Search for BSM Scalar Bosons at ATLAS

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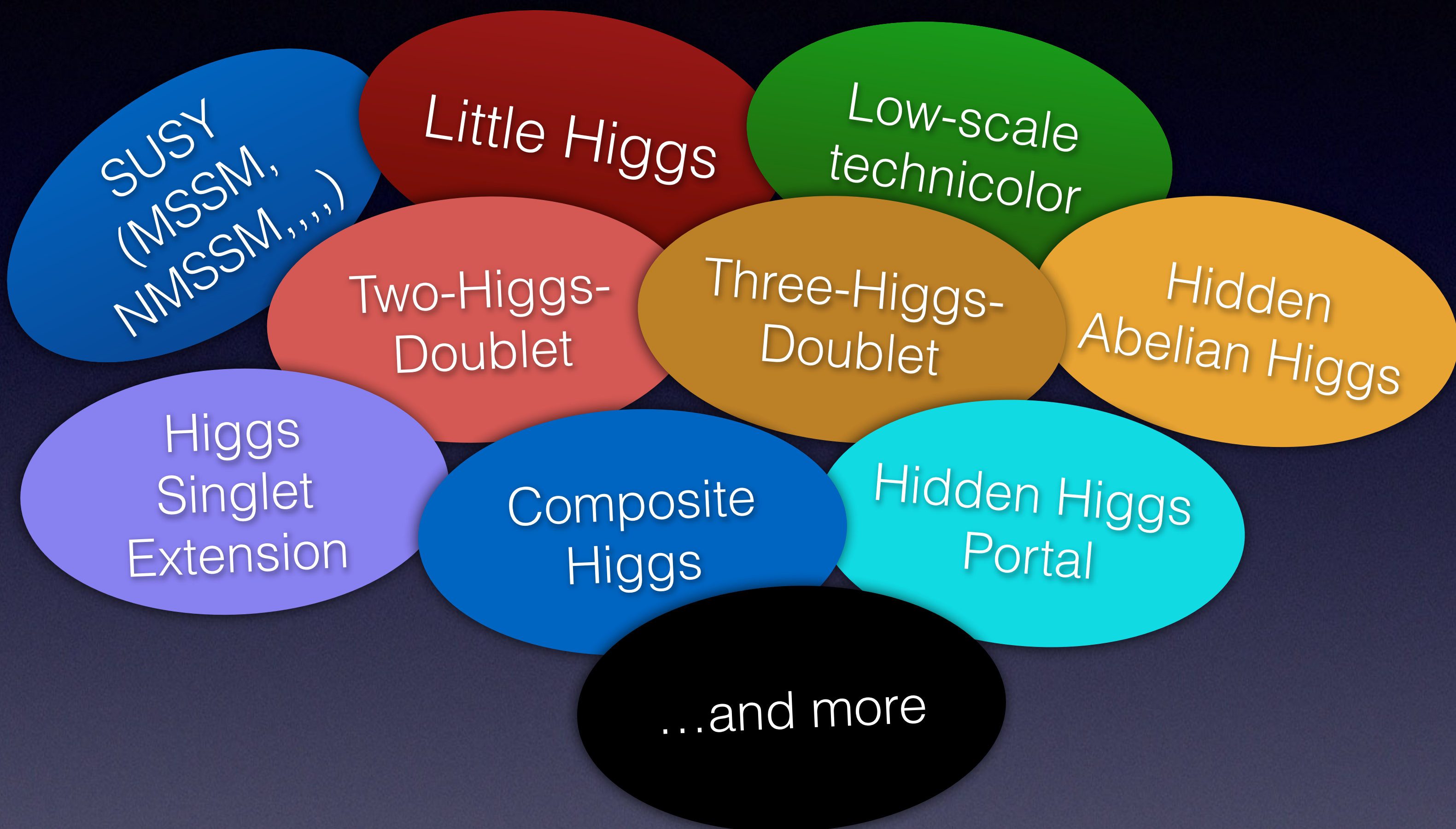
Scalars in the SM and Beyond

- What we know:
  - the SM requires a complex doublet scalar field
    - leading to one massive scalar boson (the Higgs)
  - we have observed one scalar boson at 125 GeV
    - the properties of that boson are consistent with SM predictions (so far)
- What we don't know:
  - what (if anything beyond random chance) stabilizes the Higgs mass
  - if there are scalar fields beyond the minimum prescribed in the SM

Scalars in the SM and Beyond

- What else might there be?

Many models…



… that could explain many issues

Additional scalars that might be neutral, charged, light, heavy, CP-even (H), CP-odd (A), etc.

A broad search program is required

BSM Scalar Searches at ATLAS

Low-mass

$\gamma\gamma$ resonances*
arXiv:2407.07546

$H \to Za \to Z\gamma\gamma$
Phys. Lett. B 848 (2024) 138536

$t \to H^+ b \to csb$*
arXiv:2407:10096

$t \to H^+ b \to cbb$
JHEP 09 (2023) 004

$t \to qX \to qbb$
JHEP 07 (2023) 199

High-mass

$A/H \to t\bar{t}$*
JHEP 08 (2024) 013

$t\bar{t}A/H \to t\bar{t}t\bar{t}$*
1L/2LOS: arXiv:2408:17164
2LSS/ML: JHEP 07 (2023) 203

Heavy Higgs $\to WW$
JHEP 07 (2023) 200

Multi-b, Multi-lepton
JHEP 12 (2023) 081

Heavy Higgs $\to Z\gamma$
Phys. Lett B 848 (2024) 138394

Heavy Scalar $\to 4\ell +$ MET
arXiv:2401.04742

*recent results, highlighted in this talk

All searches discussed in this talk use the Run II data set [2015-2018, 140 fb^{-1}, $\sqrt{s} = 13$ TeV]

Low-mass $\gamma\gamma$ search

Unique motivations

Light scalar partner to dark matter could explain excess of gamma rays from galactic center and AMS cosmic-ray $\bar{p}$ spectrum

Spin-0 axion with weak coupling to Higgs could account for baryon asymmetry

Searches conducted for both generic scalar (narrow and finite-width) and low-mass Higgs

Experimental complication: conversions

20 - 65% of photons convert in the inner detector (depending on η)

Converted and unconverted photons are subject to different backgrounds

Solution

Divide diphoton data into three subsets, based on the number of converted photons (UU, UC, CC)

Low-mass $\gamma\gamma$

- Search in range $62 < m_{\gamma\gamma} < 120$ GeV

above trigger turn-on effects

below SM Higgs mass

- Backgrounds: continuum $\gamma\gamma$, γj, jj, $Z \rightarrow ee$

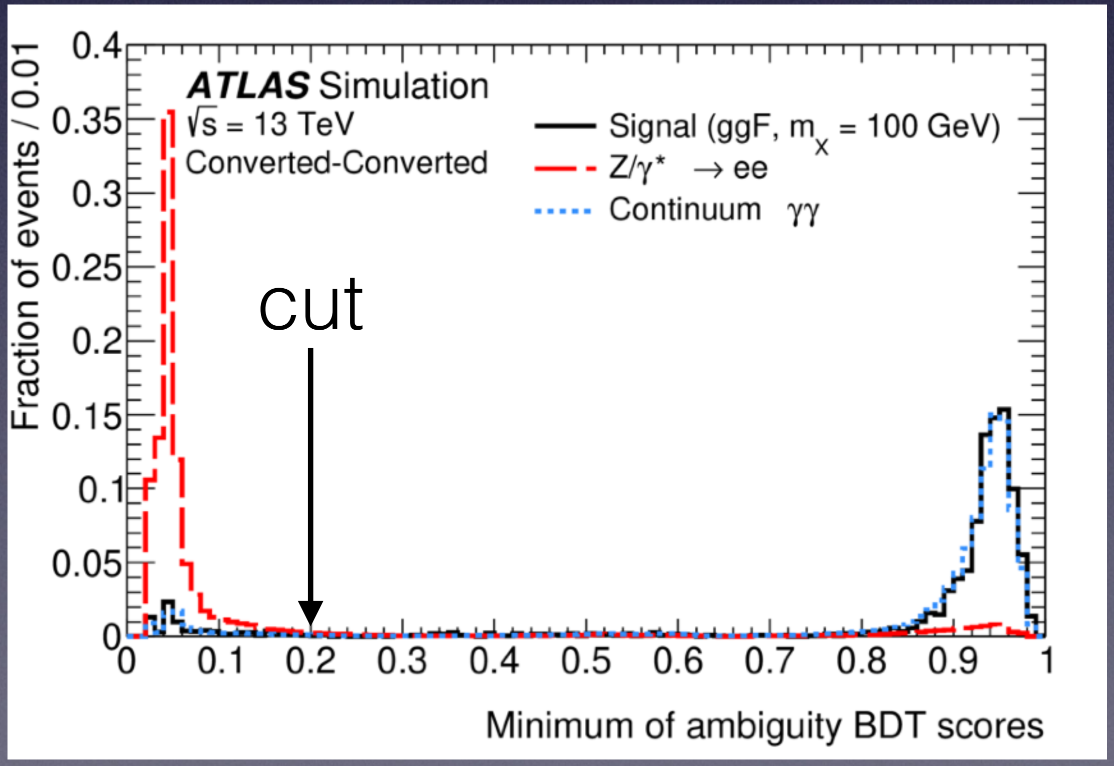
dominant

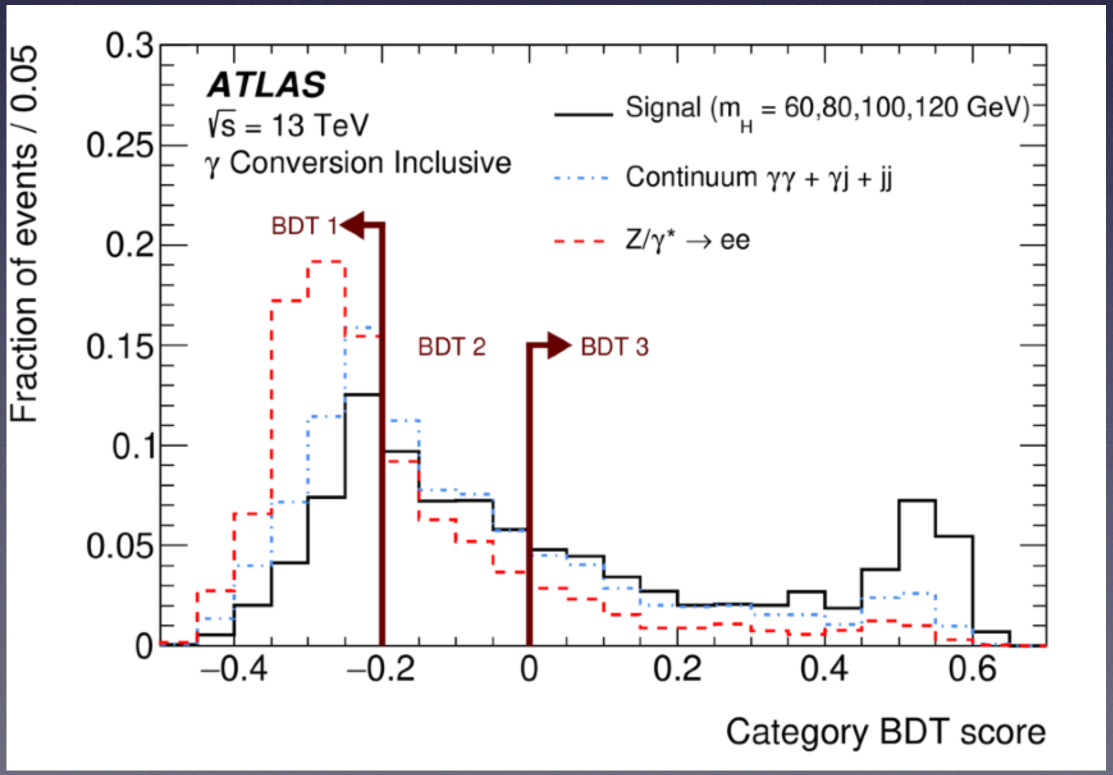
misidentified as γ

Yields determined by fitting $m_{\gamma\gamma}$ distributions

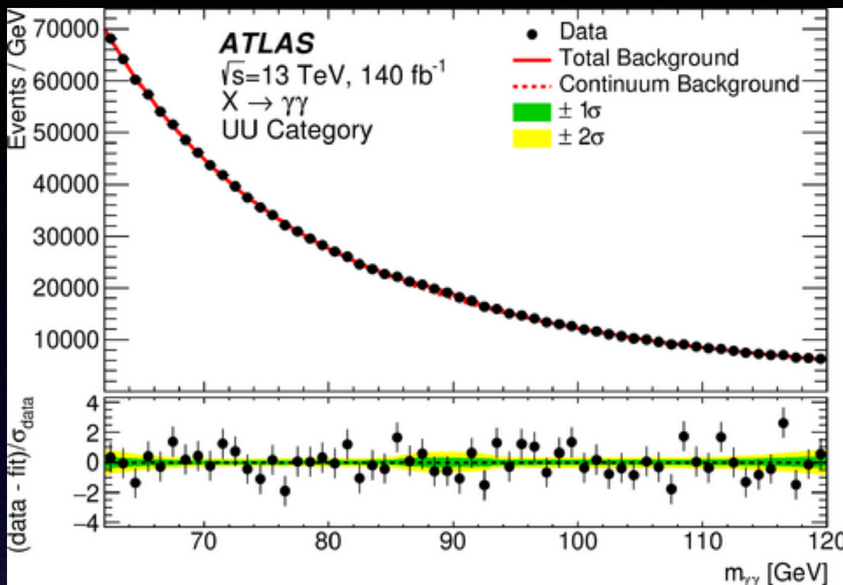
BDT used to distinguish converted γs from prompt electrons

