
The SM VH(bb) search in the ATLAS experiment at run 2 of the LHC

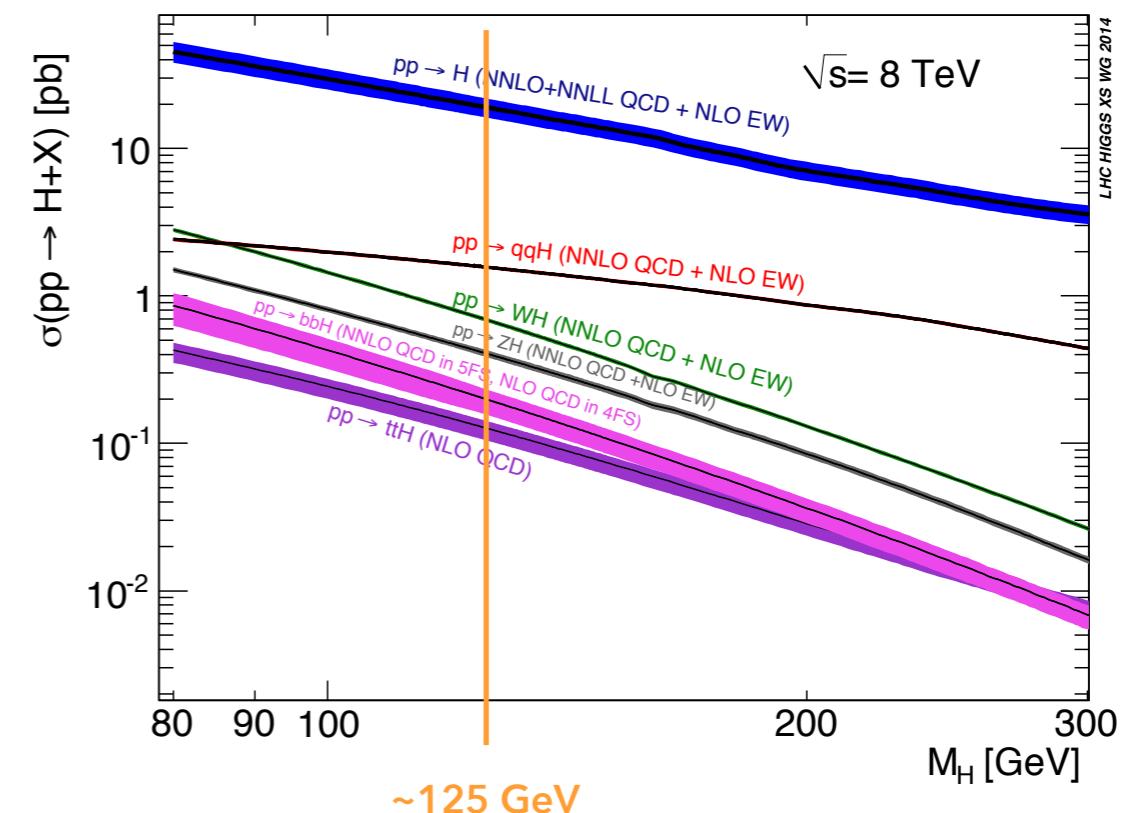
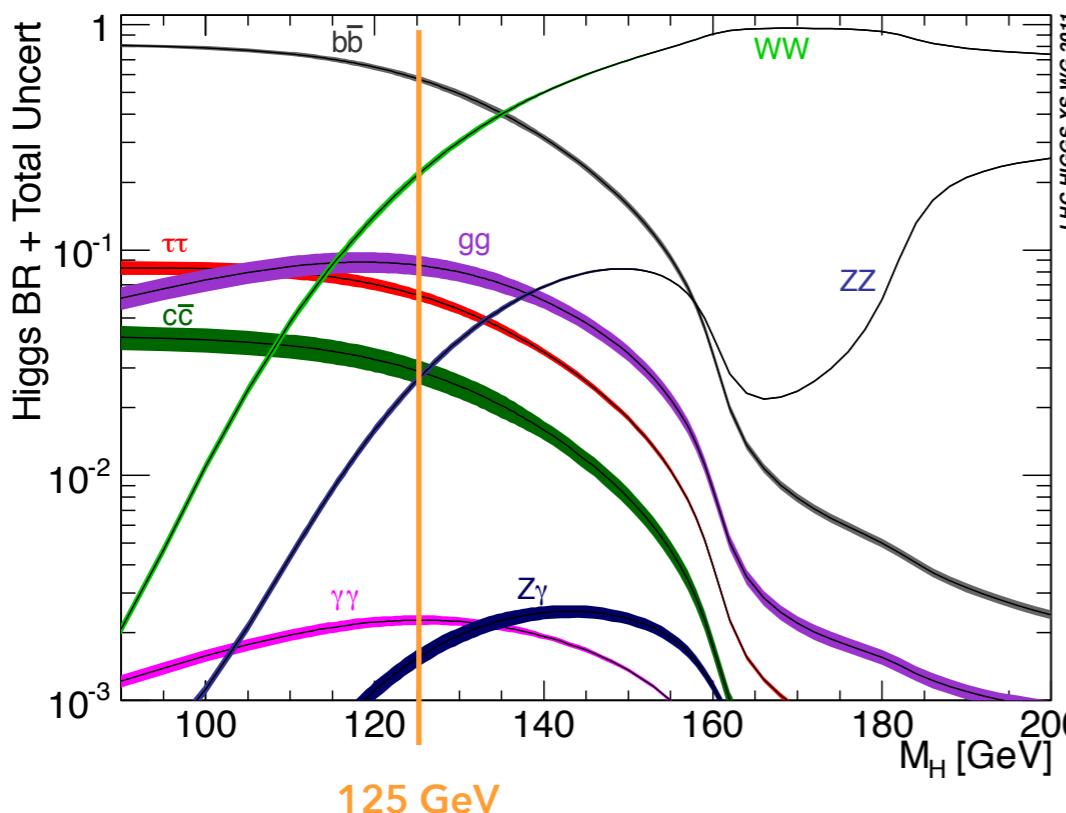
OUTLINE

- ▶ Introduction to the H->bb search
 - ▶ Motivation
 - ▶ Analysis basics
- ▶ b-Tagging
- ▶ Analysis
 - ▶ Selection
 - ▶ Multivariate method
 - ▶ Variables optimization
 - ▶ Fit
- ▶ ICHEP Results

INTRODUCTION TO THE VH(bb) SEARCH : MOTIVATION

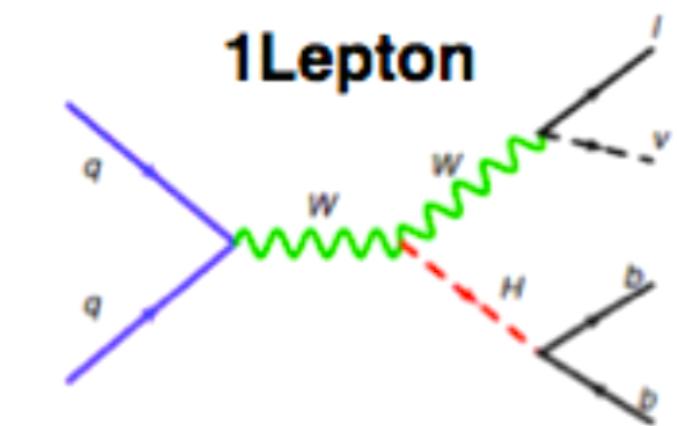
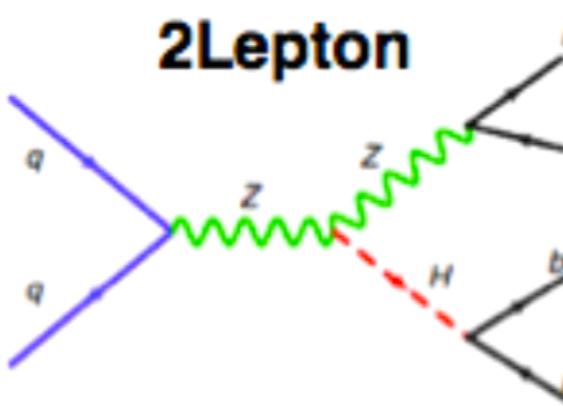
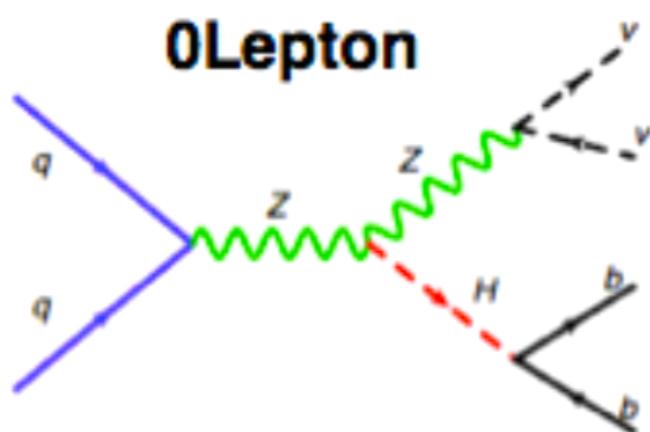
- ▶ $H \rightarrow bb$ branching ratio $\sim 57\%$ ($m_H = 125$ GeV) : largest contribution to the Higgs width
- ▶ VH subdominant production mode of Higgs bosons ($\sim 5\%$ of σ_H) production mode has specific signatures for discrimination (e.g. clean vs QCD)

VH(bb) Run-1	σ expected	σ observed	μ signal
ATLAS	2.6	1.4	0.5 ± 0.4
CMS	2.5	2.1	0.9 ± 0.4
ATLAS+CMS	3.7	2.6	0.7 ± 0.3



INTRODUCTION TO THE VH(bb) SEARCH : ANALYSIS PRESENTATION

- ▶ Analysis split in 3 channels : 0, 1, 2 lepton(s) in the final state
- ▶ For each channel, build categories : 2 jets, 3 jets (2 leptons channel : 2, ≥ 3)



▶ Expected final state

- ▶ b-jets
- ▶ MET, leptons
- ▶ V-boson decay products and bb system are back to back in the transverse plane

