Searches for additional Higgs bosons in ATLAS

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ATLAS collaboration
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Introduction

- Many BSM theories predict **extended Higgs sector**
- Typically assume additional Higgs doublet: 2 Higgs Doublet Models (**2HDM**)
- Results in 2 CP even neutral, 1 CP odd neutral, 2 charged Higgs

h	H	A	H^+	H^-

- h or H could be the one observed at 125 GeV
  - Any BSM model must be compatible with this
- 2HDM includes SUSY scenarios (type-II), typically hMSSM
- Proposed SUSY benchmarks, M_h^{125}, $M_H^{125}(\chi)$ etc.
  - See Bahl, H., Fuchs, E., Hahn, T., et al.
- Other models (eg. 3HDM) extend to a Higgs triplet
  - Also gives doubly charged scalar Higgs

BSM Higgs Searches

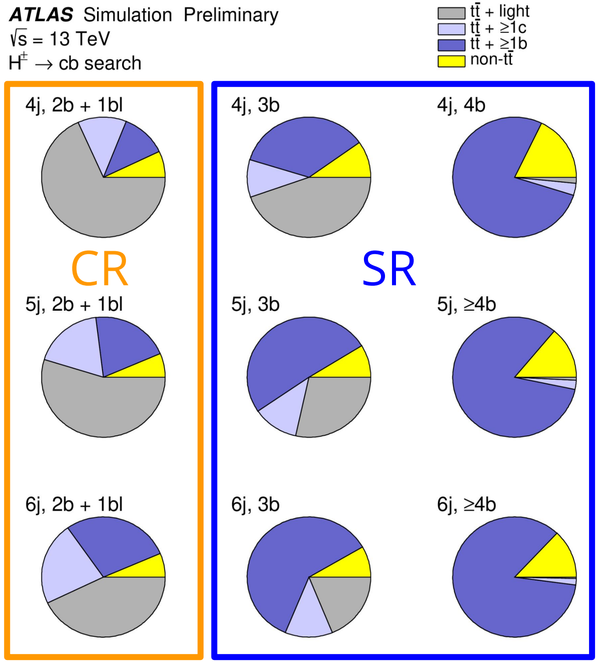
- ATLAS Higgs searches include:
  - **Heavy** and **light** (< h_{125} mass) cases
  - **Charged** and **neutral**
- General resonance searches can also apply to BSM Higgs from 2HDM
  - Talk by Shuo Han, resonance decays with l / γ final states (eg. $X \to \gamma\gamma$, $X \to ZZ \to 4l$ / $ll\nu\nu$)
  - Talk by Bill Balunas, searches for diboson decays of new particles (eg. $X \to bb\tau\tau$, $X \to bbbb$)
- Will focus on other recent ATLAS analyses with the full Run 2 dataset
- Also consider 2HDM+a models; add fermionic dark matter particle with pseudoscalar a that couples to both the SM and dark matter. See ATLAS-CONF-2021-036

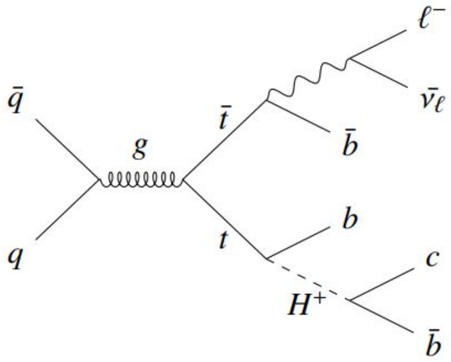
Links to selection of recent 139 fb^{-1} searches

$H^{\pm} \to cb$	ATLAS-CONF-2021-037
$X \to h_{125}h_{125} \to bbbb$	ATLAS-CONF-2021-035
$X \to h_{125}h_{125} \to bb\tau\tau$	ATLAS-CONF-2021-030
$H^{\pm\pm} \to W^{\pm}W^{\pm}$, $H^{\pm} \to W^{\pm}Z$	JHEP 06 (2021) 146
$H^{\pm} \to tb$	JHEP 06 (2021) 145
$A \to ZH \to llbb$ / $llWW$	EPJC 81, 396 (2021)
$X \to ZZ \to 4l$ / $ll\nu\nu$	EPJC, 81, 332 (2021)
$X \to h_{125}h_{125} \to bb\gamma\gamma$	ATLAS-CONF-2021-016
$h_{125} \to aa \to bb\mu\mu$	ATLAS-CONF-2021-009
$X \to VH \to qqbb$	Phys. Rev. D 102 112008 (2020)
$h_{125} \to Za \to ll\,j$	Phys. Rev. Lett. 125, 221802 (2020)
$A/H \to \tau\tau$	Phys. Rev. Lett. 125, 051801 (2020)
$h_{125} \to aa \to bbbb$	Phys. Rev. D 102, 112006
$A \to Zh_{125} \to llbb$ / $\nu\nu bb$	ATLAS-CONF-2020-043

$H^\pm \to cb$

- New 139 fb^{-1} search for $H^\pm$ produced from $t \to bH^\pm$
- In **3HDM** lightest $H^\pm$ can be lighter than t, can decay predominantly into cb: low mass $H^\pm$ search



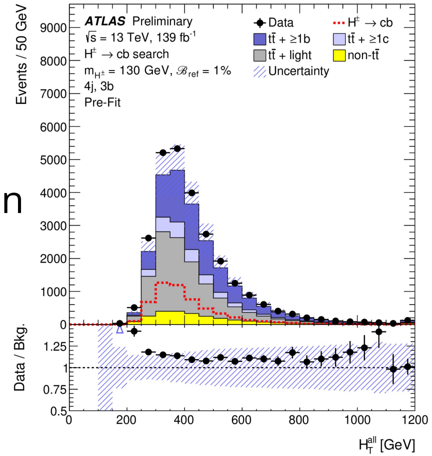


- End up with 1 lepton, 3 b-jet, 1 c-jet final state
- Use single e/μ trigger, 20-26 GeV thresholds
  - Main background from tt + jets
- Categories based on number of jets and b-jets
  - Includes a 2 b-jet + 1 bl category, where one b-jet is allowed a looser b-tag requirement

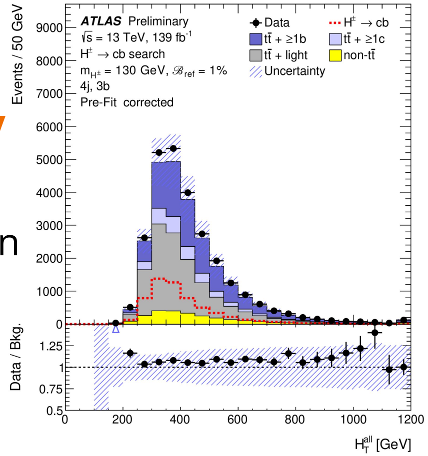
$H^{\pm} \rightarrow cb$: Top Background

- **SM tt + jets** is the main background, modelled using simulation
- Does not completely reproduce jet multiplicity and p_T distributions
- Therefore, use **data-driven correction from 2b+1bl regions**
  - The 1 borderline b-jet allows for a CR very close to the SR
  - Derive correction factor in each of 4/5/6 jet categories
- See modelling improve after correction is applied

