Charged Higgs boson searches with the ATLAS detector

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on behalf of the ATLAS collaboration

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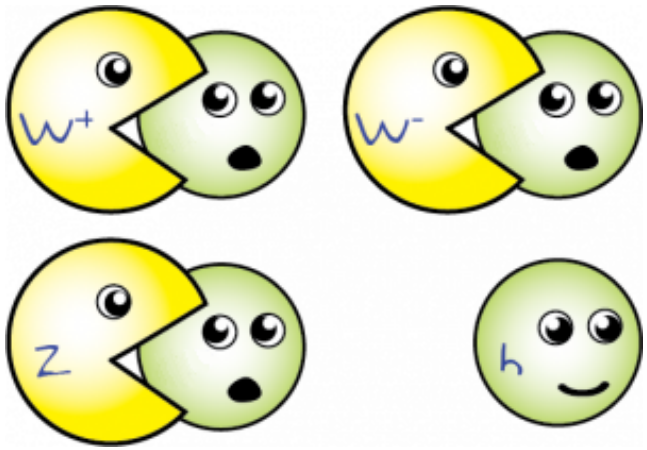
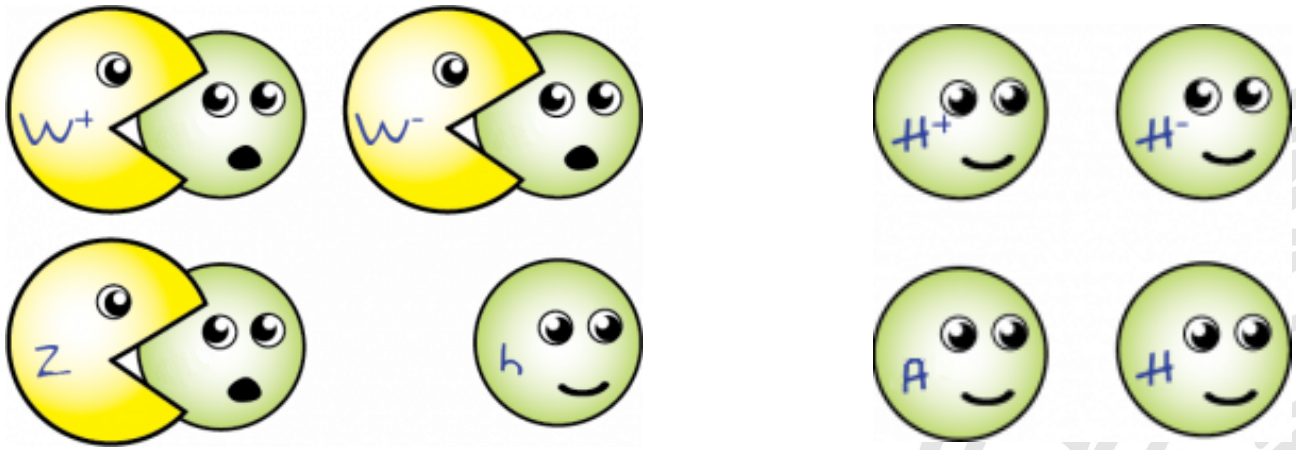
Introduction

After the discovery of **a** Higgs boson at 125 GeV, a major question is whether this is **the** scalar particle predicted by the Standard Model to break the electroweak symmetry...



Introduction

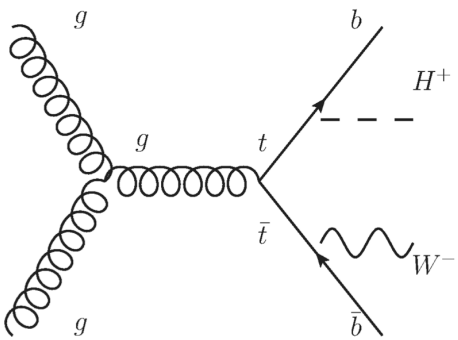
After the discovery of **a** Higgs boson at 125 GeV, a major question is whether this is **the** scalar particle predicted by the Standard Model to break the electroweak symmetry... or is it the first state of an extended Higgs sector?



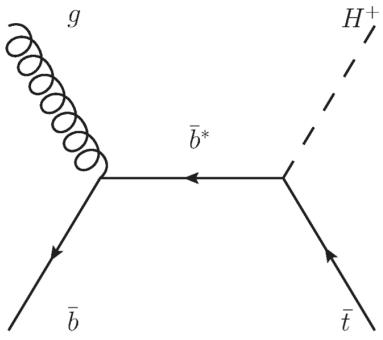
Several BSM models predict an extended scalar sector, e.g. with two Higgs doublets (2HDM) or Higgs triplets, all containing charged Higgs bosons.

Introduction

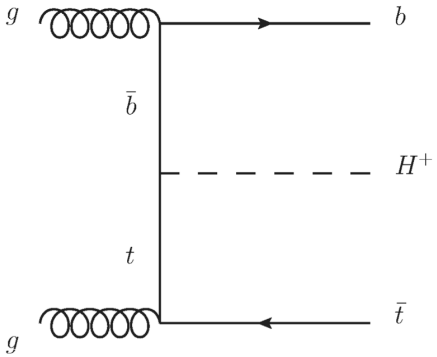
Charged Higgs bosons are primarily produced in decays of (low-mass) or in association with (high-mass) a top quark:



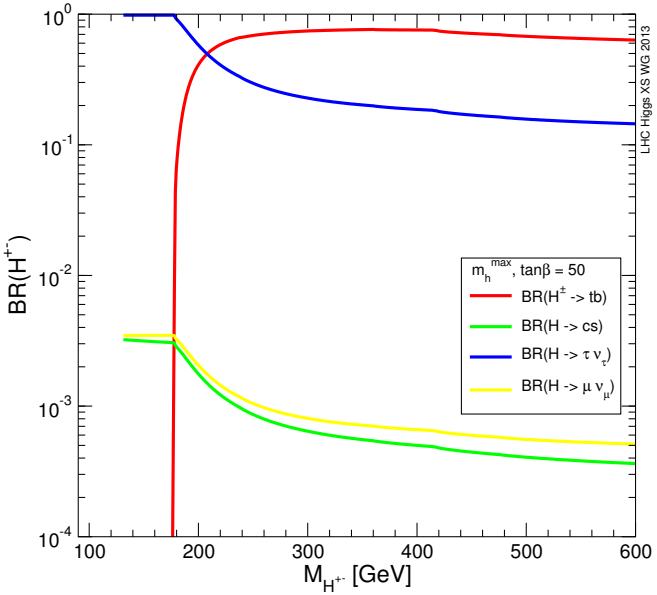
$m_{H^+} < m_{\text{top}}$



$m_{H^+} > m_{\text{top}}$, 5FS



$m_{H^+} > m_{\text{top}}$, 4FS



Short theory overview

- MSSM = type-II 2HDM;
- Tree-level charged Higgs sector determined by m_A and tan β;
- Several benchmark scenarios at NLO: m_h^{max}, $m_h^{\text{mod}\pm}$, hMSSM...
- $H^+ \to \tau\nu$ and tb dominate.

