Search for Higgs boson production via vector boson fusion with decay to bottom quark pairs at $\sqrt{s} = 13$ TeV with the ATLAS detector

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IHEP, CAS

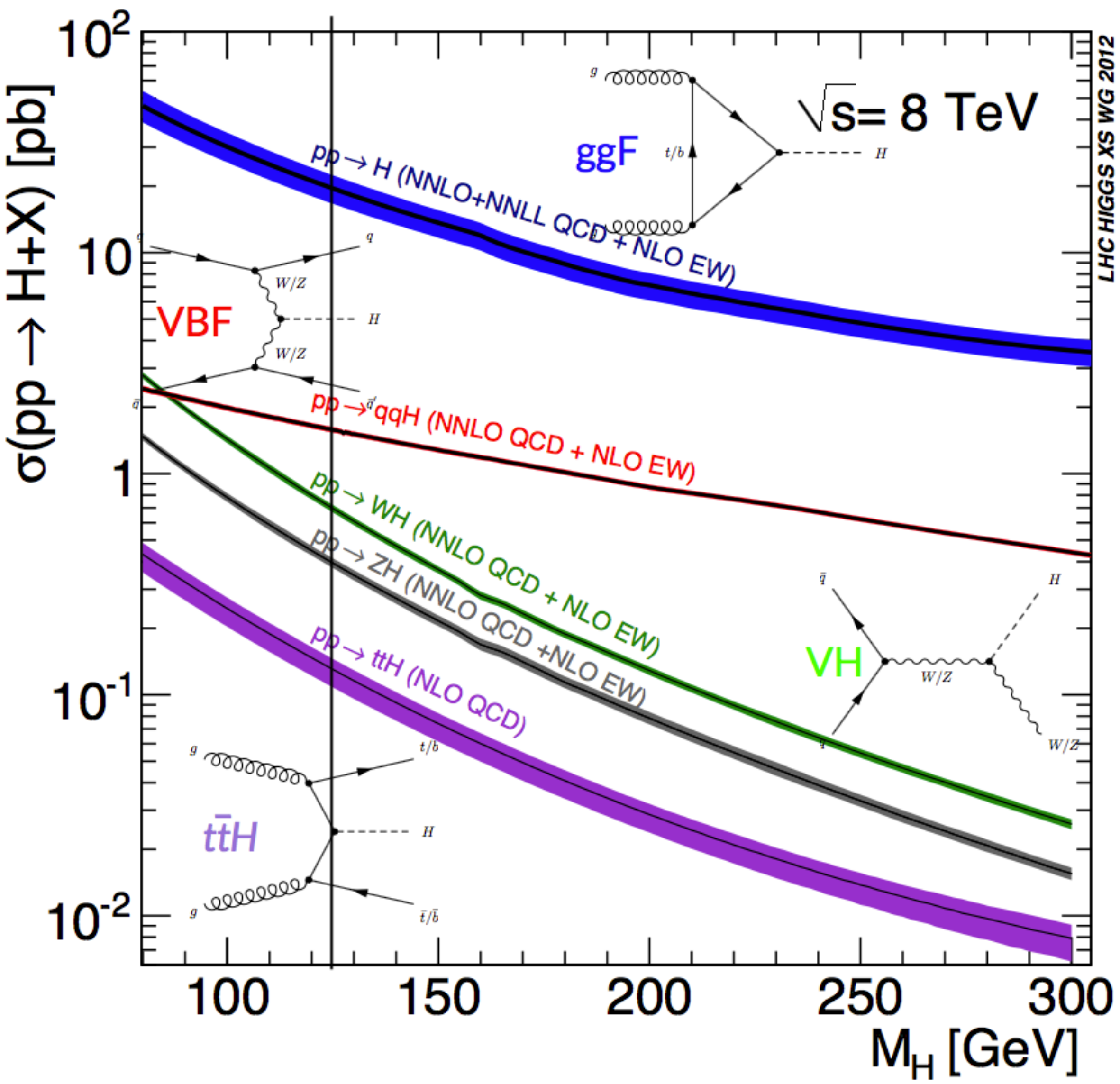
arXiv:2010.13651 (VBF+γ, submitted to JHEP)

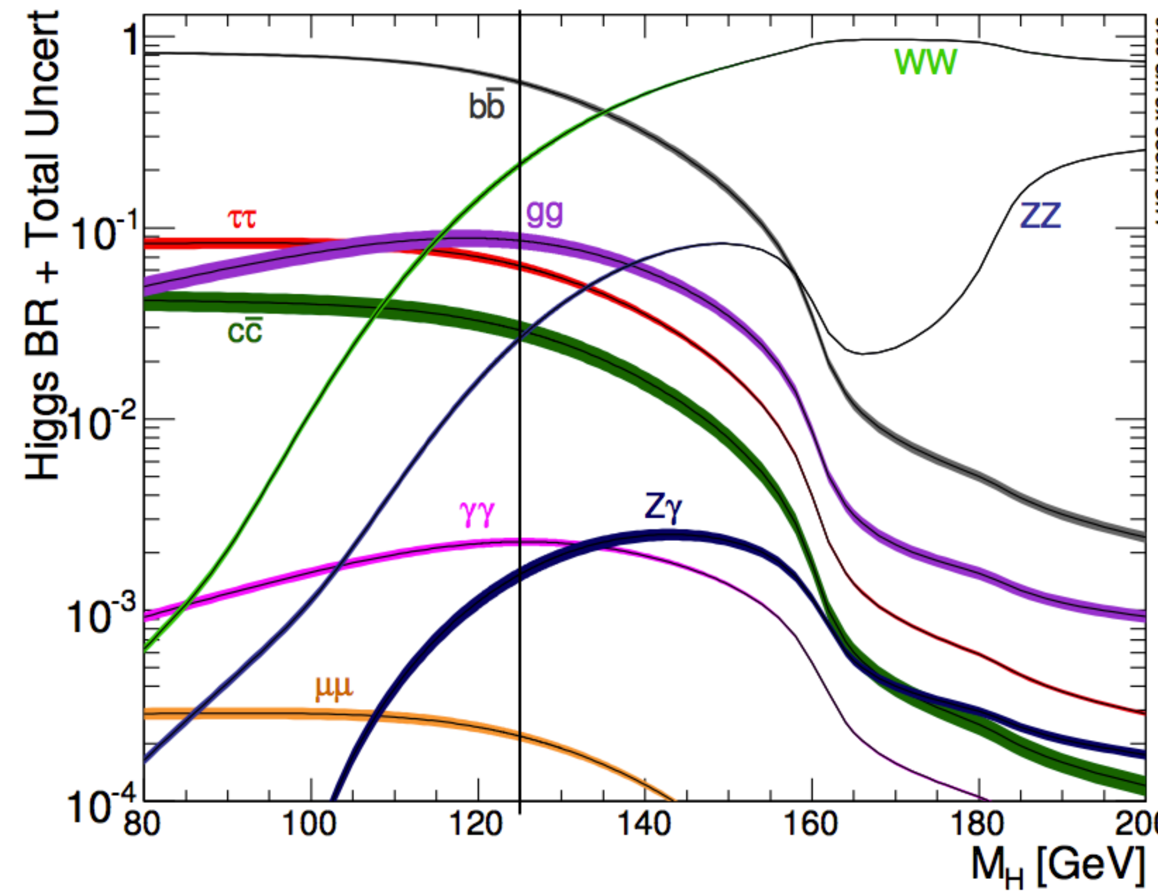
CERN-EP-2020-195 (VBF all-hadronic)

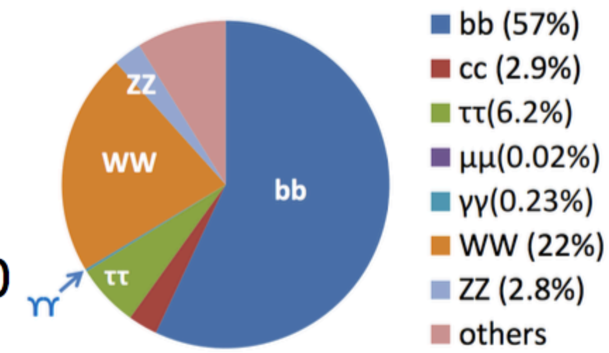
ATLAS EXPERIMENT

Introduction

- ggF process is the dominant production mode of the Higgs boson at the LHC.





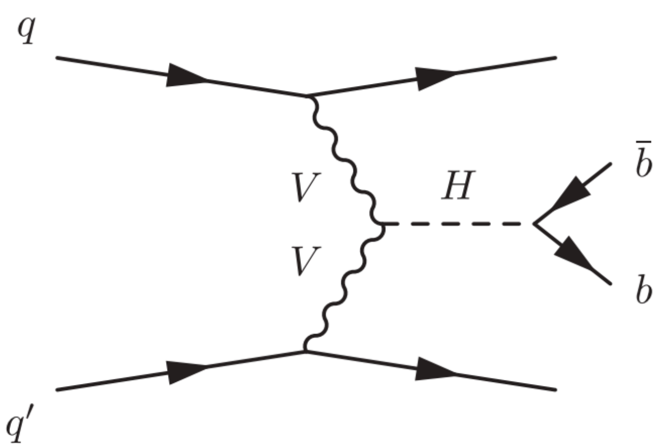


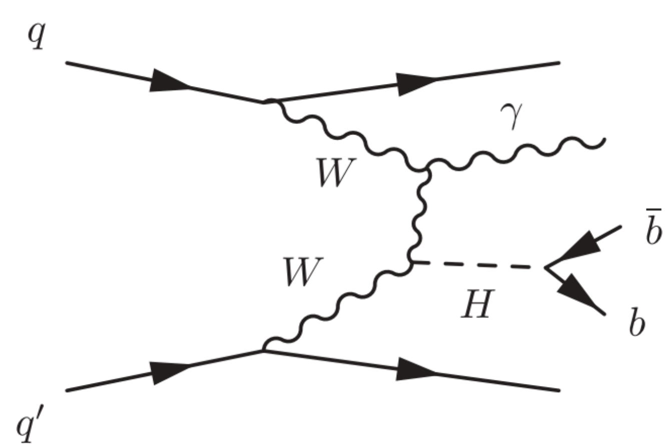
- The Higgs boson decay BR for different decay modes with $m_H = 125$ GeV.

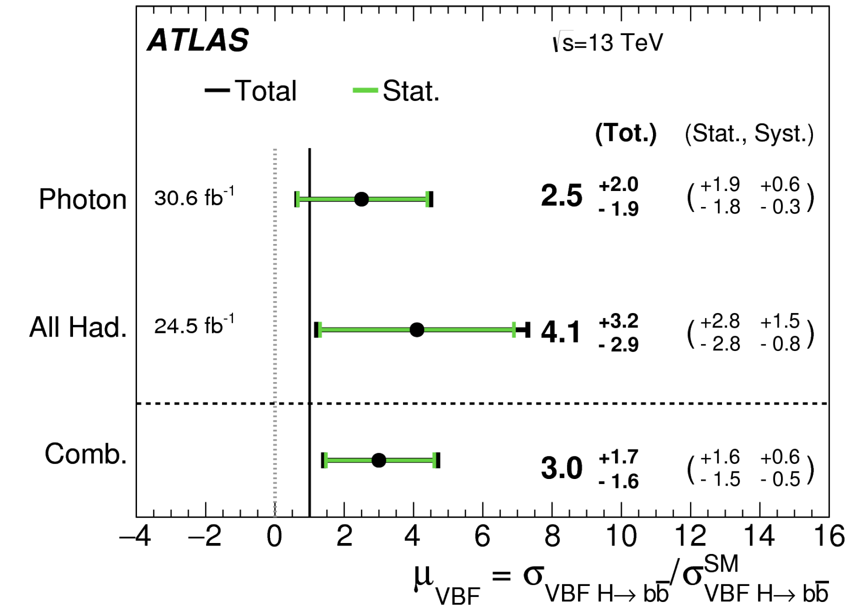
- H→bb is the dominant decay mode but hard to discover and measure
  - First observation in 2018 with combining all productions
  - Later been discovered by VH only channel
- To observe H→bb is challenging in ggF production due to large QCD background
- VBF production can help to reduce QCD contamination with forward jet requirement