Before correction

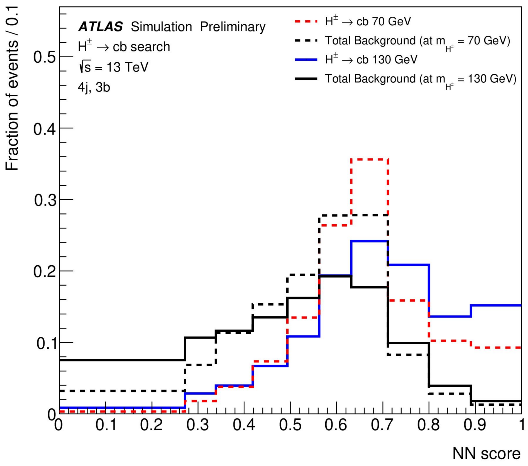


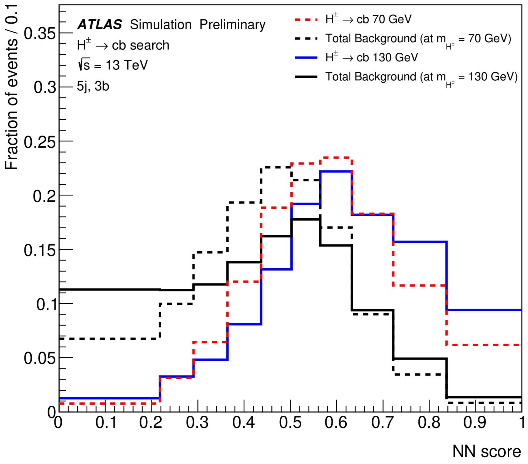
After correction



$H^{\pm} \rightarrow cb$: MVA Techniques

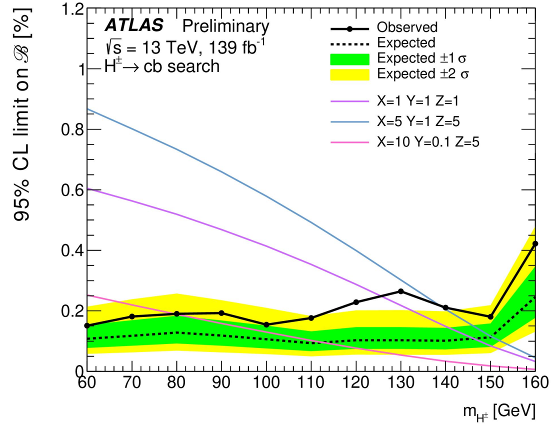
- Use feed-forward NN, total of 30 variables
- Includes low level kinematics from lepton, E_T^{miss}, jets
- Also use b-tag scores of jets and di-jet invariant mass variables:
  - Sort jets according to b-tagging scores, 4th jet expected to be the c-jet
  - Calculate invariant mass of each jet with 4th jet
- Train on events with at least 4 jets with at least 3 b-tagged
- **Parameterised as a function of H^+ signal mass**.

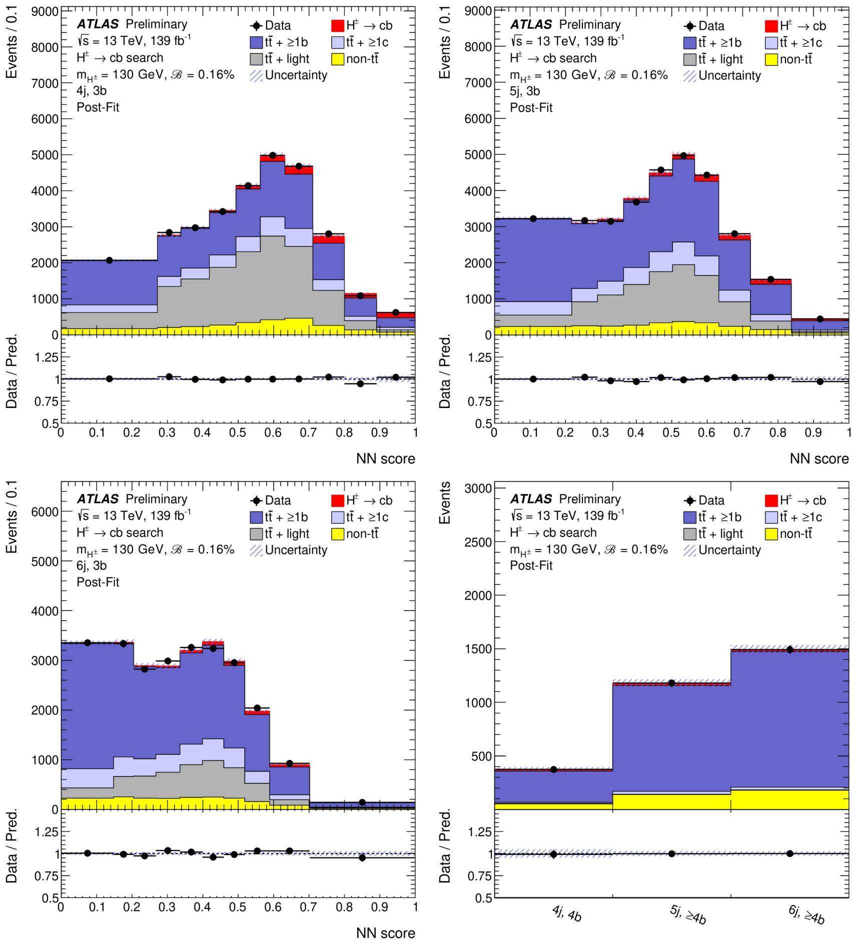




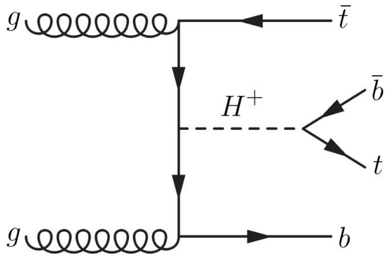
$H^{\pm} \rightarrow cb$: Results

- **NN score used as discriminating variable**, fit simultaneously across all signal regions
- 4 b-jet regions have limited stats or smaller signal contributions so only 1 bin is used
  - Also larger uncertainties here due to dominant tt+b background
- Upper limits set on $B(t \rightarrow H^{\pm}b) \times B(H^{\pm} \rightarrow cb)$, 3HDM benchmarks shown

