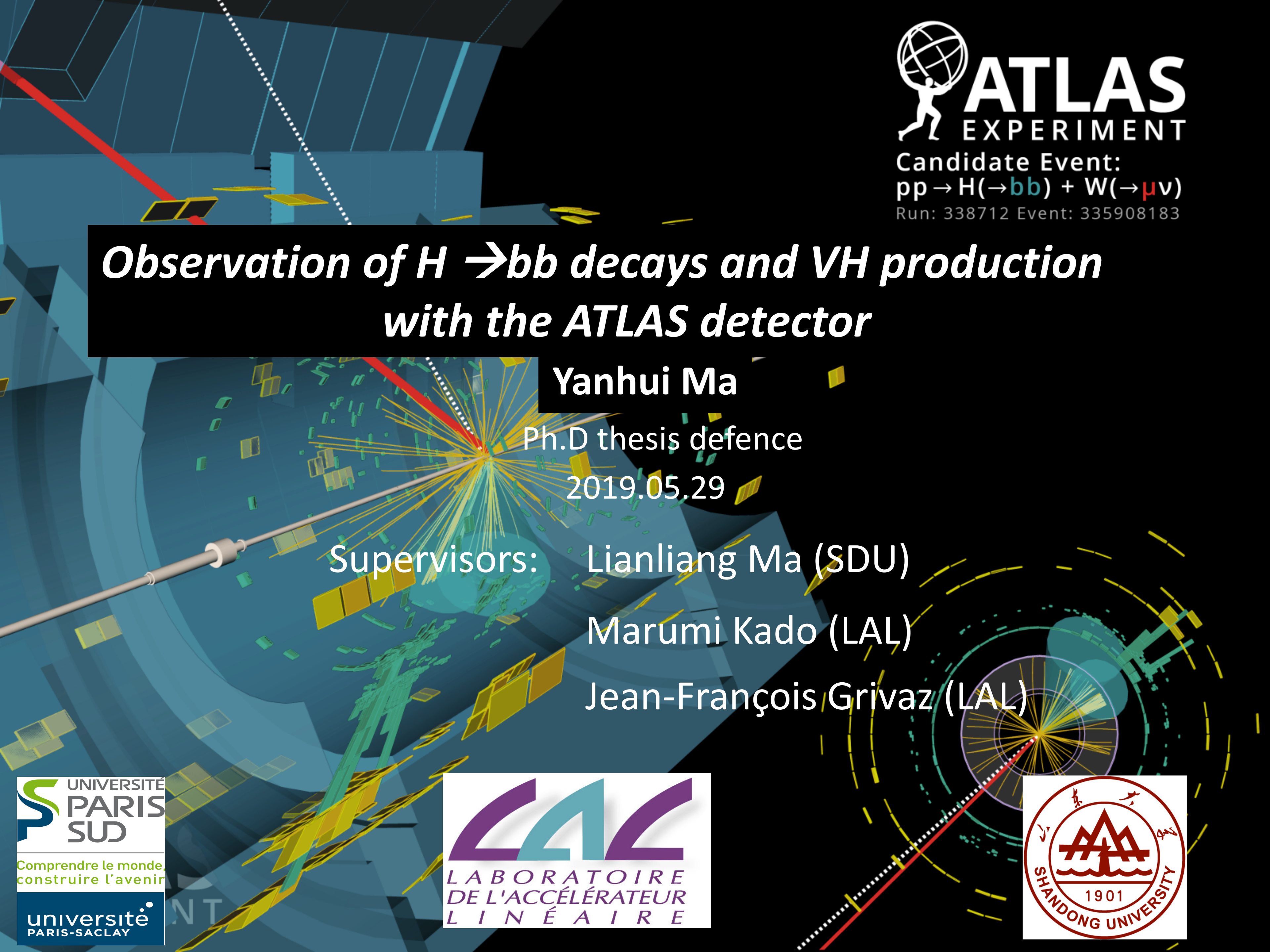

Observation of H →bb decays and VH production with the ATLAS detector

Yanhui Ma

Ph.D thesis defence

2019.05.29

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List of publications

- ATLAS paper, HIGG-2018-50, Measurements of simplified fiducial cross sections for the associated production of a weak gauge boson and a Higgs boson decaying to bb using $\sqrt{s}$ = 13 TeV pp collisions collected by the ATLAS detector (accepted by JHEP) (79.8 fb^{-1})
- ATLAS paper, HIGG-2018-04, Observation of H→bb decays and VH production with the ATLAS detector (Phys. Lett. B 786 (2018) 59) (2015-2017 dataset 79.8 fb^{-1}) ★
- ATLAS paper, HIGG-2016-29, Evidence for the H→bb decays with the ATLAS detector (JHEP 12 (2017) 024) (36.1 fb^{-1})
- ATLAS Note, Pub-HIGG-2018-56, Evaluation of theoretical uncertainties for simplified template cross section measurements of V-associated production of the Higgs boson
- ATLAS Note, CONF-HIGG-2016-17, Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a bb pair in pp collisions at 13 TeV using the ATLAS detector (ICHEP 2016)
- ATLAS Note, CONF-HIGG-2016-03, Search for a CP-odd Higgs boson decaying to ZH in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector (Moriond 2016)

★ **Present today**

List of contributions to the analysis

- Main analyzer in 1-lepton channel :
  - Developing and maintaining the analysis code.
  - Multijet background estimation in 1-lepton channel.
  - Multivariate analysis: multivariate discriminant construction, training, optimization and evaluating.
  - Various optimization for 1-lepton channel analysis: events selection optimization , adding new analysis regions, etc.
  - Producing the 1-lepton channel inputs for the statistical analysis.
- 1-lepton channel fit and combined fit (0+1+2-lepton channel) studies.
- Supporting note co-editor.
- Gave the approval talks in Higgs working group for both the evidence and observation papers.

Outline

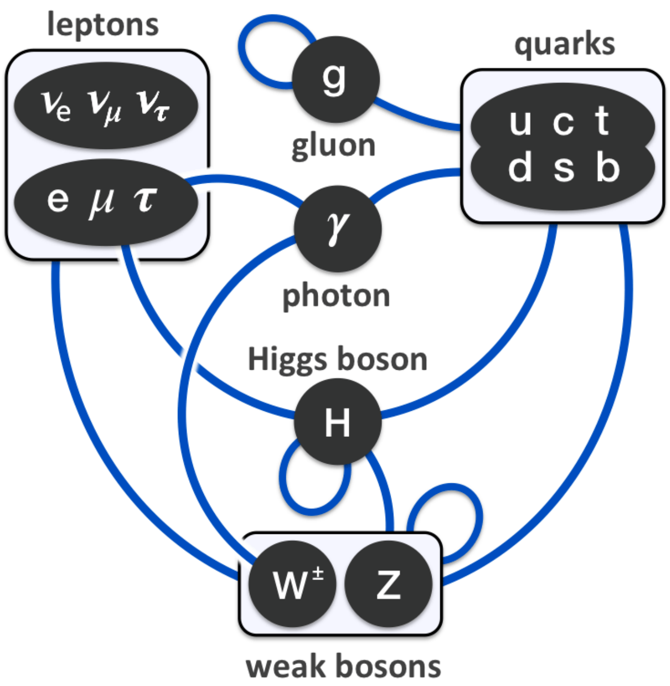
- The Standard Model (SM) and ATLAS detector
- 1-lepton channel WH analysis
- Systematic uncertainties and statistical analysis
- Analysis results and combination
- Conclusion and outlook

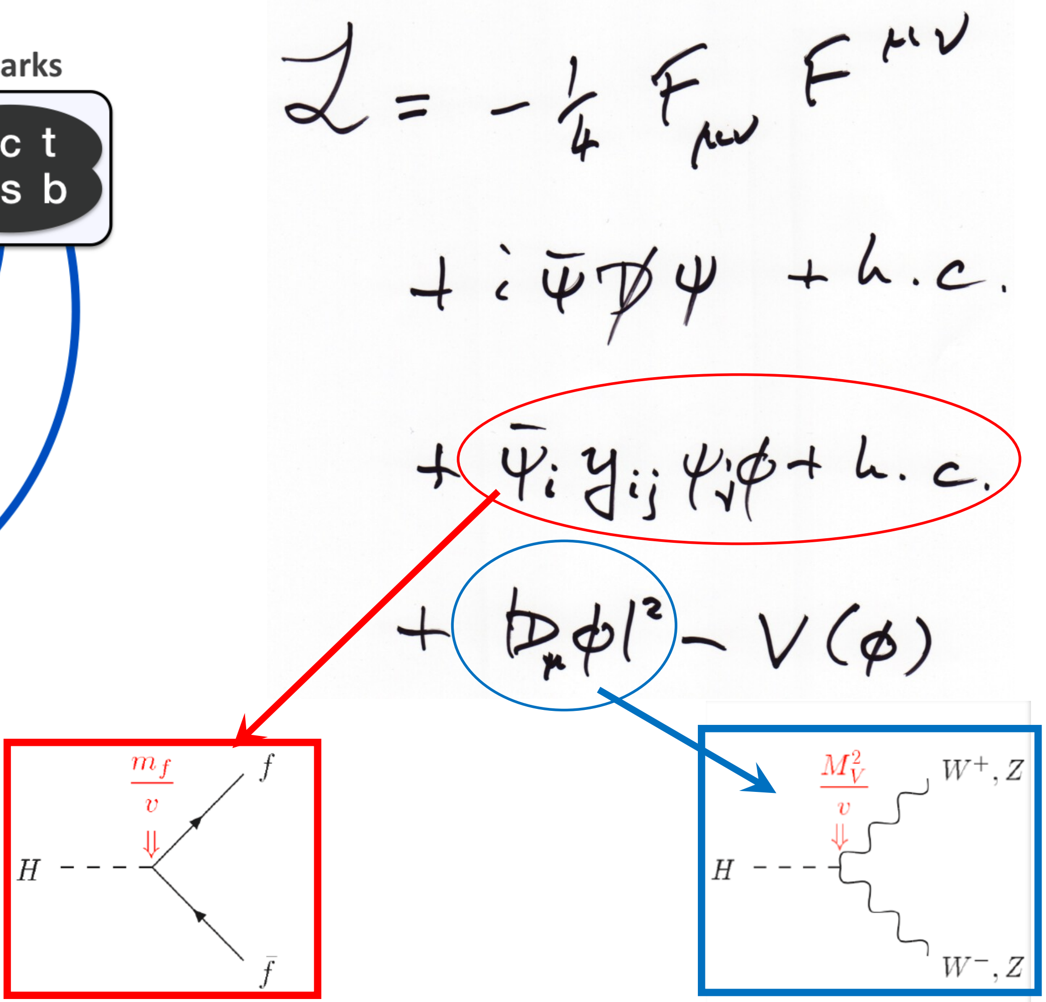
The Standard Model and ATLAS detector

The Standard Model

- The SM is the most thoroughly tested theory of particle physics that has had a great success to explain experimental results of particle physics.

- In the SM, the Higgs mechanism provides masses to bosons and fermions



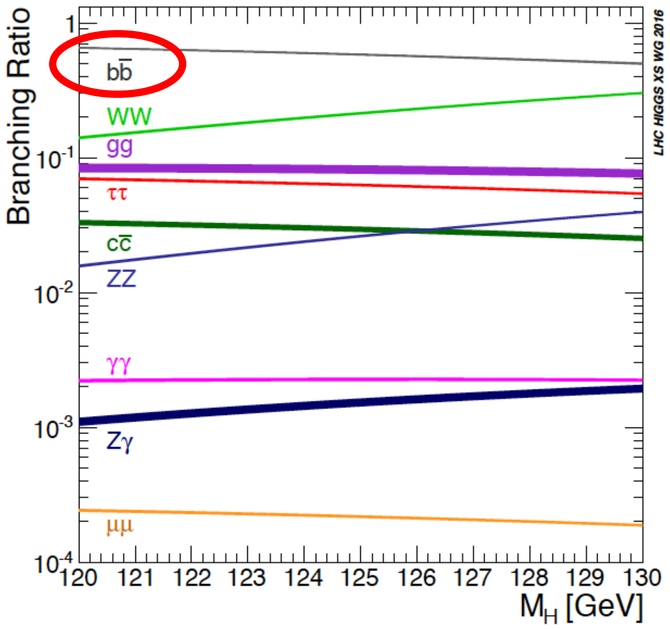


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

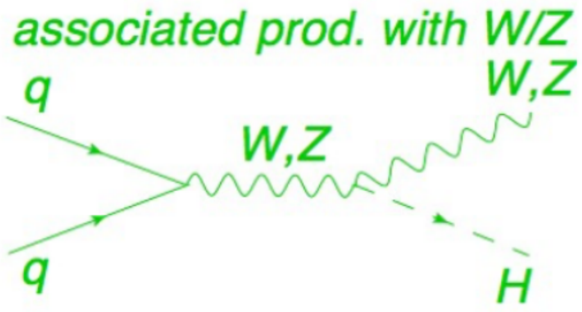
Higgs boson was discovered in 2012 with a mass ~125 GeV.

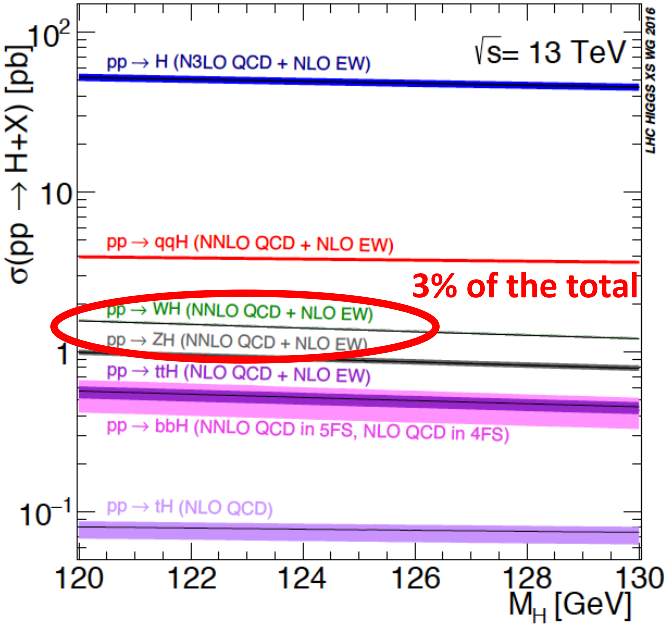
Higgs boson phenomenology at hadron colliders

- The dominant decay (BR~58%) of the SM Higgs boson is to pairs of b-quarks.
  - Measurement of the Yukawa coupling to down type quarks.
  - Constrain the Higgs boson decay width.



- VH production mode is the most sensitive channel to detect H → bb decays.
  - The leptonic decay of the vector boson allows for efficient triggering and significant reduction of the multi-jet (MJ) backgrounds.

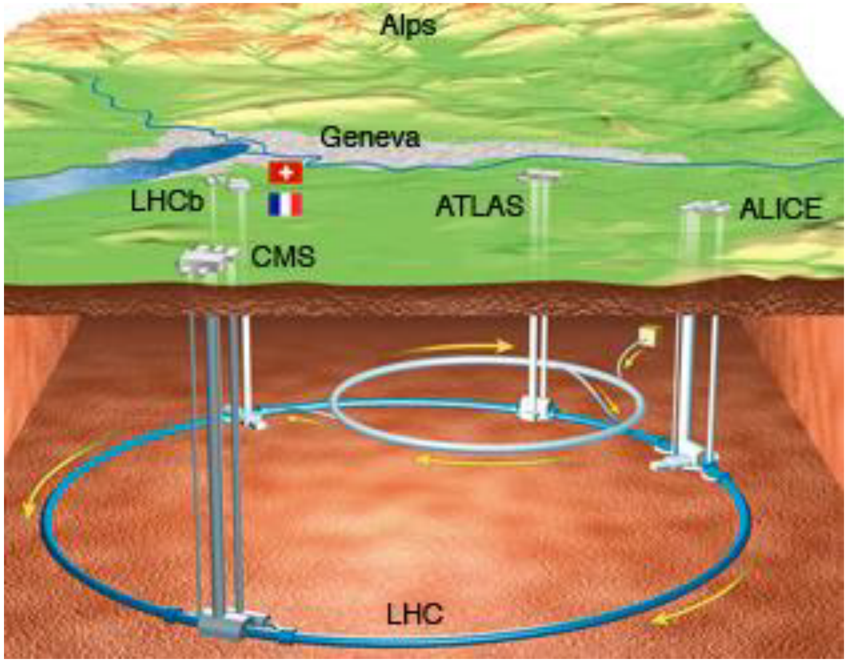


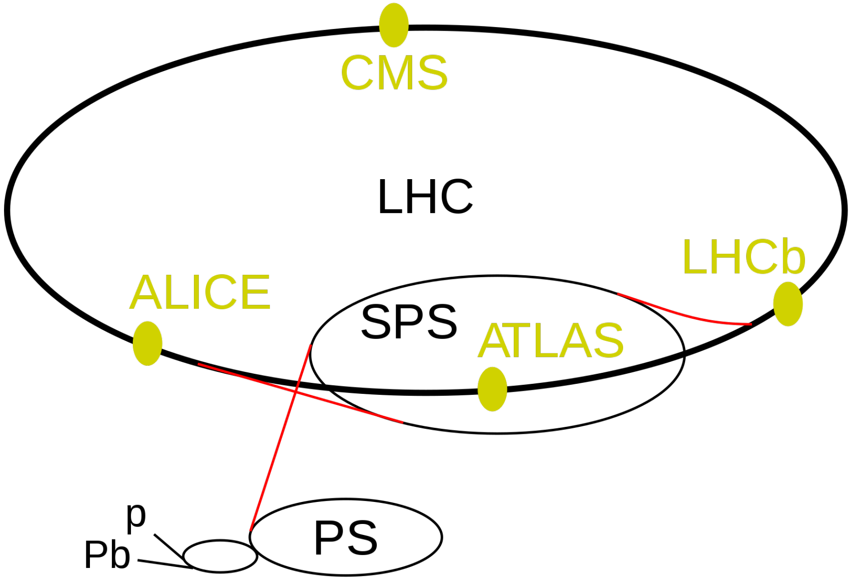


3% of the total

The LHC collider

- The largest and highest-energy particle collider in the world.
- Housed in a circular tunnel with 27 km in circumference and 45-175 m in depth underground.





- Four main experiments: ATLAS, CMS, LHCb, ALICE.
- Designed proton-proton collision energy: 14 TeV (13 TeV at Run 2).

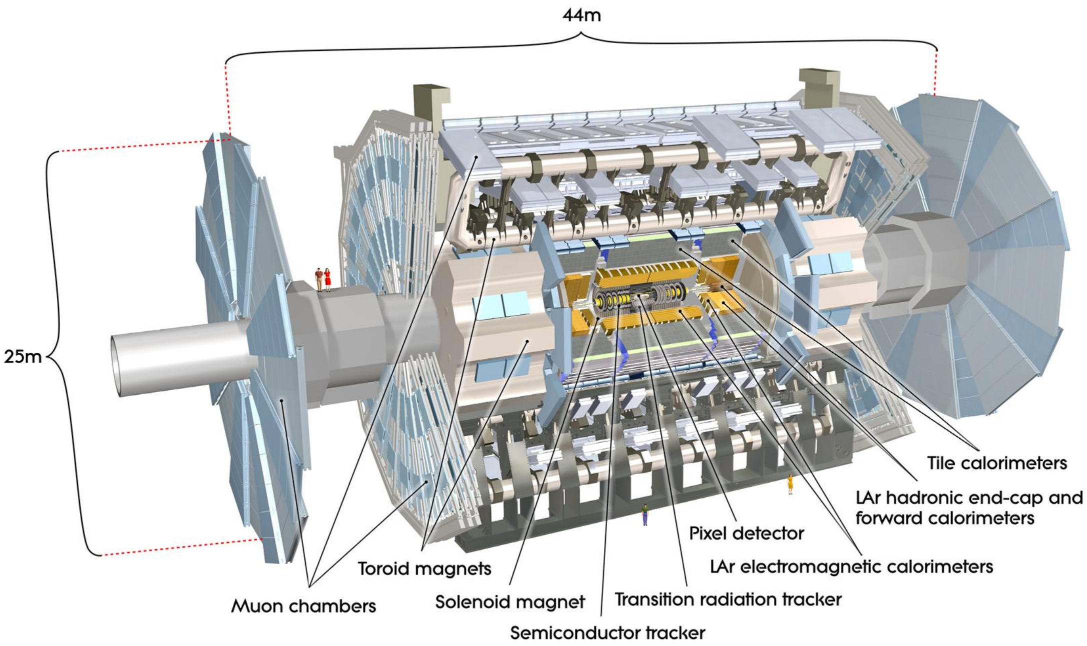
The ATLAS detector

- World's largest particle detector with a diameter of 25 m and length of 44 m.

- General-purpose detector, designed mainly to search for the Higgs boson and new physics.

- Sub-detectors:

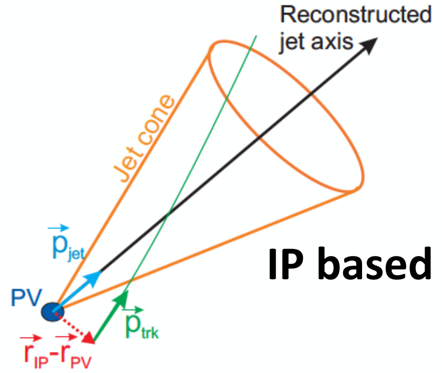
- **Inner detector**:
  - Measure the trajectories and momenta of charged particles
- **EM and Hadronic calorimeter**
  - Measure the energy of electrons, photons and hadrons
- **Muon spectrometer**
  - Measure the trajectories and momenta of muon



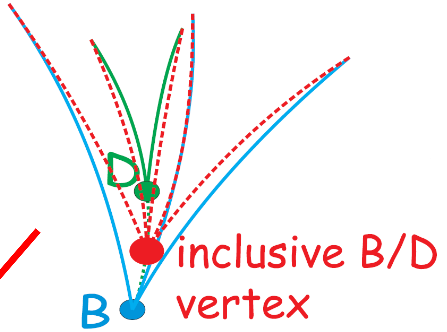
- A new pixel-detector layer, IBL, inserted during LS1, improved the performance of tracking, vertexing, b-tagging, etc.

Object identification—b-tagging

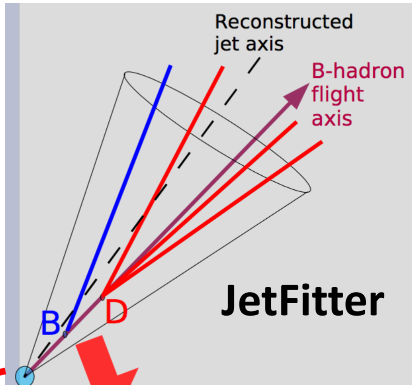
- ➢ Excellent object identification performance is the key ingredients for H→bb, especially for the b-tagging identification.



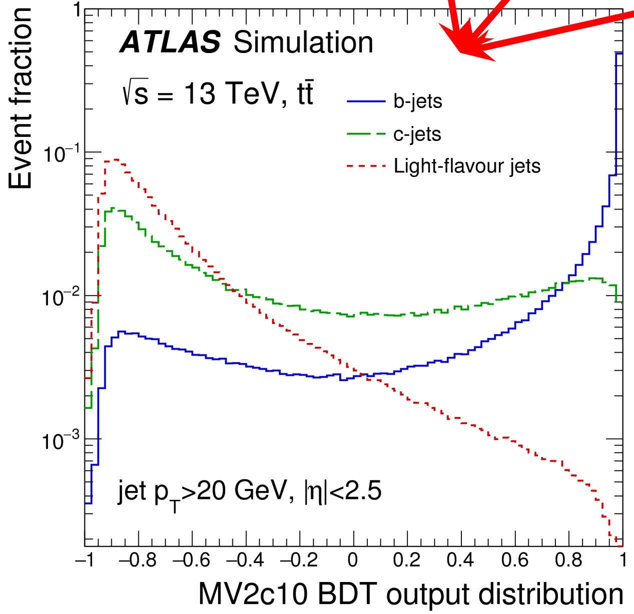
IP based (IP2D, IP3D)



secondary vertex (SV1)



JetFitter



- ➢ Multi Variate Analysis (BDT) to combine observables into a single discriminant.

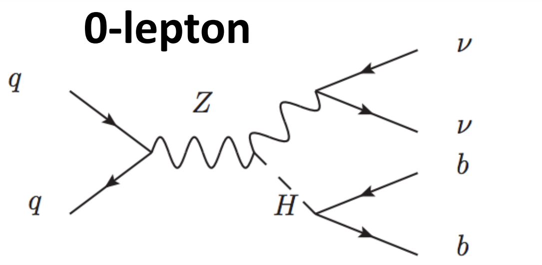
- ➢ At 70% b-jets efficiency, the rejection factor of light and c-jets are 300 and 8, respectively.

1-lepton channel WH analysis

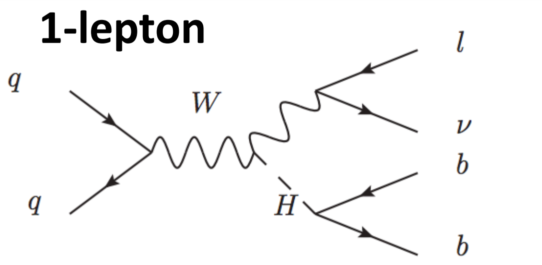
Event selection

- 3 Sub-channels: 0-lepton, 1-lepton, 2-lepton, based on the number of charge leptons (electron or muon) from the W/Z decay

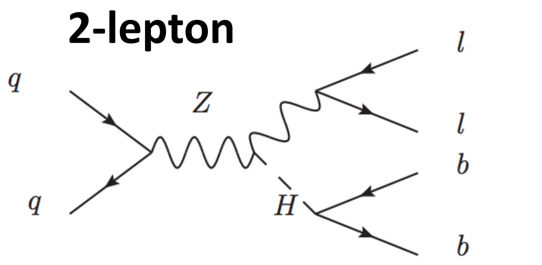
0-lepton



1-lepton



2-lepton



- Common selection
  - Exactly 2 / 3 jets (>=3 in 2-lepton)
  - Exactly 2 b-tagged jets (70% b-jet efficiency working point)

Event selection---1 lepton channel

W boson selection

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

Higgs boson candidate selection

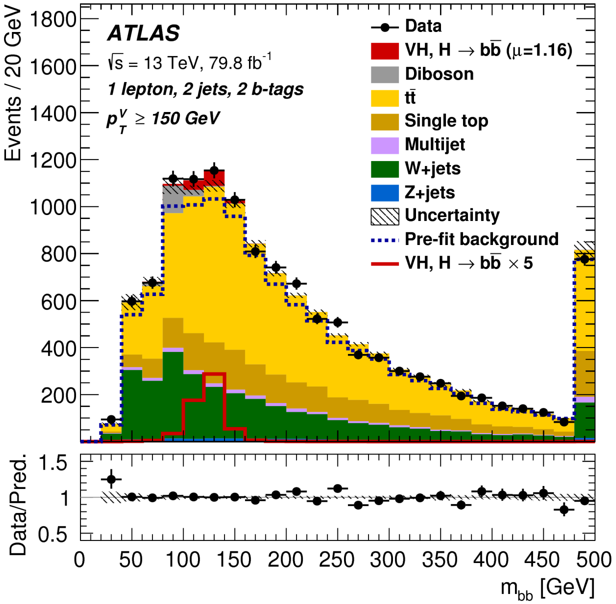
- 2 b-tagged jets, $p_T > 45$ (20) GeV
- 1 additional jet max (reducing ttbar)

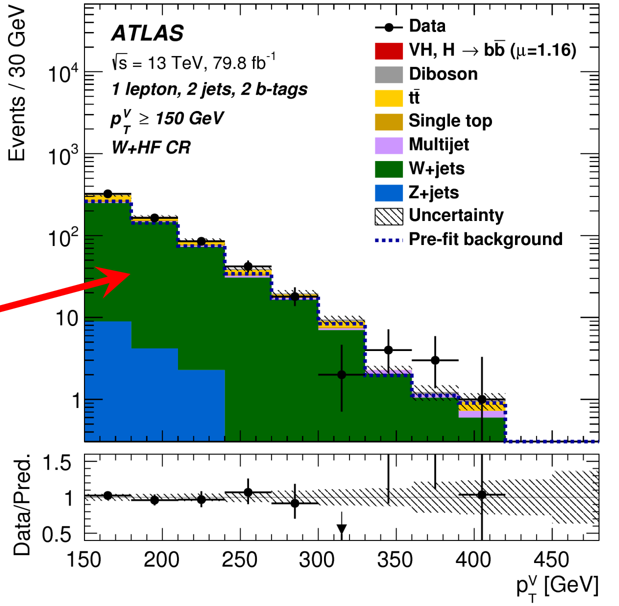
Multijet Background rejection

- $E_T^{miss} > 30$ GeV in electron channel
- Data driven estimation

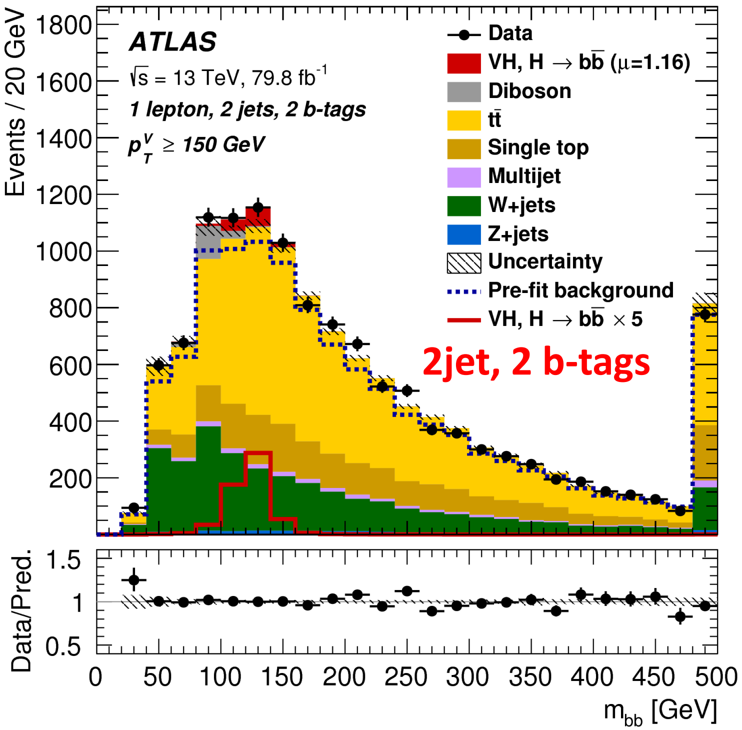
W+HF control region

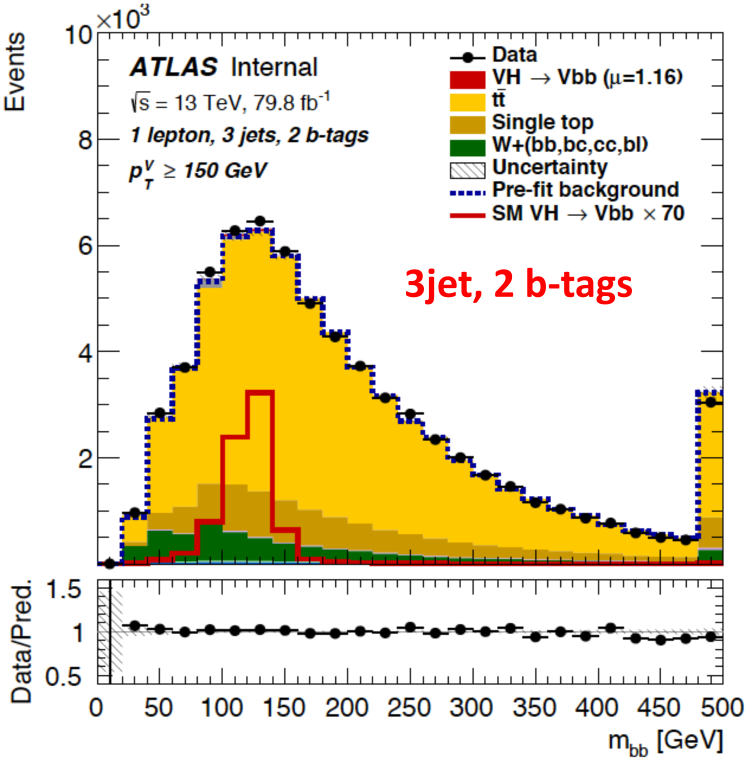
- $m_{bb} < 75$ GeV and $m_{top} > 225$ GeV
- Purity >75%





Main backgrounds after event selection





ttbar purity > 75%

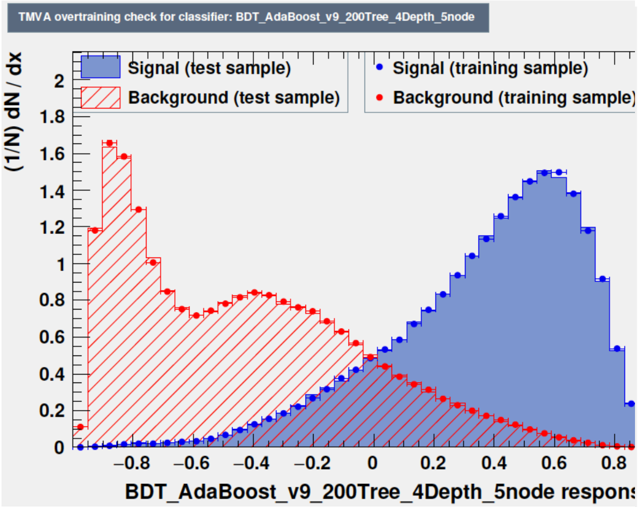
- Non-resonant backgrounds from W+jets, ttbar and single-top.
- Resonant WZ, Z → bb background, used to validate the analysis procedure.
- Small residual multi-jet background component.

Multivariate analysis (MVA)

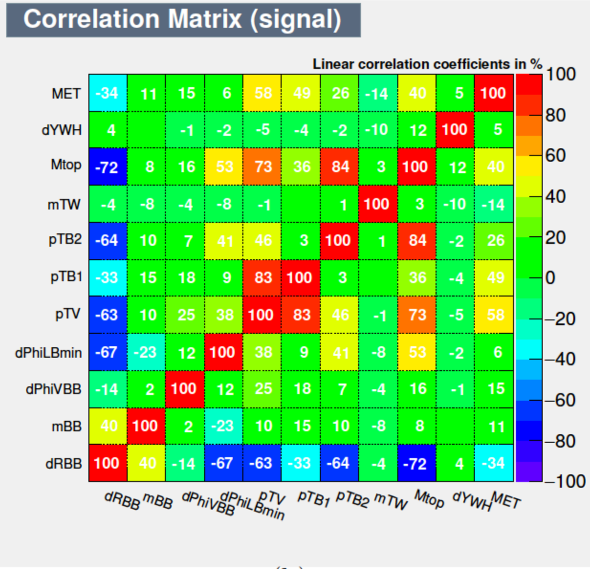
- MVA setup

- Use Boosted Decision Tree (BDT) technique.

- Input variables and training parameters tuned to yield best sensitivity, various checks performed to make sure the training works well.



Over training check



Correlation Matrix (signal)

Linear correlation coefficients in %

	dRBB	mBB	dPhiVBB	dPhiLBmin	pTV	pTB1	pTB2	mTW	Mtop	dYWH	MET
MET	-34	11	15	6	58	49	26	-14	40	5	100
dYWH	4		-1	-2	-5	-4	-2	-10	12	100	5
Mtop	-72	8	16	53	73	36	84	3	100	12	40
mTW	-4	-8	-4	-8	-1		1	100	3	-10	-14
pTB2	-64	10	7	41	46	3	100	1	84	-2	26
pTB1	-33	15	18	9	83	100	3		36	-4	49
pTV	-63	10	25	38	100	83	46	-1	73	-5	58
dPhiLBmin	-67	-23	12	100	38	9	41	-8	53	-2	6
dPhiVBB	-14	2	100	12	25	18	7	-4	16	-1	15
mBB	40	100	2	-23	10	15	10	-8	8		11
dRBB	100	40	-14	-67	-63	-33	-64	-4	-72	4	-34

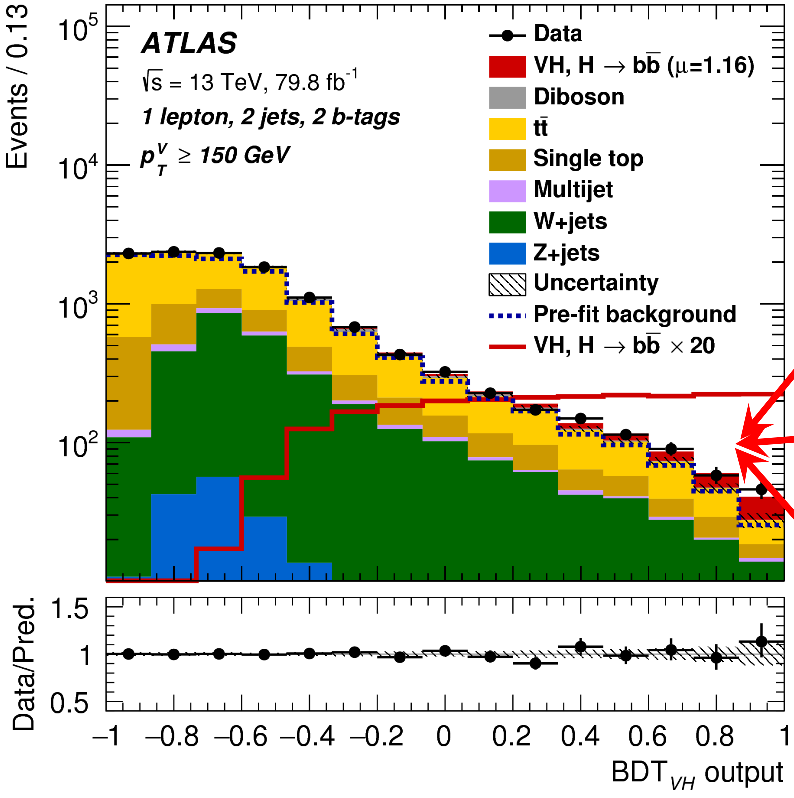
Correlation check

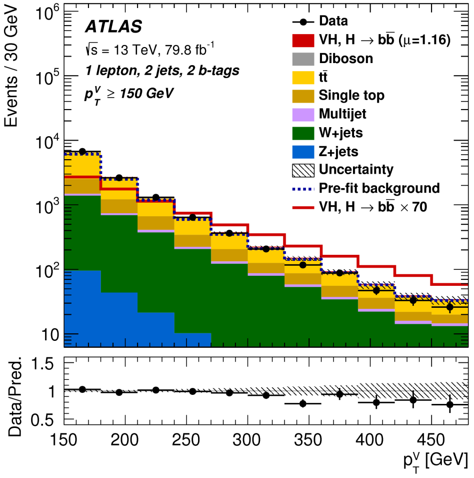
Variable	1-lepton
p_T^V	×
E_T^{miss}	×
$p_T^{b_1}$	×
$p_T^{b_2}$	×
m_{bb}	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×
$\|\Delta\eta(\vec{b_1}, \vec{b_2})\|$	
$\Delta\phi(\vec{V}, \vec{bb})$	×
$\|\Delta\eta(\vec{V}, \vec{bb})\|$	
m_{eff}	
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$	×
m_T^W	×
$m_{\ell\ell}$	
$E_T^{miss}/\sqrt{S_T}$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

Multivariate analysis (MVA)

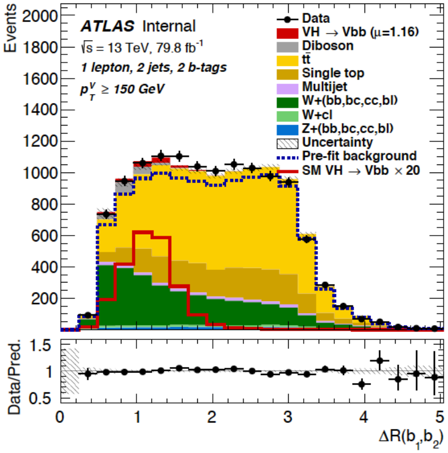
- Inputs variables

- Kinematic variables, some specific to 3-jet regions.
- m_{bb}, $\triangle R_{bb}$, p_T^V most important ones.

