Searches for additional charged and neutral Higgs bosons in ATLAS

Trisha Farooque
Michigan State University

ICHEP 6-13 July,2022, Bologna

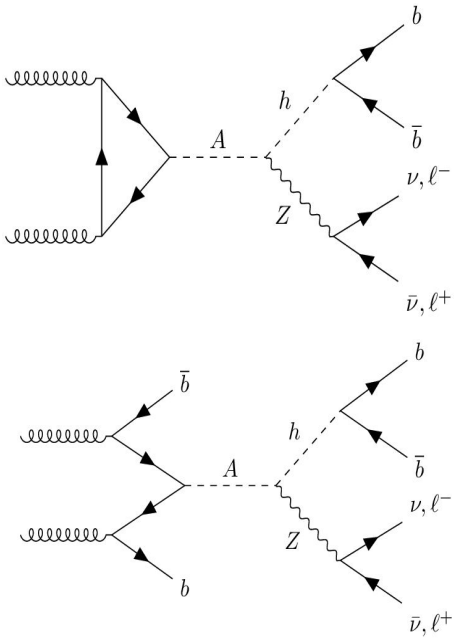
Introduction

- Discovery of (the) Higgs boson was major milestone in particle physics
  - Major evidence in support of Standard Model (SM)
- “The” Higgs boson?
  - Many puzzles remain unsolved in SM
    - Hierarchy problem
    - Baryon asymmetry
    - Dark matter
    - …
  - Many extensions of the SM propose additional neutral and charged Higgs bosons
    - E.g. $\mathbf{a^0, h^0, A^0, H^0, H^{\pm}}$ predicted in Two-Higgs Doublet Models (2HDM)
- This talk summarises recent ATLAS searches for these additional scalar particles

ATLAS-HDBS-2020-19

A->Z(ll/vv)h(bb)

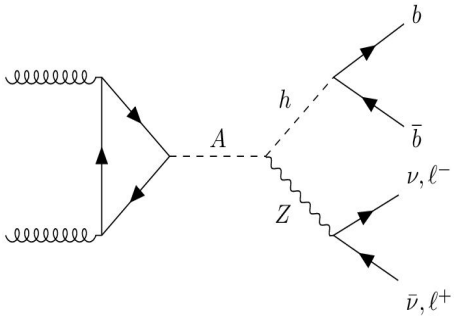
- Search for pseudoscalar (A) in ggF or b-associated production; decaying to Z boson and SM Higgs boson
  - Interpreted in Type-I, Type-II, Lepton-specific and Flipped 2HDM models
  - Also constrained Z'/W' production in Heavy Vector Triplet (HVT) model

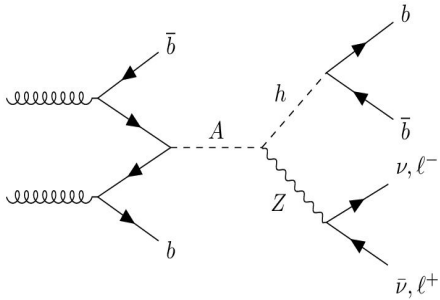


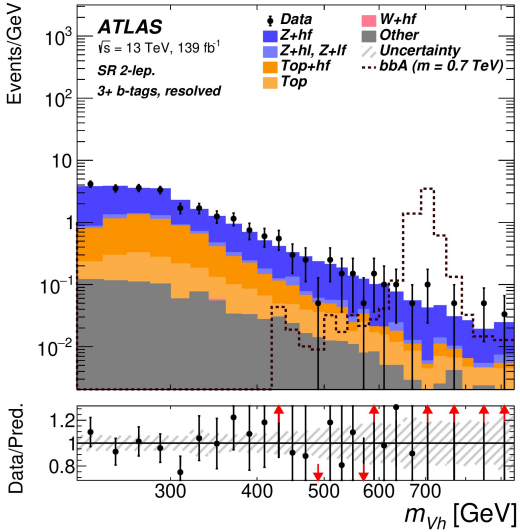
ATLAS-HDBS-2020-19

A->Z(ll/νν)h(bb)

- Search for pseudoscalar (A) in ggF or b-associated production; decaying to Z boson and SM Higgs boson
  - Interpreted in Type-I, Type-II, Lepton-specific and Flipped 2HDM models
  - Also constrained Z'/W' production in Heavy Vector Triplet (HVT) model