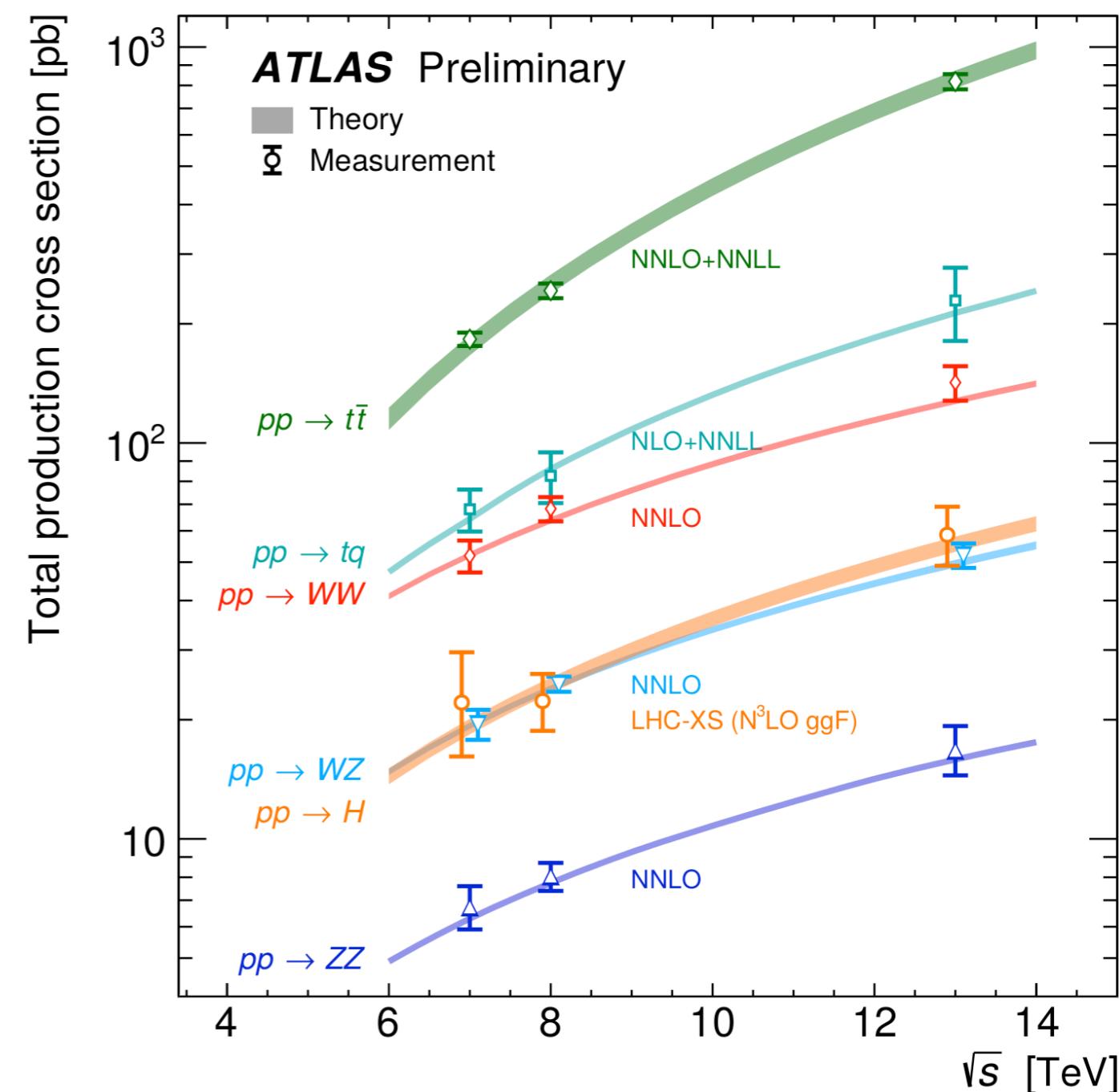
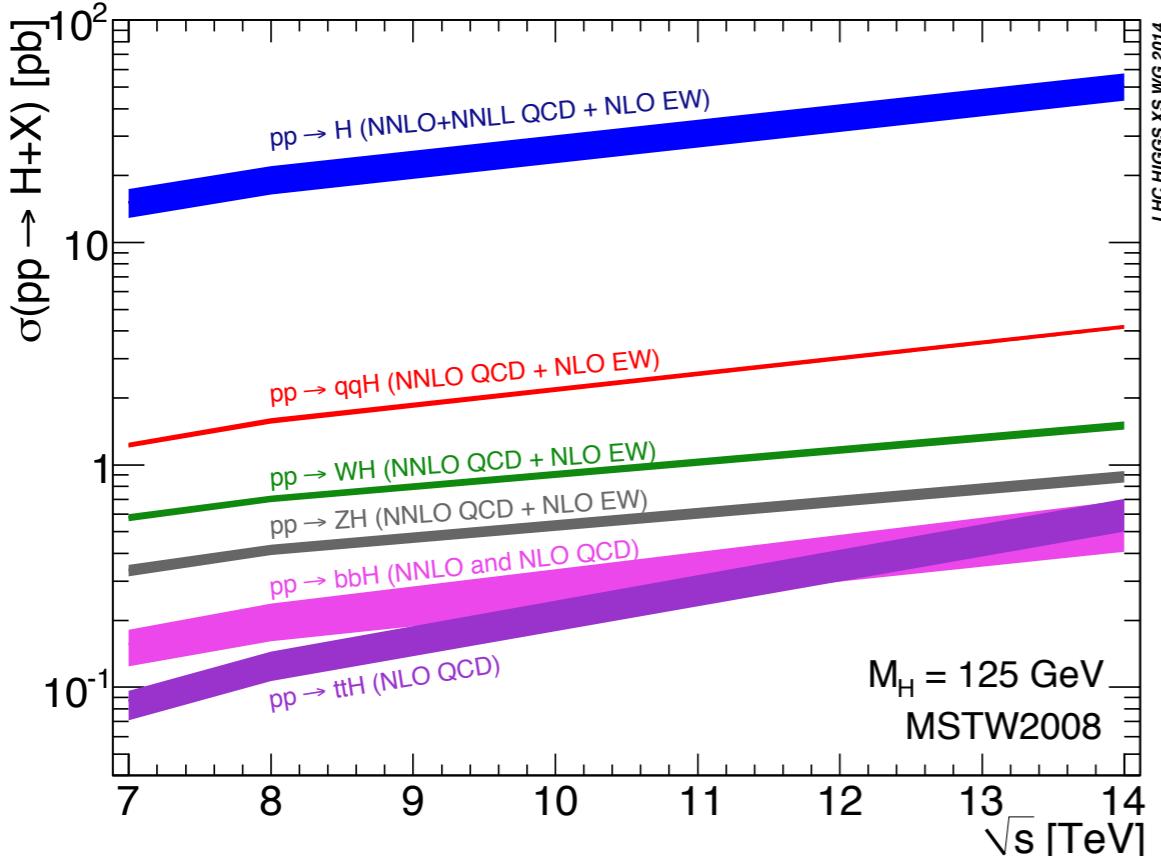
▶ Dominant backgrounds :

- ▶ ttbar
- ▶ V+jets

INTRODUCTION TO THE VH(bb) SEARCH : ANALYSIS PRESENTATION

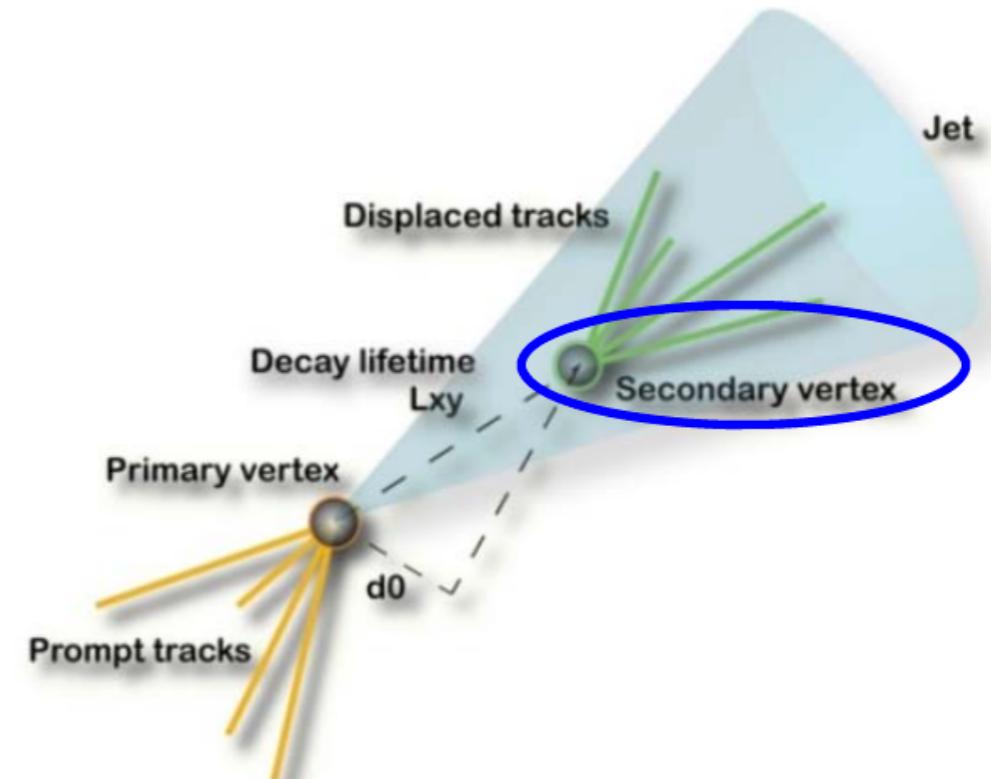
Large backgrounds, whose cross-section increased more than that of signal since run 1

- VH $\sim \times 2.3$
- V+jets $\sim \times 2$
- ttbar $\sim \times 3.3$



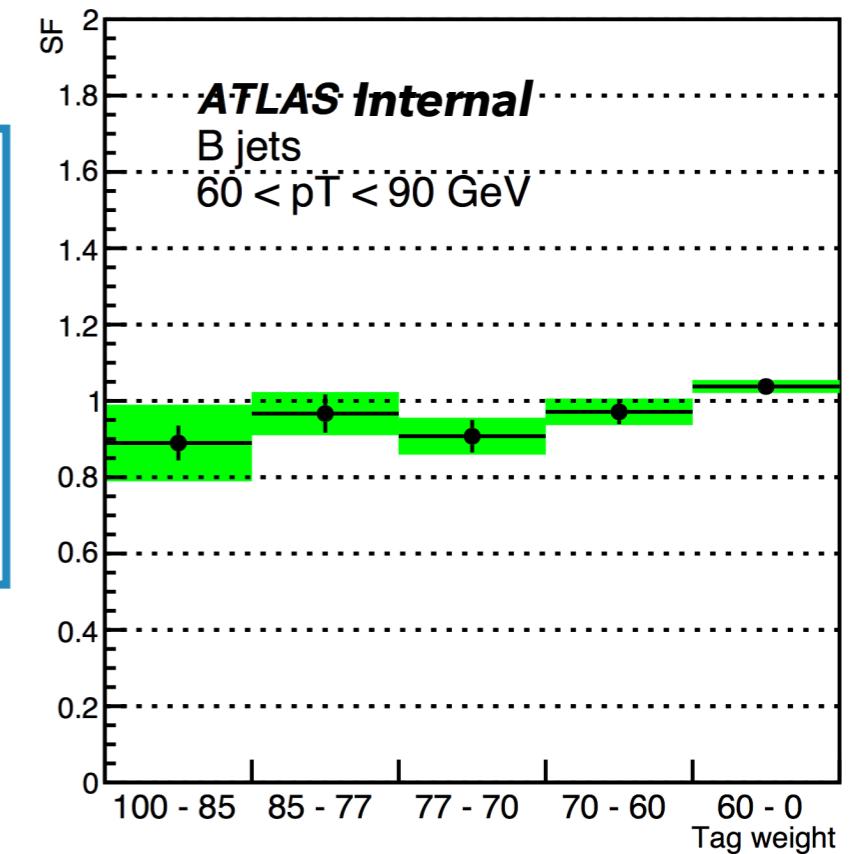
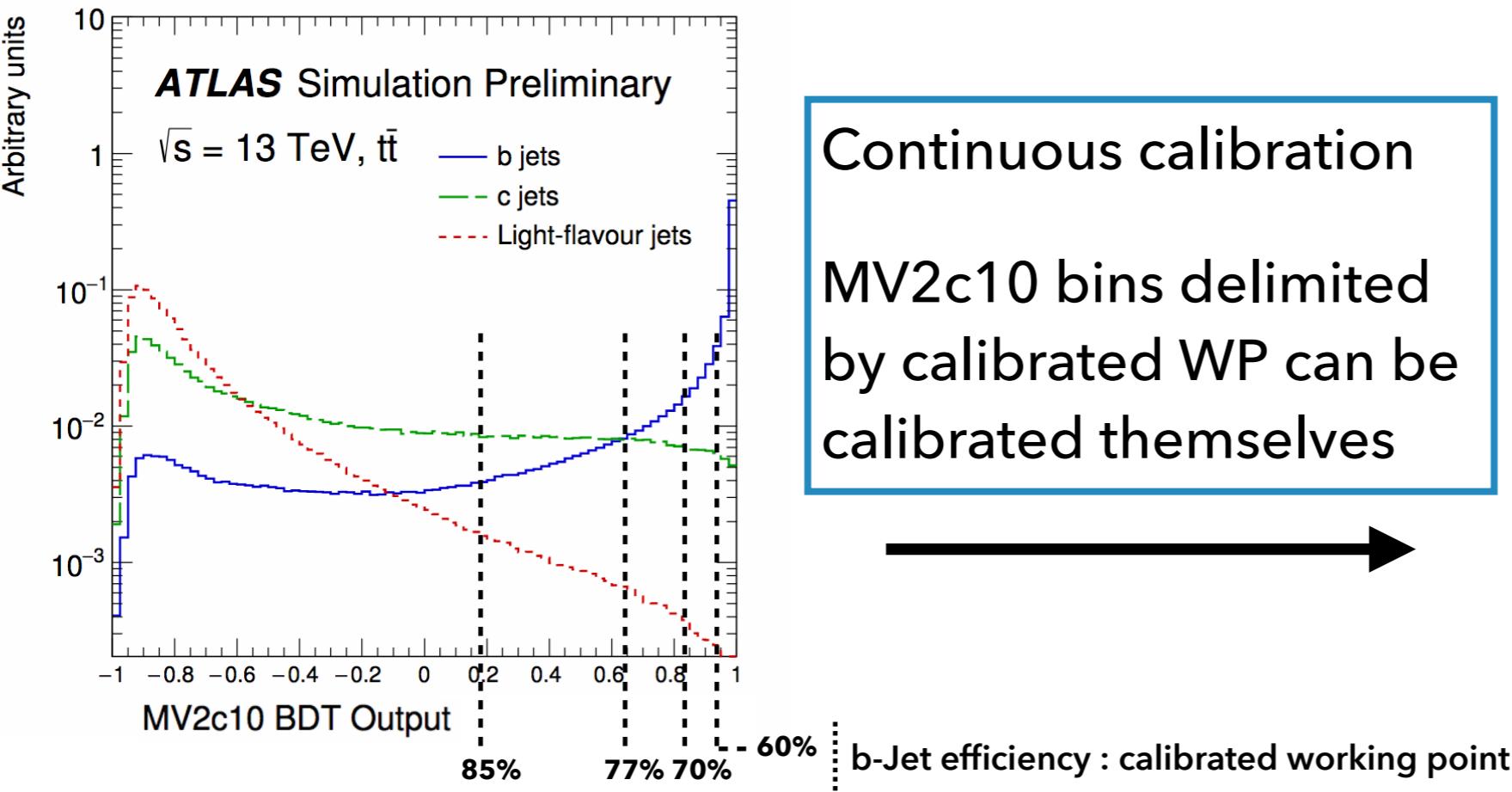
IMPORTANT INGREDIENT OF THE VH(bb) SEARCH : B-TAGGING