Previous results

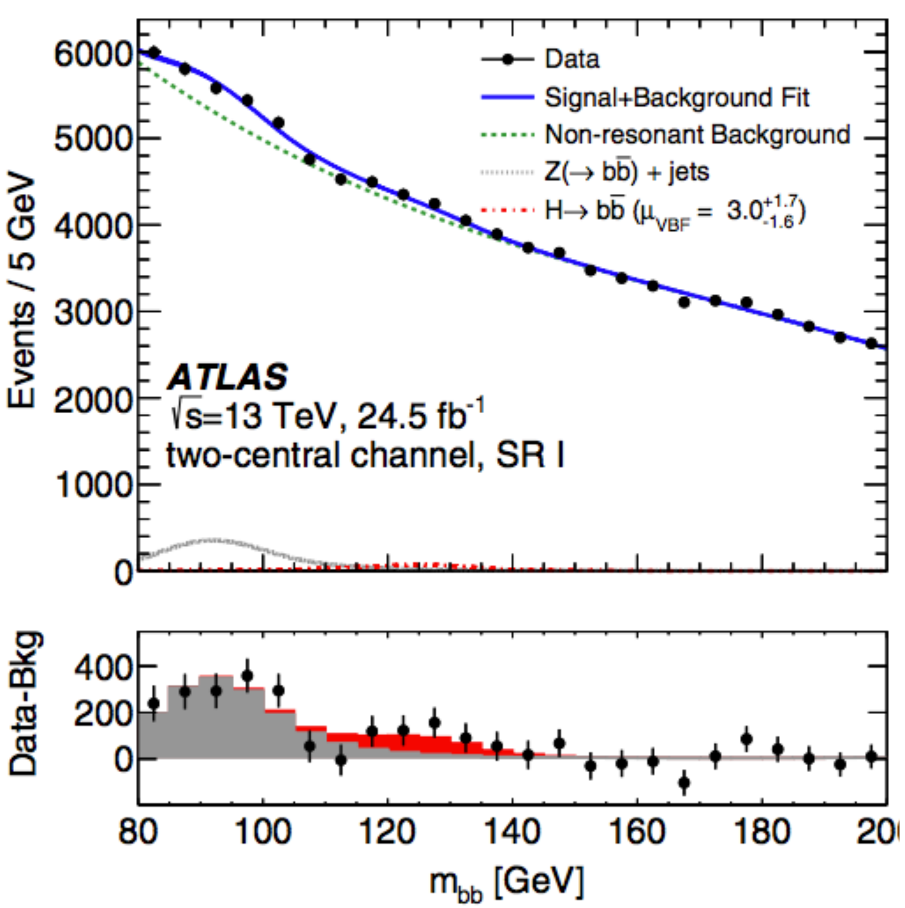
- Previous 2015+2016 dataset was published in PRD
  - *Combined observes (expects) 1.9 σ (0.7 σ) significance*

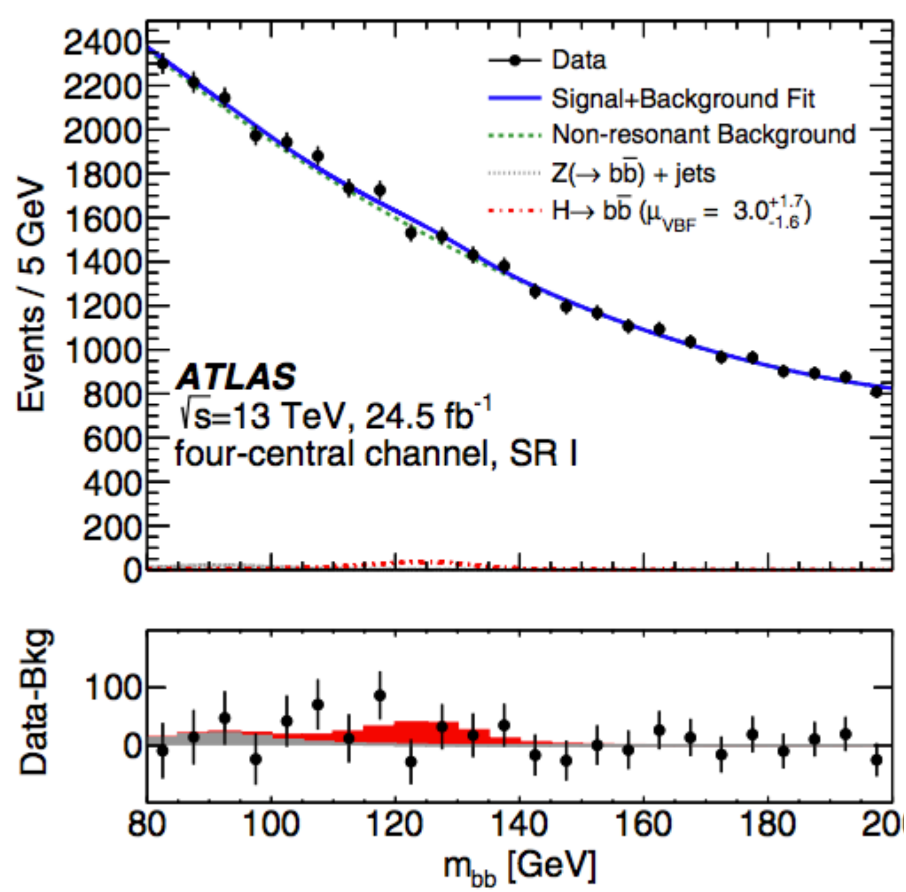


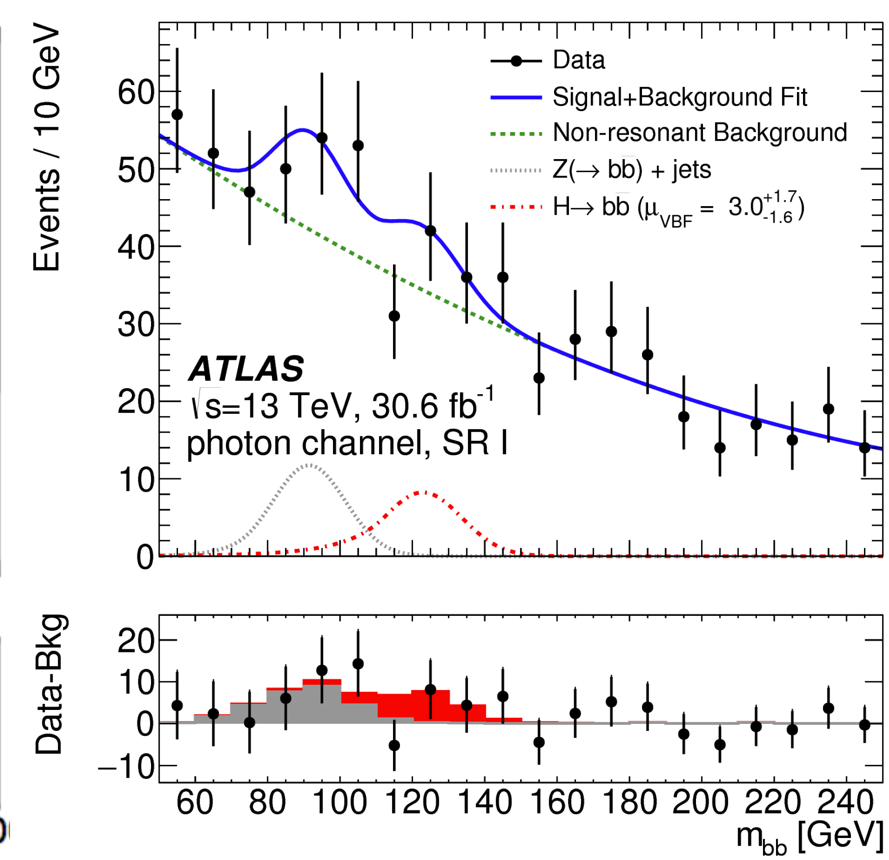




[Phys. Rev. D 98 (2018) 052003]

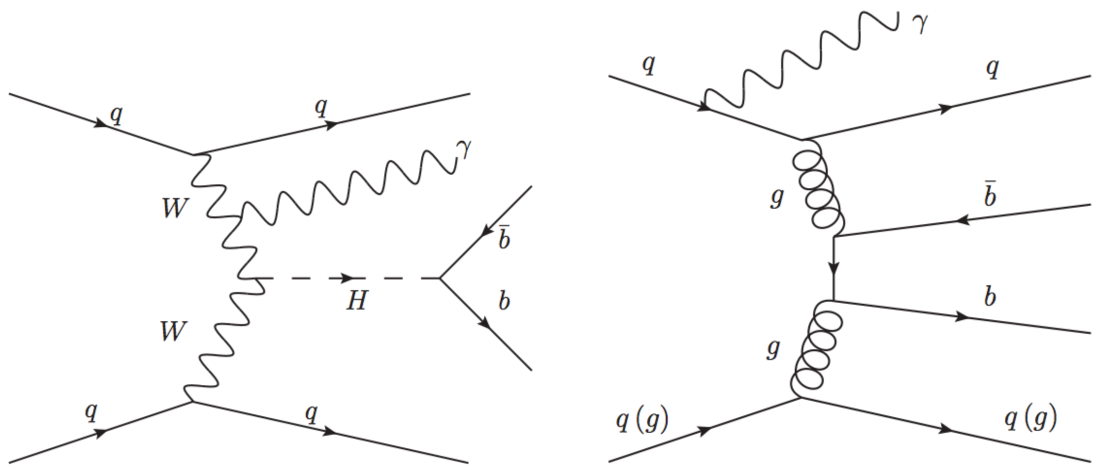






VBF+photon: introduction

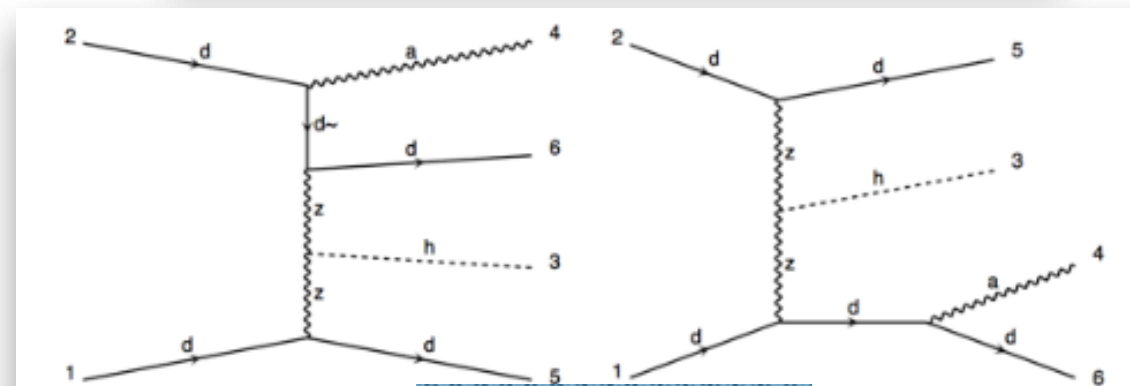
- **Add extra photon to VBF production**
  - *Heavily reduce QCD multi-jet contribution*
  - *Extra EM object help to explore low pT phase space*



- **With a photon in final state, WW fusion becomes the main process**

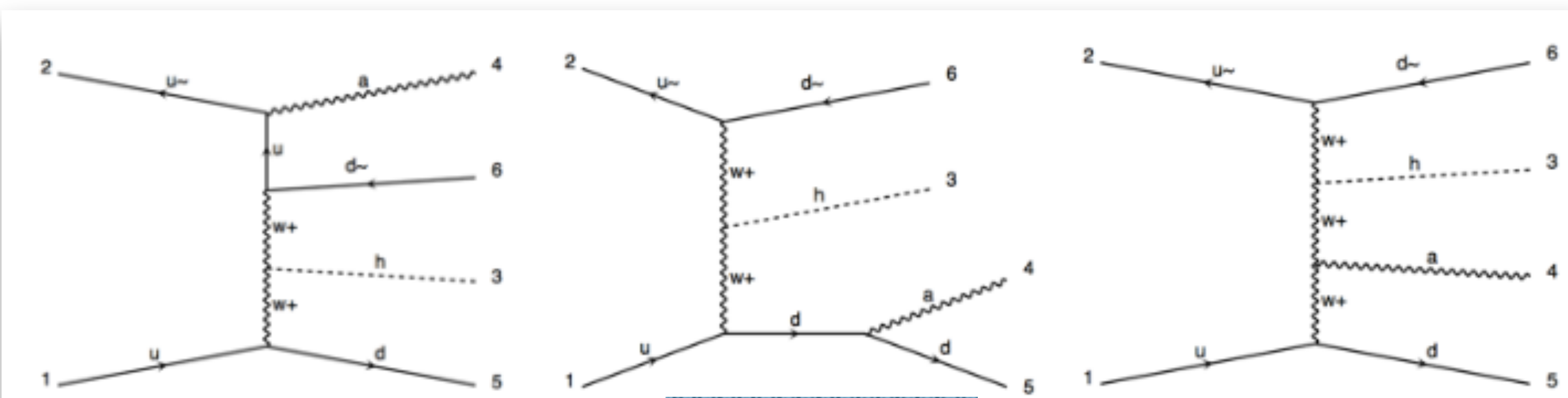
Process fractions in signal sample (at generation)