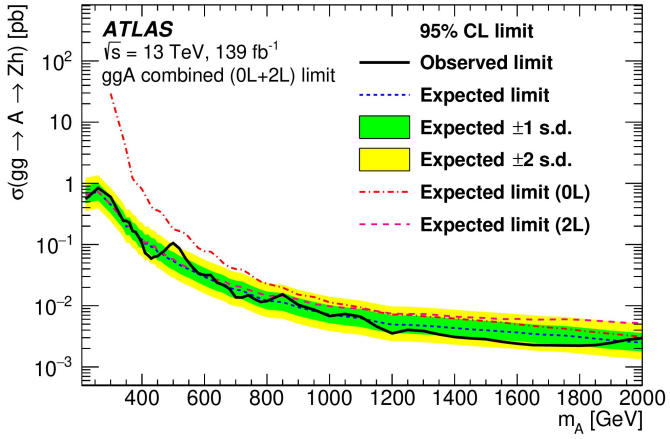


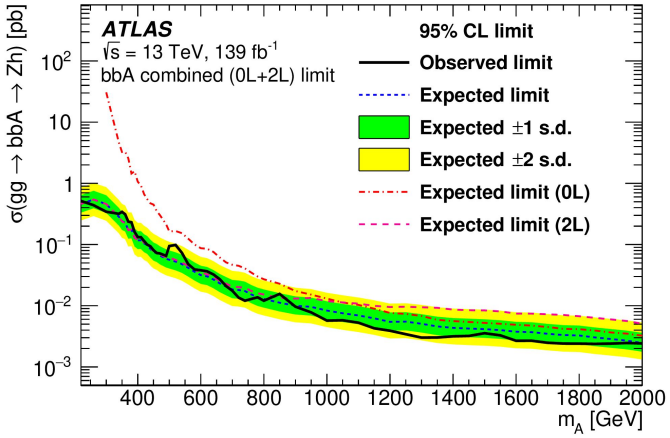


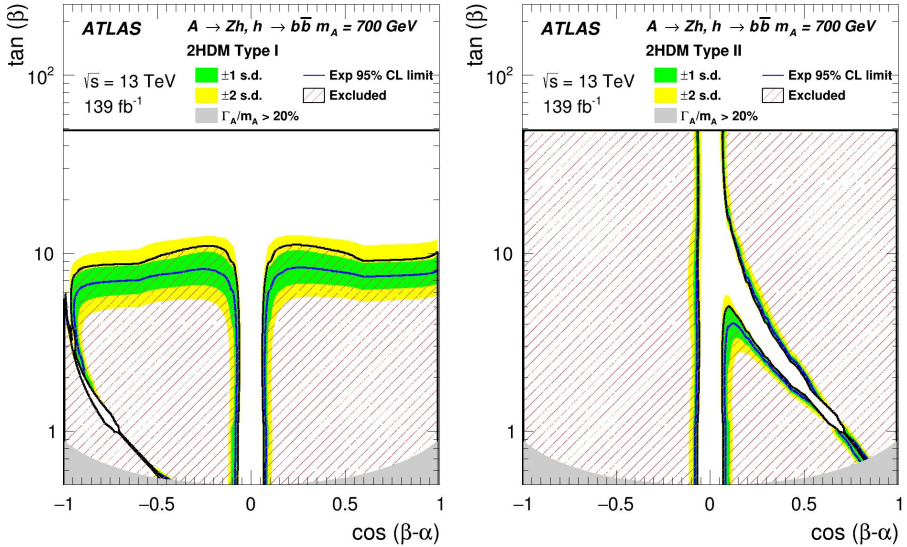
- Signal regions split by lepton Multiplicity
  - 0-lepton channel targeting Z->νν decay
  - 2-lepton channel targeting Z->ℓℓ decay
- Further splitting into regions with resolved and boosted H->bb decay
- Likelihood fit on signal discriminant: Transverse (0-lepton) or invariant (2-lepton) mass of Zh system

ATLAS-HDBS-2020-19

A->Z(ll/vv)h(bb)



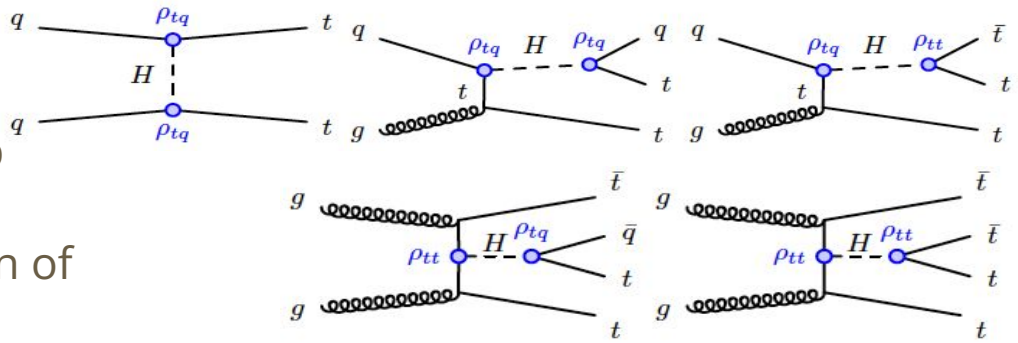




- No significant excess
- Largest deviation at 500 GeV
  - Local significance 2.1σ in ggA, 1.6σ in bbA
- More sensitive at high tan(β) for Type-II model due to larger bbA cross section
- Low sensitivity in alignment limit cos(β-α)→0 due to vanishing A->Zh branching ratio

Flavourful 2HDM

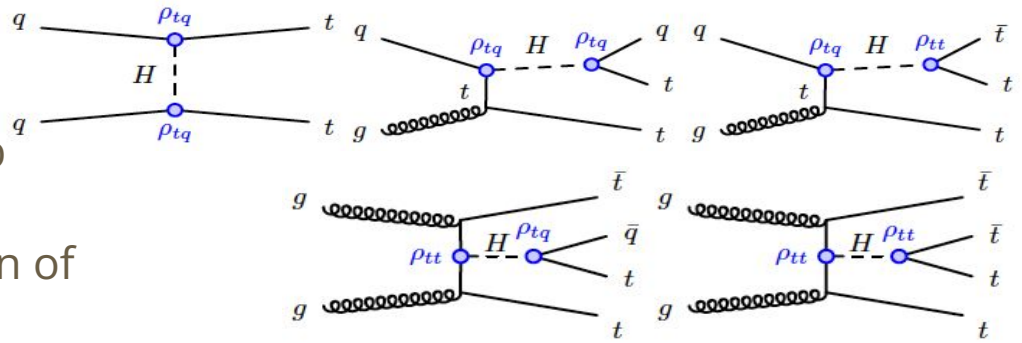
ATLAS-CONF-2022-039



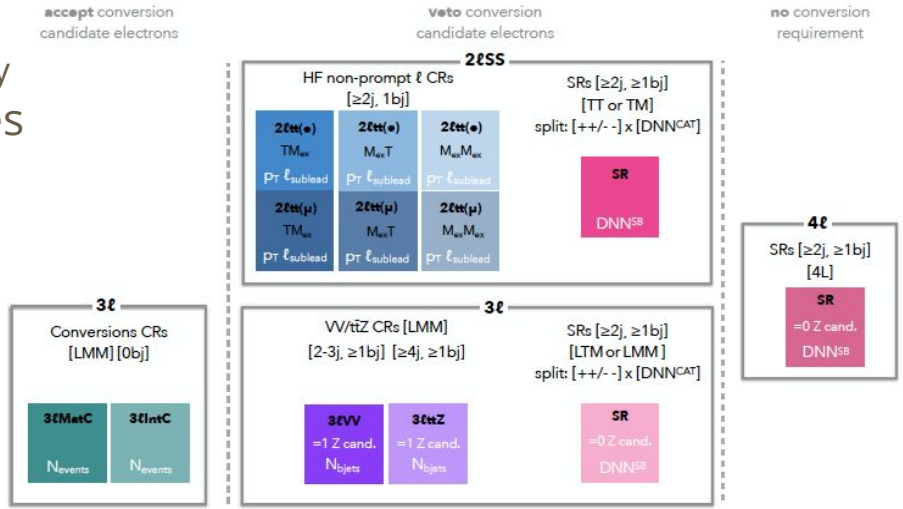
- Multilepton channel (2LSS, 3L, >=4L)
- Final states containing two to four top quarks
- First analysis to target BSM production of 3top final states
  - Targets general 2HDM with FCNH couplings (ρ_{tu}, ρ_{tc}, ρ_{tt}) of the heavy Higgs bosons
  - ρ_{tt} and ρ_{tc} can explain baryon number asymmetry

