Search for charged Higgs Bosons in $H^+ \to Wh \to l\nu bb$ decays

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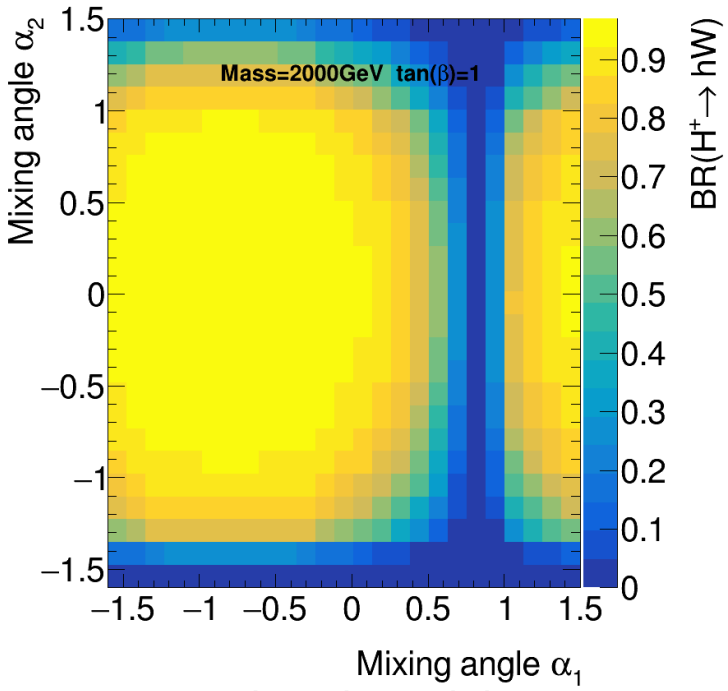
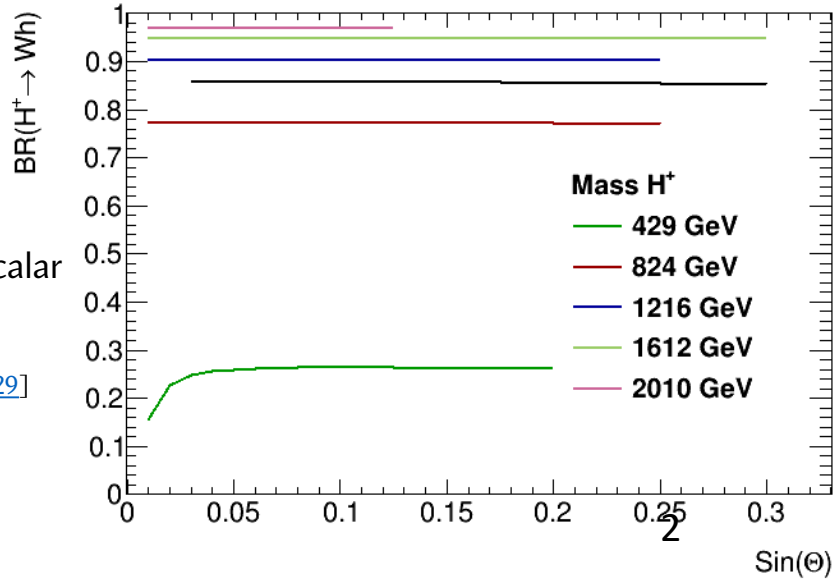
Motivation

- Several extensions of the SM predict an extended Higgs sector
  - Supersymmetric models
  - Axion models
  - Models explaining neutrino masses
- 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 [$m(H^+)>m(t)+m(b)$]
- Significant BR($H^+ \rightarrow Wh$) for:
  - 2HDM(2 Higgs Doublets) scenarios in which the 125GeV Higgs boson is the heaviest CP-even scalar
  - N2HDM(2 Higgs Doublets + Singlet) [https://arxiv.org/abs/1910.06858]
  - Georgi-Machacek model (Higgs Triplet model) [https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.015029]

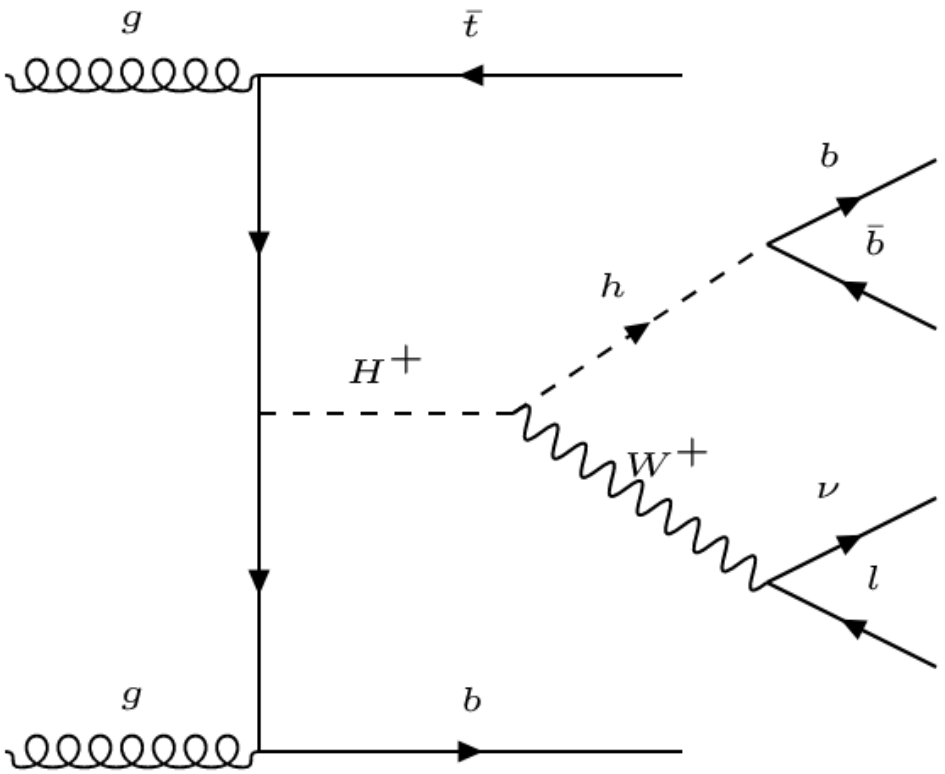
N2HDM:



