Searches for additional charged Higgs bosons in the MSSM

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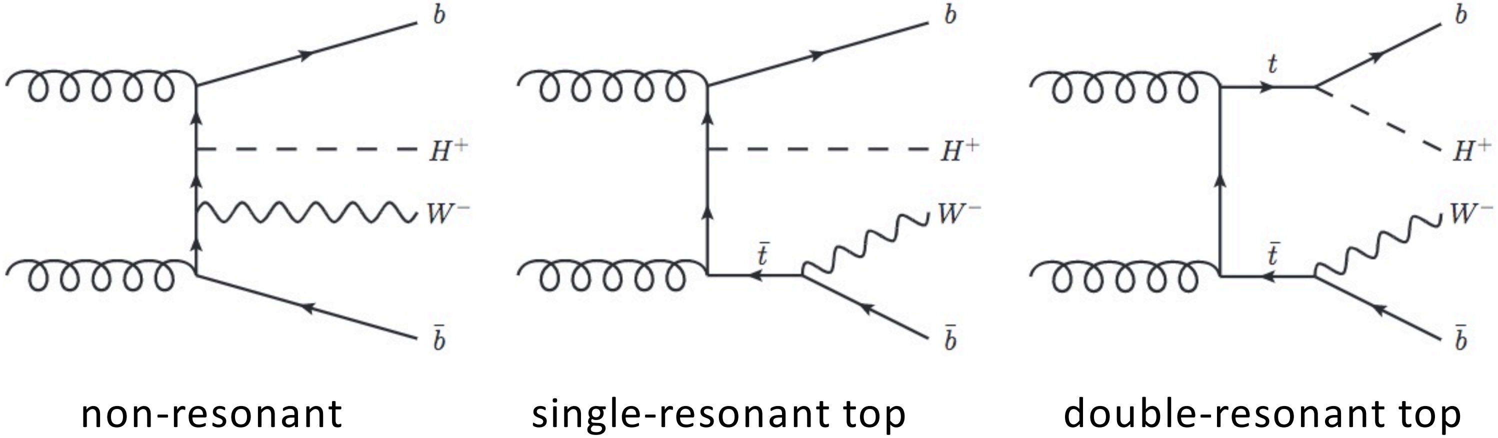
Introduction

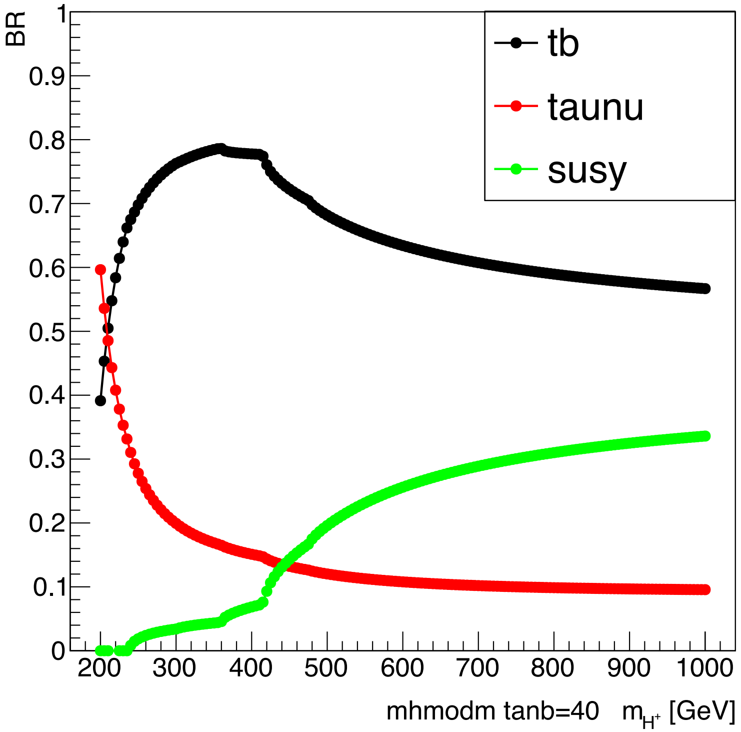
- ✓ Many BSM models include extended Higgs sector with at least one pair of charged Higgs bosons (2HDM, Higgs triplets…)



  - ➢ Single- (double-) resonant top contribution dominates at large (low) H^+ mass
  - ➢ Interference becomes most relevant in the intermediate region
- ✓ In 2HDM the decay is controlled by two parameters (besides mass)
  - ➢ tanβ: ratio of v.e.v. of two Higgs doublets
  - ➢ α: mixing angle between two CP-even Higgs bosons

Introduction (II)

- ✓ At high masses H^+ to tb dominates in decoupling and alignment limits
- ✓ For H^+ lighter than top-quark the decay to $\tau\nu$ dominates
- ✓ Present $H^+ \rightarrow \tau\nu$ and $H^+ \rightarrow tb$ searches with 2015-2016 data (36.1 fb^{-1})



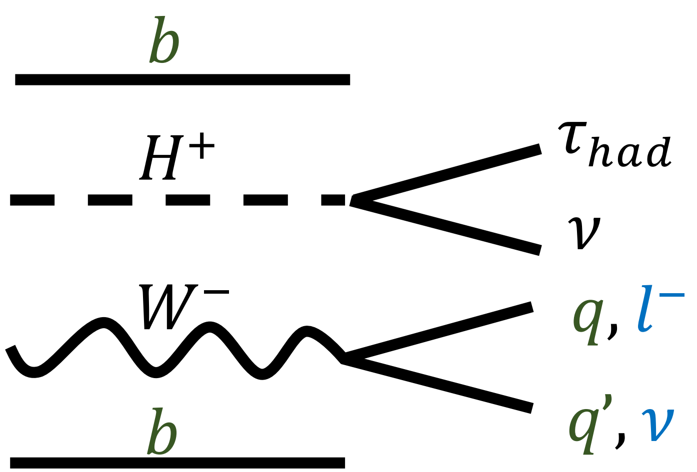
- ✓ Signal generated with (4FS) MG5_aMC + Pythia8
  - ➢ Normalisation from Santander-matched 4FS & 5FS total cross-section
  - ➢ Zero-width approximation used

$H^+ \rightarrow \tau\nu$ event selection

ATL-HIGG-2016-11

- ✓ τ_{had}+jets:
  - E_T^{miss} trigger (70, 90, 110 GeV)
  - ≥ 1 τ_{had} $p_T > 40$ GeV + 0 lepton (e,μ) $p_T > 20$ GeV
  - ≥ 3 jets (≥ 1 b-tag) $p_T > 25$ GeV
  - $E_T^{miss} > 150$ GeV, $m_T > 50$ GeV
- ✓ τ_{had}+lepton (e,μ):
  - Single lepton triggers
  - τ_{had} + lepton opposite sign $p_T > 30$ GeV each
  - ≥ 1 b-tag jet $p_T > 25$ GeV
  - $E_T^{miss} > 50$ GeV

