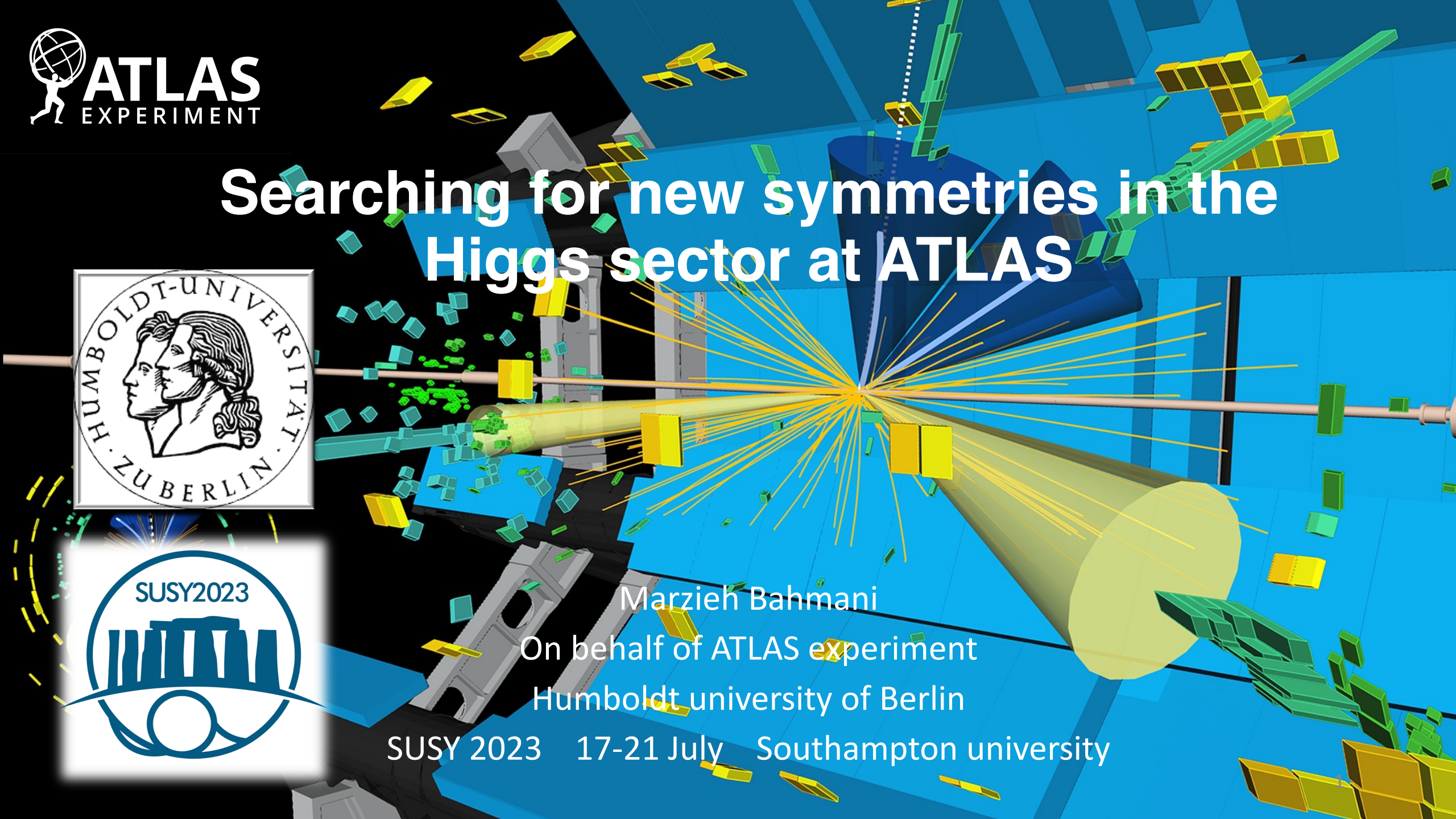

# Searching for new symmetries in the Higgs sector at ATLAS

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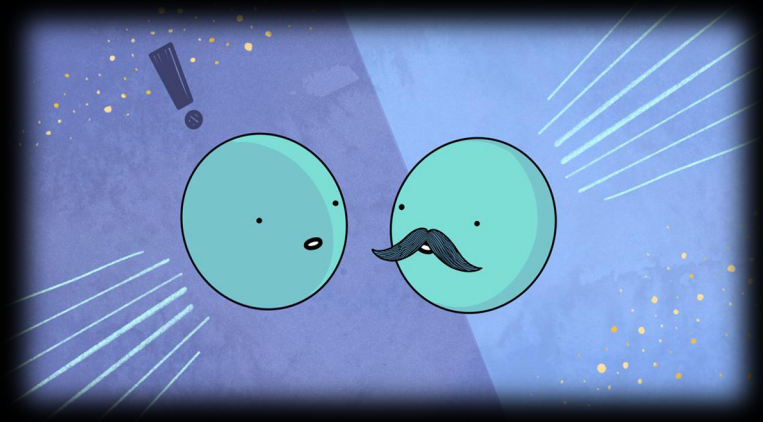
SUSY 2023 17-21 July Southampton university

# Introduction

- Discovery of the Higgs boson (EWSB)

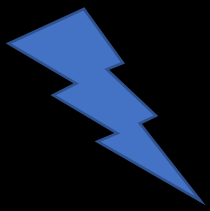

**The SM can not explain**

- Dark matter/energy
- Baryon asymmetry
- Gravity
- …



Many extensions of Beyond the Standard Model (BSM) predict additional scalar fields for EWSB.

- several new searches by the ATLAS collaboration



**New scalar resonance in FCNC top decay** arXiv:2301.03902

**$t\bar{t}$H/A $\rightarrow t\bar{t}t\bar{t}$ production in multilepton final state** arXiv:2211.01136

**Search for resonant WZ production in fully leptonic final state** arXiv:2207.03925v2

**Search for doubly charged Higgs production in multi−lepton final state** arXiv:2211.07505v2

**Search for diphoton resonances in 66 to 110 GeV** ATLAS-CONF-2023-035

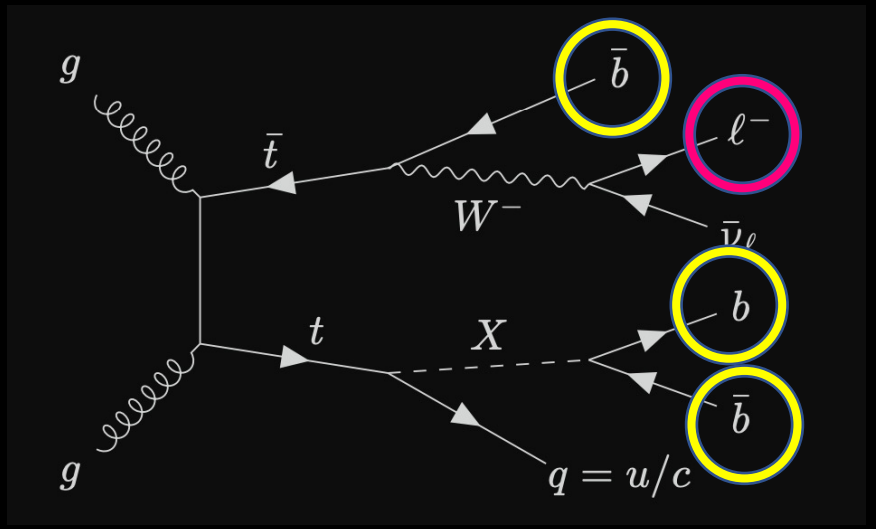
LHC Run-2 139 $fb^{-1}$ pp collisions data at $\sqrt{s}$= 13 TeV from ATLAS detector

# New scalar resonance in FCNC top decay

arXiv:2301.03902

## Motivation

- New light scalars and FCNC interaction predicted by several BSM theories such as 2HDM and composite Higgs models
- These theories predict top quark FCNC couplings with a u/c quark and a new scalar (X)
- $t \to u(c)X$ and $X \to b\bar{b}$ for m(X) < m(t)



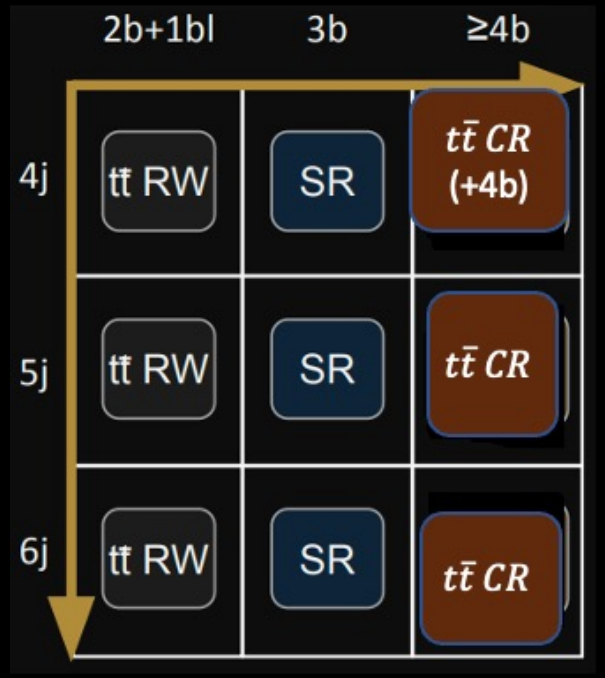

## Analysis strategy

- m(X) range 20 - 160 GeV
- Use Neural Network in order to separate signal from background

Regions are chosen by the number of jets and number of b-tagged jets (b-tags)

- Signal region (SR): single lepton ($e^{\pm}, \mu^{\pm}$), 3 b-tags + jets
- $t\bar{t}$+jets+≥4b control regions (CR)

$t\bar{t}$+jets+ 2b+1bl reweighting ($t\bar{t}$ RW)(regions to extract weights to correct the t$\bar{t}$ and $W \to cb$ simulated distributions)
(b-tags at 60% efficiency, bl at 70% ).



