Charged Higgs boson searches with the ATLAS detector

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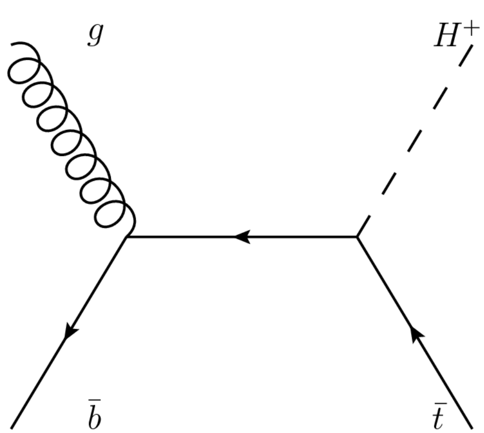
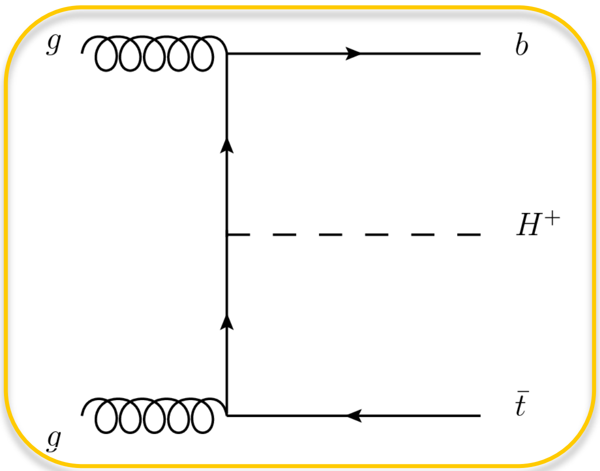
Introduction

- After the Higgs discovery a major question is if this is the SM Higgs boson
  - Or could it be the first state of a larger scalar sector?
- Many BSM models predict extended Higgs sectors containing $H^{\pm}$ bosons
  - E.g. Two Higgs doublet models (2HDM), Higgs triplets
- Present new run-2 ATLAS searches for heavy $H^{\pm}$ bosons
  - $H^{+} \rightarrow \tau\nu$ in range $200 < m(H^{\pm}) < 2000$ GeV with 14.7 fb^{-1}
  - $H^{+} \rightarrow tb$ in range $300 < m(H^{\pm}) < 1000$ GeV with 13.2 fb^{-1}
- For $m(H^{\pm}) > m(t)$, dominant production is in association with top quark



Five flavour scheme (5FS)



Four flavour scheme (4FS)

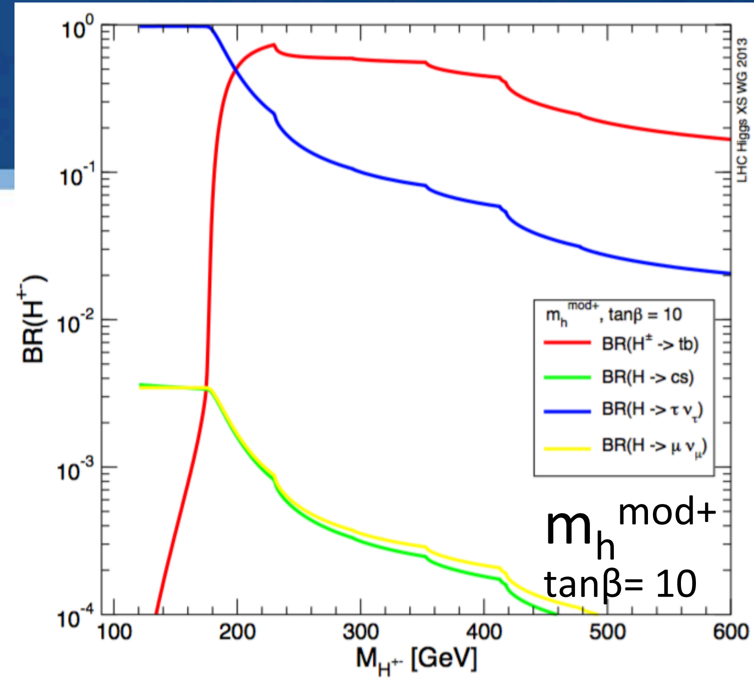
Theory Overview

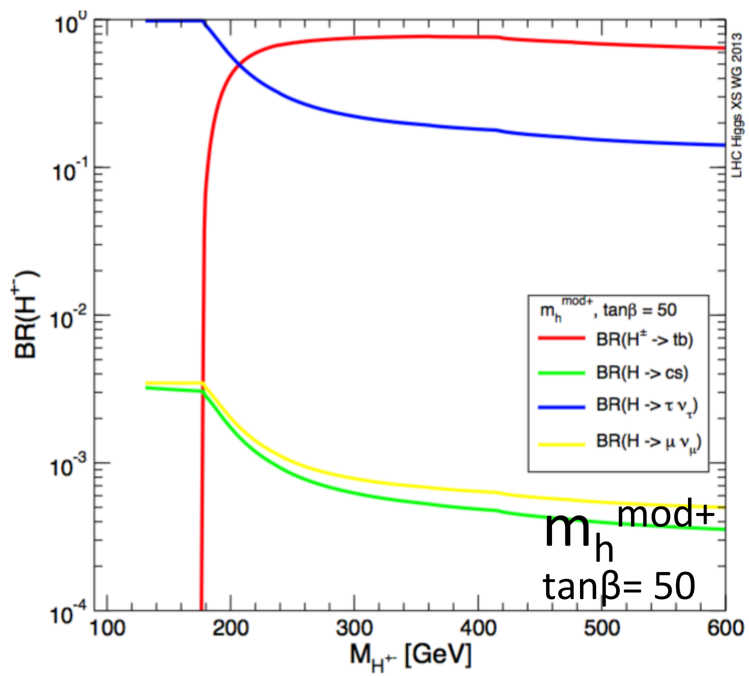
arXiv:1307.1347

- 2HDM: 5 physical bosons (h, H, A, $H^{\pm}$)
  - 4 types depending on l and u/d couplings

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

- Minimal Supersymmetric SM (MSSM)
  - Special case of type II 2HDM
- Described by tanβ and m_A at tree-level
  - Several benchmarks e.g.
    - m_h^{max} (stop mixing for max m_h)
    - $m_h^{mod\pm}$ (modified stop mixing)
- hMSSM: take m_h = 125 GeV as input
  - Enables phenomenology to be described by tanβ and m_A to good approx at higher orders
- $H^+ \rightarrow$ τν and tb decays dominate

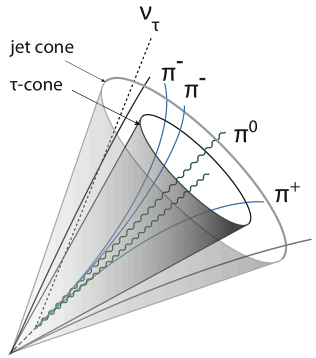


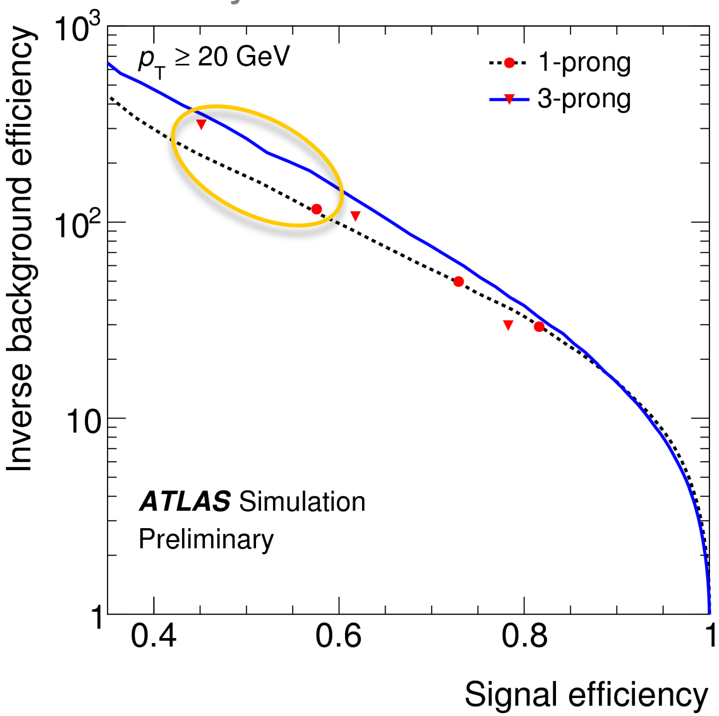


ATLAS tau and b-jet identification

taus

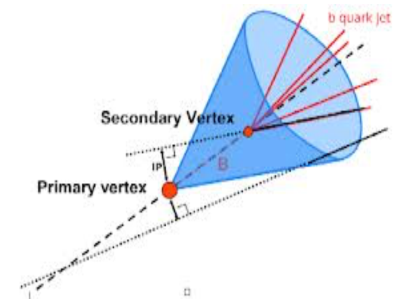
- Jets with 1 or 3 prongs within $\Delta R = 0.2$ of axis
  - Isolation annulus
- BDT ID
  - ε_τ = 55(40)% for 1(3)p
  - Jet rejection ~10^2

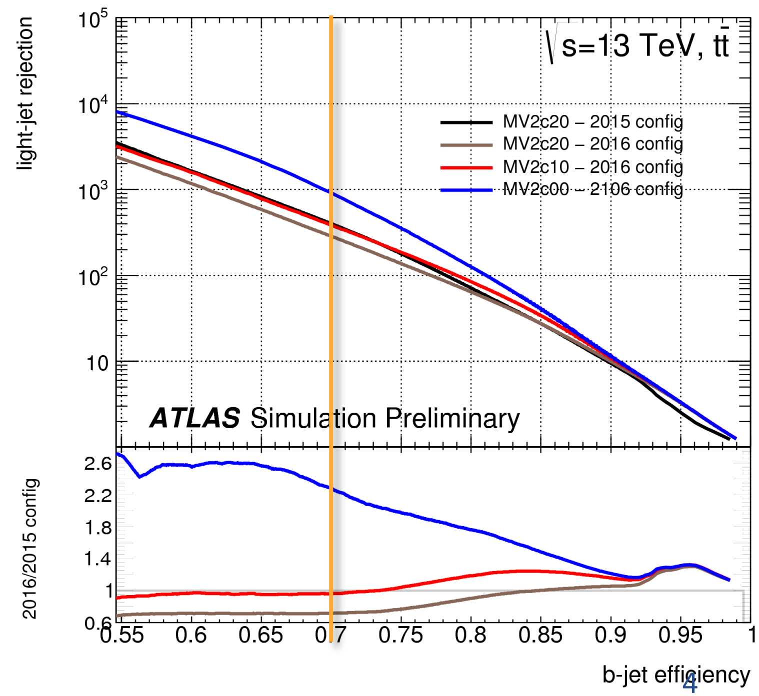




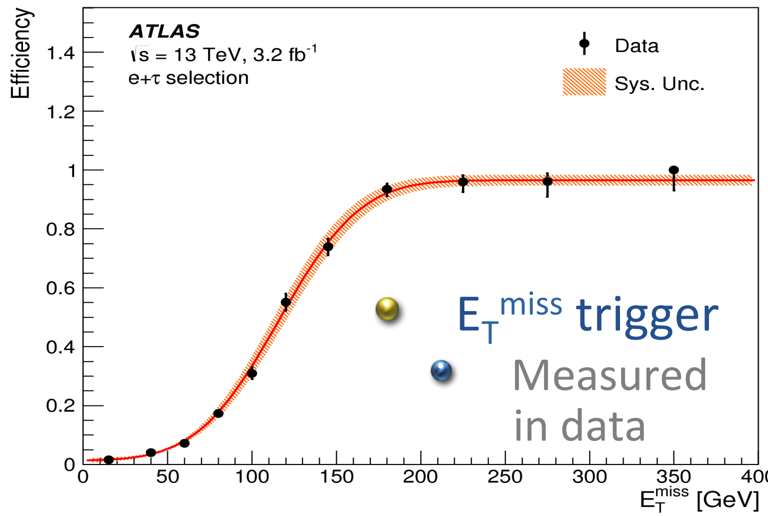
b-jets

- MVA ID
  - Impact params
  - Secondary & tertiary vertex properties
- $\varepsilon_b \approx$ 70% with l/c rejection ~400 (10)