Final state



$H^+ \rightarrow \tau\nu$ background modelling

ATL-HIGG-2016-11

- ✓ Backgrounds with prompt τ_{had}:
  - ➢ $W \rightarrow \tau\nu$ and tt : modelled with MC
    - Control region (CR) with τ_{had}+lepton selection but with e-μ pair to normalise tt
- ✓ Backgrounds with fake τ_{had}:
  - ➢ Electron misidentified as τ_{had}: estimated with MC, validated with $Z \rightarrow e^+e^-$ CR
    - One electron, one τ_{had}, muon and b-jet vetoes, and $40 < m_{\tau l} < 140$ GeV
  - ➢ Jet misidentified as τ_{had}: estimated with data-driven fake-factor (FF) method:
    - Extract FF ($FF = N^{pass}/N^{fail}$) from two orthogonal control regions:
      - ➢ Multi-jet CR: τ_{had}+jets selection with b-jet veto and $E_T^{miss} < 80$ GeV
      - ➢ W+jets CR: τ_{had}+lepton selection with b-jet veto, no E_T^{miss} requirement and $60 < m_T(l, E_T^{miss}) < 160$ GeV

$H^+ \rightarrow \tau\nu$ analysis strategy

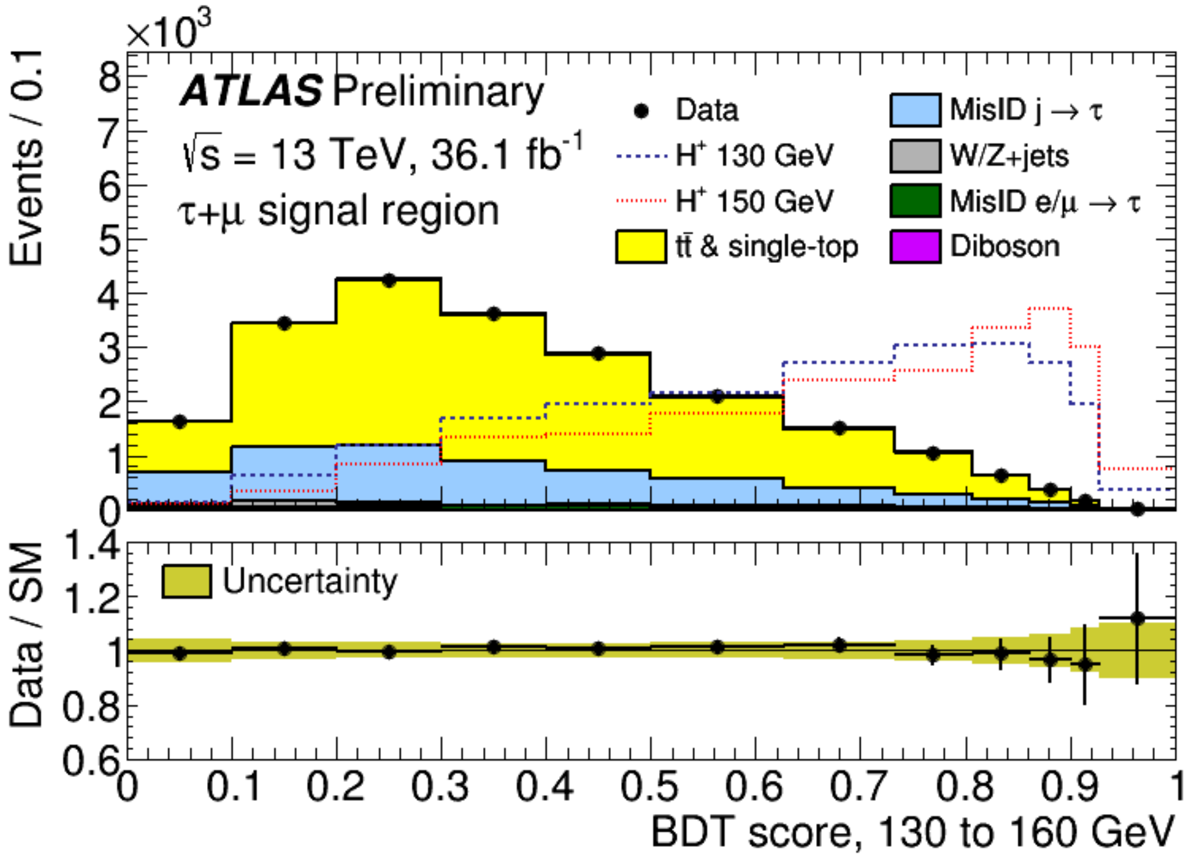
ATL-HIGG-2016-11

- ✓ Search in the 90 - 2000 GeV mass range
- ✓ $m(H^+) \sim m(t)$ region included for the first time
  - ➢ Progress on the theory side *C. Degrande et al, Phys.Lett. B772 (2017) 87-92*
- ✓ Use multivariate techniques (BDTs) to separate S/B
  - ➢ BDT trained in mass bins (90-120, 130-160, 160-180, 200-400, 500-2000 GeV)
  - ➢ Separately for τ_{had}+jets and τ_{had}+lepton channels and 1 or 3 tracks
  - ➢ τ_{had} polarization important at low mass
  - ➢ E_T^{miss}, $p_T(\tau_{had})$ and $\Delta\varphi_{\tau,miss}$ (m_T) important at high mass
- ✓ Fit to BDT output in three SRs and number of events in tt CR

