Searching for additional Higgs boson in ATLAS

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On behalf of ATLAS collaboration

9th - 13th January, 2023

ATLAS EXPERIMENT
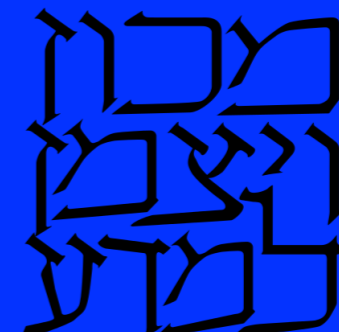
Introduction

- Discovery of a neutral scalar particle of a mass 125 GeV at the LHC confirmed the predicted electroweak symmetry breaking mechanism of the SM

- Experimental results are consistent with the SM Higgs Boson

- The discovery has completed the SM particle content

- Some questions remained open:
  - Dark Matter
  - Neutrino oscillations/Neutrino masses
  - Hierarchy/Naturalness problem
  - Matter-antimatter asymmetry

- Can be addressed in some BSM scenarios that extend the Higgs sector
- Various BSM models predict additional Higgs bosons:

  - Additional EW singlet: h,H
  - Two Higgs doublet model (2HDM): $h,H,A,H^\pm$
  - Two Higgs doublet + singlet Model (2HDM+a)
  - Higgs triplet models (SM +triplet): $H^{\pm\pm}$, etc.
  - …

  ⭐ These results will be shown today, the rest are in backup

New scalar/pseudoscalar:
$X \to \gamma\gamma$ (low mass) ⭐
$X \to \gamma\gamma$ (high mass) ⭐
$t\bar{t}H/t\bar{t}A \to 4t$ ⭐
g2HDM H in multilepton, multi-b ⭐
$t \to qX$, $X \to b\bar{b}$, $q = u,c$ ⭐

Exotic decays:
$H \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to a\tilde{\chi}_1^0\tilde{\chi}_2^0$, $a \to b\bar{b}$
$H \to Z_d Z_d \to 4l$, $H \to ZZ_d \to 4l$
$H \to aa \to b\bar{b}\mu\mu$

Charged Higgs:
$t \to H^\pm$, $H^\pm \to cb$ ⭐
$H^\pm \to W^\pm A$, $A \to \mu\mu$
$H^{\pm\pm}H^{\mp\mp} \to 4l$ ⭐

High and Low mass searches with $X \rightarrow \gamma\gamma$

▶ Search for a light axion-like particle (ALP) X, coupling to gluons in $\gamma\gamma$ spectrum in <u>mass range [10-70] GeV</u>

▶ 2 isolated photons with $E_T^\gamma > 22$ GeV and $p_T^{\gamma\gamma} > 50$ GeV

▶ Template fit to $m_{\gamma\gamma}$ distribution

▶ Exclusion limits set on $\sigma \times B(X \to \gamma\gamma)$

▶ Largest excess at 19.4 GeV with 3.1σ (1.5σ) local (global) significance

▶ Results interpreted as limits in the plane spanned by ALP mass (m_a) and decay constant (f_a)

 ▶ **Covers previously unexplored phase space!**

Lower limit on ALP decay constant
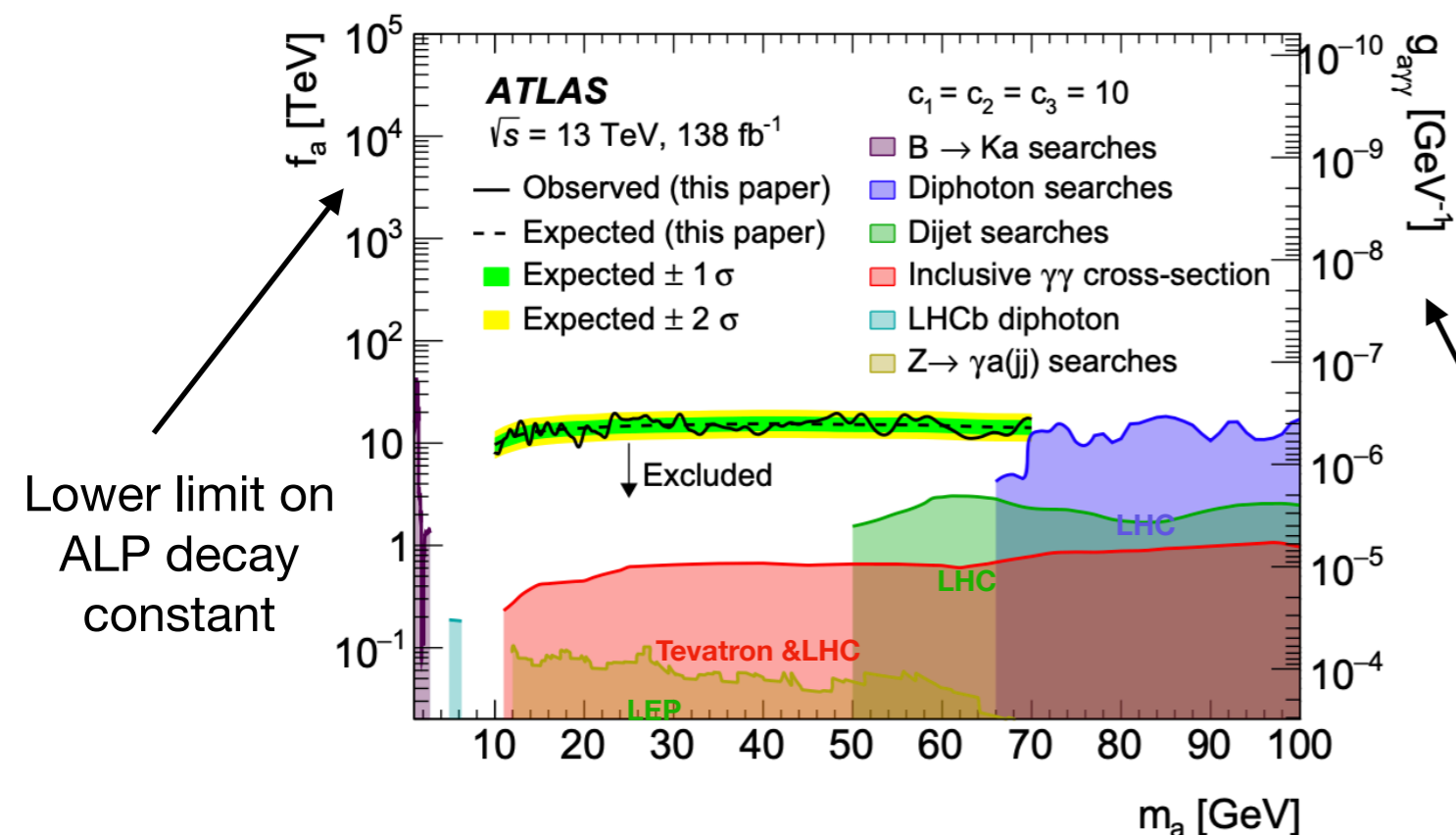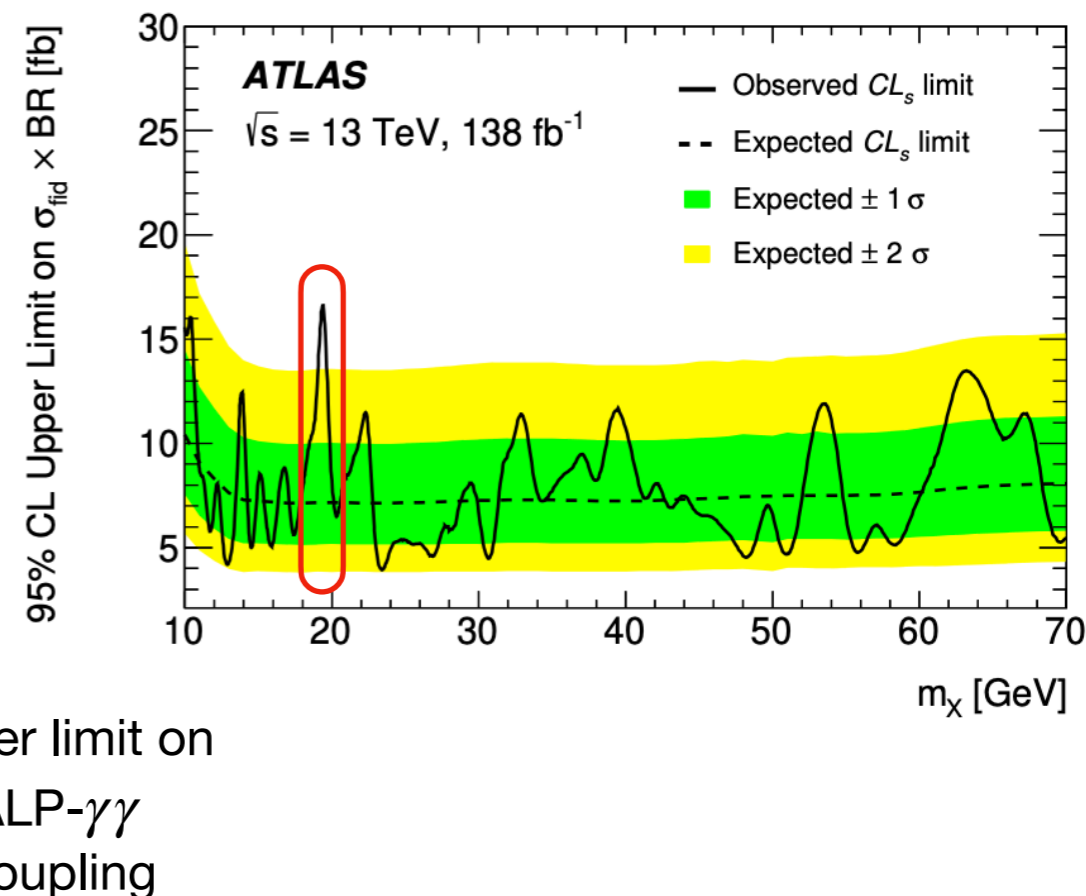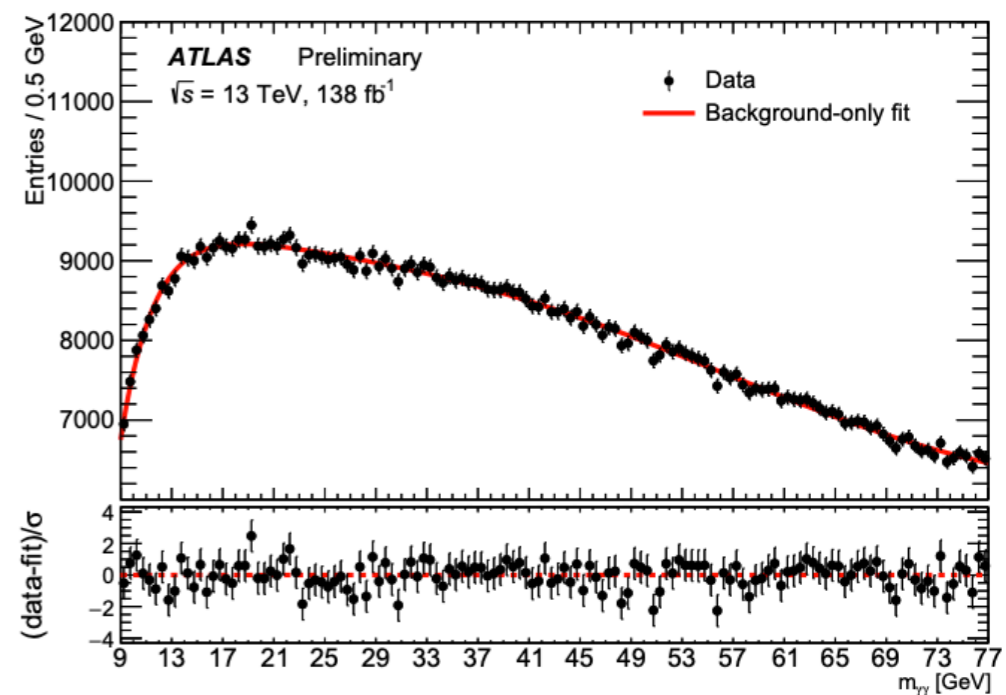
Upper limit on ALP-$\gamma\gamma$ Coupling