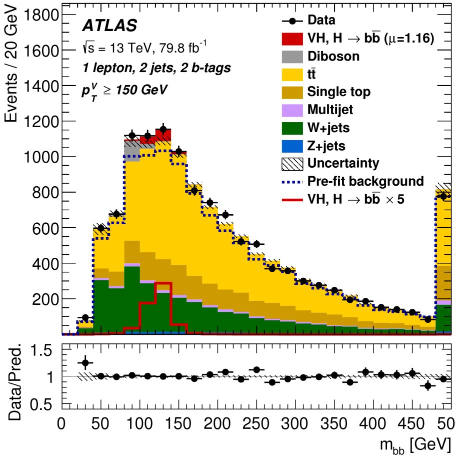




p_T^V



$\triangle R_{bb}$



m_{bb}

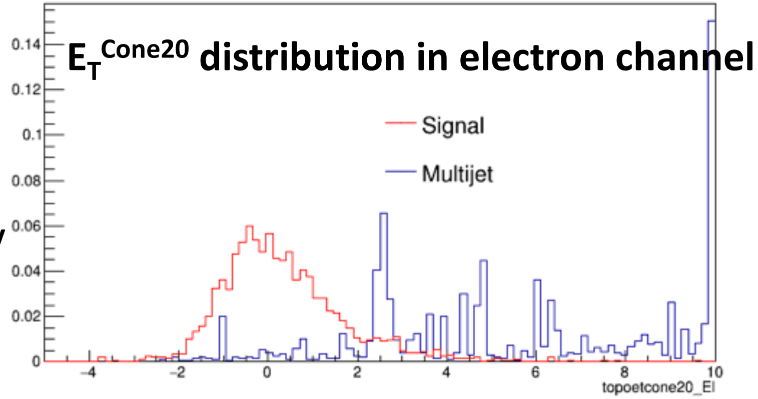
1 lepton channel Multijet estimation

Overview

- Multi-jet backgrounds produced with very large cross-sections.
  - Despite not providing genuine leptonic signatures, still have the potential to contribute a non-negligible background component.
  - Difficult to model this background using MC simulation, data driven approac is needed to estimate this background.
- The contributions to this background come from :
  - Real muons or electrons from heavy-flavour hadrons that undergo semileptonic decays.
  - Photons conversion (electron channel).

Lepton isolation requirements optimization

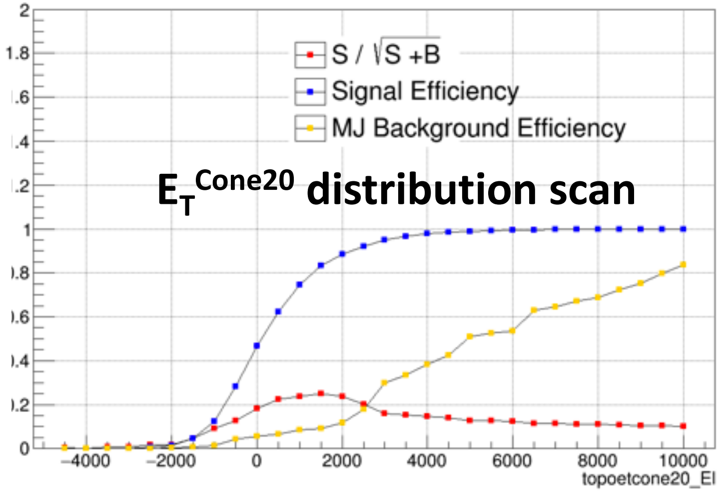
- The default lepton isolation requirements used in the previous analysis were not optimal, tested all the different isolation cuts (ptconeXX, ptvarconeXX, topoetconeXX, with XX=20,30) with signal and multijet MC samples.



E_T^{Cone20} distribution in electron channel

- New isolation WPs proposed:
  - Electron channel: LooseTrackOnly + E_T^{Cone20}<3.5 GeV
  - Muon channel: LooseTrackOnly + p_T^{Cone20}<1.25 GeV
- The optimized results are also tested and confirmed by the data-driven method.

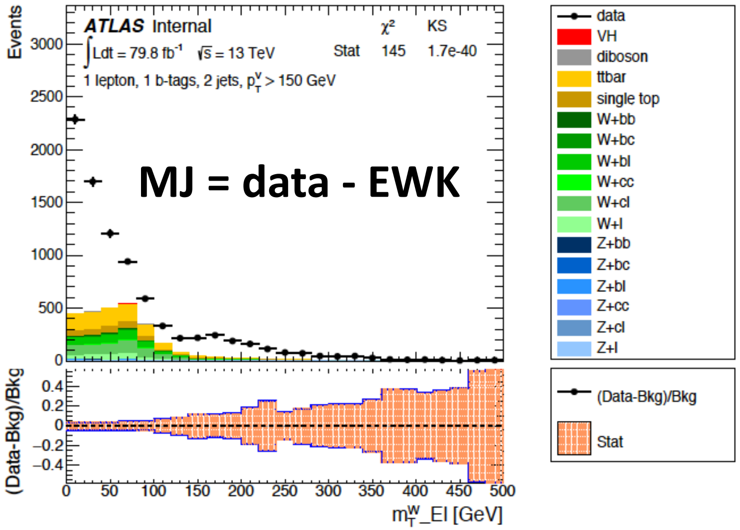
Working Points	Signal events efficiency	multijet events efficiency (PYTHIA8 samples)	multijet events efficiency (SHERPA 2.2.1 multi b-jet samples)
Electron sub-channel			
FixCutTight	98%	38% ± 7%	58% ± 4%
$E_T^{cone0.2} < 3.5$ GeV	95%	10% ± 4%	11% ± 2%
Muon sub-channel			
FixCutTrackOnly	99%	97% ± 2%	94% ± 2%
$p_T^{Cone0.2} < 1.25$ GeV	95%	29% ± 8%	31% ± 5%



E_T^{Cone20} distribution scan

MJ estimation – The whole picture

- MJ **shape** estimated by inverting the isolation requirements in 1 tag region **.**

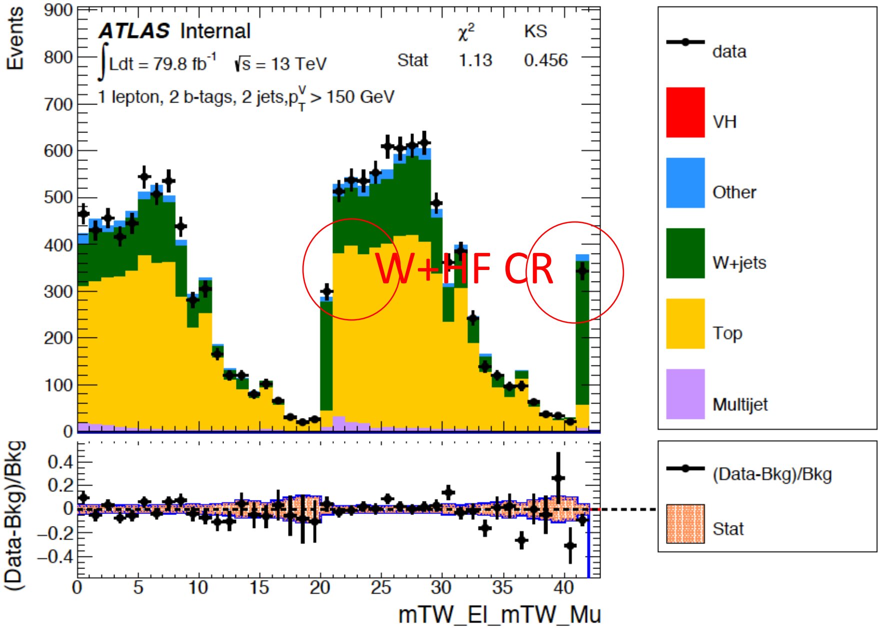


MJ = data - EWK

	Isolated Region	Inverted Isolation Region
Electron	LooseTrackOnly $E_T^{cone0.2} < 3.5$ GeV	LooseTrackOnly $E_T^{cone0.2} > 3.5$ GeV
Muon	LooseTrackOnly $p_T^{cone0.2} < 1.25$ GeV	LooseTrackOnly $p_T^{cone0.2} > 1.25$ GeV

- MJ **normalization** extracted by **fitting to** m_T^W in 2-tag signal region **.**
  - The template for the EW contribution in the signal region is obtained directly from MC predictions.
  - The variable m_T^W is chosen as it offers the clearest discrimination between the multi-jet and EW processes.
- The estimation performed separately in the electron and muon sub-channels, and in the 2- and 3-jet categories.

MJ estimation – Template fit



- Bins 1-21 correspond to the e only channel, bins 22 to 42 correspond to the μ only channel, and bins 21 and 42 represent the W + HF control region.

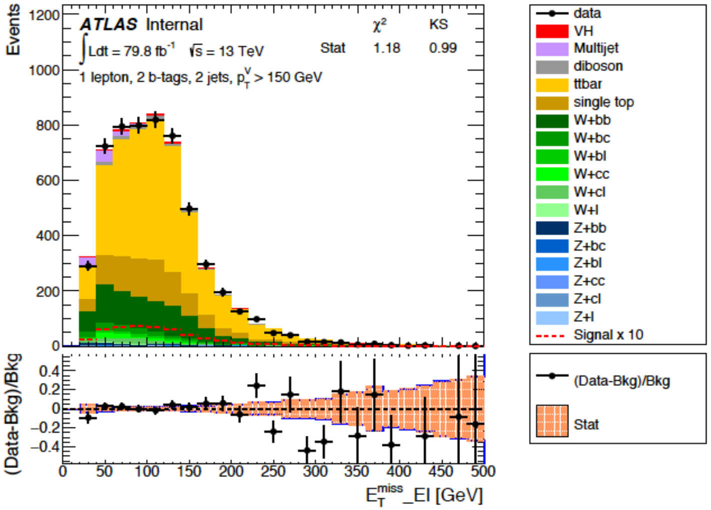
Region	Top ($t\bar{t}$ + single top)	W+jets
high p_T^V 2-tag, 2-jet	1.02 ± 0.02	1.27 ± 0.06
high p_T^V 2-tag, 3-jet	0.99 ± 0.006	1.13 ± 0.04

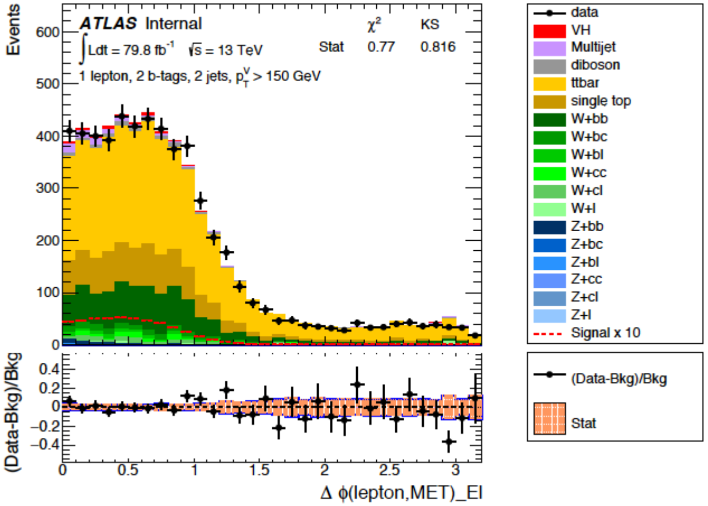
- Simultaneous fit of W+jet and top normalizations in the el and mu channel, with separate MJ normalizations.

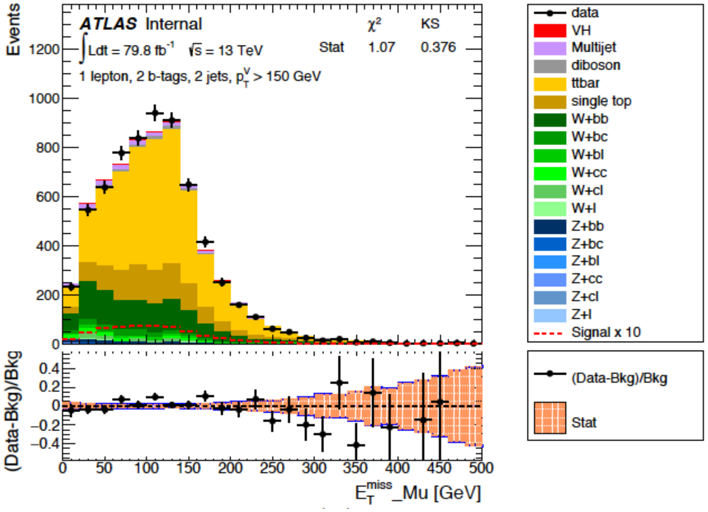
  - The m_T^W distributions of the W + jet and top quark backgrounds are sufficiently different that a common normalization factor induces a bias in the multi-jet estimate.

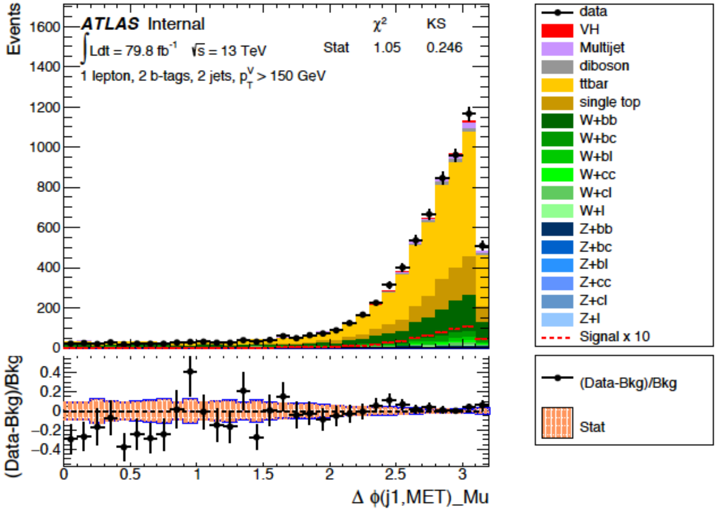
- In order to improve their relative separation, only overall yield used for the W + HF control region (one bin).

MJ estimation – Template fit









- Good data/MC agreement observed not only for the variable used for the template fit (m_T^W), but also the other variables.

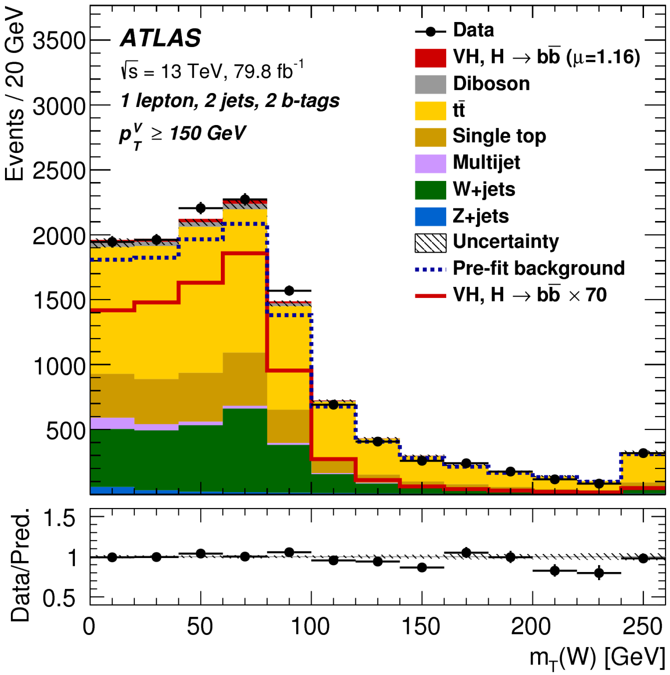
MJ estimation – Systematics uncertainties

- In generally the systematic uncertainties can have an impact on the multi-jet estimates in two ways :

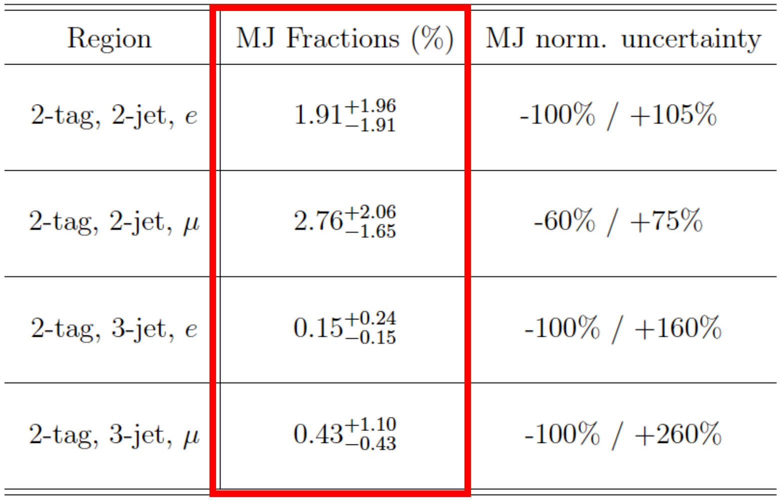
- Change the mTW distributions used in the multi-jet template fits → impact the extracted multi-jet normalizations. ★
- Change the multi-jet BDT distributions used in the global likelihood fit directly → impact the multi-jet shape. ★

- Several sources of uncertainty are considered as listed below :
  - Use the alternative variables instead of m_T^W as the template fit variable. ★
  - Include the $E_T^{miss} < 30$ GeV region for electron channel. ★
  - Use a tighter single-electron trigger to probe a potential trigger bias in the isolation requirements. ★ ★
  - Use a tighter isolation requirements to derive the MJ template. ★ ★
  - Vary the normalization of the contamination from the top and V + jets processes in the multi-jet control region. ★ ★

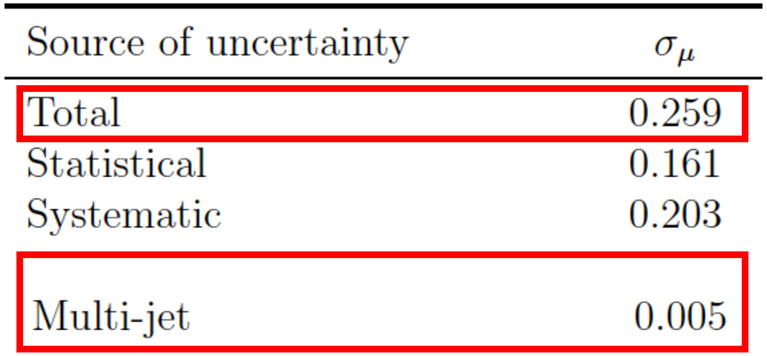
MJ estimation – Final results



- The multi-jet contribution in the 2-jet region is found to be 1.91% (2.76%) of the total background contribution in the electron (muon) sub-channel, while in the 3-jet region it is found to be 0.15% (0.43%), with normalization uncertainties from 0.15% to 2.07%



Region	MJ Fractions (%)	MJ norm. uncertainty
2-tag, 2-jet, e	$1.91^{+1.96}_{-1.91}$	-100% / +105%
2-tag, 2-jet, μ	$2.76^{+2.06}_{-1.65}$	-60% / +75%
2-tag, 3-jet, e	$0.15^{+0.24}_{-0.15}$	-100% / +160%
2-tag, 3-jet, μ	$0.43^{+1.10}_{-0.43}$	-100% / +260%



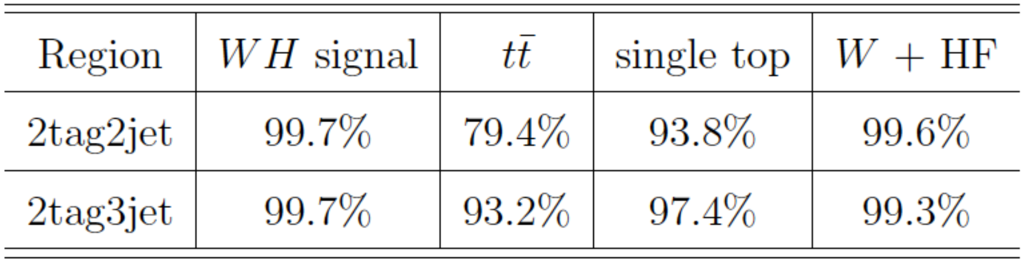
Source of uncertainty	σ_μ
Total	0.259
Statistical	0.161
Systematic	0.203
Multi-jet	0.005

- MJ impact on the mu is very small

1-lepton channel optimization

- **Hadronic decay tau veto in 1 lepton channel**
- **Using 1L medium pTV (75 GeV < pTV < 150 GeV) region**
- **Using 1L extended ttbar MC sample**
- **ttbar reduction cut study** ★
  - New cut proposed, 9% Stat. only significance increase in 3-jet region, overall ~2%
- **W(tau_had nu)H investigation** ★
  - < 4% signal events increase, not adopted **(In back up)** ★
- **1-lepton channel trigger studies** ★
  - Test the single muon trigger in muon sub-channel, ~3% signal events increase, not adopted
- **Dijet-mass analysis optimization** ★
  - Optimize the selection and categorization, Exp. Significance increased by ~5%

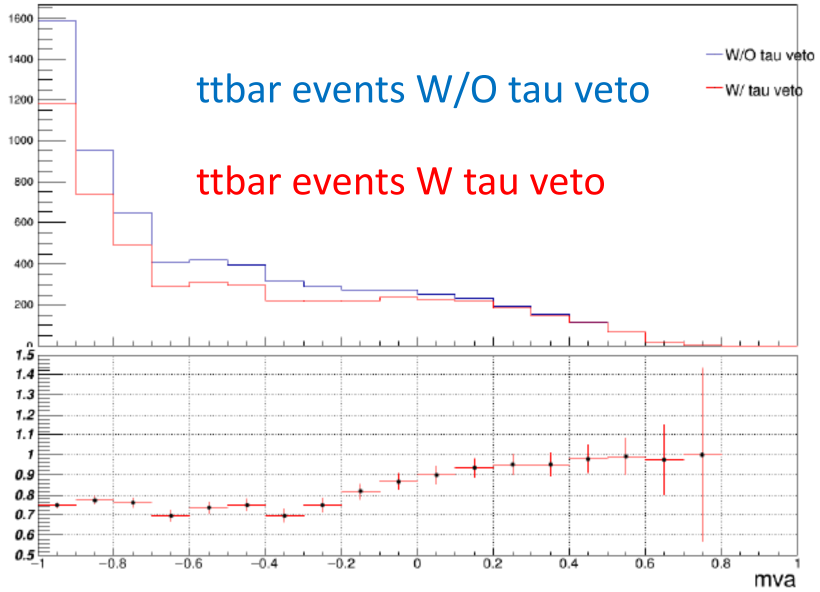
Hadronic decay tau veto in 1 lepton channel



Region	WH signal	$t\bar{t}$	single top	W + HF
2tag2jet	99.7%	79.4%	93.8%	99.6%
2tag3jet	99.7%	93.2%	97.4%	99.3%

- ➢ Considering only electron or muon, no tau veto applied by default.

- ➢ ~20% ttbar events removed in 2jet region, without signal loss.



- ➢ The removed ttbar events are mainly have low BDT value.
- ➢ The improvement of analysis sensitivity is therefore modest.

Hadronic decay tau veto in 1 lepton channel

Region	WH signal	$t\bar{t}$	single top	W + HF
2tag2jet	99.7%	79.4%	93.8%	99.6%
2tag3jet	99.7%	93.2%	97.4%	99.3%

- ➢ Considering only electron or muon, no tau veto applied by default.

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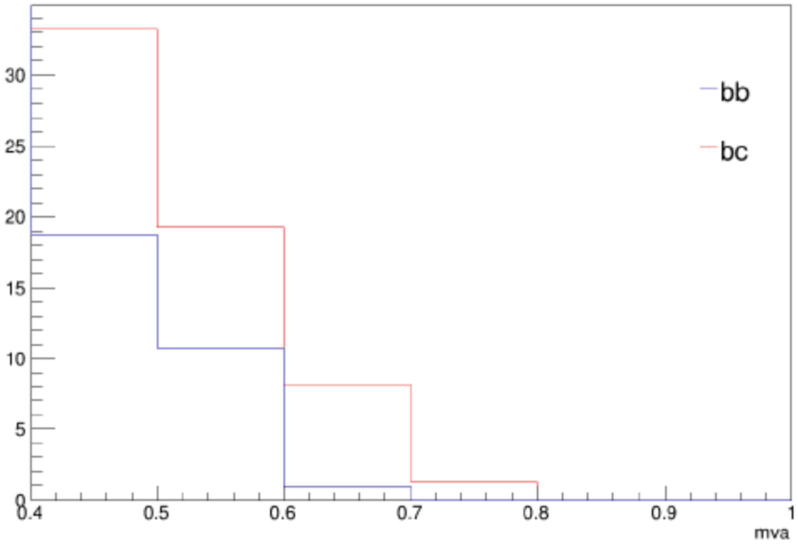


ttbar events with high BDT value (>0.4)

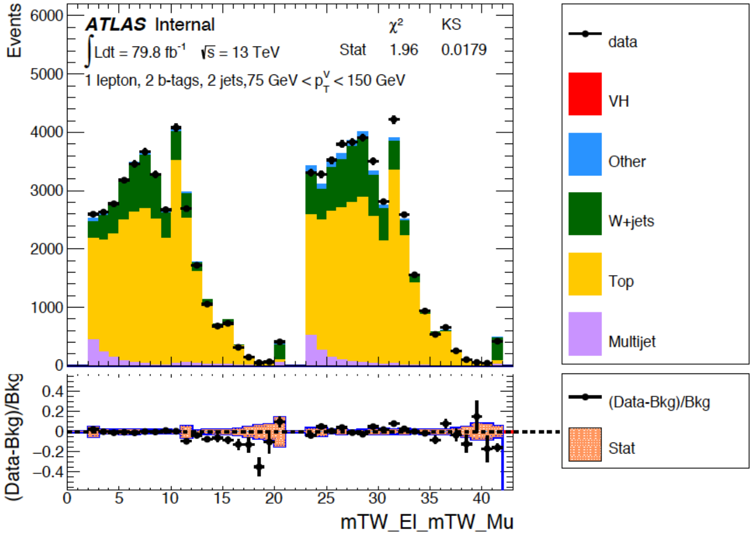
- ● bb→both the b-tagged jets in the ttbar event match the truth b-hadrons.
- ● bc→one b-tagged jet matches a truth b-hadron while another one matches a truth c-hadron.

- ● bc events dominate in the high BDT region, the tau had veto could only remove ~2% such events.

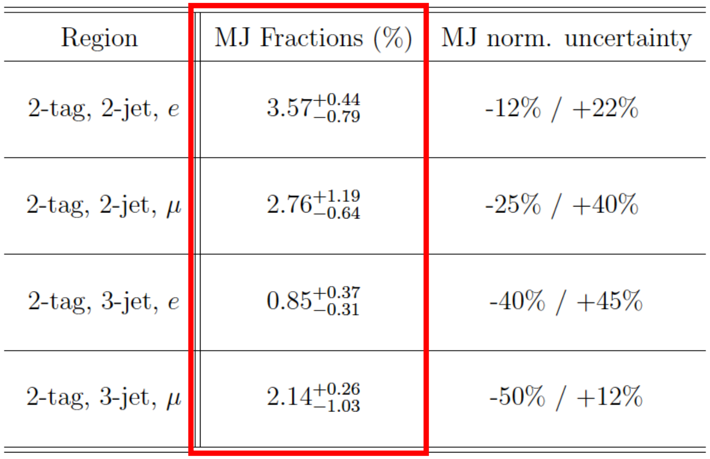
Add to the baseline for the next iteration of the analysis → work in progress

Adding 1L medium pTV region in the fit

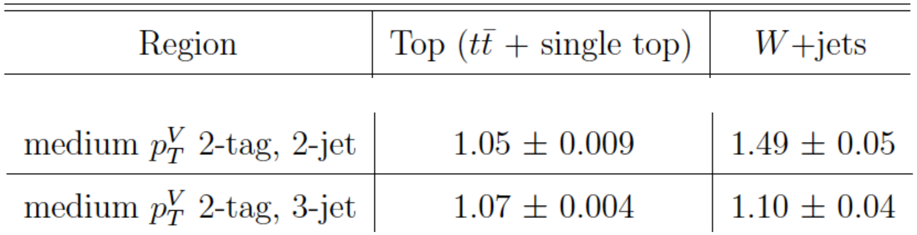
- ➢ The default 1L channel analysis consider only high pTV region (>150GeV), the medium pTV region (75-150GeV) could:
  - provide additional constraints on the largest backgrounds (V +jets and ttbar) in the global fit.
  - Recover quite a lot signal events (increase ~150%), and therefore improve the analysis sensitivity.
- ➢ The main challenge to use the medium pTV region is the much larger multijet background contribution than those in high pTV region (>150 GeV)



- Seem template fit method used to estimate the MJ in medium pTV region
- Additional mTW>20GeV cut adopted



Region	MJ Fractions (%)	MJ norm. uncertainty
2-tag, 2-jet, e	$3.57^{+0.44}_{-0.79}$	-12% / +22%
2-tag, 2-jet, μ	$2.76^{+1.19}_{-0.64}$	-25% / +40%
2-tag, 3-jet, e	$0.85^{+0.37}_{-0.31}$	-40% / +45%
2-tag, 3-jet, μ	$2.14^{+0.26}_{-1.03}$	-50% / +12%

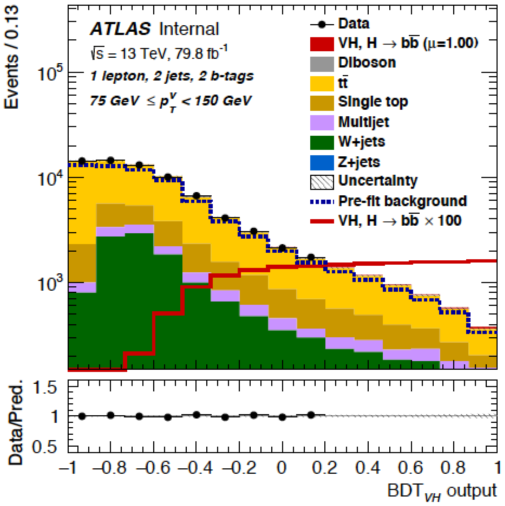


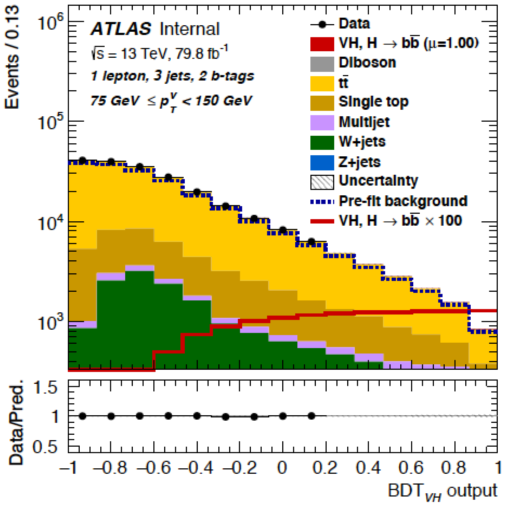
Region	Top ($t\bar{t}$ + single top)	W+jets
medium p_T^V 2-tag, 2-jet	1.05 ± 0.009	1.49 ± 0.05
medium p_T^V 2-tag, 3-jet	1.07 ± 0.004	1.10 ± 0.04

Adding 1L medium pTV region in the fit

- The 1-lepton only conditional likelihood fit to data with μ= 1 is performed with medium pTV region

- Modelling uncertainties in the medium pTV region inherited from those in high pTV region, with dedicated studies for the correlation scheme





1L high pTV region only fit

POI	Central Value	
SigXsecOverSM	1	
Set of nuisance parameters	Impact on error	
Total	+0.462 / -0.424	±0.443
DataStat	+0.270 / -0.262	±0.266
FullSyst	+0.375 / -0.333	±0.354

1L high+medium pTV region fit

POI	Central Value	
SigXsecOverSM	1	
Set of nuisance parameters	Impact on error	
Total	+0.430 / -0.391	±0.410
DataStat	+0.244 / -0.238	±0.241
FullSyst	+0.354 / -0.310	±0.332

Fit	Expected significance
1-lepton channel fit without medium p_T^V region	2.32
1-lepton channel fit with medium p_T^V region	2.51
Combined global fit without 1-lepton medium p_T^V region	4.33
Combined global fit with 1-lepton medium p_T^V region	4.57

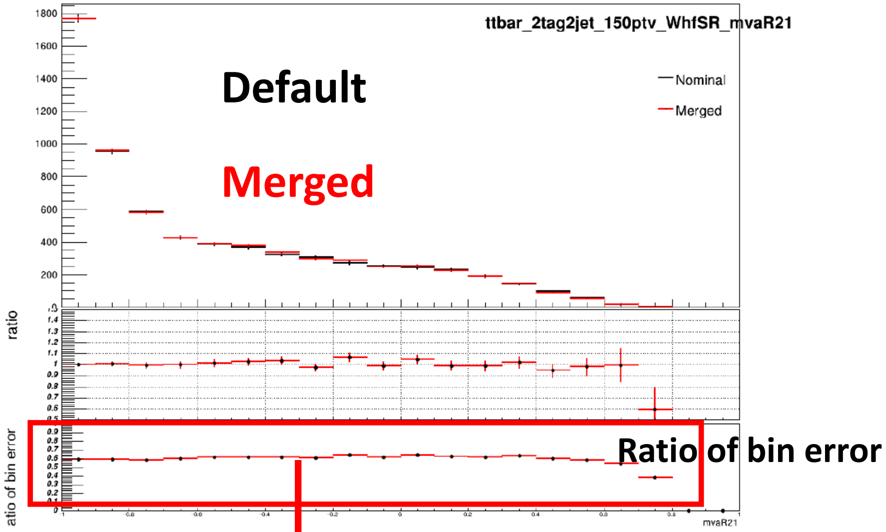
- 8.2% (5.5%) sensitivity increase in 1L (combined global) fit

Add to the baseline for the next iteration of the analysis → work in progress

Using 1L extended ttbar MC sample

- Default sample: at least one of the W bosons decays leponically (non-all-had)

- New extended sample produced with different generator level filters
  - both of the W bosons decay leptonically (dilepton)
  - non-all-had $100\ \text{GeV} < p_T^W < 200\ \text{GeV}$
  - non-all-had $p_T^W > 200\ \text{GeV}$



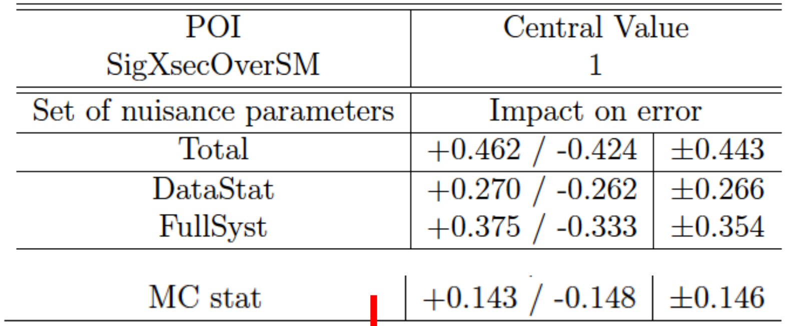
BDT distribution

MC stat. uncert. reduced by ~40%

- The expected significance increased by 4.7% in 1L fit

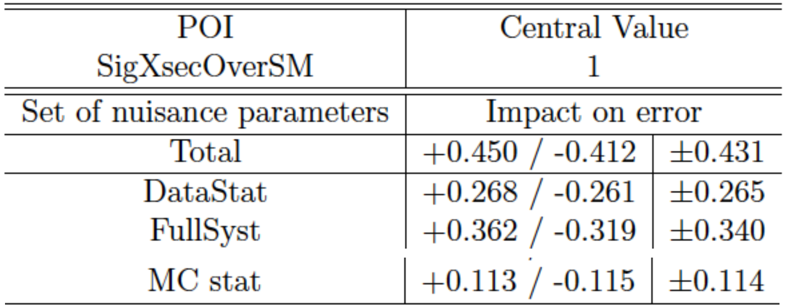
Already the baseline for the next iteration of the analysis

1L fit with default sample



POI SigXsecOverSM	Central Value 1	
Set of nuisance parameters	Impact on error	
Total	+0.462 / -0.424	±0.443
DataStat	+0.270 / -0.262	±0.266
FullSyst	+0.375 / -0.333	±0.354
MC stat	+0.143 / -0.148	±0.146

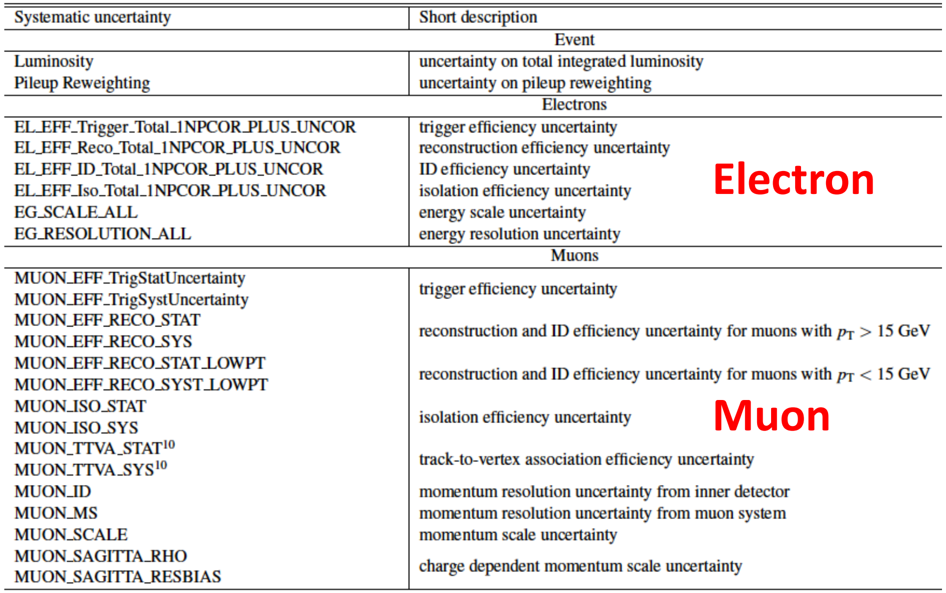
1L fit with merged sample



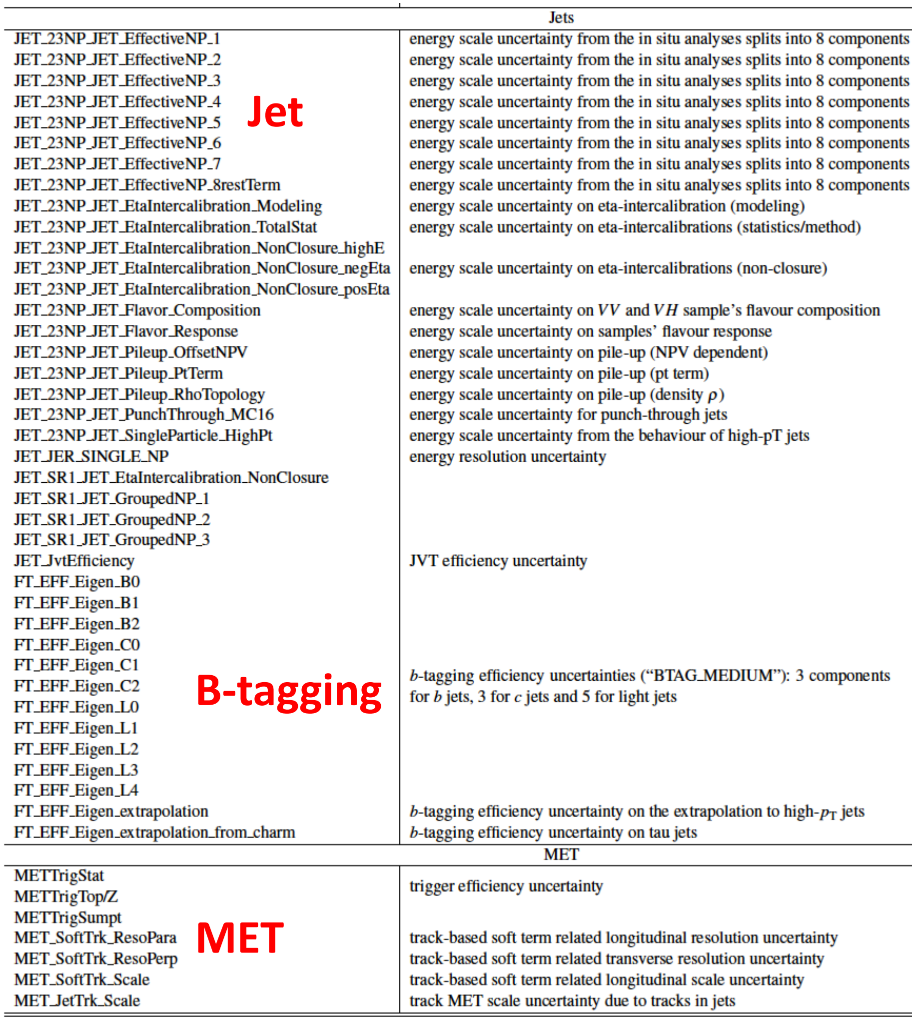
POI SigXsecOverSM	Central Value 1	
Set of nuisance parameters	Impact on error	
Total	+0.450 / -0.412	±0.431
DataStat	+0.268 / -0.261	±0.265
FullSyst	+0.362 / -0.319	±0.340
MC stat	+0.113 / -0.115	±0.114