Georgi-Machacek model:



Analysis strategy



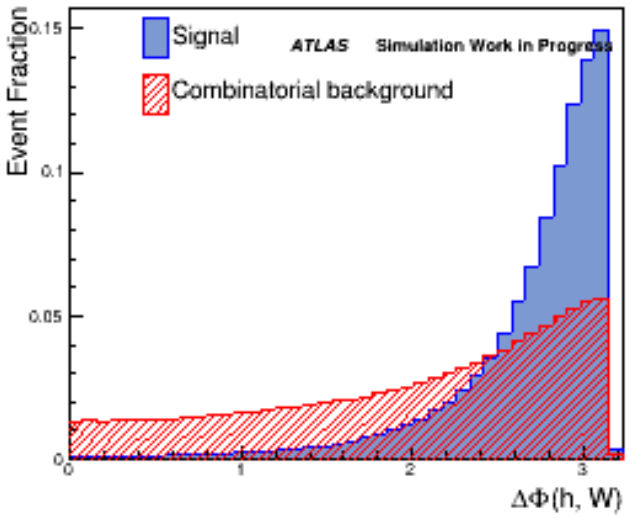
- Charged Higgs boson is produced in association with t and b (tbH^+)
- Charged Higgs boson decay mode: $H^+ \rightarrow Wh \rightarrow lvbb$
  - Consider only events with one Lepton
    - Top quark decays fully hadronic: $t \rightarrow Wb \rightarrow qqb$
  - Multiple jets in the final state
    - 6 or more
    - Up to 4-b tagged
  - Missing transverse energy E_T^{miss}
- Challenge: reconstruct charged Higgs boson (mass)
  - Reconstruct H^+ from W and h
    - Reconstruct W from lepton and E_T^{miss}
      - Neutrino is reconstructed from missing transverse energy using W boson mass constrain technique
    - Reconstruct h from 2 jets ($h \rightarrow bb$)
- Use boosted decision trees (BDTs) to choose the correct combination of a W boson and two jets

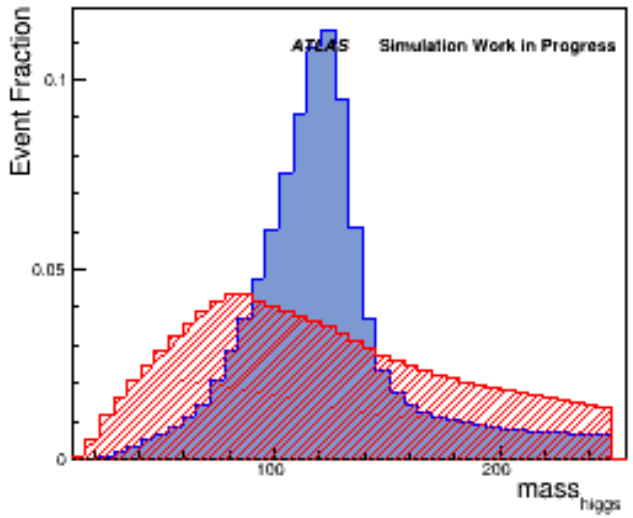
BDT training and parameters

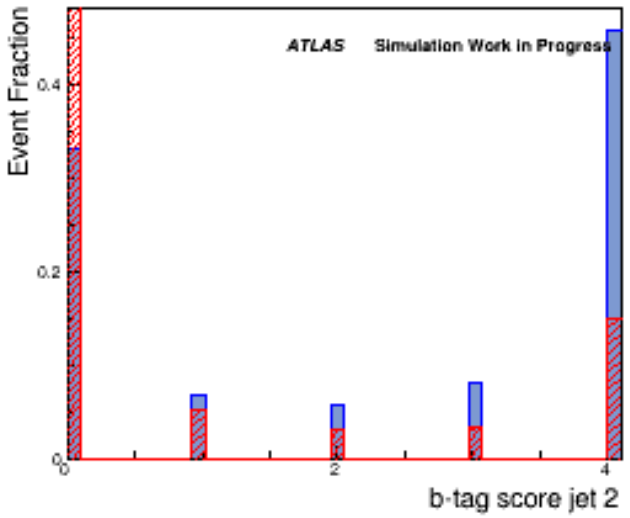
- Use BDT to reconstruct the 4-momentum of H^+
  - Evaluate every jet-jet-W combination and choose the one with the highest BDT response (max BDT response)
- Signal: correct jet pair and lepton neutrino combination of the tbH^+ events
  - the jet pair with the smallest angular separation to the generator level Higgs boson is chosen
- Combinatorial background: wrong jet pair W combinations i.e not matched to H^+ decay
- Trained on sum of 3 charged Higgs boson mass points
  - 400 GeV, 800 GeV, 1600 GeV