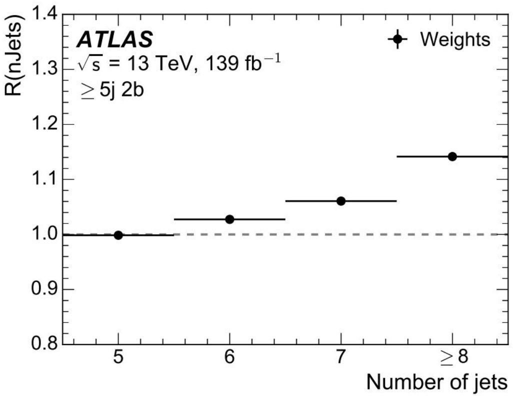


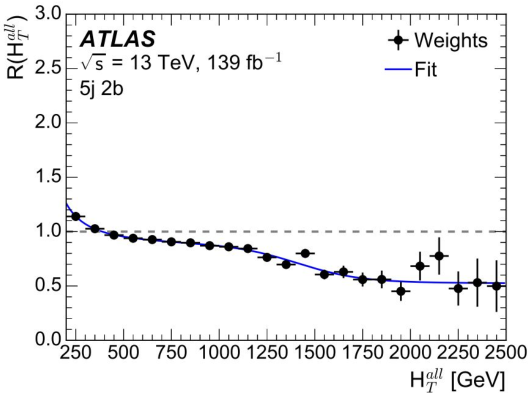


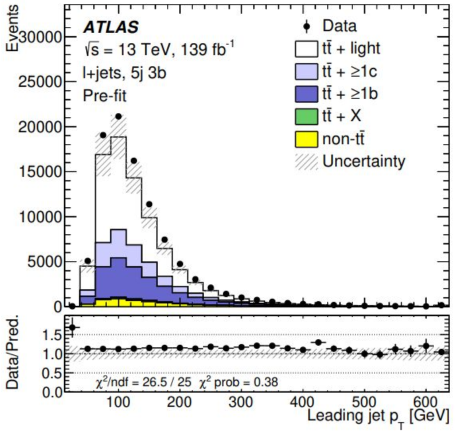
$H^{\pm} \rightarrow tb$



- **Primary H^+ decay mode for $m(H^+) > m(t)$**
- Result now with 139 fb^{-1}, update from 36 fb^{-1} result
- **Lepton + jets final states**, lepton trigger with 4 signal regions:
  - 5j 3b, 5j ≥4b, ≥6j 3b, ≥6j ≥4b (XjYb = X jets found, Y of those b-tagged)
- Estimate backgrounds from simulation, **dominated by top processes**
- Require data based correction to tt+jets, measure data/MC in =5/=6/=7/≥8j 2b regions
  - Events weighted by the product of N_{jets} (left) and Σ p_T (jets, l) (centre)

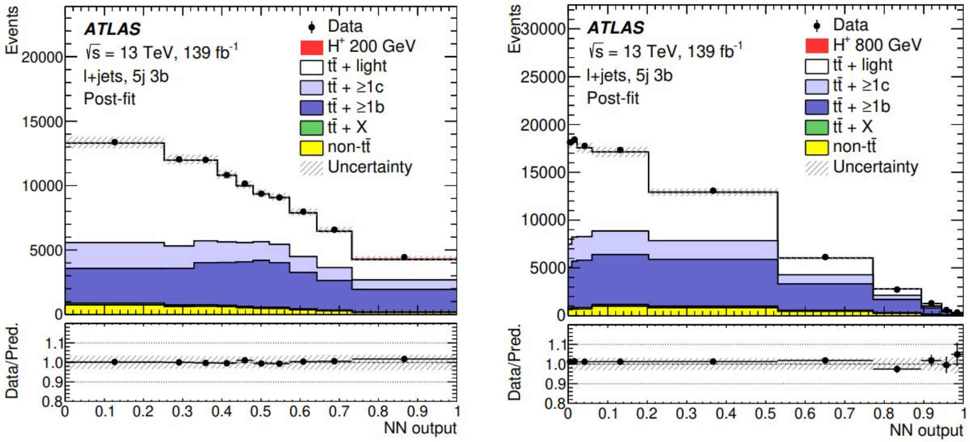






$H^{\pm} \longrightarrow tb$: MVA Technique

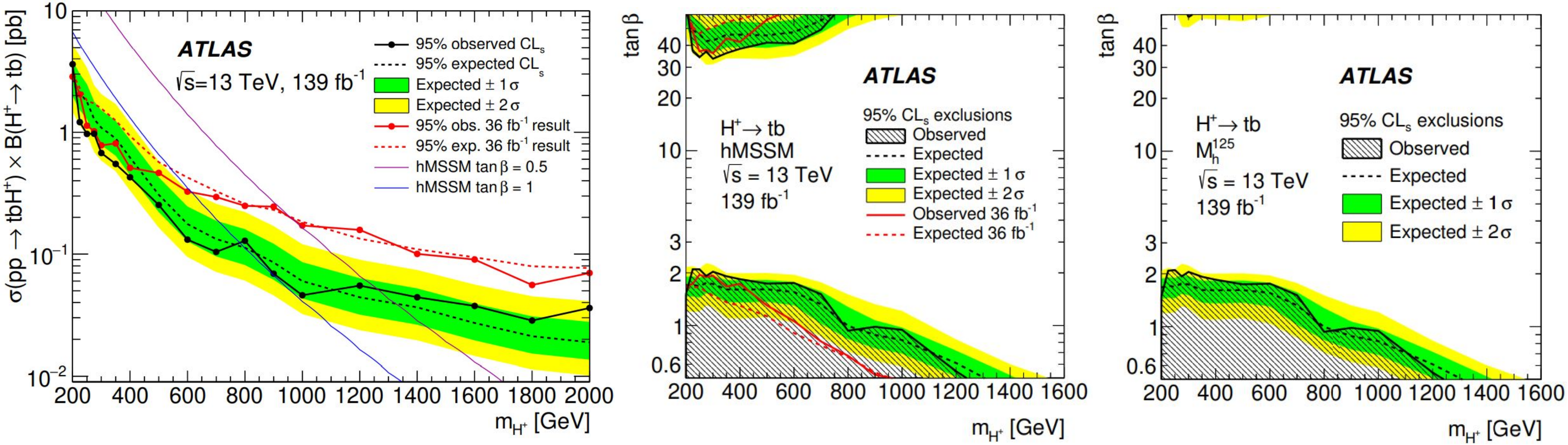
- Uses MVA discriminant in each category
- Now uses Keras NN, **parameterised as a function of H^{+} signal mass**
  Train all signals against all backgrounds, total of 15 variables used
  - Used BDTs in previous analysis



- Classifier output used as discriminating variable, perform statistical fit simultaneously in the 4 signal regions

$H^{\pm} \longrightarrow tb$: Results

- Main systematics related to tt background modelling, jet flavour tagging, jet energy scale and resolution. Consider effect on both normalisation and shape
- Results now include exclusions on M_h^{125} models, most sensitive channel for low tan β

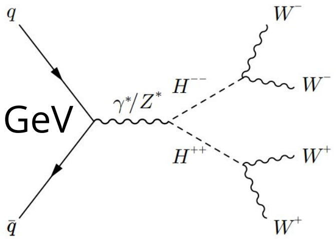


- Low mass dominated by systematics
- At high mass see improvement beyond that expected from scaling integrated luminosity. Comes from **MVA**, **tighter lepton triggers**, and **b-tagging updates**

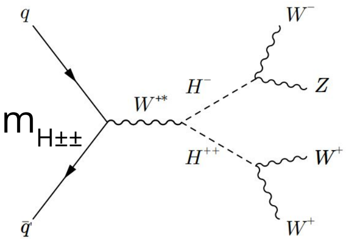
$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ and $H^{\pm} \rightarrow W^{\pm}Z$