Systematic uncertainties and statistical analysis

Experimental Systematic Uncertainties



Systematic uncertainty	Short description
Event	
Luminosity	uncertainty on total integrated luminosity
Pileup Reweighting	uncertainty on pileup reweighting
Electrons	
EL_EFF_Trigger_Total_1NPCOR_PLUS_UNCOR	trigger efficiency uncertainty
EL_EFF_Reco_Total_1NPCOR_PLUS_UNCOR	reconstruction efficiency uncertainty
EL_EFF_ID_Total_1NPCOR_PLUS_UNCOR	ID efficiency uncertainty
EL_EFF_Iso_Total_1NPCOR_PLUS_UNCOR	isolation efficiency uncertainty
EG_SCALE_ALL	energy scale uncertainty
EG_RESOLUTION_ALL	energy resolution uncertainty
Muons	
MUON_EFF_TrigStatUncertainty	trigger efficiency uncertainty
MUON_EFF_TrigSystUncertainty	
MUON_EFF_RECO_STAT	reconstruction and ID efficiency uncertainty for muons with $p_T > 15$ GeV
MUON_EFF_RECO_SYS	
MUON_EFF_RECO_STAT_LOWPT	reconstruction and ID efficiency uncertainty for muons with $p_T < 15$ GeV
MUON_EFF_RECO_SYST_LOWPT	
MUON_ISO_STAT	isolation efficiency uncertainty
MUON_ISO_SYS	
MUON_TTVA_STAT[10]	track-to-vertex association efficiency uncertainty
MUON_TTVA_SYS[10]	
MUON_ID	momentum resolution uncertainty from inner detector
MUON_MS	momentum resolution uncertainty from muon system
MUON_SCALE	momentum scale uncertainty
MUON_SAGITTA_RHO	charge dependent momentum scale uncertainty
MUON_SAGITTA_RESBIAS	



Jets	
JET_23NP_JET_EffectiveNP_1	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_2	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_3	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_4	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_5	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_6	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_7	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EffectiveNP_8restTerm	energy scale uncertainty from the in situ analyses splits into 8 components
JET_23NP_JET_EtaIntercalibration_Modeling	energy scale uncertainty on eta-intercalibration (modeling)
JET_23NP_JET_EtaIntercalibration_TotalStat	energy scale uncertainty on eta-intercalibrations (statistics/method)
JET_23NP_JET_EtaIntercalibration_NonClosure_highE	energy scale uncertainty on eta-intercalibrations (non-closure)
JET_23NP_JET_EtaIntercalibration_NonClosure_negEta	
JET_23NP_JET_EtaIntercalibration_NonClosure_posEta	
JET_23NP_JET_Flavor_Composition	energy scale uncertainty on VV and VH sample's flavour composition
JET_23NP_JET_Flavor_Response	energy scale uncertainty on samples' flavour response
JET_23NP_JET_Pileup_OffsetNPV	energy scale uncertainty on pile-up (NPV dependent)
JET_23NP_JET_Pileup_PtTerm	energy scale uncertainty on pile-up (pt term)
JET_23NP_JET_Pileup_RhoTopology	energy scale uncertainty on pile-up (density ρ)
JET_23NP_JET_PunchThrough_MC16	energy scale uncertainty for punch-through jets
JET_23NP_JET_SingleParticle_HighPt	energy scale uncertainty from the behaviour of high-pT jets
JET_JER_SINGLE_NP	energy resolution uncertainty
JET_SR1_JET_EtaIntercalibration_NonClosure	
JET_SR1_JET_GroupedNP_1	
JET_SR1_JET_GroupedNP_2	
JET_SR1_JET_GroupedNP_3	
JET_JvtEfficiency	JVT efficiency uncertainty
FT_EFF_Eigen_B0	*b*-tagging efficiency uncertainties ("BTAG_MEDIUM"): 3 components for *b* jets, 3 for *c* jets and 5 for light jets
FT_EFF_Eigen_B1	
FT_EFF_Eigen_B2	
FT_EFF_Eigen_C0	
FT_EFF_Eigen_C1	
FT_EFF_Eigen_C2	
FT_EFF_Eigen_L0	
FT_EFF_Eigen_L1	
FT_EFF_Eigen_L2	
FT_EFF_Eigen_L3	
FT_EFF_Eigen_L4	
FT_EFF_Eigen_extrapolation	*b*-tagging efficiency uncertainty on the extrapolation to high-p_T jets
FT_EFF_Eigen_extrapolation_from_charm	*b*-tagging efficiency uncertainty on tau jets
MET	
METTrigStat	trigger efficiency uncertainty
METTrigTop/Z	
METTrigSumpt	
MET_SoftTrk_ResoPara	track-based soft term related longitudinal resolution uncertainty
MET_SoftTrk_ResoPerp	track-based soft term related transverse resolution uncertainty
MET_SoftTrk_Scale	track-based soft term related longitudinal scale uncertainty
MET_JetTrk_Scale	track MET scale uncertainty due to tracks in jets

- ➢ Follow closely the combined performance (CP) group recommendations.

- ➢ The dominant experimental uncertainties originate from the b-tagging correction factors, the jet energy scale corrections and the modelling of the jet energy resolution.

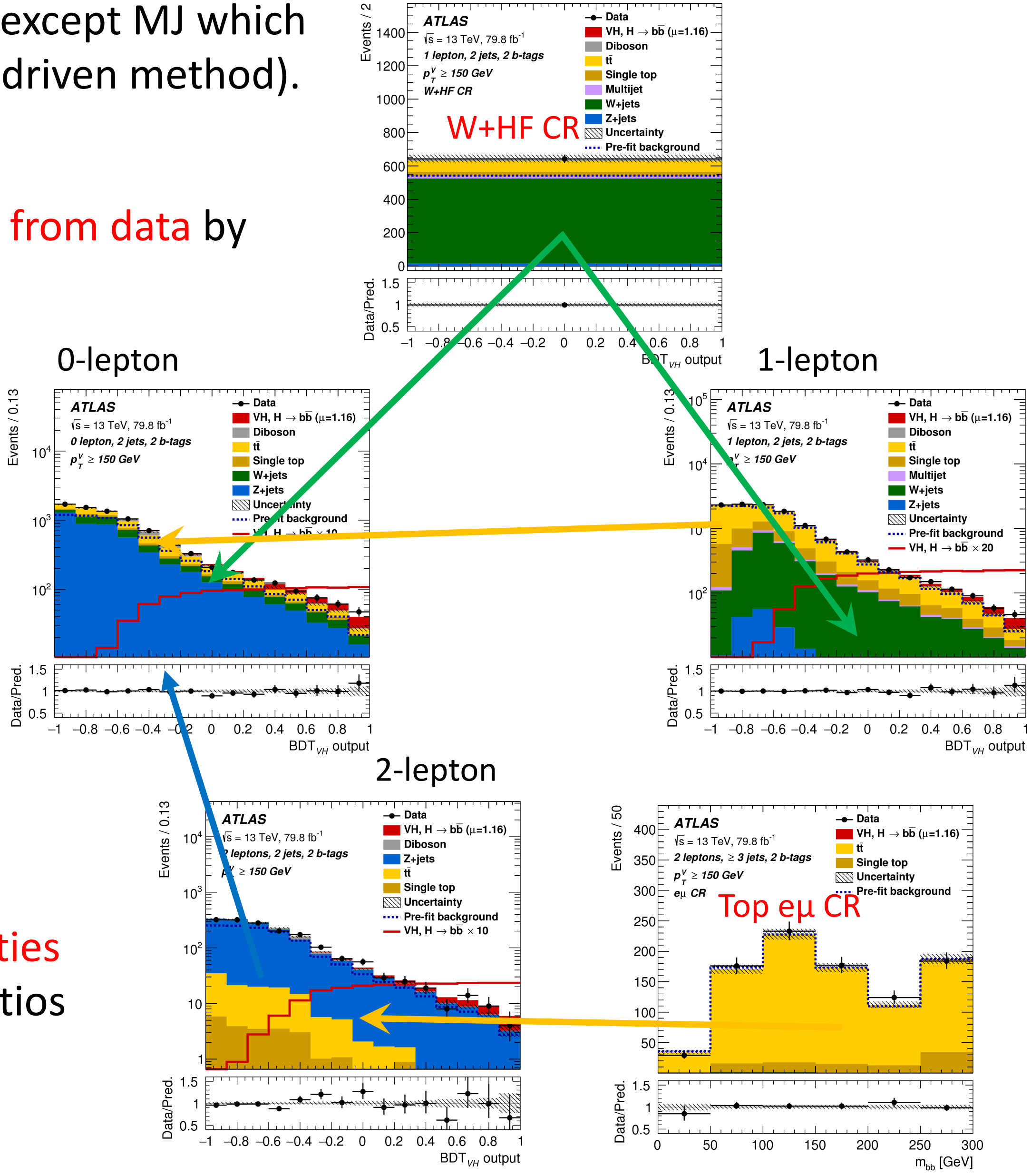
Background modelling---general picture

- ➢ Use state-of-the-art MC generators (except MJ which is modelled in 1-lepton using a data-driven method).

- ➢ Constrain (shape and normalization) from data by using high purity control regions

- ➢ Main background normalizations floating in the fit.

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



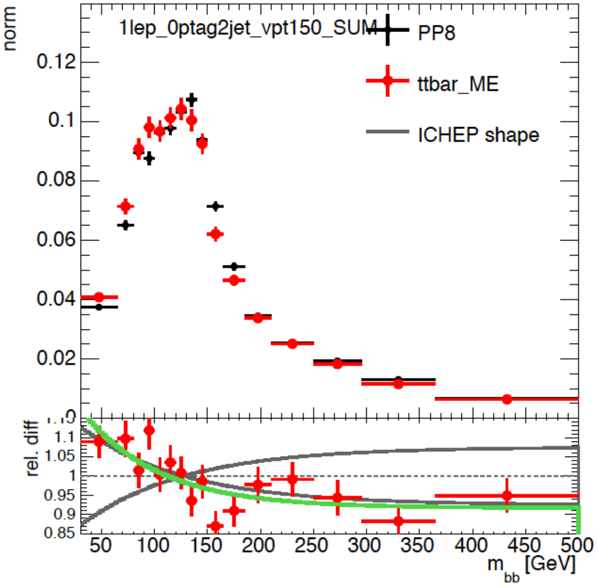
- ➢ Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields.

- ➢ Shape uncertainties on BDTs.

Background modelling---ttbar

$t\bar{t}$ (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

- The acceptance and shape uncertainties are derived from comparing the nominal sample (Powheg+Pythia8) to the alternative samples

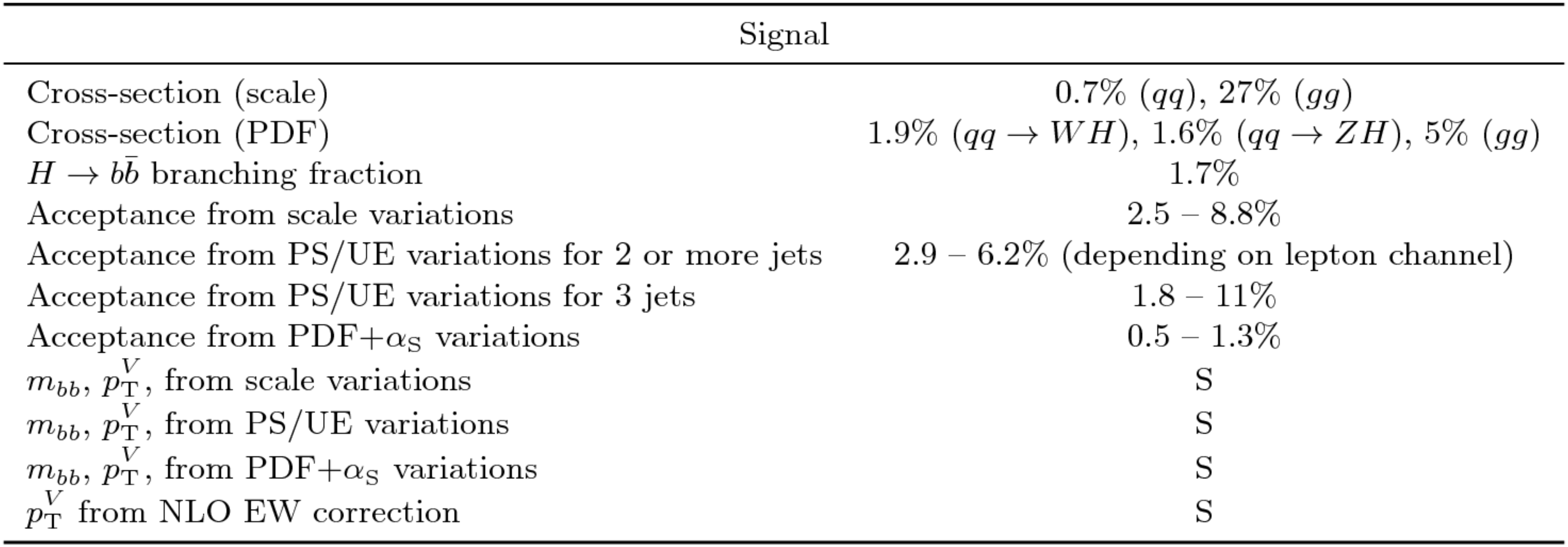


Systematic	0/1Lep 2j	0/1Lep 3j	0/1Lep 2+3j
MCstat. (PP8)	±1.6 %	±0.6 %	±0.6 %
MCstat. (RadHi)	±1.3 %	±0.5 %	±0.5 %
MCstat. (RadLo)	±1.4 %	±0.5 %	±0.5 %
MCstat. (PH7)	±1.7 %	±0.7 %	±0.6 %
MCstat. (aMCP8)	±2.6 %	±1.0 %	±0.9 %
ISR (PP8)	∓0.4 %	∓1.1 %	∓1.0 %
(PP8 VS H7)	-7.7 %	-5.8 %	-6.1 %
(aMCP8 VS PP8)	+2.5 %	+2.5 %	+2.4 %
TOTAL	±8.1 %	±6.4 %	±6.6 %

- Shape uncertainties are derived only for the m_{bb} and p_T^V distributions
  - highest ranked variables in the BDT training.
  - have only very weak correlation.

$$\frac{Acceptance[Region_A(nominalMC)]}{Acceptance[Region_B(nominalMC)]} \Bigg/ \frac{Acceptance[Region_A(alternativeMC)]}{Acceptance[Region_B(alternativeMC)]}.$$

Signal modelling



Signal	
Cross-section (scale)	0.7% (qq), 27% (gg)
Cross-section (PDF)	1.9% ($qq \to WH$), 1.6% ($qq \to ZH$), 5% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Acceptance from scale variations	2.5 – 8.8%
Acceptance from PS/UE variations for 2 or more jets	2.9 – 6.2% (depending on lepton channel)
Acceptance from PS/UE variations for 3 jets	1.8 – 11%
Acceptance from PDF+α_{S} variations	0.5 – 1.3%
m_{bb}, p_{T}^{V}, from scale variations	S
m_{bb}, p_{T}^{V}, from PS/UE variations	S
m_{bb}, p_{T}^{V}, from PDF+α_{S} variations	S
p_{T}^{V} from NLO EW correction	S

- Standard prescriptions for systematic uncertainties: from theory calculations and from comparisons of Monte Carlo modelling variations, or variations of parameters

- Separate systematic uncertainties on production from acceptance effects

Fit model

- Perform a binned maximum likelihood fit simultaneously in different categories to extract signal significance / signal strength (μ).

$$\mathcal{L}(\mu,\boldsymbol{\theta}) = \prod_{i=1}^{nbins} \frac{(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-(\mu s_i(\boldsymbol{\theta})+b_i(\boldsymbol{\theta}))} \times \mathcal{L}_{AUX}(\boldsymbol{\theta}).$$

$$\mu = \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}}$$

nuisance parameters (NP): sources of systematic uncertainty could have effect on the signal strength measurement

Channel	SR/CR	Categories			
		75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV		$p_{\mathrm{T}}^{V} >$ 150 GeV	
		2 jets	3 jets	2 jets	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}

- 8 Signal Regions (SR).

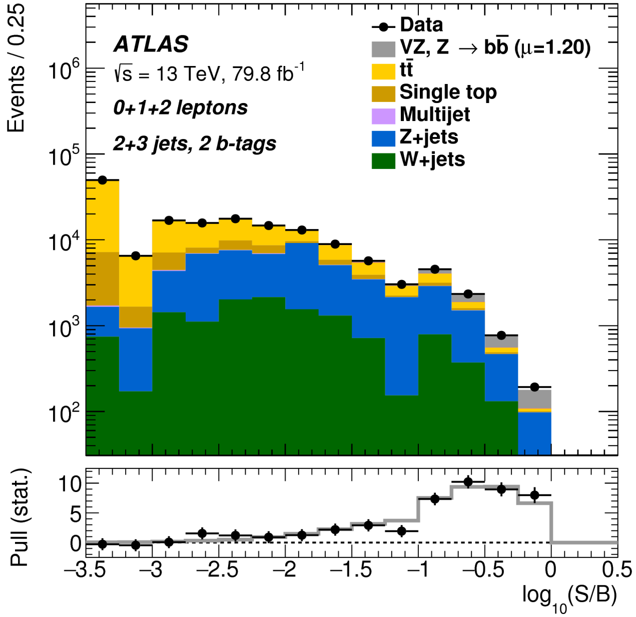
- 2 W+HF (heavy flavor) control regions (CRs) in 1-lepton channel (Purity:~75%).

- 4 Top eμ CRs in 2-lepton (Purity: ~99%)

Results

Pre-unblinding validation: Diboson MVA analysis

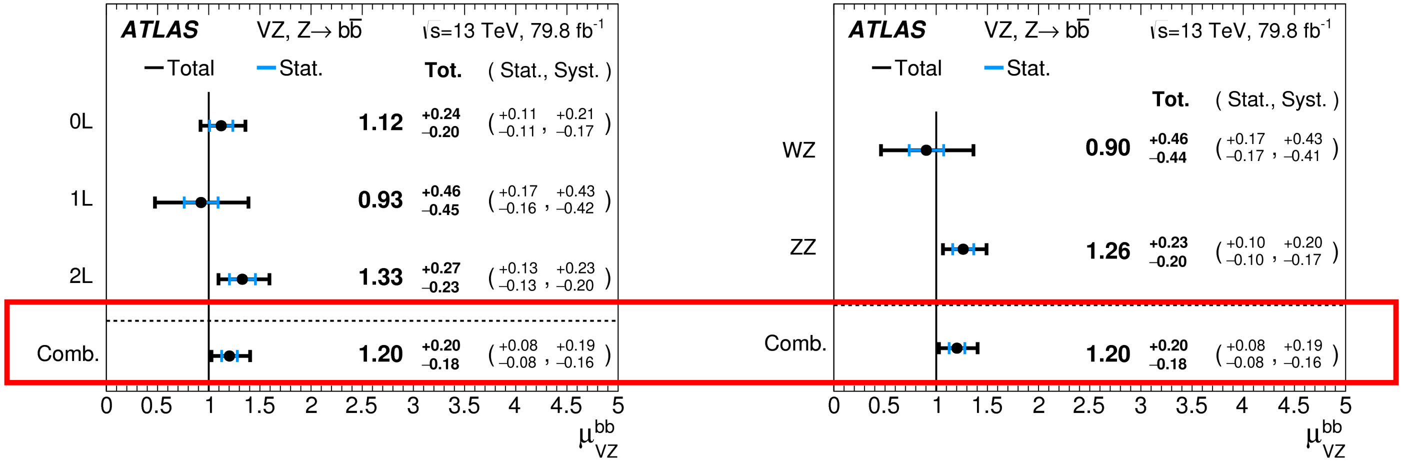
- Same analysis strategy as the VH MVA analysis
  - Re-train the BDTs to look for VZ instead of VH
  - Robust validation of background model and associated uncertainties



- Signal strength compatible with the SM prediction

- The whole analysis procedure validated

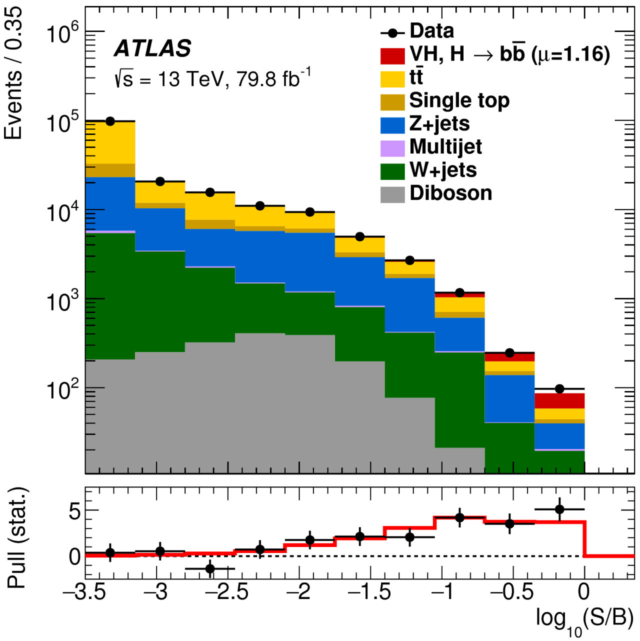
Significance >> 5 σ



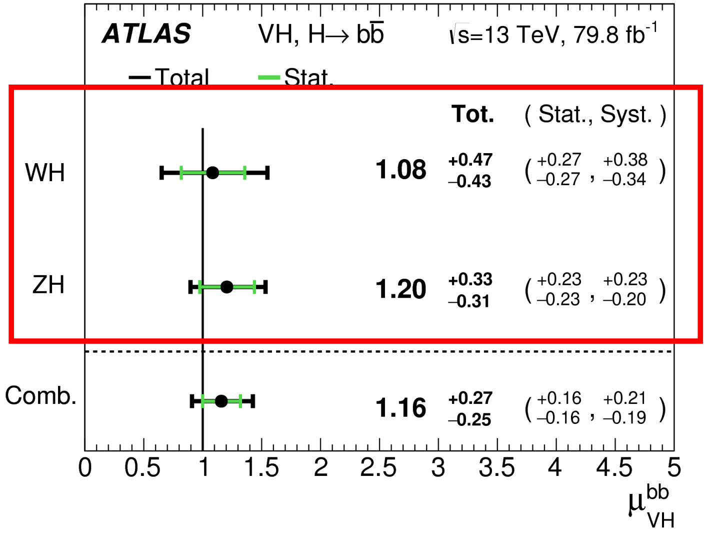
VH MVA analysis results

- ➢ Significance of VH(bb) signal at 4.9 σ (4.3 σ exp.)
  - Signal strength compatible with the SM prediction

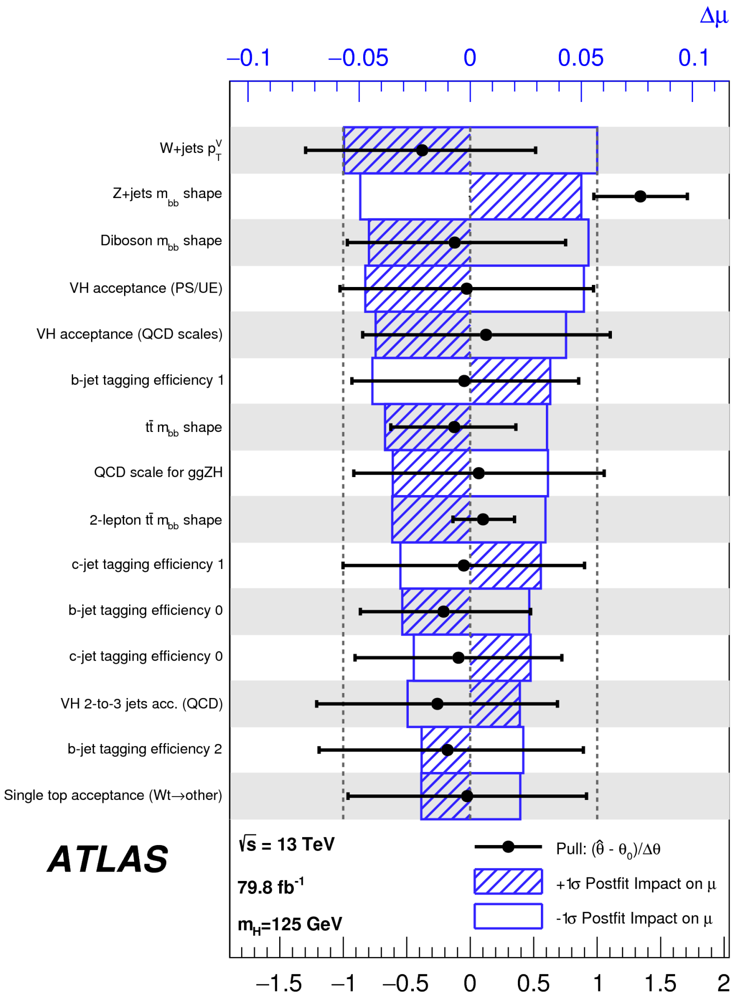
Signal strength	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH,\ H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9



- ➢ Individual production modes significances
  - 2.5 σ (2.3 σ exp.) for WH
  - 4.0 σ (3.5 σ exp.) for ZH



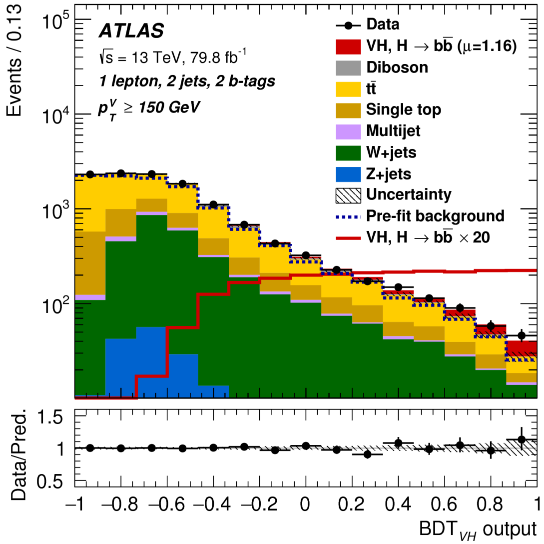
VH MVA analysis results

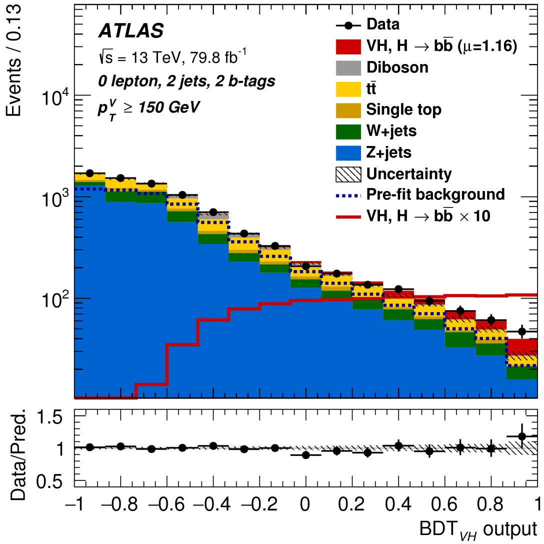


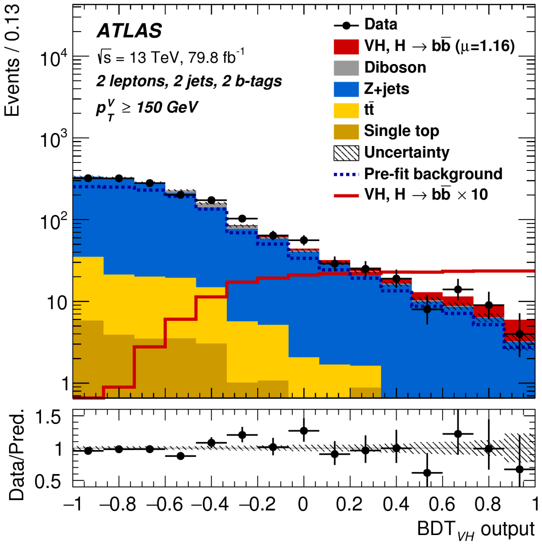
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

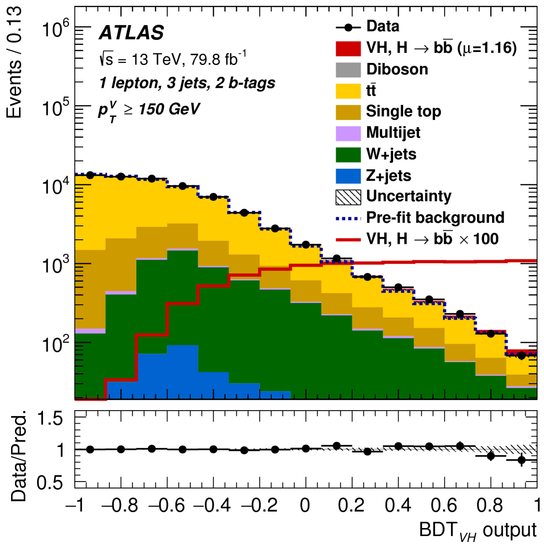
- Measurement dominated by systematics (signal and background modelling, MC statistics, b-tagging).

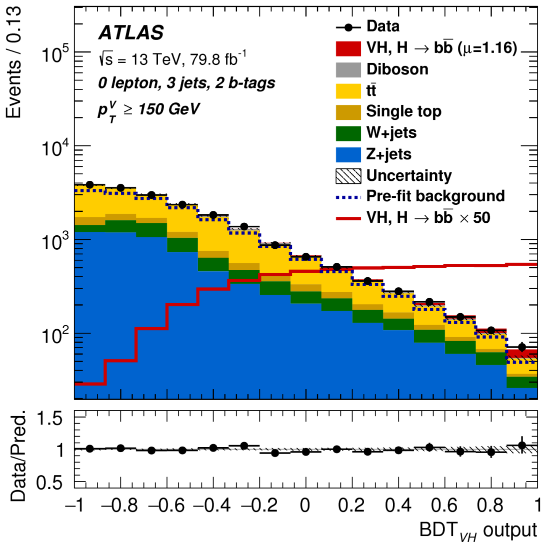
Post-fit plots VH MVA

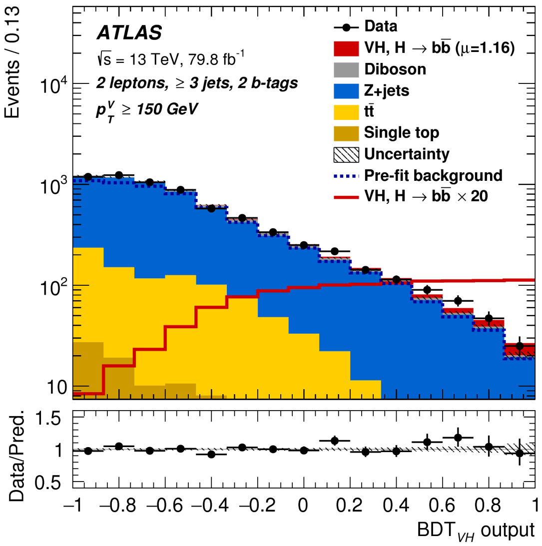






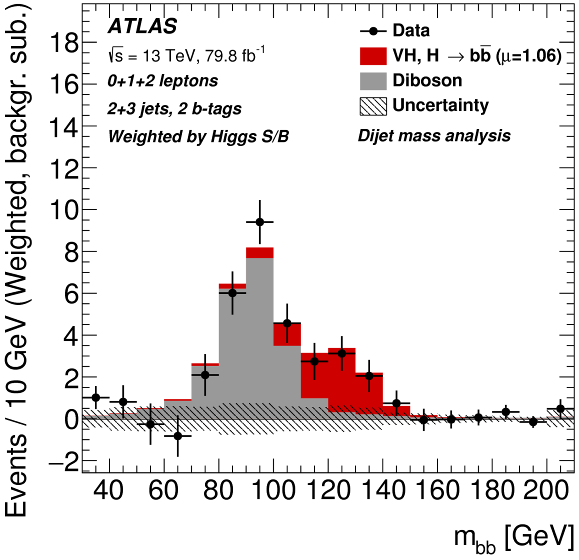


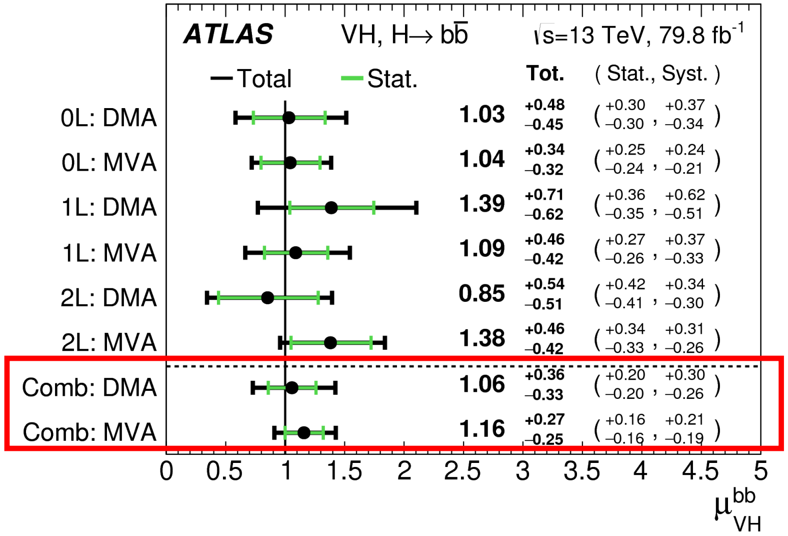




Cross check: Di-jet mass analysis (DMA)

- Important cross-check to test robustness of result
  - Additional p_T^V Split at 200 GeV
  - Additional cuts on $\triangle R_{bb}$ (p_T^V dependent), m_T^W (1 lepton), E_T^{miss} significance (2 lepton)
  - Fit m_{bb} instead of BDT output

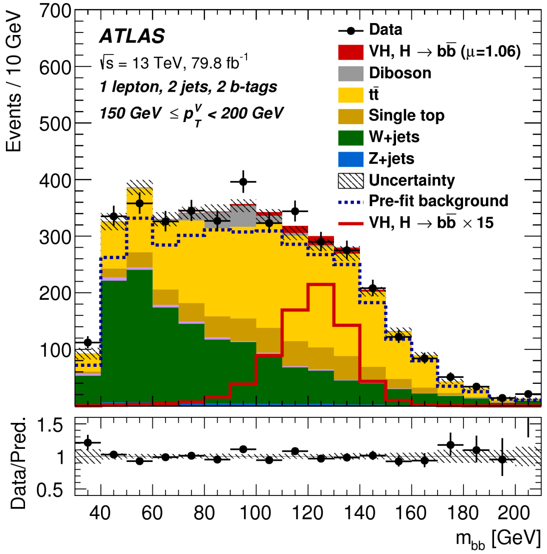


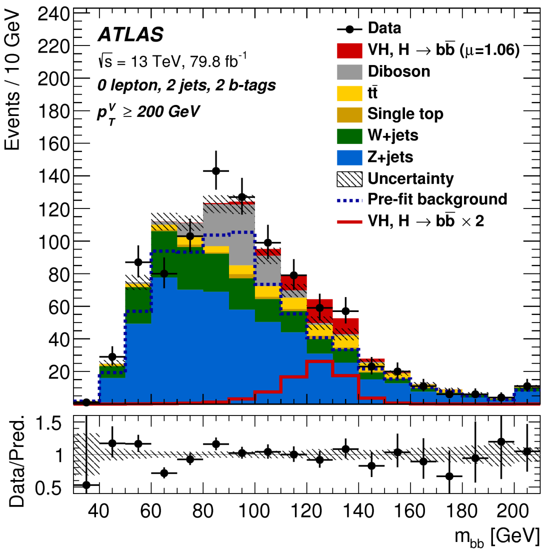


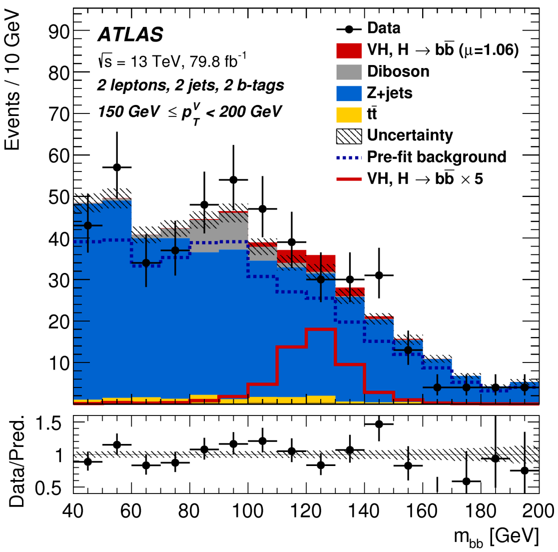
- Significance of VH(bb) signal at 3.6 σ (3.5 σ exp.)