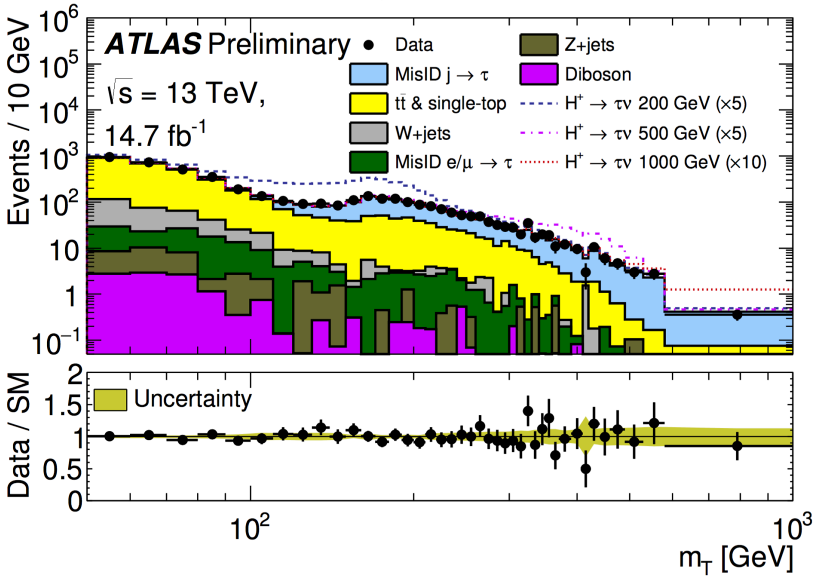


$H^+ \rightarrow \tau\nu$: selection

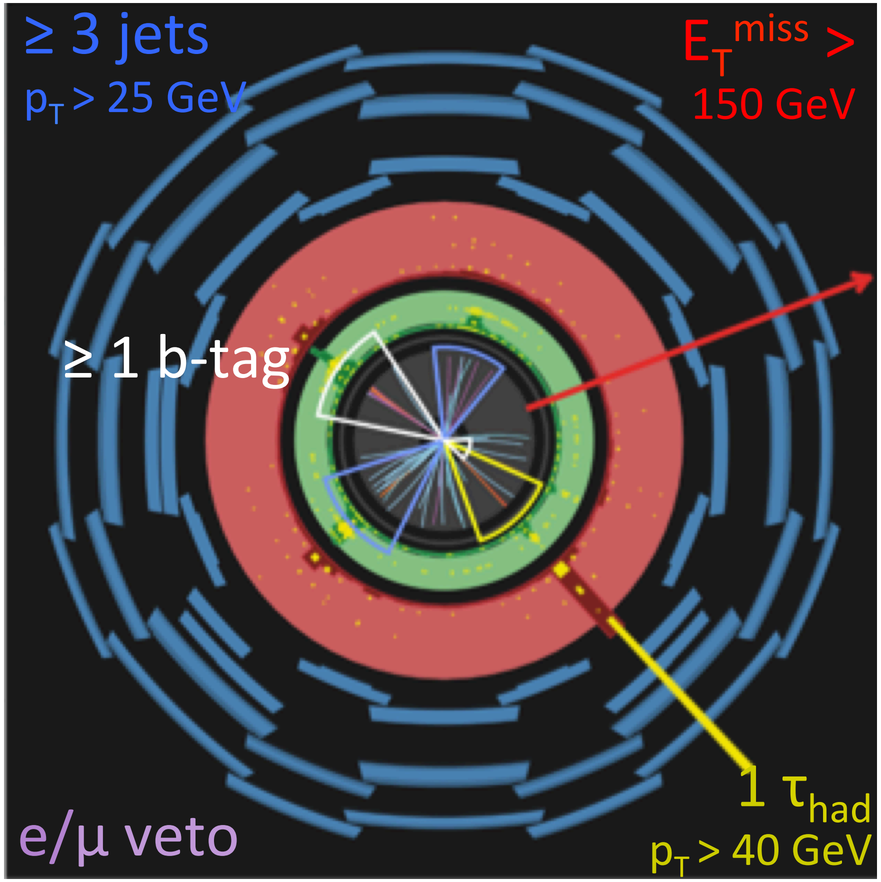


- E_T^{miss} trigger
  - Measured in data

A*ε = 1.1 - 10 % for 200 - 1000 GeV



- Hadronic τ + hadronic top decay



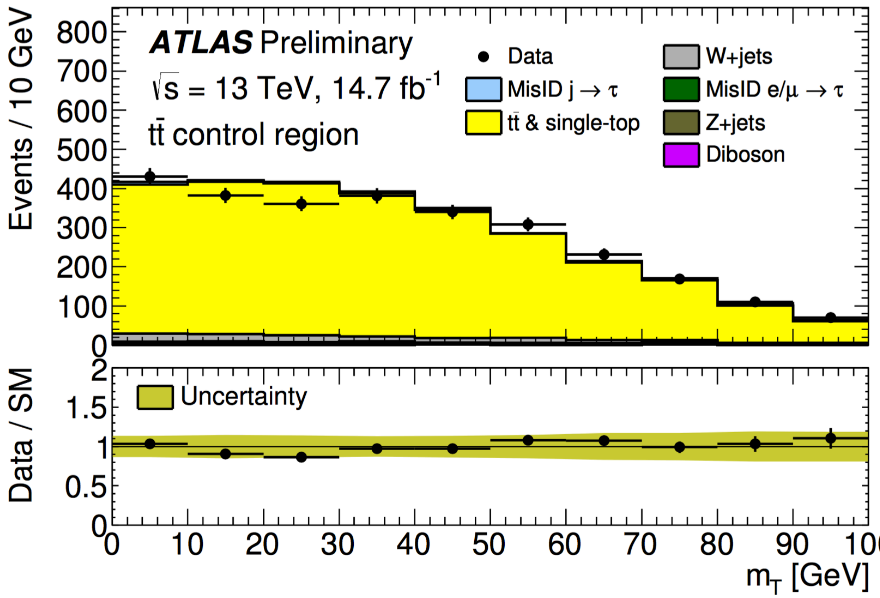
- Discriminant: m_T > 50 GeV

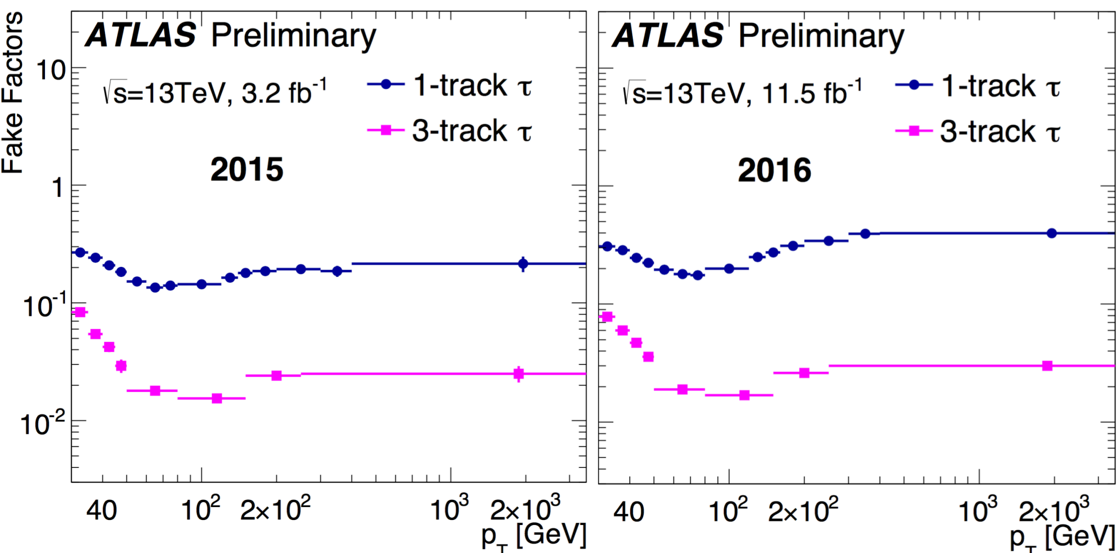
$$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi_{\tau,miss})}$$

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

- True τ_{had}: MC normalised/checked in CRs with $m_T < 100$ GeV
  - W+jets normalised in 0 b-jet
  - ttbar validated ≥ 2 b-jets
- Jet → τ_{had} fakes: Fake Factor (FF)
  - Template from anti-ID τ_{had} data
  - Normalised in $E_T^{miss} < 80$ GeV, 0 b-tag

$$N^{\tau}_{\rm fakes} = N^{\rm anti-\tau}_{\rm fakes} \times FF \qquad FF = \frac{N_{\tau-\rm id}}{N_{\rm anti-\tau-id}}$$





Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	2880 ± 770 ± 25
$W \rightarrow \tau\nu$	265 ± 51 ± 18
$Z \rightarrow \tau\tau$	43 ± 6.8 ± 7.6
diboson (WW, WZ, ZZ)	13.8 ± 2.2 ± 1.7
Misidentified e, $\mu \rightarrow \tau_{\rm had-vis}$	126 ± 24 ± 6.5
Misidentified jet $\rightarrow \tau_{\rm had-vis}$	1170 ± 110 ± 16
All backgrounds	4500 ± 1100 ± 36
H^+ (200 GeV), hMSSM $\tan\beta = 60$	523 ± 86 ± 4
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	7.5 ± 0.6 ± 0.05
Data	4645

(Small e/μ → τ_{had} fakes directly from MC)

$H^+ \rightarrow \tau\nu$: systematic uncertainties

- Systematics arise from experimental effects, determination of jet → τ_{had} fakes, modelling of MC backgrounds and signal
  - Statistical uncertainties start to dominate at high mass

Source of systematic uncertainty	Impact on the expected limit (in %) $m_{H^+} = 200$ GeV	$m_{H^+} = 1000$ GeV
Experimental		
luminosity	1.5	0.9
trigger	< 0.1	< 0.1
$\tau_{\text{had-vis}}$	1.0	1.4
jet	3.0	0.2
E_T^{miss}	< 0.1	< 0.1
Fake factors		
ff	0.8	4.7
Signal and background models		
$t\bar{t}$ modelling	13.2	3.5
H^+ signal modelling	1.4	1.4

Biggest at high m(H±)

Biggest at low m(H±)

