Search for charged Higgs bosons in $H^+ \to Wh \to l\nu bb$ decays within a resolved event topology using the ATLAS detector

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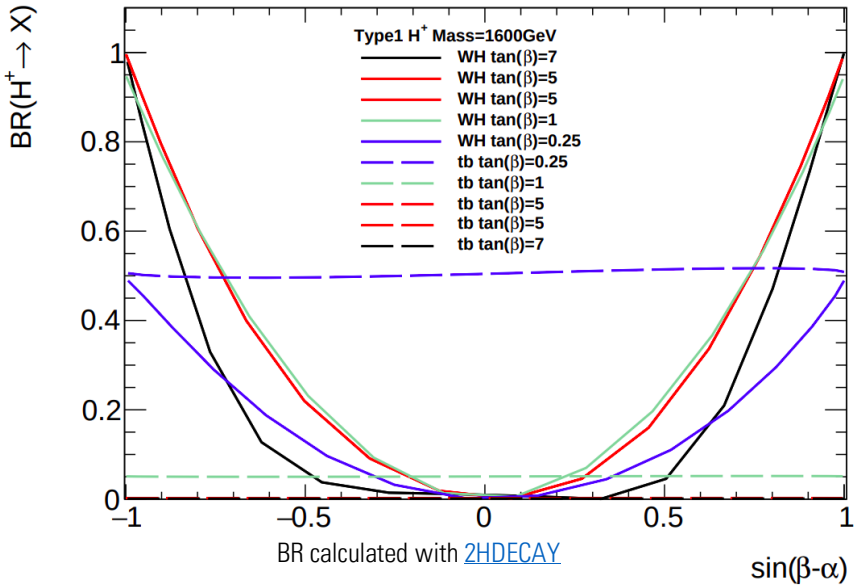
Motivation

- Several extensions of the SM predict an extended Higgs sector
  - The Higgs sector of a MSSM is a Type-2 Two Higgs Doublet model (2HDM)
- Models with additional Higgs doublets or triplets predict electrically charged scalars H^+
- Decay $H^+ \rightarrow Wh$ (h=125 GeV SM-like Higgs) is so far not explored by ATLAS and CMS searches
  - $H^+ \rightarrow tb$ or $H^+ \rightarrow \tau\nu$ is thought to be the main decay mode for a heavy charged Higgs boson [$m(H^+)>m(t)+m(b)$]
  - However $H^+ \rightarrow Wh$ becomes more important in some models
- Significant BR($H^+ \rightarrow Wh$) for:
  - N2HDM [https://arxiv.org/abs/1910.06858]
  - Georgi-Machacek model [https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.015029]
  - 2HDM scenarios in which the 125GeV Higgs boson is the heaviest CP-even scalar

2HDM

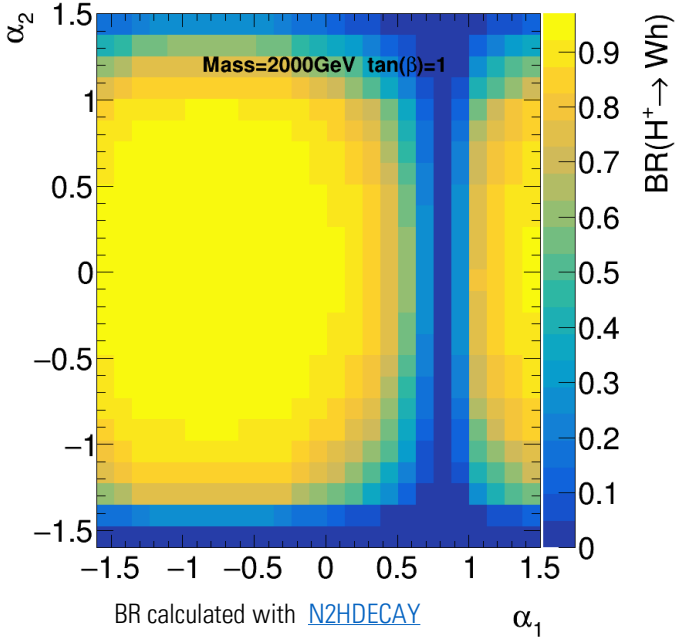
- 2 Higgs doublets
- Particles:
  - 2 CP-Even Higgs bosons h ,H
  - 1 Pseudoscalar A
  - 2 Charged Higgs bosons
- $\tan(\beta) = \left(\frac{v_1}{v_2}\right)$
- α mixing angle between h H
  - $\sin(\beta - \alpha)$->1(light Higgs boson SM-like)
  - $\sin(\beta - \alpha)$->0(heavy Higgs boson SM-like)



BR calculated with 2HDECAY

N2HDM

- 2 Higgs doublets + singlet
- Particles:
  - 3 CP-Even Higgs bosons
  - 1 Pseudoscalar A
  - 2 Charged Higgs bosons
- 3 Mixing angles: $\alpha_1, \alpha_2, \alpha_3$
- $\tan(\beta) = \left(\frac{v_1}{v_2}\right)$

