H^+ searches in ATLAS

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ATLAS EXPERIMENT

October 16
Partikeldagarna, Lund, 2018

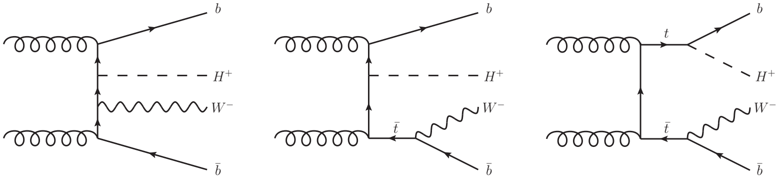
The need for physics Beyond the Standard Model

- Dark matter/energy
- Matter–anti-matter asymmetry
- Quantum theory of gravity
- Neutrino oscillations
- Anomalous muon magnetic dipole moment
- Hierarchy problem
- etc...

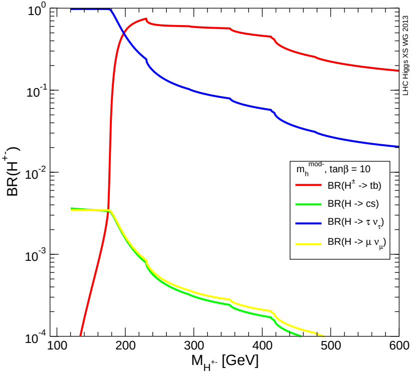
Many models addressing these points add one or several additional Higgs doublets.

- This produces a pair of charged scalar bosons $H^{\pm}$
- As well a neutral scalar pair (h, H) and a neutral pseudo-scalar A
- Some models also produces doubly charged bosons $H^{\pm\pm}$

Here we'll only consider the minimal Type-II Two Higgs Doublet Model (2HDM)



arxiv:1807.07915



- H^+ production/decay depends on
  - $\tan\beta$ (ratio of vevs)
  - α (CP-even mixing angle)
  - m_{H^+}
- Fix α in the alignment limit $\cos(\beta - \alpha) = 0$
- $m_{H^+} < m_t + m_b$: $t \to bH^+$, $H^+ \to \tau\nu$
- $m_{H^+} > m_t + m_b$: $gg \to tbH^+$, $H^+ \to tb$

$$H^+ \longrightarrow \tau\nu$$

arxiv:1807.07915
JHEP 09 (2018) 139

- $36.1\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$ from 2015+2016
- Mass range: 90–2000 GeV (including intermediate mass)
- $H^+ \to \tau\nu$ where $\tau \to \tau_{\text{had-vis}} + \nu$
- Final states based on the W decay mode:
  - τ_{had} + jets ($W \to q\bar{q}'$)
  - τ_{had} + lepton ($W \to \ell\nu$, $\ell = e, \mu$)

τ + jets

- $\geq 1\tau_{\text{had-vis}}$ and no leptons
- ≥ 3 jets ($\geq 1b$-tag)
- $E_{\text{T}}^{\text{miss}} > 150\,\text{GeV}$
- $m_{\text{T}} > 50\,\text{GeV}$

where

$$m_{\text{T}} = \sqrt{2p_{\text{T}}^{\tau}E_{\text{T}}^{\text{miss}}\left(1 - \cos\Delta\phi_{\tau,\text{miss}}\right)}.$$

τ + lepton

- $= 1$ lepton (e/μ, trigger matched)
- $= 1$ $\tau_{\text{had-vis}}$ with opposite sign
- ≥ 1 b-tagged jet
- $E_{\text{T}}^{\text{miss}} > 50\,\text{GeV}$

One additional control region using the τ+lepton selection but with an $e\mu$ pair instead of $\ell\tau$

Multivariate discriminant

- BDTs trained in 5 m_{H^+} bins
- Separate training for jet and lepton final states
- For $m_{H^+} < 500$ GeV the polarization measure Υ is included for 1-prong $\tau_{\text{had-vis}}$ candidates

where $\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^\tau} \approx 2\frac{p_T^{\tau-\text{track}}}{p_T^\tau} - 1.$

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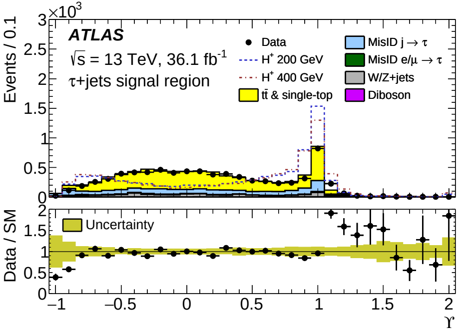


BDT bins

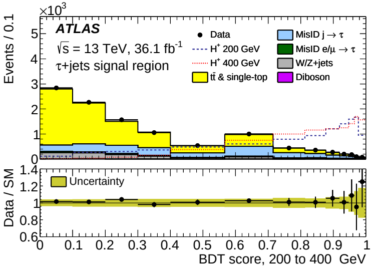
- 90–120 GeV
- 130–160 GeV†
- 160–180 GeV
- 200–400 GeV
- 500–2000 GeV

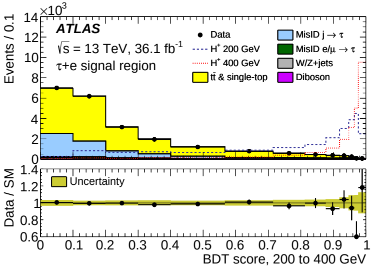
† Using an additional 160 GeV $t \to bH^+$ sample

Binned maximum likelihood fit to extract the signal strength
$\mu = \sigma(pp \to tbH^+) \times \mathcal{B}(H^+ \to \tau\nu)$

- Constrain systematic uncertainties with nuisance parameters θ ($\theta \sim$ Normal or Log-Normal)
- The full binned BDT distributions are used in the three signal regions
- In the $t\bar{t}$-enriched control region only a single bin is used

$$L(\mu, \theta) = \prod_i \prod_j \mathrm{Po}(x_{ij}|\mu, \theta) \prod_k p(\tilde{\theta}_k|\theta_k)$$





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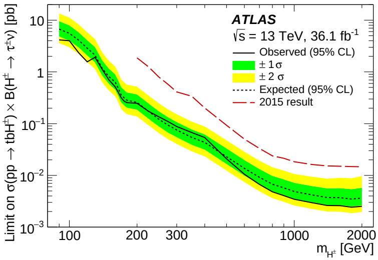

