# Searching for additional neutral Higgs bosons at ATLAS

***Giacomo Artoni*** *on behalf of the ATLAS Collaboration*

**Higgs 2024**, Uppsala, *4-8 November 2024*

# Motivation and overview

*Discovery of the Higgs boson with $m_H$ = 125 GeV*

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***Two Higgs Doublet Model (2HDM):*** SM Higgs doublet + additional doublet
*(**g2HDM** without imposing $Z_2$ symmetry to remove flavour changing neutral Higgs)*

***2HDM + singlet:*** SM Higgs doublet + additional doublet + additional singlet

***Hidden Abelian Higgs Model:*** SM Higgs doublet + $U(1)_d$ dark-sector extension

and many other models:
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*Vast research program at the ATLAS experiment: link to all public results*

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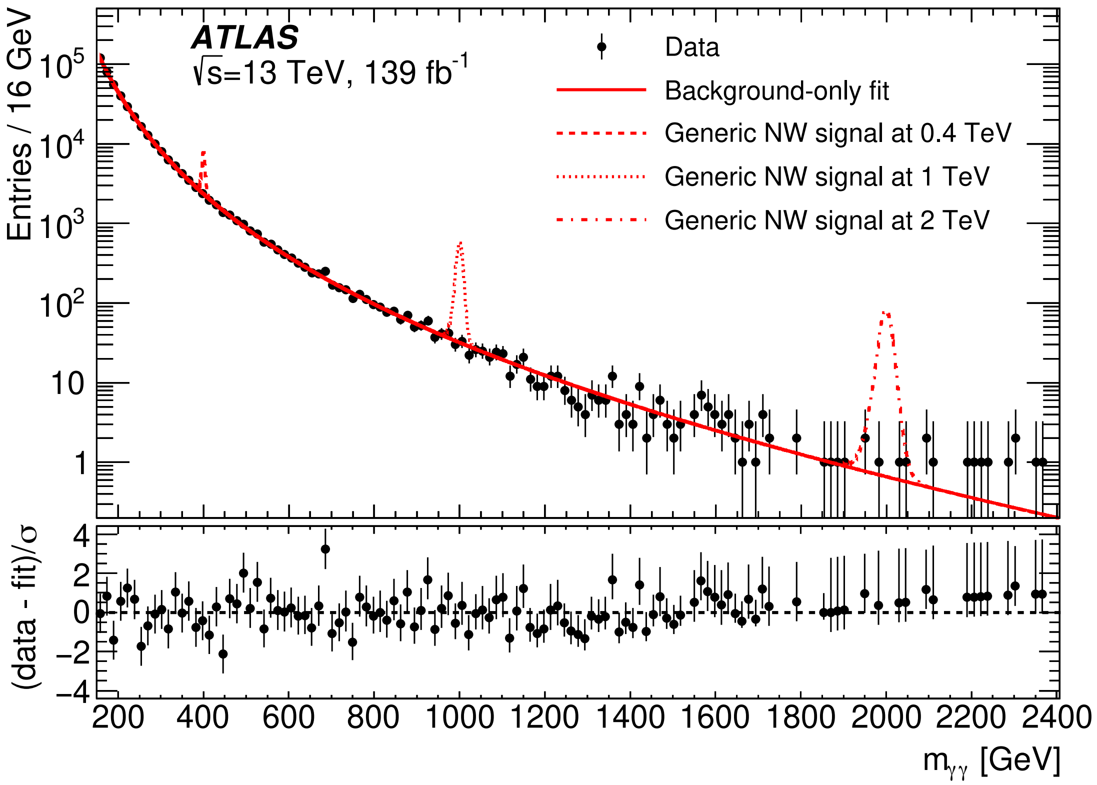
$X \to \gamma\gamma$

- Predominant background from **γγ continuum**
  - *using sidebands to estimate γj and jj contributions*
  - *10% of total background at most, 3% at high $m_{\gamma\gamma}$*
- functional decomposition used to smooth templates
  - *improved spurious signal uncertainties*
- σ×BR NWA upper limits: 1.1 fb (0.4 TeV) to 0.03 (2.8 TeV)




Phys. Lett. B 822 (2021) 136651

*October 2021*, arXiv, figures

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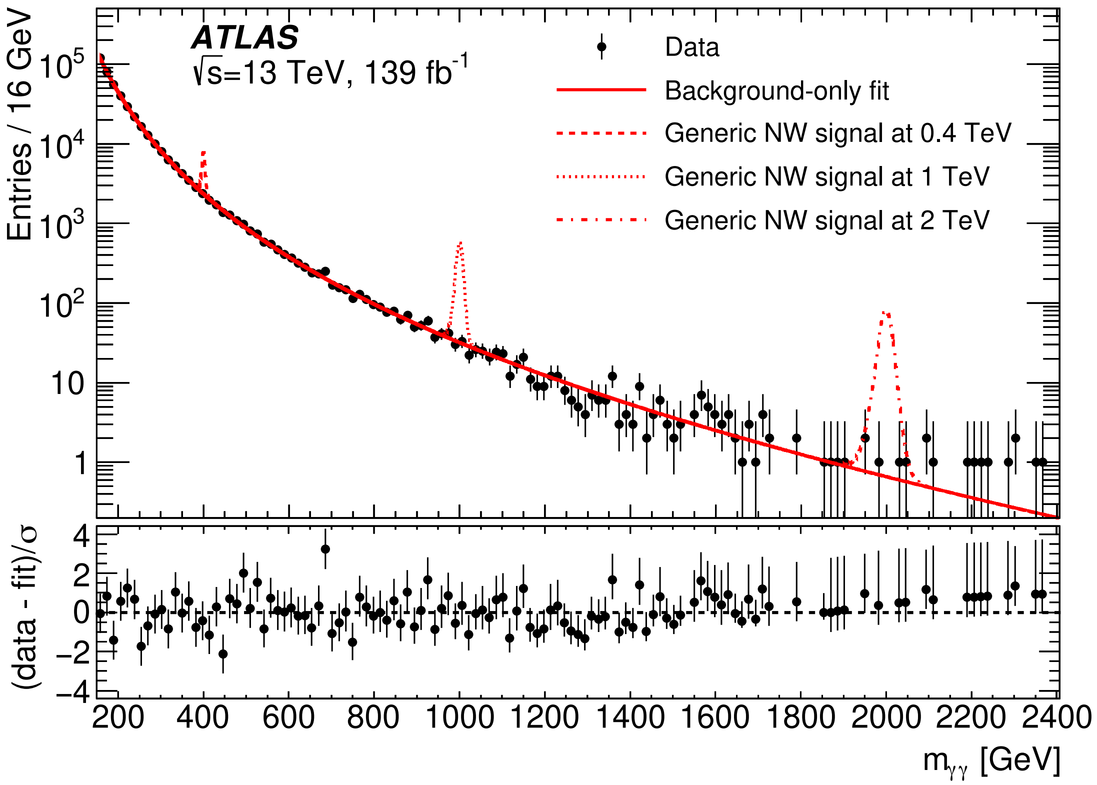


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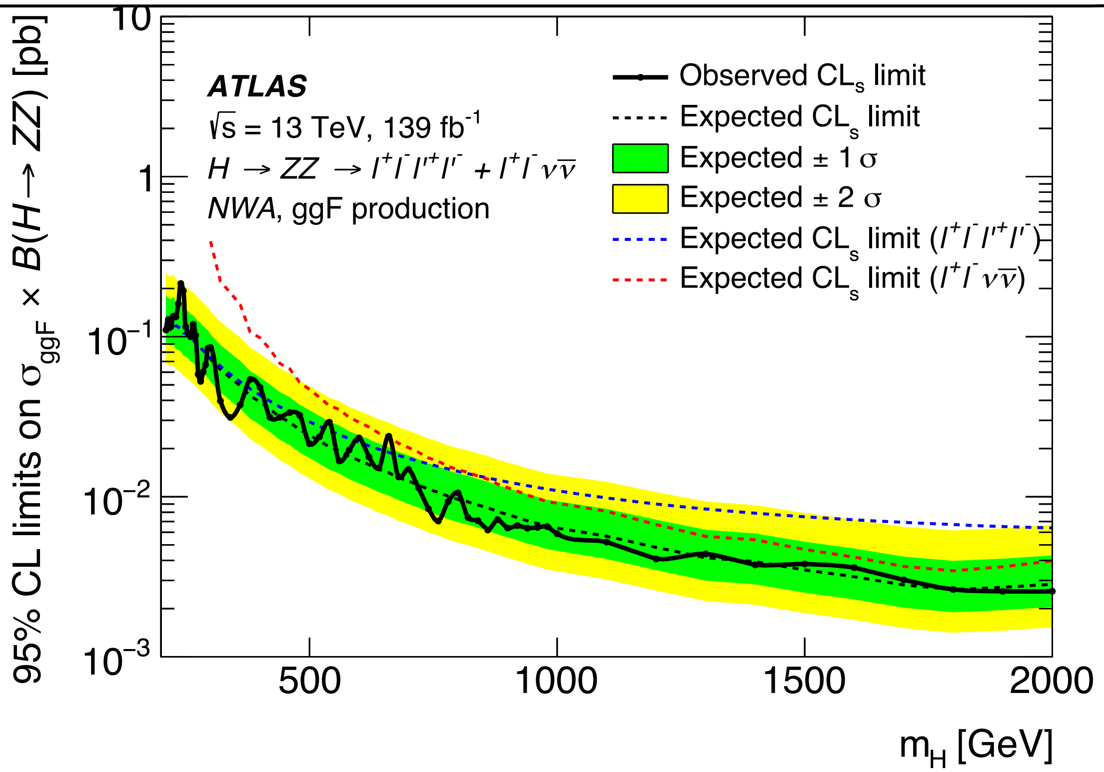
## *H→ZZ→4l/2l2v*

- Main background from *qq→ZZ*
  - *Data-driven normalisation, with parametric shape*
- DNN discriminants (NWA-only) to increase *4l* sensitivity
- Cut-based selection with $E_T^{miss}$ and sig($E_T^{miss}$) for *2l2v*
- *Final discriminants used: $m_{4l}$ and $m_T$, respectively*
- σ×BR NWA upper limits: 215 fb (0.24 TeV) to 2 (1.9 TeV)




Eur. Phys. J. C 81 (2021) 332
*September 2020*, arXiv, figures

# Extra scalar decaying to $4\ell$

***with intermediate decay to additional spin-1 bosons***

NEW!

submitted to Phys. Lett. B

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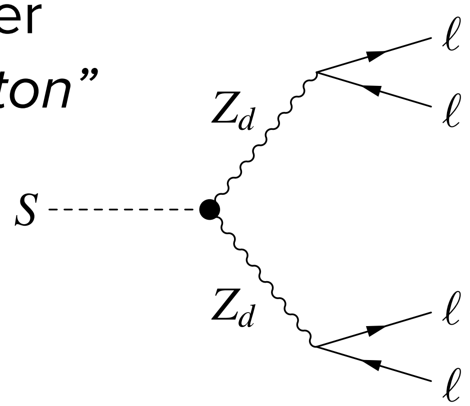


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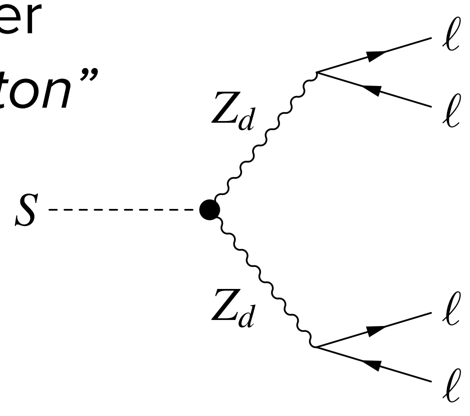


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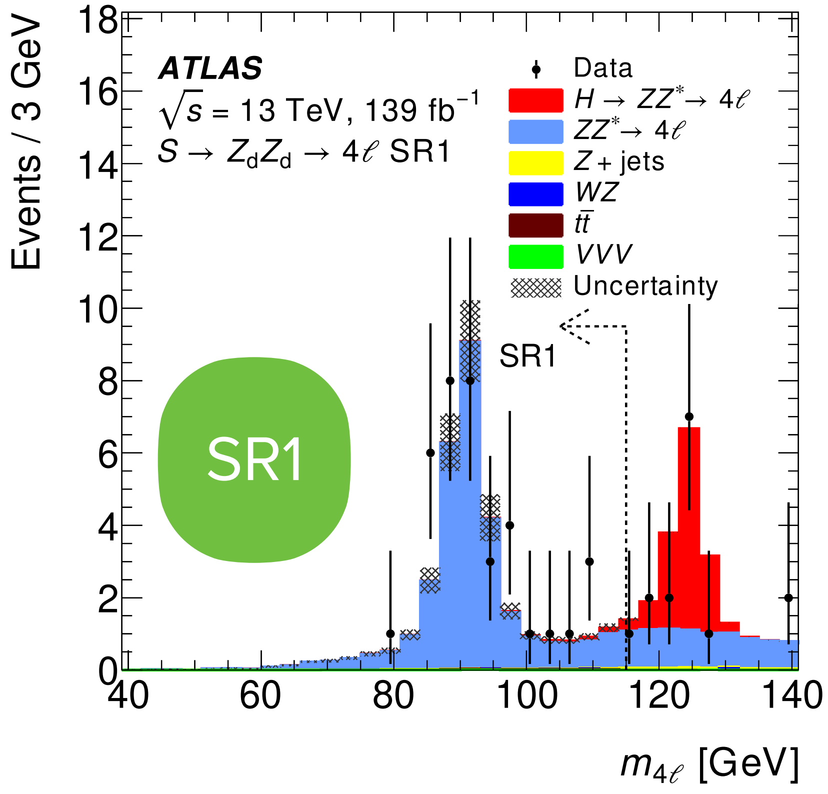
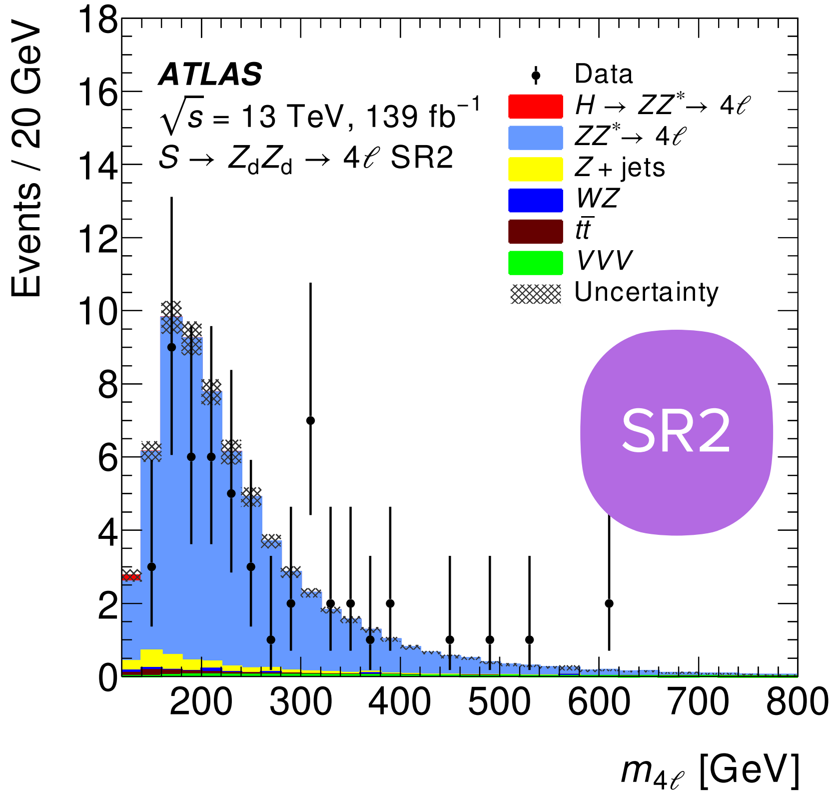



- Main event selection similar to $H \to ZZ^* \to 4\ell$
  - *targeting highest efficiency*
- Two signal regions, **low-** and **high-**$m_{4l}$
  - ***h(125)*** *mass range excluded*
  - *cut-based selection with J/ψ, Y and Z vetos*
- Main background from $ZZ^* \to 4\ell$
  - *Reducible backgrounds estimated with ABCD method*



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Largest systematics:

*lepton reconstruction (up to 17%), ME matching scale (6%), fact./renorm. scales (6%) for $ZZ^* \rightarrow 4\ell$*

Smallest *p*-values

| 2.7σ local | 2.8σ local |
| --- | --- |
| 1.6σ global | 0.5σ global |
| $m_S$ = 110 GeV | $m_S$ = 350 GeV |
| $m_{Zd}$ = 30 GeV | $m_{Zd}$ = 75 GeV |
| for SR1 ($m_{4l}$<115 GeV) | for SR2 |