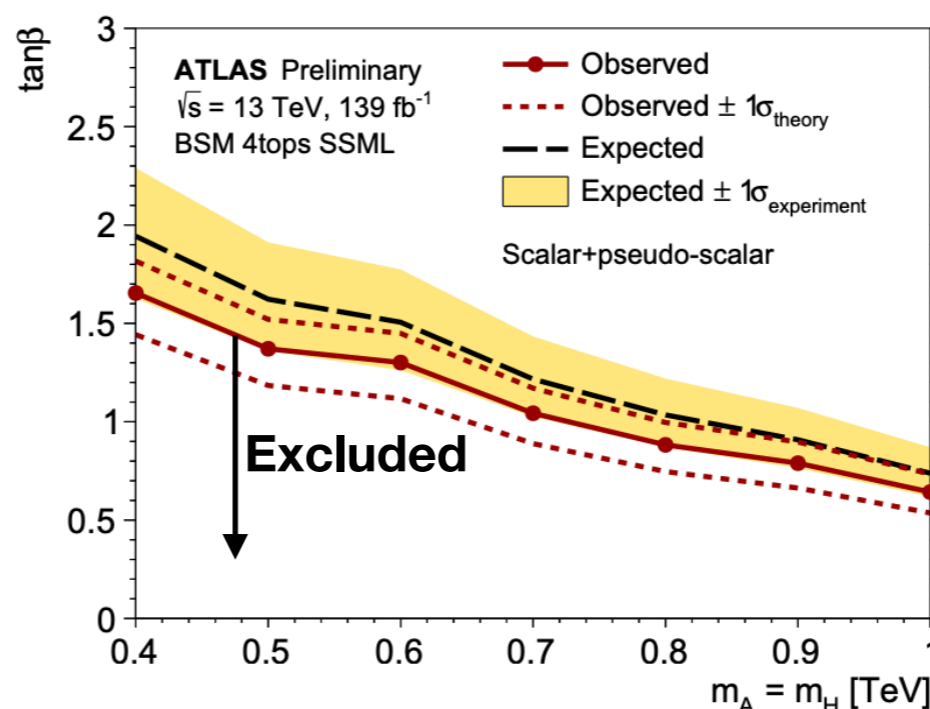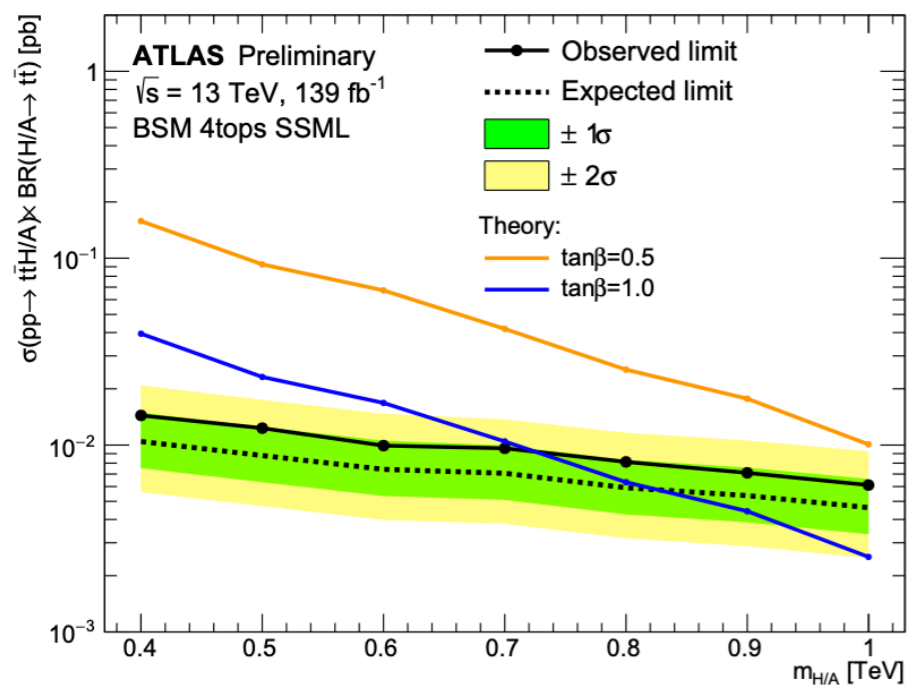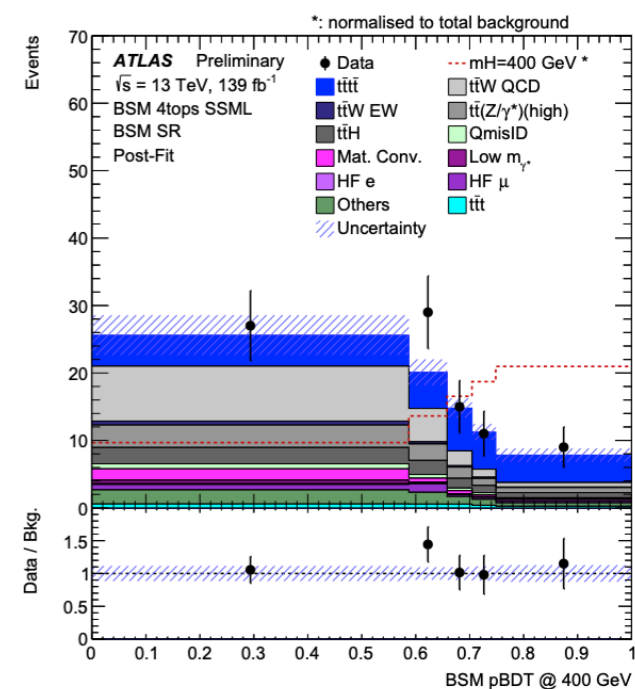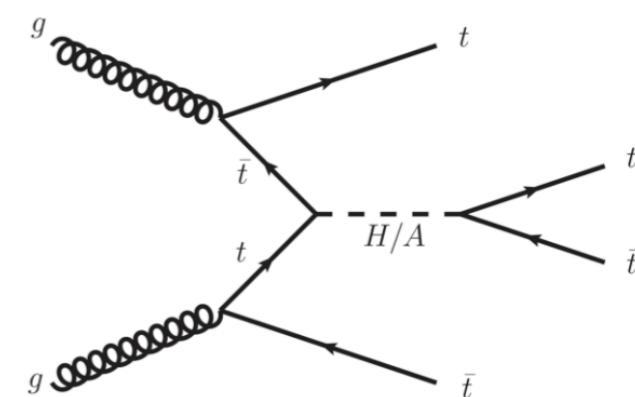- Search for a heavy scalar X in $\gamma\gamma$ final state
- 2 isolated photons with $m_{\gamma\gamma} > 150$ GeV
- Template fit to $m_{\gamma\gamma}$ distribution

- Exclusion limits set on $\sigma \times B(X \to \gamma\gamma)$
- Largest excess at 684 GeV with 3.29σ (1.30σ) local (global) significance

- Limits are provided in 2D plane of width (coupling) vs mass for spin-0 (spin-2) models
- Randal-Sundrum 1 model excluded for graviton masses $m_{G*} < 2.2, 3.9, 4.5$ TeV with couplings $k/\bar{M}_{Pl} = 0.01, 0.05, 0.1$
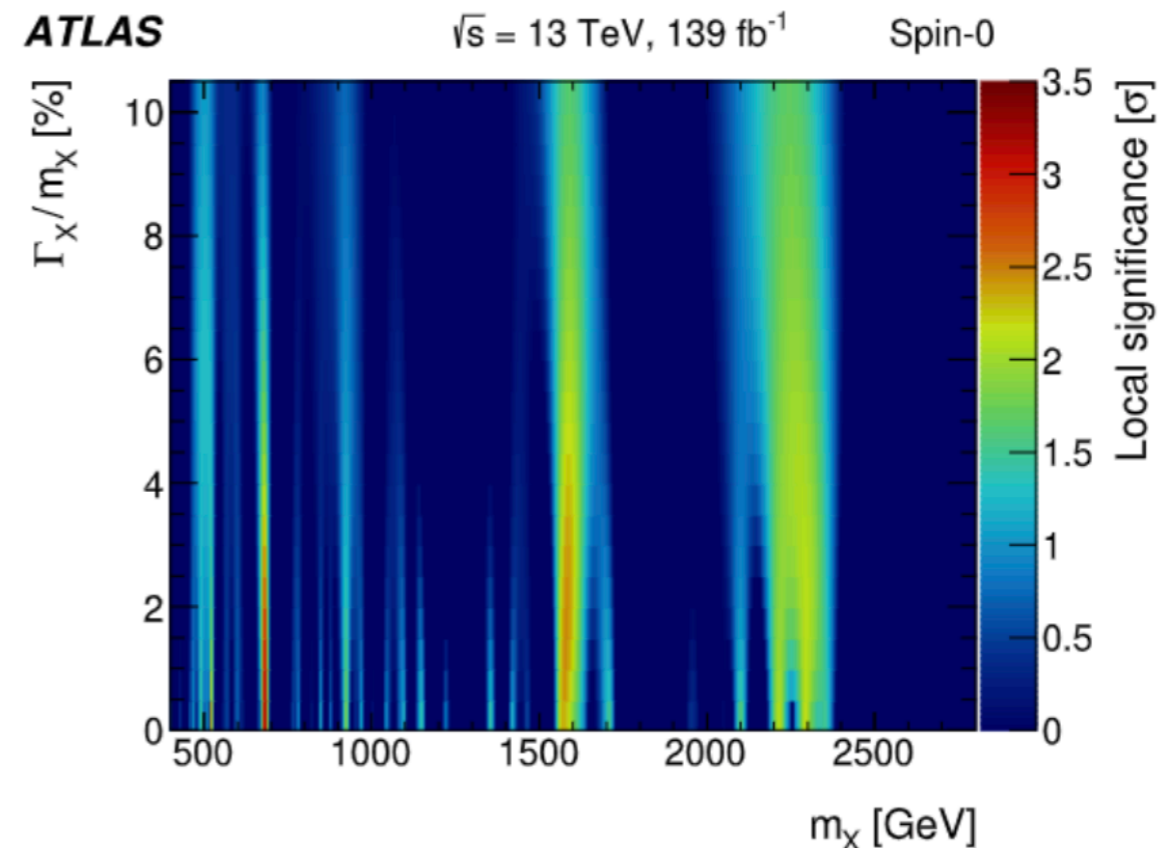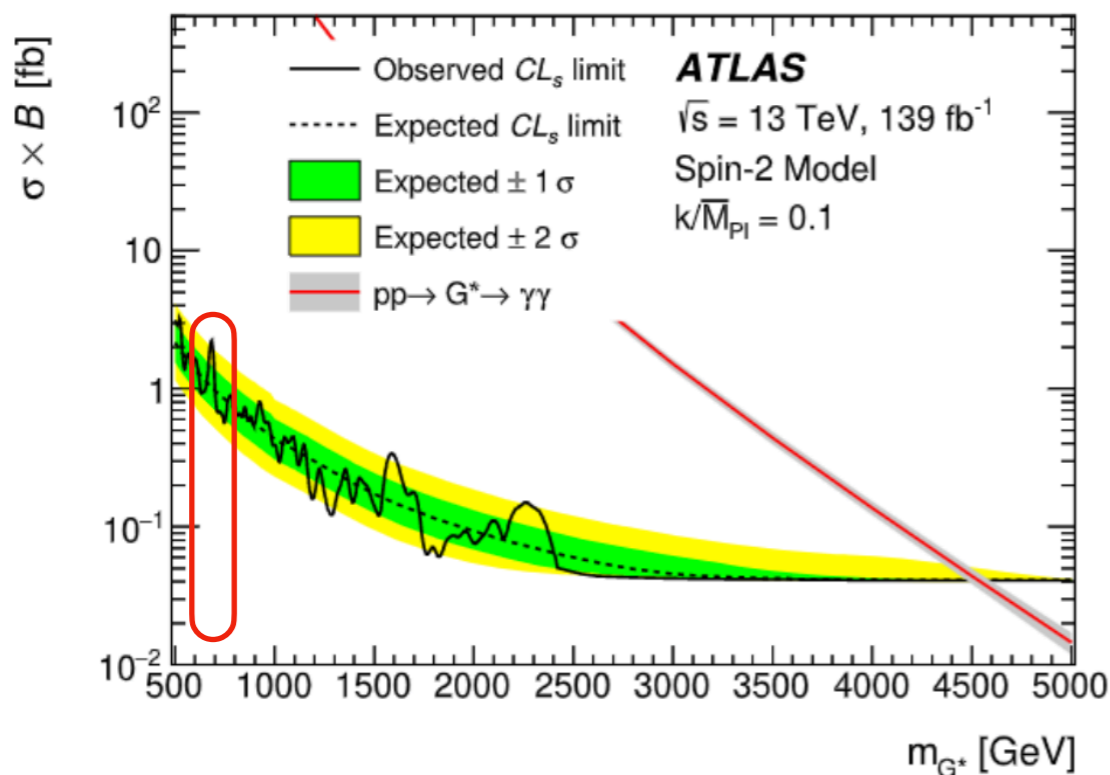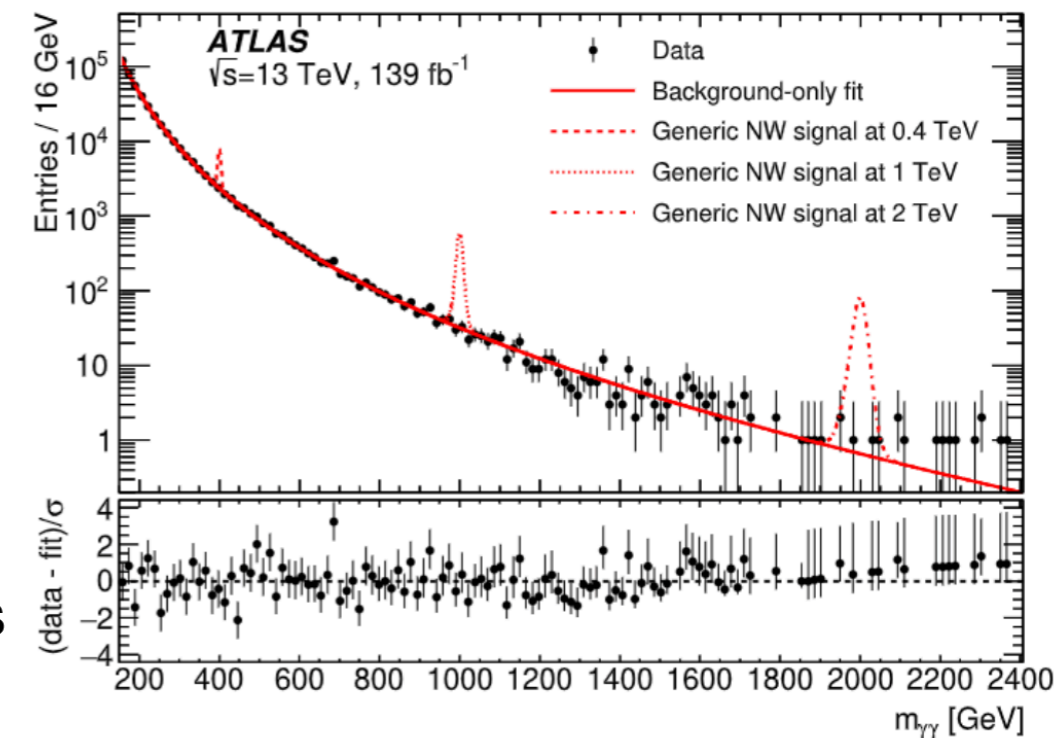
# Neutral Higgs in more complex systems