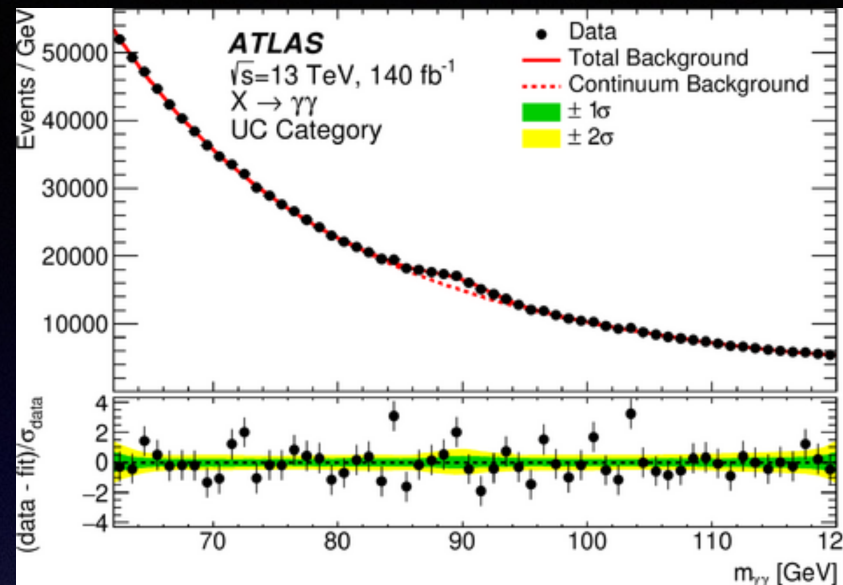
Second BDT used for S/B discrimination in H search

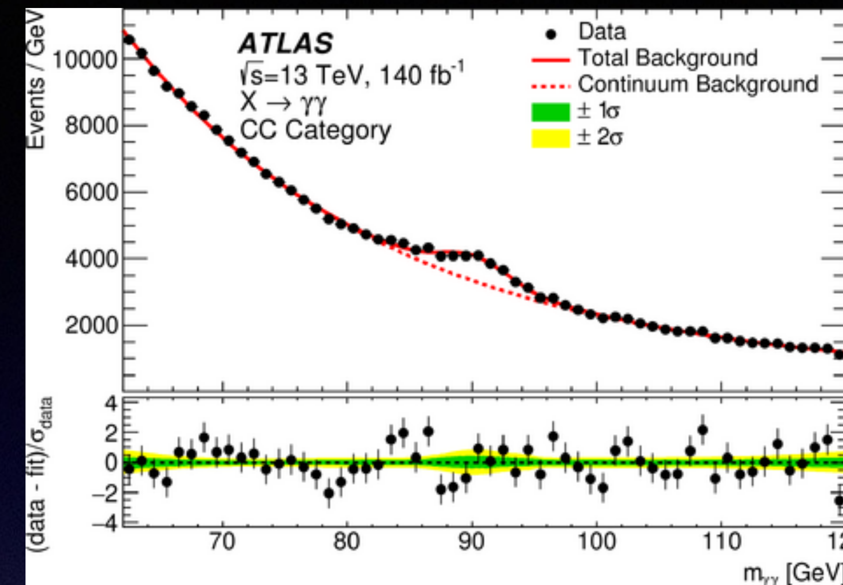




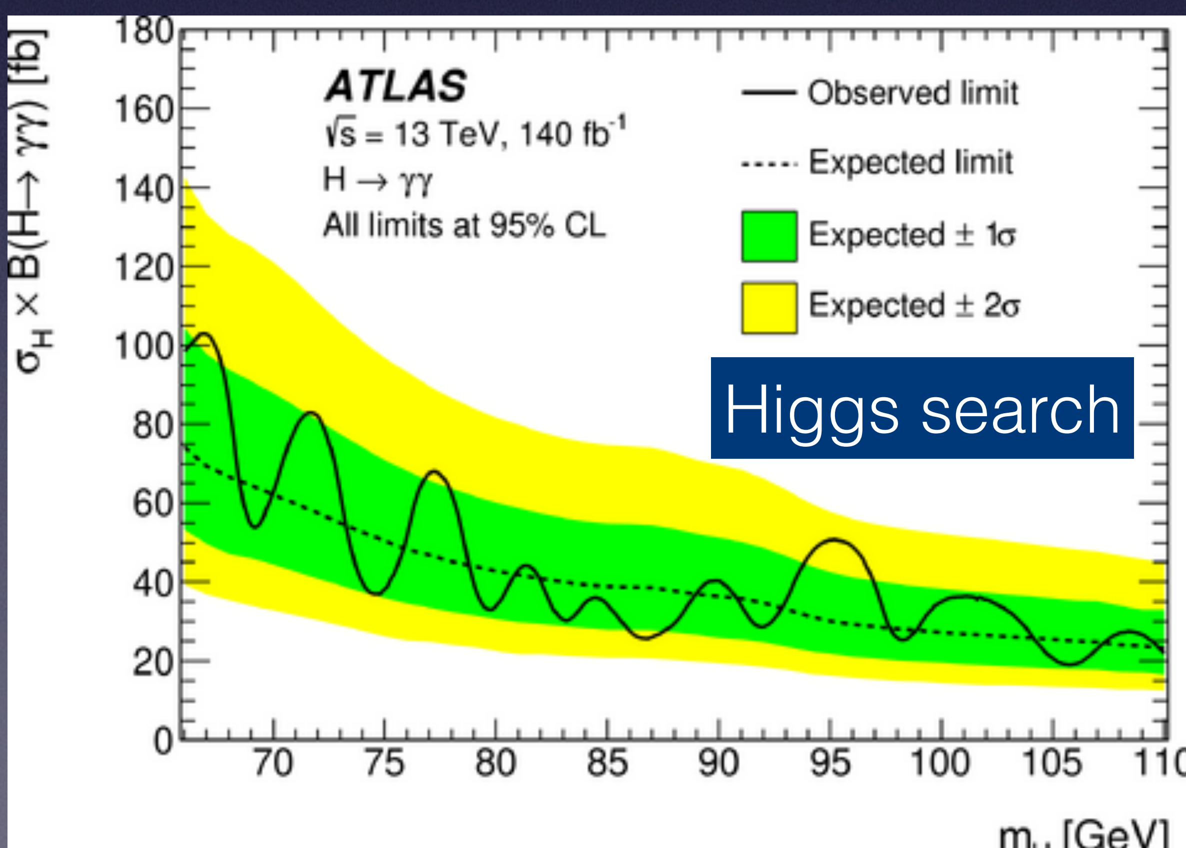
Low-mass $\gamma\gamma$ results

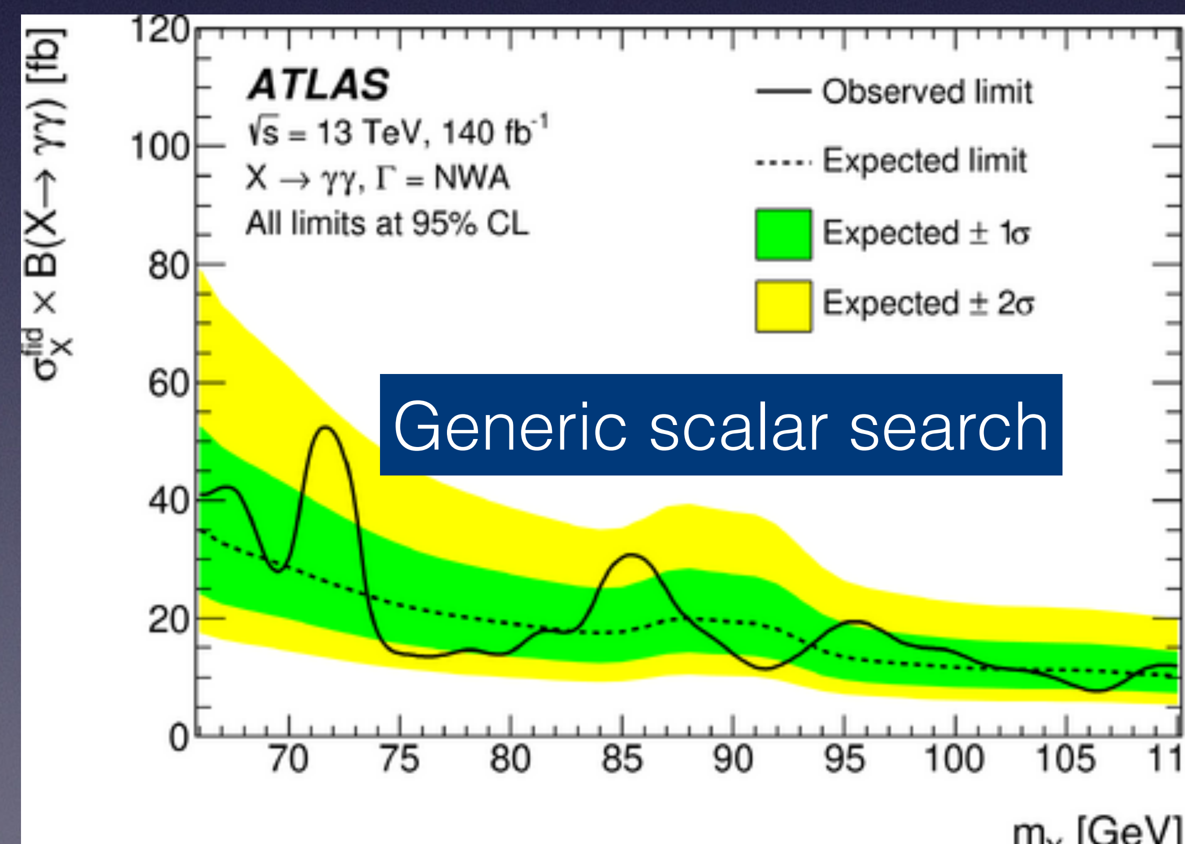






No significant deviations from background



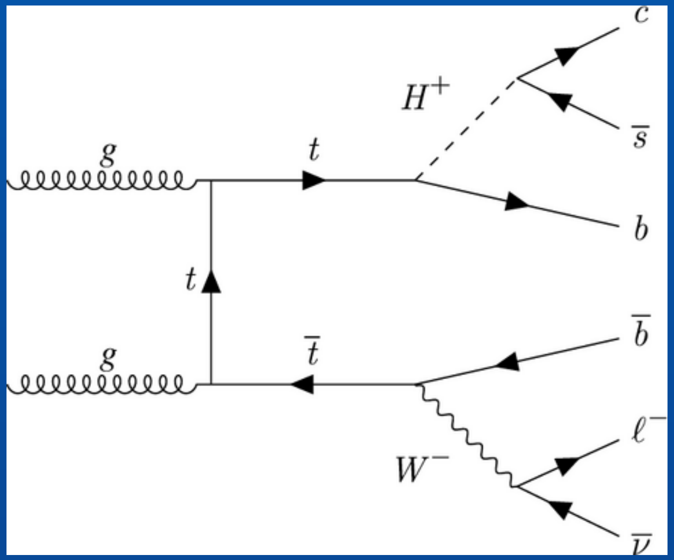


$t \to H^+ b \to csb$

Motivations

In many 2HDM models, leading source of H^+ production is via $t\bar{t}$ events (if $m_{H^+} < m_t$)

and leading decay mode is to *cs:*



S/B discrimination

Main background is $t\bar{t}$+jets
Distinguish from signal by:

Jet flavor tagging

Multivariate tagger used, with both *b*-tag and *c*-tag outputs. Based on values, jet is classified as *b*, *c* or light

Kinematic variables

$t\bar{t}$ event is reconstructed, and most likely assignment of reconstructed to true jets determined, allowing kinematic variables to be computed