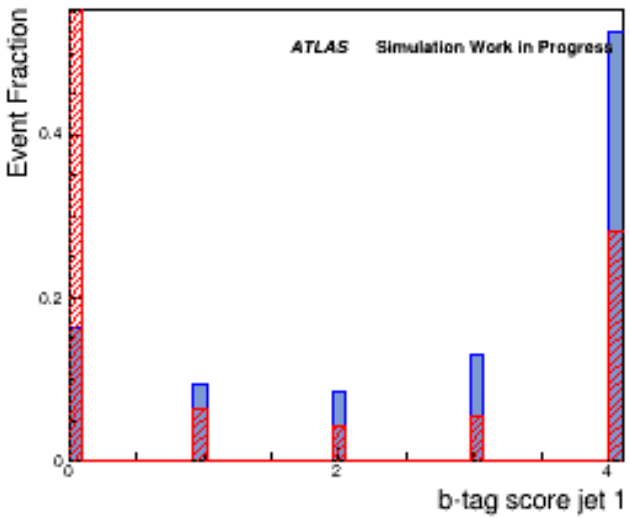
- BDT paramters:
  - 600 Trees
  - Max Depth=5
  - Boosting Algorithm: Gradient Boost
    - Loss function: $L(F, y) = \ln\left(1 + e^{-2F(\mathbf{x})y}\right)$
  - Separation: Gini Index $\text{gain}(\text{cell}) = p(1-p)$ $p = n_S/(n_S + n_B)$
- Training is based on:
  - Higgs mass(i.e di-jet mass)
  - Flavor tagging information of Higgs jets
  - Azimuthal angle $\Delta\Phi$ between Higgs and W candidate
  - p_T^{Higgs}/m_{Wh} and P_T^{W}/m_{Wh}