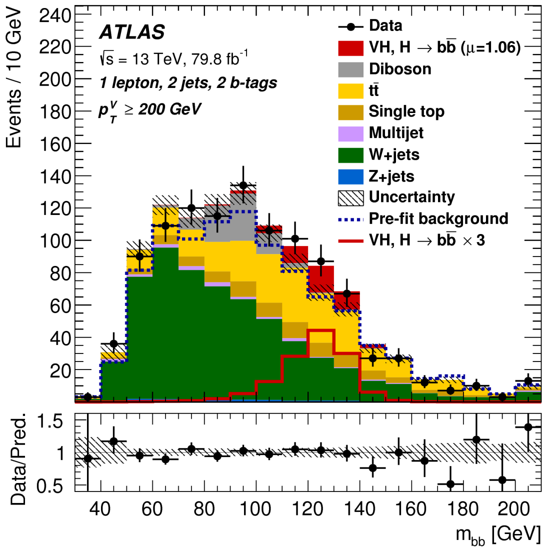
- Consistent with MVA result in all channels

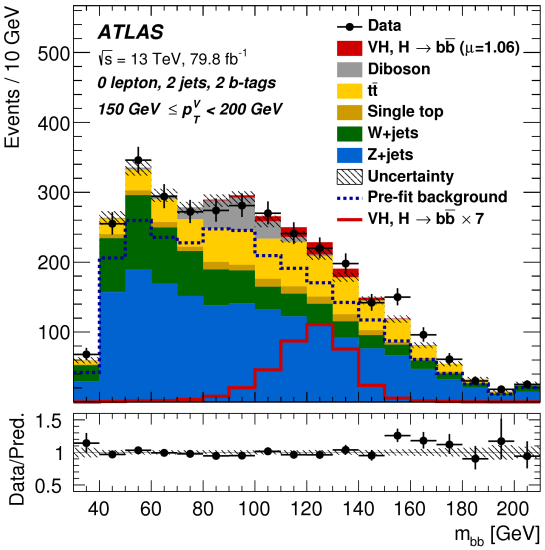
Post-fit plots VH di-jet mass analysis

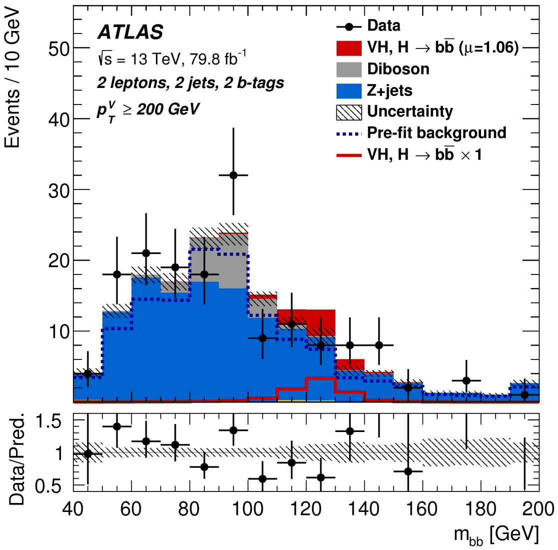






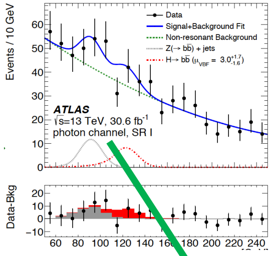


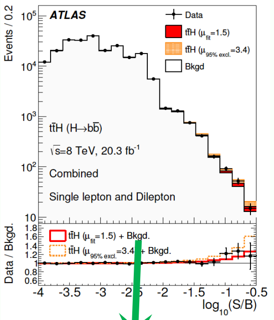


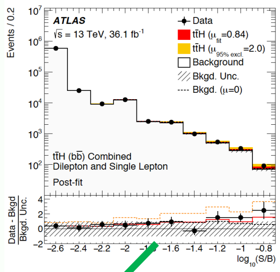


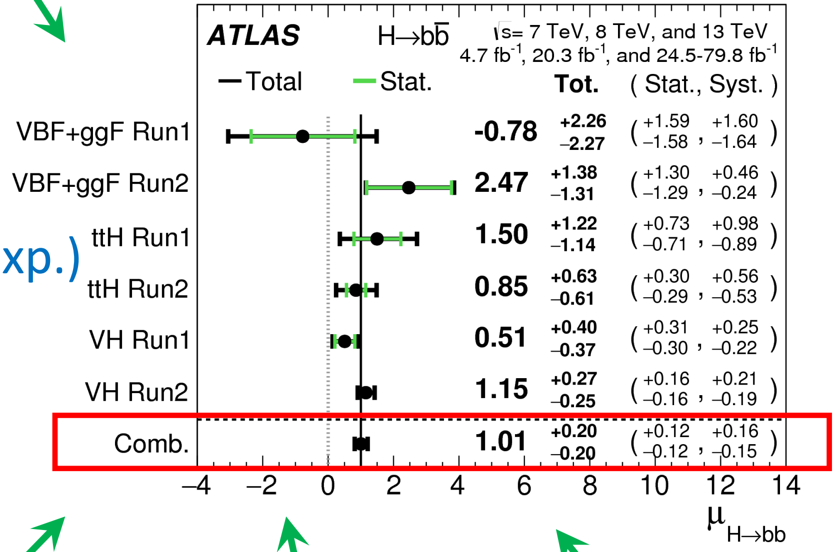
Combination of H→bb searches

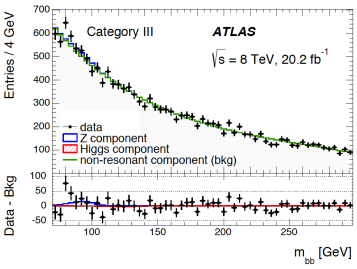
- Combine Run 1 and Run 2 analyses in VH, VBF and ttH production modes
  - Results assume SM Higgs boson production cross-section
  - Only H→bb branching ratio is correlated across the six analyses
- Observation of H→bb decays at 5.4 σ (5.5 σ exp.)
- Main contributions from VH channels (contributions of VBF and ttH channels 1.5σ and 1.9 σ)
- Compatibility of the 6 measurements 54%

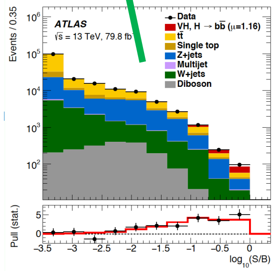


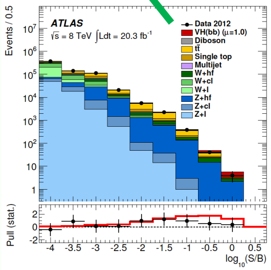






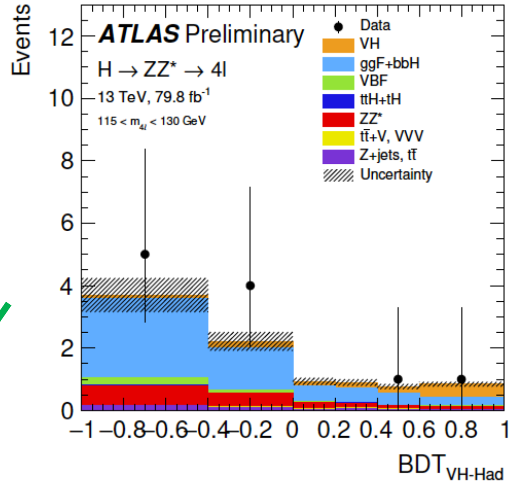


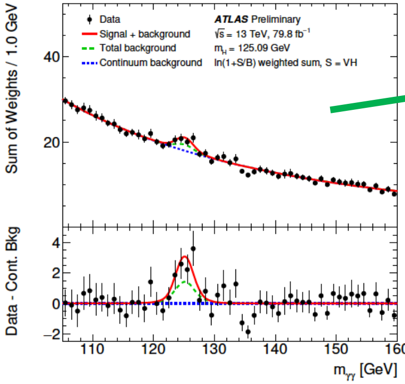


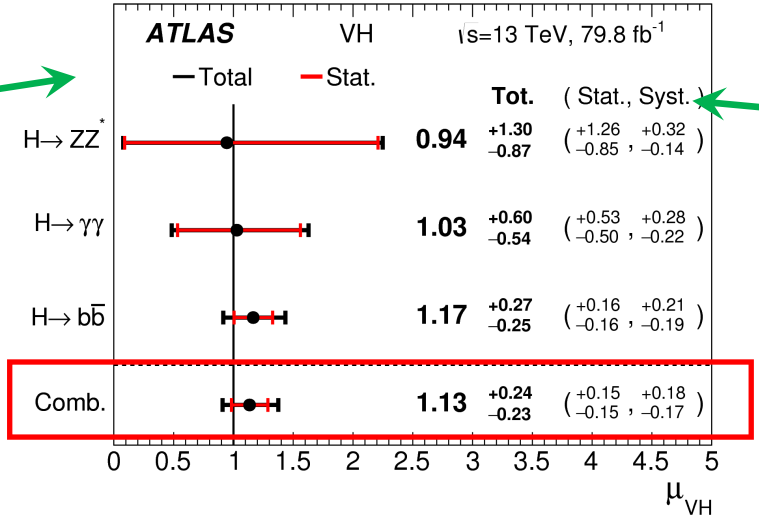


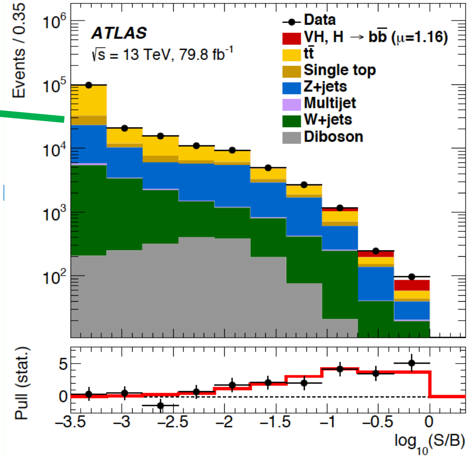
Combination of VH searches

- Combine Run 2 analyses in bb, γγ and 4l decays
  - Updated analyses with 2015-2017 Run 2 data in all channels
  - Results assume SM Higgs boson branching fractions
- Observation of VH production at 5.3 σ (4.8 σ exp.)
- Main contributions from bb channels (contributions of 4l and γγ channels 1.1σ and 1.9 σ)
- Compatibility of the 3 measurements 96%







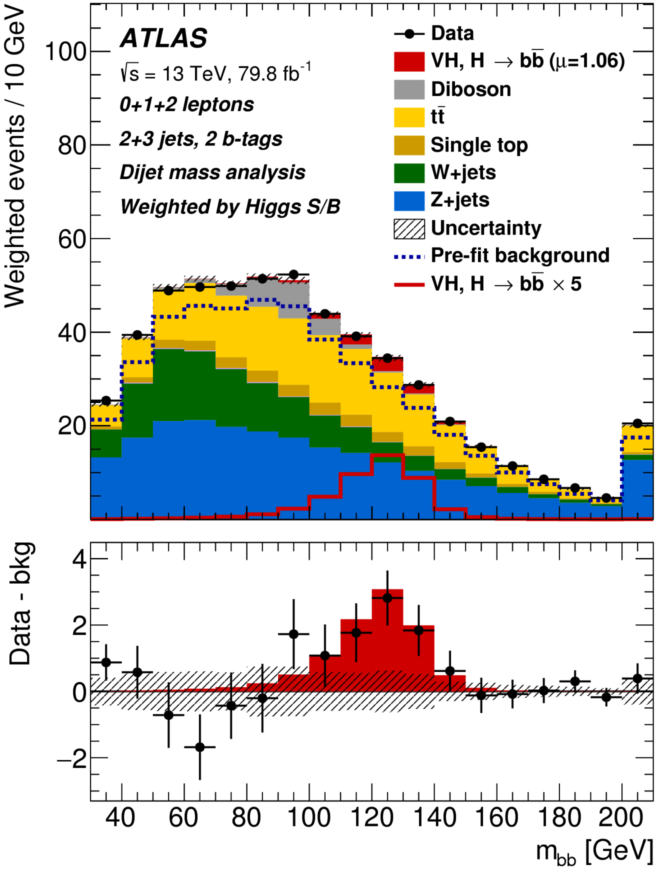


Conclusions

- ➢ VH(bb) analysis carried out on full 2015-17 dataset
  - With Run 2 79.8 fb^{-1} dataset, found strong evidence for VH(bb) with a significance of 4.9 σ (4.3 σ exp.) and a mu value of 1.16 +/-0.26

- ➢ With full Hbb combination, 5.4 (5.5) σ observed (exp.) for H→bb with mu value of 1.01 +/- 0.20

- ➢ With Run 2 VH combination, 5.3 (4.8) σ observed (exp.) for VH with mu value of 1.13 +/- 0.24



These results provide an observation of the H → bb decay mode, and also of the Higgs boson being produced in association with a vector boson.

Outlook

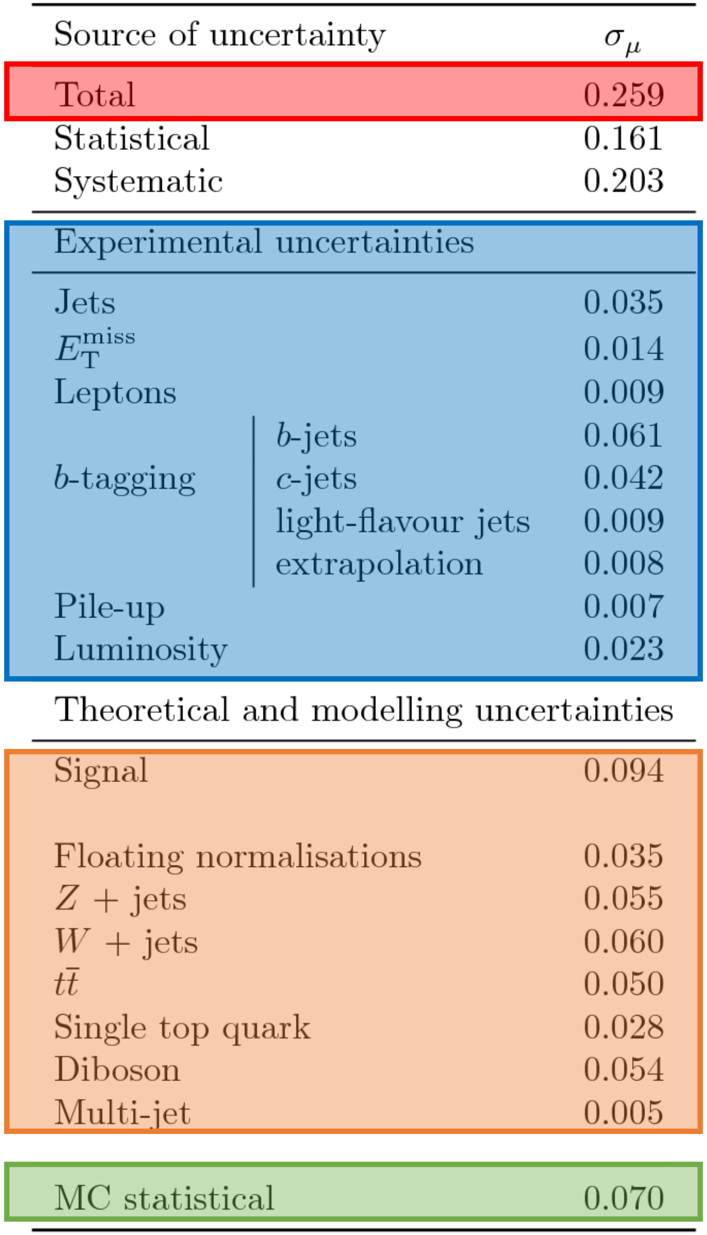
- Couplings of the Higgs boson beyond those predicted by the SM are far from ruled out.

- **More data, more precision measurements!**
  - ~60 fb^{-1} data from 2018 data taking, another 150 fb^{-1} data expected in Run 3 data taking.
  - The Higgs p_T spectrum is highly sensitive to new physics with the sensitivity increasing with higher Higgs p_T.
  - Boosted analysis techniques, simplified template cross section measurement.

- Work more closely with CP group to reduce the experimental uncertainties.

- New techniques for modelling uncertainties, more dedicated control regions/ data-driven methods.

- More dedicated filters at generator level.



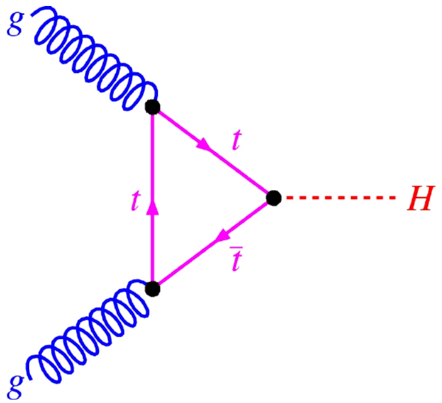
Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Thanks for your attention

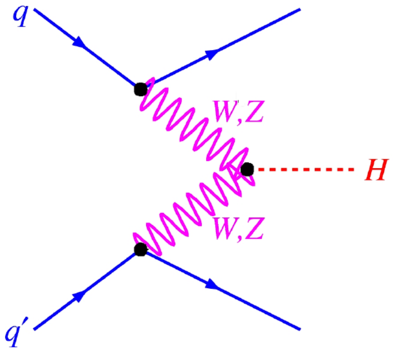
Back up

Higgs boson phenomenology at hadron colliders

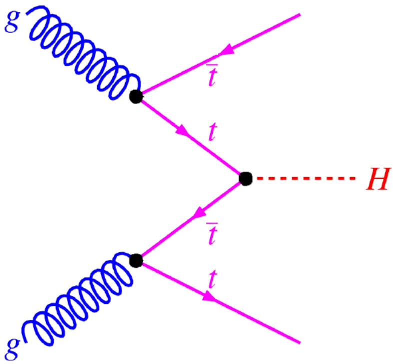
- 4 main production at the LHC, total cross section 56 pb at 13 TeV



Gluon fusion (ggF)
88% of the total



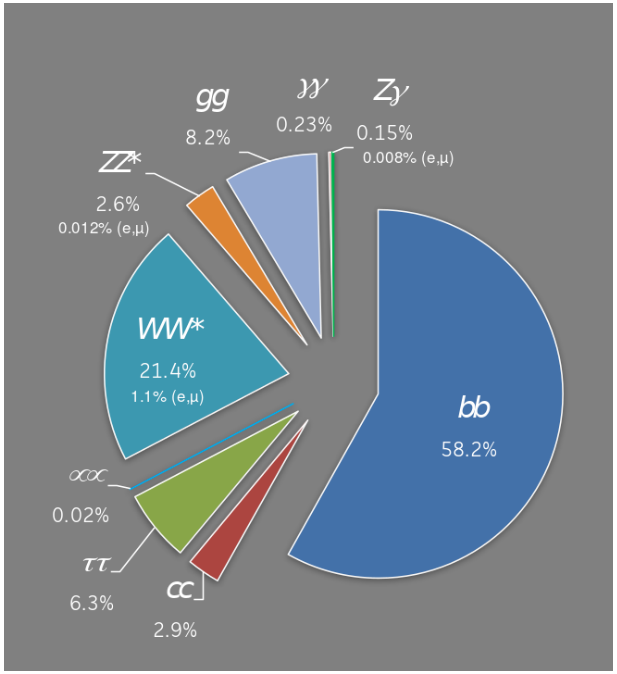
Vector boson fusion (VBF)
7% of the total



ttH
1% of the total

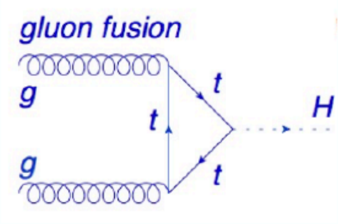
- Coupling to gg and gamma gamma through loops

- The more Higgs boson decays we see, the less "space" remains available for "undetected/invisible" decays



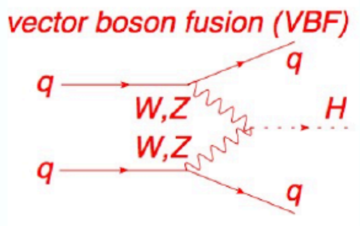
H→bb searches at the LHC

Production mode | **Primary signature**



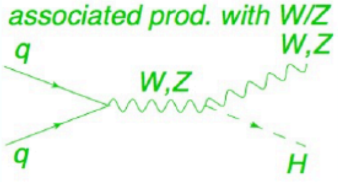
Just $H \rightarrow bb$

- Huge multi-jet background
- Triggering possible at high $p_T(H)$, but S/B expected to be ~ O(0.1%)
- Jet substructure analysis by CMS ($p_T(H)$>450 GeV)



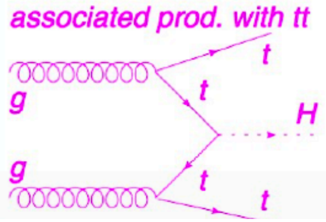
2 VBF jets (+ γ)

- Large multi-jet background
- Still a fully hadronic final state: trigger and background modeling is challenging
- Additional γ helps (~similar sensitivity, higher S/B)



W, Z

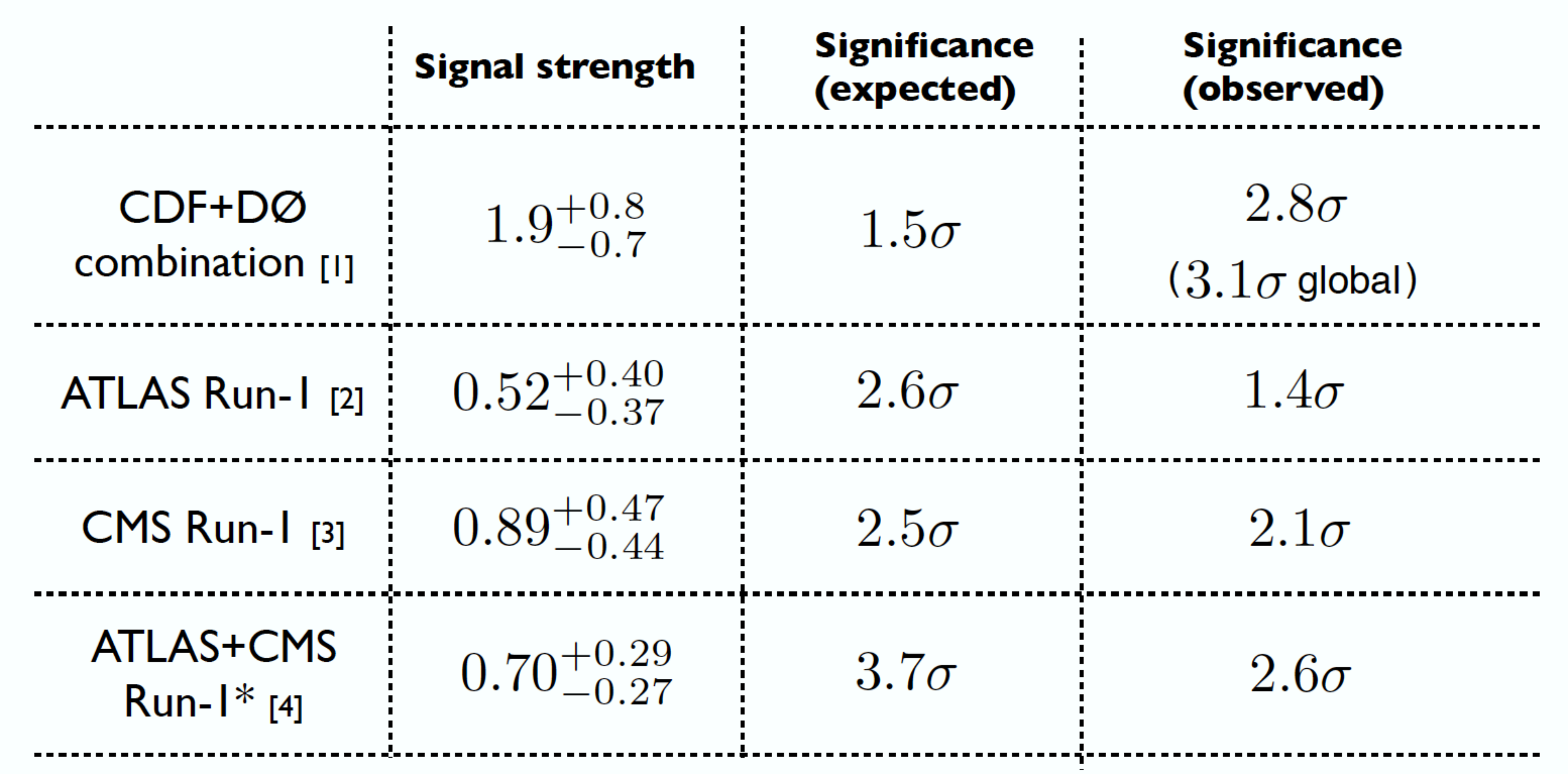
- Exploit leptonic signatures for trigger, and suppression of multi-jet background.
- *Main search channel for $H \rightarrow bb$ at the LHC!*



top+anti-top

- Leptonic signatures for trigger, but challenging due to combinatorics and tt+bb backgrounds
- But gives access also to top quark coupling!

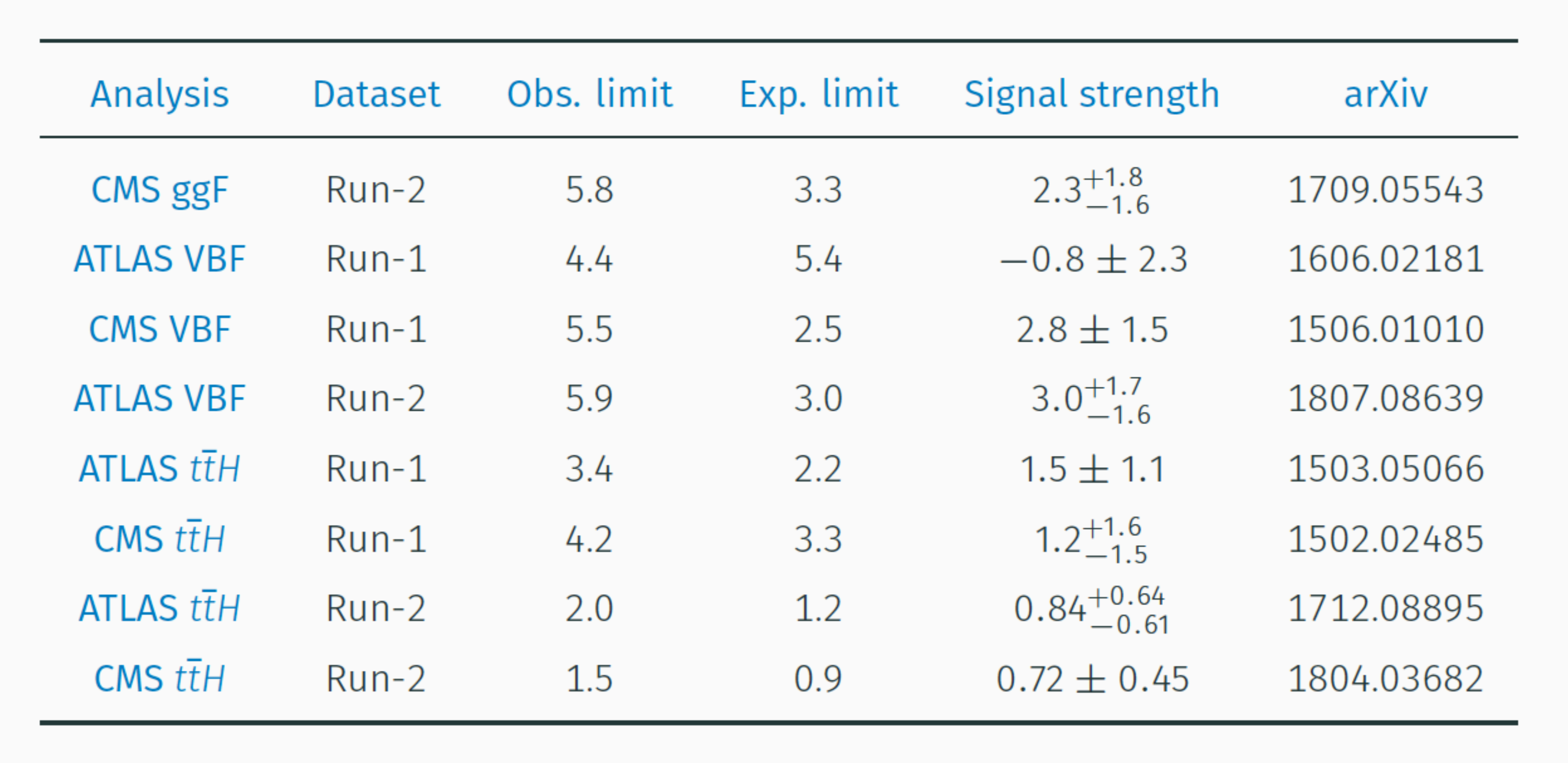
Previous results for VH, H→bb



	Signal strength	Significance (expected)	Significance (observed)
CDF+DØ combination [1]	$1.9^{+0.8}_{-0.7}$	1.5σ	2.8σ (3.1σ global)
ATLAS Run-I [2]	$0.52^{+0.40}_{-0.37}$	2.6σ	1.4σ
CMS Run-I [3]	$0.89^{+0.47}_{-0.44}$	2.5σ	2.1σ
ATLAS+CMS Run-I* [4]	$0.70^{+0.29}_{-0.27}$	3.7σ	2.6σ

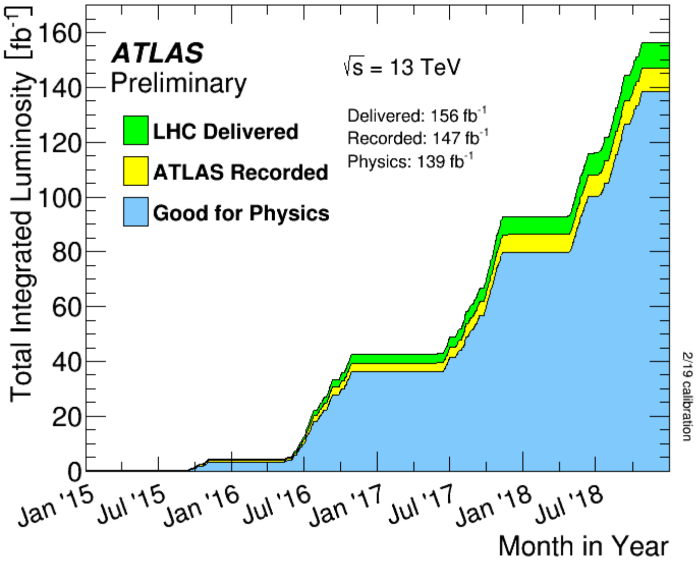
- With mH ~ 125 GeV

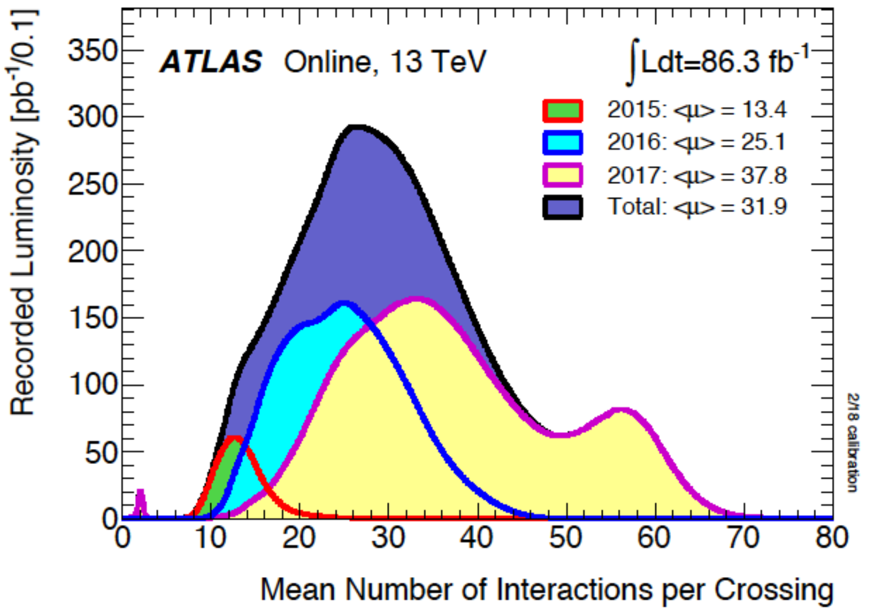
Other results for H→bb



Analysis	Dataset	Obs. limit	Exp. limit	Signal strength	arXiv
CMS ggF	Run-2	5.8	3.3	$2.3^{+1.8}_{-1.6}$	1709.05543
ATLAS VBF	Run-1	4.4	5.4	-0.8 ± 2.3	1606.02181
CMS VBF	Run-1	5.5	2.5	2.8 ± 1.5	1506.01010
ATLAS VBF	Run-2	5.9	3.0	$3.0^{+1.7}_{-1.6}$	1807.08639
ATLAS $t\bar{t}H$	Run-1	3.4	2.2	1.5 ± 1.1	1503.05066
CMS $t\bar{t}H$	Run-1	4.2	3.3	$1.2^{+1.6}_{-1.5}$	1502.02485
ATLAS $t\bar{t}H$	Run-2	2.0	1.2	$0.84^{+0.64}_{-0.61}$	1712.08895
CMS $t\bar{t}H$	Run-2	1.5	0.9	0.72 ± 0.45	1804.03682

LHC performance



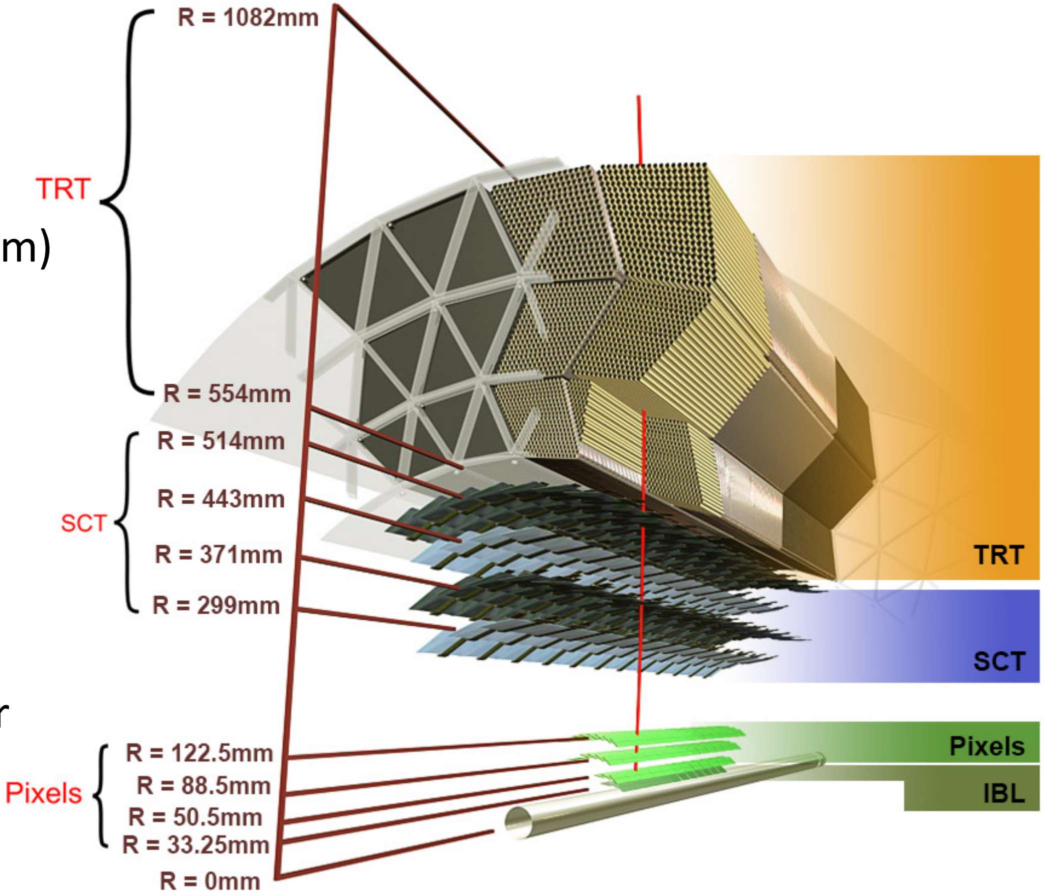


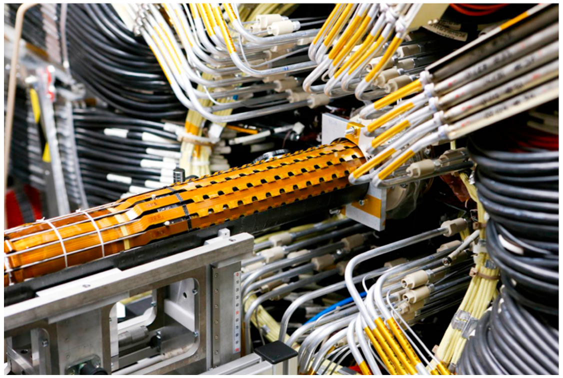
- Stunning performance of the LHC: lumi up to 2 $*10^{34}$ cm^{-2} s^{-1}
- Excellent operation of the ATLAS detector
- High rates and large pile-up: Challenges for triggers, jets reconstruction, b-tagging...

The ATLAS detector---ID and IBL

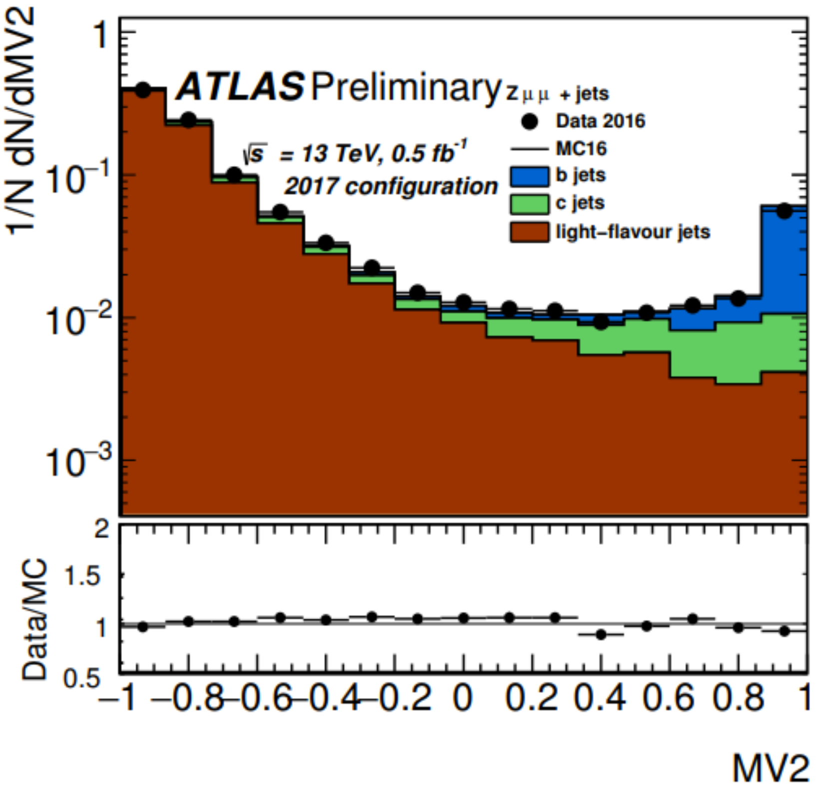
- IBL

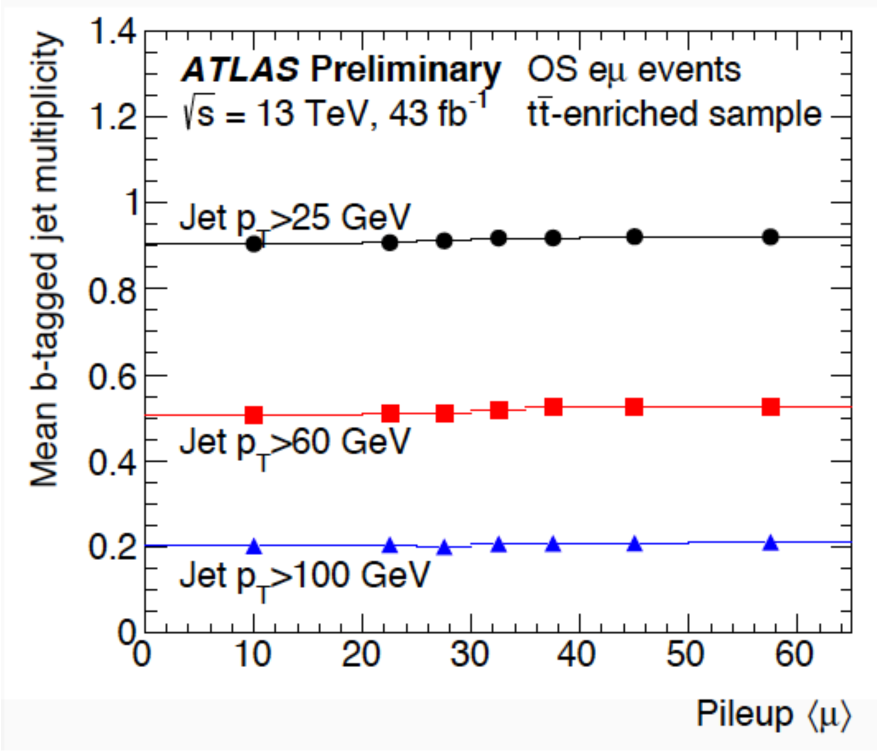
- Smaller pixel size (50x250 vs 50x400 µm)
- Closer to interaction region (R~3.3cm)
- H → bb primary physics motivation for the new detector!
- Improvement of 10% for the b-tagging algorithm performance in Run 2





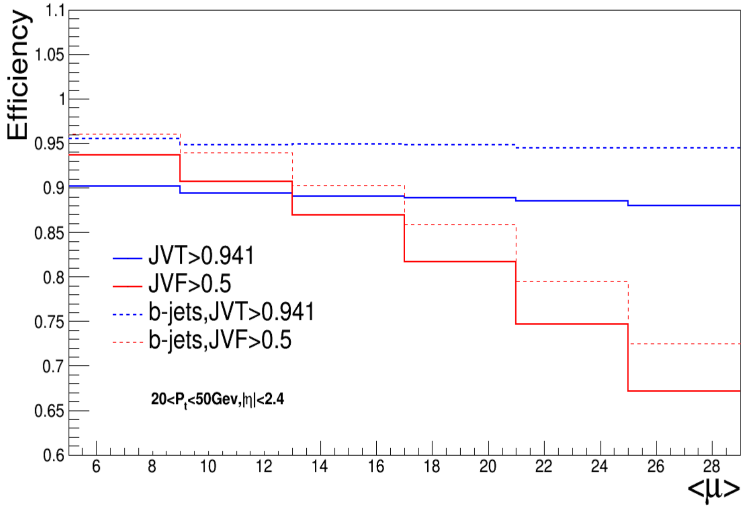
Object identification—b-tagging

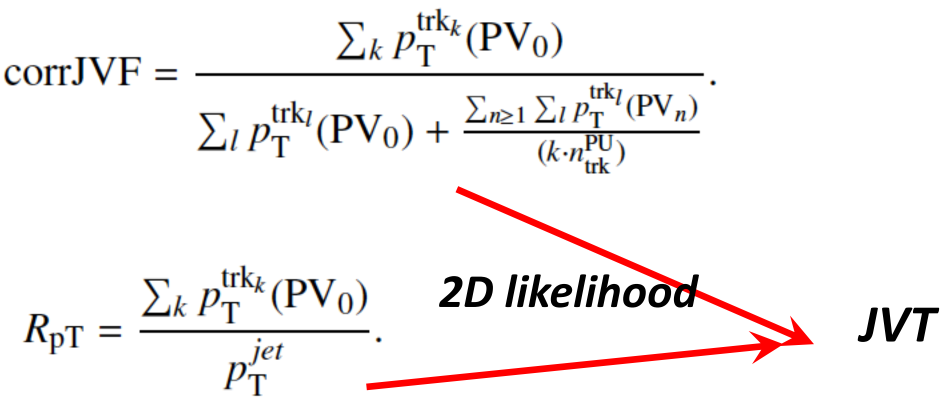




- Well modelled in simulation
- Good performance even at high pile-up

Object identification—b-tagging and JVT





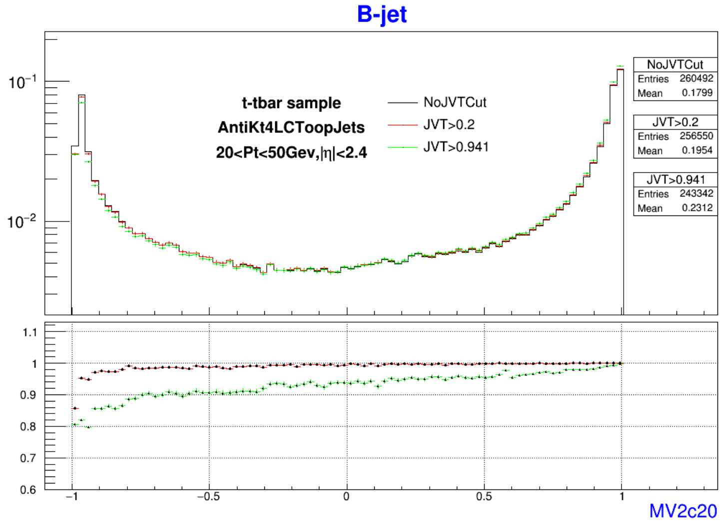
$$\mathrm{corrJVF} = \frac{\sum_k p_T^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_T^{\mathrm{trk}_l}(\mathrm{PV}_0) + \frac{\sum_{n\geq 1}\sum_l p_T^{\mathrm{trk}_l}(\mathrm{PV}_n)}{(k \cdot n_{\mathrm{trk}}^{\mathrm{PU}})}}.$$

$$R_{\mathrm{pT}} = \frac{\sum_k p_T^{\mathrm{trk}_k}(\mathrm{PV}_0)}{p_T^{jet}}.$$

2D likelihood

JVT

- ➢ New track-based pile up jets suppression variables are developed in such a way that the resulting hard-scatter jet efficiency is stable as a function of <μ>.