Flavourful 2HDM

ATLAS-CONF-2022-039



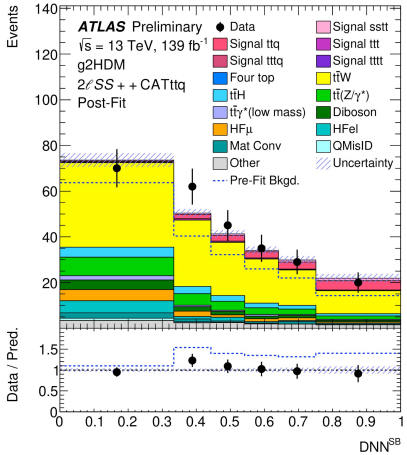
- Multilepton channel (2LSS, 3L, >=4L)
- Final states containing two to four top quarks
- First analysis to target BSM production of 3top final states
  - Targets general 2HDM with FCNH couplings (ρ_{tu}, ρ_{tc}, ρ_{tt}) of the heavy Higgs bosons
  - ρ_{tt} and ρ_{tc} can explain baryon number asymmetry
- Signal regions based on lepton multiplicities and output of multi-output deep neural network (DNN) classifier
  - Likelihood fit on score of second DNN used to discriminate signal from background in each category
- Backgrounds calibrated in dedicated control regions

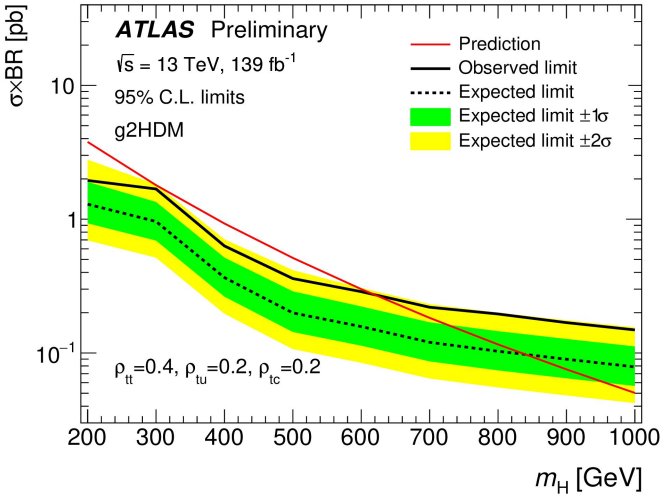


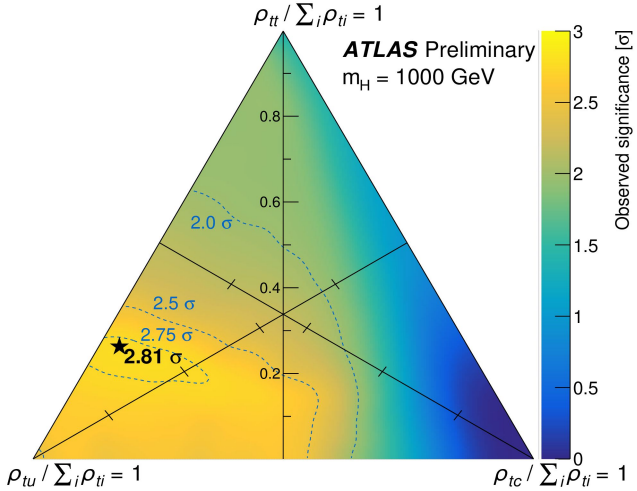
Flavourful 2HDM

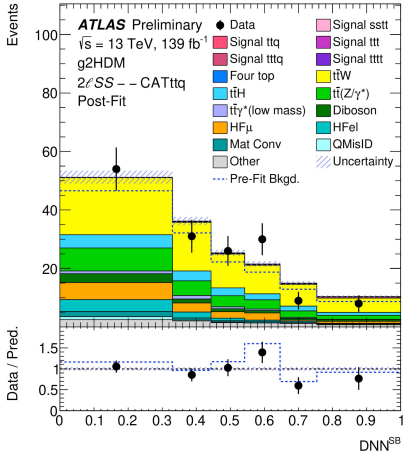
- No significant excess over SM background
- Most significant deviation observed at m_H=1 TeV and ρ_{tt}=0.2, ρ_{tc}=0.3, ρ_{tu}=0.24
  - Deviation is asymmetric in lepton charge
- Local significance 2.81σ
- Results also interpreted in RPV SUSY model

ATLAS-CONF-2022-039





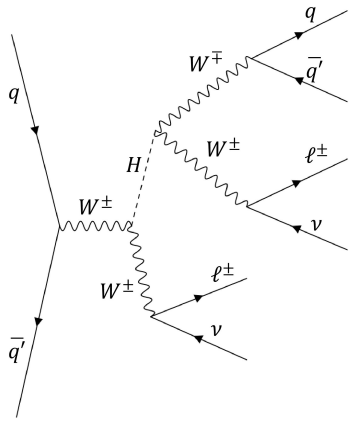




WH(WW)

ATLAS-CONF-2022-033

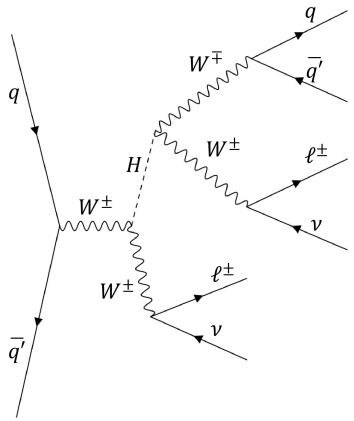
- Associated production of heavy scalar (H) with W boson
  - Complementary to gluon-gluon fusion searches
    - Involves top loop ⇒ reduced fermionic coupling would render ggF channel insensitive
  - Larger cross sections than VBF and smaller backgrounds



WH(WW)

ATLAS-CONF-2022-033

- Associated production of heavy scalar (H) with W boson
  - Complementary to gluon-gluon fusion searches
    - Involves top loop ⇒ reduced fermionic coupling would render ggF channel insensitive
  - Larger cross sections than VBF and smaller backgrounds
- Generic search in SS2L signature
- Dominant background: SM diboson production



Selections	Boosted SR	Resolved SR	*ssWW* CR	Boosted *WZ* CR	Resolved *WZ* CR
Trigger	Single lepton				
Leptons	two same-sign leptons with $p_T > 27, 20$ GeV, zero additional veto leptons			three leptons with $p_T > 27, 20, 20$ GeV, at least one SFOS lepton pair	
$m_{\ell\ell}$	> 100 GeV			-	
$m_{\ell\ell\ell}$	-			> 100 GeV	
b-jets	zero b-tagged small-R jets				
E_T^{miss}	> 80 GeV	> 60 GeV	> 40 GeV		
Large-R jets	at least one large-R jet with $p_T > 200$ GeV, $\|\eta\| < 2.0$, 50 GeV $< m_J < 200$ GeV and pass 80% W-tagger WP	zero large-R jets with $p_T > 200$ GeV, $\|\eta\| < 2.0$, 50 GeV $< m_J <$ 200 GeV		at least one large-R jet with $p_T > 200$ GeV, $\|\eta\| < 2.0$, 50 GeV $< m_J < 200$ GeV and pass 80% W-tagger WP	zero large-R jets with $p_T > 200$ GeV, $\|\eta\| < 2.0$, 50 GeV $< m_J < 200$ GeV
Small-R jets	-	at least two small-R jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$		-	at least two small-R jets with $p_T > 20$ GeV and $\|\eta\| < 2.5$
m_{jj}	-	50 GeV $< m_{jj} < 110$ GeV	> 200 GeV	-	-