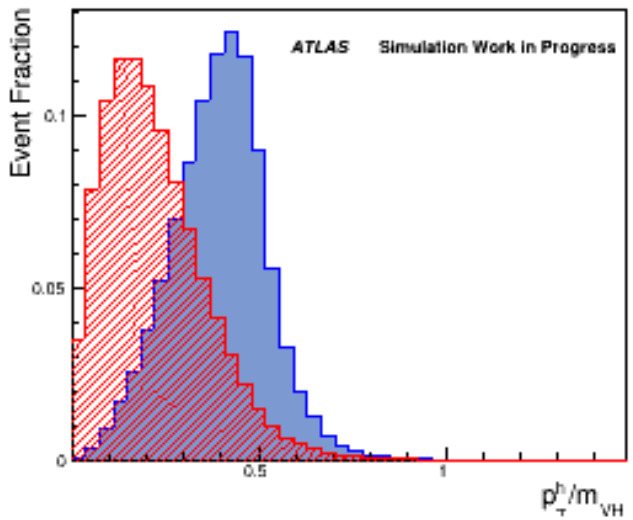
Training Results

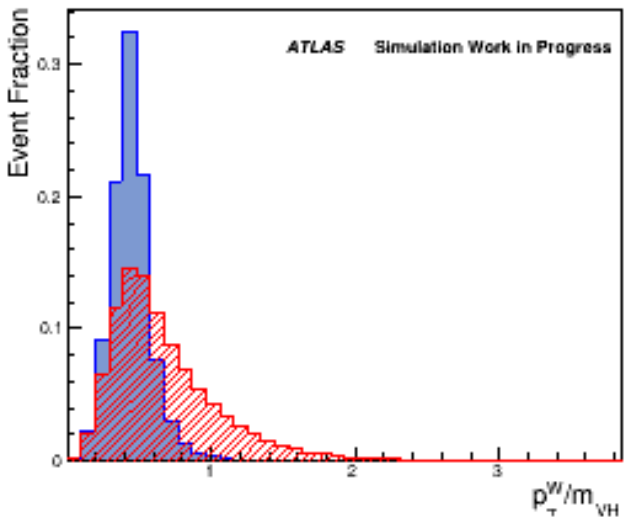




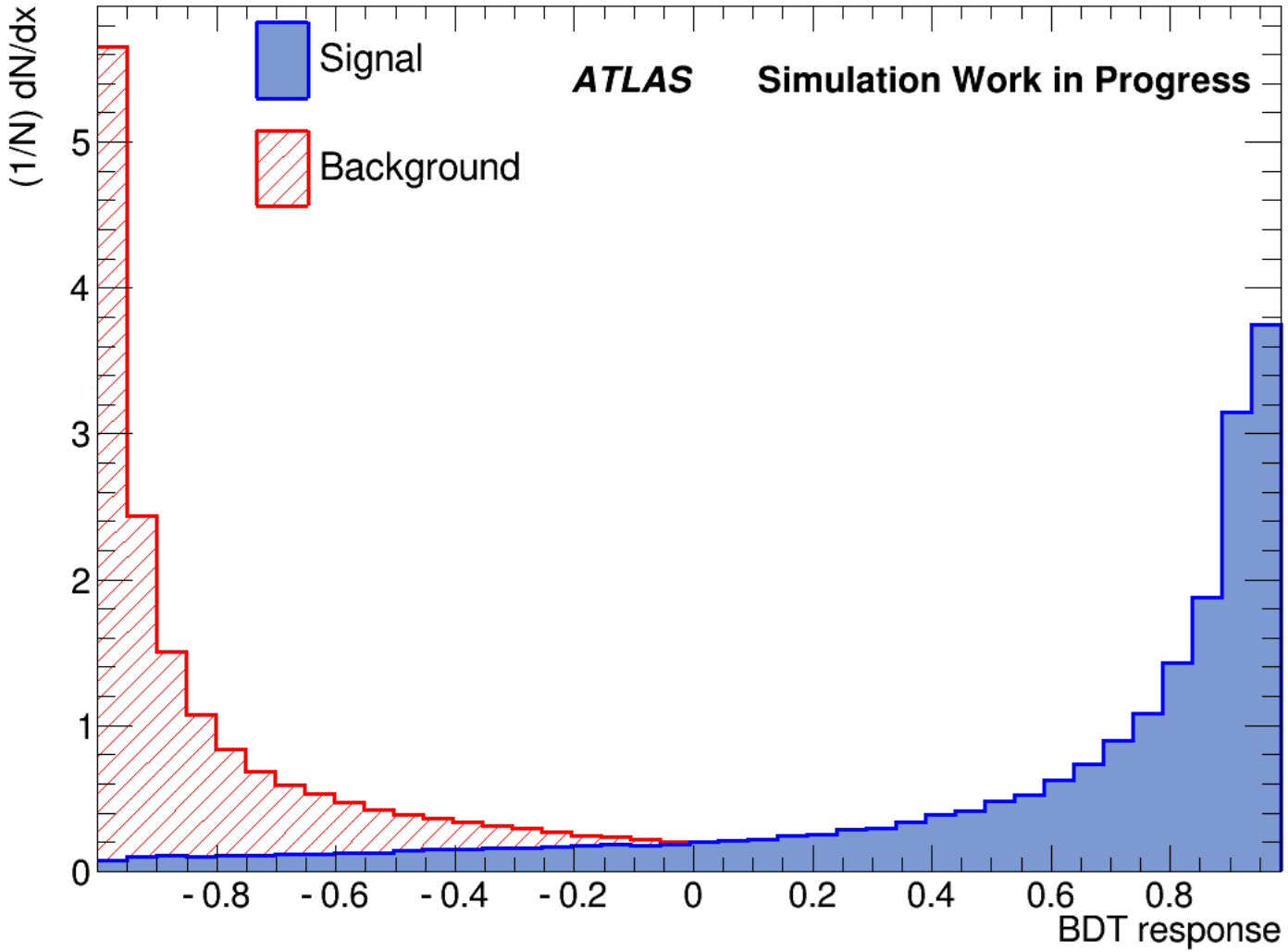








Training results



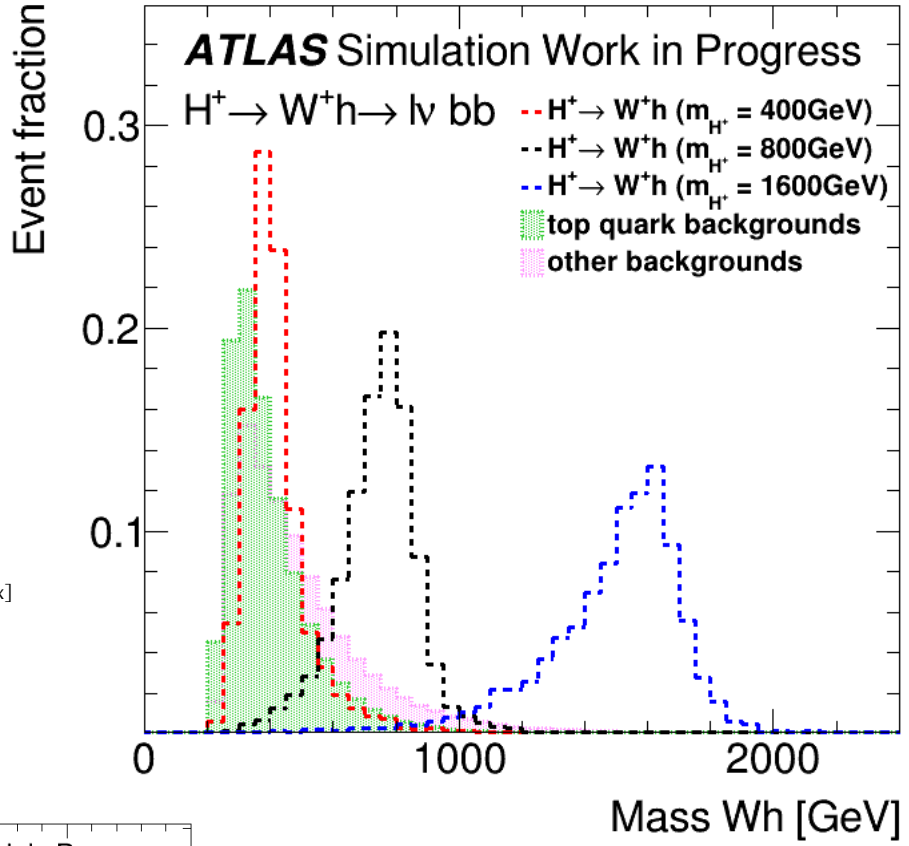
Variable name	Variable importance
Higgs boson mass	0.216
$p_{\mathrm{T}}^{h}/m_{Wh}$	0.200
$\Delta\Phi(h,W)$	0.183
$p_{\mathrm{T}}^{W}/m_{Wh}$	0.175
b-tag score jet 1	0.123
b-tag score jet 2	0.105