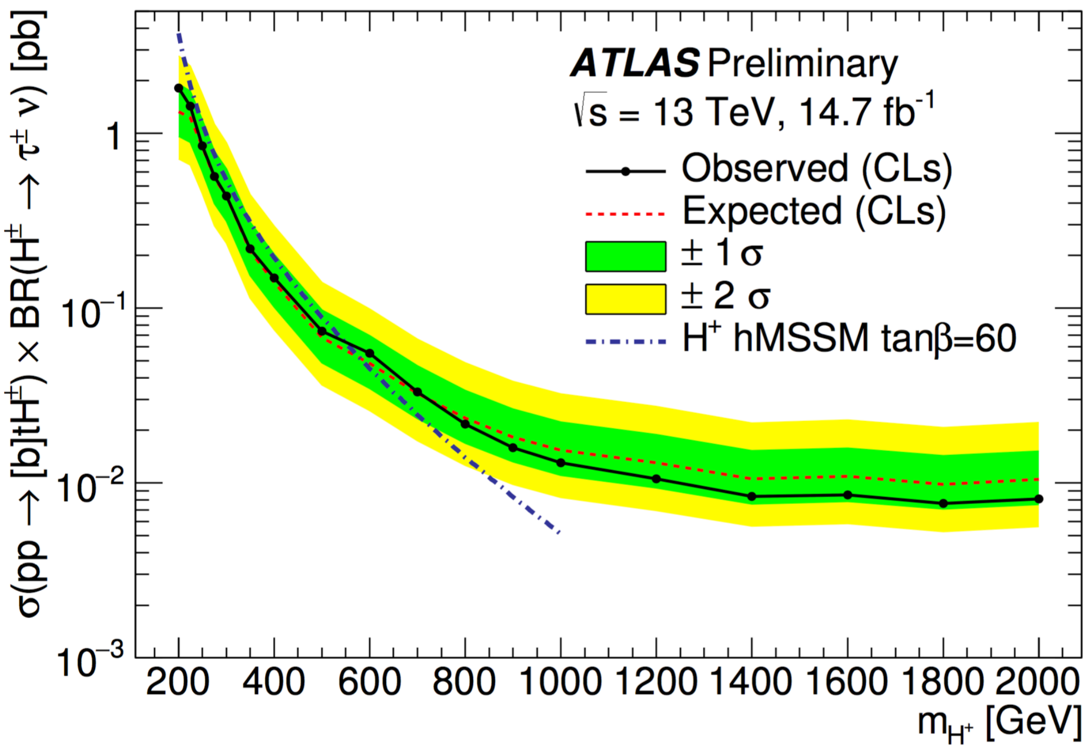
- Jet → τ_{had} fakes
  - CR stats
  - Varying anti-τ BDT cut
  - True τ_{had} subtraction

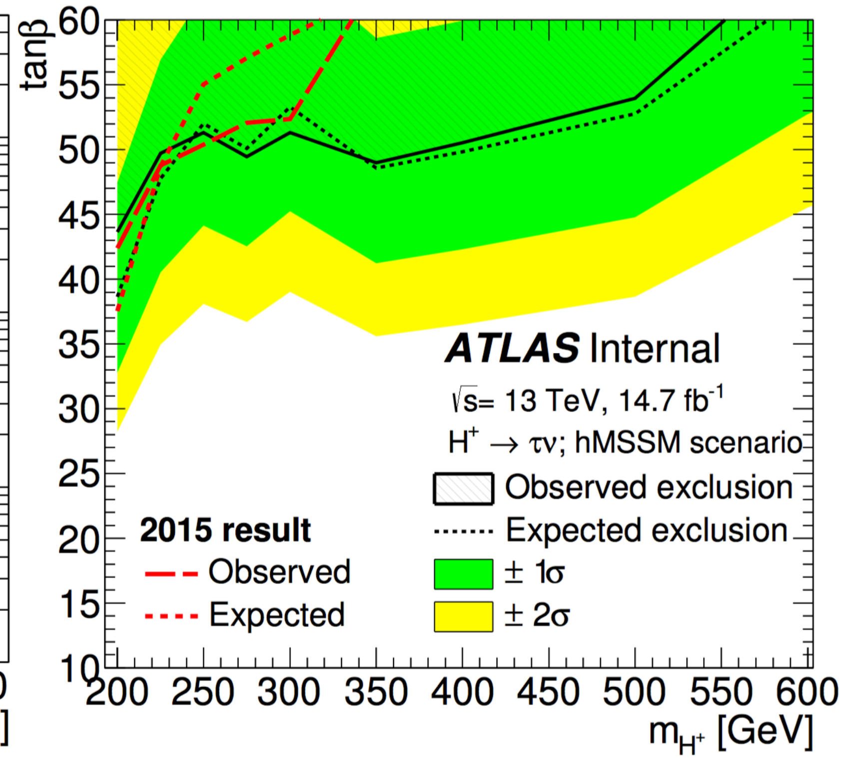
- Top modelling:
  - Cross-section, ME (Powheg vs aMC@NLO), PS (Pythia vs Herwig), ISR/FSR

- Signal modelling
  - μ_F/μ_R scale, PDF, UE tune

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

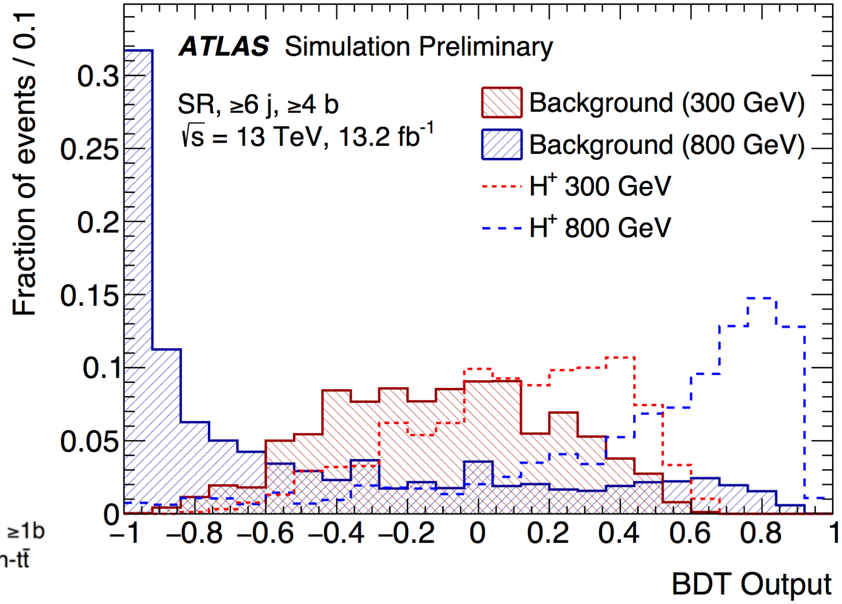
- Observed σ x BR limit:
  - 2.0 pb – 8 fb
- Obs. hMSSM exclusion:
  - 42 < tanβ < 60 @ m(H^+) = 200 GeV
  - 200 < m(H^+) < 540 GeV @ tanβ=60
  - Significantly improves 2015 result

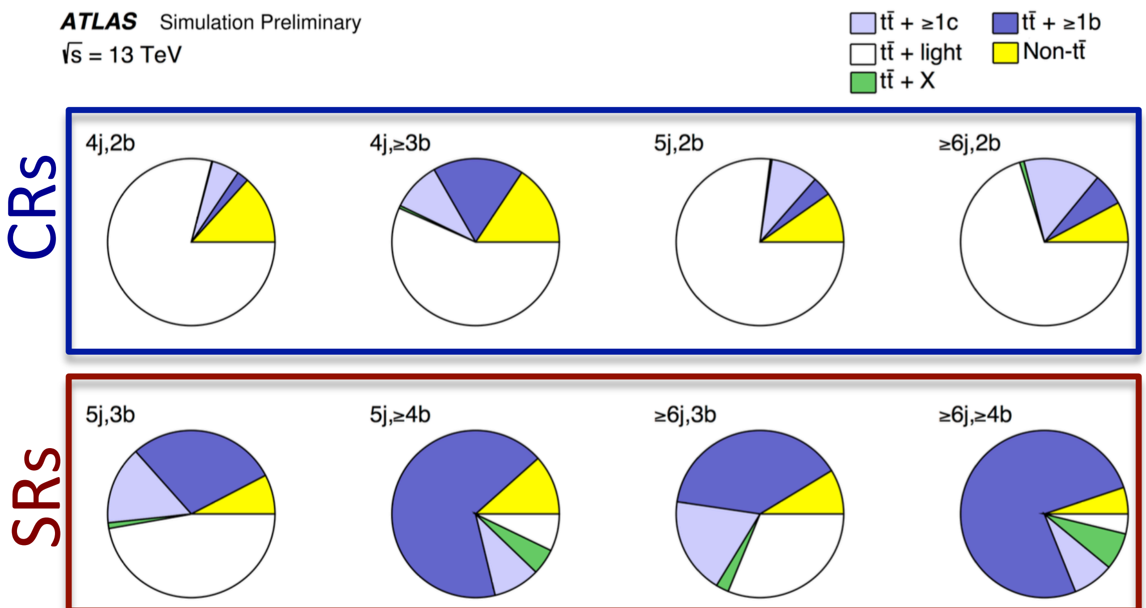




$H^+ \rightarrow tb$: selection

- Semi-leptonic selection:
  - Single lepton triggers
  - 1 lepton with $p_T > 25$ GeV
  - ≥ 4 jets with $p_T > 25$ GeV
    - ≥ 2 b-tagged
- Split into SRs and CRs based on number of jets (N_j) & b-jets (N_b)

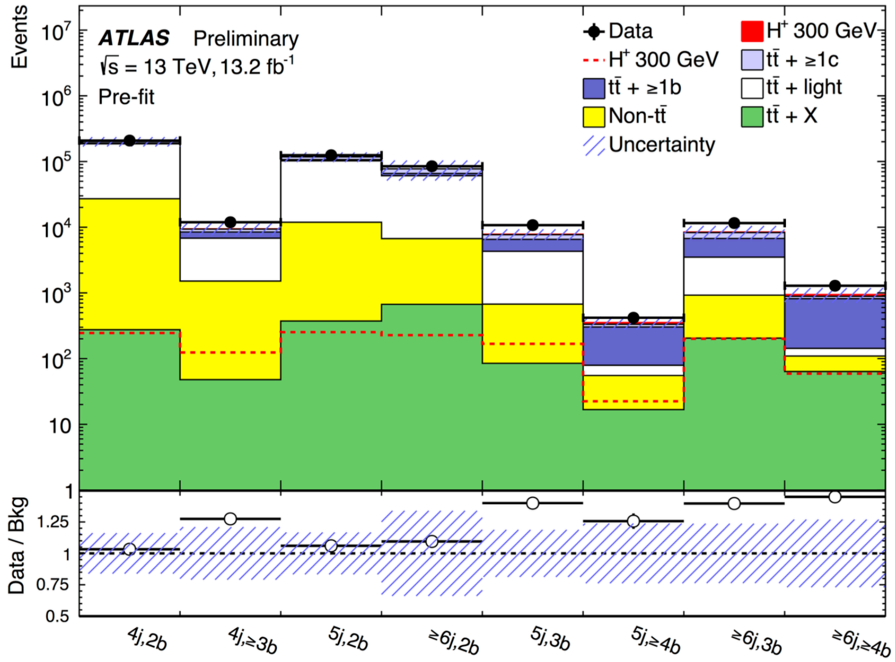




- Maximum likelihood fit to all regions using:
  - BDT in SRs
    - (Inputs in backup)
    - More discriminating at higher mass
  - H_T^{had} ($= \Sigma p_T^{jets}$) in CRs

