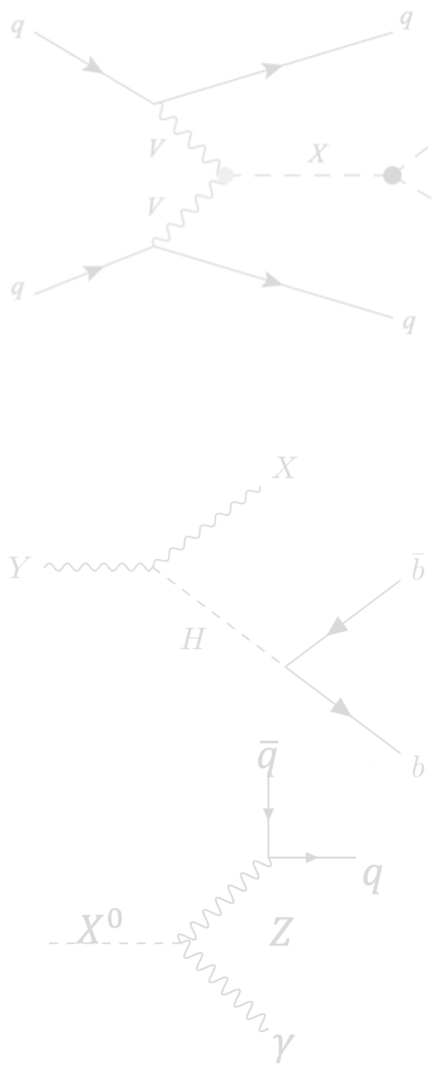
$$\mathscr{L}_{UV} \to \mathscr{L}_{SD} + \mathscr{L}_{SM_0} + \mathscr{L}_{int} \to \mathscr{L}_{SM} + \ldots$$



Searches for Higgs-Like and other Heavy Resonances in ATLAS

Jackson Barr
on behalf of the
ATLAS Collaboration

$$V = m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\,\Phi_1^\dagger\Phi_1\,\Phi_2^\dagger\Phi_2 + \lambda_4\,\Phi_1^\dagger\Phi_2\,\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right],$$

Introduction

- Searches for new heavy Higgs-like resonances encompasses a wide range of theoretical models and potential final states, e.g. 2HDM, CH, TRSM, HVT etc.
- Searches for these types of models occur across multiple different analysis groups within ATLAS – going to highlight a few recent results covering Vγ and XH type resonances

HDBS

ATLAS
Higgs Working Group

ATLAS
EXOTICS GROUP

Search for high-mass Wγ and Zγ resonances using hadronic W/Z boson decays from 139 fb^{-1} of pp collisions at $\sqrt{s}$= 13 TeV with the ATLAS detector

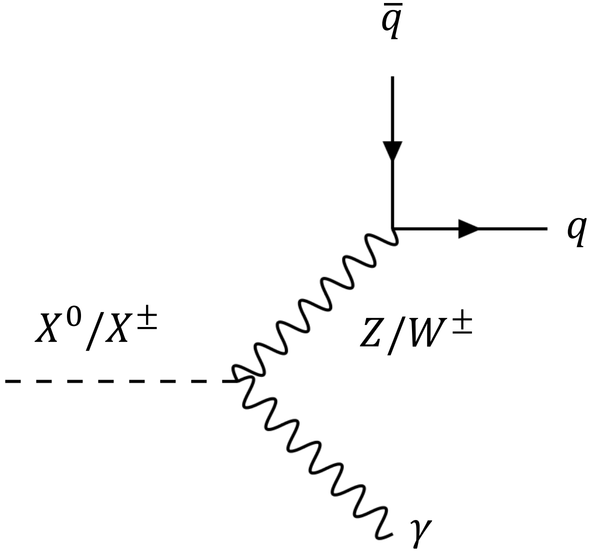
JHEP 07 (2023) 125

Search for the $Z\gamma$ decay mode of new high-mass resonances in $p\,p$ collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