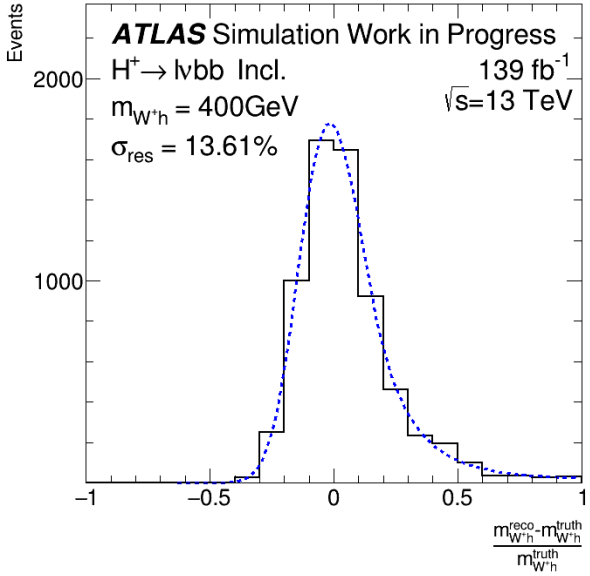
Variable Importance: How often is a variable used to split, weighted by the separation gain squared and #events at node

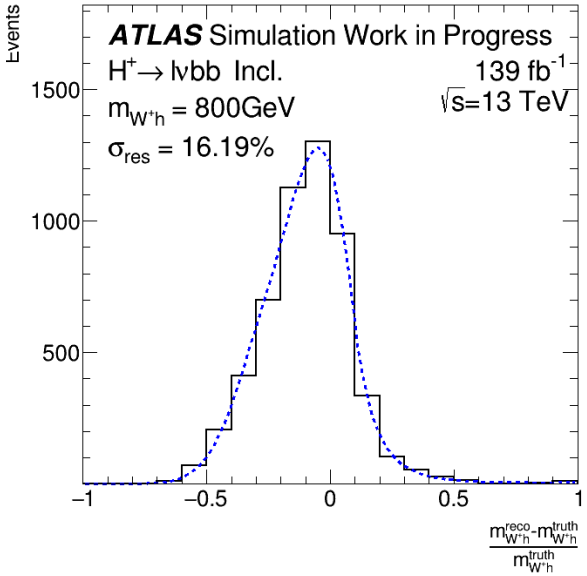
Mass resolution

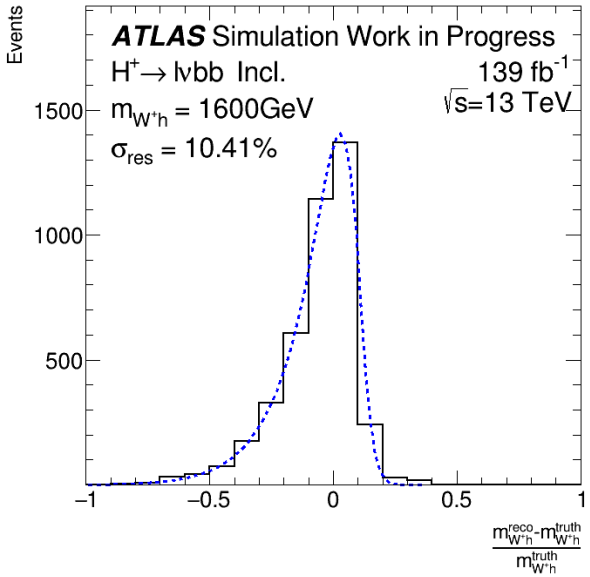
- Apply BDT to all possible lvjj combinations
- Choose the $H^+ \rightarrow$ lvbb candidate with the highest BDT output value
- BDT successfully reconstructs charged Higgs boson
- Calculate: $\frac{m_{W+h}^{reco} - m_{W+h}^{truth}}{m_{W+h}^{truth}}$
- Fit asymmetric Bukin function to data [https://github.com/root-project/root/blob/master/roofit/roofit/src/RooBukinPdf.cxx]
- Take variance
  - FWHM/2.35