Process		Fraction
VH(bb)+γ	WH	4.5 %
	ZH	3.7 %
VBF H(bb)+γ	WW fusion	87.8 %
	ZZ fusion	5.1 %



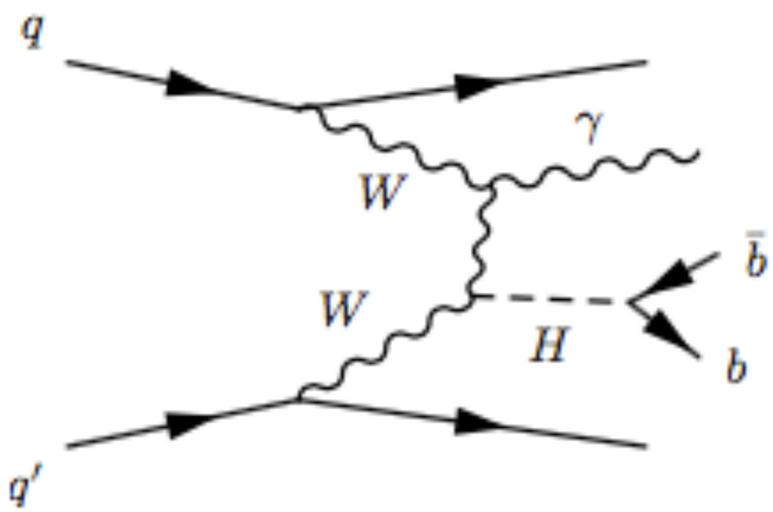
ZZ Fusion

- **Previous 2015+2016 dataset was published in PRD**
  - *Combined observes (expects) 1.4 σ (0.6 σ) significance*



WW Fusion

VBF+photon: preselection

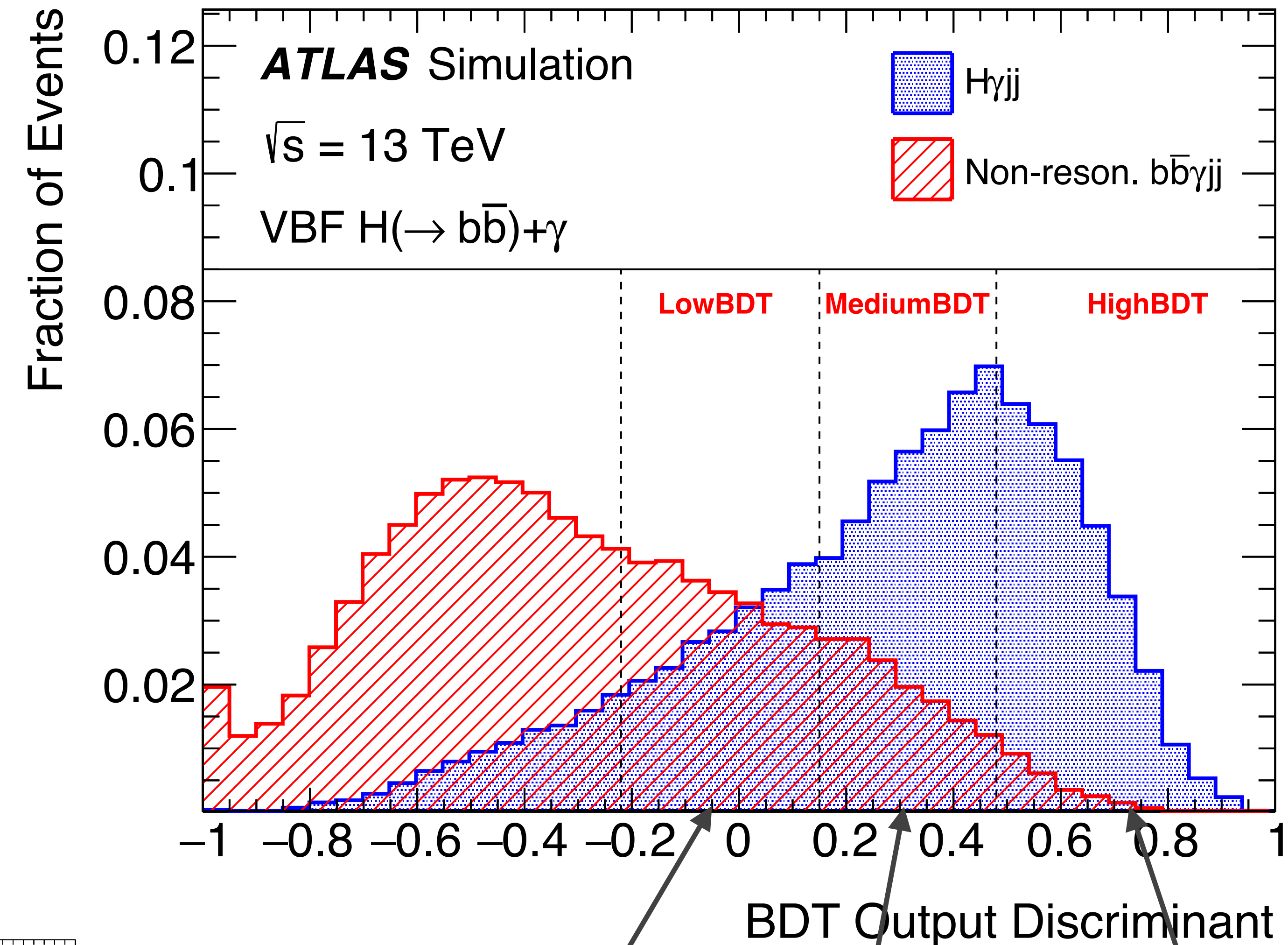


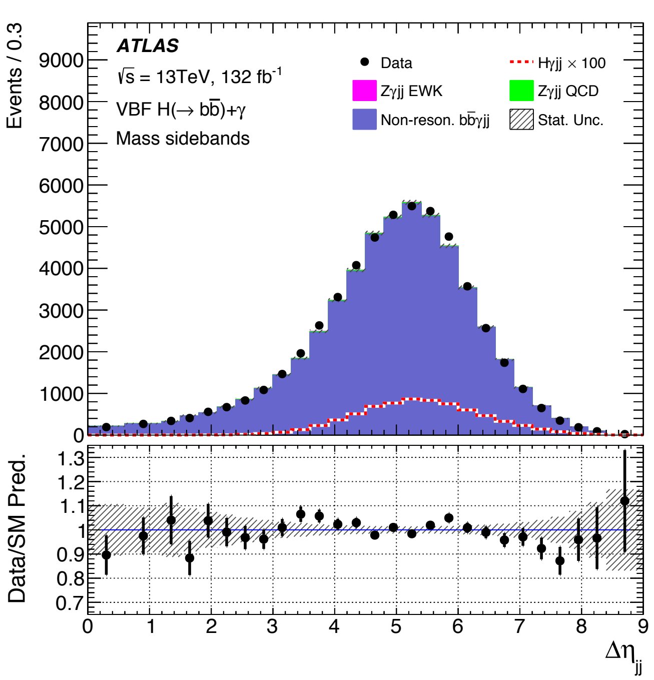
- **Dedicated trigger design with photon**
  - *With photon included helps to preserve relative low jet pT*
  - *VBF signature considered as well*
- **Offline cuts are select to be slightly above trigger threshold → fully efficient for trigger.**
- **Require slight boost *bb* system to avoid kinematic turnOn for background**
- **Veto signal leptons to be orthogonal with VH channel**

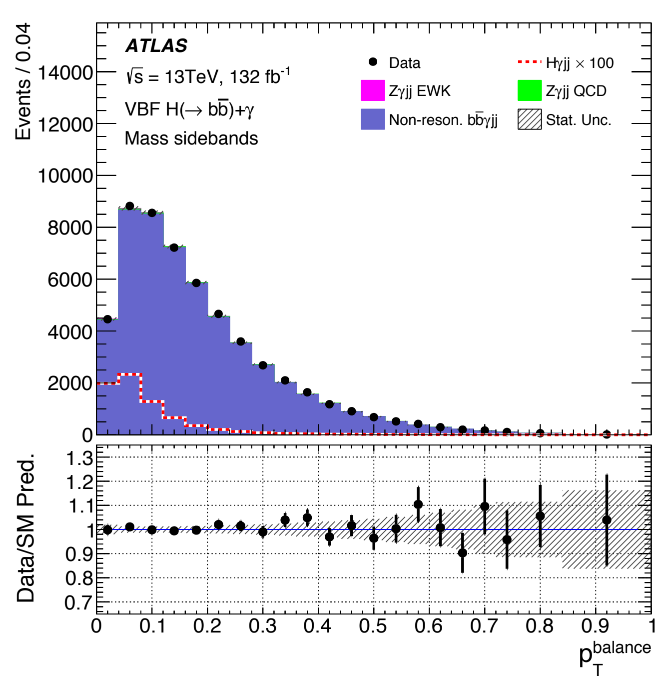
Trigger	L1	≥ 1 photon with $E_{\mathrm{T}} > 22\,\mathrm{GeV}$
	HLT	≥ 1 photon with $E_{\mathrm{T}} > 25\,\mathrm{GeV}$
		≥ 4 jets (or ≥ 3 jets and ≥ 1 b-jet) with $E_{\mathrm{T}} > 35\,\mathrm{GeV}$ and $\lvert\eta\rvert < 4.9$
		$m_{jj} > 700\,\mathrm{GeV}$
Offline		≥ 1 photon with $E_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
		≥ 2 b-jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$
		≥ 2 jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $\lvert\eta\rvert < 4.5$
		$m_{jj} > 800\,\mathrm{GeV}$
		$p_{\mathrm{T}}(b\bar{b}) > 60\,\mathrm{GeV}$
		No electrons ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.47$) or muons ($p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$)

VBF+photon: MVA

	Variable
VBF jets	m_{JJ} $\quad p_{\mathrm{T}}^{JJ}$ $\quad \Delta\eta(JJ)$
Color connection	$p_{\mathrm{T}}^{\mathrm{Bal}}$ $\quad$ centrality(γ)
Angular	$\Delta R(b_1,\gamma)$ $\quad \Delta R(b_2,\gamma)$ $\quad \Delta\Phi(bb,JJ)$ $\quad \cos\theta$ $\quad \Delta R(b_1,J_1)$