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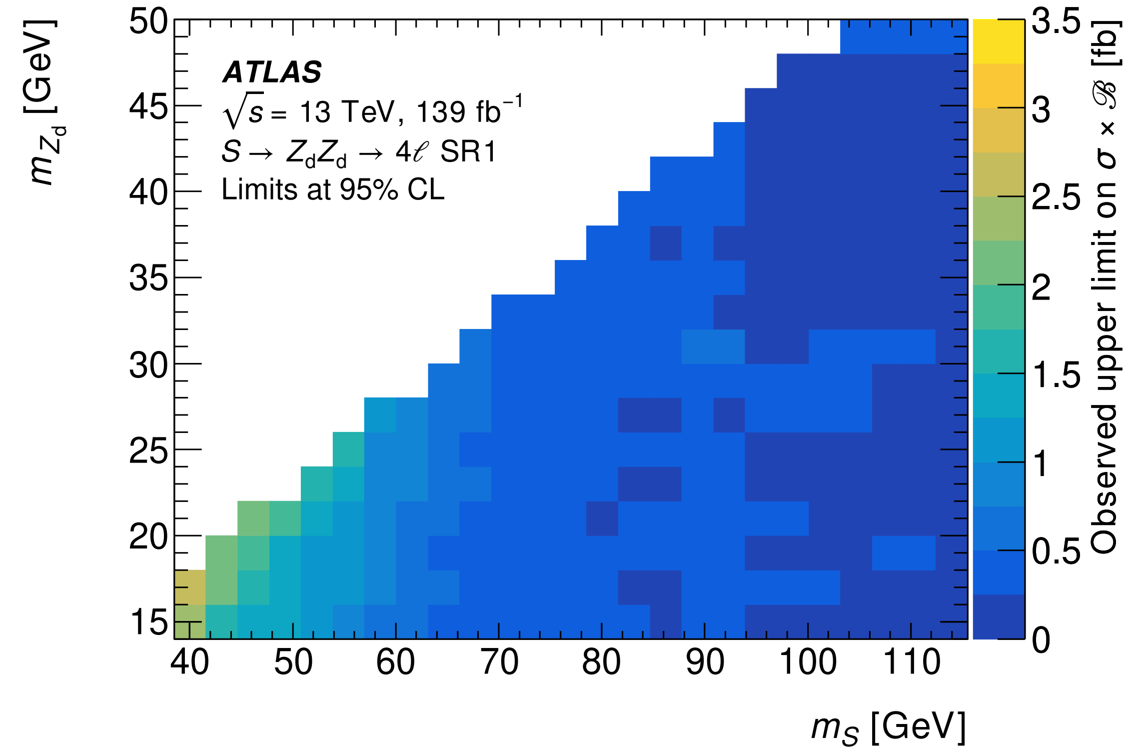


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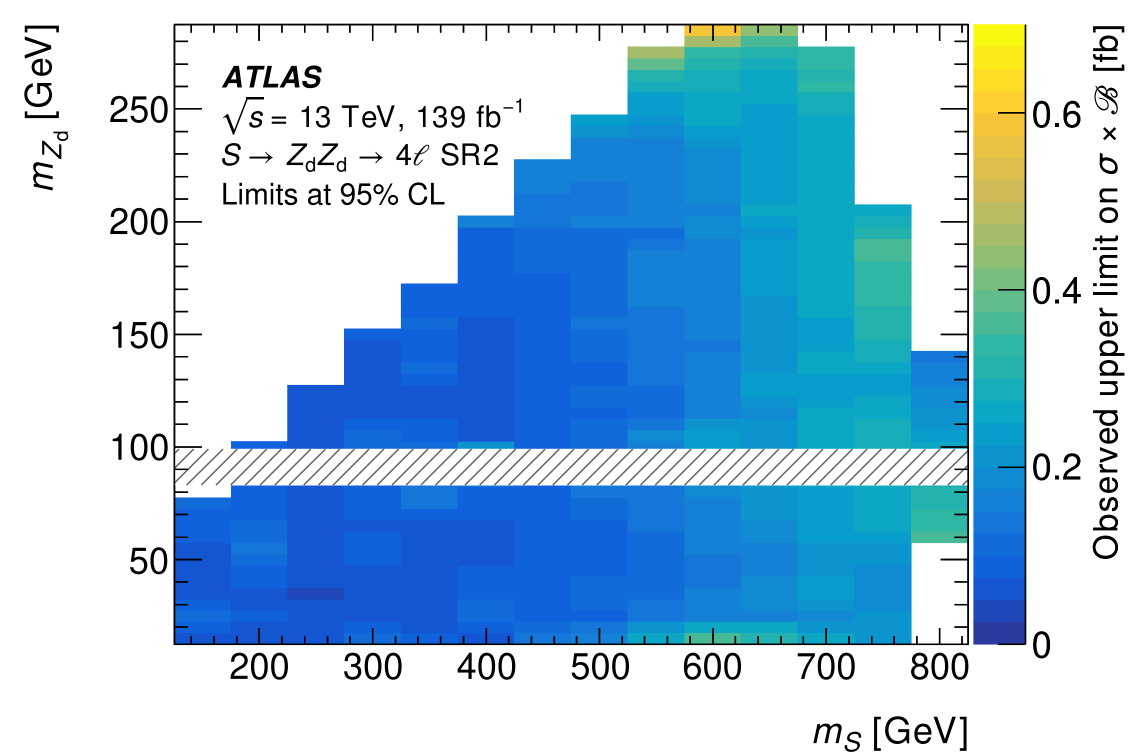


Extracting limits on $\sigma \times \mathcal{B}$ in the $m_S$, $m_{Zd}$ plane

*low-mass SR: 0.14 fb to 3.1 fb*
*high-mass SR: 0.05 fb to 0.60 fb*

# Heavy resonances to $4\ell$ + X

JHEP 10 (2024) 130
*January 2024*, arXiv, figures

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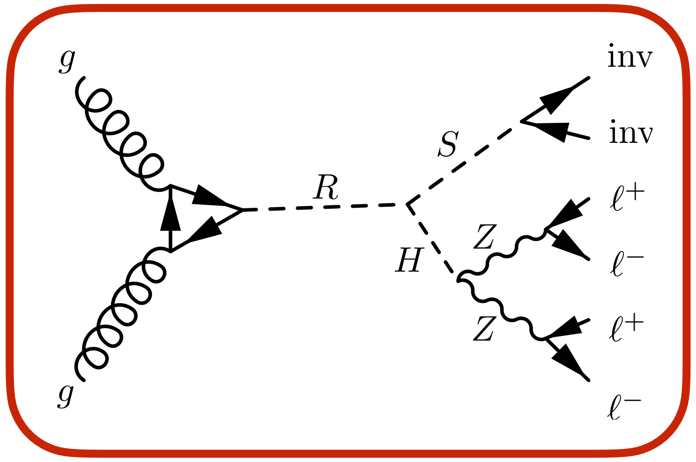


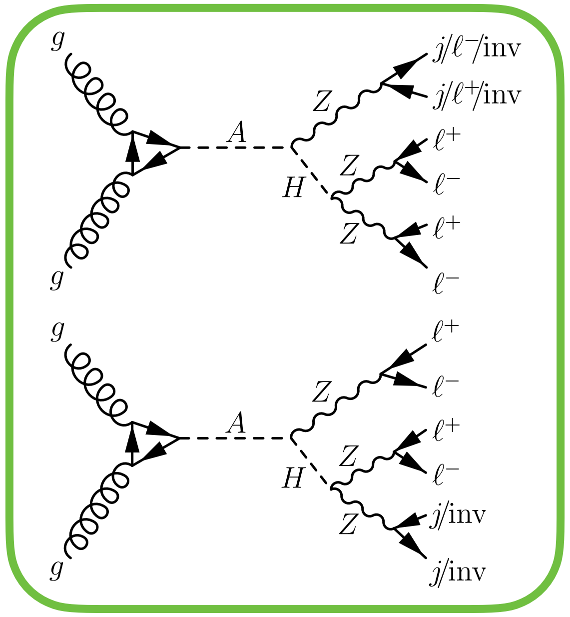


Searching for **extra, heavy scalar R** + **scalar boson S** or
CP-odd **A** decaying into *Z* + *CP-even* ***H***

S is a dark-matter portal,
decays into pairs of dark-matter candidates

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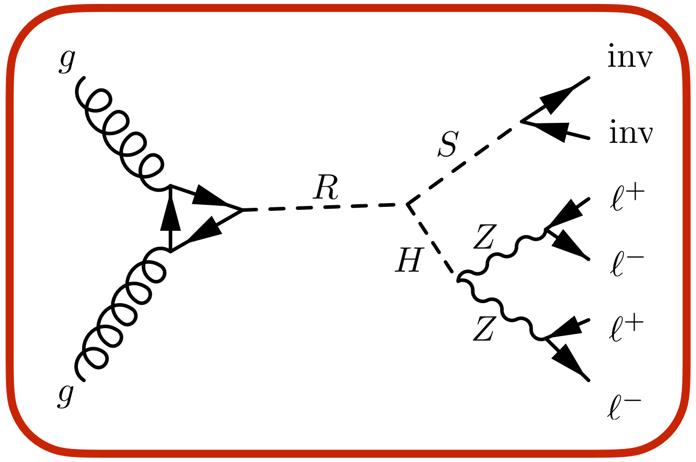


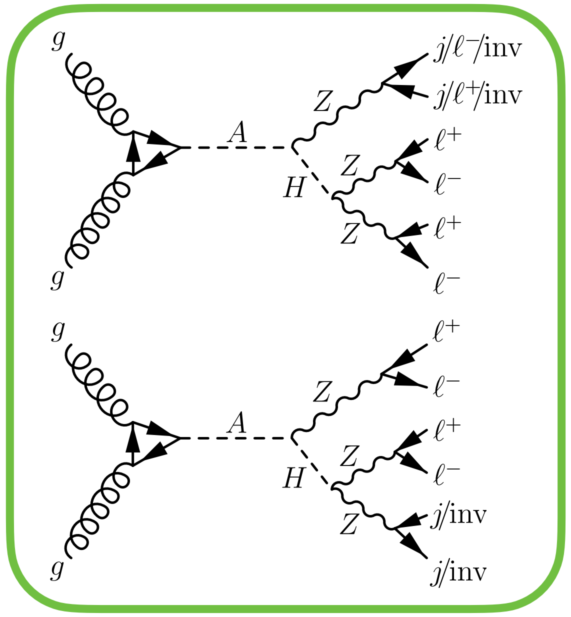


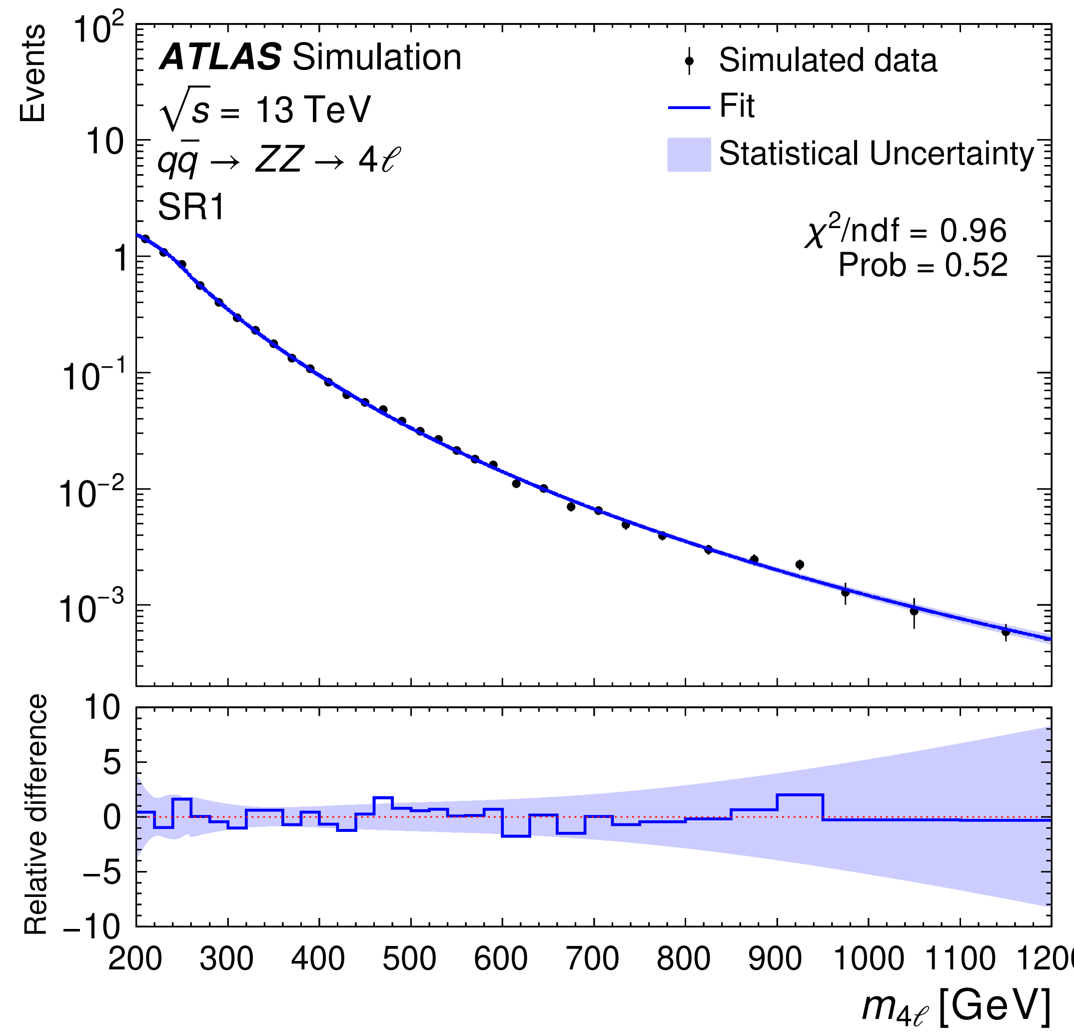


Searching for **extra, heavy scalar R** + **scalar boson S** or **CP-odd A** decaying into *Z + CP-even* ***H***

S is a dark-matter portal,
decays into pairs of dark-matter candidates

- Analysis uses several signal regions:
  - *3 based on n(b-jets), $p_T^{4l}$ and $E_T^{miss}$ significance for all processes*
  - *4 additional regions for A⟶ZH, based on (b-)jet multiplicity and $m_{jj}$*

- *Dominant background contribution from ZZ*⟶4ℓ*
  - *modelled with analytical function, with $2m_Z$-threshold and high-mass terms stitched together*

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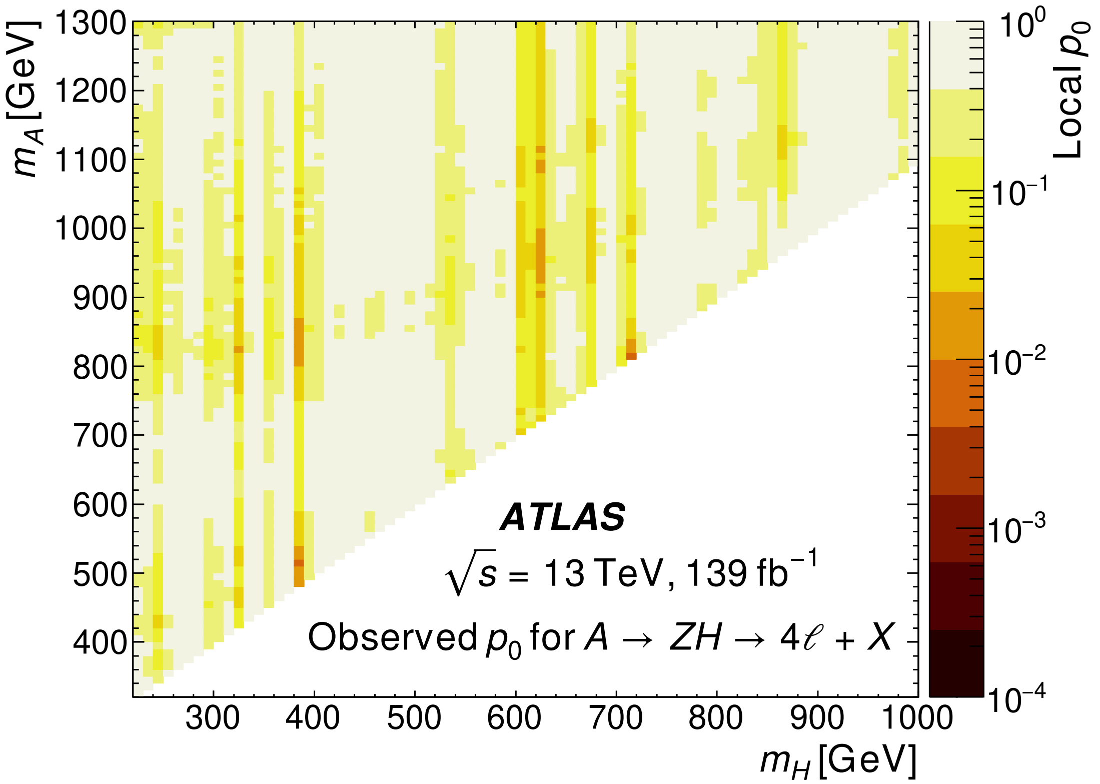
Largest systematics:
*jet reconstruction* (up to 7%), *parton showering* (up to 4%), *background parameterisation* (up to 5%)

A few points in the $m_H$, $m_A$ plane with local significances above 2σ (max 2.5σ @510, 380 GeV)