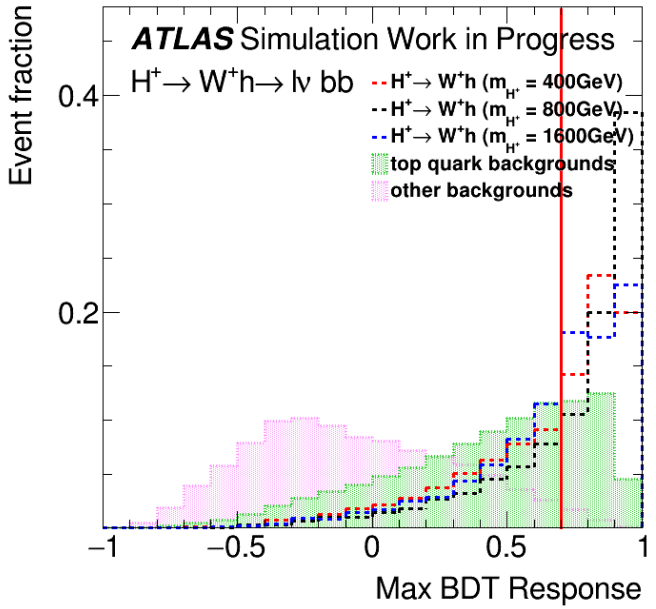
	Two b-Tags	Three b-Tags	Four+ b-Tags
400GeV	13%	13%	17%
800GeV	16%	15%	17%
1600GeV	10%	11%	12%

