Measurements and searches of Higgs boson decays to two fermions

Tatsuya Masubuchi
on behalf of the ATLAS collaboration

ICEPP, The University of Tokyo

CIPANP 2018, Palm Springs

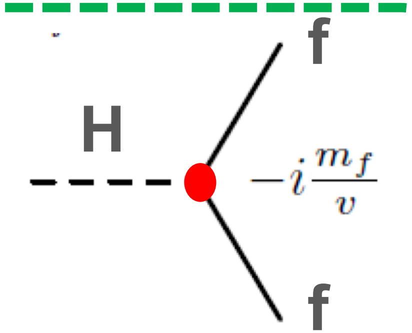
東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo

ATLAS
EXPERIMENT

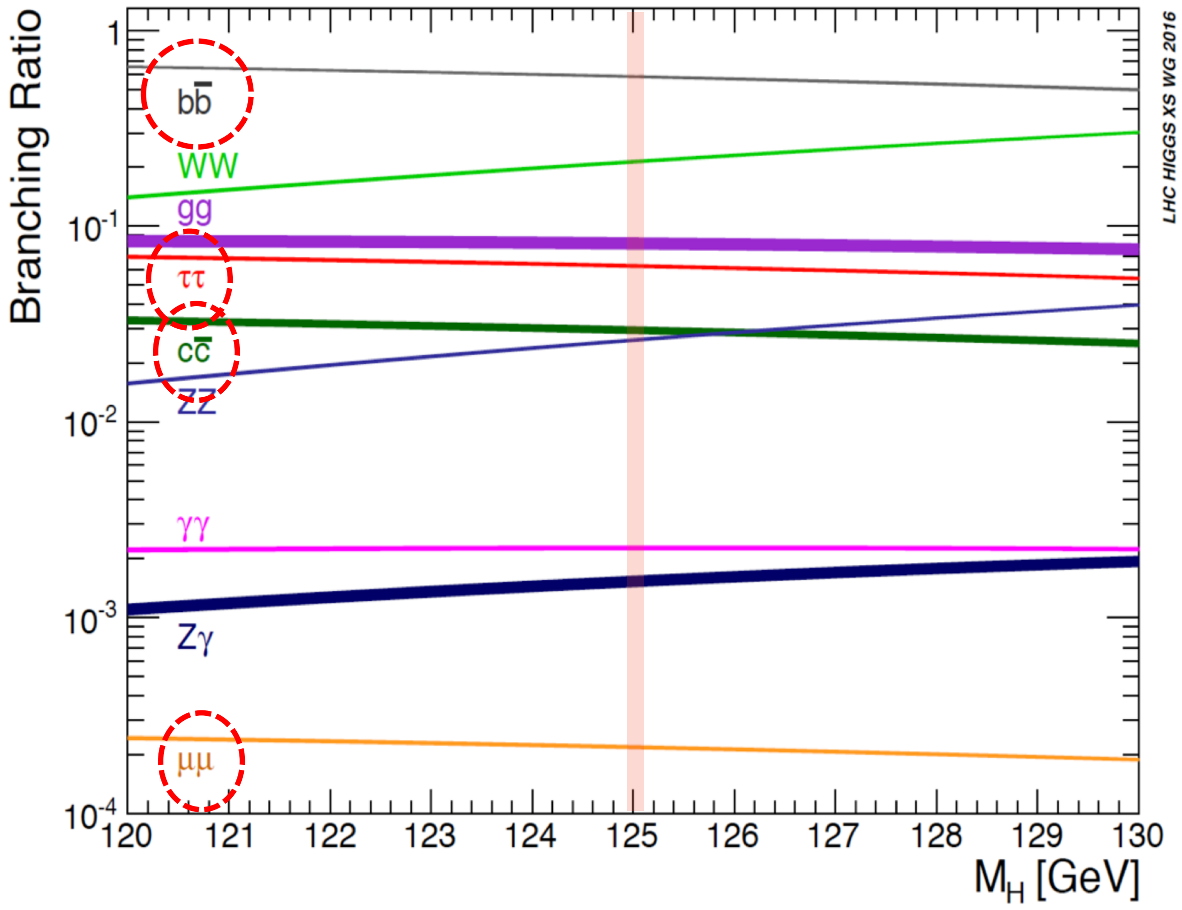
Higgs Decay to Fermion

- Higgs boson properties have been measured precisely using bosonic decay modes (γγ, ZZ→4l, WW→lνlν)
  - **Higgs mass ~125 GeV (0.2% precision)**
  - **Spin/CP, differential cross section**
- Higgs to fermion decay is still mysterious part in the Higgs sector
- Yukawa coupling is proportional to fermion mass

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

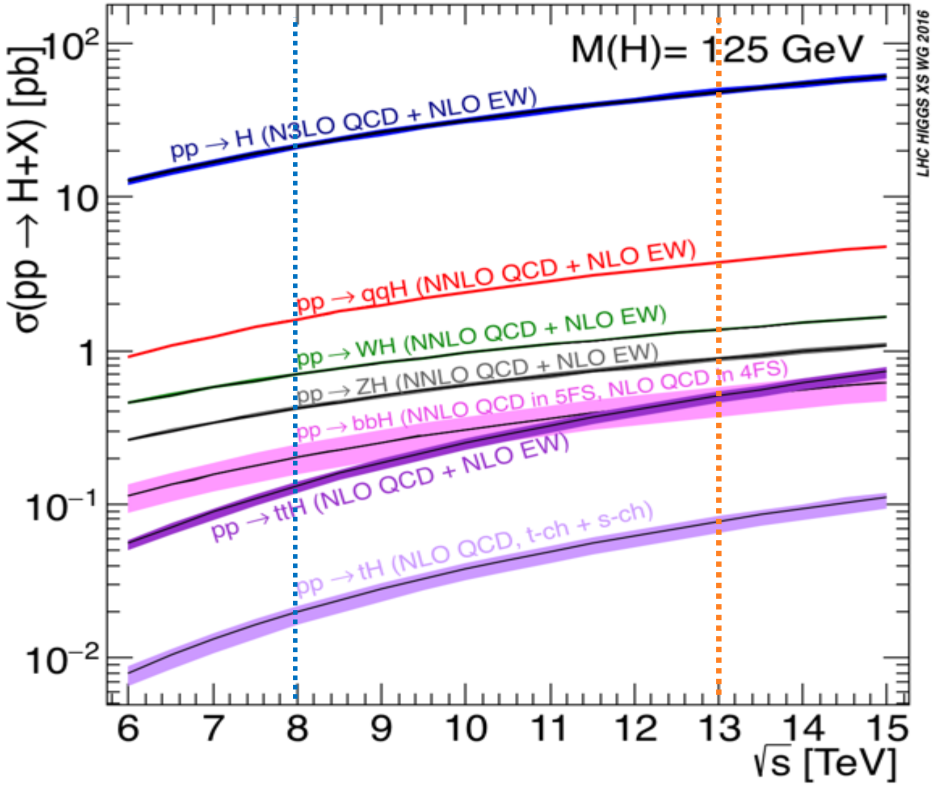


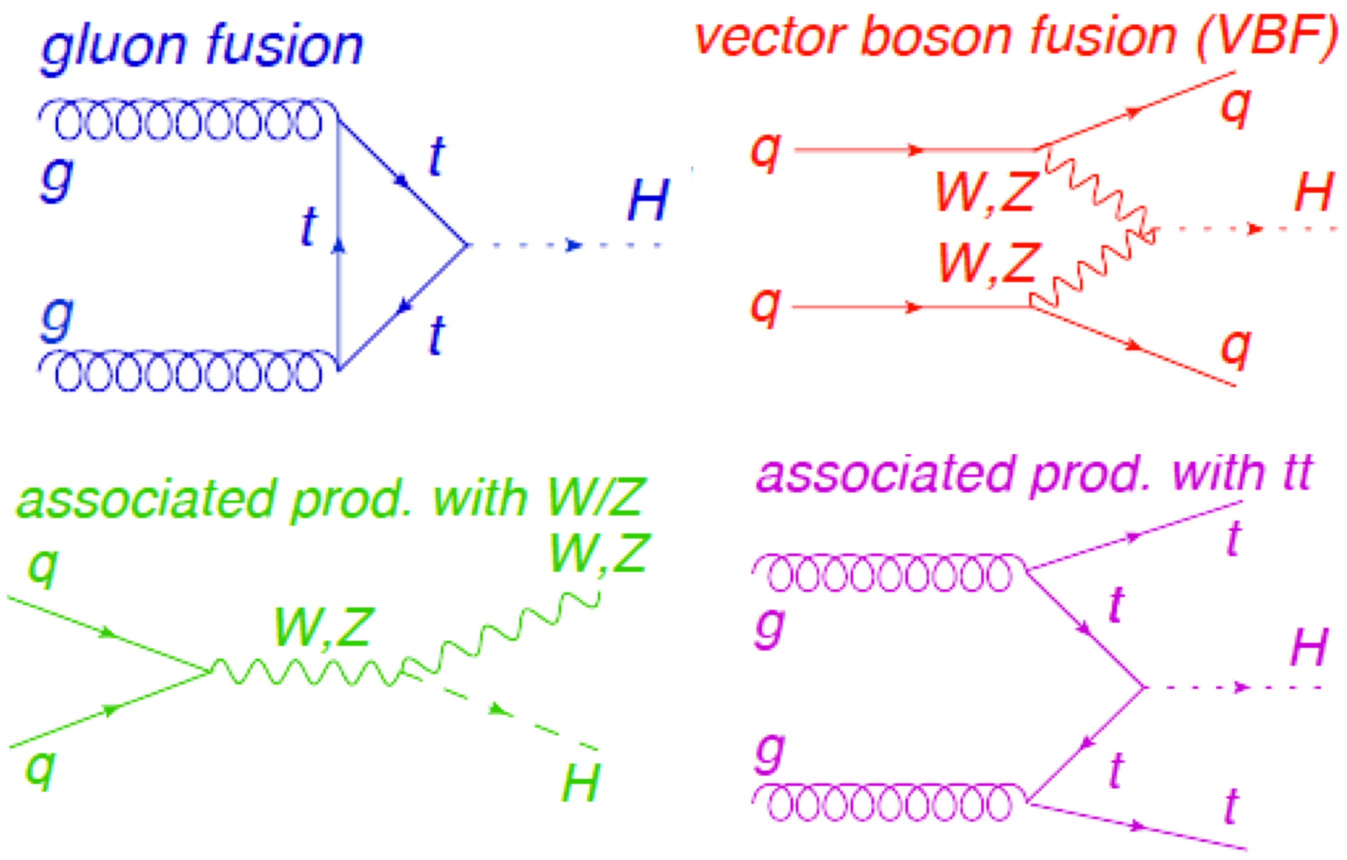
Deviation pattern of coupling (up/down, lepton, quark) provides rich information of BSM physics



Fermion Decay	bb	ττ	cc	μμ
Branching Ratio	58%	6.3%	2.9%	0.022%

Higgs Production for Fermion Decay





Process	ggF	VBF	WH	ZH	ttH
Cross section (13 TeV)	49pb	3.8pb	1.34pb	0.88pb	0.51pb

- ✓ **H→ττ/μμ** : clean final state
  - ➔ggF/VBF can be used
- ✓ **H→bb/cc** : “not clean” final state
  - ➔ ggF is very challenging (only boosted region)
  - ➔ VH, ttH, VBF are promising

Analysis status of two fermion decay mode at ATLAS

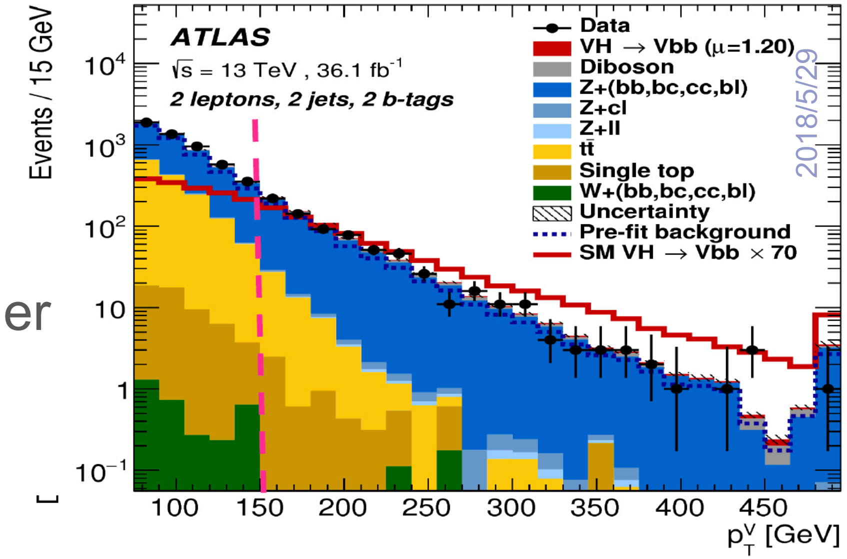
Decay mode	Production process	Run2	Run1	Reference
H→bb	VH	36.1fb^{-1}	25fb^{-1}	JHEP 12 (2017) 024
	VBF(+γ)	12.6fb^{-1}	20fb^{-1}	JHEP 11 (2016) 112, ATLAS-CONF-2016-063
H→ττ	ggF, VBF		20-25fb^{-1}	JHEP 04 (2015) 117, Phys. Rev. D 93 (2016) 092005
H→cc	VH	36.1fb^{-1}		Phys. Rev. Lett. 120 (2018) 211802
H→μμ	ggF, VBF	36fb^{-1}	25fb^{-1}	Phys. Rev. Lett. 119 (2017) 051802
H→J/ψγ	Inclusive		20fb^{-1}	Phys. Rev. Lett. 114 (2015) 121801
H→Φγ,ργ	Inclusive	36fb^{-1}		arXiv:1712.02758 (Submitted to JHEP)