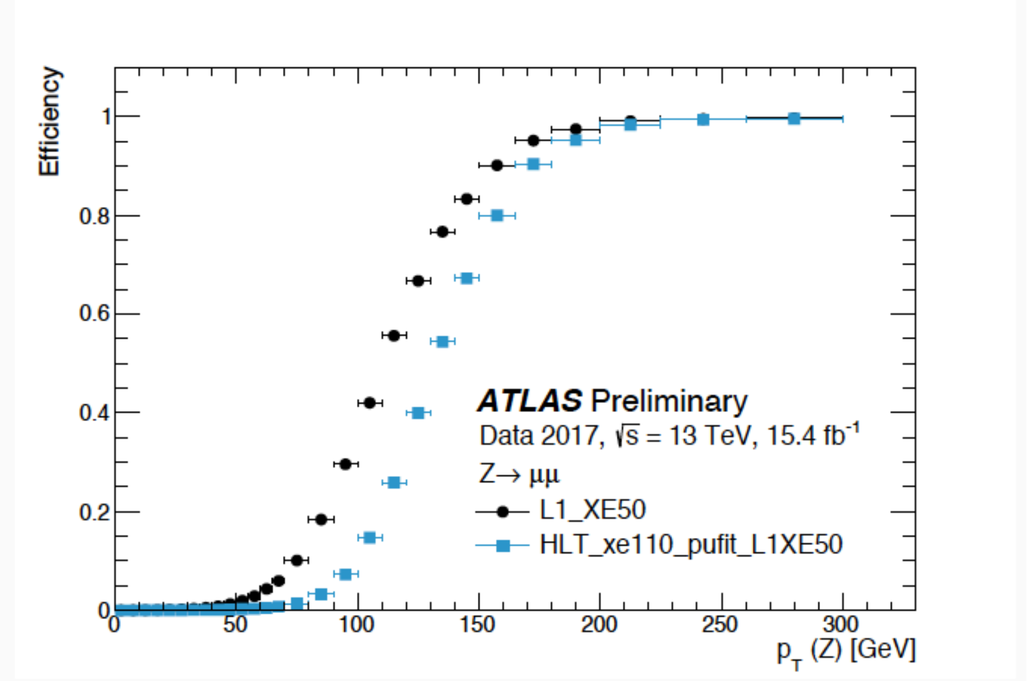


- ➢ The impact of JVT on the b-tagging output studied, in order to identify and study any JVT/b-tagging inefficiencies.

MET trigger

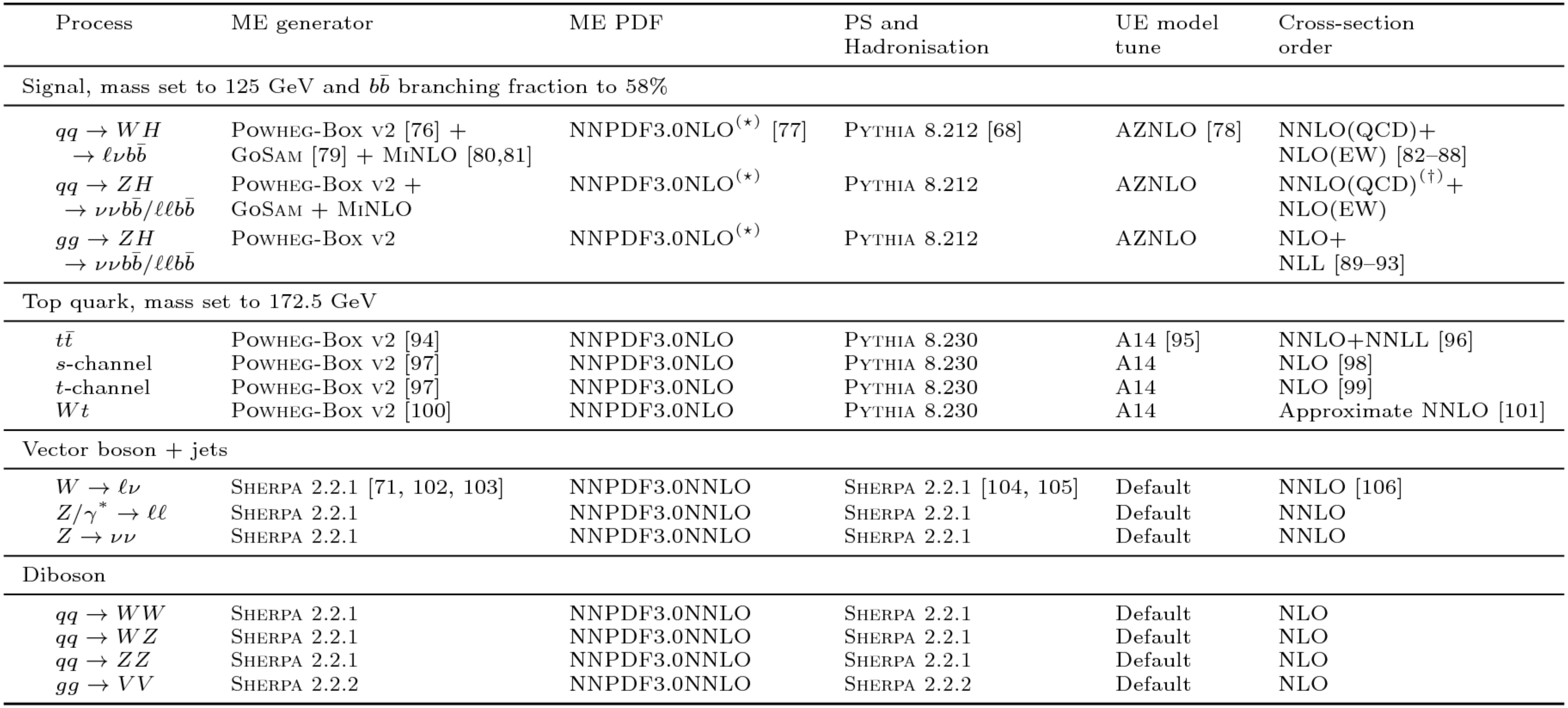
- Efficiency ~ 80% w.r.t. offline selection at MET > 150 GeV, > 95% at 200 GeV

- Efficiency measurement in Z, W and ttbar events



- The MET trigger can also be used to select events with W→mu nu cays
  - Muons are not part of the computation of MET at trigger level
  - More efficiency than single muon trigger at pTW > 150 GeV

Signal and Backgrounds Samples

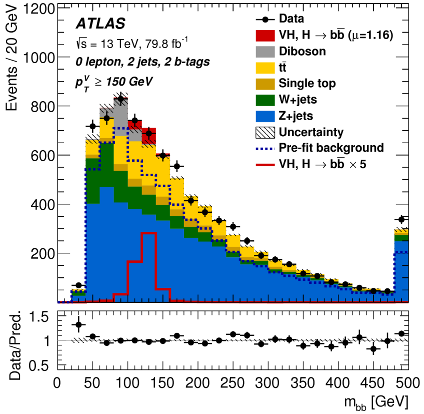


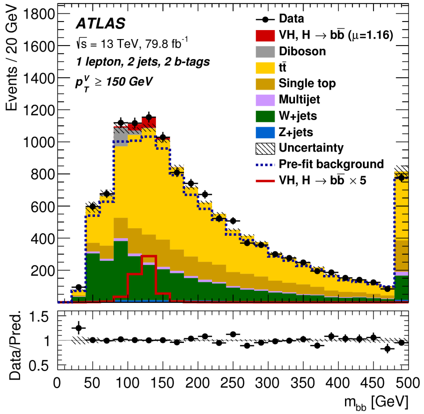
Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+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

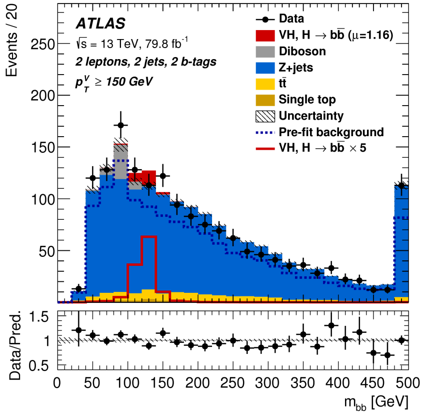
Signal and Backgrounds Samples

- **Signal**
  - Both qqVH and ggZH using latest Powheg+MiNLO + Pythia8 samples
- **Background**
  - V (W/Z)+jets : Sherpa 2.2.1 with jet flavor filter
  - Dibson : Sherpa 2.2.1 for quark induced samples (qqVV). After EPS, include also gluon induced (ggVV) samples with Sherpa 2.2.2
  - ttbar : Powheg+Pythia8, 2-lepton also incorporates di-lepton filtered sample. Dedicated MET filter ttbar samples also used in 0 lepton
  - Single-top : updated to Powheg+Pythia8 samples since EPS
  - Multijet

    Negligible in 0 and 2 lepton (confirmed by lots of detailed studies), data-driven in 1 lepton channel (fraction: ~2-3%)



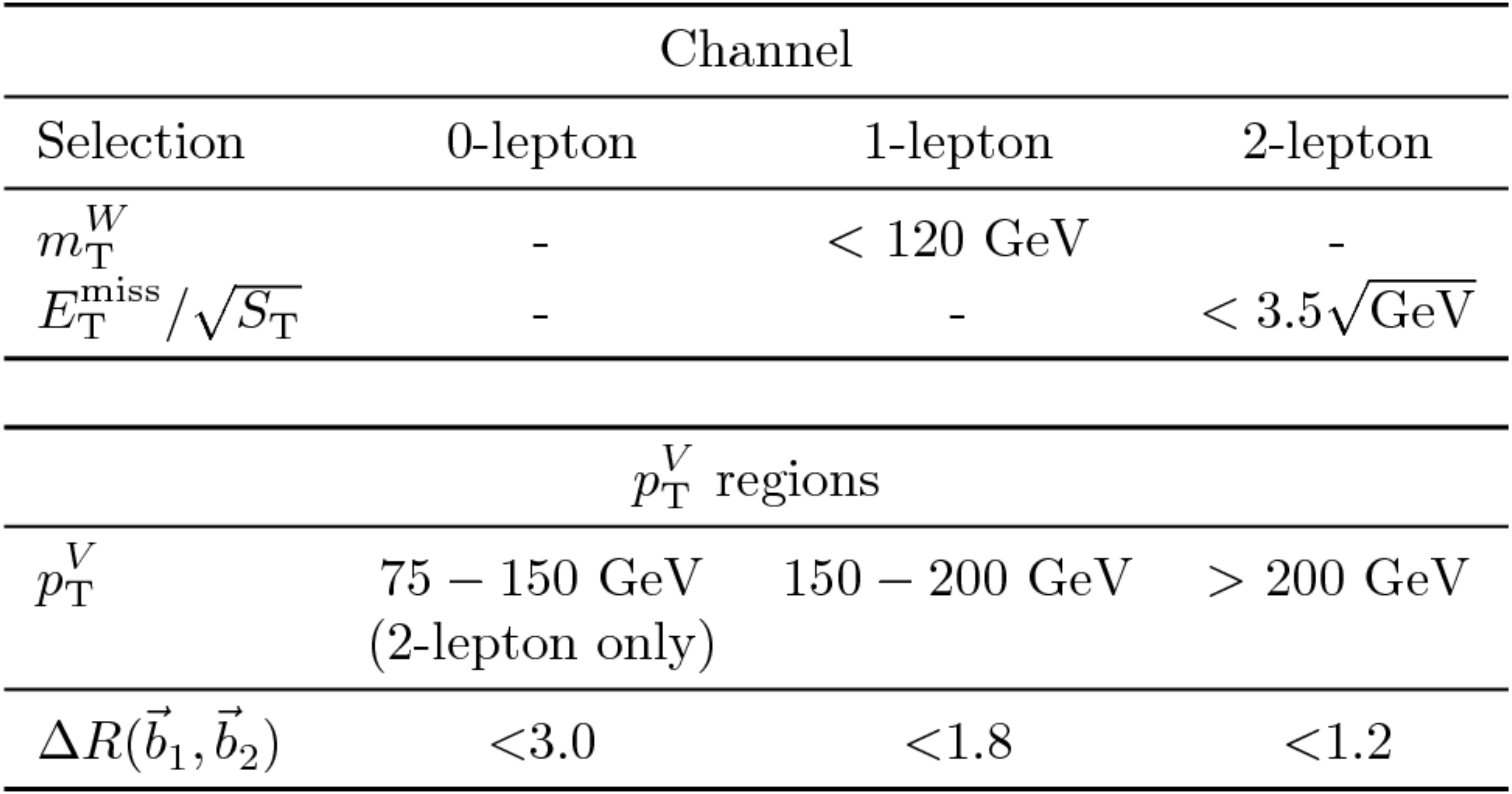




Event selections

Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–		–
p_{T}^{V} regions	> 150 GeV			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, $>$ 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

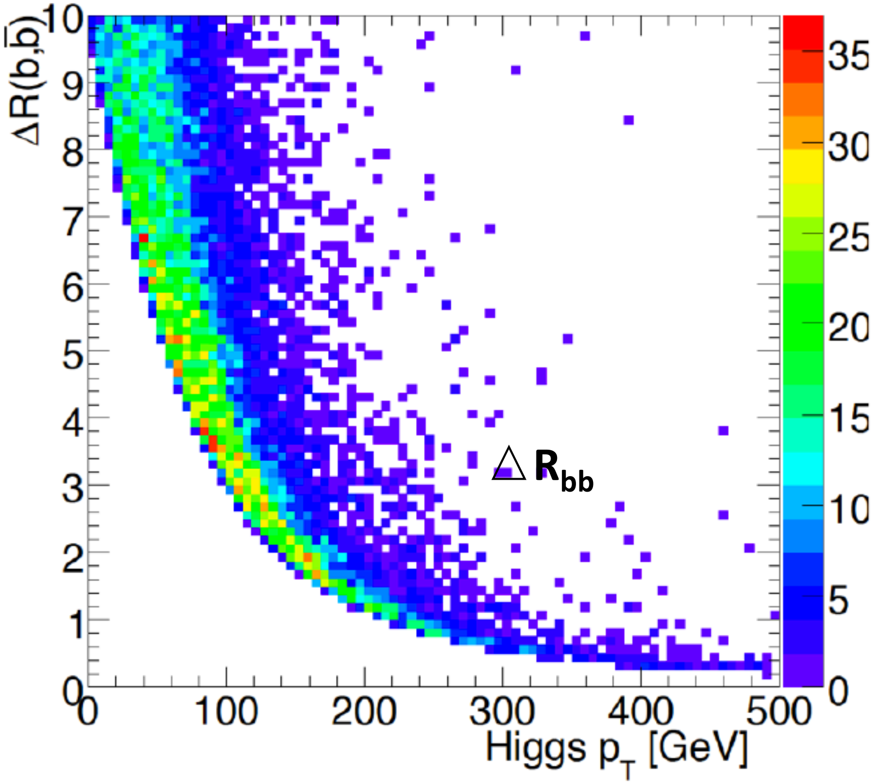
Additional cuts for di-jet mass analysis



	Channel		
Selection	0-lepton	1-lepton	2-lepton
m_{T}^{W}	-	< 120 GeV	-
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$	-	-	$< 3.5\sqrt{\mathrm{GeV}}$

	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

△R_{bb}

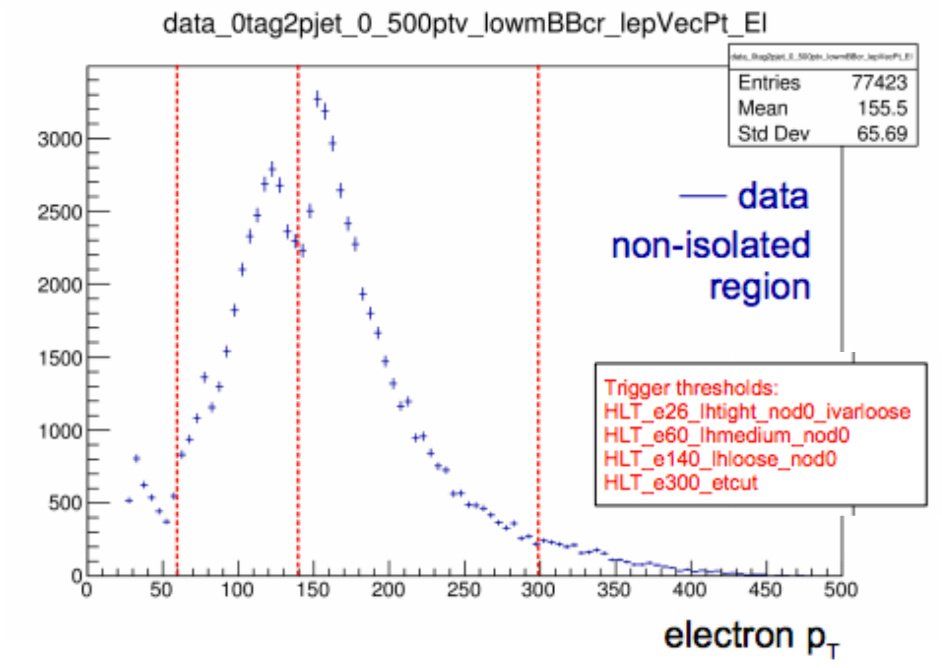


$$\Delta R(b,\bar{b}) \approx \frac{2m_H}{p_T^H},$$

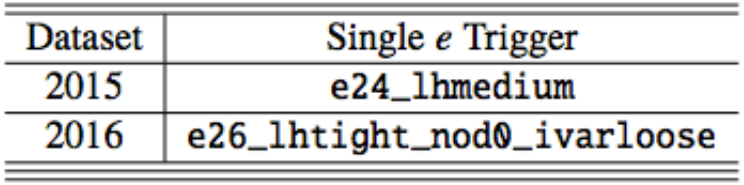
Figure 5.3: Distance in ΔR between the two b-quarks from the Higgs boson decay as a function of Higgs boson transverse momentum.

MJ estimation – Systematics Uncertainties---some details

- Trigger Bias



- Instead of using the combination of triggers, simply the lowest pT trigger is used to probe the potential trigger bias



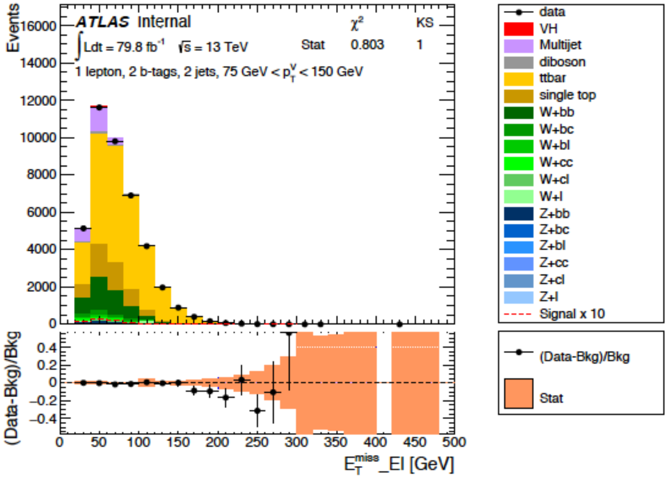
Dataset	Single *e* Trigger
2015	`e24_lhmedium`
2016	`e26_lhtight_nod0_ivarloose`

- Tighter isolation requirements

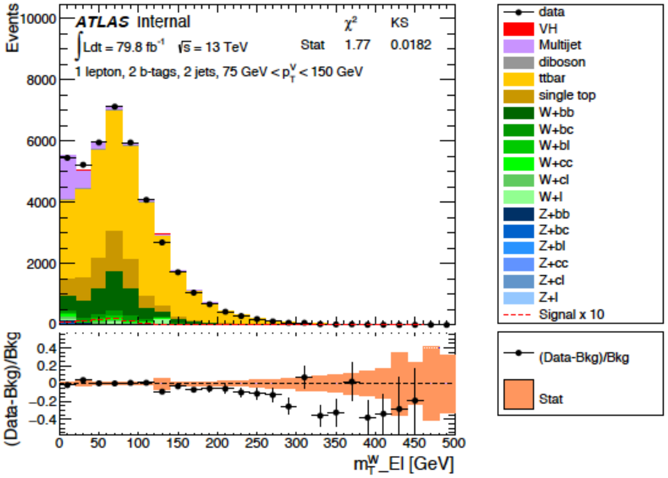
- Additional isolation cuts applied to the inverted isolation region :
  topoetcone20 < 11 GeV for electron and ptcone20 < 2.25 GeV for muon

- The additional cuts are optimized for keeping about half of data events in the full inverted regions : closer to the signal region, smaller extrapolation uncertainty

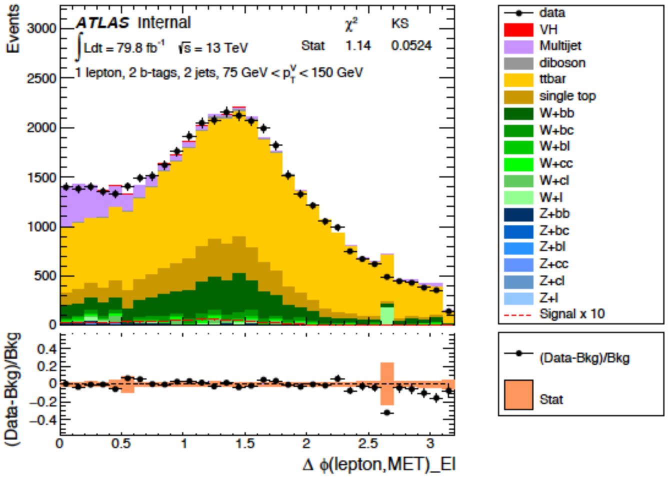
MJ estimation – post fit plots



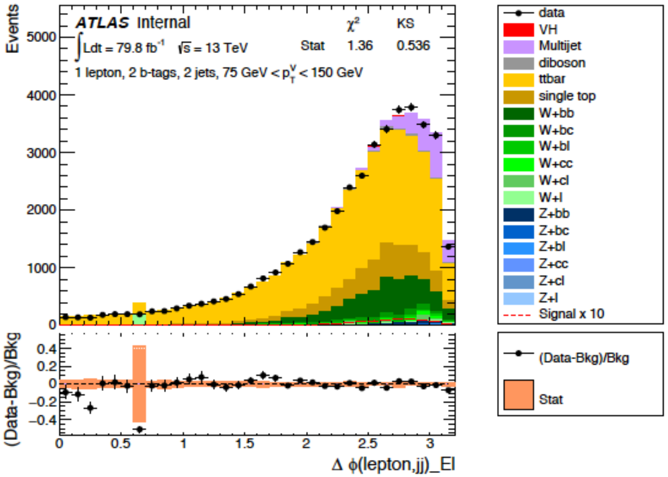
(a)



(b)



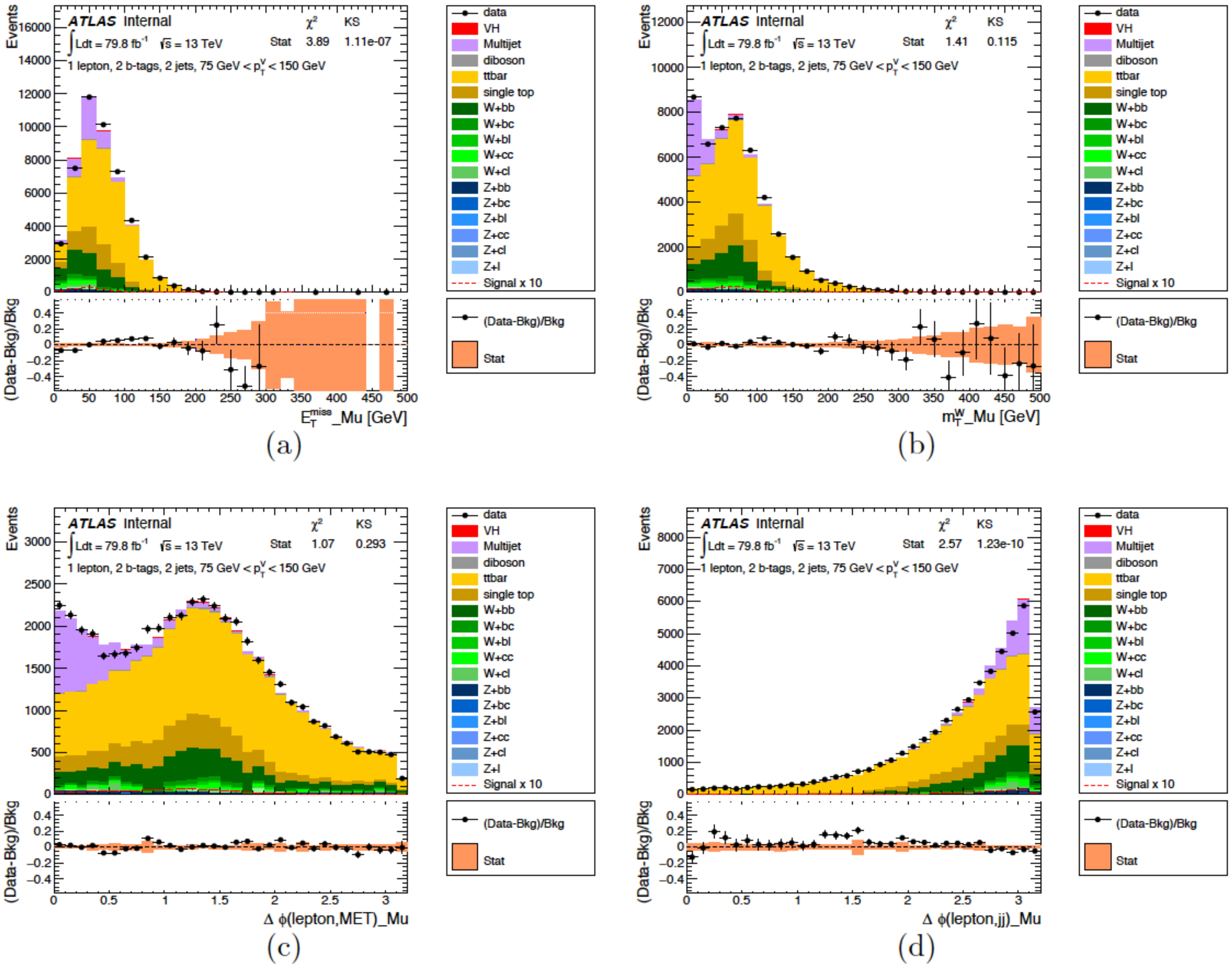
(c)



(d)

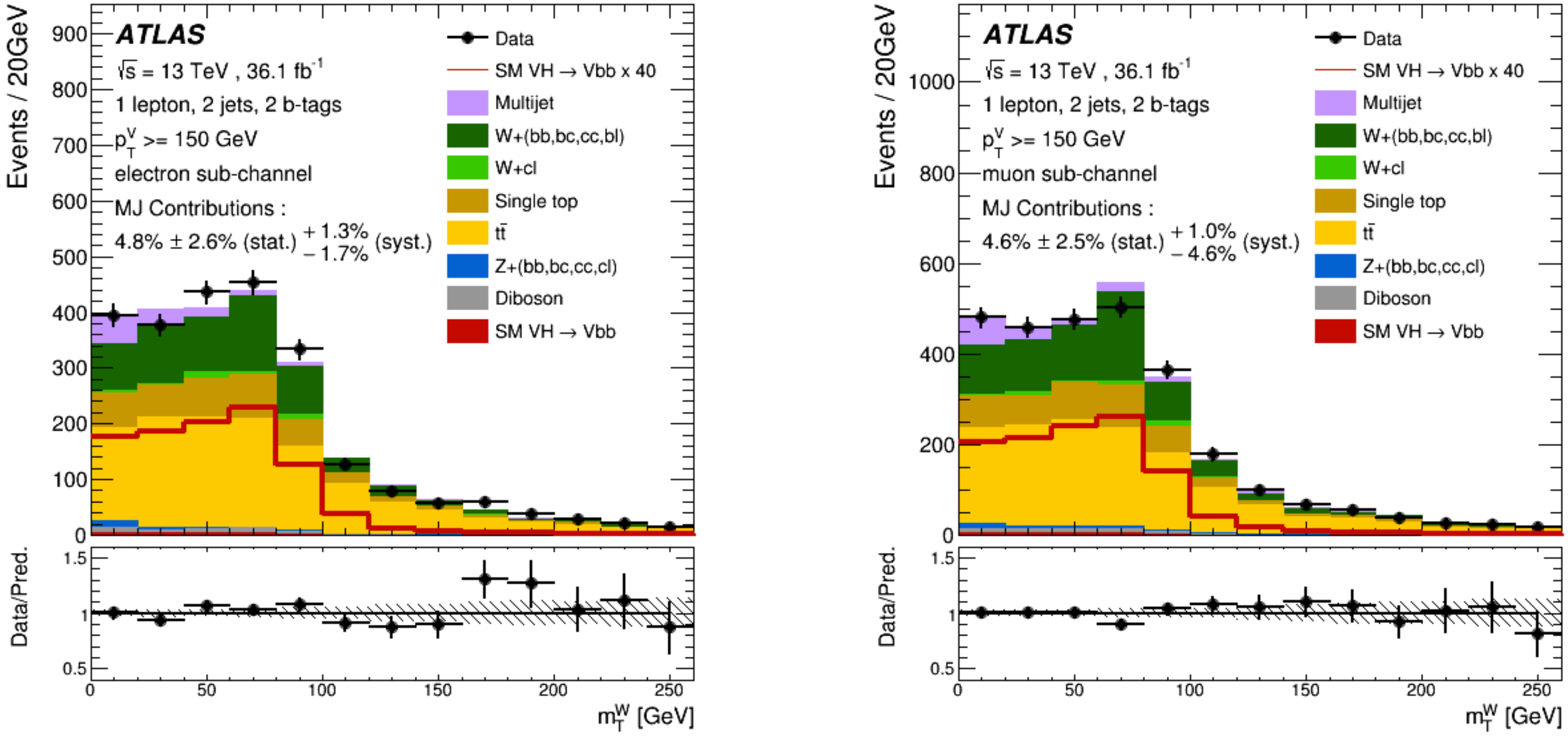
- Post fit plots in medium pTV region without m_T^W > 20 GeV cut applied

MJ estimation – post fit plots



- Post fit plots in medium pTV region without $m_T^W > 20$ GeV cut applied

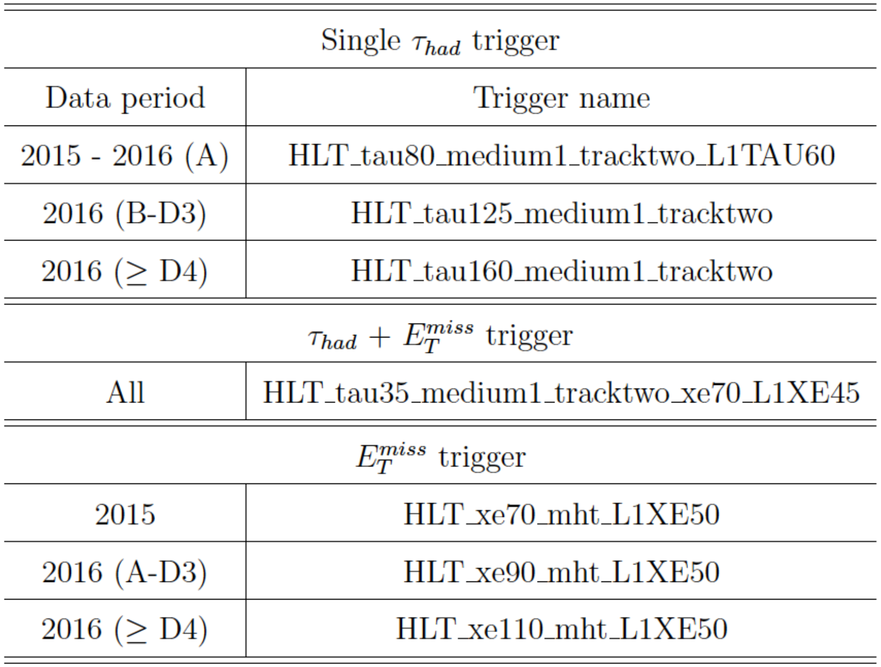
MJ estimation – evidence paper results



- The multi-jet contribution in the 2-jet region is found to be 4.8% (4.6%) of the total background contribution in the electron (muon) sub-channel, while in the 3-jet region it is found to be 0.3% (0.5%), with normalization uncertainties from 0.3% to 4.6%

W(tau nu)H investigation

- Test if a channel explicitly selecting hadronic tau decays could bring additional sensitivity for this analysis.
  - For the tau leptonic decays, current 1 lepton channel can cover the signal events.
  - For the tau hadronic decays, current 0 lepton channel has some sensitivity (No tau-veto, ~ 20% expected signal events are W(tau nu) H).



Single τ_{had} trigger	
Data period	Trigger name
2015 - 2016 (A)	HLT_tau80_medium1_tracktwo_L1TAU60
2016 (B-D3)	HLT_tau125_medium1_tracktwo
2016 ($\geq$ D4)	HLT_tau160_medium1_tracktwo
$\tau_{had} + E_T^{miss}$ trigger	
All	HLT_tau35_medium1_tracktwo_xe70_L1XE45
E_T^{miss} trigger	
2015	HLT_xe70_mht_L1XE50
2016 (A-D3)	HLT_xe90_mht_L1XE50
2016 ($\geq$ D4)	HLT_xe110_mht_L1XE50

Summary of the possible triggers can be used for the tau had selection

- Only 5.28 WH signal events can be recovered, compared to the default WH signal yield (122.92), the gain of signal yield is 4%
- Additional selections need to be considered apart from the trigger, which will reduce the gain further
- Not worth complicating the analysis

1-lepton channel trigger studies

- summarize the choices/considerations we had on the choice of triggers in 2015+2016 analysis in 1 lepton channel.
  - Single electron trigger used in the one electron sub-channel
    - Test the signal loss with the raised offline lepton pt cut due to the raise of single lepton trigger threshold
  - MET trigger used in the one muon sub-channel
    - Muons are not part of the computation of MET at trigger level, the W→μnu signature becomes analogous to Z→nunu
    - Only high pTV region(pTV > 150GeV) were considered in 2015+2016 analysis, MET trigger has very high efficiency in such region
    - Single muon trigger also tested

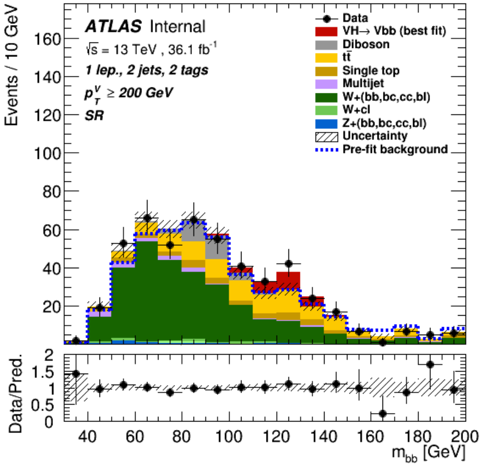
1-lepton channel trigger studies

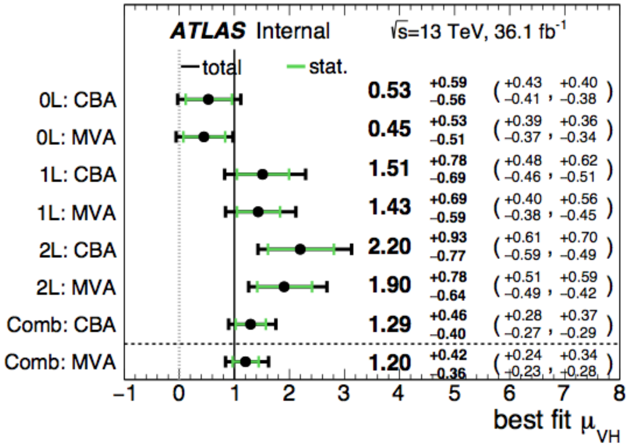
Signal Sample Muon Channel	**Yields**			
	No Trigger	MET trigger	Muon trigger	MET or Muon Trigger
2tag2jet	33.10	32.13	25.05	32.86
Efficiency(%)		97.1	75.7	99.3
2tag3jet	37.63	35.90	27.64	37.11
Efficiency(%)		95.4	73.5	98.6

- Added all other requirements except trigger selection.
- In No Trigger case , MET trigger SF added when event pass the MET trigger, inefficiency SF added when events fail the MET trigger.
- In MET or Muon Trigger case , first try the MET trigger ,if false then add the inefficiency SF and go through the muon trigger.
- In High pTV region , MET trigger efficiency is higher than muon trigger.
- Adding the muon trigger , we have a 2.2%(3.4%) efficiency increase in 2tag2jet(3jet) region, compared with MET trigger only.