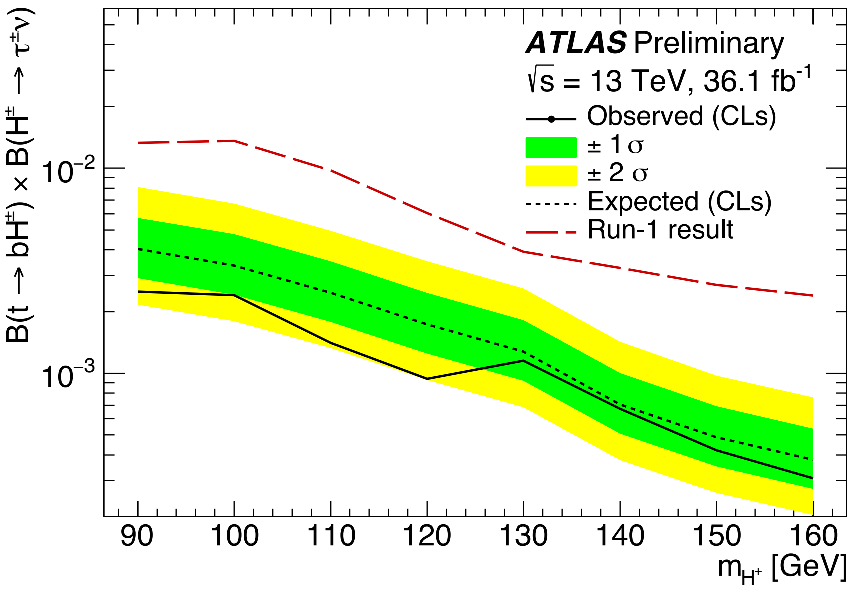
$H^+ \rightarrow \tau\nu$ results

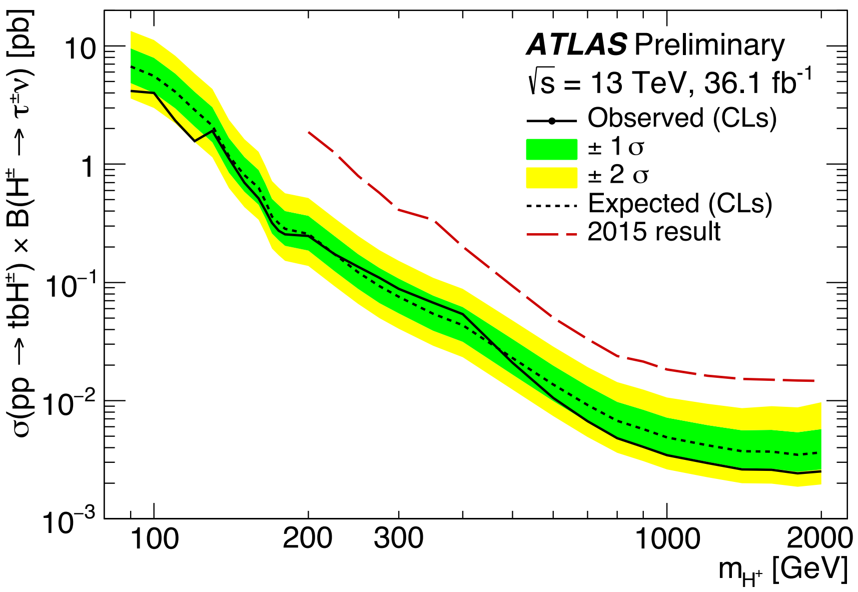
ATL-HIGG-2016-11

- ✓ No significant excess above background-only hypothesis at any mass
- ✓ Example of post-fit plot in the 130 to 160 GeV τ+μ signal region



$H^+ \rightarrow \tau\nu$ limits





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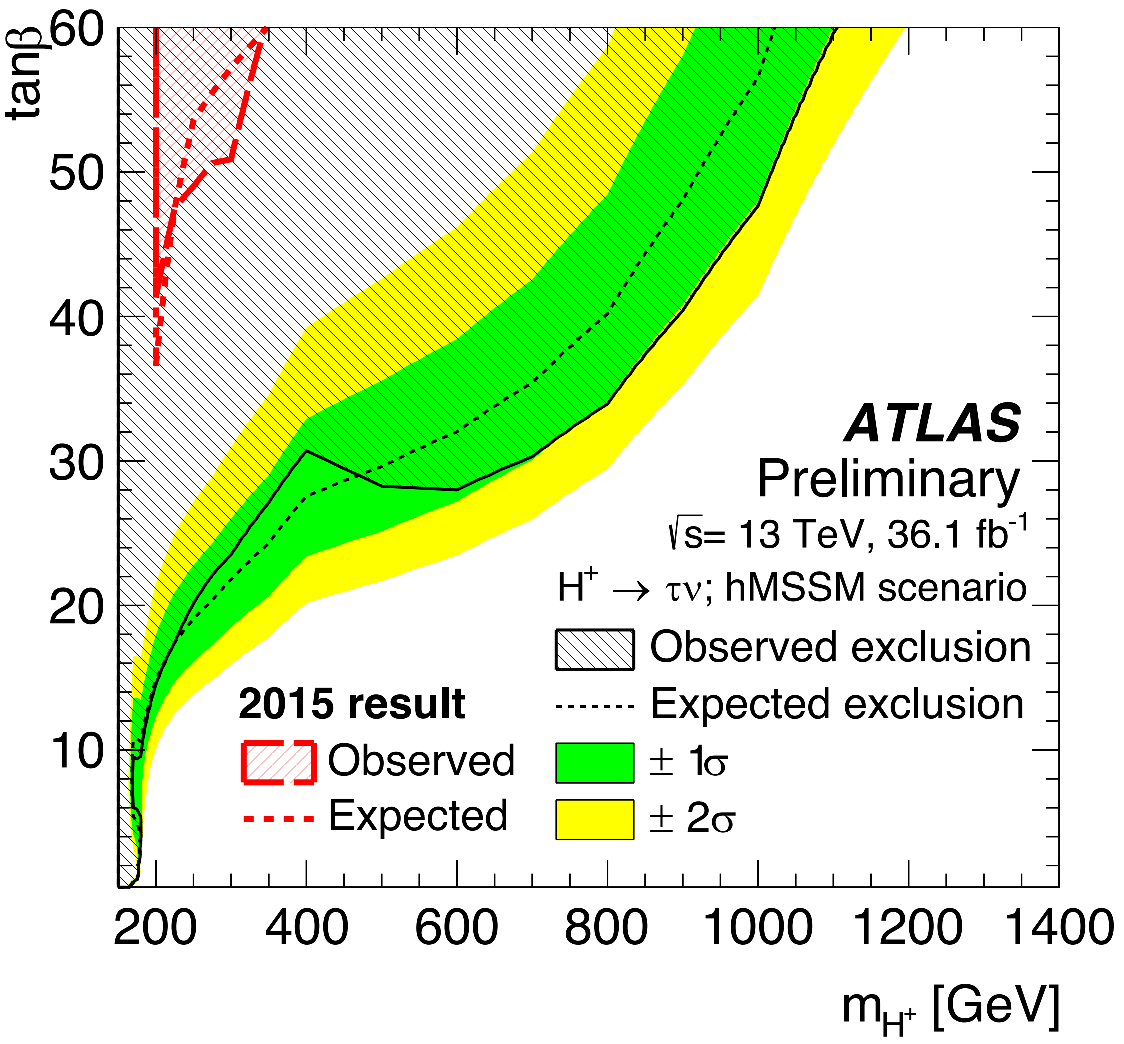

$H^+ \rightarrow tb$ event selection

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- ✓ Single lepton triggers
- ✓ Di-lepton:
  - Exactly two OS leptons (ee/eμ/μμ), leading $p_T > 27$ GeV, sub-leading $p_T > 10$ GeV
    - ee/μμ: $m_{ll} > 15$ GeV excluding $83 < m_{ll} < 99$ GeV
  - ≥ 3 jets (≥ 2 b-tags) $p_T > 25$ GeV
- ✓ Lepton+jets:
  - Exactly one lepton $p_T > 27$ GeV
  - ≥ 5 jets (≥ 3 b-tags) $p_T > 25$ GeV
  - Veto di-lepton selection
- ✓ Divide selected sample into signal/control regions according to jet/b-tag multiplicities

