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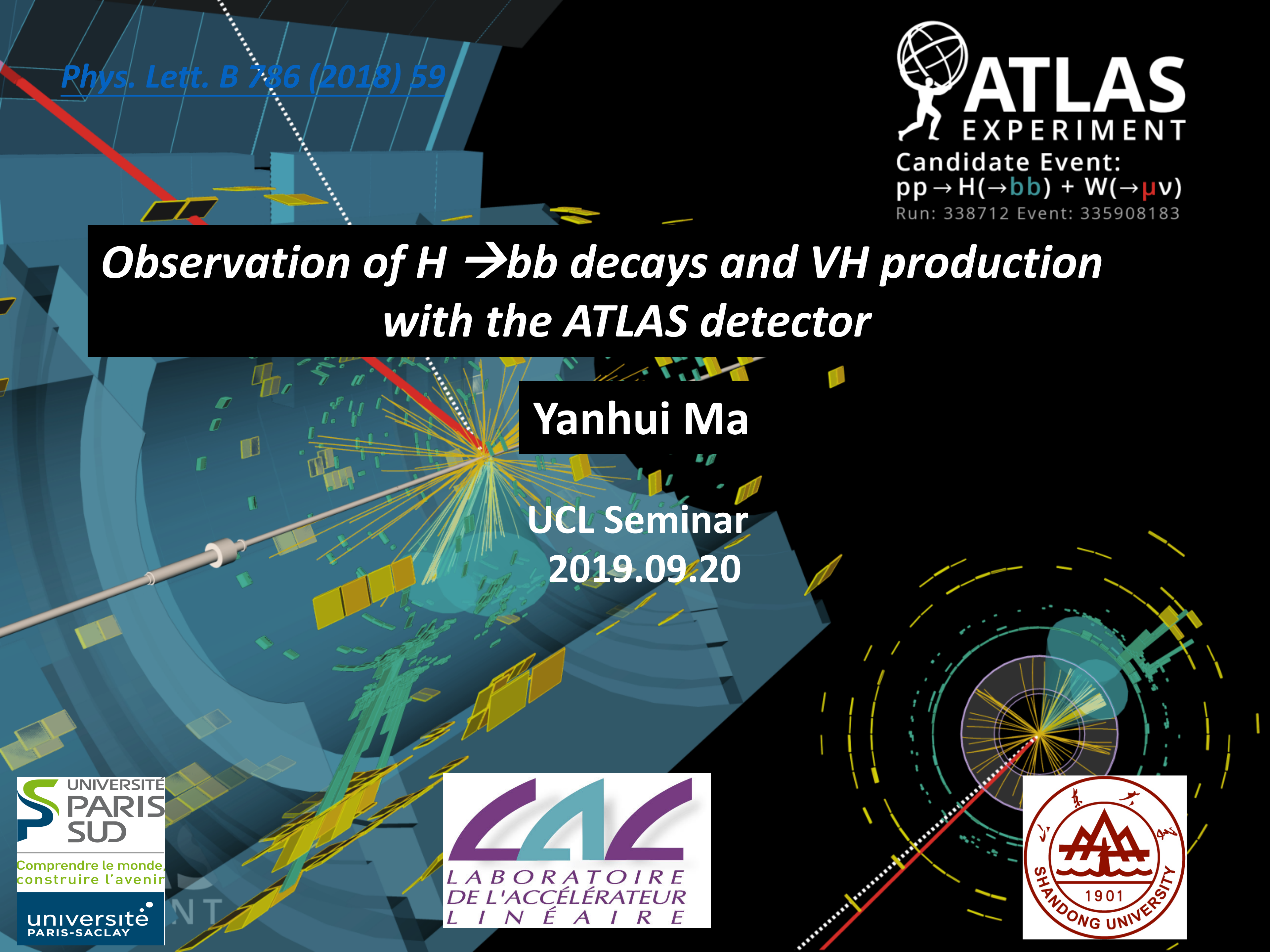

Observation of H →bb decays and VH production with the ATLAS detector

Yanhui Ma

UCL Seminar
2019.09.20

UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir
université PARIS-SACLAY

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

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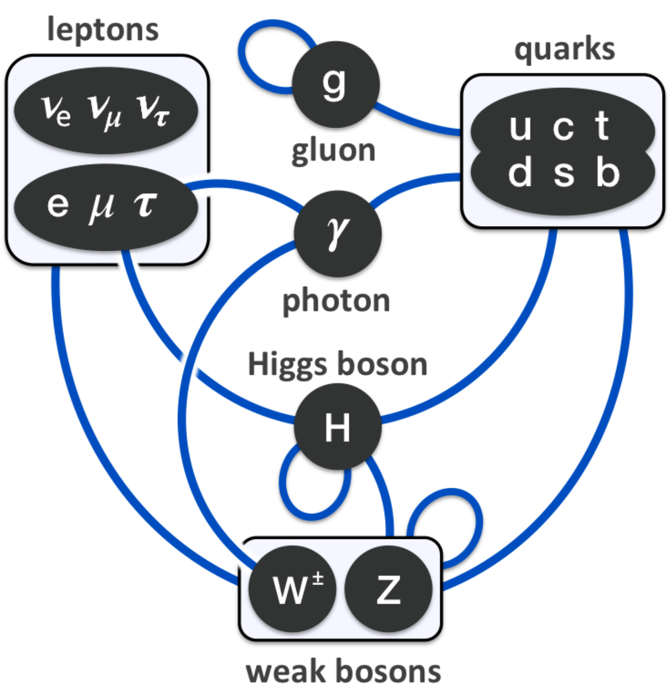
Outline

- Higgs boson physics and the role of $H \rightarrow bb$
- Run 2 VH(bb) analysis with $80 fb^{-1}$ data
- Combinations with the other results
- Conclusion and outlook

The Higgs boson in the Standard Model (SM)

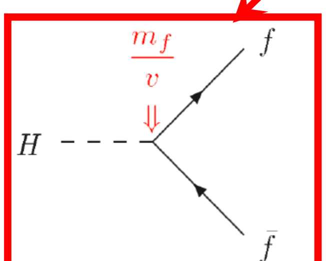
- The SM is the most thoroughly tested theory of particle physics that has had a great success to explain experimental results of particle physics.

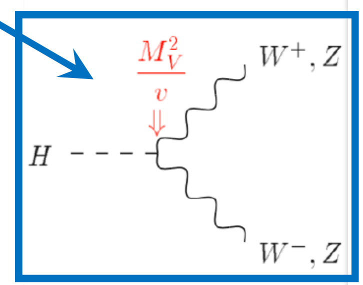
- In the SM, the Higgs mechanism provides masses to bosons and fermions



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

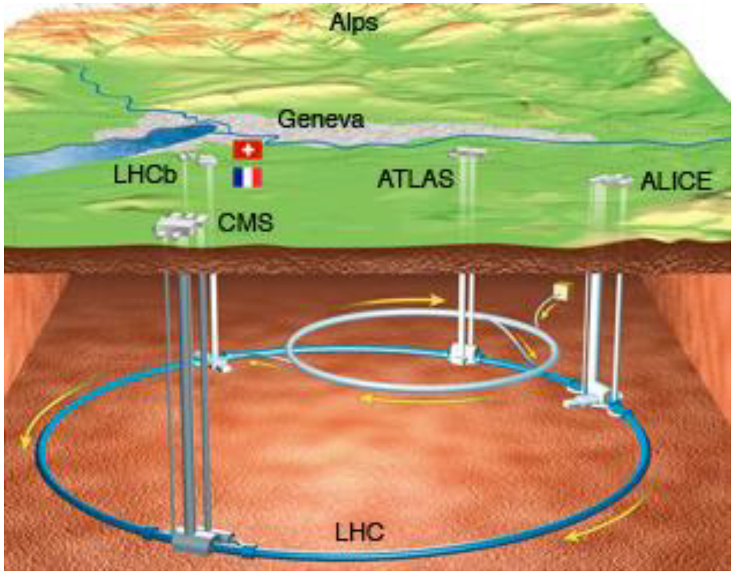
Higgs boson was discovered in 2012 with a mass ~125 GeV.



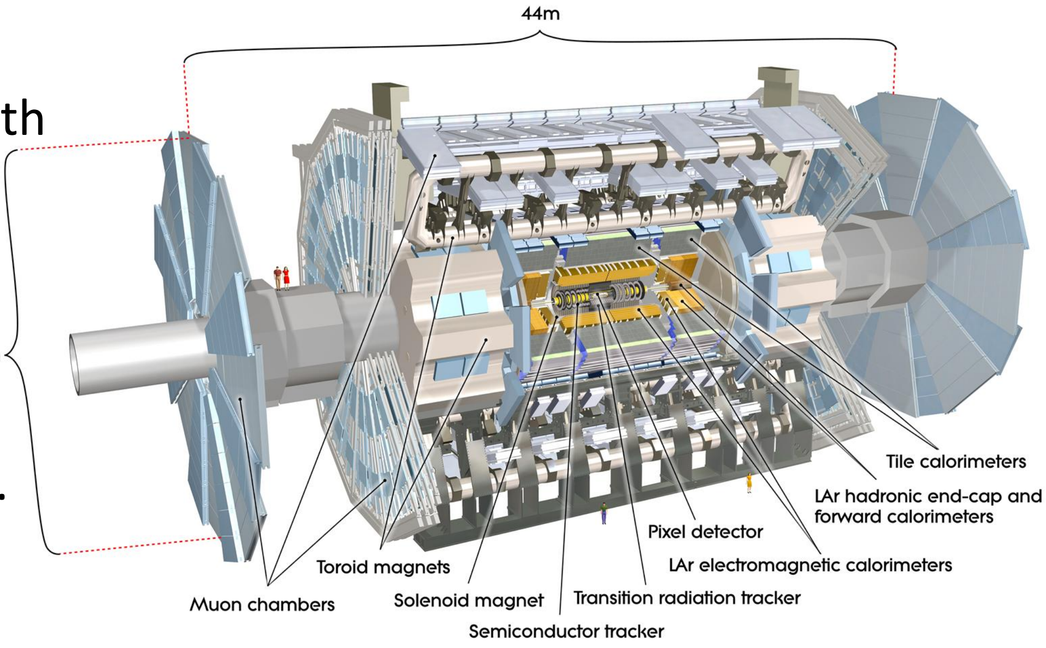


The LHC collider and the ATLAS detector

- 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.

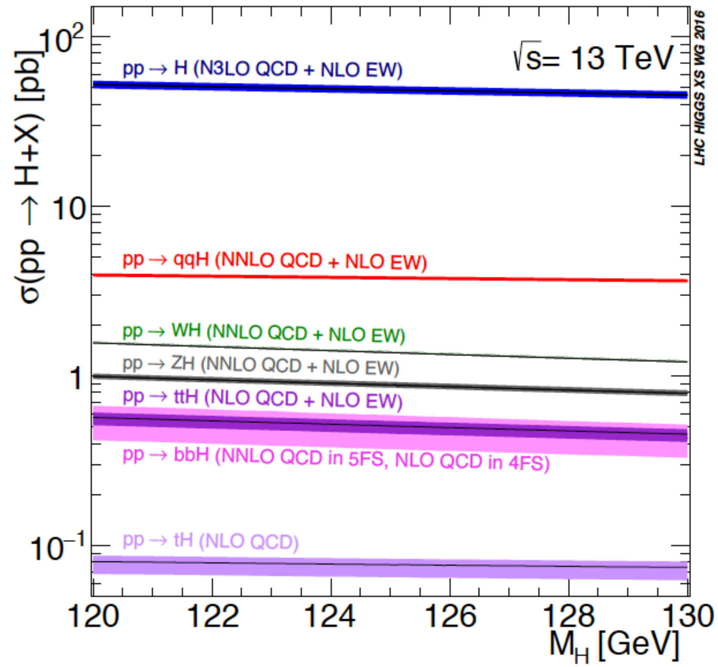


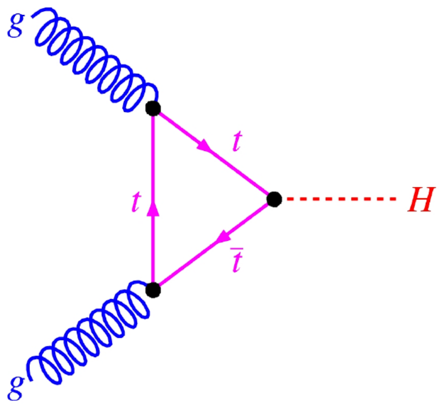
- World's largest particle detector with a diameter of 25 m and length of 44 m.
- General-purpose detector, designed mainly to search for the Higgs boson and new physics.



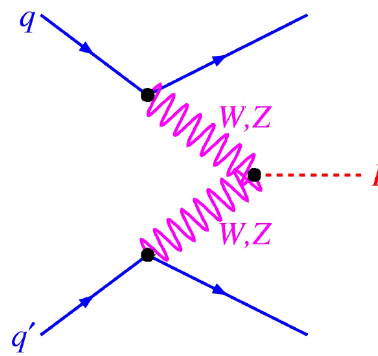
Higgs boson phenomenology at the LHC

- **4 main production** at the LHC
- total cross section 56 pb at 13 TeV
- ggF the dominant mode

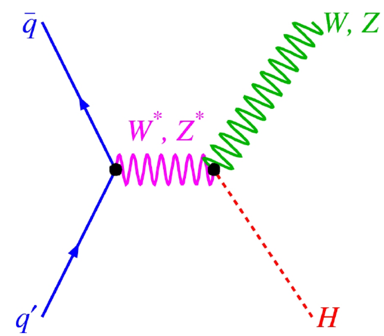




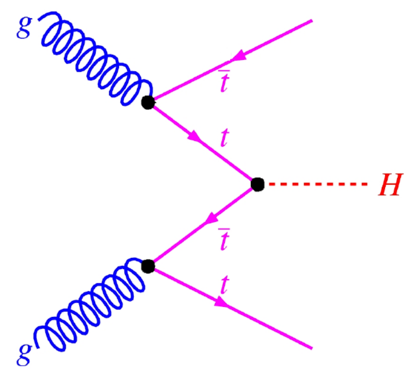
Gluon fusion (ggF)
88% of the total



Vector boson fusion (VBF)
7% of the total



VH (V=W/Z)
3% of the total

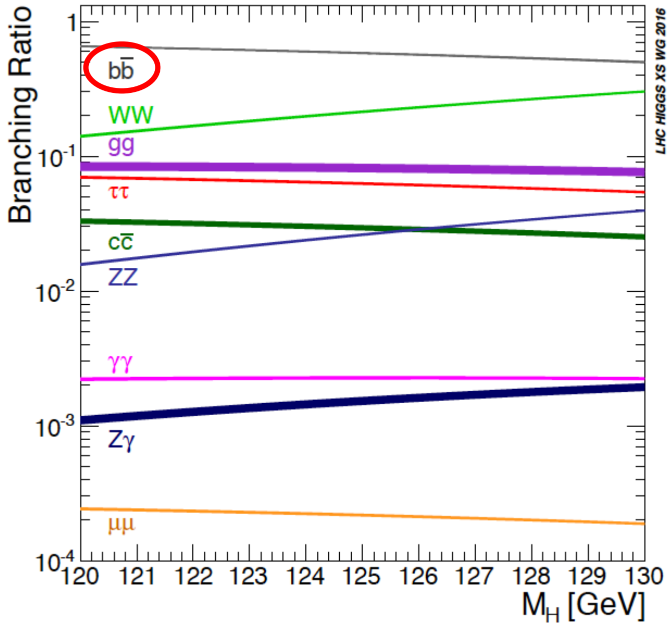


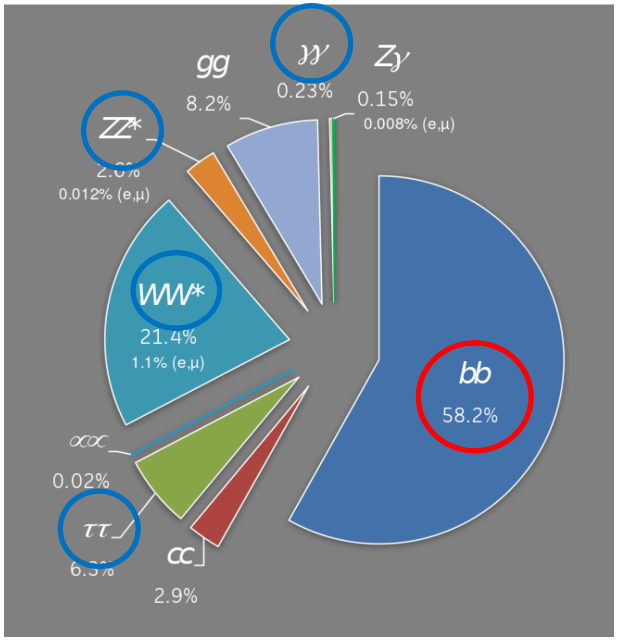
ttH
1% of the total

Higgs boson phenomenology at the LHC

- ➢ Observed decays ~ 31% by Run 1 data
- ➢ Dominant bb decay, BR ~ 58%

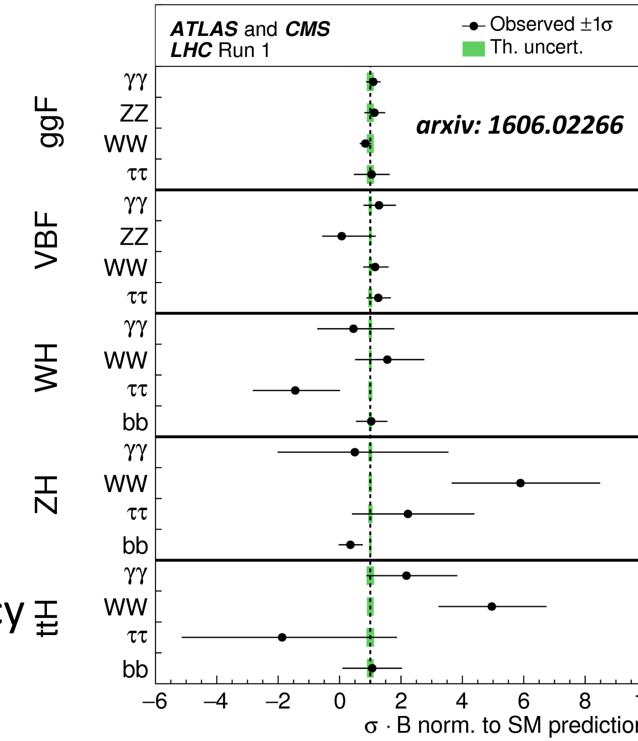
- Provides direct probe of coupling to fermions
- Drives the uncertainty on the total decay width, and thus on measurement of absolute couplings
- The more Higgs boson decays we see, the less "space" remains available for "undetected/invisible" decays