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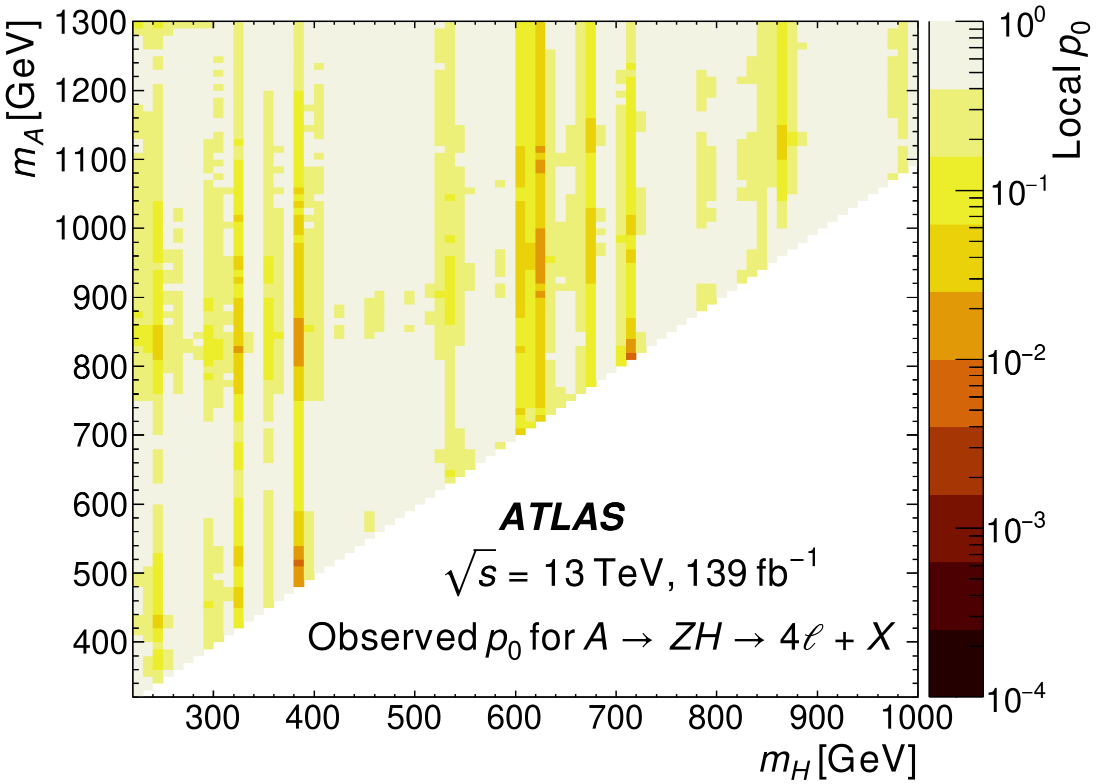
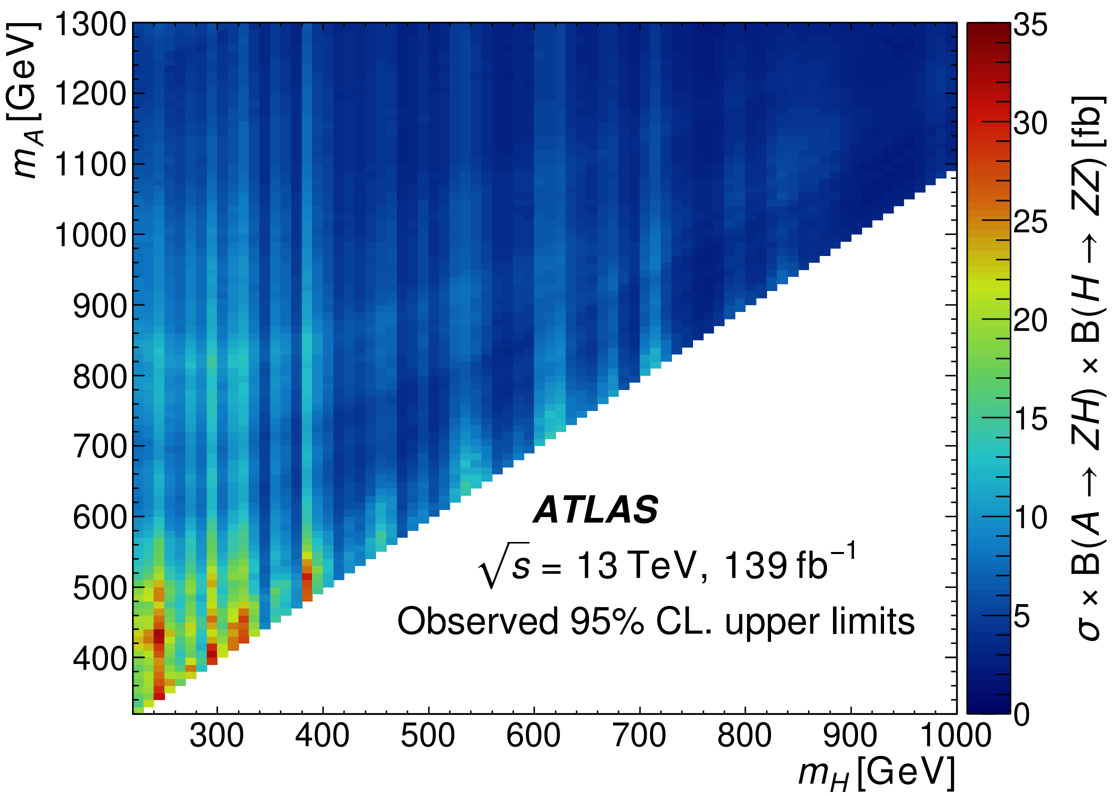
Upper limits (expected in parentheses)

σ×$\mathcal{B}$(R⟶SH)×$\mathcal{B}$(H⟶ZZ):
*from 6.8 (7.7) fb for ($m_R$, $m_H$) = (1300, 980) GeV to 119.2 (70.3) fb for ($m_R$, $m_H$) = (410, 240) GeV*

σ×$\mathcal{B}$(A⟶ZH)×$\mathcal{B}$(H⟶ZZ):
*from 2.1 (2.9) fb for ($m_H$, $m_A$) = (1300, 760) GeV to 32.3 (18.8) fb for ($m_H$, $m_A$) = (430, 240) GeV*



# Heavy Higgs to multi-$\ell$ and multi-$b$

***with flavour-violating couplings***

JHEP 12 (2023) 081

*July 2023*, arXiv, figures

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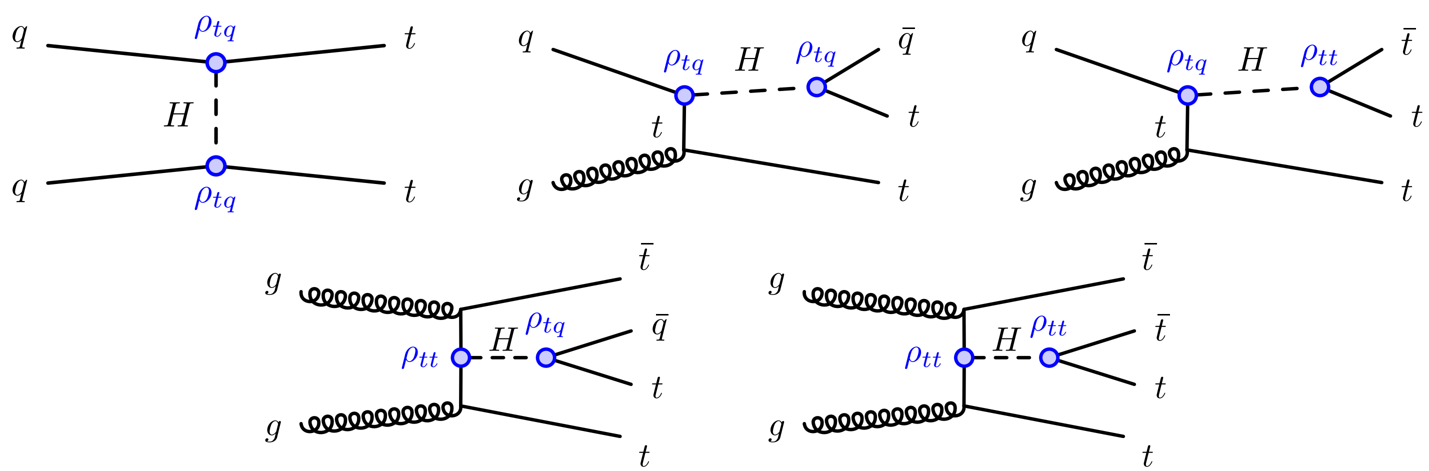


Targeting g2HDM model with flavour changing neutral Higgs

Considering only couplings between heavy Higgs and top quark

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[JHEP 12 (2023) 081]

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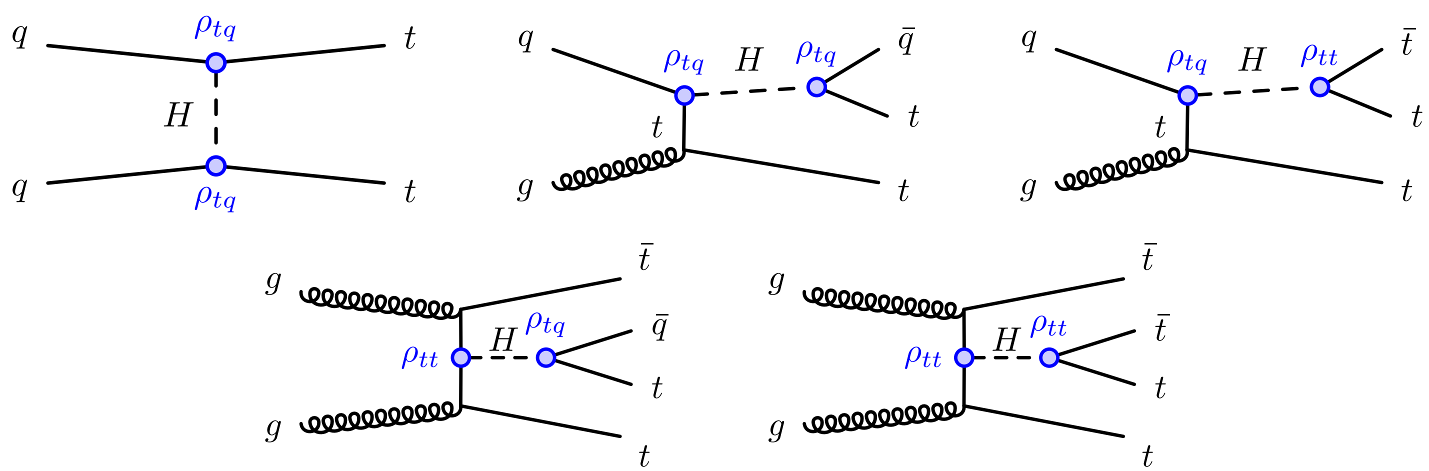
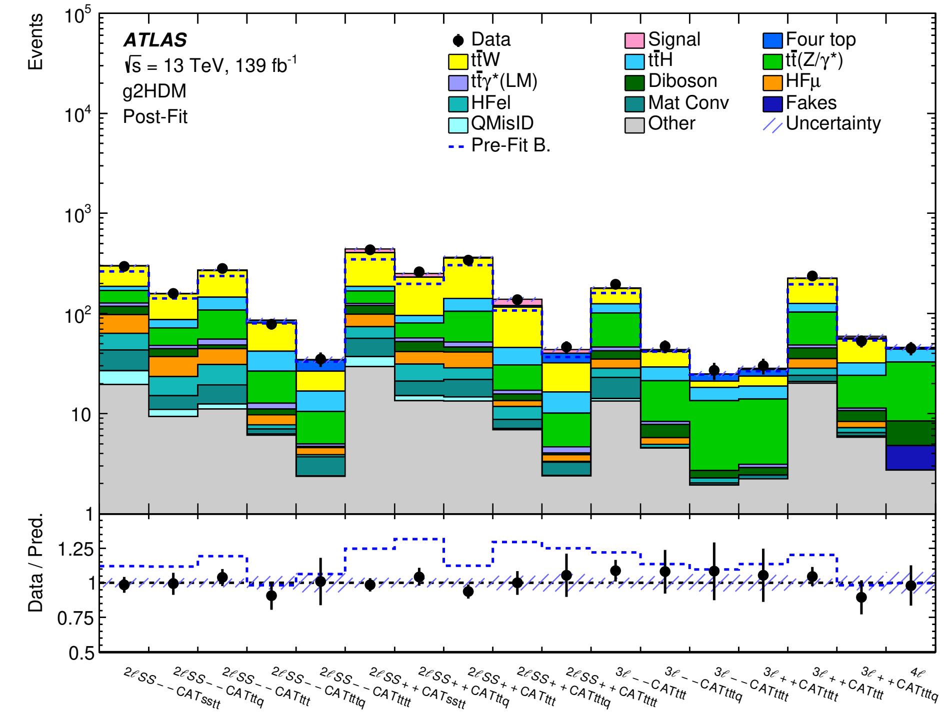
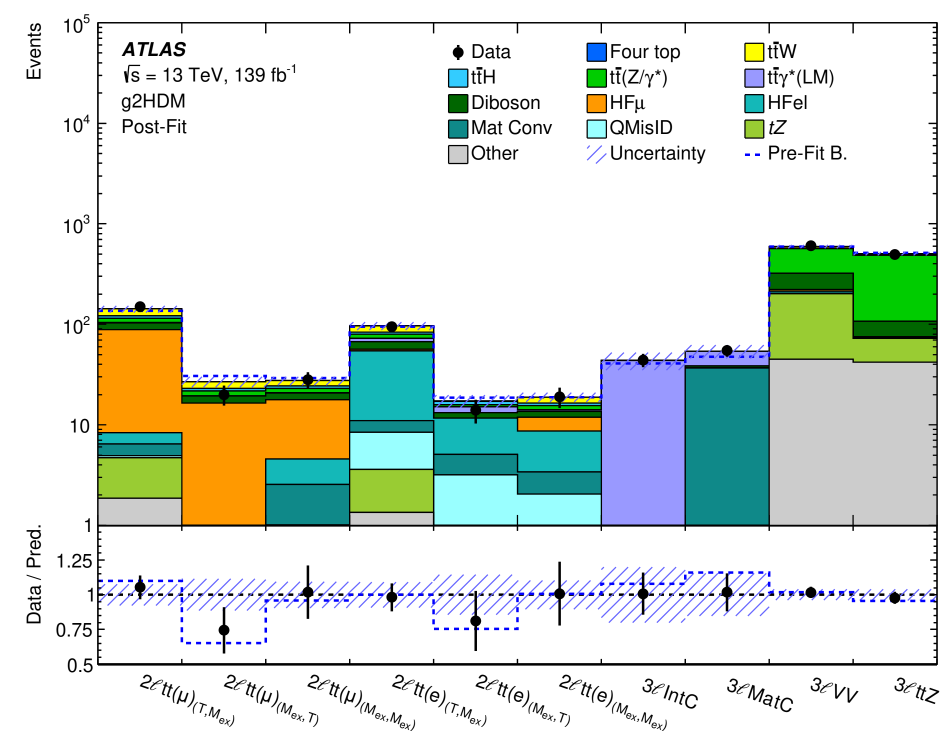


Targeting g2HDM model with flavour changing neutral Higgs

Considering only couplings between heavy Higgs and top quark

- Decays into **2 (SS), 3 or 4 top-quarks**:
  - › *final states comprising 2, 3, or 4 leptons + b-jets*
- **17 signal regions**, using number/charge of leptons
  - › *plus DNNs to differentiate production/decay modes*
- **10 control regions**
  - › *controlling HF non-prompt leptons, ttZ, γ conversions*