- ✓ **Focus on the results using Run2 data**
- ✓ Meson+γ modes are covered by Elliot Reynolds

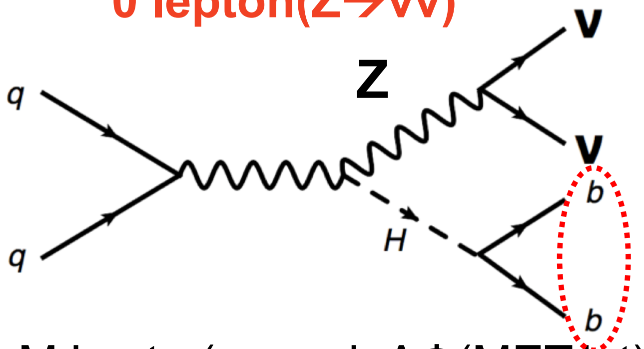
JHEP 12 (2017) 024

Analysis Overview H→bb decay

- VH production is "**golden**" channel
  - Lepton(e, μ)/MET from vector boson decay can be used for trigger
  - Optimize selection for each channel (0/1/2lepton)
  - 2 b-tagged jets requirement
  - High-p_T^V region enhances signal-to-background ratio

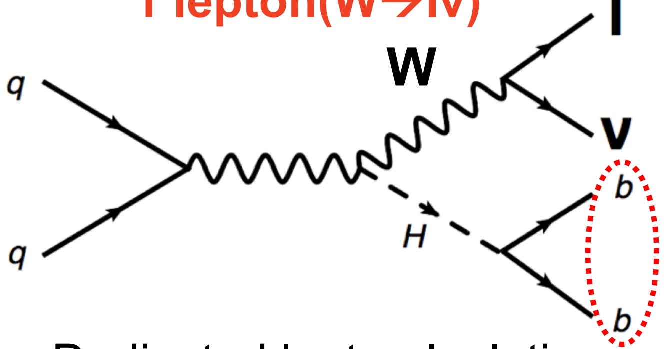


0 lepton(Z→νν)



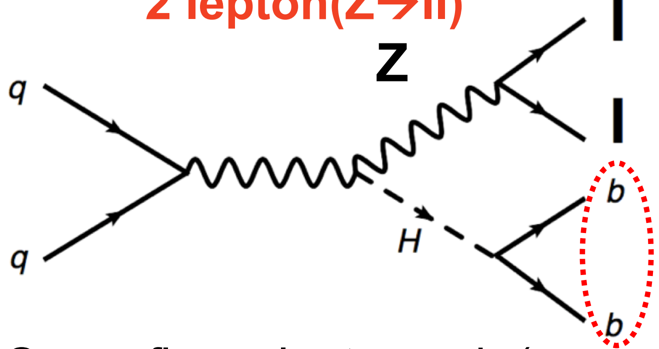
MJ veto (e.g. minΔΦ(MET,jet))
High-MET(p_T^Z)

1 lepton(W→lν)



Dedicated lepton Isolation
(Multi-jet rejection)
High-p_T^W

2 lepton(Z→ll)



Same-flavor lepton pair (ee or μμ)
Z mass selection ($81<m_{ll}<101$)

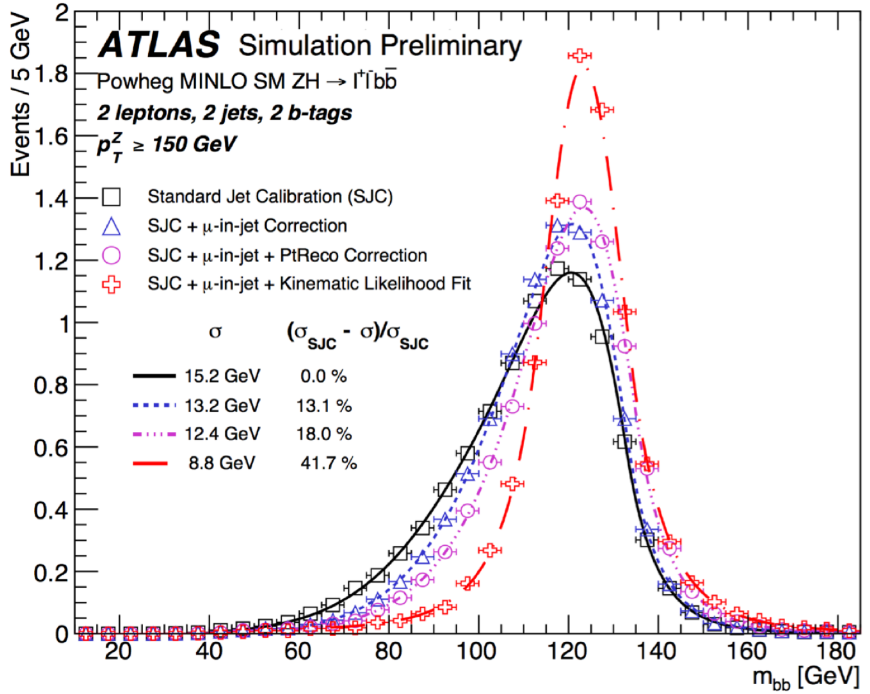
Categorization	0lepton	1lepton	2lepton
p_T^V	**MET>150 GeV**	**p_T^W>150 GeV**	**$75<p_T^Z<150$, p_T^Z>150 GeV**
N_{jets}	2,3jets	2,3jets	2,≧3jets

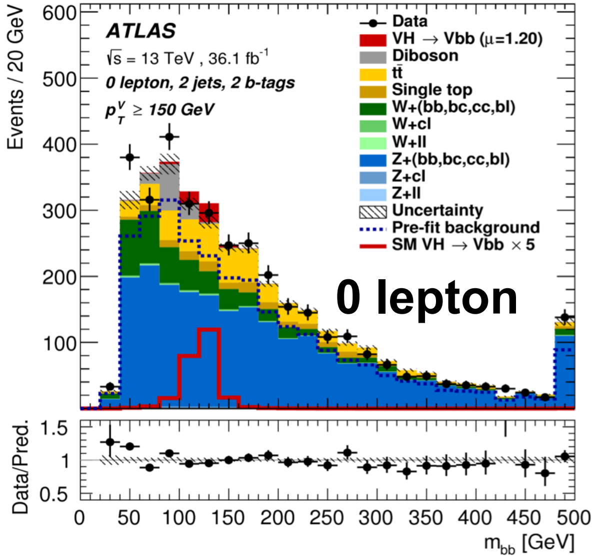
Main Backgrounds

- W+bb, Z+bb
- top (ttbar, single top)
- multi-jet
- diboson

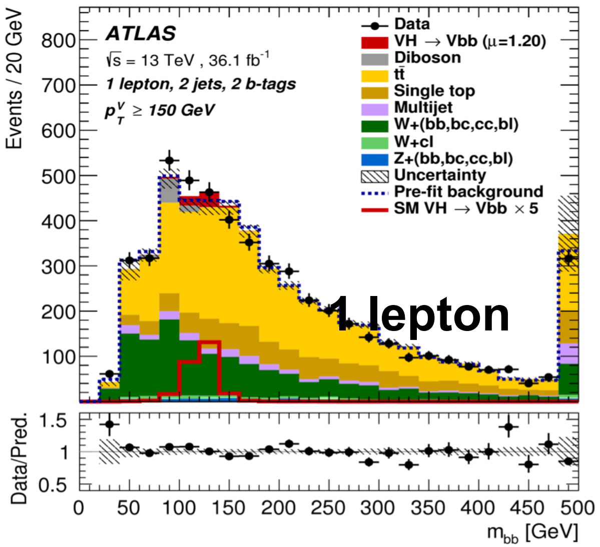
Keys of H→bb decay

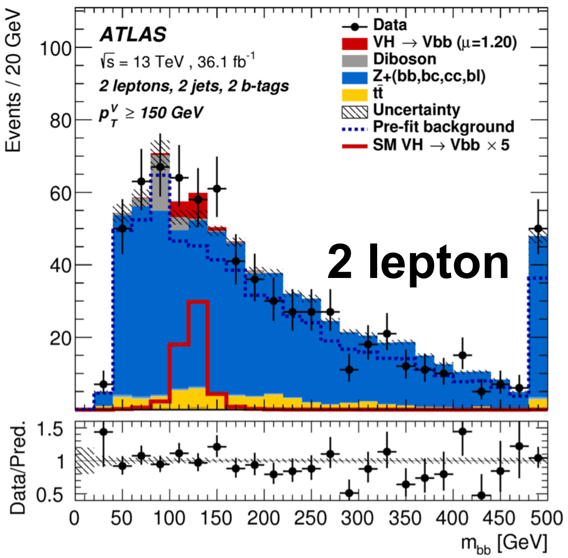
- m_{bb} resolution and multi-variate analysis(BDT) are keys
  - **Muon-in-jet correction** : Add momentum of muon inside b-jet
  - **PtReco correction** : Apply correction factor accounting for missing neutrino energy and out-of-cone effect based on MC response
  - **Kinematic Fit (2lepton)** : Correct b-jet energy by constraint of llbb balance (no intrinsic missing E_T)





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}	×	×	×





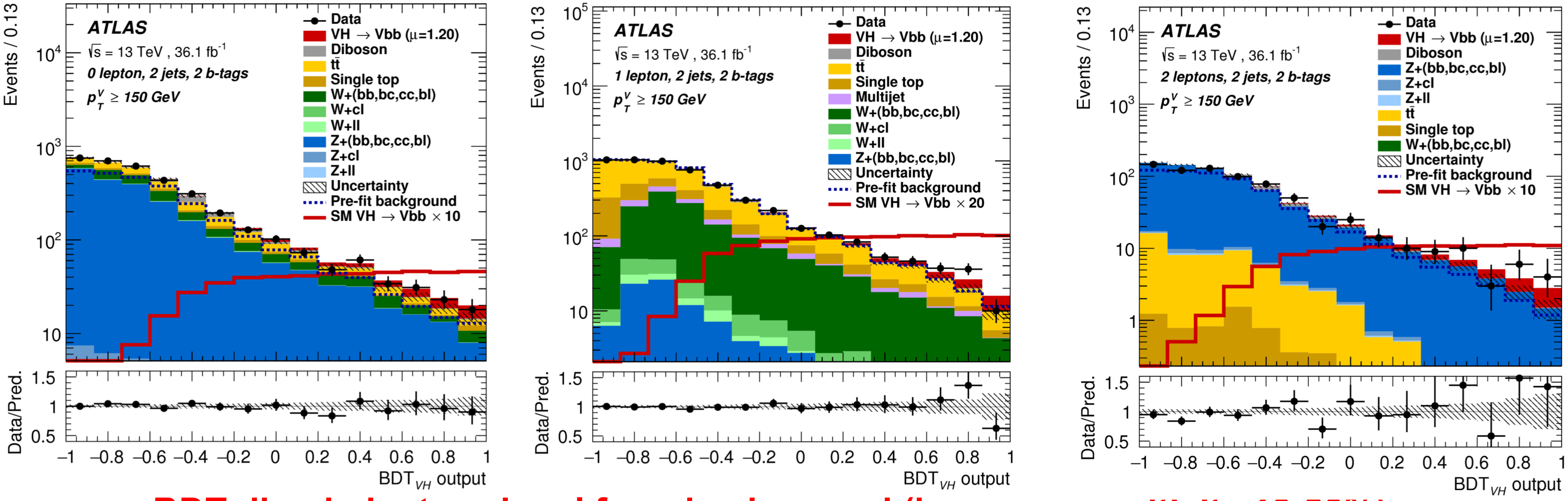
Final discriminant : BDT distribution

Fit Scheme and Analysis Validation

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

- Fit 8 signal regions and W+jets (1lepton) and ttbar control regions (2lepton) simultaneously
- Validate fit scheme using SM diboson VZ(→bb) : $\mu_{VZ}^{b\bar{b}} = 1.11^{+0.25}_{-0.22}$ **(Obs. 5.8σ)**
- After validation of background modeling, **VH→bb** signal regions are opened