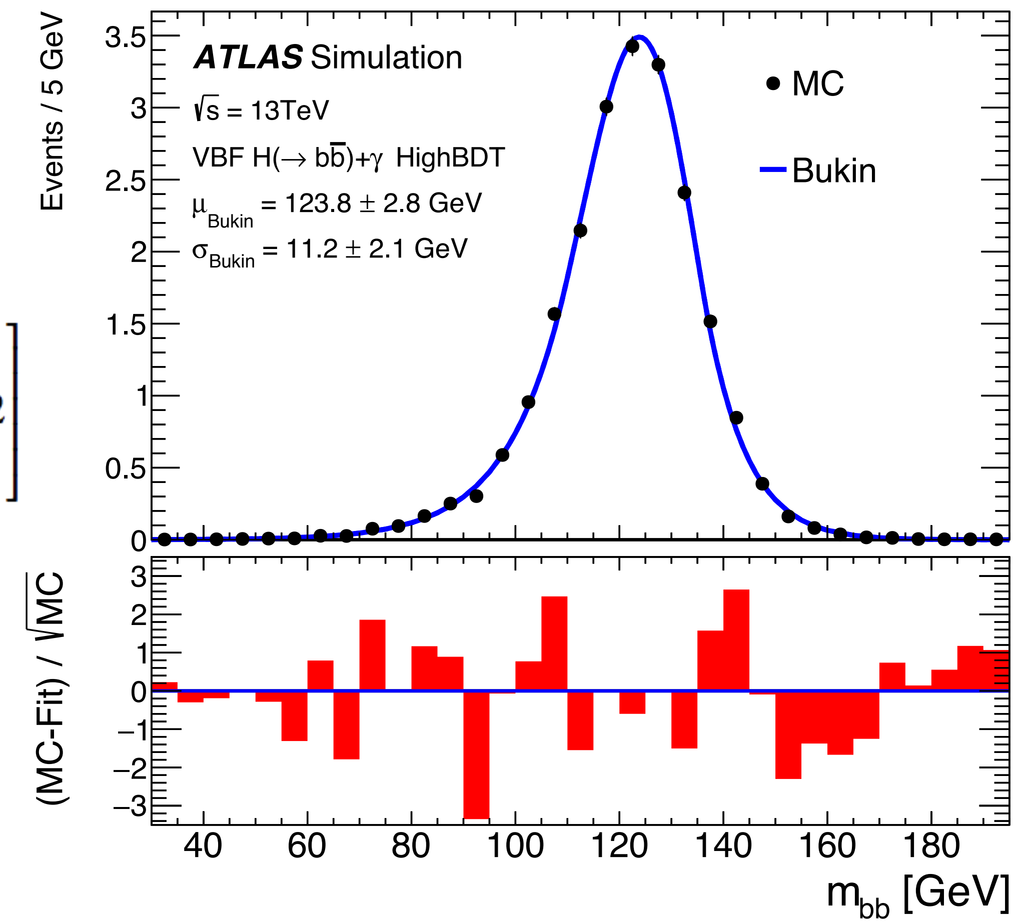


Category	LowBDT	MediumBDT	HighBDT
BDT Output	$(-0.22, 0.15)$	$(0.15, 0.48)$	$(0.48, 1)$
VBF+VH	11.31 ± 0.12	21.07 ± 0.17	18.33 ± 0.15
ggF	1.71 ± 0.41	1.08 ± 0.33	0.19 ± 0.13
$t\bar{t}H$	0.75 ± 0.14	0.19 ± 0.03	0.05 ± 0.01
$Z\gamma jj$ EWK	8.50 ± 0.14	8.91 ± 0.14	5.37 ± 0.11
$Z\gamma jj$ QCD	15.9 ± 1.7	7.2 ± 1.1	1.65 ± 0.52
Non-resonant $b\bar{b}\gamma jj$	2834 ± 42	1507 ± 33	322 ± 17
Expected Yield	2872 ± 42	1545 ± 33	348 ± 17
Data	2964	1522	318

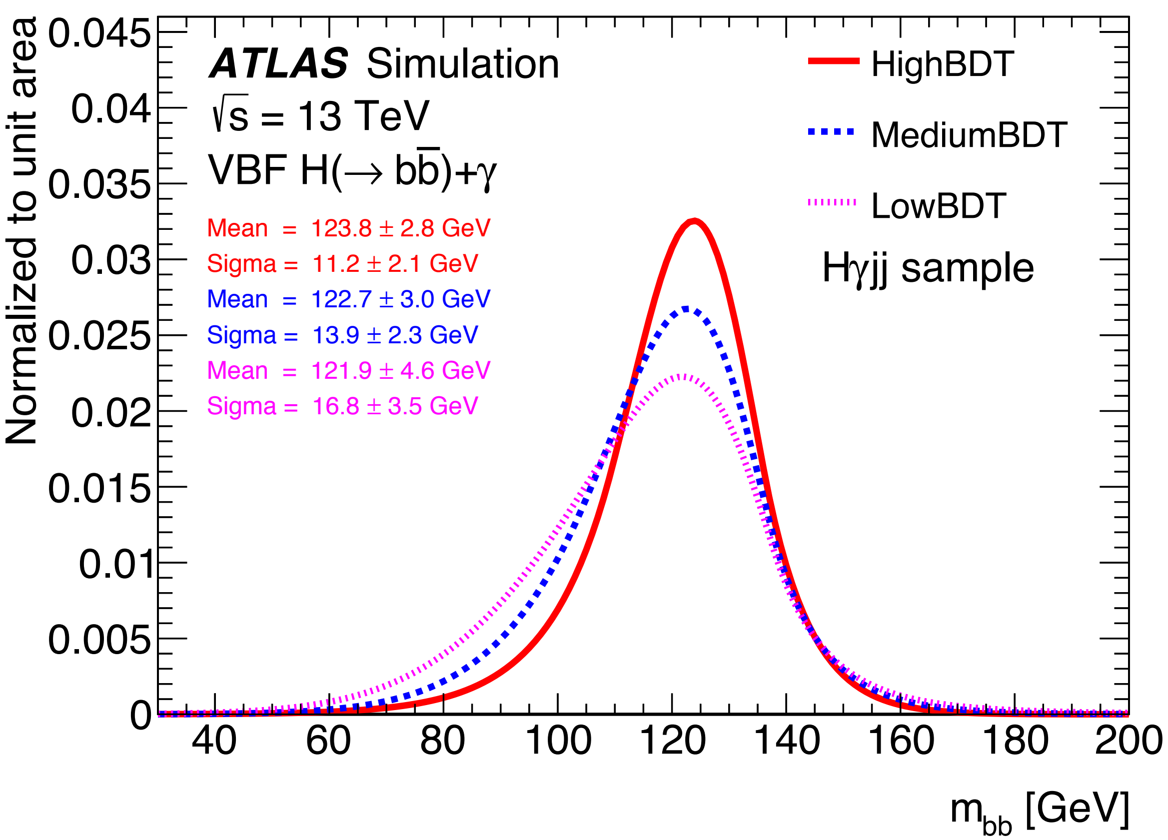
VBF+photon: Higgs and Z signal modeling

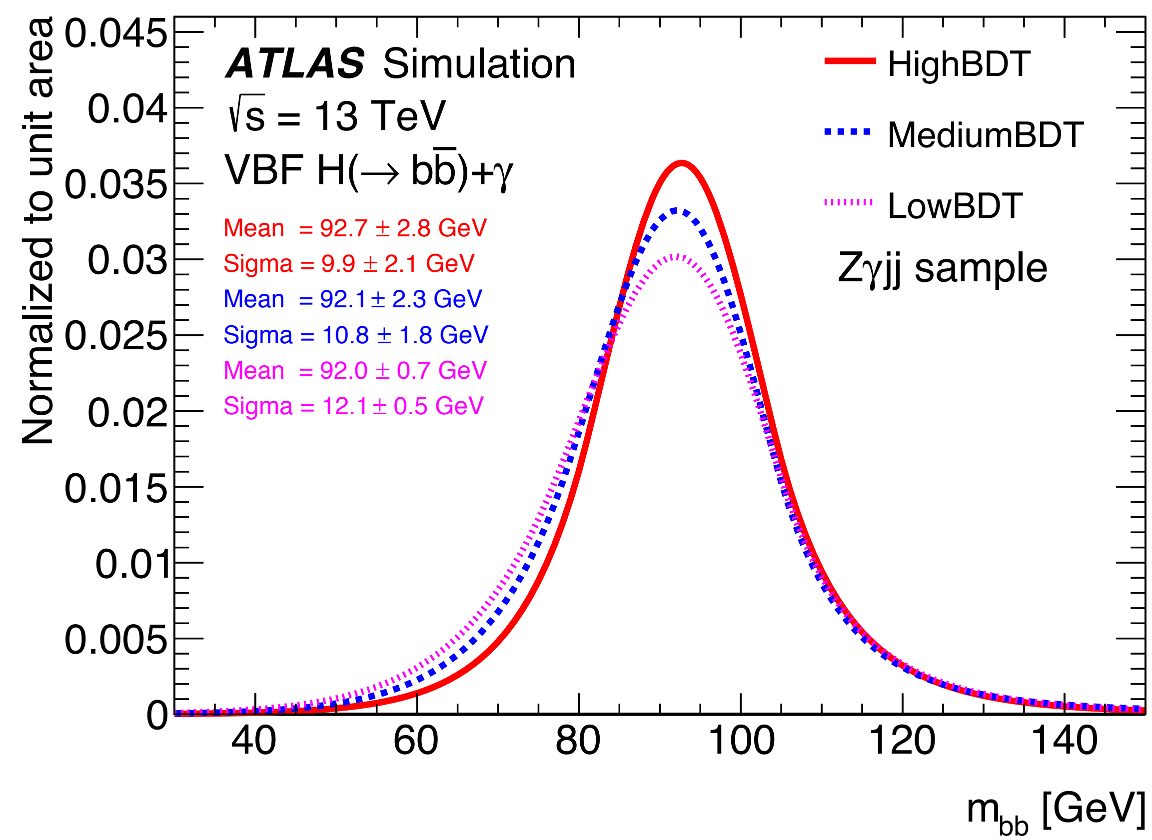
- Using ***Burkin function*** for signal modelling
- **Pretty good signal modelling observed**

$$S(m_{b\bar{b}}\ m^{p}_{b\bar{b}}, \sigma_p, \xi, \rho) = A_p \exp\left[\frac{\xi\sqrt{\xi^2+1}(m_{b\bar{b}} - m^{1}_{b\bar{b}})\sqrt{2\ln 2}}{\sigma_p \left(\sqrt{\xi^2+1}-\xi\right)^2 \ln\left(\sqrt{\xi^2+1}+\xi\right)} + \rho \left(\frac{m_{b\bar{b}} - m^{i}_{b\bar{b}}}{m^{p}_{b\bar{b}} - m^{i}_{b\bar{b}}} \right)^2 - \ln 2 \right]$$