# New scalar resonance in FCNC top decay

arXiv:2301.03902

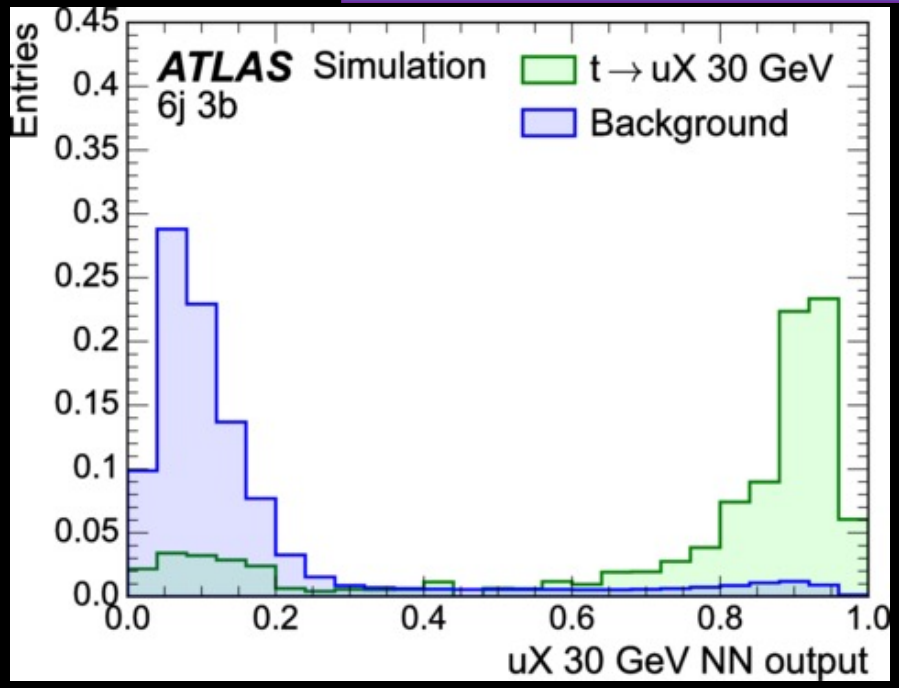
## Neural Network

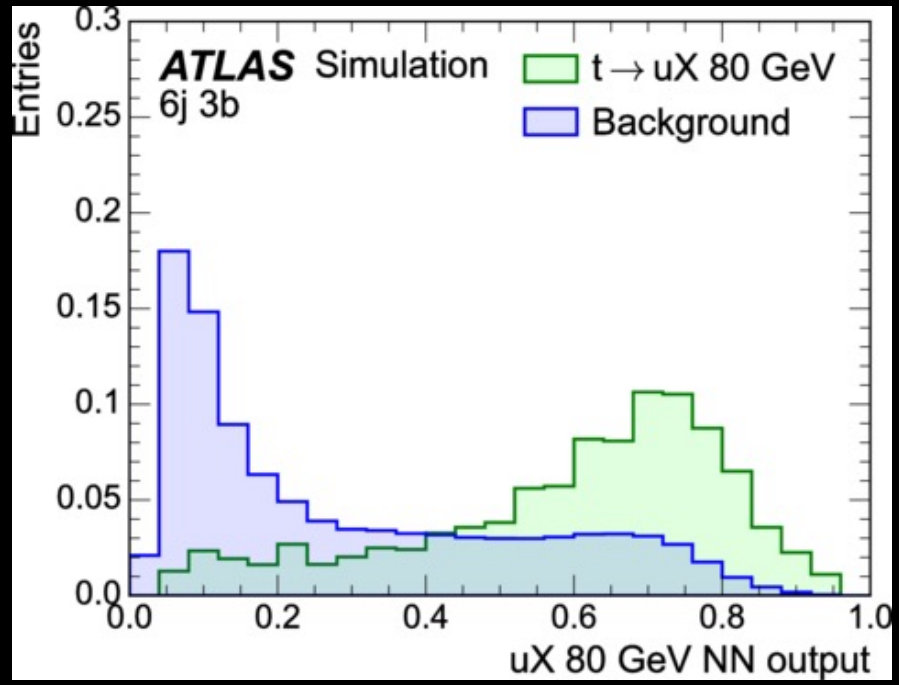
Neural network trained for t→cX and t→uX

Input parameters:

- $p_T, \eta$ of leptons, $p_T, \eta, \varphi$ of first six leading jets and b-tag information of jets,
- Missing transverse momentum magnitude and $\phi$,
- Various m(bb) and $\Delta R(bb)$,
- Parameter $m_X$

The output of NN depends on $m_X$



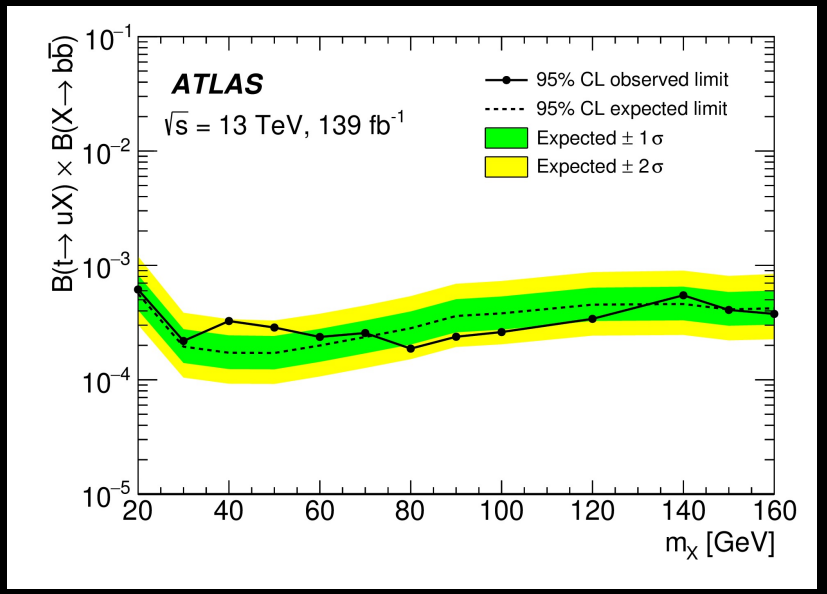
# New scalar resonance in FCNC top decay

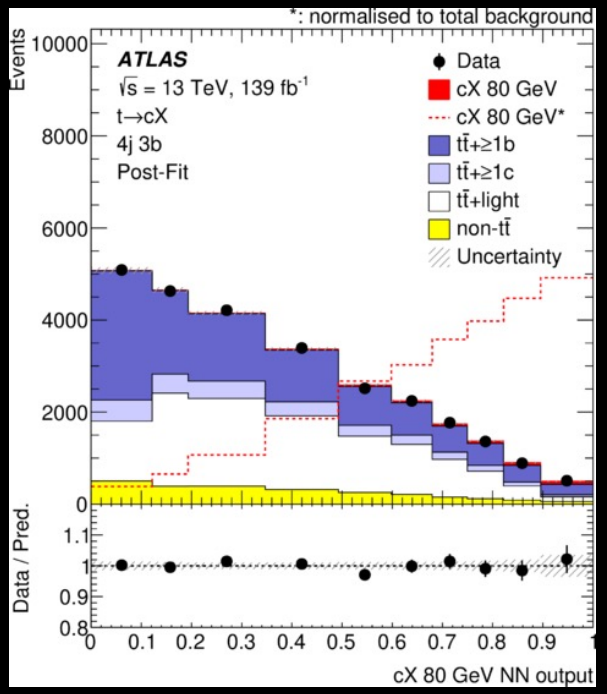
arXiv:2301.03902

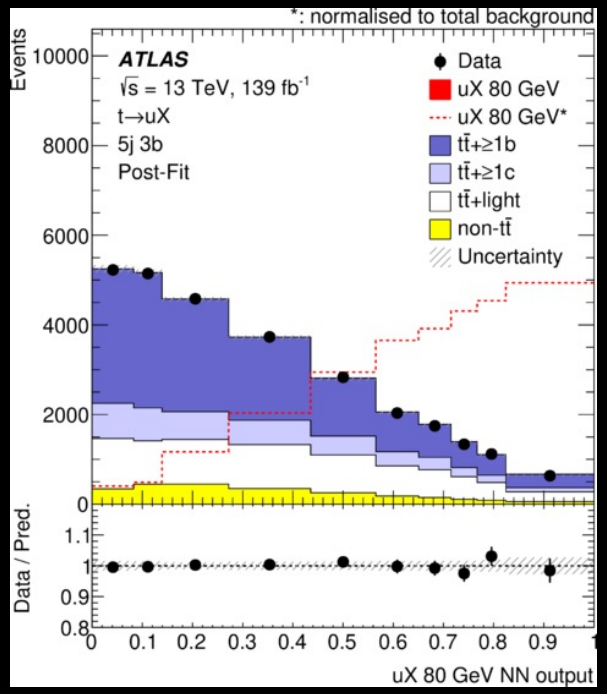
## Fit Result and exclusion limit

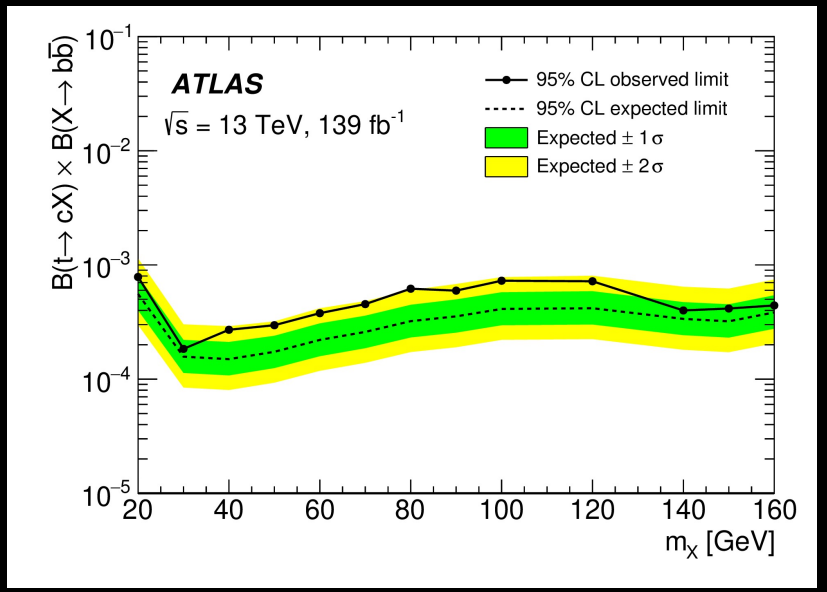
- 95% CL upper limit *for the observed (expected):*
- 0.019%(0.017%) *and 0.062%(0.056%) for* $\mathcal{B}(t \to uX) \times \mathcal{B}(X \to b\bar{b})$
  0.018% (0.015%) and 0.078%(0.056%) for $\mathcal{B}(t \to cX) \times \mathcal{B}(X \to b\bar{b})$

- *Same NN for SM Higgs: limits of 0.077% (0.088%) for* $\mathcal{B}(t \to uH)$ *and 0.12% (0.076%) for* $\mathcal{B}(t \to cH)$



# $t\bar{t}$H/A → $t\bar{t}t\bar{t}$ production in multilepton final state

arXiv:2211.01136

## Motivation and Benchmark model

- $t\bar{t}t\bar{t}$ is sensitive to Top Yukawa coupling, Higgs CP properties and BSM
- SM 4top analysis: Eur. Phys. J.C 83(2023)496
- Benchmark model:
  - 2HDM type-II with interpretation on low tan(β) region in the alignment limit tan(β-α) → 1 (all couplings as SM )
  - mass range of [400 -1000]GeV

## Analysis strategy

**based on the SM $t\bar{t}t\bar{t}$ analysis**

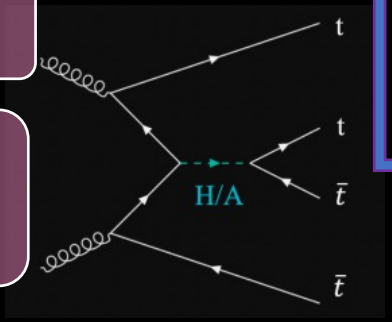
**Dedicated CRs to constrain the dominant BG, MVA (2 sequential BDTs)**