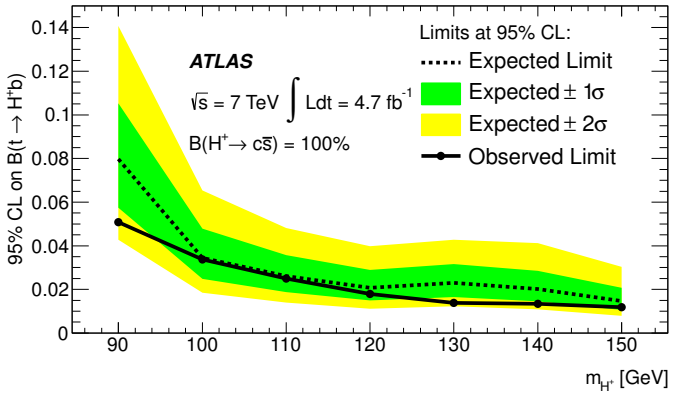
Outline

1. Run-1 legacy
2. Run-2 searches
   - $H^+ \to \tau\nu$
   - $H^+ \to tb$

Run-1 low-mass H^+ searches

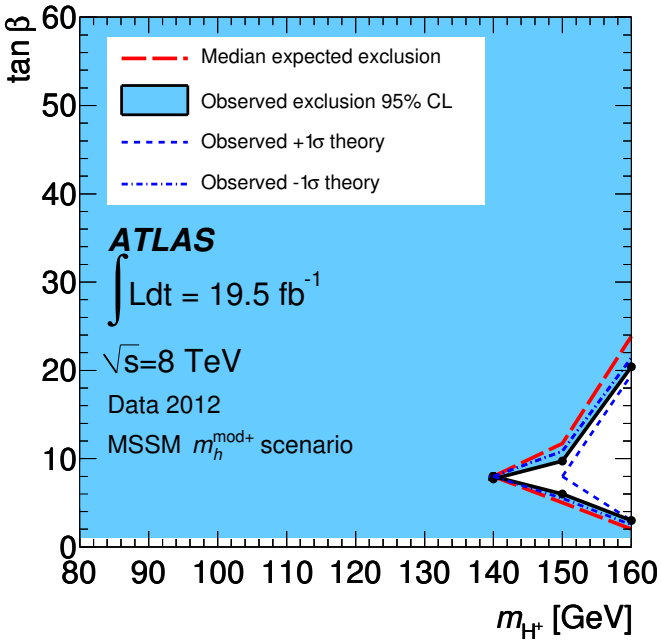
$H^+ \to cs$

- Search in lepton+jets $t\bar{t}$ events (7 TeV, 4.7/fb);
- 95% C.L limits on Br($t \to bH^+$) in the range 1-5%, assuming that Br($H^+ \to cs$) = 100%;
- Eur. Phys. J. C, 73 6 (2013) 2465.



$H^+ \to \tau\nu$

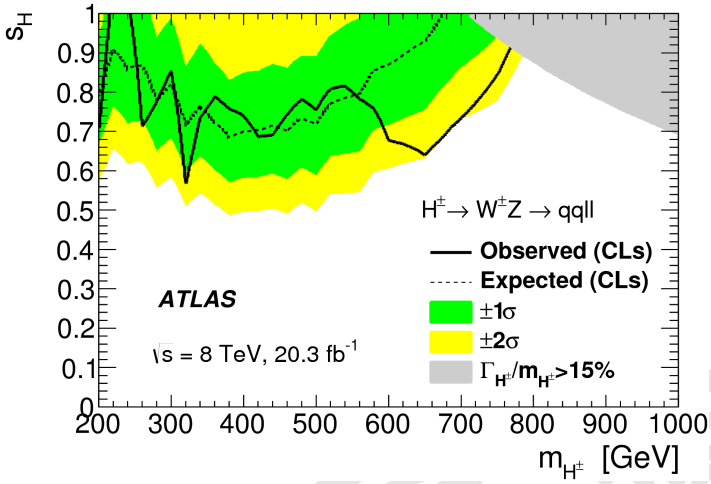
- Most sensitive search in τ_{had}+jets $t\bar{t}$ events (8 TeV, 19.5/fb);
- 95% C.L limits on Br($t \to bH^+$) in the range 0.2-1.3%, assuming that Br($H^+ \to \tau\nu$) = 100%;
- Low-mass MSSM parameter space(s) almost excluded;
- JHEP03 (2015) 088.



Run-1 high-mass H^+ searches

VBF $H^+ \to WZ \to qq\ell\ell$ events (8 TeV, 20.3/fb)

- 95% C.L limits in the range 31-1020 fb for $200 \leq m_{H^+}$ (GeV) ≤ 1000;
- Interpretation: Georgi-Machacek Higgs Triplet Model;
- Phys. Rev. Lett. 114, 231801 (2015).



Top-quark associated $H^+ \to \tau\nu$ and tb searches (8 TeV, 19.5-20.3/fb)

- Analysis strategies similar to Run-2 searches (see upcoming slides);
- $H^+ \to \tau\nu$: 95% C.L limits of 4.5-760 fb for $180 \leq m_{H^+}$ (GeV) ≤ 1000 [JHEP03 (2015) 088];
- $H^+ \to tb$: broad excess of $\simeq 2\sigma$ in the range $200 \leq m_{H^+}$ (GeV) ≤ 600, however not compatible with signal [JHEP03 (2016) 127].

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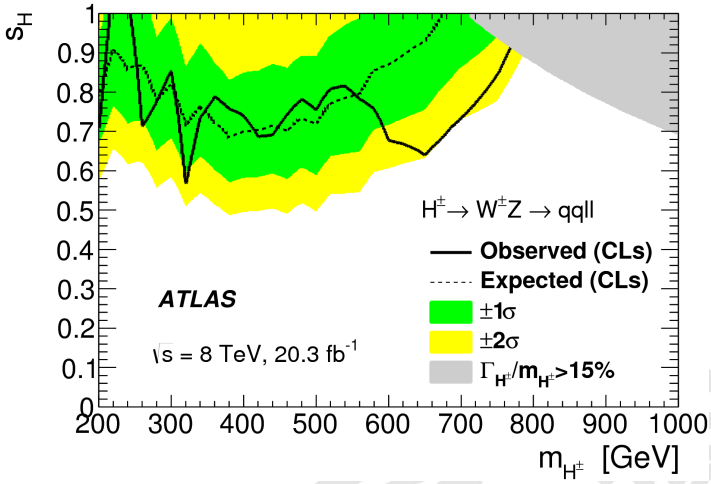

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Physics objects

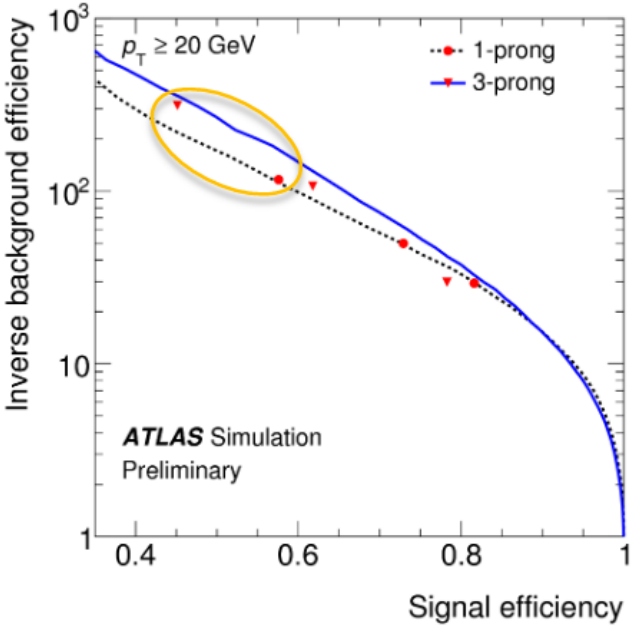
H^+ searches rely on excellent τ- and b-jet identification. Both use anti-k_t jets with $R = 0.4$ as seeds.

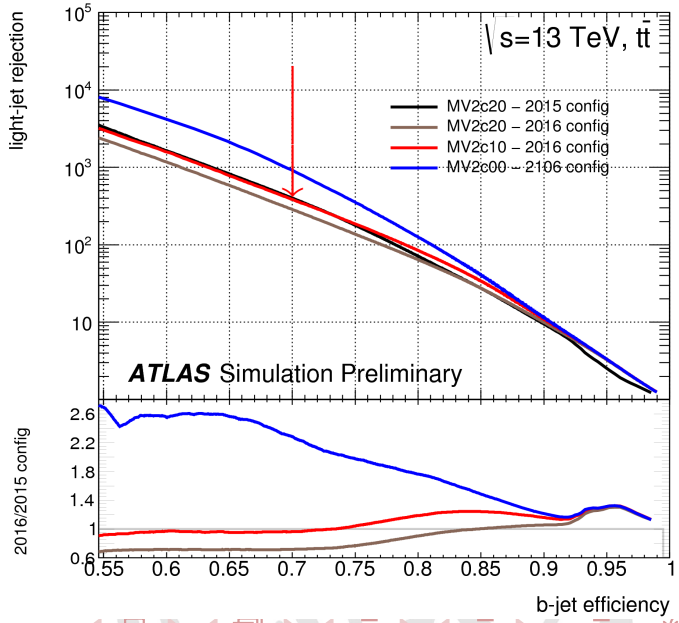
τ objects

- One or three prongs, narrow jet with an isolation annulus of $\Delta R = 0.2$;
- BDT-based ID: $\varepsilon = 55/40\%$ and jet rejection of $\mathcal{O}(10^2)$ for 1/3-prong taus.

b-tagged jets

- Impact parameters + secondary and tertiary vertices used for b-tagging;
- MVA-based ID: $\varepsilon = 70\%$ and c- or light-jet rejection of 10/400.