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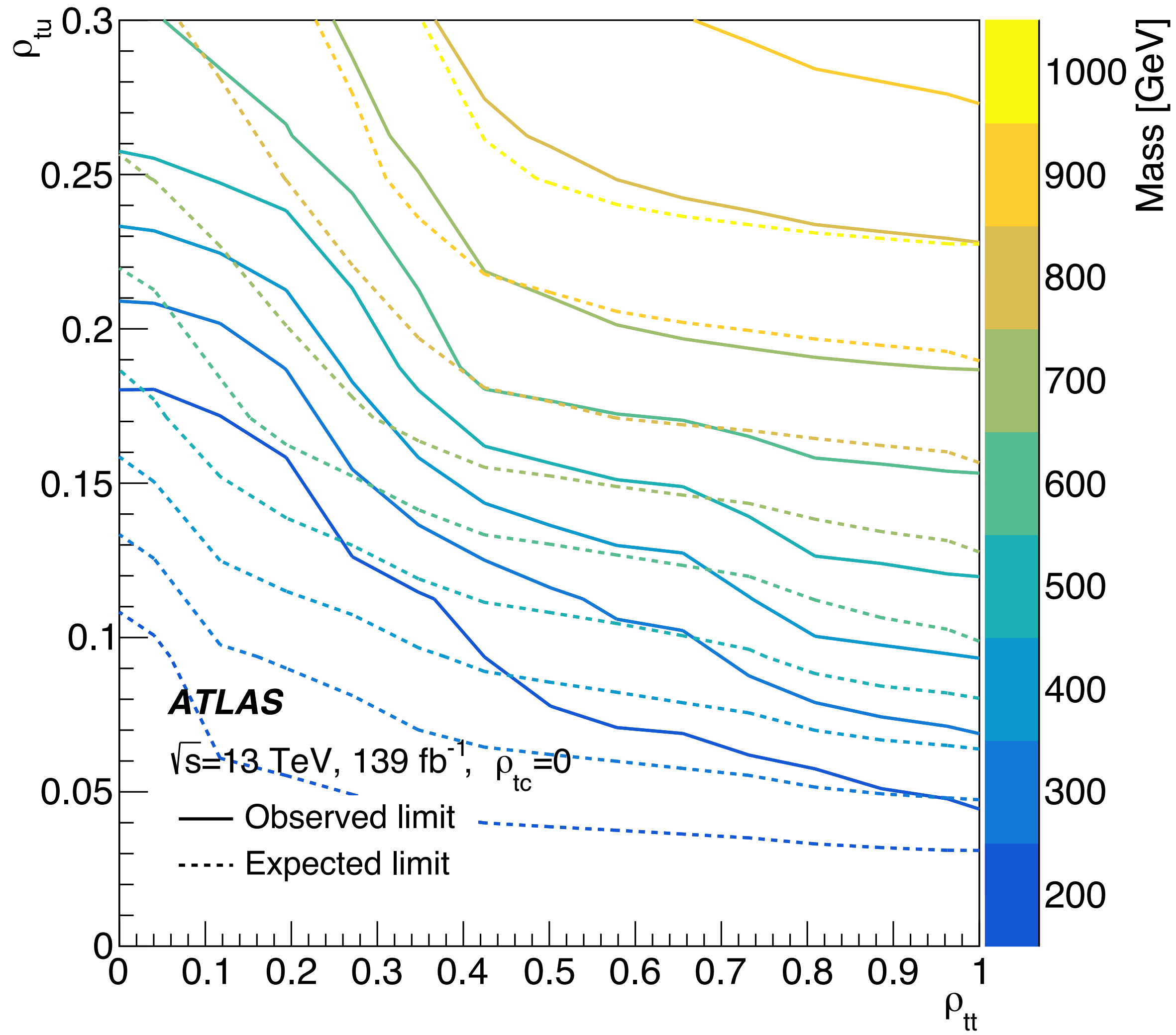
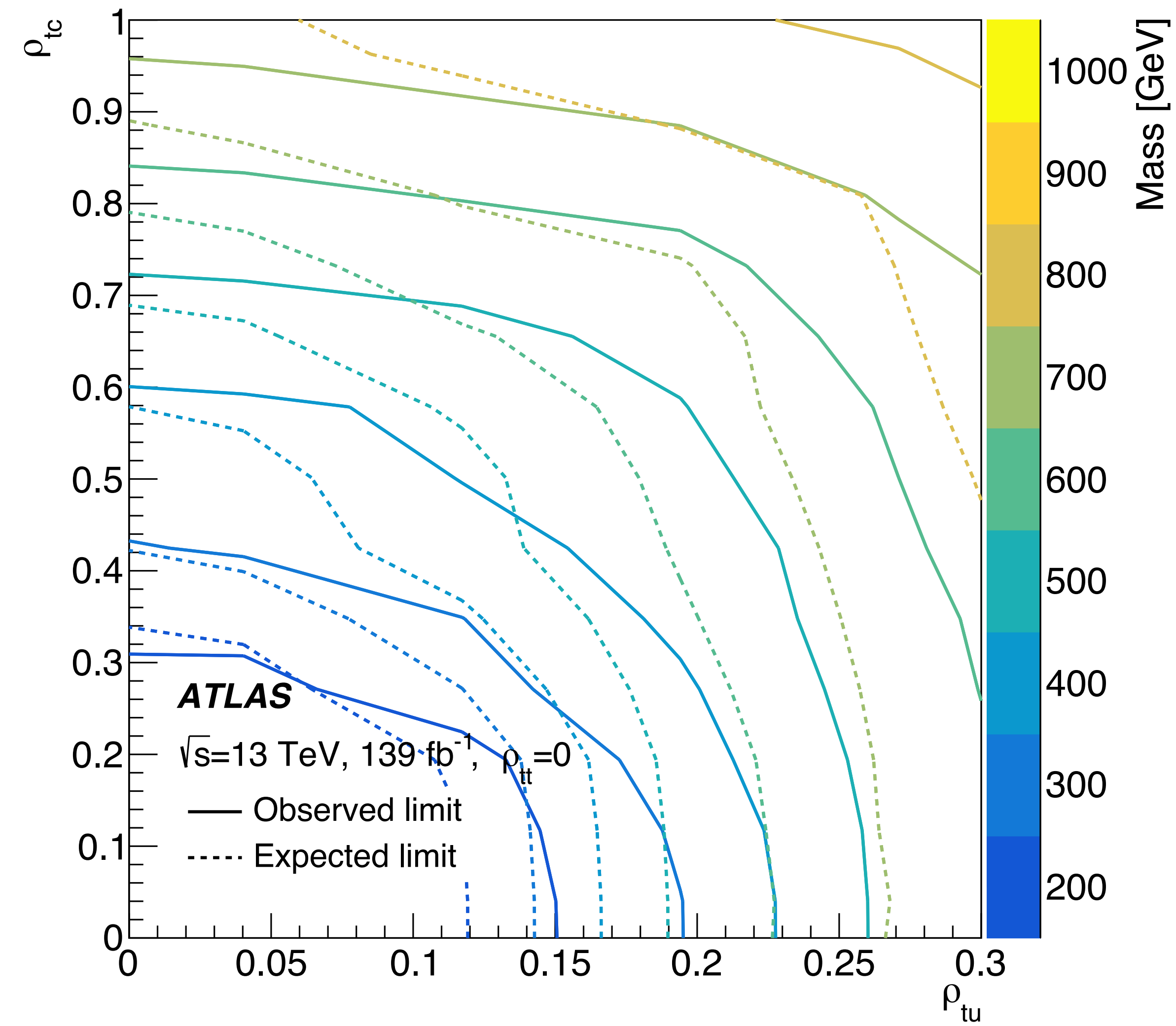
Additional scalar boson with couplings $\rho_{tt}$ = 0.4, $\rho_{tc}$ = 0.2, $\rho_{tu}$ = 0.2 excluded at 95% CL for mH in the 200-620 GeV range



# Scalar resonance in FCNC top decays

JHEP 07 (2023) 199
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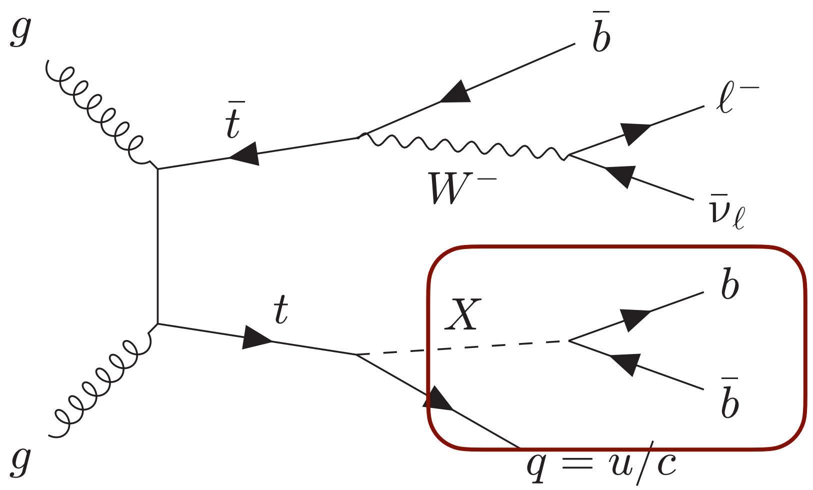
Searching for **light scalar *X*** (*flavon* from the Froggatt-Nielsen mechanism) in top-pair production




*$X \to bb$ is the leading decay in this model (with $m_X < 200$ GeV)*

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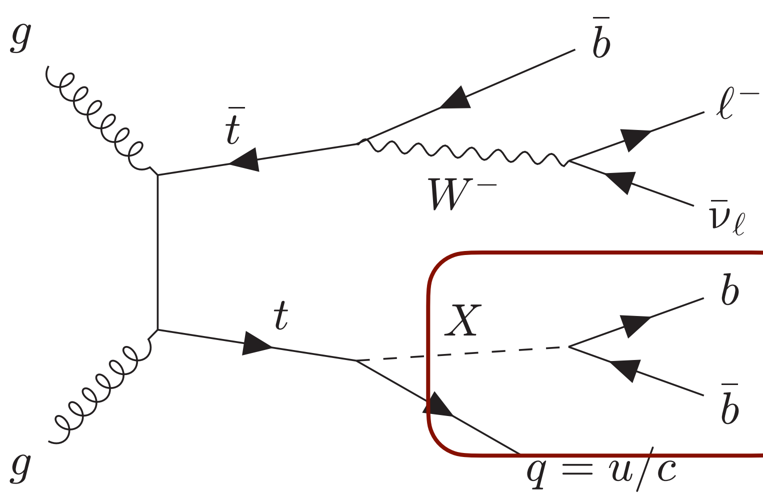
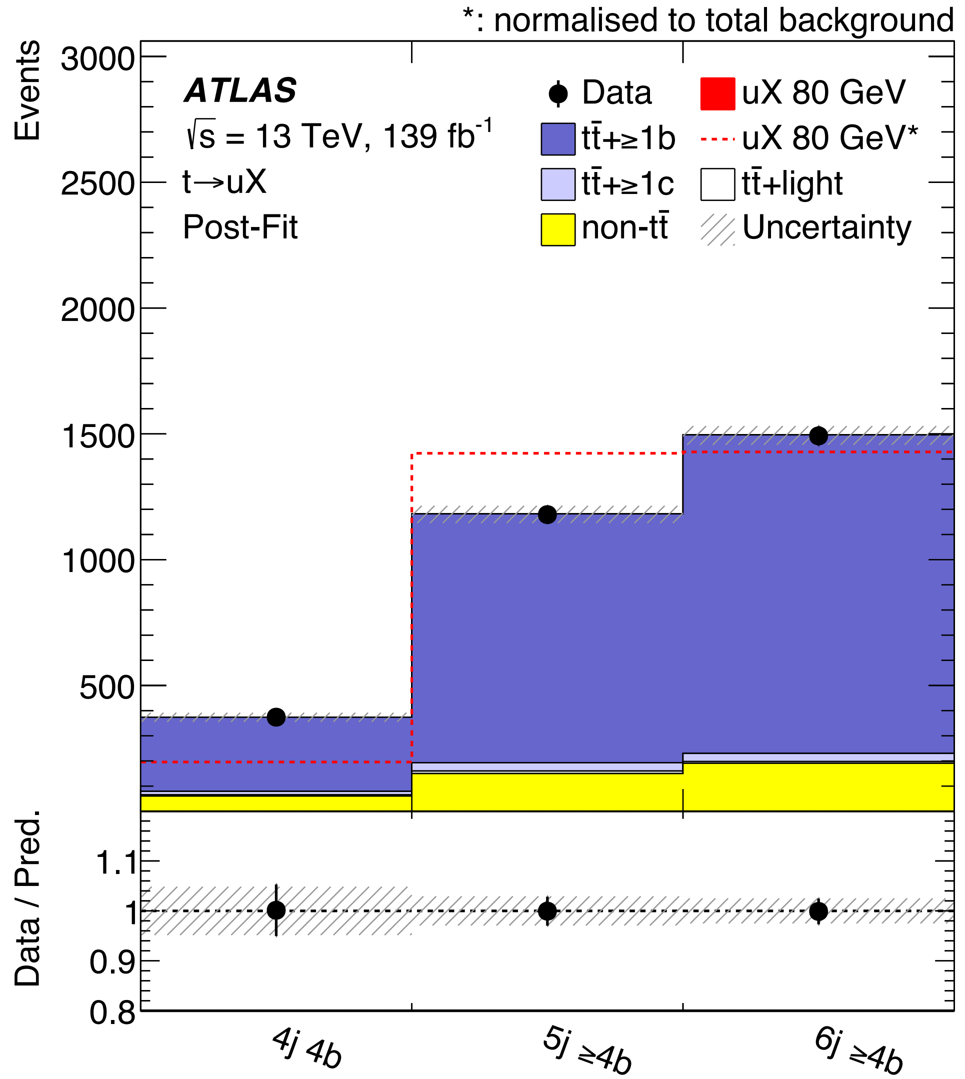



*X→bb is the leading decay in this model (with $m_X$ < 200 GeV)*

- Final state: 1 lepton, ≥4 jets and 3 *b*-jets
  - *3 signal regions: 4j 3b, 5j 3b, 6j 3b*
  - *3 control regions targeting tt+jets (main background from tt+light, tt+b) by requiring ≥4 b-jets*
  - *3 reweighing regions, requiring 2 b-jets*
    - *correct mismodelling coming from extra radiation in the parton shower*
- *cX* and *uX* channels searched for separately
  - *With mass-dependent NN, with best performance for lower values of $m_X$*



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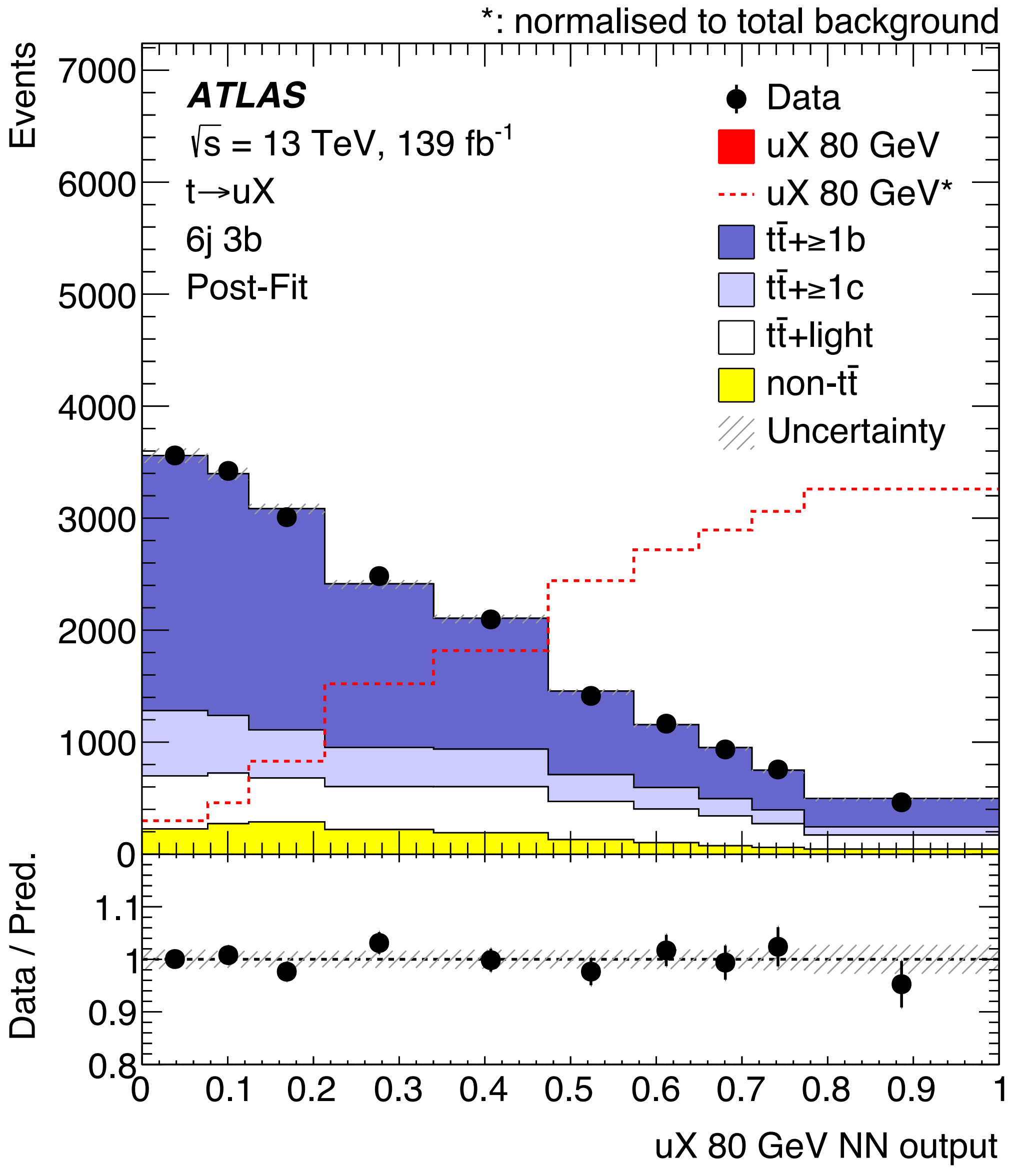
*Main uncertainties:*

- Data statistics (6-7%)
- tt+≥1b modelling/normalisation (3% to 10%)
- Jet tagging efficiency (1% to 8%)