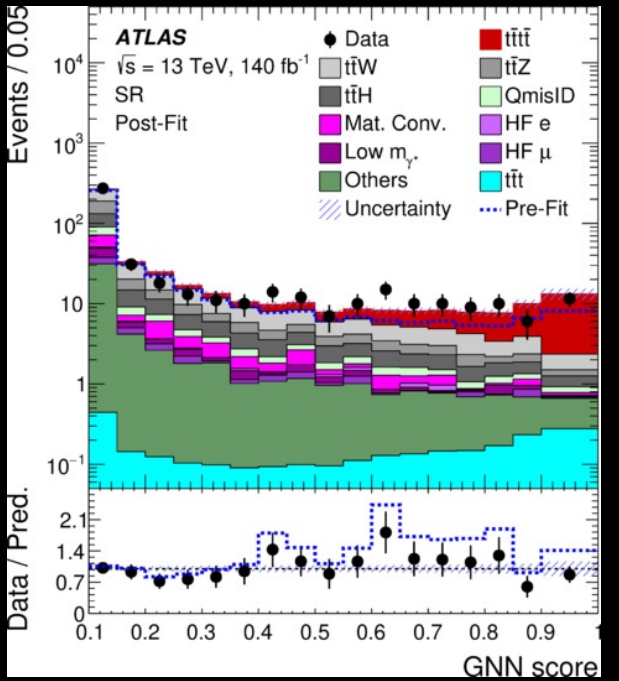
**Baseline SR: High jet and b-jet multiplicities and high HT (≥ 6 jets, ≥ 2 b-tag)**

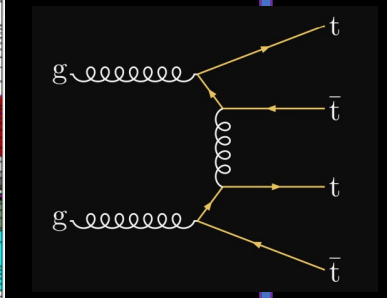
HT is the scaler sum of the pT of leptons and jets in the event

Same-sign di-lepton (SS) and Multi-lepton (ML) categories

$t\bar{t}$H/A is not subject to interference with SM 4top, unlike in A/H->$t\bar{t}$, where the huge interference completely cancels the resonance peak




ATLAS:

6.1 observed significance $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}$ consistent with the SM prediction $12.0^{+2.2}_{-2.5} fb\ (NLO)$ with 1.8 standard deviation

CMS:arXiv:2305.13439

5.6 observed significance $\sigma_{t\bar{t}t\bar{t}} = 17.75^{+4.4}_{-4.0}$

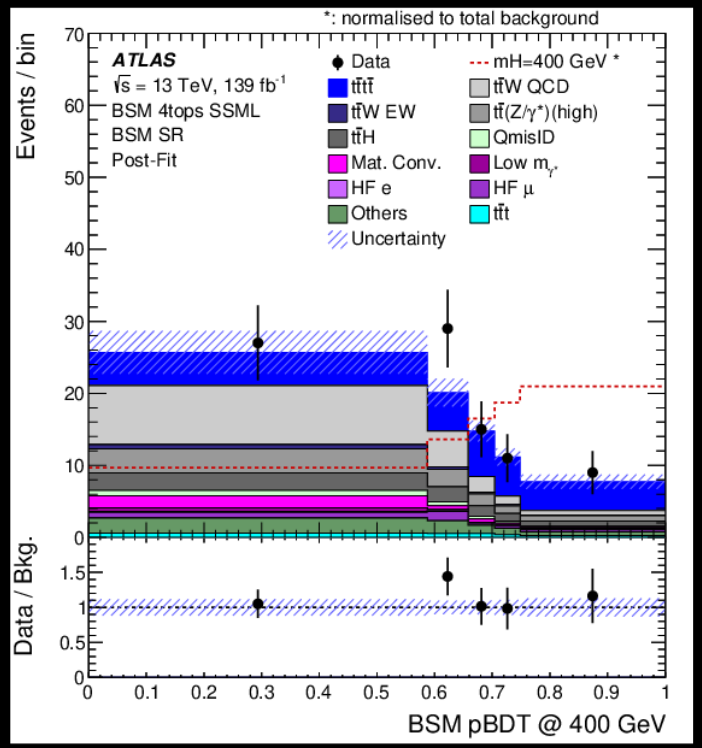
# $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$ production in multilepton final state

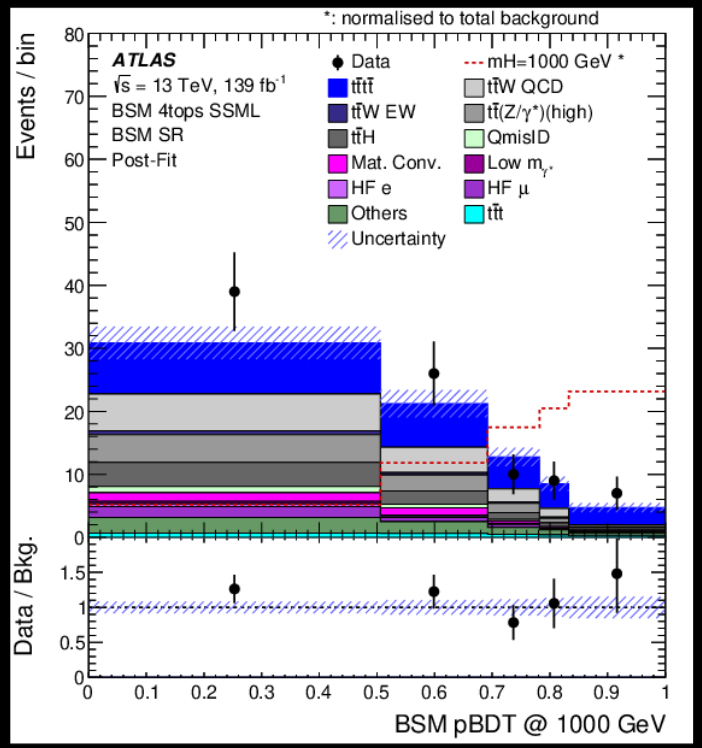
arXiv:2211.01136

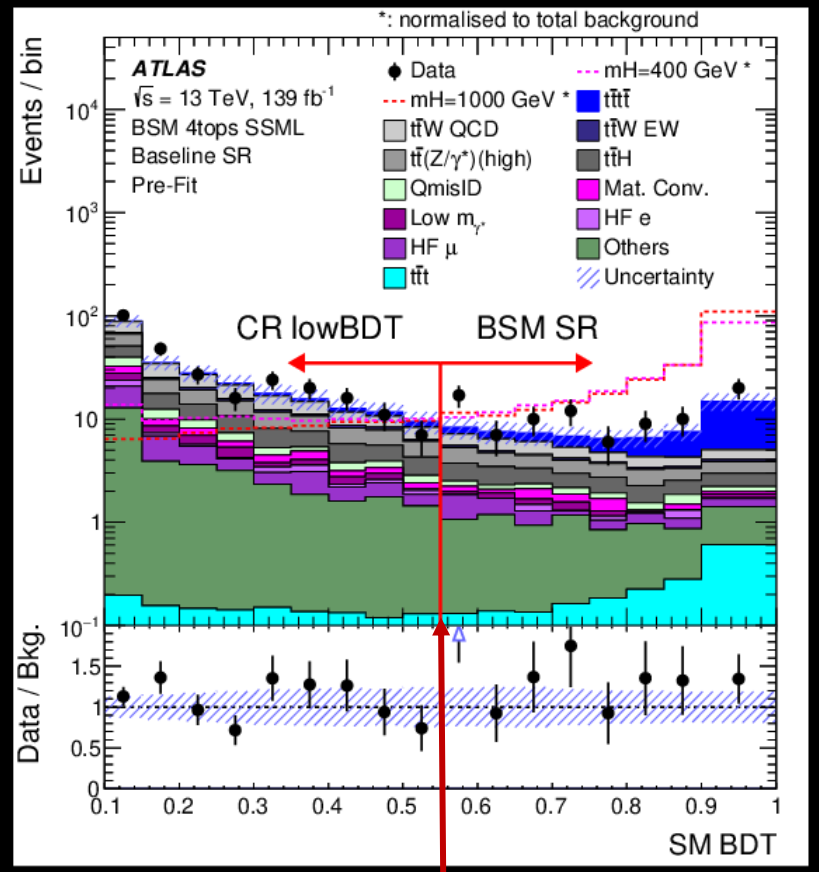
The signal is separated from the SM background by using two sequential BDT classifiers:

1- SM BDT to select SM 4-top-like events from remaining BG. (to define SR, training is done on the SR-baseline )

2- Mass-parametrized BSM BDT (pBDT) to separate BSM 4-top from all BG



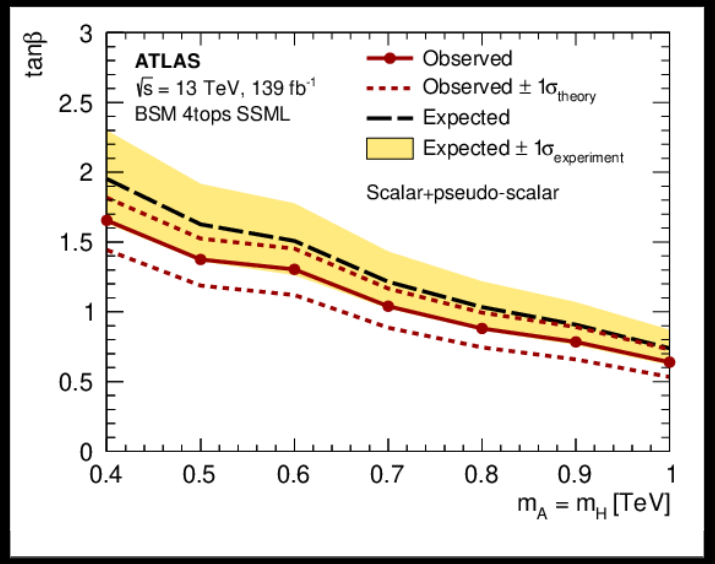

0.55

Fit results (background-only fit): no significant excess over SM expectation

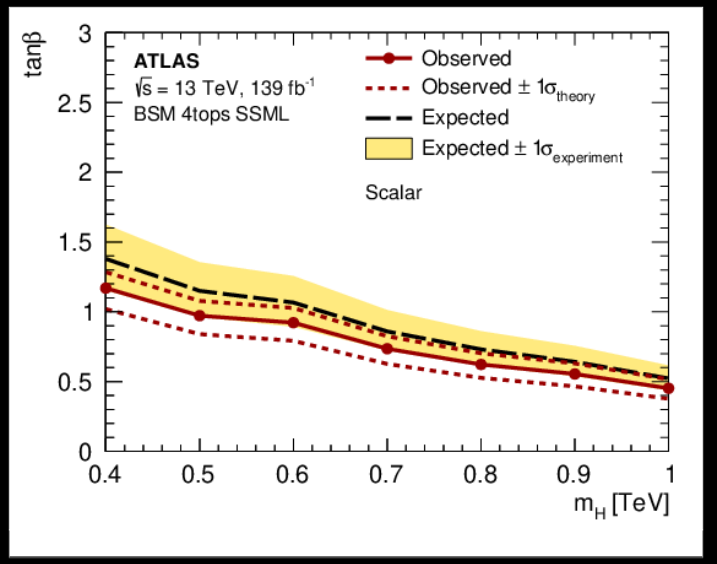
# $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$ production in multilepton final state