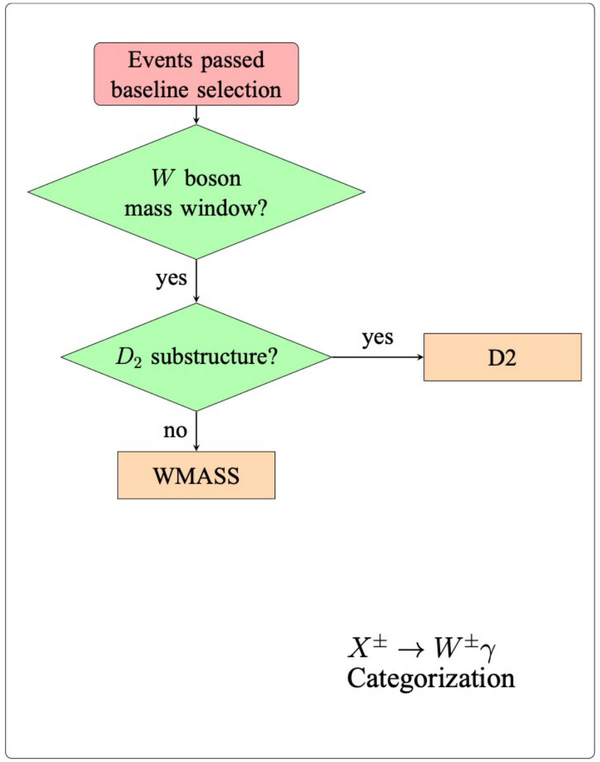
Phys. Lett. B 848 (2024) 138394

Motivation

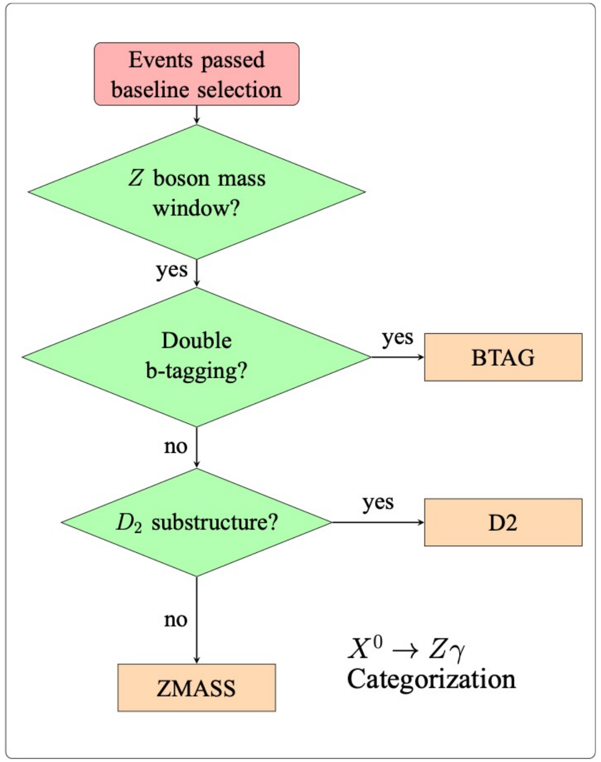
- Investigating Vγ final states allow searches for both neutral, X^0, and charged, $X^\pm$, scalars predicted by different BSM theories e.g. HVT
- Pair of analyses looks for spin-1 charged bosons and spin-0/2 neutral bosons from production of gluon-gluon fusion or $q\bar{q}$ annihilation
- Follow up on previous partial Run 2 searches, PRD.98.032015 and JHEP 10 (2017) 112 in hadronic and leptonic final states respectively
- Hadronic analysis better probes high masses and leptonic analysis covers lower masses – **much smaller backgrounds**



Event Selection and Reconstruction

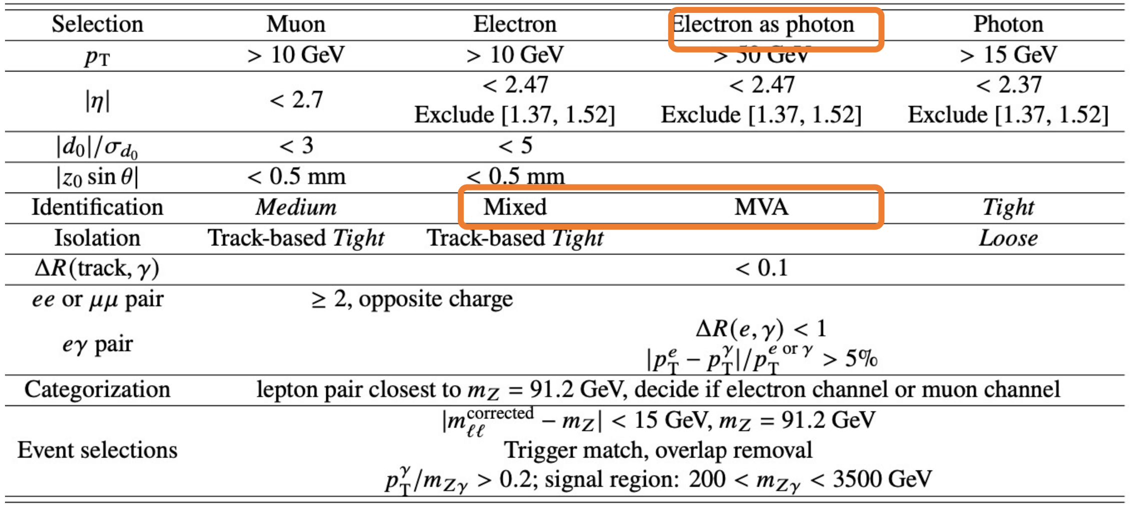


$X^{\pm} \rightarrow W^{\pm}\gamma$ Categorization



$X^{0} \rightarrow Z\gamma$ Categorization

- Hadronic analysis categorises using both b-tagging and the D_2 substructure variable to better select W/Z candidates
- At high pT, leptons highly collimated and sub-leading electron often mis-identified as photon – leptonic analysis used custom BDT trained for both cases



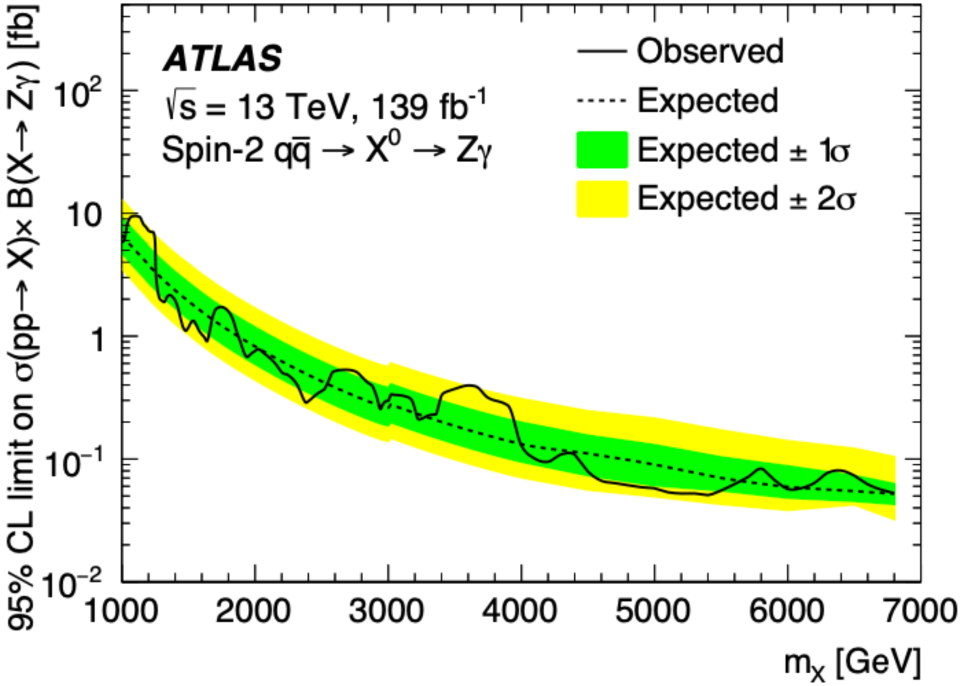
Selection	Muon	Electron	Electron as photon	Photon
p_{T}	> 10 GeV	> 10 GeV	> 30 GeV	> 15 GeV
$\lvert\eta\rvert$	< 2.7	< 2.47 Exclude [1.37, 1.52]	< 2.47 Exclude [1.37, 1.52]	< 2.37 Exclude [1.37, 1.52]
$\lvert d_0\rvert/\sigma_{d_0}$	< 3	< 5		
$\lvert z_0 \sin\theta\rvert$	< 0.5 mm	< 0.5 mm		
Identification	*Medium*	Mixed	MVA	*Tight*
Isolation	Track-based *Tight*	Track-based *Tight*		*Loose*
$\Delta R(\text{track}, \gamma)$			< 0.1	
ee or $\mu\mu$ pair	≥ 2, opposite charge			
$e\gamma$ pair			$\Delta R(e,\gamma) < 1$ $\lvert p_{\mathrm{T}}^{e} - p_{\mathrm{T}}^{\gamma}\rvert / p_{\mathrm{T}}^{e \text{ or } \gamma} > 5\%$	
Categorization	lepton pair closest to $m_Z = 91.2$ GeV, decide if electron channel or muon channel			
Event selections	$\lvert m_{\ell\ell}^{\text{corrected}} - m_Z\rvert < 15$ GeV, $m_Z = 91.2$ GeV Trigger match, overlap removal $p_{\mathrm{T}}^{\gamma}/m_{Z\gamma} > 0.2$; signal region: $200 < m_{Z\gamma} < 3500$ GeV			