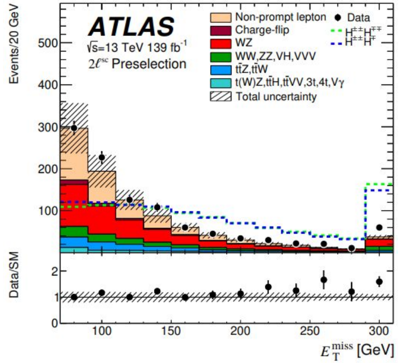
- Doubly charged H arise in **Type II seesaw models**
  - With non-zero neutrino mass, $H^{\pm\pm}$ predominantly decay to WW and leptonic decays suppressed
- **Final states of leptons, MET and jets**. Use categories based on leptons: 2l (++), 3l (++-), 4l (++-- or +++-)
  - Preselection based on E_T^{miss}, N_{jets}, $N_{b\text{-}jets}$ for the 3 channels
- Added $H^{\pm\pm}$ $H^{\pm}$ production channel since 36 fb^{-1} result
- Target two production modes where $H^{\pm\pm}$ decays predominantly to $W^{\pm}W^{\pm}$:

$m_{H\pm} > m_{H\pm\pm}$ + 100 GeV

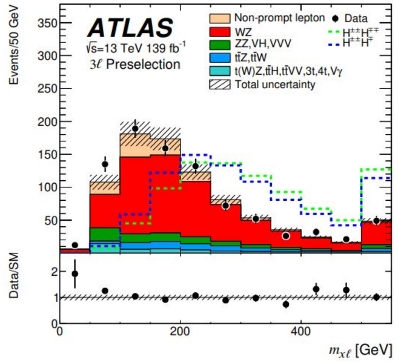


$m_{H\pm} \approx m_{H\pm\pm}$



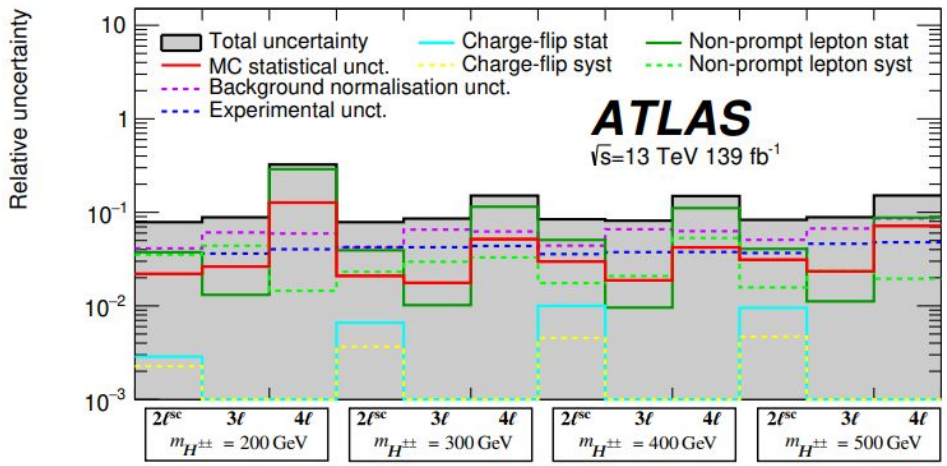


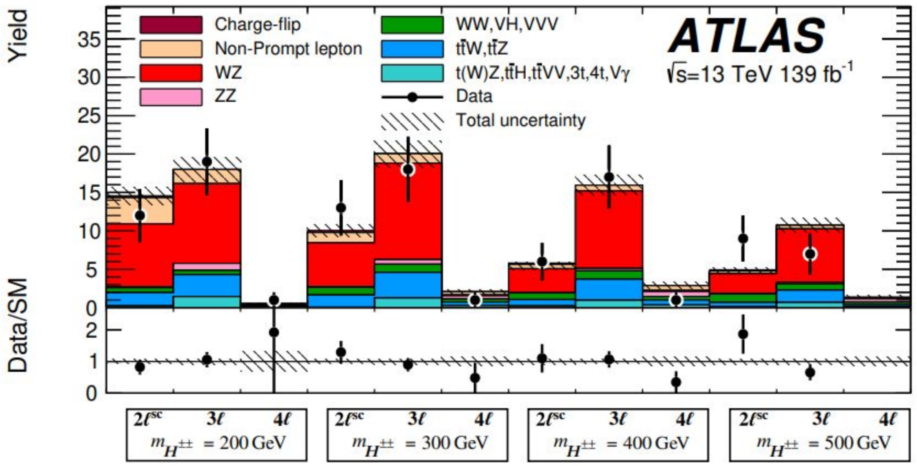
- Main backgrounds:
  - **SM WZ**: MC estimate with scale factor correction from data
  - **Non-prompt leptons**: data-driven fake factor method in 2l 3l.
    4l uses MC + scale factor measured from data (due to low stats)
  - **Electron charge-flip**: measure flip prob. from data in large Zee sample, apply to SR-like region but with opposite sign leptons
- Validate in preselection region, examples on right



$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$, $H^{\pm} \rightarrow W^{\pm}Z$: Selection

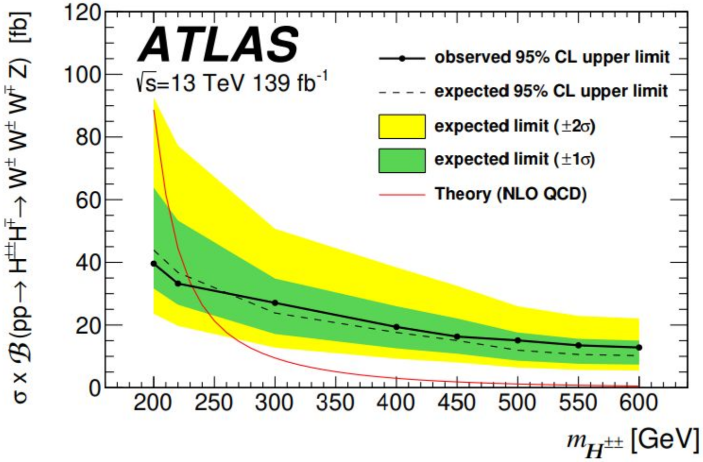
- Final selection adds requirements on invariant mass of jets/leptons, angular variables, E_T^{miss}, p_T
- SR for each N leptons category **further split into subregions for each signal mass**
  - Selection is optimised for each N leptons and signal mass
- Systematics considered for each background source, summarised in left plot
- Right plot shows obtained yields in each category

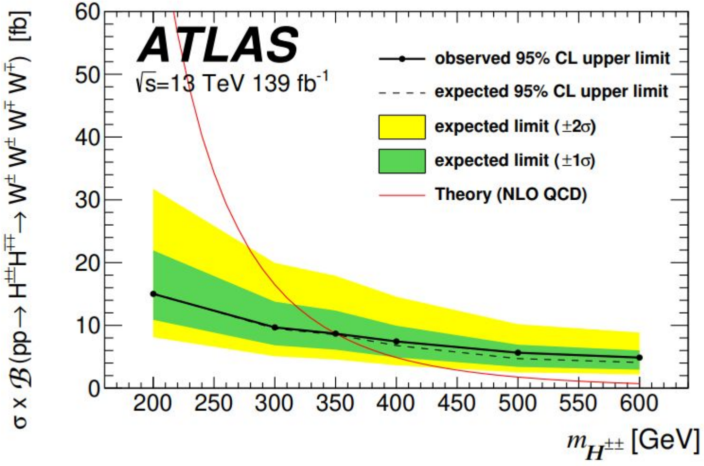




$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$, $H^{\pm} \rightarrow W^{\pm}Z$: Results