The above are combined in a BDT

$t \to H^+b \to csb$

26 variables used in the BDT

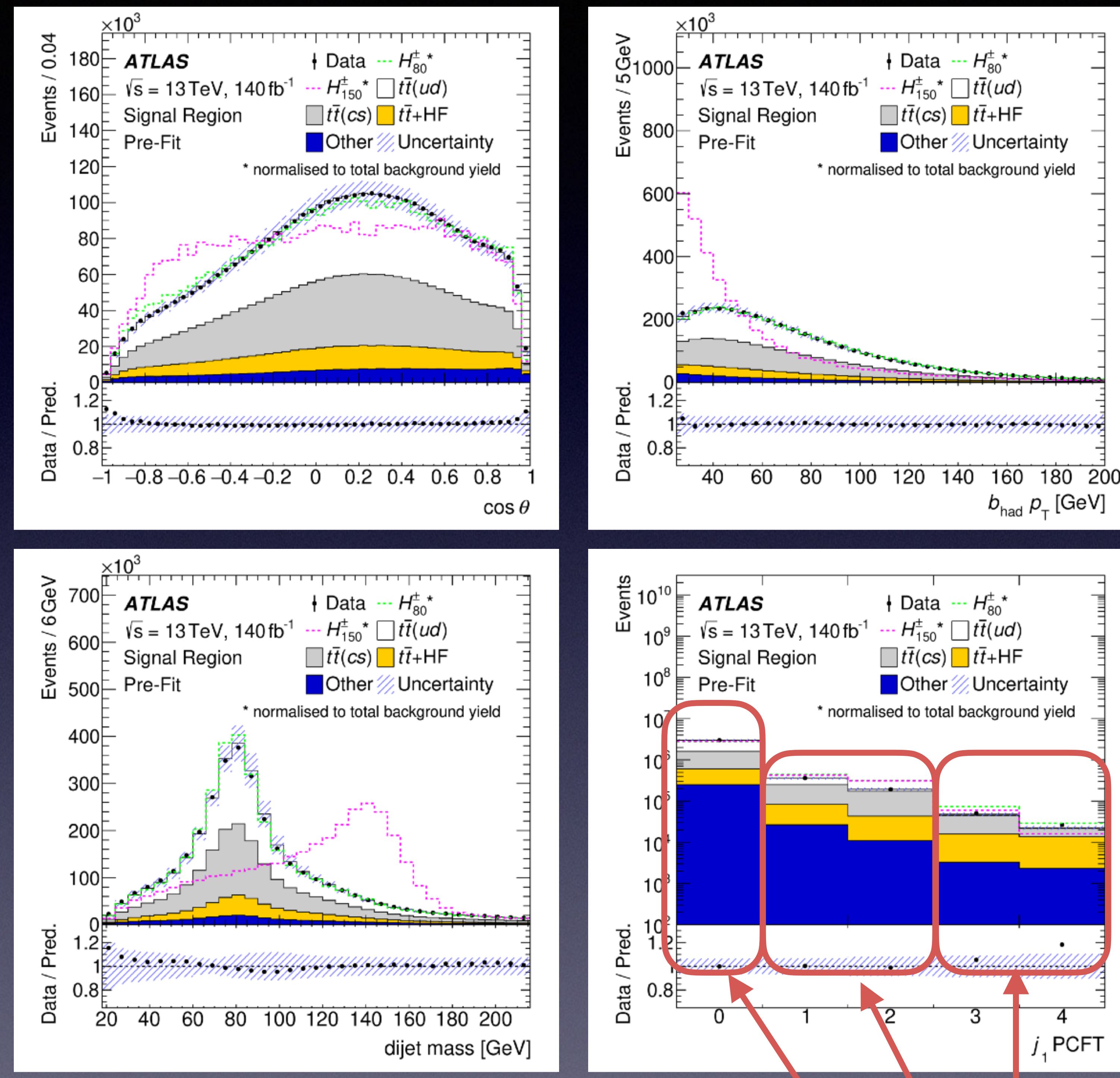
Four important ones shown here

$\cos\theta$ based on angle between up-type quark jet and *b* jet in *H*+/*W* frame

Only variable sensitive to the boson's spin

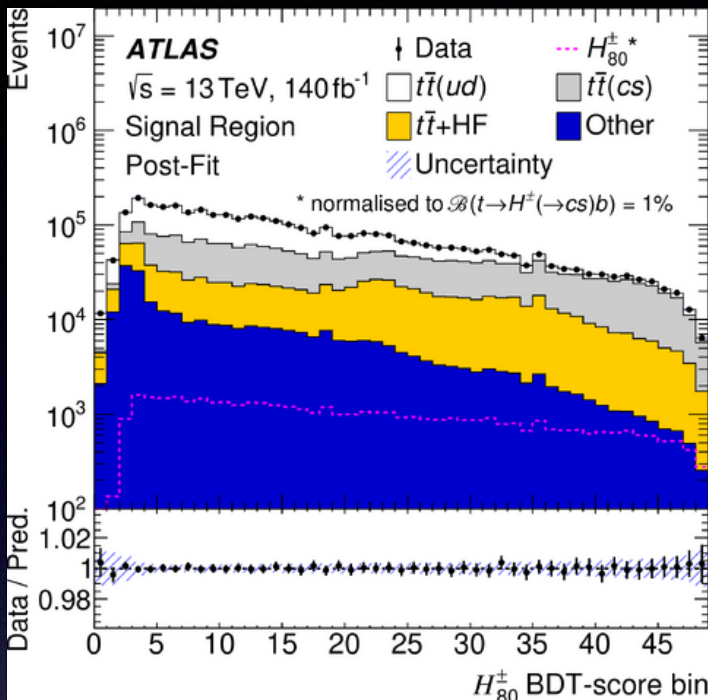
Most variables depend on *H*+ mass

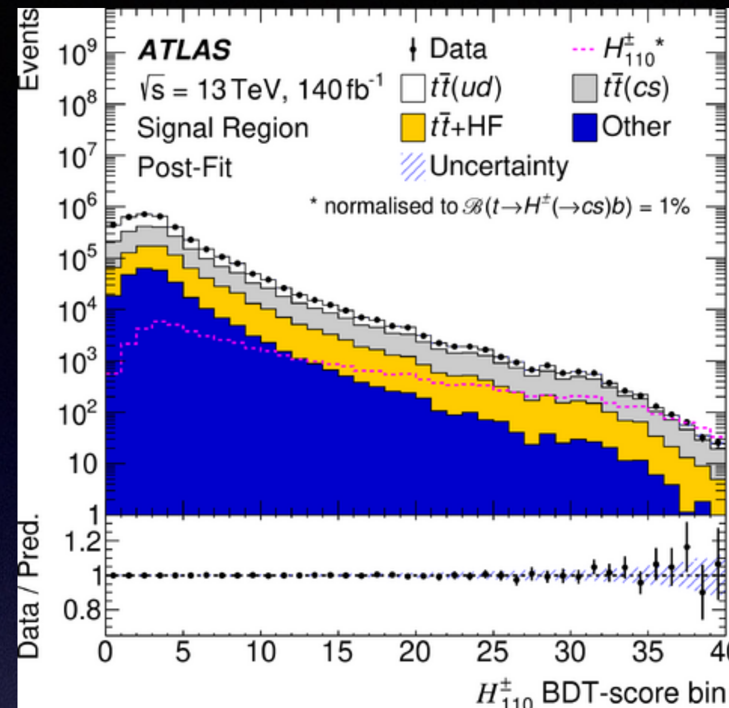
Separate BDTs are used for each mass hypothesis

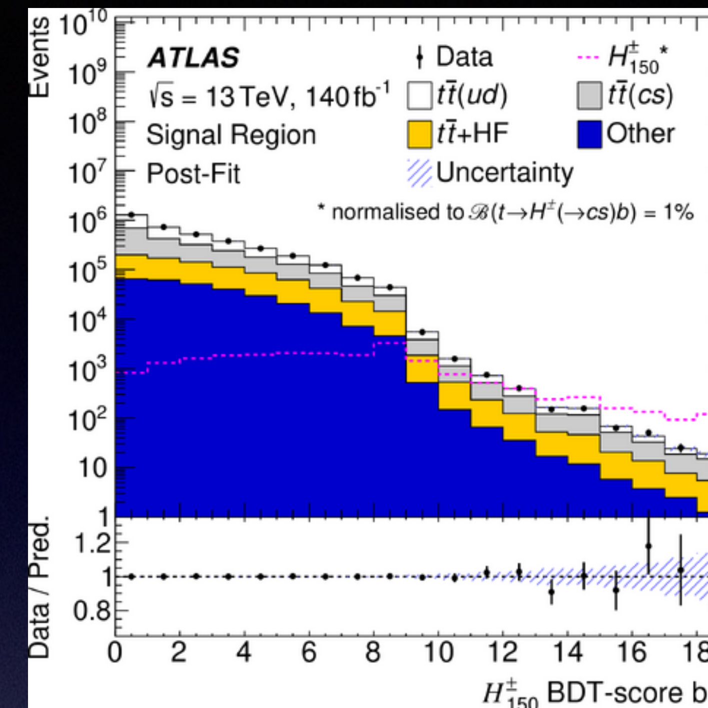


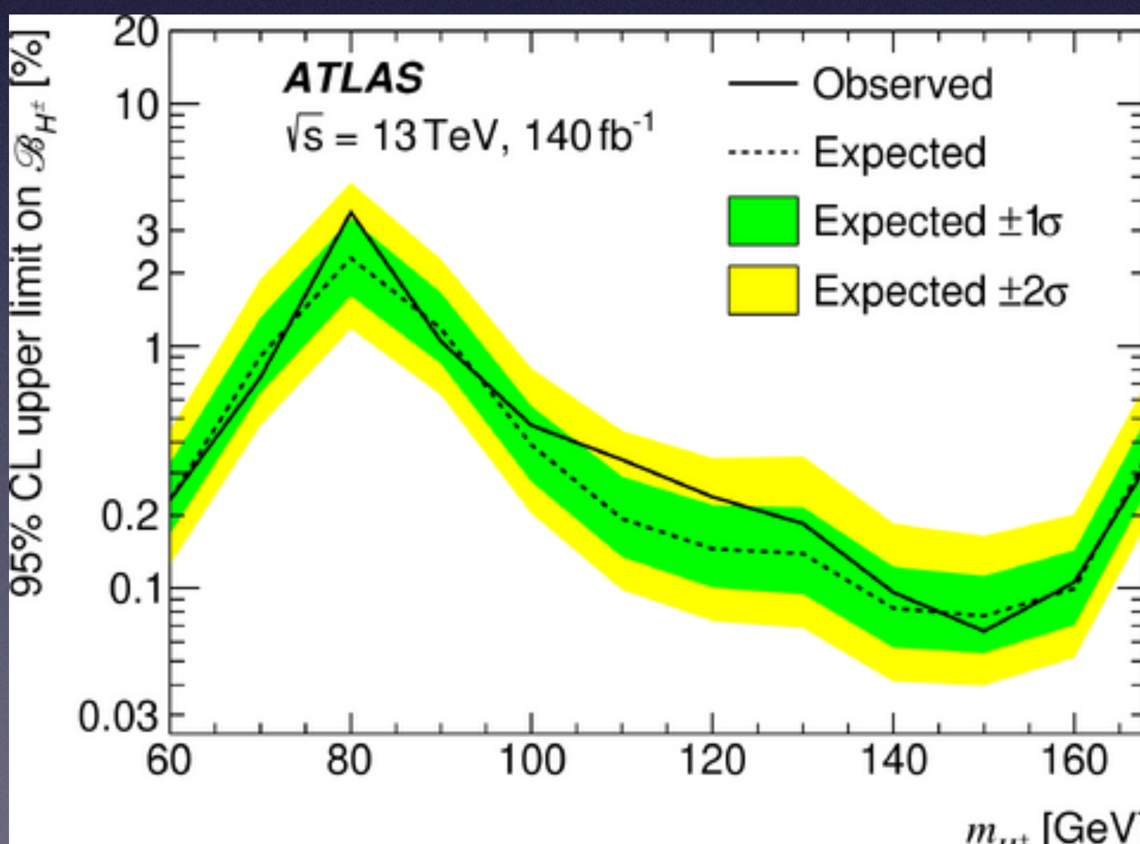
Jet flavor: light, *c*, *b*

$t \to H^+b \to csb$ results





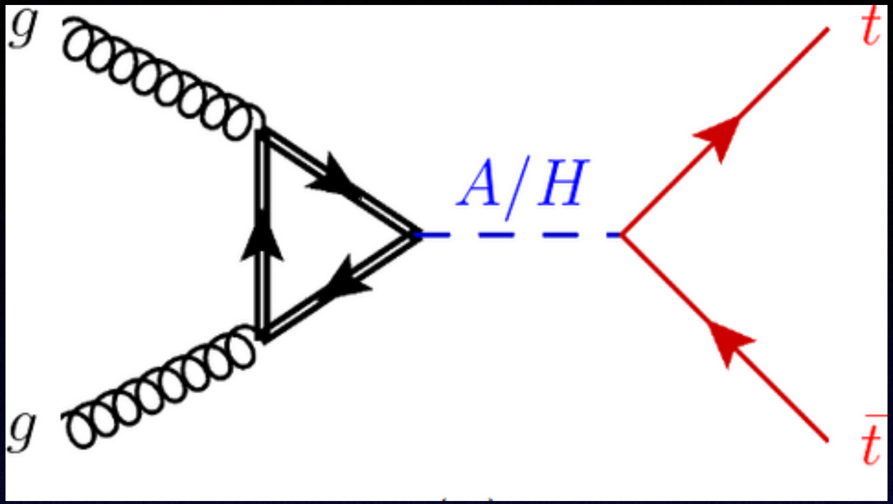




First direct limits on $\mathscr{B}(t \to H^{\pm}(\to cs)b)$ for some mass points