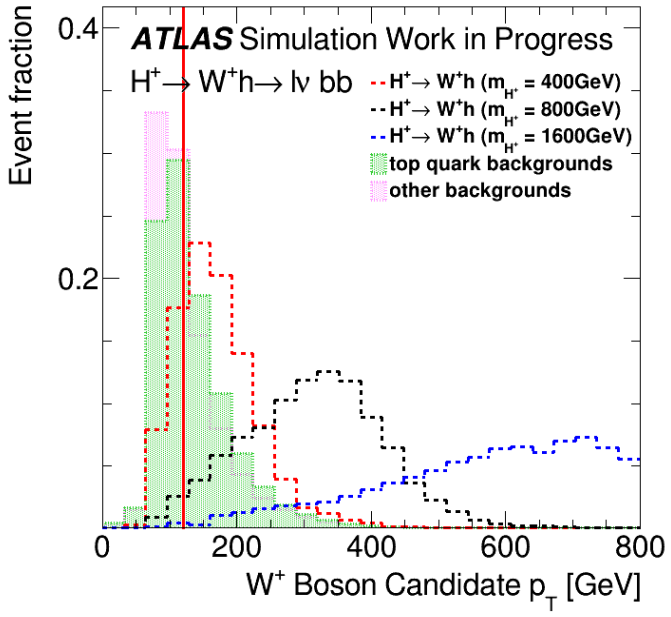


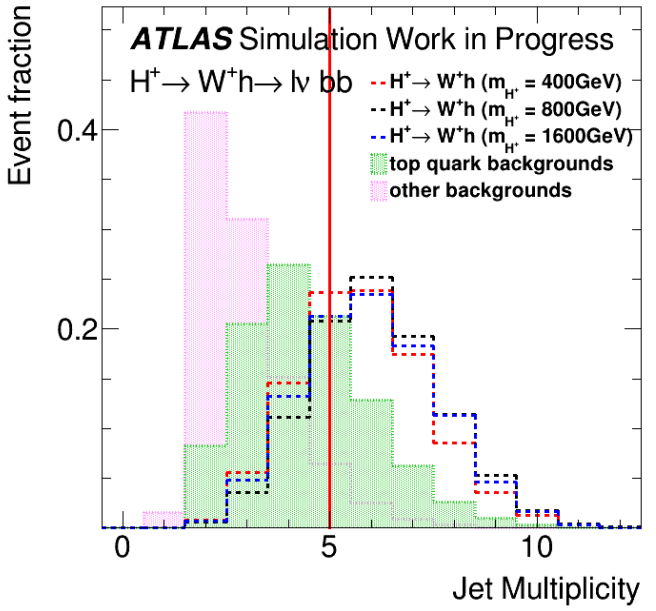


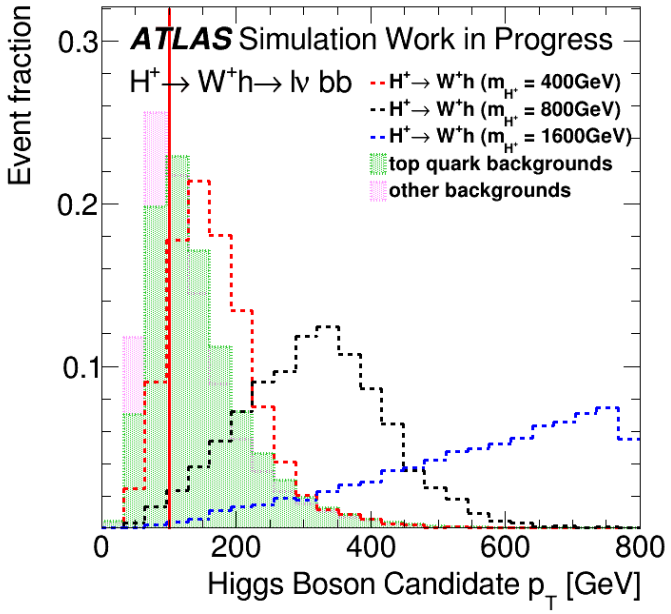












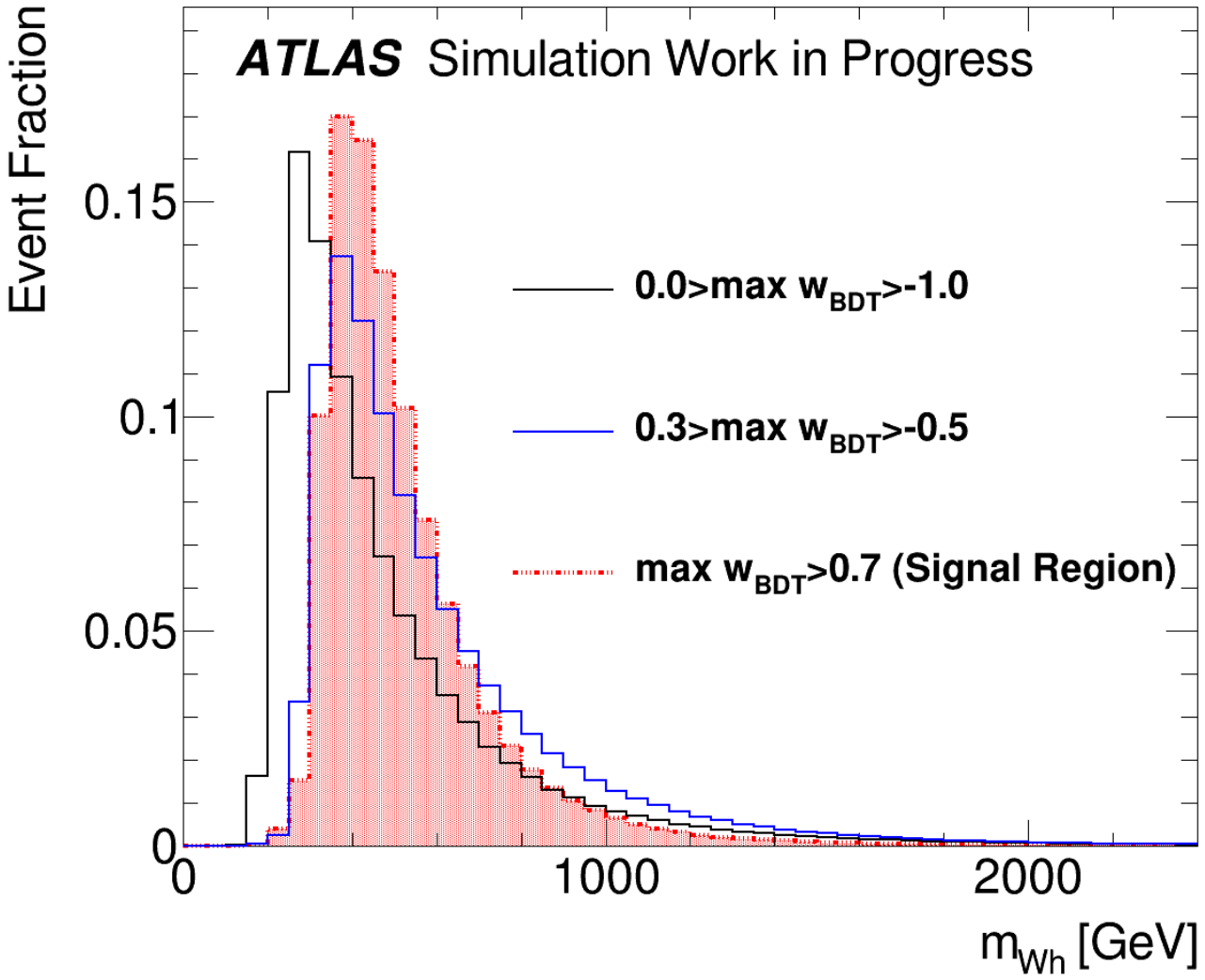
Event selection

- Introduce additional selection criteria to enhance the signal (H^+) over the SM backgrounds
  - The dominant backgrounds stem from top quarks
- Cut based event selection
  - Compare shapes of different variables
  - Calculate $\frac{\#s}{\sqrt{\#b}}$ for different cut values to find the optimal selection citeria
- BDT not only reconstructs signal but can also distinguish between signal and SM backgrounds
- Categorize events by # b-tags
  - 2 tags
  - 3 tags
  - 4+ tags