Dijet-mass analysis optimization

Channel CBA Vs. MVA	Exp. significance (Asimov)	Exp. Significance (data)	Obs. Significance
1-lepton (SR + CR)	1.43(1.81)	1.49(1.81)	2.02(2.30)
0,1,2-lepton (SR + CR)	2.78(3.19)	2.78(3.03)	3.51(3.54)



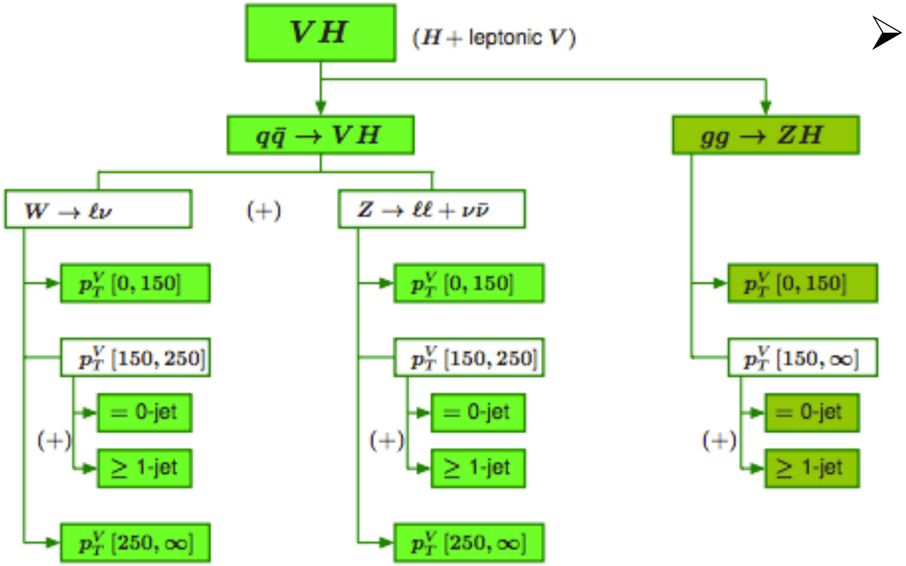


- ➢ Very nice mass peak in cut based analysis
- ➢ Compatible mu values for the individual fit and combined fits

- ➢ Sensitivity typically 10-15% lower than MVA in Asimov fit, less in data
- ➢ We may need to pay more attention to CBA when moving towards measurements
- ➢ Before going too far with the hybrid cutbased-MVA approach, good to see if there is still space for optimization with current cut-based selections (never had a real re-examination of these cuts before)

Dijet-mass analysis optimization

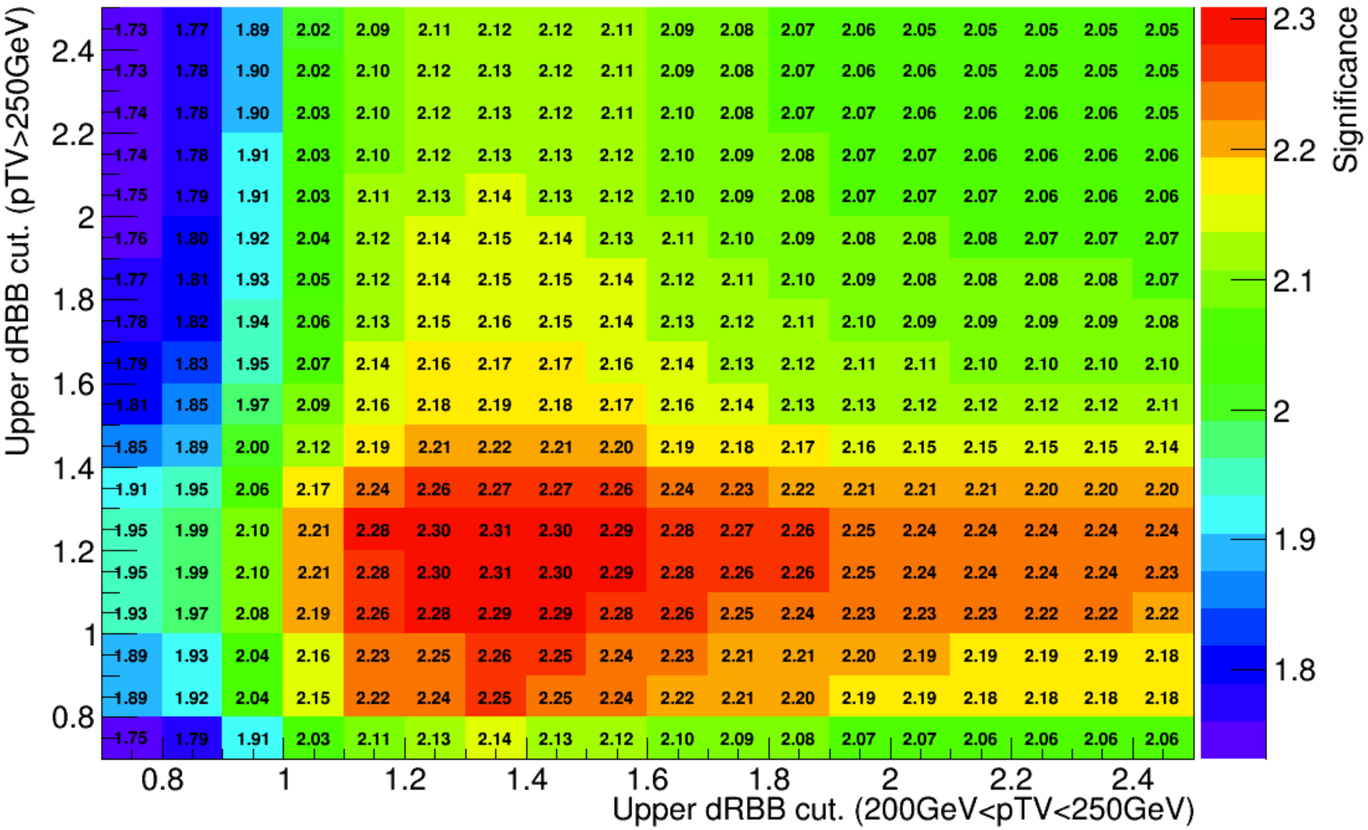
- ➢ Consider a new split at 250 GeV in view of the simplified template cross section
  - Split the pTV >200GeV region into two regions: 200_250 and >250GeV
  - Or consider two regions split at 250GeV : 150_250 and >250GeV
  - Also tried split also at 300GeV : 150_250; 250_300; 300GeV_



- ➢ After many different studies, new split at only 250GeV proposed (150_200; 200_250; 250GeV_)
  - Avoid pTV bin (pTV>300GeV) with very large statistical fluctuation
  - 150_250GeV pTV bin maybe too large
  - Minimum change wrt the default one, only add a additional split at 250GeV

Dijet-mass analysis optimization

2D plot for 200_250 and >250GeV regions



1.73	1.77	1.89	2.02	2.09	2.11	2.12	2.12	2.11	2.09	2.08	2.07	2.06	2.05	2.05	2.05	2.05	2.05
1.73	1.78	1.90	2.02	2.10	2.12	2.13	2.12	2.11	2.09	2.08	2.07	2.06	2.06	2.05	2.05	2.05	2.05
1.74	1.78	1.90	2.03	2.10	2.12	2.13	2.12	2.11	2.10	2.08	2.07	2.07	2.06	2.06	2.06	2.06	2.05
1.74	1.78	1.91	2.03	2.10	2.12	2.13	2.13	2.12	2.10	2.09	2.08	2.07	2.07	2.06	2.06	2.06	2.06
1.75	1.79	1.91	2.03	2.11	2.13	2.14	2.13	2.12	2.10	2.09	2.08	2.07	2.07	2.07	2.06	2.06	2.06
1.76	1.80	1.92	2.04	2.12	2.14	2.15	2.14	2.13	2.11	2.10	2.09	2.08	2.08	2.08	2.07	2.07	2.07
1.77	1.81	1.93	2.05	2.12	2.14	2.15	2.15	2.14	2.12	2.11	2.10	2.09	2.08	2.08	2.08	2.08	2.07
1.78	1.82	1.94	2.06	2.13	2.15	2.16	2.15	2.14	2.13	2.12	2.11	2.10	2.09	2.09	2.09	2.09	2.08
1.79	1.83	1.95	2.07	2.14	2.16	2.17	2.17	2.16	2.14	2.13	2.12	2.11	2.11	2.10	2.10	2.10	2.10
1.81	1.85	1.97	2.09	2.16	2.18	2.19	2.18	2.17	2.16	2.14	2.13	2.13	2.12	2.12	2.12	2.12	2.11
1.85	1.89	2.00	2.12	2.19	2.21	2.22	2.21	2.20	2.19	2.18	2.17	2.16	2.15	2.15	2.15	2.15	2.14
1.91	1.95	2.06	2.17	2.24	2.26	2.27	2.27	2.26	2.24	2.23	2.22	2.21	2.21	2.21	2.20	2.20	2.20
1.95	1.99	2.10	2.21	2.28	2.30	2.31	2.30	2.29	2.28	2.27	2.26	2.25	2.24	2.24	2.24	2.24	2.24
1.95	1.99	2.10	2.21	2.28	2.30	2.31	2.30	2.29	2.28	2.26	2.26	2.25	2.24	2.24	2.24	2.24	2.23
1.93	1.97	2.08	2.19	2.26	2.28	2.29	2.29	2.28	2.26	2.25	2.24	2.23	2.23	2.23	2.22	2.22	2.22
1.89	1.93	2.04	2.16	2.23	2.25	2.26	2.25	2.24	2.23	2.21	2.21	2.20	2.19	2.19	2.19	2.19	2.18
1.89	1.92	2.04	2.15	2.22	2.24	2.25	2.25	2.24	2.22	2.21	2.20	2.19	2.19	2.18	2.18	2.18	2.18
1.75	1.79	1.91	2.03	2.11	2.13	2.14	2.13	2.12	2.10	2.09	2.08	2.07	2.07	2.06	2.06	2.06	2.06

- For dRBB cuts scan and stats. only significance calculation, different dRBB cuts proposed in different pTV region :

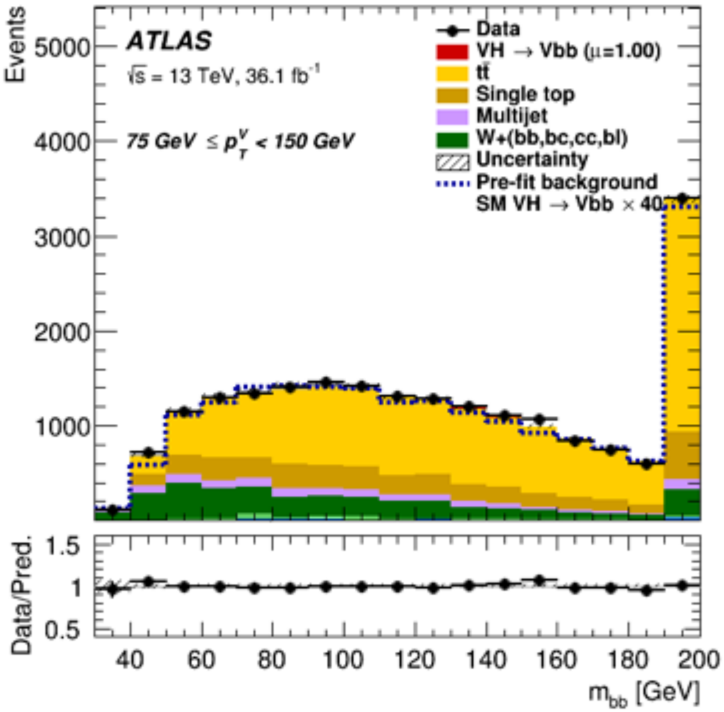
dRBB < 1.7 (150_200GeV); dRBB < 1.4 (200_250GeV); dRBB < 1.2 (250GeV_)

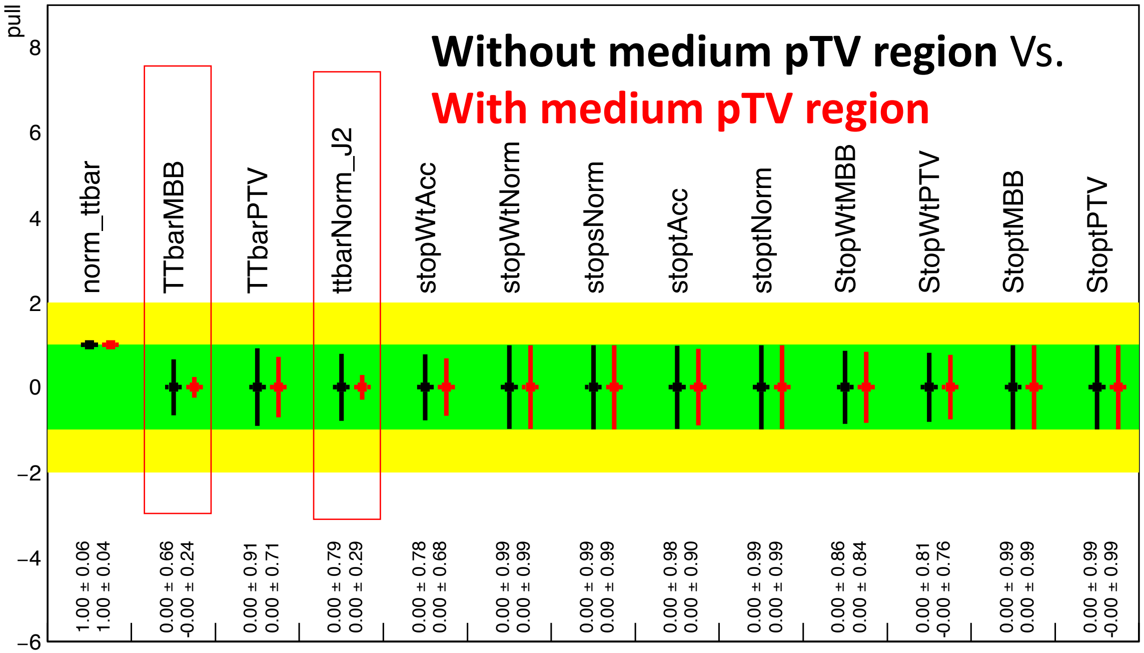
Dijet-mass analysis optimization

	Default (V1)	**New_Set2 (V2)**	**NewSet2_WithMediumpTV Region (V3)**
pTV Categories (GeV)	150_200;200	150_200;200_250;250_	V2 + 75_150
mTW cuts (GeV)	mTW<120GeV	mTW<120GeV	V2 + mTW>20GeV
dRBB cuts	1.8;1.2	1.7;1.4;1.2	V2 + 0.8 < dRBB < 3.0
Exp Significance (asimov)	1.61	1.69 (+5.0%)	1.81 (+7.1%) (+12.4%)

- Comparing V2 (new cuts, new split in high pTV region) to V1, the Exp. Significance is increased ~5%
- Also tried to add medium pTV region in the analysis (preliminary study shows the multijet background can be controlled well in the region)
- Comparing V3 (medium pTV region added) to V2, the Exp. Significance is increased ~7%

Dijet-mass analysis optimization

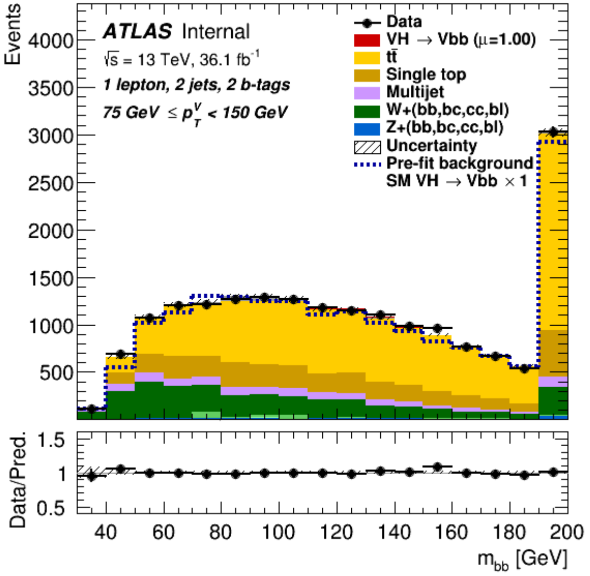


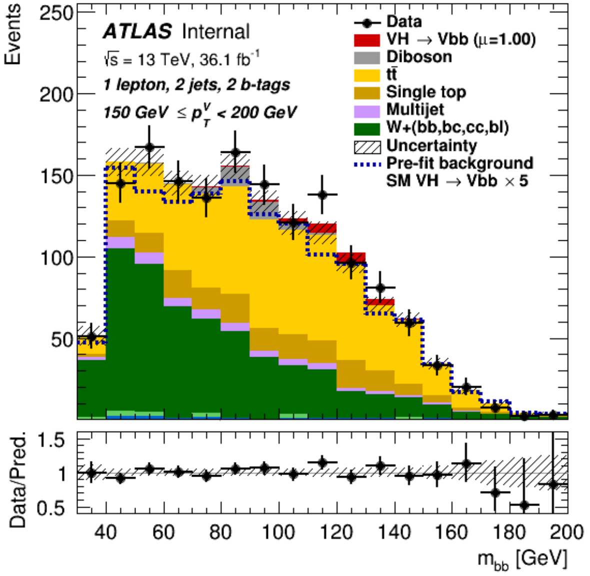


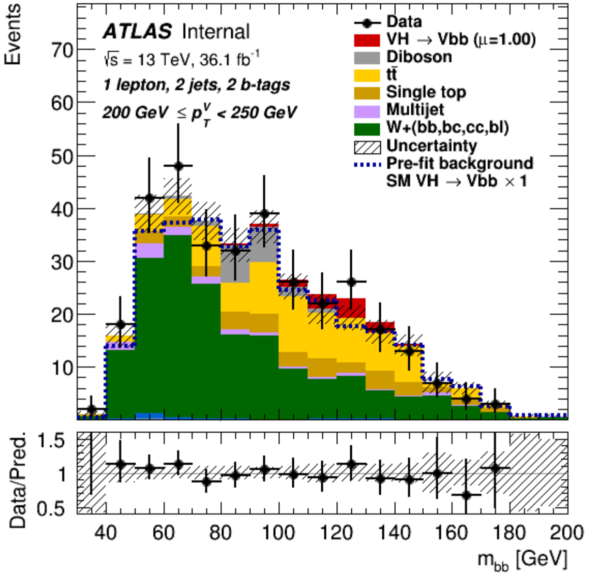
- ➢ High statistics medium pTV region dominated by the top background, high constraints will be propagated to the high pTV regions

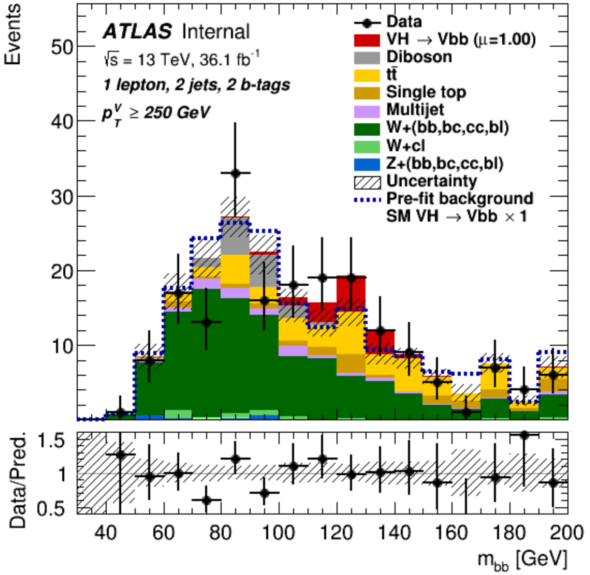
- ➢ Can be alleviated by decorrelations (see this talk page 8)

Dijet-mass analysis optimization



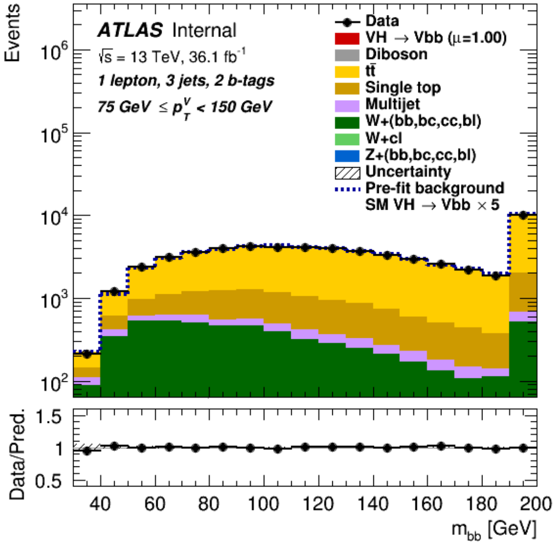


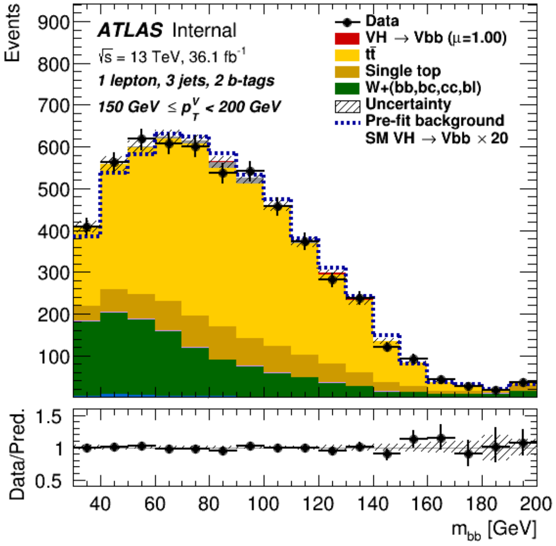


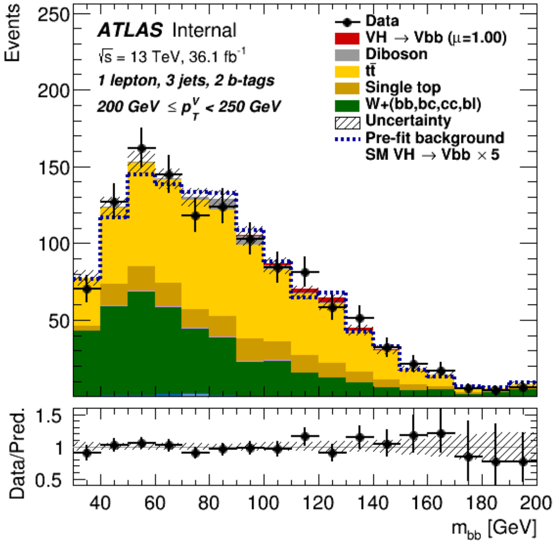


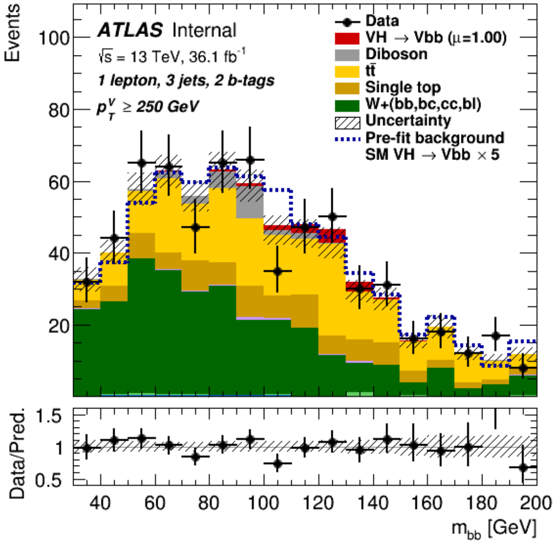
- Good agreement for the postfit data/MC comparison

Dijet-mass analysis optimization









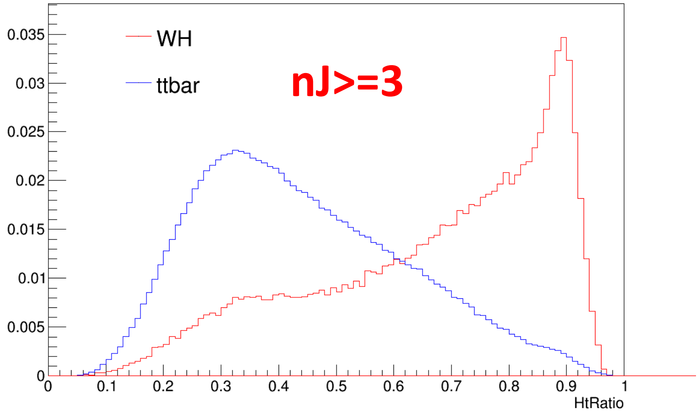
- Good agreement for the postfit data/MC comparison

ttbar reduction cut study

- Default 1 lepton analysis remove events which have more than 3 jets in order to reduce the large background arising from ttbar production.

- Try to find a discriminating variable to cut on in instead of removing such events directly.

- HtRatio (Ht(two b jets) / Ht(all jets)) could be a discriminating variable for signal and ttbar events.

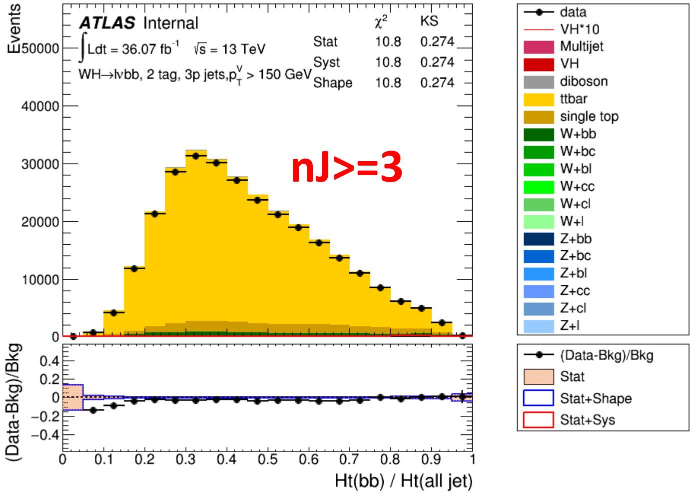


- Scan the HtRatio distribution to find the cut value yields the best sensitivity (Stat. only, calculated with mBB distribution).

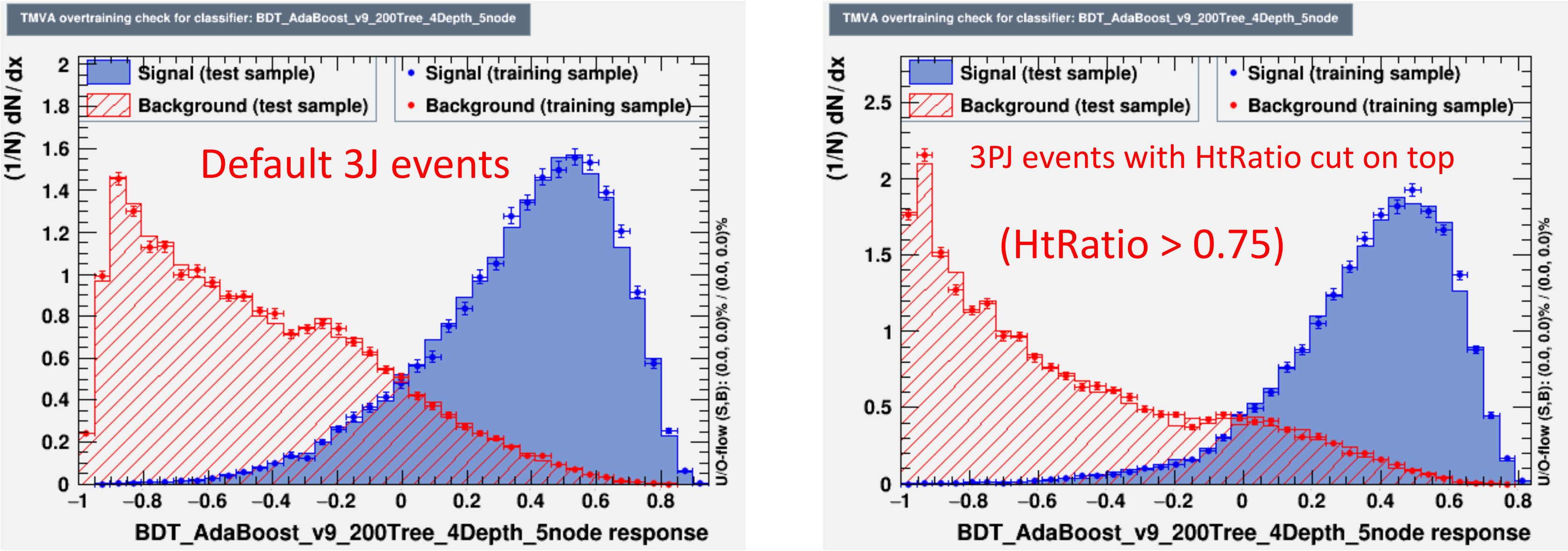
$$S = \sqrt{\sum_{i=1}^{n}(2 \times ((s_i + b_i) \times ln(1 + s_i/b_i) - s_i))},$$

- Retrain the BDT in the nJ>=3 region with the HtRatio cut on top.

- Recalculate the sensitivity with BDT distribution.



ttbar reduction cut study



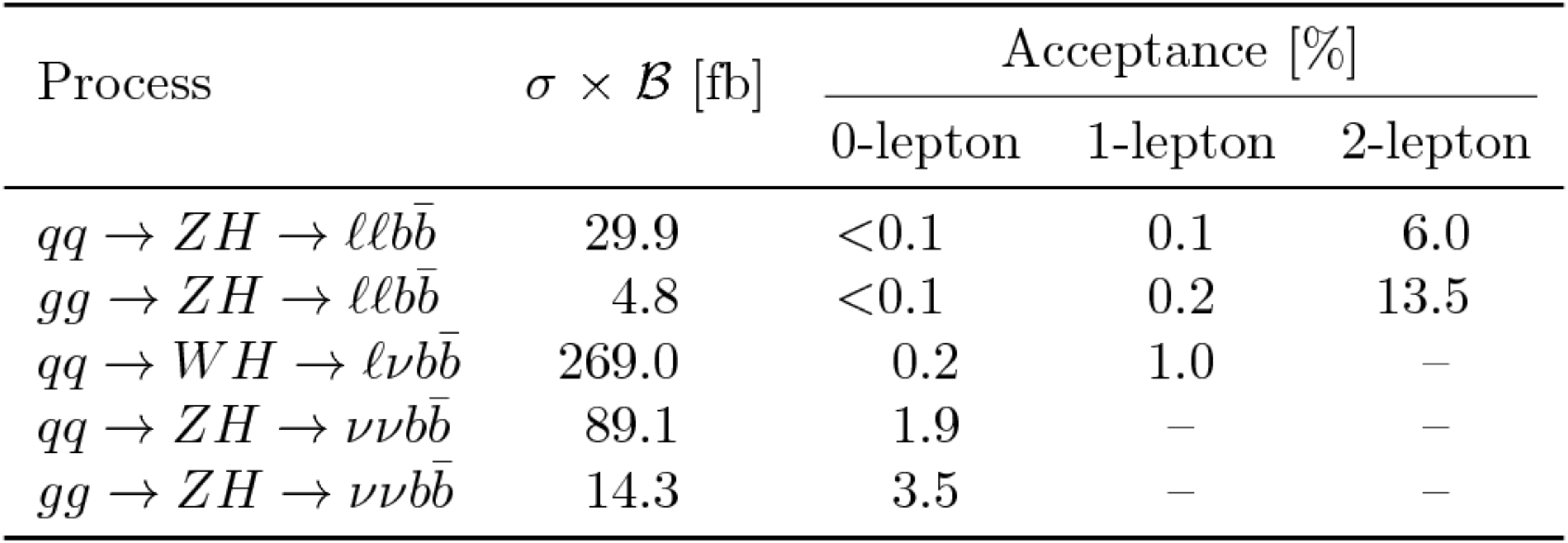
- ➢ Clear better signal and background separation.

- ➢ 9% sensitivity improvement can be achieved by using the HtRatio cut in the 3+-Jet region.

Region	WH signal events	ttbar events	Sensitivity (S)
2-tag 3-jet (Baseline)	58.35	22095.3	1.65
2-tag 3+-jet (No HtRatio cut)	129.44	259073	1.21
2-tag 3+-jet (HtRatio > 0.75)	58.25	16838.75	1.79

- ➢ The main analysis sensitivity comes from the 2Jet region, the overall improvement when considering also the 2Jet region is only 2%→not adopted.

Signal acceptance



Process	$\sigma \times \mathcal{B}$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	<0.1	0.1	6.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	<0.1	0.2	13.5
$qq \to WH \to \ell\nu b\bar{b}$	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	–	–

Background Modelling

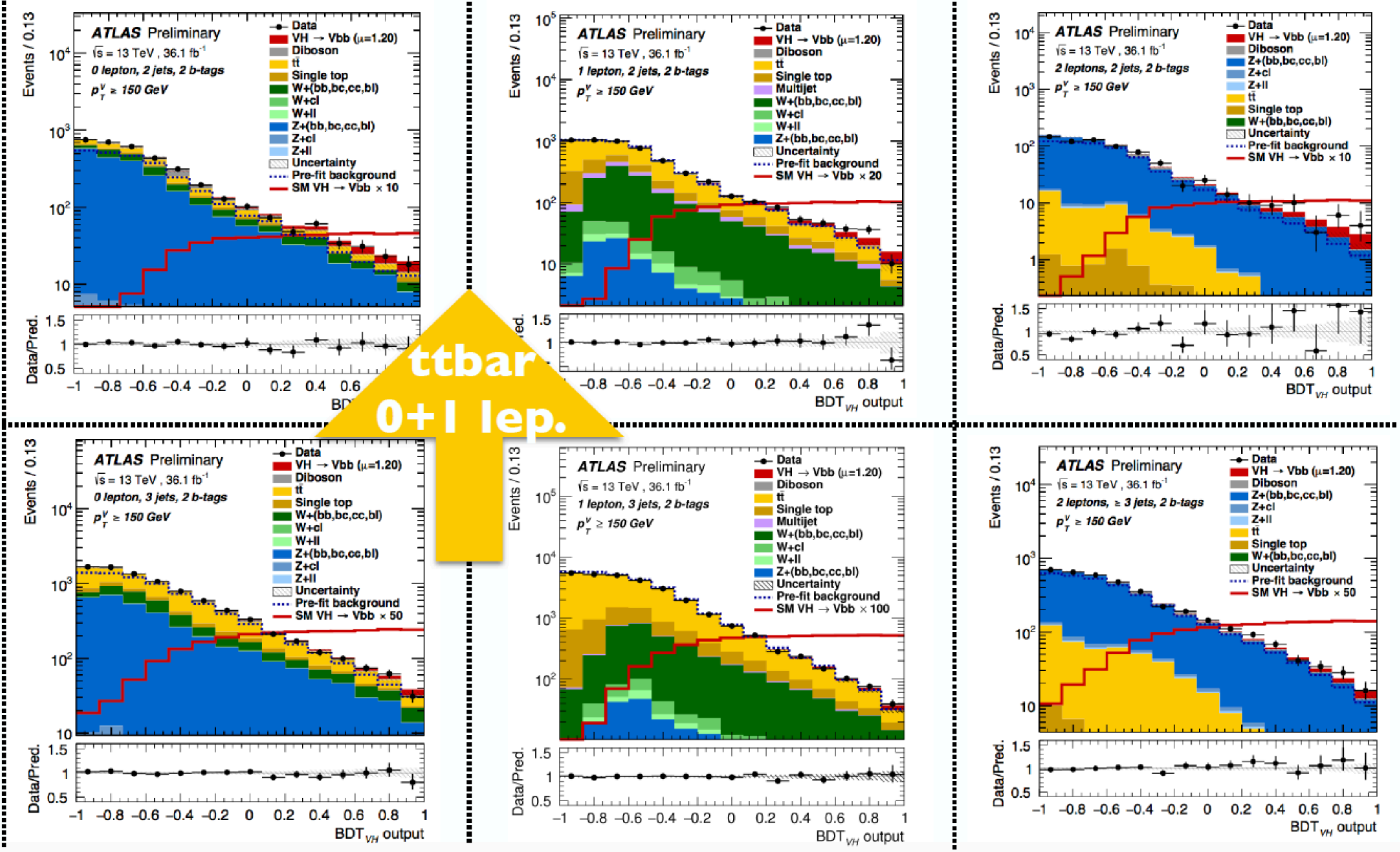
0-lepton

1-lepton

2-lepton

2 jets

3 (≥3) jets



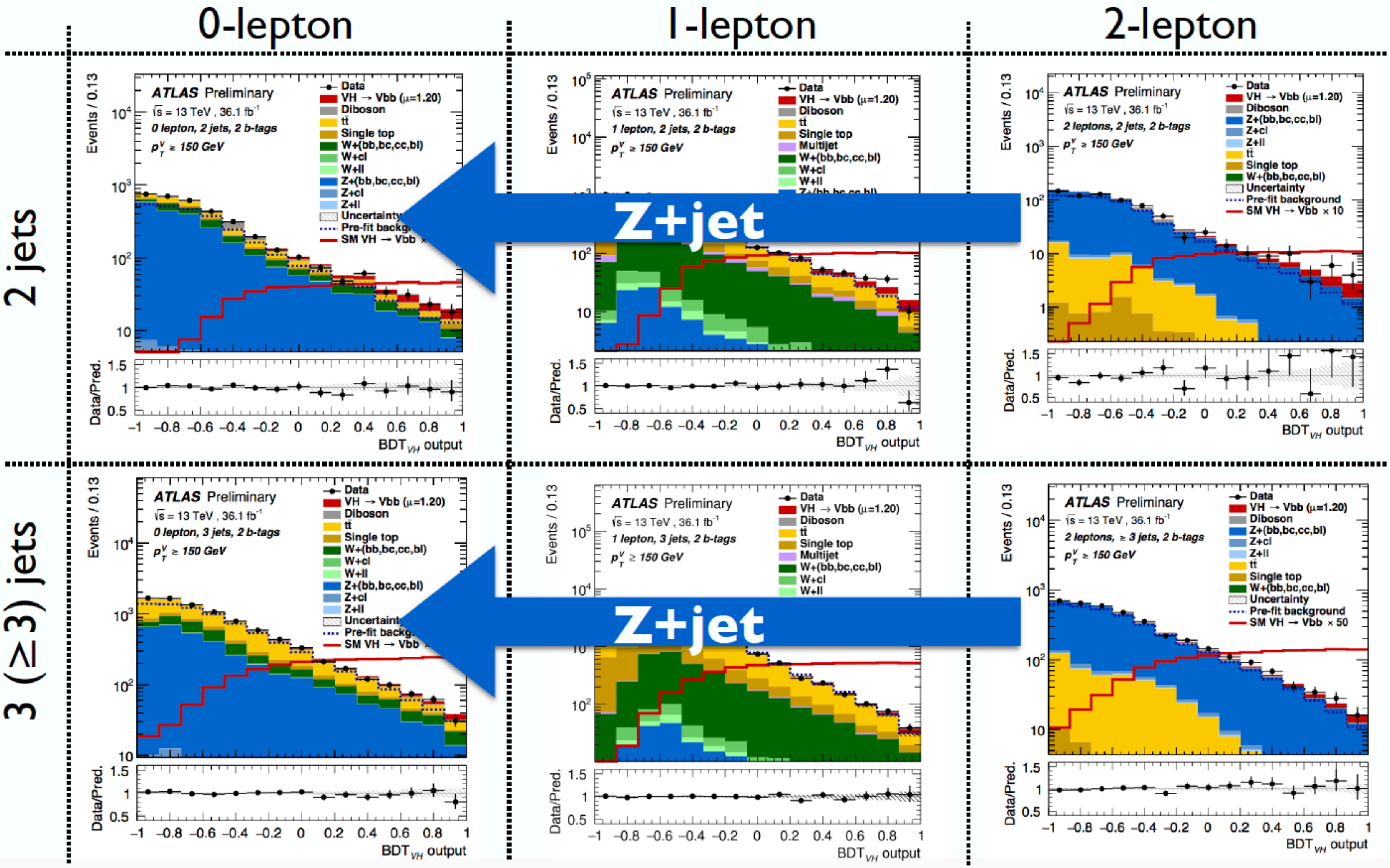
ttbar
0+1 lep.