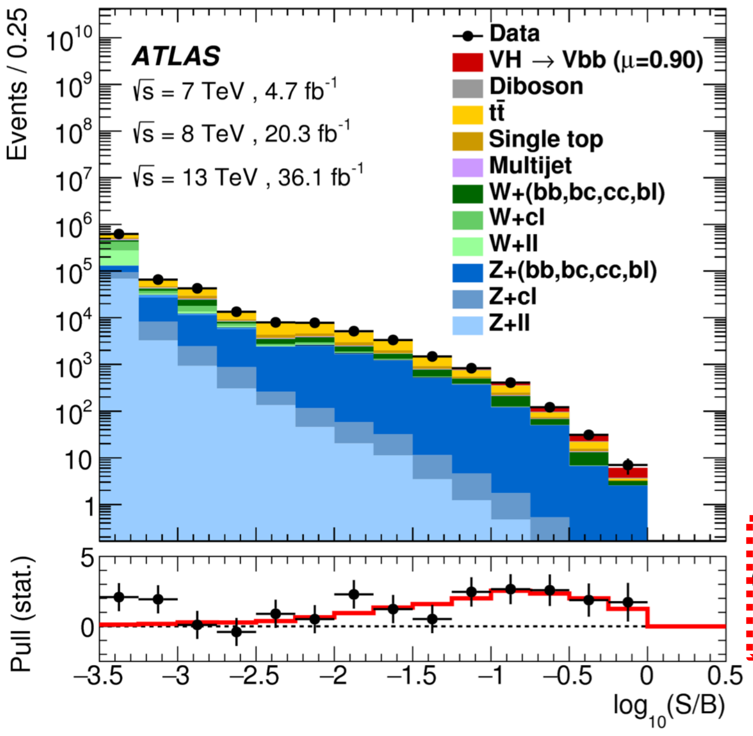
0 lepton **1 lepton** **2 lepton**

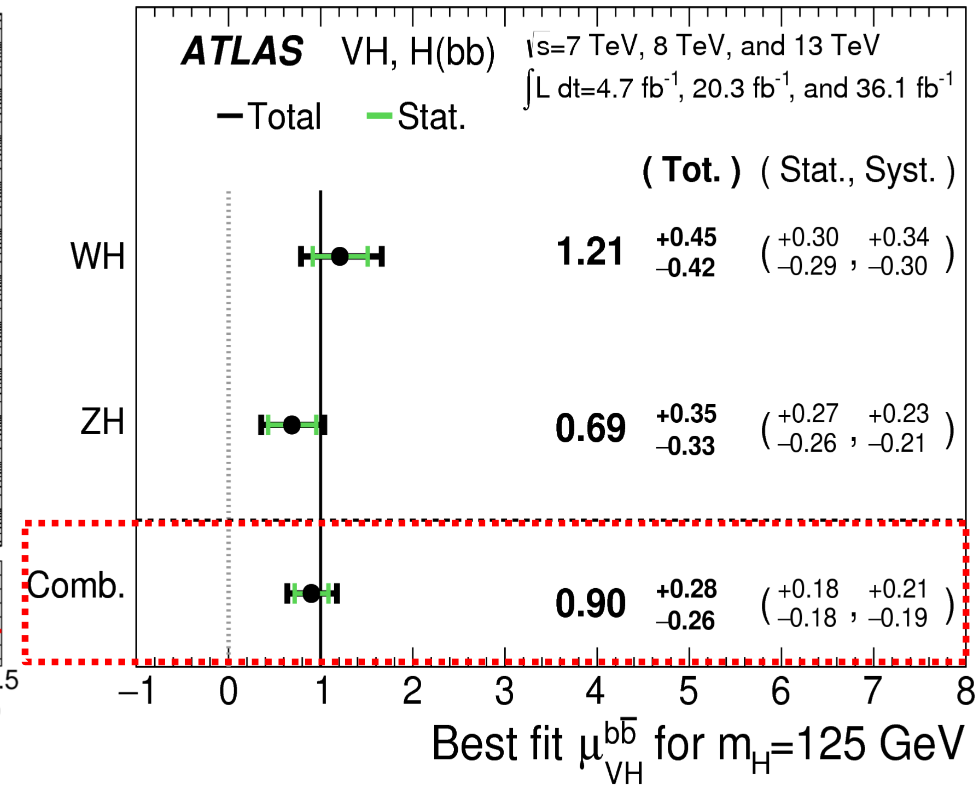


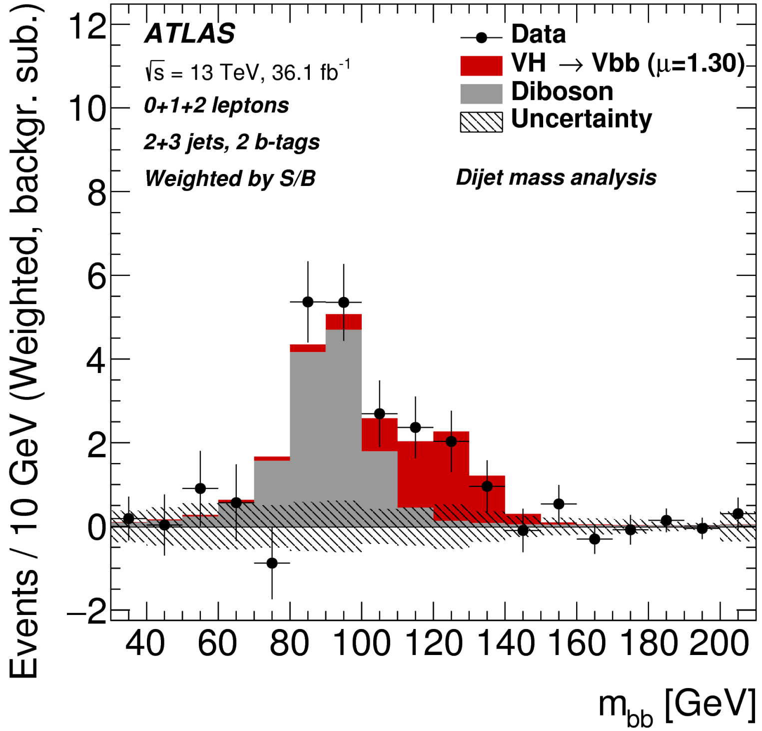
BDT discriminates signal from background (improve sensitivity 10-20%)

Evidence for H→bb Decay

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







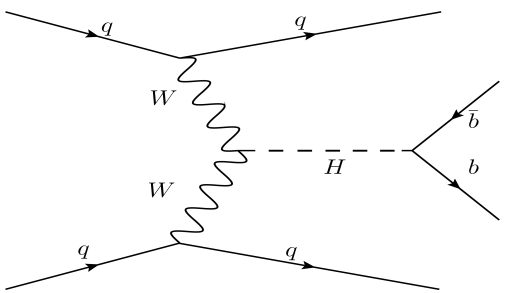
Observed significance 3.6σ (Expected 4.0σ)

Di-jet mass analysis (Fit to m_{bb}) gives consistent results with MVA

Run2 only : $\mu(m_{bb})$ = 1.30 vs μ(MVA)=1.20

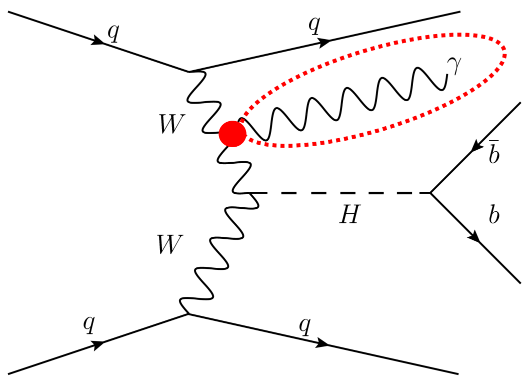
Search for VBF H→bb

ATLAS-CONF-2016-063

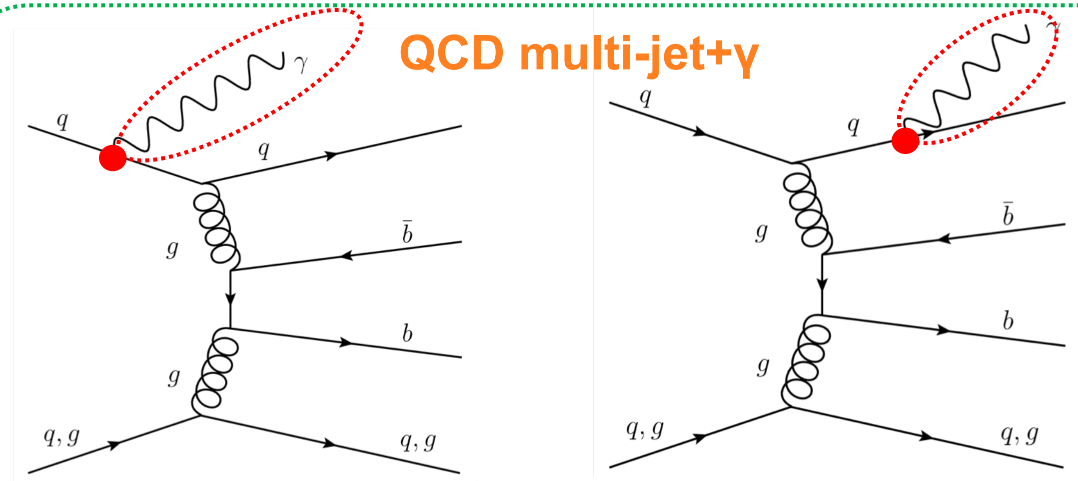


- Using VBF topology is quite challenging for H→bb search
  - Difficult to trigger bb+VBF(jj) topology due to high rate
  - Suffers from huge QCD multi-jet background
- A high energy photon requirement greatly reduce multi-jet background

Signal VBF+γ H→bb



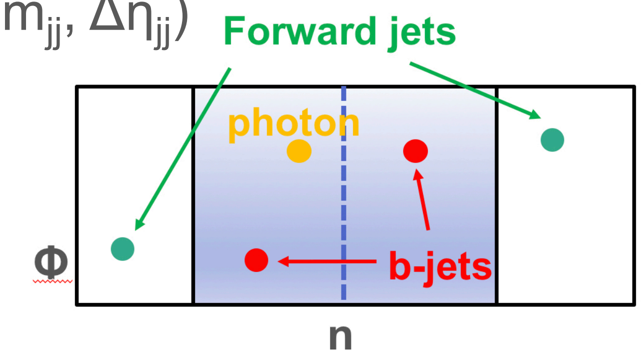
QCD multi-jet+γ



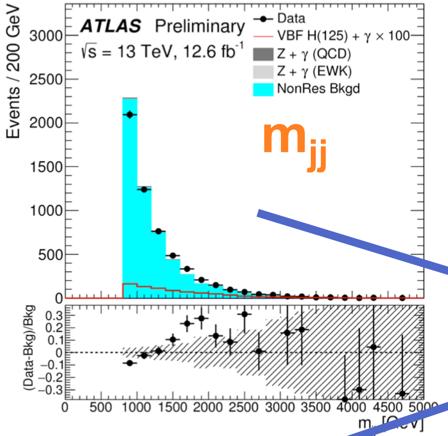
  - **High-p_T photon signature for efficient trigger**
    - $p_T(\gamma)$>25 GeV, 4jets with p_T(jet)>35 GeV, m_{jj} > 700 GeV
  - **Destructive interference between ISR and FSR photon emission diagram** further reduces multi-jet background (**more than one order w.r.t. α_{EW}**)
- Event preselection : $p_T(\gamma)$>30 GeV, 4jets p_T(jets)>40 GeV,**2 b-jets(77% eff)**, m_{jj} > 800 GeV