$H^+ \to \tau\nu$: event selection

Selection of $pp \to [b]tH^+ \to [b](bjj)(\tau_{\text{had}}\nu)$ topologies

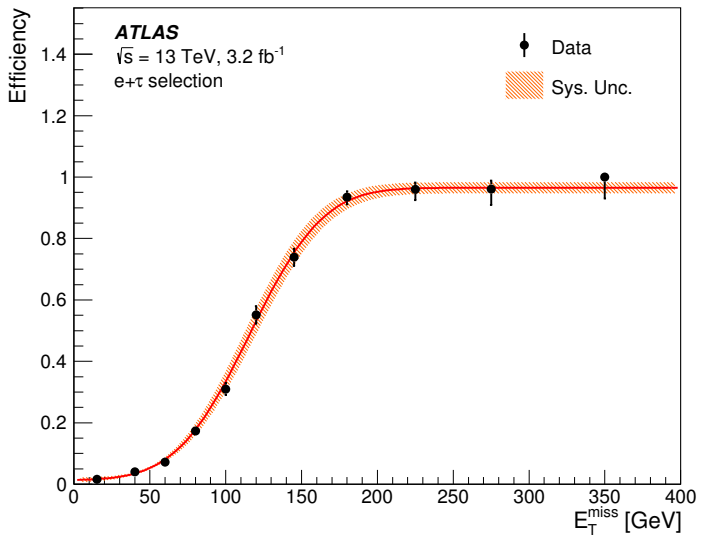
1) E_T^{miss} trigger: the efficiency is measured in data and then applied to simulated events.

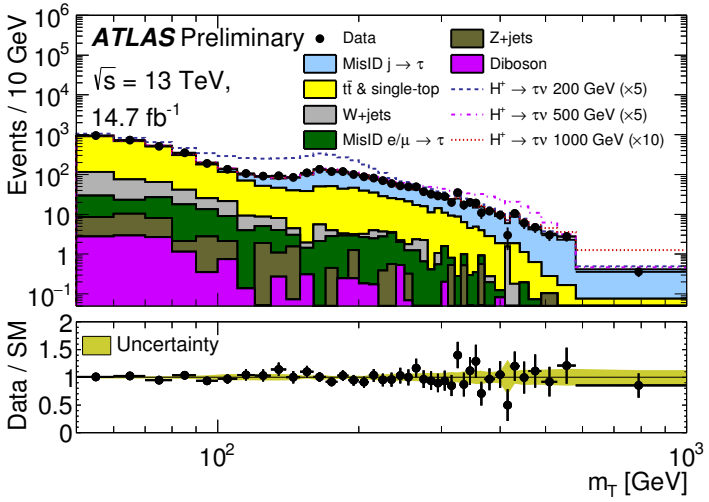
2) Select events with hadronic τ and top-quark decays:

- One τ object with $p_T^\tau > 40$ GeV,
- $\geq$3 jets with $p_T > 25$ GeV, including $\geq$1 b-tag,
- Electron and muon veto,
- $E_T^{\text{miss}} > 150$ GeV.

3) Select events with the discriminant $m_T > 50$ GeV:

$$m_T = \sqrt{2 p_T^\tau E_T^{\text{miss}} \cos \Delta\phi_{\tau,\text{miss}}}$$





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

- Backgrounds with a true τ: simulation, with rescaling (validation) in control regions enriched in W+jets ($t\bar{t}$) events;
- Backgrounds with $e, \mu \to \tau$ fakes: simulation + data-driven corrections;
- Backgrounds with $j \to \tau$ fakes: data-driven method.

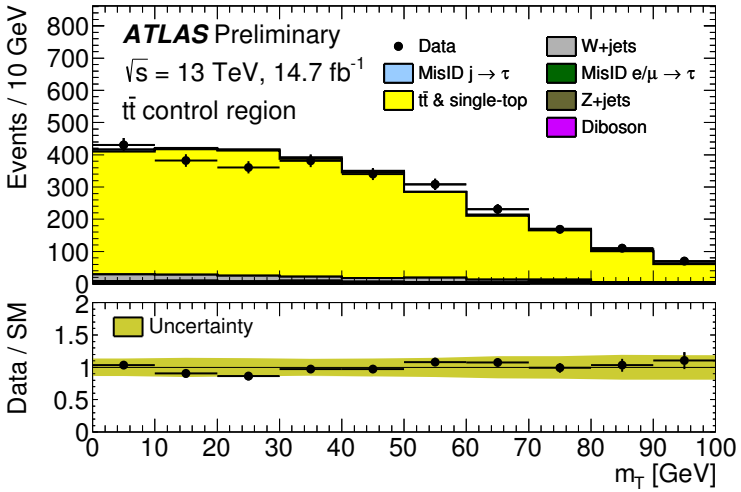
Fake factor (FF) method

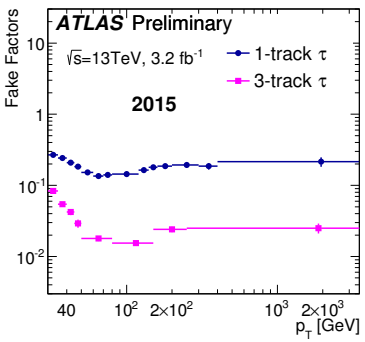
- Anti-τ template in the signal region: fail τ-ID + lower cut on the BDT;
- Simulated events with a true τ are subtracted from all anti-τ samples;
- FFs measured in a control region with 0 b-tag, $E_T^{miss} < 80$ GeV:

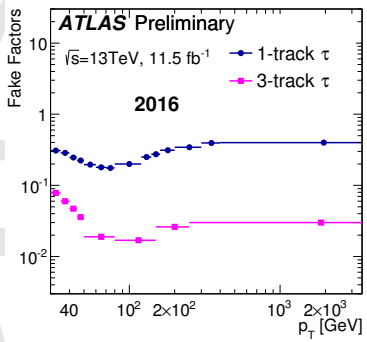
$$\mathrm{FF} = N_{CR}^{\tau} / N_{CR}^{\text{anti-}\tau} \quad \Longrightarrow$$

in bins of p_T and N_{prong};

- $N_{SR,fakes}^{\tau} = \sum_i N_{SR}^{\text{anti-}\tau}(i) \times \mathrm{FF}(i)$







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

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
$E_{\text{T}}^{\text{miss}}$	< 0.1	< 0.1
Fake factors	0.8	4.7
Signal and background models		
$t\bar{t}$ modelling	13.2	3.5
H^+ signal modelling	1.4	1.4

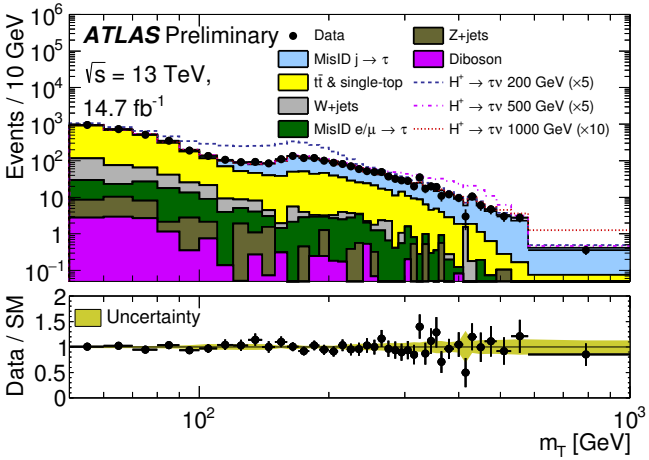
Low-mass: $t\bar{t}$ modelling uncertainties dominate: cross section (6%), matrix element (MG5_MC@NLO vs Powheg), parton shower (Pythia vs Herwig), ISR/FSR.