H+ → tb : background modelling

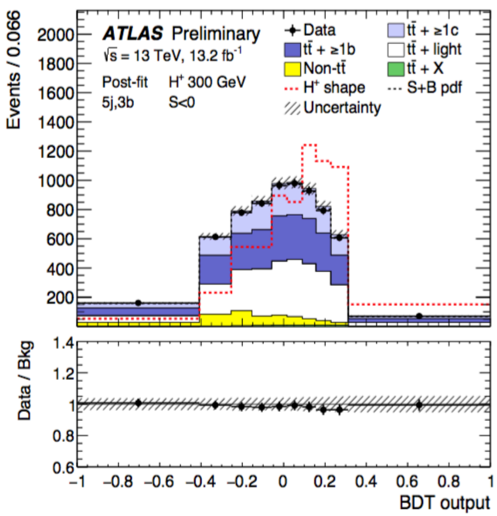
- Background dominated by ttbar + jets production
  - Split into light/heavy flavour based on extra jets: tt + light, tt + ≥1c, tt + ≥1b
- Modelled using Powheg + Pythia 6
  - tt+light and tt+≥1c reweighted to NNLO prediction for p_T^{ttbar} and p_T^{t}
    - A. Mitov et al (arXiv:1606.03350)
  - tt+≥1b kinematics reweighted to NLO Sherpa+OpenLoops prediction
    - Inclusive normalisation maintained
- Inclusive ttbar σ = 832^{+46}_{-51} pb
  - Normalisation of tt + ≥1c and tt + ≥1b freely floating in fit
- BDT trained against
  - Only tt+≥1b for m(H±) ≤ 500 GeV
  - All ttbar background for m(H±) ≥ 500 GeV

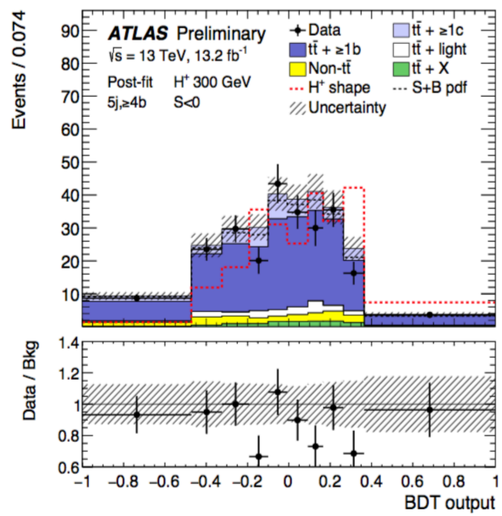


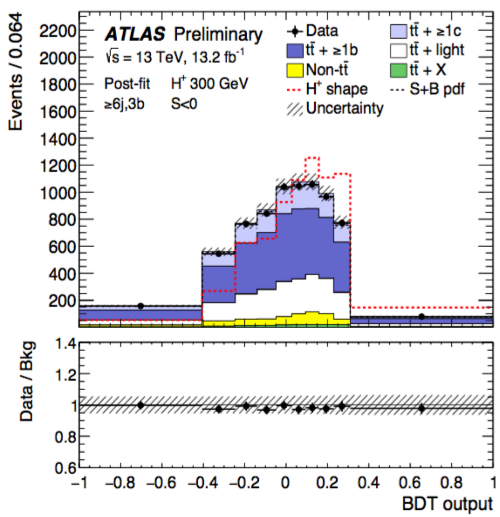
Pre-fit background description
(signal normalised to 1 pb)

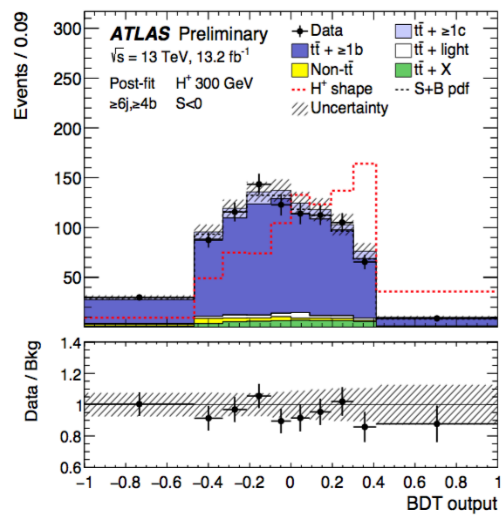
$H^+ \rightarrow tb$: post-fit distributions

- SR and CR normalisation and shape well described after fit

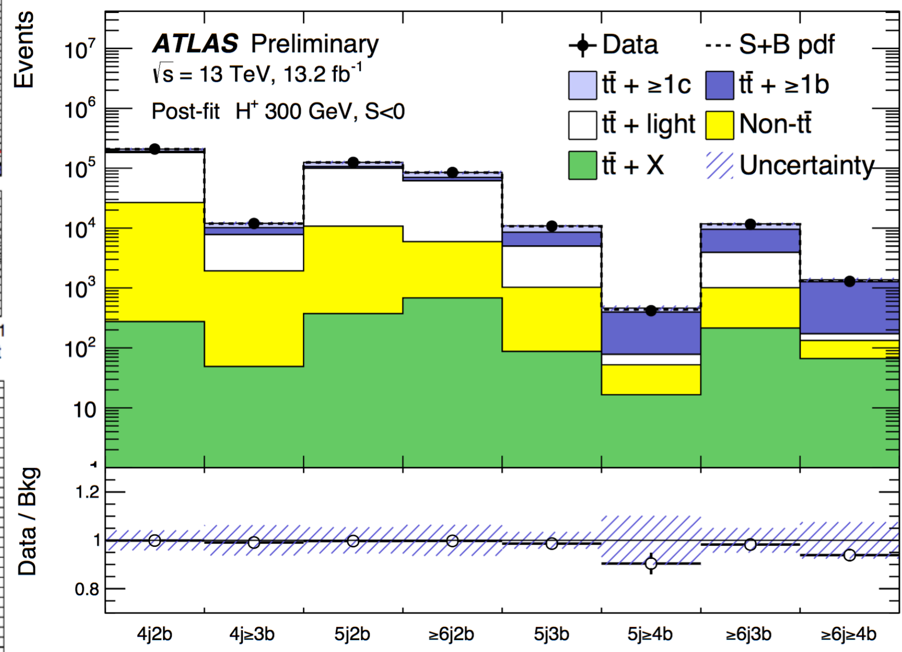








- Shown here for 300 GeV
- (H_T & 800 GeV BDT in backup)



Post-fit background description
(signal strength slightly < 0)

$H^+ \rightarrow tb$: systematic uncertainties

- Systematic uncertainties dominated by ttbar modelling, especially heavy flavour

Uncorrelated amongst l/c/b

- tt + ≥1b NLO
  - Alternative MG5_aMC@NLO+Pythia6 generator
  - μ_F/μ_R
  - Vary PDFs & shower recoil scheme
  - 50% MPI uncertainty
- tt + ≥1c from ME vs PS
  - MG5_aMC@NLO + Herwig++
- Inclusive
  - PS, ME, ISR/FSR (as τν)
  - Cross section

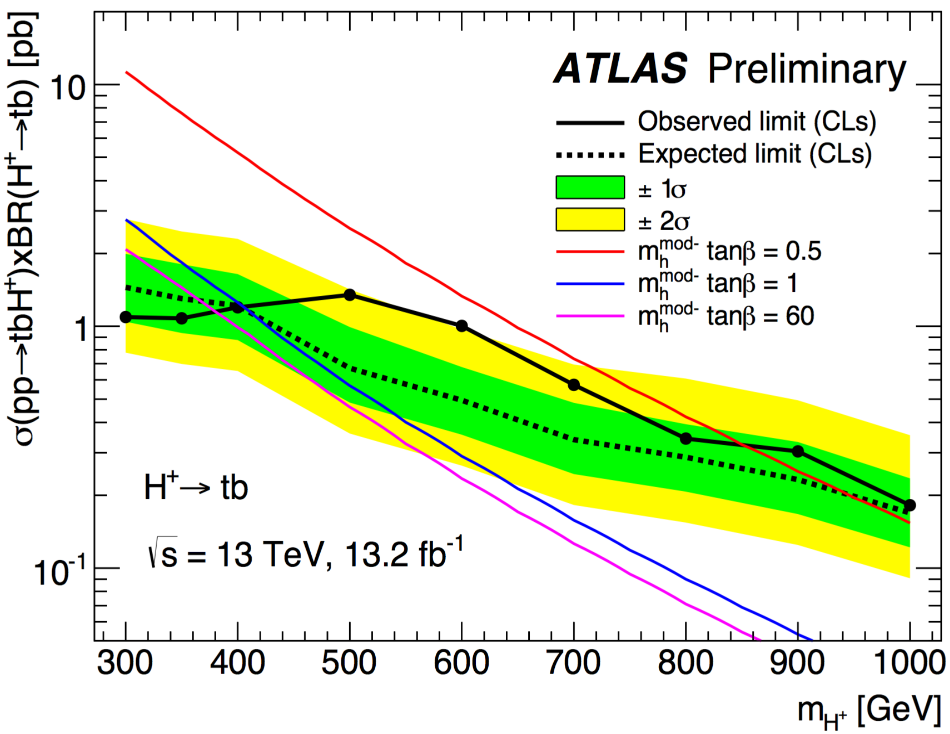
Ordered impact on fitted signal strength for 300 & 800 GeV H^+

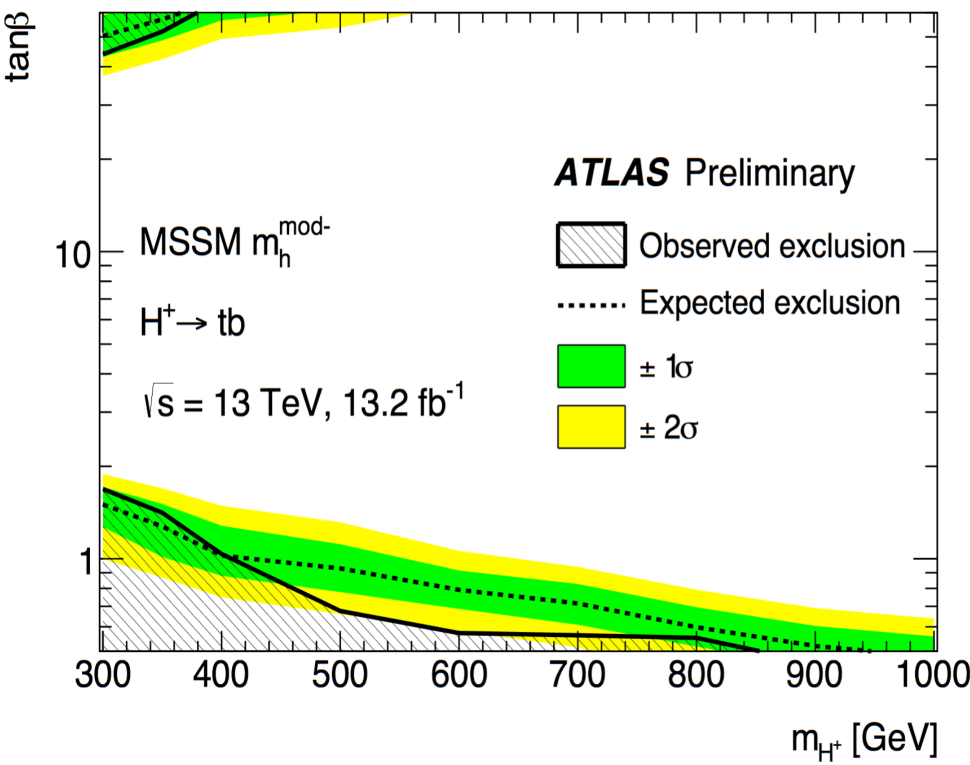
Uncertainty Source	$\Delta\mu(H^+_{300})$		$\Delta\mu(H^+_{800})$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53	+0.07	−0.07
Jet flavour tagging	+0.30	−0.29	+0.07	−0.07
$t\bar{t}+\geq 1c$ modelling	+0.23	−0.22	+0.03	−0.03
Background model statistics	+0.19	−0.19	+0.05	−0.05
Jet energy scale and resolution	+0.18	−0.17	+0.03	−0.03
$t\bar{t}$+light modelling	+0.16	−0.16	+0.03	−0.03
Other background modelling	+0.15	−0.14	+0.03	−0.03
Jet-vertex association, pileup modelling	+0.12	−0.11	+0.01	−0.01
Luminosity	+0.12	−0.12	+0.01	−0.01
Light lepton (e, μ) ID, isolation, trigger	+0.01	−0.01	$< +0.01$	< -0.01
Total systematic uncertainty	+0.72	−0.79	+0.13	−0.11
$t\bar{t}+\geq 1b$ normalisation	+0.36	−0.36	+0.03	−0.03
$t\bar{t}+\geq 1c$ normalisation	+0.15	−0.14	+0.02	−0.02
Total statistical uncertainty	+0.44	−0.43	+0.08	−0.08
Total	+0.84	−0.90	+0.15	−0.13