Signal region

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

Control regions

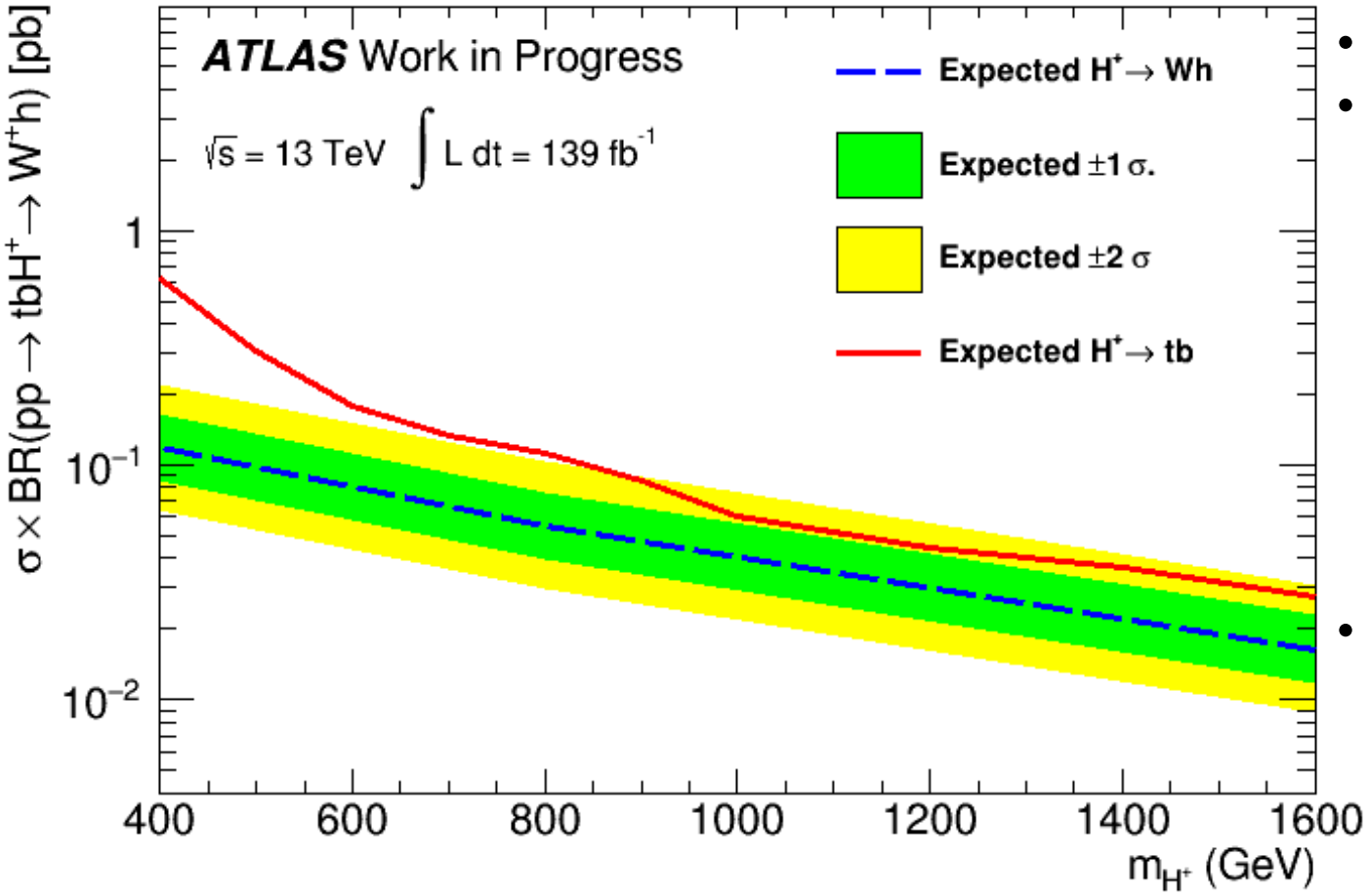


- Define a control region (CR) to verify the m_{Wh} distribution of the SM backgrounds
- Ensure similar kinematic properties as in the SR
  - Define CR via max BDT response
- Find a region where m_{Wh} distribution of the SM backgrounds is similar wrt. m_{Wh} distribution in the SR
  - For most regions in BDT response this is the case
- Choose the region 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

Expected limits on the tbH$^+$cross section



- Signal region still blinded
- Perform maximum likelihood fit for the signal and background m_{Wh} distributions to pseudo data(drawn from background sum)
  - Simultaneous fit in the 2 b-tag, 3 b-tag and 4+ b-tag region
  - Use likelihood function:

$$L(\mu,\Theta) = \prod_{i}^{N_{category}} \prod_{j}^{N_{bins}} P(N_{i,j}|S_{i,j}(\mu,\Theta) + B_{i,j}(\Theta)) \prod_{m} f(\Theta),$$

- Expected limits competitive with H$^+$→tb[https://arxiv.org/abs/2102.10076v1.]
  - Both decay channels study similar final states
  - Background contributions are also similar

Conclusion/Next steps

- Feasibility of the search for the $H^+ \to Wh$ decays evaluated for the first time at the LHC
- A successful strategy for the $H^+ \to Wh \to l\nu bb$ channel has been developed
  - Charged Higgs bosons can be reconstructed by means of BDTs
- Expected limits: 0.121 pb (400 GeV) to 0.017 pb (1600 GeV)
  - Limits are comparable with those from the H^+ searches in the $H^+ \to tb$ channel
- More H^+ signal mass points are being produced
  - Include these in the analysis
- Explore new methods to distinguish between $H^+ \to Wh \to l\nu bb$ and $H^+ \to Wh \to qqbb$ decays
  - Include both in the analysis