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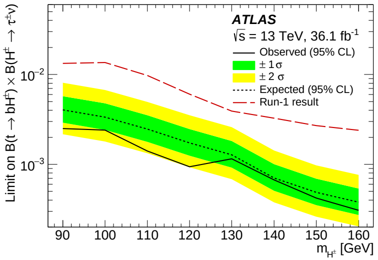

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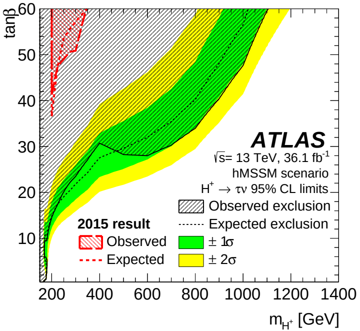


- No significant excess is observed
- Set model independent 95% CL upper limits on
  - $\sigma(pp \to tbH^+) \times \mathcal{B}(H^+ \to \tau\nu)$
  - $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to \tau\nu)$ for low masses
- Limits on $\tan\beta$ vs m_{H^+} in the hMSSM scenario

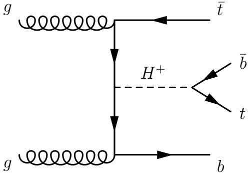
$H^+ \longrightarrow tb$

arxiv:1808.03599

Submitted to JHEP

- 36.1 fb^{-1} at $\sqrt{s}$ = 13 TeV from 2015+2016
- 18 mass points in the range 200–2000 GeV
- Final stated based on W decay modes
  - Single lepton (ℓ+jets), where ℓ can come from either the W from the associated t, or the t from the $H^+ \to tb$ decay.
  - Dilepton ($\ell\ell$), where both Ws in the event decay leptonically

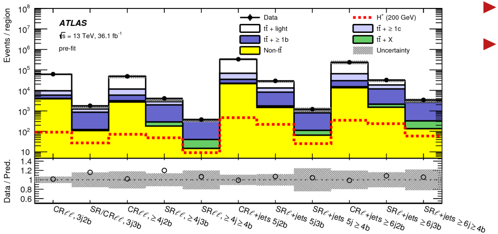
arxiv:1808.03599



ℓ + jets

- At least one lepton (trigger matched)
- $\geq$ 5 jets with $\geq 2b$-tags

arxiv:1808.03599



Dilepton

- At least one lepton (trigger matched)
- One additional lepton with opposite sign
- $\geq$ 3 jets with $\geq 2b$-tags
- Same flavour channel requires $m_{\ell\ell}$ > 15 GeV and $\notin$ [83, 99] GeV

$t\bar{t}+\geq 1b$ background modelling

- Largest irreducible background
- Similar kinematics to the signal for low m_{H^+}
- Divided into subcategories
  - $t\bar{t}+bb$: Exactly two jets matched to b-hadrons
  - $t\bar{t}+b$: Exactly one jet matched to a b-hadron
  - $t\bar{t}+B$: Exactly one jet matched to ≥ 2 b-hadrons
  - $t\bar{t}+\geq 3b$: Other configurations
  - $t\bar{t}+b$ (MPI/FSR): Jets matched to b-hadrons from multi-parton interactions or final-state gluon radiation

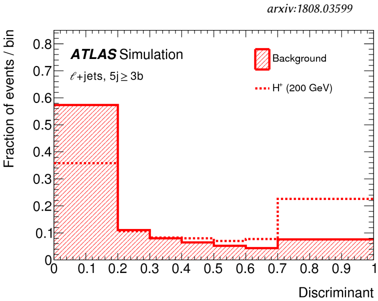
  where the matching is done at particle level
- Reweight the relative normalizations to NLO prediction from Sherpa 2.1.1 + OpenLoops
- Sequential reweighting on the kinematical distributions based on subcategory

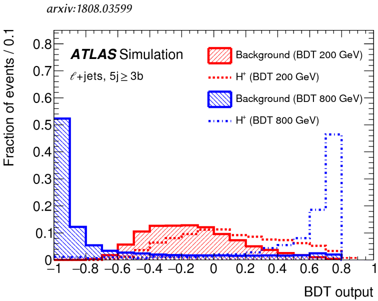
Remaining $t\bar{t}$ events classified as either $t\bar{t}+c$ or $t\bar{t}+$ light.

Multivariate discriminant

- BDTs trained separately for each mass point in each signal region
- In ℓ+jets the $5j3b$ and $5j \geq 4b$ are combined to increase statistics
- ℓ+jets train against all backgrounds
- Dilepton train against only ttbar
- For $m_{H^+} \leq 300$ GeV a kinematic discriminant D is used as an additional input

where D, defined as $D = \frac{P_{H^+}(x)}{P_{H^+}(x)+P_{t\bar{t}}(x)}$, is the probability of an event x being compatible with $H^+ \to tb$ or $t\bar{t}$.





Binned maximum likelihood fit to extract the signal strength $\mu = \sigma(pp \to tbH^+) \times \mathcal{B}(H^+ \to tb)$

- Constrain systematic uncertainties with nuisance parameters θ ($\theta \sim$ Normal or Log-Normal)
- The full binned BDT distributions are used in the signal regions
- Single bin for each control region

$$L(\mu,\theta) = \prod_i \prod_j \mathrm{Po}(x_{ij}|\mu,\theta) \prod_k p(\tilde{\theta}_k|\theta_k)$$

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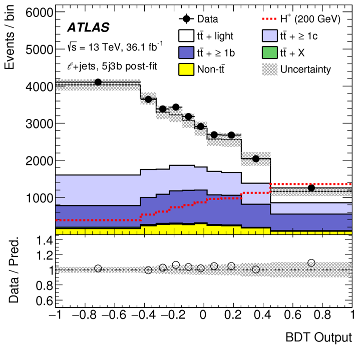

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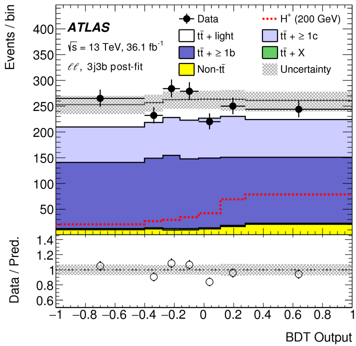

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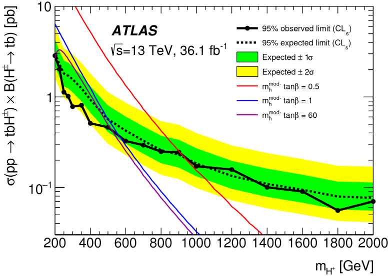