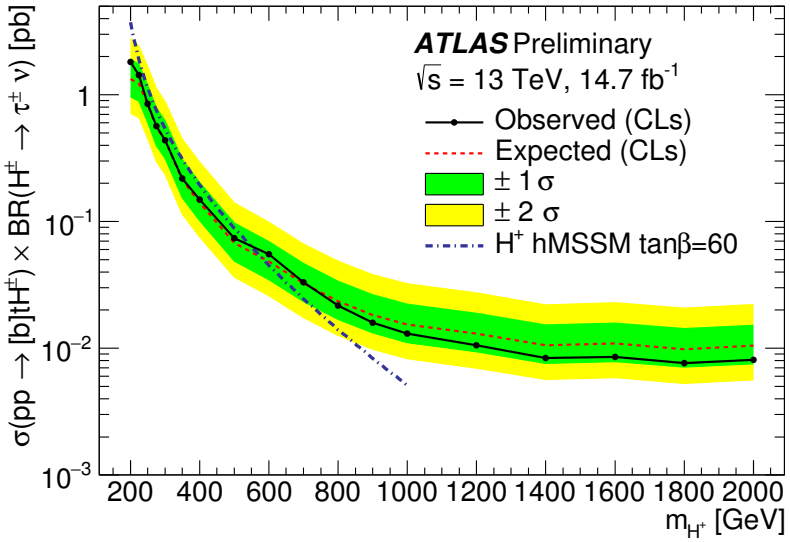
High-mass: FF method uncertainties dominate: BDT score cut in the anti-τ sample, contamination of events with true τ, size of the control sample.

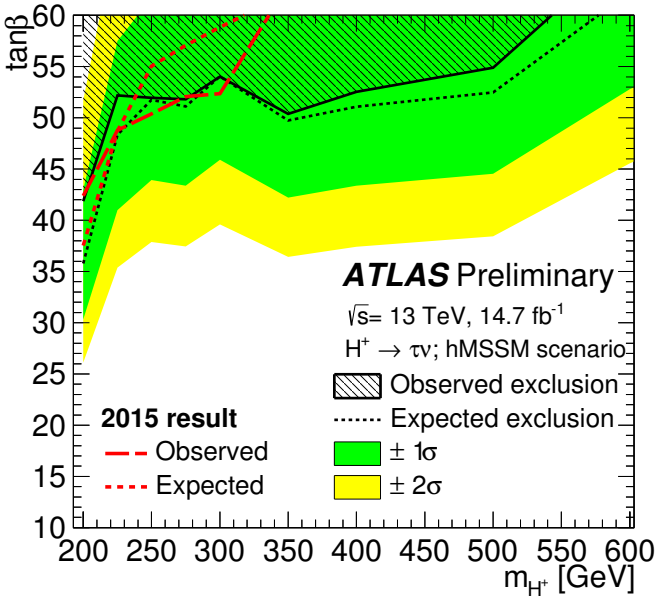
The high-mass search is dominated by statistical uncertainties.

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

Sample	Event yield
True τ_{had}	
$t\bar{t}$ & single-top-quark	$2880 \pm 770 \pm 25$
$W \to \tau\nu$	$265 \pm 51 \pm 18$
$Z \to \tau\tau$	$43 \pm 6.8 \pm 7.6$
diboson (WW, WZ, ZZ)	$13.8 \pm 2.2 \pm 1.7$
Misidentified e, $\mu \to \tau_{\text{had-vis}}$	$126 \pm 24 \pm 6.5$
Misidentified jet $\to \tau_{\text{had-vis}}$	$1170 \pm 110 \pm 16$
All backgrounds	$4500 \pm 800 \pm 36$
H^+ (200 GeV), hMSSM $\tan\beta = 60$	$523 \pm 86 \pm 4$
H^+ (1000 GeV), hMSSM $\tan\beta = 60$	$7.5 \pm 0.6 \pm 0.05$
Data	4645





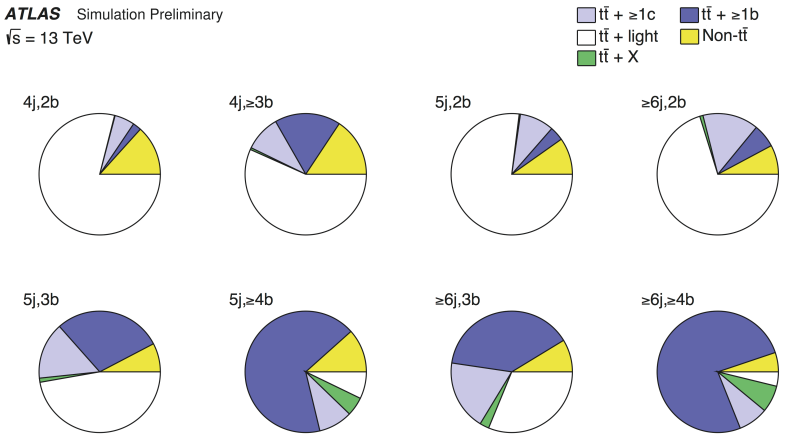


$H^+ \to tb$: analysis strategy

Selection of $pp \to [b]tH^+ \to [b](bjj)(bb\ell\nu)$ topologies

Event selection

- single-lepton trigger & one e/μ with $p_T > 25$ GeV;
- $\geq$4 jets with $p_T > 25$ GeV, including $\geq$2 b-tags;
- Split in signal and control regions based on the jet and b-jet multiplicities.



Simultaneous maximum likelihood fit to all regions:

$\Longrightarrow$ $H_T^{had} = \sum p_T^{jets}$ in CRs

$\Longrightarrow$ BDT output in the SRs

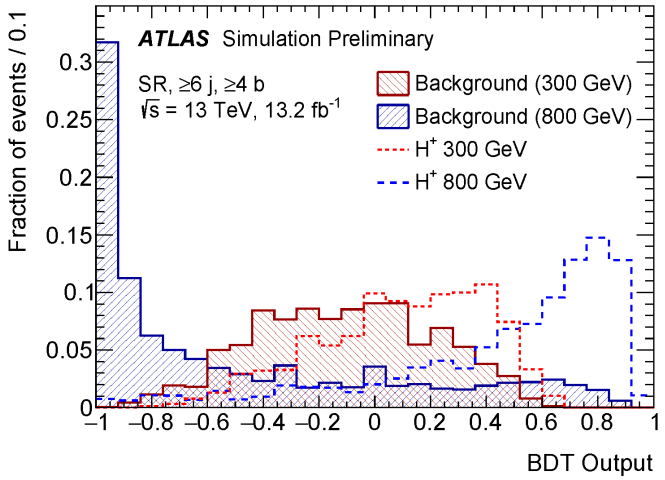
$H^+ \to tb$: background modelling and rejection

The dominating background is $t\bar{t}$+jets ($\sigma = 832^{+46}_{-51}$ pb).

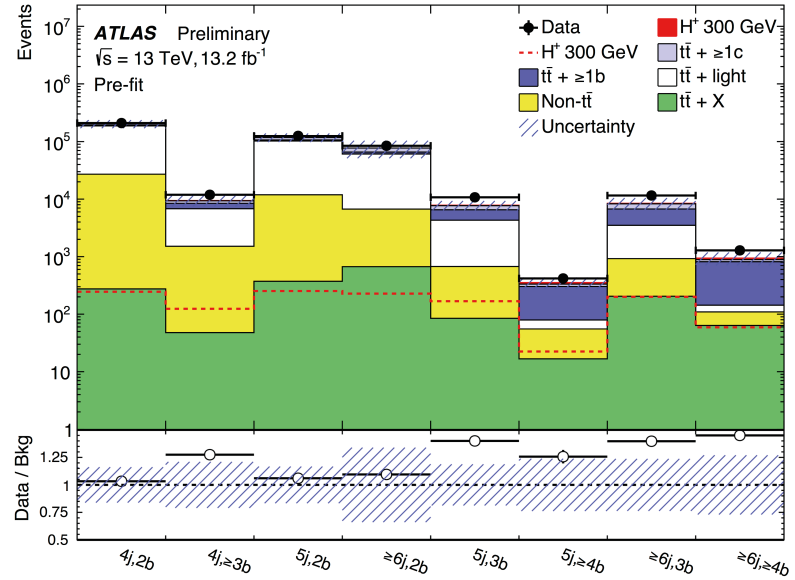
- Model = Powheg+Pythia6, split into light and heavy flavors based on additional jets:
  - $t\bar{t}$ + light-jets, $t\bar{t}$ + $\geq$1c reweighted to the NNLO prediction for $p_T^{t\bar{t}}$ and p_T^t,
  - $t\bar{t}$ + $\geq$1b event kinematics reweighted to the NLO Sherpa+OpenLoops predictions.
- Normalisation of $t\bar{t}$ + $\geq$1c and $t\bar{t}$ + $\geq$1b freely floating in the fit.