- ▶ Allows to discriminate jets produced from B hadrons from other flavours
- ▶ Exploit specific properties of B-hadrons
 - ▶ Longer lifetime \rightarrow results in displaced vertices from which emerge tracks
 - ▶ Large mass \rightarrow results in tracks with large Impact Parameters
- ▶ Information condensed in a discriminant
- ▶ MV2c10 (BDT output)



IMPORTANT INGREDIENT OF THE VH(bb) SEARCH : B-TAGGING

- ▶ Cut on MV2c10 to keep, e.g. 70% of true b-Jets (b-labelled jets) in MC
 - ▶ Calibrate each flavour to correct the MC to agree with data : 4 calibrated Working Points



SELECTION

► 0-lepton channel :

- 0 loose lepton
- MET > 150 GeV
- 2 b-Tagged jets
- anti-QCD cuts

MAIN YIELDS : L = 13.8 FB-1

Sample	2j	3j
VH	17,3	20,3
Zbb	467,2	797,2
Wbb	99,7	249,5
t <bar>t</bar>	160,8	1227,1
Total Background	890,0	2669,9

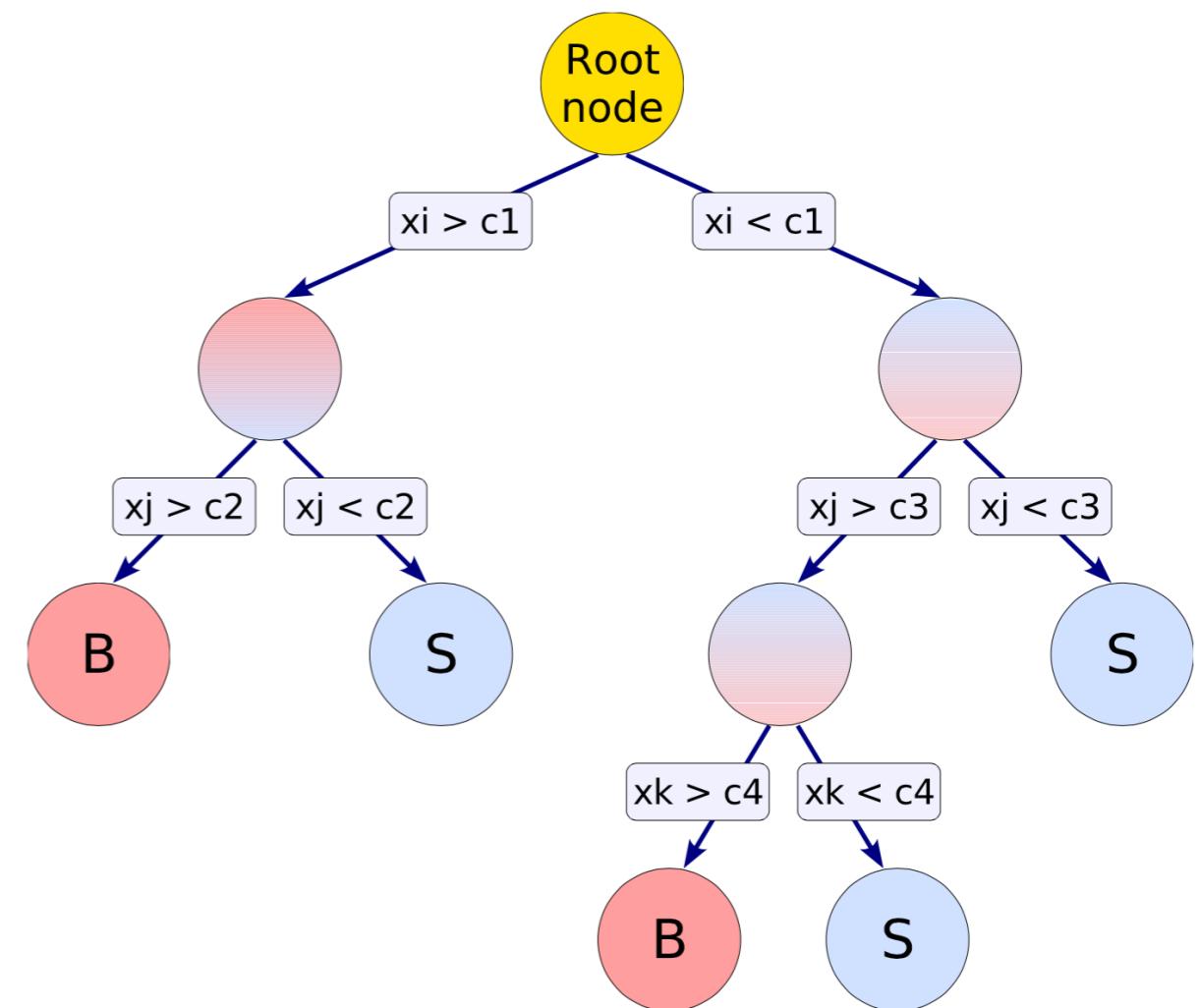
INTRODUCTION TO BOOSTED DECISION TREES

- ▶ Classification technique allowing to exploit fine correlations between variables
- ▶ A Boosted Decision Tree (BDT) is a series of Decision Trees

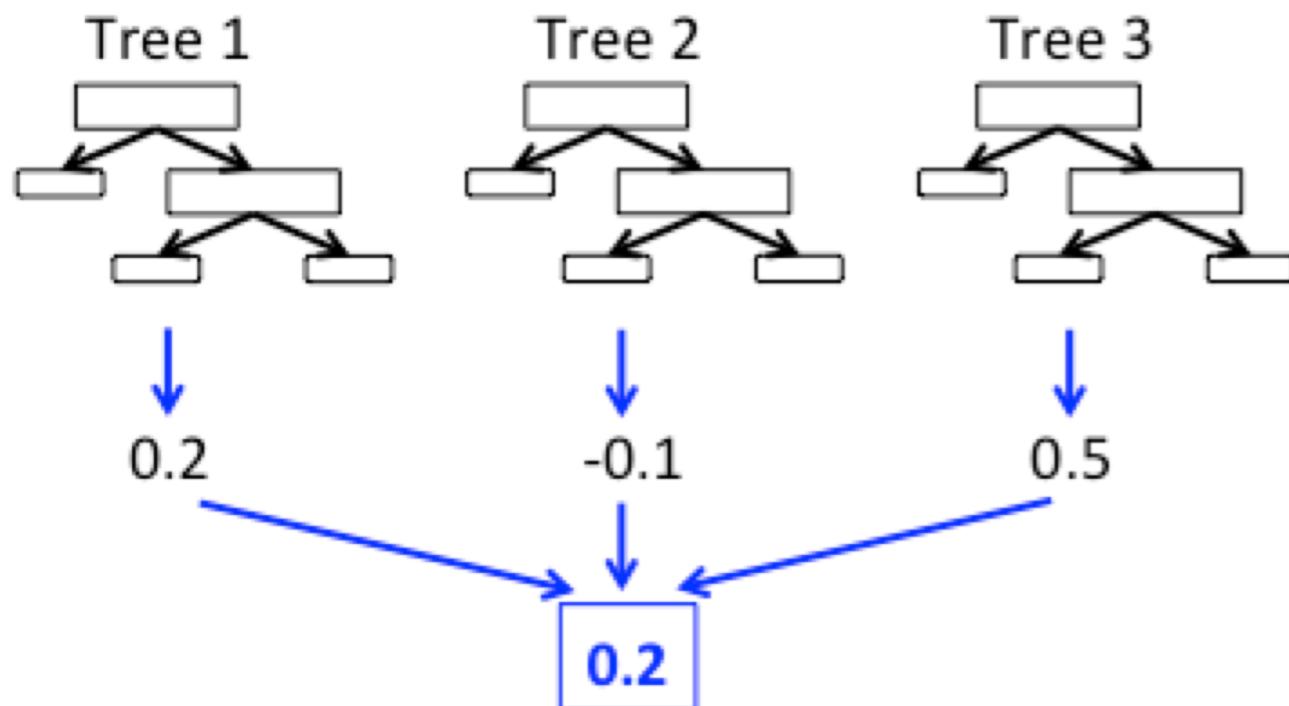
Decision Tree

Series of cut on discriminating variables, allowing to classify events as signal-like or background-like

The training consists of determining the best cuts to maximise the separation of true-signal and true-background events



INTRODUCTION TO BOOSTED DECISION TREES



Evaluation of the BDT

Event's BDT value rely on the classification result of each Decision Tree

- ▶ Signal/Background like decision
- ▶ Misclassification rate of the Tree

Boosted Decision Tree

Series of Decision Trees trained sequentially on the same events

Between the training of two consecutive Decision Trees, enhance the weight of misclassified events (e.g. true-signal event classified as background-like) so that future trees learn those better

VH(bb) MULTIVARIATE ANALYSIS

- ▶ Multivariate analysis : build a BDT discriminant out of several variables
- ▶ Separate BDT per channel and jet categories
- ▶ Evaluate the sensitivity after fitting to data

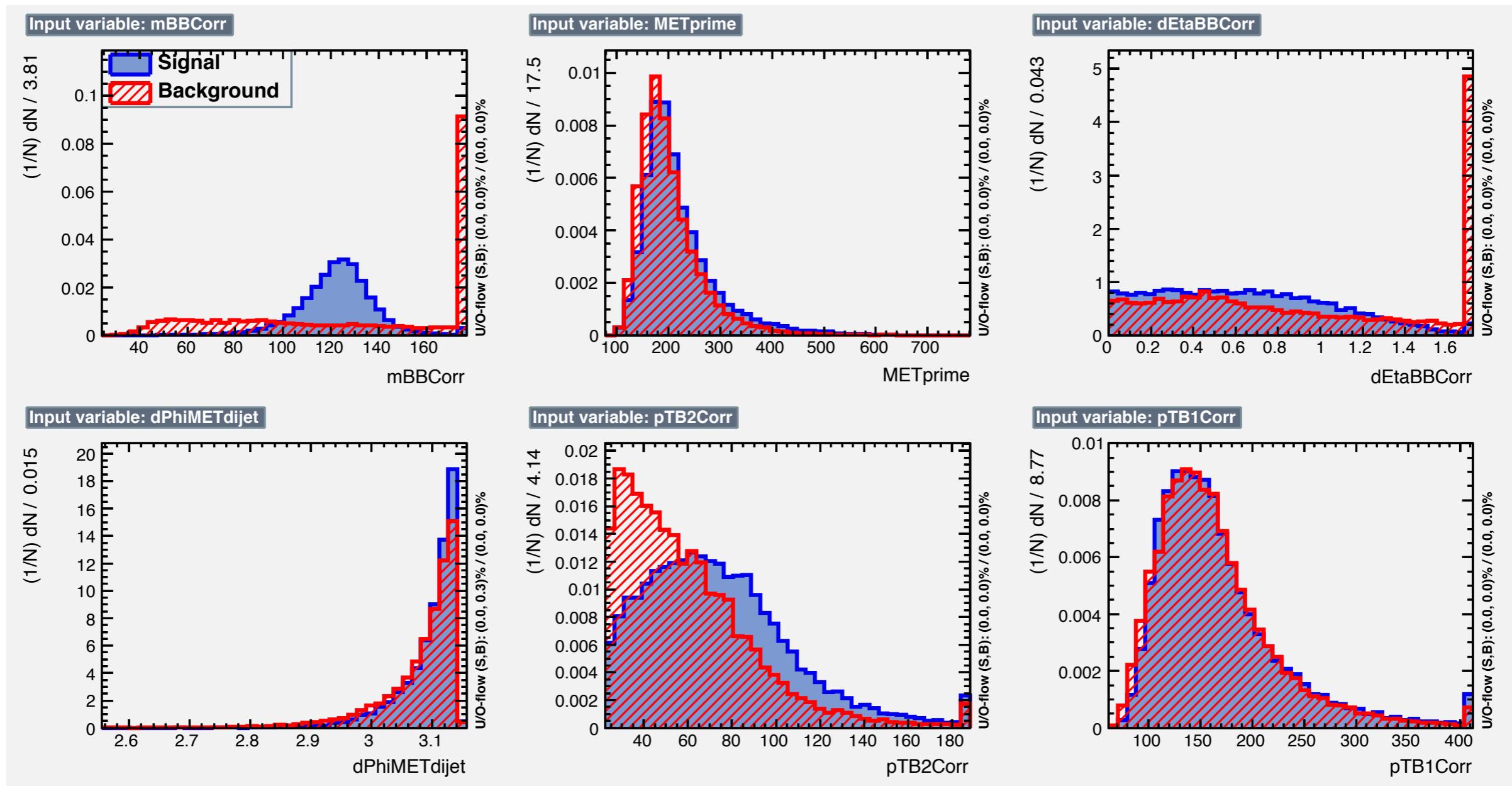
Variable	0-lepton	1-lepton	2-lepton
p_T^V		✗	✗
E_T^{miss}	✗	✗	✗
$p_T^{b_1}$	✗	✗	✗
$p_T^{b_2}$	✗	✗	✗
m_{bb}	✗	✗	✗
$\Delta R(b_1, b_2)$	✗	✗	✗
$ \Delta\eta(b_1, b_2) $	✗		✗
$\Delta\phi(V, bb)$	✗	✗	✗
$ \Delta\eta(V, bb) $			✗
H_T	✗		
$\min[\Delta\phi(\ell, b)]$		✗	
m_T^W		✗	
m_{ll}			✗
m_{Top}		✗	
$ \Delta Y(V, H) $		✗	
Only in 3-jet events			
$p_T^{\text{jet}_3}$	✗	✗	✗
m_{bbj}	✗	✗	✗