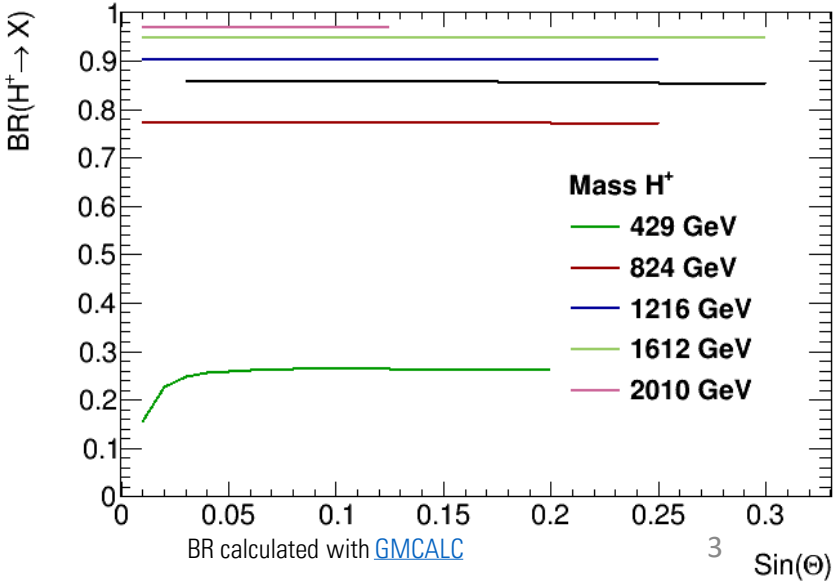


BR calculated with N2HDECAY

Georgi-Machacek

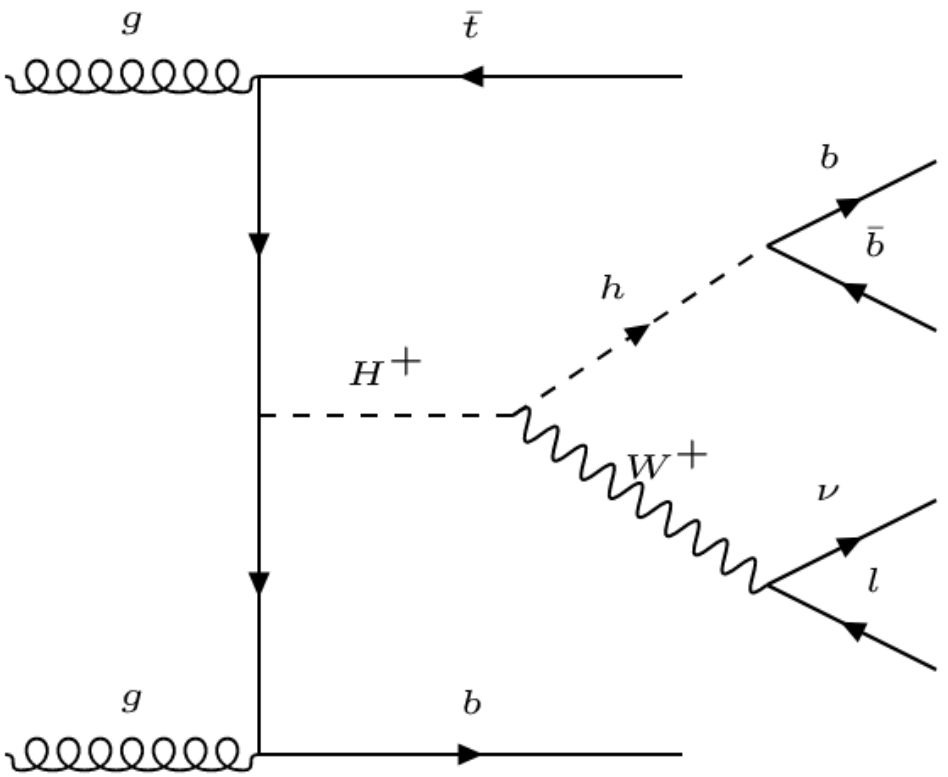
- Additional real and complex Higgs triplet
- Particles:
  - Fiveplet states:
    - $H_5^{++} \backslash H_5^{--}, H_5^{+} \backslash \mathrm{H}_5^{-}, H_5$
  - Triplet states:
    - $H_3^{+} \backslash \mathrm{H}_3^{-}, H_3$
  - Singlet states:
    - h, H

$$\sin\Theta = \frac{2\sqrt{2}v_\chi}{v} \qquad v_\chi = \text{VEV-Triplet}, \quad v = \text{SM-VEV}$$



BR calculated with GMCALC

Analysis Strategy



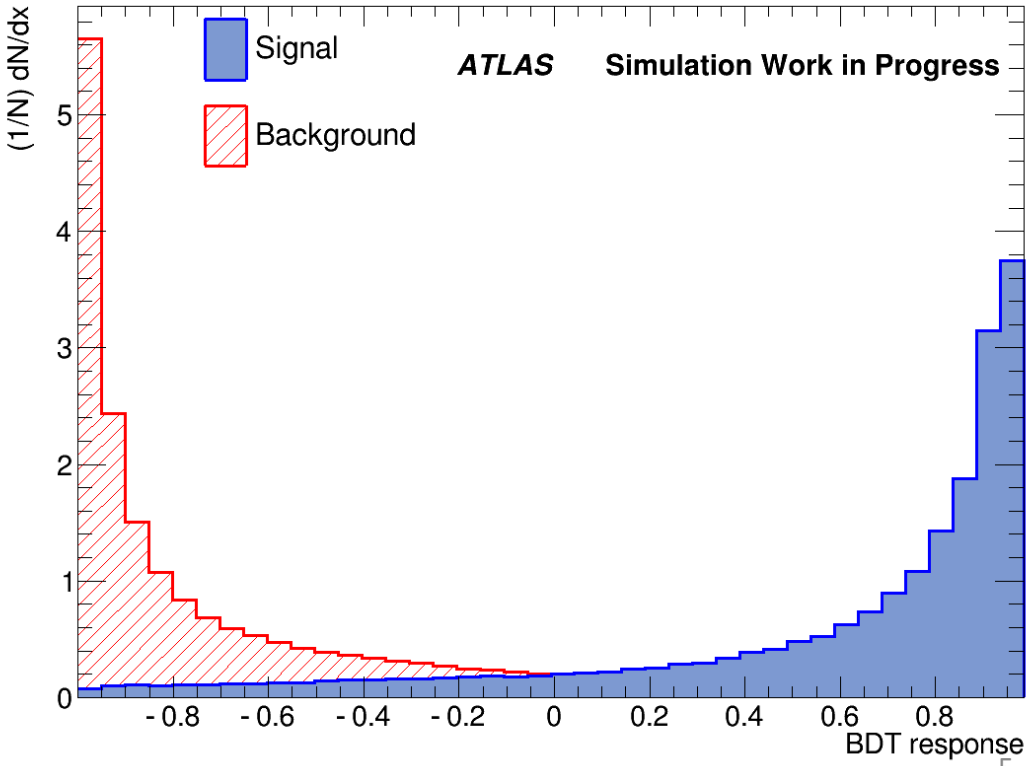
- Charged Higgs boson is produced in association with t and b
- Charged Higgs boson decay mode: $H^+ \rightarrow Wh \rightarrow lvbb$
  - Consider only events with one Lepton
    - Top quark decays fully hadronic: $t \rightarrow Wb \rightarrow qqb$
  - Multiple jets in the final state
    - 6 or more
    - 4 b tagged
  - MET
- Challenge: reconstruct charged Higgs boson (mass)
  - Reconstruct H^+ from W and h
    - Reconstruct W from lepton and MET
      - Neutrino is reconstructed from Missing Transverse Energy using W boson mass constrain technique
    - Reconstruct h from 2 Jets
      - Which 2 jets stem from h?
  - Use boosted decision trees (BDTs) to choose the correct combination of a W boson with two jets from the h decay
    - Select the W di-jet combination with highest BDT score
- Hadronic decaying W: $H^+ \rightarrow Wh \rightarrow qqbb$ T59.8 by Shubham Bansal
- Merged event topology: T87.3 by Patrick Bongratz

BDT Training and Parameters

- Boosted Decision Trees provided by

  TMVA Root package were used
- Signal: correct jet pair and lepton neutrino combination of the tbH^+ events
  - (the jet pair that is closest in dR to the truth Higgs boson is chosen, but dR<0.3 is required)
- Background: All the wrong combination
- Trained on 3 charged Higgs boson mass points
  - 400 GeV, 800 GeV, 1600 GeV