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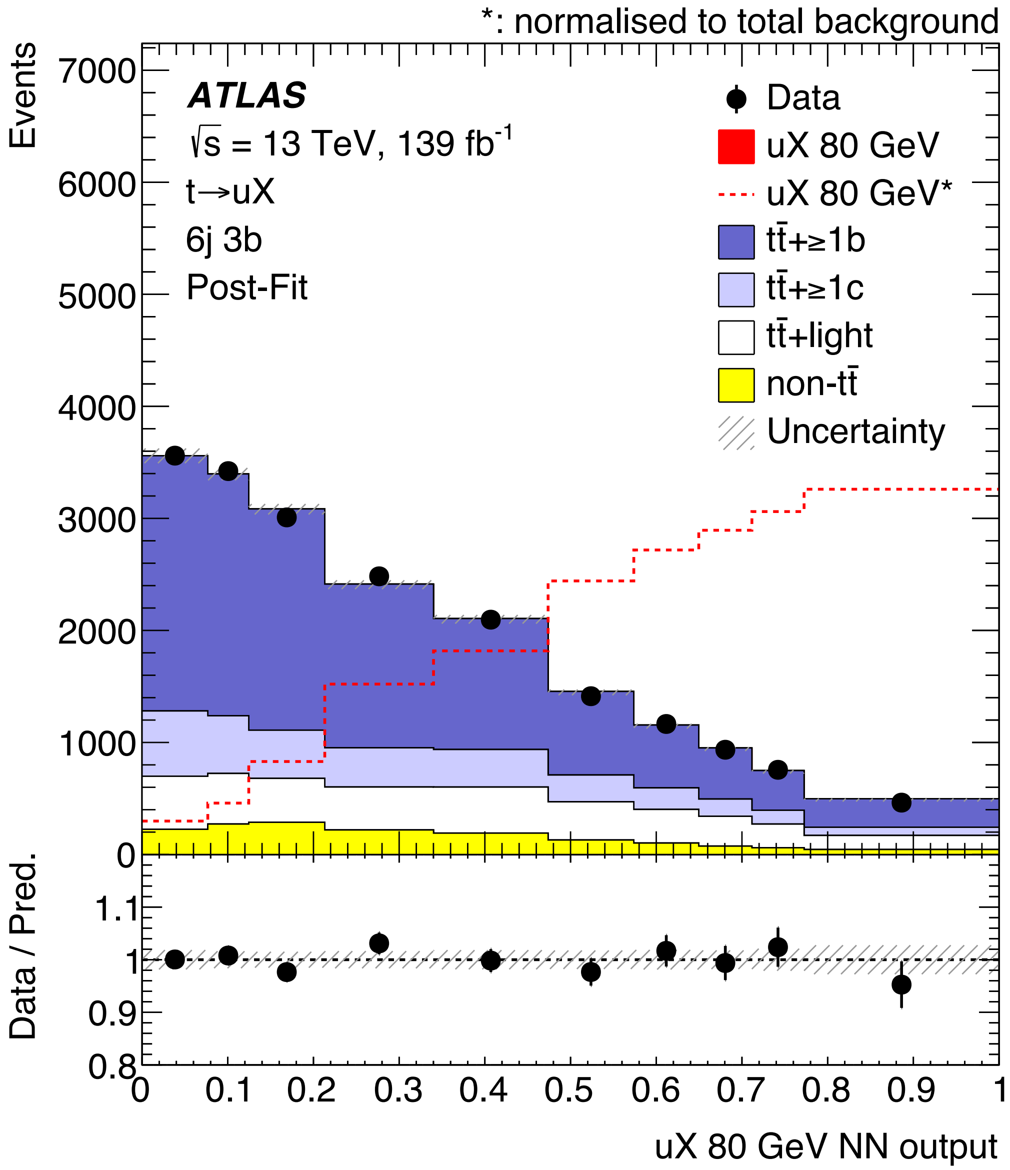
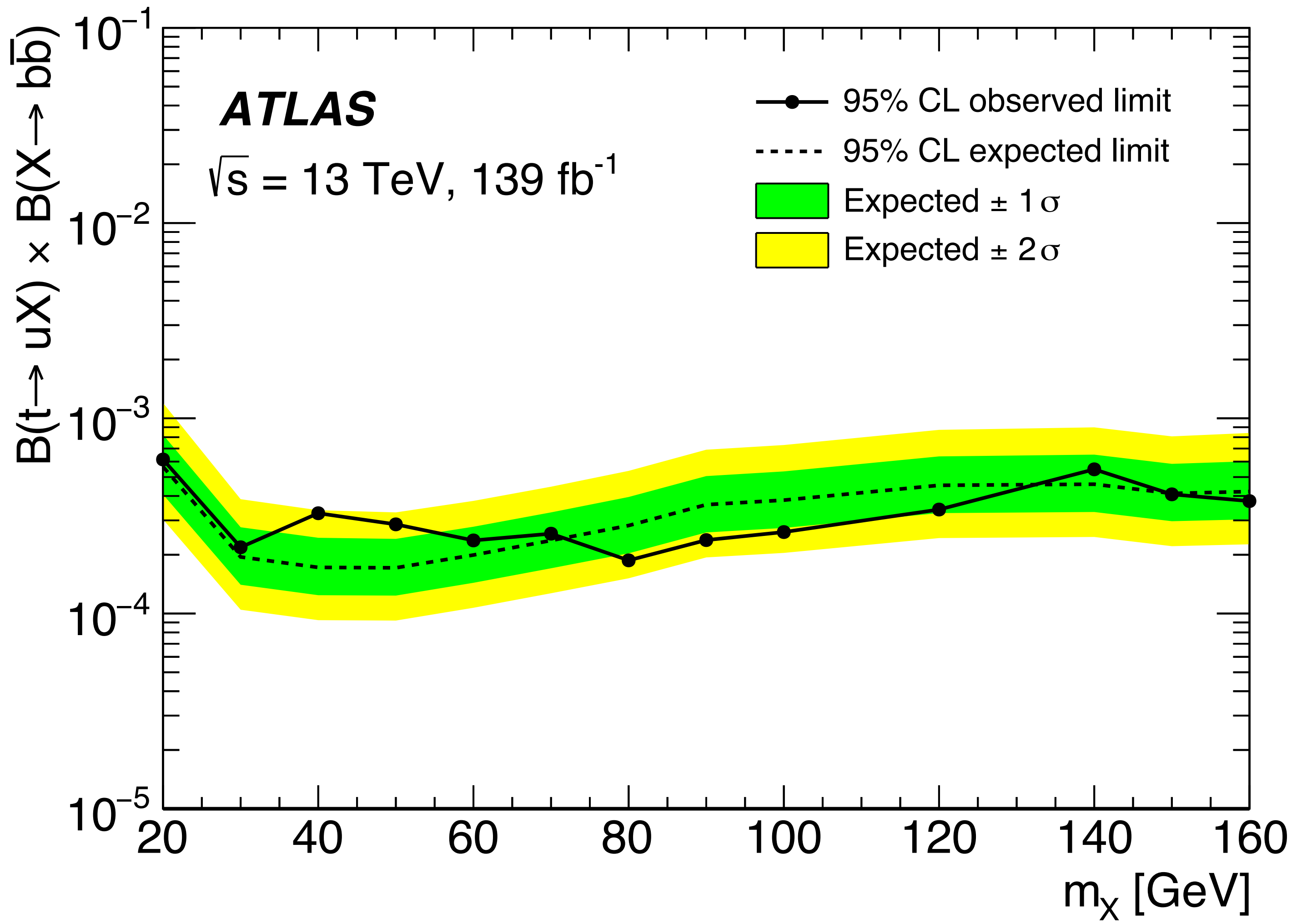
No significant deviations from SM expectations

small excess (1.8σ local) in the *uX* channel for $m_X$=40 GeV

Setting upper limits, as a function of mX, on $\mathcal{B}(t \to uX) \times \mathcal{B}(X \to bb)$ and $\mathcal{B}(t \to cX) \times \mathcal{B}(X \to bb)$



# ttA/H → tttt

JHEP 07 (2023) 203
*November 2022*, arXiv, figures

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

JHEP 07 (2023) 203
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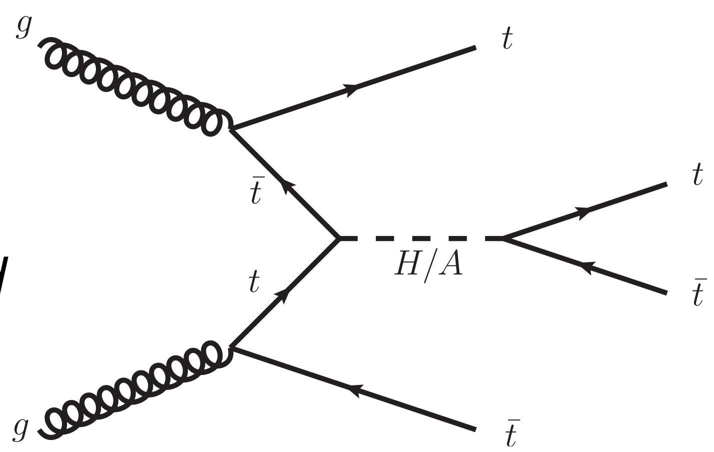
Searching for an **additional scalar S** or **pseudo scalar A** in association with a top-quark pair

*searches for gluon-gluon fusion H/A→tt are challenging because of destructive interference with the SM tt background*




*Analysis focusing on 2 same-sign leptons or more than 3 leptons (plus ≥6 jets and ≥2 b-jets)*

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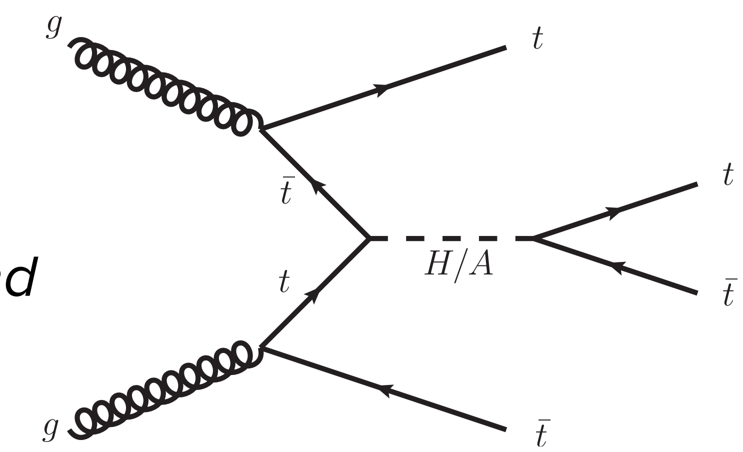
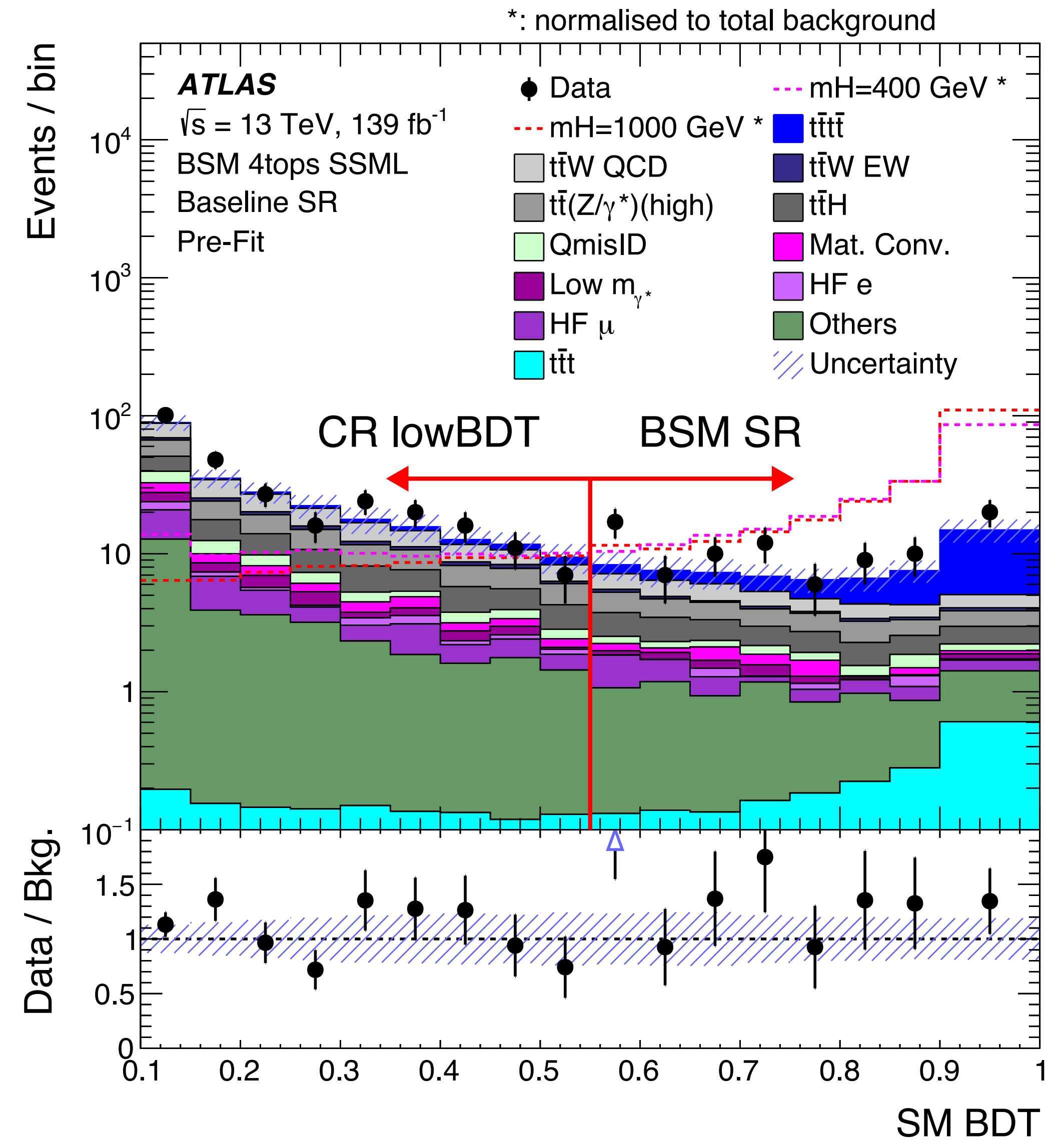



*Analysis focusing on 2 same-sign leptons or more than 3 leptons (plus ≥6 jets and ≥2 b-jets)*

- BDT to separate SM 4*t* from other backgrounds
  - *defining signal region and low-BDT control region*
- Other control regions built to measure various background components:
  - *conversions, leptons from HF, ttW events*
- BDT used as final discriminant
  - *parameterised as a function of the heavy Higgs mass*



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submitted to EPJC
*August 2024*, arXiv, figures

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*Extending search to final states containing exactly one lepton or two opposite-charge leptons*

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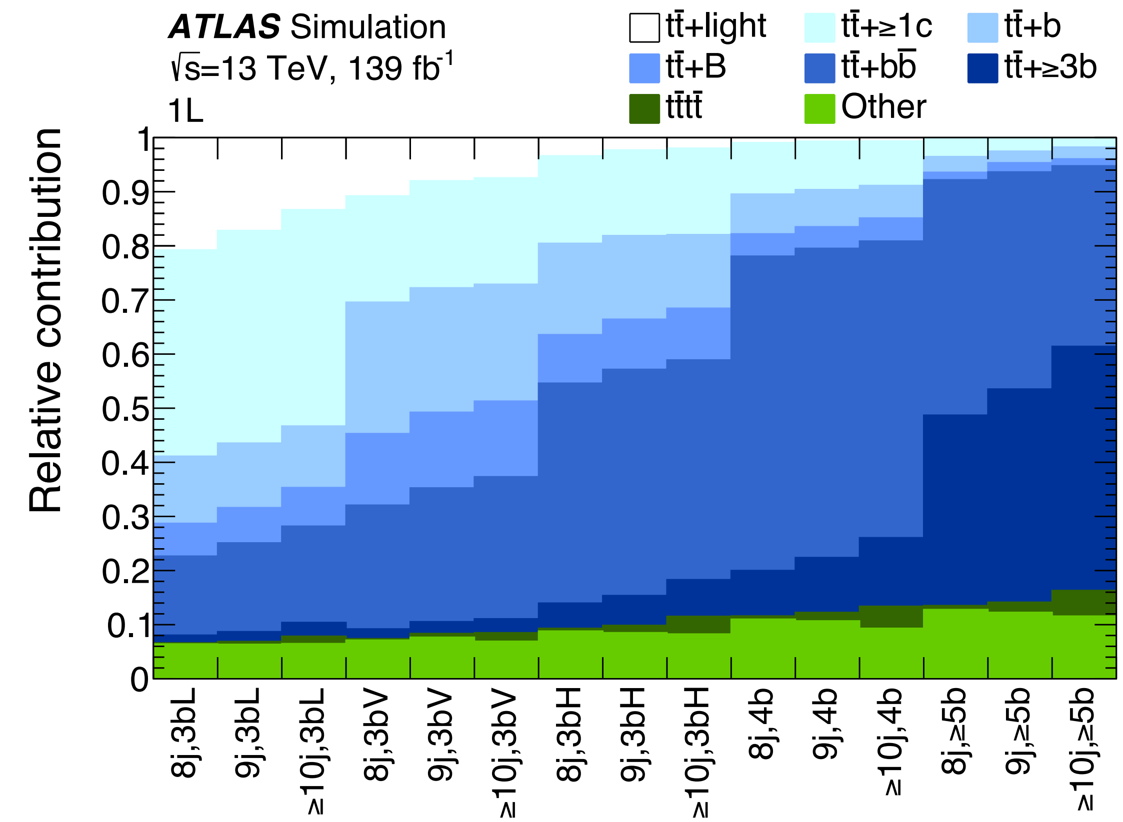
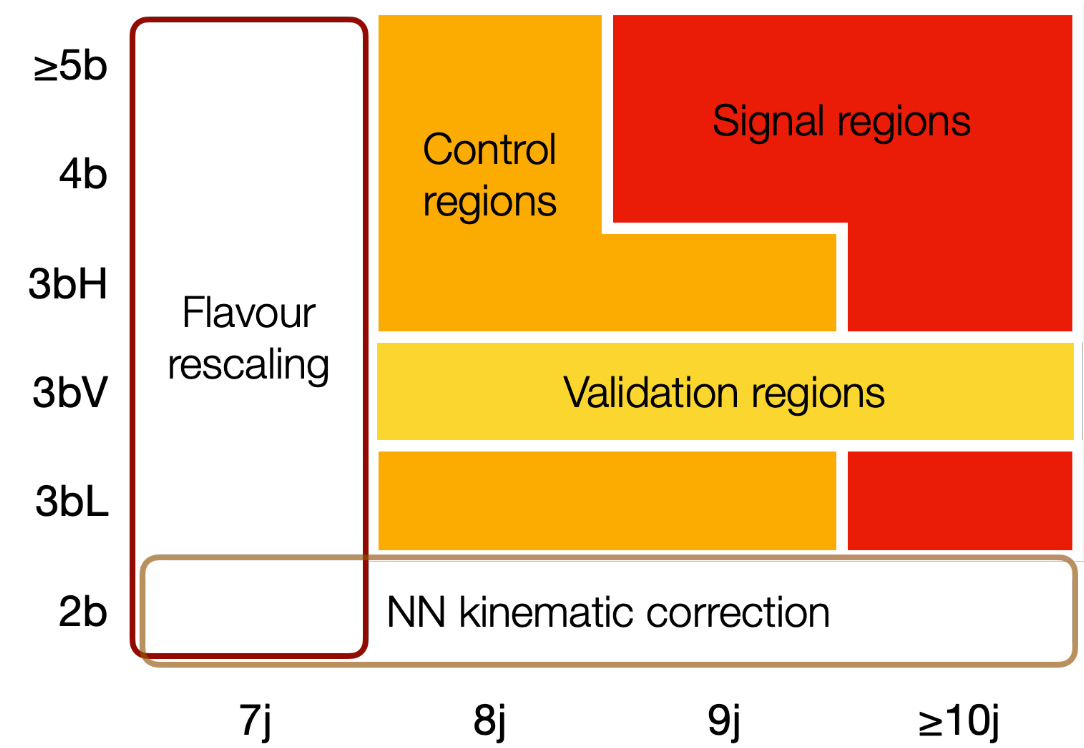
*Extending search to final states containing exactly one lepton or two opposite-charge leptons*