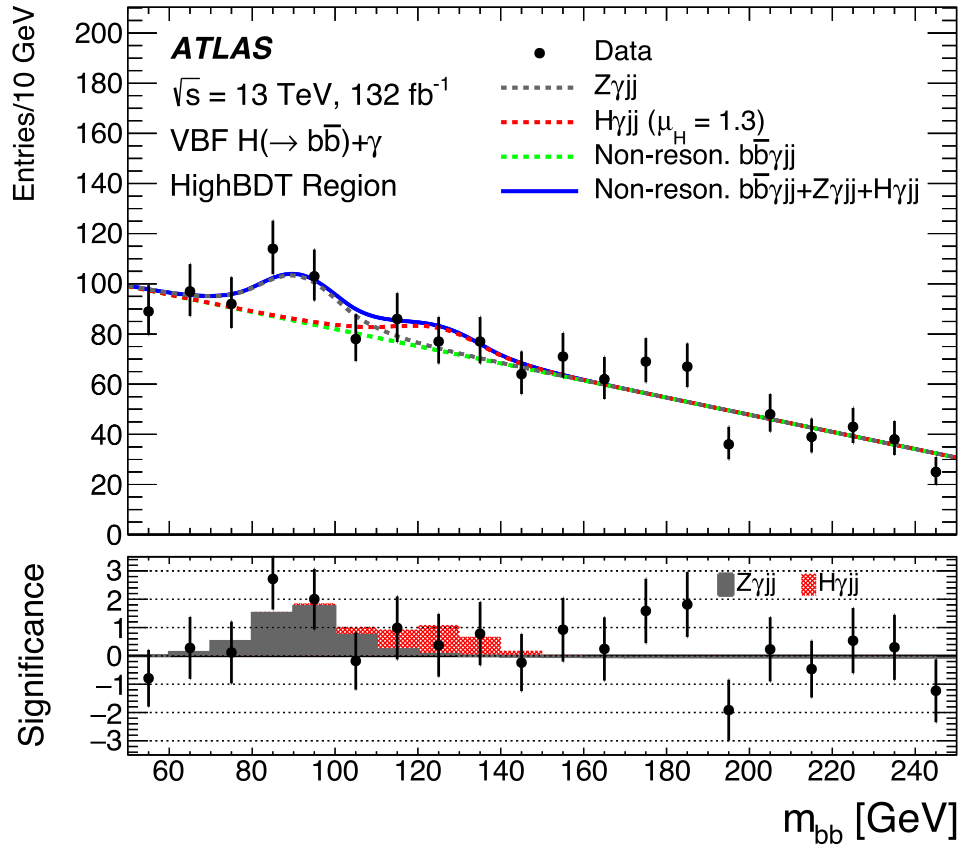


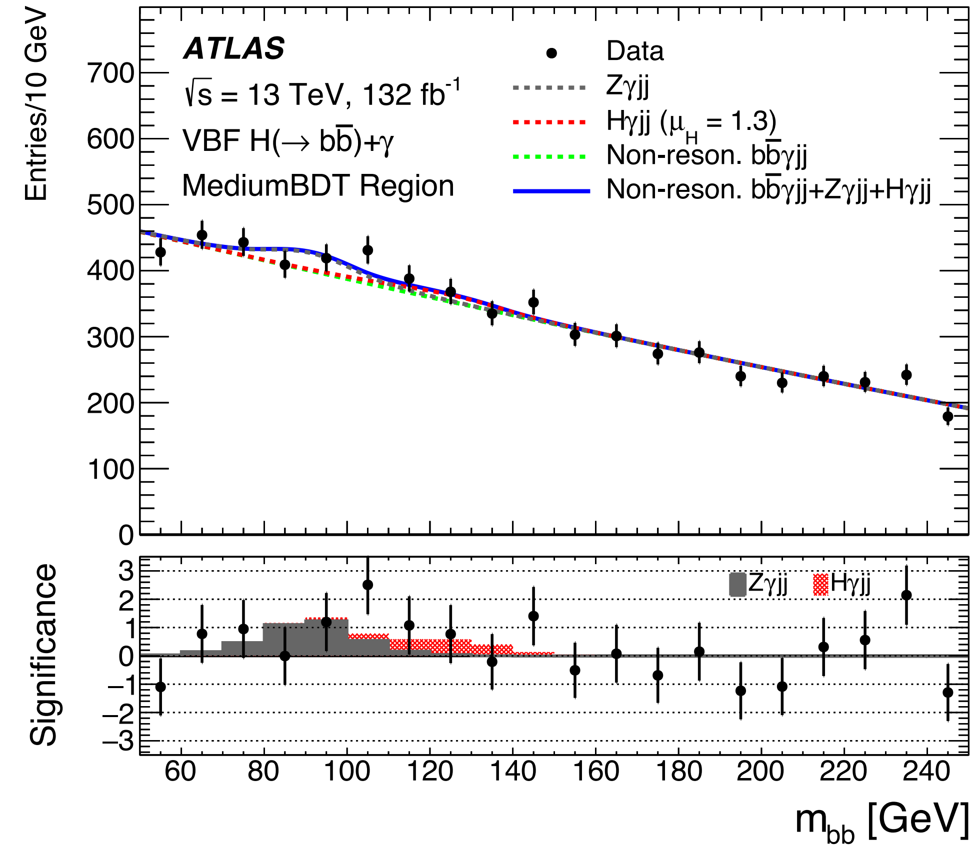
- **Narrow signal shape in HighBDT due to less contamination in "signal-like" region**

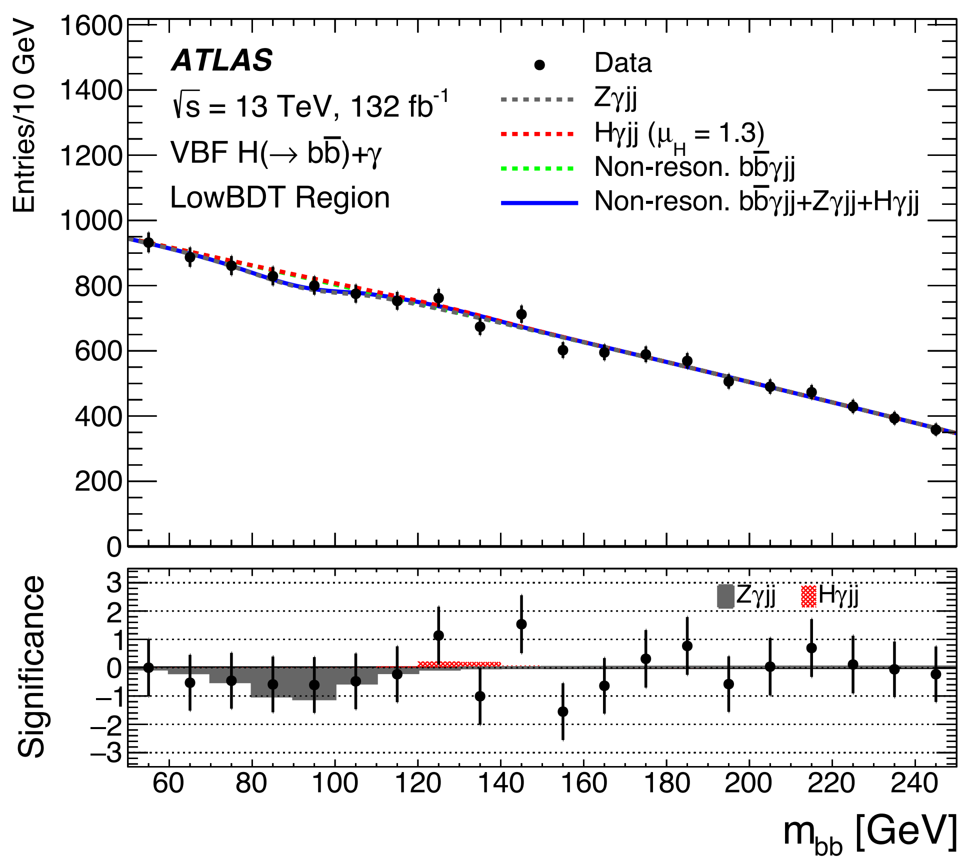




VBF+photon: Signal region distribution







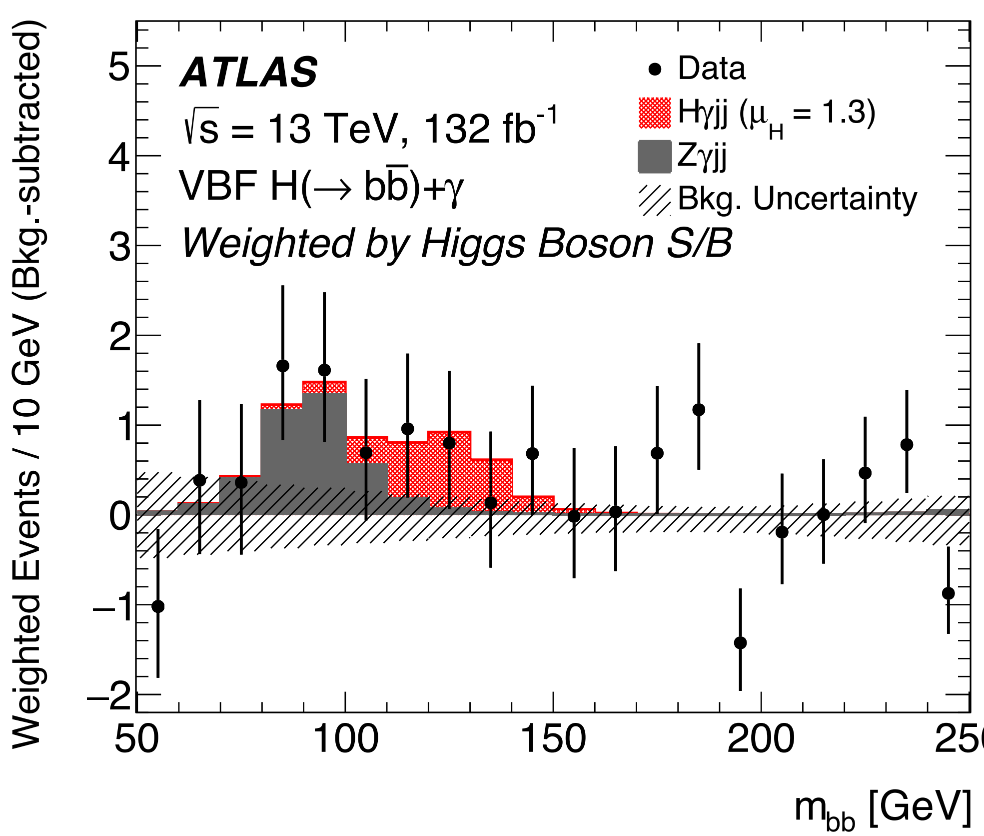
- **Background is modelled with polynomial function**
  - *Functional form is chosen with spurious signal test and F-test*
  - *Background function parameters are determined with S+B fit to data distribution*
- **Signal yield parameter is shared among categories.**
- **Separated *Z* boson yield in various categories**

VBF+photon: Fit results

μ_H	1.3 ± 1.0
Exp. Sig	1.0σ
Obs. Sig	1.3σ

$$\mu_H = \frac{\sigma^{\text{Measured}}}{\sigma^{\text{Predicted}}_{\text{VBF+VH}} + \sigma^{\text{Predicted}}_{ggF} + \sigma^{\text{Predicted}}_{ttH}}$$

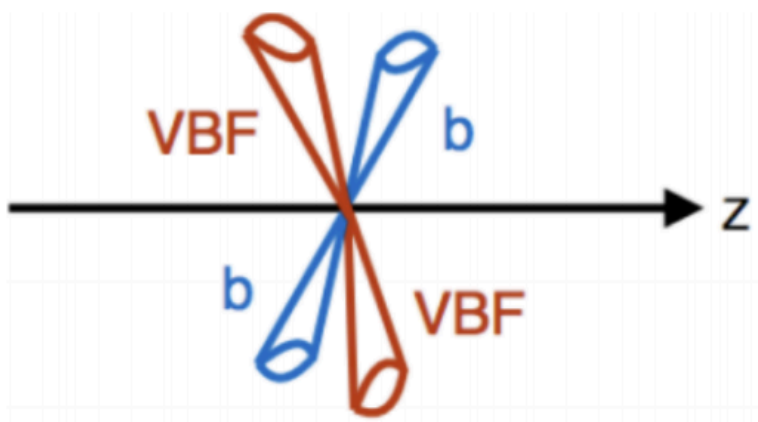
- ***Observed Higgs boson signal slightly higher than SM prediction***



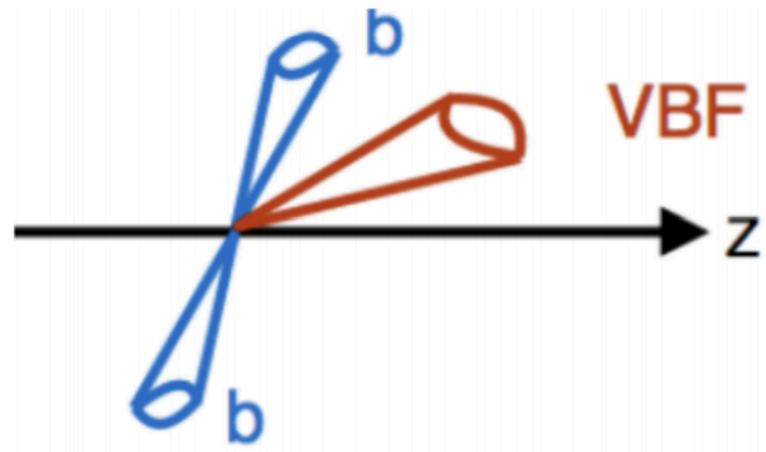
Source of absolute uncertainty	$\sigma(\mu_H)$ down	$\sigma(\mu_H)$ up
Statistical		
Data statistical	−0.78	+0.80
Bkg. fit shapes	−0.19	+0.22
Bkg. fit normalizations	−0.51	+0.52
Z boson normalizations	−0.15	+0.14
Systematic		
Spurious signal	−0.24	+0.21
Theoretical	−0.01	+0.08
Photon	−0.01	+0.03
Jet	−0.06	+0.20
b-tagging	−0.02	+0.11
Auxiliary	−0.01	+0.04
Total	−0.99	+1.04
Total statistical	−0.96	+0.99
Total systematic	−0.25	+0.32

- **Combine all categories weighted by S/B**
- **Background is subtracted**
- **Clearly Z boson peak**
- **Small Higgs boson excess**

VBF all-hadronic: selection



Central channel
(2j, 2b, 0fj)



Central channel
(1fj, 2b)