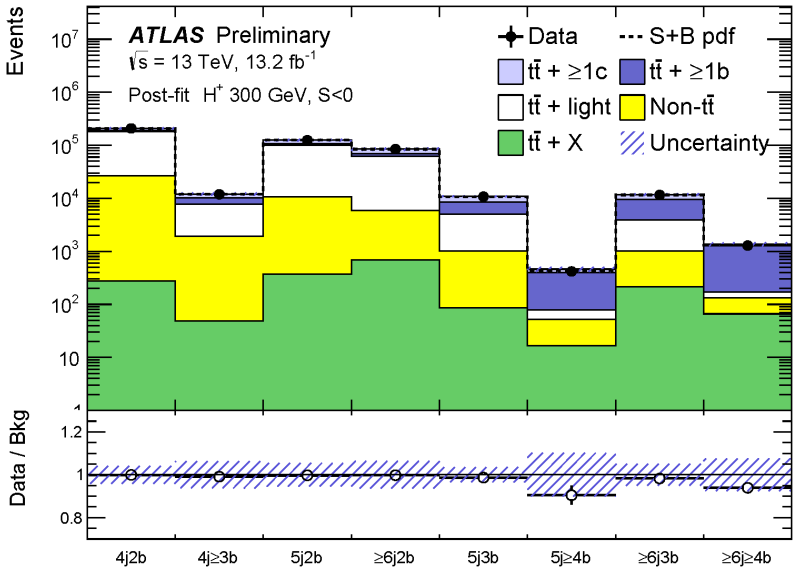
Multi-variate technique (BDT) used to separate signal and background in the SRs. The BDT is trained:

- separately for each m_{H^+} and SR,
- against $t\bar{t}$ + $\geq$1b events for $m_{H^+} \leq 500$ GeV,
- against inclusive $t\bar{t}$ for $m_{H^+} > 500$ GeV.



$H^+ \to tb$: event yields





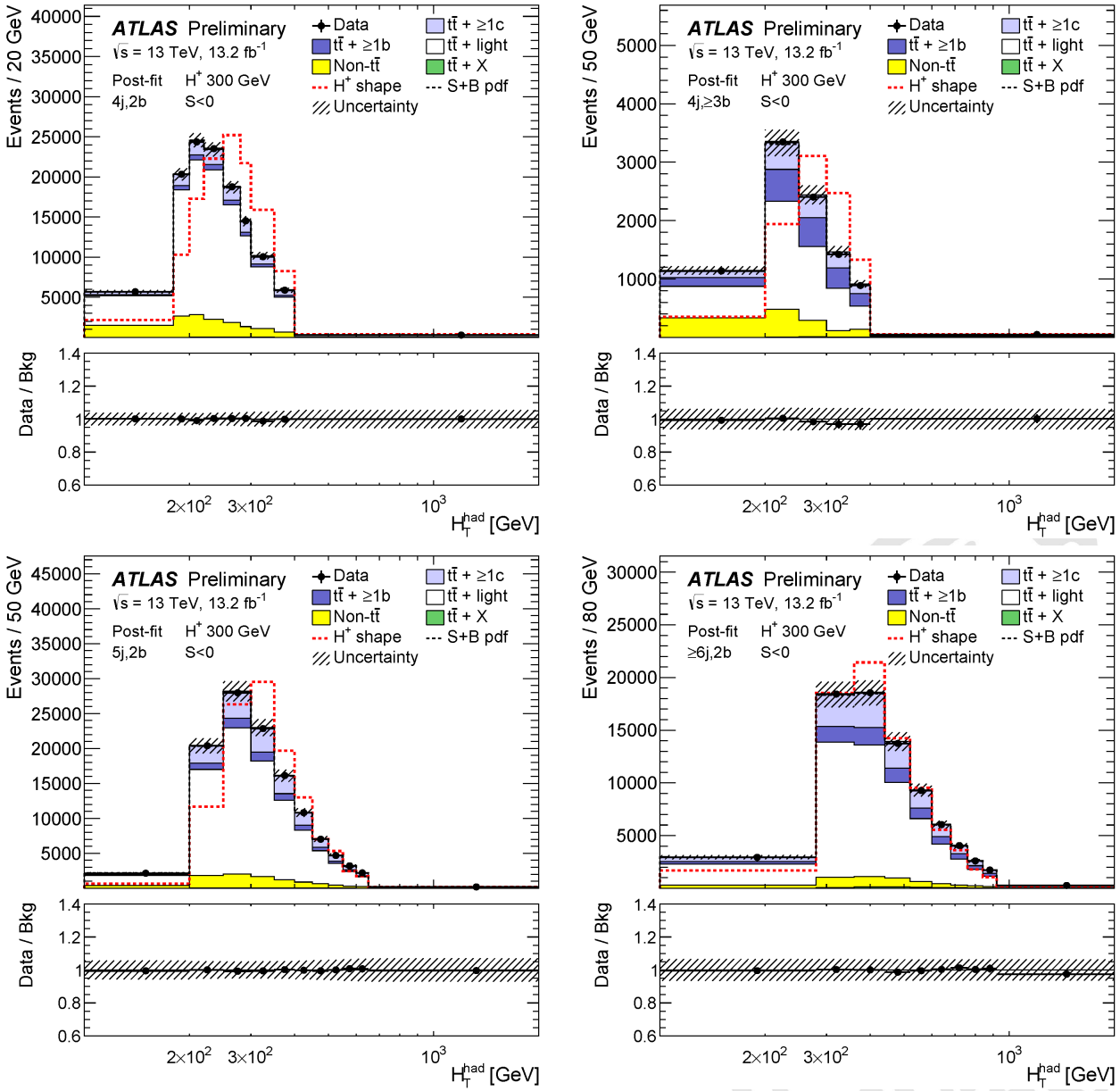
Pre-fit:

- Signal (300 GeV, 1 pb) shown both stacked and separately,
- Simulated yields below data in all categories.

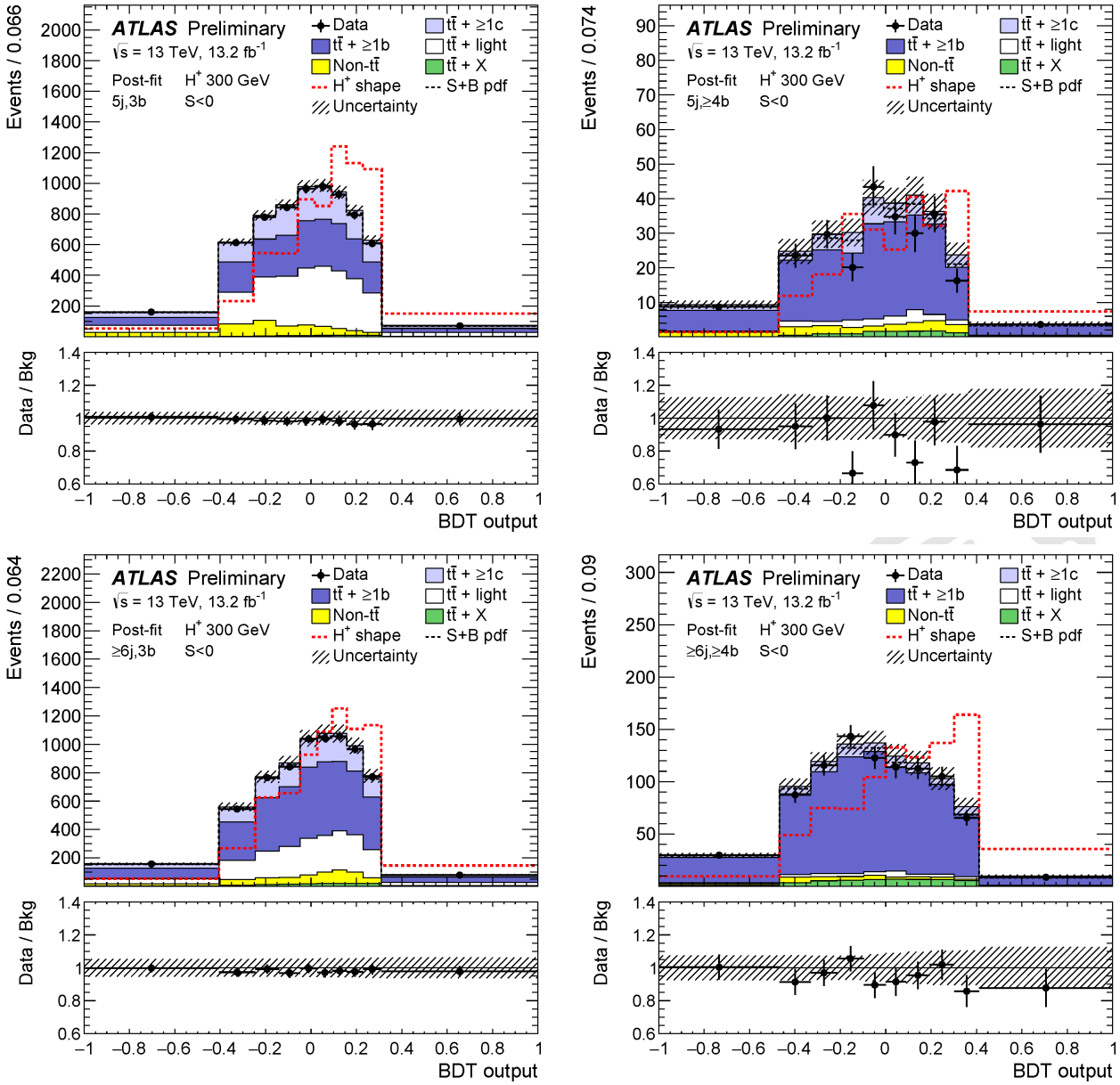
Post-fit:

- Slightly negative signal at this mass,
- Good post-fit agreement in the SRs,
- Reduced uncertainties (constrained in CRs).

$H^+ \to tb$: post-fit CR distributions (300 GeV)



$H^+ \to tb$: post-fit SR distributions (300 GeV)



$H^+ \to tb$: systematic uncertainties

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

$\longleftarrow$

$\longleftarrow$

Largest instrumental uncertainties: *b*-tagging, jet energy scale and resolution.

$t\bar{t}$ background modelling uncertainties

- Inclusive $t\bar{t}$: same as $H^+ \to \tau\nu$ (uncorrelated across categories).
- $t\bar{t}$ + light-jets & $\geq$1c: apply or not reweighting in $p_T^{t\bar{t}}$ and p_T^t.
- $t\bar{t}$ + $\geq$1c: *c*-jets in matrix element vs parton shower.
- $t\bar{t}$ + $\geq$1b: different scales, PDFs and shower recoil schemes in Sherpa+OpenLoops; matrix element; parton shower; multi-parton interactions.

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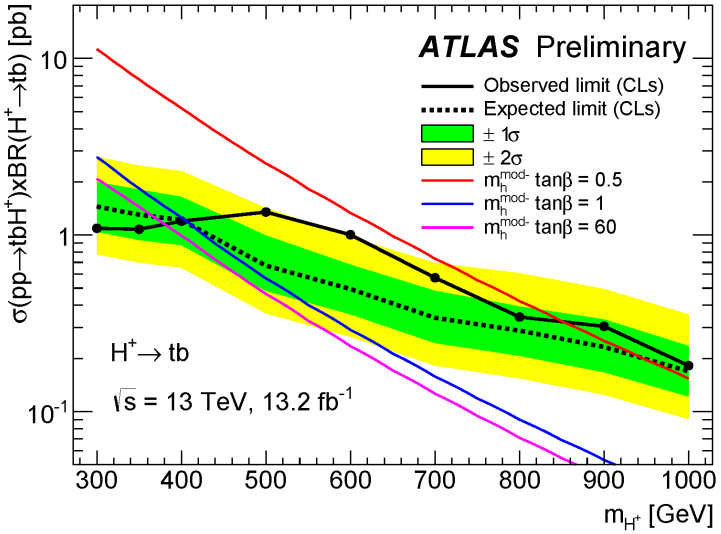
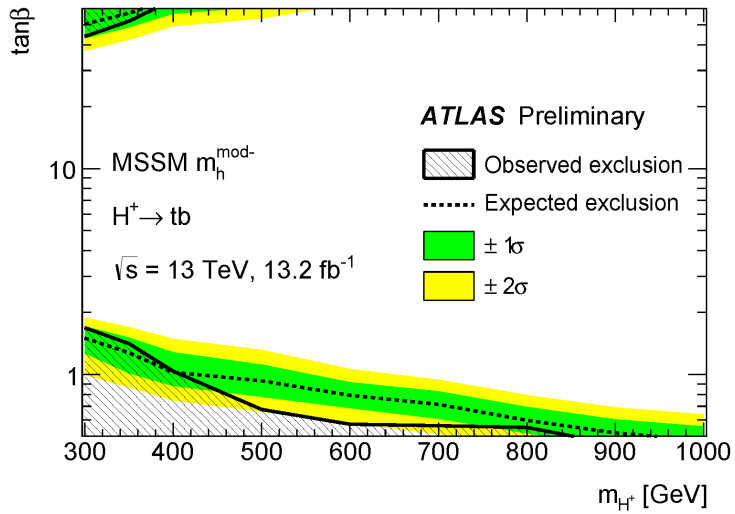
- $t\bar{t}$ + $\geq$1c: c-jets in matrix element vs parton shower.
- $t\bar{t}$ + $\geq$1b: different scales, PDFs and shower recoil schemes in Sherpa+OpenLoops; matrix element; parton shower; multi-parton interactions.

$H^+ \to tb$: results

Post-fit event yields, $m_{H^+} = 300$ 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





Conclusion

ATLAS has conducted two searches for charged Higgs bosons based on Run-2 *pp* collision data at the LHC:

- $H^+ \to \tau\nu$: ATLAS-CONF-2016-088,
- $H^+ \to tb$: ATLAS-CONF-2016-089.

Unfortunately no significant excess, but improved exclusions with respect to Run-1 at high mass.

We already have three times more data to analyse, stay tuned for improved H^+ searches in a near future!

Disclaimer

I didn't cover searches for *doubly* charged Higgs bosons in this talk... but have a look at the back-up slides!

Conclusion

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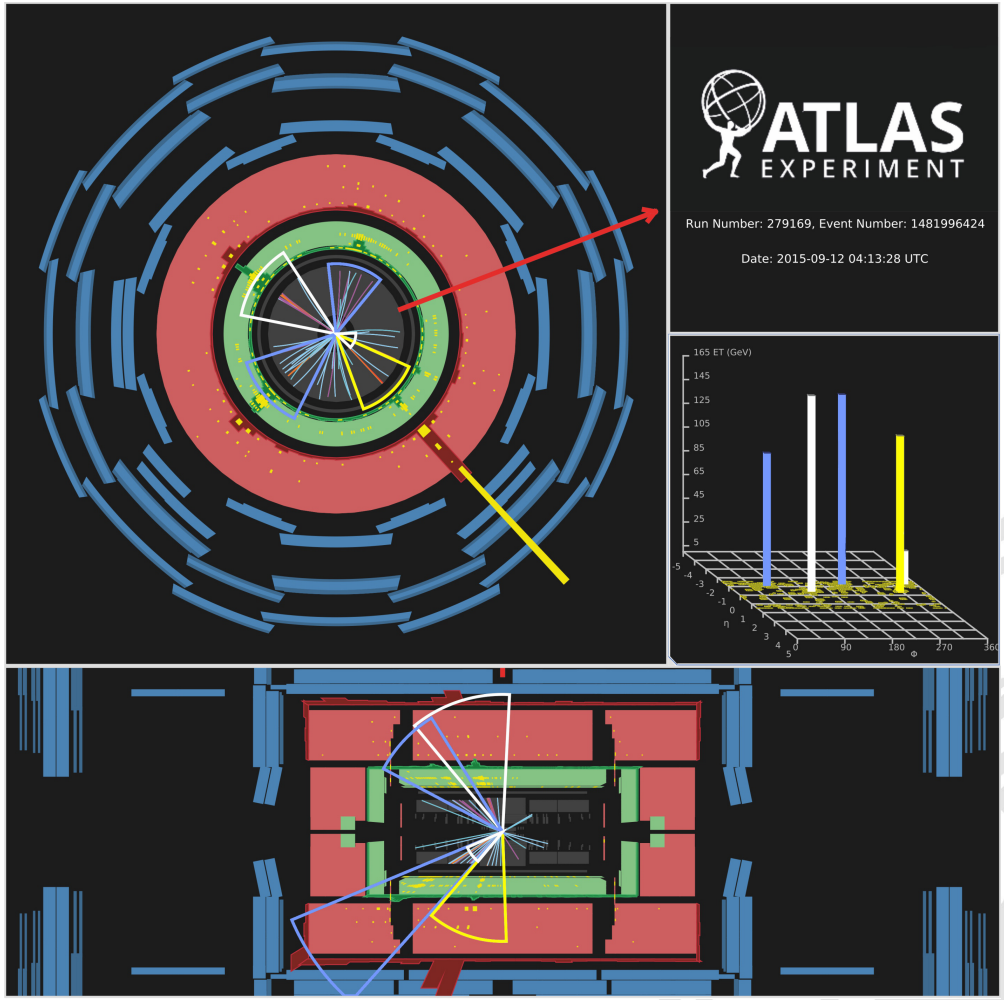
Thank you for your attention! Do you have any questions?