arXiv:2211.01136

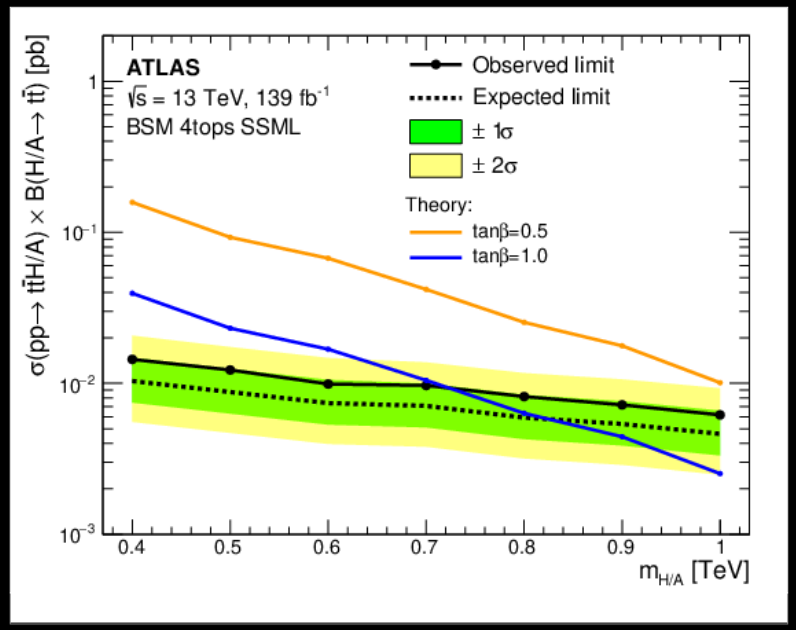
## Fit Result and exclusion limit




Limits on tan($\beta$) assuming that both H and A boson contribute to the final state




Limits on tan($\beta$) assuming that only the scalar H contribute to the final state. The limits for the pseudo-scalar A boson alone are similar to H.




- 95% CL exclusion limits on cross-section of 2HDM type II scalar (H) and pseudo-scalar (A) Higgs boson
- The observed (expected) upper limits range between 14(10)fb and 6(5) fb for the studied mass range

# Search for resonant WZ production in fully leptonic final state

arXiv:2207.03925v2

## Motivation

- Diboson searches are useful tools to test the EW sector in BSM theories
- The fully leptonic channel is more sensitive to resonances with mass < ~ 1TeV because of Clean signature (despite of low BR)

## Analysis strategy

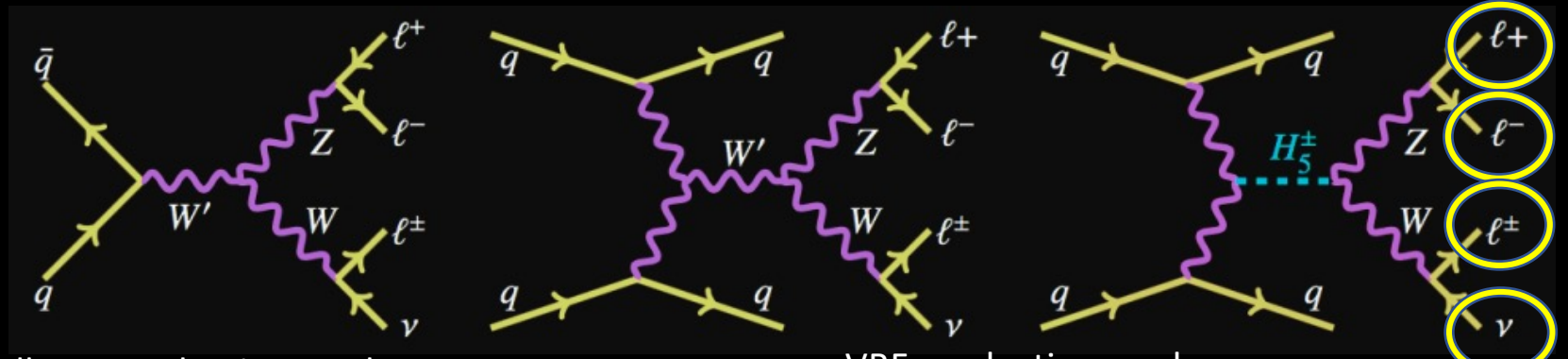
**A cut-based selection to build DY SR**

**ANN trained for VBF SR**

Invariant mass of WZ built with lepton and $E_T^{miss}$

Invariant mass of WZ as discriminating variable

- Two benchmark models: Georgi-Machacek (GM) model and Heavy Vector Triplet (HVT)
- Fully leptonic $(e, \mu)$ WZ decay in Drell-Yan[DY] process or VBF




Drell-Yan production mode

VBF production mode

# Search for resonant WZ production in fully leptonic final state

arXiv:2207.03925v2

| WZ basline selection | | | |
|---|---|---|---|
| SR | WZ-QCD CR | ZZ CR | DY selection. |
| SR | WZ-QCD CR | ZZ CR | VBF selection. |

- Irreducible Backgrounds: leptons from SM processs and reducible Backgrounds: processes with jets or photons which are misidentified as lepton

## Event selection- baseline for WZ

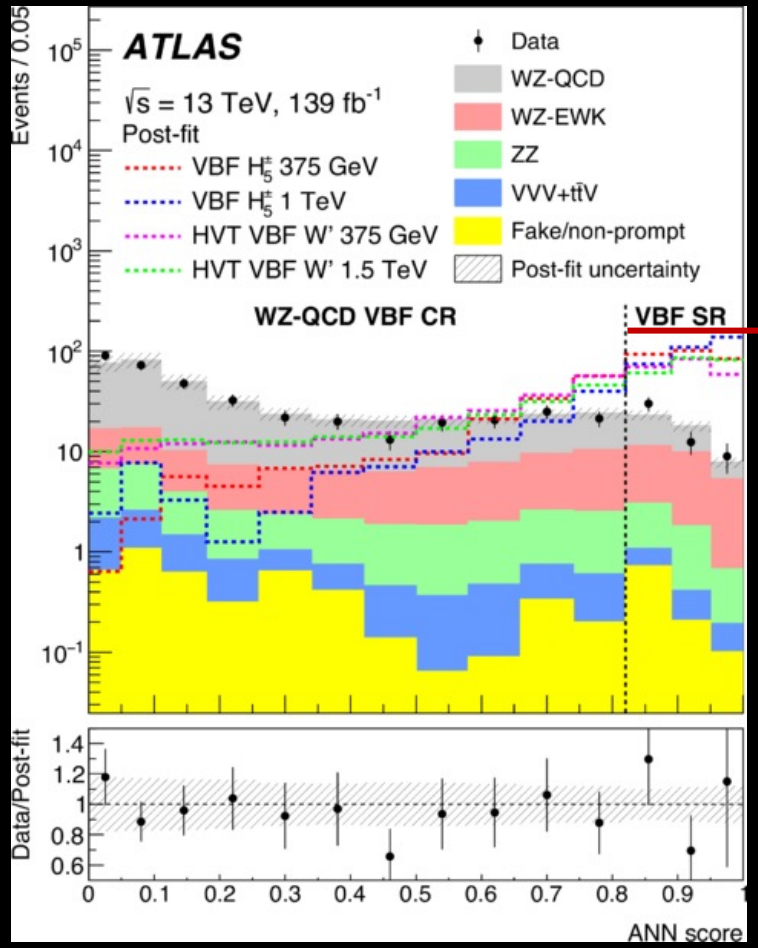
- Exactly 3 leptons
- To reduce ZZ BG, events with 4 leptons are vetoed
- Z candidate: 2 SF OS leptons $|m_{ll} - m_z| < 20$ GeV
- Third lepton as W boson candidate
- Missing transverse energy assumed to be neutrino

Drell-Yan selections: Boson $p_T$/ WZ mass > 0.35 for both bosons
VBF selection:

- $\geq$ 2 jets with large rapidity gap,
- For the highest-pT pair, $m_{jj} >$ 100 GeV

## ANN for VBF

- ANN: Training on the simulated $H_5^{\pm}$ SR against the SM WZ-(EWS,QCD) BG
- A 4-fold cross-validation technique, kinematic variables of jets and leptons used as input variables.