- No significant excess is observed
- Model independent 95% CL upper limits on $\sigma(pp \to tbH^+) \times \mathcal{B}(H^+ \to tb)$
- Upper limits on $\tan\beta$ vs m_{H^+} in the $m_{\mathrm{h}}^{\mathrm{mod-}}$ and hMSSM scenarios

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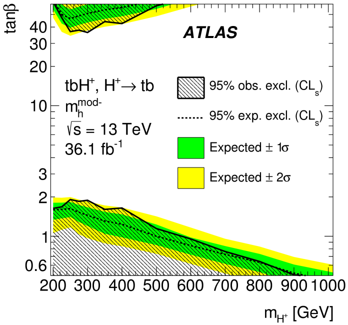

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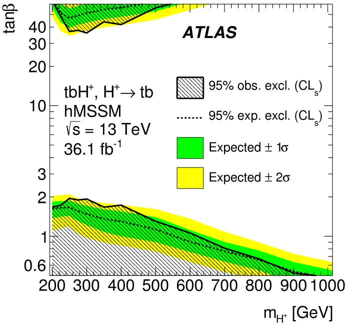
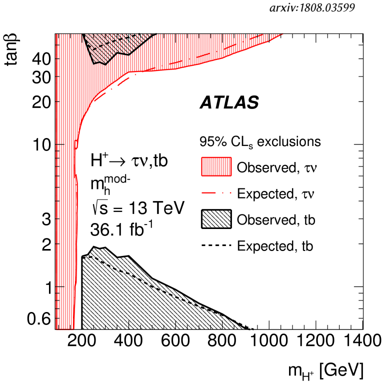
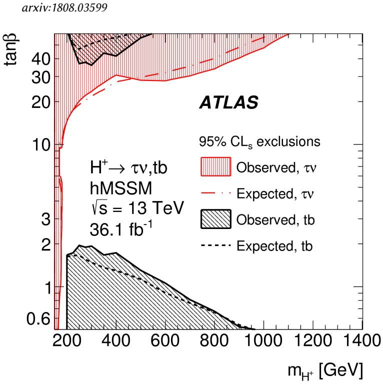




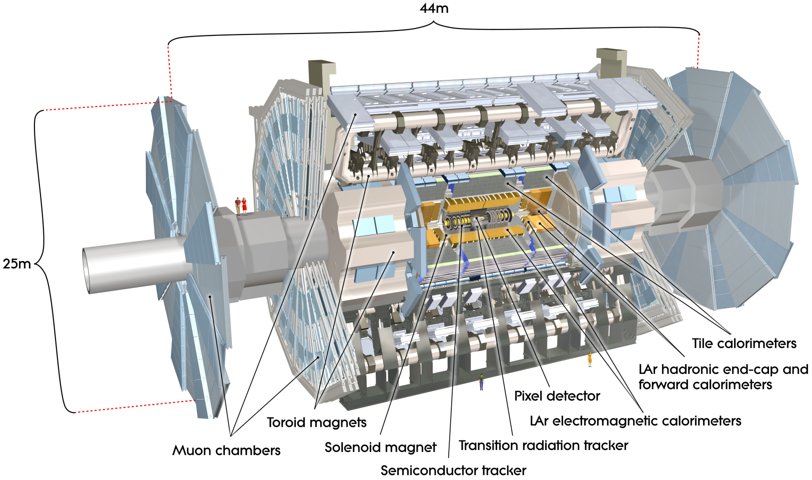


- Projecting the $H^+ \to \tau\nu$ limits together with the $H^+ \to tb$ limits shows the total exclusion in the $m_{H^+} - \tan\beta$ plane using this dataset.

Conclusions

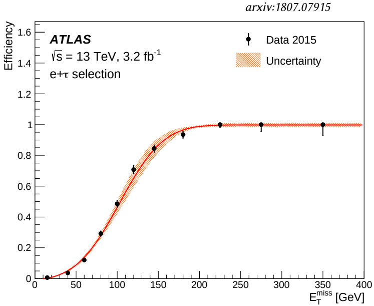
- No significant excess has been seen in either channel
- Model independent upper limits on $\sigma \times \mathcal{B}$ has been set
- Exclusion limits in the $m_{H^+} - \tan\beta$ plane has been set for the $m_{\mathrm{h}}^{\mathrm{mod-}}$ and hMSSM scenarios

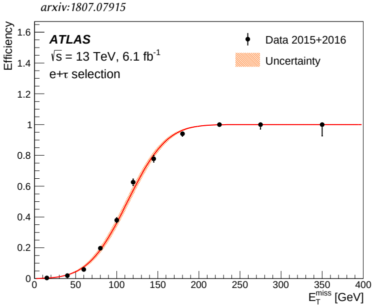
Backup

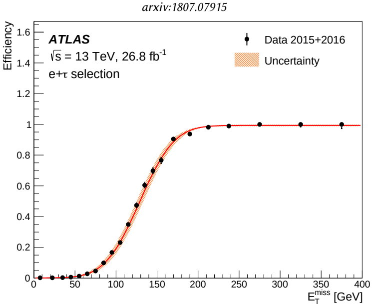


https://cds.cern.ch/record/1095924

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







Turn on curves for the E_T^{miss} trigger at 70, 90, and 110 GeV.

Fake factors

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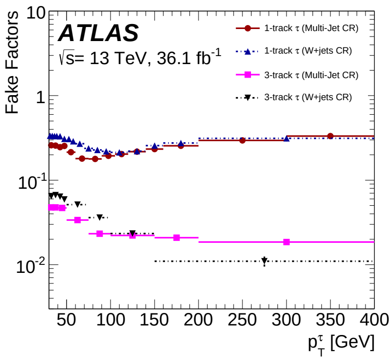

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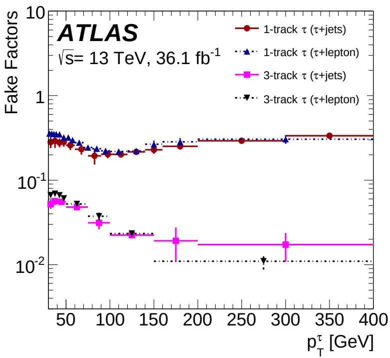

$$FF = \frac{N^{\mathrm{CR}}_{\tau_{\mathrm{had-vis}}}}{N^{\mathrm{CR}}_{\mathrm{anti-}\tau_{\mathrm{had-vis}}}}$$