- Search for heavy additional neutral Higgs-like scalar and pseudo-scalar in 4 top processes in <u>mass range [0.4, 1] TeV</u>
- Avoids large negative interference from SM $t\bar{t}$
- Dominant decay of H/A is $gg \to t\bar{t}$

- Only multi-lepton events are selected (2 same sign or ≥ 3 leptons) with at least 6 jets and at least 2b-tagged jets, $H_T > 500$ GeV
- Trained 2 BDTs: a) to separate the SM 4t production from other SM backgrounds (SM BDT) and b) to separate signal from SM 4t (BSM pBDT)
- Simultaneous binned likelihood fit over various discriminating variables in CRs and SRs
- Results are interpreted in Type-II 2HDM
- Limits on $\sigma \times BR$ (with $m_H = m_A$) and translated to limits on $\tan\beta$

▶ Search for a new heavy scalar with Flavour-violating decays in g2HDM
▶ First to target BSM production leading to 3 top and the first to probe g2HDM
▶ Consider tt, tc & tu couplings only

▶ Final states containing 2,3 or 4 top quarks
▶ Multi-leptons channel (2LSS, 3L, $\geq$4L)
▶ $\geq$2 jets, with $\geq$ 1 or $\geq$ 2 b-tagged

▶ Signal regions based on lepton multiplicities, total lepton charge and multi-output DNN^{cat} classifier output (17 SR)
▶ DNN^{cat} is trained to identify each of the 5 possible production modes (in 2LSS,3L)

5 possible g2HDM production and decay modes:
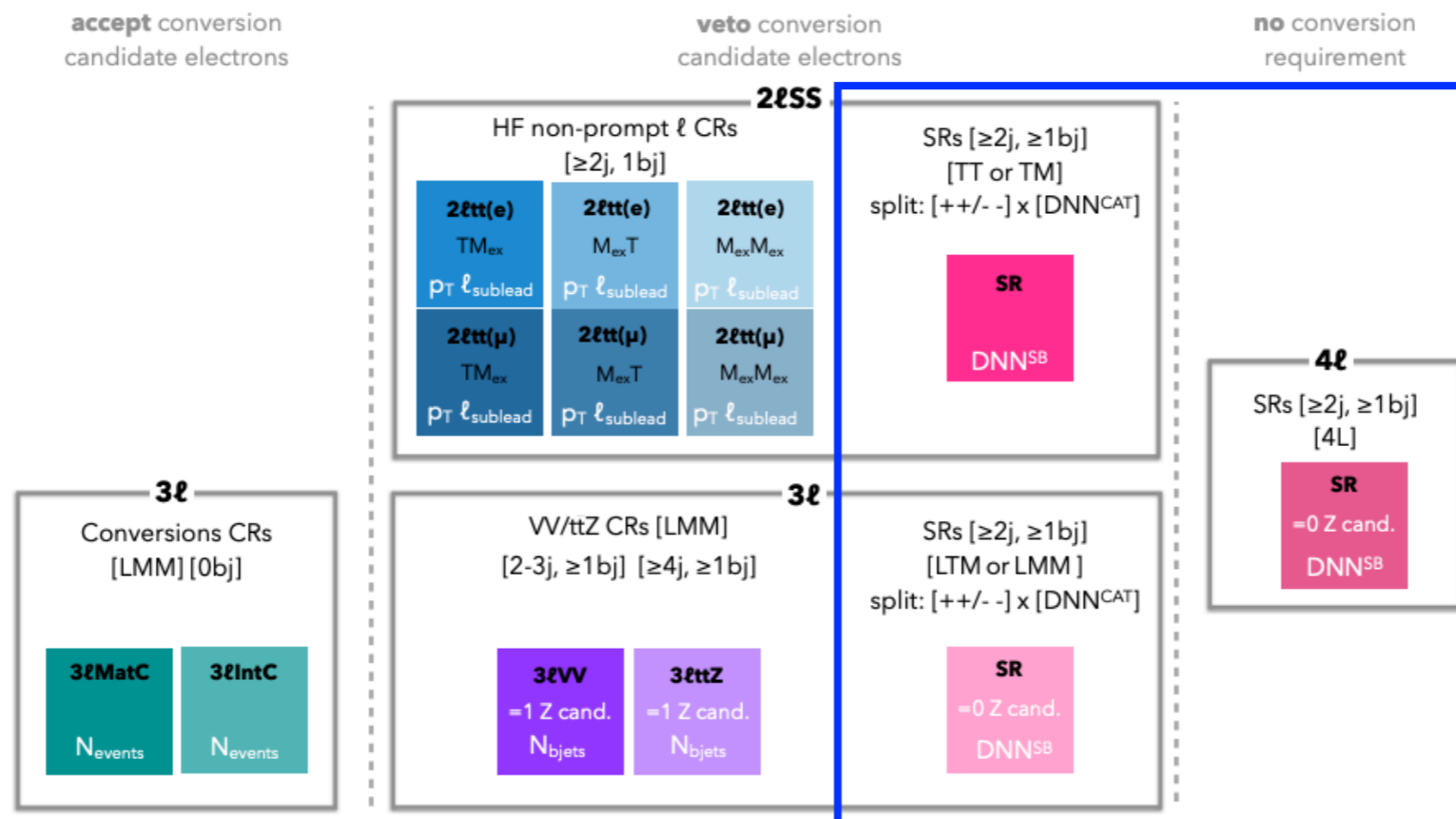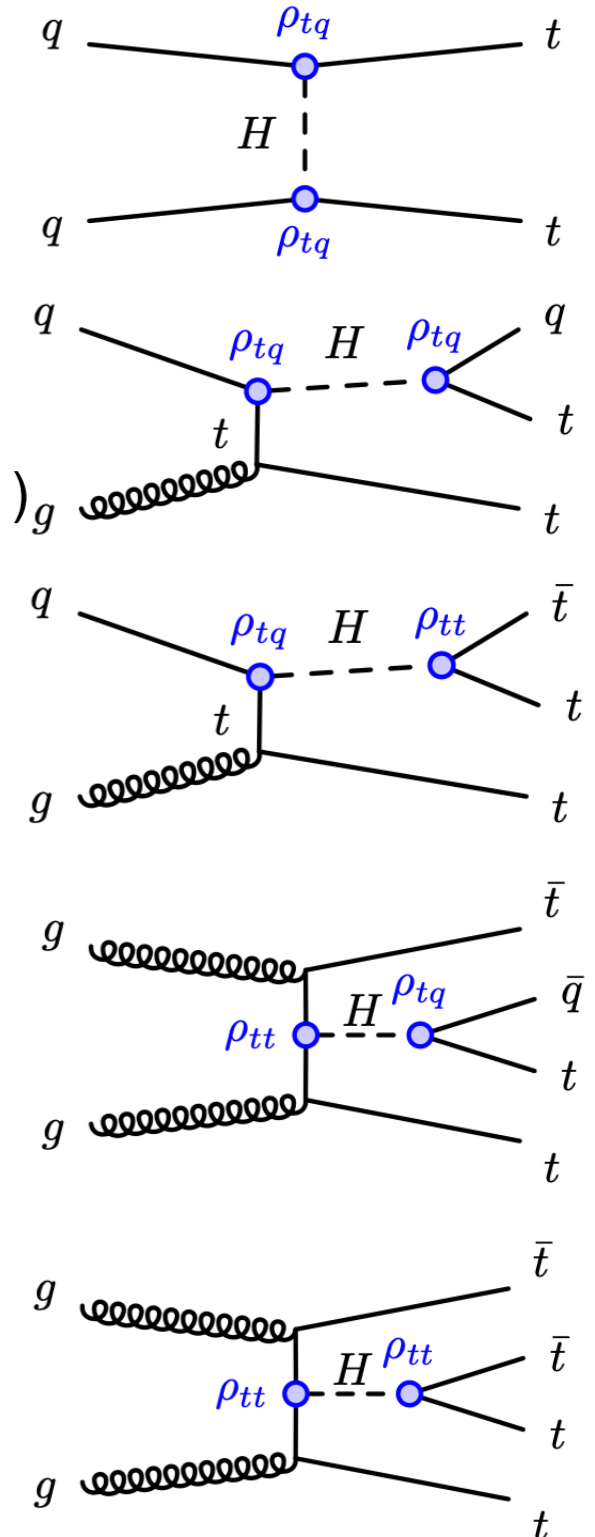
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▸ Signal regions based on lepton multiplicities, total lepton charge and multi-output DNN^{cat} classifier output (17 SR)
▸ DNN^{cat} is trained to identify each of the 5 possible production modes (in 2LSS,3L)
▸ Another DNN^{SB} is used to discriminate signal from background in each SR

▸ Upper limits on the m_H and couplings ρ are estimated
▸ 2.81σ local significance at 1TeV and $(\rho_{tt}, \rho_{tc}, \rho_{tu})$ = (0.32,0.05,0.85)
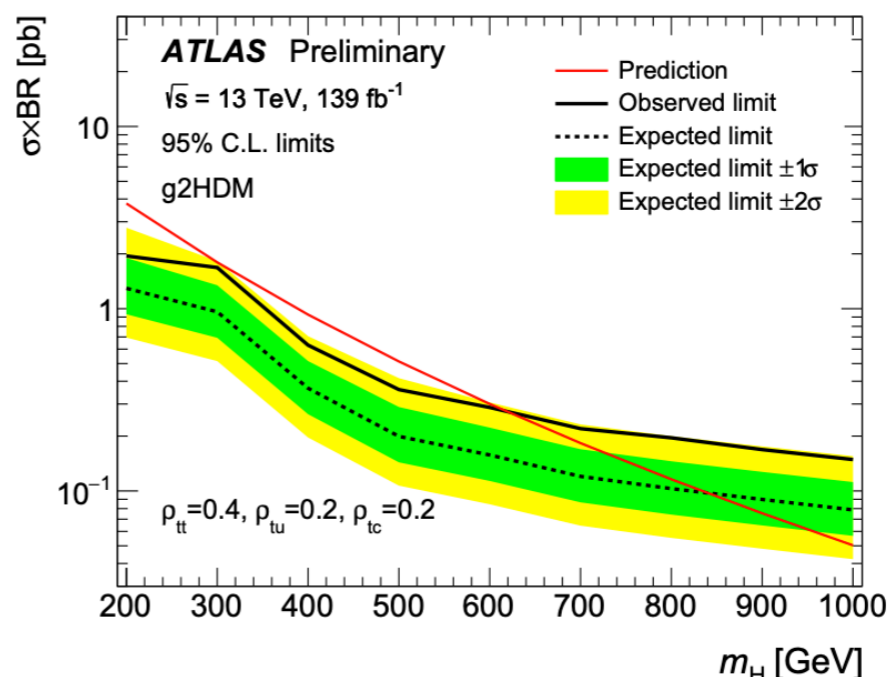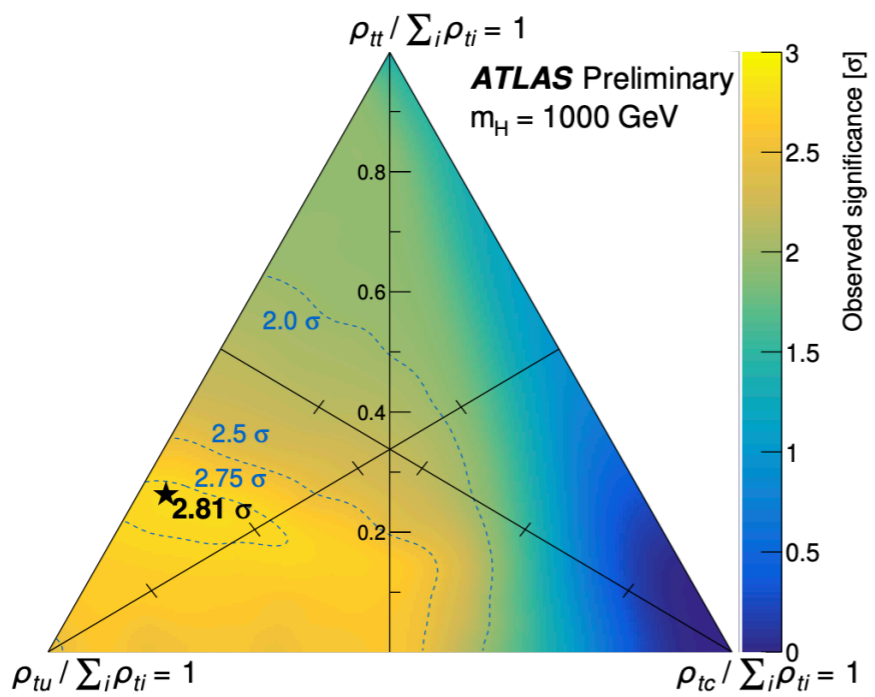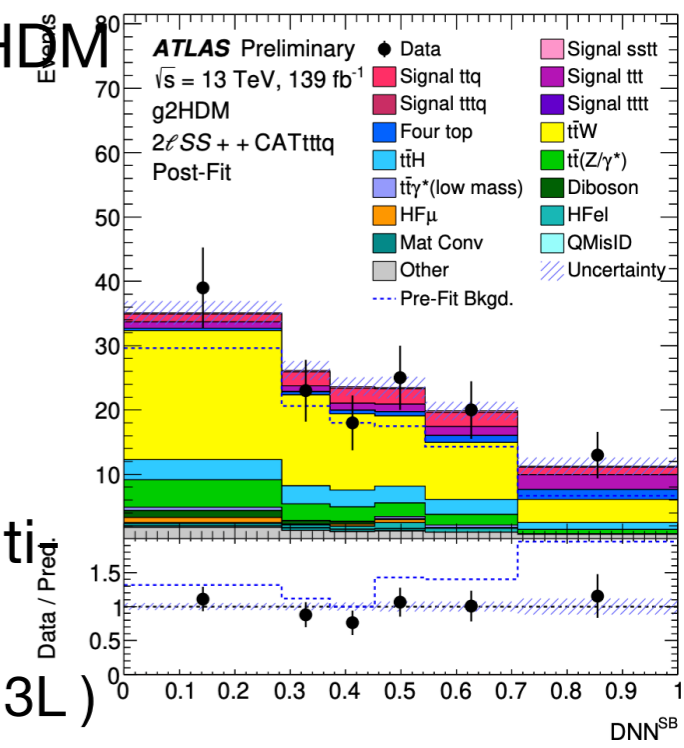
▸ Search for a flavour-changing neutral currents in top quark decays $t \to qX$, $X \to b\bar{b}$, with X being a light scalar, in <u>mass range</u> <u>[20,160] GeV</u>