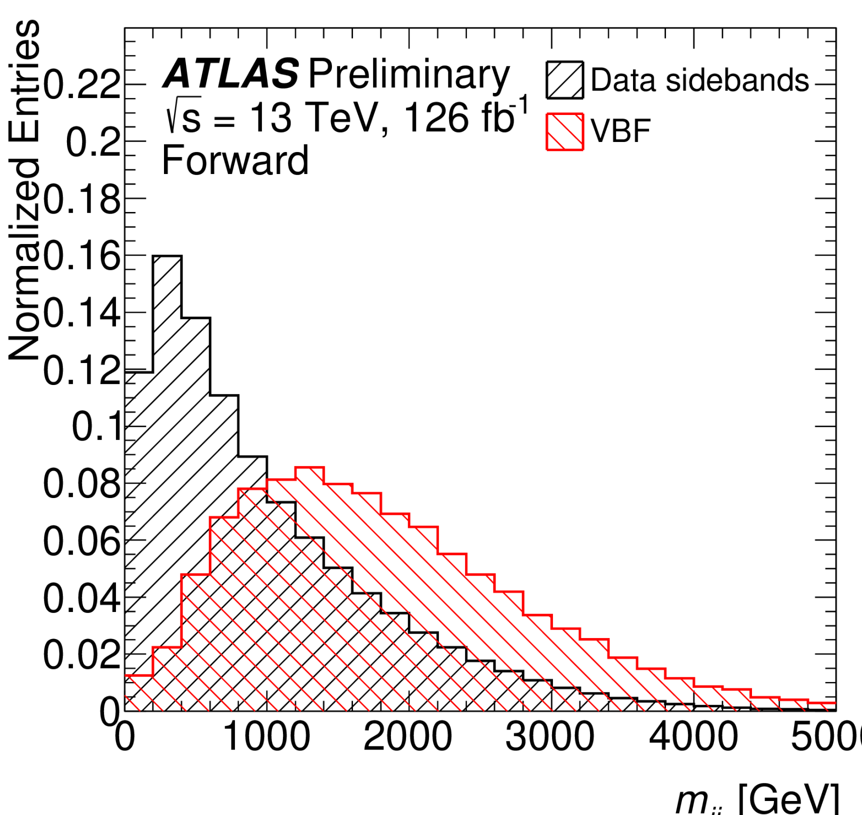
- **Also dedicated triggers designed based on signal signature**
- **Category into central and forward channels**
- **Require boost bb system to avoid kinematic turnOn effects**

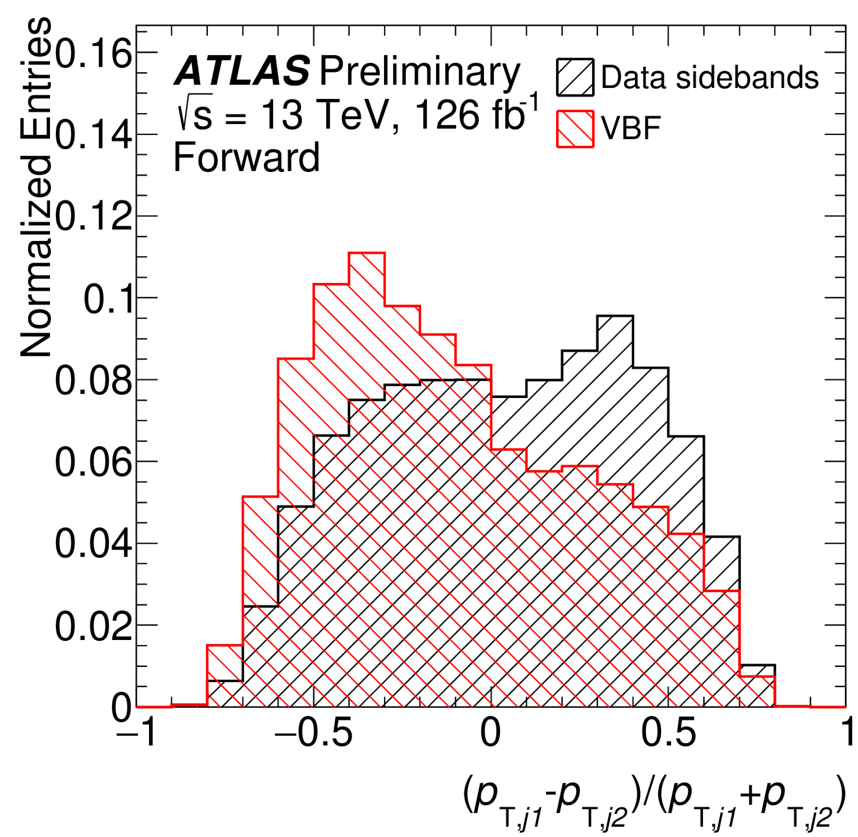
	Forward Channel Event Selection
b_1	≥ 1 b-tagged jet at 77% efficiency working point with $p_T > 85$ GeV and $\lvert\eta\rvert < 2.5$
b_2	≥ 1 b-tagged jet at 85% efficiency working point with $p_T > 65$ GeV and $\lvert\eta\rvert < 2.5$
j_1	≥ 1 jet with $p_T > 60$ GeV and $3.2 < \lvert\eta\rvert < 4.5$
j_2	≥ 1 jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$
	$p_{T,bb} > 150$ GeV
	Central Channel Event Selection
b_1,b_2	≥ 2 b-tagged jets at 77% efficiency working point with $p_T > 65$ GeV and $\lvert\eta\rvert < 2.5$
j_1	≥ 1 jet with $p_T > 160$ GeV and $\lvert\eta\rvert < 3.1$
j_2	≥ 1 jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$
	no jets with $p_T > 60$ GeV and $3.2 < \lvert\eta\rvert < 4.5$
	$p_{T,bb} > 150$ GeV, $m_{jj} > 800$ GeV

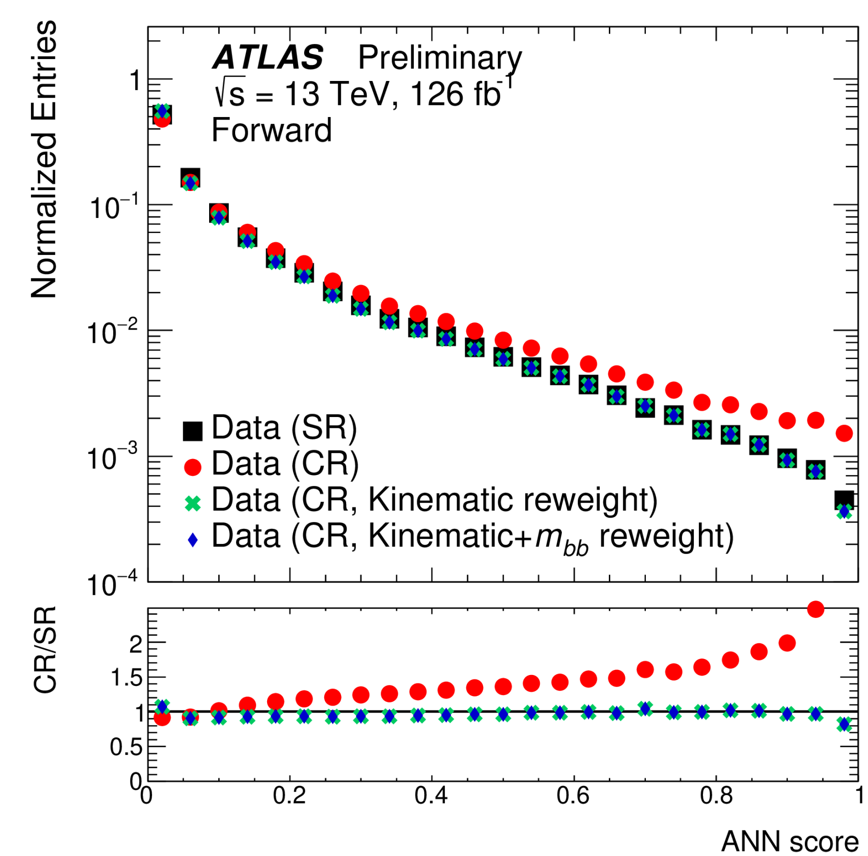
VBF all-hadronic: MVA

Variable	
VBF jets	m_{JJ} p_{T}^{JJ} $\Delta\eta(JJ)$ $(p_{\mathrm{T}}^{J1} - p_{\mathrm{T}}^{J2})/(p_{\mathrm{T}}^{J1} + p_{\mathrm{T}}^{J2})$
Color connection	$p_{\mathrm{T}}^{\mathrm{Bal}}$ n_J
Angular	$\Delta\Phi(bb, JJ)$ $\Delta\eta(bb, JJ)$ $\min\Delta R(J_{1(2)})$ $\tan^{-1}(\tan(\Delta\phi(bb)/2)/\tanh(\Delta\eta(bb)/2))$
q/g tagger	n_{trk}^{J1} n_{trk}^{J2}

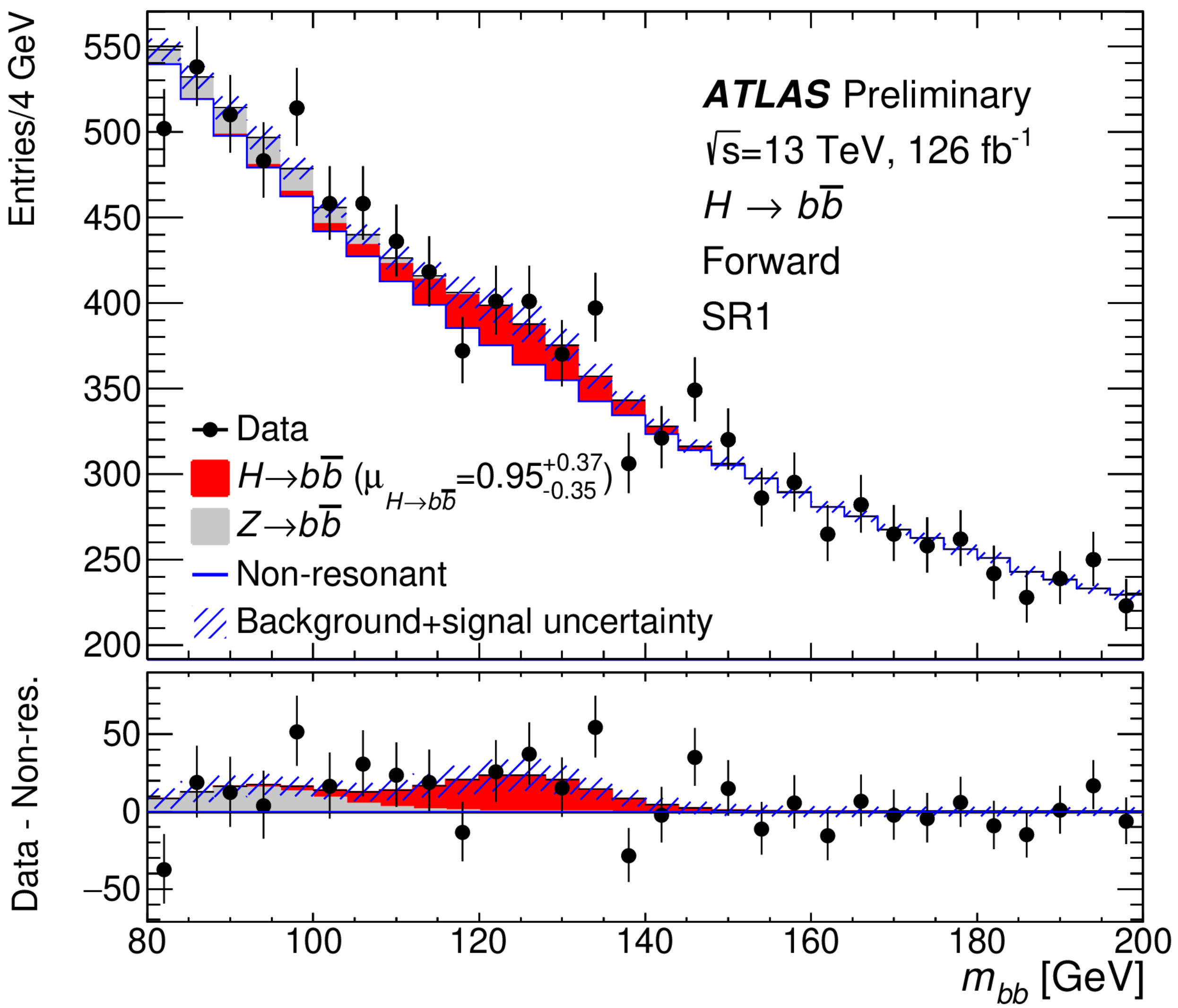
- **VBF all-hadronic channel use Adversarial Neural network (ANN)**
  - **Training is optimised to have little correlation between ANN score and mbb**
- **Signal is modelled with MC sample and parameterised with Burkin function as well**
- **Background shape is take from control regions with one or more selection inverted**