Background Modelling

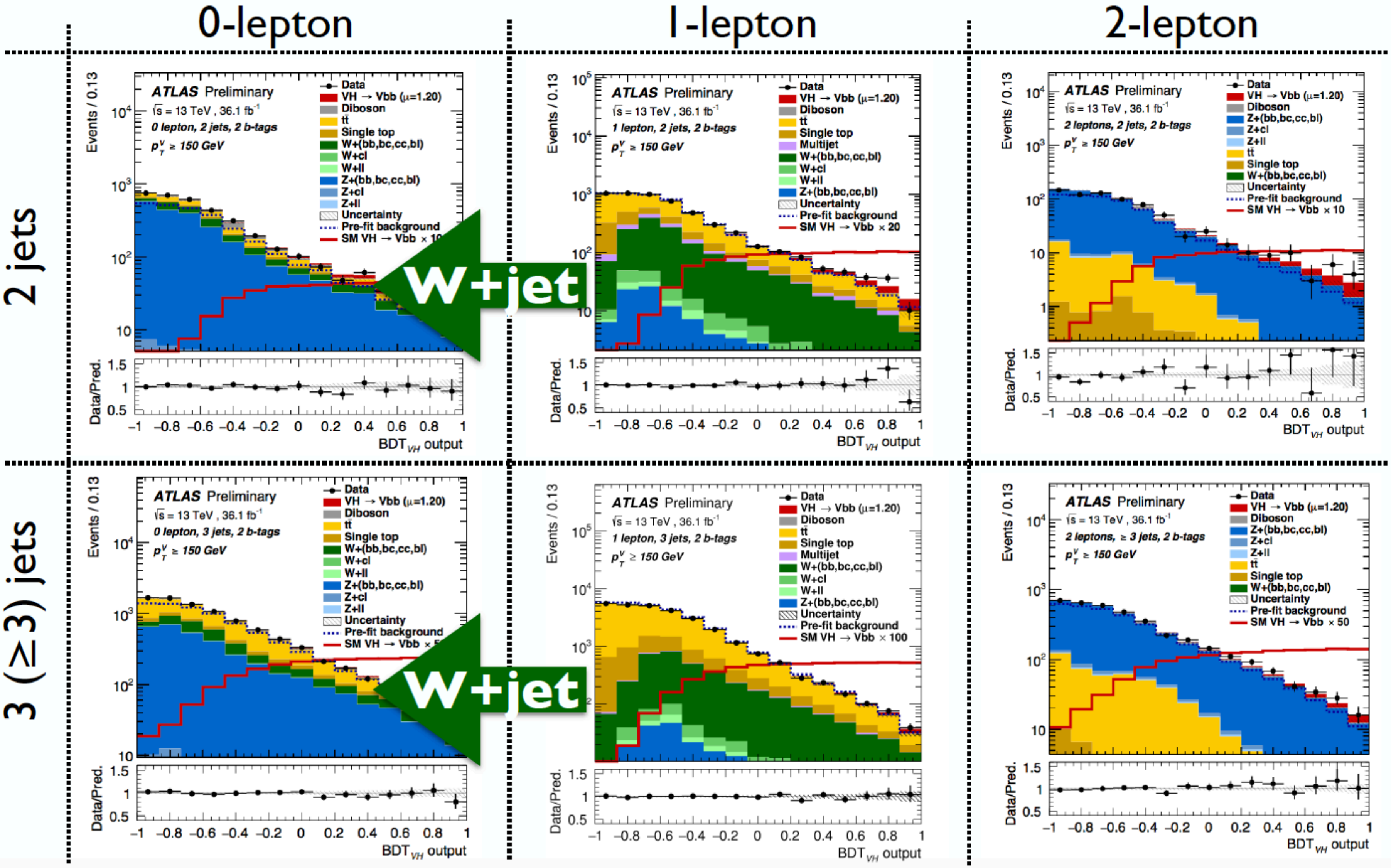
0-lepton | 1-lepton | 2-lepton

2 jets

3 (≥3) jets



Background Modelling

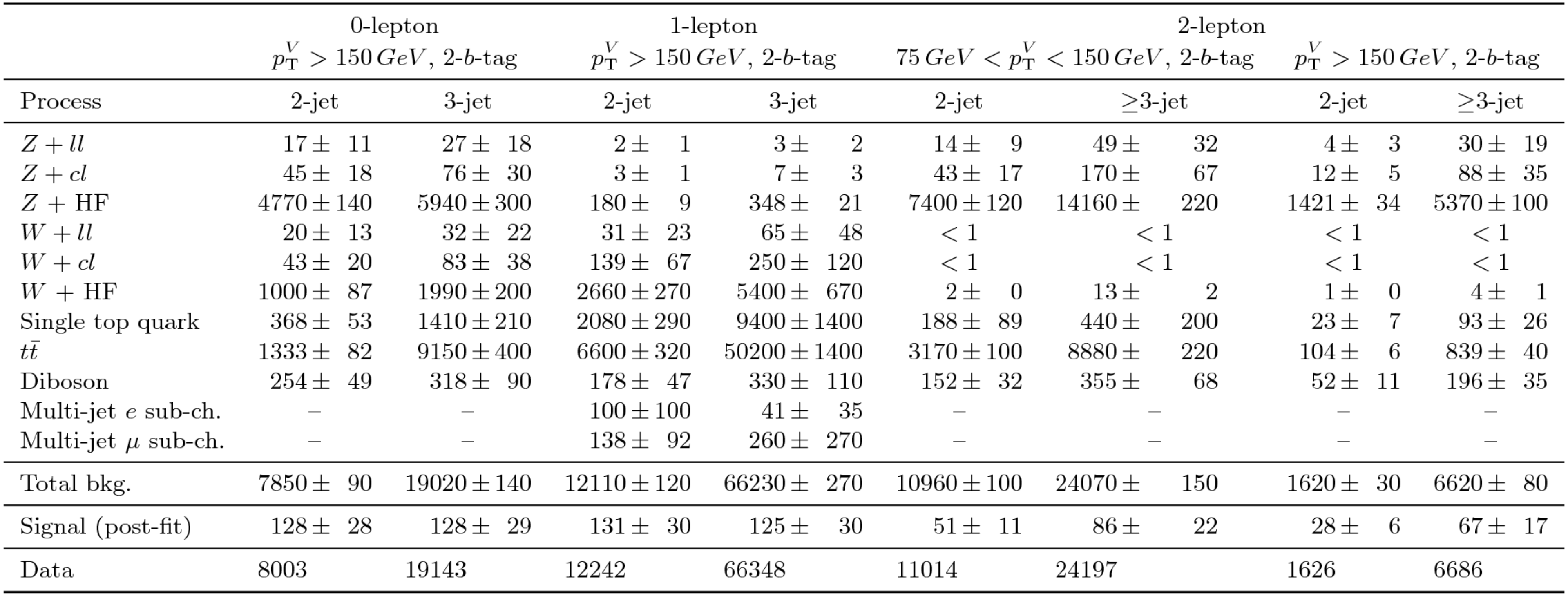


Background Modelling

Z + jets	
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
Z + HF normalisation	Floating (2-jet, 3-jet)
$Z + bc$-to-$Z + bb$ ratio	30 – 40%
$Z + cc$-to-$Z + bb$ ratio	13 – 15%
$Z + bl$-to-$Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_{T}^{V}	S
W + jets	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
W + HF normalisation	Floating (2-jet, 3-jet)
$W + bl$-to-$W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc$-to-$W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc$-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
$t\bar{t}$ (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), 55% ($Wt(bb)$), 24% (Wt(other))
Acceptance 3-jet	20% (t-channel), 51% ($Wt(bb)$), 21% (Wt(other))
m_{bb}, p_{T}^{V}	S (t-channel, $Wt(bb)$, Wt(other))
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 90 – 140% (3-jet)
BDT template	S

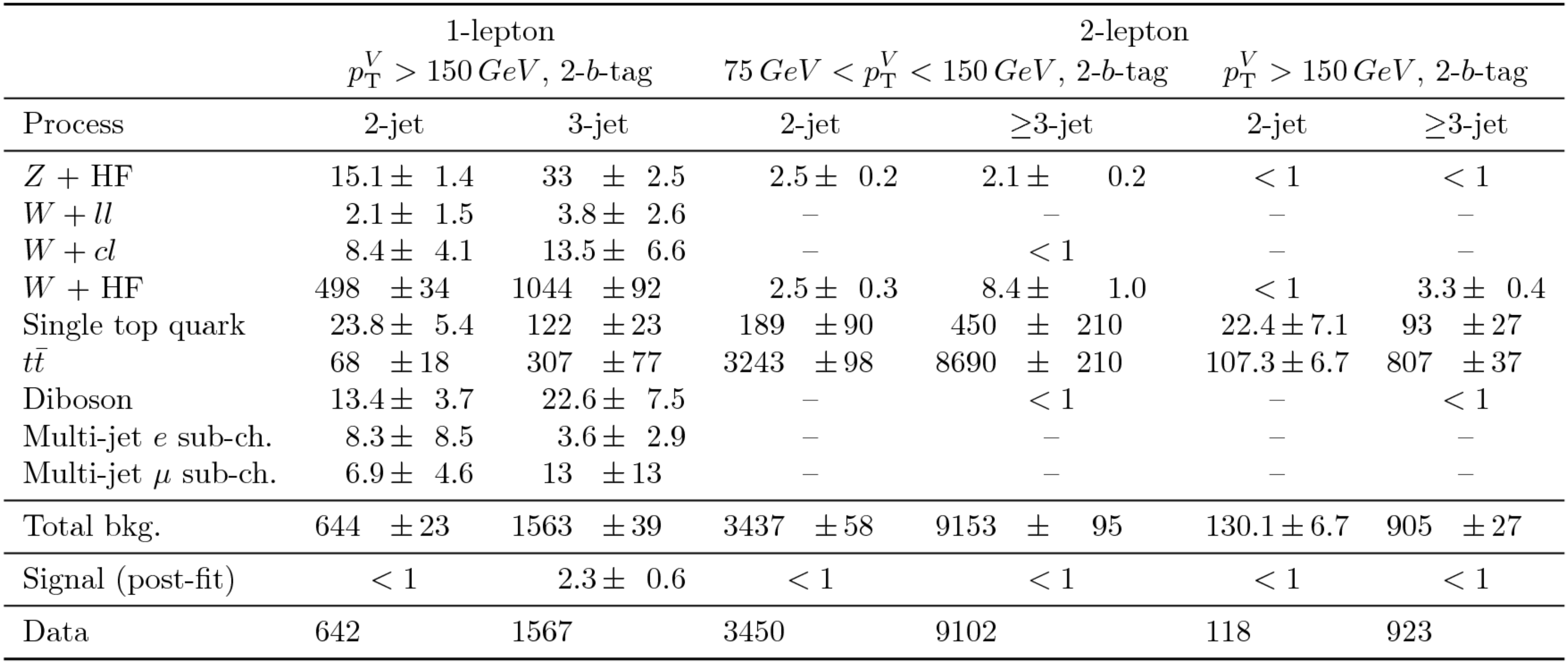
ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations	10 – 18%
Acceptance from PS/UE variations for 2 or more jets	6%
Acceptance from PS/UE variations for 3 jets	7% (0-lepton), 3% (2-lepton)
m_{bb}, p_{T}^{V}, from scale variations	S (correlated with WZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE variations	S (correlated with WZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale variations	13 – 21%
Acceptance from PS/UE variations for 2 or more jets	4%
Acceptance from PS/UE variations for 3 jets	11%
m_{bb}, p_{T}^{V}, from scale variations	S (correlated with ZZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE variations	S (correlated with ZZ uncertainties)
m_{bb}, from matrix-element variations	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%

Post-fit yields---signal region



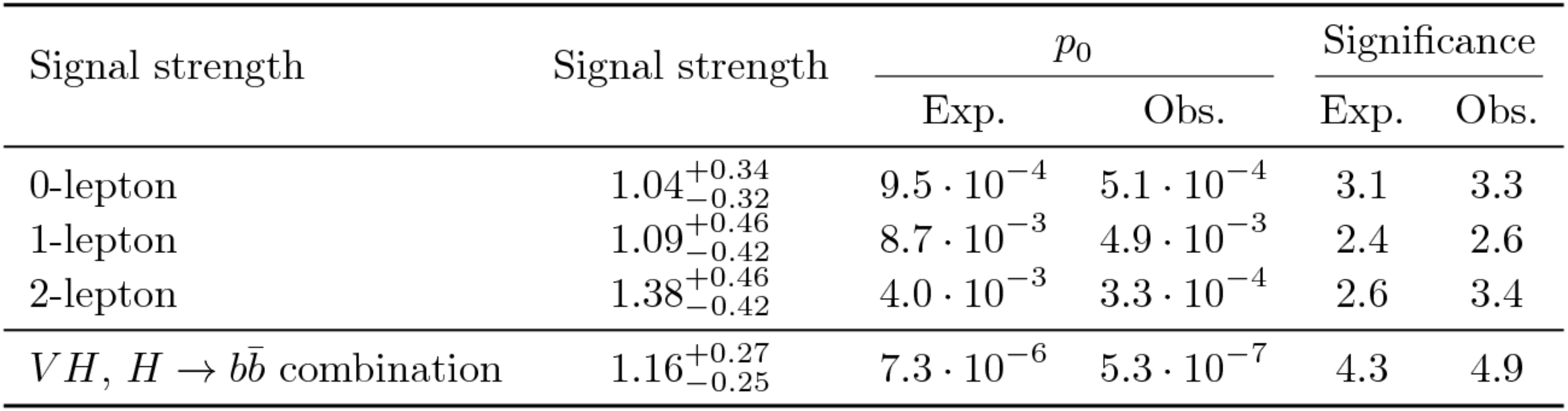
	0-lepton		1-lepton		2-lepton			
	$p_{\mathrm{T}}^{V} > 150\,GeV$, 2-$b$-tag		$p_{\mathrm{T}}^{V} > 150\,GeV$, 2-$b$-tag		$75\,GeV < p_{\mathrm{T}}^{V} < 150\,GeV$, 2-$b$-tag		$p_{\mathrm{T}}^{V} > 150\,GeV$, 2-$b$-tag	
Process	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z + ll$	17 ± 11	27 ± 18	2 ± 1	3 ± 2	14 ± 9	49 ± 32	4 ± 3	30 ± 19
$Z + cl$	45 ± 18	76 ± 30	3 ± 1	7 ± 3	43 ± 17	170 ± 67	12 ± 5	88 ± 35
Z + HF	4770 ± 140	5940 ± 300	180 ± 9	348 ± 21	7400 ± 120	14160 ± 220	1421 ± 34	5370 ± 100
$W + ll$	20 ± 13	32 ± 22	31 ± 23	65 ± 48	< 1	< 1	< 1	< 1
$W + cl$	43 ± 20	83 ± 38	139 ± 67	250 ± 120	< 1	< 1	< 1	< 1
W + HF	1000 ± 87	1990 ± 200	2660 ± 270	5400 ± 670	2 ± 0	13 ± 2	1 ± 0	4 ± 1
Single top quark	368 ± 53	1410 ± 210	2080 ± 290	9400 ± 1400	188 ± 89	440 ± 200	23 ± 7	93 ± 26
$t\bar{t}$	1333 ± 82	9150 ± 400	6600 ± 320	50200 ± 1400	3170 ± 100	8880 ± 220	104 ± 6	839 ± 40
Diboson	254 ± 49	318 ± 90	178 ± 47	330 ± 110	152 ± 32	355 ± 68	52 ± 11	196 ± 35
Multi-jet e sub-ch.	–	–	100 ± 100	41 ± 35	–	–	–	–
Multi-jet μ sub-ch.	–	–	138 ± 92	260 ± 270	–	–	–	–
Total bkg.	7850 ± 90	19020 ± 140	12110 ± 120	66230 ± 270	10960 ± 100	24070 ± 150	1620 ± 30	6620 ± 80
Signal (post-fit)	128 ± 28	128 ± 29	131 ± 30	125 ± 30	51 ± 11	86 ± 22	28 ± 6	67 ± 17
Data	8003	19143	12242	66348	11014	24197	1626	6686

Post-fit yields---control region

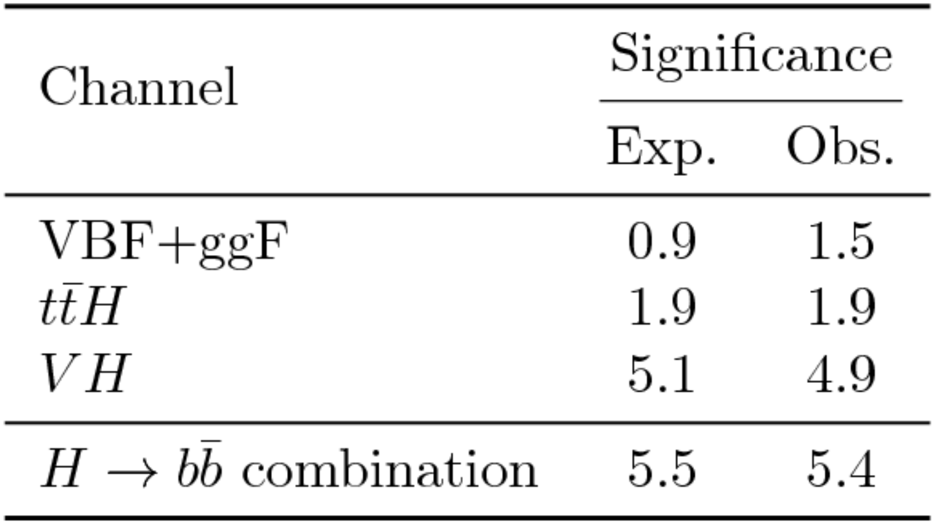


	1-lepton		2-lepton			
	$p_{\mathrm{T}}^{V} > 150\,GeV$, 2-$b$-tag		$75\,GeV < p_{\mathrm{T}}^{V} < 150\,GeV$, 2-$b$-tag		$p_{\mathrm{T}}^{V} > 150\,GeV$, 2-$b$-tag	
Process	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
Z + HF	15.1 ± 1.4	33 ± 2.5	2.5 ± 0.2	2.1 ± 0.2	< 1	< 1
$W + ll$	2.1 ± 1.5	3.8 ± 2.6	–	–	–	–
$W + cl$	8.4 ± 4.1	13.5 ± 6.6	–	< 1	–	–
W + HF	498 ± 34	1044 ± 92	2.5 ± 0.3	8.4 ± 1.0	< 1	3.3 ± 0.4
Single top quark	23.8 ± 5.4	122 ± 23	189 ± 90	450 ± 210	22.4 ± 7.1	93 ± 27
$t\bar{t}$	68 ± 18	307 ± 77	3243 ± 98	8690 ± 210	107.3 ± 6.7	807 ± 37
Diboson	13.4 ± 3.7	22.6 ± 7.5	–	< 1	–	< 1
Multi-jet e sub-ch.	8.3 ± 8.5	3.6 ± 2.9	–	–	–	–
Multi-jet μ sub-ch.	6.9 ± 4.6	13 ± 13	–	–	–	–
Total bkg.	644 ± 23	1563 ± 39	3437 ± 58	9153 ± 95	130.1 ± 6.7	905 ± 27
Signal (post-fit)	< 1	2.3 ± 0.6	< 1	< 1	< 1	< 1
Data	642	1567	3450	9102	118	923

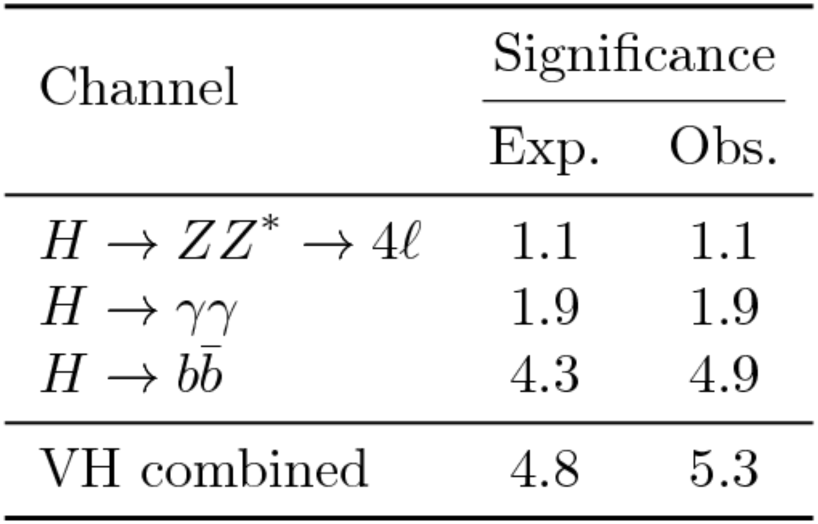
Significance



Signal strength	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
VH, $H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

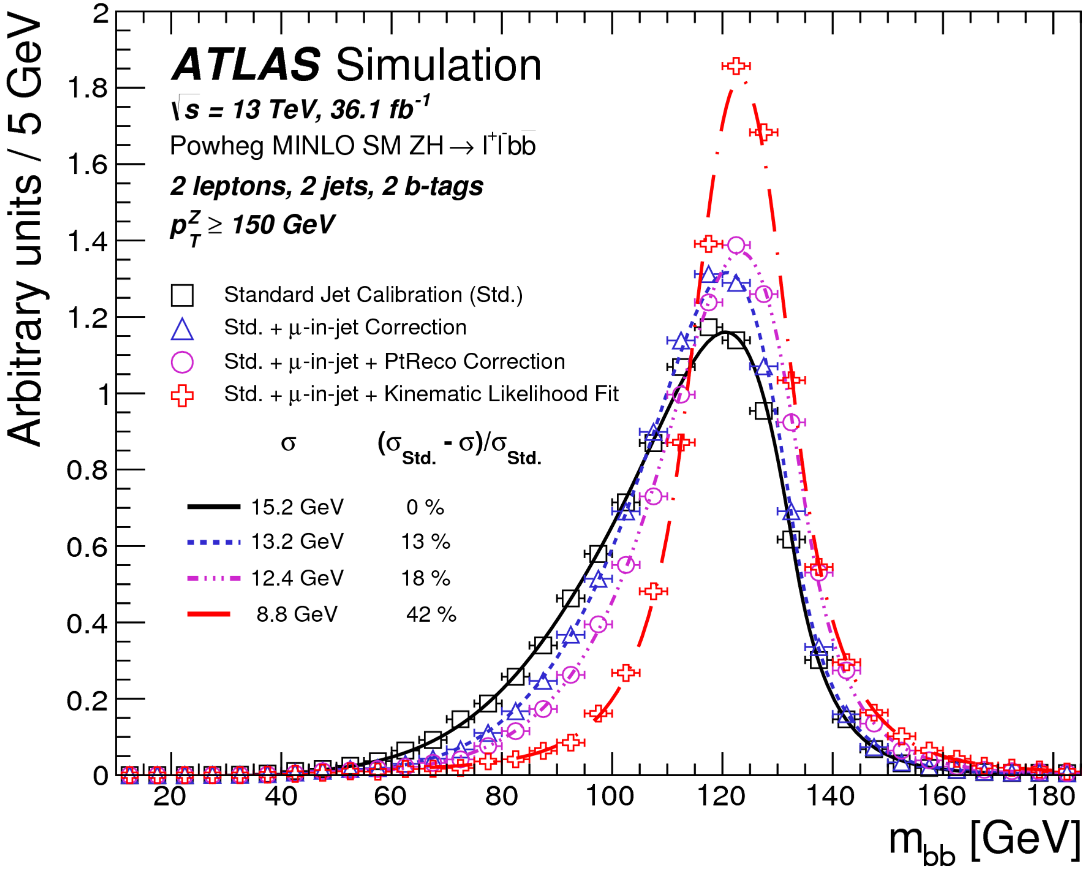


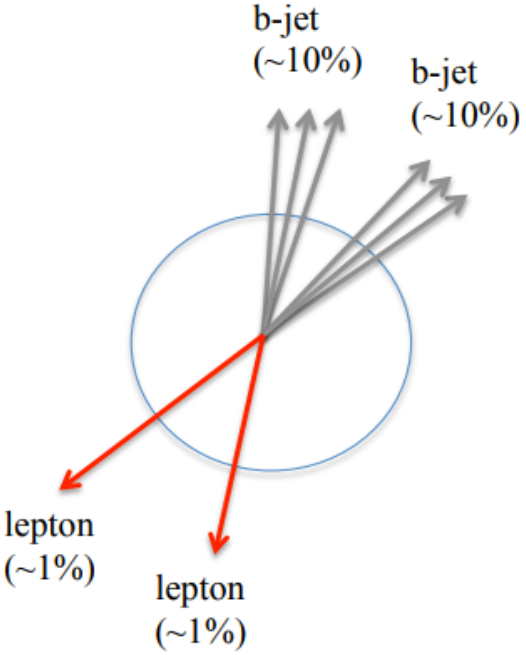
Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4



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

Jet energy correction





$$\vec{p}_{T,b\bar{b}} = \sum_{\ell} \vec{p}_{T,\ell}$$

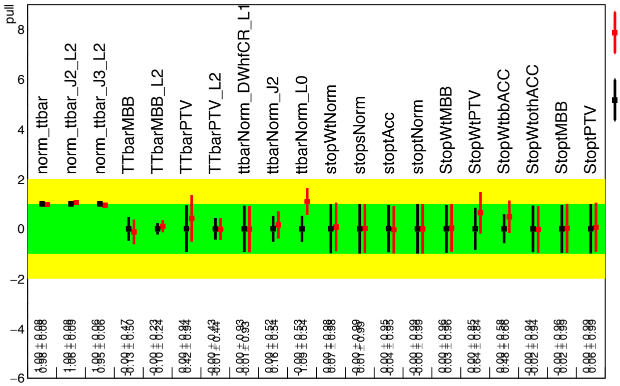
- muon-in-jet correction in all three channels;
- PtReco in 0- and 1-lepton channel;
- Kinematic fit in 2-lepton channel;

VH MVA analysis : backgrounds pulls

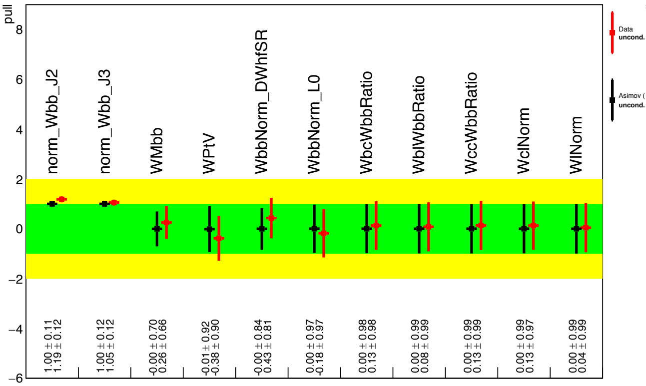
Asimov

Data

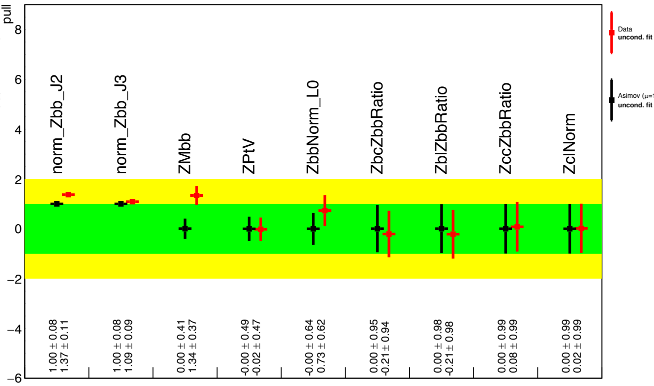
Top



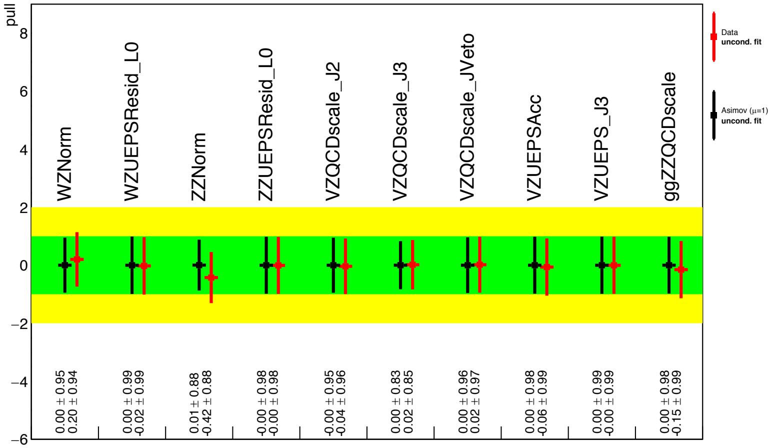
W+jet



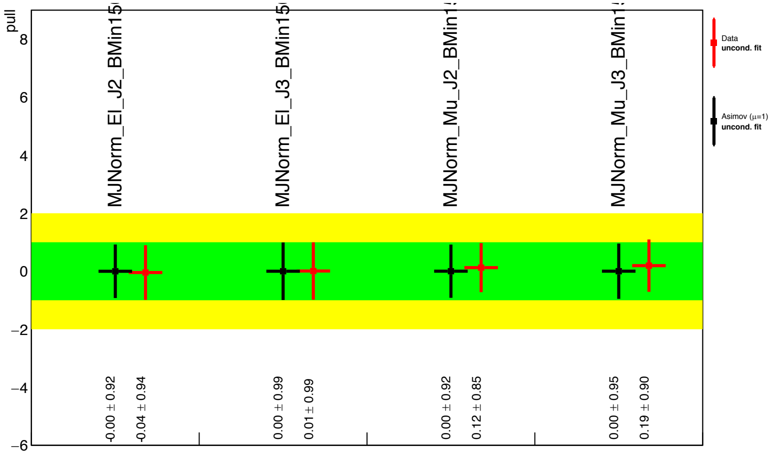
Z+jet



Diboson

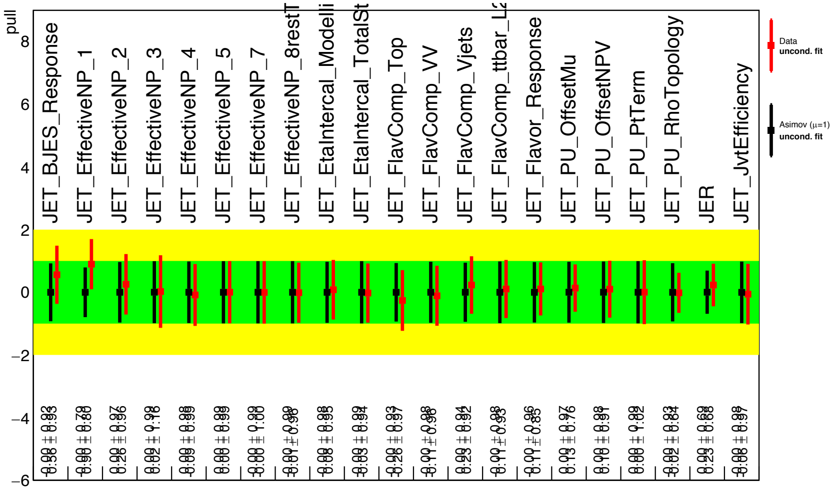


MJ

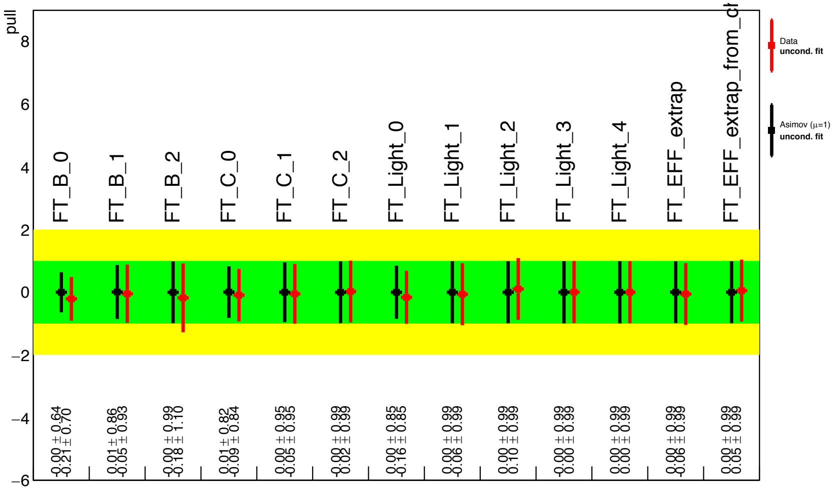


VH MVA analysis : experimental systematics

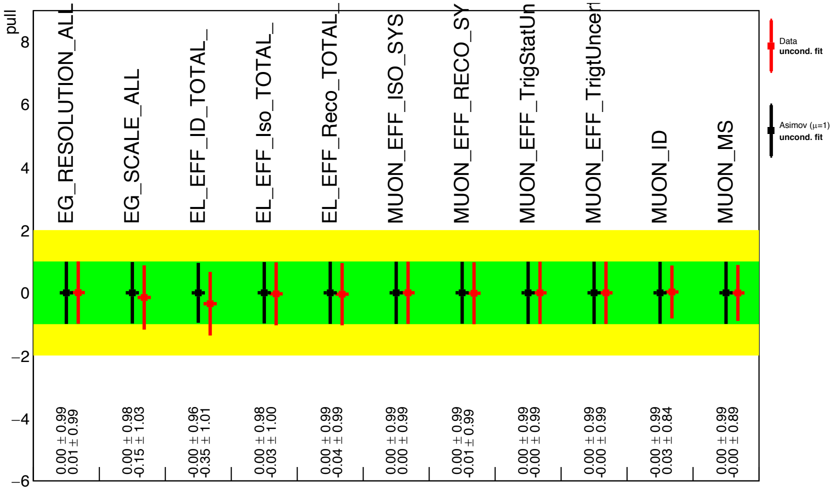
Jet



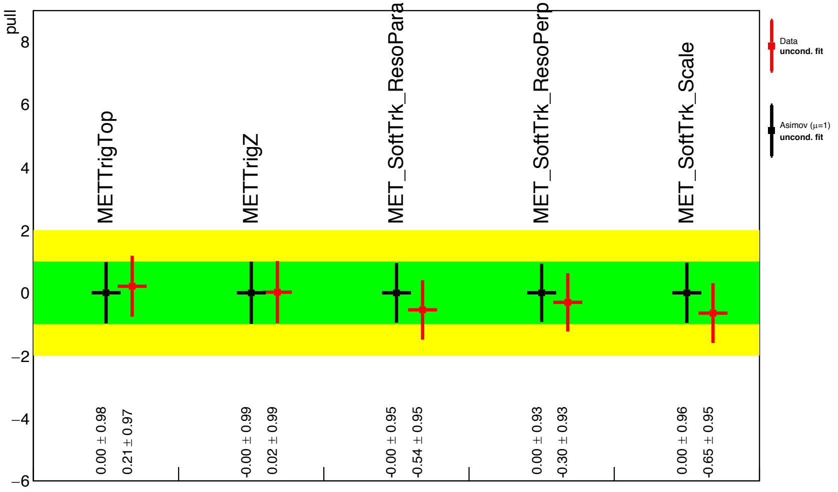
B-Tagging



Lepton

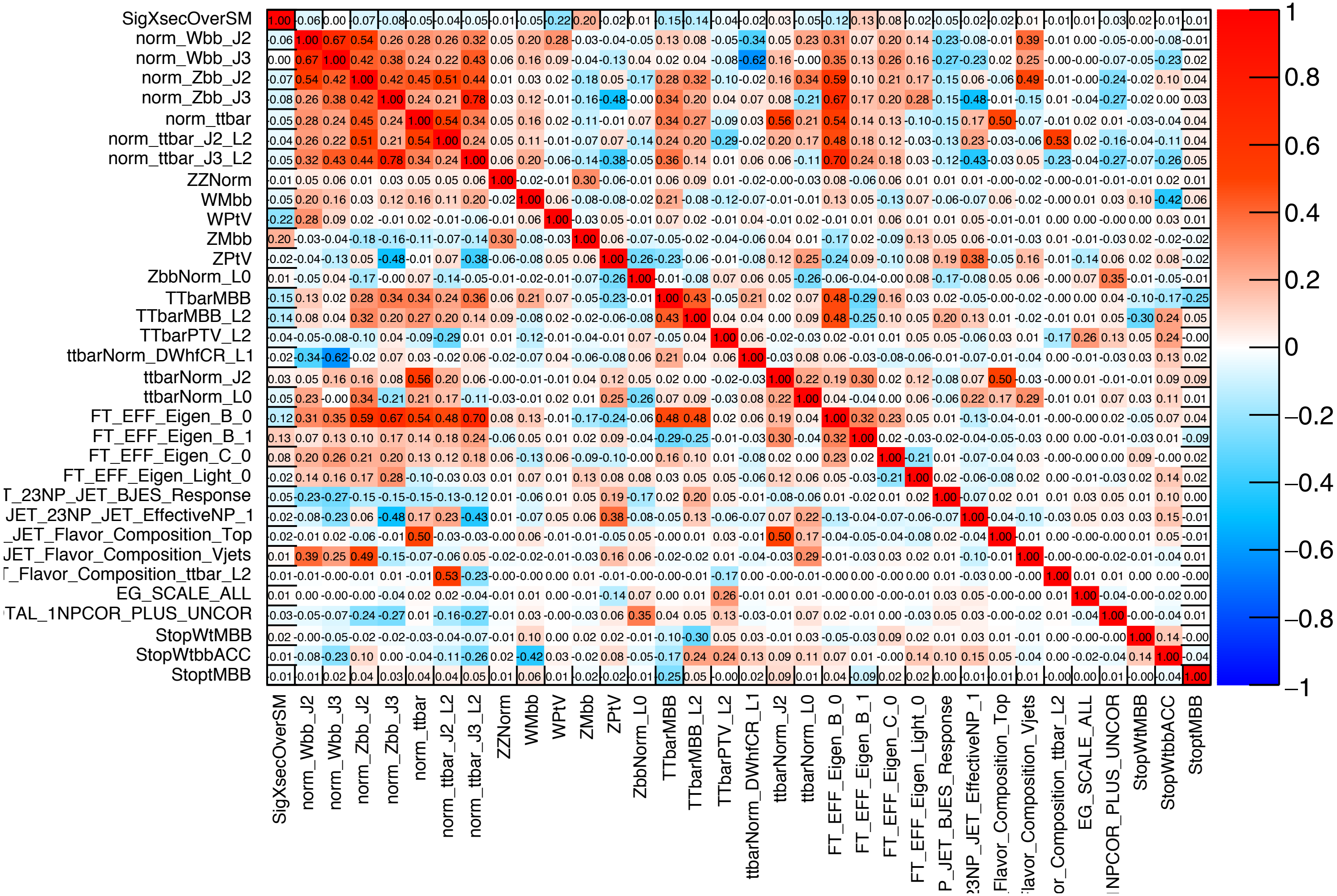


MET



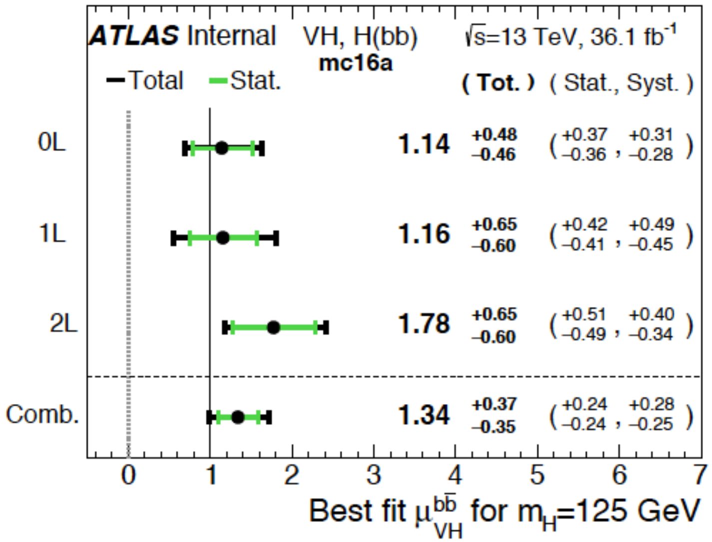
VH MVA analysis : correlations

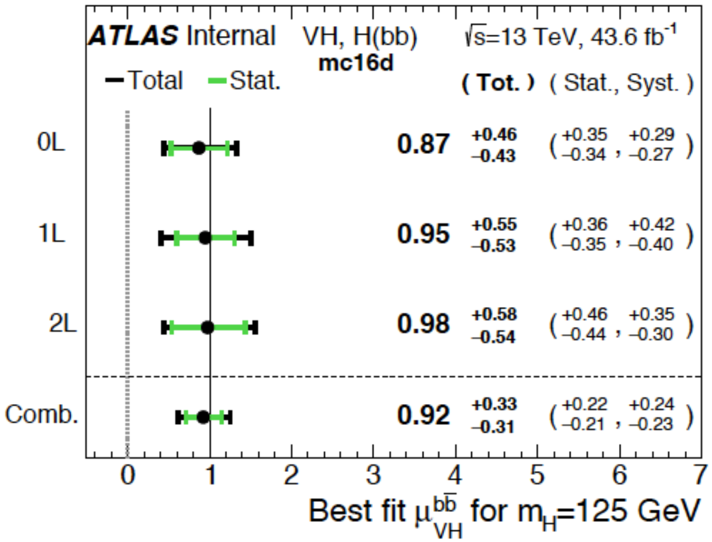
- Correlation of NPs from data fit.