Currently the most stringent limits for all H^+ masses

$A/H \to t\bar{t}$ (1 and 2 lepton)



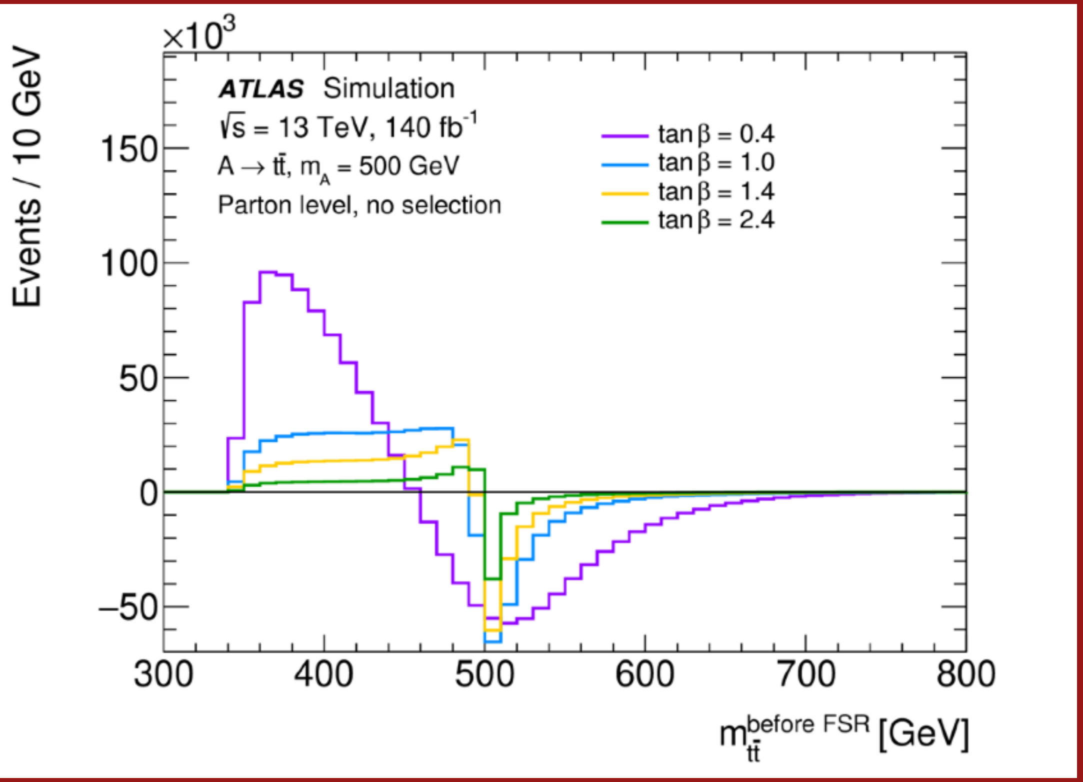
Motivation

$t\bar{t}$ is dominant *A/H* decay mode at low $\tan\beta$

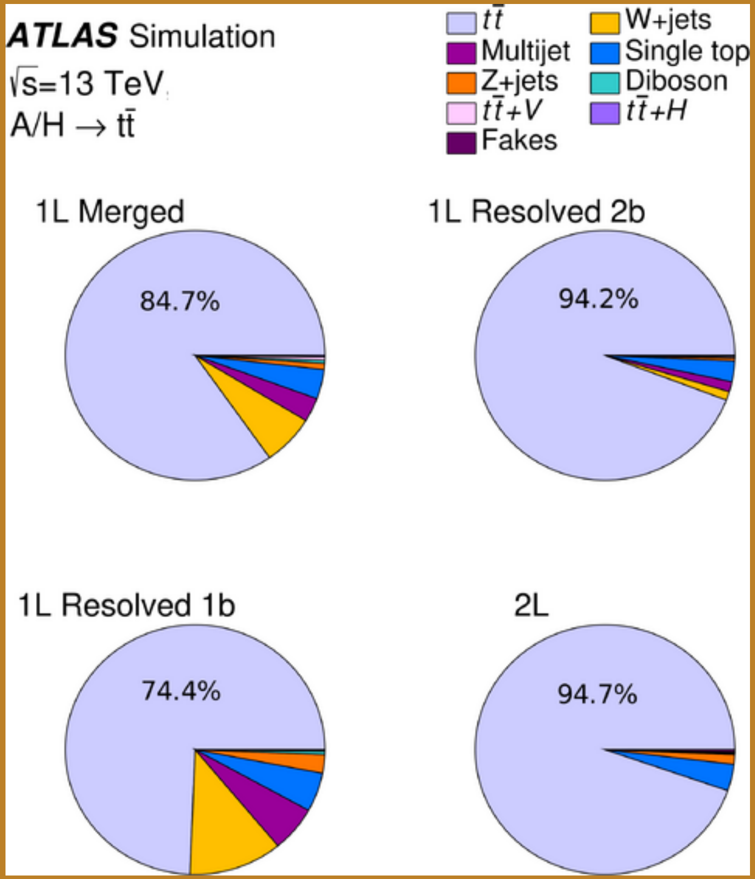
Challenges

Large SM $t\bar{t}$ background

Significant interference with SM diagrams



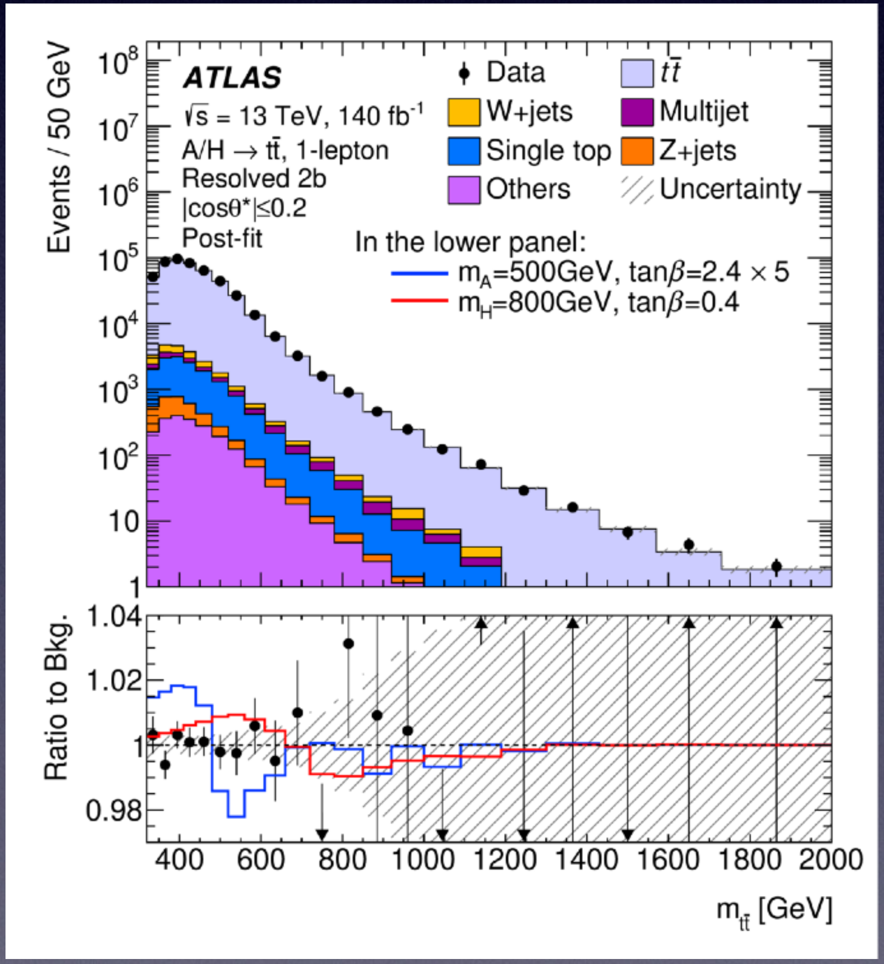
Search categories

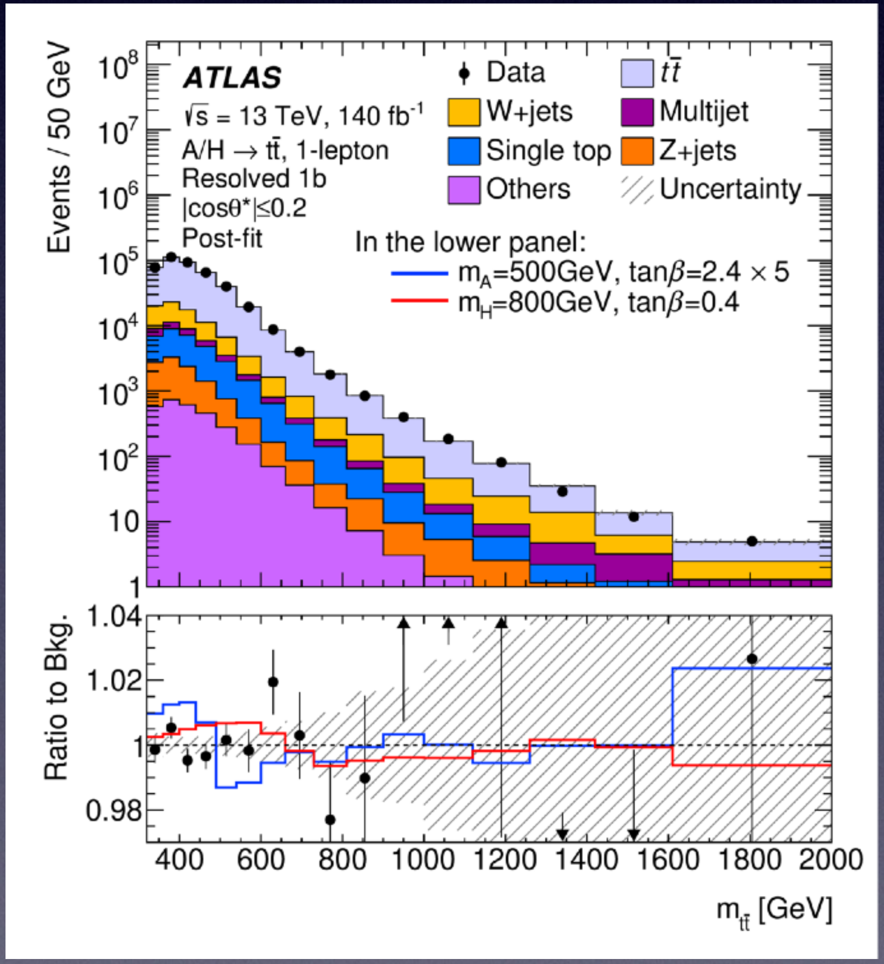


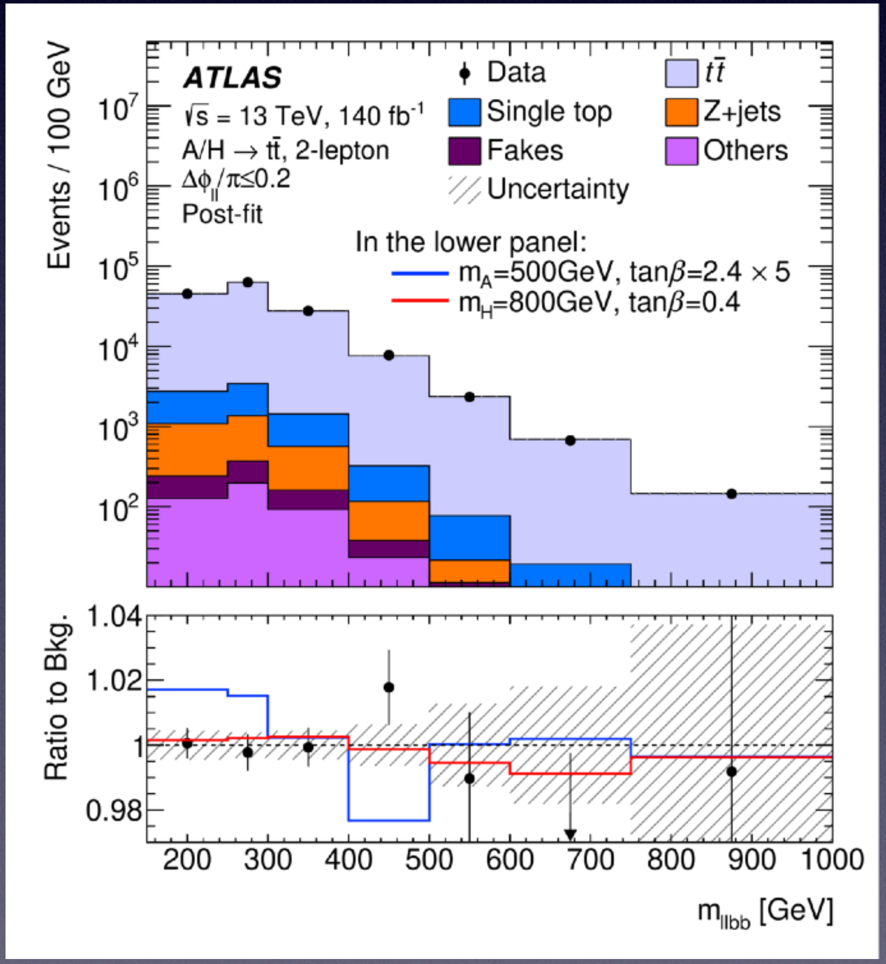
$A/H \to t\bar{t}$ (1 and 2 lepton) results