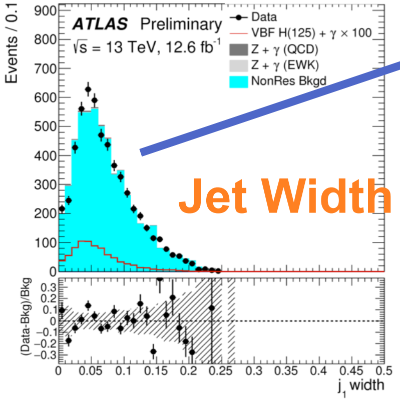
VBF H→bb Results

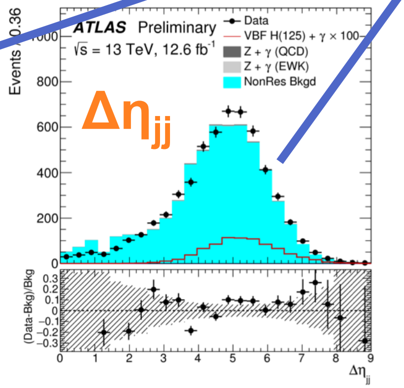
- Apply BDT to discriminate multi-jet background with VBF topology (high m_{jj}, $\Delta\eta_{jj}$)
  - Information of Higgs decay product is not used ➔ Less bias on m_{bb} shape

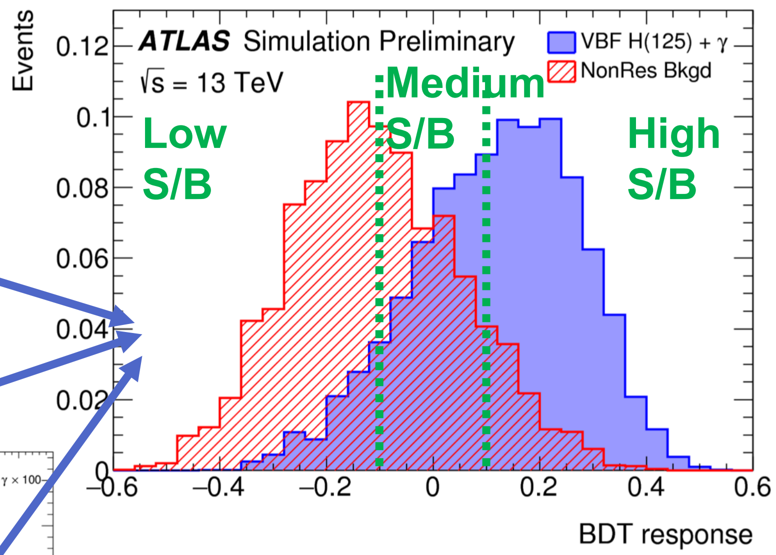


- m_{bb} shape fitting after BDT categorization
  - Non-resonant background shape : 2nd order polynomial function
  - Resonant H→bb signal, Z→bb : Crystal Ball

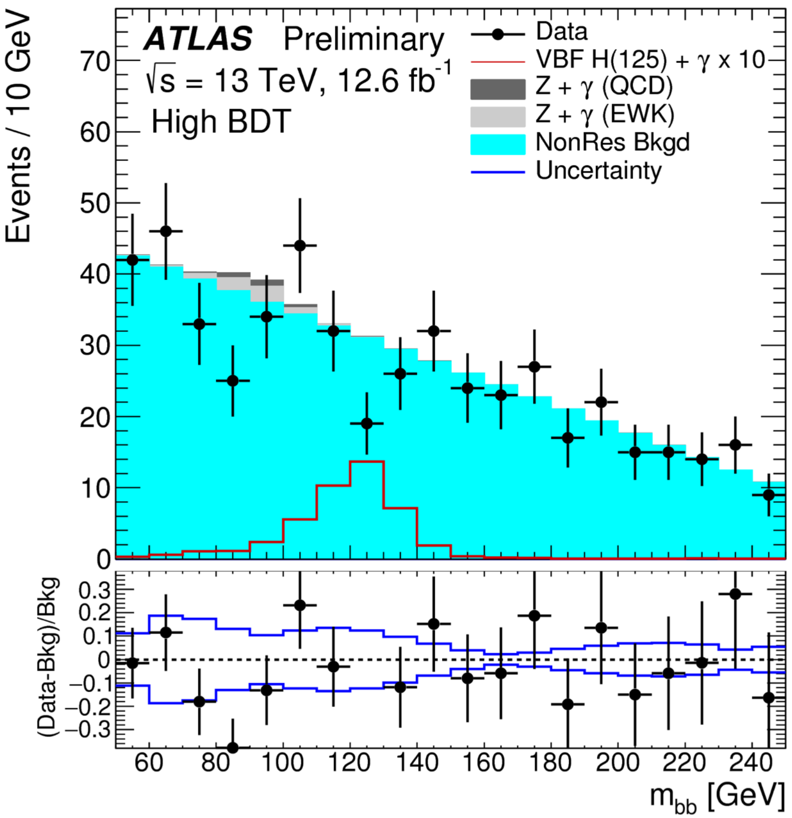








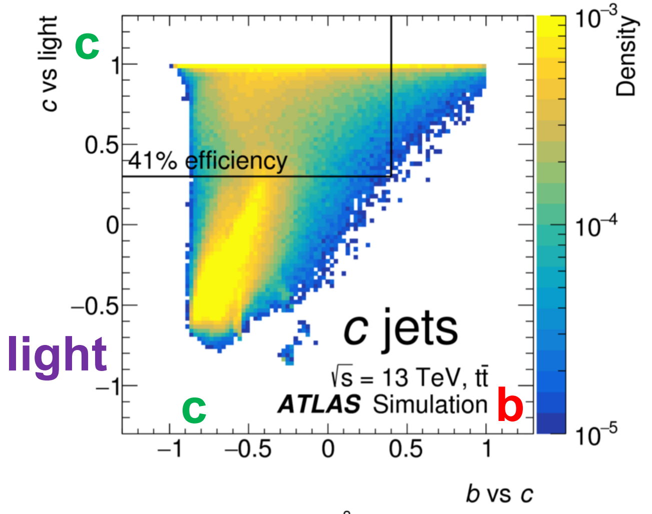
Obs μ= -3.9$^{+2.8}_{-2.7}$
Observed(Expected) limit on μ : 4.0(6.0) @ 95% C.L.
Still statistically limited

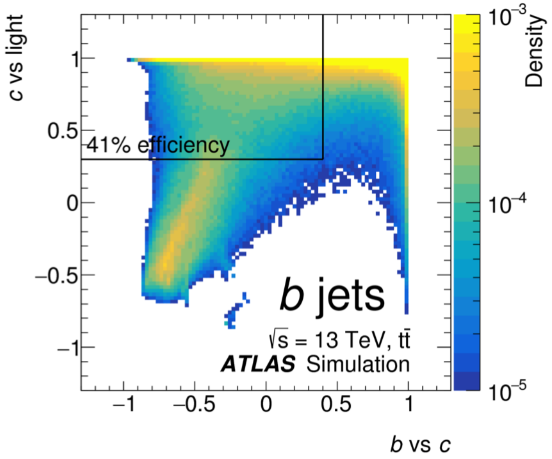


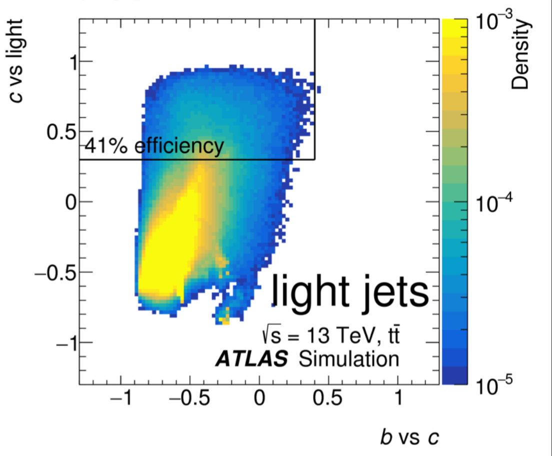
arXiv:1802.04329

Search for H→cc Decay

- Direct search for Y_c (BR(H→cc) ~2.9%)
- **Dedicated c-tagging strategy** has been developed
  - c-tagging is challenging (shorter lifetimes and lower track multiplicity)
  - Construct two multivariate discriminants (**c** vs **b** , **c** vs **light**)
  - Eff(**c**) = 41%, Eff(**b**) = 25%, Eff(**light**)=5%
- Search for ZH→llcc topology : Similar selection to ZH→llbb analysis but **1 or 2 c-tagging requirement**
- Fit to m_{cc} distribution

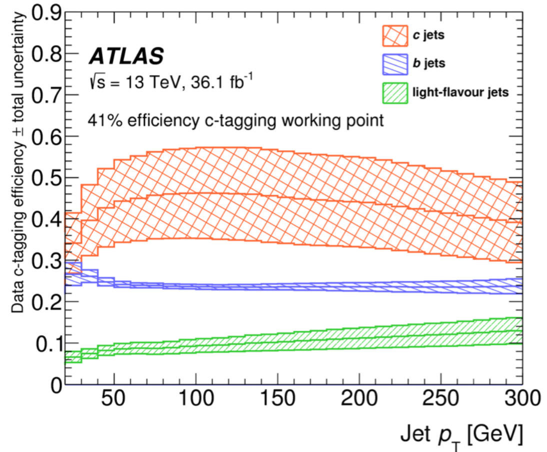






Event Selection/Categorization

Categorization	At least 2 jets	
c-tagging	**1 or 2 c-tagged jets**	**1 or 2 c-tagged jets**
p_T^V	**75 < p_T^V <150 GeV**	**150 < p_T^V**
ΔR_{cc}	**< 2.2**	**< 1.5 (150<p_T^V<200), <1.3 (200<p_T^V)**



2018/5/29

CIPANP2018 at Pal

H→cc Results

- Validate analysis procedure with ZZ→llcc, ZW→ll(cs/cd) events

$\mu_{ZV} = 0.6^{+0.5}_{-0.4}$

Observed Significance 1.4σ (exp. 2.2σ)

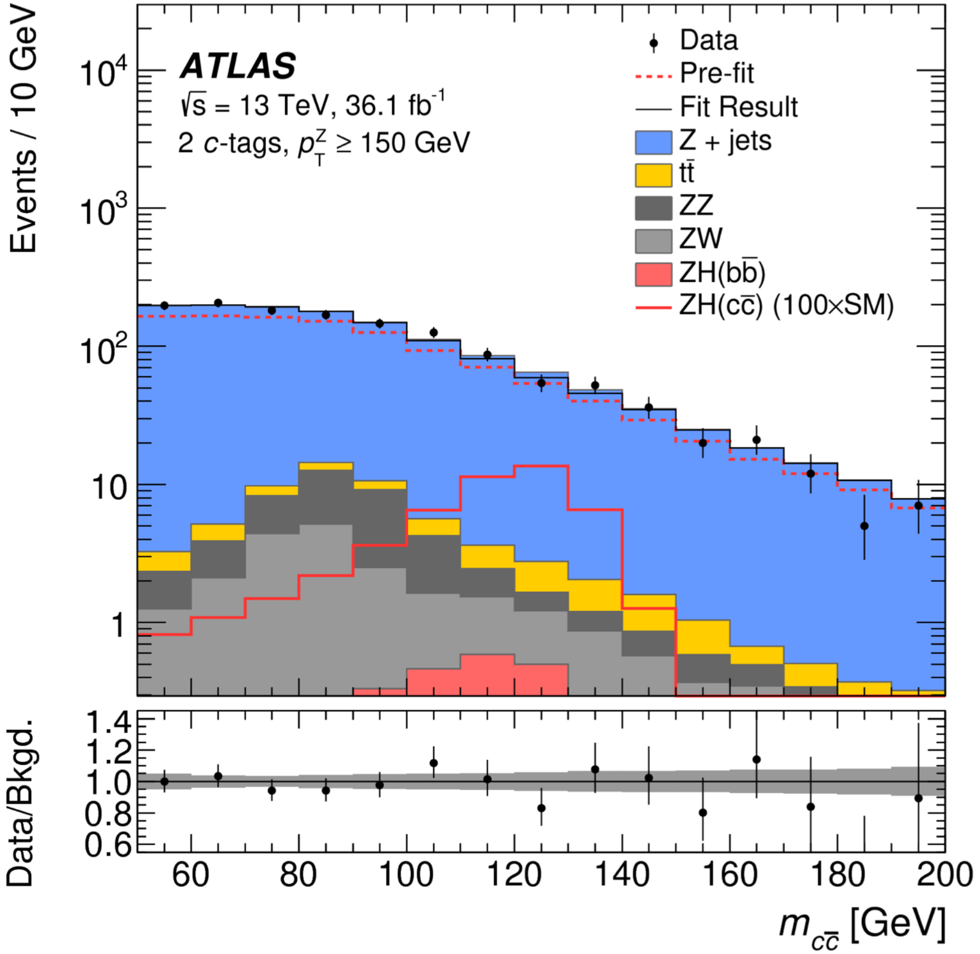
- Upper limit on σ(pp→ZH) × BR(H→cc) @ 95% C.L.