Background modelling I

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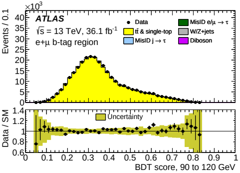

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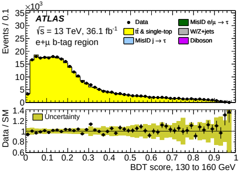

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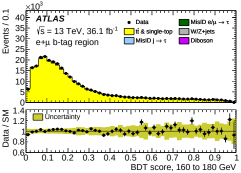

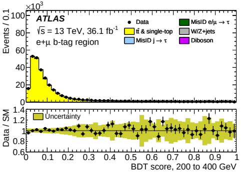

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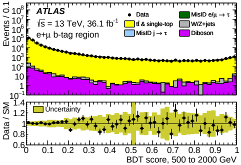

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Background modelling II

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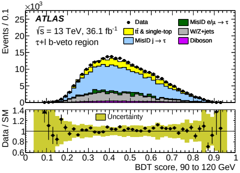

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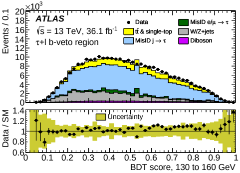

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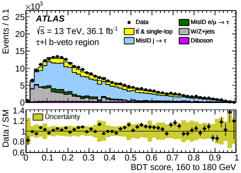

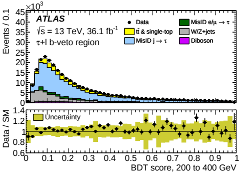

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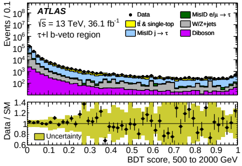

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BDT input variables

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

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Expected event yields

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Sample	Event yields $\tau_{\text{had-vis}}$+jets		
True τ_{had}			
$t\bar{t}$	6900	$\pm$ 60	$\pm$ 1800
Single-top-quark	750	$\pm$ 20	$\pm$ 100
$W \to \tau\nu$	1050	$\pm$ 30	$\pm$ 180
$Z \to \tau\tau$	84	$\pm$ 42	$\pm$ 28
Diboson (WW, WZ, ZZ)	63.2	$\pm$ 4.6	$\pm$ 7.2
Misidentified e, $\mu \to \tau_{\text{had-vis}}$	265	$\pm$ 12	$\pm$ 35
Misidentified jet $\to \tau_{\text{had-vis}}$	2370	$\pm$ 20	$\pm$ 260
All backgrounds	11500	$\pm$ 80	$\pm$ 1800
H^+ (170 GeV), hMSSM $\tan\beta = 40$	1400	$\pm$ 10	$\pm$ 170
H^+ (1000 GeV), hMSSM $\tan\beta = 40$	10.33	$\pm$ 0.06	$\pm$ 0.78
Data	11021		

Sample	Event yields $\tau_{\text{had-vis}}$+electron			Event yields $\tau_{\text{had-vis}}$+muon		
True τ_{had}						
$t\bar{t}$	16000	$\pm$ 80	$\pm$ 2500	14600	$\pm$ 80	$\pm$ 2400
Single-top-quark	1260	$\pm$ 20	$\pm$ 110	1260	$\pm$ 20	$\pm$ 110
$Z \to \tau\tau$	433	$\pm$ 27	$\pm$ 80	352	$\pm$ 48	$\pm$ 43
Diboson (WW, WZ, ZZ)	39.3	$\pm$ 2.1	$\pm$ 4.5	32.3	$\pm$ 1.7	$\pm$ 3.6
Misidentified e, $\mu \to \tau_{\text{had-vis}}$	626	$\pm$ 27	$\pm$ 59	454	$\pm$ 16	$\pm$ 27
Misidentified jet $\to \tau_{\text{had-vis}}$	5640	$\pm$ 40	$\pm$ 450	5460	$\pm$ 40	$\pm$ 410
All backgrounds	24000	$\pm$ 100	$\pm$ 2600	22200	$\pm$ 100	$\pm$ 2500
H^+ (170 GeV), hMSSM $\tan\beta = 40$	850	$\pm$ 12	$\pm$ 65	852	$\pm$ 11	$\pm$ 66
H^+ (1000 GeV), hMSSM $\tan\beta = 40$	0.82	$\pm$ 0.02	$\pm$ 0.07	1.05	$\pm$ 0.02	$\pm$ 0.09
Data	22645			21419		

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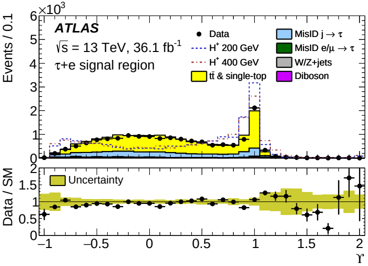

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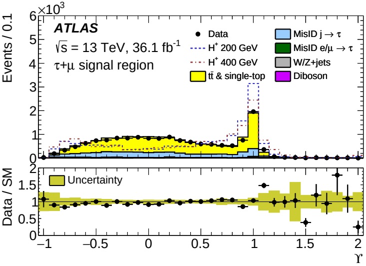

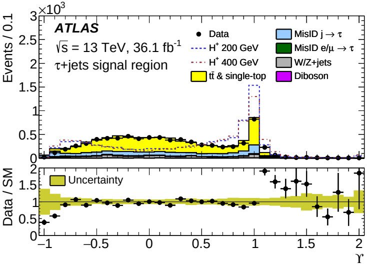

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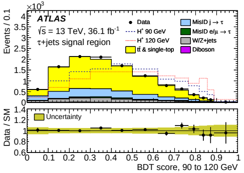
Post-fit plots I

arxiv:1807.07915



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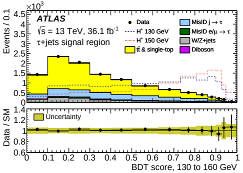

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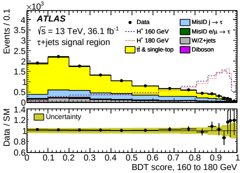

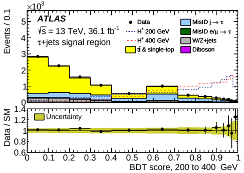

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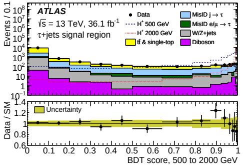

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Post-fit plots II

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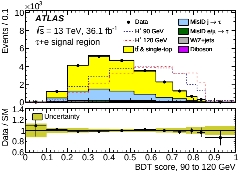