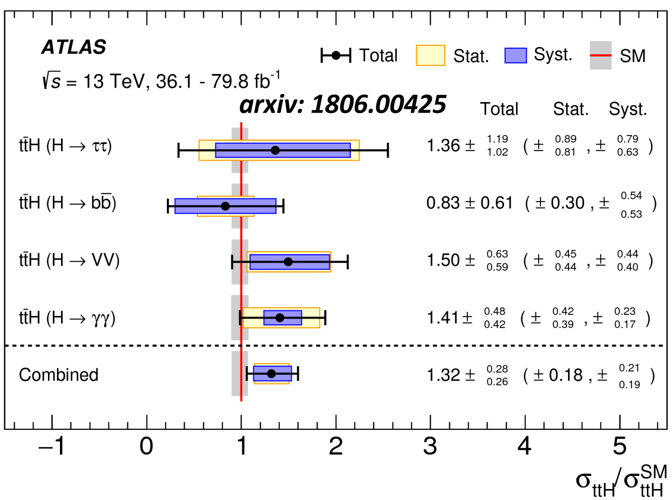




Higgs hunting status in Spring 2018

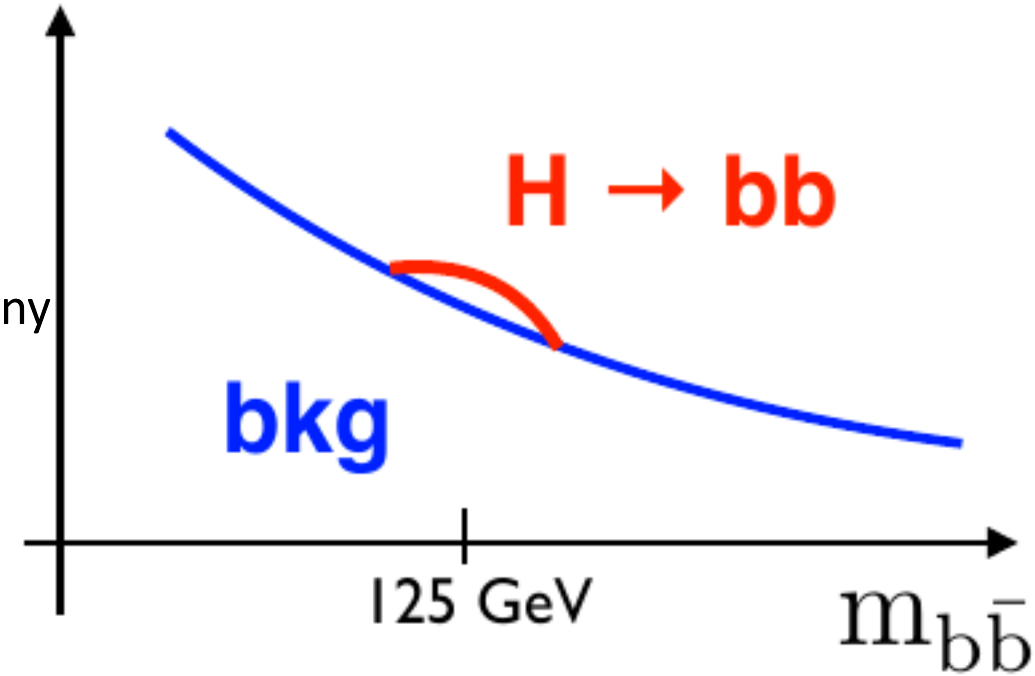
- Run 1 Achievements
  - ggF and VBF production mode observed
  - Observation of decays to vector bosons (γ,W,Z)
  - Observation of Yukawa couplings to τ leptons
- Run 2 Achievements
  - Many measurements much better than Run 1 accuracy
  - Direct top Yukawa coupling observation
  - Evidence of the H→bb decay (36 fb^{-1} data)
- Observation of H→bb decays and VH production still missing
- Yukawa coupling to second generation fermions not yet in reach





Why is H→bb so difficult in term of the largest BR

- Very large multi-b-jets production cross section at the LHC



- Without additional handles, signal overwhelmed by background by many orders of magnitude

- Production modes with additional signatures can help reduce the backgrounds

  - ggF: only possible in very boosted regime
  - VBF: still in fully hadronic final state, challenging for trigger and background modelling; additional γ helps
  - VH: leptonic signatures for trigger and multi-jet background suppression; Most sensitive channel
  - ttH: give access also to top quark coupling

Previous VH, H→bb results (with mH~125 GeV)

	Signal strength	Significance (expected)	Significance (Observed)	References
Tevatron Legacy	$1.9^{+0.8}_{-0.7}$	1.5σ	2.8σ	arXiv:1207.6436
ATLAS Run 1	$0.52^{+0.40}_{-0.37}$	2.6	1.4	arXiv:1409.6212
CMS Run1	$0.89^{+0.47}_{-0.44}$	2.5	2.1	arXiv:1310.3687
LHC Run 1 Combination	$0.70^{+0.29}_{-0.27}$	3.7	2.6	arXiv:1606.02266
ATLAS Run 2 2015-2016	$1.20^{+0.42}_{-0.36}$	3.0	3.5	arXiv:1708.03299
CMS Run 2 2015-2016	$1.19^{+0.40}_{-0.38}$	2.8	3.3	arXiv:1709.07497

- The analysis described in this seminar is based on 80 fb^{-1} of good quality Run-2 data collected from 2015 to 2017

- Analysis already dominated by systematic uncertainties

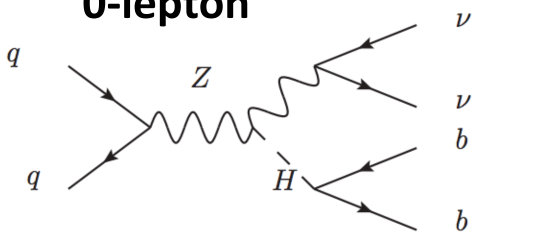
Larger pile-up; Adding new data not enough;
Better control of the main backgrounds; Precision on jets and b-tagging calibration

ATLAS Run 2 VH, H→bb analysis with 80 fb^{-1} data

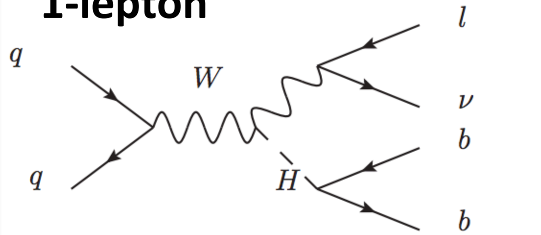
Looking for VH, H→bb

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

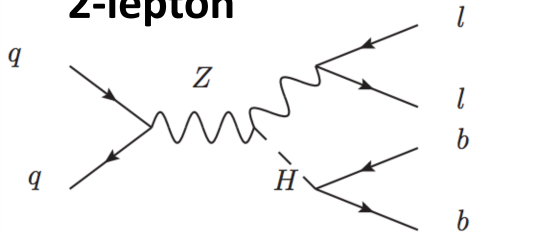
0-lepton



1-lepton



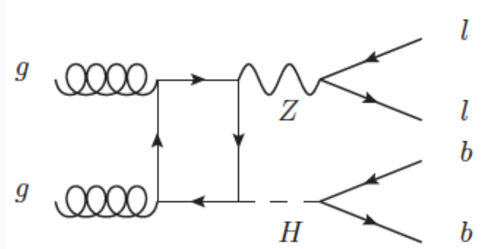
2-lepton



- H→bb decays
  - Two high pT b-jets
  - Possibly additional jets

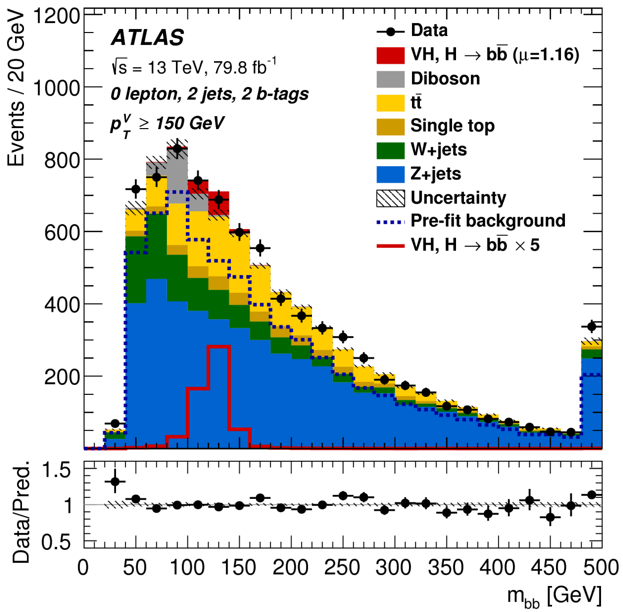
Process	$\sigma \times \mathcal{B}$ [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$qq \to ZH \to \ell\ell b\bar{b}$	29.9	<0.1	0.1	6.0
$gg \to ZH \to \ell\ell b\bar{b}$	4.8	<0.1	0.2	13.5
$qq \to WH \to \ell\nu b\bar{b}$	269.0	0.2	1.0	–
$qq \to ZH \to \nu\nu b\bar{b}$	89.1	1.9	–	–
$gg \to ZH \to \nu\nu b\bar{b}$	14.3	3.5	–	–

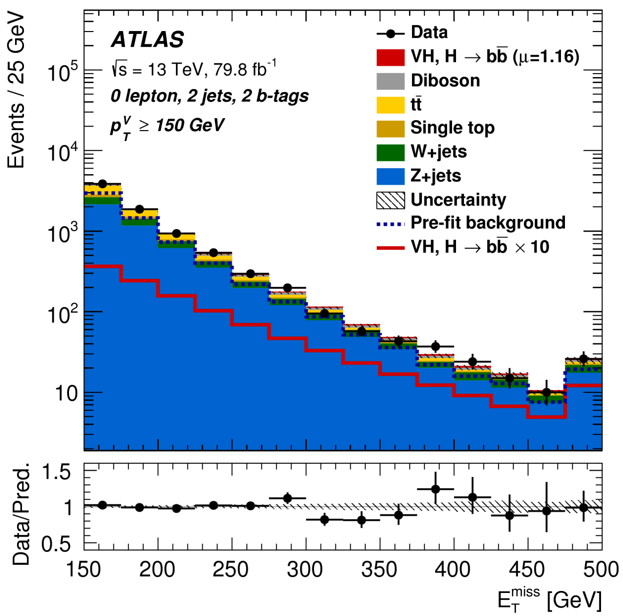
- Additional gg induced diagrams for ZH



Event selection---0 lepton channel

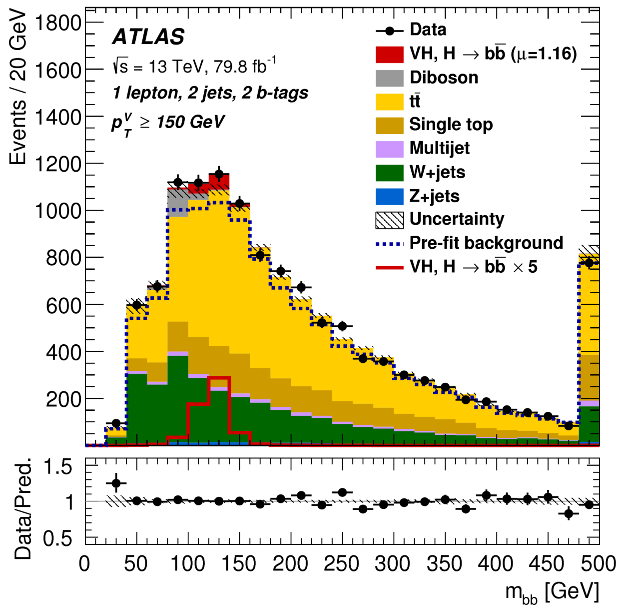
- **Z boson selection**
  - E_T^{miss} trigger
  - Veto leptons with p_T>7 GeV
  - E_T^{miss} > 150GeV
- **Higgs boson candidate selection**
  - 2 b-tagged jets, p_T > 45 (20) GeV
  - 1 additional jet max (reducing ttbar)
- **Multijet Background rejection**
  - A set of angular cuts remove it completely
- **About 20% of expected signal events are WH(τν)**

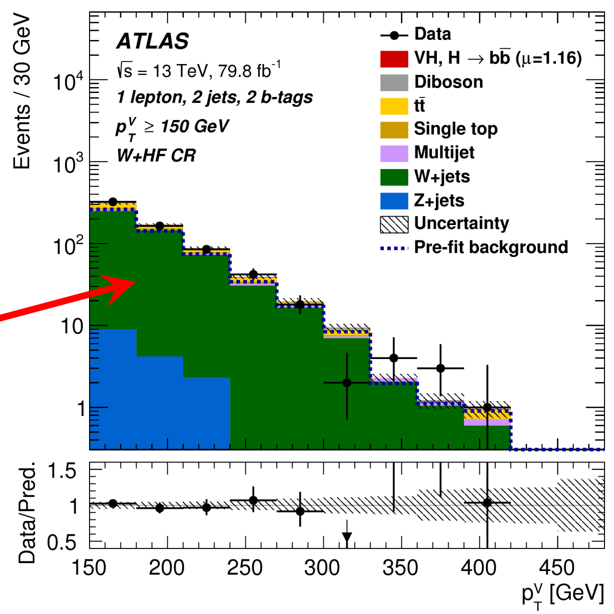




Event selection---1 lepton channel

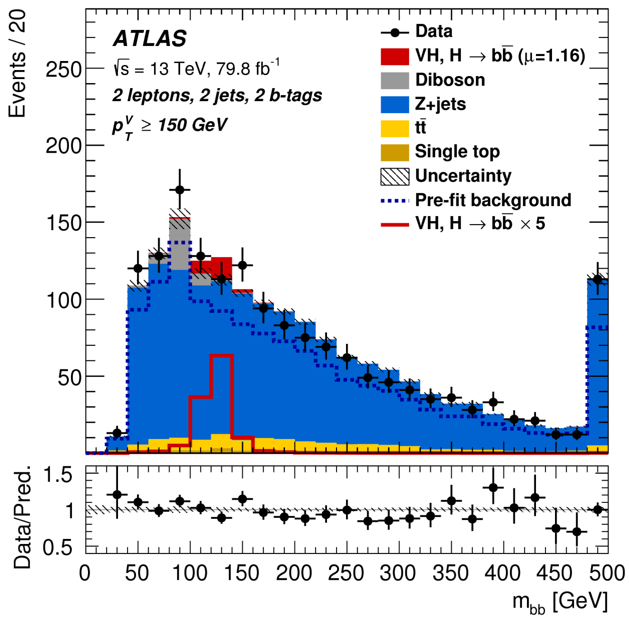
- **W boson selection**
  - Single-electron or E_T^{miss} trigger
  - Well identified, isolated electron (>27 GeV) or muon (>25 GeV)
  - Veto additional leptons p_T>7 GeV
  - p_T^W > 150GeV
- **Higgs boson candidate selection**
  - 2 b-tagged jets, p_T > 45 (20) GeV
  - 1 additional jet max (reducing 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%





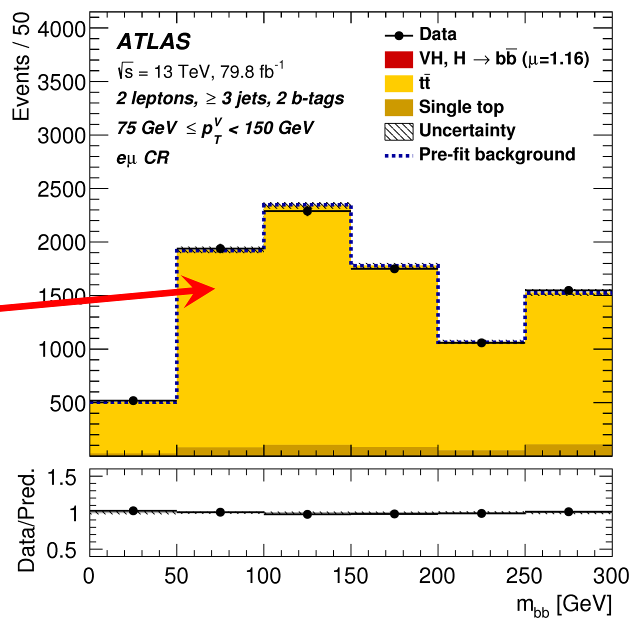
Event selection---2 lepton channel

- **Z boson selection**
  - Single-lepton triggers
  - 2 electrons or muons, p_T>27 (7) GeV
  - Z mass 81 < m_{ll} < 101 GeV
  - 75 GeV < p_T^Z < 150 GeV or p_T^Z > 150GeV



- **Higgs boson candidate selection**
  - 2 b-tagged jets, p_T > 45 (20) GeV
  - 0 or >=1 additional jet

- **Top eμ control region**
  - Opposite-flavour events
  - Purity ~ 99%



Analysis key elements

- First ATLAS sensitivity studies ~20 years ago predicted marginal sensitivity to VH, H → bb, based on projections to 30 fb^{-1} of 14 TeV data

- What enables H→bb at the LHC

  - Thanks to the excellent LHC and ATLAS performance, > 100 fb^{-1} of data were collected at centre-of-mass-energy of 7 TeV, 8 TeV and 13 TeV.