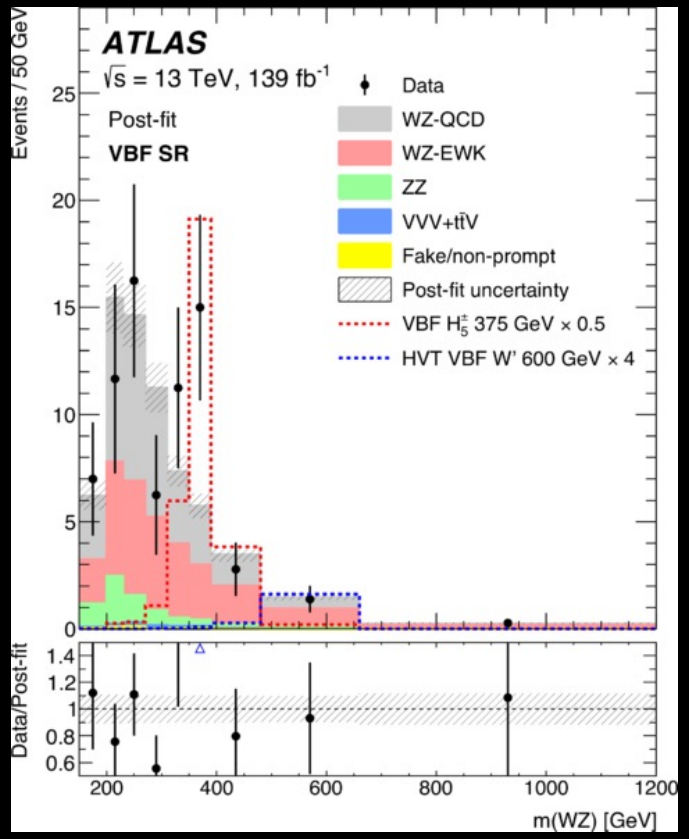


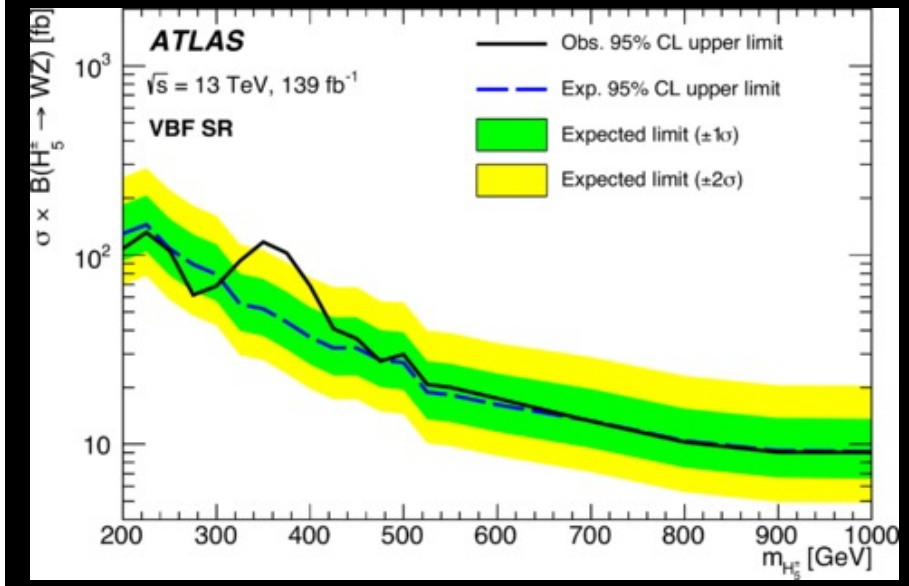

ANN score 0.82

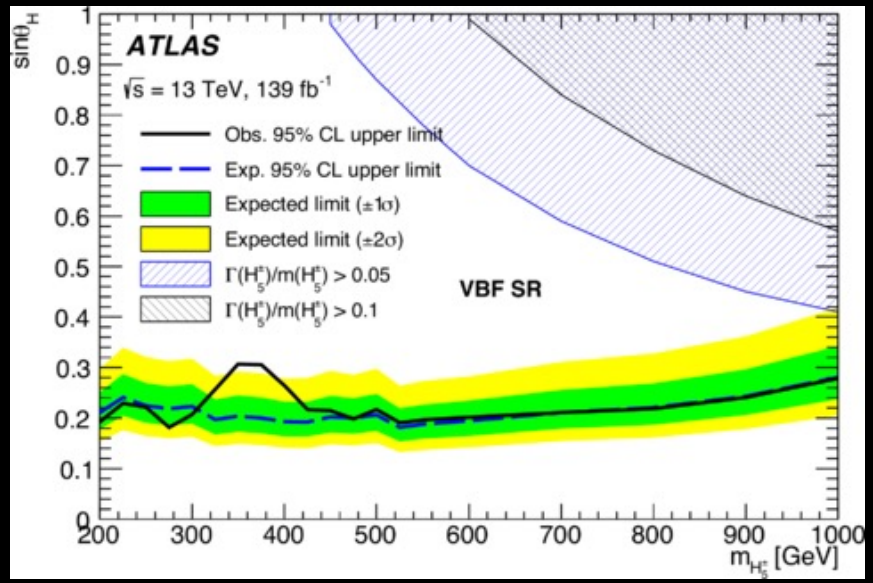
# Search for resonant WZ production in fully leptonic final state

arXiv:2207.03925v2

## Fit Result and exclusion limit for GM model




*The limits are about 35% stronger than the previous limit set by ATLAS*

Local excess in the VBF at m(WZ) ~ 375 GeV

Local significance for $W'$ and $H_5^{\pm}$ are 2.5 and 2.8.

Their Global significance are 1.7 and 1.6

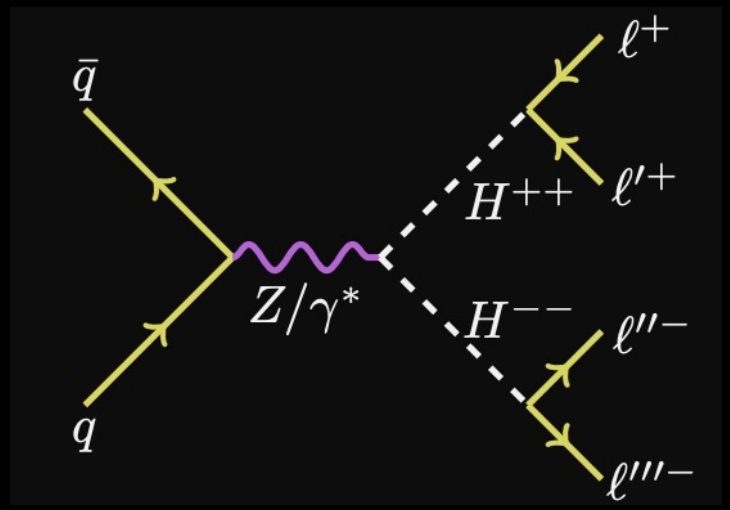
# Search for doubly charged Higgs production in multi–lepton final state

arXiv:2211.07505v2

## Motivation

- Various BSM models predict doubly charged H boson decaying into same-charge lepton pairs
- Benchmark model: Left-right symmetric type-II seesaw model, assume small vacuum expectation of the LR spontaneous symmetry breaking , where only decays into a pair of same-charge leptons are considered

## Signature




## Analysis strategy

Combination of five signal regions

- SR2L: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
- SR3L: $l^{\pm}l^{\pm}\,l^{\mp}$
- SR4L: $l^{+}l^{+}l^{-}\,l^{-}$

Main variable to distinguish CRs, VRs and SRs invariant mass of the two SS leptons with the highest $p$T in the event, $m(l^{\pm}, l'^{\pm})_{lead}$, where $l, l' = e, \mu$

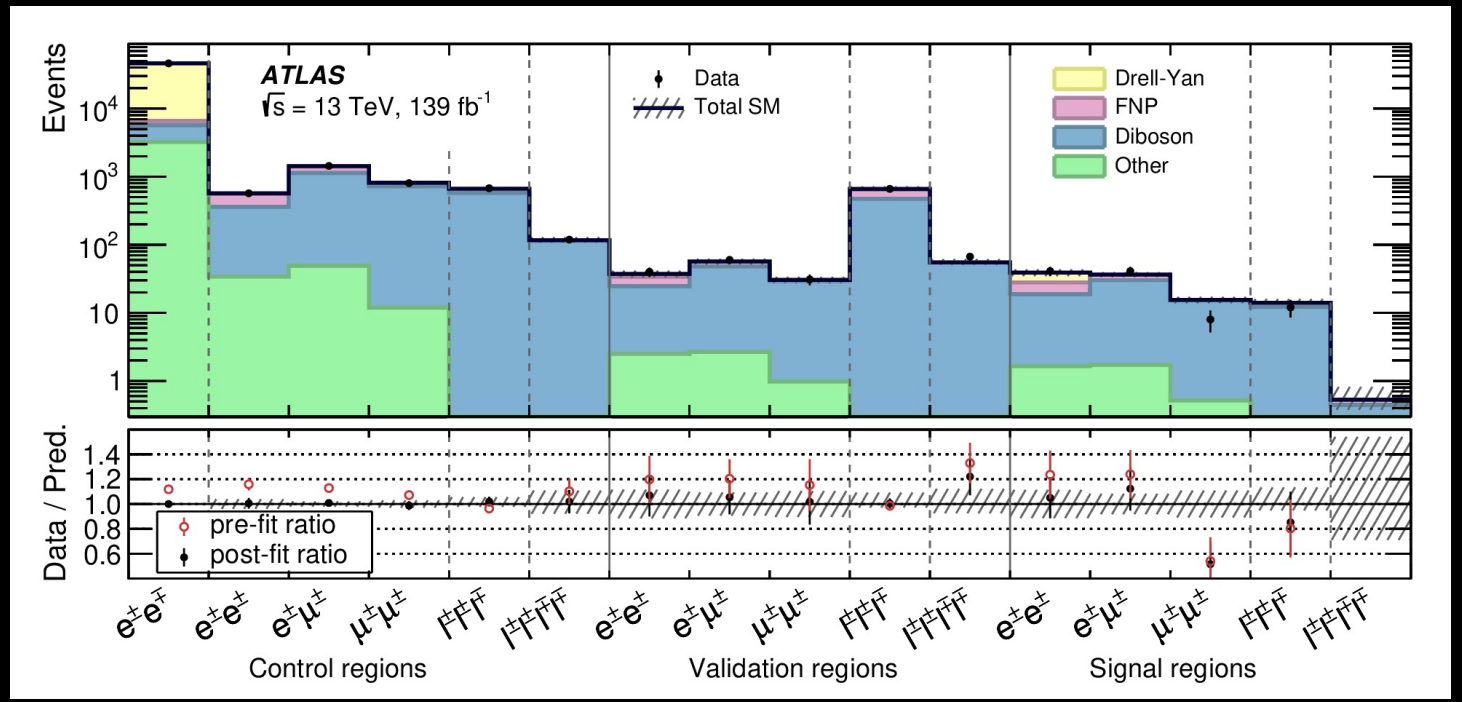
# Search for doubly charged Higgs production in multi−lepton final state

arXiv:2211.07505v2

SR: $m(l^{\pm}, l'^{\pm})_{lead}$ > 300 GeV,
SR2L: $\Delta R(l^{\pm}, l'^{\pm}) < 3.5$
SR2L and SR3L: $p_T(l^{\pm}, l'^{\pm})_{lead}$> 300GeV
SR4L: average invariant mass $\bar{m} = \frac{m_{l^+l'^+} + m_{l^-l'^-}}{2} > 300\ GeV$