	2 b-tags	3 b-tags	≥ 4 b-tags
3 jets	CR	SR/CR	SR
≥ 4 jets	CR	SR	SR

	2 b-tags	3 b-tags	≥ 4 b-tags
5 jets	CR	SR	SR
≥ 6 jets	CR	SR	SR

$H^+ \to tb$ background modelling

ATL-HIGG-2017-04

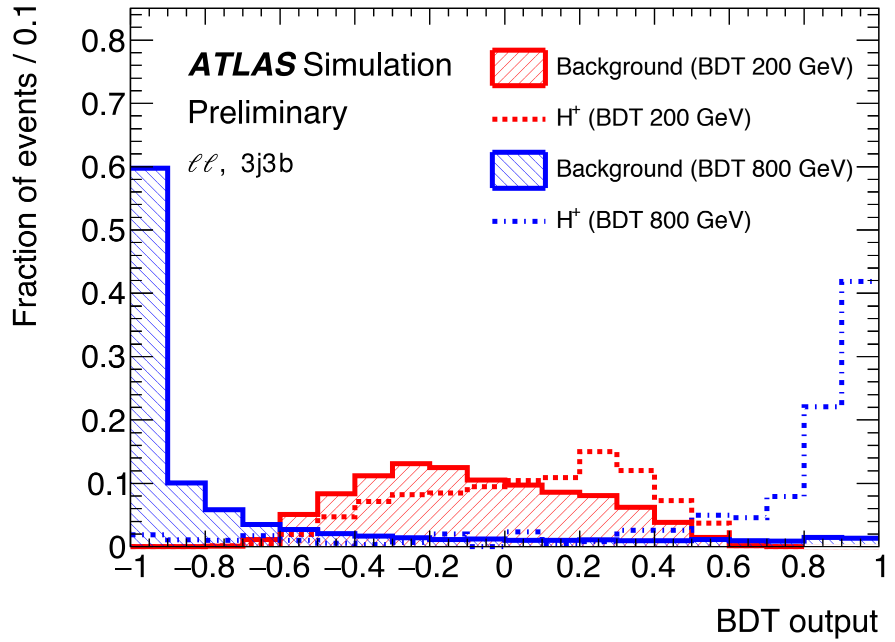
- ✓ tt is the largest background
  - ➢ Modelled with Powheg + Pythia8
  - ➢ Subdivided into tt + light flavor, tt + ≥1b and tt + ≥1c
  - ➢ Modelling improved by sequential re-weighting of tt + ≥1b to Sherpa + OpenLoops
    1. Reweight p_T of tt system
    2. Reweight p_T of top quark
    3. Reweight p_T of HF quark (if only one) or ΔR of HF quarks and p_T of di-jet system (if more)
  - ➢ Number of events with high leading jet p_T overestimated in simulation ⇒ re-weighting function for leading jet p_T by comparing simulation/data
- ✓ Other backgrounds
  - ➢ tt + V/H
  - ➢ Single top, di-boson, tH, tV, W/Z + jets, QCD multi-jets
  - ➢ W/Z + HF corrected using data-driven methods
  - ➢ Multi-jets modelled using
    - ✓ Matrix method (lepton+jets)
    - ✓ Monte Carlo (di-lepton)

$H^+ \to tb$ analysis strategy

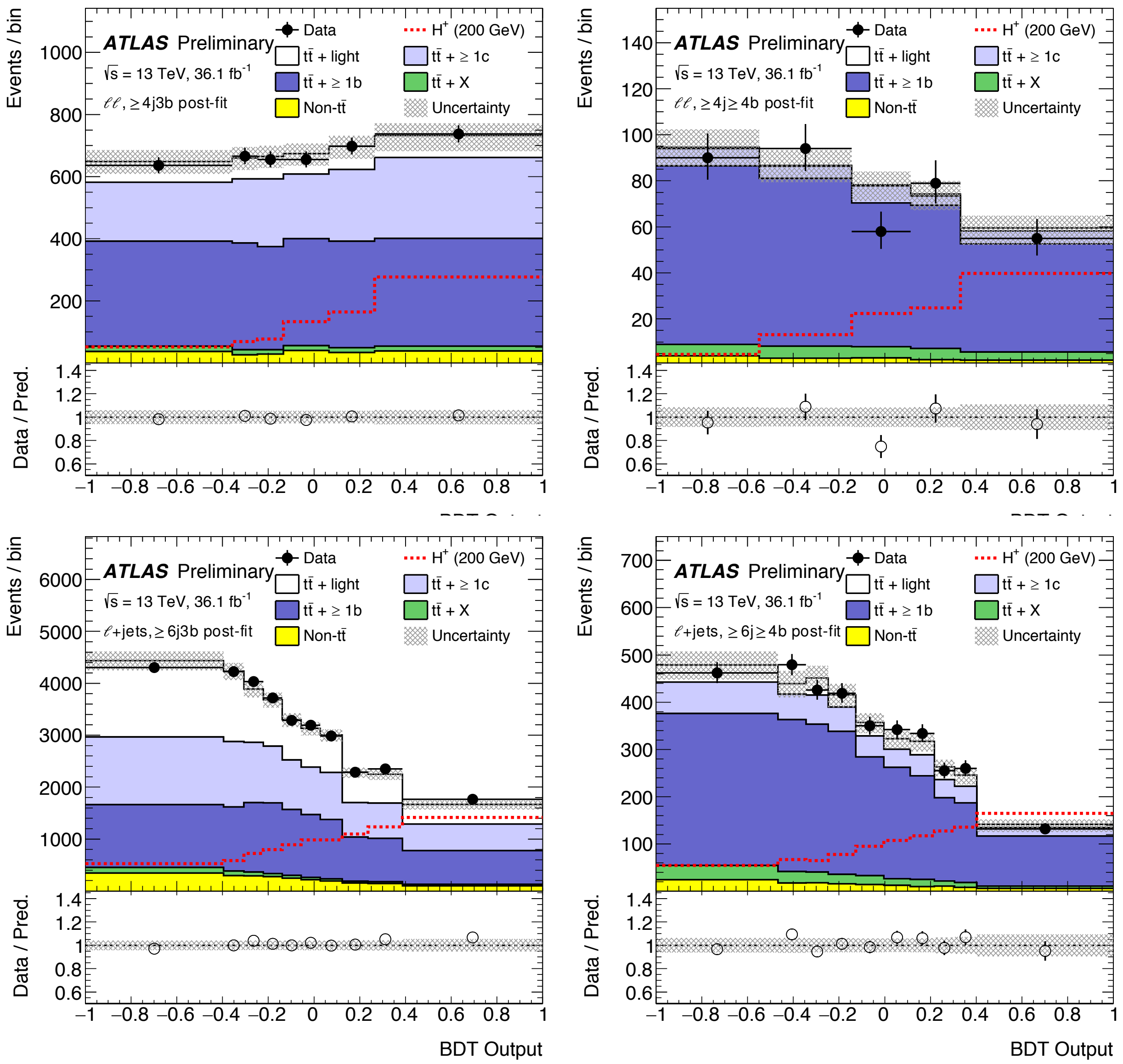
ATL-HIGG-2017-04

- ✓ Search in the 200 - 2000 GeV mass range
- ✓ Signal fraction very small even in the most sensitive regions
  - ➢ Use multivariate techniques (BDTs) to separate S/B in the SRs
  - ➢ Lepton+jets BDT includes a kinematic discriminant $D = P(H^+) / (P(H^+)+P(t\bar{t}))$ that reflects compatibility of event with $H^+ \to tb$ and $t\bar{t}$ hypotheses