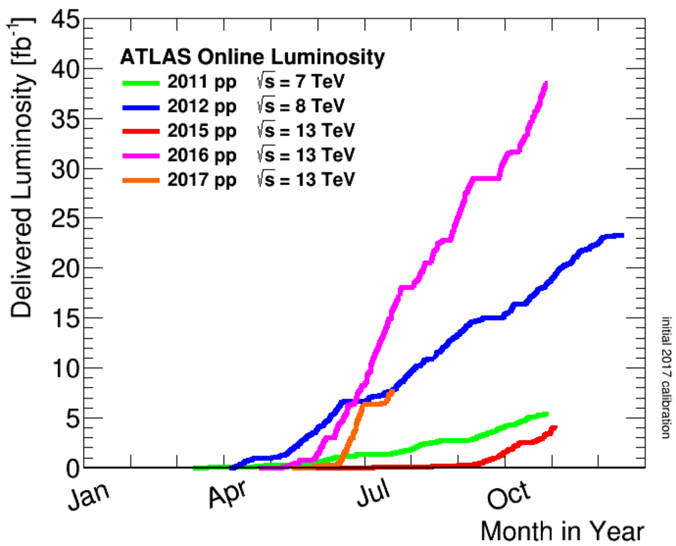
  - Excellent object identification performance (especially for B-jet identification)

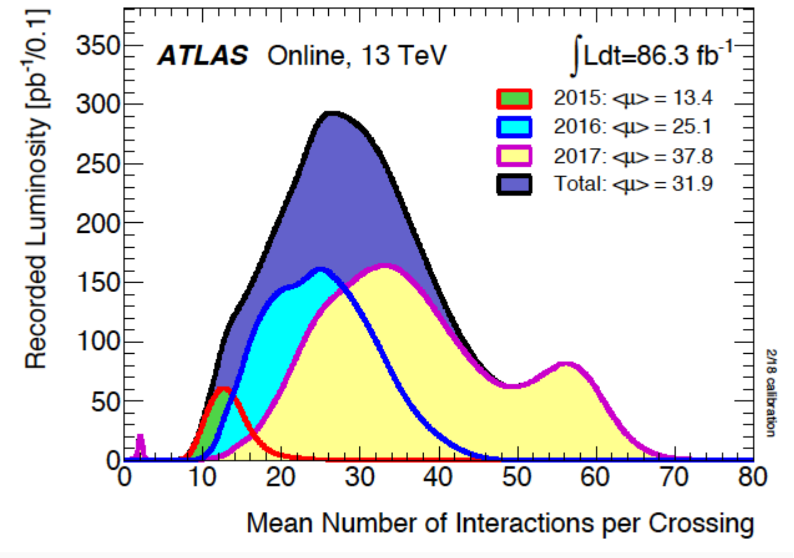
  - The “high pT” regime

  - Improved Dijet mass resolution

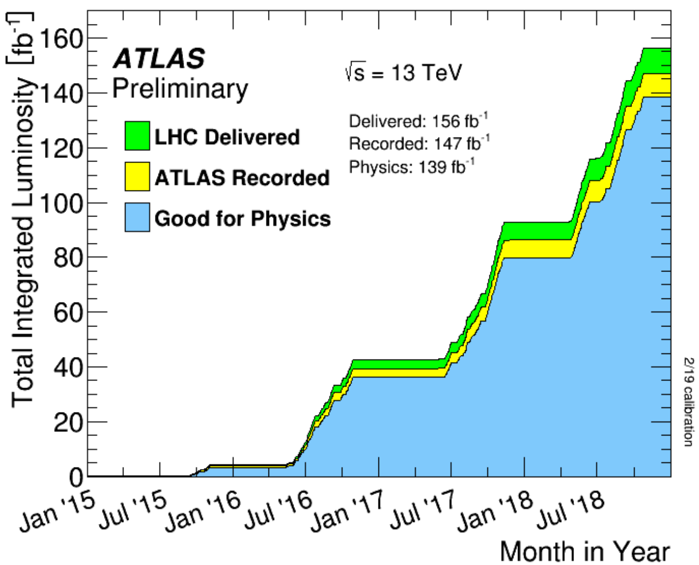
  - Multivariate analysis techniques

Analysis key elements---data



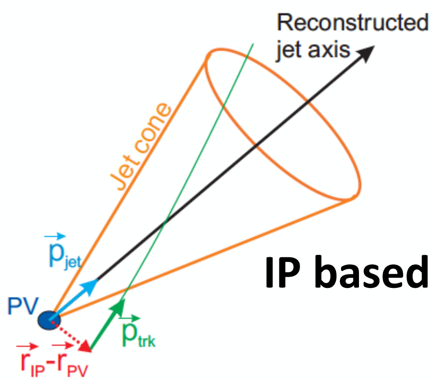


- Stunning performance of the LHC: lumi up to 2 $*10^{34}$ cm^{-2} s^{-1}
- Excellent operation of the ATLAS detector, high data quality
- High rates and large pile-up: Challenges for triggers, jets reconstruction, b-tagging...

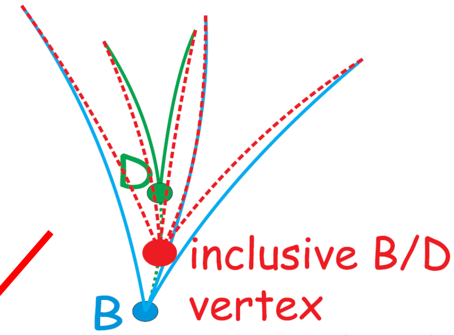


Analysis key elements---b-tagging

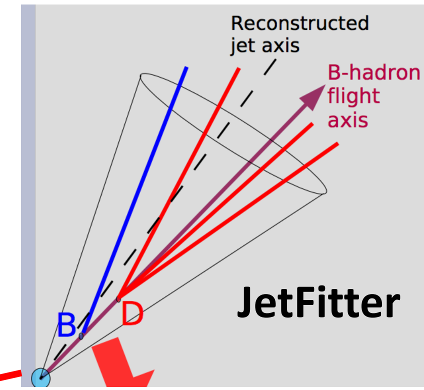
- Excellent object identification performance is the key ingredients for H→bb, especially for the b-tagging identification.



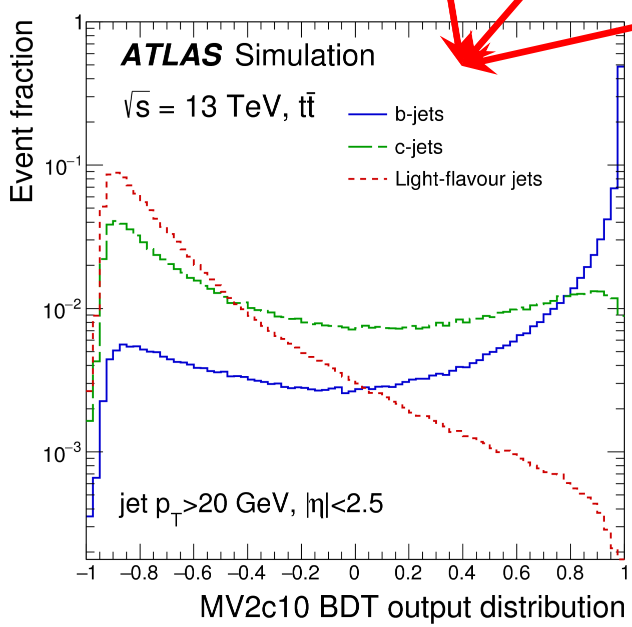
IP based (IP2D, IP3D)



secondary vertex (SV1)



JetFitter

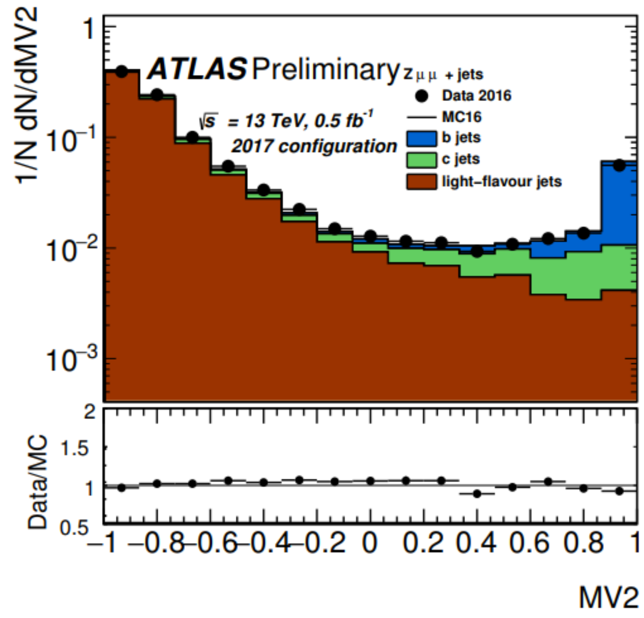


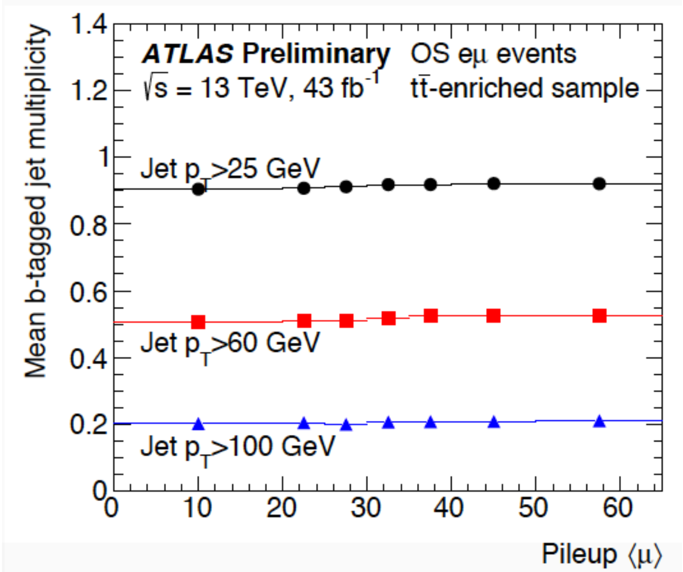
- Multi Variate Analysis (BDT) to combine observables into a single discriminant.
- 70% b-jets efficiency working point has been choose for the analysis

Analysis key elements---b-tagging

➢ **Run 2 performance**

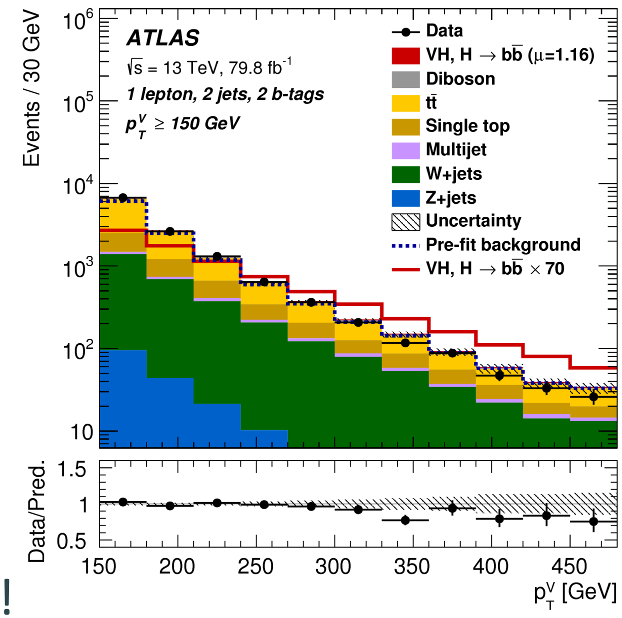
- New IBL detector installed in LS1 (2013-2014)
- Tracking optimized for high-PU and high-pT environments
- Better ML algorithms
- At 70% b-jets efficiency, the rejection factor of light and c-jets are 300 and 8, respectively.
- Well modelled in simulation
- Good performance even at high pile-up

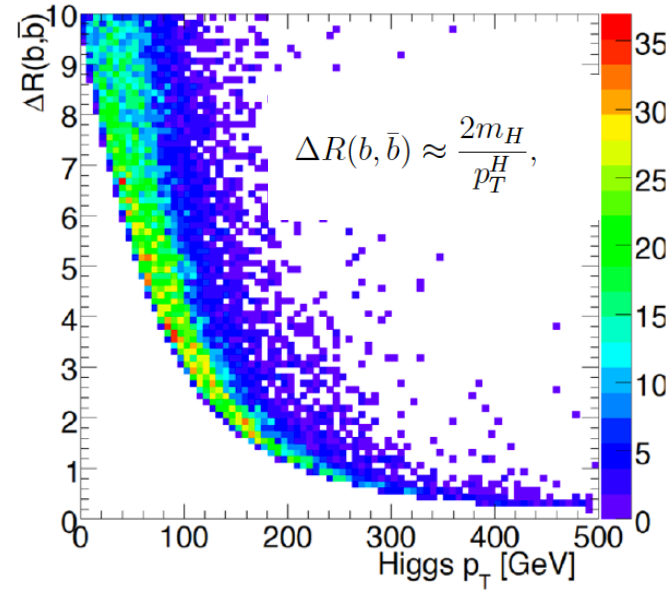




Analysis key elements--- The "high pT" regime

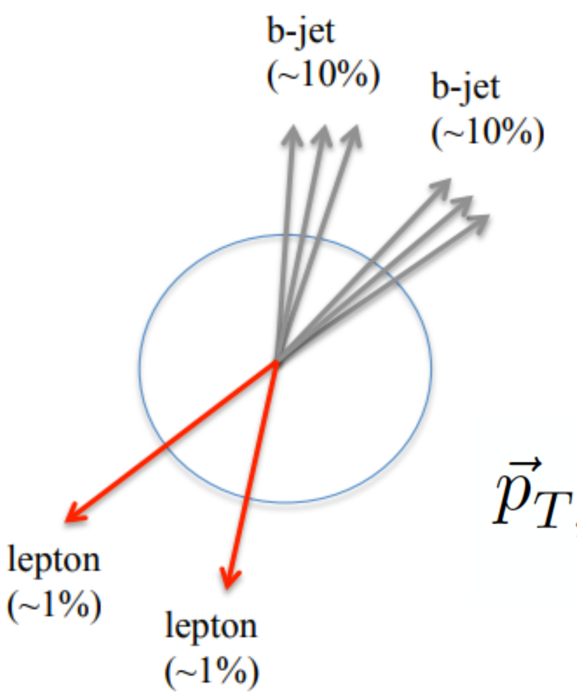
- Requiring high pT(V) (or pT(H)) suppresses background significantly more than signal, improving S/B ratio
- Exploited in event categorization:
  - 75 < pT(V) ≤ 150 GeV (2-lepton)
  - pT(V) > 150 GeV (all channels)
- Need large bkg MC statistics in tails of distributions!
- H→bb is a simple 2-body decay
  - At high pT, can cut hard on ΔR_{bb} with very high signal efficiency
  - Backgrounds (esp. ttbar) significantly suppressed



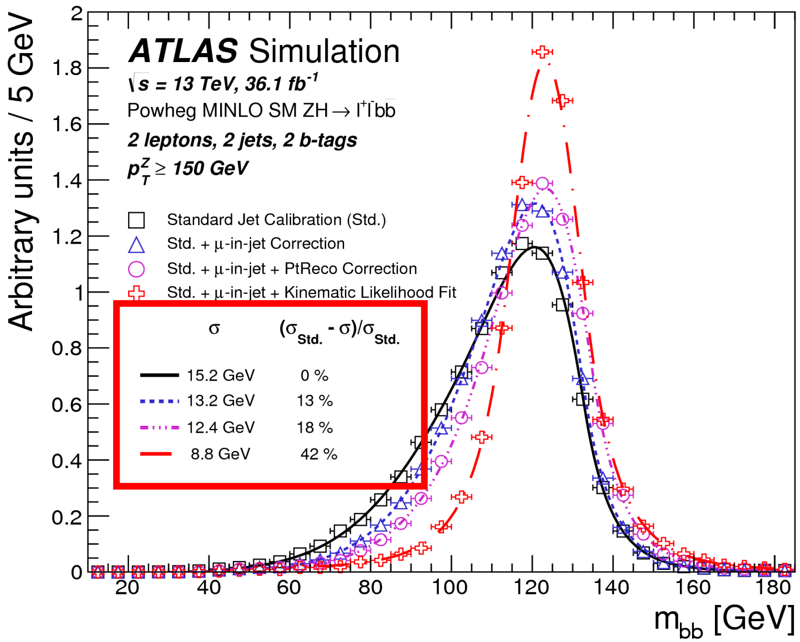


Analysis key elements--- Dijet mass resolution

- **Sharpening signal mass peak** directly improves sensitivity
- if available, **add muon to jet momentum**
- Simple **average jet pT correction**
  - Accounts for neutrinos, and interplay of resolution and pT spectrum effects.
- Mass resolution improvement ~18%



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



- **Kinematic fit** in 2-lepton channel
  - Final state fully reconstructed
  - High resolution on leptons
  - Constrain jet kinematics better
- Mass resolution improvement ~40%

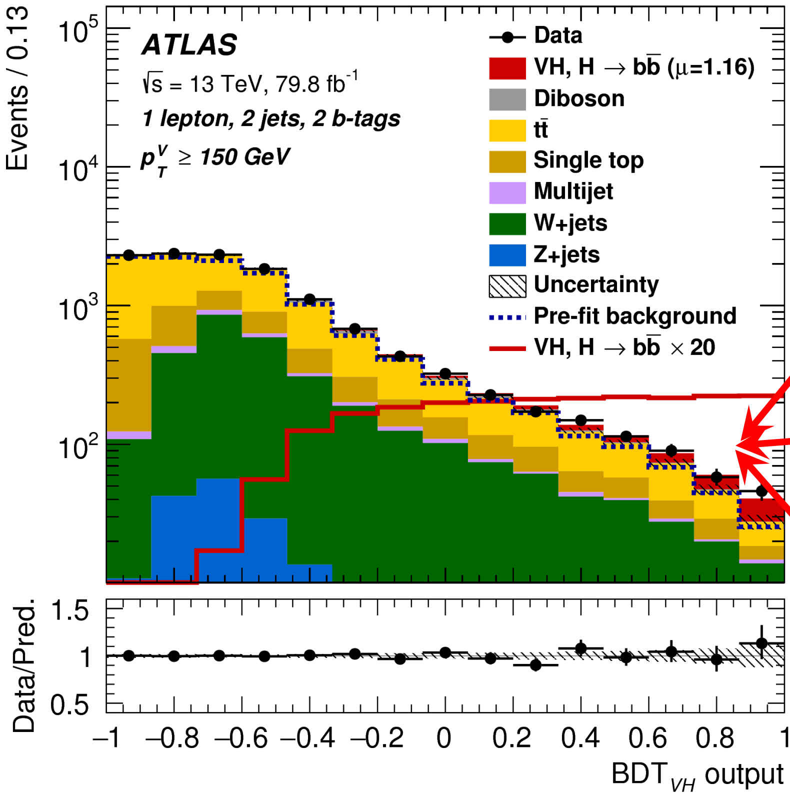
Analysis key elements--- Multi Variate Analysis techniques

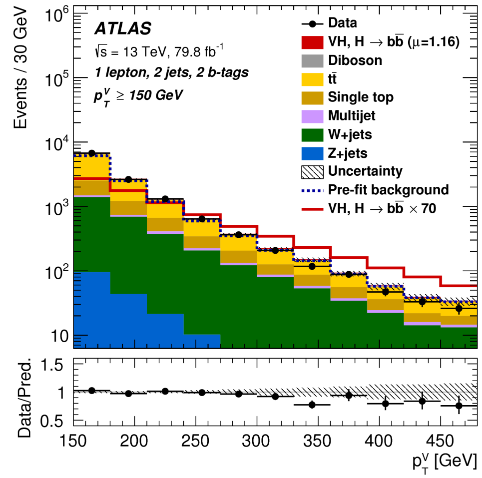
- MVA set up
  - Simple and robust BDT with cross-validation
  - Input variables and hyper parameters tuned to yield best sensitivity
- Inputs variables
  - Kinematic variables, some specific to 3-jet regions.
  - m_{bb}, $\triangle R_{bb}$, p_T^V most important ones.