Observed limit 2.7 pb

Expected $3.9^{+2.1}_{-1.1}$pb (SM prediction ~2.6×10^{-2}pb)

- Dominant systematic source

Source	$\sigma/\sigma_{\text{tot}}$
Statistical	**49%**
Floating $Z+$jets normalization	31%
Systematic	**87%**
Flavor tagging	73%
Background modeling	47%
Lepton, jet and luminosity	28%
Signal modeling	28%
MC statistical	6%



Analysis and c-tagging improvement is on-going for the next round of Run2 analysis

Search for H→μμ

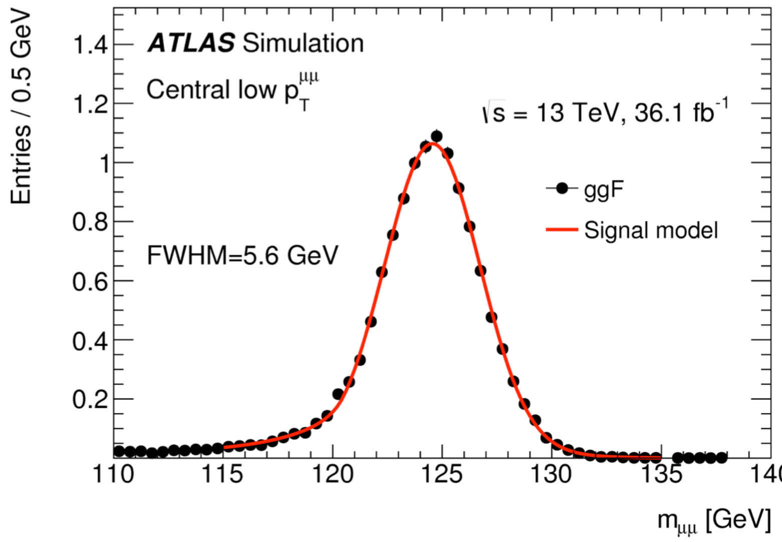
[Phys. Rev. Lett. 119 (2017) 051802]

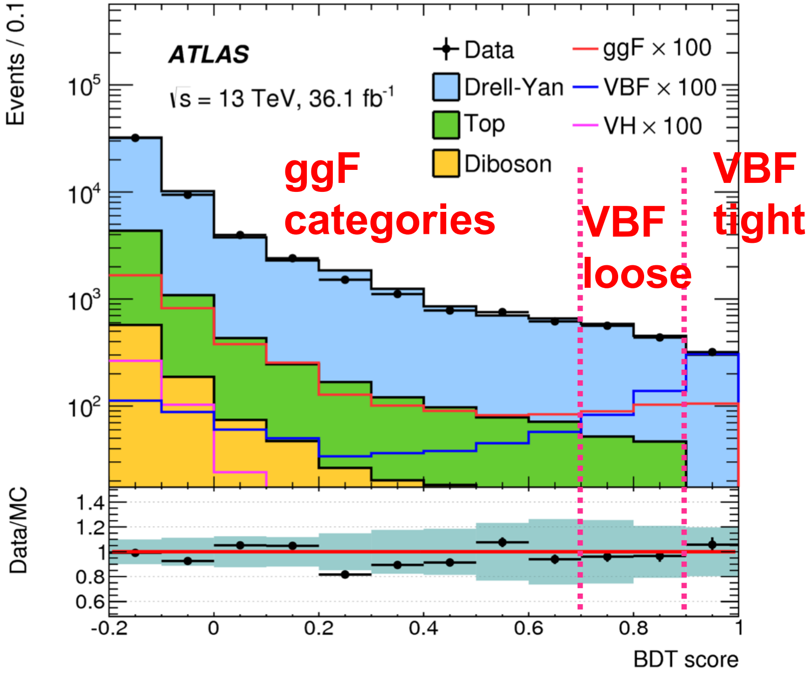
- Direct search for Y_μ
  - Extremely small signal yield : BR(H→μμ) ~0.022%
  - Narrow $m_{\mu\mu}$ peak ($\sigma(m_H)$~2-3%)
- Event selection : 2 OS muons, MET < 80 GeV, b-jet veto
- Dominant background : Drell-Yan (Z→μμ)
- Categorization
  - **VBF-enrich (BDT classification)** : m_{jj}, $\Delta\eta_{jj}$, $p_T^{\mu\mu}$, ΔR_{jj}, $p_T^{\mu\mu jj}$….
  - **ggF-enrich : $p_T^{\mu\mu}$ and muon η**

  ➔ **Extract high S/B region (8 categories)**

	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

VBF tight : S/B ~0.04





H→μμ Results

- Fit to $m_{\mu\mu}$ ($110 < m_{\mu\mu} < 160$ GeV) using analytic function
  - Signal model

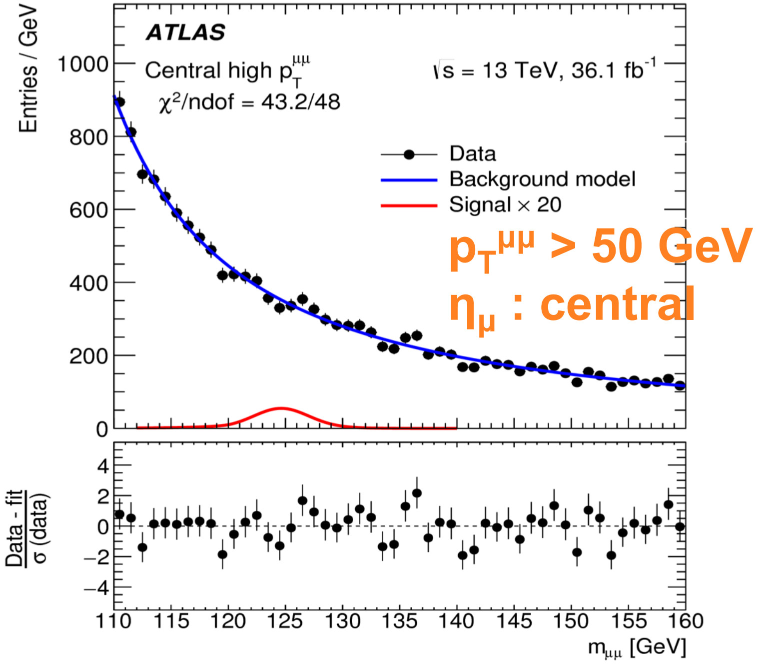
$$P_S(m_{\mu\mu}) = f_{CB} \times CB(m_{\mu\mu}, m_{CB}, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \times GS(m_{\mu\mu}, m_{GS}, \sigma_{GS}^{S})$$

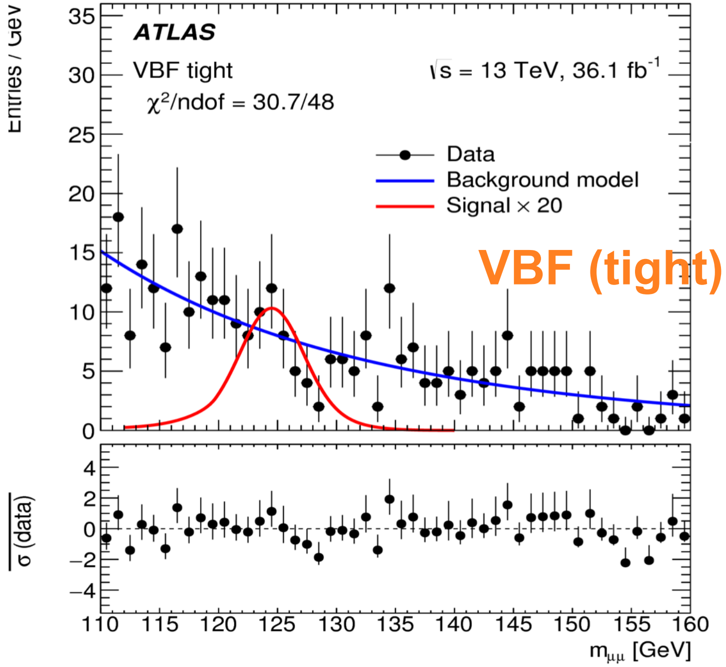
  - Background model

Z→μμ modeling

$$P_B(m_{\mu\mu}) = f \times [BW(m_{BW}, \Gamma_{BW}) \otimes GS(\sigma_{GS}^{B})](m_{\mu\mu}) + (1 - f) \times e^{A \cdot m_{\mu\mu}} / m_{\mu\mu}^3$$

Other backgrounds modeling





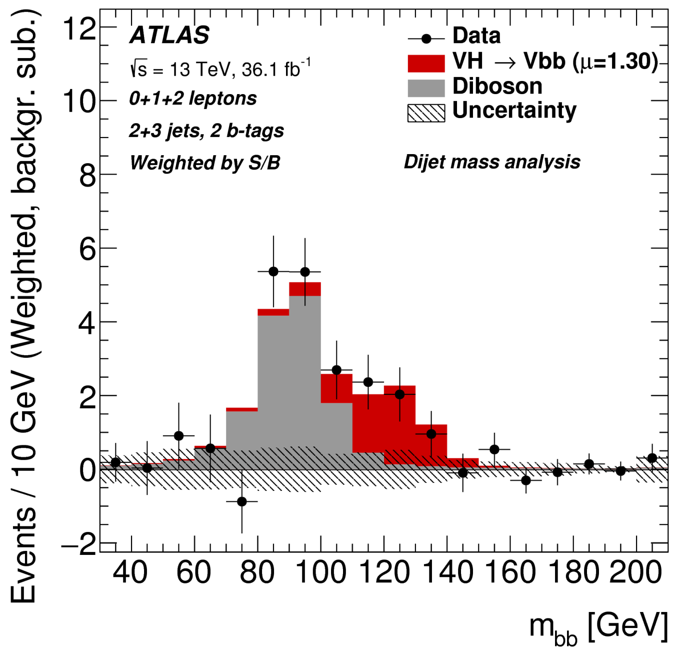
Run1+Run2 combination
95% C.L. upper limit on μ
Observed 2.8
(Expected 2.9)

Statistically Limited

Summary

- Higgs boson interaction with each fermion needs to be confirmed experimentally
  - Observation of H→ττ decay in Run1
  - **Evidence for H→bb decay in Run2**
  - ➔ No significant deviation from the SM, so far..
  - ➔ Now entering the measurement stage
- Coupling measurement of Higgs to 2nd gen. fermion just at the beginning of a long journey
- More data opens up new observations of coupling to 2nd gen.!!
  - LHC ATLAS experiment accumulating much more data in Run2 (~150fb^{-1} in Run2)
  - 300fb^{-1} in Run3 and 3000fb^{-1} in HL-LHC

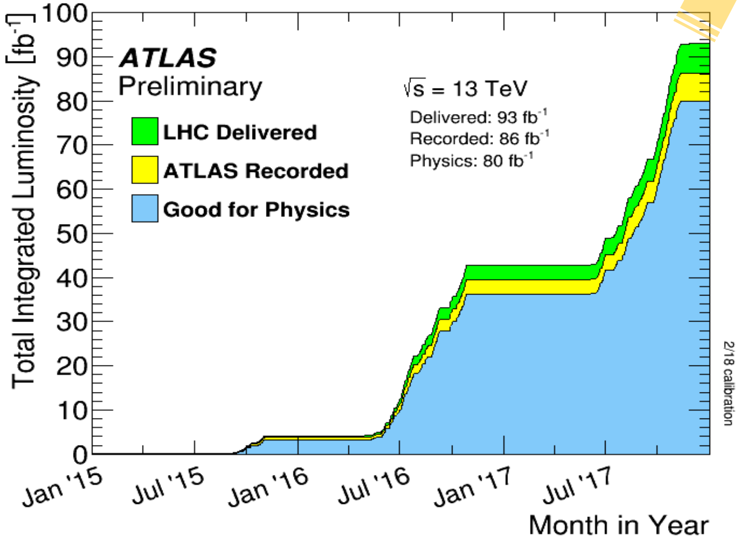
Stay Tuned!!