- On the detector side, the b-tagging and jet enery scale/resolution uncertainties are the largest contributions

$H^+ \rightarrow tb$: results

- Observed σ x BR limit:
  - 1.1 pb -0.18 pb
  - Unlike run 1, no broad excess
- Obs. m_h^{mod-} exclusion:
  - tanβ = 0.5 for m(H^+) ≤ 855 GeV
  - Starts to exclude high tanβ
    - m(H^+) ≤ 380 GeV
  - Surpases run 1 results





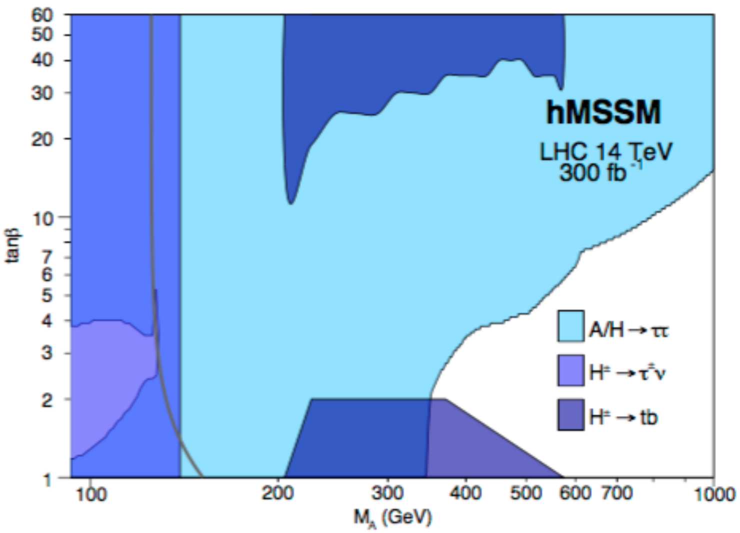
Summary

- ATLAS has preformed run-2 searches for heavy charged bosons in $H^{\pm} \rightarrow \tau\nu$ and $H^{\pm} \rightarrow tb$ decays
  - ATLAS-CONF-2016-088
  - ATLAS-CONF-2016-089

  To appear soon

- Unfortunately, no excess observed but significant improvement on run 1 exclusions at high masses
  - Benefits from large increase in production cross section at 13 TeV

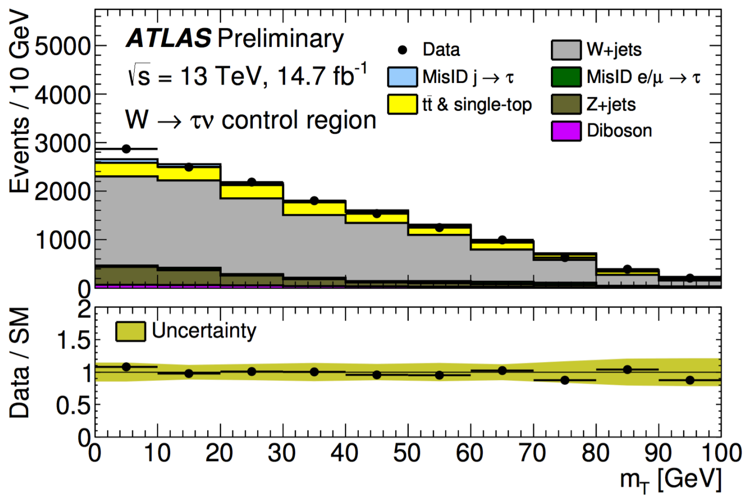
- Looking forward to many new and improved $H^{\pm}$ searches soon
  - $H^{+} \rightarrow tb$ starting to probe high tanβ
  - Lower masses can be probed
  - Probe other extended Higgs sectors
    - e.g. Higgs triplets



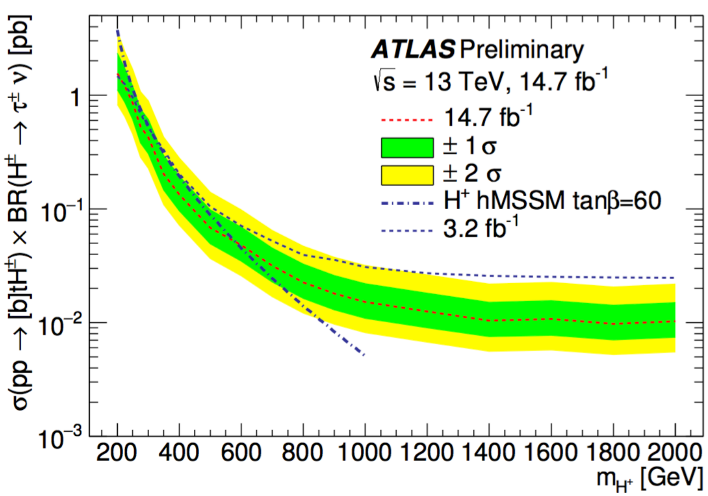
arXiv:1502:05653

H⁺ → τν (1)

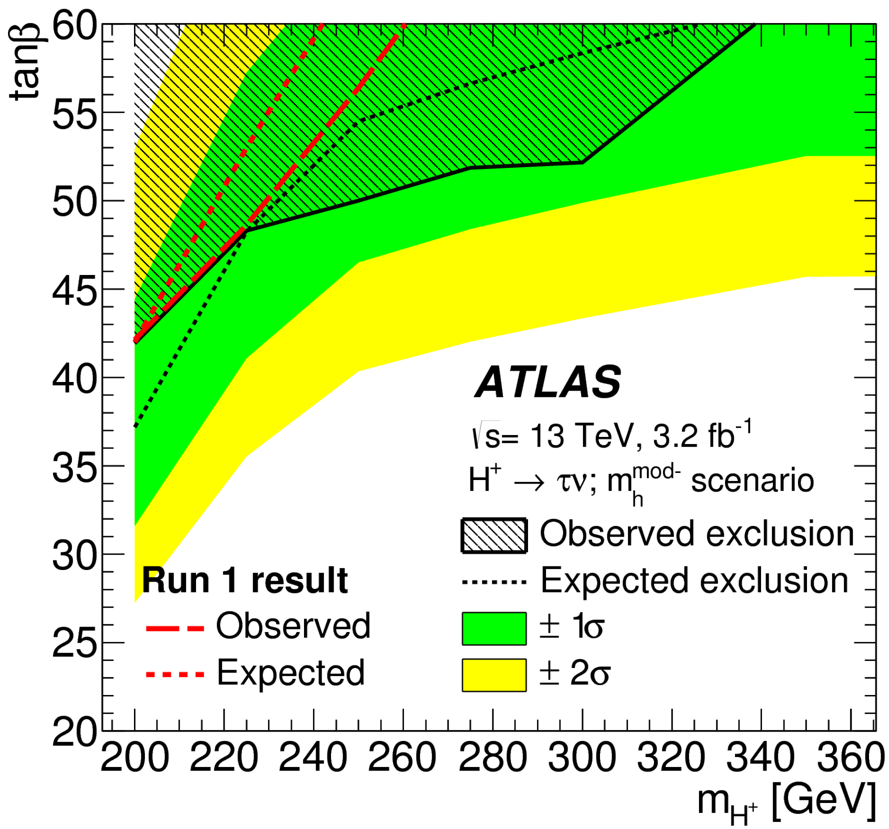
- W+jets CR



- 2015 comparison

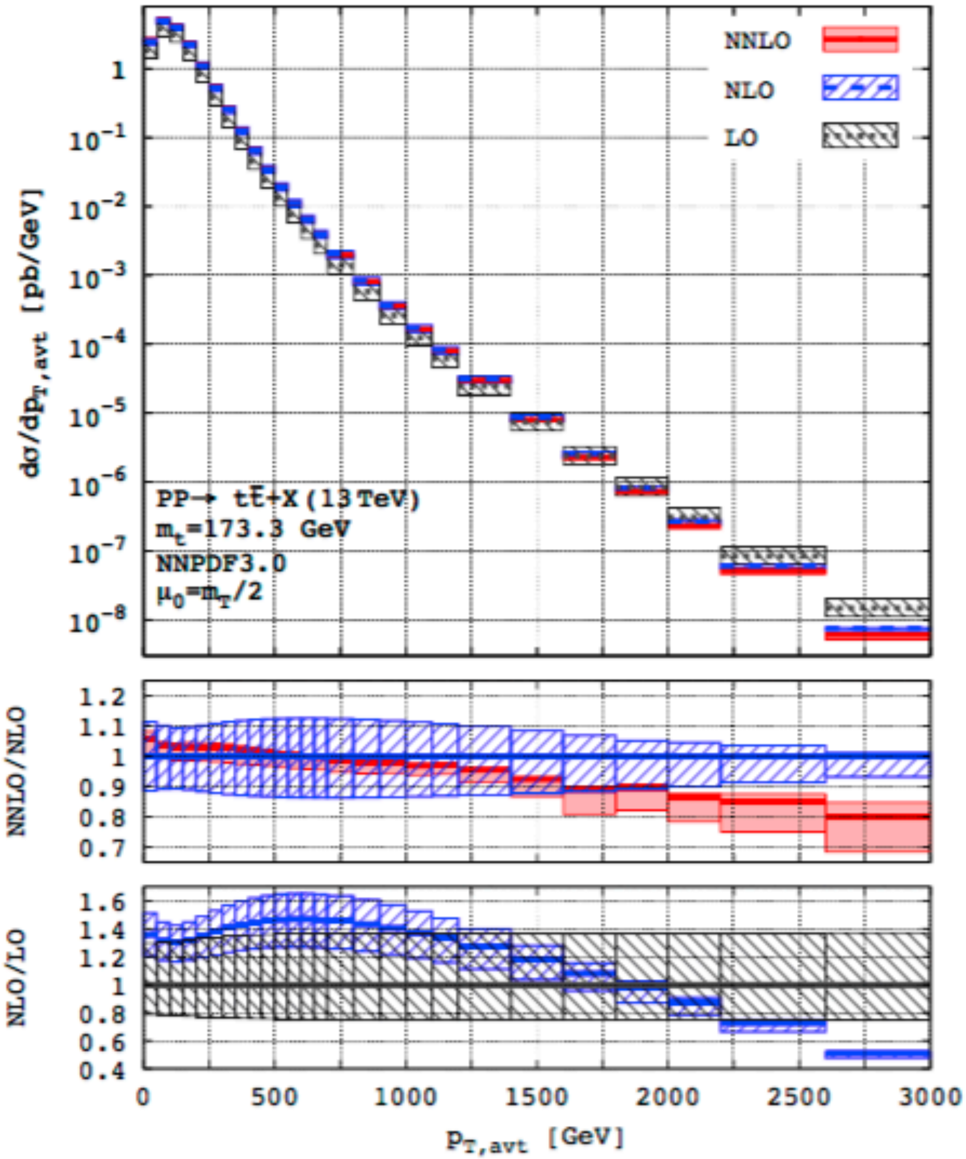


- m_h^{mod-} exclusion



$H^+ \rightarrow tb$ (1)

