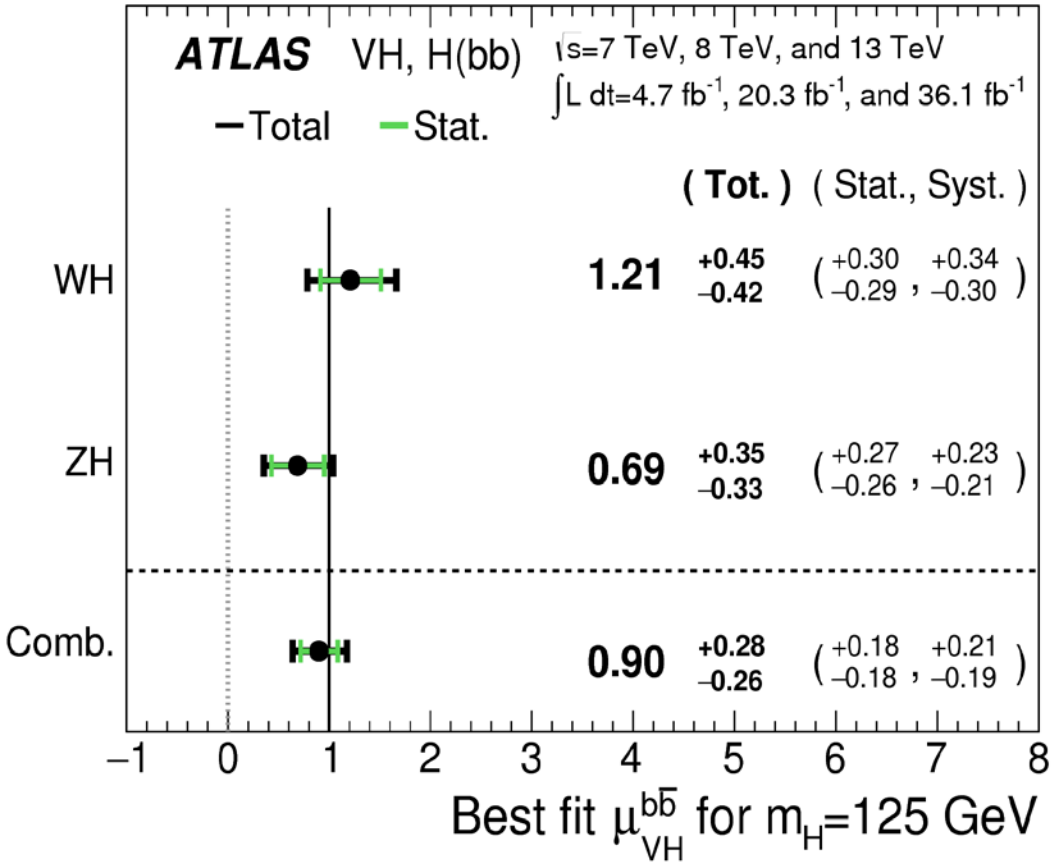
Tighter selection with additional $p_T(V)$category.
Perform fit on m_{bb}.



Consistent results with MVA
Run2 only : $\mu(m_{bb}) = 1.30^{+0.46}_{-0.40}$ vs $\mu(\mathrm{MVA}) = 1.20^{+0.42}_{-0.36}$

Combined MVA analysis result

Run2(36.1fb^{-1})+ Run1(4.7fb^{-1}+20.3fb^{-1})



Observed significance 3.6 σ
(Expected 4.0 σ)