WH(WW)

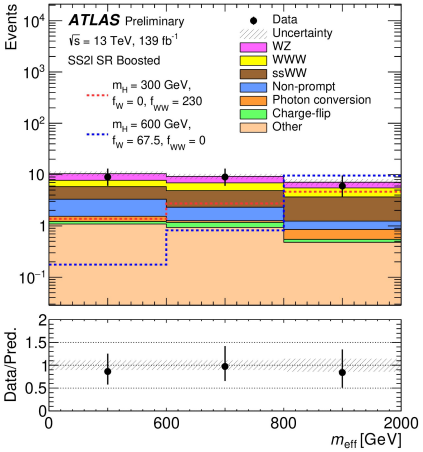
ATLAS-CONF-2022-033

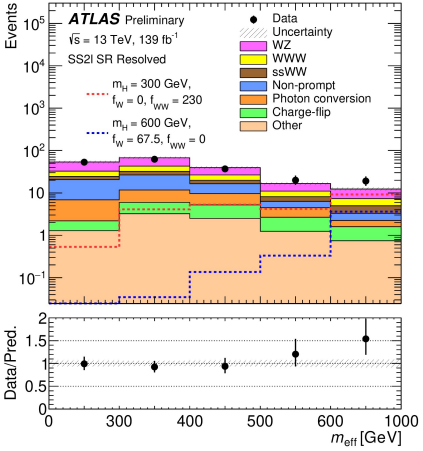
$$m_{\text{eff}} \equiv \sum_i p_{\text{T}}^i(\text{lepton}) + p_{\text{T}}(\text{leading J}) + E_{\text{T}}^{\text{miss}}, \text{ boosted category}$$

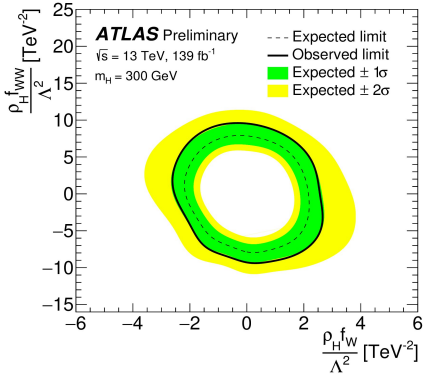
$$m_{\text{eff}} \equiv \sum_i p_{\text{T}}^i(\text{lepton}) + p_{\text{T}}(\text{leading j}) + p_{\text{T}}(\text{sub-leading j}) + E_{\text{T}}^{\text{miss}}, \text{ resolved category.}$$

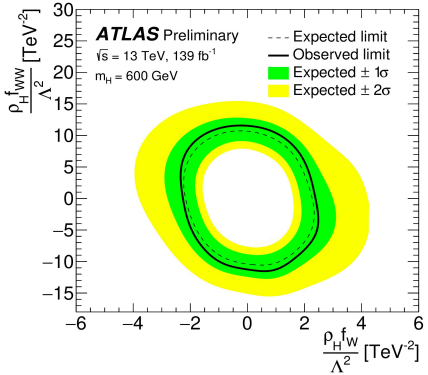
- Binned likelihood fit on "effective mass" (m_{eff}) distribution in signal regions and total yield in control regions
- Limits set on BSM HVV coupling strengths in an Effective Field Theory

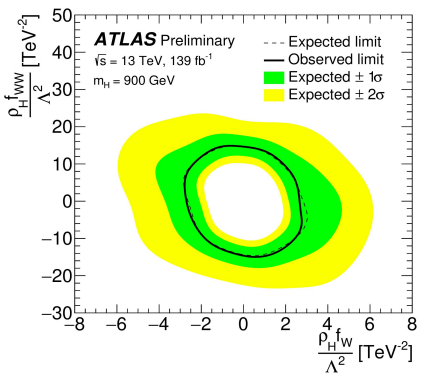
ρ_H = sin(β-α) in 2HDM models
f_W, f_{ww} = anomalous coupling to W







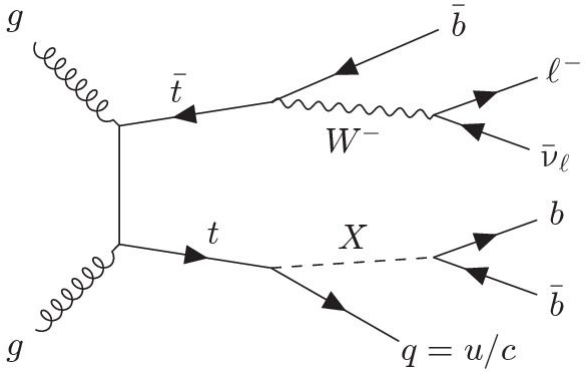




FCNC top quark decay t->qX(bb); q=u,c

ATLAS-CONF-2022-027

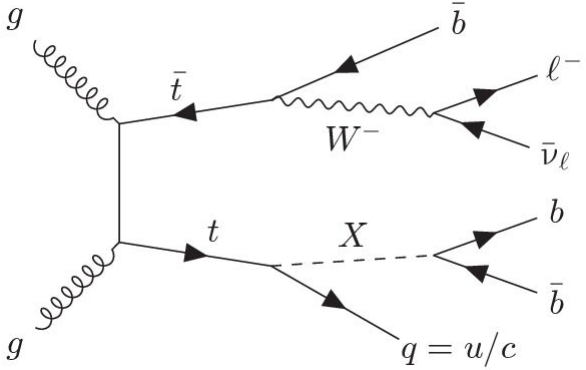
- Search for FCNC decay of top quark t->qX in ttbar events
  - **X**: light scalar with flavour charge (***flavon***) ; X->bb dominant decay for masses below 200 GeV