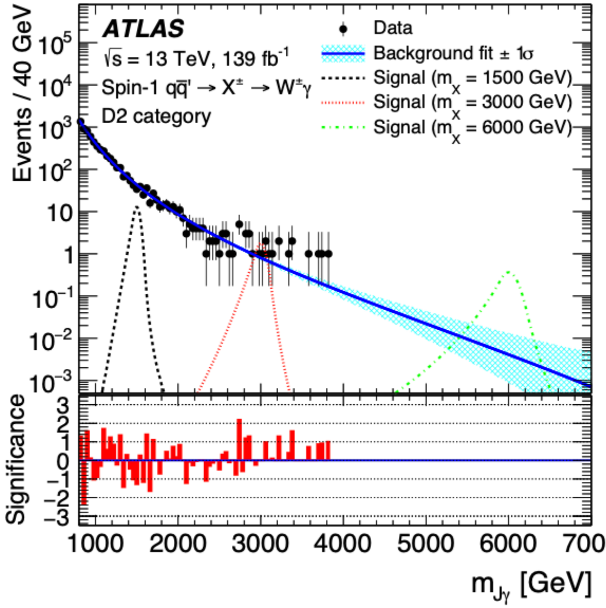
Variable Types	MVA Variables
Calorimeter Shower	R_{η}, R_{had}, R_{φ}, ΔE_{s}, E_{ratio}
Track-Based	E/p, eProbabilityHT, $\Delta\eta_1$, d_0, $n_{\mathrm{innermost}}$, n_{Pixel}, n_{Si}, n_{TRT}
Additional	$\Delta\varphi_{\mathrm{rescaled}}$

JINST **14** (2019) P12006

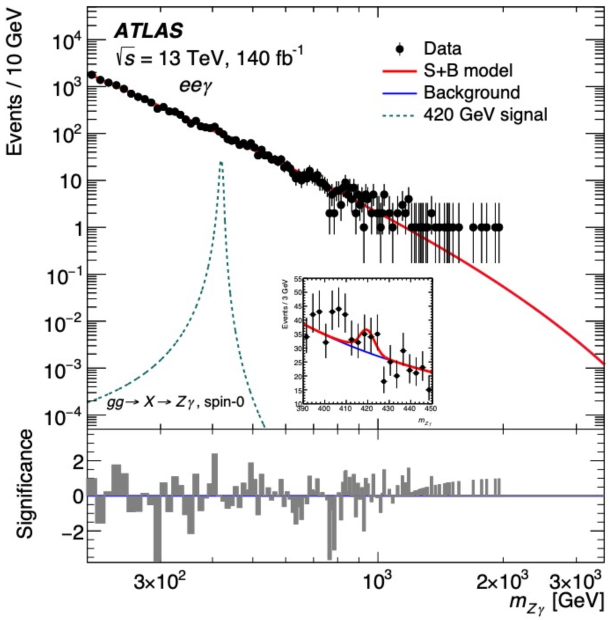
Results

- Signal modelled by double-sided crystal ball function for both analyses and a data driven background estimate is used
- Background dominated by Z+γ (~91%) and Z+jets (10%) determined by fit of photon isolation variable
- Upper limits on x-sections set from 1 – 6.8 TeV for Hadronic channel and 220 – 3400 GeV for leptonic channel
- **factor of two improvement in the limits** relative to what expected increase from integrated luminosity only