## Background composition

- Diboson (dominant)
- FNP lepton (fake/non-prompt)
- Drell-Yan
- Other

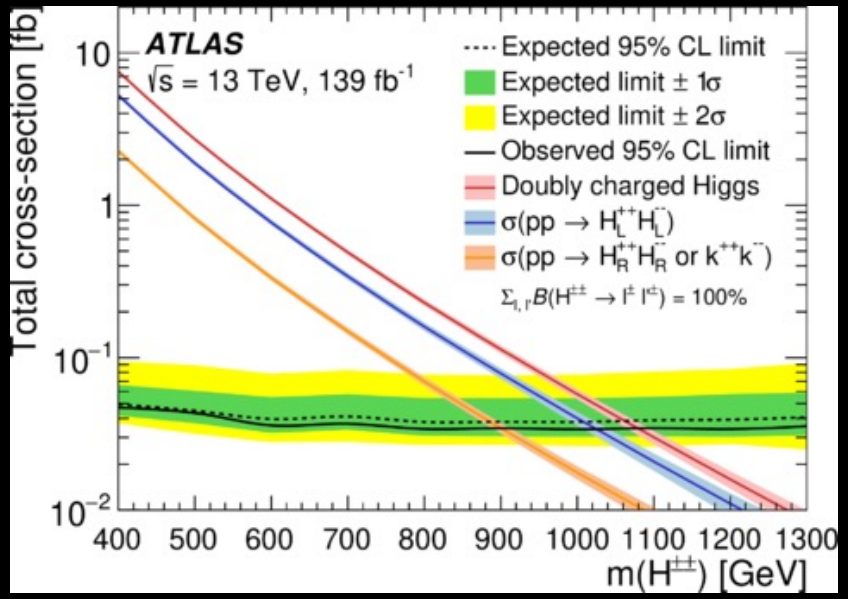


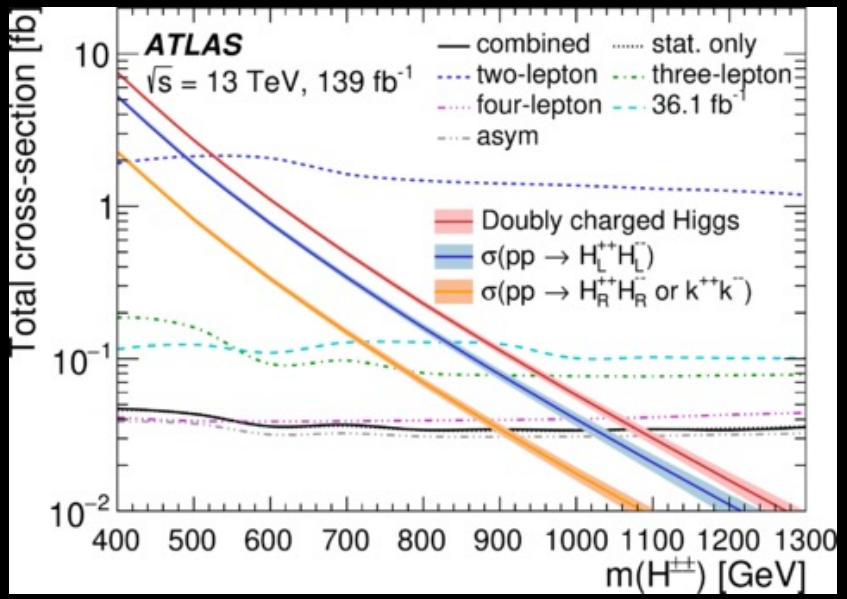

The observed and expected yields in all CRs, VRs and SRs

# Search for doubly charged Higgs production in multi–lepton final state

arXiv:2211.07505v2

## Fit Result and exclusion limit




The observed combined lower limit on the $H^{\pm\pm}$mass:
For LRSM: 1080 GeV and is consistent with the expected limit of $1040^{+40}_{-60}$GeV
For Zee-Babu model: 900 GeV and consistent with the expected limit $880^{+30}_{-40}$GeV

this search provides a first direct test of the Zee–Babu model at the LHC

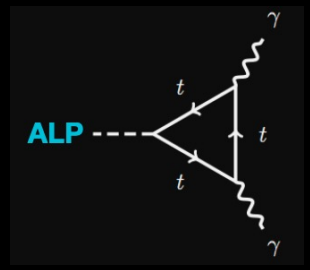
# Search for diphoton resonances in 66 to 110 GeV

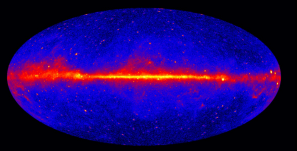
ATLAS-CONF-2023-035

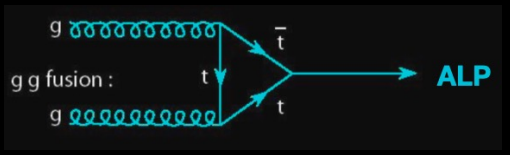
## Motivation

Additional spin-0 boson mass < 125 GeV:

- Explain the excess of GeV-scale $\gamma$ rays from the galactic centre
- If this spin-0 boson is ALP, even a weak coupling to Higgs sector allow the EW baryogenesis to explain baryon asymmetry

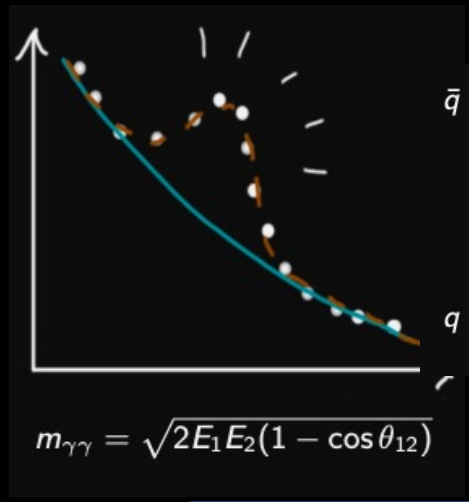


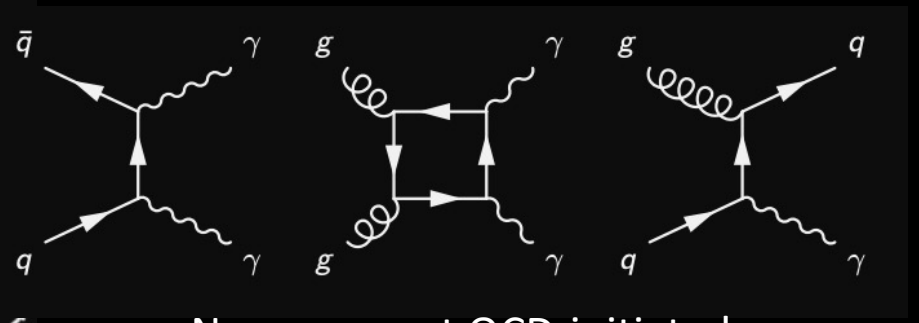



## Analysis strategy

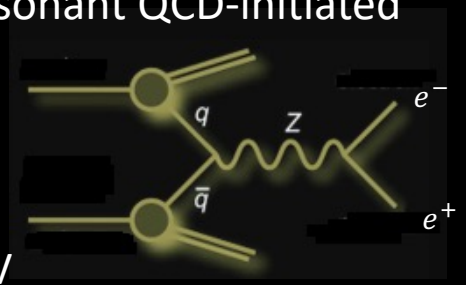
- Several categories defined based on photon conversion status (+ BDT categories) for a model-independent (model-dependent) search
- The resonant $m_{\gamma\gamma}$ signal and BGs modelled using analytic function (parameters determined using MC simulation and data-driven BG estimation)




## Background componenets




Non resonant QCD-initiated




Resonant DY

## Event selection

- Two photons 62 < $m_{\gamma\gamma}$<120 GeV
- Each photon $E_T/m_{\gamma\gamma} > 0.38$

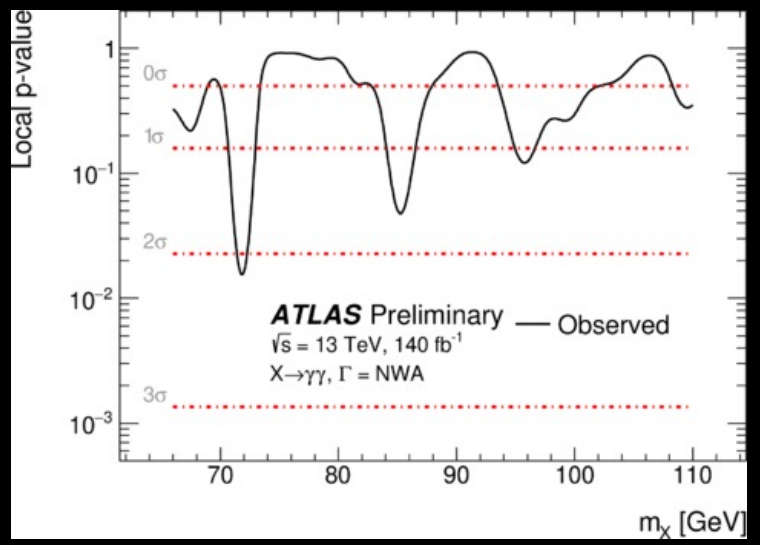
# Search for diphoton resonances in 66 to 110 GeV

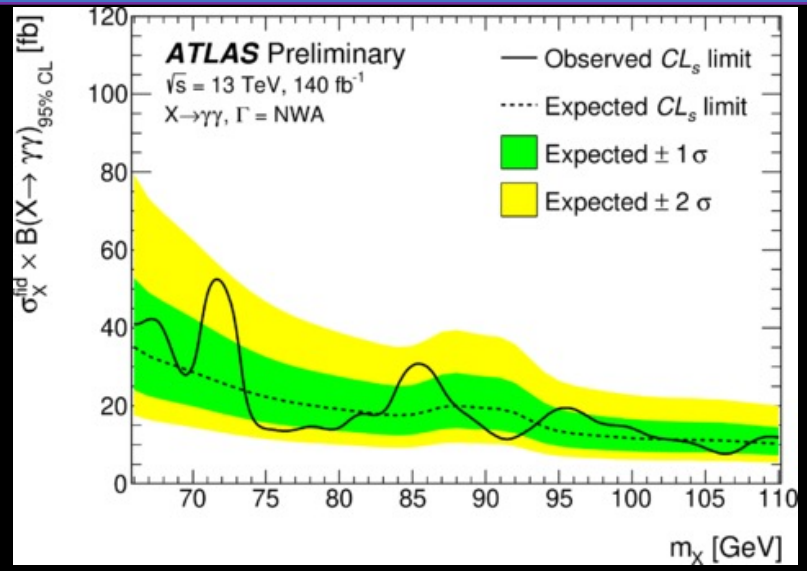
ATLAS-CONF-2023-035

## Fit Result and exclusion limit

Model-independent search:

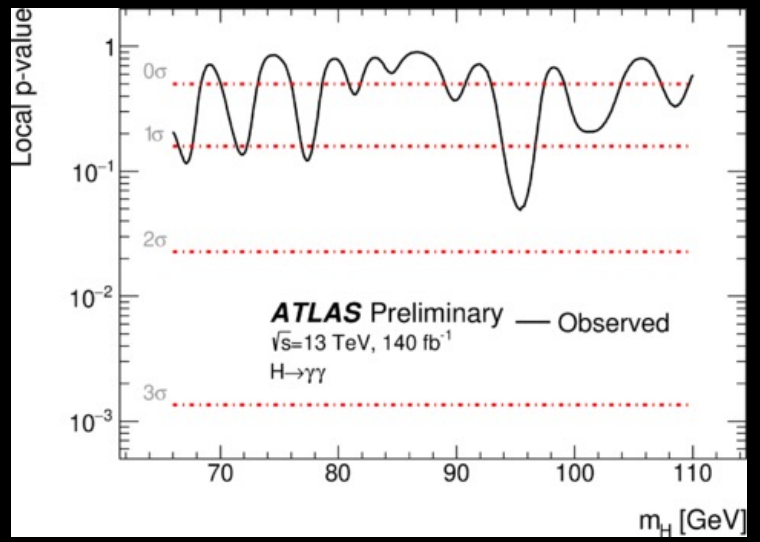
- the observed upper limit on the $\sigma_X^{fid} \times \mathrm{B}(X \to \gamma\gamma)$ for a generic spin−0 signal range from 8 to 53 fb
- Local significance of 2.2$\sigma$ at 71.8 GeV