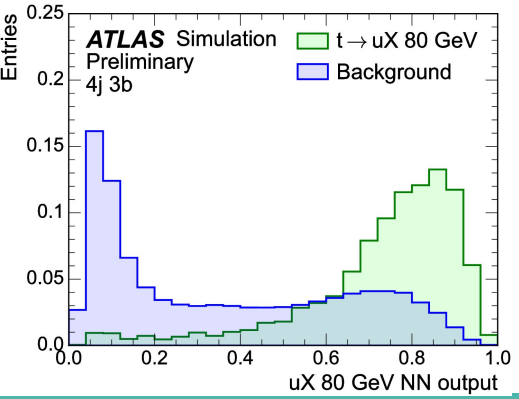


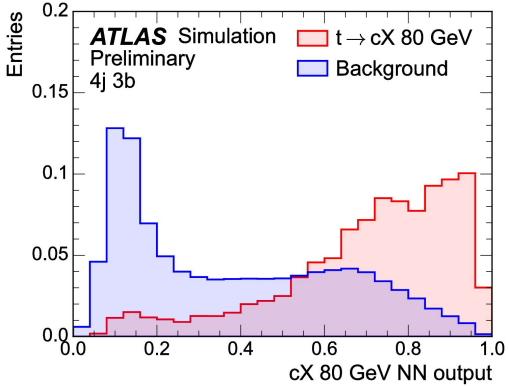
FCNC top quark decay t->qX(bb); q=u,c

ATLAS-CONF-2022-027

- Search for FCNC decay of top quark t->qX in ttbar events
  - **X**: light scalar with flavour charge (***flavon***) ; X->bb dominant decay for masses below 200 GeV
- Signal discrimination using NN trained on jet, lepton kinematics and b-tagging information



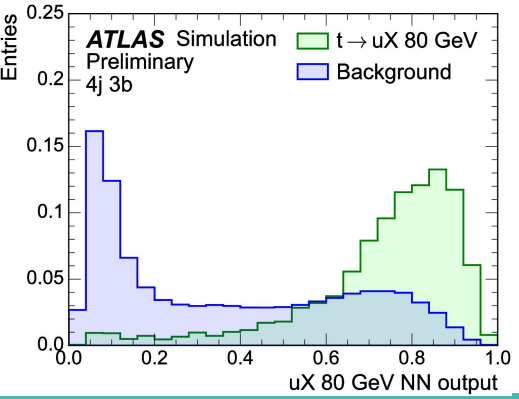


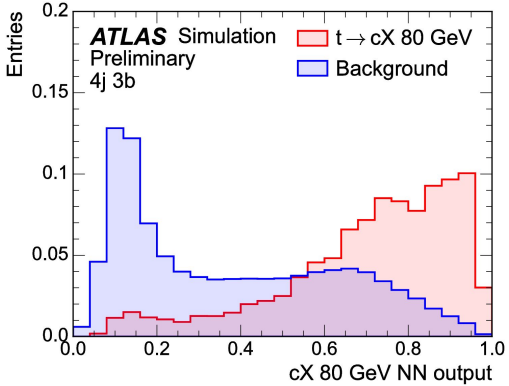


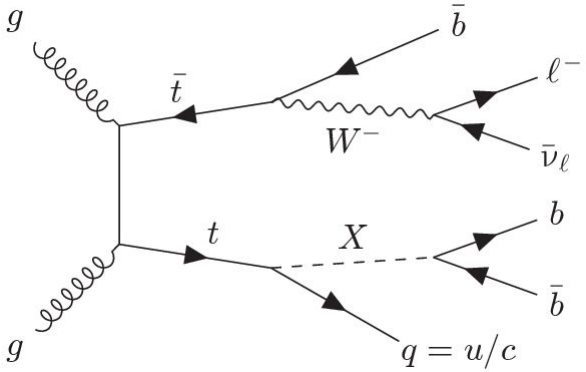
FCNC top quark decay t->qX(bb); q=u,c

ATLAS-CONF-2022-027

- Search for FCNC decay of top quark t->qX in ttbar events
  - **X**: light scalar with flavour charge (***flavon***) ; X->bb dominant decay for masses below 200 GeV
- Signal discrimination using NN trained on jet, lepton kinematics and b-tagging information
- Profile likelihood fit on NN score across [4-6]j3b signal regions and total yield in [4-6]j>=4b background control regions



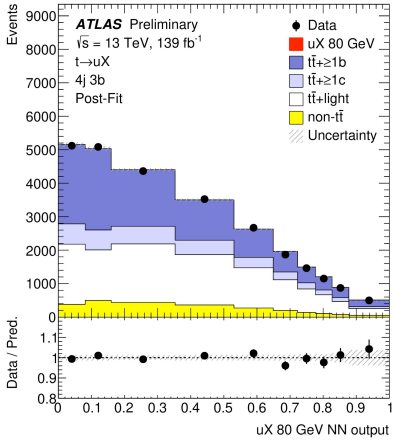


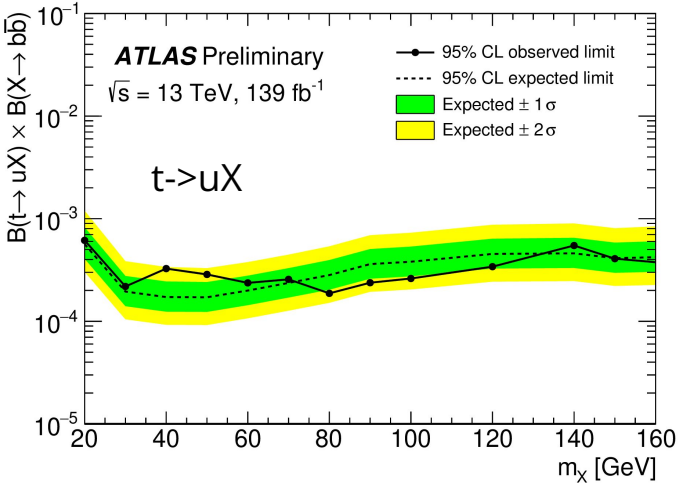


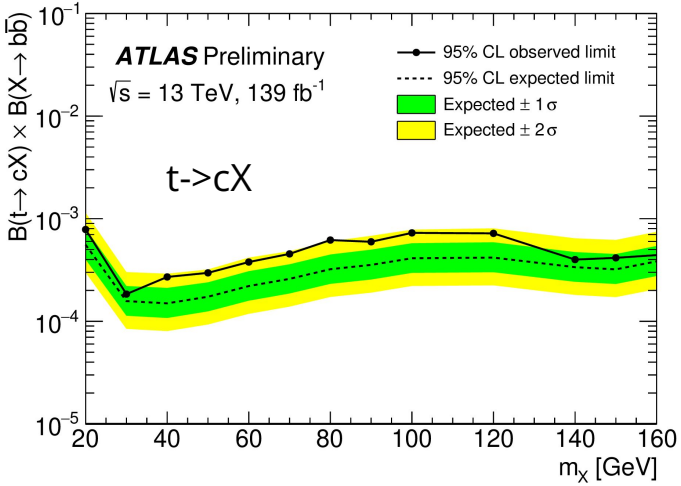
FCNC top quark decay t->qX(bb); q=u,c

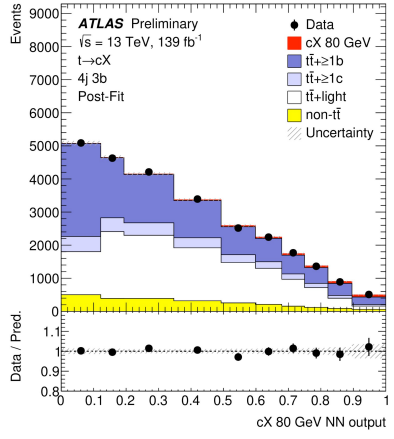
- No significant excess observed
- Small deviation in observed limit for t->cX process but not for t->uX
  - Both processes have similar kinematics
  - Difference arises in flavour and b-tagging score of 4th jet