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

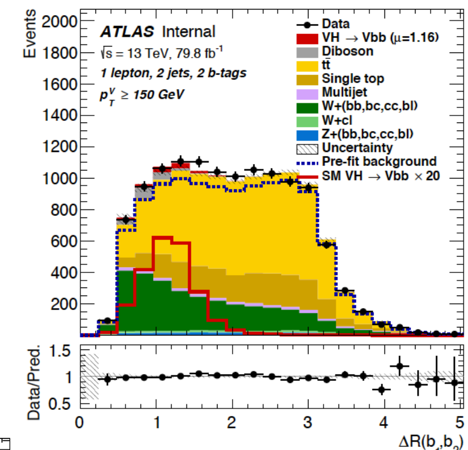
Analysis key elements--- Multi Variate Analysis techniques

- Combine all observables into a single final discriminant
- One BDT per channel and analysis region

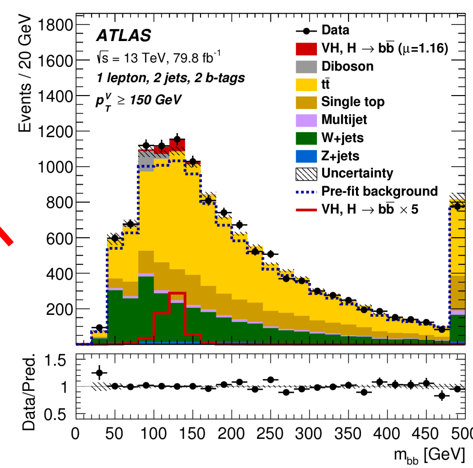




p_T^V



$\triangle R_{bb}$



m_{bb}

Putting all together--- Main analysis strategy

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

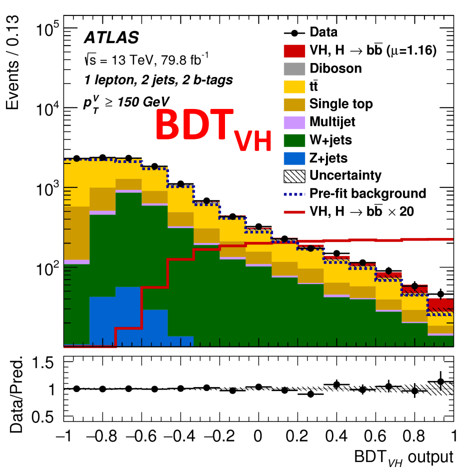
$$\mathcal{L}(\mu,\boldsymbol{\theta}) = \prod_{i=1}^{nbins} \frac{(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))} \times \mathcal{L}_{AUX}(\boldsymbol{\theta}).$$

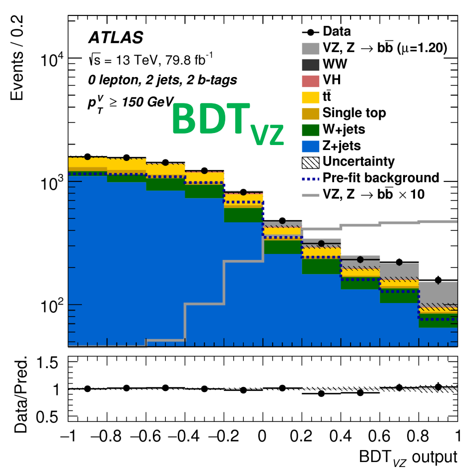
$$\mu = \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}}$$

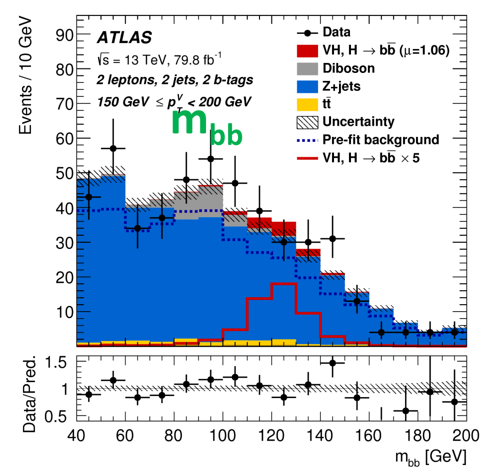
nuisance parameters (NP): sources of systematic uncertainty could have effect on the signal strength measurement

- Shape and relative normalizations across regions parametrized by NP, constrained within allowed systematics uncertainties

- A nominal analysis (main observable: BDT_{VH} output), two validation analyses (main observable: BDT_{VZ} output and m_{bb}).







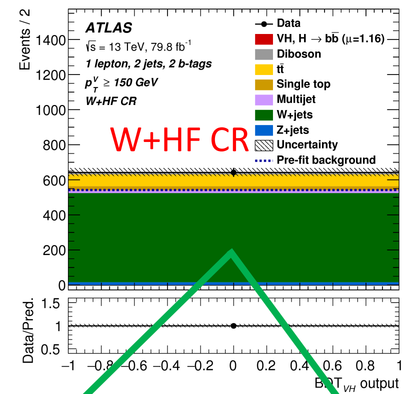
Background modelling---general picture

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

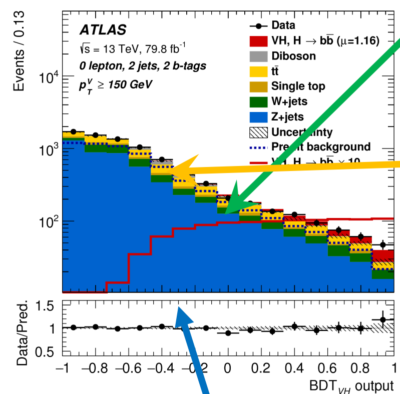
- Constrain (shape and normalization) from data by using high purity control regions

- Main background normalizations floating in the fit.

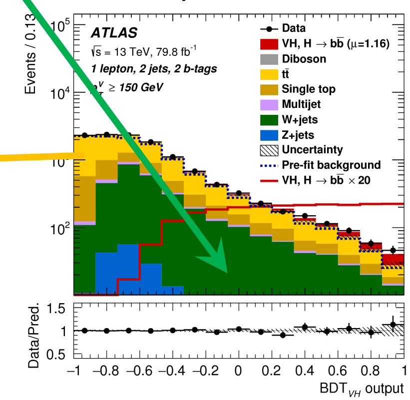
Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
$W+\mathrm{HF}$ 2-jet	1.19 ± 0.12
$W+\mathrm{HF}$ 3-jet	1.05 ± 0.12
$Z+\mathrm{HF}$ 2-jet	1.37 ± 0.11
$Z+\mathrm{HF}$ 3-jet	1.09 ± 0.09



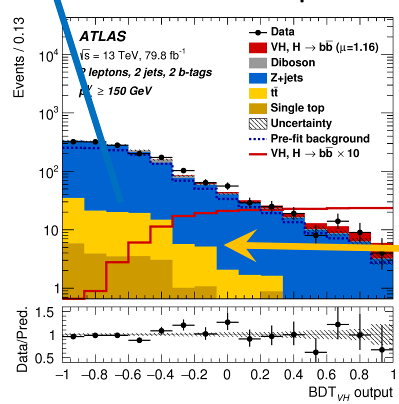
0-lepton

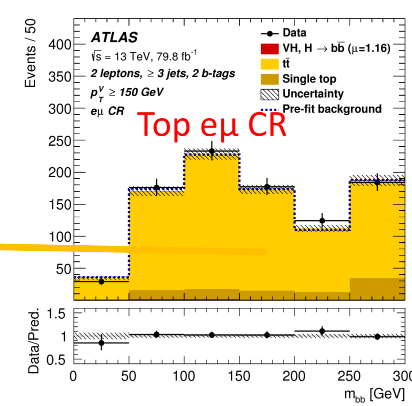


1-lepton



2-lepton





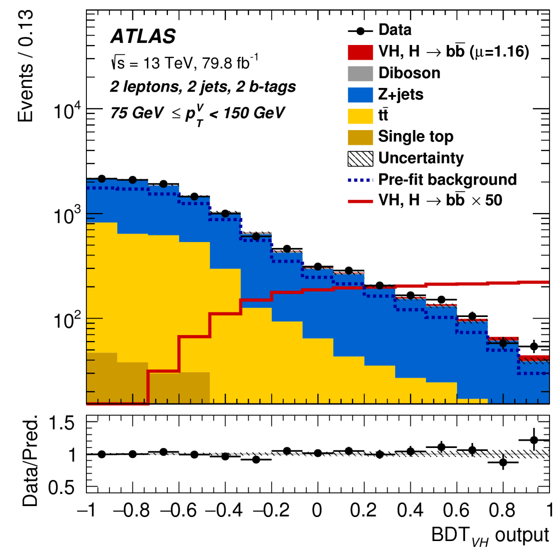
- Parametrize extrapolation uncertainties across regions as uncertainties on ratios of yields.

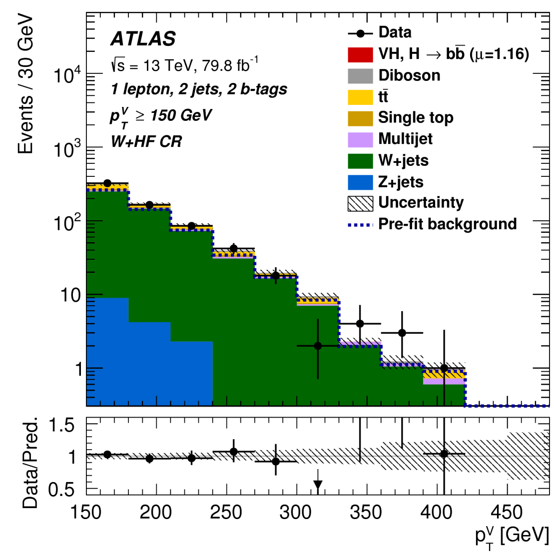
- Shape uncertainties on BDTs.

Background modelling---W/Z +HF

- 2 lepton low pTV region can constrain Z normalizations and shapes
- 1 lepton W+HF CR constrains W norm.
- Normalization factors 1.2 for both Z+hf and W+hf
- Extrapolations to 0-lepton or 1-lepton SR
- Uncertainties on flavour composition

$Z+$ 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





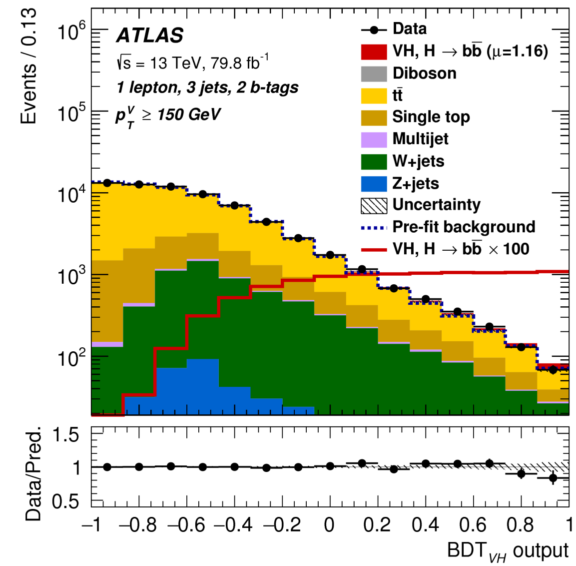
Background modelling---ttbar

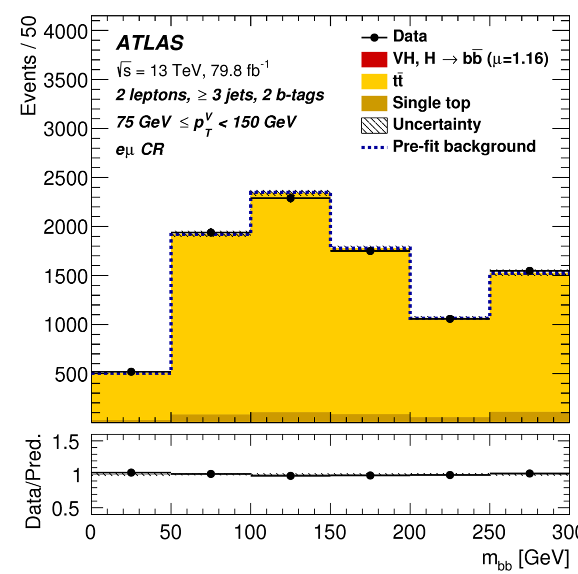
- Due to the very different regions of phase space probed, the ttbar background model in the 2-lepton channel is decorrelated from the 0- and 1-lepton channels

- 0 and 1 lepton: some jets and/or leptons not recontructed, dominant background in 3-jet regions
- 2 lepton: all leptons and jets in the acceptance; very high purity eμ CR

- Normalization factors: 1:0
- Extrapolation to 0/1 lepton 2-jet regions
- Extrapolation to W+ HF CRs

$t\bar{t}$ (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





Signal modelling

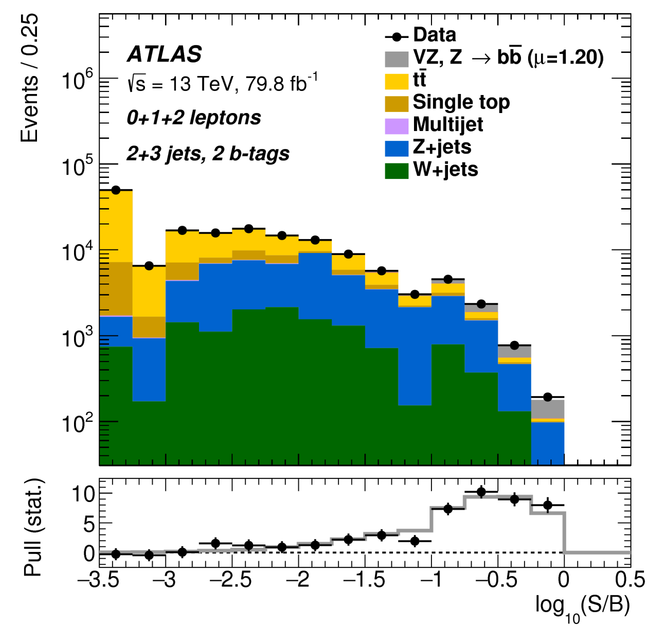
- Standard prescriptions for systematic uncertainties: from theory calculations and from comparisons of Monte Carlo modelling variations, or variations of parameters

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

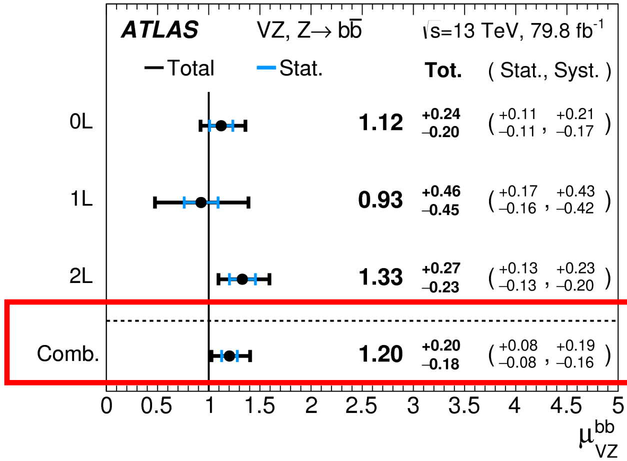
Results

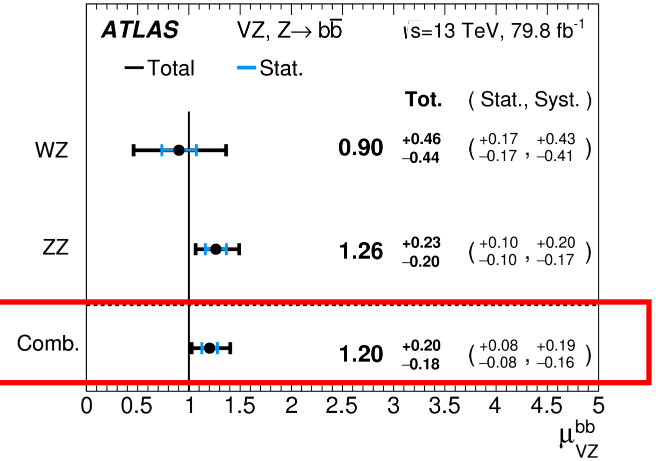
Pre-unbinding validation: Diboson MVA analysis