▸ Search for exactly $1l$, at least 4-jets including at least 3 b-tagged
▸ Six analysis regions based on number of jets and b-jets
▸ Signal discrimination using mass parametrised DNN trained on jet, lepton and b-tagging information (training is done for $t \to uX$ and $t \to cX$ separately)

▸ Profile likelihood fit on NN score across SRs and CRs is performed
▸ Upper limits set on $B(t \to qX)$, excluding values larger than 0.08%
▸ Results are consistent with SM

$t \to uX$

$t \to cX$
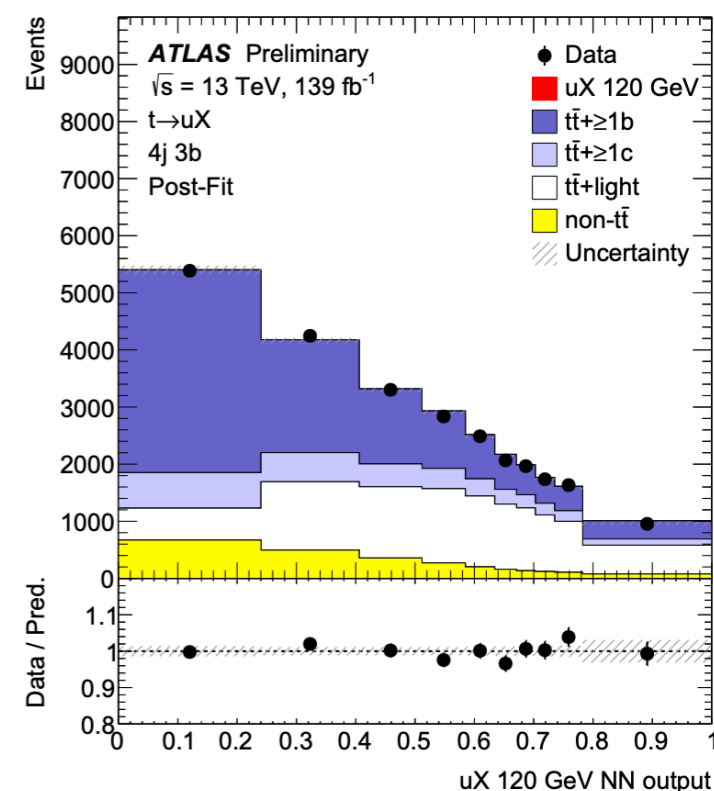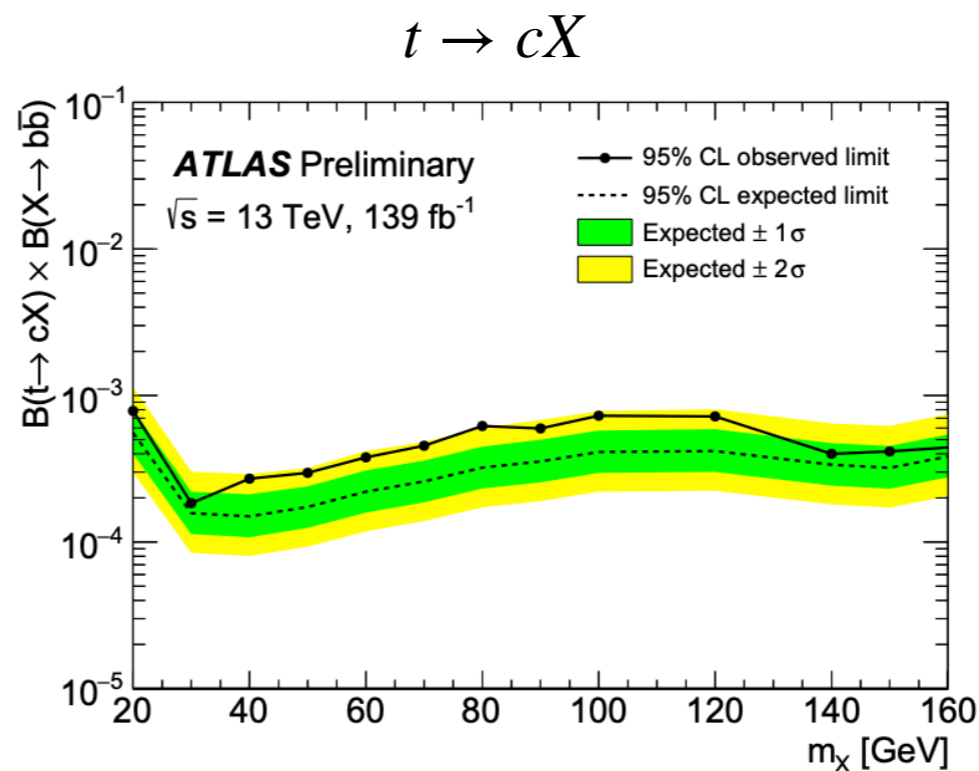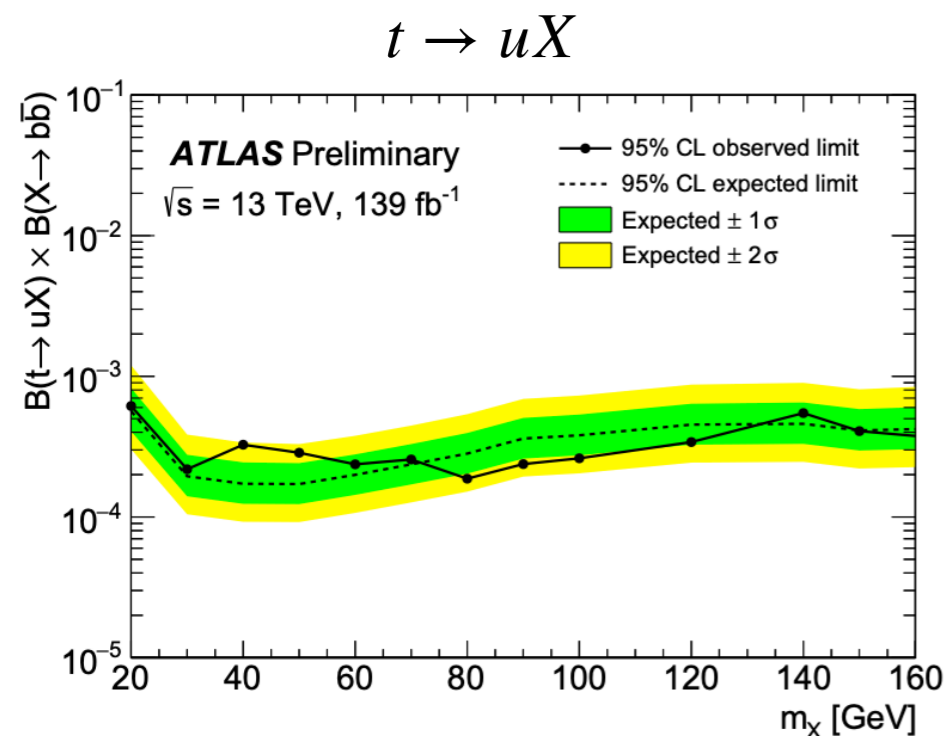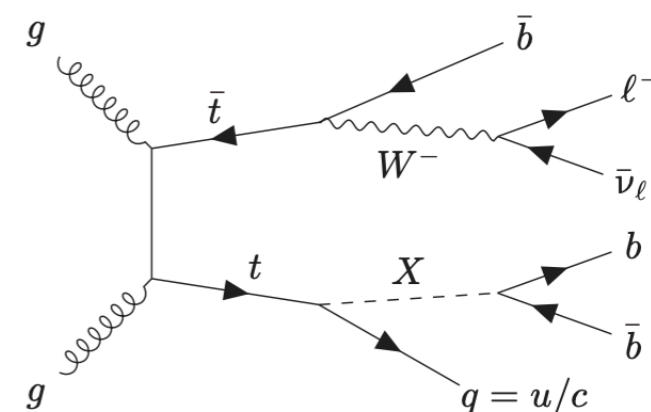
Charged Higgs

▸ Search for a charged Higgs in jets + lepton final state in $t\bar{t}$ events in <u>mass range [60,160] GeV</u>

▸ High multiplicity of jets (≥ 4) with b-jets (≥ 3) and 1 lepton
▸ 6 analysis regions based on number of jets and b-jets
▸ Mass parametrised NN classifier is used to discriminate single from background (use kinematic information from jets, leptons and E_T^{miss})

▸ Upper limits set on $BR(t \to H^{\pm}b) \times BR(H^{\pm} \to cb)$
▸ Improves previous LHC result by factor x5
▸ Observed local significance of 3σ at 130 GeV (1.6σ global)
▸ Broad excess is consistent with the expected mass resolution
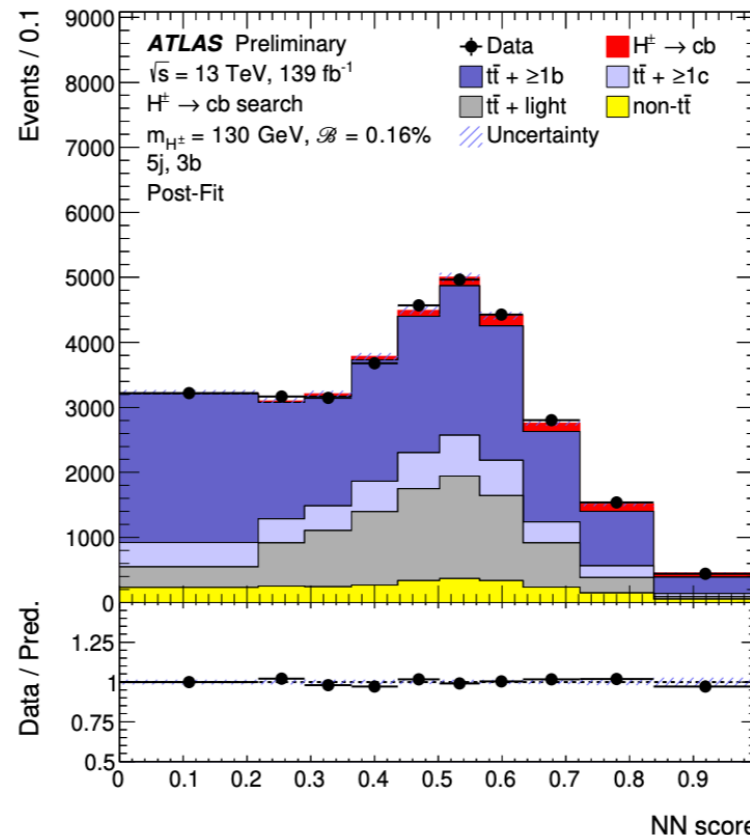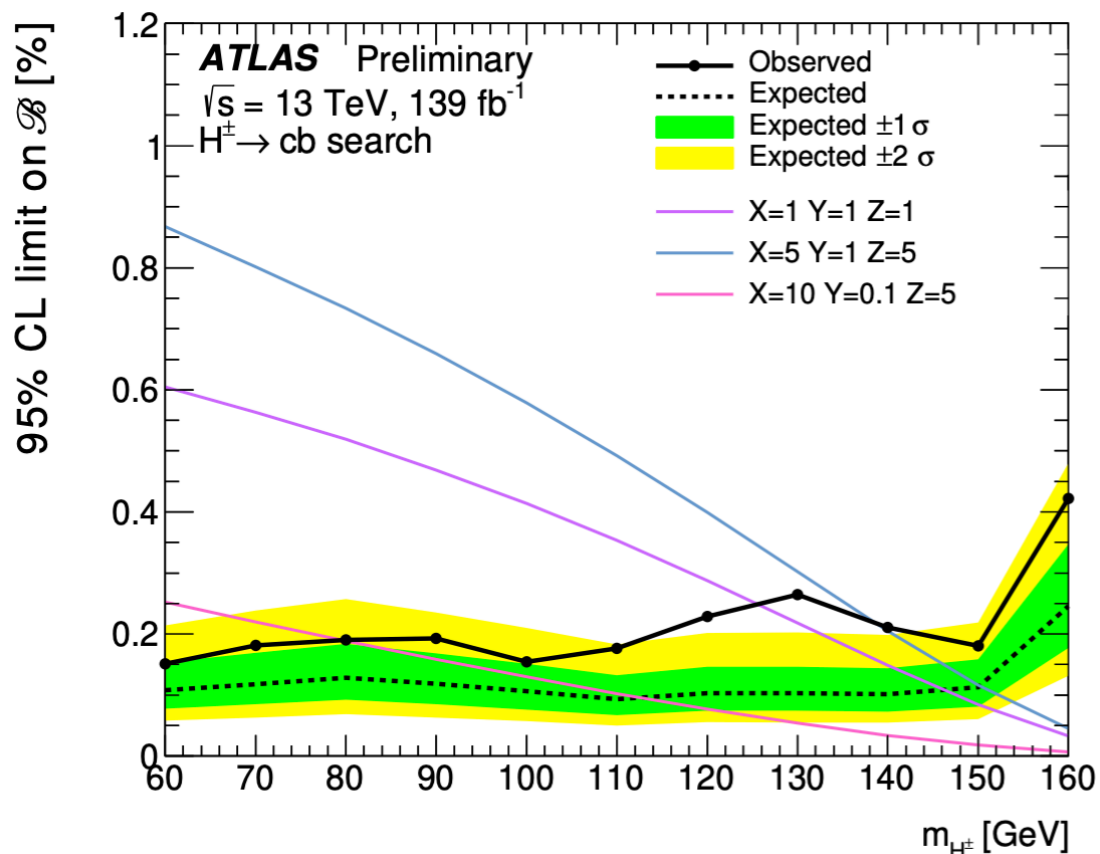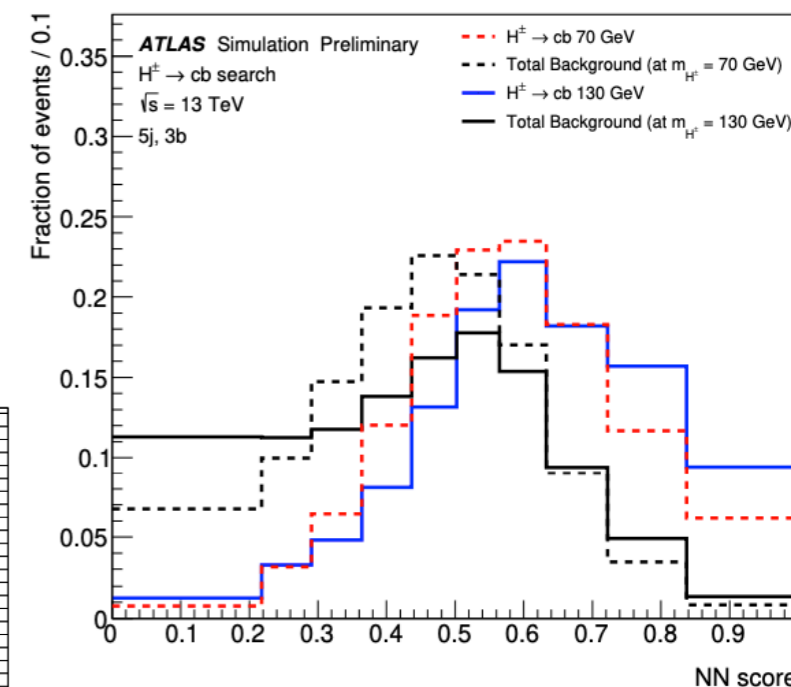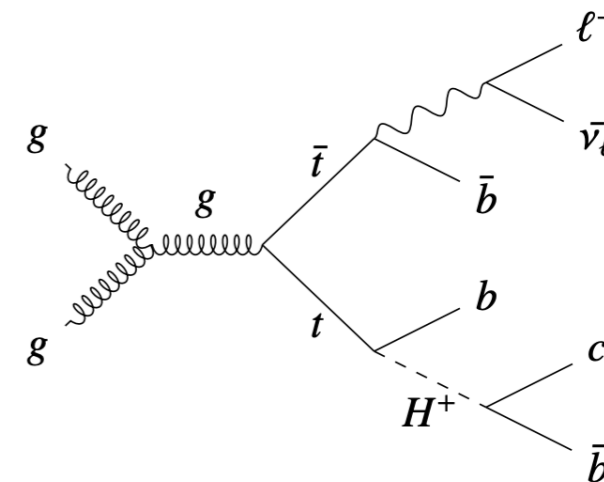
- Search for a pair production of double charged Higgs with $H^{\pm\pm} \to l^{\pm}l^{\pm}$ and $l = e, \mu, \tau$ in mass range [400,1300] GeV
- Predicted by Left-right symmetric models, Type-II seesaw models and sensitive to a lepton-violation scenarios