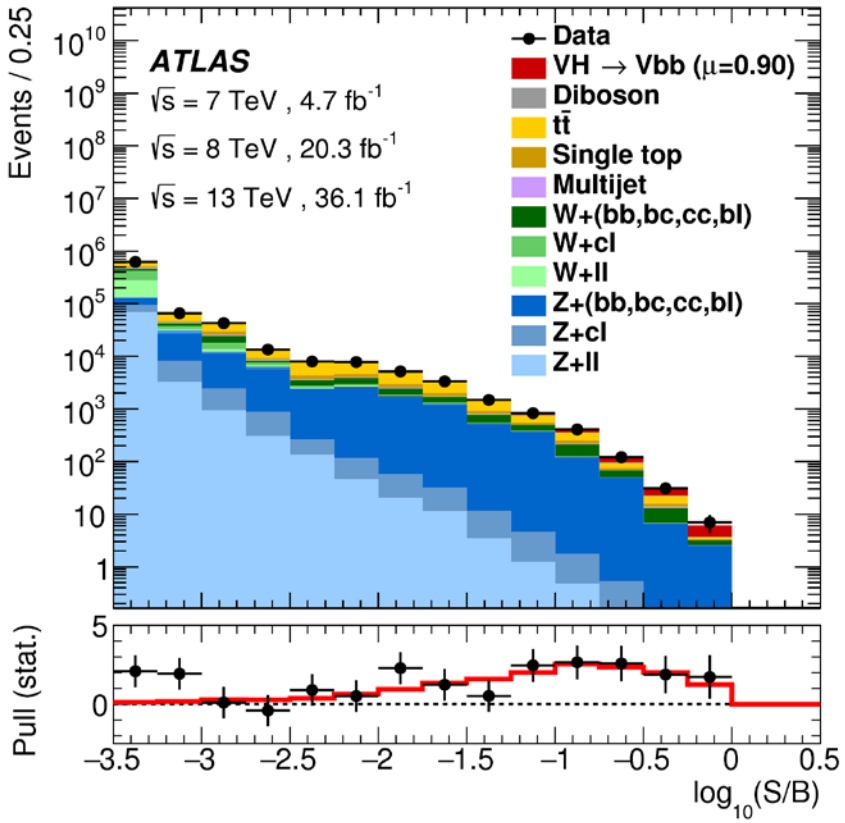
Summary

- H→bb is a key channel to probe the Higgs Yukawa coupling to fermions.
- ATLAS is developing VH, VBF and ttH analyses.
- In the VH analysis, an excess is observed at m_{bb}=125 GeV in the data corresponding to an integrated luminosity of 36.1 fb^{-1} at √s=13 TeV. After combining with Run 1 result:

$$\mu = 0.90 \pm 0.18(\text{stat.})^{+0.21}_{-0.19}(\text{syst.}).$$

Observed (expected) significance : **3.6 σ** (4.0 σ)

- This is an evidence for H→bb.



One more step forward to Discovery. Stay tuned!!!

Extra slides

About dijet mass analysis (Run-2)

- Additional cross check of MVA analysis.
- Tightened event selection
  - Add categories pT(V) > 200 GeV with ΔR(b,b).

Channel			
Selection	0-lepton	1-lepton	2-lepton
m_T^W	-	< 120 GeV	-
$E_T^{miss}/\sqrt{S_T}$	-	-	$< 3.5\sqrt{\text{GeV}}$

p_T^V regions			
p_T^V	(75, 150] GeV (2-lepton only)	(150, 200] GeV	(200, ∞) GeV
$\Delta R(\vec{b}_1, \vec{b}_2)$	<3.0	<1.8	<1.2

Dijet mass analysis:

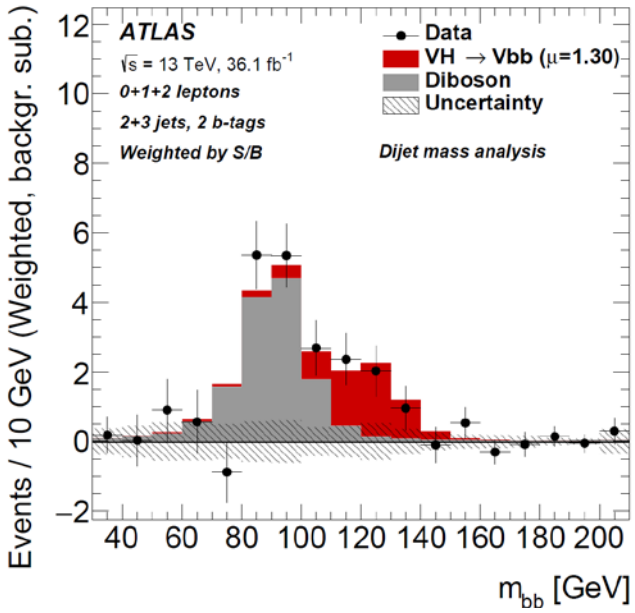
$$\mu = 1.30^{+0.28}_{-0.27}(\text{stat.})^{+0.37}_{-0.29}(\text{syst.})$$