- ✓ BDTs trained separately at each mass and SR
- ✓ Simultaneous fit to BDT output distributions in SRs and number of events in CRs
- ✓ $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$ allowed to vary freely



H+ → tb fit results

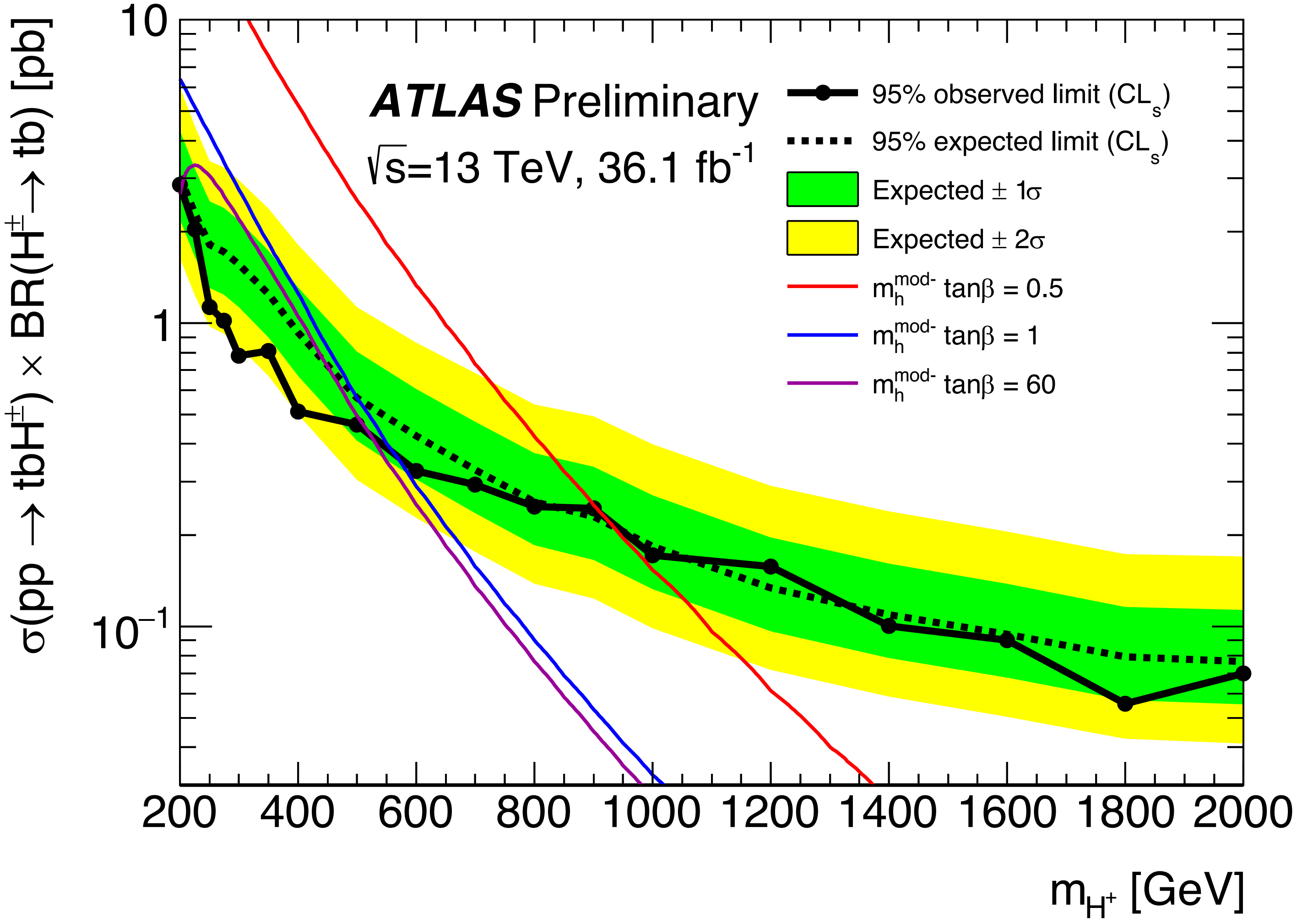


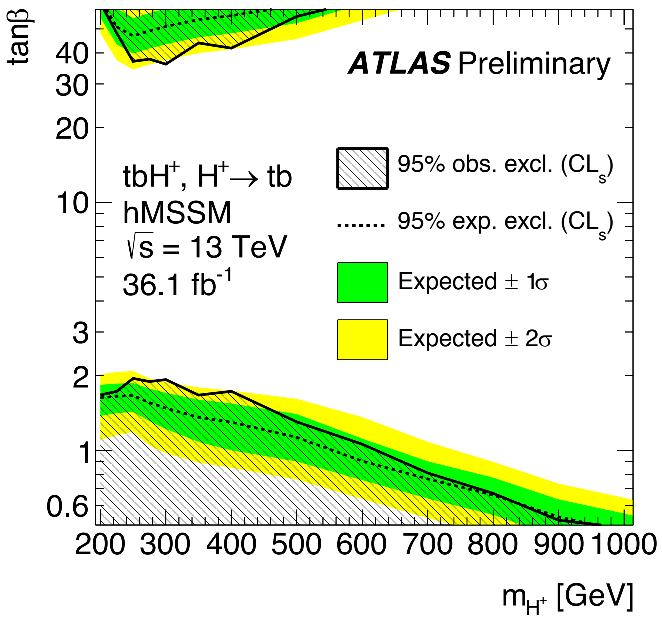
ATL-HIGG-2017-04

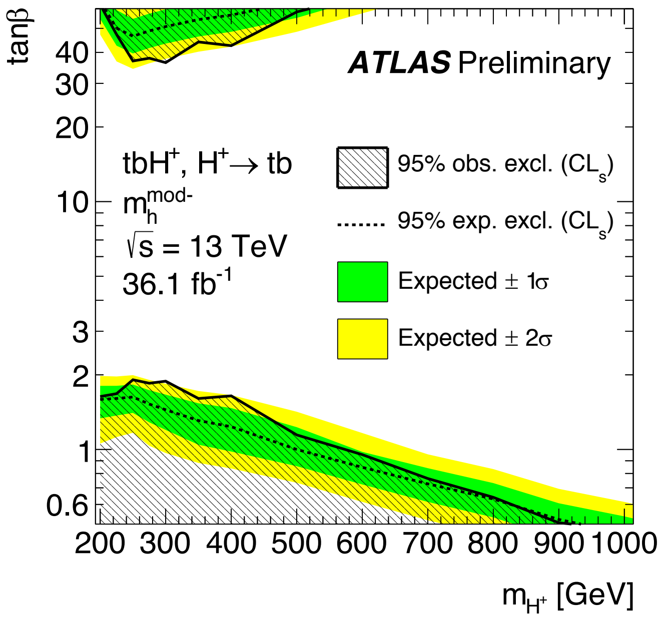
- ✓ No significant excess above background-only hypothesis at any mass
- ✓ Example of post-fit plots for the 200 GeV mass hypothesis