- Signal regions are separated by lepton multiplicities (2L,3L,4L)
- $m_{l^{\pm}l^{\pm}}$ is used as a discriminant in 2L and 3L regions; total yield in 4L regions

- Limits set on total production cross section, assuming democratic decays to lepton flavours
- Doubly charged Higgs excluded for masses below 1080 GeV
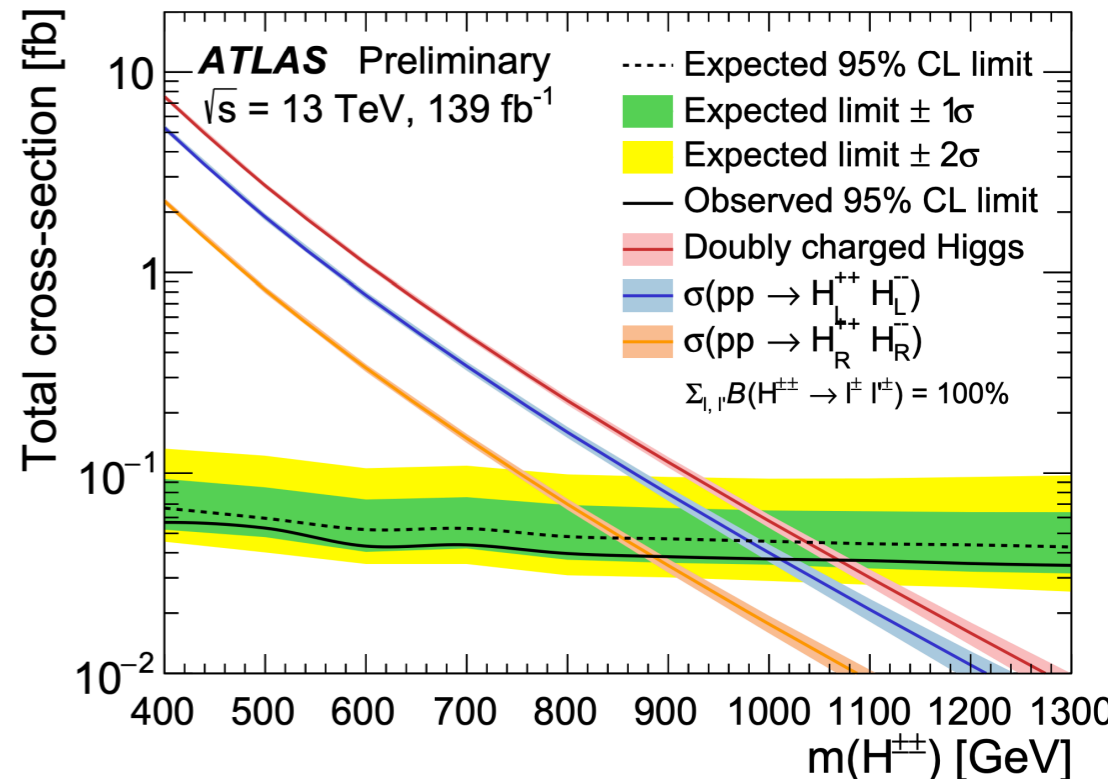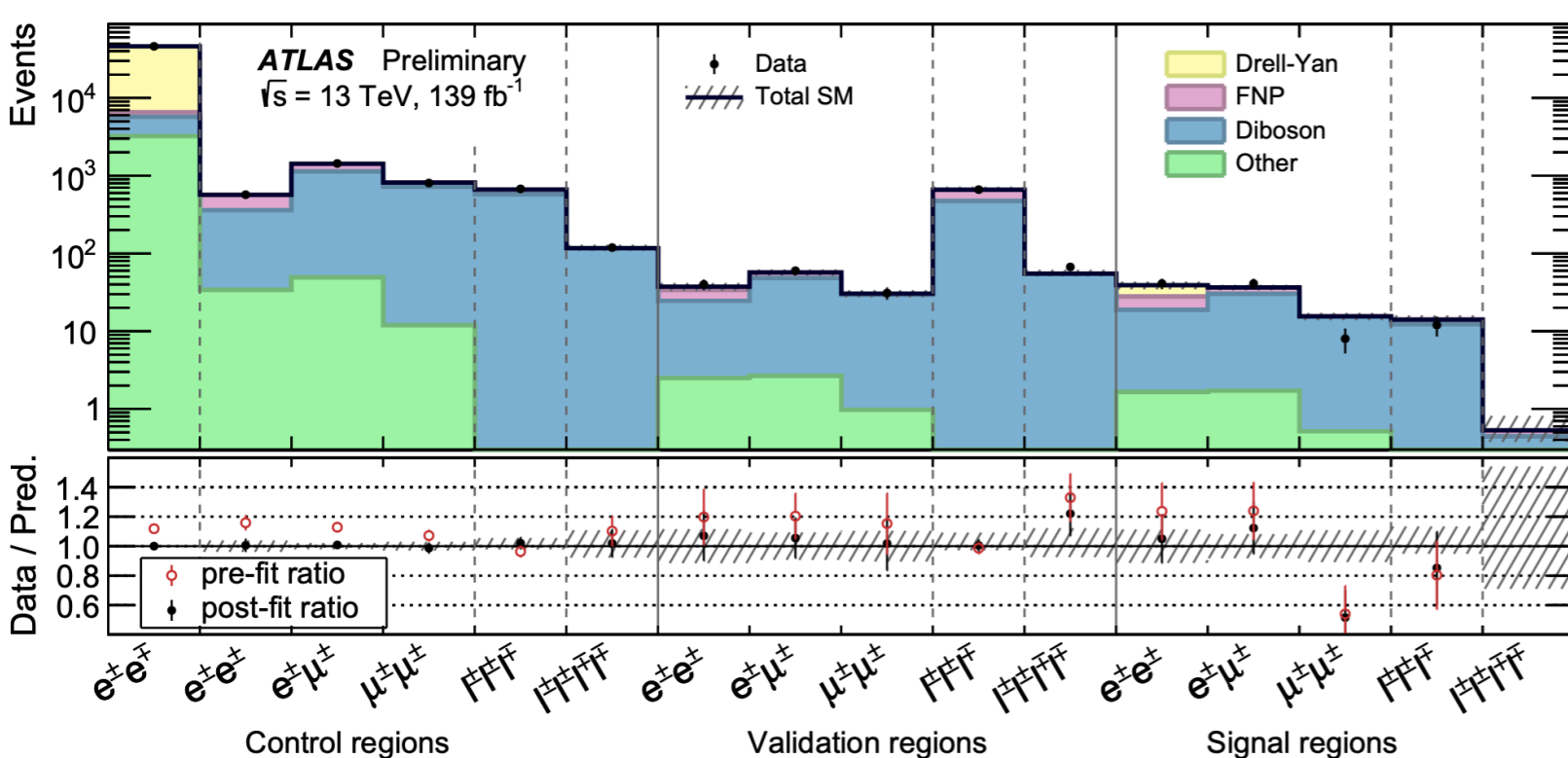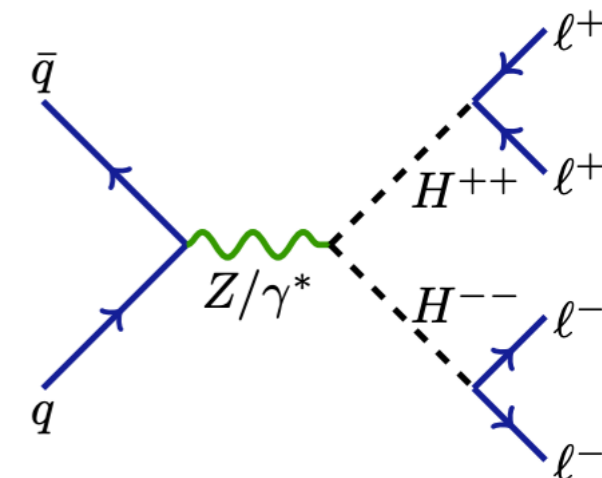
Conclusions

- New scalar particles are key experimental signatures for many extensions of the Standard Model

- Broad comprehensive programme targeting signatures of new scalars, pseudo-scalars and beyond the Standard Model Higgs decays is ongoing

- Results in general consistent with SM expectations (few local excesses are observed and it is worthwhile to pay attention to them)

- Looking forward to Run 3 results !

New scalar/pseudoscalar:

$X \to \gamma\gamma$ (low mass) ★
$X \to \gamma\gamma$ (high mass) ★
$t\bar{t}H/t\bar{t}A \to 4t$ ★
g2HDM H in multilepton, multi-b ★
$t \to qX,\ X \to b\bar{b},\ q = u, c$ ★

Exotic decays:

$H \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to a\tilde{\chi}_1^0 \tilde{\chi}_2^0,\ a \to b\bar{b}$
$H \to Z_d Z_d \to 4l,\ H \to ZZ_d \to 4l$
$H \to aa \to b\bar{b}\mu\mu$

Charged Higgs: ★
$t \to H^\pm,\ H^\pm \to cb$
$H^\pm \to W^\pm A,\ A$ ★ $\to \mu\mu$