- 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

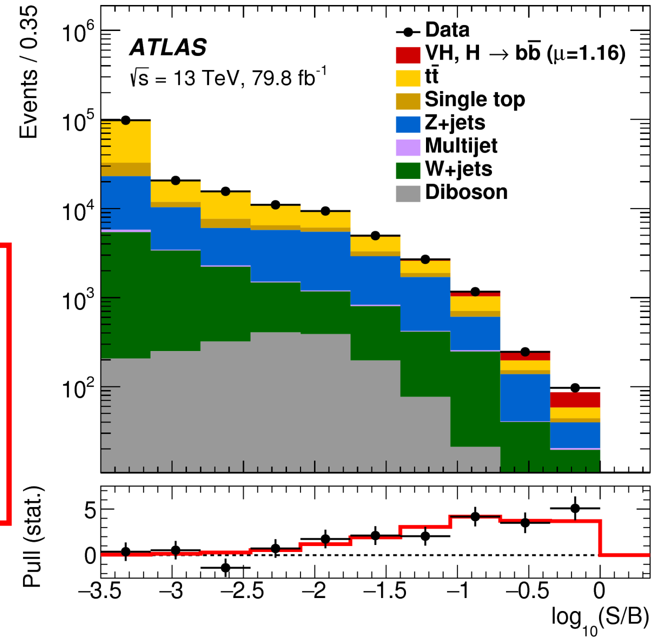




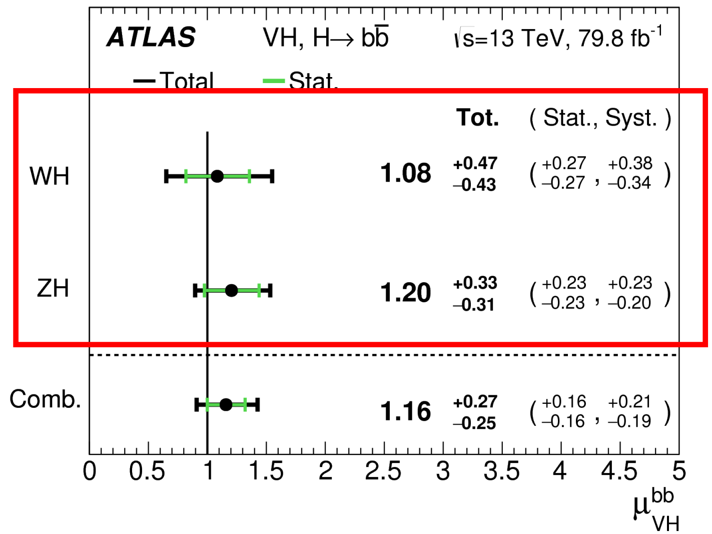
VH MVA analysis results

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

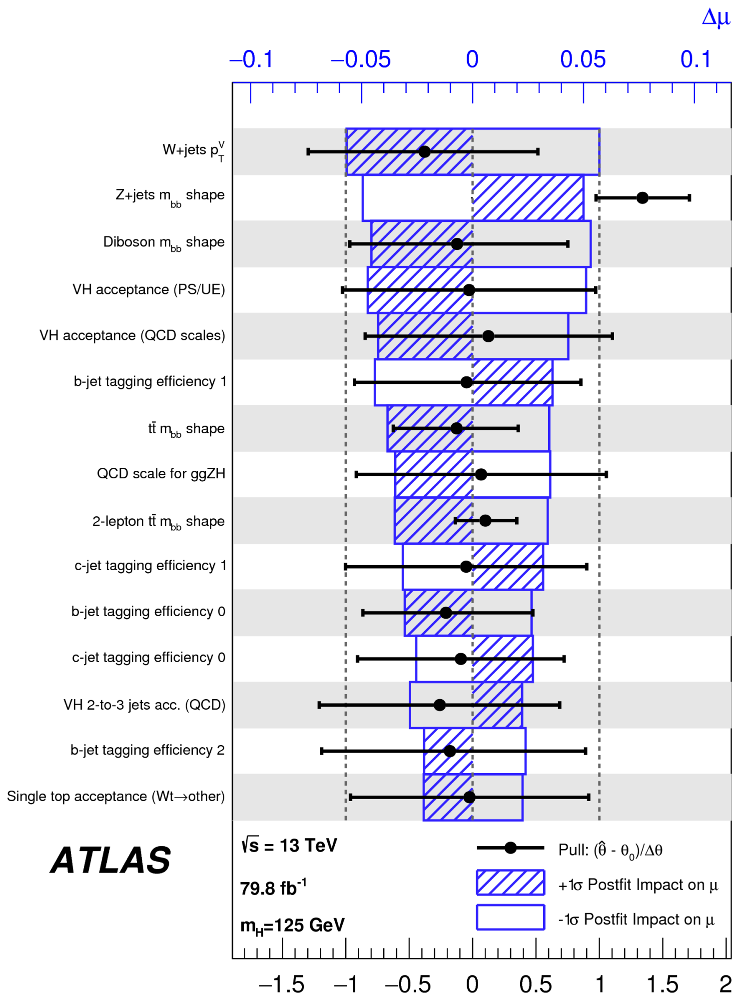
Signal strength	Signal strength	p_0 Exp.	p_0 Obs.	Significance Exp.	Significance Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	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



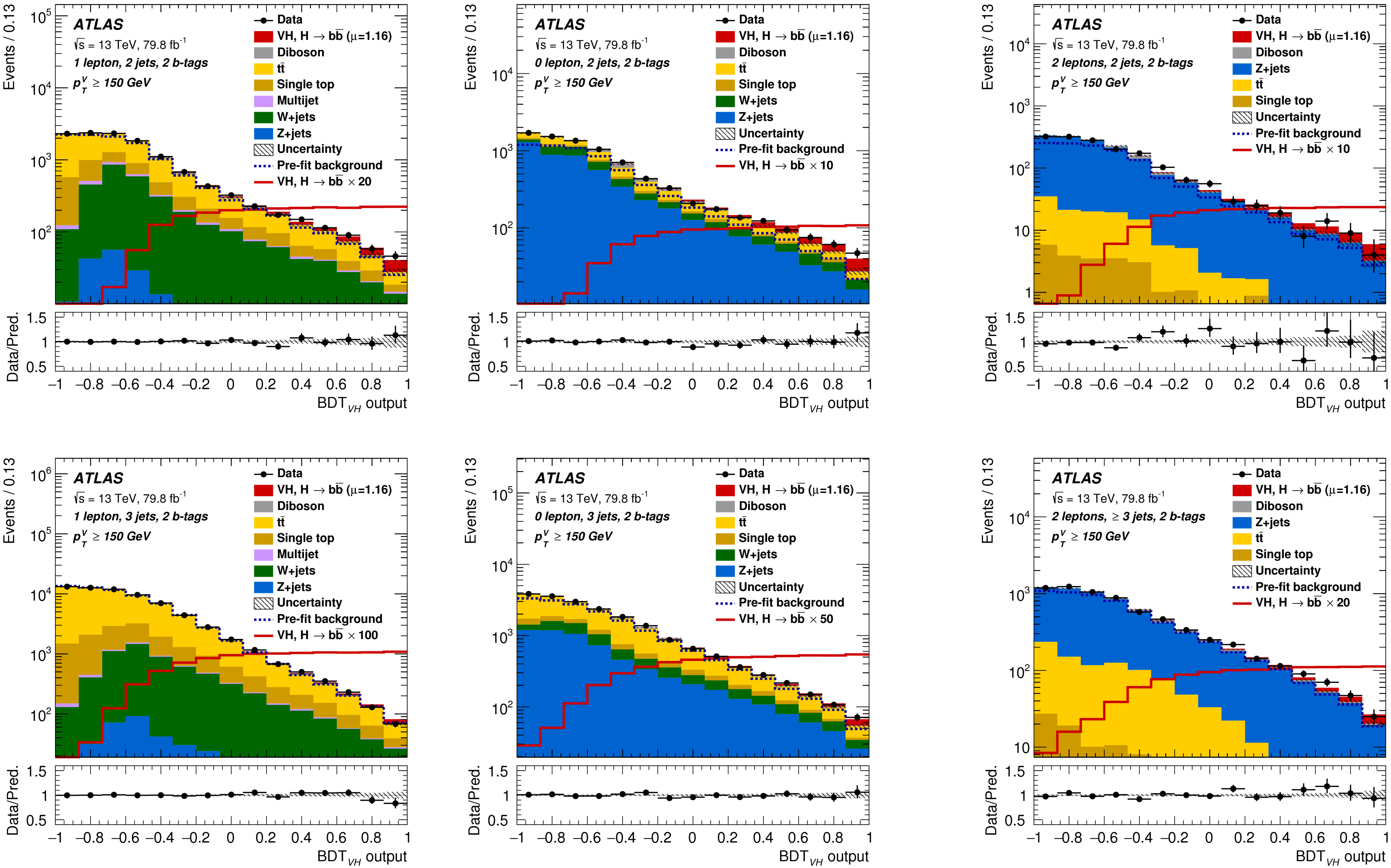
VH MVA analysis results



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

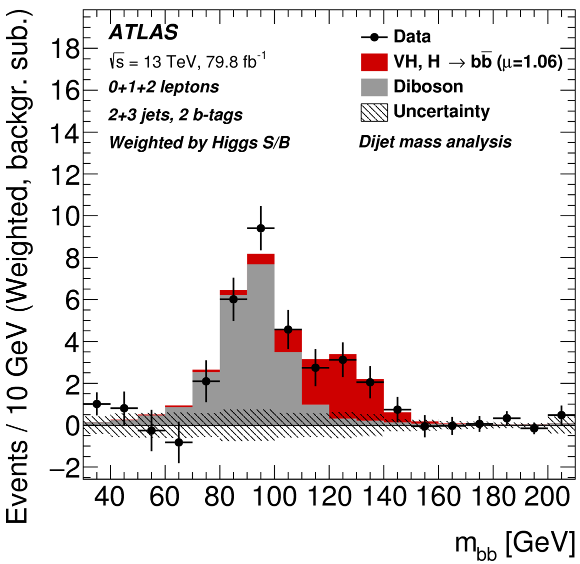
- Measurement dominated by systematics (signal and background modelling, MC statistics, b-tagging).

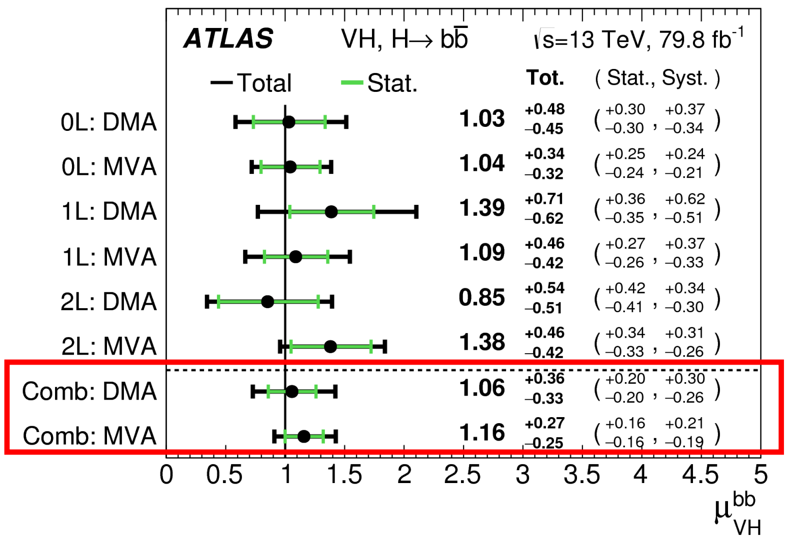
Post-fit plots VH MVA



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 ΔR_{bb} (p_T^V dependent), m_T^W (1 lepton), E_t^{miss} (2 lepton)
  - Fit m_{bb} instead of BDT output

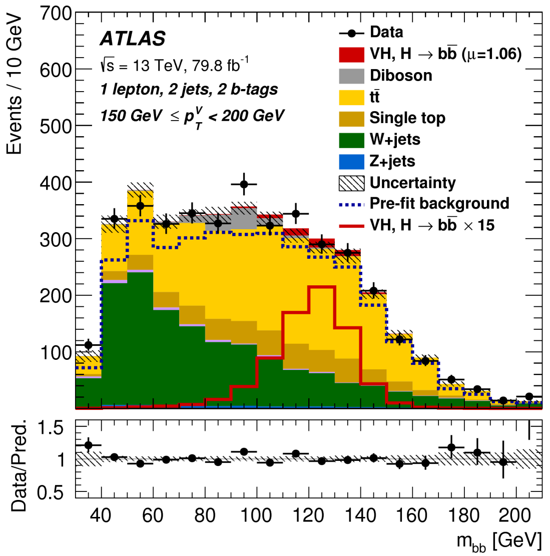


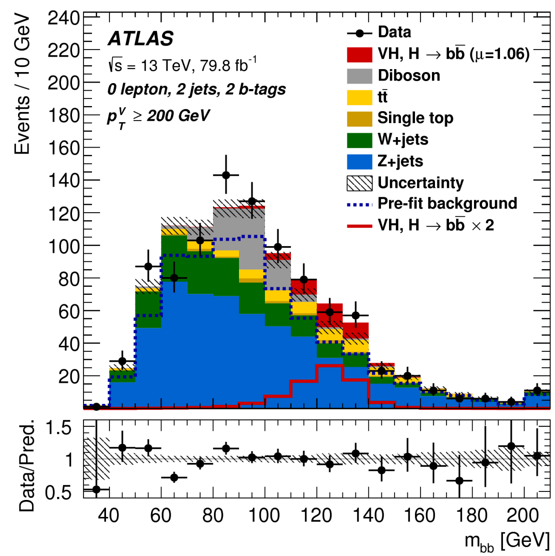


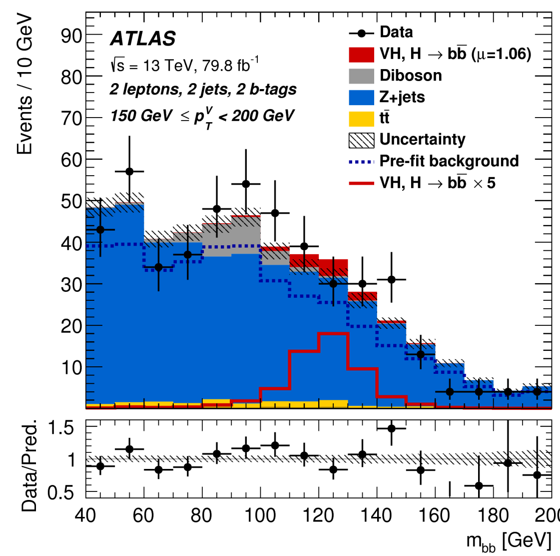
- Significance of VH(bb) signal at 3.6 σ (3.5 σ exp.)

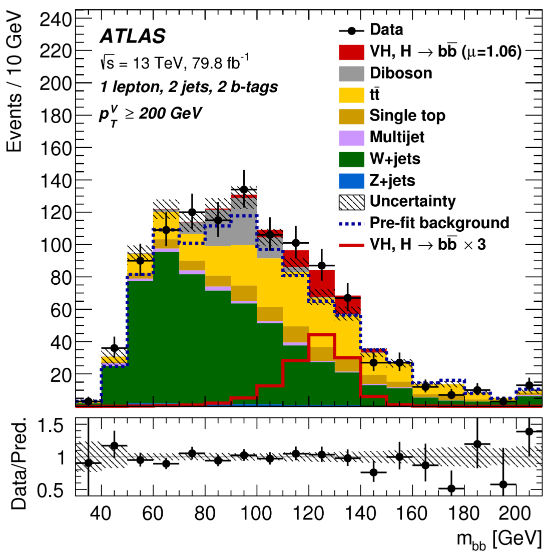
- Consistent with MVA result in all channels

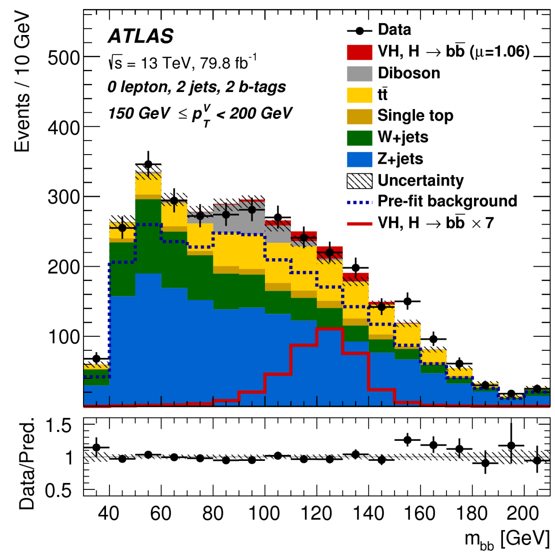
Post-fit plots VH di-jet mass analysis

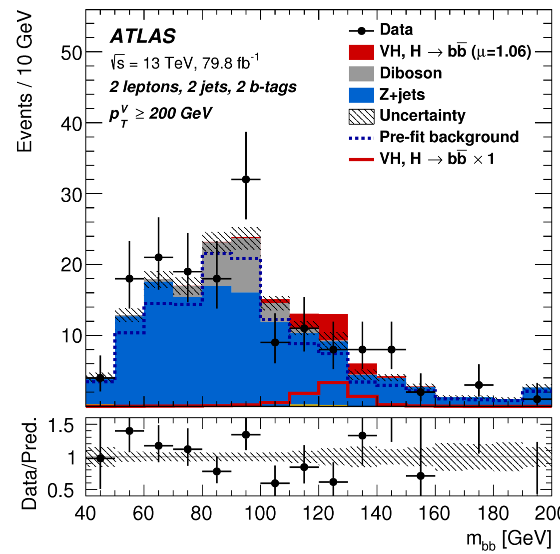












Combinations with the other results

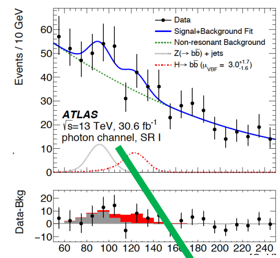
Combination of H→bb searches

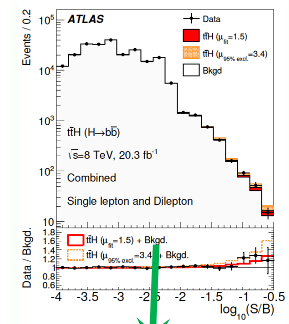
- Combine Run 1 and Run 2 analyses in VH, VBF and ttH production modes
  - Results assume SM Higgs boson production cross-section
  - Only H→bb branching ratio is correlated across the six analyses

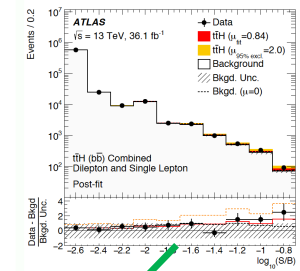
- Observation of H→bb decays at 5.4 σ (5.5 σ exp.)