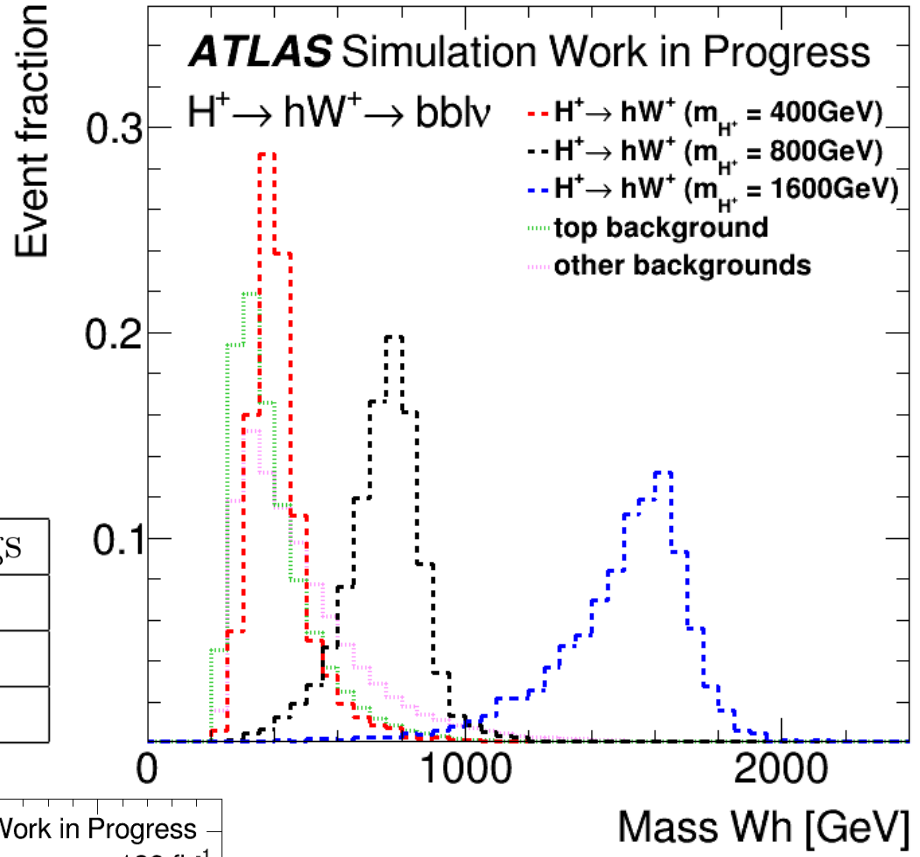
- Trained on:
  - Higgs Mass, Pseudo continuous b-tag score of Higgs jets, Azimuthal angle $\Delta\Phi$ between Higgs and W candidate, p_{THiggs}/m_{hW}, P_{TW}/m_{hW}

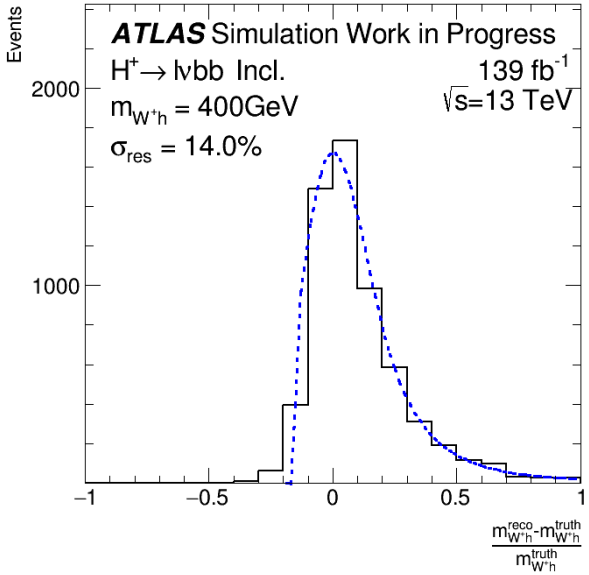


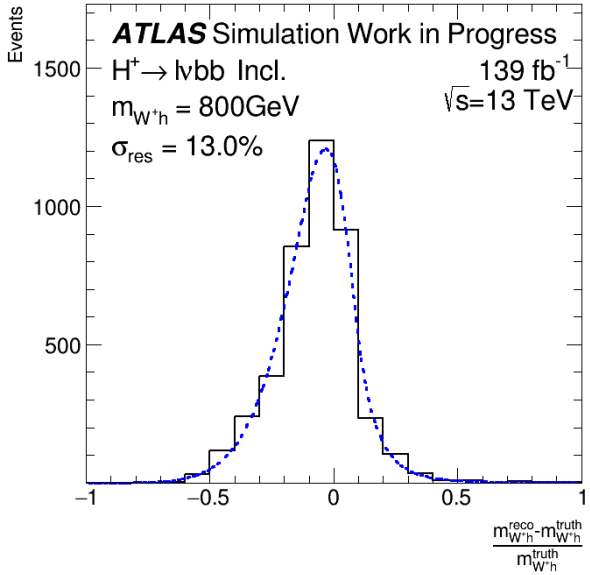
Mass Resolution

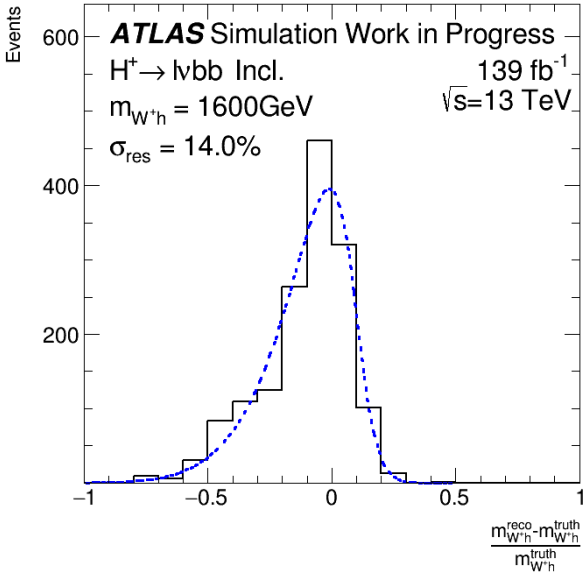
- BDT successfully reconstructs charged Higgs boson
- Calculate $\frac{m^{reco}_{W+h} - m^{truth}_{W+h}}{m^{truth}_{W+h}}$
- Fit asymmetric Bukin function to data
  - [https://github.com/root-project/root/blob/master/roofit/roofit/src/RooBukinPdf.cxx]
- Take variance
  - FWHM/2.35

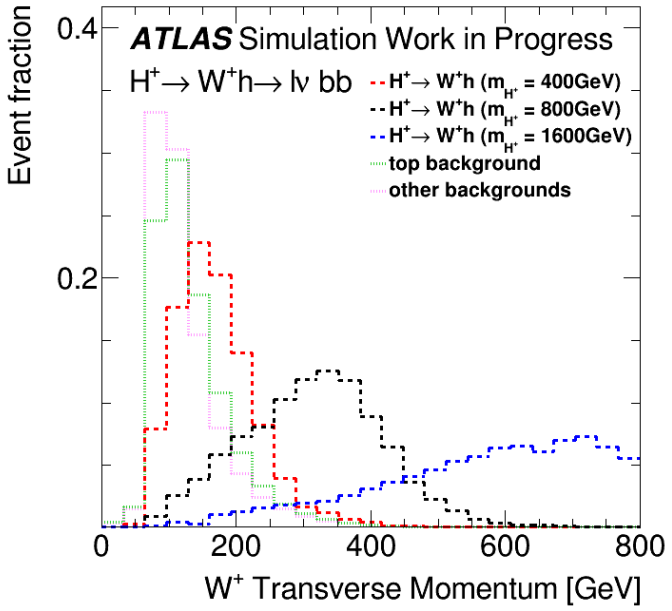
	Two b-Tags	Three b-Tags	Four+ b-Tags
400GeV	13%	13%	17%
800GeV	16%	15%	17%
1600GeV	10%	11%	12%