Examples of data/background comparisons

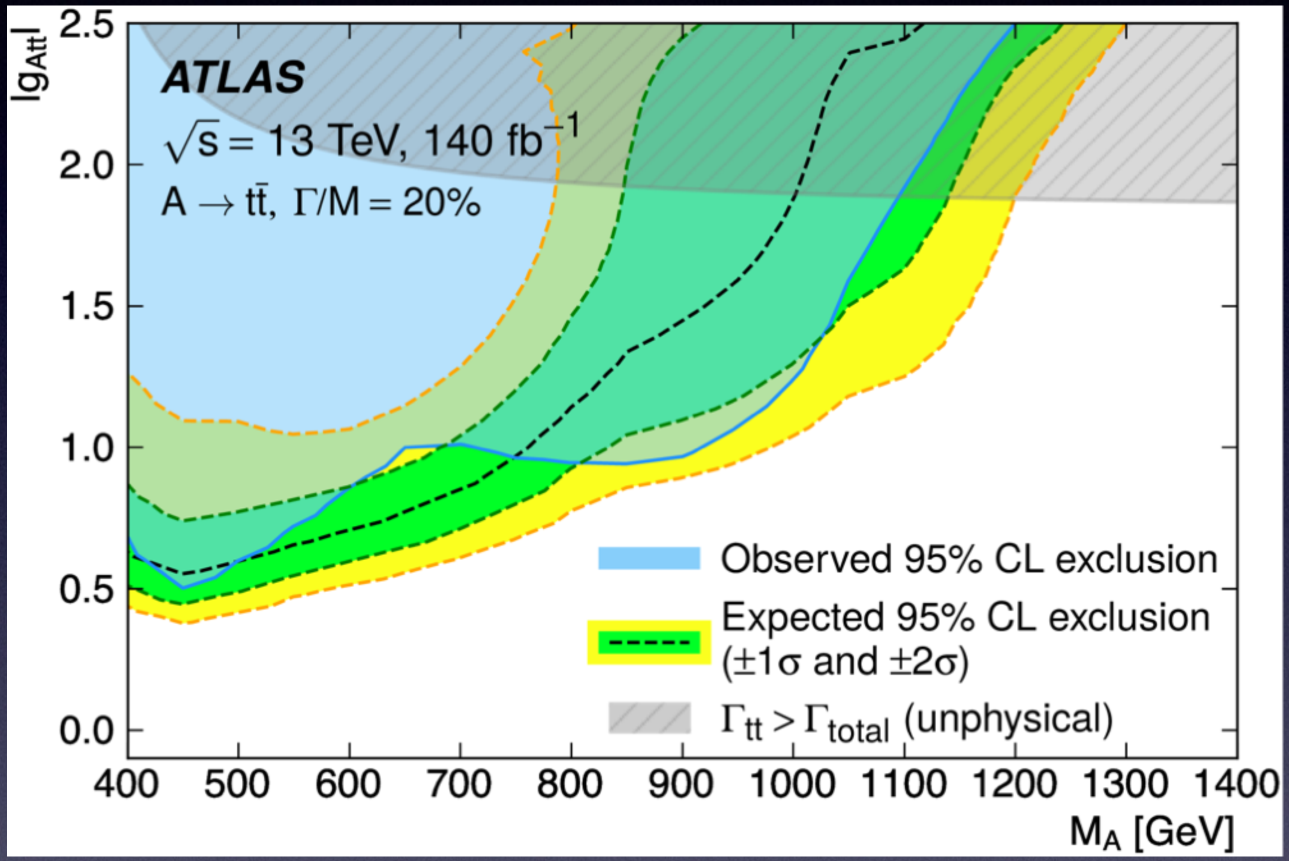
No significant deviations, leading to model-dependent limits

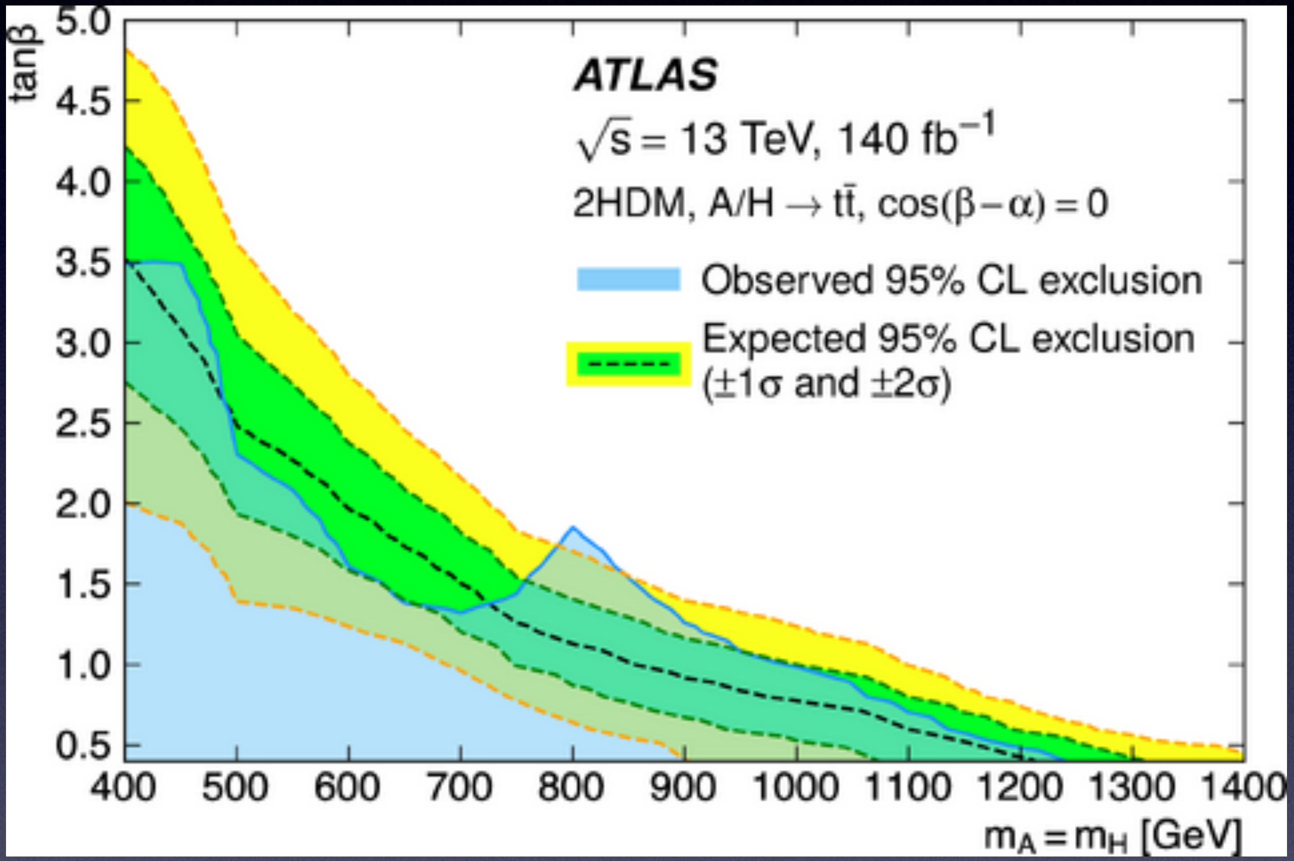






$A/H \to t\bar{t}$ (1 and 2 lepton) results

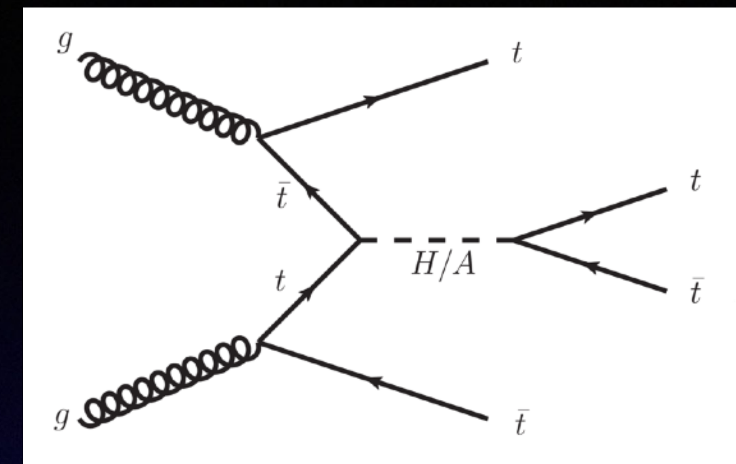




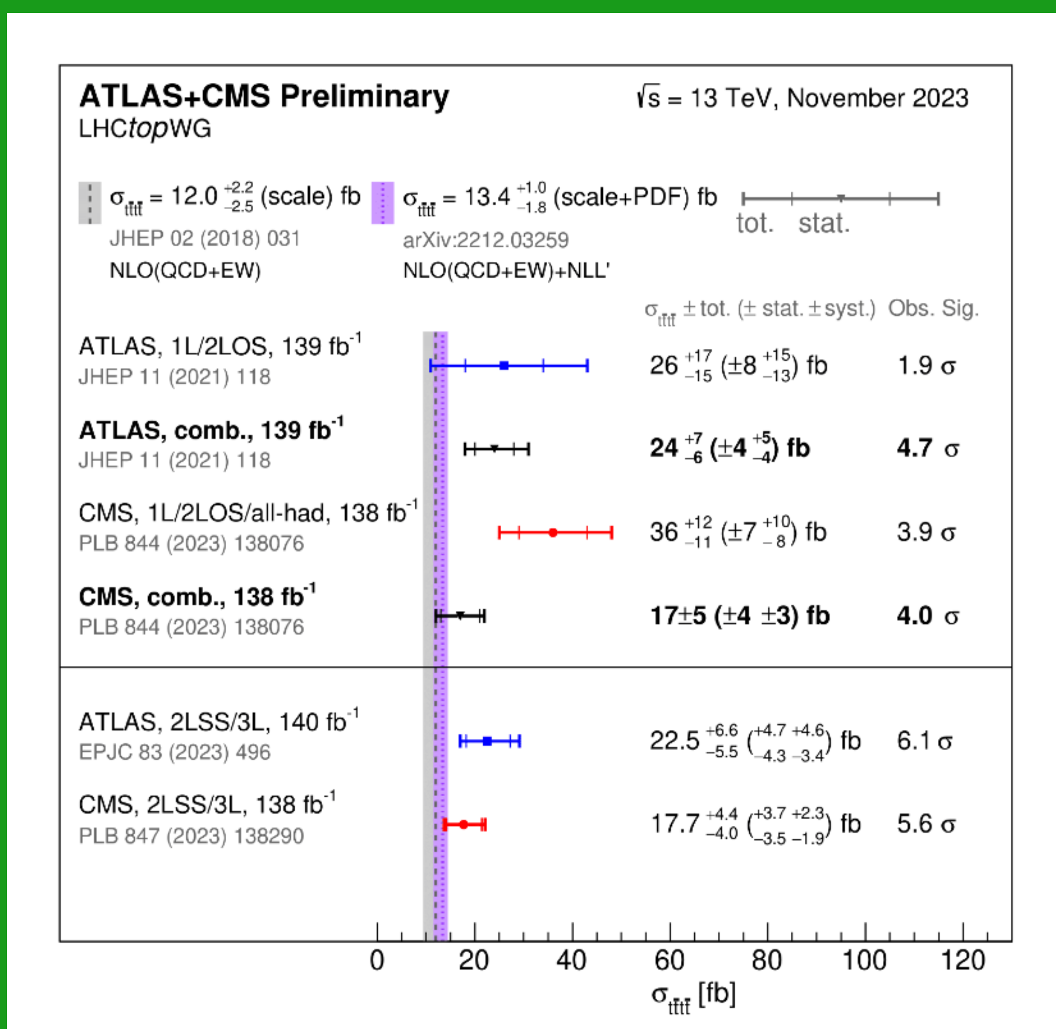
$t\bar{t}A/H \to t\bar{t}t\bar{t}$

$A/H \to t\bar{t}$ also accessible in $t\bar{t}t\bar{t}$ events

Interference effects are much smaller



$t\bar{t}t\bar{t}$ recently observed, and measured cross section leaves room for BSM contributions



Analysis topologies:

Single lepton or two opposite-sign leptons (1L/2LOS)