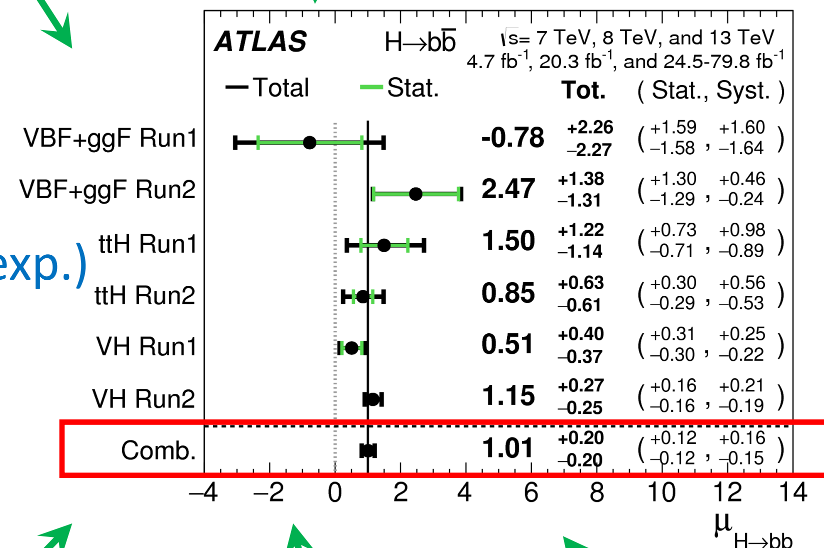
- Main contributions from VH channels (contributions of VBF and ttH channels 1.5σ and 1.9 σ)

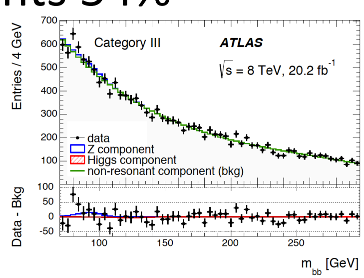
- Compatibility of the 6 measurements 54%

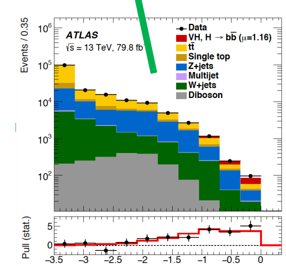


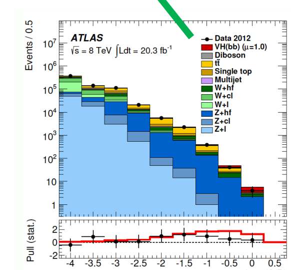






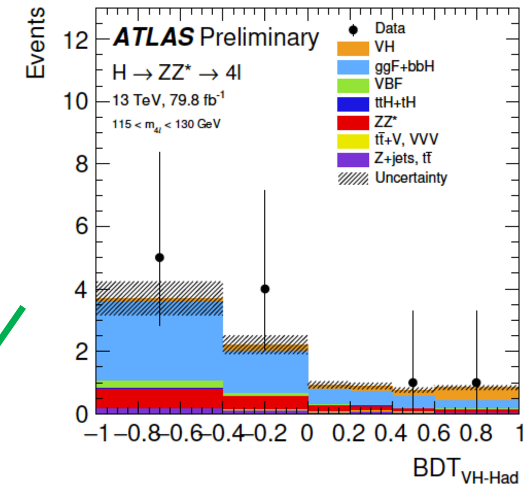


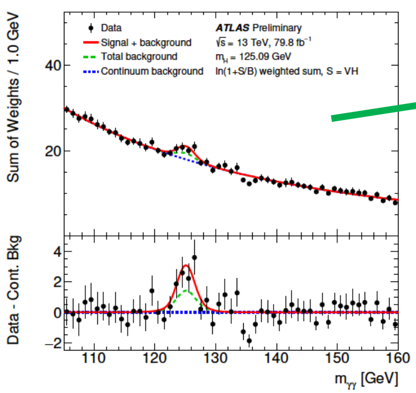


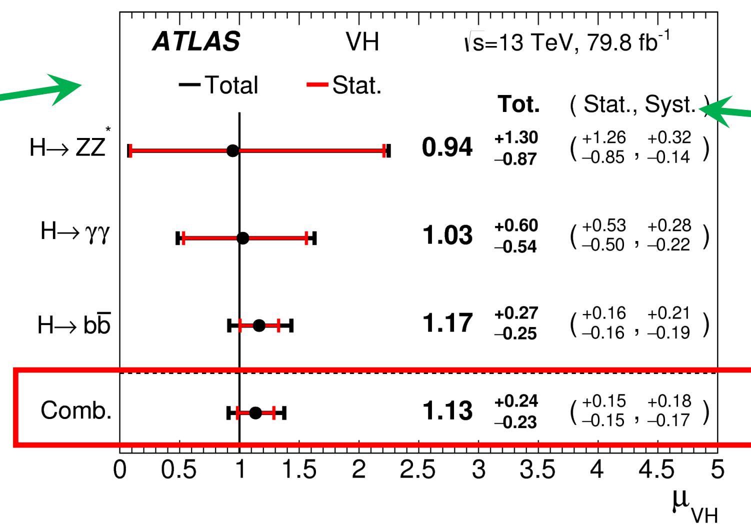


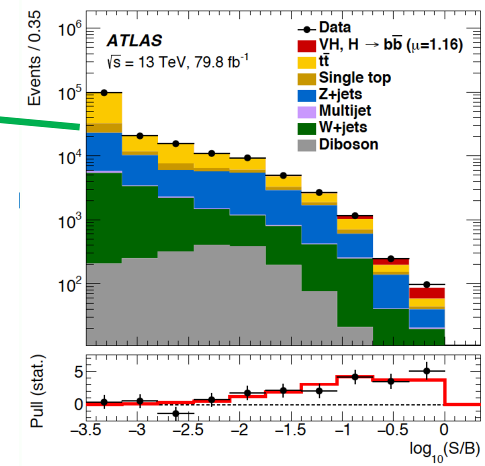
Combination of VH searches

- 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%







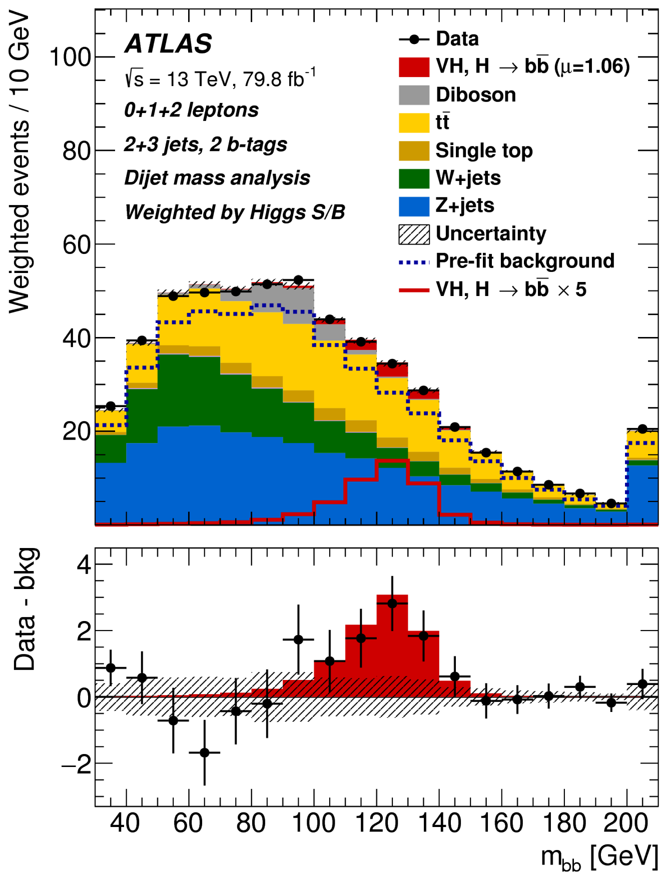


Conclusions

- ➢ 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
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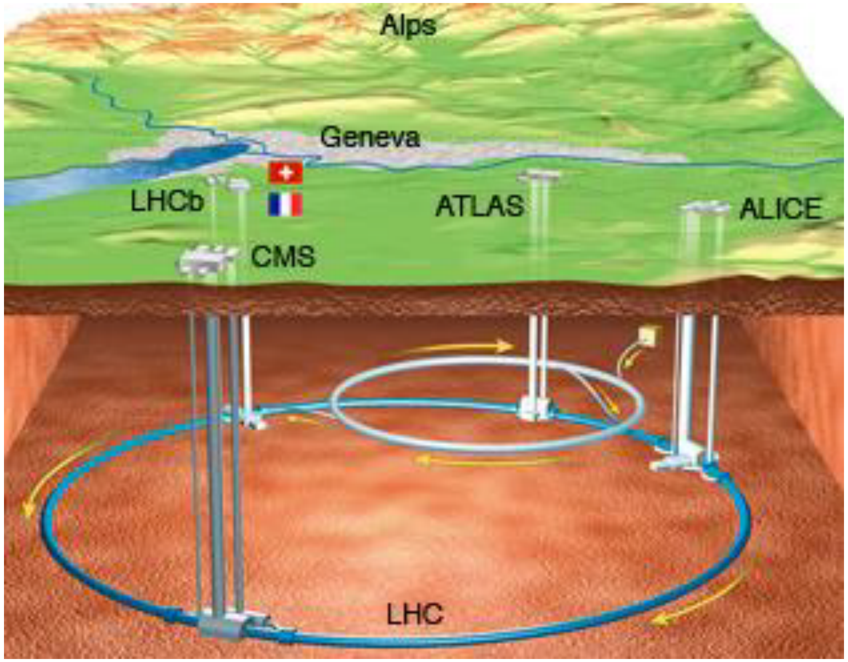
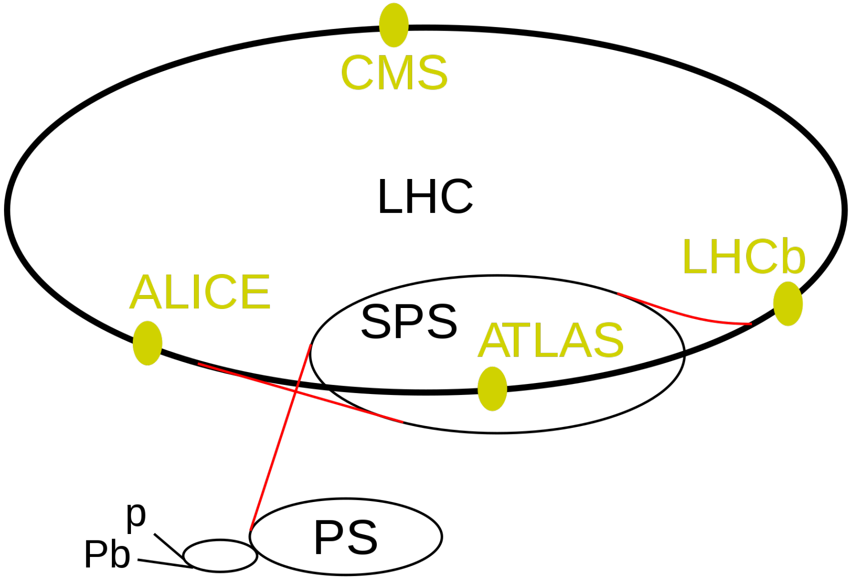
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Back up

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).

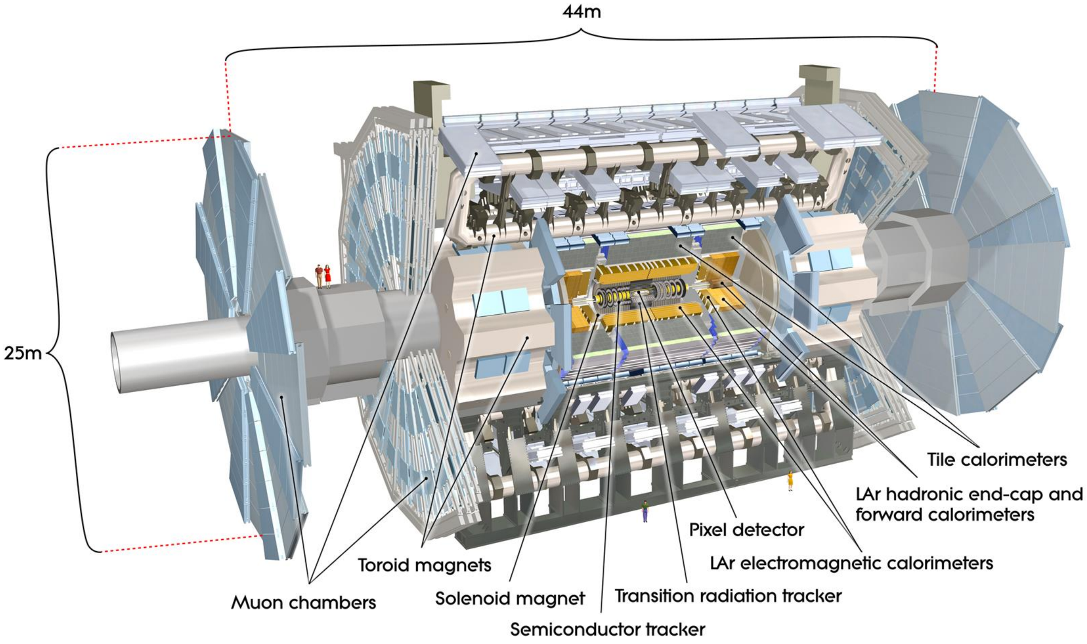
The ATLAS detector

- 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

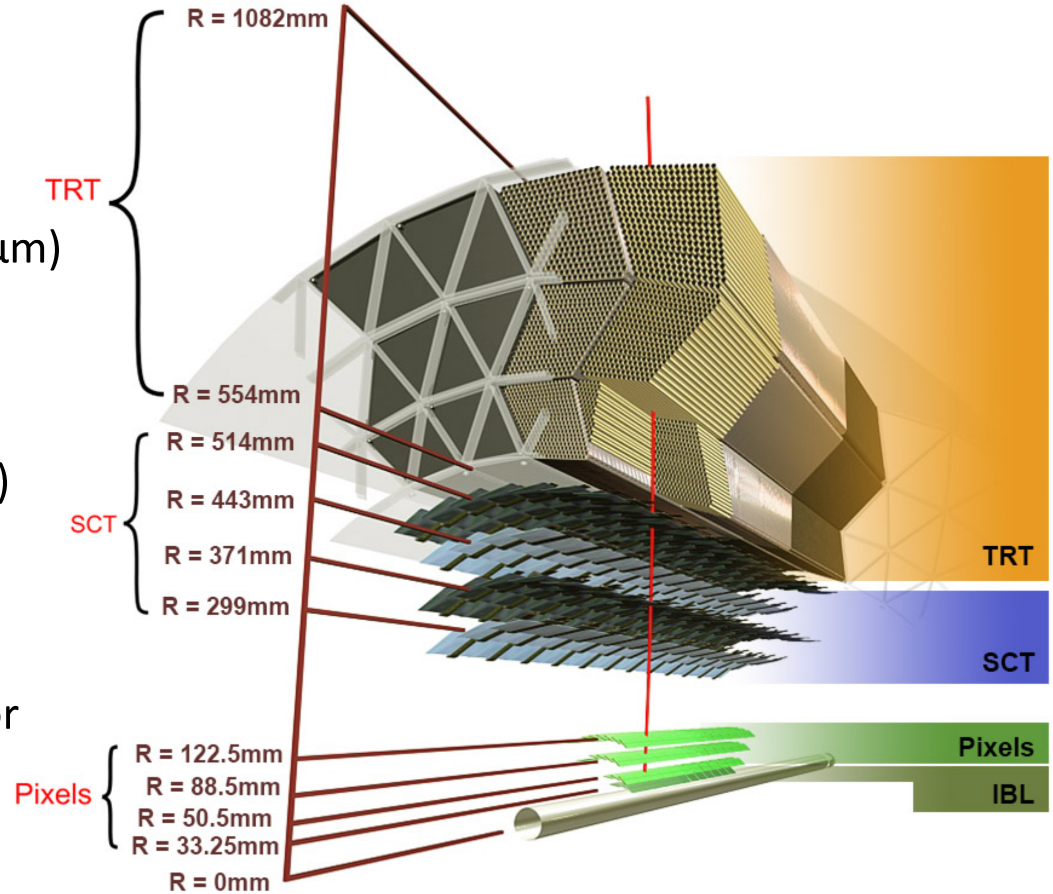


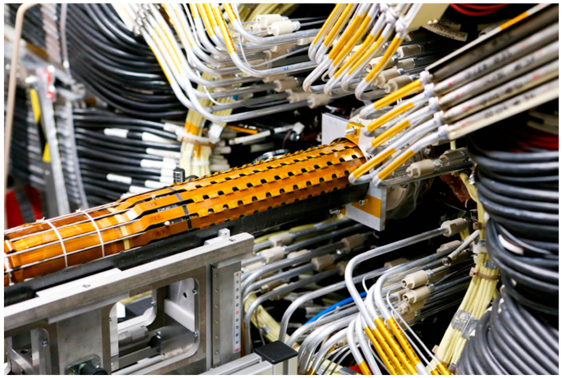
- A new pixel-detector layer, IBL, inserted during LS1, improved the performance of tracking, vertexing, b-tagging, etc.