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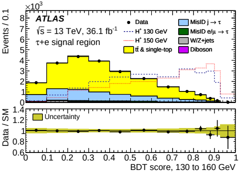

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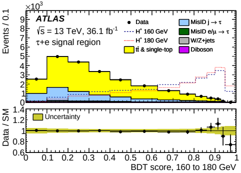

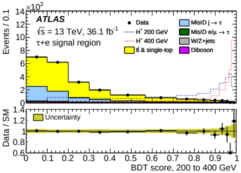

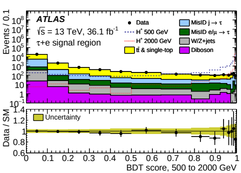

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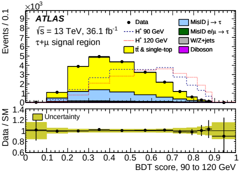
Post-fit plots III

arxiv:1807.07915



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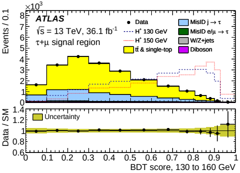

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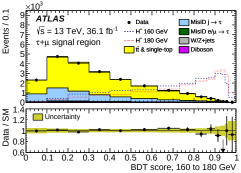

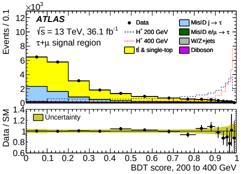

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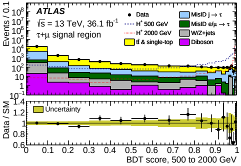


arxiv:1807.07915

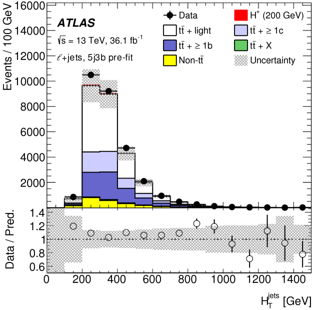
Systematic uncertainties

Source of systematic uncertainty	Impact on the expected limit (stat. only) in %	
	$m_{H^+} = 170$ GeV	$m_{H^+} = 1000$ GeV
Experimental		
luminosity	2.9	0.2
trigger	1.3	<0.1
$\tau_{\text{had-vis}}$	14.6	0.3
jet	16.9	0.2
electron	10.1	0.1
muon	1.1	<0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	9.9	<0.1
Fake-factor method	20.3	2.7
Υ modelling	0.8	–
Signal and background models		
$t\bar{t}$ modelling	6.3	0.1
W/Z+jets modelling	1.1	<0.1
cross-sections ($W/Z/VV/t$)	9.6	0.4
H^+ signal modelling	2.5	6.4
All	52.1	13.8

arxiv:1807.07915

$H^+ \to tb$ material

arxiv:1808.03599



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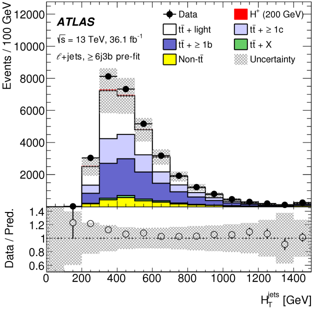

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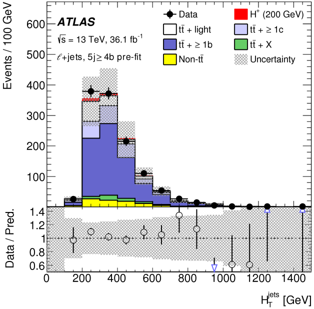

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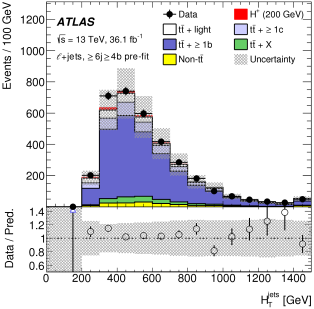

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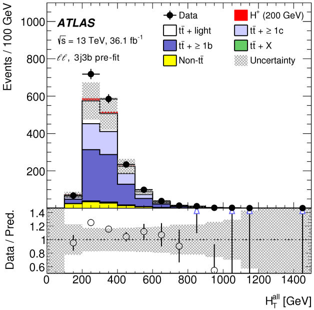

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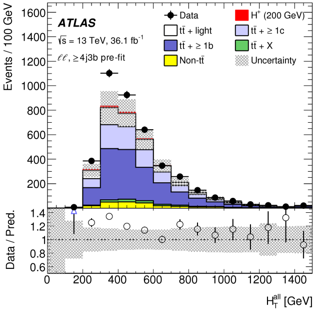

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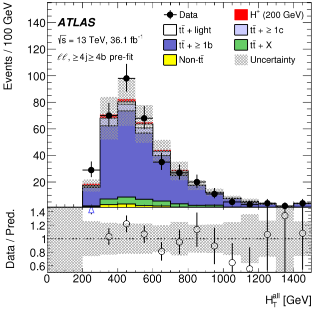

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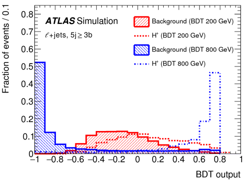

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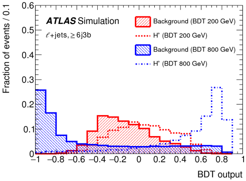

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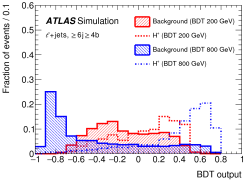

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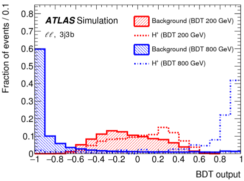

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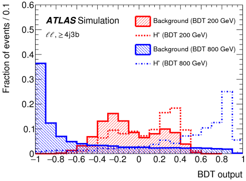

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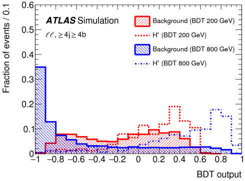

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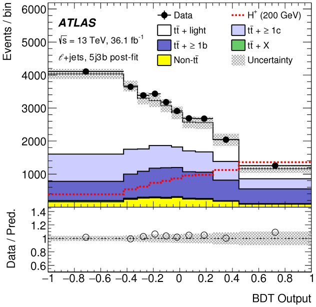