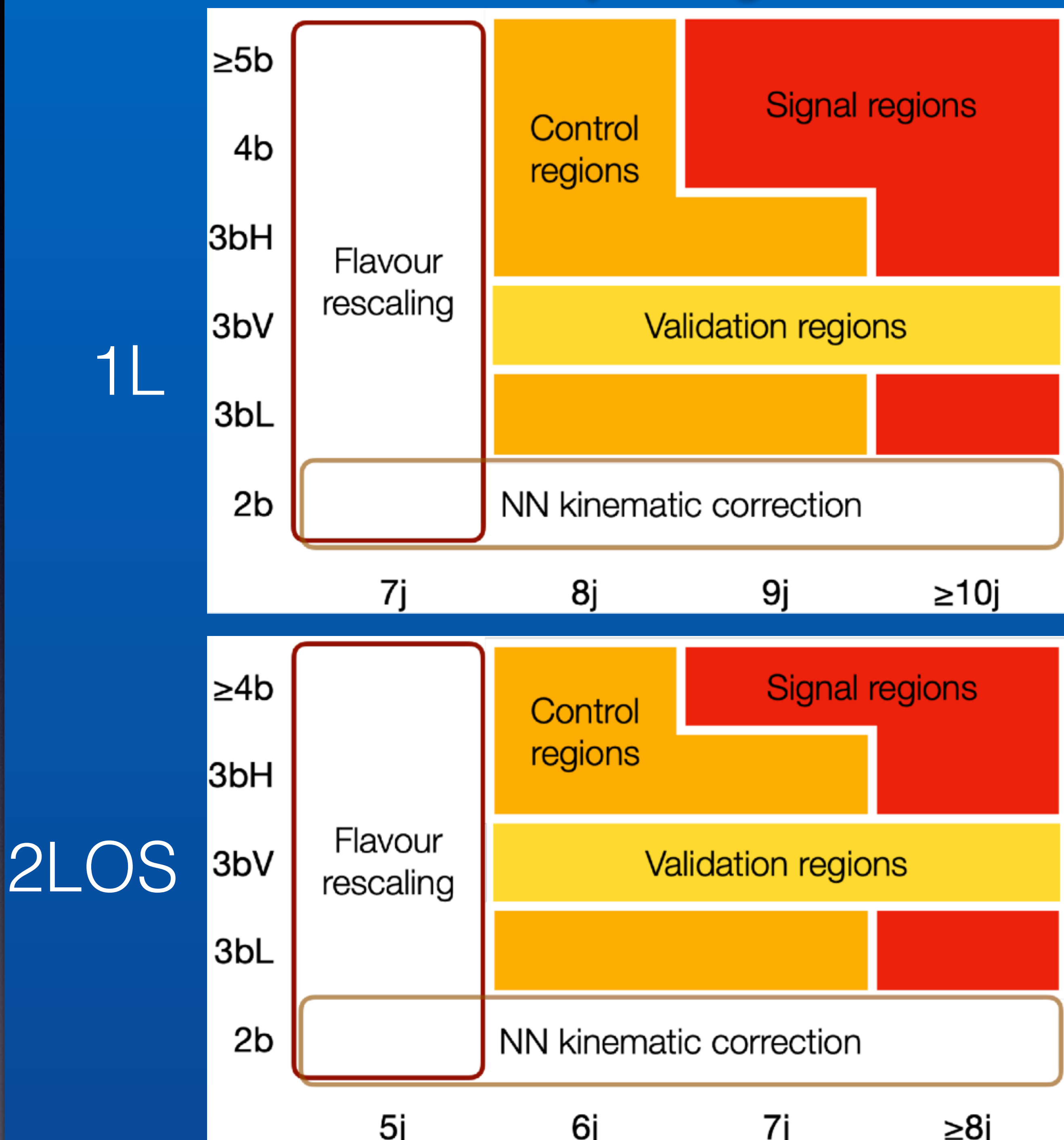
Large branching fraction, but also large background from $t\bar{t}+$ jets

Two same-sign leptons or ≥ 3 leptons (2LSS/ML)

Smaller branching fraction, but much smaller backgrounds (dominant: $t\bar{t} + (W, Z, H)$)

$t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

1L/2LOS analysis regions



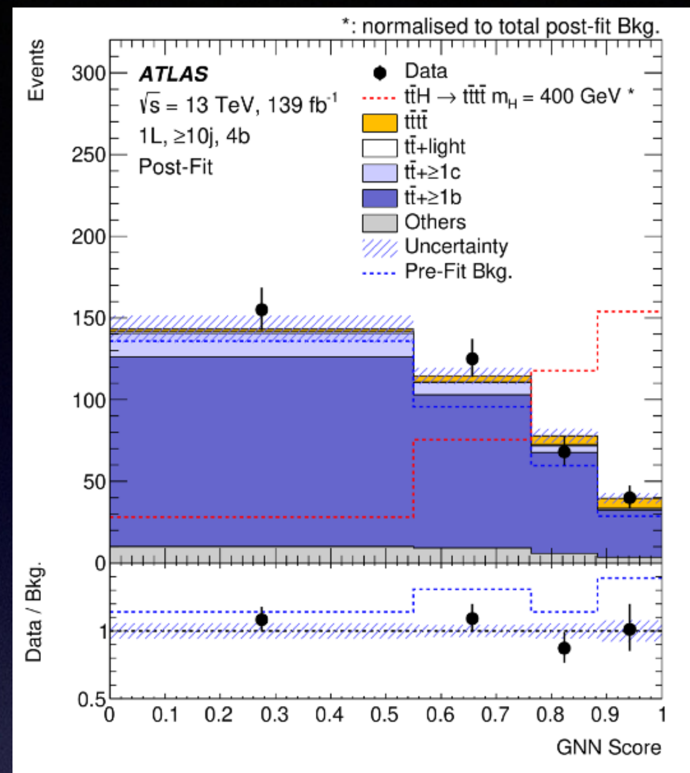
GNN used for S/B discrimination

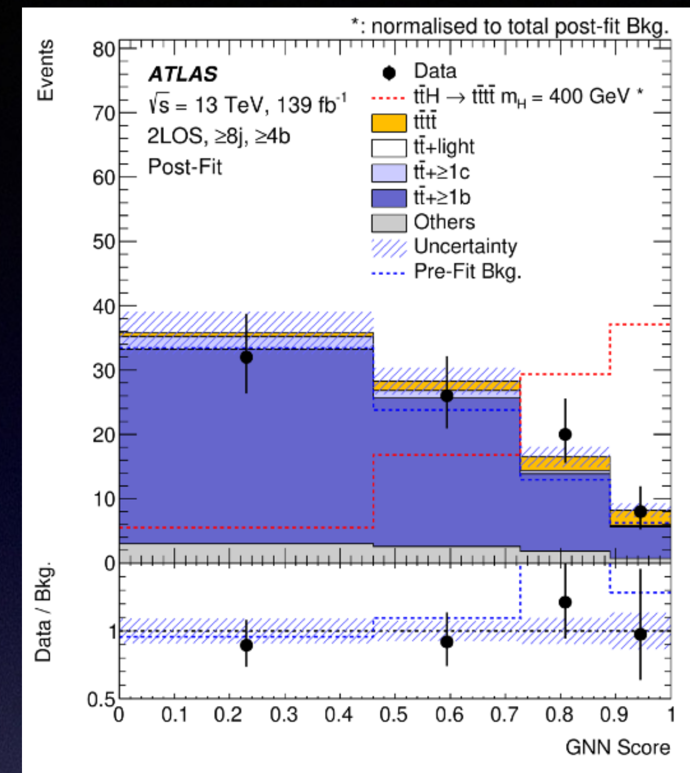
Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	–	= 2	–
3bL	≤ 2	= 3	–
3bH	= 3	= 3	> 3
3bV	= 3	= 3	= 3
≥4b (2LOS)	–	≥ 4	–
4b (1L)	–	= 4	–
≥5b (1L)	–	≥ 5	–

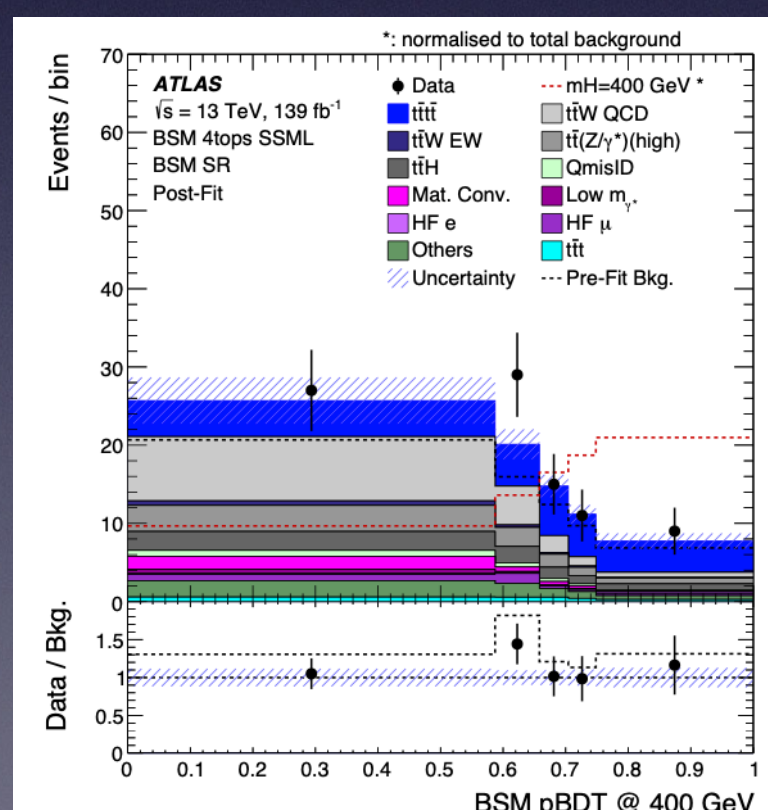
2LSS/3L analysis uses a single signal region with: ≥ 6 jets (≥ 2 of them *b*-tagged), H_T > 500 GeV, and BDT trained for SM > 0.55

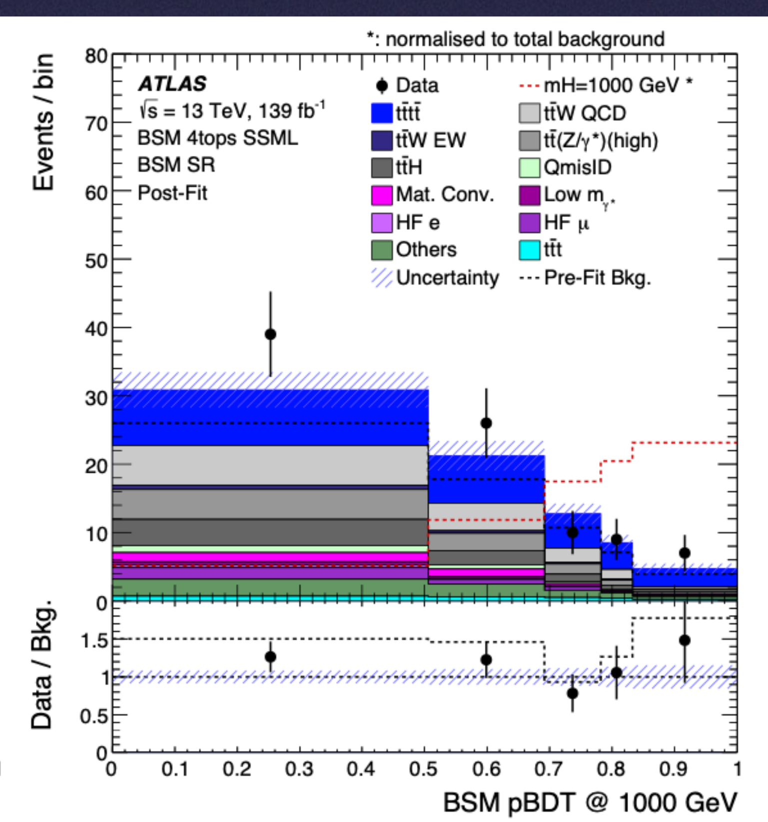
Separate BDT is trained to discriminate A/H production from SM $t\bar{t}t\bar{t}$