BDT training variables in each channel :
 continuous tagging was used in run 1, not
 for ICHEP, hopefully for next publications

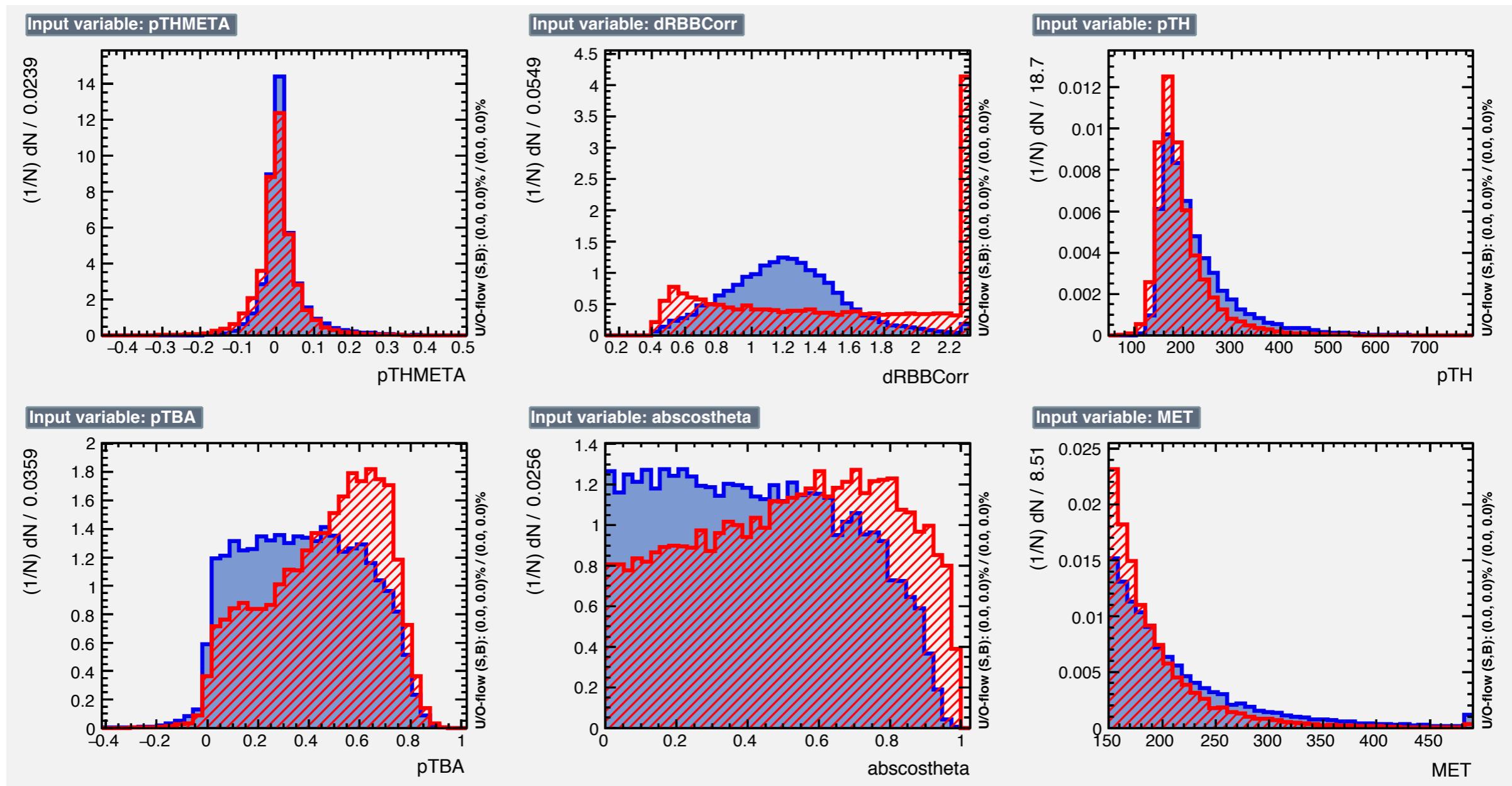
OPTIMIZATION OF THE CHOICE OF TRAINING VARIABLES + TESTS OF NEW VARIABLES

- ▶ Classify the BDT training variables by decreasing discrimination power
- ▶ Iteratively :
 - ▶ train a series of BDT{mBB+1 variable} amongst which BDT{mBB+var1} performs best
 - ▶ train a series of BDT{mBB+var1+1 variable}, ...
- ▶ Focusing on the 2 jets category (for this talk only !)
- ▶ $\text{absyBB} = |\eta(\text{bJet1}, \text{bJet2})|$
- ▶ $\text{costhetastar} = \cos(\theta^*)$
- ▶ $\text{pTBA} = (\text{pTB1} - \text{pTB2}) / (\text{pTB1} + \text{pTB2})$
- ▶ $\text{pTH} = \text{pT}(\text{bJet1} + \text{bJet2})$
- ▶ $\text{pTHMET} = (\text{pTH} - \text{MET}) / (\text{pTH} + \text{MET})$
- ▶ $\text{METprime} = 2 * \text{mBB} / \text{dRBB}$