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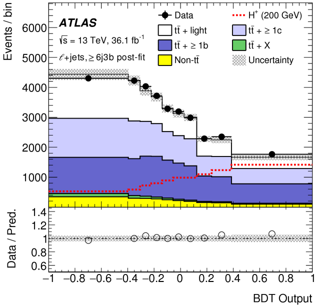

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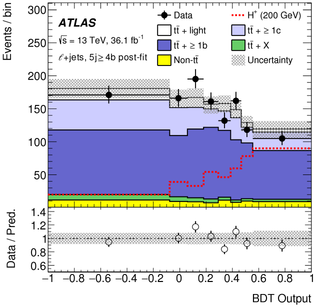

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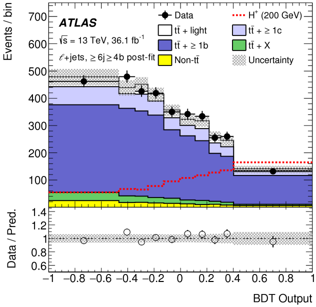

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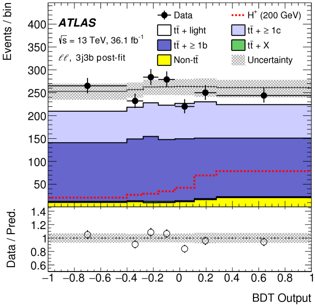

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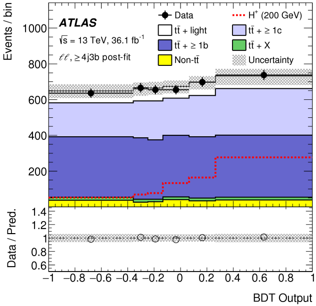

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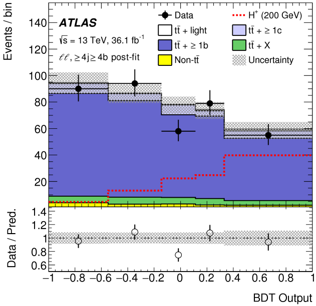

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Physics process	Generator	Parton shower generator	Cross-section normalisation	PDF set	Tune
tbH^+	MG5_aMC	Pythia 8.186	–	NNPDF2.3NLO	A14
$t\bar{t}$ + jets	Powheg-Box v2	Pythia 8.210	NNLO+NNLL	NNPDF3.0NLO	A14
$t\bar{t}b\bar{b}$	Sherpa 2.1.1	Sherpa 2.1.1	NLO for $t\bar{t}b\bar{b}$	CT10F4	Sherpa default
$t\bar{t}V$	MG5_aMC	Pythia 8.210	NLO	NNPDF3.0	A14
$t\bar{t}H$	MG5_aMC	Pythia 8.210	NLO	NNPDF3.0NLO	A14
Single top, Wt	Powheg-Box v1	Pythia 6.428	aNNLO	CT10	Perugia 2012
Single top, t-channel	Powheg-Box v1	Pythia 6.428	aNNLO	CT10F4	Perugia 2012
W+jets	Sherpa 2.2.1	Sherpa 2.2.1	NNLO	NNPDF3.0NNLO	Sherpa default
Z+jets	Sherpa 2.2.1	Sherpa 2.2.1	NNLO	NNPDF3.0NNLO	Sherpa default

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Systematic uncertainty	Type	Number of components
Luminosity	N	1
Pile-up	NS	1
Electron reconstruction	NS	6
Muon reconstruction	NS	13
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	NS	28
Flavour tagging, 70% efficiency calibration (*)	NS	27
Flavour tagging, step-wise efficiency calibration (*)	NS	126
Signal modelling	NS	31
Background modelling, $t\bar{t}$ + jets	NS	29
Background modelling, other top	NS	25
Background modelling, non-top (ℓ+jets final state)	N	13
Background modelling, non-top ($\ell\ell$ final state)	N	4

Post-fit event yields

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Process	CR 5j2b	SR 5j3b	SR 5j≥4b	CR ≥6j2b	SR ≥6j3b	SR ≥6j≥4b
$t\bar{t}+\geq 1b$	$15\ 300 \pm 2300$	7400 ± 1000	750 ± 110	17100 ± 2800	$11\ 100 \pm 1500$	2410 ± 260
$t\bar{t}+\geq 1c$	$47\ 000 \pm 12\ 000$	6400 ± 1700	260 ± 80	$55\ 000 \pm 11\ 000$	9400 ± 2000	450 ± 180
$t\bar{t}$ + light	$226\ 000 \pm 11\ 000$	$12\ 200 \pm 1100$	89 ± 35	$132\ 000 \pm 10\ 000$	8500 ± 1100	260 ± 120
Non-prompt leptons	$15\ 000 \pm 6000$	600 ± 500	11 ± 8	$13\ 000 \pm 6000$	700 ± 400	4 ± 5
$t\bar{t}W$	340 ± 50	29 ± 4	0.66 ± 0.22	540 ± 80	72 ± 11	5.0 ± 1.2
$t\bar{t}Z$	390 ± 50	78 ± 10	12.2 ± 2.2	720 ± 90	183 ± 23	50 ± 7
Single top Wt	8900 ± 2400	690 ± 210	23 ± 13	5400 ± 1800	640 ± 260	53 ± 31
Other top	328 ± 27	28.2 ± 2.6	3.1 ± 0.6	183 ± 20	46 ± 11	14 ± 5
Diboson	410 ± 210	29 ± 15	2.0 ± 2.1	340 ± 170	37 ± 19	4.3 ± 2.5
W + jets	9000 ± 4000	540 ± 240	16 ± 9	5200 ± 2100	470 ± 200	27 ± 12
Z + jets	2100 ± 600	104 ± 35	4.9 ± 1.8	1300 ± 400	130 ± 40	11 ± 4
$t\bar{t}H$	252 ± 24	127 ± 13	30 ± 4	520 ± 50	315 ± 32	117 ± 16
tH	19.5 ± 2.4	10.6 ± 1.3	2.21 ± 0.32	27.2 ± 3.5	15.7 ± 2.0	5.0 ± 0.7
Total	$328\ 000 \pm 7000$	$28\ 400 \pm 900$	1220 ± 60	$233\ 000 \pm 6000$	$31\ 800 \pm 800$	3410 ± 150
Data	334 813	29 322	1210	234 053	32 151	3459
H^+ (200 GeV)	470 ± 50	220 ± 23	25.3 ± 3.3	340 ± 50	235 ± 34	60 ± 9
H^+ (800 GeV)	630 ± 90	390 ± 70	56 ± 12	1230 ± 190	1020 ± 170	350 ± 70