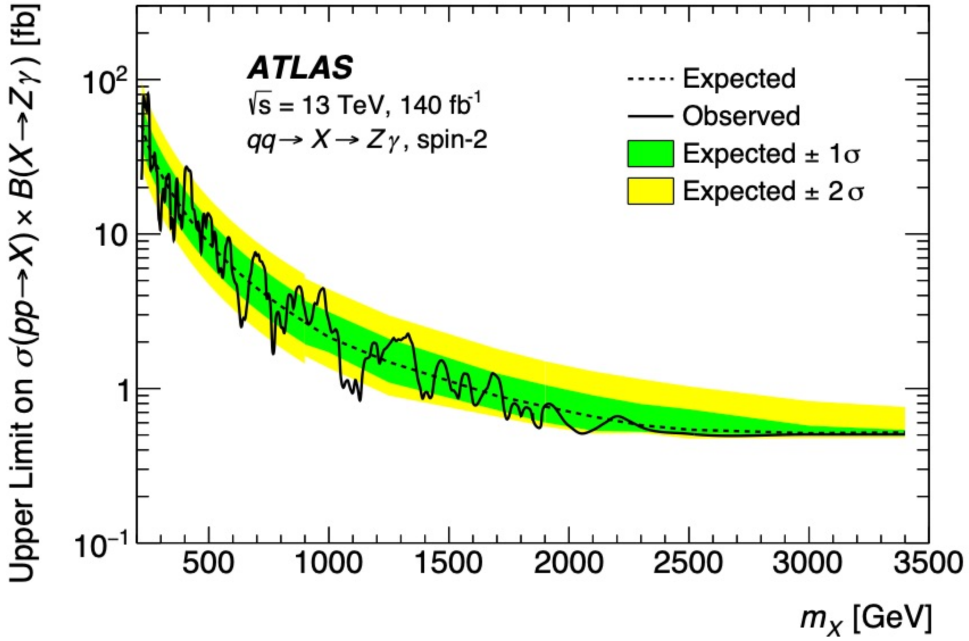




Hadronic $m_{J\gamma}$ distribution



Leptonic $m_{Z\gamma}$ distribution

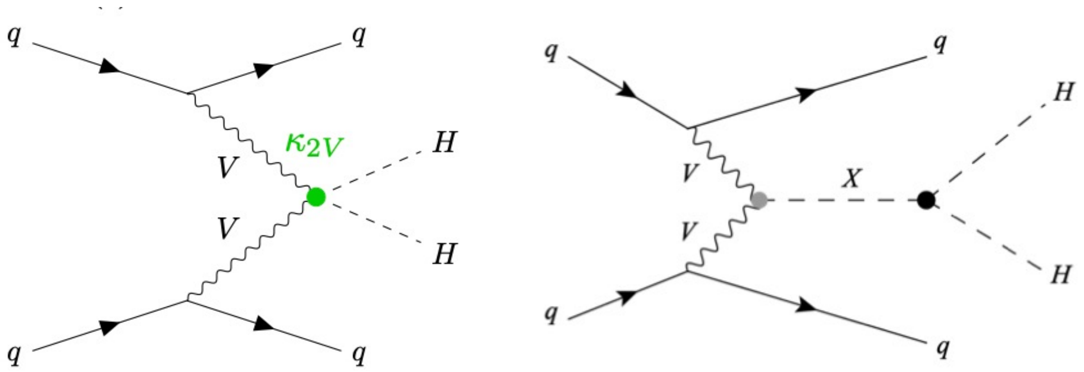


Search for pair production of boosted Higgs bosons via vector-boson fusion production in the bbbb final state using pp collisions at $\sqrt{s}$=13TeV with the ATLAS detector

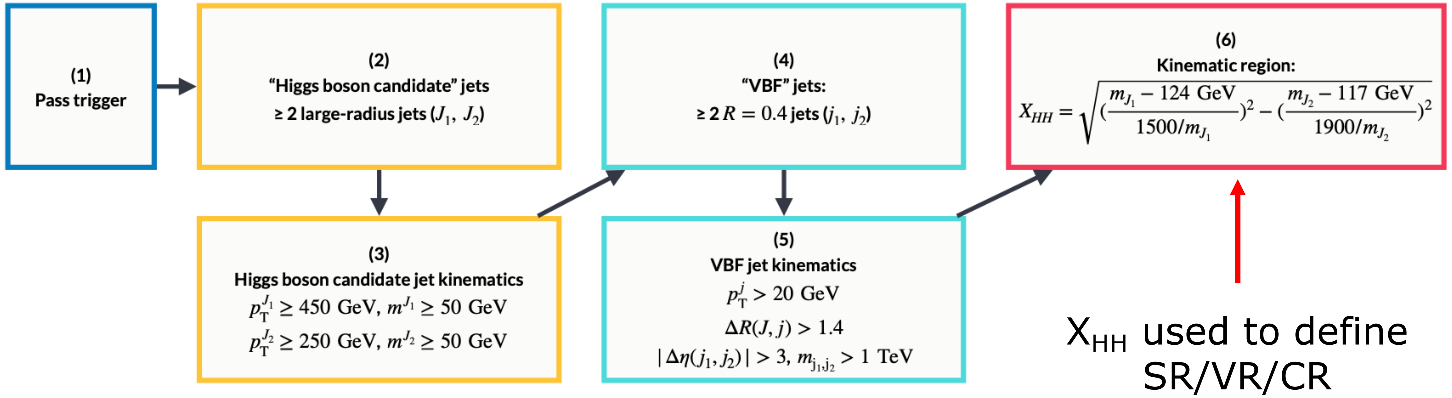
ATLAS-CONF-2024-003

Motivation

- Higgs trilinear self-coupling (κ_λ) and quartic coupling (κ_{2V}) yet to be precisely measured
- First ATLAS study of boosted VBF channel – considers non-resonant SM and resonant production
- Considering two different resonant models
    - Narrow Width Γ_X = 40 MeV (2HDMs)
    - Broad Width $\Gamma_X = 0.2\ m_X$



Event Selection



(1)
Pass trigger

(2)
"Higgs boson candidate" jets
≥ 2 large-radius jets (J_1, J_2)

(3)
Higgs boson candidate jet kinematics
$p_T^{J_1} \geq 450$ GeV, $m^{J_1} \geq 50$ GeV
$p_T^{J_2} \geq 250$ GeV, $m^{J_2} \geq 50$ GeV