- Example of NNLO p_T^t



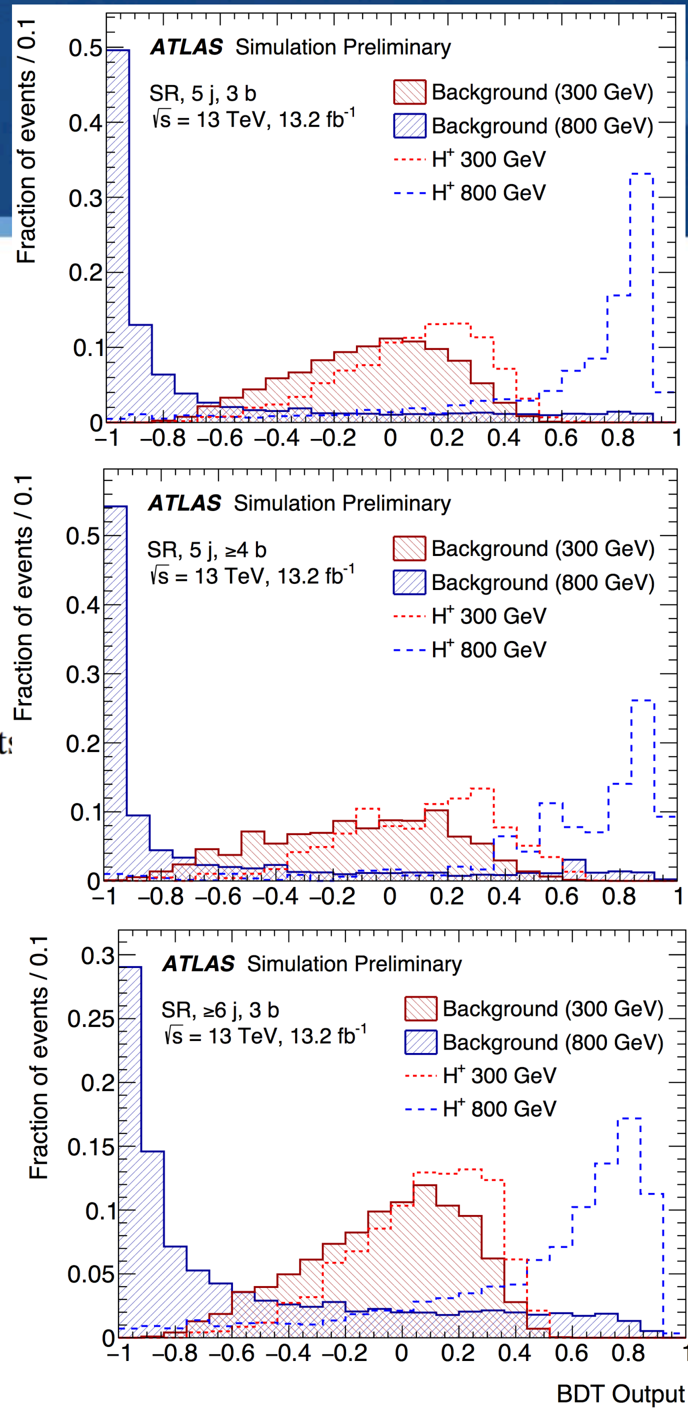
H+ → tb (2)

- BDT details

BDT Parameter	Value
BoostType	GradientBoost
Shrinkage	0.20
MinNodeSize	1%
NTrees	120
MaxDepth	3

The variables entering the BDT training are :

- The highest jet p_T.
- The mass of the bb pair with minimum ΔR.
- The p_T of the fifth jet, ordered by b-tagged jets and then non–b-tagged jets
- The second Fox-Wolfram moment calculated using all jets and leptons.
- The average ΔR of all bb pairs.
- The ΔR of the lepton and the bb pair with smallest ΔR.
- The mass of the untagged jet-pair with minimum ΔR.
- The scalar sum of E_T calculated using all jets.
- The mass of the bb pair with maximum p_T.
- The mass of the bb pair with maximum mass.
- The mass of the jet triplet with maximum p_T.
- The centrality calculated using all jets and leptons.



$H^+ \rightarrow tb$ (3)

- Pre-fit event yields

Process	$4j2b$	$4j \geq 3b$	$5j2b$	$\geq 6j2b$
$t\bar{t}+ \geq 1c$	10800 ± 2300	890 ± 300	10800 ± 2000	11500 ± 3600
$t\bar{t}+ \geq 1b$	4580 ± 930	1650 ± 490	4440 ± 540	4800 ± 1200
$t\bar{t}$ + light	160000 ± 30000	5310 ± 1550	91000 ± 17000	54000 ± 24000
Fakes	9200 ± 4400	820 ± 360	3700 ± 1600	1560 ± 670
$t\bar{t} + W$	99 ± 17	4.33 ± 0.99	130 ± 22	204 ± 40
$t\bar{t} + Z$	113 ± 21	15.7 ± 4.1	147 ± 25	270 ± 46
Single top	5900 ± 1600	243 ± 84	3470 ± 1140	2060 ± 820
Other top	4330 ± 1620	157 ± 30	1480 ± 280	630 ± 160
Diboson	420 ± 220	19 ± 12	200 ± 110	164 ± 88
W + jets	5250 ± 2370	183 ± 98	2300 ± 1100	1350 ± 650
Z + jets	1210 ± 580	42 ± 23	410 ± 210	260 ± 130
ttH	63.8 ± 8.9	28.0 ± 4.9	96 ± 11	198 ± 28
tH	9.6 ± 2.8	5.2 ± 1.6	8.1 ± 2.4	9.9 ± 3.1
Total	202000 ± 36000	9300 ± 2000	118000 ± 23000	77000 ± 27000
Data	208329	11904	124688	84556
H^+_{300}	245 ± 24	124 ± 18	253 ± 20	228 ± 32
H^+_{800}	170 ± 16	80 ± 15	249 ± 19	477 ± 49

Process	$5j3b$	$5j \geq 4b$	$\geq 6j3b$	$\geq 6j \geq 4b$
$t\bar{t}+ \geq 1c$	1170 ± 330	30 ± 11	1550 ± 530	71 ± 36
$t\bar{t}+ \geq 1b$	2240 ± 460	222 ± 62	3200 ± 800	670 ± 190
$t\bar{t}$ + light	3640 ± 880	24 ± 15	2600 ± 1100	34 ± 22
Fakes	260 ± 130	19.9 ± 9.3	300 ± 130	1.2 ± 0.6
$t\bar{t} + W$	8.3 ± 1.8	0.19 ± 0.07	20.8 ± 4.6	1.24 ± 0.39
$t\bar{t} + Z$	27.1 ± 5.9	4.8 ± 1.5	66 ± 12	17.9 ± 4.2
Single top	218 ± 85	8.1 ± 5.0	210 ± 100	21 ± 14
Other top	87 ± 17	6.3 ± 2.5	66 ± 16	8.3 ± 2.3
Diboson	15.6 ± 9.6	0.39 ± 0.29	14.4 ± 8.3	2.0 ± 1.3
W + jets	165 ± 100	2.3 ± 3.1	106 ± 54	10.4 ± 7.0
Z + jets	37 ± 27	0.72 ± 0.65	14.7 ± 7.9	1.17 ± 0.74
ttH	49.7 ± 7.0	11.8 ± 2.3	119 ± 18	44.9 ± 9.2
tH	4.4 ± 1.3	1.02 ± 0.35	5.9 ± 1.9	1.92 ± 0.68
Total	7900 ± 1500	331 ± 94	8300 ± 1900	890 ± 240
Data	10755	418	11561	1285
H^+_{300}	173 ± 23	24.1 ± 4.0	201 ± 31	62 ± 12
H^+_{800}	138 ± 21	20.0 ± 4.3	366 ± 51	117 ± 24

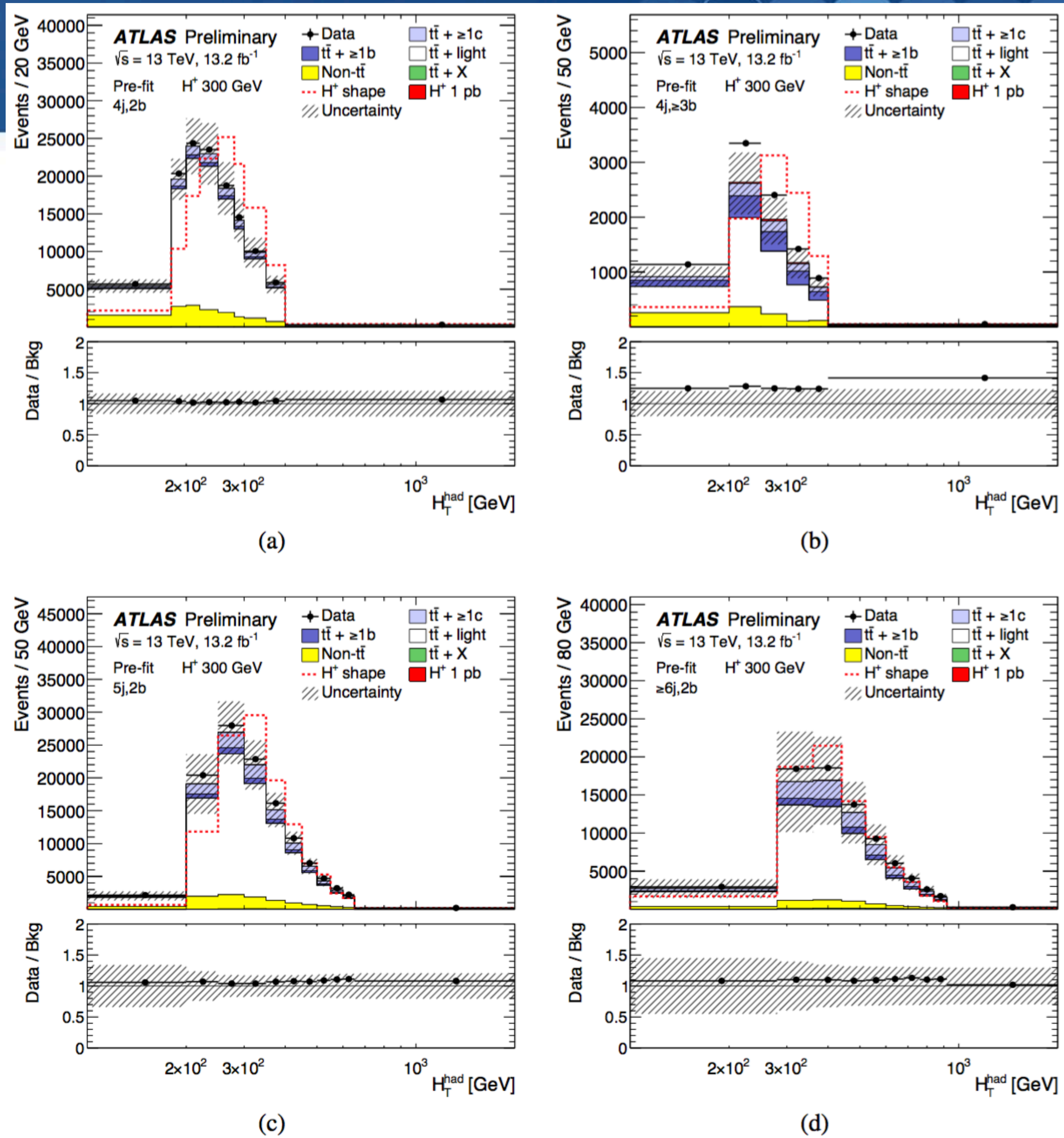
$H^+ \rightarrow tb$ (4)