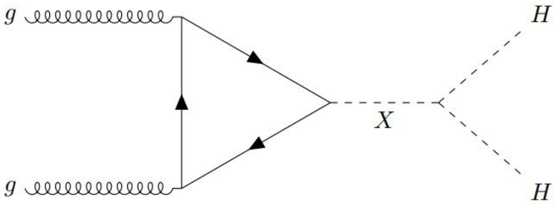
- Separate profile likelihood test for each signal mass, **combine 2/3/4 l categories**



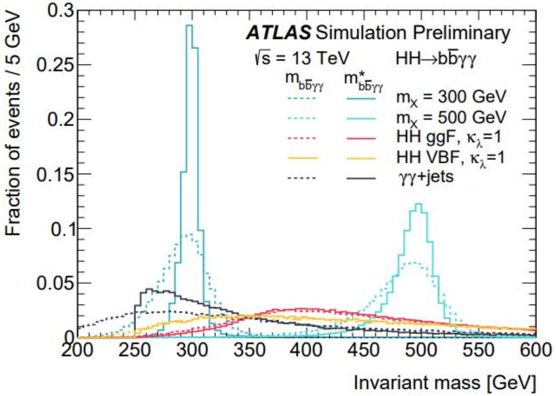


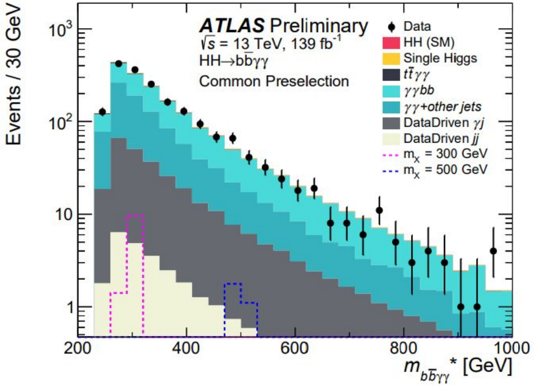
- Tighter limits obtained for $H^{\pm\pm}$ pair production channel. Has higher branching fraction, and analysis was optimised to target that mode

$X \rightarrow h_{125}h_{125} \rightarrow bb\gamma\gamma$

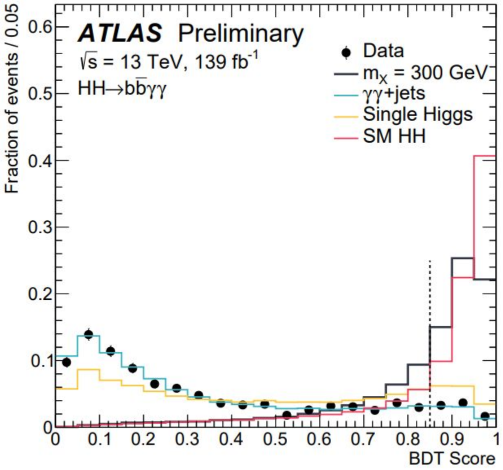


- Search for **new spin-0 scalar decaying to h_{125} pair**
  - Applicable to models with additional Higgs (eg. 2HDM)
- Combine high-rate to bb with clean γγ signal
- Includes both **resonant and non-resonant search**
  - Focus on resonant search in this talk, several mass hypotheses tested
- Common pre-selection:
  - γγ trigger, 2 high quality γ, e/μ veto, 2 to 5 central jets of which 2 are b-tagged
- Main background in resonant channel from γγ + jets
- **Use $m^*_{bb\gamma\gamma}$** $= m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV
  - Improves resolution and provides cancellation of experimental resolution effects, see top plot
- Lower plot shows events after preselection





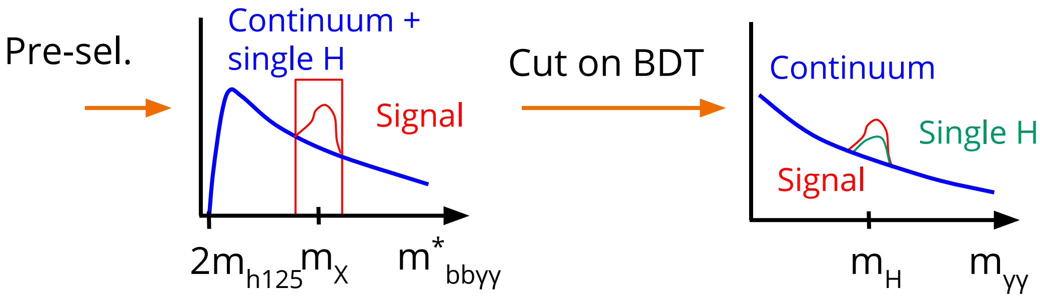
$X \rightarrow h_{125}h_{125} \rightarrow bb\gamma\gamma$: MVA

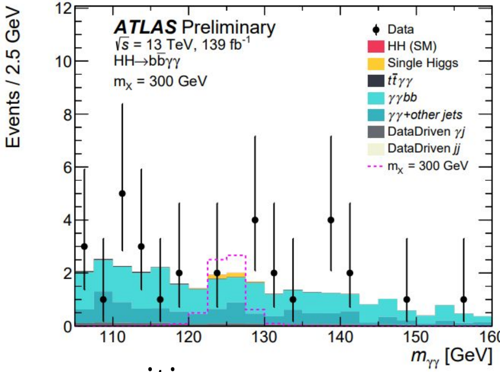


- Train **2 BDTs** for resonant search, one for γγ and ttγγ, other for single H
  - Reweight signal to match $m^*_{bb\gamma\gamma}$ of background
  - Gives **training independent of signal mass**
  - Scores combined in quadrature:

$$\mathrm{BDT_{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2\left(\frac{\mathrm{BDT}_{\gamma\gamma}+1}{2}\right)^2 + C_2^2\left(\frac{\mathrm{BDT}_{\mathrm{Single}H}+1}{2}\right)^2}$$

- Select events within 2σ of expected mean $m^*_{bb\gamma\gamma}$ (4σ for 900, 1000 GeV), **cut on combined BDT score**
  - **Cut value and coefficients optimised to maximise significance**