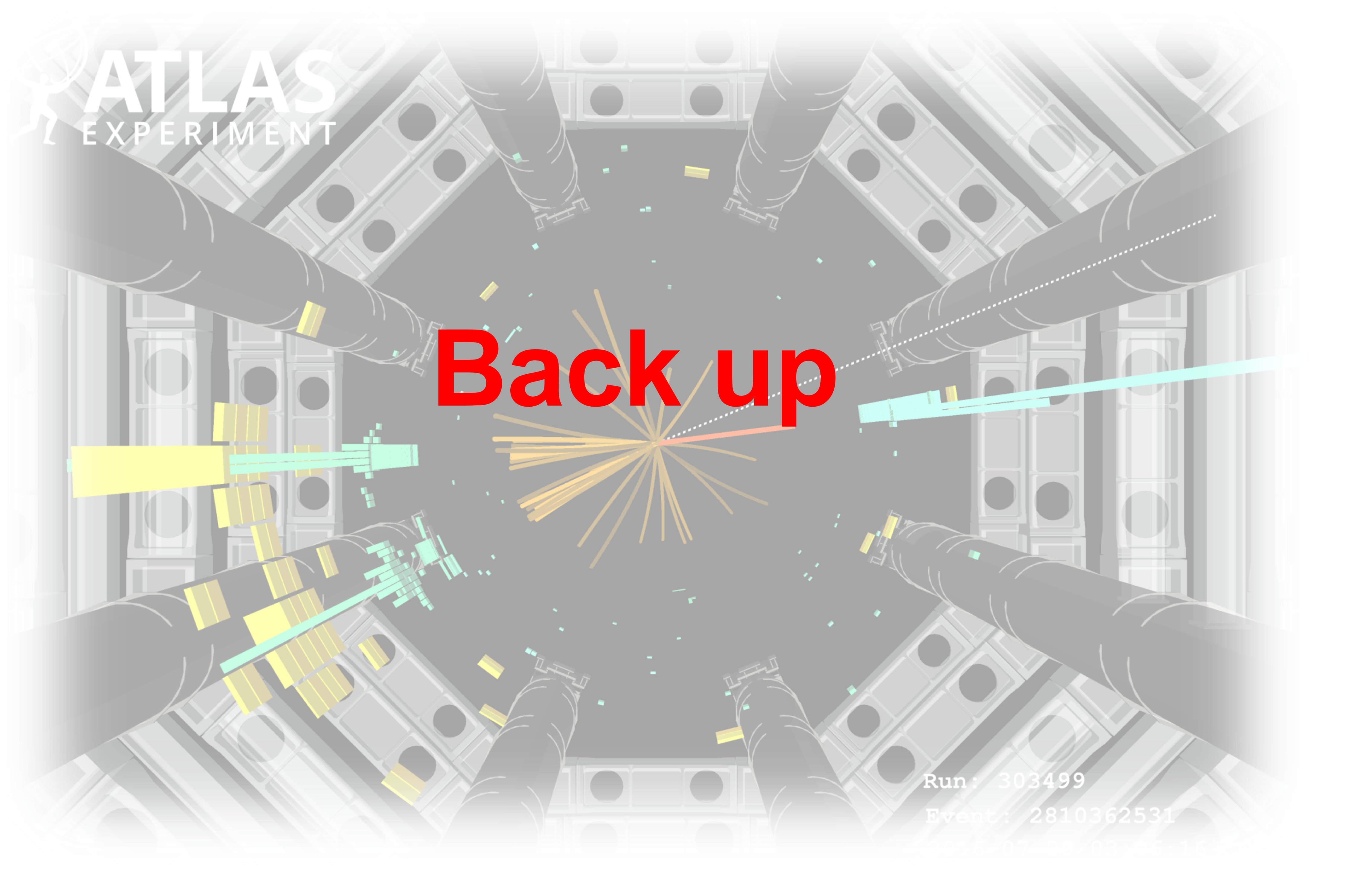
3000fb^{-1}

300fb^{-1}

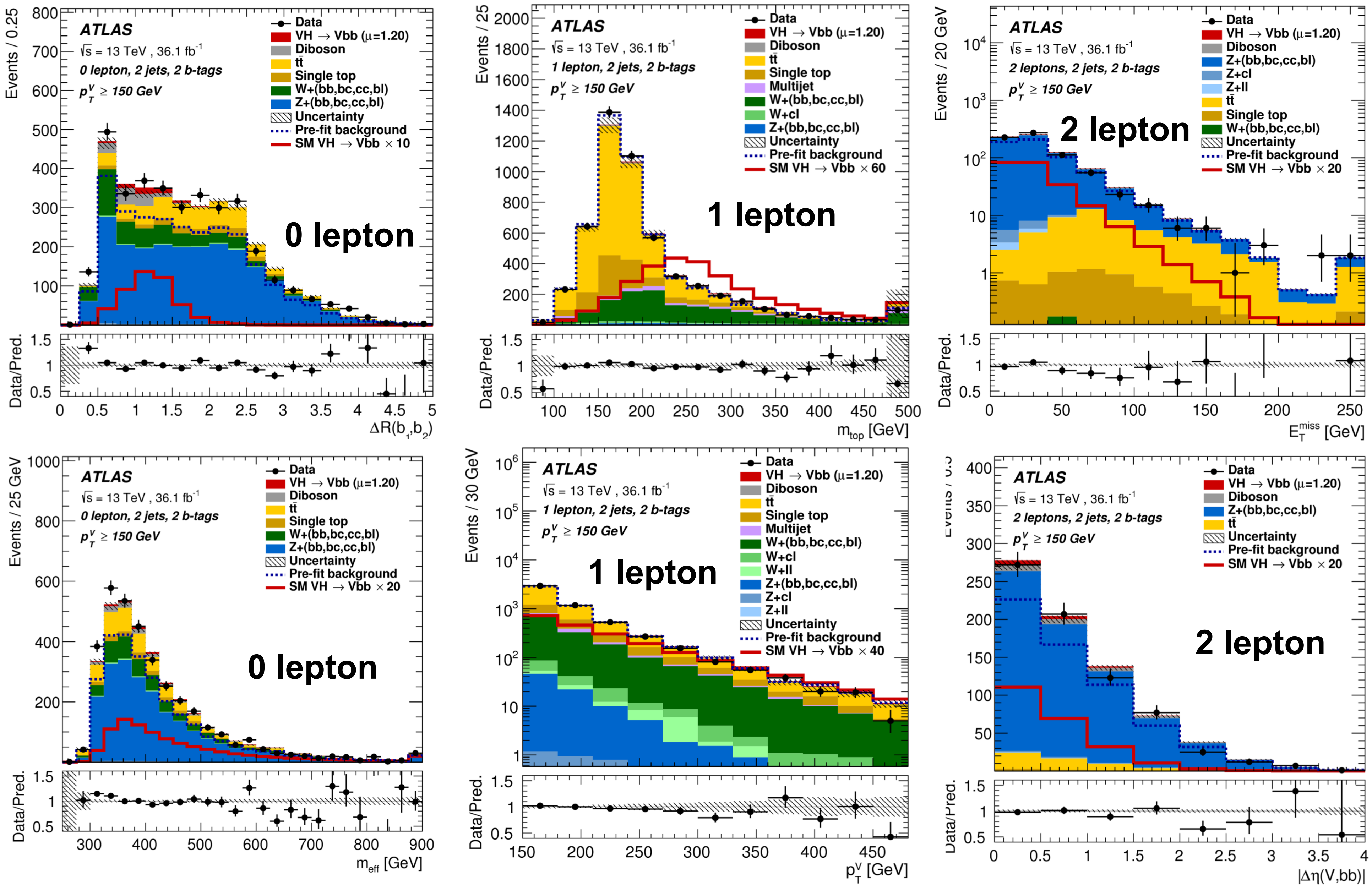
150fb^{-1}



Back up



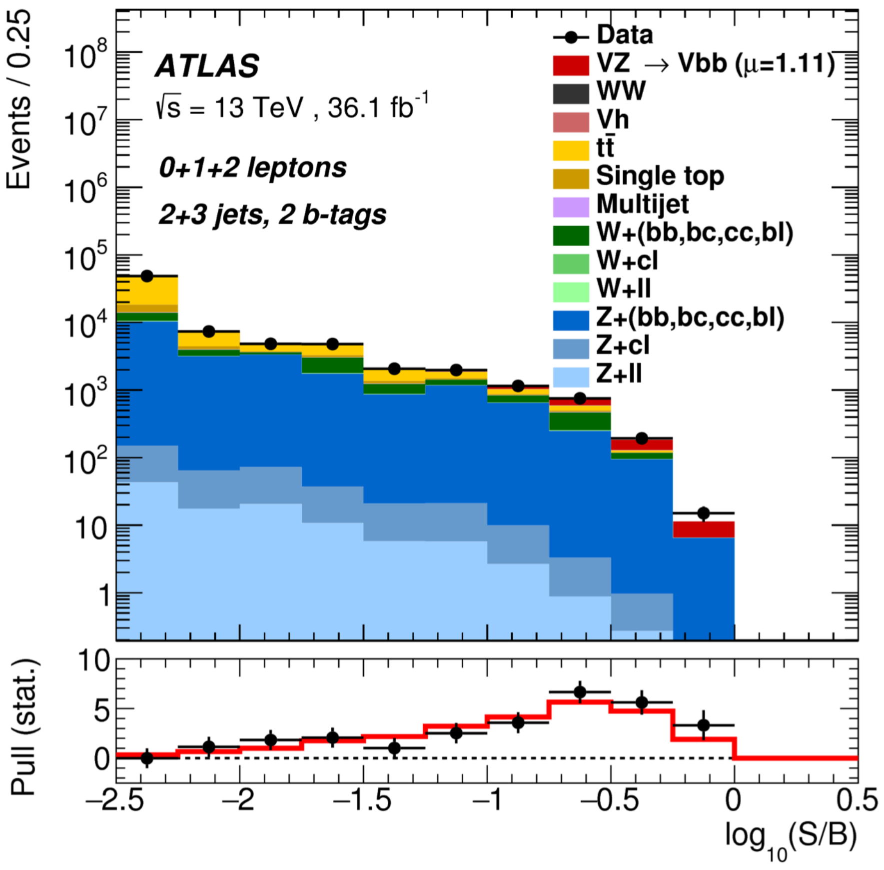
Evidence for H→bb Decay

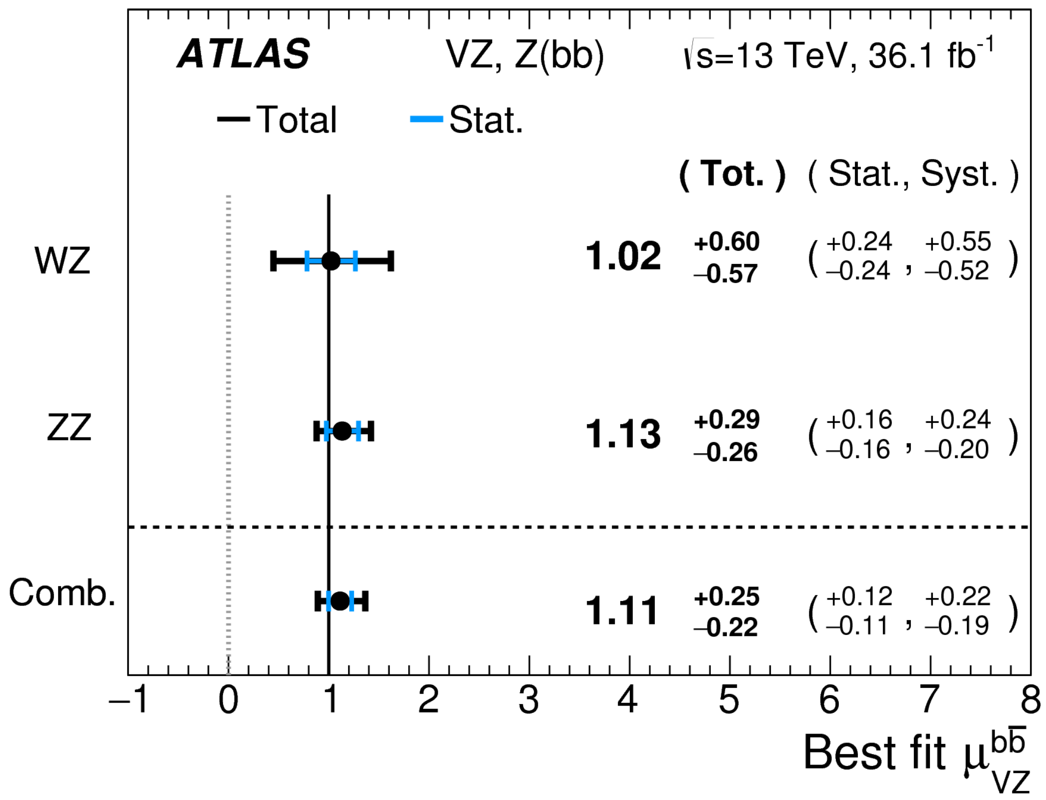


Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
m_{eff}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}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