$H^+ \rightarrow tb$ limits

ATL-HIGG-2017-04

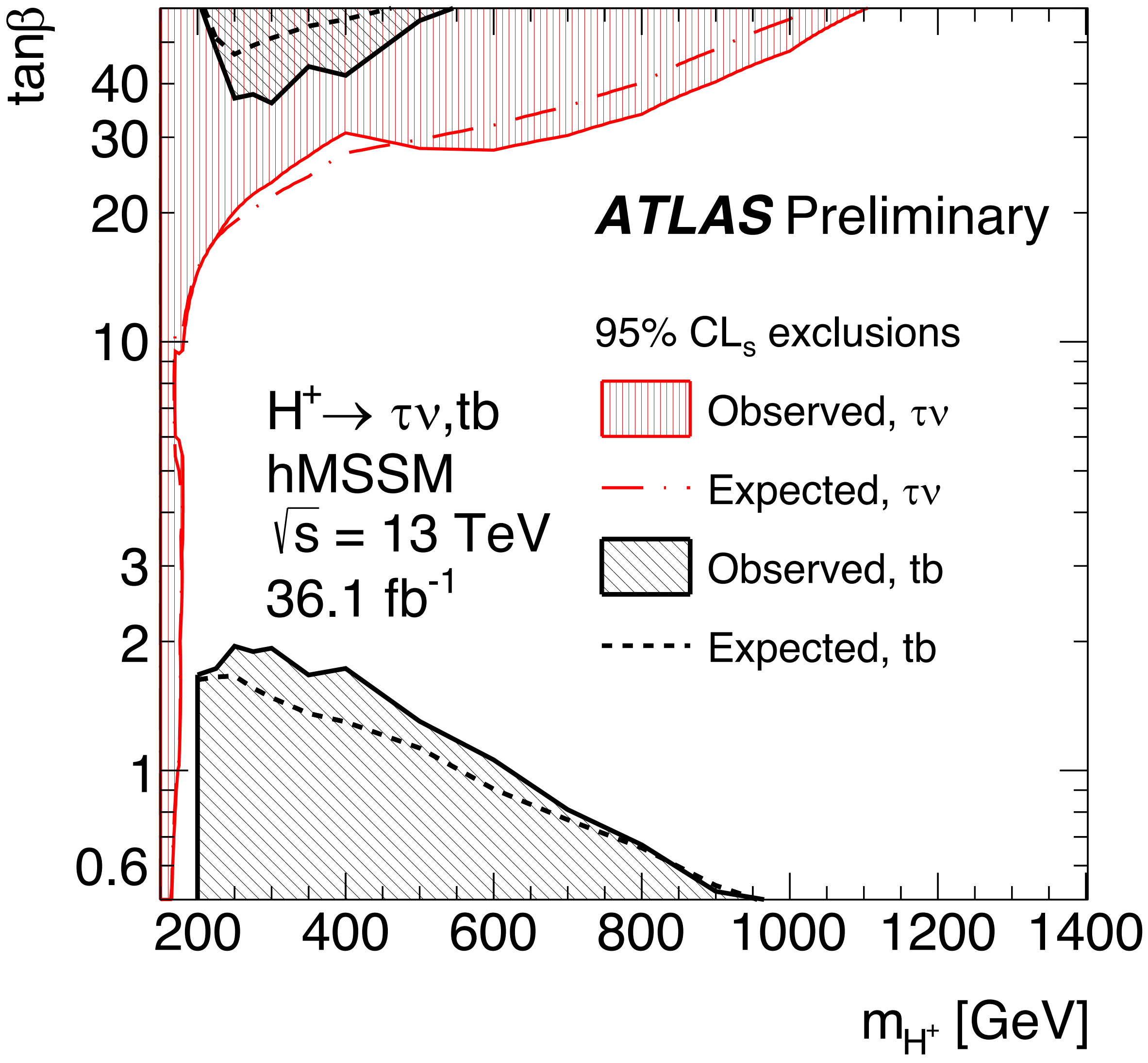


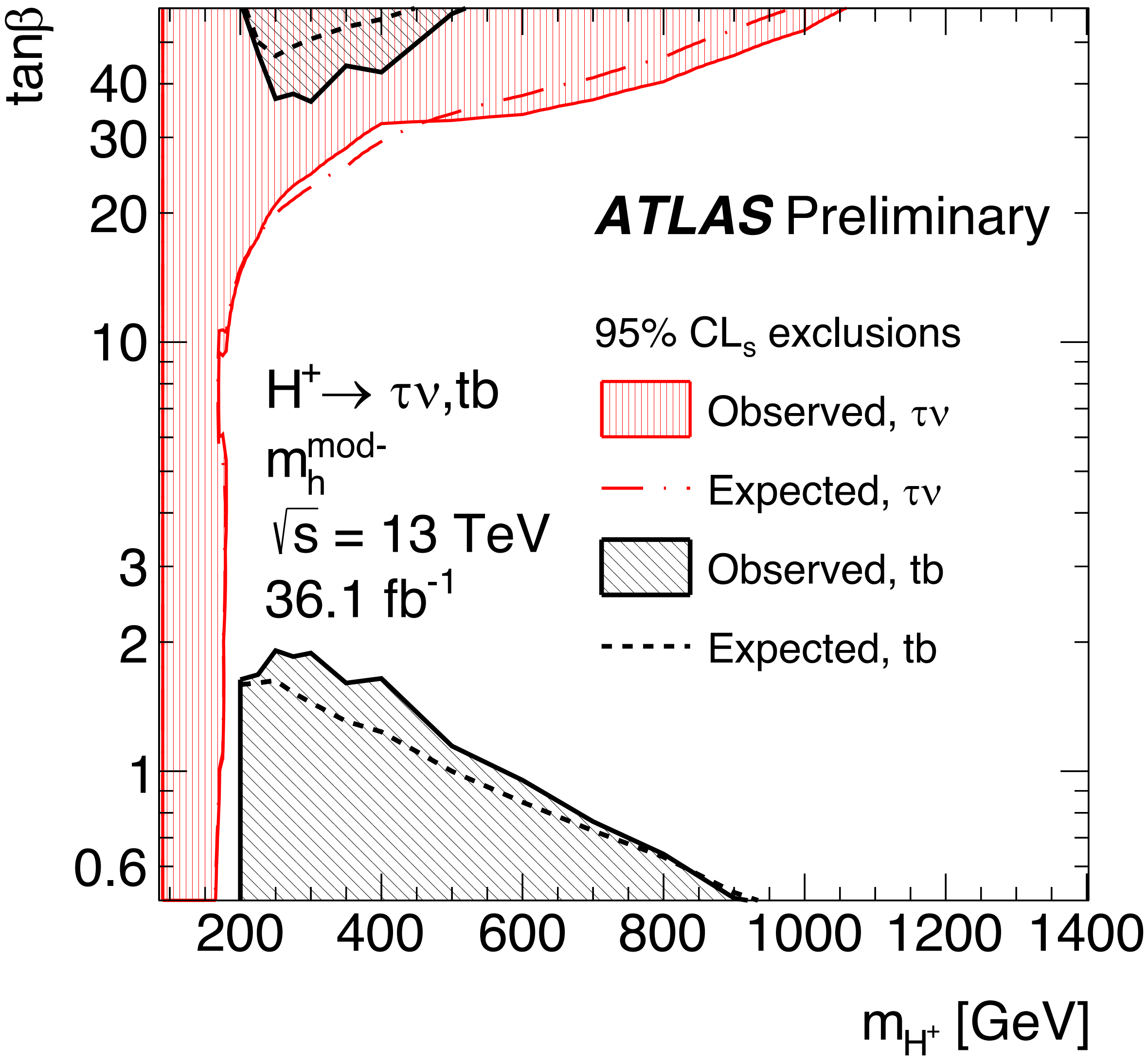




$H^+ \to tb$ and $H^+ \to \tau\nu$ superposition

ATL-HIGG-2017-04





Summary

- ✓ ATLAS performed searches for heavy charged bosons in the $H^+ \rightarrow \tau\nu$ and $H^+ \rightarrow tb$ decays using 36 fb^{-1} of Run2 data
- ✓ No excess with respect to SM predictions observed
  - Improved exclusions
  - New final states and extended mass range w.r.t. previous searches
- ✓ Other ATLAS charged Higgs results:
  - H^+ to W^+Z ($l^+\nu l^+l^-$) in *Searches for new phenomena in leptonic final states using the ATLAS detector* by Borut Kersevan on *Beyond the SM* session on July 6th
  - H^{++} to l^+l^+ in *Search for doubly charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton–proton collisions at $\sqrt{s}$ =13TeV*, Eur. Phys. J. C (2018) 78: 199

Backup

$H^+ \to \tau\nu$ object reconstruction

Electrons
- Loose (tight) LH in τ+jets(lepton)
- Calorimeter and track isolation
- $|\eta| < 2.4$ excluding (1.37,1.52)

Muons
- Loose (tight) LH in τ+jets(lepton)
- Calorimeter and track isolation
- $|\eta| < 2.5$

Jets
- AntiKt4EMtopo
- $p_T > 25$ GeV
- $|\eta| < 2.5$

b-jets
- MV2C10 algorithm
- Uses impact parameter + secondary/tertiary vertices
- 70% efficient
- 13, 56 and 380 rejection factors (c, taus, light/gluon)

Taus
- Seeded by antiKt jets with $E_T > 10$ GeV and 1 or 3 tracks in $\Delta R = 0.2$
- $|\eta| < 2.3$ excluding (1.37,1.52)
- Identification BDT 75 (60)% efficient for 1(3) prongs and 30-80 (200-1000) rejection factors
- Likelihood-based veto 95% efficient with 20-200 rejection factors for electrons depending on η

$H^+ \rightarrow tb$ object reconstruction

Electrons

- Tight LH
- Calorimeter and track isolation
- $|\eta| < 2.4$ excluding (1.37,1.52)

Muons

- Medium LH
- Calorimeter and track isolation
- $|\eta| < 2.5$

Jets

- AntiKt4EMtopo
- $p_T > 25$ GeV
- $|\eta| < 2.5$

b-jets

- MV2C10 algorithm
- Uses impact parameter + secondary/tertiary vertices
- 70% efficient
- 13, 56 and 380 rejection factors (c, taus, light/gluon)
- Multiple points for $m(H^+) < 300$ GeV ($p_T < 250$ GeV) in lepton+jets

$H^+ \to \tau\nu$ BDT variables

BDT input variable	$\tau_{\text{had-vis}}$+jets	$\tau_{\text{had-vis}}$+lepton
$E_{\text{T}}^{\text{miss}}$	✓	✓
p_{T}^{τ}	✓	✓
$p_{\text{T}}^{b\text{-jet}}$	✓	✓
p_{T}^{ℓ}		✓
$\Delta\phi_{\tau,\,\text{miss}}$	✓	✓
$\Delta\phi_{b\text{-jet},\,\text{miss}}$	✓	✓
$\Delta\phi_{\ell,\,\text{miss}}$		✓
$\Delta R_{\tau,\,\ell}$		✓
$\Delta R_{b\text{-jet},\,\ell}$		✓
$\Delta R_{b\text{-jet},\,\tau}$	✓	
Υ	✓	✓

Important at low mass

Important at high mass

$H^+ \to tb$ single lepton BDT variables