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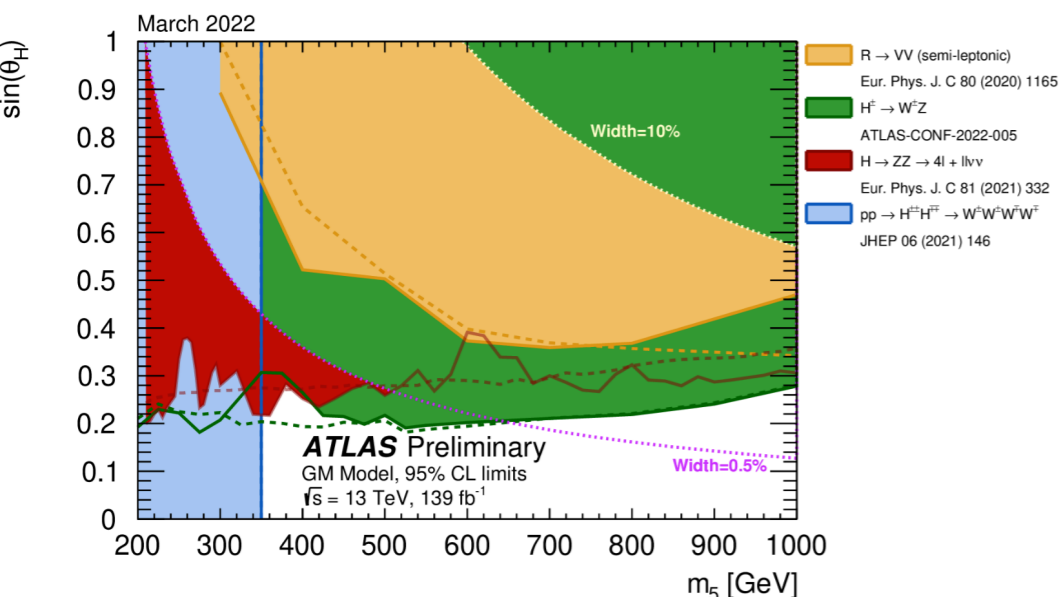
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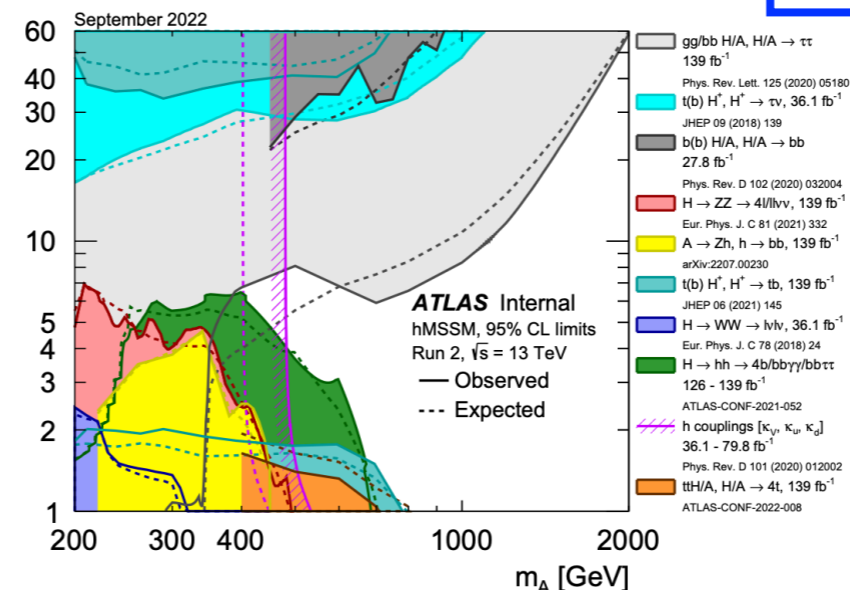
Thank you!

Backup slides

Heavy Neutral Higgs: $X \to \gamma\gamma$

- ▶ Search for a heavy scalar X in $\gamma\gamma$ final state
- ▶ 2 isolated photons with $m_{\gamma\gamma} > 150$ GeV
- ▶ Template fit to $m_{\gamma\gamma}$ distribution

- ▶ Exclusion limits set on $\sigma \times B(X \to \gamma\gamma)$
- ▶ Largest excess at 684 GeV with 3.29σ (1.30σ) local (global) significance

- ▶ Limits are provided in 2D plane of width (coupling) vs mass for spin-0 (spin-2) models
- ▶ Randal-Sundrum 1 model excluded for graviton masses $m_{G*} < 2.2, 3.9, 4.5$ TeV with couplings $k/\bar{M}_{Pl} = 0.01, 0.05, 0.1$
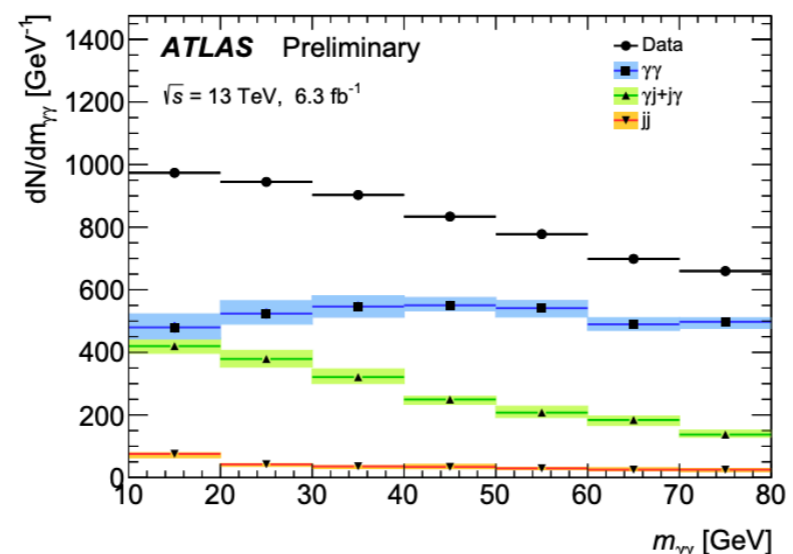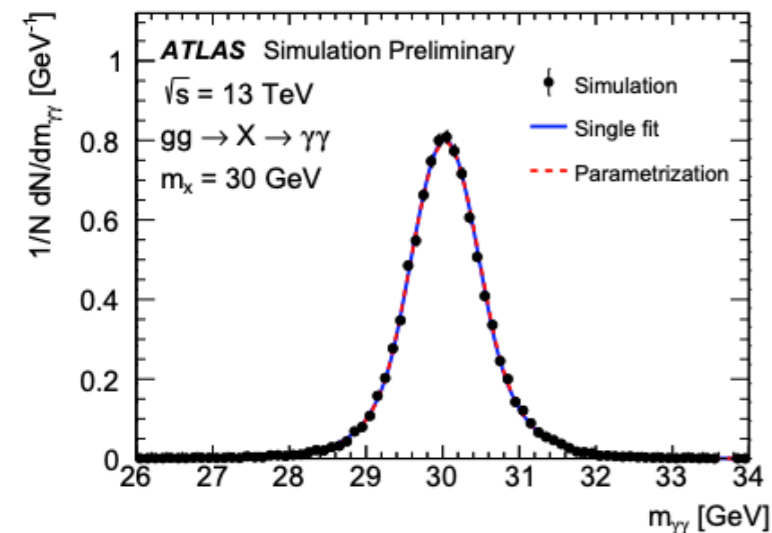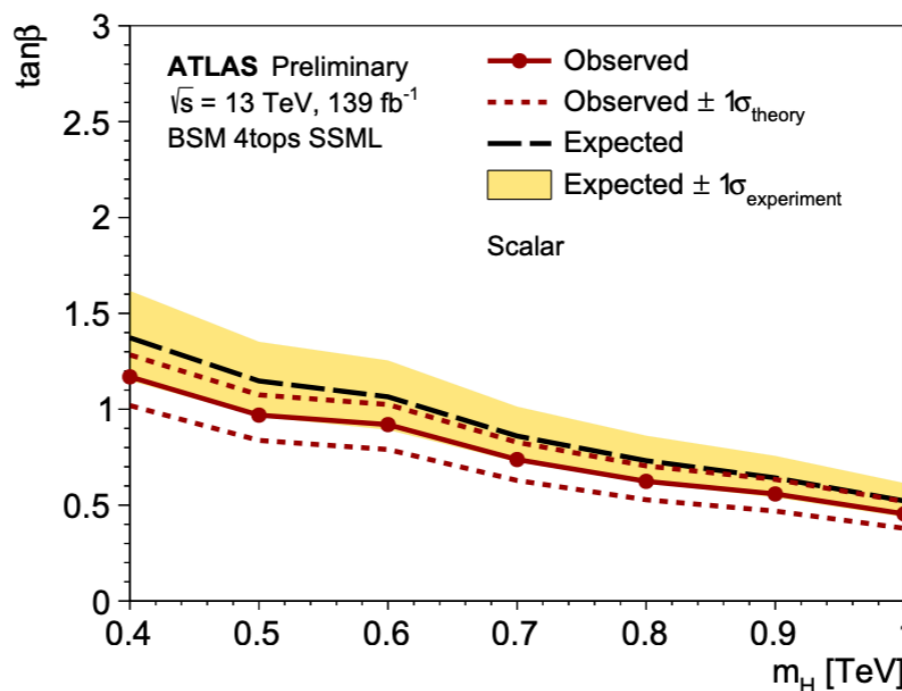
spin-0

spin-2

Neutral Higgs: $X \to \gamma\gamma$ (low mass)

arXiv:2211.04172

NEW!
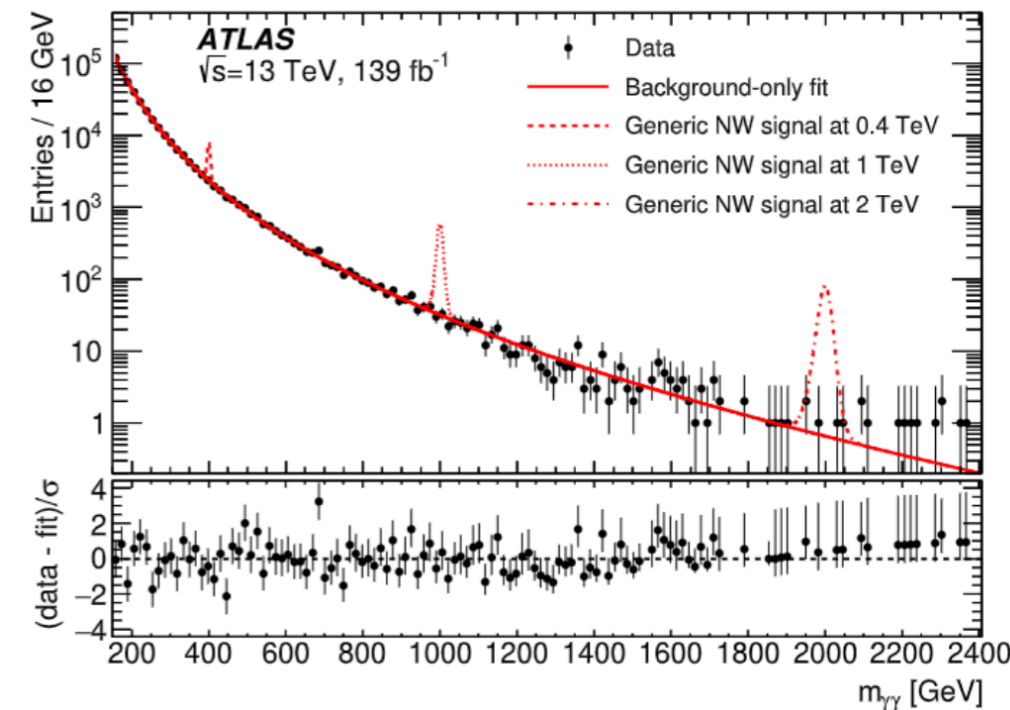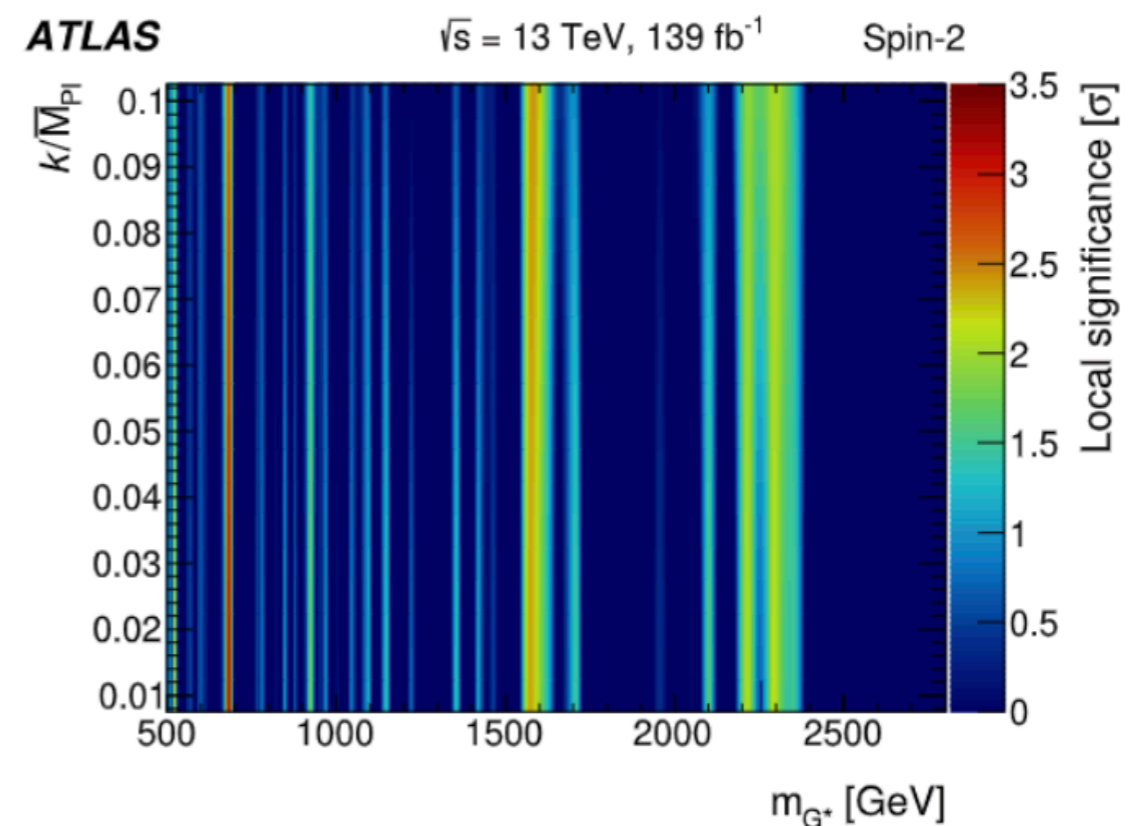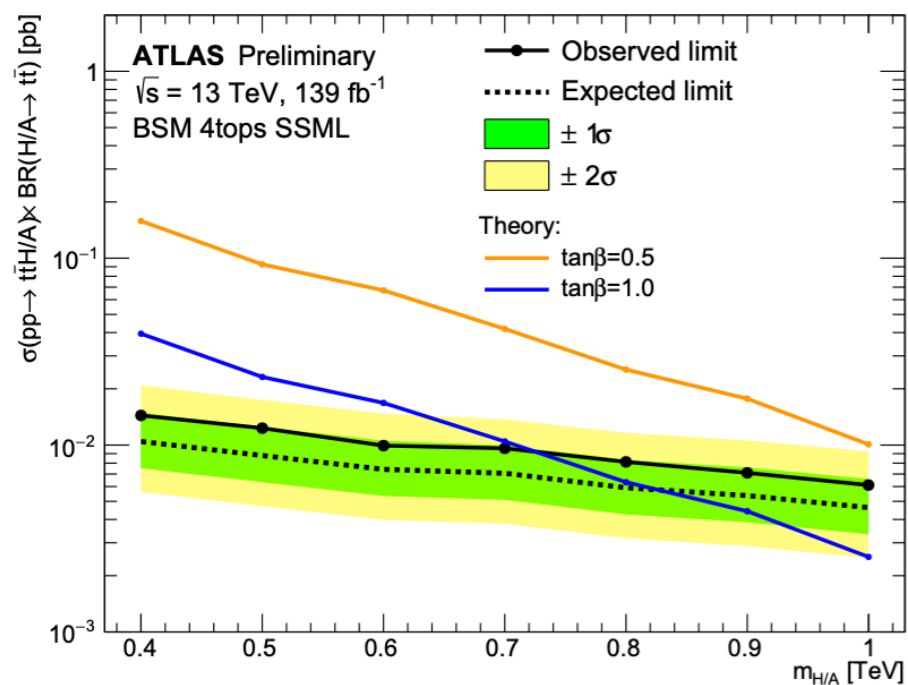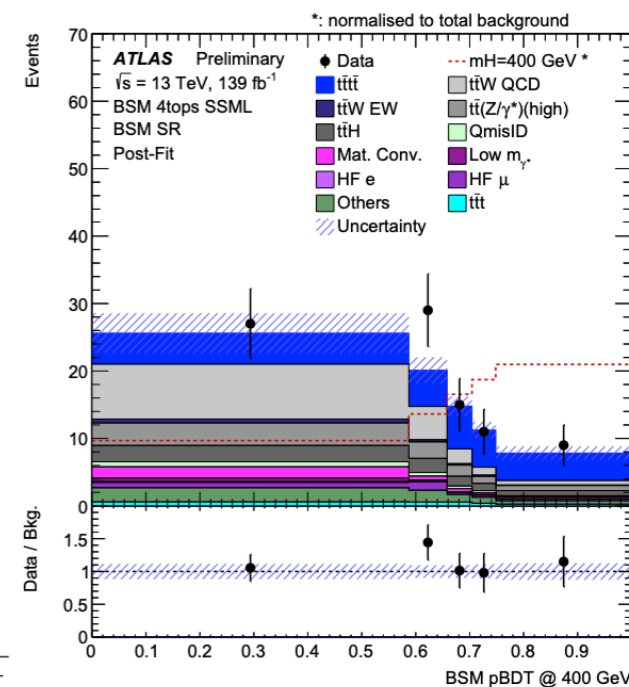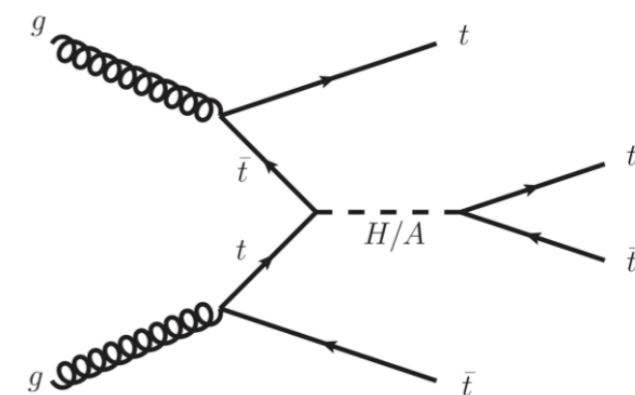
▸ Signal shape modelled by double-sided Crystal Ball
▸ Background shape is modelled by analytical function
▸ More complex fit around the turn-on region at 20 Gev