Evidence for H→bb decay mode

- Validation with VZ diboson and m_{bb} analysis in Run2 analysis



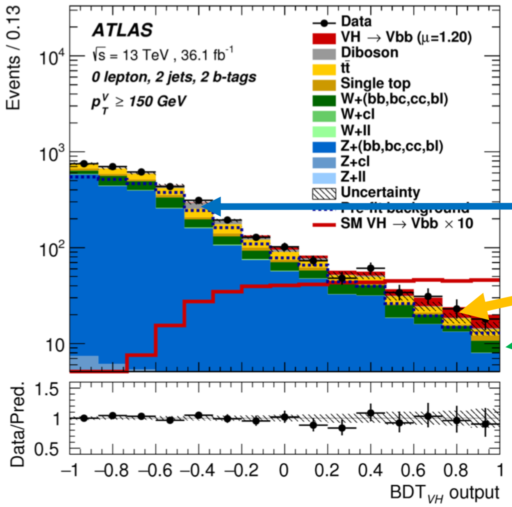


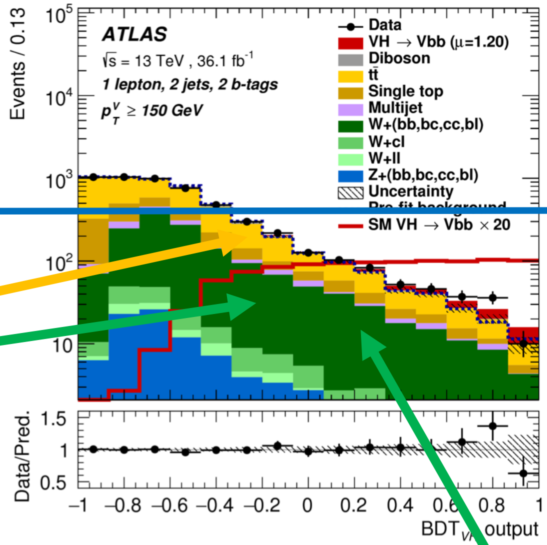
$$\mu_{VZ}^{b\bar{b}} = 1.11^{+0.25}_{-0.22}$$

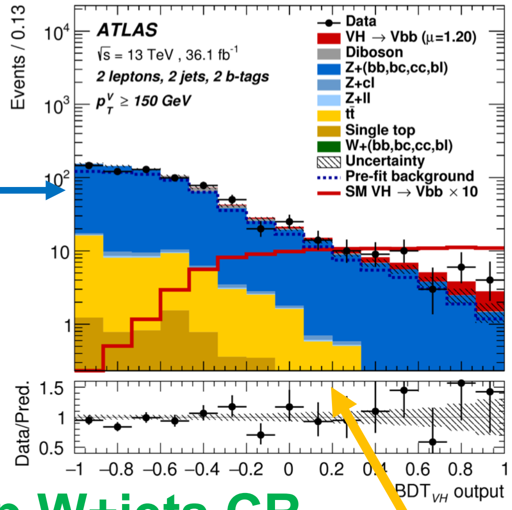
Observed significance 5.8σ (exp. 5.3σ)

VH→bb background modeling

Fit 8 signal regions and control regions simultaneously
➔ constrain background modeling uncertainty



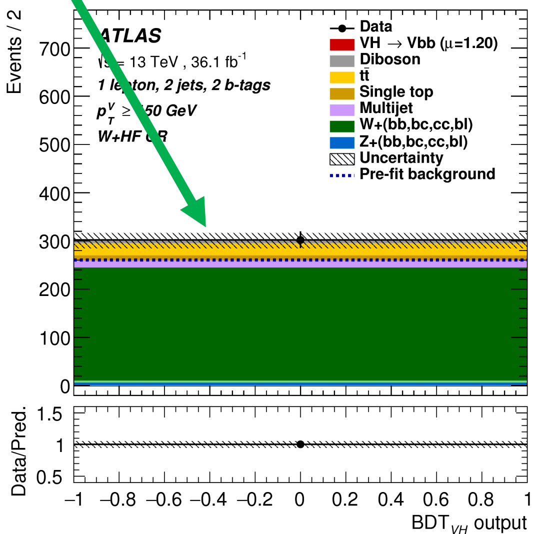


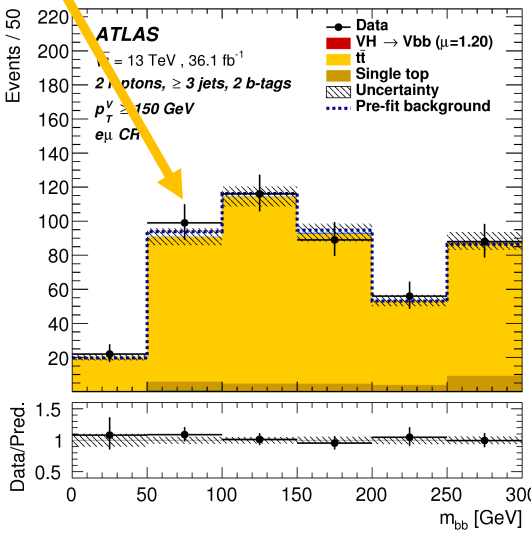


1lep W+jets CR

2 lep eμ CR

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



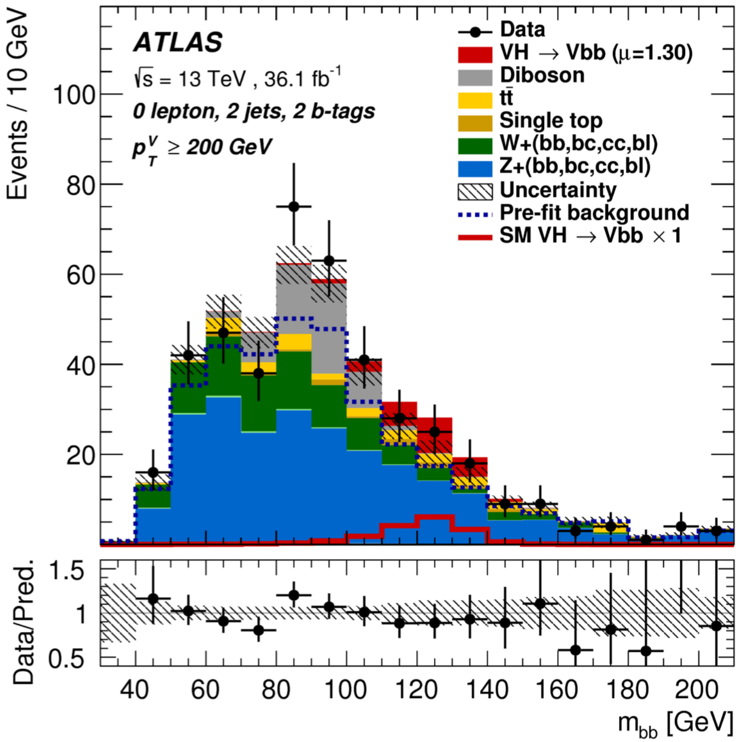


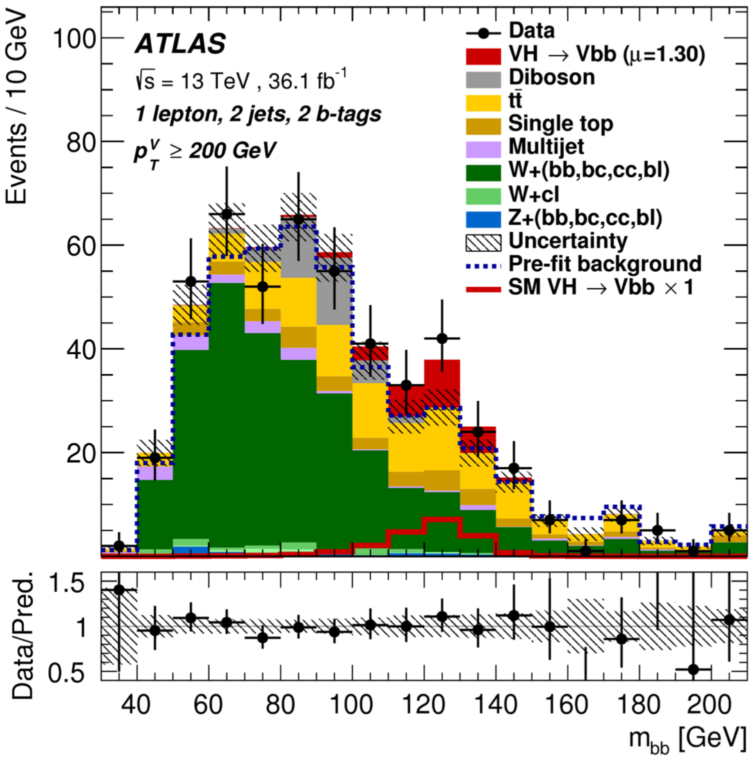
VH→bb m_{bb} distribution in m_{bb} analysis

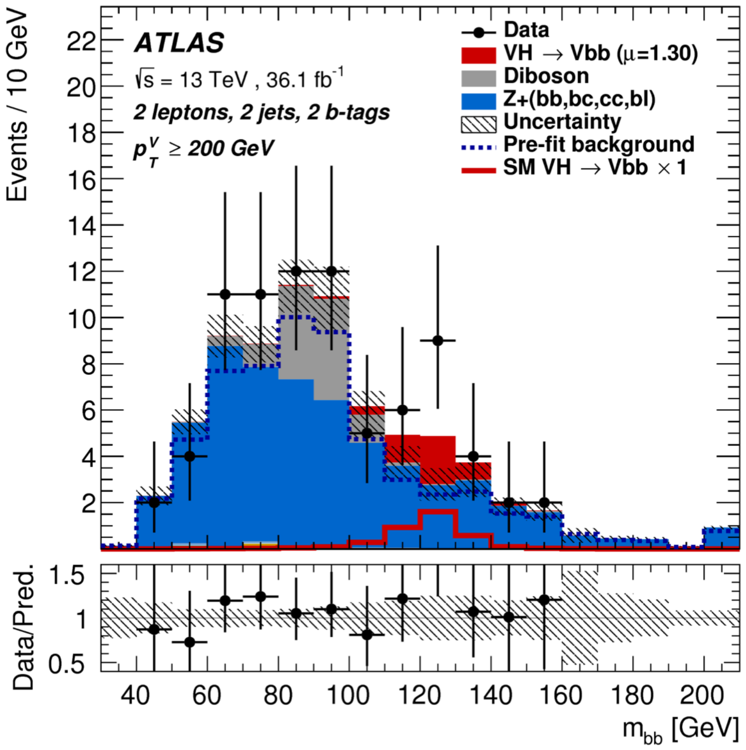
- Dijet mass analysis requires tighter event selection than MVA analysis
- Divide p_T^V category into 150-200 GeV and 200- GeV
- ΔR cut depending on p_T^V region

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







VH→bb Systematic Uncertainty

- Impact on μ measurement in VH→bb analysis in Run2 36.1fb^{-1}

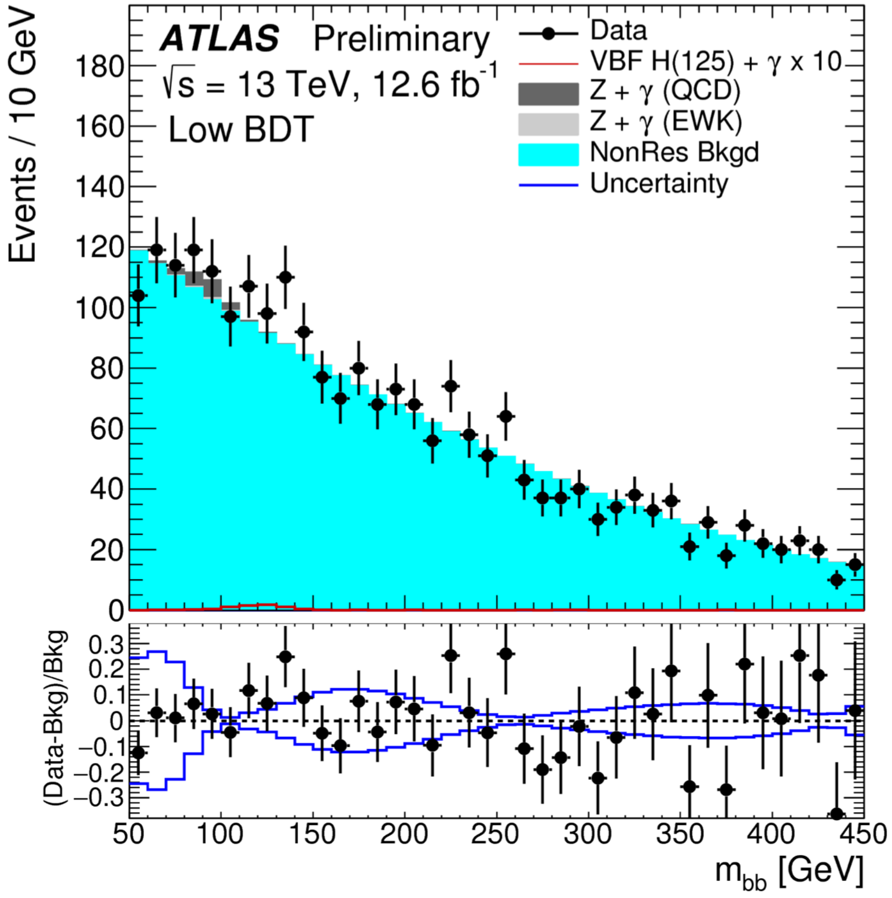
$$\mu = 1.20^{+0.24}_{-0.23}(stat.)^{+0.34}_{-0.28}(syst.)$$