BACK-UP SLIDES

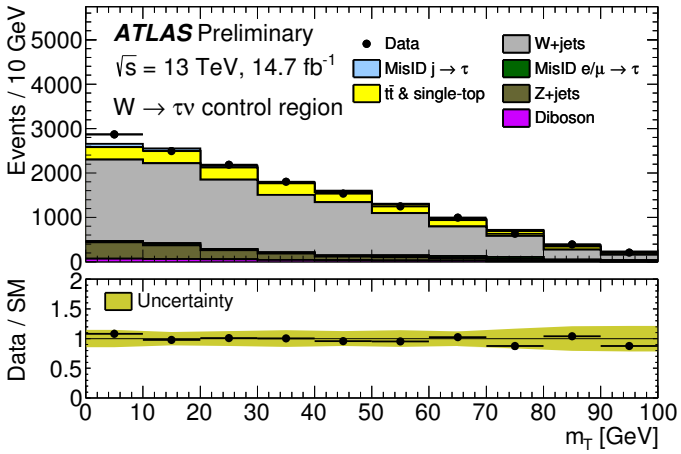
$H^+ \to \tau\nu$: event display



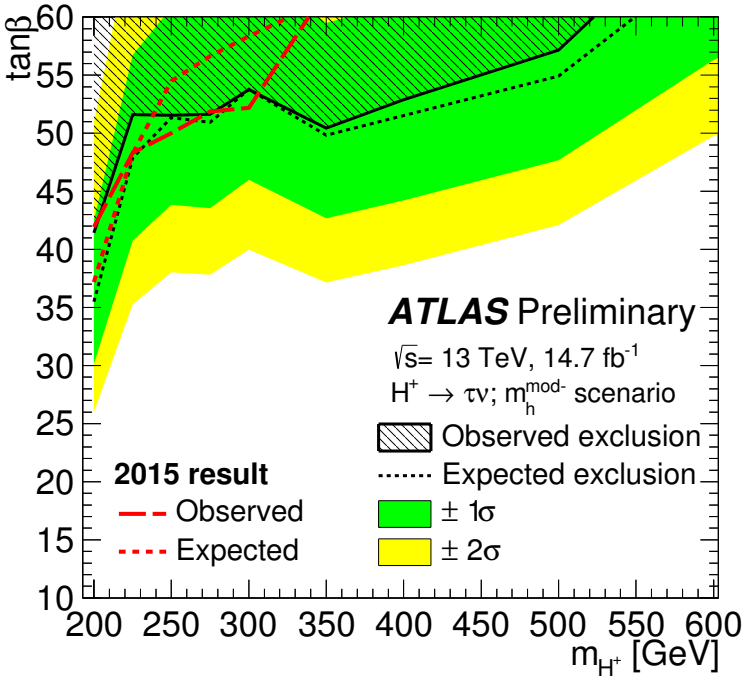
This event has four jets (white and blue cones), including two b-tagged jets (blue cones), and one 3-prong τ object (yellow cone). The red arrow displays the direction of the missing transverse momentum. The p_T of the τ is 137 GeV. The p_T of the jets are: $p_{T,1}$ = 175 GeV (b-tagged), $p_{T,2}$ = 169 GeV, $p_{T,3}$ = 124 GeV (b-tagged), $p_{T,4}$ = 33 GeV. The missing transverse momentum amounts to 152 GeV and m_T = 162 GeV.

$H^+ \to \tau\nu$

Control region enriched in W+jets events (0 b-tag).



$m_h^{\text{mod}-}$ interpretation:

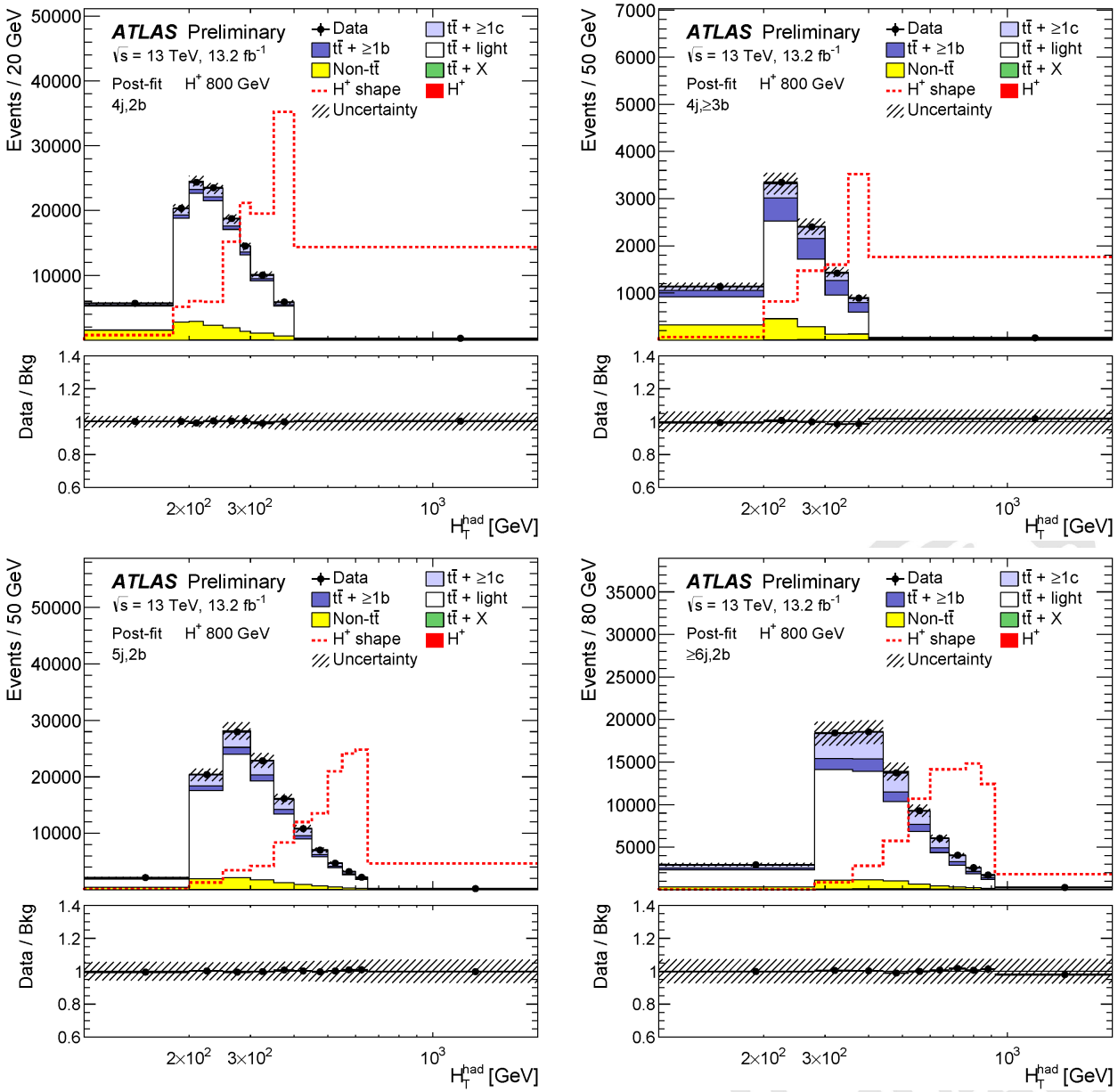


$H^+ \to tb$: BDT details

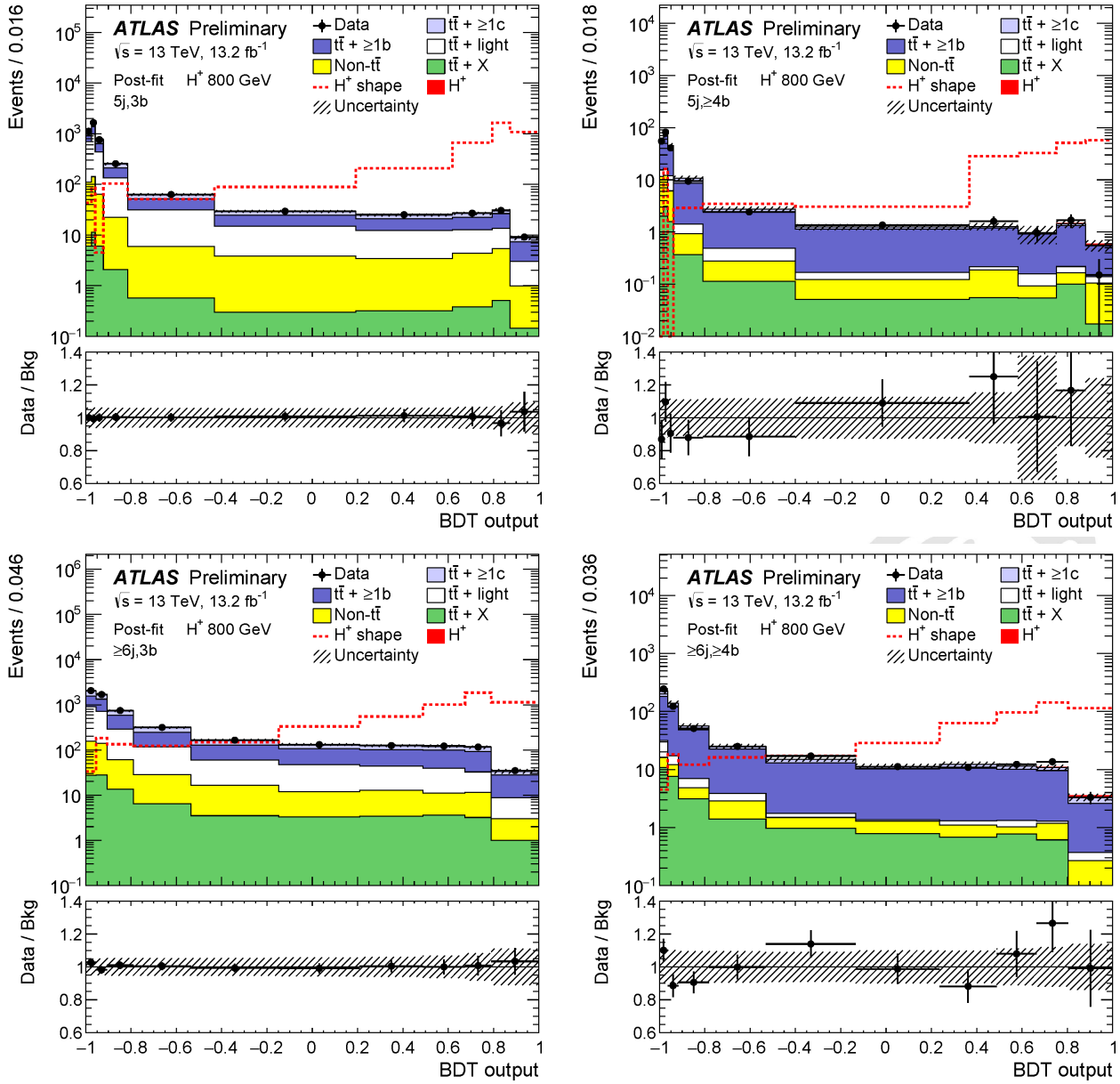
BDT variables:

- Highest jet p_T
- Mass of bbbar pair with minimum ΔR
- p_T of 5th jet, having *b*-tagged jets first followed by non–*b*-tagged jets
- Second Fox-Wolfram, moment calculated using jets and leptons
- Average ΔR of all bbbar pairs
- ΔR of the lepton and the bbbar pair with smallest ΔR
- Mass of untagged jet pair with minimum ΔR
- Scalar sum of E_T calculated using all jets
- Mass of bbbar pair with maximum p_T
- Mass of bbbar pair with maximum mass
- Mass of jet triplet with maximum p_T
- Centrality, calculated using jets and leptons

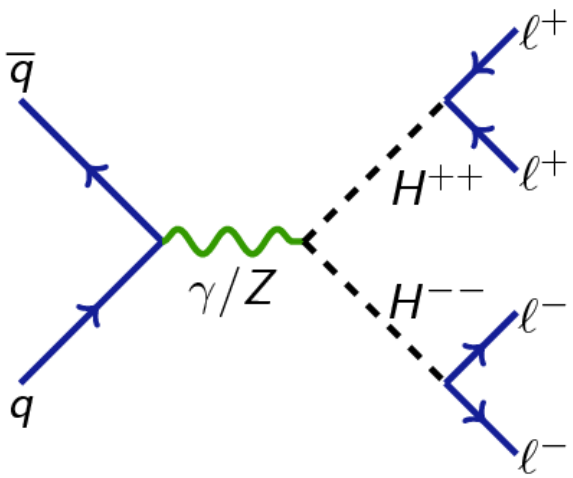
$H^+ \to tb$: post-fit CR distributions (800 GeV)



$H^+ \to tb$: post-fit SR distributions (800 GeV)



$H^{++} \to e^+e^+$ (ATLAS-CONF-2016-051)

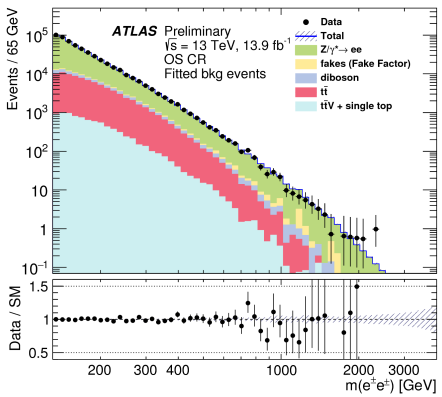


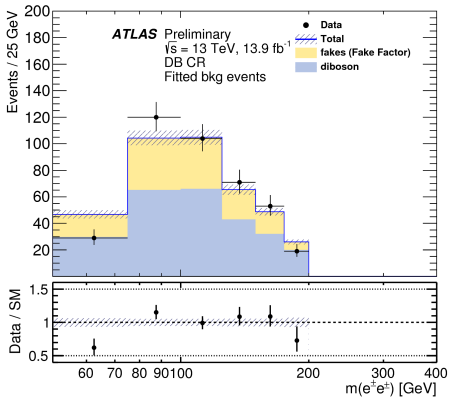
The analysis considers only the electron channel.

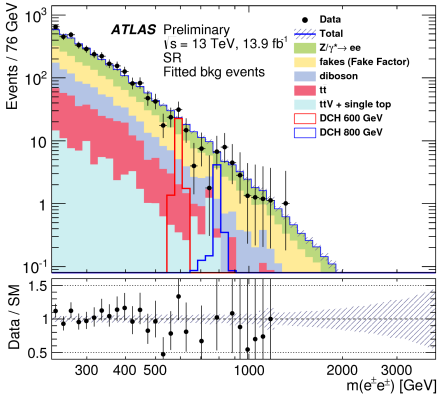
Signal region = at least same-sign (SS) electron pair with m_{ee} above 300 GeV.

Two control regions:

- OSCR = 1 OS pair, 0 SS pair;
- DBCR = 1 OS pair (Z) + SS pairs ($m_{ee} < 200$ GeV).







$H^{++} \to e^+e^+$ (ATLAS-CONF-2016-051)

BumpHunter is used to look for excesses or deficits in the post-fit SR distribution.

Limits for $H_R^{\pm\pm}$ and $H_L^{\pm\pm}$ at 420 GeV and 570 GeV, assuming a 100% branching fraction to electrons.