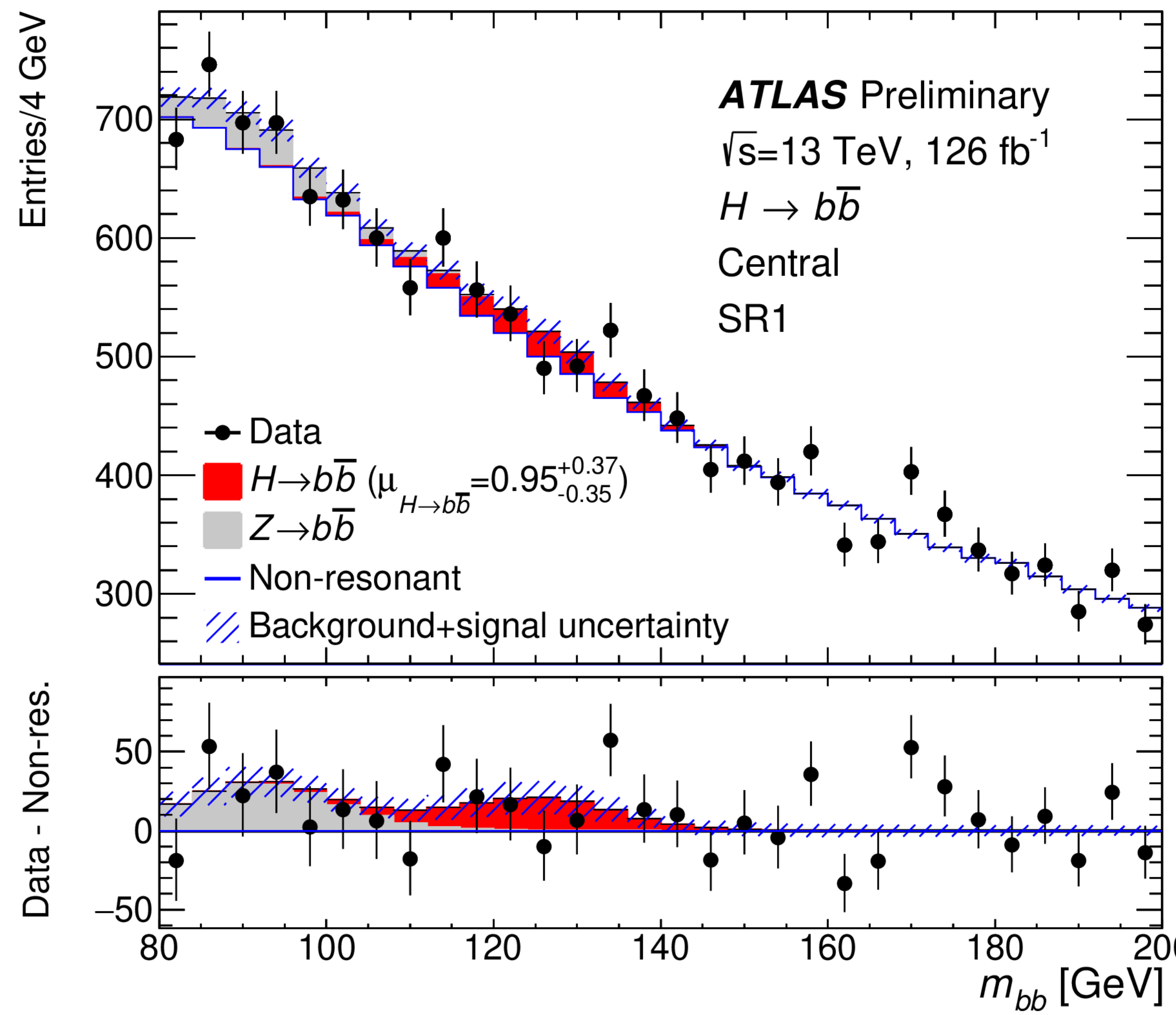






VBF all-hadronic: Distribution

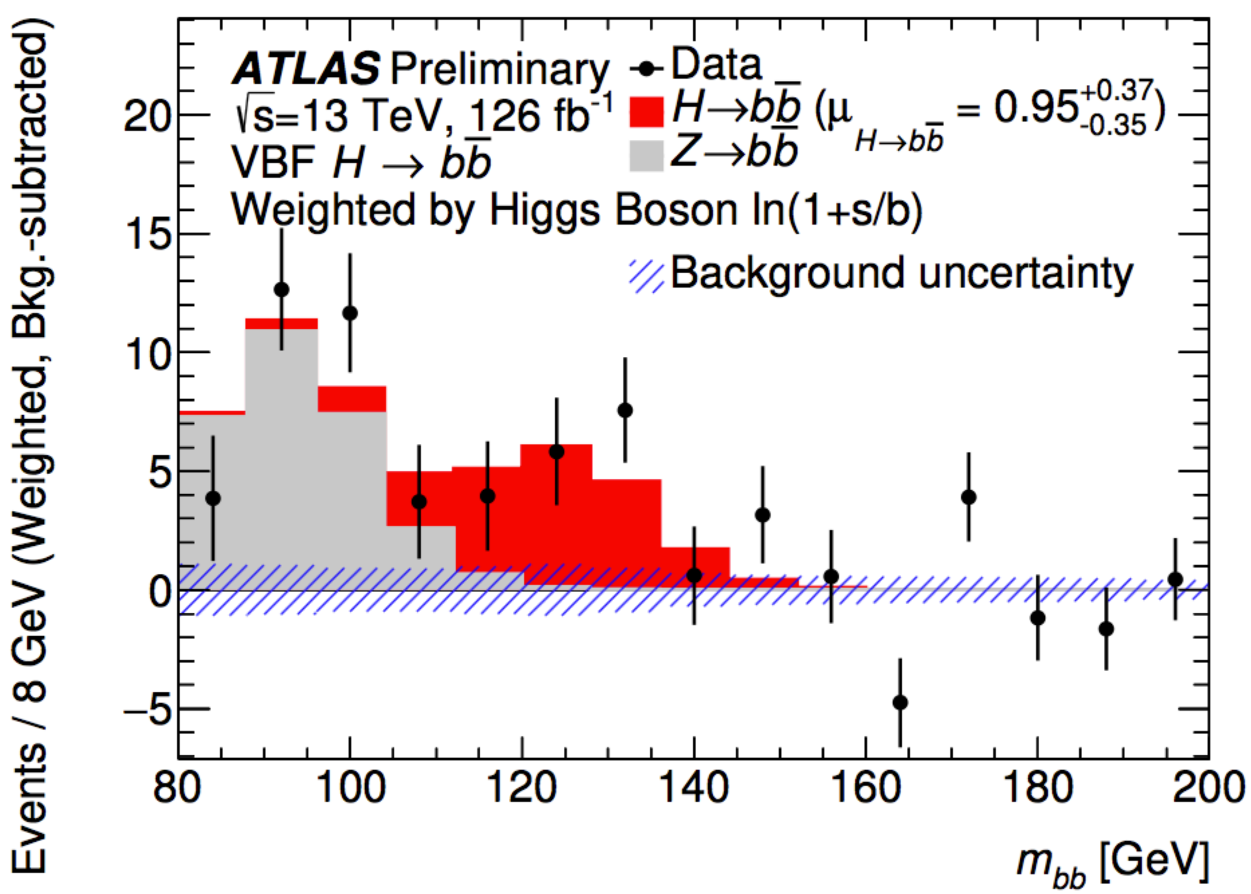




- **Both Higgs boson and Z boson yields shared among categories**
- **Clear peaks in most sensitivity regions**

VBF all-hadronic: results

Results	Inclusive Production	VBF Production	$p_T > 200$ GeV
Expected significance	2.9σ	2.8σ	2.3σ
Observed significance	2.7σ	2.6σ	2.2σ
Expected signal strength	$1.00^{+0.37}_{-0.36}$	$1.00^{+0.38}_{-0.37}$	$1.00^{+0.45}_{-0.43}$
Observed signal strength	$0.95^{+0.37}_{-0.35}$	$0.95^{+0.38}_{-0.36}$	$0.93^{+0.45}_{-0.43}$