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

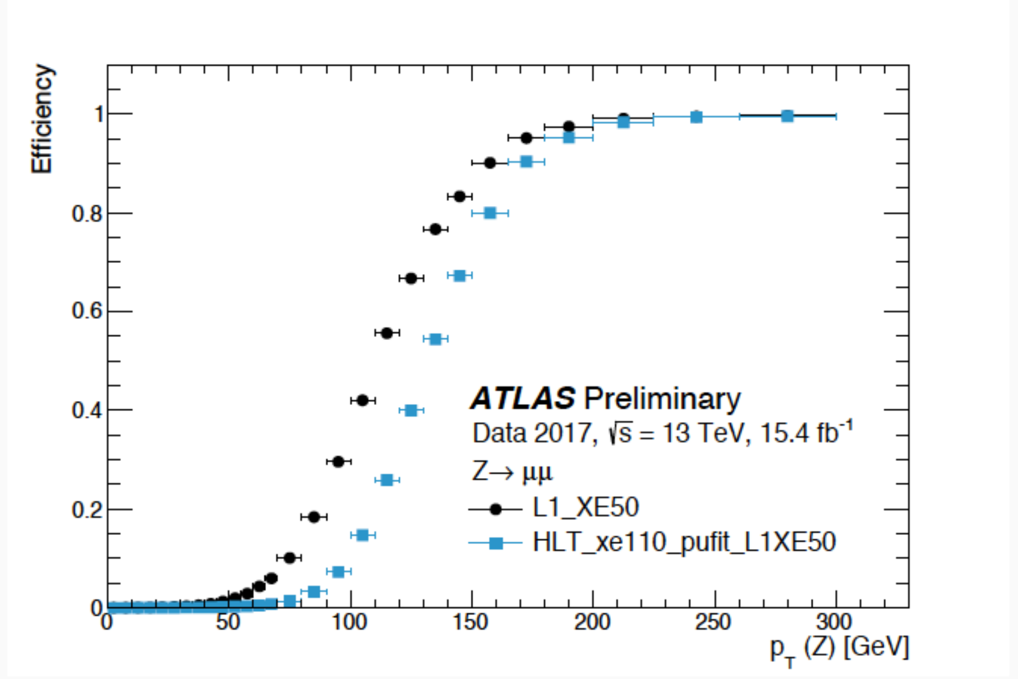




MET trigger

- 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

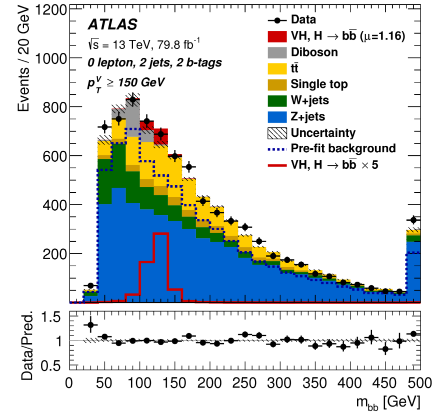
Signal and Backgrounds Samples

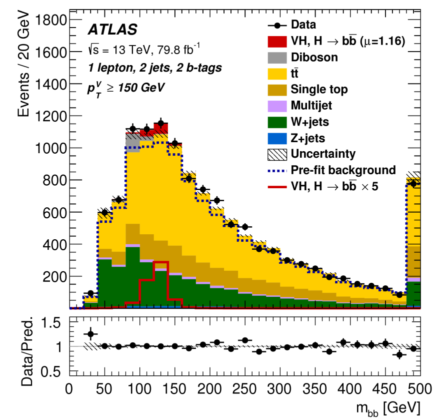
Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80,81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+ 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

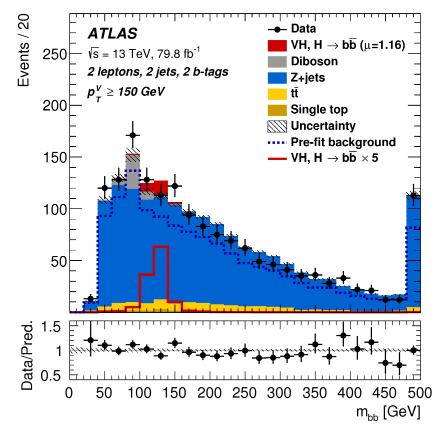
Signal and Backgrounds Samples

- **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: e sub-channel	1-lepton: μ sub-channel	2-lepton
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

Regions used in likelihood fit

Channel	SR/CR	Categories			
		$75\ \text{GeV} < p_T^V < 150\ \text{GeV}$		$p_T^V > 150\ \text{GeV}$	
		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}

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%

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 approach is needed to estimate this background.

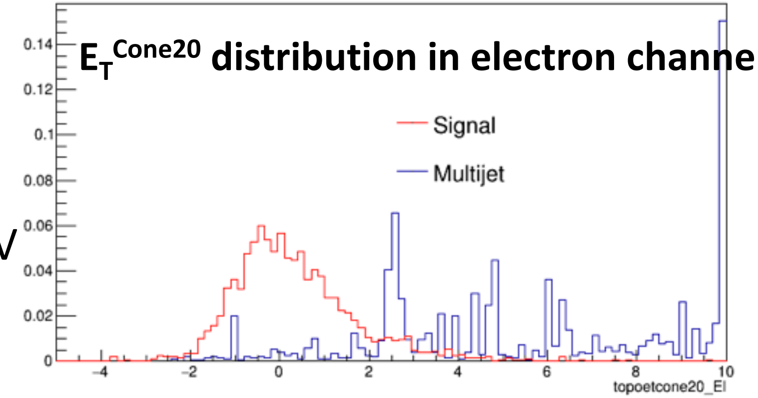
- The contributions to this background come from :

  - Real muons or electrons from heavy-flavour hadrons that undergo semileptonic decays.

  - Photons conversion (electron channel).

Lepton isolation requirements optimization

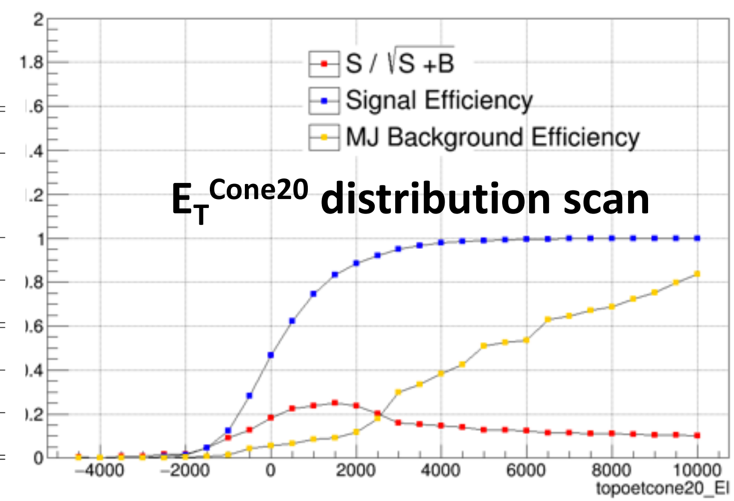
- The default lepton isolation requirements used in the previous analysis were not optimal, tested all the different isolation cuts (ptconeXX, ptvarconeXX, topoetconeXX, with XX=20,30) with signal and multijet MC samples.



- New isolation WPs proposed:
  - Electron channel: LooseTrackOnly + E_T^{Cone20}<3.5 GeV
  - Muon channel: LooseTrackOnly + p_T^{Cone20}<1.25 GeV

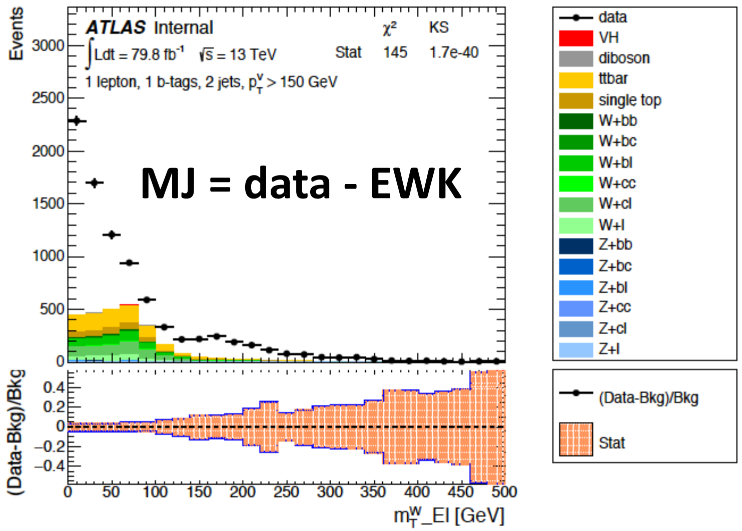
- The optimized results are also tested and confirmed by the data-driven method.

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%



MJ estimation – The whole picture

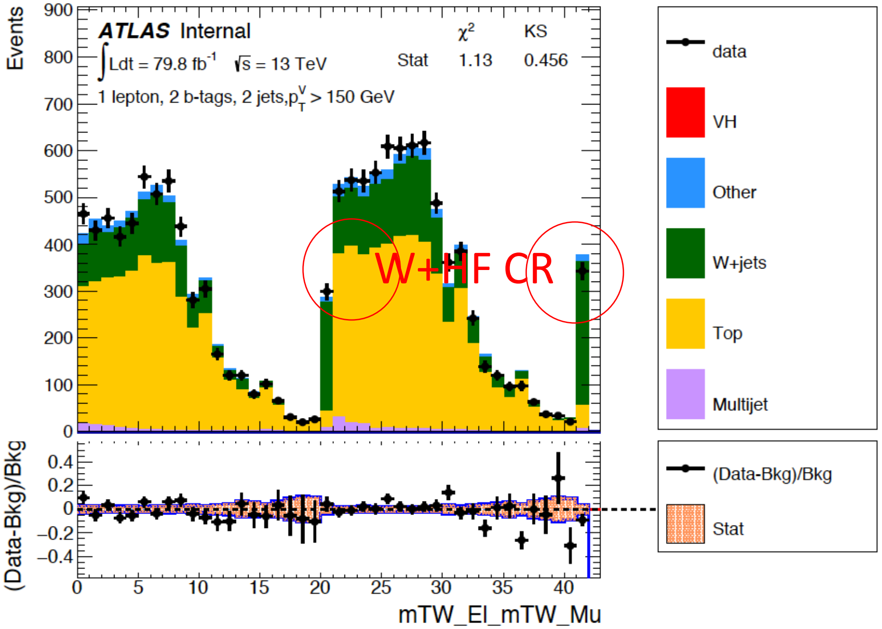
- MJ **shape** estimated by inverting the isolation requirements in 1 tag region **.**



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

- 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.

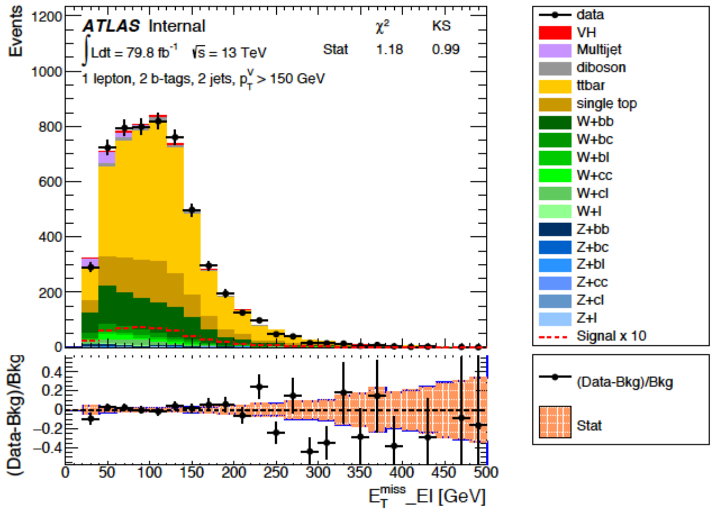
Region	Top ($t\bar{t}$ + single top)	W+jets
high p_T^V 2-tag, 2-jet	1.02 ± 0.02	1.27 ± 0.06
high p_T^V 2-tag, 3-jet	0.99 ± 0.006	1.13 ± 0.04

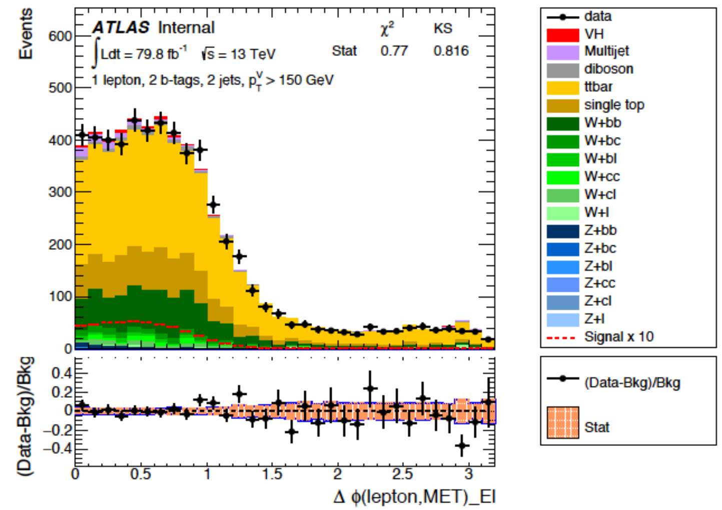
➢ Simultaneous fit of W+jet and top normalizations in the el and mu channel, with separate MJ normalizations.

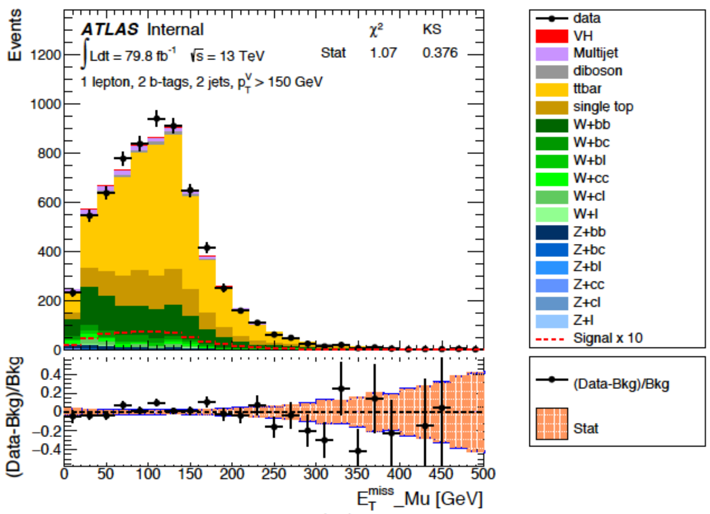
- The m_T^W distributions of the W + jet and top quark backgrounds are sufficiently different that a common normalization factor induces a bias in the multi-jet estimate.

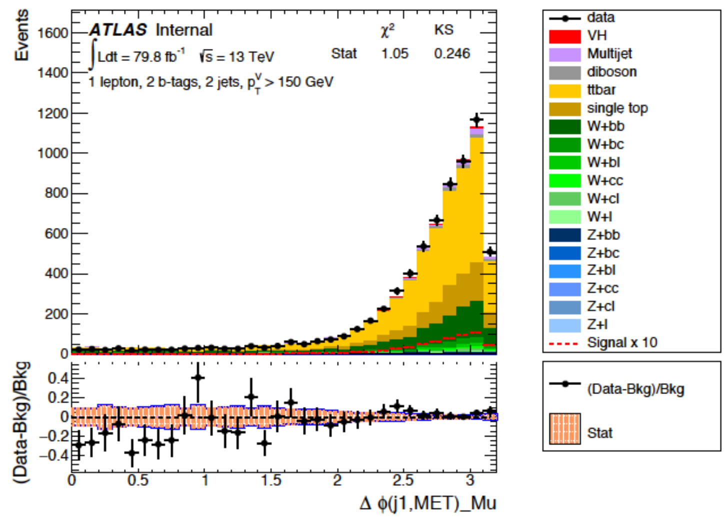
➢ In order to improve their relative separation, only overall yield used for the W + HF control region (one bin).