- Categorisation performed according to jet and b-jet multiplicities
  - *three operating points used for b-tagging*
- tt+light, tt+c and tt+b difficult to model in simulation
  - *flavour rescaling regions used to derive correct normalisations for these processes (main background)*
- NN used to correct for kinematic discrepancies
- *Graph neural networks (with $m_{H/A}$-dependent parameterisation) used to separate signal from tt+jets background*



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*Dominant uncertainties:*

- tt+≥1*b* modelling (max 10%)
- SM 4t, tt+jets (max 3%)
- Jet energy scale and reso (max 4%)

# ttA/H → tttt

submitted to EPJC
*August 2024*, arXiv, figures

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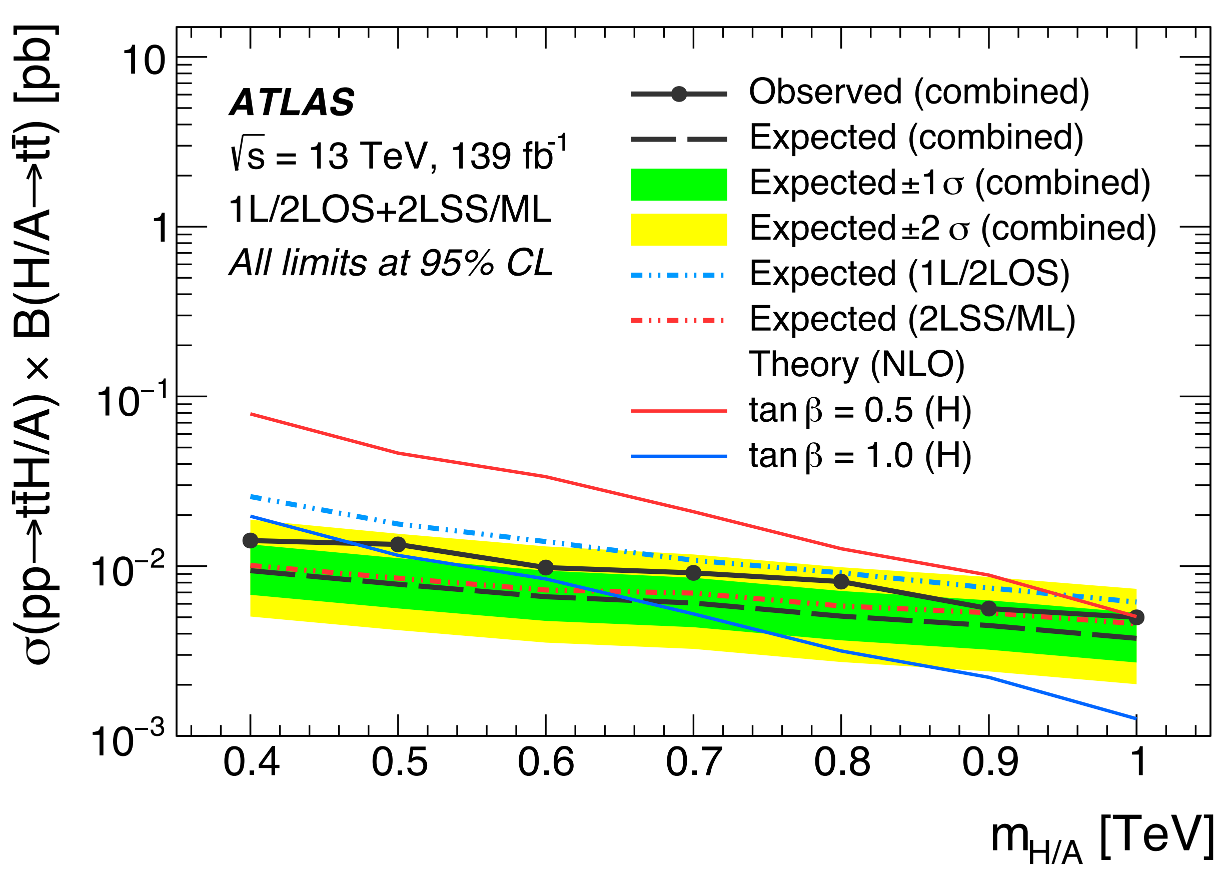
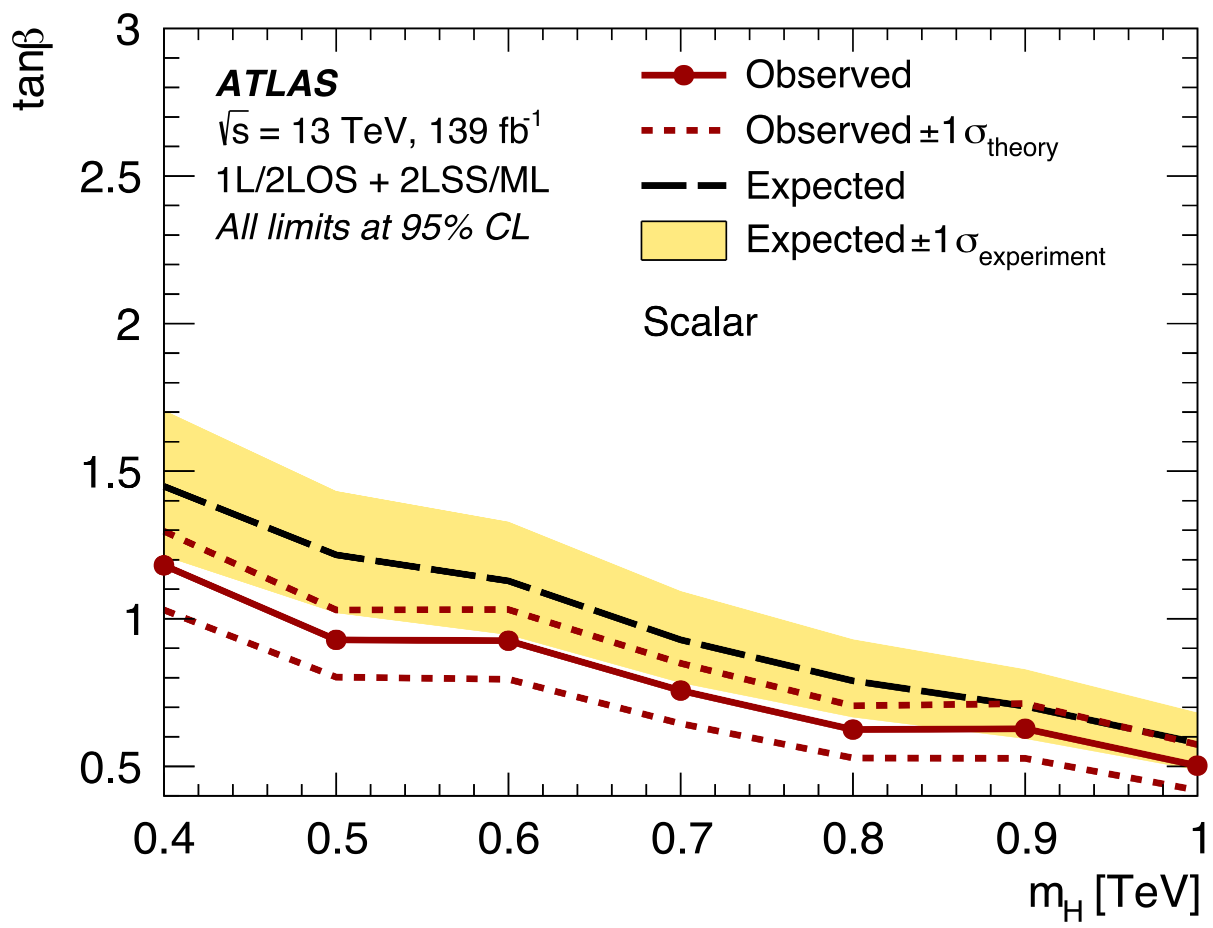
- tt+≥1*b* modelling (max 10%)
- SM 4t, tt+jets (max 3%)
- Jet energy scale and reso (max 4%)

Observed (expected) limits on σ×ℬ(H/A→tt) at 95% CL
from 14 (9.4) fb at 400 GeV to 5 (3.8) fb at 1 TeV
up to 19% improvement with respect to 2lSS+ML!

tanβ values below 1.2 (400 GeV) and 0.5 (1 TeV) are excluded
at 95% CL for the case where only *H or A* contribute
Higher limits by ~40% when both *H and A* contribute



# Conclusions

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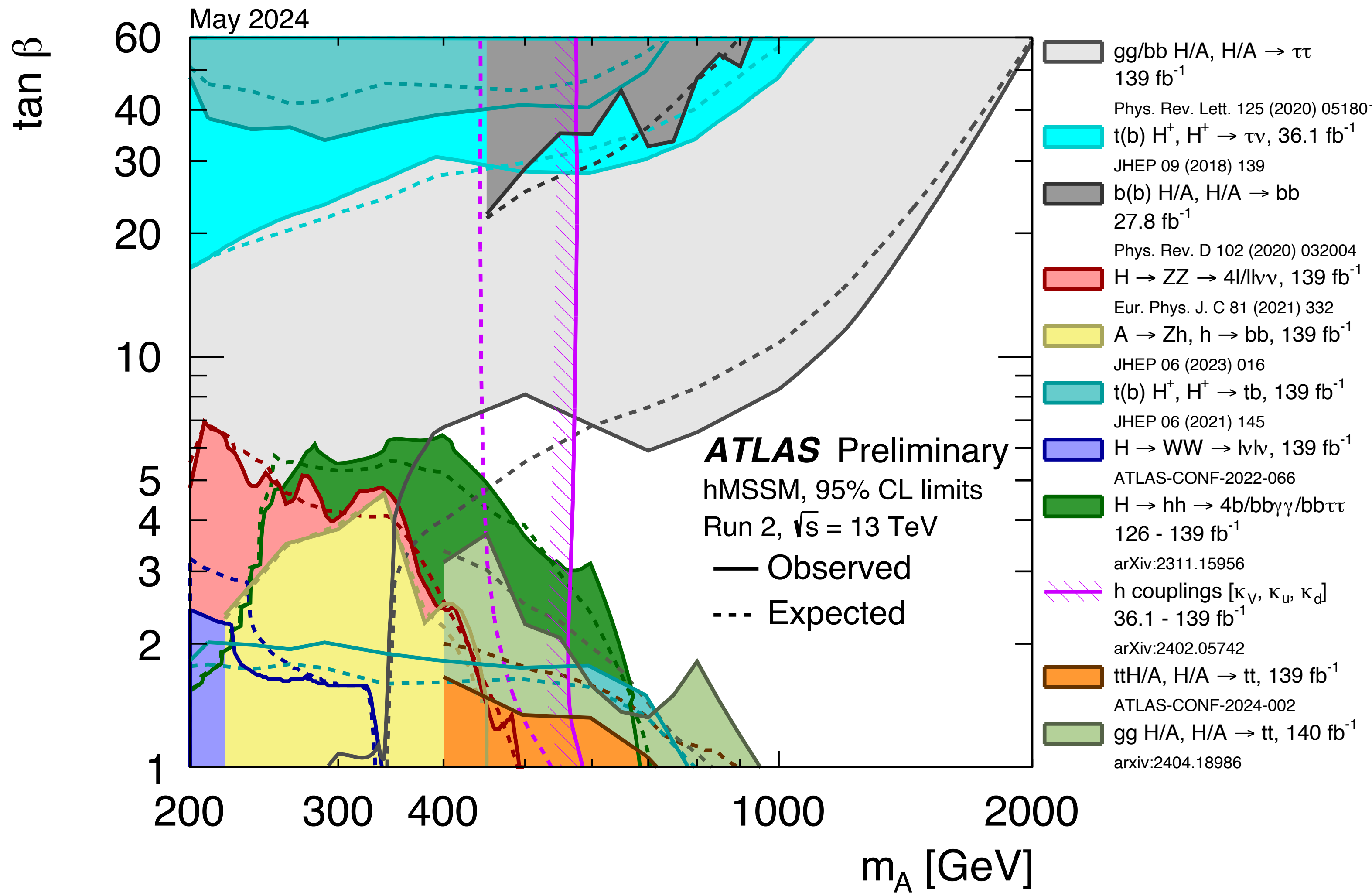
*Many BSM models motivating searches for additional neutral Higgs bosons*

**Full Run 2 (140 fb$^{-1}$) results now covering:**

- *Broad mass range*
- *Several production modes*
- *Different decays modes*



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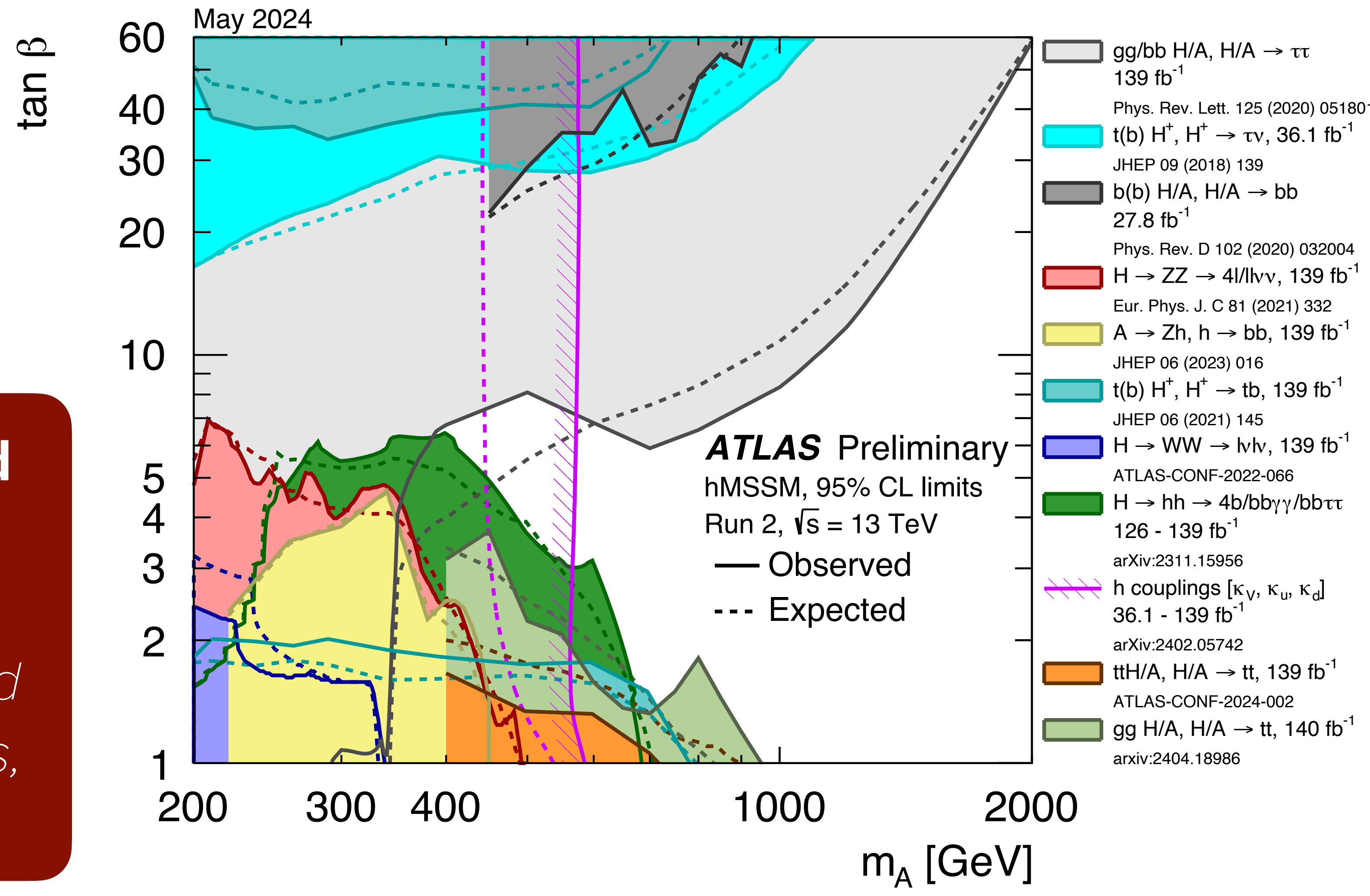
- *LHC Run 3 still ongoing, with **>180 fb⁻¹** already collected*
- *Stay tuned for improved results, and more analyses!*