ATLAS-CONF-2022-027









Low mass X->γγ

ATLAS-CONF-2022-018

- Light *axion-like particle (**ALP**)* with gluon coupling
  - Abundant production in pp collisions
  - Diphoton decay suppressed, but favourable search channel due to clean signature

Low mass X->γγ

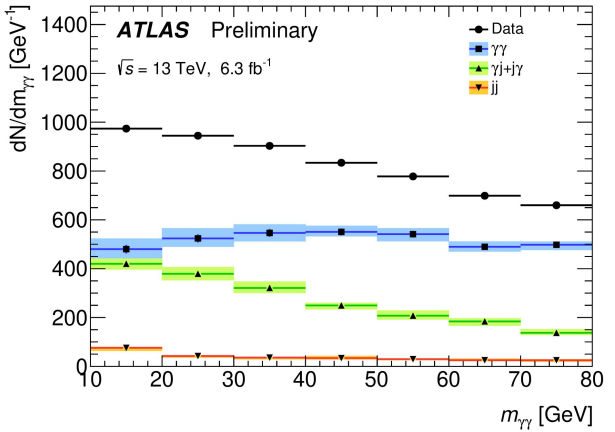
ATLAS-CONF-2022-018

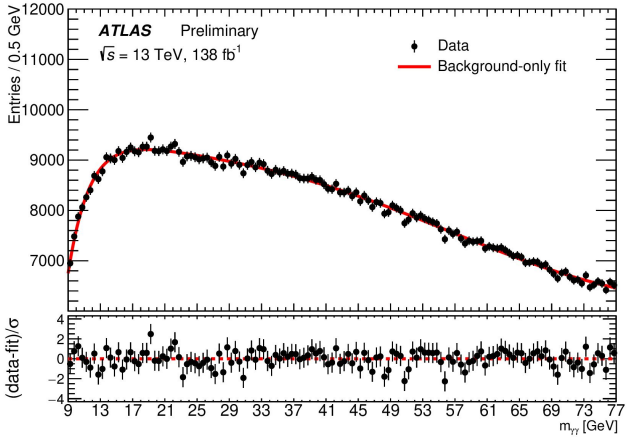
- Light *axion-like particle (**ALP**)* with gluon coupling
  - Abundant production in pp collisions
  - Diphoton decay suppressed, but favourable search channel due to clean signature
- Low mass X->γγ search affected by trigger threshold
  - Mitigated by selecting boosted close-by photon pairs with pT>50 GeV
  - Search reaches down to 10 GeV resonance mass

Low mass X->γγ

ATLAS-CONF-2022-018

- Light *axion-like particle (**ALP**)* with gluon coupling
  - Abundant production in pp collisions
  - Diphoton decay suppressed, but favourable search channel due to clean signature
- Low mass X->γγ search affected by trigger threshold
  - Mitigated by selecting boosted close-by photon pairs with pT>50 GeV
  - Search reaches down to 10 GeV resonance mass



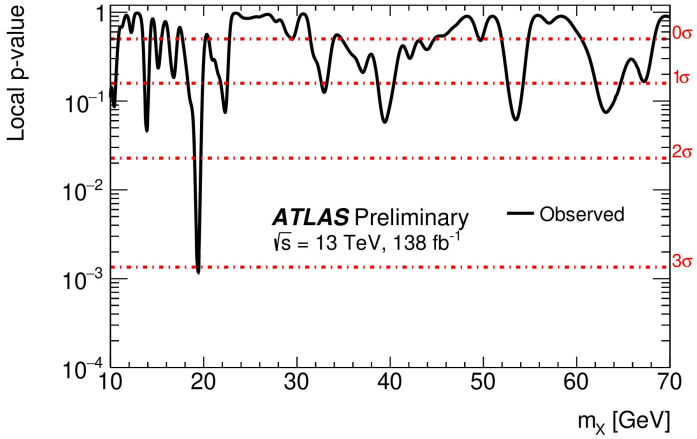


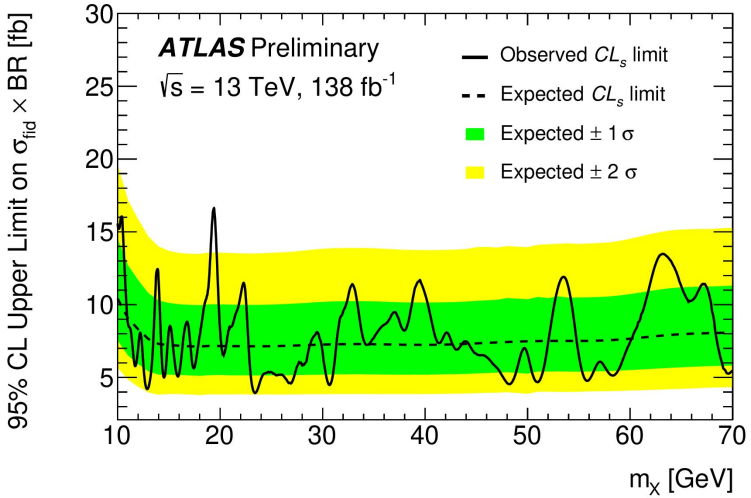
- Signal discriminant: invariant mass of diphoton system
- Data-driven estimation of continuum SM background

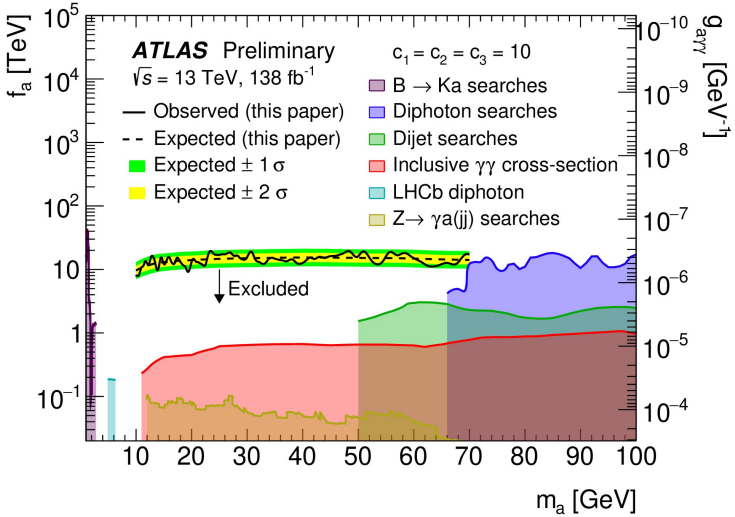
Low mass X->yy

- Most significant deviation from background observed at 19.4 GeV
  - Local significance 3.05σ (global significance 1.48σ)
- Results interpreted as limits in the plane spanned by ALP mass (m_a) and decay constant(f_a)
- Significantly extends previous limits at low m_a from complementary searches