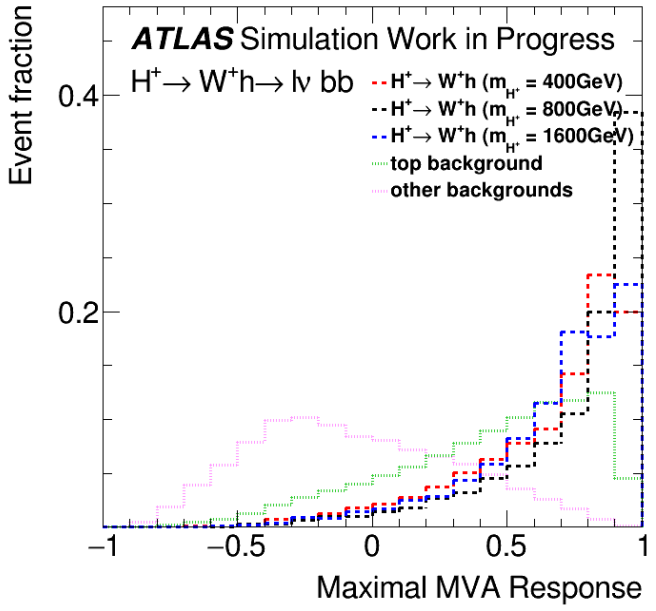


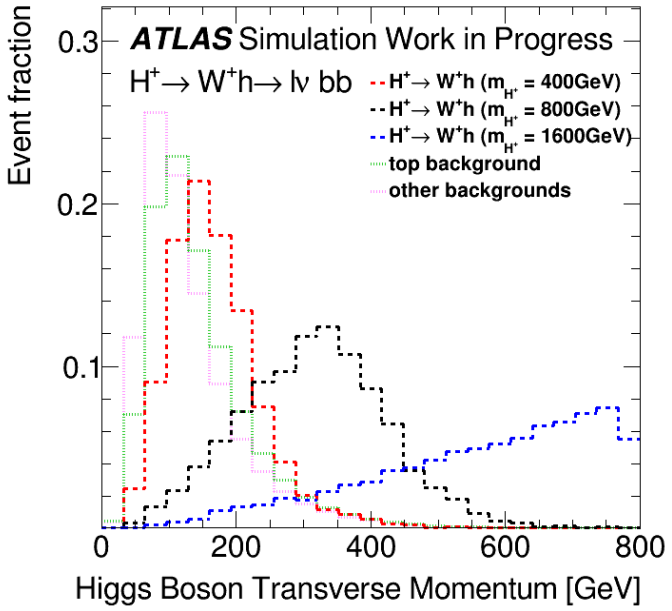


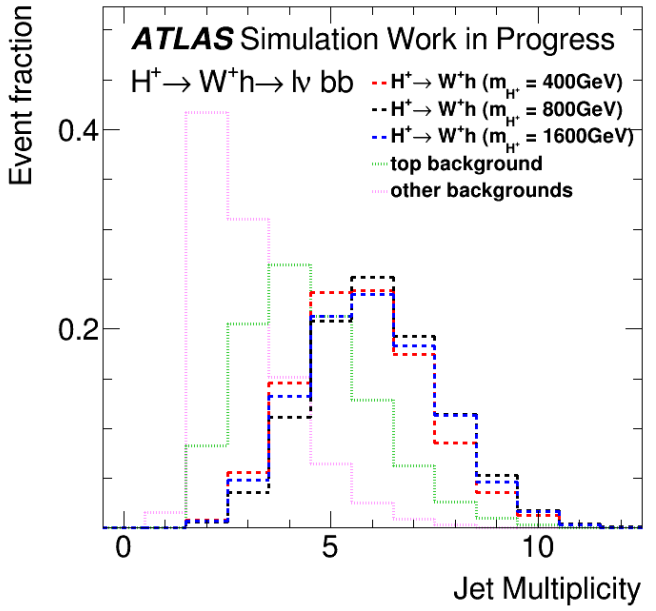












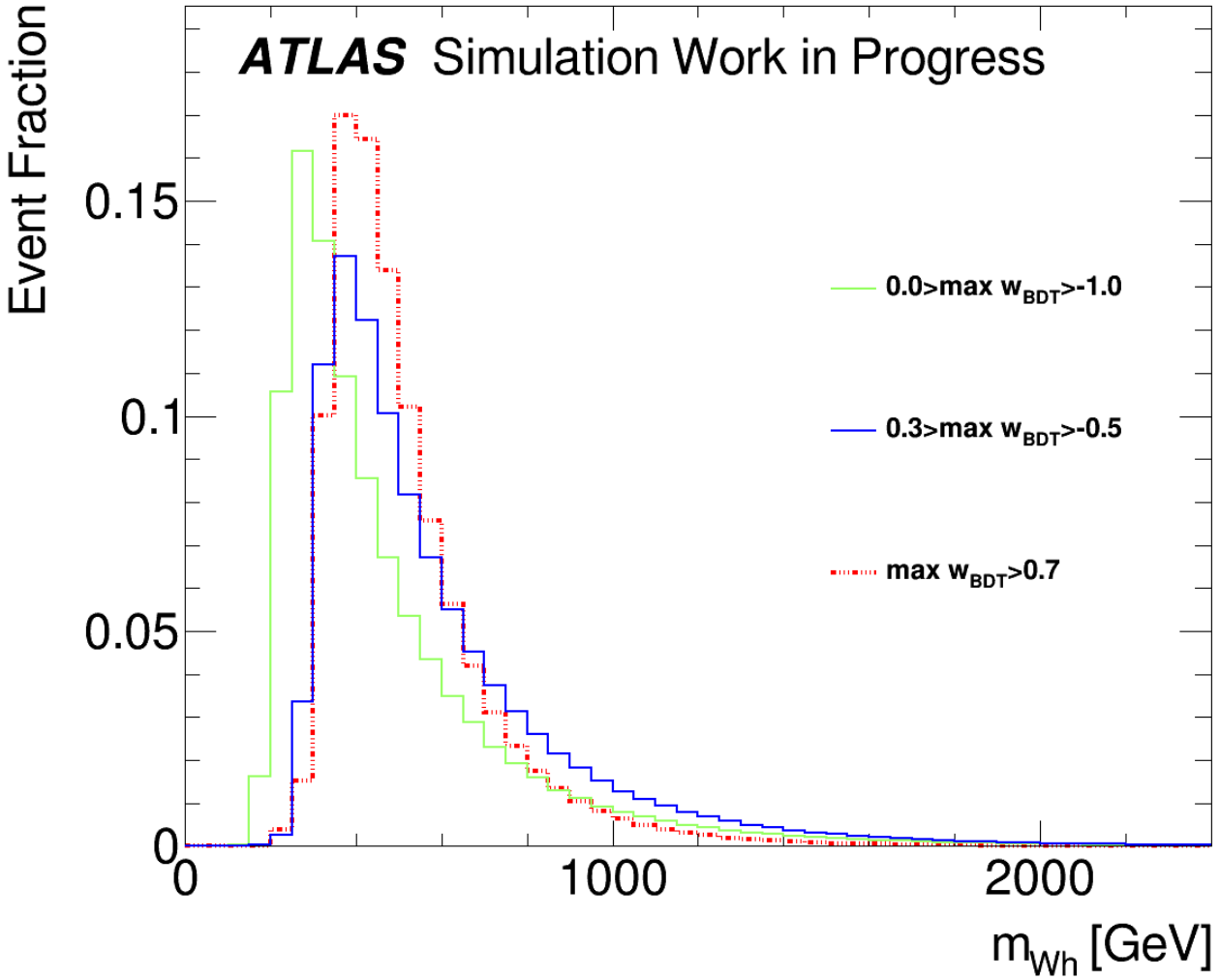
Event Selection

- Categorize events by # b-tags
  - 2 tags
  - 3 tags
  - 4+ tags
- Cut based event selection
  - Compare shapes of different variables
  - Calculate $\frac{\#s}{\sqrt{\#b}}$ for different cut-values to find the optimal one
- BDT not only reconstructs signal but can also distinguish between signal and background