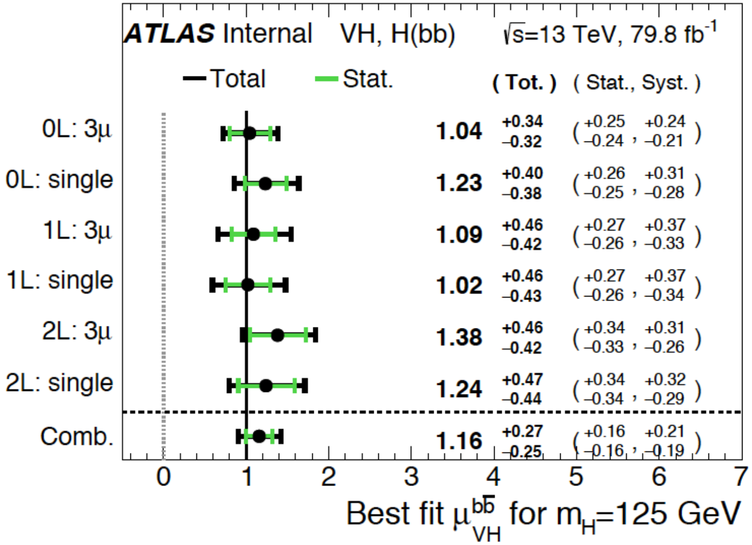


	SigXsecOverSM	norm_Wbb_J2	norm_Wbb_J3	norm_Zbb_J2	norm_Zbb_J3	norm_ttbar	norm_ttbar_J2_L2	norm_ttbar_J3_L2	ZZNorm	WMbb	WPtV	ZMbb	ZPtV	ZbbNorm_L0	TTbarMBB	TTbarMBB_L2	TTbarPTV_L2	ttbarNorm_DWhfCR_L1	ttbarNorm_J2	ttbarNorm_L0	FT_EFF_Eigen_B_0	FT_EFF_Eigen_B_1	FT_EFF_Eigen_C_0	FT_EFF_Eigen_Light_0	P_JET_BJES_Response	23NP_JET_EffectiveNP_1	Flavor_Composition_Top	lavor_Composition_Vjets	or_Composition_ttbar_L2	EG_SCALE_ALL	NPCOR_PLUS_UNCOR	StopWtMBB	StopWtbbACC	StoptMBB
SigXsecOverSM	1.00	-0.06	0.00	-0.07	-0.08	-0.05	-0.04	-0.05	-0.01	-0.05	-0.22	0.20	-0.02	0.01	-0.15	-0.14	-0.04	-0.02	0.03	-0.05	-0.12	0.13	0.08	-0.02	-0.05	-0.02	-0.02	0.01	-0.01	0.01	-0.03	0.02	-0.01	-0.01
norm_Wbb_J2	-0.06	1.00	0.67	0.54	0.26	0.28	0.26	0.32	0.05	0.20	0.28	-0.03	-0.04	-0.05	0.13	0.08	-0.05	-0.34	0.05	0.23	0.31	0.07	0.20	0.14	-0.23	-0.08	-0.01	0.39	-0.01	0.00	-0.05	-0.00	-0.08	-0.01
norm_Wbb_J3	0.00	0.67	1.00	0.42	0.38	0.24	0.22	0.43	0.06	0.16	0.09	-0.04	-0.13	0.04	0.02	0.04	-0.08	-0.62	0.16	-0.00	0.35	0.13	0.26	0.16	-0.27	-0.23	0.02	0.25	-0.00	-0.00	-0.07	-0.05	-0.23	0.02
norm_Zbb_J2	-0.07	0.54	0.42	1.00	0.42	0.45	0.51	0.44	0.01	0.03	0.02	-0.18	0.05	-0.17	0.28	0.32	-0.10	-0.02	0.16	0.34	0.59	0.10	0.21	0.17	-0.15	0.06	-0.06	0.49	-0.01	-0.00	-0.24	-0.02	0.10	0.04
norm_Zbb_J3	-0.08	0.26	0.38	0.42	1.00	0.24	0.21	0.78	0.03	0.12	-0.01	-0.16	-0.48	-0.00	0.34	0.20	0.04	0.07	0.08	-0.21	0.67	0.17	0.20	0.28	-0.15	-0.48	-0.01	-0.15	0.01	-0.04	-0.27	-0.02	0.00	0.03
norm_ttbar	-0.05	0.28	0.24	0.45	0.24	1.00	0.54	0.34	0.05	0.16	0.02	-0.11	-0.01	0.07	0.34	0.27	-0.09	0.03	0.56	0.21	0.54	0.14	0.13	-0.10	-0.15	0.17	0.50	-0.07	-0.01	0.02	0.01	-0.03	-0.04	0.04
norm_ttbar_J2_L2	-0.04	0.26	0.22	0.51	0.21	0.54	1.00	0.24	0.05	0.11	-0.01	-0.07	0.07	-0.14	0.24	0.20	-0.29	-0.02	0.20	0.17	0.48	0.18	0.12	-0.03	-0.13	0.23	-0.03	-0.06	0.53	0.02	-0.16	-0.04	-0.11	0.04
norm_ttbar_J3_L2	-0.05	0.32	0.43	0.44	0.78	0.34	0.24	1.00	0.06	0.20	-0.06	-0.14	-0.38	-0.05	0.36	0.14	0.01	0.06	0.06	-0.11	0.70	0.24	0.18	0.03	-0.12	-0.43	-0.03	0.05	-0.23	-0.04	-0.27	-0.07	-0.26	0.05
ZZNorm	-0.01	0.05	0.06	0.01	0.03	0.05	0.05	0.06	1.00	-0.02	-0.01	0.30	-0.06	-0.01	0.06	0.09	0.01	-0.02	-0.00	-0.03	0.08	-0.06	0.06	0.01	0.01	0.01	-0.00	-0.02	-0.00	-0.01	-0.01	-0.01	0.02	0.01
WMbb	-0.05	0.20	0.16	0.03	0.12	0.16	0.11	0.20	-0.02	1.00	0.06	-0.08	-0.08	-0.02	0.21	-0.08	-0.12	-0.07	-0.01	-0.01	0.13	0.05	-0.13	0.07	-0.06	-0.07	0.06	-0.02	-0.00	0.01	0.03	0.10	-0.42	0.06
WPtV	-0.22	0.28	0.09	0.02	-0.01	0.02	-0.01	-0.06	-0.01	0.06	1.00	-0.03	0.05	-0.01	0.07	0.02	-0.01	0.04	-0.01	0.02	-0.01	0.01	0.06	0.01	0.01	0.05	-0.01	-0.01	0.00	0.00	-0.00	0.00	0.03	0.01
ZMbb	0.20	-0.03	-0.04	-0.18	-0.16	-0.11	-0.07	-0.14	0.30	-0.08	-0.03	1.00	0.06	-0.07	-0.05	-0.02	-0.04	-0.06	0.04	0.01	-0.17	0.02	-0.09	0.13	0.05	0.06	-0.01	-0.03	0.01	-0.01	-0.03	0.02	-0.02	-0.02
ZPtV	-0.02	-0.04	-0.13	0.05	-0.48	-0.01	0.07	-0.38	-0.06	-0.08	0.05	0.06	1.00	-0.26	-0.23	-0.06	-0.01	-0.08	0.12	0.25	-0.24	0.09	-0.10	0.08	0.19	0.38	-0.05	0.16	-0.01	-0.14	0.06	0.02	0.08	-0.02
ZbbNorm_L0	0.01	-0.05	0.04	-0.17	-0.00	0.07	-0.14	-0.05	-0.01	-0.02	-0.01	-0.07	-0.26	1.00	-0.01	-0.08	0.07	0.06	0.05	-0.26	-0.06	-0.04	-0.00	0.08	-0.17	-0.08	0.05	0.06	-0.00	0.07	0.35	-0.01	-0.05	-0.01
TTbarMBB	-0.15	0.13	0.02	0.28	0.34	0.34	0.24	0.36	0.06	0.21	0.07	-0.05	-0.23	-0.01	1.00	0.43	-0.05	0.21	0.02	0.07	0.48	-0.29	0.16	0.03	0.02	-0.05	-0.00	-0.02	-0.00	0.00	0.04	-0.10	-0.17	-0.25
TTbarMBB_L2	-0.14	0.08	0.04	0.32	0.20	0.27	0.20	0.14	0.09	-0.08	0.02	-0.02	-0.06	-0.08	0.43	1.00	0.04	0.04	0.00	0.09	0.48	-0.25	0.10	0.05	0.20	0.13	0.01	-0.02	-0.01	0.01	0.05	-0.30	0.24	0.05
TTbarPTV_L2	-0.04	-0.05	-0.08	-0.10	0.04	-0.09	-0.29	0.01	0.01	-0.12	-0.01	-0.04	-0.01	0.07	-0.05	0.04	1.00	0.06	-0.02	-0.03	0.02	-0.01	0.01	0.05	0.05	-0.06	0.03	0.01	-0.17	0.26	0.13	0.05	0.24	-0.00
ttbarNorm_DWhfCR_L1	-0.02	-0.34	-0.62	-0.02	0.07	0.03	-0.02	0.06	-0.02	-0.07	0.04	-0.06	-0.08	0.06	0.21	0.04	0.06	1.00	-0.03	0.08	0.06	-0.03	-0.08	-0.06	-0.01	-0.07	-0.01	-0.04	0.00	-0.01	-0.03	0.03	0.13	0.02
ttbarNorm_J2	0.03	0.05	0.16	0.16	0.08	0.56	0.20	0.06	-0.00	-0.01	-0.01	0.04	0.12	0.05	0.02	0.00	-0.02	-0.03	1.00	0.22	0.19	0.30	0.02	0.12	-0.08	0.07	0.50	-0.03	-0.00	0.01	-0.01	-0.01	0.09	0.09
ttbarNorm_L0	-0.05	0.23	-0.00	0.34	-0.21	0.21	0.17	-0.11	-0.03	-0.01	0.02	0.01	0.25	-0.26	0.07	0.09	-0.03	0.08	0.22	1.00	0.04	-0.04	0.00	0.06	-0.06	0.22	0.17	0.29	-0.01	0.01	0.07	0.03	0.11	0.01
FT_EFF_Eigen_B_0	-0.12	0.31	0.35	0.59	0.67	0.54	0.48	0.70	0.08	0.13	-0.01	-0.17	-0.24	-0.06	0.48	0.48	0.02	0.06	0.19	0.04	1.00	0.32	0.23	0.05	0.01	-0.13	-0.04	-0.01	-0.00	-0.00	0.02	-0.05	0.07	0.04
FT_EFF_Eigen_B_1	0.13	0.07	0.13	0.10	0.17	0.14	0.18	0.24	-0.06	0.05	0.01	0.02	0.09	-0.04	-0.29	-0.25	-0.01	-0.03	0.30	-0.04	0.32	1.00	0.02	-0.03	-0.02	-0.04	-0.05	-0.03	0.00	0.00	-0.01	-0.03	0.01	-0.09
FT_EFF_Eigen_C_0	0.08	0.20	0.26	0.21	0.20	0.13	0.12	0.18	0.06	-0.13	0.06	-0.09	-0.10	-0.00	0.16	0.10	0.01	-0.08	0.02	0.00	0.23	0.02	1.00	-0.21	0.01	-0.07	-0.04	0.03	-0.00	-0.00	0.00	0.09	-0.00	0.02
FT_EFF_Eigen_Light_0	-0.02	0.14	0.16	0.17	0.28	-0.10	-0.03	0.03	0.01	0.07	0.01	0.13	0.08	0.08	0.03	0.05	0.05	-0.06	0.12	0.06	0.05	-0.03	-0.21	1.00	0.02	-0.06	-0.08	0.02	0.00	-0.01	-0.03	0.02	0.14	0.02
T_23NP_JET_BJES_Response	-0.05	-0.23	-0.27	-0.15	-0.15	-0.15	-0.13	-0.12	0.01	-0.06	0.01	0.05	0.19	-0.17	0.02	0.20	0.05	-0.01	-0.08	-0.06	0.01	-0.02	0.01	0.02	1.00	-0.07	0.02	0.01	0.01	0.03	0.05	0.01	0.10	0.00
JET_23NP_JET_EffectiveNP_1	-0.02	-0.08	-0.23	0.06	-0.48	0.17	0.23	-0.43	0.01	-0.07	0.05	0.06	0.38	-0.08	-0.05	0.13	-0.06	-0.07	0.07	0.22	-0.13	-0.04	-0.07	-0.06	-0.07	1.00	-0.04	-0.10	-0.03	0.05	0.03	0.03	0.15	-0.01
_JET_Flavor_Composition_Top	-0.02	-0.01	0.02	-0.06	-0.01	0.50	-0.03	-0.03	-0.00	0.06	-0.01	-0.01	-0.05	0.05	-0.00	0.01	0.03	-0.01	0.50	0.17	-0.04	-0.05	-0.04	-0.08	0.02	-0.04	1.00	-0.01	0.00	-0.00	-0.00	0.01	0.05	-0.01
JET_Flavor_Composition_Vjets	0.01	0.39	0.25	0.49	-0.15	-0.07	-0.06	0.05	-0.02	-0.02	-0.01	-0.03	0.16	0.06	-0.02	-0.02	0.01	-0.04	-0.03	0.29	-0.01	-0.03	0.03	0.02	0.01	-0.10	-0.01	1.00	-0.00	-0.00	-0.02	-0.01	-0.04	0.01
T_Flavor_Composition_ttbar_L2	-0.01	-0.01	-0.00	-0.01	0.01	-0.01	0.53	-0.23	-0.00	-0.00	0.00	0.01	-0.01	-0.00	-0.00	-0.01	-0.17	0.00	-0.00	-0.01	-0.00	0.00	-0.00	0.00	0.01	-0.03	0.00	-0.00	1.00	0.01	0.01	0.00	0.00	-0.00
EG_SCALE_ALL	0.01	0.00	-0.00	-0.00	-0.04	0.02	0.02	-0.04	-0.01	0.01	0.00	-0.01	-0.14	0.07	0.00	0.01	0.26	-0.01	0.01	0.01	-0.00	0.00	-0.00	-0.01	0.03	0.05	-0.00	-0.00	0.01	1.00	-0.04	-0.00	-0.02	0.00
TAL_1NPCOR_PLUS_UNCOR	-0.03	-0.05	-0.07	-0.24	-0.27	0.01	-0.16	-0.27	-0.01	0.03	-0.00	-0.03	0.06	0.35	0.04	0.05	0.13	-0.03	-0.01	0.07	0.02	-0.01	0.00	-0.03	0.05	0.03	-0.00	-0.02	0.01	-0.04	1.00	-0.00	-0.04	0.01
StopWtMBB	0.02	-0.00	-0.05	-0.02	-0.02	-0.03	-0.04	-0.07	-0.01	0.10	0.00	0.02	0.02	-0.01	-0.10	-0.30	0.05	0.03	-0.01	0.03	-0.05	-0.03	0.09	0.02	0.01	0.03	0.01	-0.01	0.00	-0.00	-0.00	1.00	0.14	-0.00
StopWtbbACC	-0.01	-0.08	-0.23	0.10	0.00	-0.04	-0.11	-0.26	0.02	-0.42	0.03	-0.02	0.08	-0.05	-0.17	0.24	0.24	0.13	0.09	0.11	0.07	0.01	-0.00	0.14	0.10	0.15	0.05	-0.04	0.00	-0.02	-0.04	0.14	1.00	-0.04
StoptMBB	-0.01	-0.01	0.02	0.04	0.03	0.04	0.04	0.05	0.01	0.06	0.01	-0.02	-0.02	-0.01	-0.25	0.05	-0.00	0.02	0.09	0.01	0.04	-0.09	0.02	0.02	0.00	-0.01	-0.01	0.01	-0.00	0.00	0.01	-0.00	-0.04	1.00

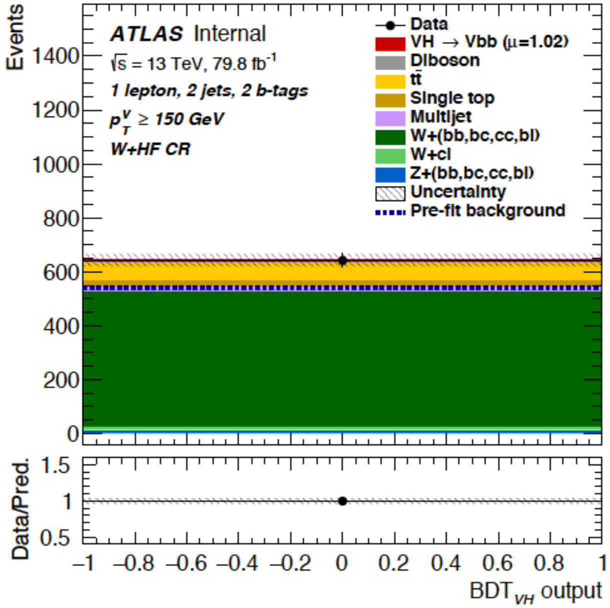
VH MVA analysis results

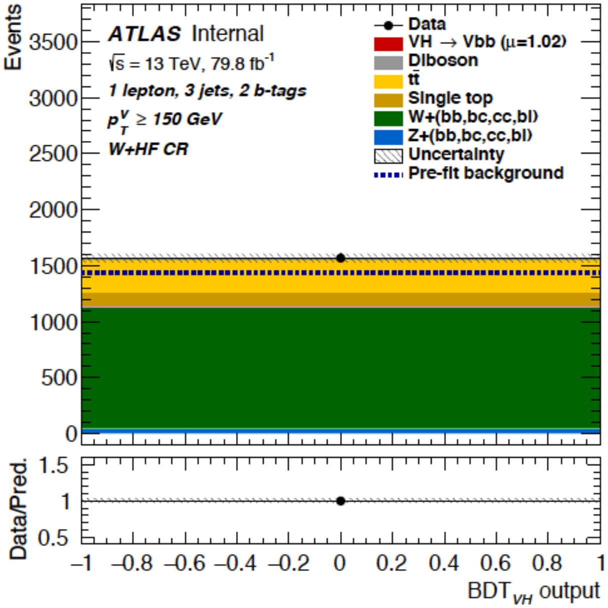


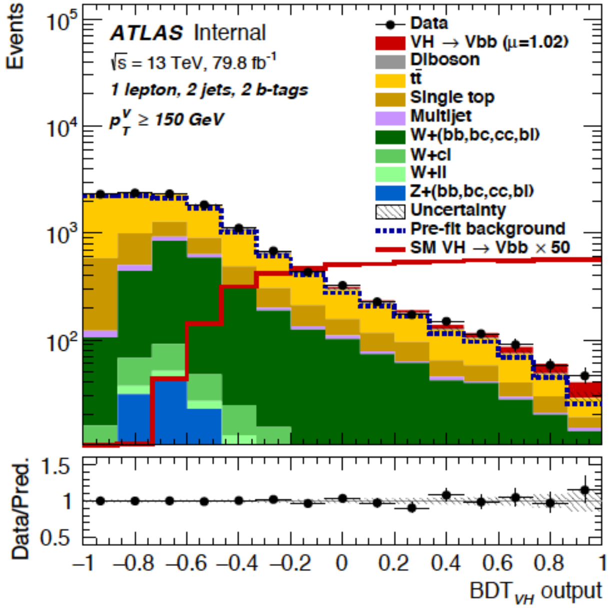


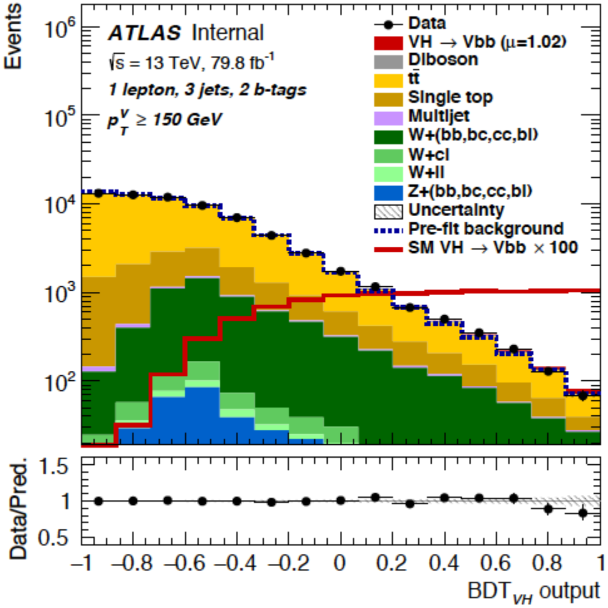


1-lepton only fit result

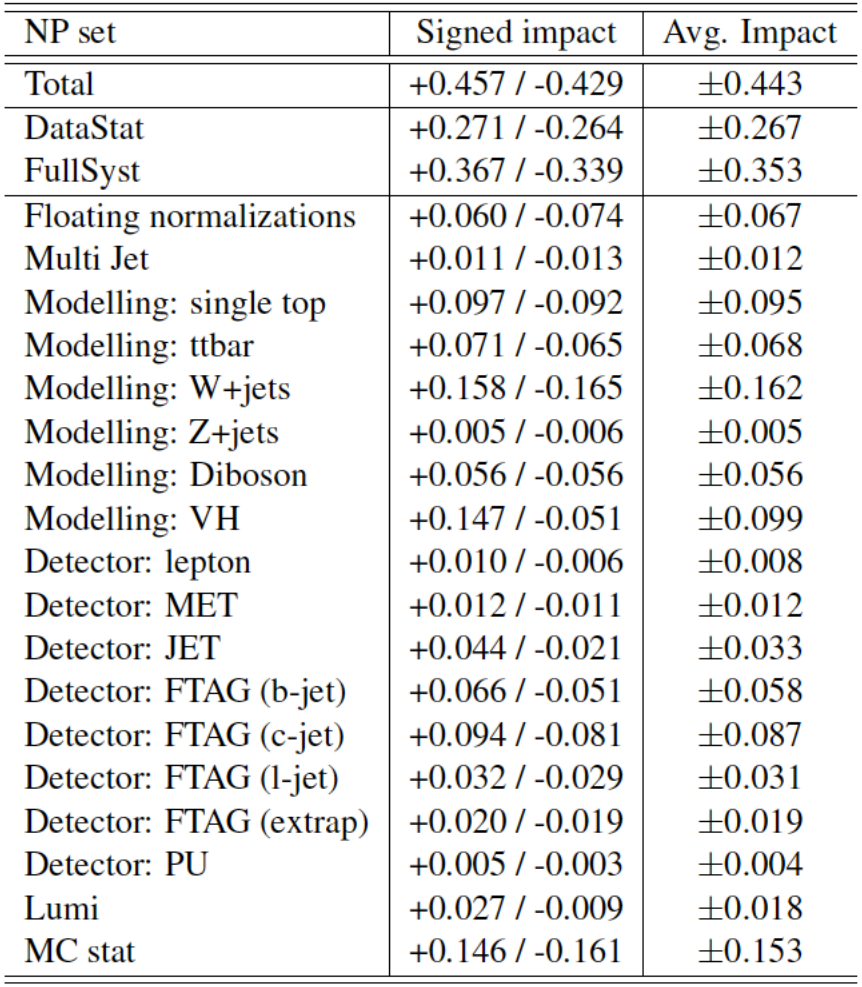




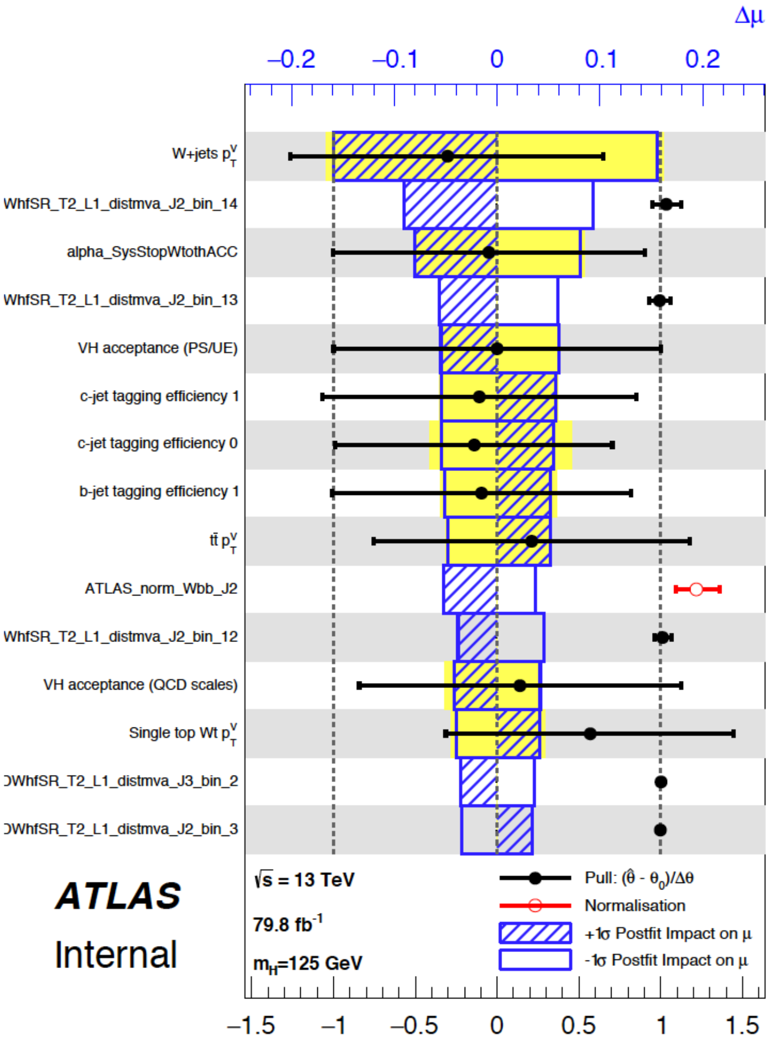




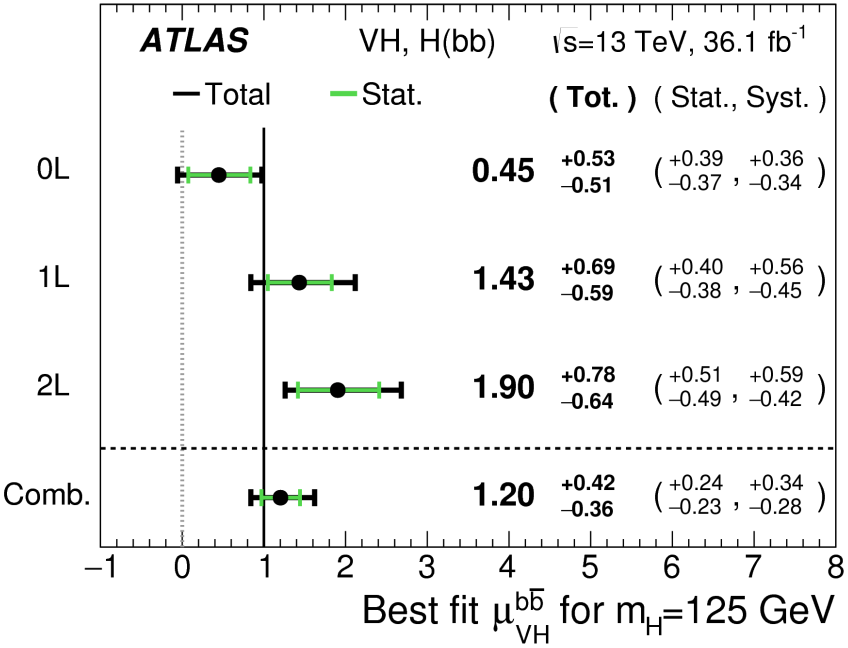
1-lepton only fit result

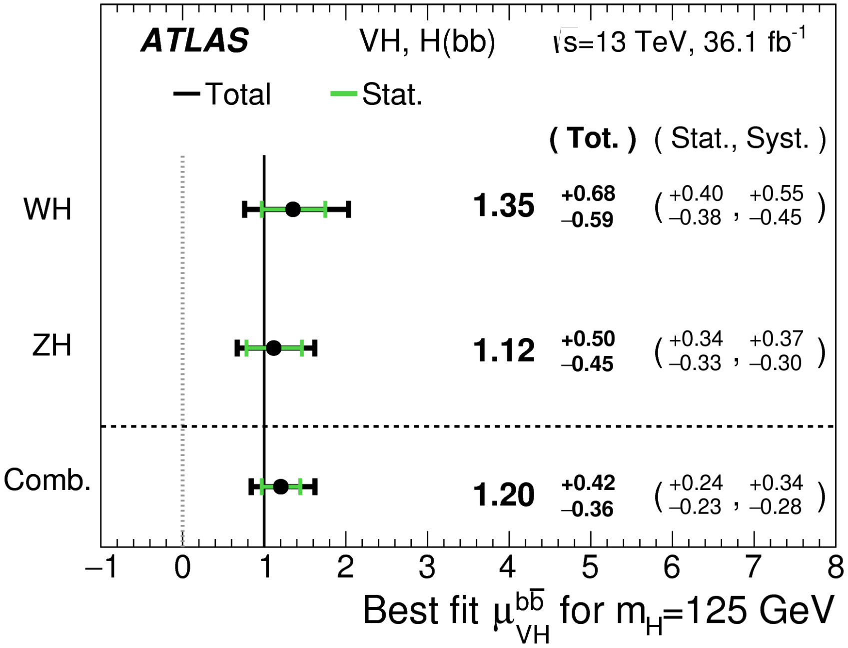


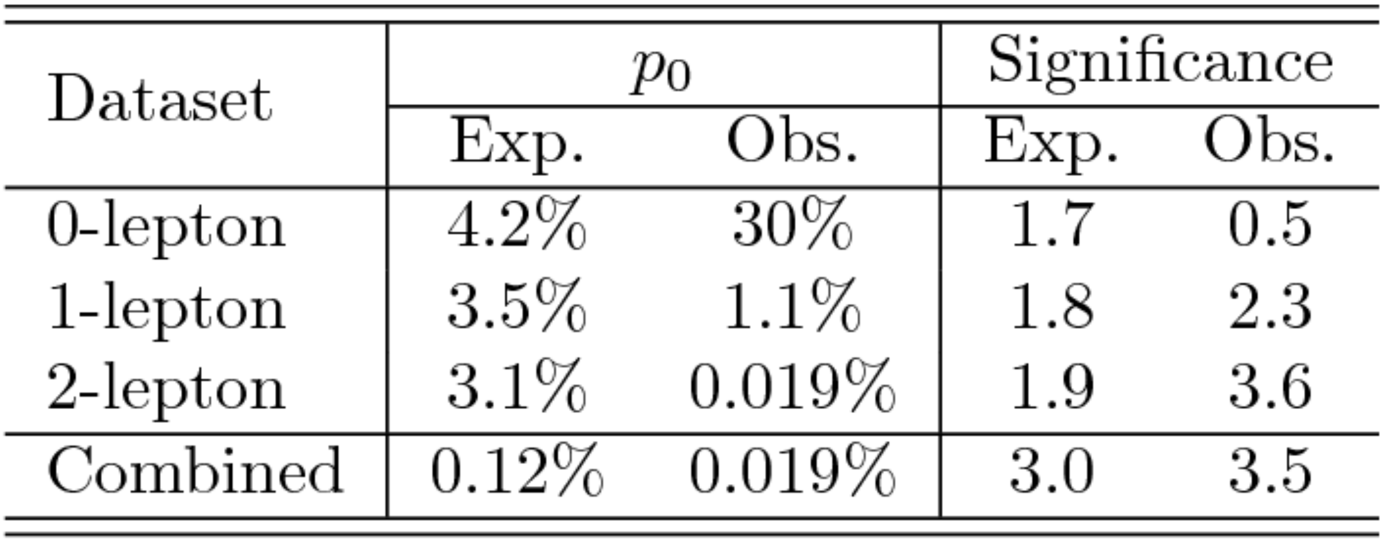
NP set	Signed impact	Avg. Impact
Total	+0.457 / -0.429	±0.443
DataStat	+0.271 / -0.264	±0.267
FullSyst	+0.367 / -0.339	±0.353
Floating normalizations	+0.060 / -0.074	±0.067
Multi Jet	+0.011 / -0.013	±0.012
Modelling: single top	+0.097 / -0.092	±0.095
Modelling: ttbar	+0.071 / -0.065	±0.068
Modelling: W+jets	+0.158 / -0.165	±0.162
Modelling: Z+jets	+0.005 / -0.006	±0.005
Modelling: Diboson	+0.056 / -0.056	±0.056
Modelling: VH	+0.147 / -0.051	±0.099
Detector: lepton	+0.010 / -0.006	±0.008
Detector: MET	+0.012 / -0.011	±0.012
Detector: JET	+0.044 / -0.021	±0.033
Detector: FTAG (b-jet)	+0.066 / -0.051	±0.058
Detector: FTAG (c-jet)	+0.094 / -0.081	±0.087
Detector: FTAG (l-jet)	+0.032 / -0.029	±0.031
Detector: FTAG (extrap)	+0.020 / -0.019	±0.019
Detector: PU	+0.005 / -0.003	±0.004
Lumi	+0.027 / -0.009	±0.018
MC stat	+0.146 / -0.161	±0.153



Evidence paper results

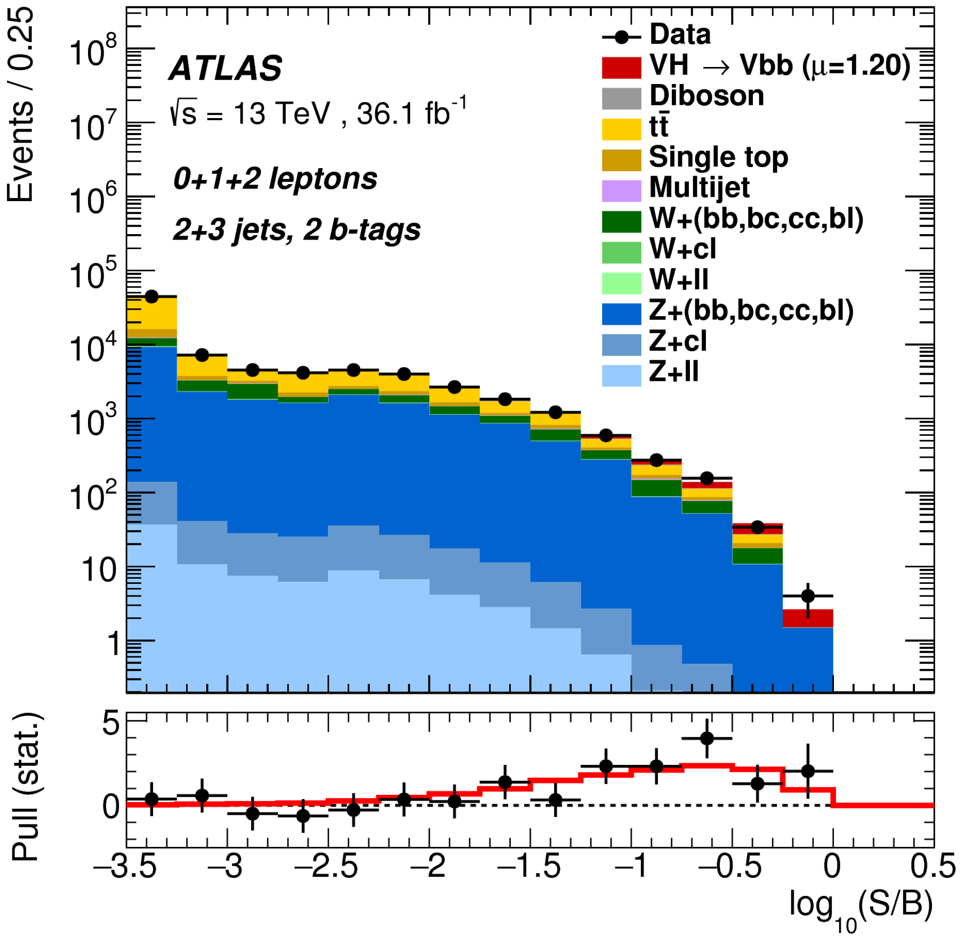






Dataset	p_0		Significance	
	Exp.	Obs.	Exp.	Obs.
0-lepton	4.2%	30%	1.7	0.5
1-lepton	3.5%	1.1%	1.8	2.3
2-lepton	3.1%	0.019%	1.9	3.6
Combined	0.12%	0.019%	3.0	3.5

Evidence paper results



Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
$E_{\mathrm{T}}^{\mathrm{miss}}$		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

- m_{bb}: invariant mass of the dijet system constructed from the two b-tagged jets
- $\Delta R(b_1, b_2)$: distance in η and ϕ between the two b-tagged jets
- $p_T^{b_1}$: transverse momentum of the b-tagged jet in the dijet system with the higher p_T
- $p_T^{b_2}$: transverse momentum of the b-tagged jet in the dijet system with the lower p_T
- p_T^V: transverse momentum of the vector bosos; given by E_T^{miss} in the 0 lepton channel, vectorial sum of E_T^{miss} and the transverse momentum of the lepton in the 1 lepton channel and vectorial sum of the transverse momenta of the two leptons in the 2 lepton channel
- $\Delta\phi(V, bb)$: distance in ϕ between the vector boson candidate, i.e. E_T^{miss} in the 0 lepton channel, E_T^{miss} and the lepton in the 1 lepton channel and the di-lepton system in the 2 lepton channel, and the Higgs boson candidate, i.e. the dijet system constructed from the two b-tagged jets
- p_T^{jet3}: transverse momentum of the jet with the highest transverse momentum amongst the jets that are not b-tagged; only used for events with 3 or more jets
- m_{bbj}: invariant mass of the two b-tagged jets and the jet with the highest transverse momentum amongst the jets that are not b-tagged; only used for events with 3 or more jets

0 lepton channel uses two additional variables:

- $|\Delta\eta(b_1, b_2)|$: distance in η between the two b-tagged jets
- m_{eff} : scalar sum of E_T^{miss} and the p_T of all jets present in the event

1 lepton channel uses two additional variables:

- E_T^{miss}: missing transverse energy of the event
- $min[\Delta\phi(l, b)]$: distance in ϕ between the lepton and the closest b-tagged jet
- m_T^W : transverse mass of the W boson candidate, more details see 5.3
- $\Delta Y(V, bb)$: difference in rapidity between the Higgs boson candidate and W boson candidate, the four-vector of the neutrino in the W boson decay is estimated as explained in Section 5.3 for m_{top}.
- m_{top}: reconstructed mass of the leptonically decaying top quark, more details see Section 5.3.

2 lepton channel uses three additional variables:

- E_T^{miss} significance: quasi-significance of the E_T^{miss} in the event, defined as $E_T^{miss}/\sqrt{S_T}$ with S_T the scalar sum of the p_T of the leptons and jets in the event.
- $|\Delta\eta(V, bb)|$: distance in η between the dilepton and dijet system of the b-tagged jets
- m_{ll}: invariant mass of the dilepton system