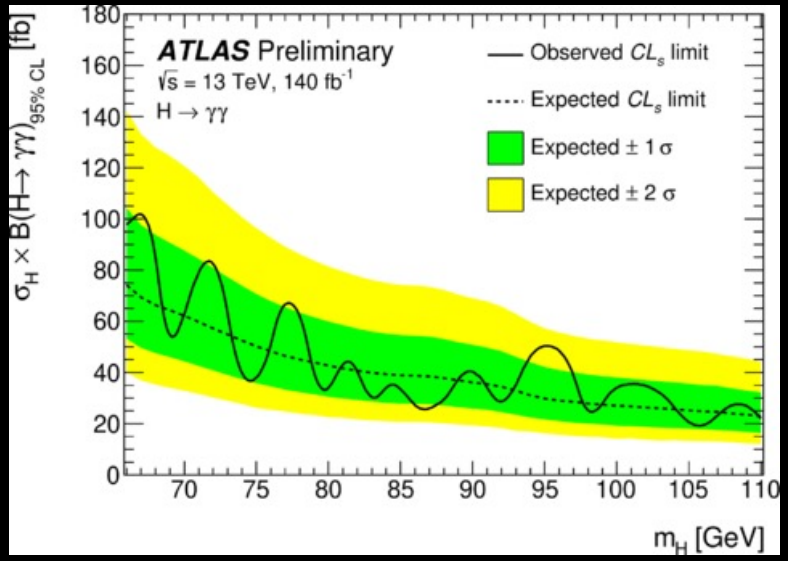


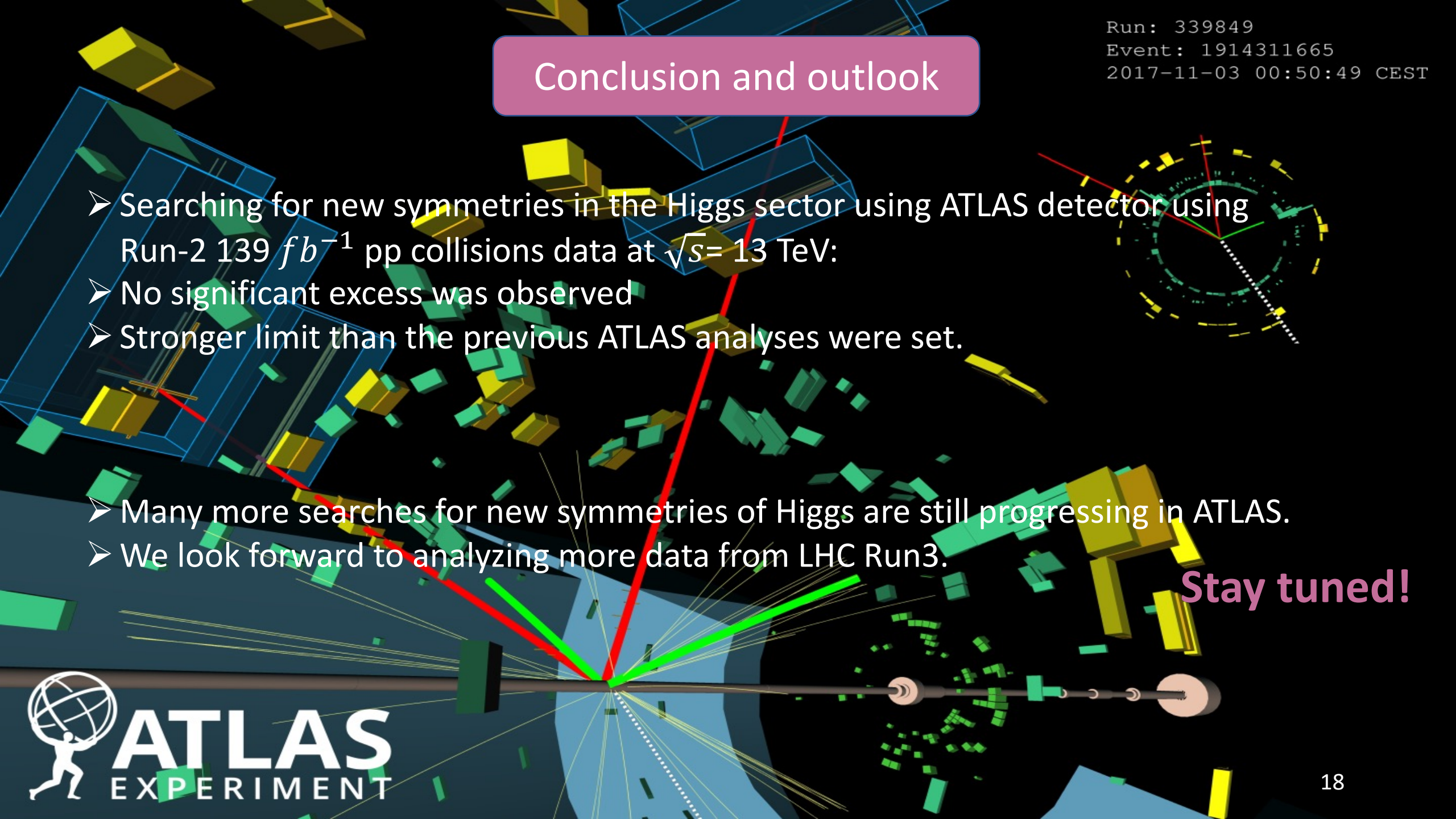

Model-dependent search:

- the observed upper limit on the $\sigma_H \times \mathrm{B}(H \to \gamma\gamma)$ for SM-like Higgs boson range from 19 to 102 fb
- Local significance of 1.7$\sigma$ at 95.4 GeV



# Conclusion and outlook




- Searching for new symmetries in the Higgs sector using ATLAS detector using Run-2 139 $fb^{-1}$ pp collisions data at $\sqrt{s}$= 13 TeV:
- No significant excess was observed
- Stronger limit than the previous ATLAS analyses were set.

- Many more searches for new symmetries of Higgs are still progressing in ATLAS.
- We look forward to analyzing more data from LHC Run3.

**Stay tuned!**

ATLAS EXPERIMENT

# Backup

## Systematic uncertainties

| Searches | Dominant source of systematic uncertainties |
|---|---|
| **New scalar resonance in FCNC top decay** | Main uncertainties: $t\bar{t}$+jets modelling and b-tagging |
| **Search for resonant WZ production in fully leptonic final state** | *normalization of the irreducible backgrounds WZ-QCD and ZZ, modelling of the WZ background, shape and normalization of the reducible background* |
| **Search for diphoton resonances** | *the limited number of $pp$ collisions collected and the choice of analytic functions to model the continuum background* |

# Backup

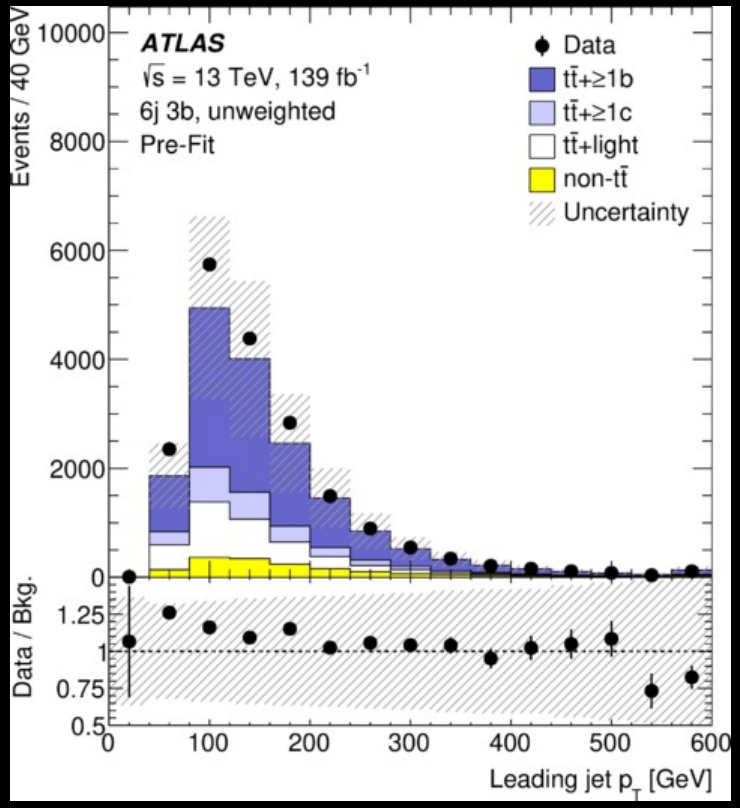
## Mismodeling correction

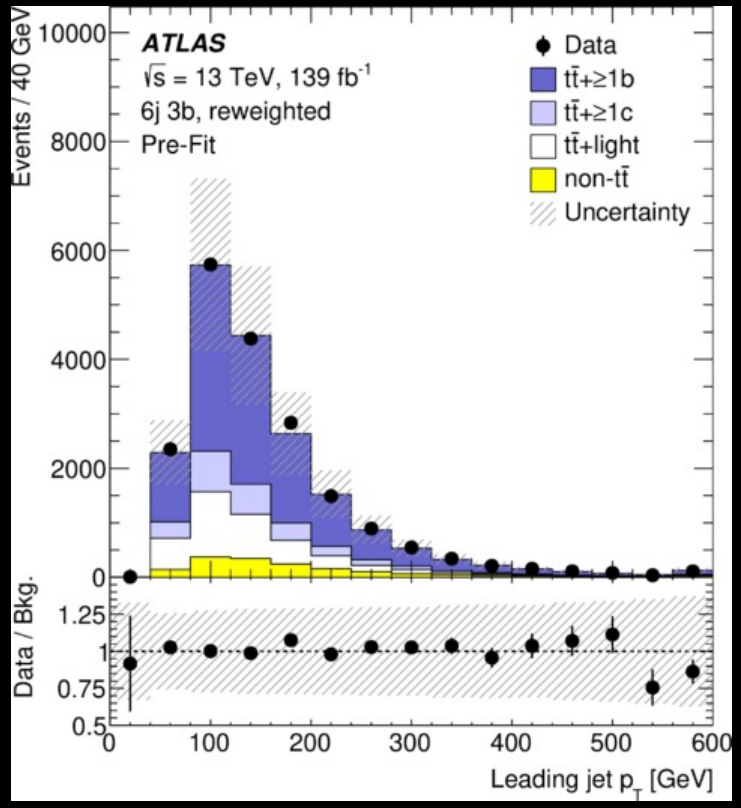
The simulation does not provide a satisfactory description of the data jet multiplicity and the transverse energy distributions.

$$R = \frac{N_{data} - N_{MC}^{non-t\bar{t}}}{N_{MC}^{t\bar{t}}}$$

R is as a function of $H_T^{all}$ for all Jet multiplicities. $H_T^{all}$ is the scalar sum of the transverse momenta of all selected objects in the event