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Process	CR 3j2b	SR/CR 3j3b	CR ≥4j2b	SR ≥4j3b	SR ≥4j≥4b
$t\bar{t}+\geq 1b$	2330 ± 330	940 ± 130	3300 ± 500	2050 ± 280	322 ± 35
$t\bar{t}+\geq 1c$	6100 ± 1300	520 ± 140	9900 ± 2000	1310 ± 290	30 ± 14
$t\bar{t}$ + light	$50\ 700 \pm 2300$	260 ± 70	$32\ 500 \pm 2100$	420 ± 120	4 ± 5
Non-prompt leptons	420 ± 110	6.7 ± 2.4	620 ± 160	48 ± 13	2.2 ± 0.8
$t\bar{t}W$	48 ± 7	1.48 ± 0.17	129 ± 7	9.8 ± 1.1	0.55 ± 0.21
$t\bar{t}Z$	43 ± 5	5.8 ± 1.1	174 ± 10	32.9 ± 2.0	7.0 ± 1.3
Single top Wt	1700 ± 500	40 ± 12	1110 ± 330	63 ± 26	3.9 ± 2.0
Other top	3.9 ± 0.5	0.12 ± 0.05	21.8 ± 3.5	5.8 ± 2.2	2.0 ± 0.9
Diboson	36 ± 4	1.2 ± 0.4	46 ± 6	3.1 ± 0.9	0.48 ± 0.28
Z + jets	1600 ± 500	42 ± 16	1300 ± 400	82 ± 29	5.3 ± 2.0
$t\bar{t}H$	26.2 ± 1.3	8.5 ± 0.5	116 ± 6	52.2 ± 3.5	16.0 ± 1.9
tH	1.95 ± 0.27	0.42 ± 0.10	5.7 ± 0.7	2.14 ± 0.32	0.48 ± 0.09
Total	$62\ 800 \pm 2800$	1810 ± 110	$49\ 300 \pm 2300$	4060 ± 200	390 ± 28
Data	62 399	1774	48 356	4047	376
H^+ (200 GeV)	92 ± 12	27 ± 4	72 ± 12	49 ± 8	9.0 ± 1.6
H^+ (800 GeV)	70 ± 12	32 ± 7	212 ± 33	157 ± 27	44 ± 9

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Uncertainty Source	$\Delta\mu(H^+_{200})$ [pb]	$\Delta\mu(H^+_{800})$ [pb]
Jet flavour tagging	0.70	0.050
$t\bar{t}+\geq 1b$ modelling	0.65	0.008
Jet energy scale and resolution	0.44	0.031
$t\bar{t}$+light modelling	0.44	0.019
MC statistics	0.37	0.044
$t\bar{t}+\geq 1c$ modelling	0.36	0.032
Other background modelling	0.36	0.039
Luminosity	0.24	0.010
Jet-vertex assoc., pile-up modelling	0.10	0.006
Lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, ID, isol., trigger	0.08	0.003
H^+ modelling	0.03	0.006
Total systematic uncertainty	1.4	0.11
$t\bar{t}+\geq 1b$ normalisation	0.61	0.022
$t\bar{t}+\geq 1c$ normalisation	0.28	0.012
Total statistical uncertainty	0.69	0.050
Total uncertainty	1.5	0.12

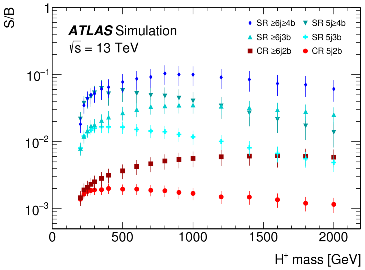
ℓ+jets channel	
$p_{\mathrm{T}}(j_1)$	Leading jet transverse momentum
$m(b\text{-pair}^{\Delta R^{\min}})$	Invariant mass of pair of b-tagged jets with smallest ΔR
$p_{\mathrm{T}}(j_5)$	Transverse momentum of fifth jet
H_2	Second Fox–Wolfram moment [130] calculated using all jets and leptons
$\Delta R^{\mathrm{avg}}(b\text{-pair})$	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
$H_{\mathrm{T}}^{\mathrm{jets}}$	Scalar sum of all jets transverse momenta
$m(b\text{-pair}^{p_{\mathrm{T}}^{\max}})$	Invariant mass of the b-tagged jet pair with maximum transverse momentum
$m^{\max}(b\text{-pair})$	Largest invariant mass of any two b-tagged jets
$m^{\max}(j\text{-triplet})$	Largest invariant mass of any three jets
D	Kinematic discriminant based on mass templates (for $m_{H^+} \leq 300\,GeV$)

$\ell\ell$ channel, $m \leq 600\,GeV$		3j3b	≥4j3b	≥4j≥4b
$m((j,b)^{p_{\mathrm{T}}^{\max}})$	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	✓		
$\Delta m(j_1 + j_2, j_1 + j_3 + \ell_2 + E_{\mathrm{T}}^{\mathrm{miss}})$	Inv. mass difference between $j_1 + j_2$ and $j_1 + j_3 + \ell_2 + E_{\mathrm{T}}^{\mathrm{miss}}$	✓		
$\Delta R(j_2, j_1 + \ell_2 + E_{\mathrm{T}}^{\mathrm{miss}})$	Angular difference between subleading jet and $j_1 + \ell_2 + E_{\mathrm{T}}^{\mathrm{miss}}$	✓		
$p_{\mathrm{T}}(b_1)$	p_{T} of leading b-tagged jet	✓		
$p_{\mathrm{T}}((\ell,b)^{\Delta\eta^{\max}})$	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 $\Delta\phi$		✓	
$\Delta E(b_1, \ell_1 + E_{\mathrm{T}}^{\mathrm{miss}})$	Energy difference between the leading b-tagged jet and $\ell_1 + E_{\mathrm{T}}^{\mathrm{miss}}$		✓	
$\Delta m(j_2 + j_3, j_1 + \ell_1 + \ell_2)$	Inv. mass difference between $j_2 + j_3$ and $j_1 + \ell_1 + \ell_2$		✓	
$\Delta m(\ell_1 + j_3 + E_{\mathrm{T}}^{\mathrm{miss}}, j_1 + j_2 + \ell_2)$	Inv. mass difference between $\ell_1 + j_3 + E_{\mathrm{T}}^{\mathrm{miss}}$ and $j_1 + j_2 + \ell_2$		✓	
$\Delta p_{\mathrm{T}}(j_1, j_3)$	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		✓	✓
$p_{\mathrm{T}}(b_2 + \ell_1 + \ell_2 + E_{\mathrm{T}}^{\mathrm{miss}})$	p_{T} of $b_2 + \ell_1 + \ell_2 + E_{\mathrm{T}}^{\mathrm{miss}}$			✓
$\Delta R(\ell_2, j_2 + j_3 + \ell_1 + E_{\mathrm{T}}^{\mathrm{miss}})$	Angular difference between ℓ_2 and $j_2 + j_3 + \ell_1 + E_{\mathrm{T}}^{\mathrm{miss}}$			✓
$H_{\mathrm{T}}^{\mathrm{all}}$	Scalar sum of all jets and leptons transverse energy			✓