Signal Region

$P_T^{Higgs} > 100$GeV
$p_T^W > 120$ GeV
#Jets>5
BDT Response>0.7

Event Selection

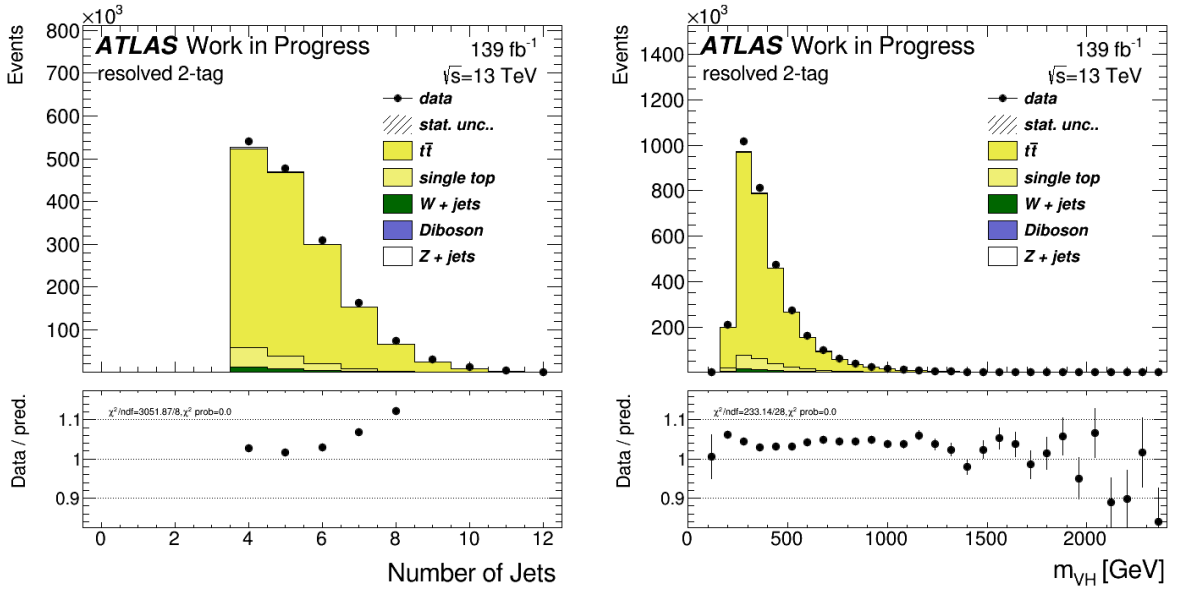


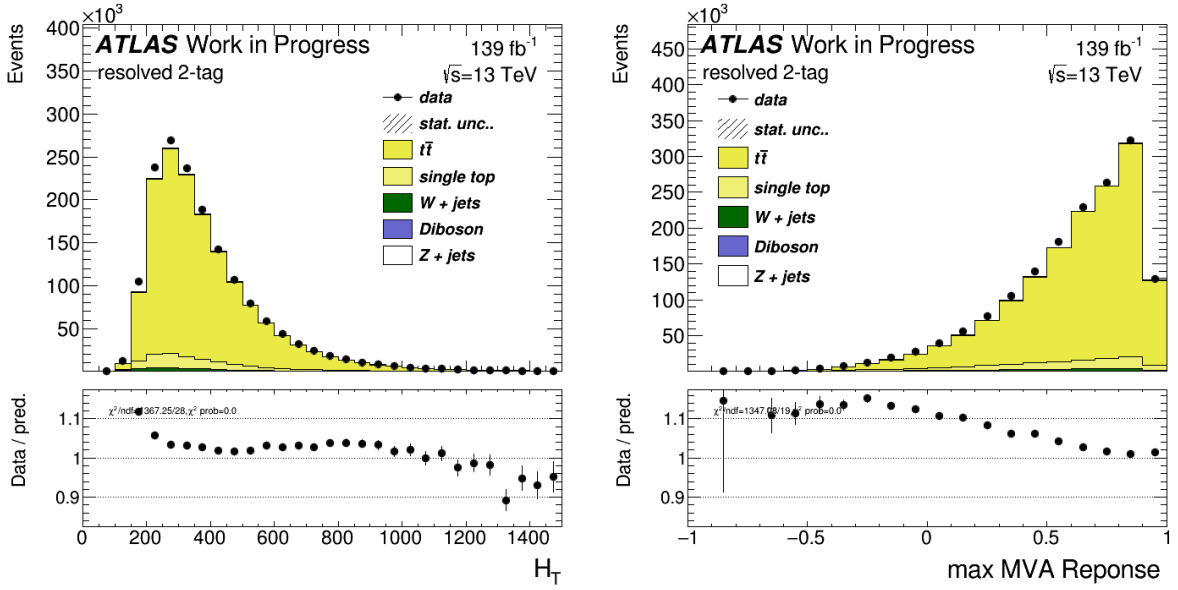
- The region with BDT Response > 0.7 is defined as the signal region
- Find a region where m_{hW} distribution of the SM-background is similar wrt. m_{hW} distribution in the SR
- For most regions in BDT Response this is the case
- Choose the one where the background is most enhanced over the signal

Control Region

-0.5<max BDT<0.3
P_T^{Higgs}> 100GeV
p_T^W>120 GeV
#Jets>5

Data-MC Comparison





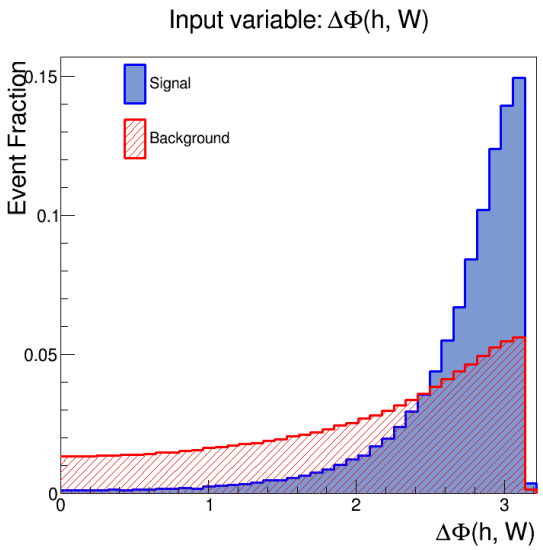
- Compare Data vs. MC in 2 b-tag region
  - Low sensitivity for signal
  - No further cuts (like SR/CR)
- Mismodeling is present
  - $t\bar{t}$ modelling systematic uncertainty
  - Currently under investigation: exploring different event re-weighting methods, checking the impact of pile-up