ATLAS-CONF-2022-018



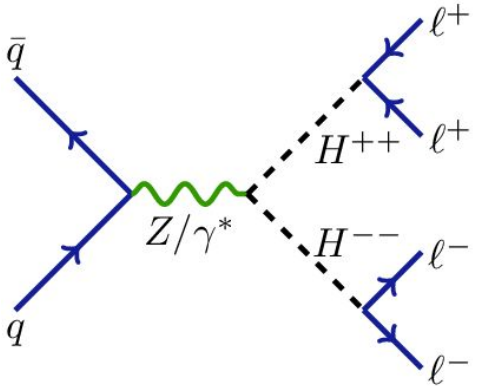




$H^{++}H^{--}$ -> 4l

ATLAS-CONF-2022-010

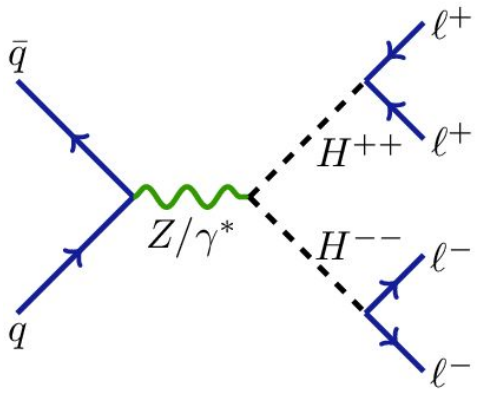
- H^{++}/H^{--} predicted by many BSM theories, e.g. Left-Right Symmetric (LRS) models, Type-II seesaw models, etc.
  - LH and RH chiralities
  - Decays to same-charge lepton pairs; LFV decays permitted

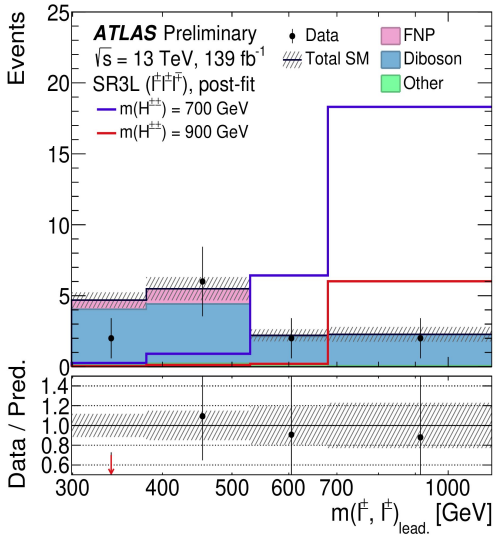


$H^{++}H^{--}$ -> 4l

ATLAS-CONF-2022-010

- H^{++}/H^{--} predicted by many BSM theories, e.g. Left-Right Symmetric (LRS) models, Type-II seesaw models, etc.
  - LH and RH chiralities
  - Decays to same-charge lepton pairs; LFV decays permitted
- Signal regions separated by lepton multiplicities (2L, 3L, 4L)
  - $m(\ell^{\pm}, \ell'^{\pm})$ used as discriminant in 2L and 3L regions; total yield in 4L regions
- Main backgrounds: Diboson (DB), Drell-Yan (DY), fake lepton and charge mis-ID

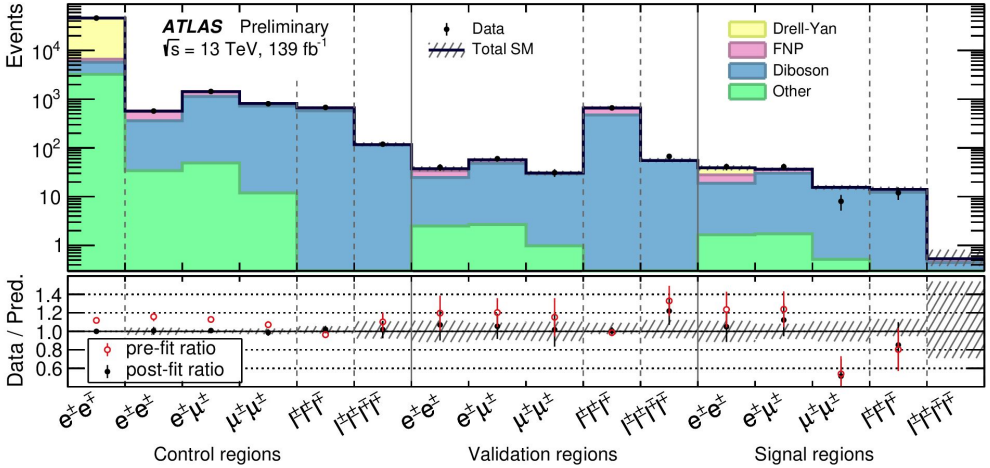


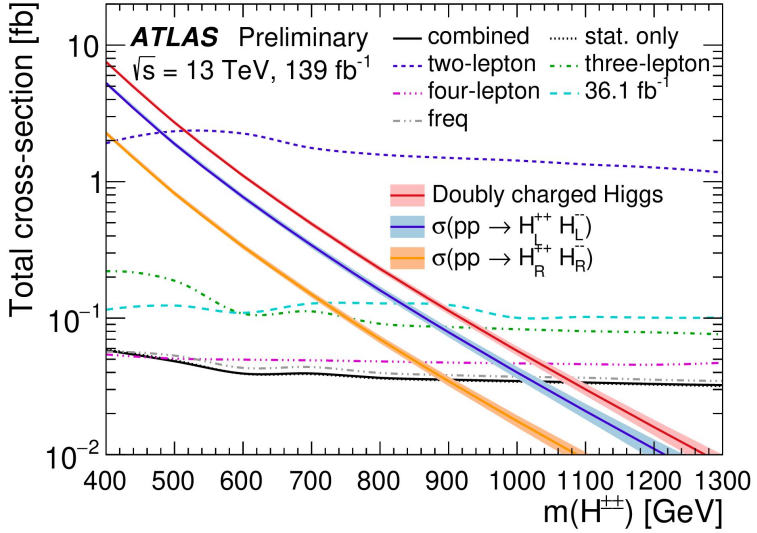


$H^{++}H^{--}$ -> 4l

ATLAS-CONF-2022-010

- Limits set on pair production cross section of H^{++}/H^{-}, assuming democratic decays to lepton flavours
- Sensitivity driven by 4L channel
- Higher sensitivity to LH scalars, due to larger production cross section
- Combined lower mass limit at 1080 GeV