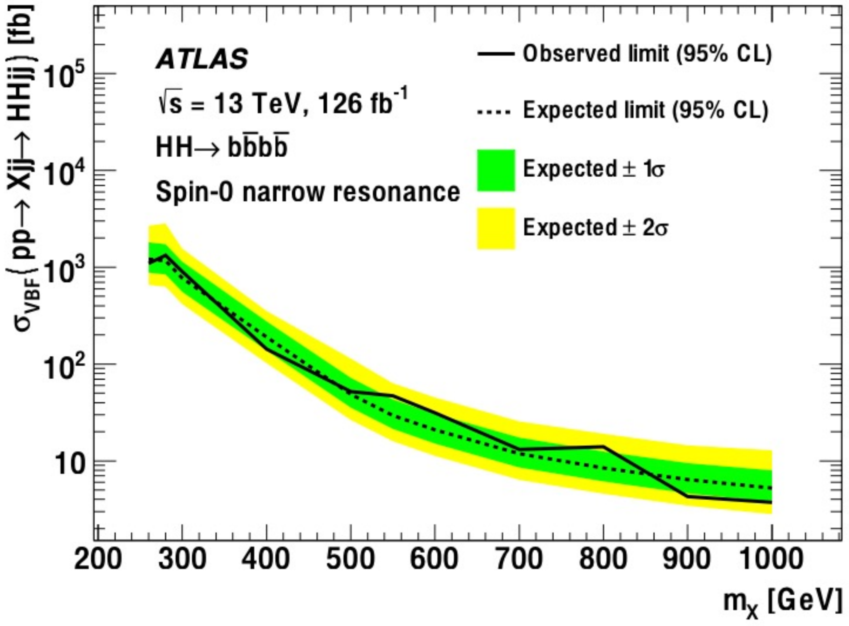
(4)
"VBF" jets:
≥ 2 $R = 0.4$ jets (j_1, j_2)

(5)
VBF jet kinematics
$p_T^j > 20$ GeV
$\Delta R(J, j) > 1.4$
$|\Delta\eta(j_1, j_2)| > 3$, $m_{j_1 j_2} > 1$ TeV

(6)
Kinematic region:

$$X_{HH} = \sqrt{(\frac{m_{J_1} - 124\ \text{GeV}}{1500/m_{J_1}})^2 - (\frac{m_{J_2} - 117\ \text{GeV}}{1900/m_{J_2}})^2}$$

X_{HH} used to define SR/VR/CR

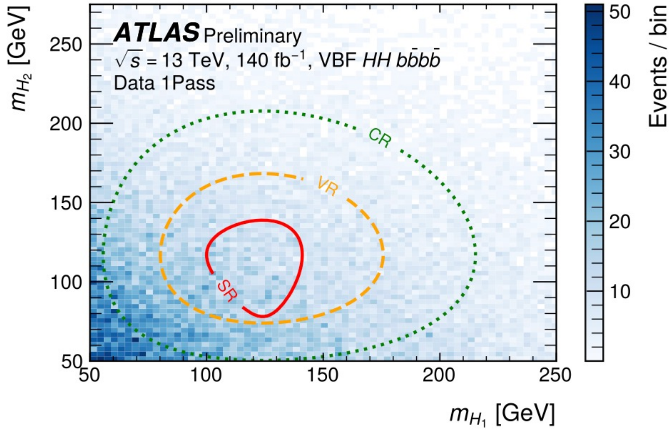


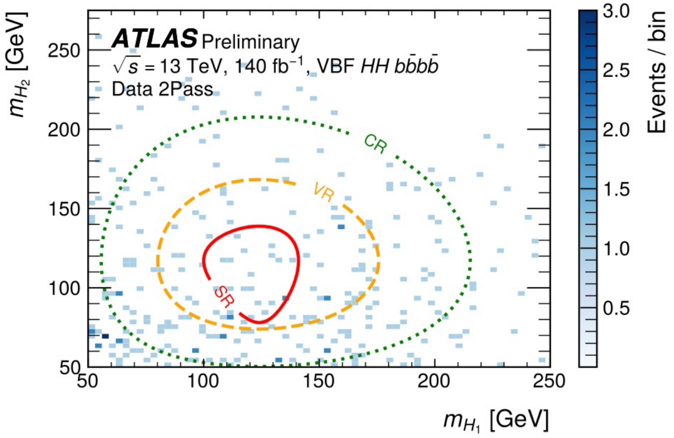
Previous resolved resonant VBF ATLAS search, 260 < m_x < 1000 GeV