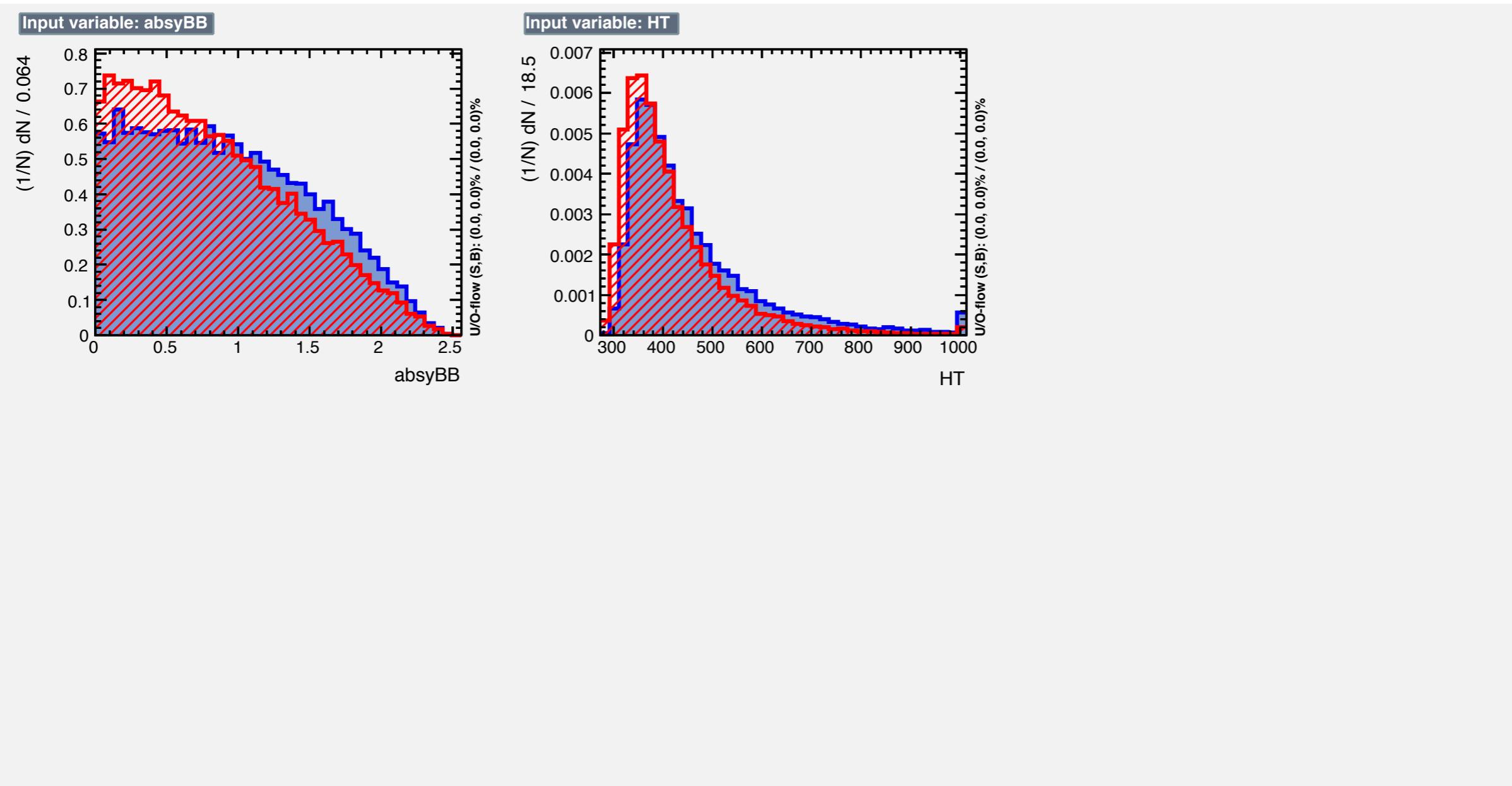
TRAINING VARIABLES



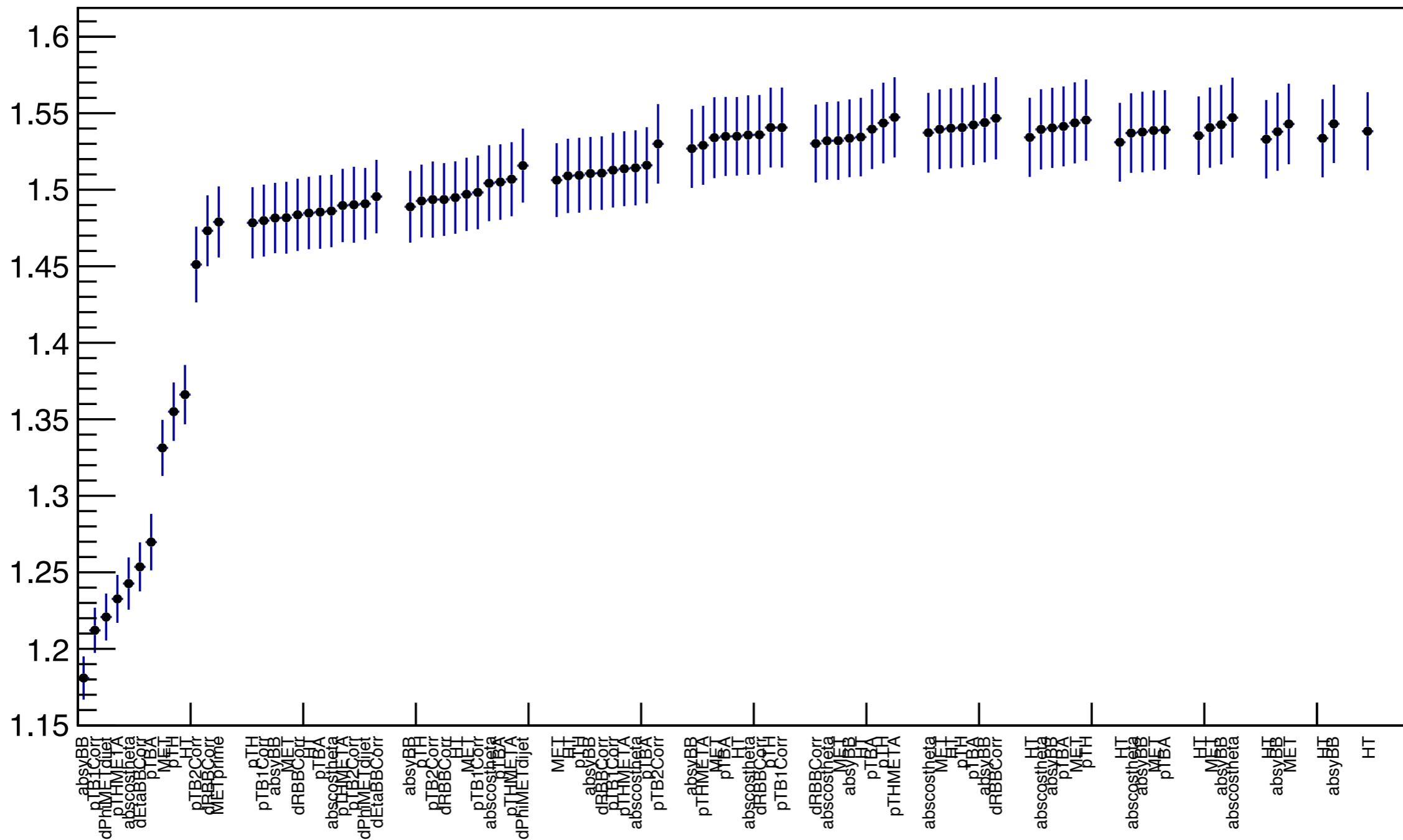
TRAINING VARIABLES



TRAINING VARIABLES

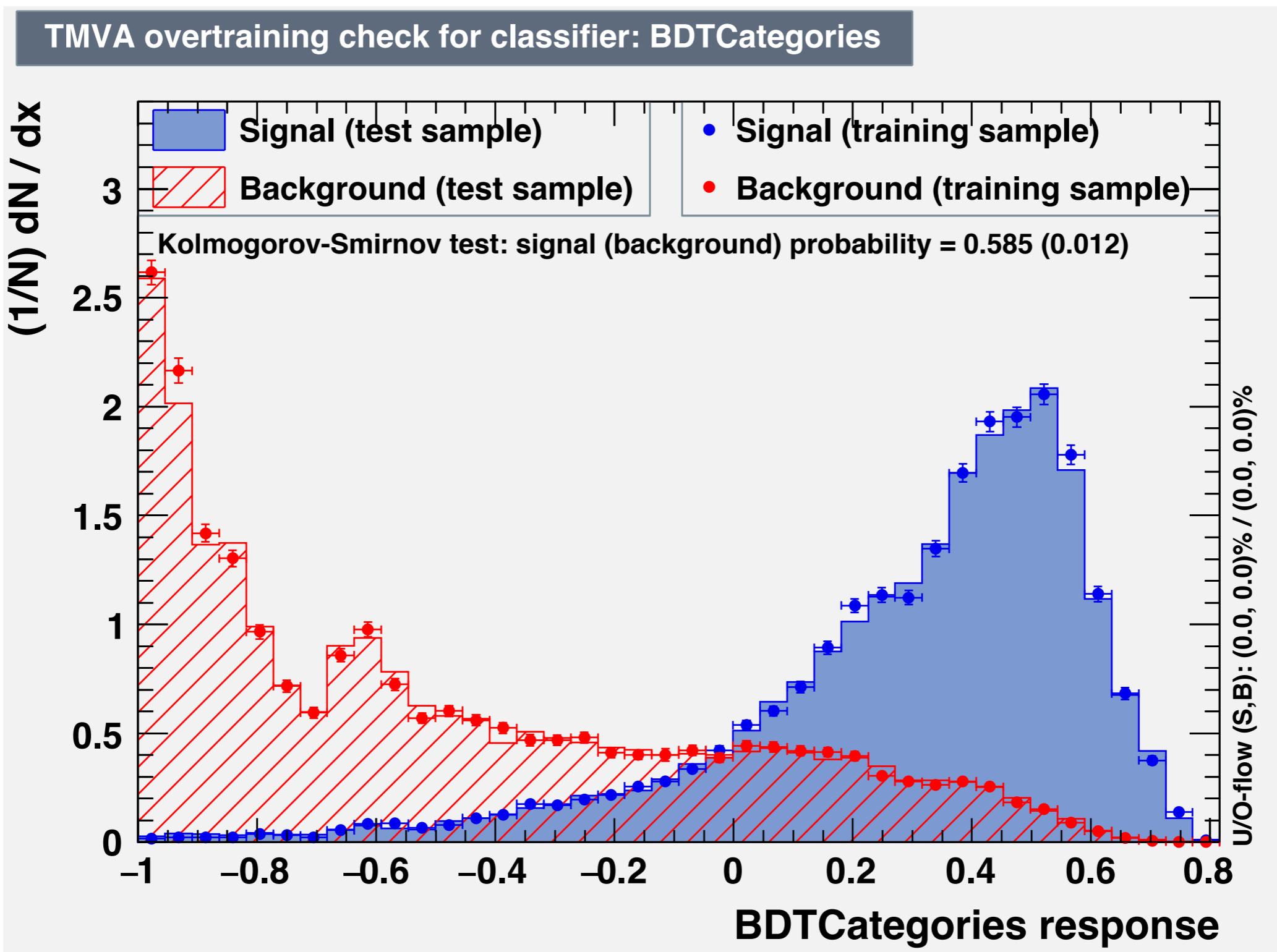


VARIABLES RANKING



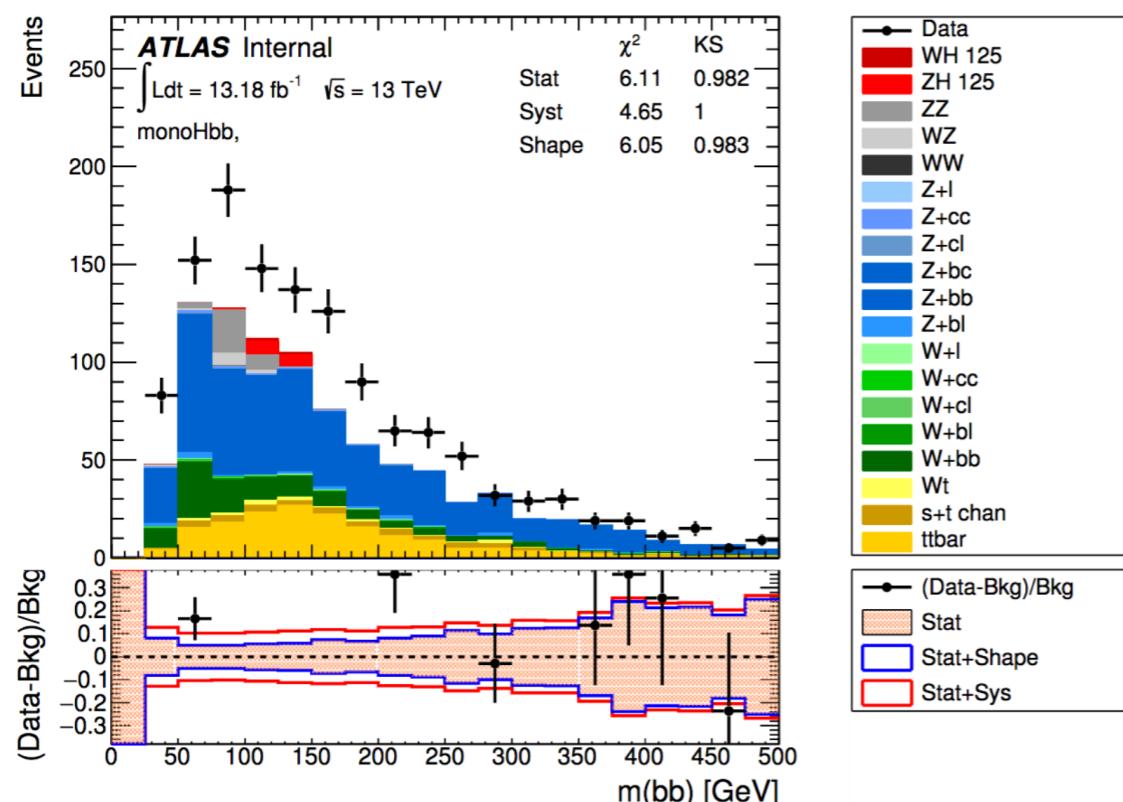
- ▶ Significance reaches a “plateau” quite early : variables largely correlated
 - ▶ Drops when adding variables

VH(bb) MULTIVARIATE ANALYSIS - BDT OUTPUT



PRE-FIT DISTRIBUTIONS – REBINNING

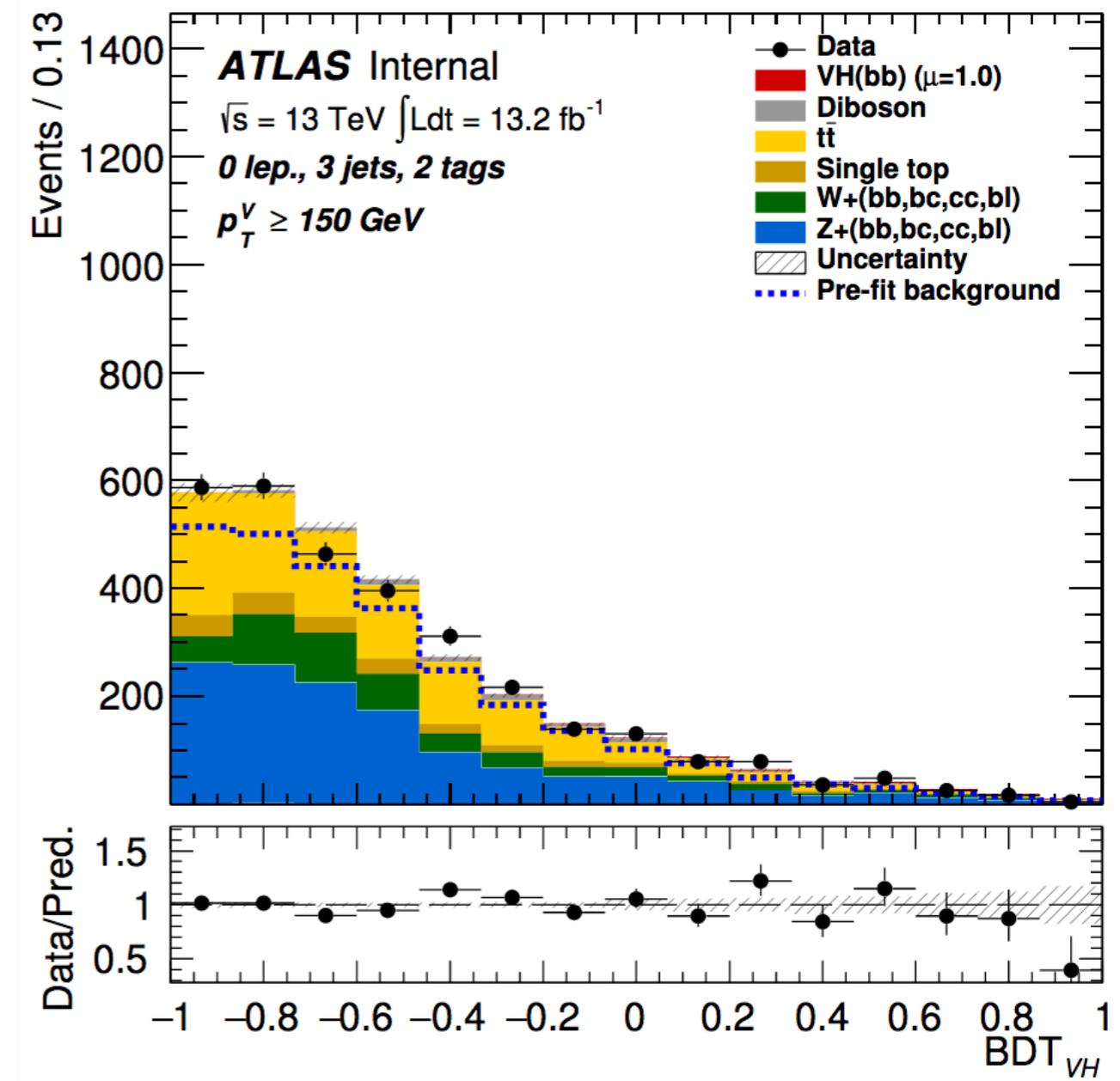
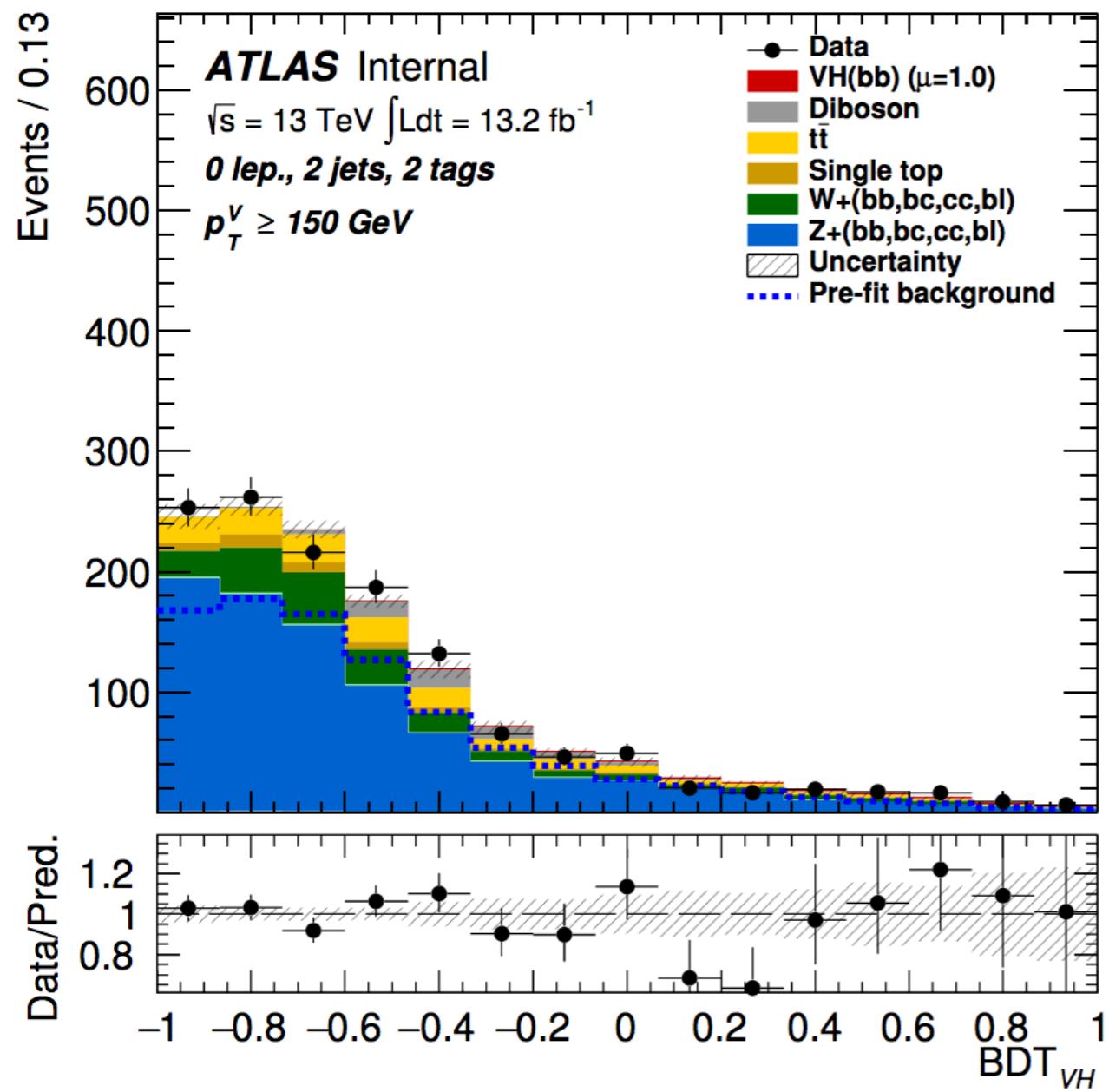
- ▶ Background modelling : normalisation can be improved
 - ▶ Floating normalisation of major backgrounds (Zbb, Wbb, ttbar)
- ▶ Systematics encoded as nuisance parameters
- ▶ Systematic uncertainties extracted from MC variations (varying b-tag SF within $\pm 1\sigma$ uncertainty, varying JES, ...)