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

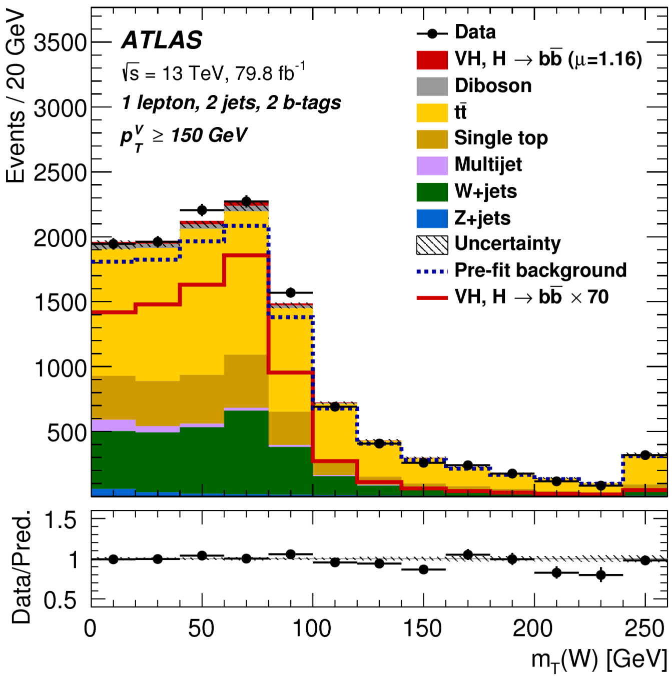
- In generally the systematic uncertainties can have an impact on the multi-jet estimates in two ways :

- 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%

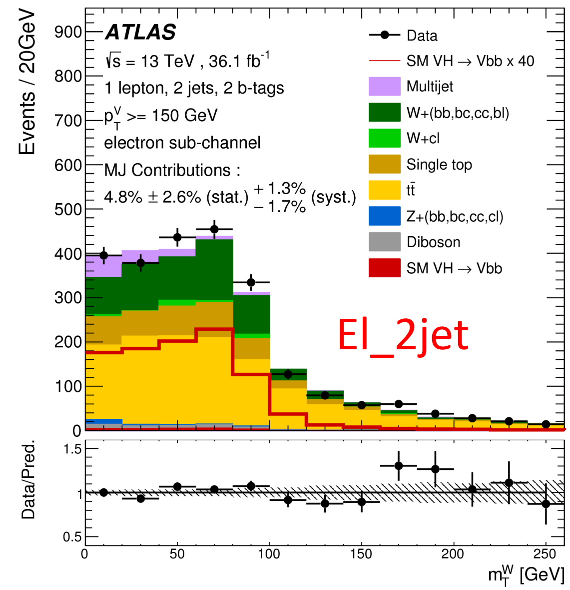
Source of uncertainty	σ_μ
Total	0.259
Statistical	0.161
Systematic	0.203
Multi-jet	0.005

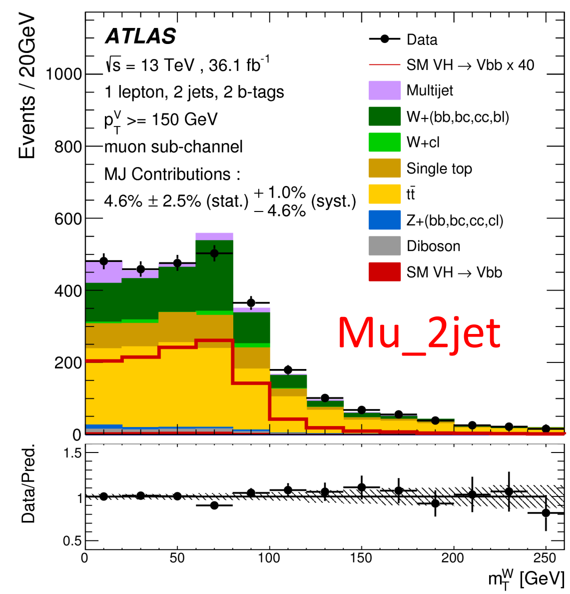
- MJ impact on the mu is very small

1 lepton channel MJ estimation

- **Dedicated isolation WPs to further reduce MJ background**
  - Topoetcone20 <3.5GeV for electron channel;
  - Ptcone20<1.25GeV for muon channel
- **Use inverted isolation region in 1 tag region to estimate MJ shape**
- **Use fit to mTW in 2-tag signal region to extract MJ normalization**
  - The template for the EW contribution in the signal region is obtained directly from MC predictions
  - The variable mTW is chosen as it offers the clearest discrimination between the multi-jet and EW processes
- **Main assumption: shape in inverted region accurately depicts that in SR**
  - 1tag Vs. 2tag; inverted isolation requirements
- **Systematics to cover this assumption**
- **Estimated separately in the electron and muon sub-channels, and in the 2- and 3-jet categories, using similar procedures**

	MJ contamination (2-jet)	MJ contamination (3-jet)
e-channel	1.91%	0.15%
mu-channel	2.76%	0.43%





Post-fit yields---signal region

	0-lepton $p_T^V > 150\,GeV$, 2-b-tag		1-lepton $p_T^V > 150\,GeV$, 2-b-tag		2-lepton $75\,GeV < p_T^V < 150\,GeV$, 2-$b$-tag		2-lepton $p_T^V > 150\,GeV$, 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 $p_{\mathrm{T}}^{V} > 150\,GeV$, 2-$b$-tag		2-lepton $75\,GeV < p_{\mathrm{T}}^{V} < 150\,GeV$, 2-$b$-tag		2-lepton $p_{\mathrm{T}}^{V} > 150\,GeV$, 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

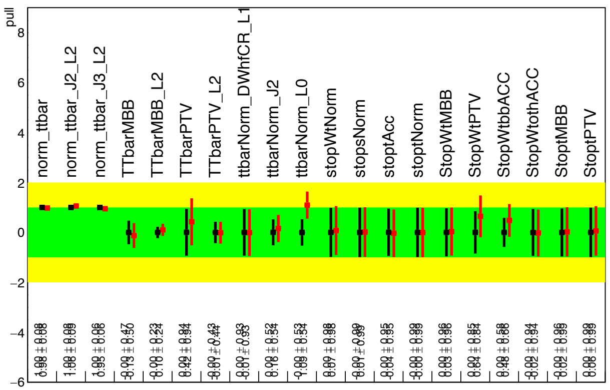
Channel	Significance	
	Exp.	Obs.
$H \to ZZ^* \to 4\ell$	1.1	1.1
$H \to \gamma\gamma$	1.9	1.9
$H \to b\bar{b}$	4.3	4.9
VH combined	4.8	5.3

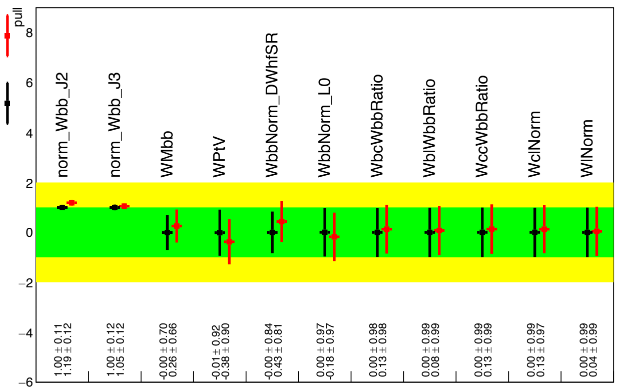
VH MVA analysis : backgrounds pulls

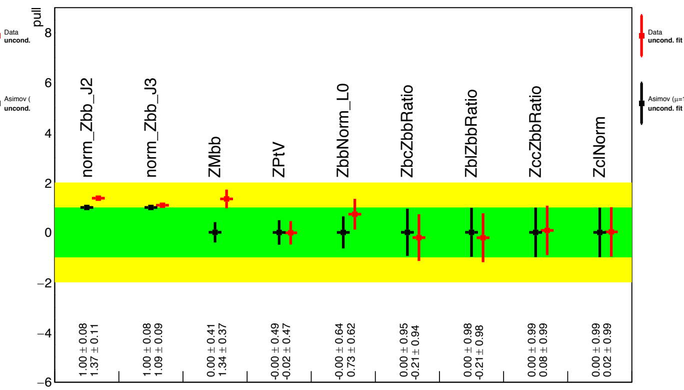
Top | W+jet | Z+jet

Asimov

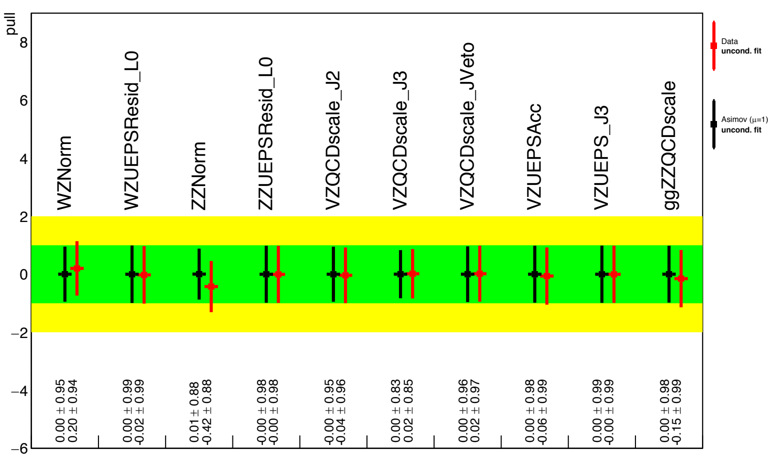
Data

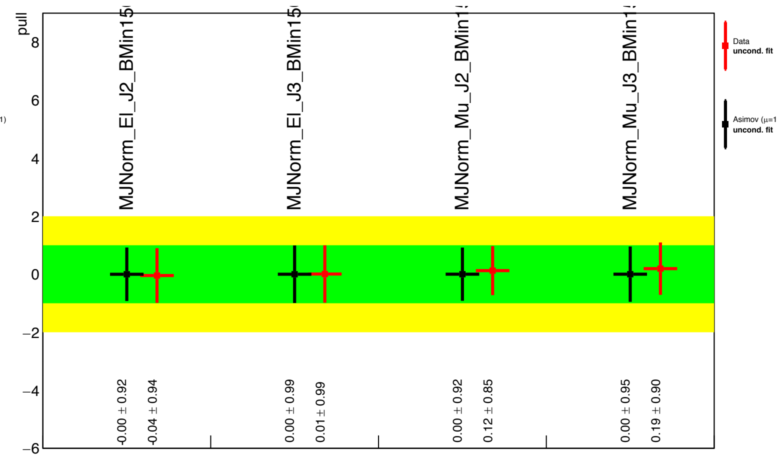






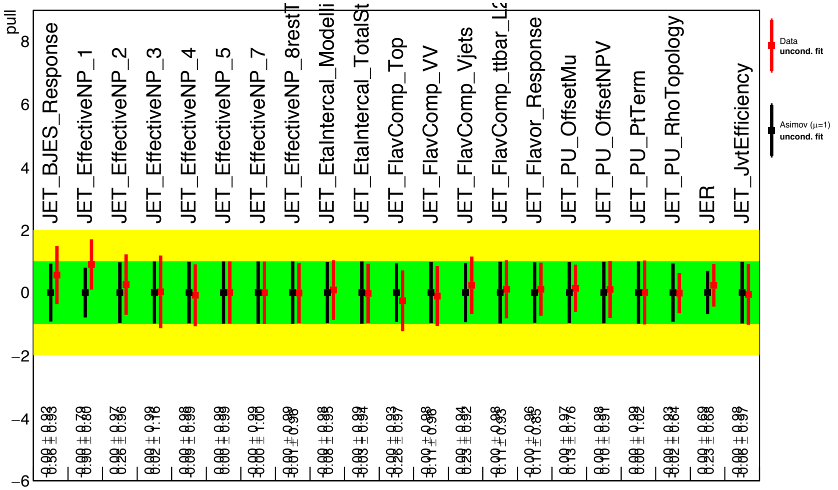
Diboson | MJ



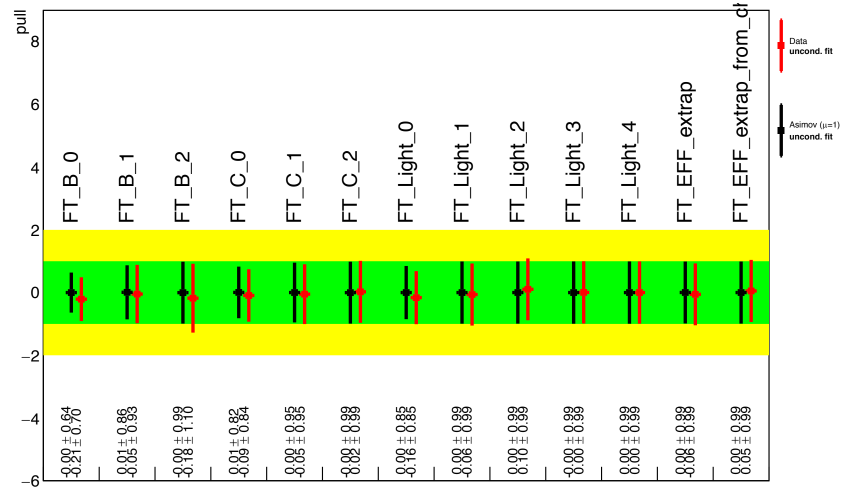


VH MVA analysis : experimental systematics

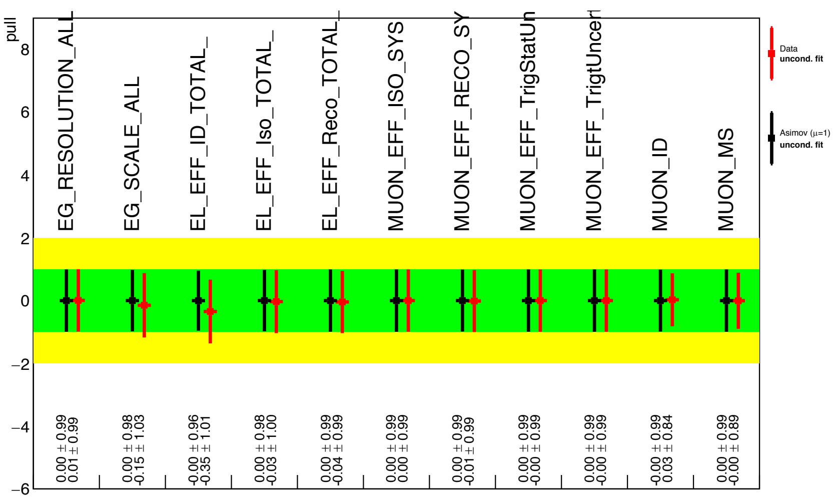
Jet



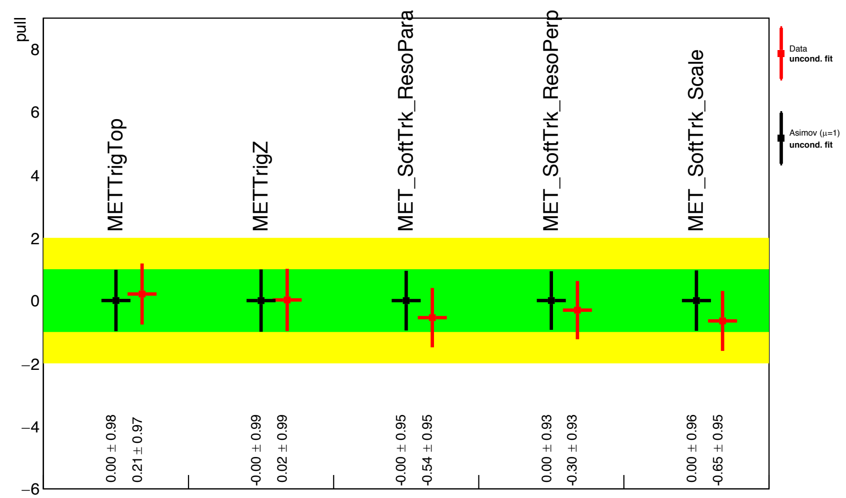
B-Tagging



Lepton

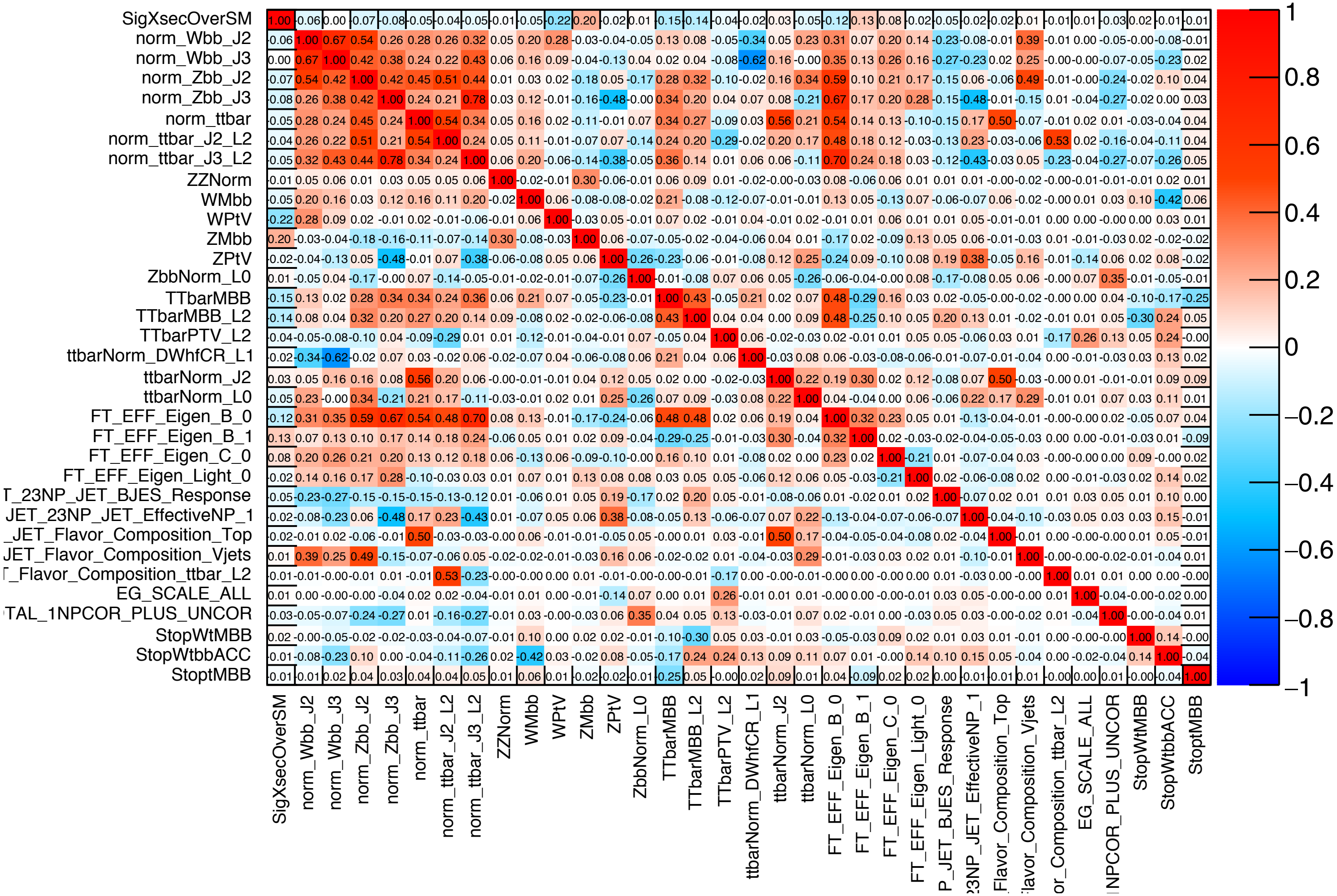


MET



VH MVA analysis : correlations

- Correlation of NPs from data fit.



VH MVA analysis results