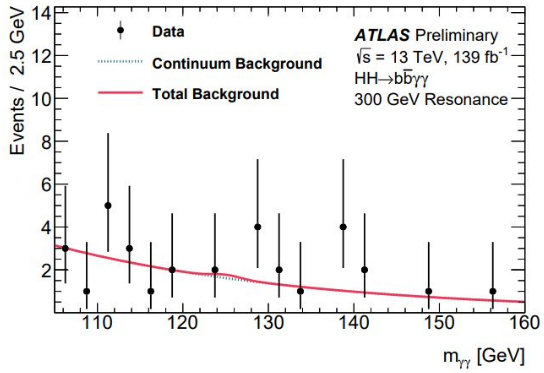


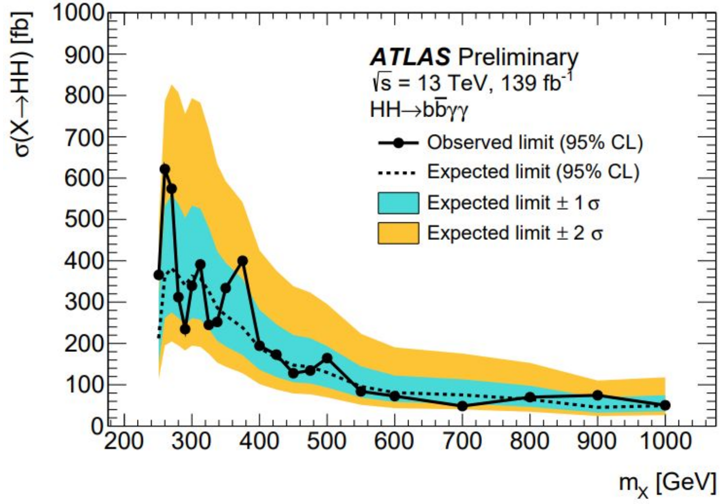


- Right plot shows events after BDT selection, used to illustrate background composition
- Overall continuum normalised to sidebands

$X \rightarrow h_{125}h_{125} \rightarrow bb\gamma\gamma$: Results

- Extract signal and background by fitting analytic functions to $m_{\gamma\gamma}$
- Continuum γγ background fit from high-stats MC template, normalised to data sidebands (105 to 120 and 130 to 160 GeV)
  - Include dedicated **systematic for spurious signal**: measure bias for choice of given functional form
  - **Dominant background is γγ + jets**
- Then perform maximum likelihood fit in search $m_{\gamma\gamma}$
- This analysis particularly sensitive to low mass X to di-Higgs, due to low mass γγ trigger and γ resolution

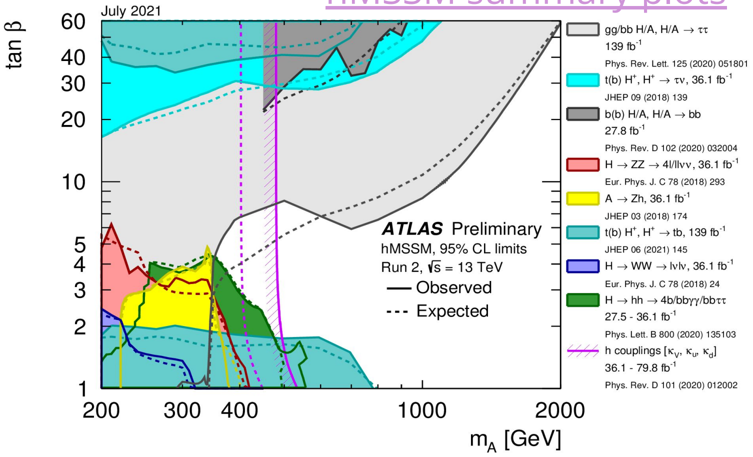




Summary

- Many results available with the full Run 2 dataset
- Benefit from larger dataset, but also have other improvements:
    - MVA techniques, parameterised NN becoming common
    - Updated reconstruction algorithms
    - New analysis methods
- Results in direct searches set stringent limits on models with extended Higgs sectors
    - See limits from H → ττ and H$^{\pm}$ → tb on the top plot
    - But, also exploring many other signatures, including H → $h_{125}h_{125}$, see bottom plot
- No significant excess seen so far
- More results available on HDBSPublicResults page

hMSSM summary plots



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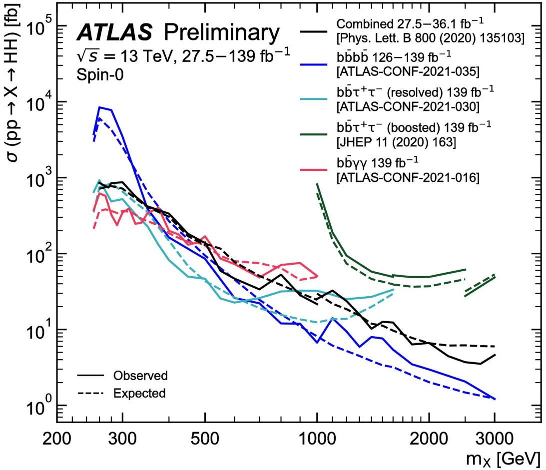
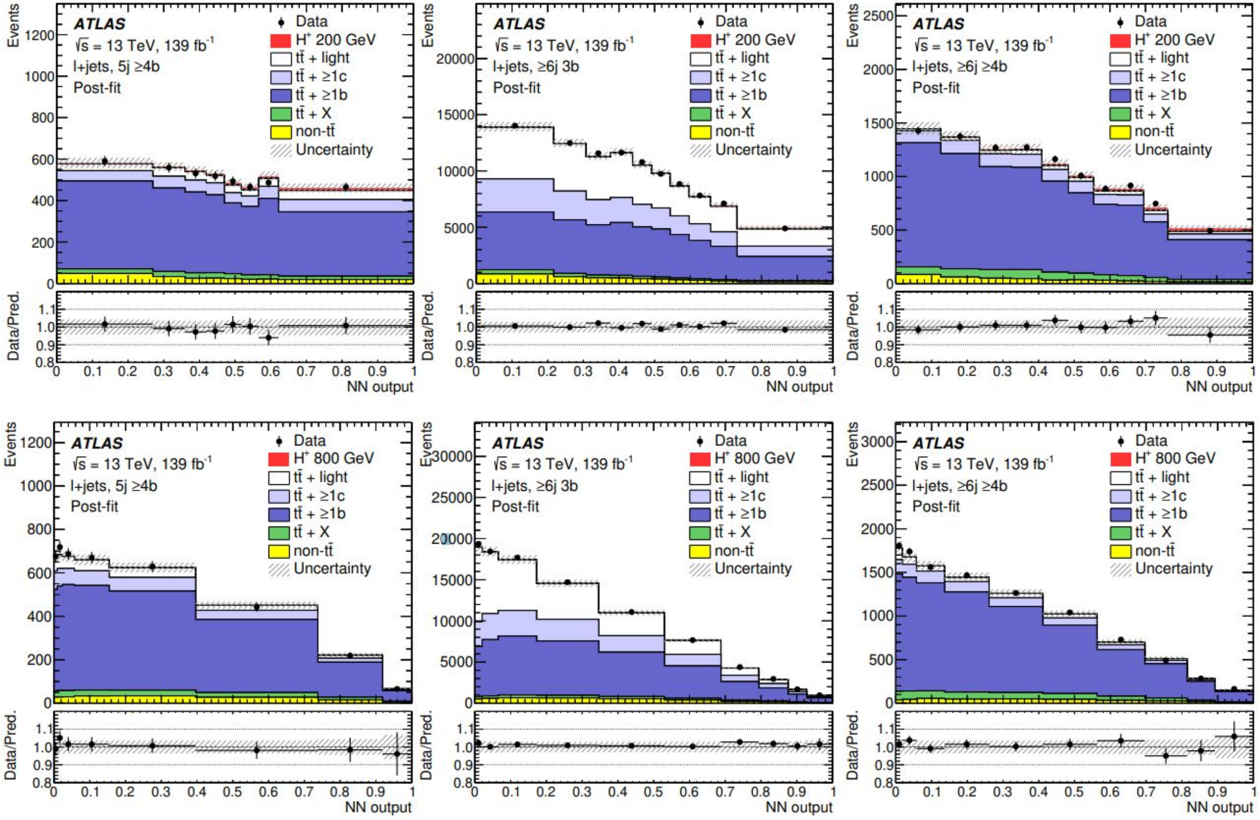