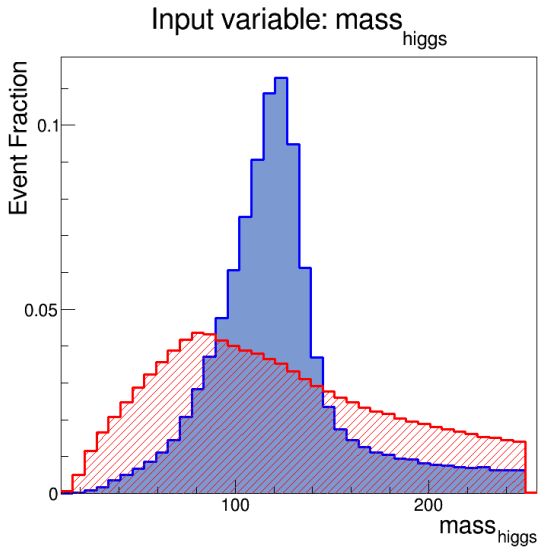
Conclusion/Next Steps

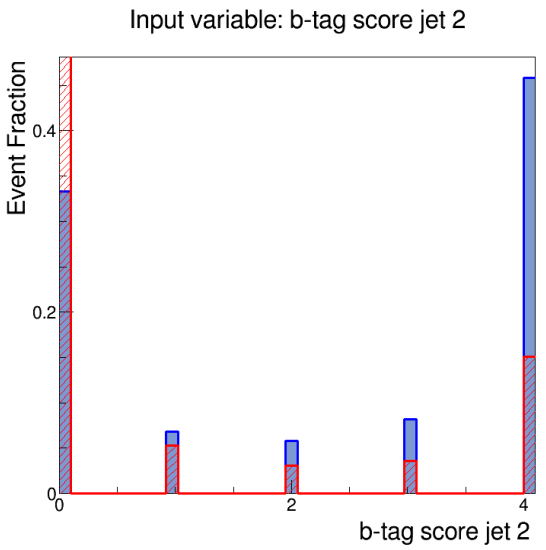
- $H^+ \rightarrow Wh$ studied for the first time at the LHC
  - Complementary to other H^+ searches e.g $H^+ \rightarrow tb$
- A first strategy for the $H^+ \rightarrow Wh \rightarrow l\nu bb$ channel has been developed
  - Charged Higgs bosons can be reconstructed by means of BDTs
  - Preliminary event selection criteria for the signal and control regions in data are in place
- More signal mass points are being produced
  - Re-train BDT
- Further investigate Data-MC discrepancies
  - Find method to deal with this
- Evaluate the signal sensitivity using the full-scale statistical interpretation framework