- Post-fit event yields
  - 300 GeV

Process	$4j2b$	$4j \geq 3b$	$5j2b$	$\geq 6j2b$
H^+_{300}	-240 ± 210	-120 ± 110	-250 ± 220	-170 ± 150
$t\bar{t}+ \geq 1c$	18500 ± 7300	1860 ± 670	18600 ± 6600	14800 ± 5600
$t\bar{t}+ \geq 1b$	6500 ± 1300	2310 ± 450	6900 ± 1200	8400 ± 1300
$t\bar{t}$ + light	156800 ± 7400	5910 ± 710	88800 ± 6400	55700 ± 5300
Fakes	8100 ± 2000	1330 ± 300	3080 ± 750	1360 ± 310
$t\bar{t} + W$	99 ± 16	5.2 ± 0.9	131 ± 22	208 ± 40
$t\bar{t} + Z$	113 ± 20	15.9 ± 4.1	147 ± 23	276 ± 40
Single top	5400 ± 1300	250 ± 74	2950 ± 830	1630 ± 540
Other top	4400 ± 1200	172 ± 49	1540 ± 450	670 ± 200
Diboson	450 ± 220	23 ± 12	220 ± 110	184 ± 88
W + jets	6700 ± 2200	250 ± 110	2120 ± 780	1140 ± 440
Z + jets	1310 ± 560	49 ± 21	460 ± 200	300 ± 130
ttH	62.9 ± 6.8	27.8 ± 3.4	95.7 ± 9.5	200 ± 22
tH	9.5 ± 2.7	5.1 ± 1.5	8.1 ± 2.3	9.9 ± 2.9
Total	208400 ± 8600	12010 ± 750	125000 ± 6800	84800 ± 5400
Data	208329	11904	124688	84556
H^+_{300}	-170 ± 150	-25 ± 21	-200 ± 180	-62 ± 53
$t\bar{t}+ \geq 1c$	2390 ± 720	66 ± 21	2240 ± 780	102 ± 44
$t\bar{t}+ \geq 1b$	3490 ± 540	320 ± 37	5580 ± 640	1090 ± 90
$t\bar{t}$ + light	3990 ± 610	36 ± 13	2940 ± 550	40 ± 21
Fakes	420 ± 110	19.2 ± 0.8	410 ± 110	1.2 ± 0.6
$t\bar{t} + W$	9.5 ± 1.7	0.2 ± 0.1	23.6 ± 4.7	1.4 ± 0.4
$t\bar{t} + Z$	28.0 ± 5.7	4.7 ± 1.3	68.8 ± 9.8	18.5 ± 3.5
Single top	202 ± 64	5.9 ± 3.1	173 ± 71	16.5 ± 9.5
Other top	94 ± 26	6.3 ± 2.2	71 ± 22	8.7 ± 2.3
Diboson	17.4 ± 9.0	0.4 ± 0.2	16.7 ± 8.3	2.3 ± 1.1
W + jets	164 ± 81	2.1 ± 0.9	97 ± 43	8.2 ± 3.6
Z + jets	39 ± 24	0.7 ± 0.3	17.5 ± 7.6	1.6 ± 0.7
ttH	49.6 ± 5.2	11.6 ± 1.6	122 ± 13	46.4 ± 6.2
tH	4.5 ± 1.3	1.0 ± 0.3	6.0 ± 1.8	2.0 ± 0.6
Total	10900 ± 380	462 ± 47	11800 ± 600	1300 ± 100
Data	10755	418	11561	1285

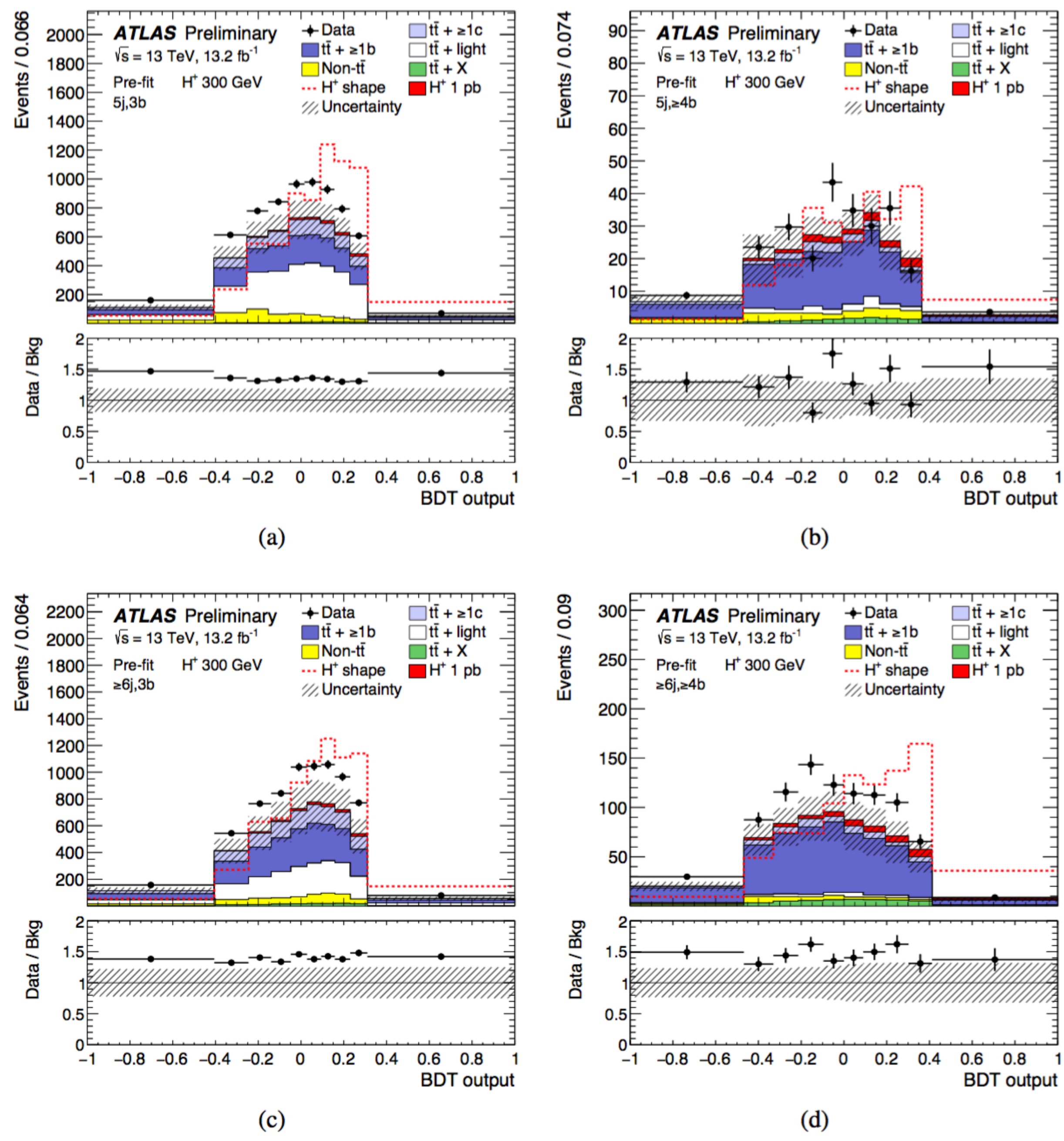
$H^+ \rightarrow tb$ (5)

- Pre-fit plots in CR



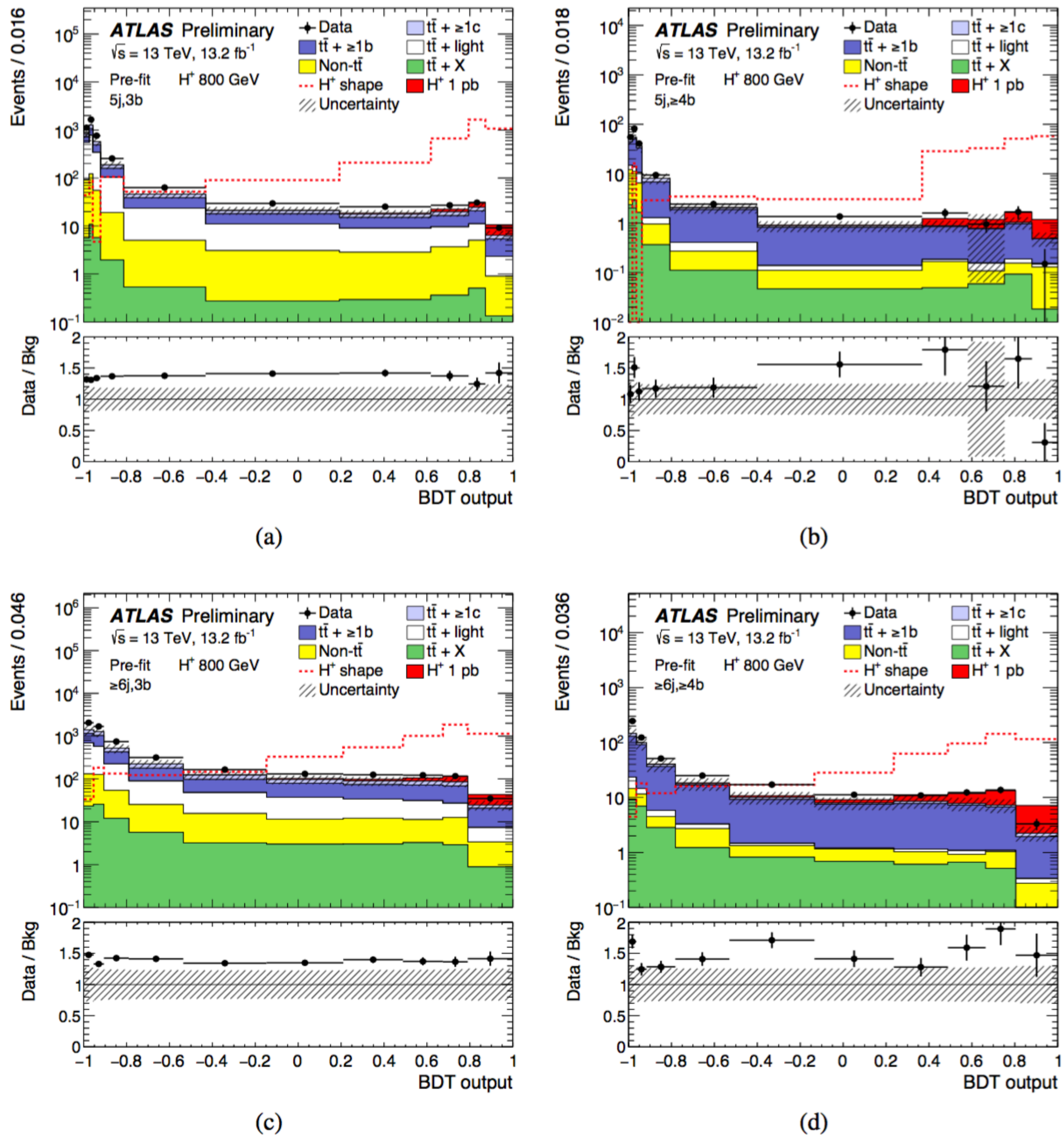
H+ → tb (6)