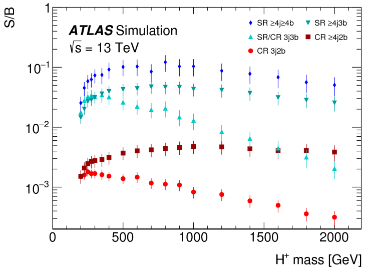
$\ell\ell$ channel, $m > 600\,GeV$		3j3b	≥4j3b	≥4j≥4b
$p_{\mathrm{T}}((\ell,b)^{\Delta\eta^{\min}})$	p_{T} of the pair of lepton and b-tagged jet with smallest $\Delta\eta$	✓		✓
$\Delta p_{\mathrm{T}}(j_1, j_3)$	p_{T} difference between leading and third jets	✓		✓
$\Delta m(j_2 + \ell_1 + E_{\mathrm{T}}^{\mathrm{miss}},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

Signal-over-background

arxiv:1808.03599

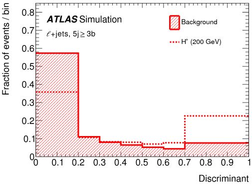


arxiv:1808.03599

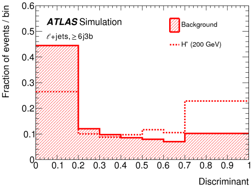


Kinematic discriminant

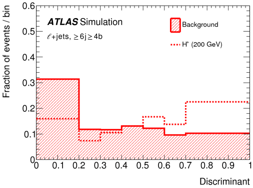
arxiv:1808.03599



arxiv:1808.03599



arxiv:1808.03599

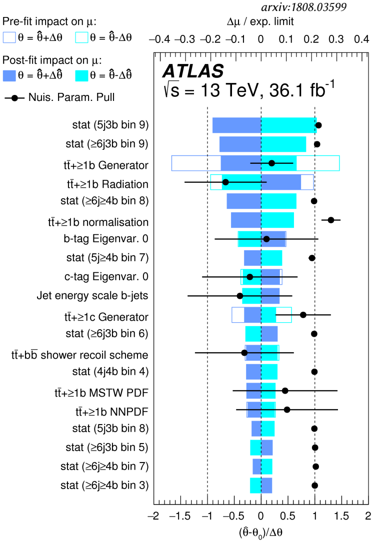


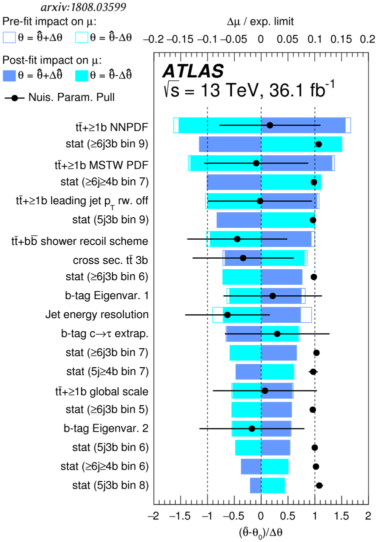
$$D = \frac{P_{H^+}(x)}{P_{H^+}(x) + P_{t\bar{t}}(x)}$$

where

$$P_{H^+}(x) = p(m_{t_\ell})p(m_{W_h})p(m_{t_h} - m_{W_h})p(m_{H^+} - m_{t_{H^+}})$$

and $P_{t\bar{t}}(x)$ is defined similarly. All masses refer to the reconstructed ones and the neutrino is reconstructed from the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the constraint $m_W^2 = (p_\ell^2 + p_\nu)^2$.


arxiv:1808.03599
Pre-fit impact on μ:
θ = θ̂+Δθ
θ = θ̂-Δθ
Post-fit impact on μ:
θ = θ̂+Δθ̂
θ = θ̂-Δθ̂
Nuis. Param. Pull
Δμ / exp. limit
ATLAS
√s = 13 TeV, 36.1 fb-1
stat (5j3b bin 9)
stat (≥6j3b bin 9)
tt̄+≥1b Generator
tt̄+≥1b Radiation
stat (≥6j≥4b bin 8)
tt̄+≥1b normalisation
b-tag Eigenvar. 0
stat (5j≥4b bin 7)
c-tag Eigenvar. 0
Jet energy scale b-jets
tt̄+≥1c Generator
stat (≥6j3b bin 6)
tt̄+bb̄ shower recoil scheme
stat (4j4b bin 4)
tt̄+≥1b MSTW PDF
tt̄+≥1b NNPDF
stat (5j3b bin 8)
stat (≥6j3b bin 5)
stat (≥6j≥4b bin 7)
stat (≥6j≥4b bin 3)
(θ̂-θ0)/Δθ


arxiv:1808.03599
Pre-fit impact on μ:
θ = θ̂+Δθ
θ = θ̂-Δθ
Post-fit impact on μ:
θ = θ̂+Δθ̂
θ = θ̂-Δθ̂
Nuis. Param. Pull
Δμ / exp. limit
ATLAS
√s = 13 TeV, 36.1 fb-1
tt̄+≥1b NNPDF
stat (≥6j3b bin 9)
tt̄+≥1b MSTW PDF
stat (≥6j≥4b bin 7)
tt̄+≥1b leading jet pT rw. off
stat (5j3b bin 9)
tt̄+bb̄ shower recoil scheme
cross sec. tt̄ 3b
stat (≥6j3b bin 6)
b-tag Eigenvar. 1
Jet energy resolution
b-tag c→τ extrap.
stat (≥6j3b bin 7)
stat (5j≥4b bin 7)
tt̄+≥1b global scale
stat (≥6j3b bin 5)
b-tag Eigenvar. 2
stat (5j3b bin 6)
stat (≥6j≥4b bin 6)
stat (5j3b bin 8)
(θ̂-θ0)/Δθ