Histogram binning defined in order to limit the statistical uncertainty and avoid bad sensitivity estimates from statistical fluctuations

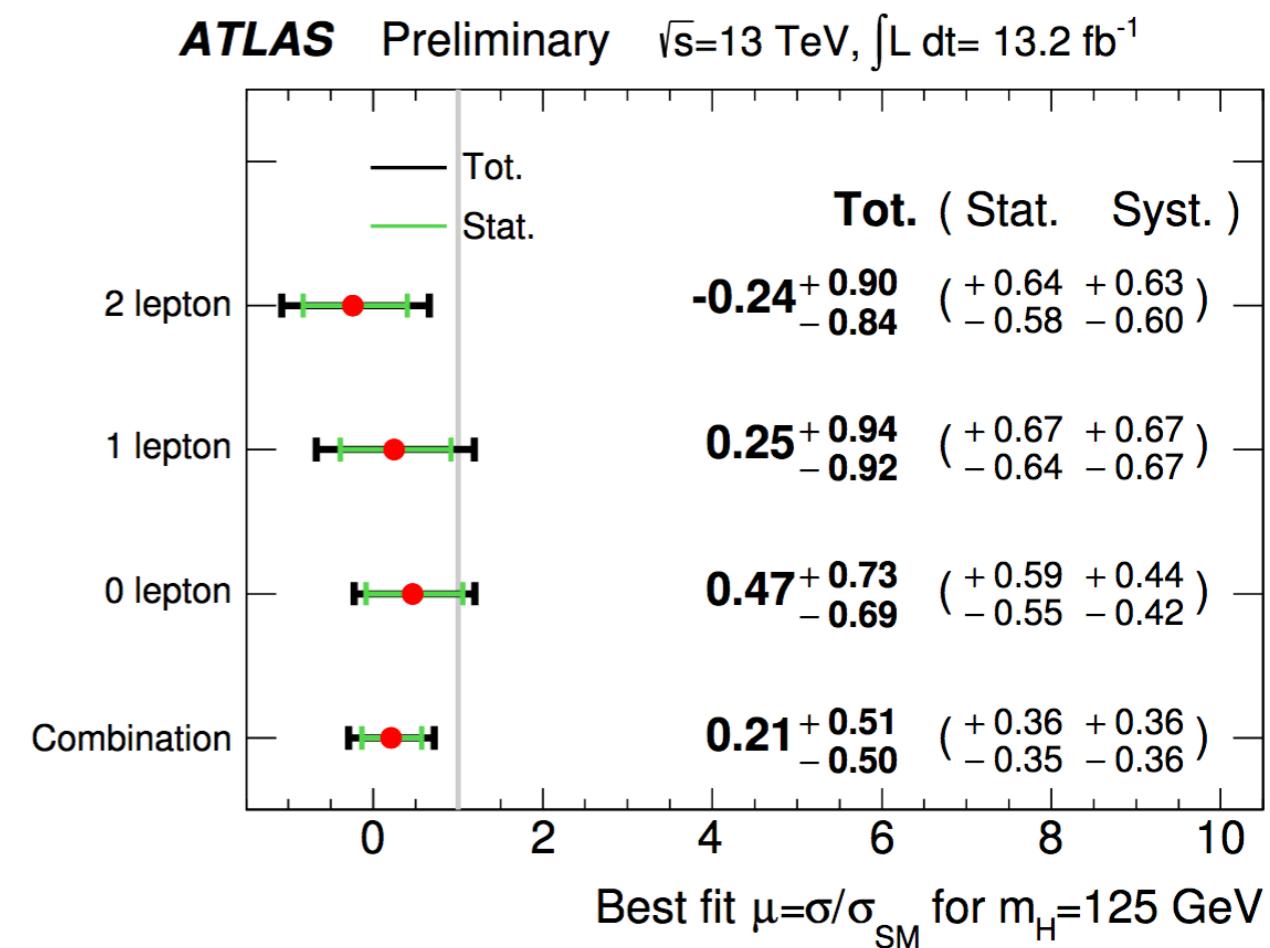
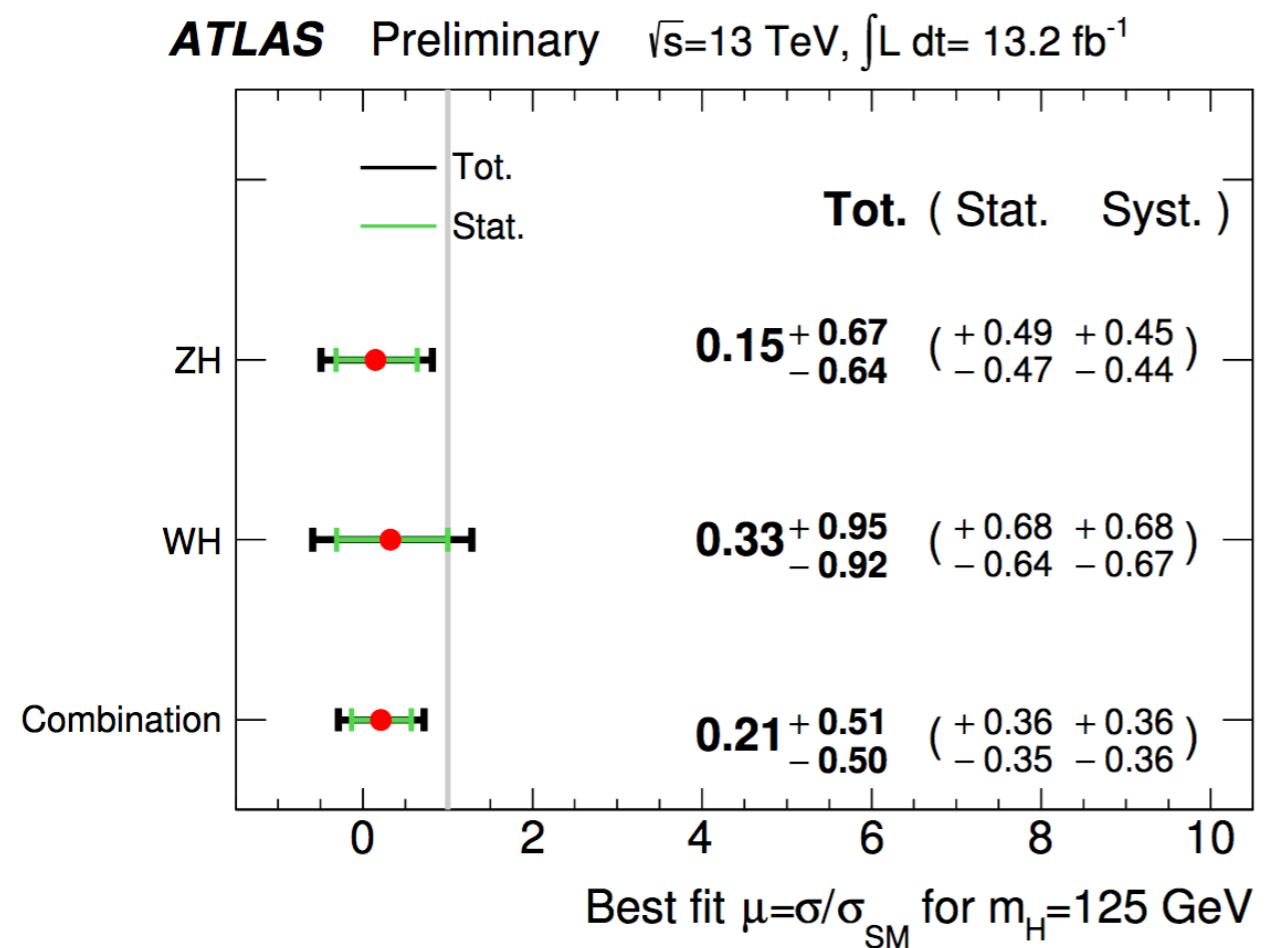
Rebin and fit are on the BDT output

POST-FIT DISTRIBUTIONS



BDT discriminant distribution in the 2 jets (left) and 3 jets (right) in the 0-lepton channel

ICHEP RESULTS



- Expected significance $\sigma_{\text{exp}} = 1.94$
- Observed significance $\sigma_{\text{obs}} = 0.42$
- Signal strength $\mu = \sigma_{\text{measured}} / \sigma_{\text{SM}} (m_H = 125 \text{ GeV}) = 0.21 \pm 0.36(\text{stat.}) \pm 0.36(\text{syst.})$