ℓ+jets channel	
$p_T(j_1)$	Leading jet transverse momentum
$m(b\text{-pair}^{\Delta R^{\min}})$	Invariant mass of pair of b-tagged jets with smallest ΔR
$p_T(j_5)$	Transverse momentum of fifth jet
H_2	Second Fox-Wolfram moment [120] calculated using all jets and leptons
$\Delta R^{\text{avg}}(b\text{-pair})$	Average ΔR between all b-tagged jet pairs in the event
$\Delta R(\ell, b\text{-pair}^{\Delta R^{\min}})$	ΔR between the lepton and the b-tagged jet pair with smallest ΔR
$m(u\text{-pair}^{\Delta R^{\min}})$	Invariant mass of the non-b-tagged jet-pair with minimum ΔR
H_T^{jets}	Scalar sum of all jets transverse momenta
$m(b\text{-pair}^{p_T^{\max}})$	Invariant mass of the b-tagged jet pair with maximum transverse momentum
$m^{\max}(b\text{-pair})$	Maximal b-tagged jet pair invariant mass
$m^{\max}(j\text{-triplet})$	Maximal jet triplet invariant mass
D	Kinematic discriminant based on mass templates (for $m_{H^+} \leq 300$ GeV)

Important at low mass

Important at high mass

$H^+ \to tb$ di-lepton BDT variables

$\ell\ell$ channel, $m \leq 600$ GeV		3j3b	≥4j3b	≥4j≥4b
$m((j,b)^{p_T^{max}})$	Inv. mass of the jet and b-tagged jet with largest p_T	✓		
$\Delta E(j_3, \ell_2)$	Energy difference between the third jet and the subleading lepton	✓		
$E(j_3)$	Energy of third jet	✓		
$\Delta m(j_1 + j_2, j_1 + j_3 + \ell_2 + E_T^{miss})$	Inv. mass difference between $j_1 + j_2$ and $j_1 + j_3 + \ell_2 + E_T^{miss}$	✓		
$\Delta R(j_2, j_1 + \ell_2 + E_T^{miss})$	Angular difference between subleading jet and $j_1 + \ell_2 + E_T^{miss}$	✓		
$p_T(b_1)$	p_T of leading b-tagged jet	✓		
$p_T((\ell,b)^{\Delta\eta^{max}})$	p_T of the pair of lepton and b-tagged jet with largest $\Delta\eta$	✓		
$m((\ell,b)^{\Delta\phi^{min}})$	Inv. mass of the pair of lepton and b-tagged jet with smallest $\Delta\phi$		✓	
$\Delta E(b_1, \ell_1 + E_T^{miss})$	Energy difference between the leading b-tagged jet and $\ell_1 + E_T^{miss}$		✓	
$\Delta m(j_2 + j_3, j_1 + \ell_1 + \ell_2)$	Inv. mass difference between $j_2 + j_3$ and $j_1 + \ell_1 + \ell_2$		✓	
$\Delta m(\ell_1 + j_3 + E_T^{miss}, j_1 + j_2 + \ell_2)$	Inv. mass difference between $\ell_1 + j_3 + E_T^{miss}$ and $j_1 + j_2 + \ell_2$		✓	
$\Delta p_T(j_1, j_3)$	p_T difference between leading and third jet		✓	✓
$m^{min}(b\text{-pair})$	Smallest invariant mass of any b-tagged jet pair		✓	✓
$m^{min}(\ell, b)$	Smallest invariant mass of any pair of lepton and b-tagged jet		✓	✓
$p_T(b_2 + \ell_1 + \ell_2 + E_T^{miss})$	p_T of $b_2 + \ell_1 + \ell_2 + E_T^{miss}$			✓
$\Delta R(\ell_2, j_2 + j_3 + \ell_1 + E_T^{miss})$	Angular difference between ℓ_2 and $j_2 + j_3 + \ell_1 + E_T^{miss}$			✓
H_T^{all}	Scalar sum of all jets and leptons transverse energy			✓