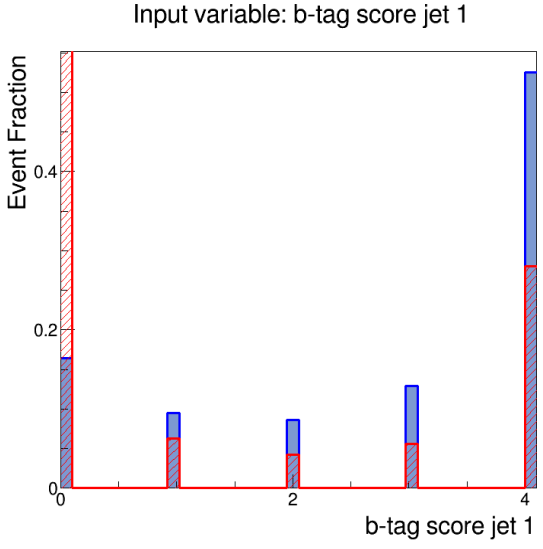
BACKUP

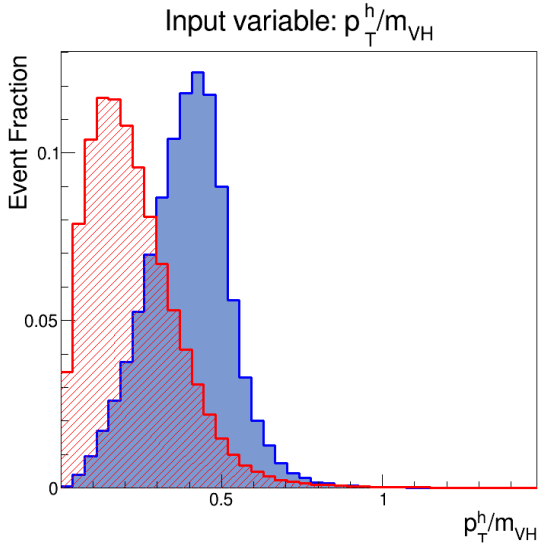
Training Results

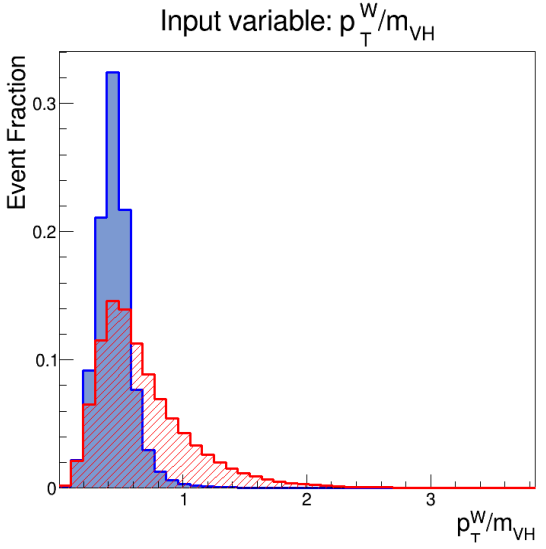






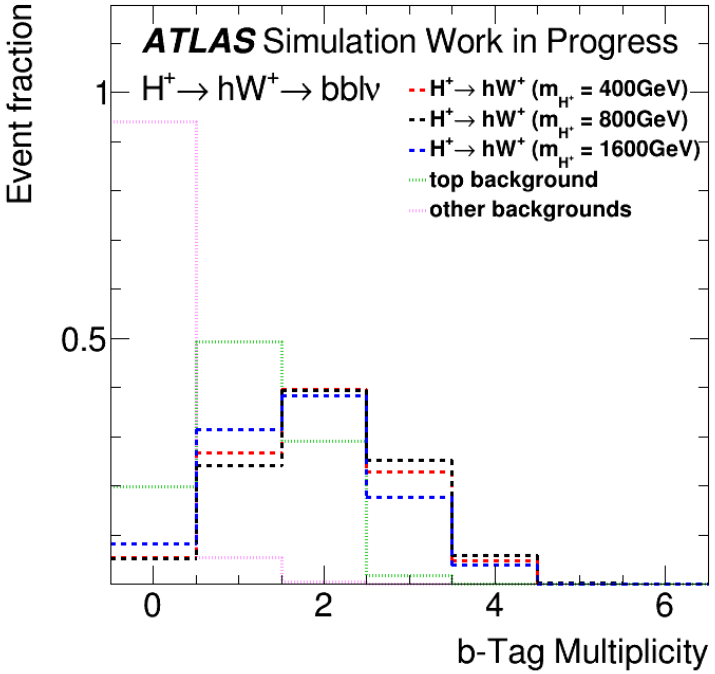


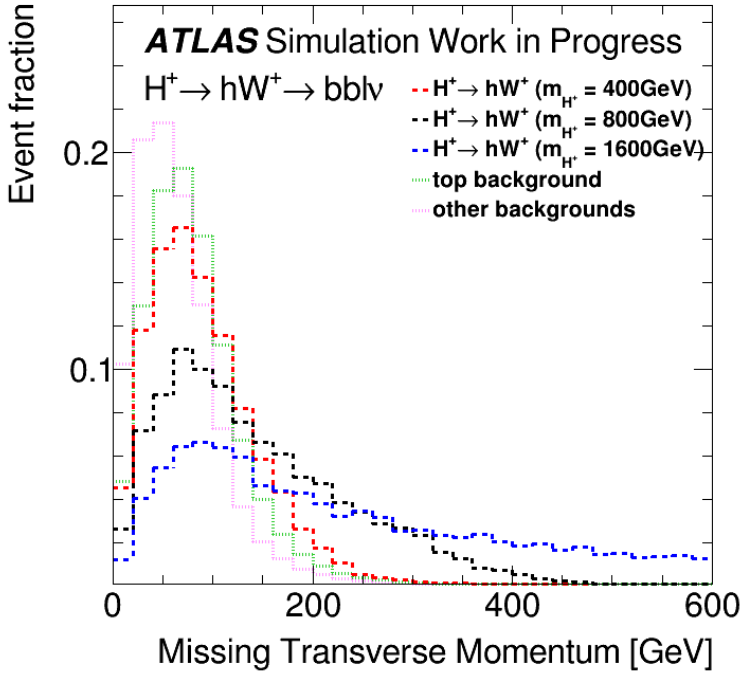


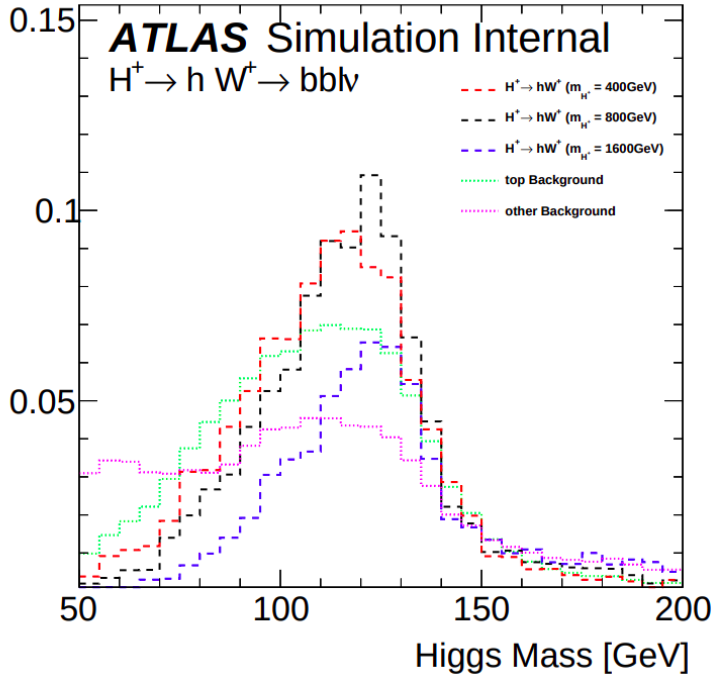


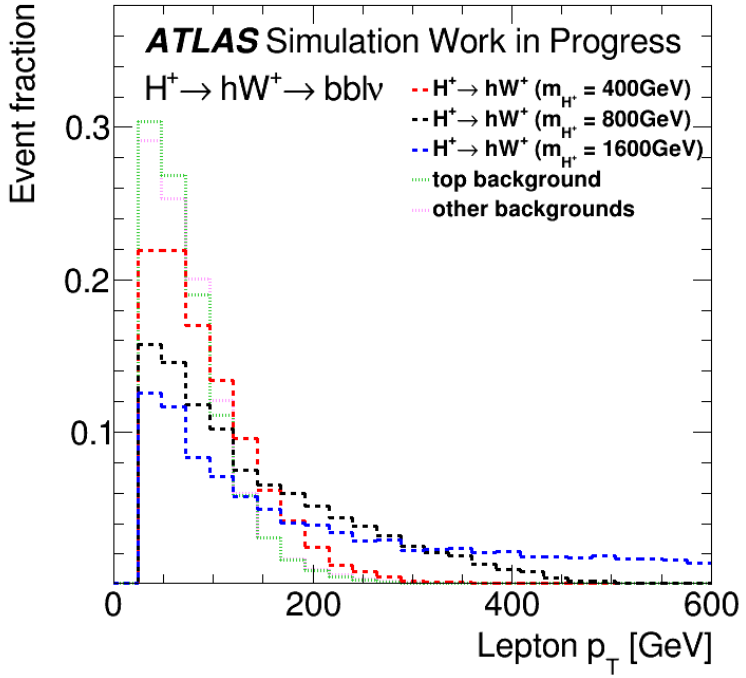
$$\frac{\#\text{Events in CR}}{\#\text{ of all Event} * \text{Intergral Lenght}}$$