## New scalar resonance in FCNC top decay



# Backup

Systematic uncertainties

## Search for doubly charged Higgs production in multi−lepton final state

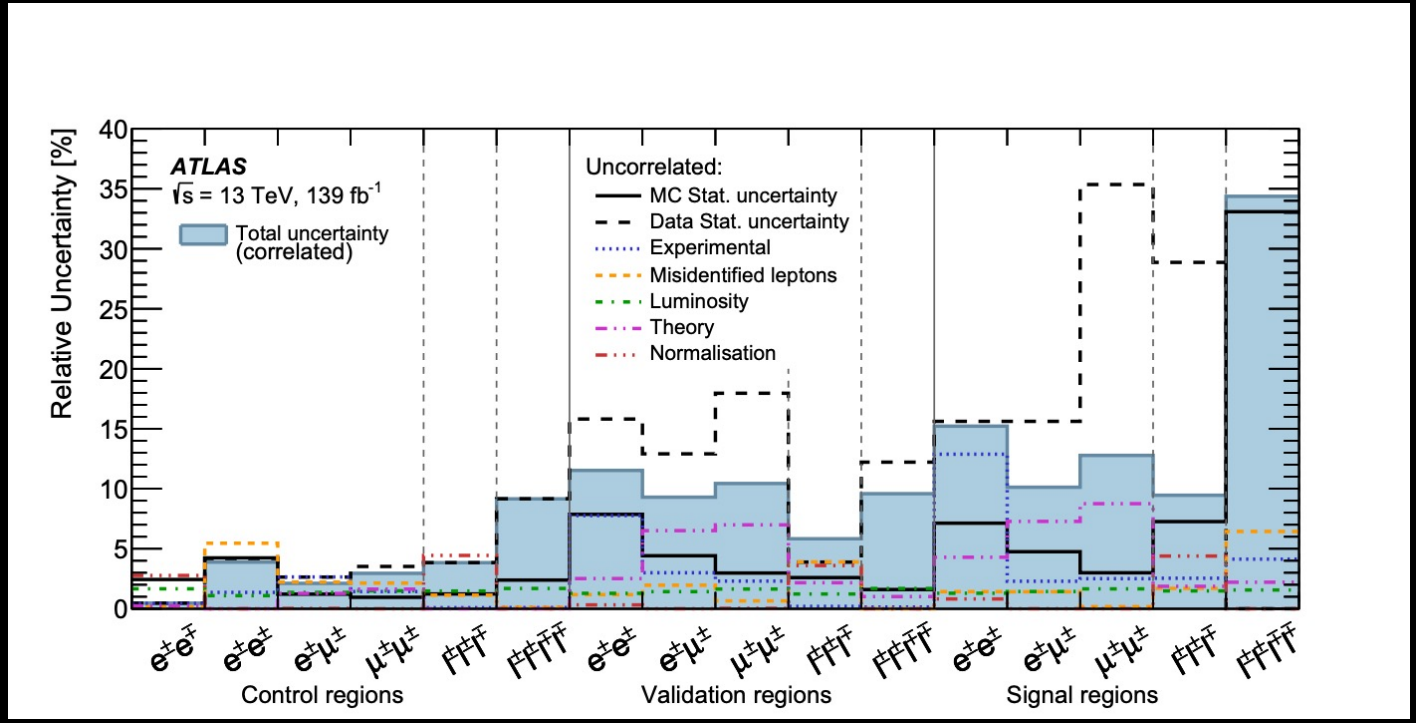
CR definition:

1- two electron OS (DYCR)$m(e^{\pm}, e^{\mp})_{lead}$ > 300 GeV

2- Diboson 2L(DB2L) CR: $m(l^{\pm}, l'^{\pm})_{lead} \in [200,300) GeV$

3- DB3L: $m(l^{\pm}, l'^{\pm})_{lead}$ > 300 GeV, $\geq 1\ Z\ boson$

4- DB4L: 100 < $m(l^{\pm}, l'^{\pm})_{lead}$ < 200 GeV



# Backup

## Search for resonant WZ production in fully leptonic final state

Irreducible BG

Background estimation

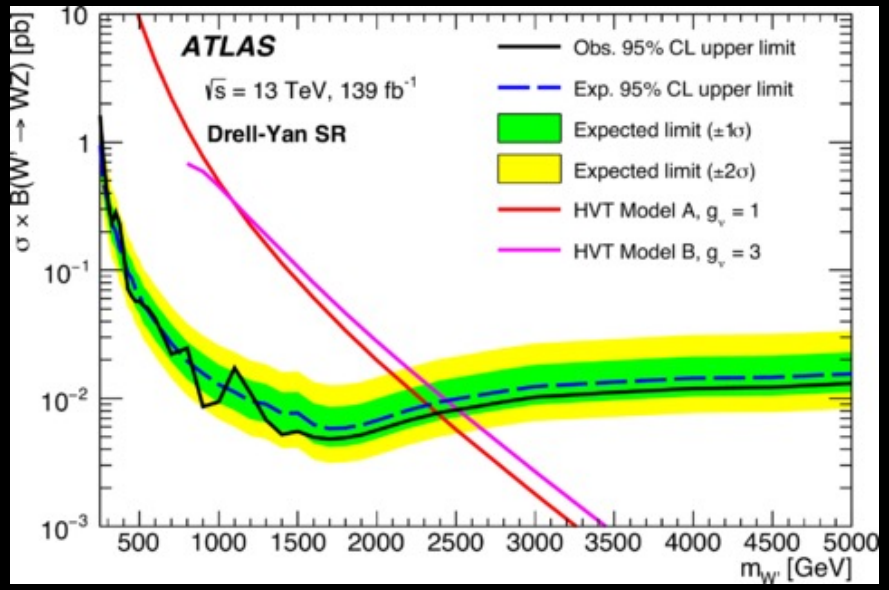
| | |
|---|---|
| WZ-QCD DY CR | • Subsample of WZ events fulfil all DY selection<br>• Boson $p_T$ to resonance mass < 0.1 |
| WZ-QCD VBF CR | • Subsample of WZjj<br>• The events that fails ANN with $m_{jj}$ > 500 GeV |
| ZZ DY CR | • at least a 4th lepton candidate satisfy Baseline |
| ZZ VBF CR | • at least two VBF tagged-jets |
| VR for $t\bar{t}V$ BG modelling | • The WZjj events to have ≥ 1 b-tagged jet (no significant mismodeling) |

Backup

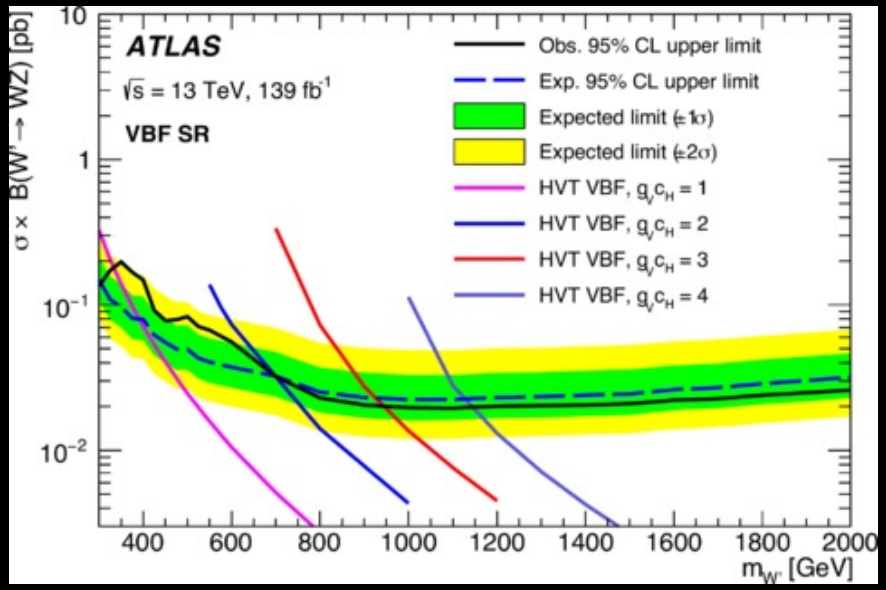
arXiv:2207.03925v2

## Search for resonant WZ production in fully leptonic final state

### Fit Result and exclusion limit for HVT model




Masses below 2.4 (2.5) TeV are excluded for the HVT models considered




Masses below 340 GeV, 700 GeV, 945 GeV and 1145 GeV are excluded for the HVT VBF model with $c_f = 0, g_v c_H = 1.0, 2.0, 3.0, 4.0$ respectively

# Backup

- New scalar resonance in FCNC top decay
  - The use of a NN instead of a likelihood discriminant, a better $b$-tagging algorithm, and better $t\bar{t}$ background modelling are the main improvements
  - *The expected limits are on average a factor of **three** better than the previous ATLAS results scaled to the same integrated luminosity, and slightly better than the CMS results*

- Search for resonant WZ production in fully leptonic final state
  - *This search extends searches for resonant WZ production, performed by ATLAS in Run 2 of the LHC using $pp$ collision data at 13 TeV with 36 $fb^{-1}$ of integrated luminosity.*
  - in addition to the larger data set, several improvements relative to the previously published analysis have been implemented, most notably the implementation of multivariate techniques for the VBF signal selection.

# Backup

- $t\bar{t}$H/A $\rightarrow t\bar{t}t\bar{t}$ production in multilepton final state
  - Due to a significantly larger dataset and improved analysis techniques, including the use of multivariate classifiers based on boosted decision trees (BDTs), the expected sensitivity of the present search exceeds that of the previous ATLAS search with 36 $fb^{-1}$ by about a factor of four

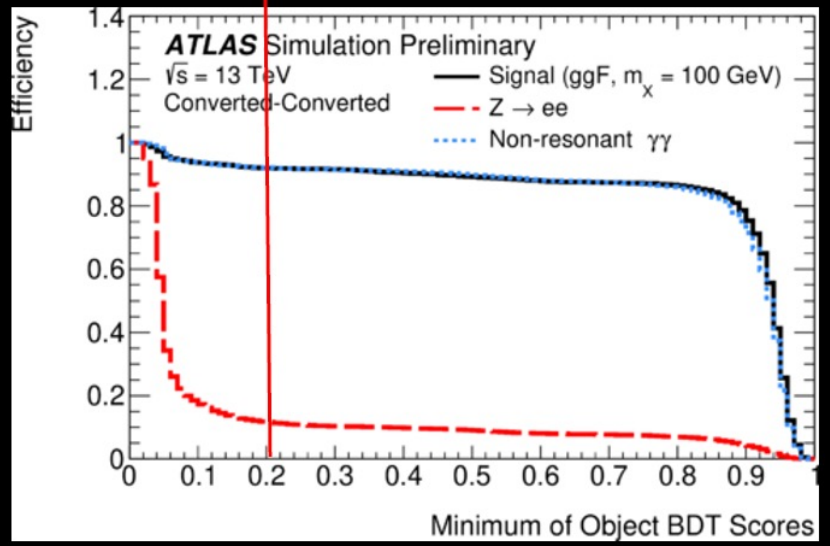
- Search for doubly charged Higgs production in multi−lepton final state
  - The lower limits on the LRSM $H$ ±± masses are 300 GeV higher than those from the previous ATLAS result. Moreover, this search provides a first direct test of the Zee–Babu model at the LHC

# Backup

## Search for diphoton resonances in 66 to 110 GeV

- Backgrounds due to jets misidentified as photons can largely be reduced using **photon identification** and **isolation criteria**
- Reduce the ee background (electron misidentified as photon) Using BDT

Signal efficiency 93%
Reduction of ee BG 65-90%



# Backup

## Search for doubly charged Higgs production in multi−lepton final state

The back-to-back electrons have a pT of 517 GeV($e^+$) and 306 GeV($e^-$)
Muon exit very close to the beam line and has lower pT 82 GeV