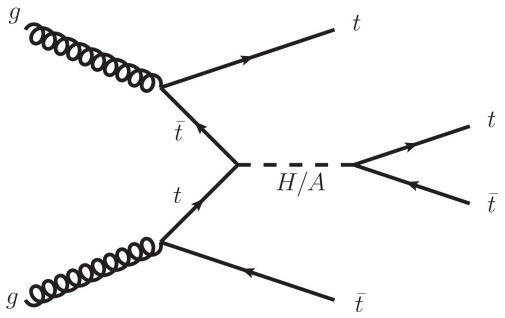




ttH/A->4tops

ATLAS-CONF-2022-008

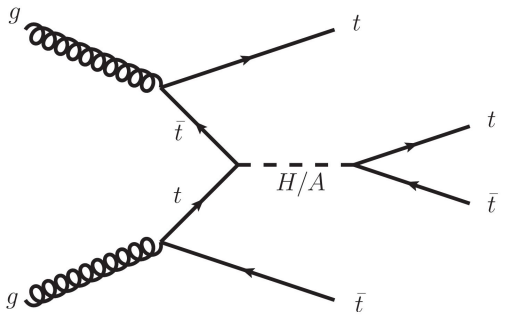
- Search for heavy scalar (H)/pseudoscalar (A) from 2HDM models
  - H/A->tt decays dominate when $m_{H/A} > 2m_{top}$
- Inclusive searches for gg->H/A->tt difficult due to large negative interference with SM ttbar
  - Associated production with top quarks benefits from sizable cross section and low backgrounds



ttH/A->4tops

ATLAS-CONF-2022-008

- Search for heavy scalar (H)/pseudoscalar (A) from 2HDM models
  - H/A->tt decays dominate when $m_{H/A} > 2m_{top}$
- Inclusive searches for gg->H/A->tt difficult due to large negative interference with SM ttbar
  - Associated production with top quarks benefits from sizable cross section and low backgrounds
- Search performed in SS+3L channel
- Two BDTs used for signal discrimination:
  - SMBDT to discriminate SM 4tops from other SM background
    - Used to define BSM signal region
  - Parameterised BSM BDT to discriminate BSM 4tops from SM background
    - Discriminant in likelihood fit

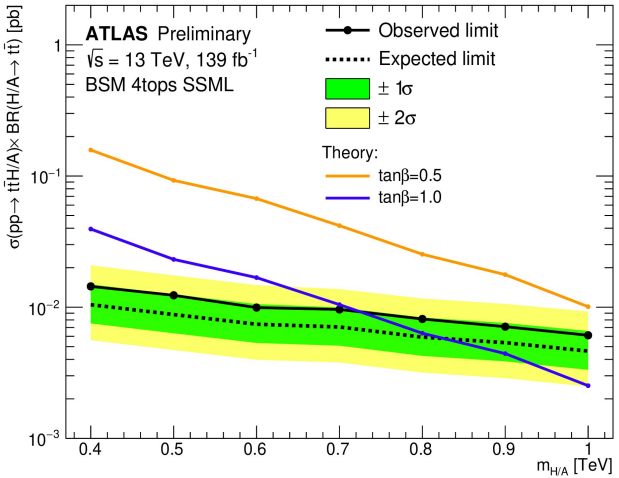


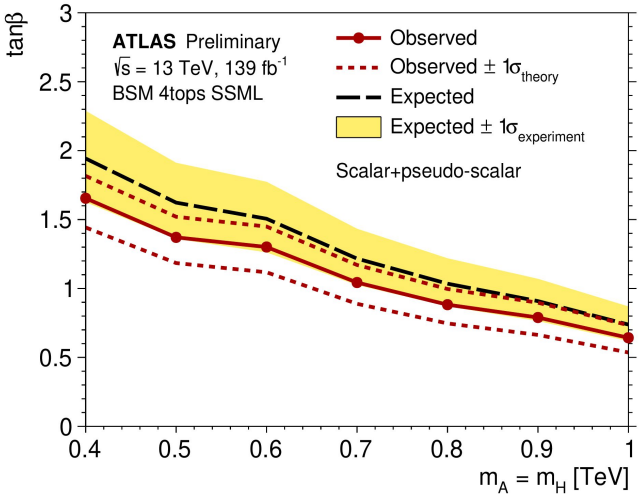
Region	Channel	N_j	N_b	Other selection cuts	Fitted variable
CR Conv	$e^\pm e^\pm$ || $e^\pm \mu^\pm$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1]$ GeV $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	eee || $ee\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR HF μ	$e\mu\mu$ || $\mu\mu\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR $t\bar{t}W$	$e^\pm \mu^\pm$ || $\mu^\pm \mu^\pm$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1]$ GeV, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$; for $N_b \geq 3$, $H_T < 500$ GeV	$\sum p_T^\ell$
CR lowBDT	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT < 0.55	SM BDT
BSM SR	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT ≥ 0.55	BSM pBDT

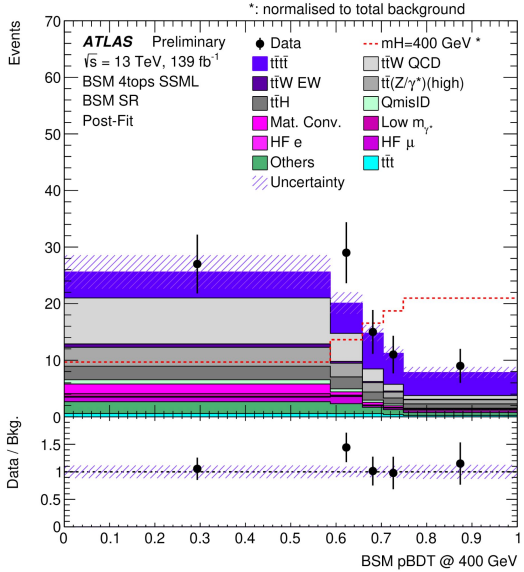
ttH/A->4tops

ATLAS-CONF-2022-008

- No significant excess above SM predictions
- Results interpreted in Type-II 2HDM model
  - SM 4-top contribution constrained to predicted cross section
  - tan(β) below 1.6 (0.6) excluded for $m_{A/H}$ = 0.4 (1.0) TeV
  - Production of both A and H particles considered simultaneously







Conclusions

- New scalar particles are a key feature of many extensions of the Standard Model
- ATLAS has a broad programme of searches targeting scalar particles across a large mass range, including scalars with exotic charges
- No significant deviation from the Standard Model has been seen so far
    - Worthwhile to pay attention to a few mild excesses that have emerged in some channels
    - Looking forward to uncovering more of the phase space in the imminent Run-3!