▶ Search for heavy additional neutral Higgs-like scalar and pseudo-scalar in 4 top processes in <u>mass range [0.4, 1] TeV</u>

▶ Avoids large negative interference from SM $t\bar{t}$

▶ Dominant decay of H/A is $gg \to t\bar{t}$

▶ Only multi-lepton events are selected (2 same sign or ≥ 3 leptons) with at least 6 jets and at least 2b-tagged jets, $H_T > 500$ GeV

▶ Trained 2 BDTs: a) to separate the SM 4t production from other SM backgrounds (SM BDT) and b) to separate signal from SM 4t (BSM pBDT)

▶ Simultaneous binned likelihood fit over various discriminating variables in CRs and SRs

▶ Results are interpreted in Type-II 2HDM

▶ Limits on $\sigma \times BR$ (with $m_H = m_A$) and translated to limits on $\tan \beta$

▸ Search for a cascade $H \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to a\tilde{\chi}_1^0\tilde{\chi}_2^0, a \to b\bar{b}$ Higgs from ZH production

▸ NMSSM scenario: $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ light neutralinos, a - light scalar

▸ Select on $Z \to ll$ to reduce backgrounds, 2jets + high MET

▸ Model of background distribution constructed from fits on Control region

▸ Limits via fits of signal distribution and background model to m_{jj}

▸ Results are consistent with SM
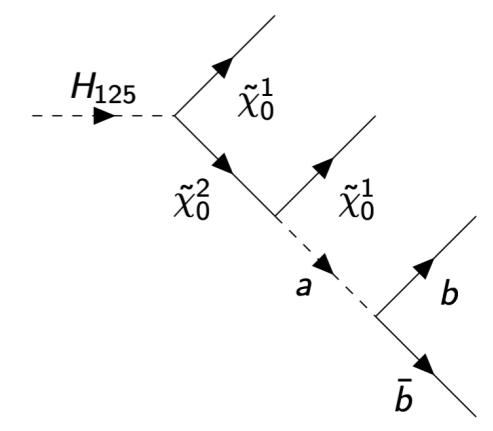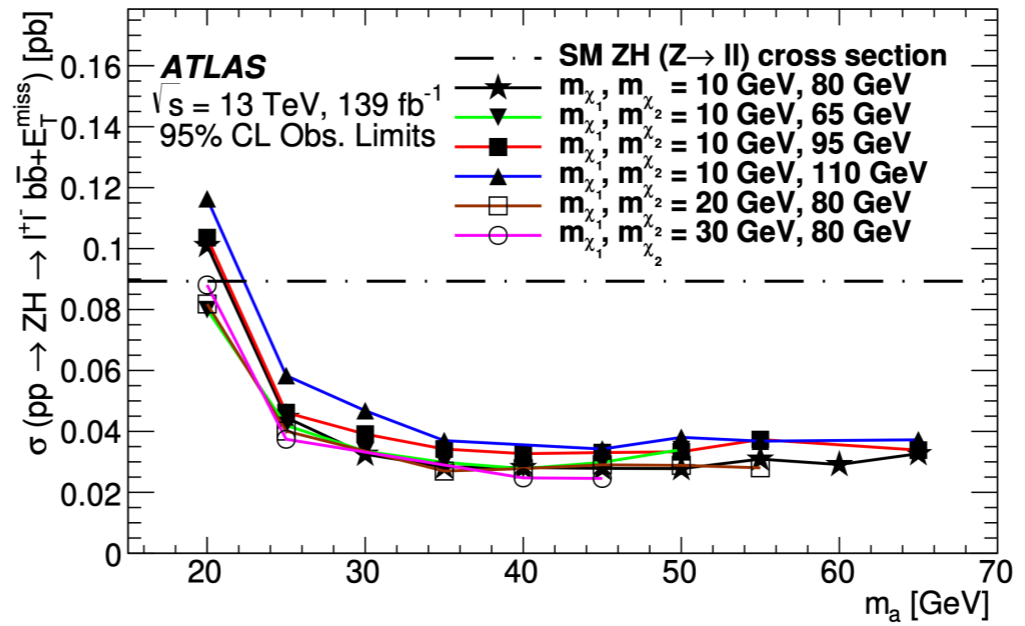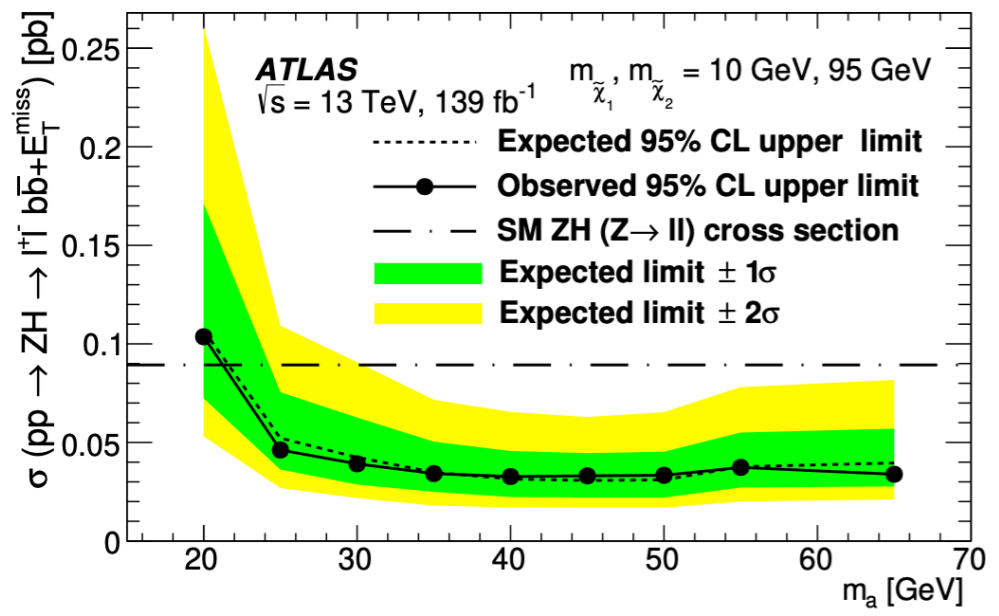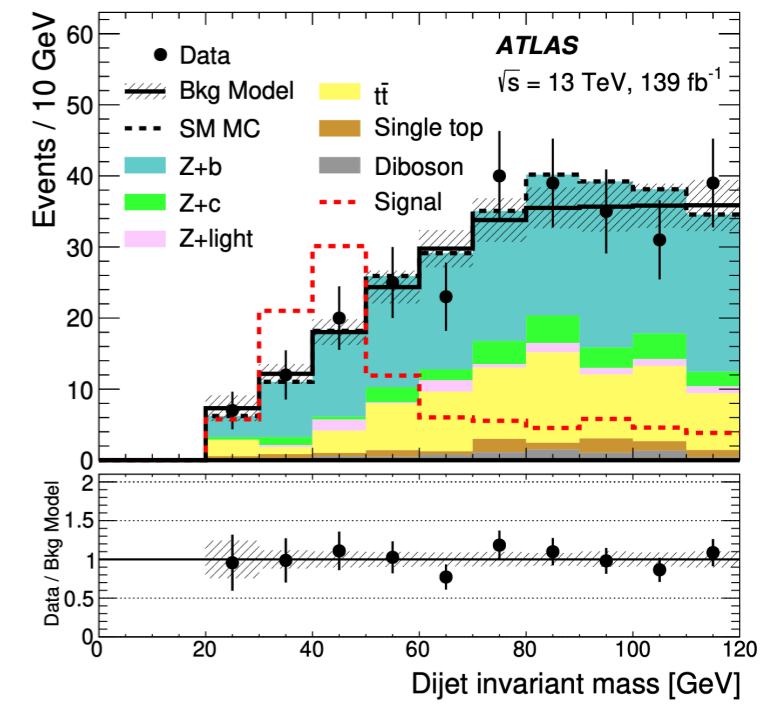
▶ Search for ggF-produced Higgs boson decay to one or two BSM vector bosons in $4l$ final state

▶ Searches in High mass $Z_d Z_d$ (HM $4l$): 15-60 GeV, Low mass $Z_d Z_d$ (LM 4μ): 1-15 GeV and Single Z_d ($4l$): 15-55 GeV