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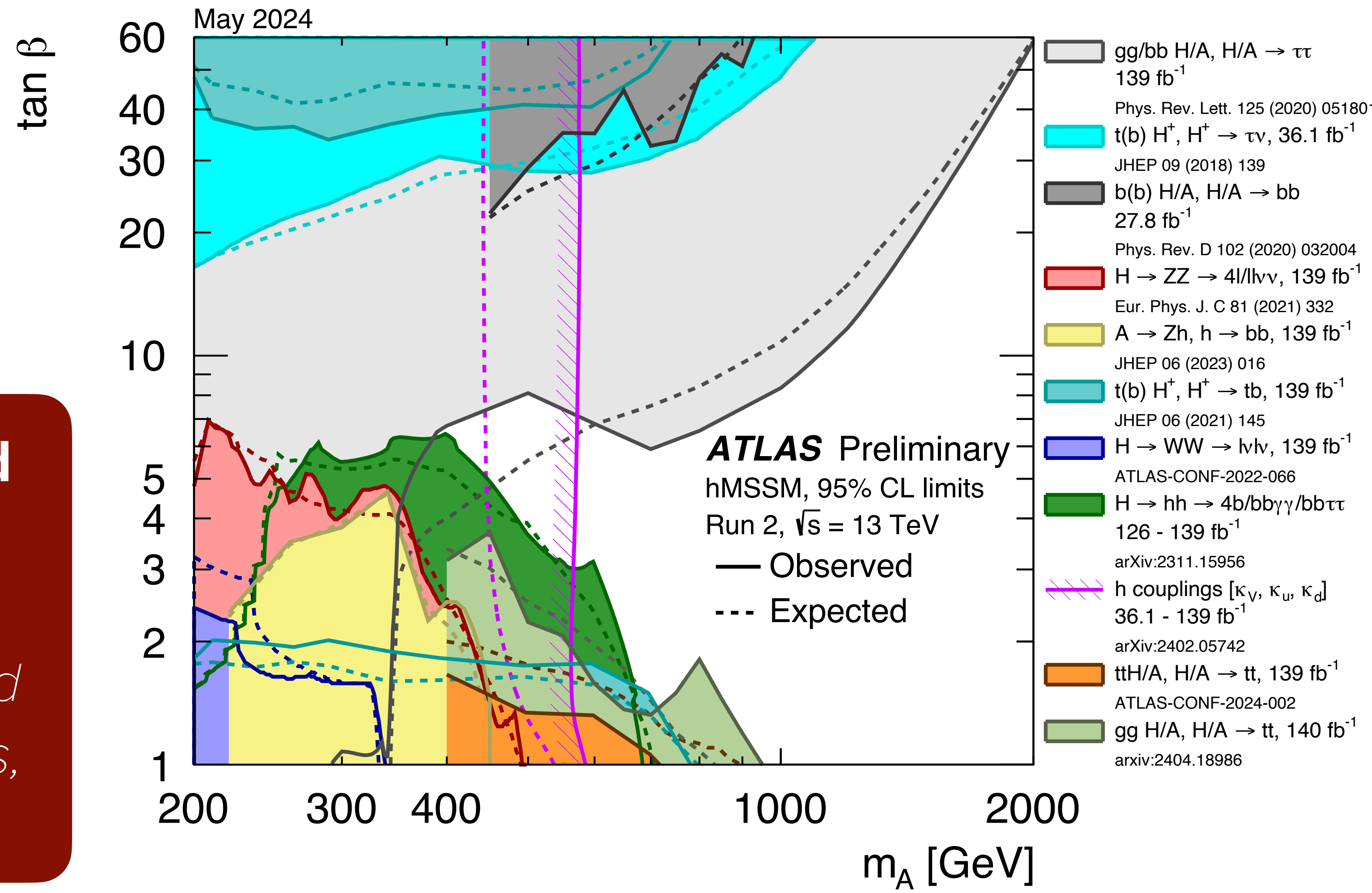


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*Other related Higgs 2024 talks:*

Nadav Michael Tamir: *"Searches for axion-like-particles in Higgs boson decays in ATLAS"*

Shikma Bressler: *"Exotic Higgs decays at ATLAS"*

Otilia Anamaria Ducu: *"Searches for singly- and doubly-charged Higgs bosons in ATLAS"*

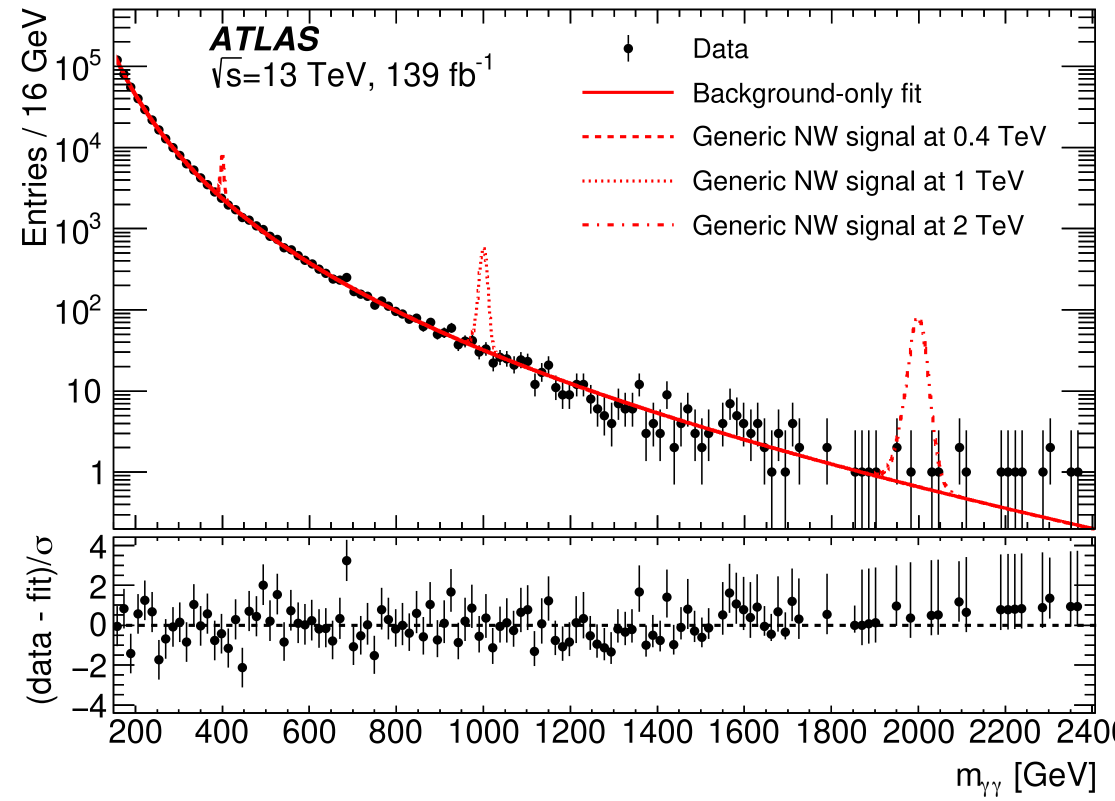
# Backup Slides

# New resonances in diphoton pairs

Phys. Lett. B 822 (2021) 136651
*October 2021*, arXiv, figures

Looking for new high-mass resonances with two main benchmarks:
***spin-0 resonant state*** and ***spin-2 graviton***

- Tight **identification/isolation** criteria on photons
  - *minimise background from jets*
- Predominant background from **γγ continuum**
- Using sidebands to estimate contributions from **γj** and **jj events**
  - *10% of total background at most, 3% at high $m_{\gamma\gamma}$*
- functional decomposition used to smooth templates
  - *Improved spurious signal uncertainties*




| | | |
|---|---|---|
| | *Spin-0* | |
| $m_X$ | 400 GeV | 2800 GeV |
| NWA | 1.1 fb | 0.03 fb |
| $\Gamma_X/m_X = 2\%$ | 2.5 fb | 0.03 fb |
| $\Gamma_X/m_X = 6\%$ | 4.4 fb | 0.03 fb |
| $\Gamma_X/m_X = 10\%$ | 8.3 fb | 0.04 fb |
| | *Spin-2* | |
| $m_{G^*}$ | 500 GeV | 5000 GeV |
| $k/\overline{M}_{\rm Pl} = 0.01$ | 1.9 fb | 0.04 fb |
| $k/\overline{M}_{\rm Pl} = 0.05$ | 2.3 fb | 0.04 fb |
| $k/\overline{M}_{\rm Pl} = 0.1$ | 3.2 fb | 0.04 fb |

Main uncertainty from spurious signal:
*40-10% of data statistical uncertainty (160-3000 GeV, NWA)*

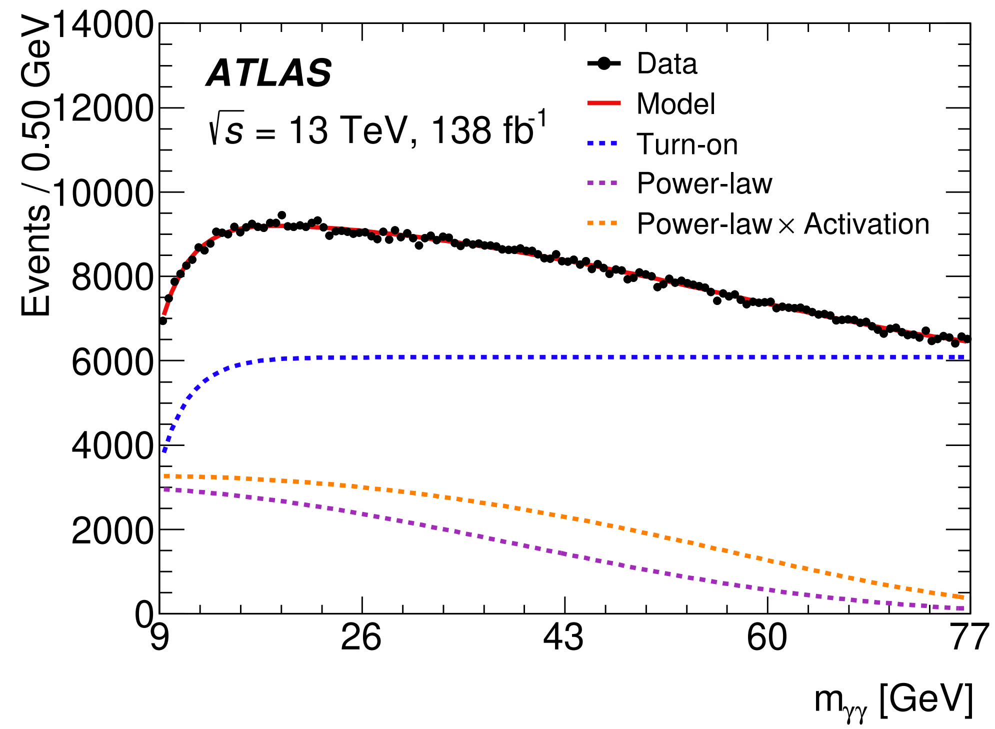
Largest signal uncertainties:
***production*** (7-3%) and ***photon energy resolution*** (10-50%)

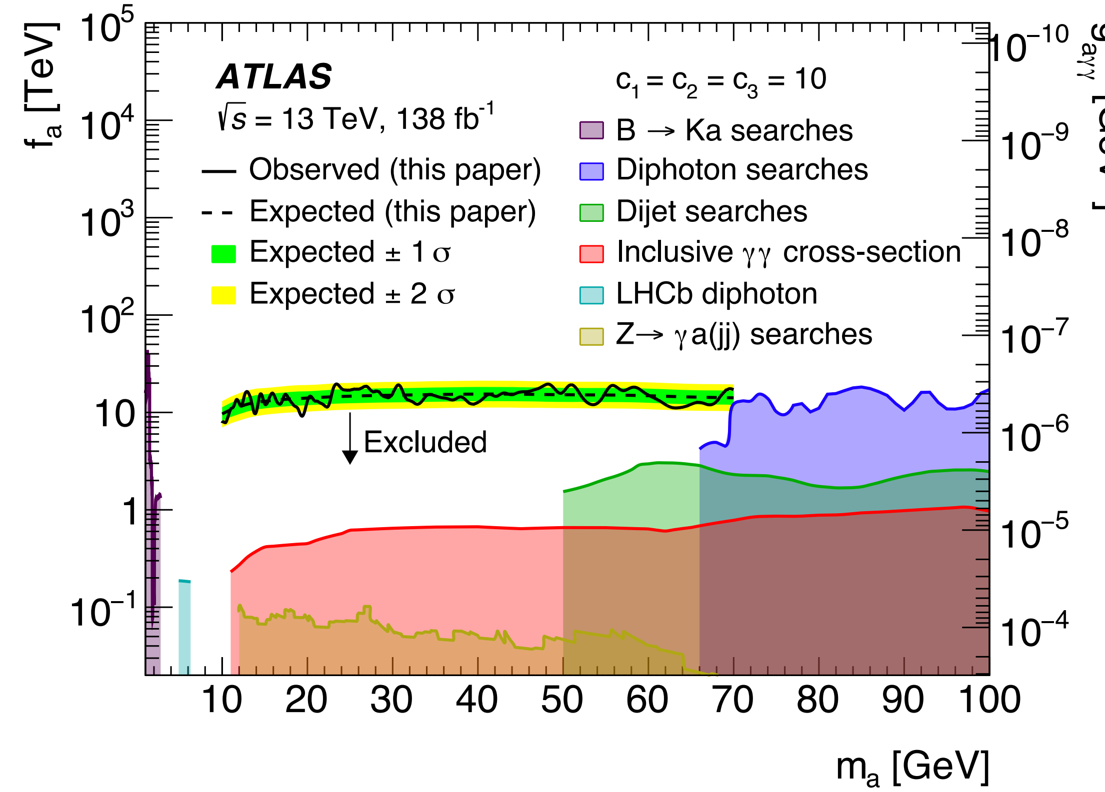
# Low-mass diphoton resonances

JHEP 07 (2023) 155
*November 2022*, arXiv, figures

Searching for resonances below 70 GeV, extending the LHC coverage to particular BSM scenarios

- Challenging region in $m_{\gamma\gamma}$, because of trigger thresholds and potential sculpting of the $\gamma\gamma$ spectrum
  - *focus on* ***close-by photons****, with* ***large*** $p_T^{\gamma\gamma}$
- Same backgrounds as previous search
  - *much* **different γγ purity**, *ranging from 50% to 70%*
- Two components required for background modelling:
  - **turn-on** *(to reach 10 GeV) and* **power-law with activation ➔ *10*** *parameters in total*




Main uncertainty from spurious signal:
*10-30% of statistical uncertainty (mass-dependent)*

Main uncertainties on $\sigma_{fid}\times\mathcal{B}(X\rightarrow\gamma\gamma)$ all in the 1-3% range:
*pileup, isolation/identification, energy scale resolution*

# Heavy resonances in 4ℓ and 2ℓ2ν

Eur. Phys. J. C 81 (2021) 332
*September 2020*, arXiv, figures

Same benchmarks as high-mass diphoton search

Deriving also limits (vs cos(α-β), tan(β), $m_H$) for Type-I and Type-II 2HDM models

- Choosing maximal efficiency on lepton reconstruction
  - › *minimal contributions from "fake" backgrounds*
- *DNNs* used for classifications (NWA-only)
  - › ***20-40% improvement** in expected limits*