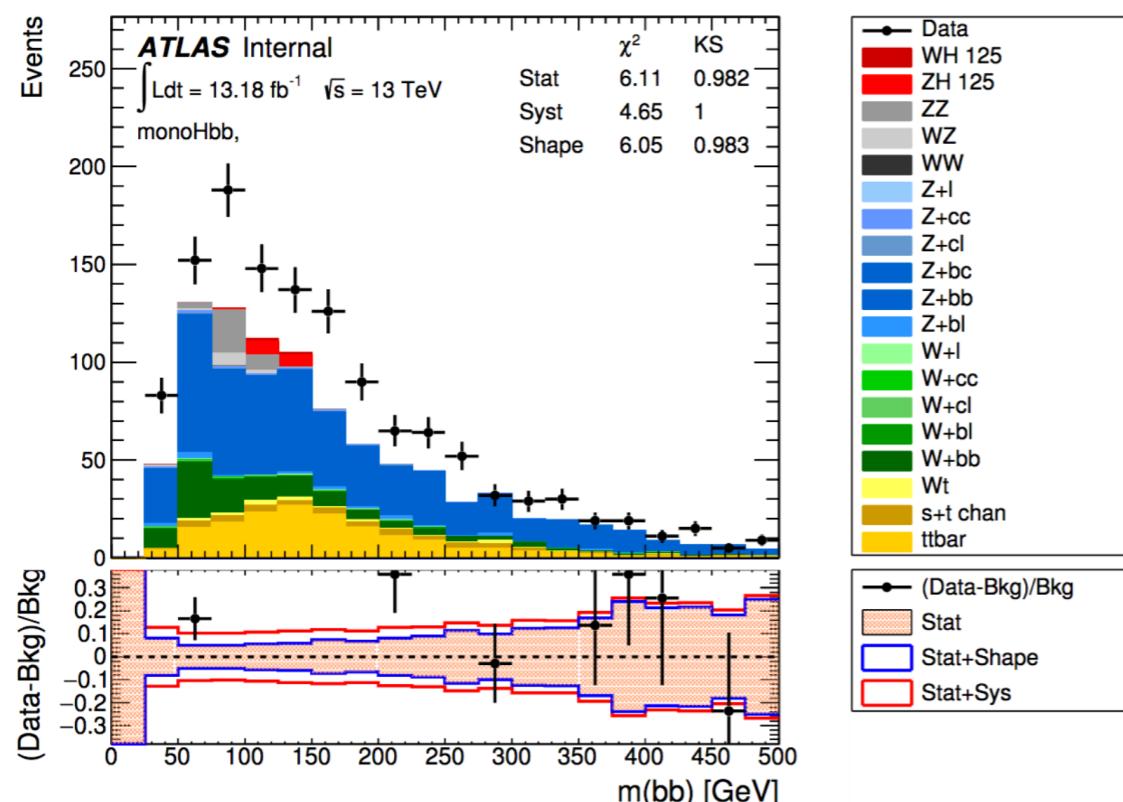
CONCLUSION

- ▶ VH(bb) analysis performed : $\mu = 0.21 \pm 0.36(\text{stat.}) \pm 0.36(\text{syst.})$ at ICHEP time
- ▶ Work of training variables ongoing : further improvements from systematics effects to be evaluated eventually
- ▶ Prospects
 - ▶ Uncertainty on the use of continuous tagging (will be available ?)
 - ▶ ~ 15% expected significance improvement
 - ▶ Expected sensitivity $> 3\sigma$ with the full 2016 dataset
 - ▶ Differential studies with full run2 dataset ($L \sim 100 \text{ fb}^{-1}$)
 - ▶ Probe of V-V-H coupling
 - ▶ Probe of down quark Yukawa coupling

BACKUP

PRE-FIT DISTRIBUTIONS – REBINNING

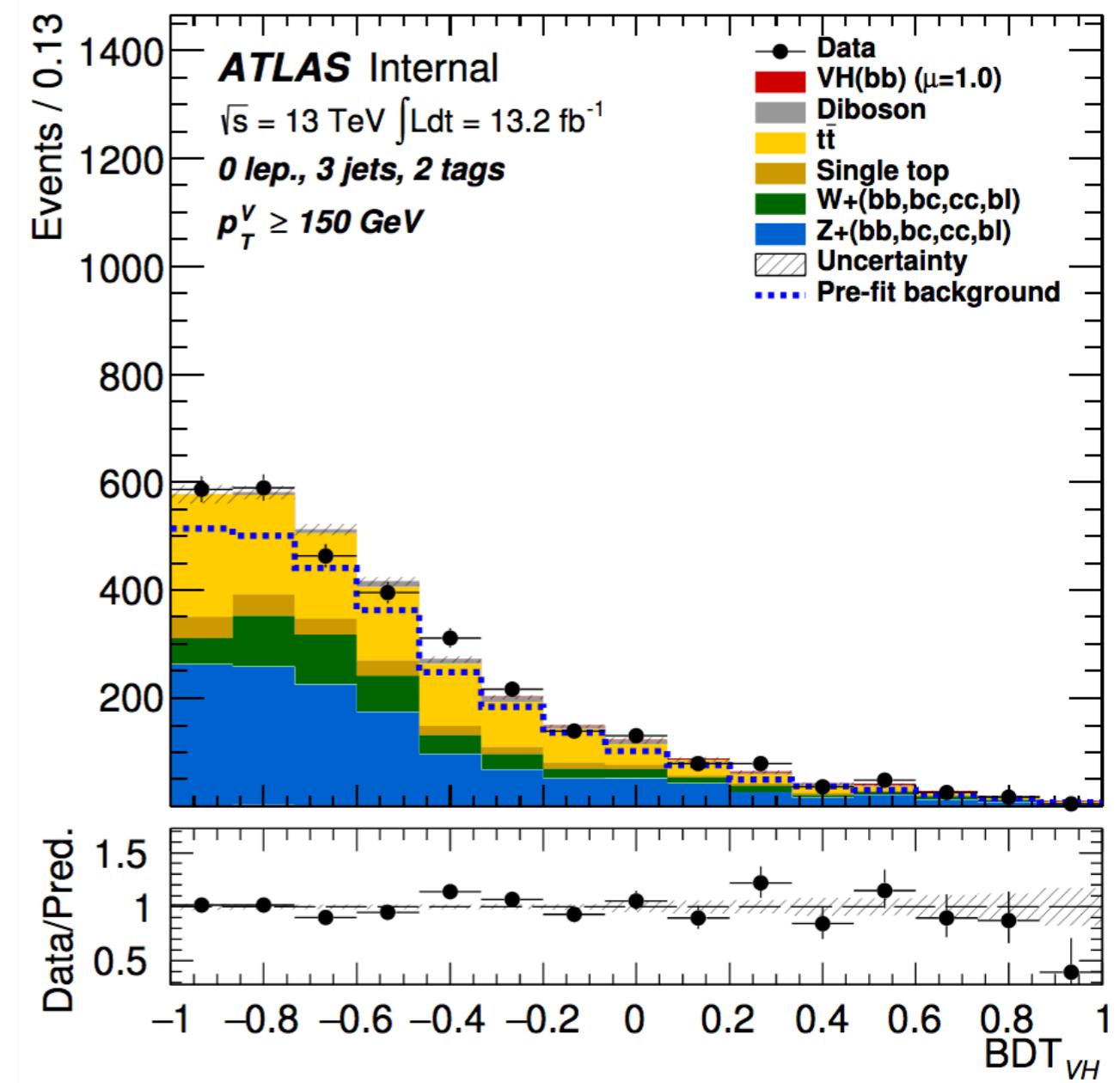
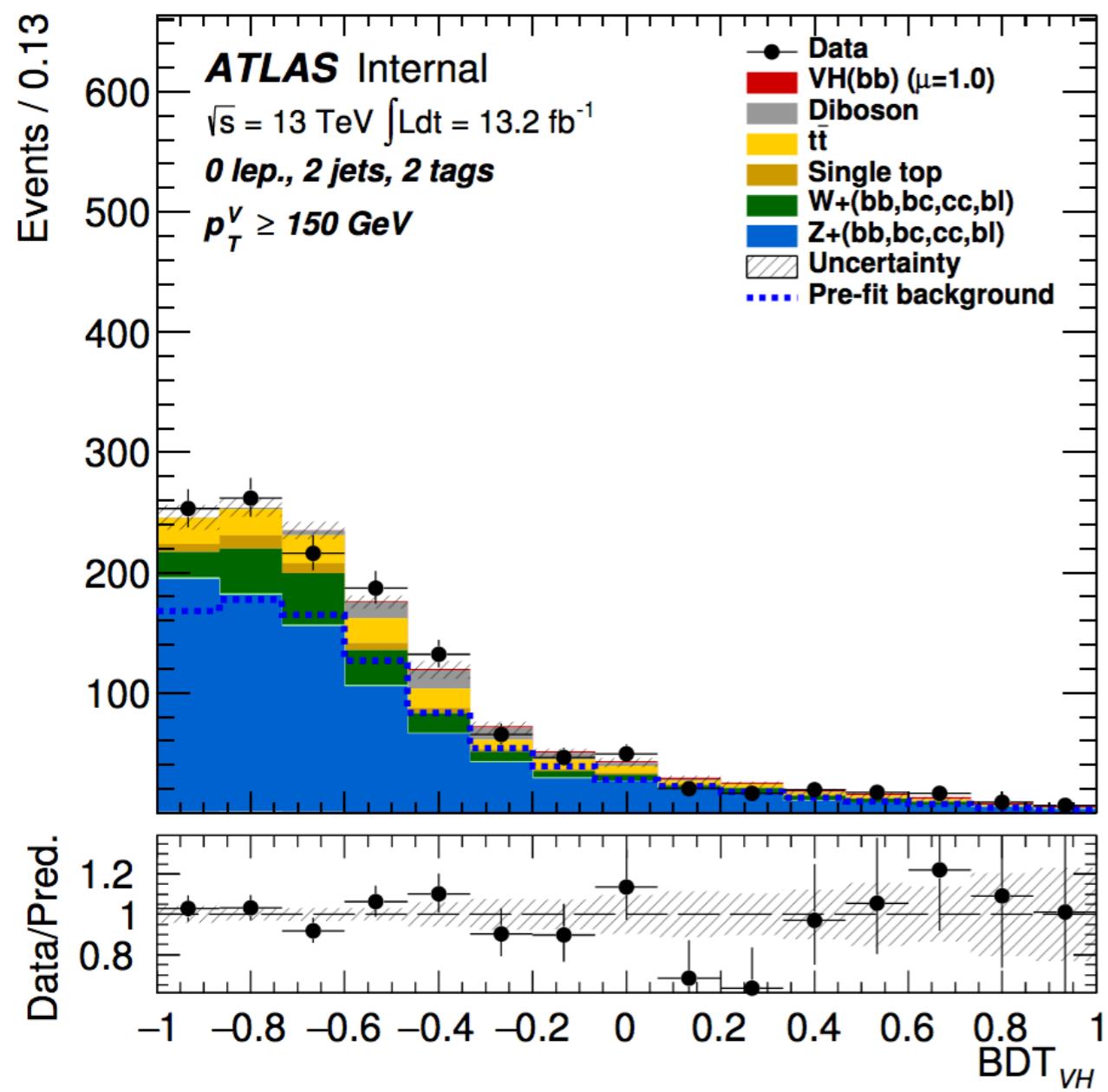
- ▶ Background modelling : normalisation can be improved
 - ▶ Floating normalisation of major backgrounds (Zbb, Wbb, ttbar)
- ▶ Systematics encoded as nuisance parameters
- ▶ Systematic uncertainties extracted from MC variations (varying b-tag SF within $\pm 1\sigma$ uncertainty, varying JES, ...)



Histogram binning defined in order to limit the statistical uncertainty and avoid bad sensitivity estimates from statistical fluctuations

Rebin and fit are on the BDT output

POST-FIT DISTRIBUTIONS



BDT discriminant distribution in the 2 jets (left) and 3 jets (right) in the 0-lepton channel