$t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ results

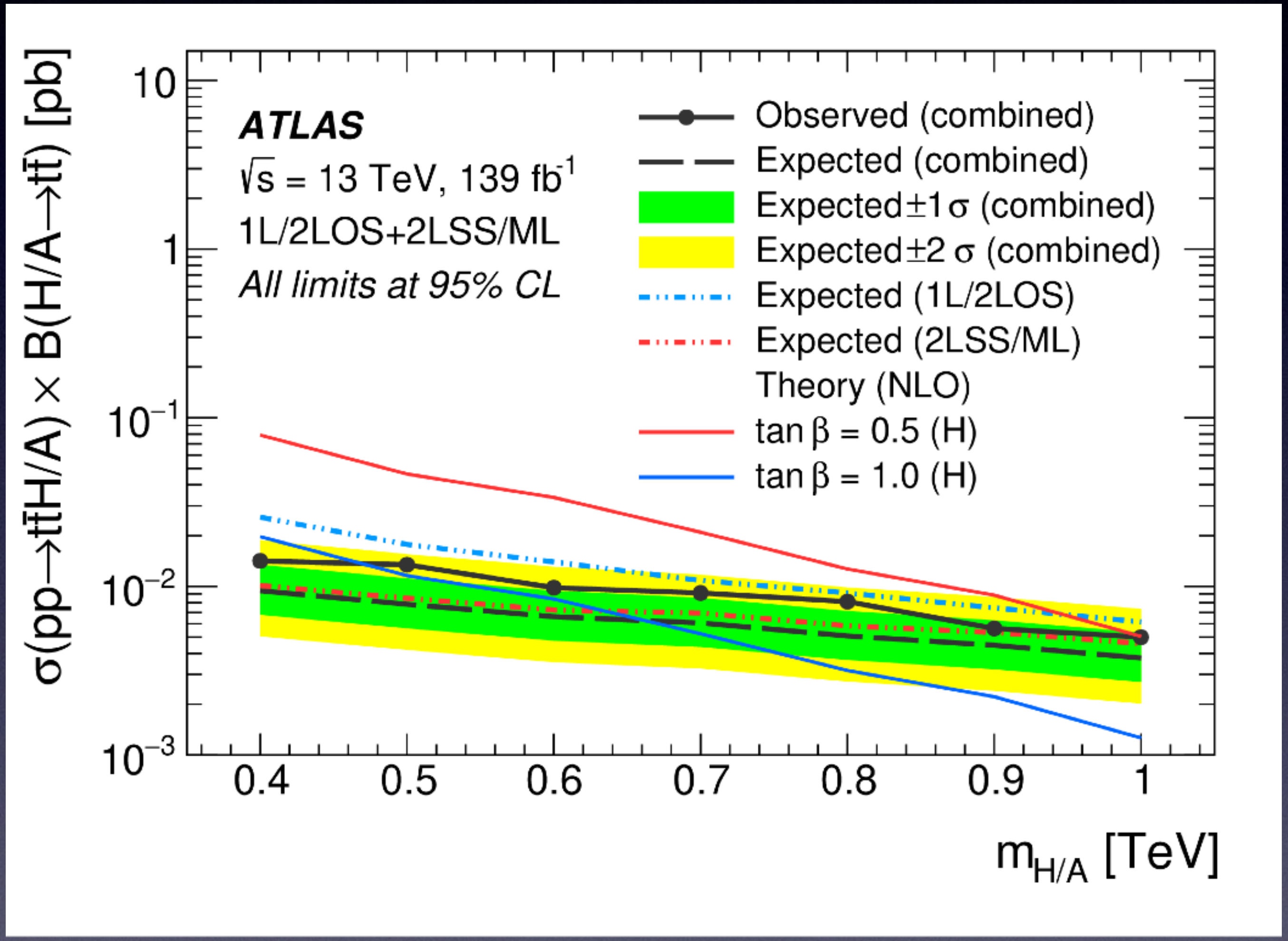


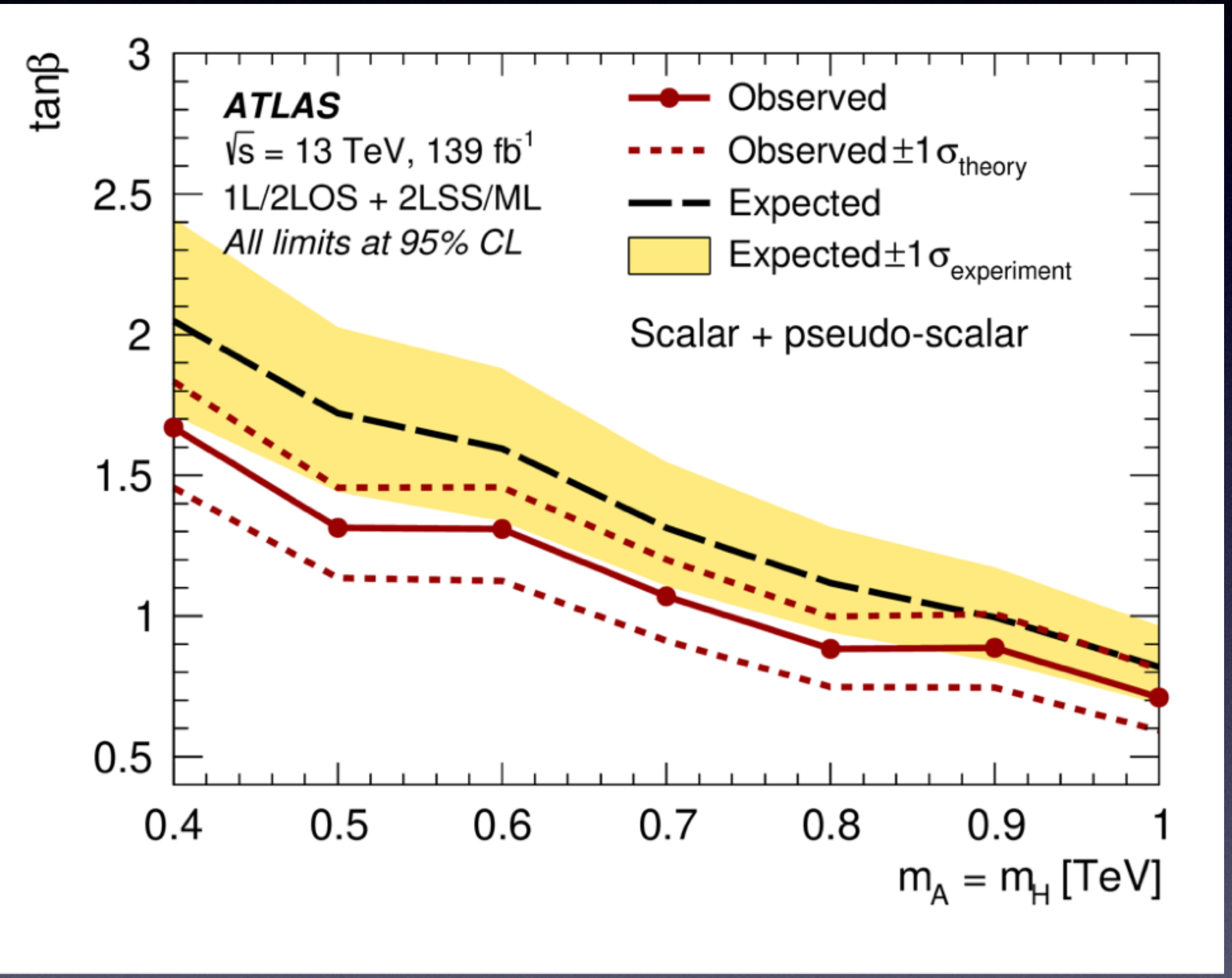






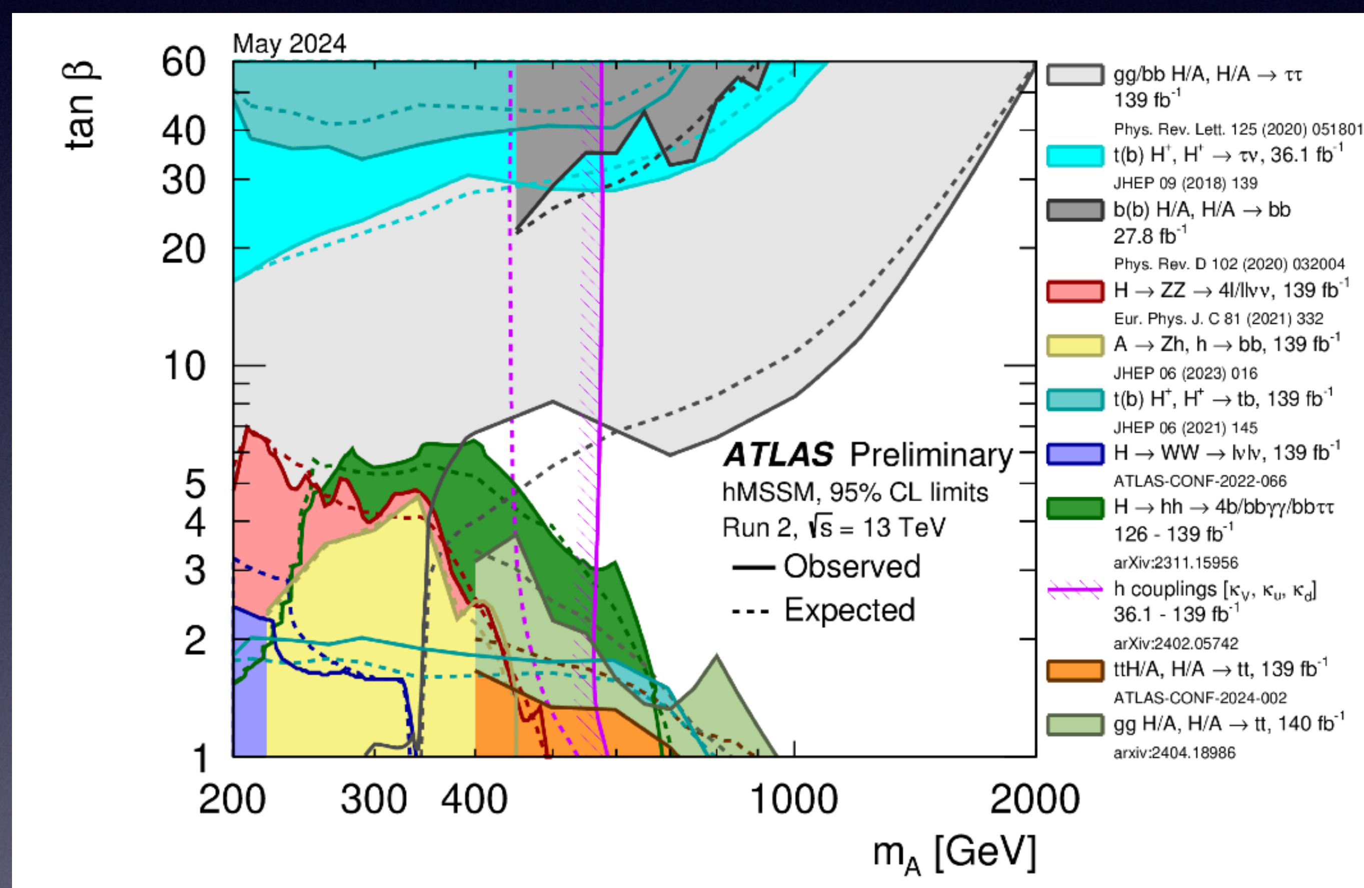
$t\bar{t}A/H \to t\bar{t}t\bar{t}$ results





Summary

- The ATLAS search program for additional scalar bosons spans a wide range of masses, couplings, and signatures
  - no evidence uncovered so far, leading to exclusions of some models/parameters



Still plenty of reasons to look for additional scalars, and many places left to search

Backup

Low-mass $\gamma\gamma$ Uncertainties

Source	Uncertainty [%]	Remarks
Signal yield		
Luminosity	±0.83	
Electron-photon ambiguity BDT efficiency	±0.7	
Trigger efficiency	±1.0 – 1.5	m_X-dependent
Photon identification efficiency	±1.8 – 3.0	m_X-dependent
Photon isolation efficiency	±1.6 – 2.4	m_X-dependent
Photon energy scale	±0.1 – 0.3	m_X-dependent
Photon energy resolution	±0.1 – 0.15	m_X-dependent
Pile-up	±1.6 – 5.0	m_X-dependent
Production mode	±4.3 – 29	m_X-dependent (model-independent only)
Signal modelling		
Photon energy scale	±0.3 – 0.5	m_X- and category–dependent
Photon energy resolution	±3 – 10	m_X- and category-dependent
Migration between categories		
Material	−2.0 / +1.0 / +4.1	category-dependent
DY background modelling		
Peak position	±0.1 – 0.2	category-dependent
Peak width	±1.9 – 3.5	category-dependent
Normalisation	±7.1 – 13	category-dependent
Continuum background (model-dependent)		
Spurious signal, NWA	9 – 171 events, (10% – 50%)	m_X- and category-dependent
Continuum background (model-independent)		
Spurious signal, NWA	37 – 310 events, (20% – 50%)	m_X- and category-dependent
Spurious signal, Γ_X/m_X = 1.0%	65 – 539 events, (20% – 50%)	m_X- and category-dependent
Spurious signal, Γ_X/m_X = 2.5%	92 – 879 events, (20% – 50%)	m_X- and category-dependent