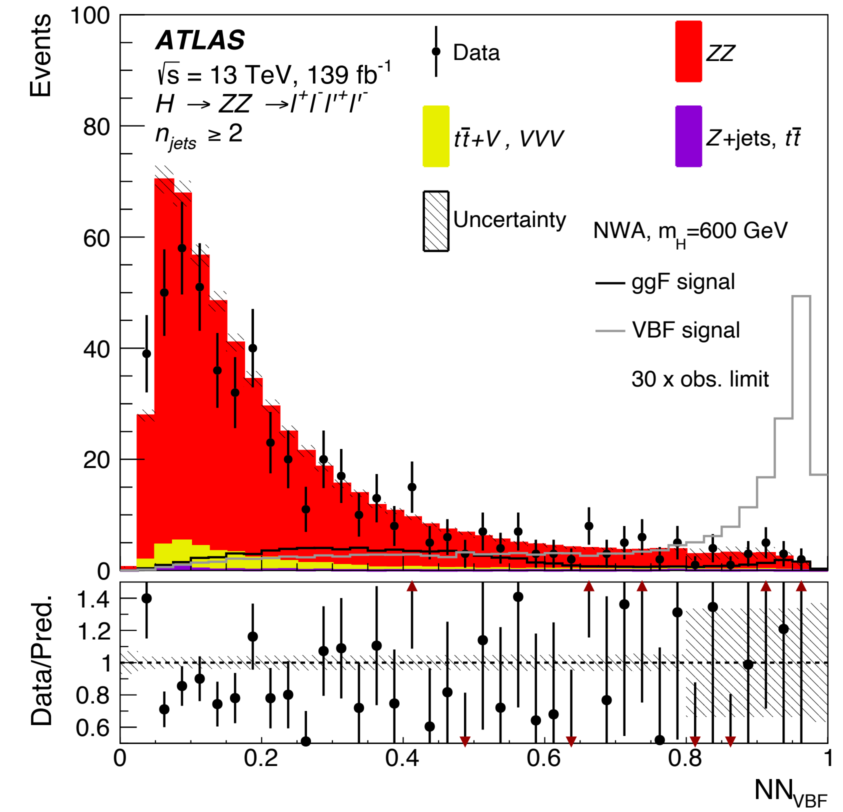
**4ℓ**

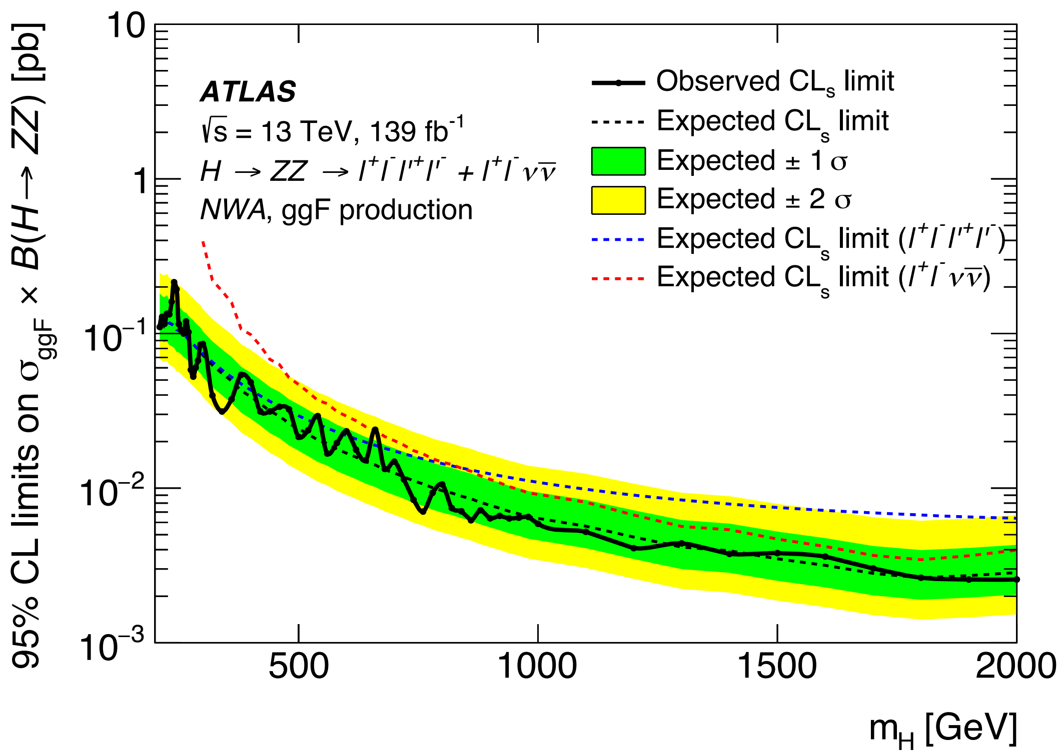
- $E_T^{miss}$ > 120 GeV and large statistical significance of $E_T^{miss}$
  - › *required to reduce Z+jets contamination*
- Data-driven background estimation
  - › *for ZZ continuum, only* **normalisation** *taken from data*

**2ℓ2ν**

Data statistical uncertainty: 50-60%

Largest systematic uncertainties: ***parton showering*** (up to 10%), ***EW corrections*** (up to 10%), ***qq→ZZ QCD scale*** (up to 8%)



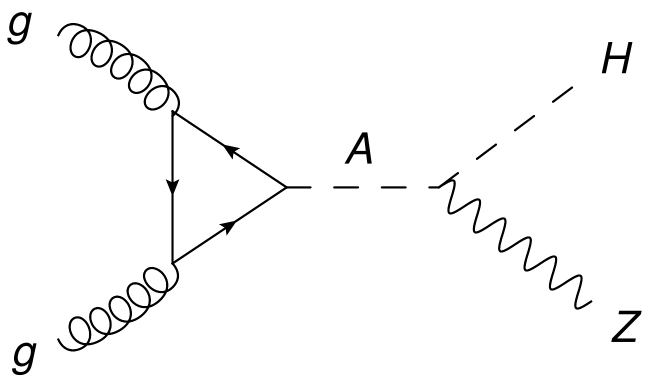



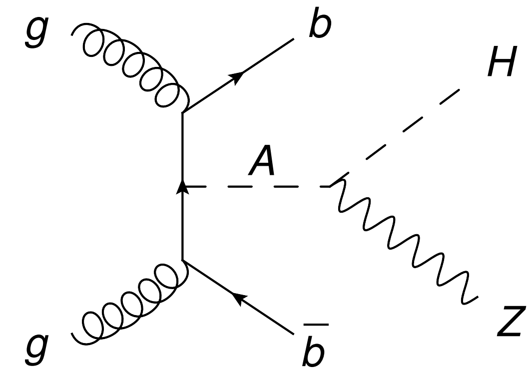
# $A \to ZH \to lltt/\nu\nu bb$

JHEP 02 (2024) 197
*November 2023*, arXiv, figures

Searching for **heavy CP-odd scalar *A*** decaying to **heavy CP-even Higgs** and a *Z*-boson

*Production through either gluon-gluon fusion or in association with b-quark pairs*




*lltt*: covering the unexplored mH > $2m_{top}$ phase-space

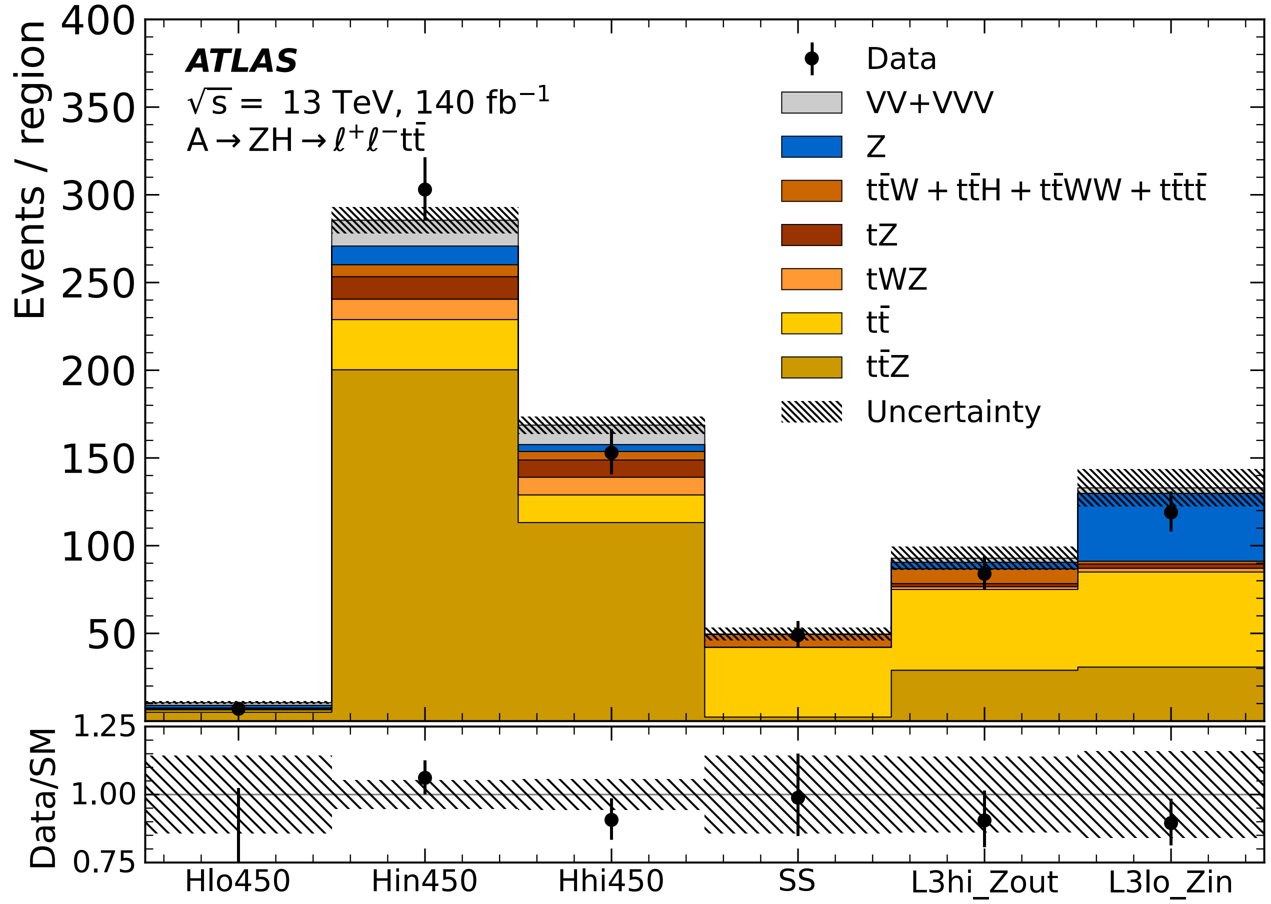
*vvbb*: complementing the *llbb* search (exploit higher *Z* BR to neutrinos)

## *lltt*

- Signal region: 3l, ≥4 jets and 2 *b*-jets
- 3 control regions:
  - *constraining tt and ttZ backgrounds*

## *vvbb*

- 2 signal regions: 0*l*, $E_T^{miss}$ and 2 or ≥3 *b*-jets
- 8 control regions:
  - *for Z+HF and tt backgrounds*



# $A \to ZH \to lltt/\nu\nu bb$

JHEP 02 (2024) 197
*November 2023*, arXiv, figures

*Final discriminants used:*

- *lltt*: mass difference between *A* and *H*
- *ννbb*: transverse mass of the *ZH* system

*Uncertainties:*

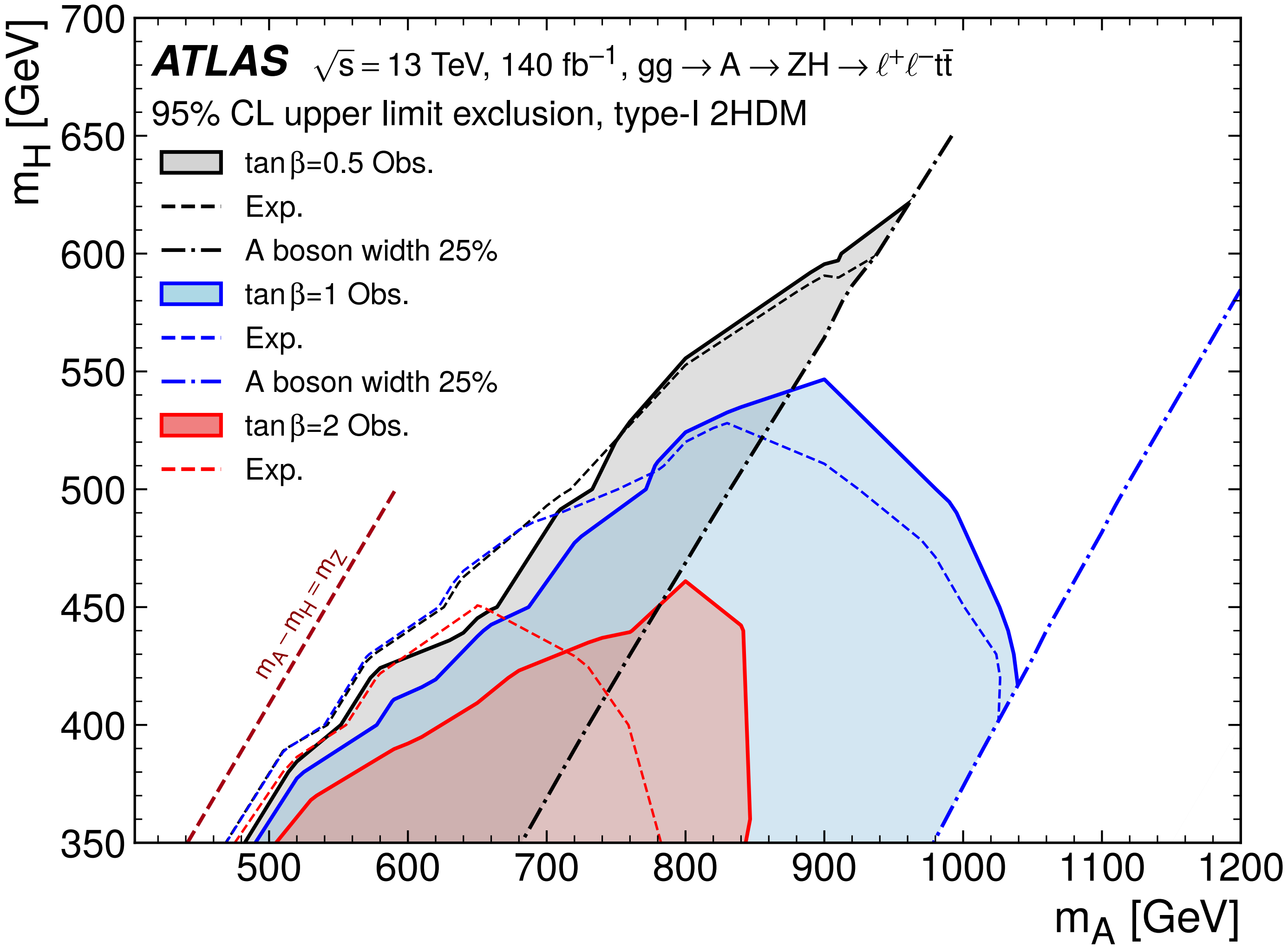
- *lltt*: largely dominated by statistical uncertainties
- *ννbb*: systematics dominated, specifically by *W/Z*+HF and jet reconstruction

Largest deviation from background-only hypothesis:
2.85σ local (2.35 global)

*lltt* channel for ($m_A$, $m_H$) = (650, 450) GeV

Upper limits extracted in the $m_A$, $m_H$ plane on
$\sigma\times\mathcal{B}(A\to ZH)\times\mathcal{B}(H\to tt)$ and $\sigma\times\mathcal{B}(A\to ZH)\times\mathcal{B}(H\to bb)$
2HDM models, for different tanβ values

in the sensitivity range, H width is much smaller than experimental resolution



| Title | Journal reference | Date | | |
|---|---|---|---|---|
| ttH/A → tttt (2+ leptons) | JHEP 07 (2023) 203 | 2 November 2022 | figures | pdf |
| ttH/A → tttt (1 or 2 OC leptons) | Submitted to: EPJC | 30 August 2024 | figures | pdf |
| A → SH → 4l + MET or 4l + jets | JHEP 10 (2024) 130 | 9 January 2024 | figures | pdf |
| multilepton, flavour changing | JHEP 12 (2023) 081 | 27 July 2023 | figures | pdf |
| tt → X + q, flavour changing | JHEP 07 (2023) 199 | 10 January 2023 | figures | pdf |
| A → AZ → lltt or ννbb | JHEP 02 (2024) 197 | 7 November 2023 | figures | pdf |
| H → aa → bbμμ | Phys. Rev. D 105 (2022) 012006 | 1 October 2021 | figures | pdf |
| S → ZdZd → 4l | Submitted to: Phys. Lett. B. | 22 October 2024 | figures | pdf |
| H → ZZ → 4l | Eur. Phys. J. C 81 (2021) 332 | 30 September 2020 | figures | pdf |
| spin 0 or 2 → γγ | Phys. Lett. B 822 (2021) 136651 | 26 February 2021 | figures | pdf |
| γγ low mass | JHEP 07 (2023) 155 | 8 November 2022 | figures | pdf |