Backup

Backup: 2HDM

- Commonly see Type-II used in BSM H searches, but others are being explored
  - Type-I: all fermions couple to only one Higgs doublet
  - Type-II: down-type quarks and leptons couple to different doublet than up-type quarks
  - Lepton-specific: quarks to one doublet, leptons to other
  - Flipped: up-type quarks and leptons couple to different doublet than down-type quarks
  - Type-III: quarks and leptons couple to both doublets can have FCNC

Backup: $H^{\pm} \to tb$, NN output in other signal regions



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Backup: $H^{\pm} \longrightarrow tb$, Systematics

- Systematics on Tt + jets background

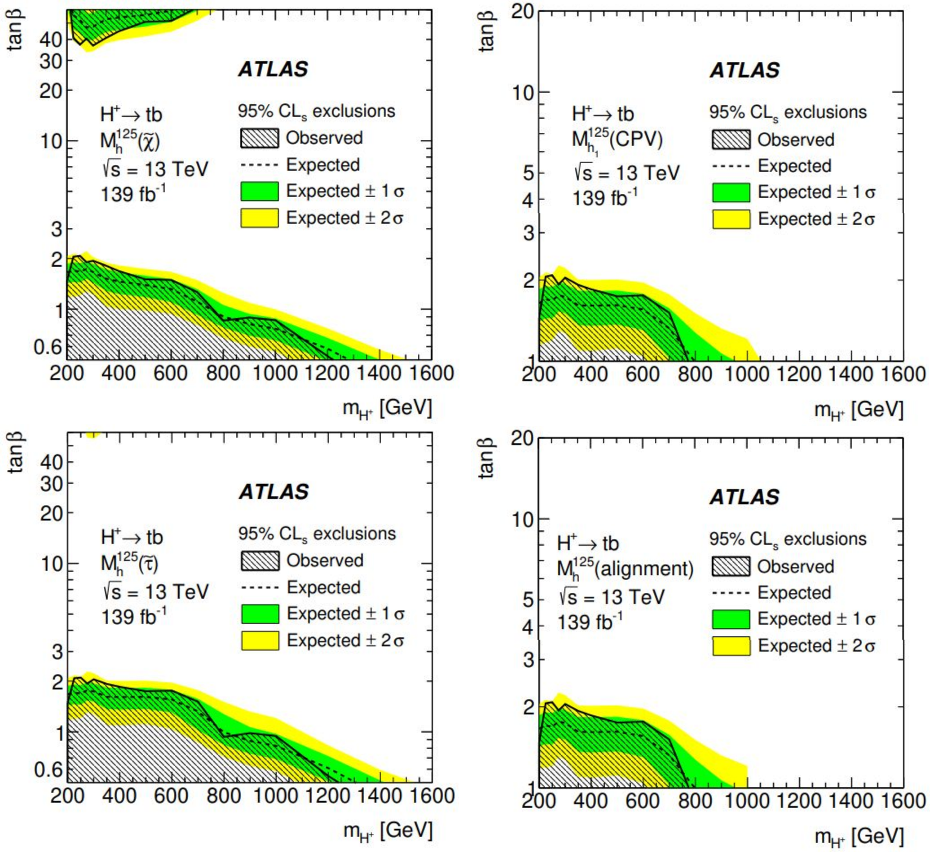
Uncertainty source	Description		Components
$t\bar{t}$ cross-section	Up or down by 6%		$t\bar{t}$ + light
$t\bar{t}$ reweighting	Statistical uncertainties of fitted function (six) parameters		All $t\bar{t}$ and Wt
$t\bar{t} + \geq 1b$ modelling	4FS vs. 5FS		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	Free-floating		$t\bar{t} + \geq 1c$
NLO matching	MadGraph5_aMC@NLO+Pythia	vs. PowhegBox+Pythia	All $t\bar{t}$
PS & hadronisation	PowhegBox+Herwig	vs. PowhegBox+Pythia	All $t\bar{t}$
ISR	Varying α_S^{ISR}	in PowhegBox+Pythia	All $t\bar{t}$
μ_f	Scaling by 0.5 (2.0)	in PowhegBox+Pythia	All $t\bar{t}$
μ_r	Scaling by 0.5 (2.0)	in PowhegBox+Pythia	All $t\bar{t}$
FSR	Varying α_S^{FSR}	in PowhegBox+Pythia	All $t\bar{t}$

Backup: $H^{\pm} \longrightarrow tb$, Systematics

- Uncertainties on
  $\mu = \sigma(pp \rightarrow tbH^{\pm}) \times B(H^{\pm} \rightarrow tb)$

Uncertainty source	$\Delta\mu(H^+_{200})$ [pb]	$\Delta\mu(H^+_{800})$ [pb]
$t\bar{t} + \geq 1b$ modelling	1.01	0.025
Jet energy scale and resolution	0.35	0.009
$t\bar{t} + \geq 1c$ modelling	0.32	0.006
Jet flavour tagging	0.20	0.025
Reweighting	0.22	0.007
$t\bar{t}$ + light modelling	0.33	0.009
Other background modelling	0.19	0.011
MC statistics	0.11	0.008
JVT, pile-up modelling	<0.01	0.001
Luminosity	<0.01	0.002
Lepton ID, isolation, trigger, E_T^{miss}	<0.01	<0.001
H^+ modelling	0.05	0.002
Total systematic uncertainty	1.35	0.049
$t\bar{t} + \geq 1b$ normalisation	0.23	0.007
$t\bar{t} + \geq 1c$ normalisation	0.045	0.015
Total statistical uncertainty	0.43	0.025
Total uncertainty	1.42	0.055

Backup: $H^{\pm} \rightarrow tb$, Other M_h^{125} Limits



Backup: $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$, $H^{\pm} \rightarrow W^{\pm}Z$ Preselection