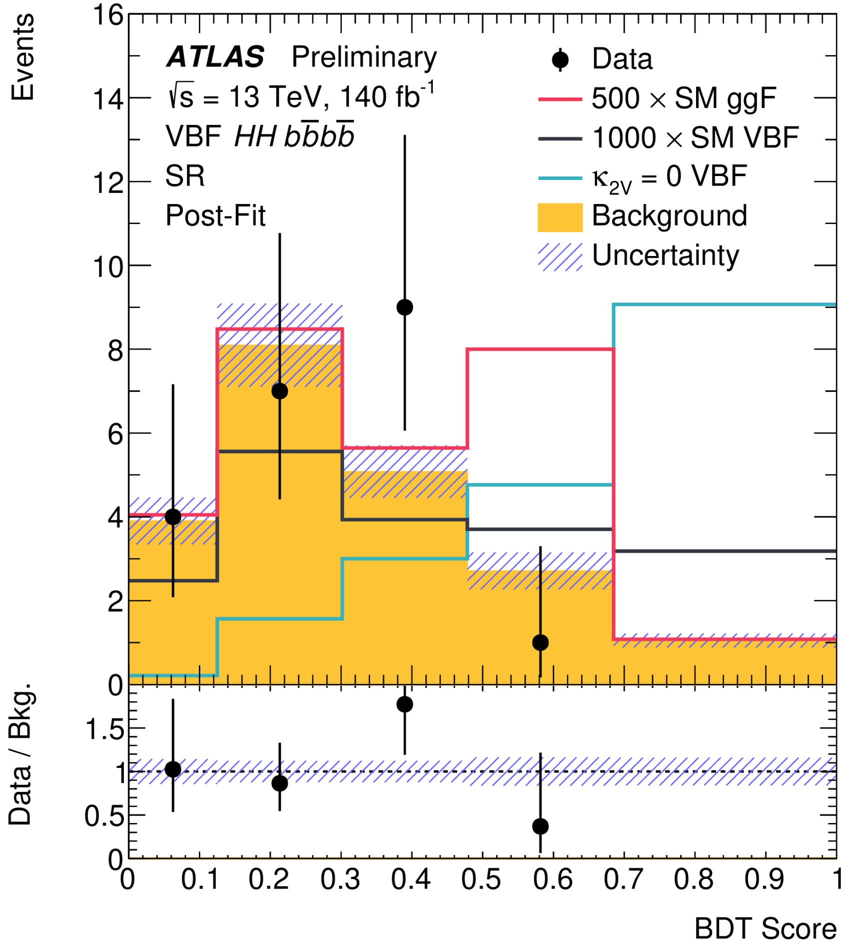
Analysis Strategy

Relevant Objects	Kinematics used in training
Higgs Boson Candidate ($H_i, i = 1, 2$)	$p_{\mathrm{T}}^{H_i}, \eta_{H_i}$
Di-Higgs System (HH)	$p_{\mathrm{T}}^{HH}, \eta_{HH}, m_{HH}$
VBF Jets ($j_i, i = 1, 2$)	$p_{\mathrm{T}}^{j_i}, \eta_{j_i}, E_{j_i}$

- Higgs boson candidates identified with boosted H→bb (Xbb) tagger, ATL-PHYS-PUB-2020-019
- SR defined by X_{HH} <1.6, VR/CR by X_{HH} <100/170
- Large multi-jet background modelled with data driven background estimate using 1Pass region
- Signal separated from background using a BDT, resonant analysis uses resonance mass as parameterised variable

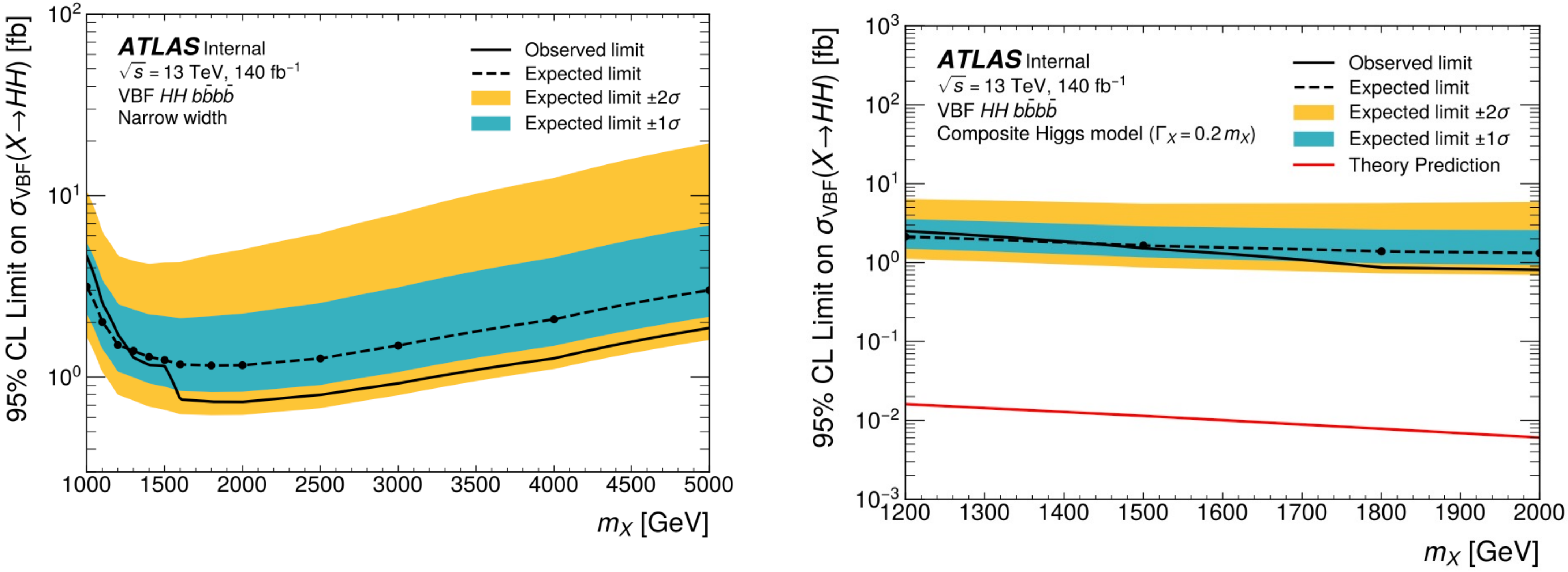






Results

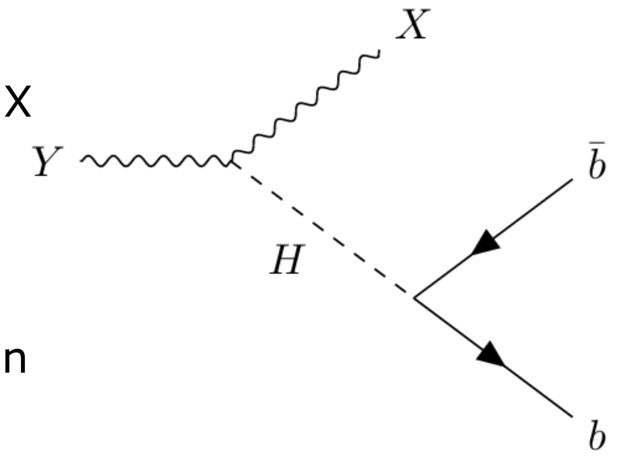
- Combination of boosted and resolved analyses **excludes κ_{2V}=0 at 3.8σ**, (see yesterday's talk by Shahzad for non-resonant discussion)
- No significant excesses observed in resonant analysis and upper limits are set from 1 – 5 TeV in the narrow width assumption and from 1.2 – 2 TeV in the broad width assumption