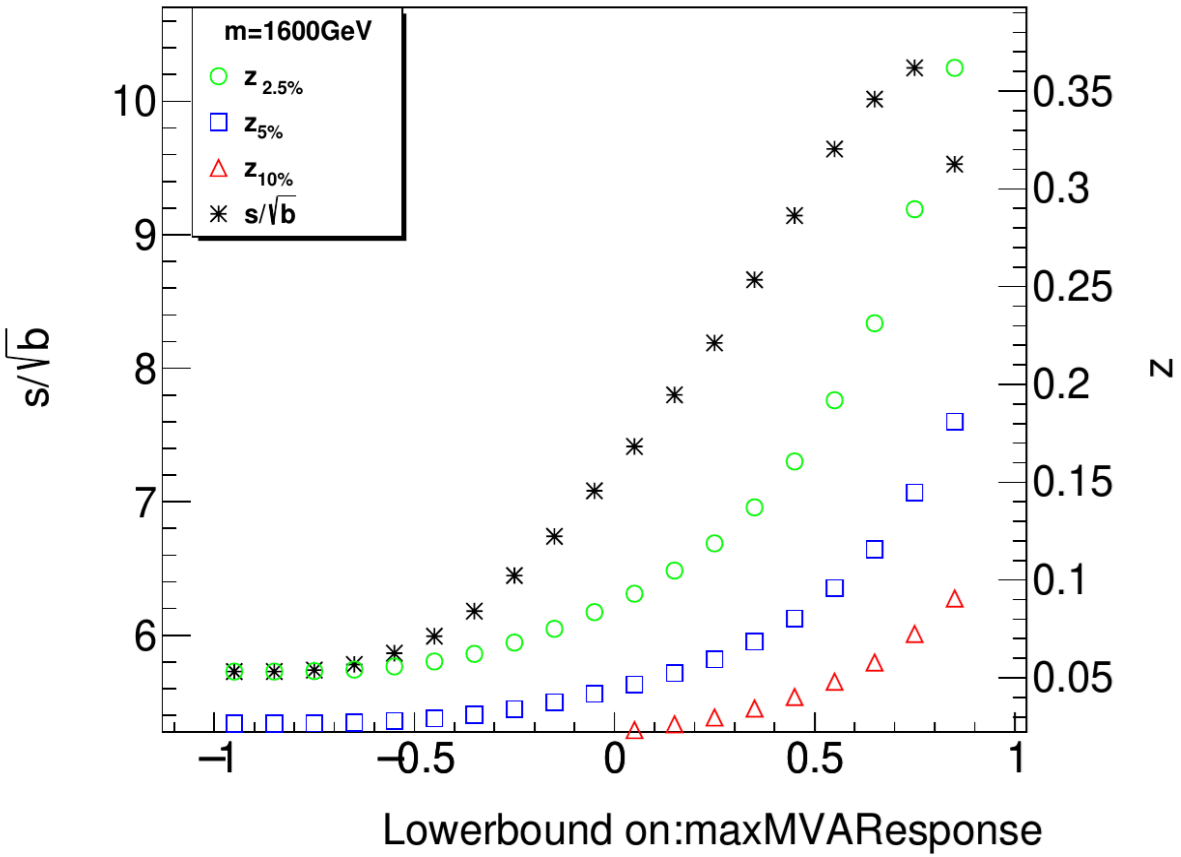
	m=400GeV	m=800GeV	m=1600GeV	Background
$0.0 < Maxw_{BDT} < 0.5$	0.36	0.24	0.32	0.77
$-0.1 < Maxw_{BDT} < 0.5$	0.32	0.21	0.28	0.73
$-0.2 < Maxw_{BDT} < 0.5$	0.28	0.19	0.26	0.699
$0.0 < Maxw_{BDT} < 0.4$	0.30	0.20	0.26	0.75
$-0.1 < Maxw_{BDT} < 0.4$	0.27	0.18	0.23	0.7
$-0.2 < Maxw_{BDT} < 0.4$	0.24	0.16	0.21	0.67
$-0.3 < Maxw_{BDT} < 0.4$	0.21	0.14	0.19	0.63
$0.0 < Maxw_{BDT} < 0.6$	0.42	0.29	0.39	0.8
$-0.1 < Maxw_{BDT} < 0.6$	0.38	0.26	0.35	0.76
$-0.2 < Maxw_{BDT} < 0.6$	0.34	0.23	0.32	0.72
$-1.0 < Maxw_{BDT} < 0.0$	0.05	0.02	0.03	0.43
$-0.5 < Maxw_{BDT} < 0.0$	0.06	0.04	0.06	0.39
$-0.5 < Maxw_{BDT} < 0.3$	0.13	0.09	0.12	0.51
$-0.2 < Maxw_{BDT} < 0.3$	0.19	0.13	0.17	0.62
$-0.3 < Maxw_{BDT} < 0.3$	0.17	0.11	0.15	0.58

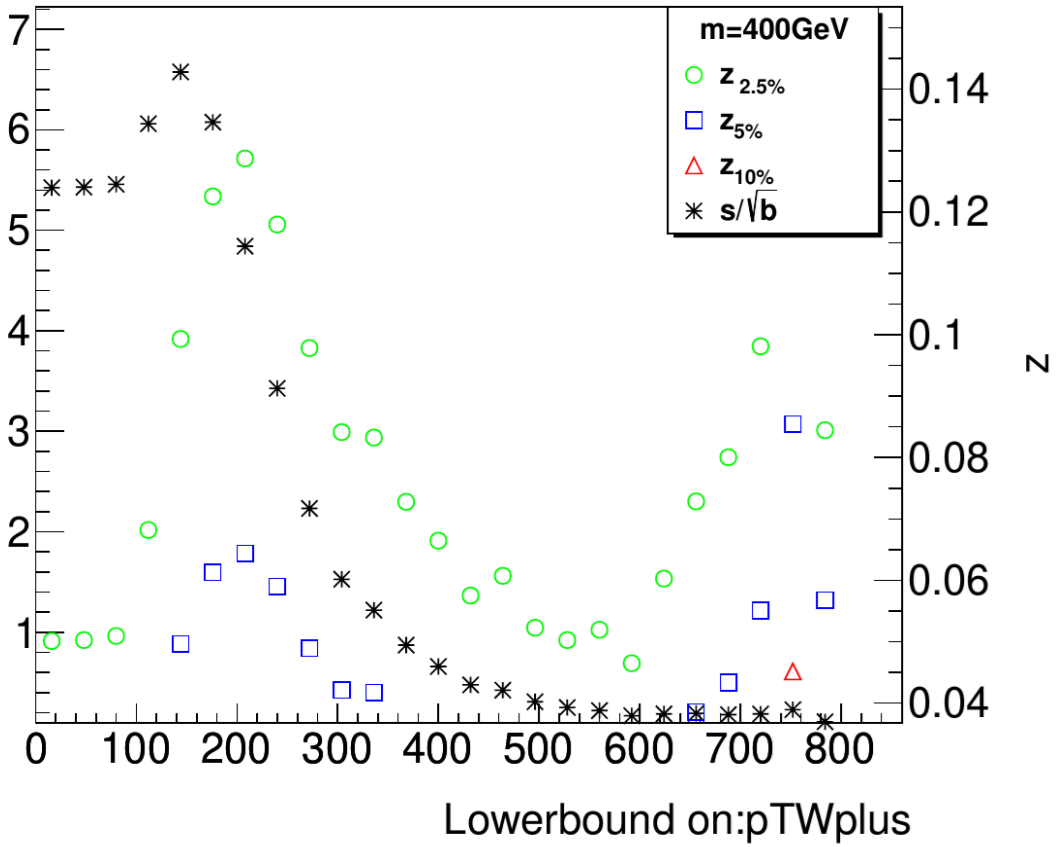

ATLAS Simulation Work in Progress
H+→ hW+→ bblν
H+→ hW+ (mH+ = 400GeV)
H+→ hW+ (mH+ = 800GeV)
H+→ hW+ (mH+ = 1600GeV)
top background
other backgrounds
Event fraction
b-Tag Multiplicity


ATLAS Simulation Work in Progress
H+→ hW+→ bblν
H+→ hW+ (mH+ = 400GeV)
H+→ hW+ (mH+ = 800GeV)
H+→ hW+ (mH+ = 1600GeV)
top background
other backgrounds
Event fraction
Missing Transverse Momentum [GeV]


ATLAS Simulation Internal
H+→ h W+→ bblν
H+→ hW+ (mH+ = 400GeV)
H+→ hW+ (mH+ = 800GeV)
H+→ hW+ (mH+ = 1600GeV)
top Background
other Background
Higgs Mass [GeV]


ATLAS Simulation Work in Progress
H+→ hW+→ bblν
H+→ hW+ (mH+ = 400GeV)
H+→ hW+ (mH+ = 800GeV)
H+→ hW+ (mH+ = 1600GeV)
top background
other backgrounds
Event fraction
Lepton pT [GeV]





MaxMVA> 0.7

pT W> 120

MC-MC Comparison

- Dominant background from top
- m_{VH} background distribution peaks around 400 GeV
- 2-tag region has the least signal ➡ Use as validation region