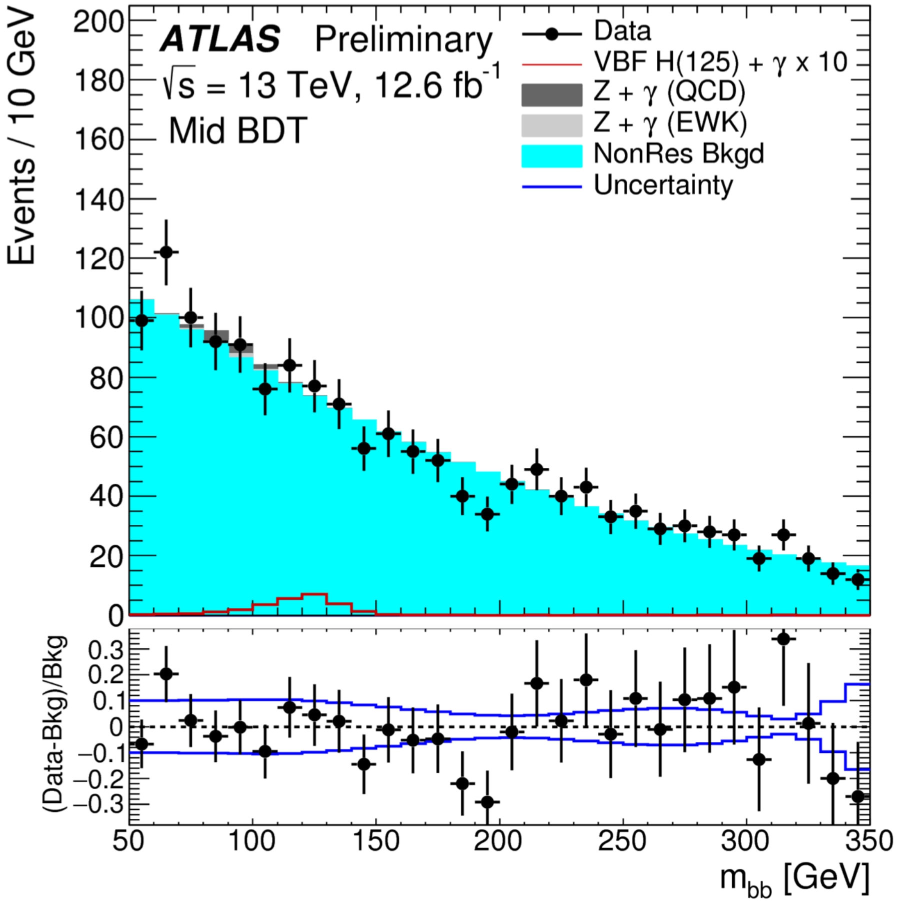
- Dominant systematic source
  - **Flavor tagging uncertainty** : comes from efficiency calibration, data/MC scale factor
  - **Signal uncertainty** : dominant source is underlying event/parton shower systematic (Generator difference)
  - **Modeling uncertainty** : W-p_T shape modeling in 1 lepton, ttbar m_{bb} shape modeling in 2 lepton, single top Wt channel (interference modeling)
  - **MC statistics**...

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
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
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

VBF H→bb

- m_{bb} distribution in low/medium BDT regions



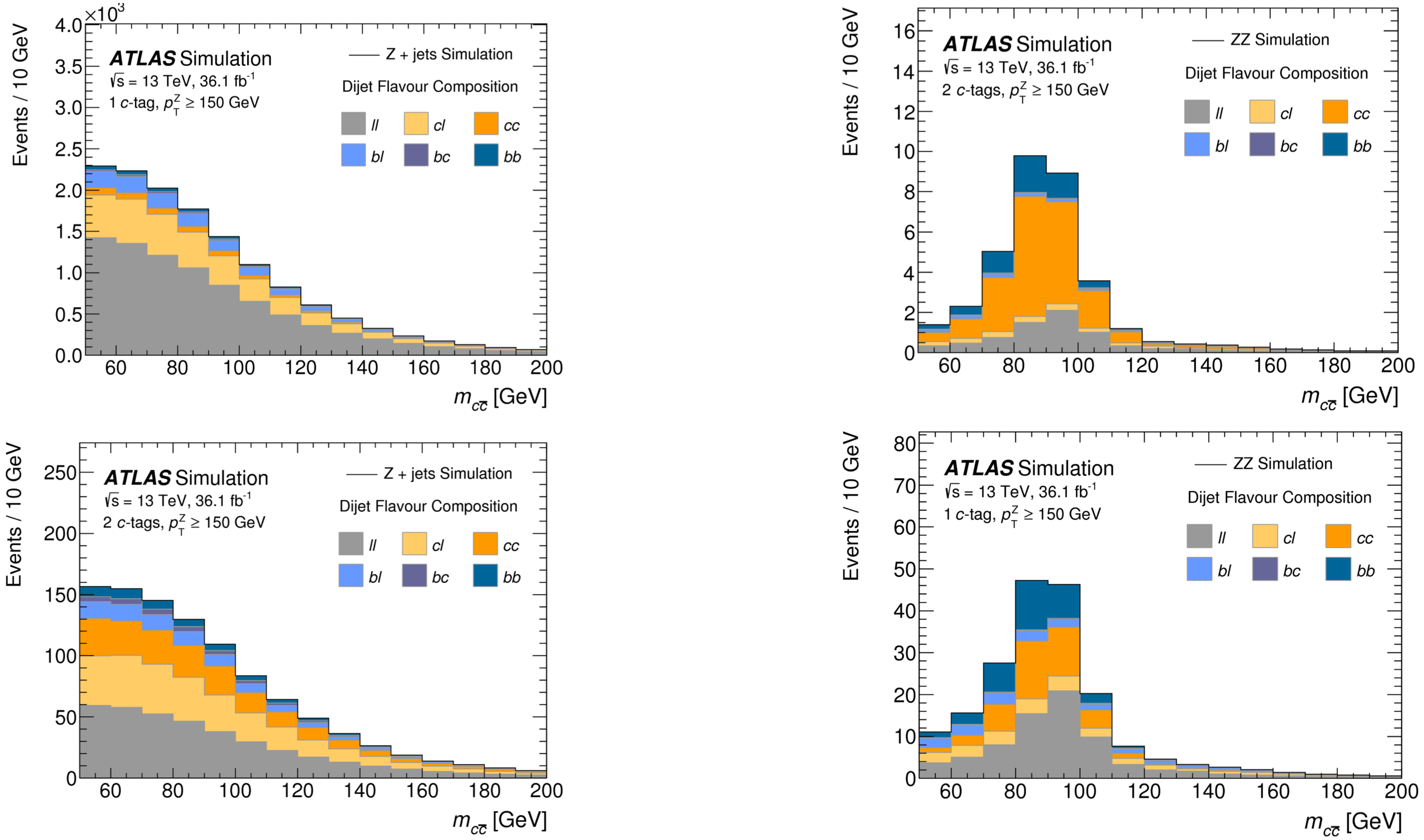


VBF $H \rightarrow bb$

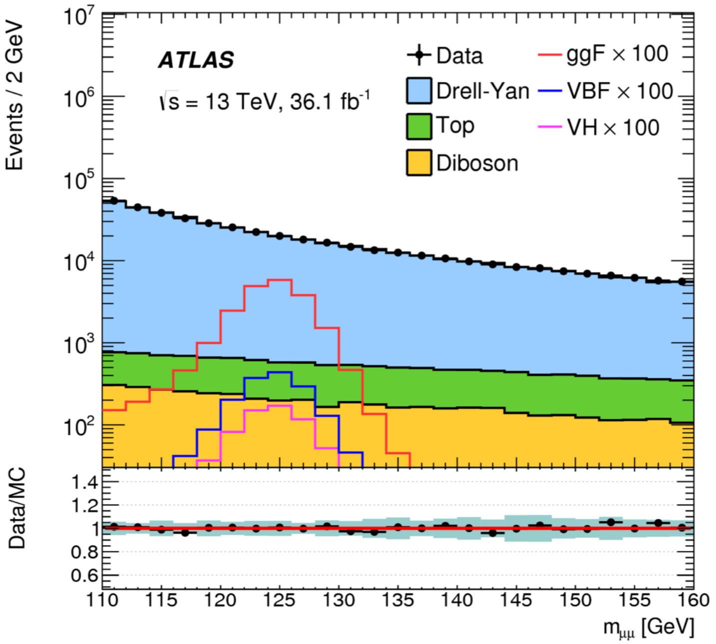
- Systematic uncertainty
  - Background modeling uncertainties are dominant source (can be improved with higher stat data)
  - H+γ theory modeling
  - Jet energy calibration

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 η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

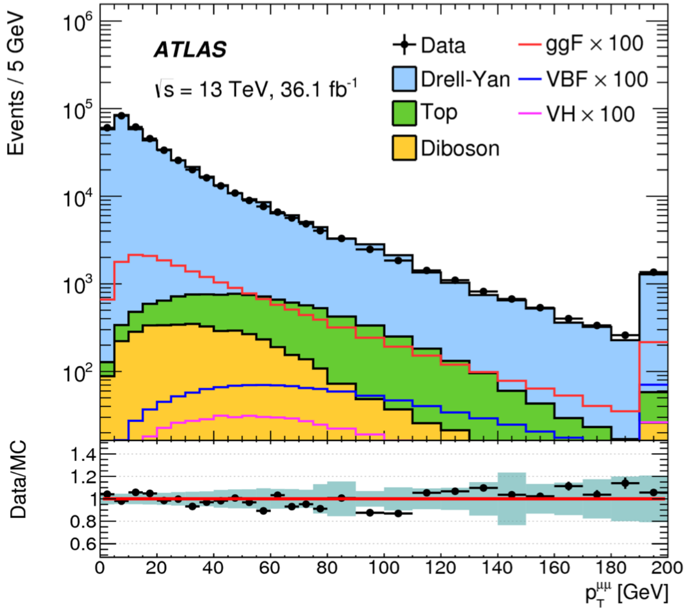
Search for VH→cc

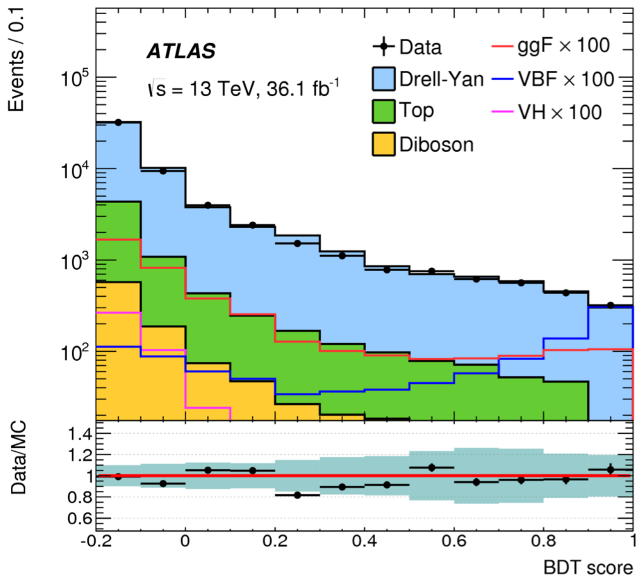


Search for H→μμ



	ggF	VBF	VH
Central low $p_{\mathrm{T}}^{\mu\mu}$	11	0.1	0.0
Non-central low $p_{\mathrm{T}}^{\mu\mu}$	31	0.3	0.2
Central medium $p_{\mathrm{T}}^{\mu\mu}$	23	0.7	0.3
Non-central medium $p_{\mathrm{T}}^{\mu\mu}$	63	2.0	1.2
Central high $p_{\mathrm{T}}^{\mu\mu}$	13	1.8	0.9
Non-central high $p_{\mathrm{T}}^{\mu\mu}$	32	4.6	2.8
VBF loose	1.5	1.8	0.0
VBF tight	0.9	2.6	0.0





Search for H→μμ

- Categorization in muon η
  - Central : Both muon with |η|<1.05
  - Non-central : The rest (either of muons with |η|> 1.05)
    - High-p_T category has worse resolution
  - VBF category does not separate due to low stat