Selection criteria	$2\ell^{sc}$	3ℓ	4ℓ
At least one offline tight lepton with $p_T^{\ell} > 30$ GeVthat triggered the event			
N_ℓ (type L)	=2	=3	=4
N_ℓ (type L*)	—	—	=4
N_ℓ (type T)	=2	$\geq$2 ($\ell_{1,2}$)	$\geq$1
$\lvert\sum Q_\ell\rvert$	=2	=1	$\neq$4
Lepton p_T	$p_T^{\ell_1,\ell_2} > 30, 20$ GeV	$p_T^{\ell_0,\ell_1,\ell_2} > 10, 20, 20$ GeV	$p_T^{\ell_1,\ell_2,\ell_3,\ell_4} > 10$ GeV
E_T^{miss}	> 70 GeV	> 30 GeV	> 30 GeV
N_{jets}	≥ 3	≥ 2	—
$N_{b\text{-jets}}$	=0		
Low SFOC $m_{\ell\ell}$ veto	—	$m_{\ell\ell}^{oc} > 15$ GeV	
Z boson decay veto	$\lvert m_{ee}^{sc} - m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}^{oc} - m_Z\rvert > 10$ GeV	

Backup: $H^{\pm\pm} \longrightarrow W^{\pm}W^{\pm}$, $H^{\pm} \longrightarrow W^{\pm}Z$ Final Selection

Charged Higgs boson mass	$m_{H^{\pm\pm}} = 200$ GeV	$m_{H^{\pm\pm}} = 300$ GeV	$m_{H^{\pm\pm}} = 400$ GeV	$m_{H^{\pm\pm}} = 500$ GeV
Selection criteria	$2\ell^{sc}$ channel			
m_{jets} [GeV]	[100, 450]	[100, 500]	[300, 700]	[400, 1000]
S	<0.3	<0.6	<0.6	<0.9
$\Delta R_{\ell^{\pm}\ell^{\pm}}$	<1.9	<2.1	<2.2	<2.4
$\Delta\phi_{\ell\ell,E_{\text{T}}^{\text{miss}}}$	<0.7	<0.9	<1.0	<1.0
$m_{x\ell}$ [GeV]	[40, 150]	[90, 240]	[130, 340]	[130, 400]
$E_{\text{T}}^{\text{miss}}$ [GeV]	>100	>130	>170	>200
Selection criteria	3ℓ channel			
$\Delta R_{\ell^{\pm}\ell^{\pm}}$	[0.2, 1.7]	[0.0, 2.1]	[0.2, 2.5]	[0.3, 2.8]
$m_{x\ell}$ [GeV]	>160	>190	>240	>310
$E_{\text{T}}^{\text{miss}}$ [GeV]	>30	>55	>80	>90
$\Delta R_{\ell\text{jet}}$	[0.1, 1.5]	[0.1, 2.0]	[0.1, 2.3]	[0.5, 2.3]
$p_{\text{T}}^{\text{leading jet}}$ [GeV]	>40	>70	>100	>95
Selection criteria	4ℓ channel			
$m_{x\ell}$ [GeV]	>230	>270	>360	>440
$E_{\text{T}}^{\text{miss}}$ [GeV]	>60	>60	>60	>60
$p_{\text{T}}^{\ell_1}$ [GeV]	>65	>80	>110	>130
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\text{min}}$	[0.2, 1.2]	[0.2, 2.0]	[0.5, 2.4]	[0.6, 2.4]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\text{max}}$	[0.3, 2.0]	[0.5, 2.6]	[0.4, 3.1]	[0.6, 3.1]

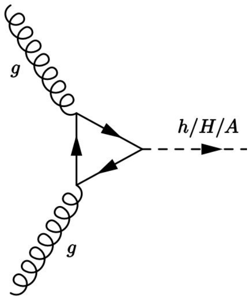
Backup: $X \to h_{125}h_{125} \to bb\gamma\gamma$, resonant BDT

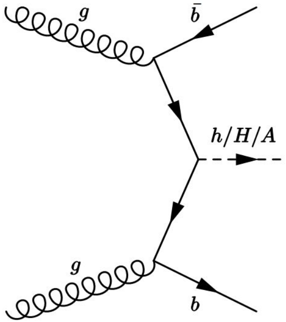
Variable	Definition
Photon-related kinematic variables	
$p_T^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the di-photon system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angular distance and ΔR between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}$, $p_T^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the b-tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angular distance and ΔR between the two b-tagged jets
N_{jets} and $N_{b\text{-jets}}$	Number of jets and number of b-tagged jets
H_T	Scalar sum of the p_T of the jets in the event
Photons and jets-related kinematic variables	
$m_{b\bar{b}\gamma\gamma}$	Invariant mass built with the di-photon and b-tagged jets system
$\Delta y_{\gamma\gamma,b\bar{b}}$, $\Delta\phi_{\gamma\gamma,b\bar{b}}$ and $\Delta R_{\gamma\gamma,b\bar{b}}$	Distance in rapidity, azimuthal angle and ΔR between the di-photon and the b-tagged jets system

Backup: $X \rightarrow h_{125}h_{125} \rightarrow bb\gamma\gamma$ Systematics

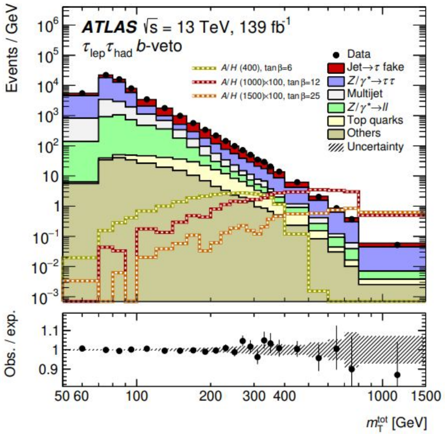
		Relative impact of the systematic uncertainties in %	
Source	Type	Non-resonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy scale	Norm. + Shape	5.2	2.7
Photon energy resolution	Norm. + Shape	1.8	1.6
Flavor tagging	Normalization	0.5	< 0.5
Theoretical			
Heavy flavor content	Normalization	1.5	< 0.5
Higgs boson mass	Norm. + Shape	1.8	< 0.5
PDF+α_s	Normalization	0.7	< 0.5
Spurious signal	Normalization	5.5	5.4

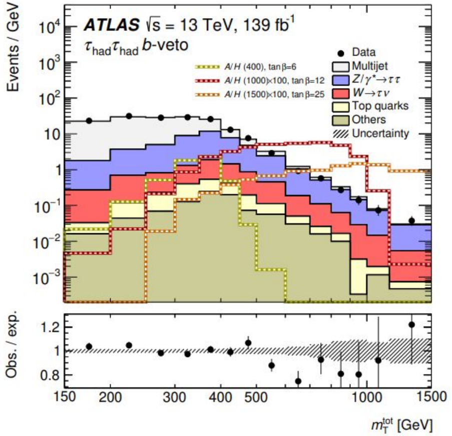
Backup: H/A $\rightarrow \tau\tau$ Search





- ATLAS full Run 2 result with 139 fb^{-1} from July 2020
- MSSM with high tanβ enhances couplings to τ and b
- $\tau_{lep}\tau_{had}$ (e/μ trigger) and $\tau_{had}\tau_{had}$ (τ trigger) channels
  - Each split into b-veto and b-tag category
- BDT to distinguish jet from τ, or e/μ from τ
  - Improved τ/jet BDT over 36 fb^{-1} result, better multijet rejection
- Also improvements in background modelling





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Backup: H/A $\rightarrow \tau\tau$ Results

- Set limits on σ x B, and new M_h^{125} scenarios (hMSSM and other M_h^{125} variations included in aux. material)