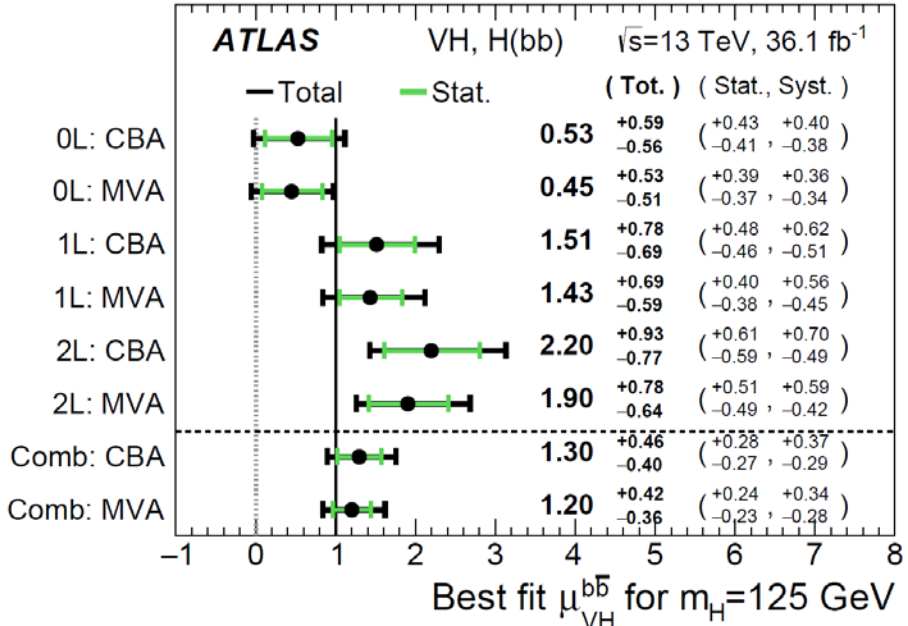
3.5 (2.8) σ observed (expected) significance.

MVA analysis (main):

$$\mu = 1.20^{+0.24}_{-0.23}(\text{stat.})^{+0.34}_{-0.28}(\text{syst.}).$$

3.5 (3.0) σ observed (expected) significance.





Event selection and acceptance of VH analysis

Table 2: Summary of the event selection in the 0-, 1- and 2-lepton channels.

Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 loose leptons with $p_T > 7$ GeV	1 tight electron $p_T > 27$ GeV	1 medium muon $p_T > 25$ GeV	2 loose leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T > 27$ GeV
E_T^{miss}	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_T	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_T	> 45 GeV			
H_T	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\boldsymbol{E}_T^{miss}, \mathbf{jets})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{bb})$	$> 120°$	–		–
$\Delta\phi(\boldsymbol{b}_1, \boldsymbol{b}_2)$	$< 140°$	–		–
$\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{E}_{T,trk}^{miss})$	$< 90°$	–		–
p_T^V regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{top} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV		Different-flavour leptons

$m_H = 125$ GeV at $\sqrt{s} = 13$ TeV				
Process	Cross-section × B [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	< 0.1	< 0.1	7.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	< 0.1	< 0.1	15.7
$qq \to WH \to \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \to ZH \to \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \to ZH \to \nu\nu b\bar{b}$	14.3	3.5	–	–