$H^+ \rightarrow tb$ di-lepton BDT variables

$\ell\ell$ channel, $m > 600$ GeV		3j3b	≥4j3b	≥4j≥4b
$p_T((\ell, b)^{\Delta\eta^{min}})$	p_T of the pair of lepton and b-tagged jet with smallest $\Delta\eta$	✓		✓
$\Delta p_T(j_1, j_3)$	p_T difference between leading and third jets	✓		✓
$\Delta m(j_2 + \ell_1 + E_T^{miss}, j_1 + j_3 + \ell_1)$	Inv. mass difference between $j_2 + \ell_1 + E_T^{miss}$ and $j_1 + j_3 + \ell_1$	✓		
$p_T((\ell, b)^{\Delta R^{min}})$	p_T of the pair of lepton and b-tagged jet with smallest ΔR	✓		
$m(j\text{-pair}^{\Delta\eta^{min}})$	Inv. mass of the jet pair with smallest $\Delta\eta$	✓		
$\Delta p_T(j_1, j_2 + E_T^{miss})$	p_T difference between leading jet and $j_2 + E_T^{miss}$	✓		
$p_T(j_1 + j_2 + j_3 + \ell_1)$	p_T of $j_1 + j_2 + j_3 + \ell_1$	✓		
$\Delta E(\ell_1 + E_T^{miss}, j_1 + j_2)$	Energy difference between $\ell_1 + E_T^{miss}$ and $j_1 + j_2$	✓		
$E(j_1)$	Energy of the leading jet	✓	✓	
$p_T^{max}(j\text{-pair})$	Maximum p_T of any jet pair	✓	✓	
$m(b_1 + b_2 + \ell_1 + \ell_2 + E_T^{miss})$	Inv. mass of $b_1 + b_2 + \ell_1 + \ell_2 + E_T^{miss}$		✓	
$p_T((\ell, b)^{\Delta\eta^{min}})$	p_T of the lepton-b-jet pair with smallest separation in η		✓	
$\Delta p_T(\ell_2, u_1 + b_2 + E_T^{miss})$	p_T difference between subleading lepton and $u_1 + b_2 + E_T^{miss}$		✓	
$\Delta p_T(\ell_2, u_1 + b_1 + E_T^{miss})$	p_T difference between subleading lepton and $u_1 + b_1 + E_T^{miss}$		✓	
$\Delta p_T(\ell_2, \ell_1 + E_T^{miss})$	p_T difference between subleading lepton and $\ell_1 + E_T^{miss}$		✓	
$\Delta p_T(j_1, j_3 + \ell_1 + E_T^{miss})$	p_T difference between leading jet and $j_3 + \ell_1 + E_T^{miss}$		✓	
$\Delta E(\ell_1, j_2 + E_T^{miss})$	Energy difference between leading lepton and $j_2 + E_T^{miss}$		✓	
$m^{min}(b\text{-pair})$	Smallest invariant mass of any b-tagged jet pair		✓	✓
H_T^{all}	Scalar sum of all jets and leptons transverse momenta			✓
$p_T(j_3 + \ell_1)$	p_T of $j_3 + \ell_1$			✓
$\Delta p_T(b_2, b_1 + \ell_2)$	p_T difference between subleading b-tagged jet and $b_1 + \ell_2$			✓
$\Delta p_T(j_2, j_3 + \ell_1 + E_T^{miss})$	p_T difference between subleading jet and $j_3 + \ell_1 + E_T^{miss}$			✓
$\Delta E(j_3, j_2 + \ell_1 + \ell_2 + E_T^{miss})$	Energy difference between third jet and $j_2 + \ell_1 + \ell_2 + E_T^{miss}$			✓
$\Delta m(j_2 + \ell_2 + E_T^{miss}, j_1 + \ell_2 + E_T^{miss})$	Inv. mass difference between $j_2 + \ell_2 + E_T^{miss}$ and $j_1 + \ell_2 + E_T^{miss}$			✓

$H^+ \to tb$ background modelling (II)

- ✓ tt systematic uncertainties:
  - Inclusive cross section (including μ_F, μ_R, PDF, α_S, m_t) 6%
  - Generator: Powheg + Pythia8 vs 5FS SherpaOL
  - PS and hadronisation: Powheg + Pythia8 vs Powheg + Herwig7
  - ISR/FSR: Vary μ_R, μ_F, hdamp and A14 eigentune
- ✓ $tt + \geq 1$b systematic uncertainties:
  - $tt + \geq 3$b cross section (difference between 4FS and various 5FS predictions) 50%
  - Powheg + Pythia8 vs 4FS SherpaOL (5FS inclusive tt vs 4FS $tt + bb$ predictions)
  - Reweighting:
    - Varying scale choices
    - Varying PDF sets (MSTW and NNPDF)
    - UE and PS with alternative sets of tuned parameters
    - 50% due to tt + b from MPI/FSR absence in SherpaOL
- ✓ $tt + \geq 1$c systematic uncertainties:
  - Powheg + Pythia8 vs MG5_aMC + Herwig++ (4FS inclusive tt vs 3FS $tt + cc$ in ME)
- ✓ Leading jet p_T reweighting (comparison with no reweighting + 15% normalisation $p_T > 400$ GeV)

$H^{++}H^{--} \rightarrow l^+l^+l^-l^-$ (Eur. Phys. J. C (2018) 78: 199)

- ✓ Consider a left-right symmetric model with additional triplet and doubly charged Higgs bosons
- ✓ BR depends on mass and v.e.v. of triplet
- ✓ 36.1 fb-1 @13 TeV, 250 ≤ m(H±±) ≤ 1300 GeV
- ✓ Fit $m(l^{\pm}l^{\pm})$ if 2 or 3 leptons or $M=0.5\times(m^{++}+m^{--})$ if four leptons