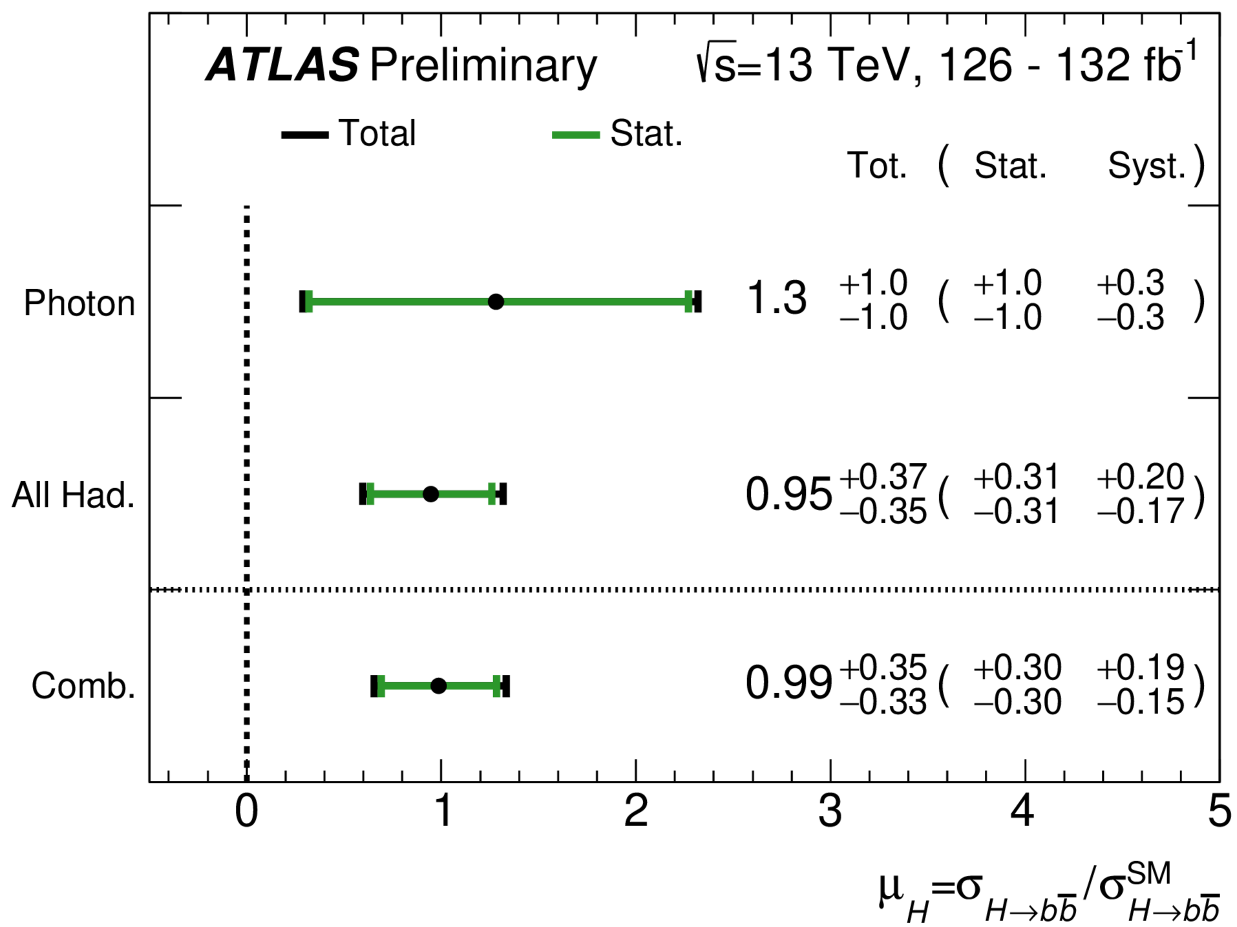


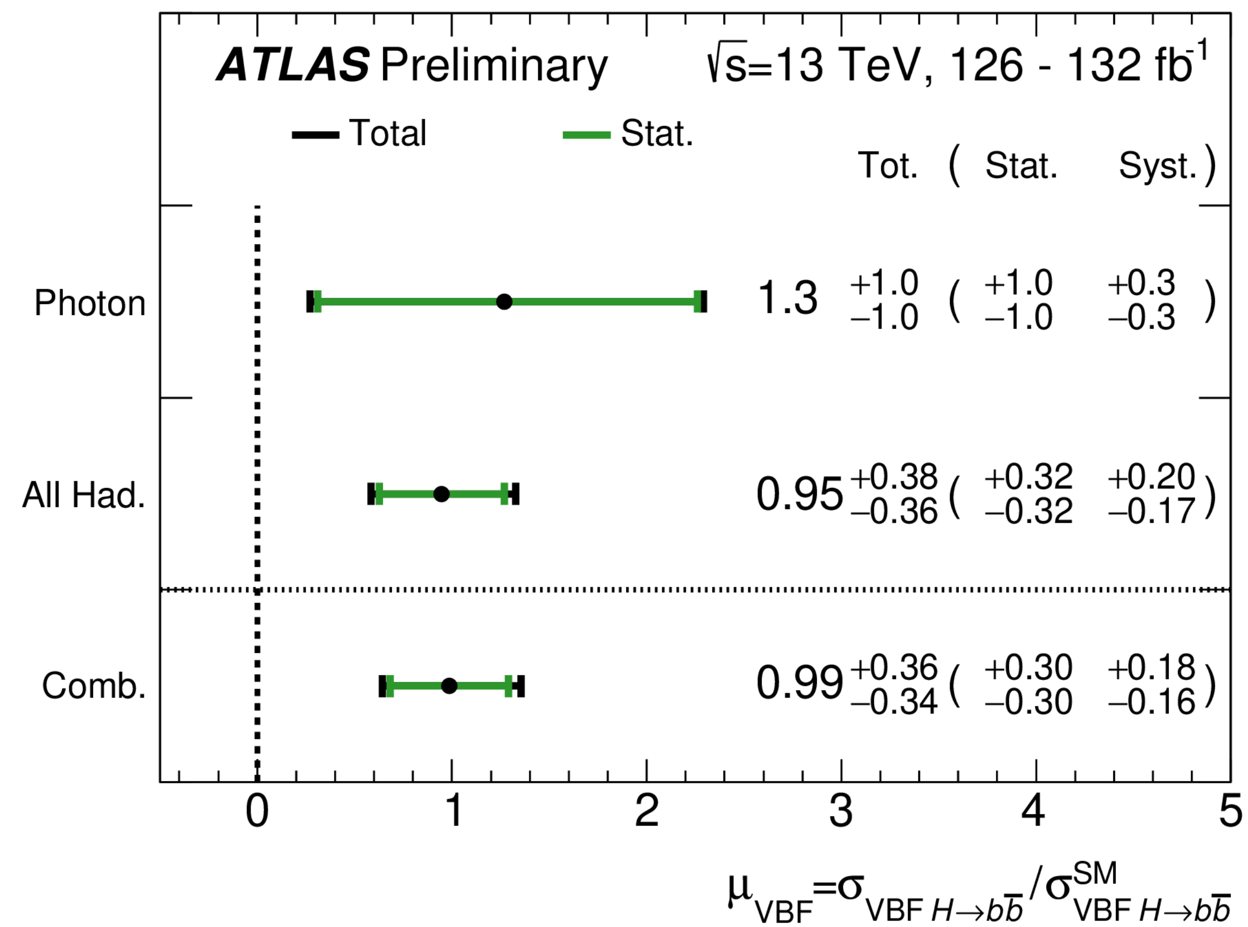
Uncertainty	$\sigma(\mu_{H\to b\bar{b}})$
Statistics	± 0.31
NR Background Bias	± 0.15
Embedded Z	± 0.05
Experimental	$+0.10/-0.05$
Trigger	$+0.07/-0.03$
Jet	$+0.06/-0.04$
Flavor Tagging	$+0.02/-0.01$
Other	$+0.02/-0.01$
Signal Theory	$+0.06/-0.03$

With all-hadronic only, about 2.7 σ significance observed.
Analysis is still dominated by statistical uncertainty

VBF: combined results

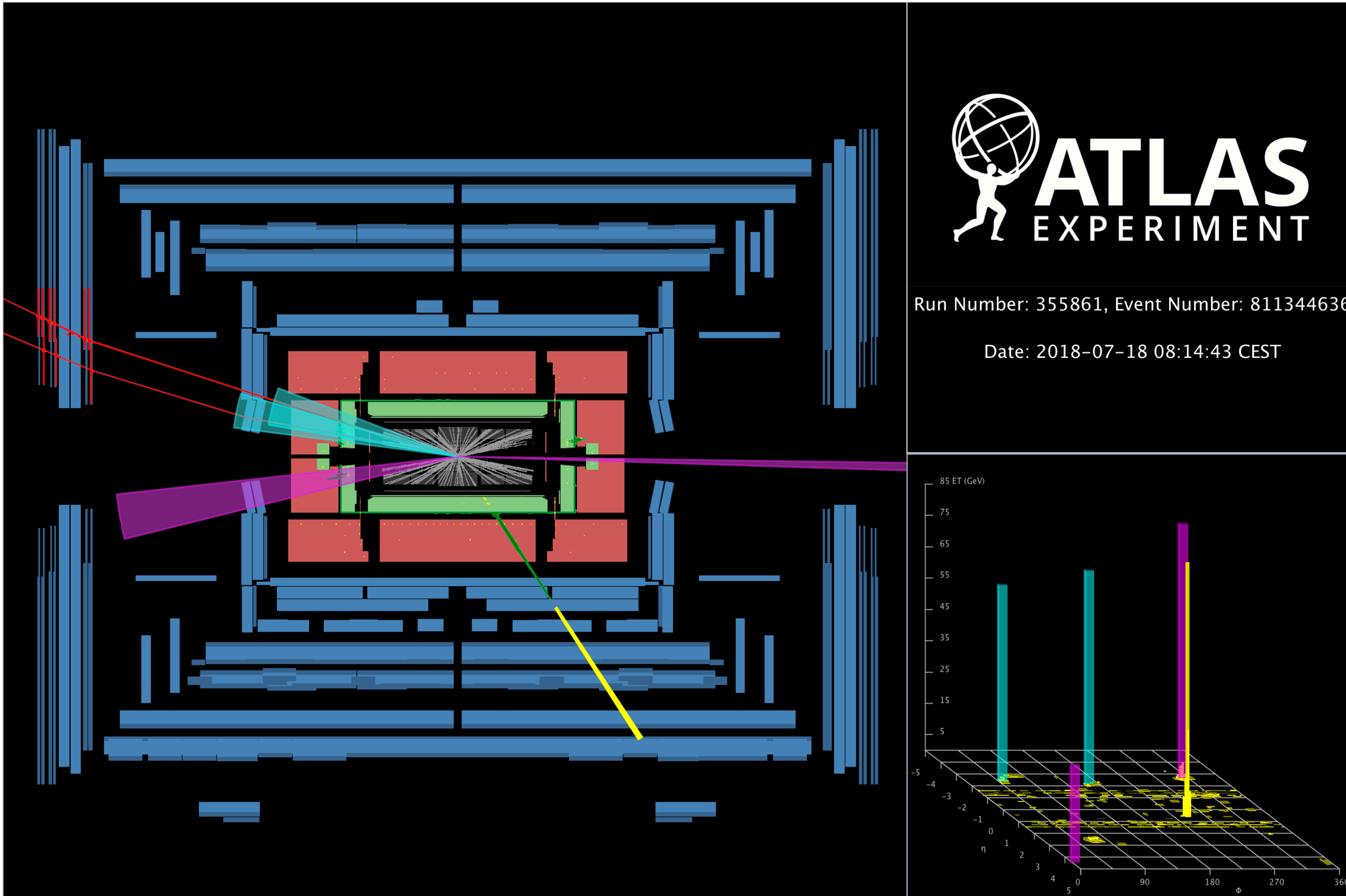
Results	Inclusive Production	VBF Production
Expected significance	3.0σ	2.9σ
Observed significance	3.0σ	2.9σ
Expected signal strength	$1.00^{+0.35}_{-0.34}$	$1.00^{+0.36}_{-0.34}$
Observed signal strength	$0.99^{+0.35}_{-0.33}$	$0.99^{+0.36}_{-0.34}$





- ***Combining both all-hadronic and photon channel, a 3σ significance observed for H→bb. Analysis is still limited by data statistics***

Event display



m=120 GeV Higgs candidate

Summary

- **VBF (H->bb) analysis with full run-II dataset has been finalised**
  - Both VBF all-hadronic and VBF+photon analysis presented
- **Almost 4 times statistics compared to 2015+2016 dataset**
  - *Result is still dominated by the statistical uncertainty*
- **Both analysis have dedicated triggers and perform MVA to separate signal and large QCD backgrounds**
  - VBF+photon use BDT method
  - VBF all-hadronic channel use ANN
- **A combined result show an evidence of $H \rightarrow bb$ in VBF production mode**
  - Even with increased luminosity, these channel is still dominated by the statistical uncertainty
  - Run-III data results would be more interesting

Backup

Variable definition

1. $\Delta\eta(jj)$, the η difference between the two VBF jets;
2. $p_{\mathrm{T}}^{\mathrm{balance}}$, the transverse momentum balance for selected final state objects, defined as

$$p_{\mathrm{T}}^{\mathrm{balance}} = \frac{|\vec{p_{\mathrm{T}}}^{b1} + \vec{p_{\mathrm{T}}}^{b2} + \vec{p_{\mathrm{T}}}^{j1} + \vec{p_{\mathrm{T}}}^{j2} + \vec{p_{\mathrm{T}}}^{\gamma}|}{p_{\mathrm{T}}^{b1} + p_{\mathrm{T}}^{b2} + p_{\mathrm{T}}^{j1} + p_{\mathrm{T}}^{j2} + p_{\mathrm{T}}^{\gamma}}; \tag{1}$$

3. m_{jj}, the invariant mass of the two VBF jets;
4. centrality$(\gamma, j1, j2)$, the rapidity of the photon with respect to the VBF jet rapidities, defined as

$$\mathrm{centrality}(\gamma, j1, j2) = \left|\frac{y_{\gamma} - \frac{y_{j1}+y_{j2}}{2}}{y_{j1} - y_{j2}}\right|; \tag{2}$$

5. $\Delta R(b1, \gamma)$, the angular distance between the leading b-jet and the photon;
6. $\Delta R(b2, \gamma)$, the angular distance between the subleading b-jet and the photon;
7. $\cos\theta$, the cosine of the angle between the VBF jets plane and b-jets plane in the centre-of-mass frame of the $b\bar{b}jj$ system [2];
8. $\Delta\phi(b\bar{b}, jj)$, the azimuthal angle difference between the bb-jet system and the VBF jet system;
9. p_{T}^{jj}, the transverse momentum of the VBF jets system; and
10. $\Delta R(b1, j1)$, the angular distance between the leading b-jet and the leading VBF jet.

VBF all-hadron: CR defintion

	Forward Channel CR Event Selection
b_1	≥ 1 b-tagged jet at 77% efficiency working point with $p_T > 85$ GeV and $\lvert\eta\rvert < 2.5$
b_2	≥ 1 b-tagged jet at 85% efficiency working point with $p_T > 65$ GeV and $\lvert\eta\rvert < 2.5$
j_1	≥ 1 jet with $p_T > 60$ GeV, $3.2 < \lvert\eta'\rvert < 4.5$, and $\lvert\eta\rvert < 2.5$
j_2	≥ 1 jet with $p_T > 30$ GeV, $\lvert\eta'\rvert < 4.5$, and $\lvert\eta\rvert < 2.5$
	$p_{T,bb} > 150$ GeV
	no jets with $p_T > 60$ GeV, $3.2 < \lvert\eta\rvert < 4.5$
	no jet pair (not including b_1, b_2) with $m_{jj} > 800$ GeV
	$m'_{jj} > 800$ GeV
	Central Channel CR Event Selection
b_1,b_2	≥ 2 b-tagged jets at 77% efficiency working point with $p_T > 65$ GeV and $\lvert\eta\rvert < 2.5$
j_1	≥ 1 jet with $p_T > 160$ GeV and $\lvert\eta\rvert < 3.1$
j_2	≥ 1 jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$
	no jets with $p_T > 60$ GeV and $3.2 < \lvert\eta\rvert < 4.5$
	$p_{T,bb} > 150$ GeV, m_{jj} <800 GeV
	$\Delta\phi_{jj} > \pi/4$
	$m'_{jj} > 800$ GeV

Categorization

- Sequential optimization (only partial BDT bins):
  - *Step1: only count SRI*
  - *Step2: only count SRI+SRII*
  - *....*

$$Z_{\mathrm{A}} = \left[2\left((s+b)\ln\left[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right] - \frac{b^2}{\sigma_b^2}\ln\left[1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right]\right)\right]^{1/2}$$

$$\mathrm{Sensitivity} = \sqrt{\sum Z^2}$$

- *Background uncertainty quoted is the envelop of fitted band*
- *The relative uncertainty has been studies as a function of number of background events in mass signal region [100, 140]*