$t \to H^+ b \to csb$ BDT inputs

Variable type	Variable name	Definition
Top-quark kinematic variables		
t_{had}	j_1 p_{T}	p_{T} of j_1-labelled jet
	j_2 p_{T}	p_{T} of j_2-labelled jet
	b_{had} p_{T}	p_{T} of b_{had}-jet
	$b_{\mathrm{had}}^{t_{\mathrm{had}}-\mathrm{rest}}$ p	Momentum of b_{had}-jet in t_{had} rest frame
	dijet mass	Invariant mass of j_1+j_2 jets
	(j_1+b_{had}) mass	Invariant mass of j_1+b_{had} jets
	(j_2+b_{had}) mass	Invariant mass of j_2+b_{had} jets
	$\cos\theta$	Boson spin sensitive variable
t_{lep}	b_{lep} p_{T}	p_{T} of b_{lep}-jet
	Lepton p_{T}	p_{T} of reconstructed lepton
	W mass	Invariant mass of reconstructed W boson
	t_{lep} mass	Invariant mass of reconstructed t_{lep}
	t_{lep} p_{T}	p_{T} of reconstructed t_{lep}
$t\bar{t}$-system	$\Delta R(b_{\mathrm{lep}}, b_{\mathrm{had}})$	ΔR between the b_{lep}-jet and b_{had}-jet
	$t\bar{t}$ mass	Invariant mass of t_{had}+t_{lep}
Event variables		
Event level	N_{jets}	Number of jets in the event
	S_{T}	Scalar p_{T} sum of all calibrated objects
	$\overline{P}_{t\bar{t}}$	Normalised probability of correct jet labelling
Flavour-tagging variables		
Flavour-tagging score	j_1 PCFT	PCFT score of j_1
	j_2 PCFT	PCFT score of j_2
	b_{had} PCFT	PCFT score of b_{had}-jet
	b_{lep} PCFT	PCFT score of b_{lep}-jet
Number of tags	$N_{c\text{-tagLo}}$	Number of jets passing loose c-tag WP (b-veto)
	$N_{c\text{-tagTi}}$	Number of jets passing tight c-tag WP (b-veto)
	$N_{b\text{-tag70}}$	Number of jets passing 70 % b-tag WP
	$N_{b\text{-tag60}}$	Number of jets passing 60 % b-tag WP

$t \to H^{+}b \to csb$ Uncertainties

$H^{\pm}_{80}$ Category	Relative contribution	$H^{\pm}_{150}$ Category	Relative contribution
Data statistical	6 %	**Data statistical**	38 %
Systematic	99.8 %	**Systematic**	93 %
Flavour-tagging	64 %	$t\bar{t}$ modelling	72 %
MC statistical	64 %	MC statistical	35 %
$t\bar{t}$ modelling	50 %	Weak-boson & MJ modelling	27 %
$\mu_{t\bar{t}}$ & f_{LF}	21 %	Single-top-quark modelling	25 %
Jet	19 %	$\mu_{t\bar{t}}$ & f_{LF}	24 %
Single-top-quark modelling	16 %	Jet	23 %
Luminosity & pileup	15 %	Flavour-tagging	20 %
Weak-boson & MJ modelling	12 %	Lepton & $E_{\mathrm{T}}^{\mathrm{miss}}$	8 %
Signal modelling	8 %	Luminosity & pileup	7 %
Lepton & $E_{\mathrm{T}}^{\mathrm{miss}}$	7 %	Signal modelling	5 %

$A/H \to t\bar{t}$ (1 and 2 lepton) Uncertainties

Uncertainty component	Fractional contribution [%] m_A = 800 GeV $\tan\beta$ = 0.4	Fractional contribution [%] $m_A = m_H$ = 500 GeV $\tan\beta$ = 2.0
Experimental	**30**	**42**
Small-R jets (JER, JES)	22	29
Large-VR jets	11	20
Flavour tagging	13	17
Leptons	4	5
Other ($E_{\mathrm{T}}^{\mathrm{miss}}$, luminosity, pile-up, JVT)	10	14
Modelling: SM $t\bar{t}$ and signal	**91**	**79**
$t\bar{t}$ NNLO	49	28
$t\bar{t}$ lineshape	27	29
$t\bar{t}$ ME-PS ($p_{\mathrm{T}}^{\mathrm{hard}}$)	36	30
$t\bar{t}$ ME-PS (h_{damp})	41	25
$t\bar{t}$ ISR& FSR	9	13
$t\bar{t}$ PS	29	41
$t\bar{t}$ cross-section	21	31
$t\bar{t}$ Scales & PDF	21	16
m_t	6	4
Signal	19	9
Modelling: other	**41**	**16**
W+jets	11	8
Z+jets	1	2
Multijet	27	10
Fakes	<1	1
Other bkg.	29	10
MC statistics	**18**	**26**
Total systematic uncertainty	**±100**	**±100**
Total statistical uncertainty	**< 1**	**< 1**

$t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ GNN variables (1L/2LOS)

Variable	Description
$\sum_{i\in[1,6]} \mathrm{pcb}_i$	Sum of the pcb scores of the six jets with the highest scores
H_{T}	p_{T} sum of all reconstructed leptons and jets
N_{jets}	Number of jets
$H_{\mathrm{T}}^{\mathrm{ratio}}$	p_{T} sum of the four leading jets in p_{T} divided by the p_{T} sum of the remaining jets
$dR_{jj}^{\mathrm{avg.}}$	Average ΔR across all jet pairs
m_{T}^{W}	W boson transverse mass calculated using the lepton four-momenta and $E_{\mathrm{T}}^{\mathrm{miss}}$ (1L only)
$\Delta R_{bb}^{\mathrm{min.}}$	Minimum ΔR between any pair of jets b-tagged at the 70% OP
$\Delta R_{\ell b}^{\mathrm{min.}}$	Minimum ΔR between any pair of lepton and jet b-tagged at the 70% OP
$m_{bbb}^{\mathrm{avg.}}$	Average invariant mass of all triplets of jets b-tagged at the 70% OP
$m_{jjj}^{\mathrm{avg.}}$	Average invariant mass of all triplets of jets with an angular separation of $\Delta R < 3$
$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} over all large-R jets
$\sum d_{23}$	Sum of the second k_t splitting scale d_{23} over all large-R jets
$N_{\mathrm{LR\text{-}jets}}$	Number of large-R jets with a mass greater than 100 GeV
Centrality	$\sum_i p_{\mathrm{T}}^i / \sum_i E_i$ where the sums are performed over all reconstructed jets and leptons
$m_{\ell\ell}$	Invariant mass of the two leptons (2LOS only)

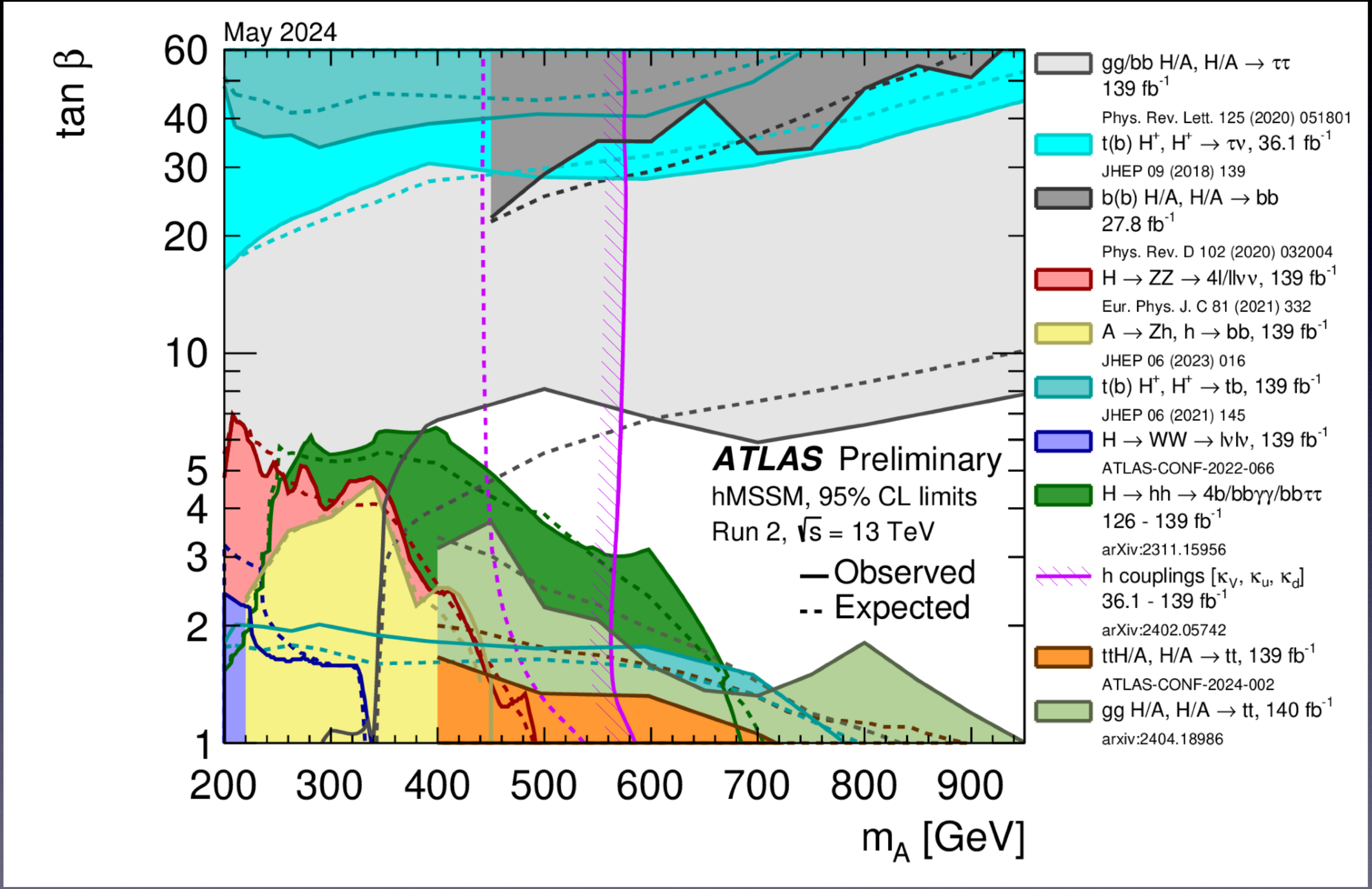
$t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ Uncertainties (1L/2LOS)

Uncertainty source	$\Delta\sigma_{t\bar{t}H/A\rightarrow t\bar{t}t\bar{t}}$ [fb]					
	$m_{H/A}$=400 GeV		$m_{H/A}$=700 GeV		$m_{H/A}$=1000 GeV	
Signal Modelling						
BSM $t\bar{t}t\bar{t}$ modelling	< 1		+0.1	< 0.1	< 0.1	
Background Modelling						
$t\bar{t}+\geq1b$ modelling	+11	-10	+3.7	-3.4	+1.9	-1.7
SM $t\bar{t}t\bar{t}$ modelling	+3	-3	+2.1	-2.1	+0.9	-0.9
$t\bar{t}$+jets reweighting	+3	-3	+1.0	-1.0	+0.5	-0.5
$t\bar{t}+\geq1c$ modelling	+2	-2	+0.9	-0.8	+0.4	-0.4
$t\bar{t}$+light modelling	+1	-1	+0.2	-0.2	< 0.1	
Other background modelling	< 1		+0.4	-0.4	+0.2	-0.2
Experimental						
Jet energy scale and resolution	+4	-2	+1.3	-0.8	+0.5	-0.3
MC statistical uncertainties	+2	-3	+0.6	-0.7	+0.4	-0.4
b-tagging efficiency	+2	-1	+0.7	-0.4	+0.4	-0.4
Other uncertainties	< 1		+0.3	-0.5	+0.1	-0.2
Luminosity	< 1		+0.3	-0.1	< 0.1	
Total systematic uncertainty	+13	-12	+4.8	-4.6	+2.5	-2.4
Statistical uncertainty	+6	-6	+3.3	-3.2	+2.3	-2.2
Total uncertainty	+14	-13	+5.6	-5.4	+3.2	-3.0

$t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ Uncertainties (2LSS/ML)

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}H(\rightarrow t\bar{t})$	+0.01	−0.00
Background modelling		
$t\bar{t}t\bar{t}$	+0.17	−0.17
$t\bar{t}W$	+0.07	−0.07
$t\bar{t}t$	+0.06	−0.05
Non-prompt leptons	+0.05	−0.05
$t\bar{t}Z$	+0.05	−0.05
$t\bar{t}H$	+0.03	−0.03
Other background	+0.03	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.09
Jet flavour tagging (b-jets)	+0.05	−0.04
Jet flavour tagging (light-flavour jets)	+0.04	−0.03
Luminosity	+0.03	−0.02
Jet flavour tagging (c-jets)	+0.02	−0.02
Other experimental uncertainties	+0.02	−0.02
MC statistical uncertainty		
Simulation sample size	+0.04	−0.04
Total systematic uncertainty	+0.31	−0.28
Statistical		
HF, Mat. Conv., and Low $m_{\gamma*}$ normalisation	+0.05	−0.04
$t\bar{t}W$ QCD normalisation	+0.05	−0.04
Total statistical uncertainty	+0.35	−0.32
Total uncertainty	+0.46	−0.41

Additional Exclusion Plots



Additional Exclusion Plots