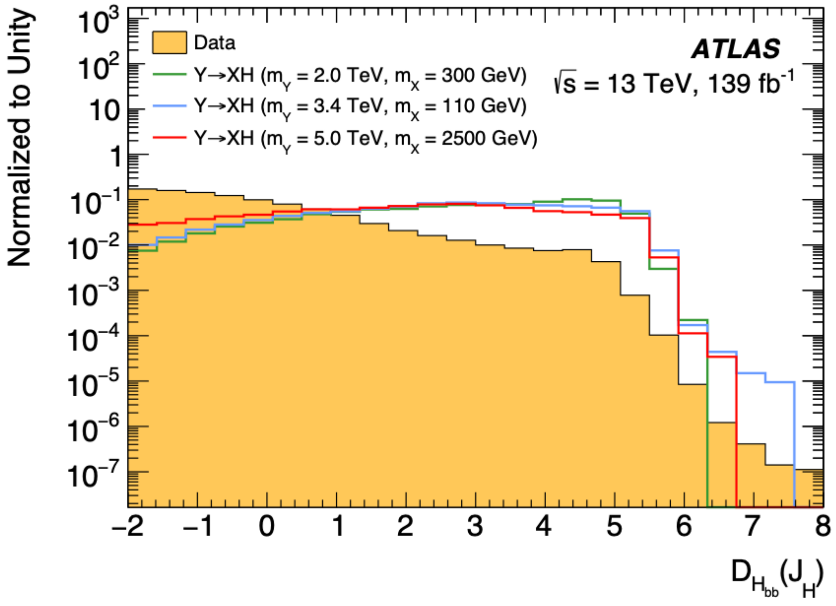
Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states using $\sqrt{s}=13$ TeV pp collisions with the ATLAS detector

Phys. Rev. D 108 (2023) 052009

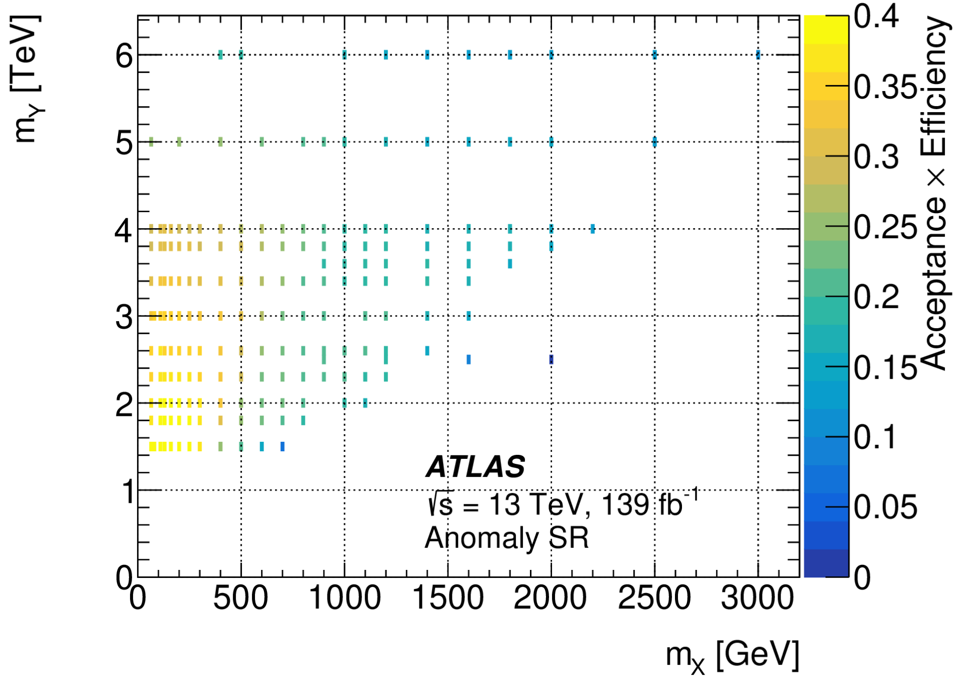
Motivation



- Search for heavy resonance Y decaying to SM Higgs boson and another particle X
- Only constraint required is a hadronically decaying X, quite model independent but HVT model used as benchmark for x-section upper limits
- Large Y masses result in mostly boosted X and H with separate resolved X region also considered
- Identified Higgs candidate by boosted H→bb (Xbb) tagger



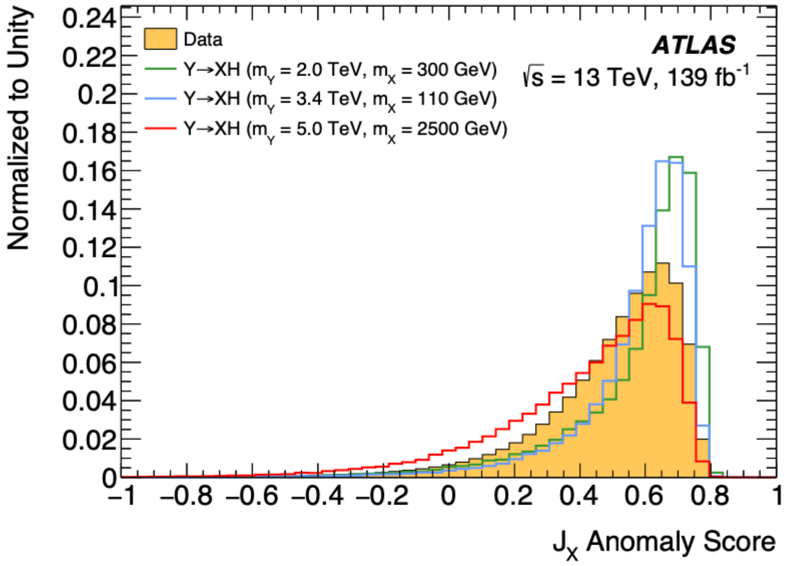
Xbb tagger scores for data and signal models