Cut based analysis

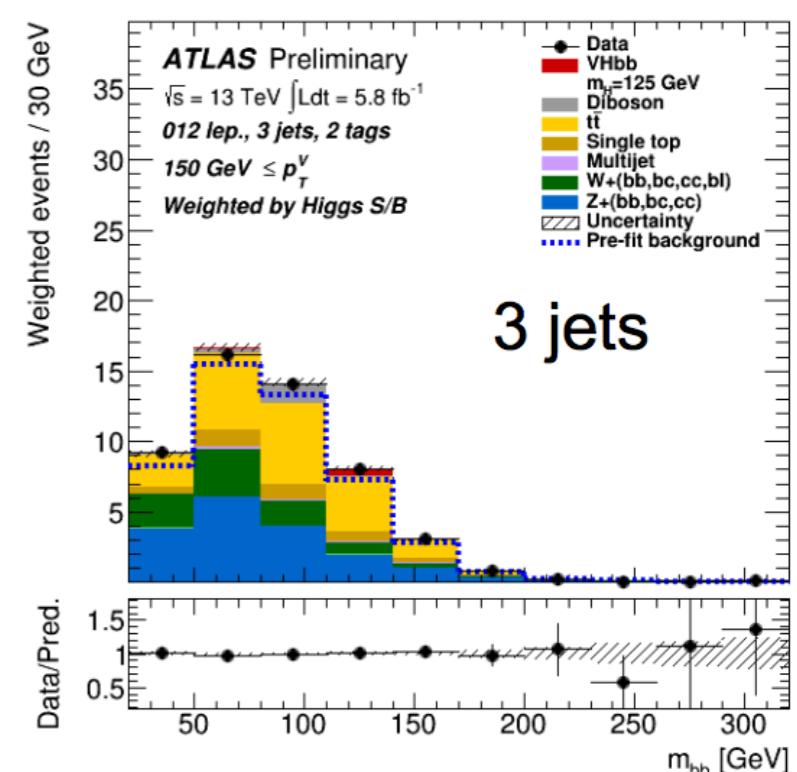
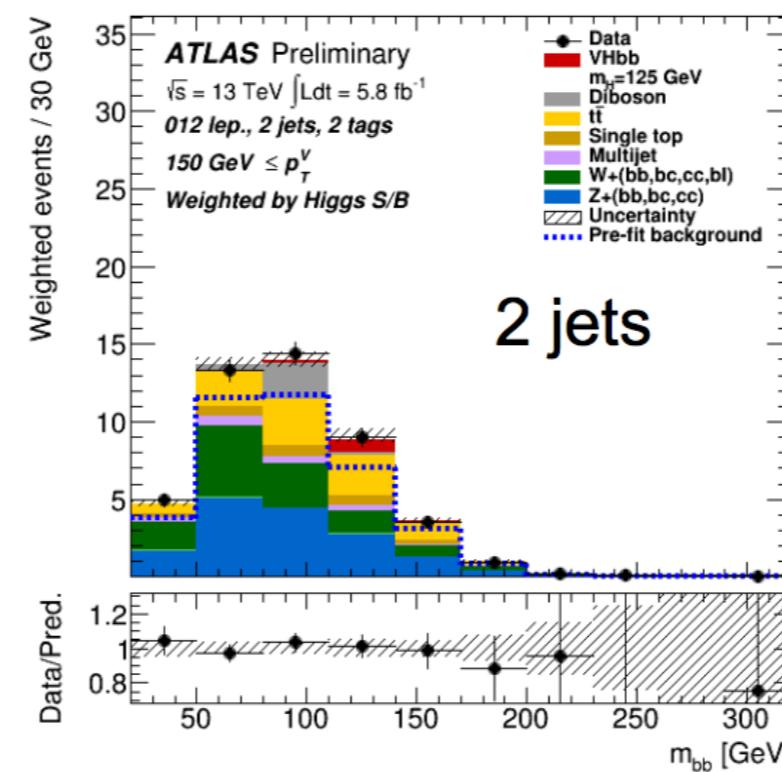
The analysis consists in applying the base selection with additional cuts :

- For the three channels : $\Delta R(b1,b2) < 1.8$ for $p_T^V < 200$ GeV and $\Delta R(b1,b2) < 1.2$ for $p_T^V > 200$ GeV and p_T^V categories
- For 1-lepton : $m_{T,W} < 120$ GeV
- For 2 lepton : $81 < m_{\parallel} < 101$ GeV and $\text{MET}/\sqrt{H_T} < 3.5 \sqrt{\text{GeV}}$

The invariant mass of the two selected b-jets is used as discriminant variable

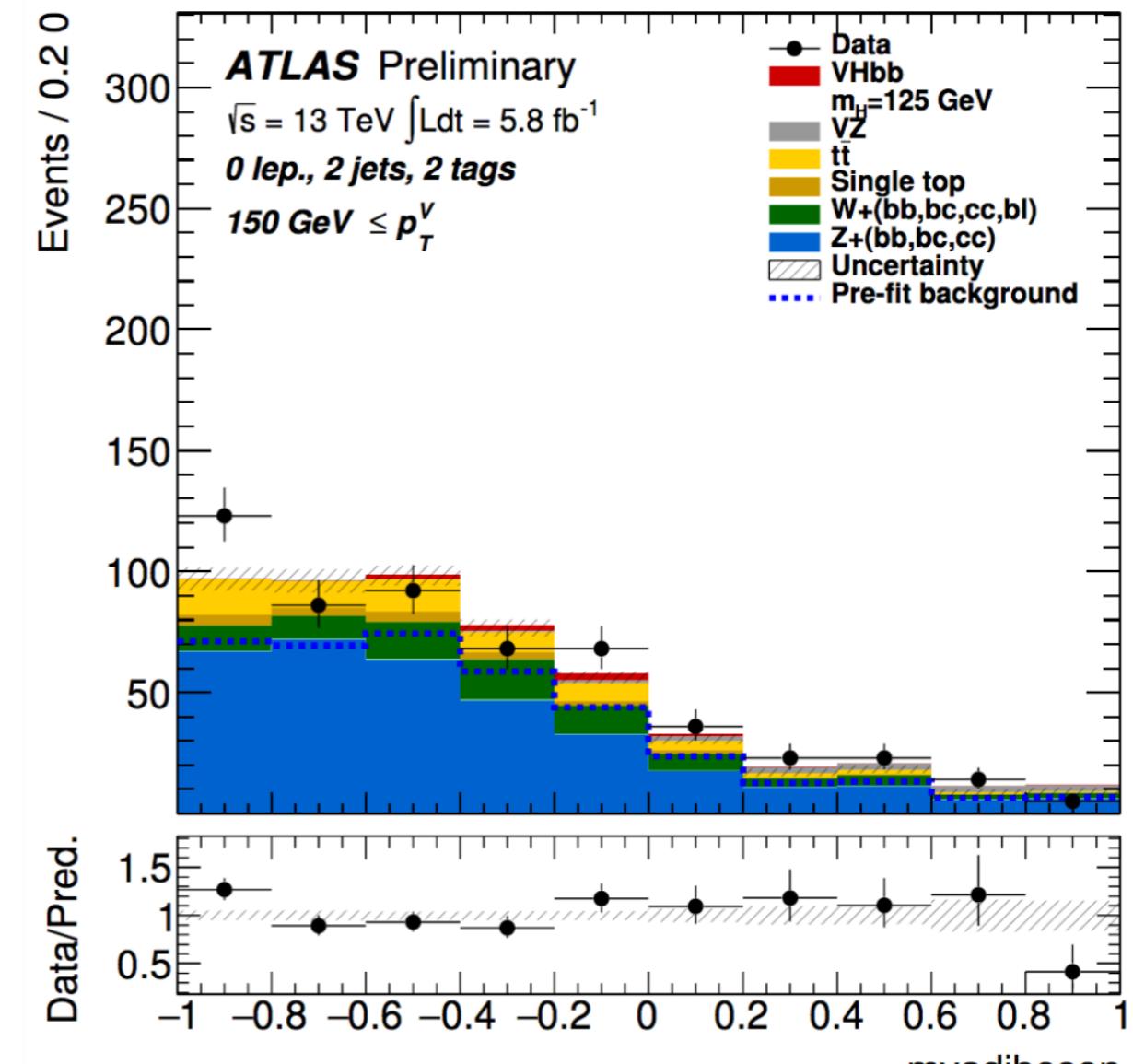
Significance	Expected	Observed
Cut Based	1.53	1.91
MVA	1.94	0.42

	Signal strength factor	
	MVA	Cut Based
0 lepton	0.7 ± 0.74	0.96 ± 1.02
1 lepton	0.1 ± 0.97	2.26 ± 1.5
2 leptons	-0.14 ± 0.88	0.76 ± 1.38
Combined	0.21 ± 0.51	1.28 ± 0.74



DIBOSON CROSS-CHECK

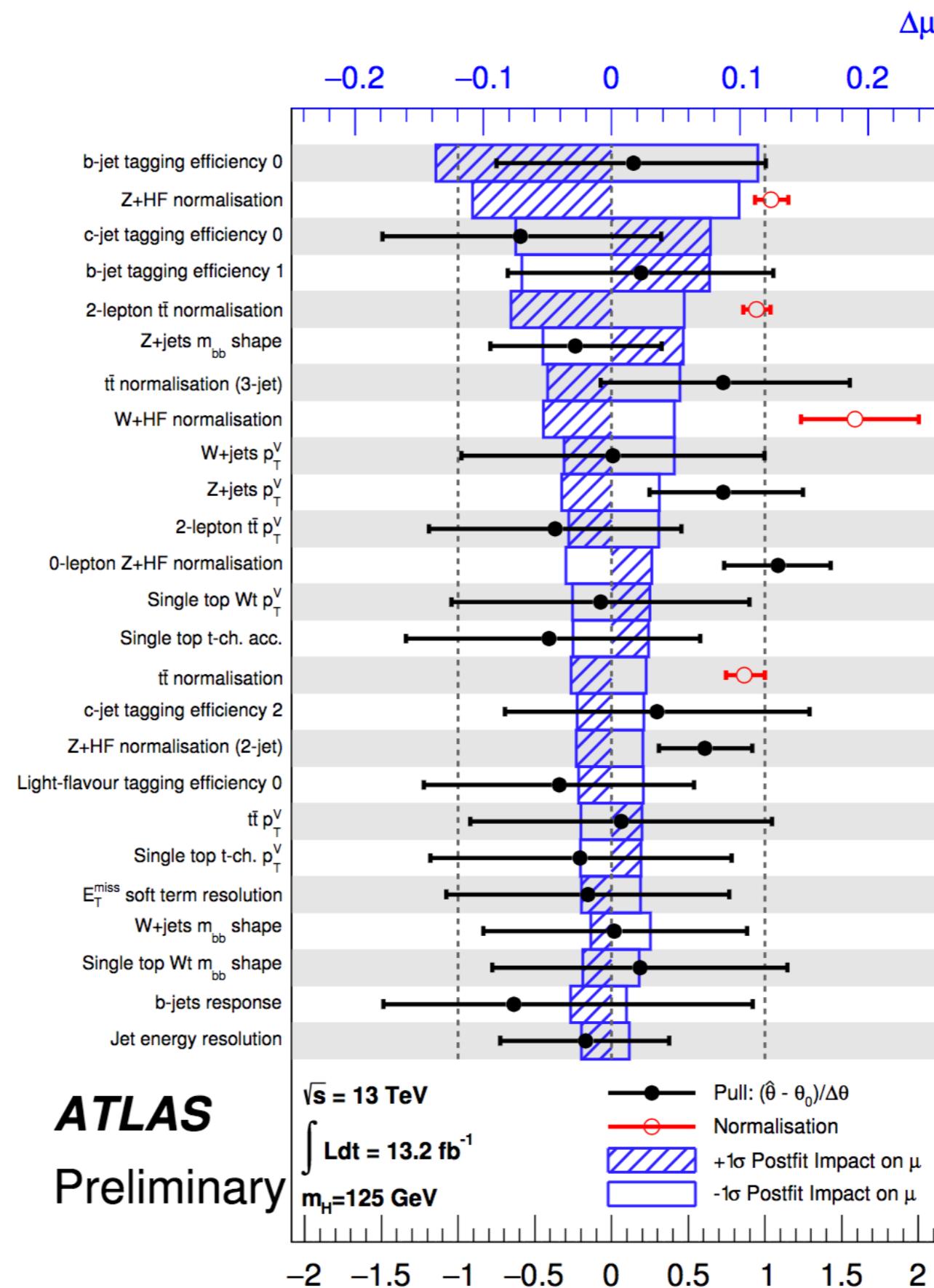
- ▶ Produce an identical analysis where signal is ZZ/WZ
 - ▶ Train the BDT with ZZ/WZ/WW as signal (VH is now a background !)
- ▶ Benefits from the more abundant signal to validate the analysis
- Expected significance $\sigma_{\text{exp}} = 3.2$
- Observed significance $\sigma_{\text{obs}} = 3.0$
- Signal strength $\mu = 0.91 \pm 0.17(\text{stat.})^{+0.32}_{-0.27}(\text{syst.})$



CORRECTIONS TO THE 1-LEPTON CHANNEL ANALYSIS SINCE ICHEP

- e120 trigger was missing in 1lepton analysis
 - missing in both data and MC
- mu26 trigger was used not only for latter 2016 but also 2015 and early 2016
 - low p_T^W region is affected
- muon p_T cut was used even when MET trigger is used in 1lepton
 - VH signal muon $pT > 25$ GeV is additionally required, so no big impact
- electron trigger SF for medium ID electron was used in 1lepton
 - change to tight ID
- for VH signal correction in 1lepton, reconstructed p_T^W was used as argument
 - fix to use truth p_T^W

PULLS



LIMITS

For all lepton channels combined the observed limit on the ratio of the cross section times branching ratio with respect to the SM expectation for $m_H = 125$ GeV is 1.2, to be compared to an expected limit, in the absence of signal, of $1.0^{+0.4}_{-0.3}$. The probability p_0 of obtaining from background alone a result at least as signal-like as the observation is 34% for a tested Higgs boson mass of 125 GeV. In the presence of a Higgs boson with that mass and the SM signal strength, the expected p_0 value is 3%. This corresponds to an observed excess with a significance of 0.42 standard deviations, to be compared to an expectation of 1.94 standard deviations. Table 8 shows the expected and observed 95% CL limits, p_0 and significance values for the separate lepton channel fits and for the lepton channels combined in the global fit. For all

Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4^{+0.6}_{-0.4}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0^{+0.8}_{-0.6}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8^{+0.7}_{-0.5}$	1.7	0.13	0.57	1.14	-0.17
Combined	$1.0^{+0.4}_{-0.3}$	1.2	0.03	0.34	1.94	0.42