- Pre-fit plots in SR
  300 GeV



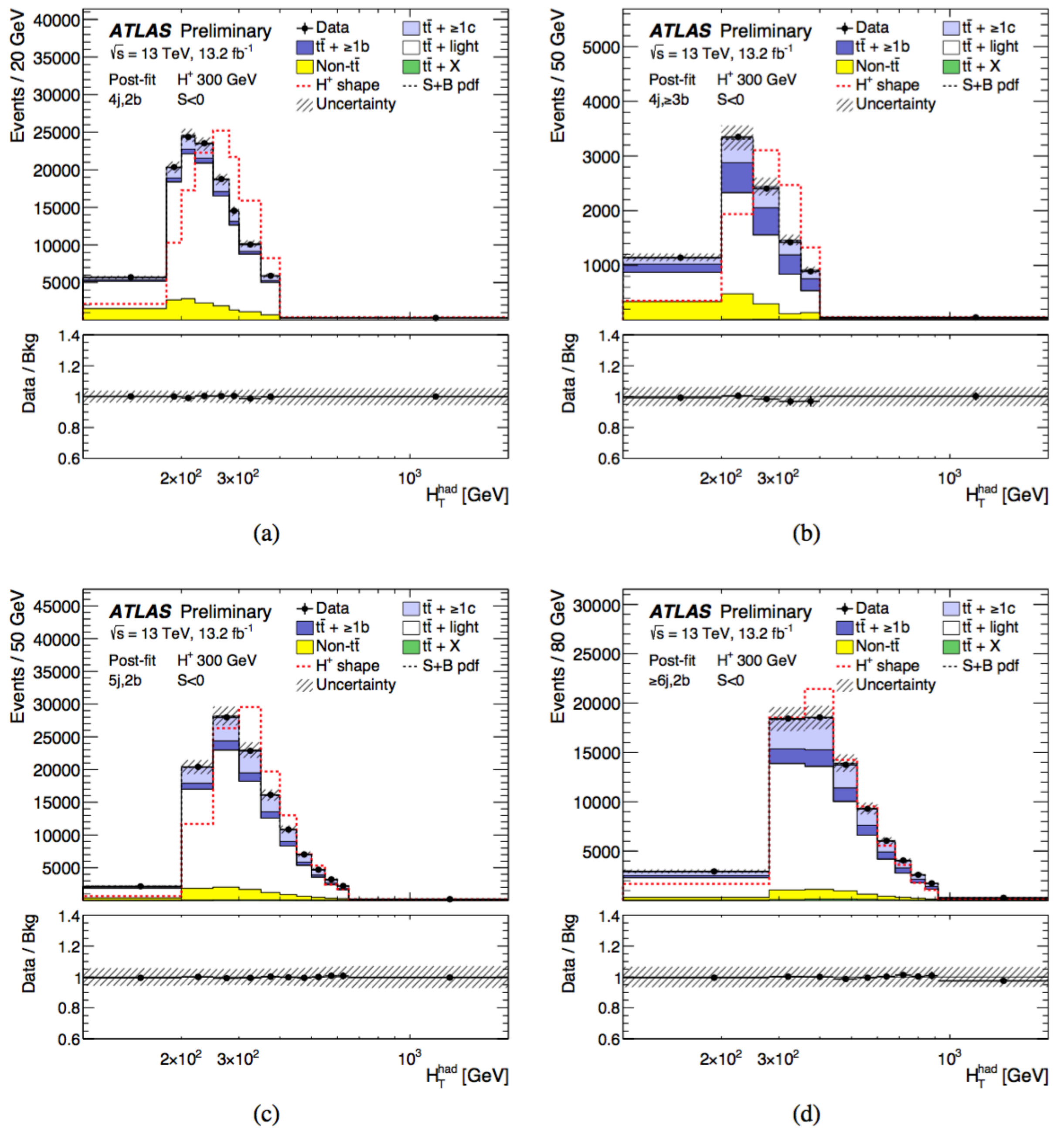
H+ → tb (7)

- Pre-fit plots in SR
  - 800 GeV



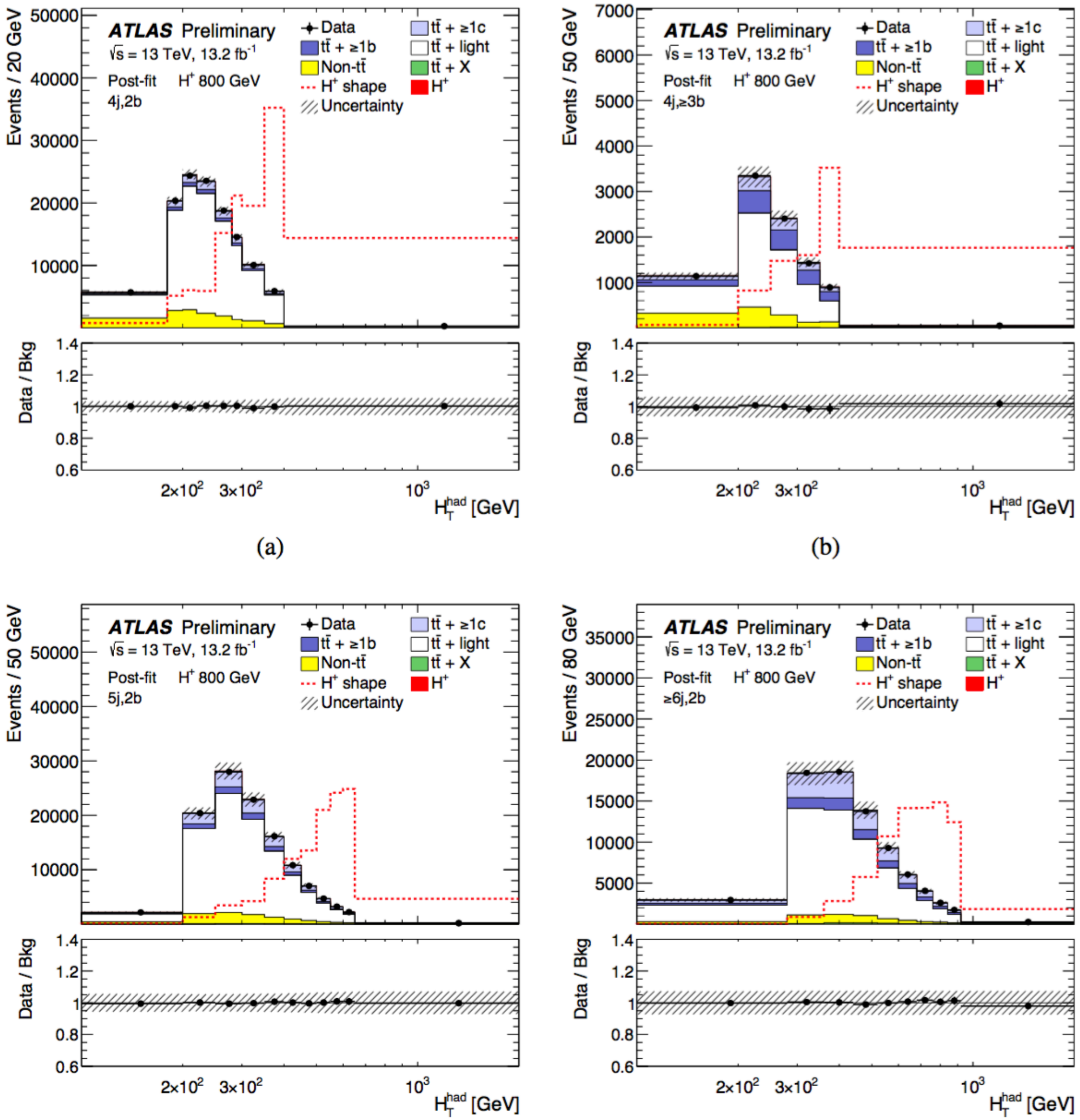
H+ → tb (8)

- Post-fit plots in CR
  - 300 GeV



H+ → tb (9)

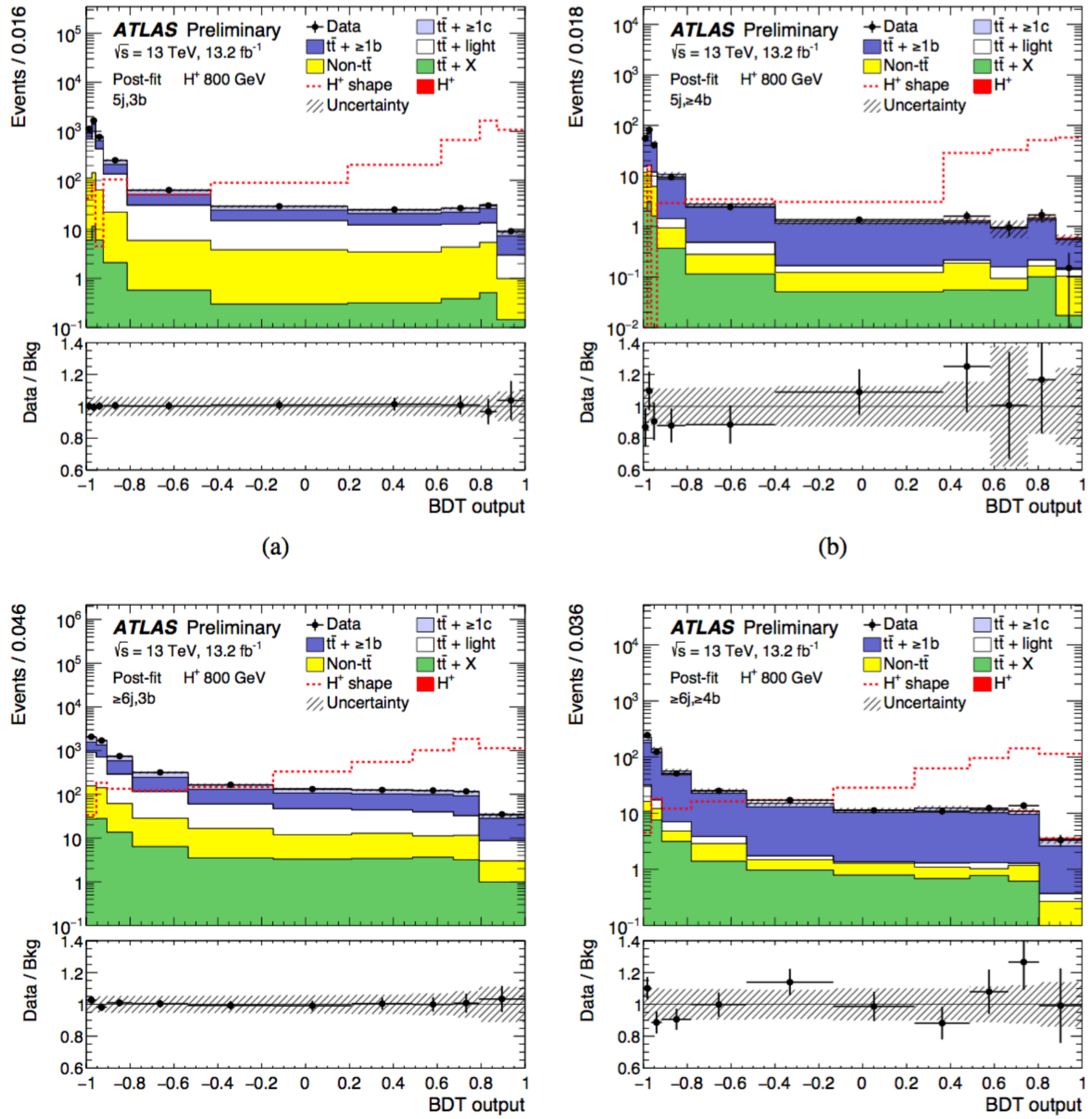
- Post-fit plots in CR
  - 800 GeV



(a) (b) (c) (d)

H+ → tb (10)

- Post-fit plots in SR
  - 800 GeV



(a) (b)

(c) (d)