▶ Template fits to $<m_{ll}> = \frac{1}{2}(m_{12} + m_{34})$ or m_{34}
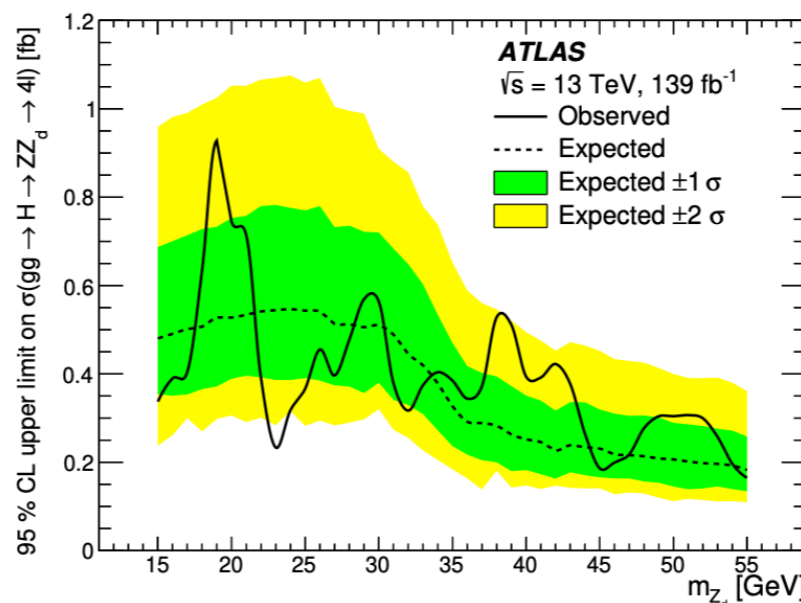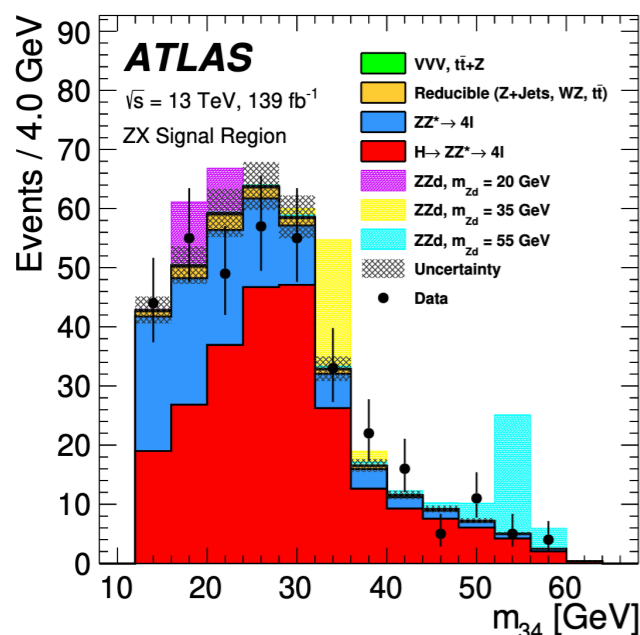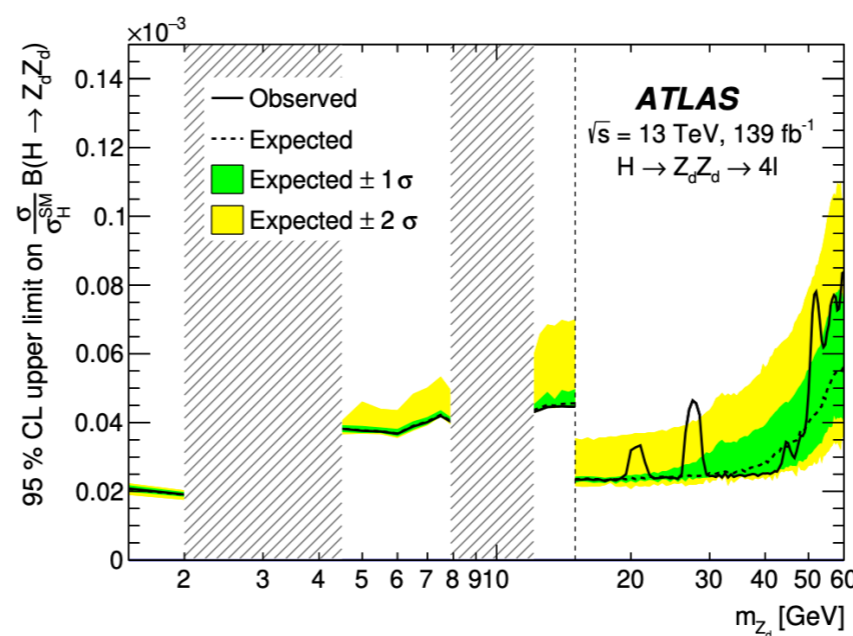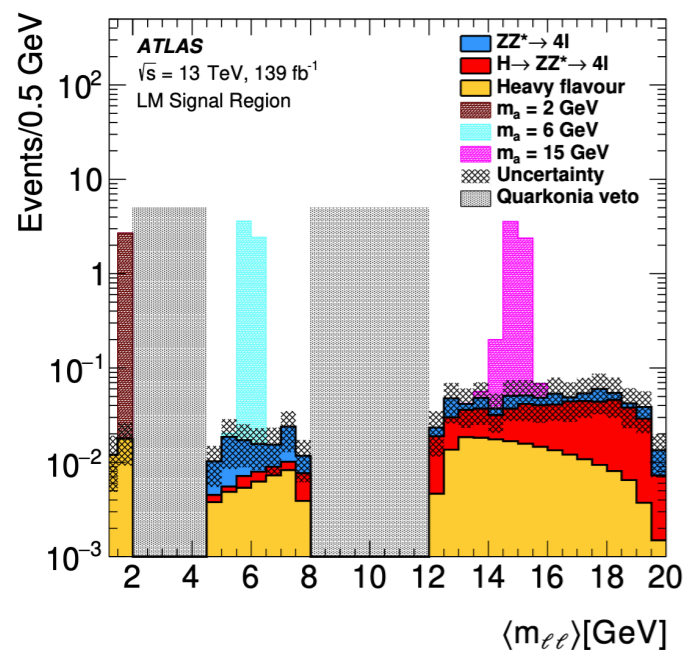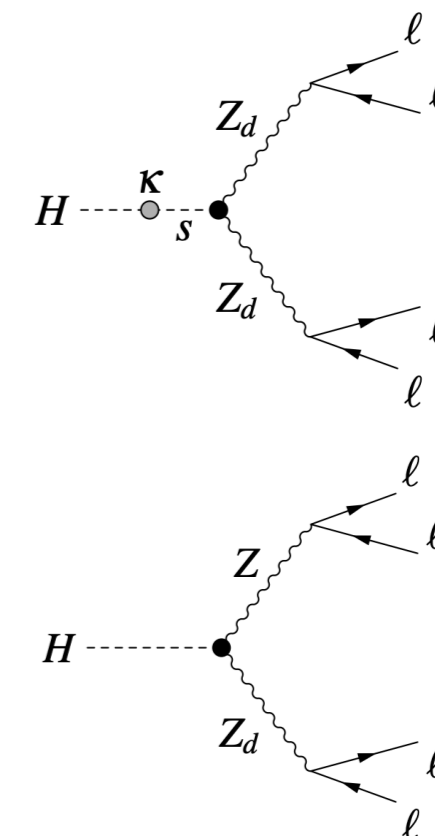
▶ Small access of 2.5σ local at 28 GeV is observed

▸ $H \to aa \to \mu\mu bb$ in gluon-gluon fusion production

▸ $a \to bb$ has large BR and $a \to \mu^+\mu^-$ is clean decay mode

▸ Choose 2μ, 2 b-tagged jets in mass range 15 GeV $< m_{\mu\mu} <$ 65 GeV

  and $m_{\mu\mu bb} <$ 140 GeV

▸ Train BDT to improve signal selection

▸ Fit $m_{\mu\mu}$

▸ 3.3σ local significance is observed (with 1.7σ global)
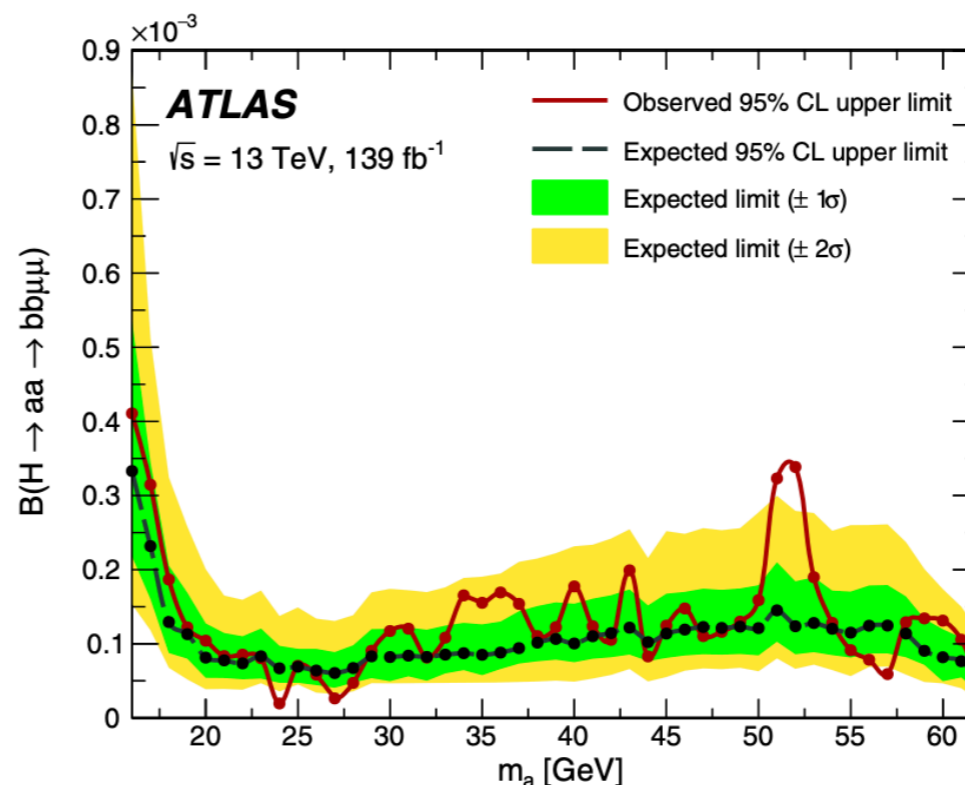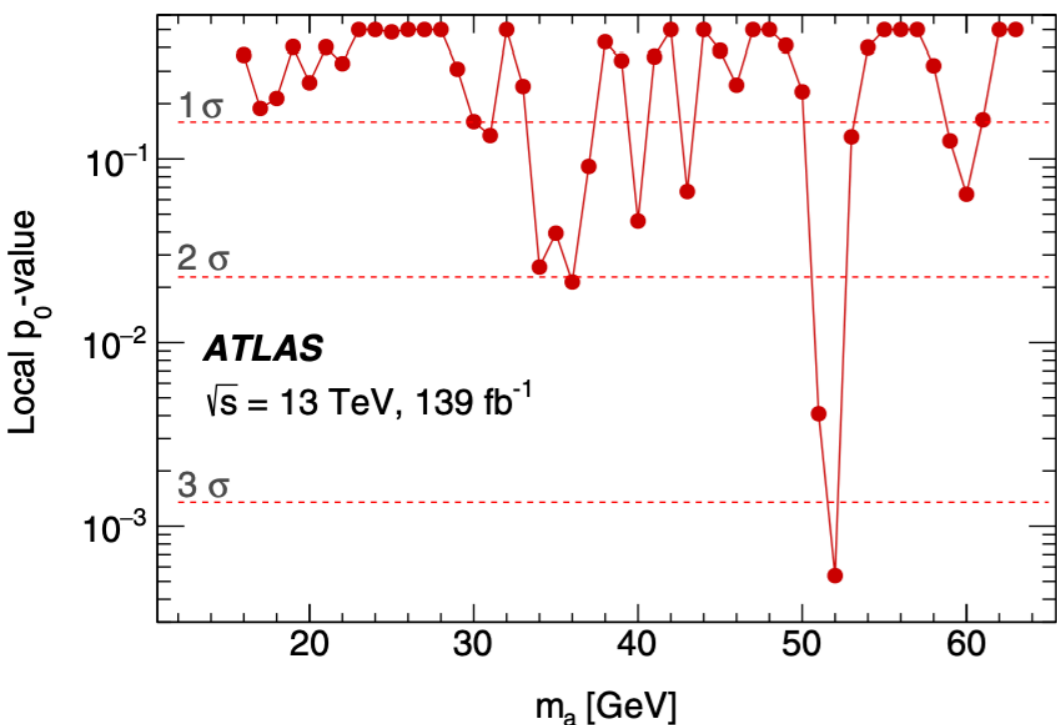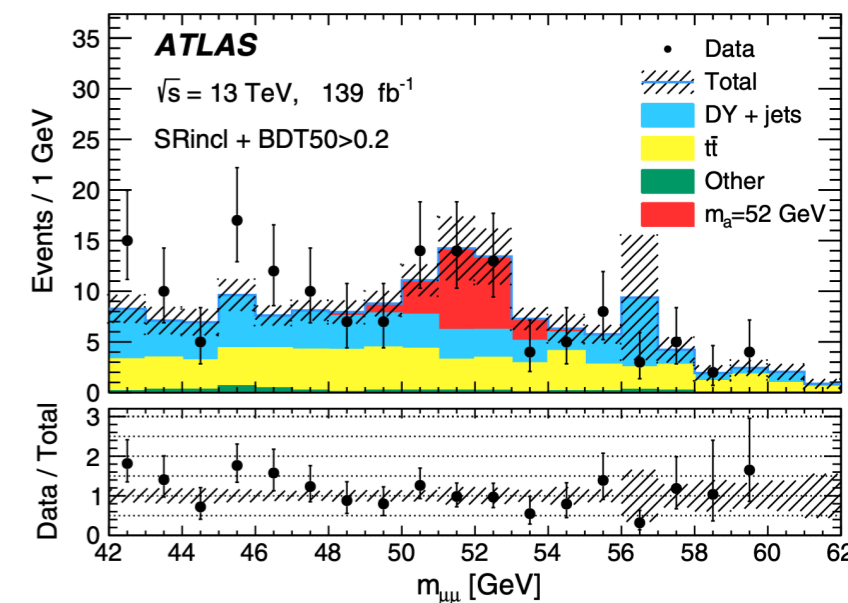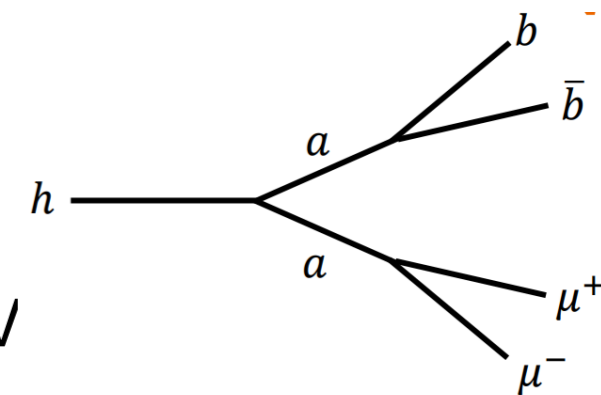
- Search for a charged Higgs Boson decaying to a pseudo scalar A and a W produced in association with a top quark
- $\mu\mu e$ final state is easy to reconstruct
- A signal has at least 3 jets (1b-tagged) with one electron and two muons
- Search is performed in mass range 15-75 GeV
- Upper limits are computed as a function of m_A for various $m_{H^{\pm}}$ hypotheses
- First lower limits on $tan\beta$ for a 2HDM type-I model