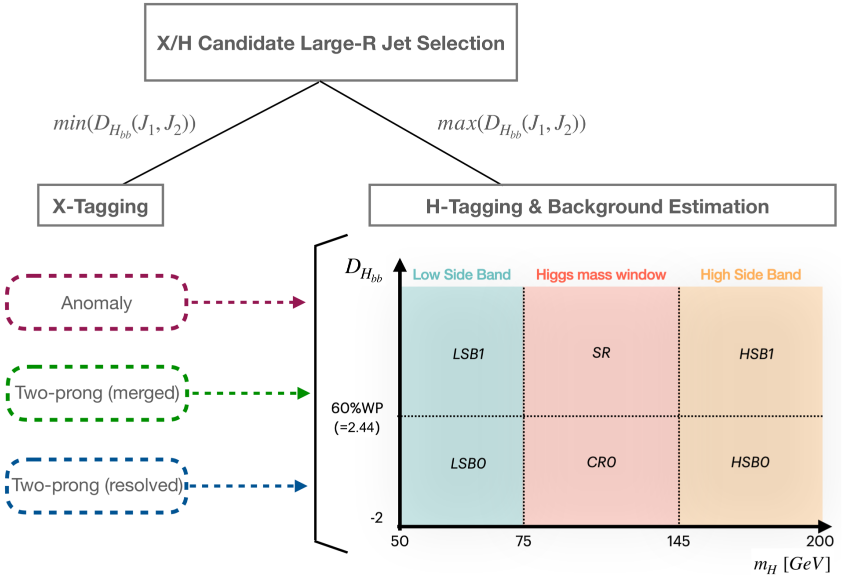


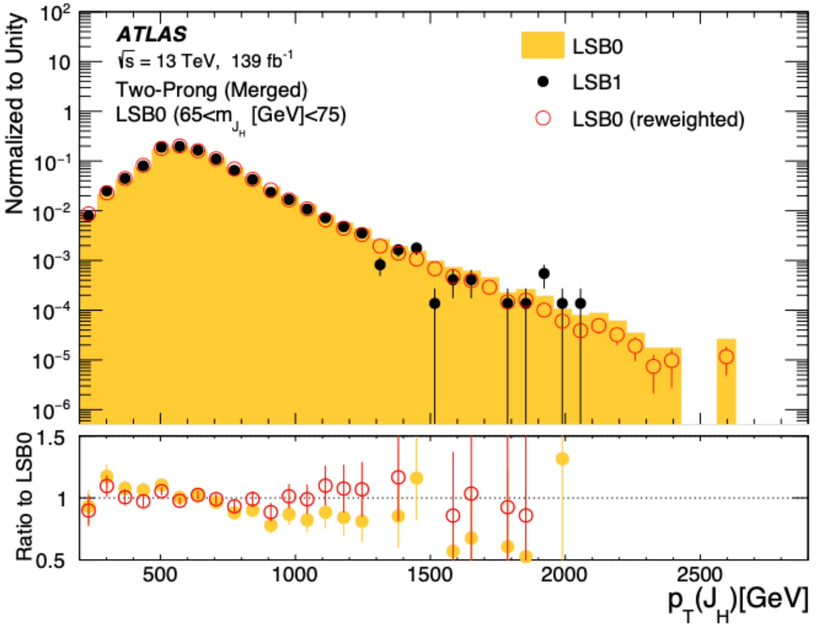
Mass grid considered in analysis

Anomaly Detection

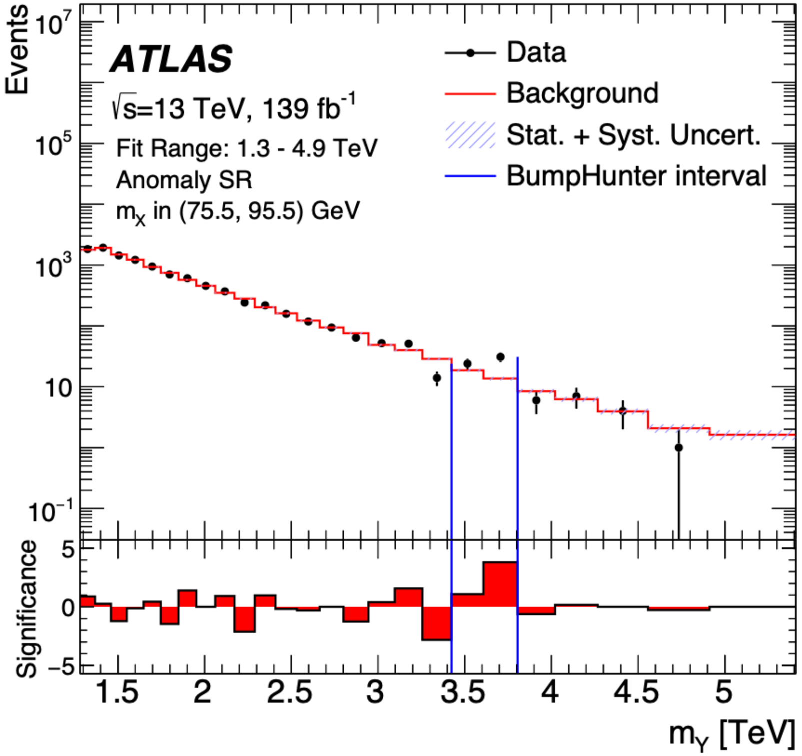
- Analysis uses novel Anomaly Detection (AD) to identify boosted X-candidates
- Variational Recurrent Neural Network (VRNN), [JINST 16 P08012](), trained over jet 4-vectors from data – model reduces events to small latent dimension and then attempts to reconstruct them again
- Events where the model fails to be accurately reconstructed are considered more anomalous – cut on score to get anomalous SR
- Data driven background estimate formed using DNN reweighting derived in Higgs mass sidebands, learns to weight Xbb tagger fail to Xbb tagger pass region

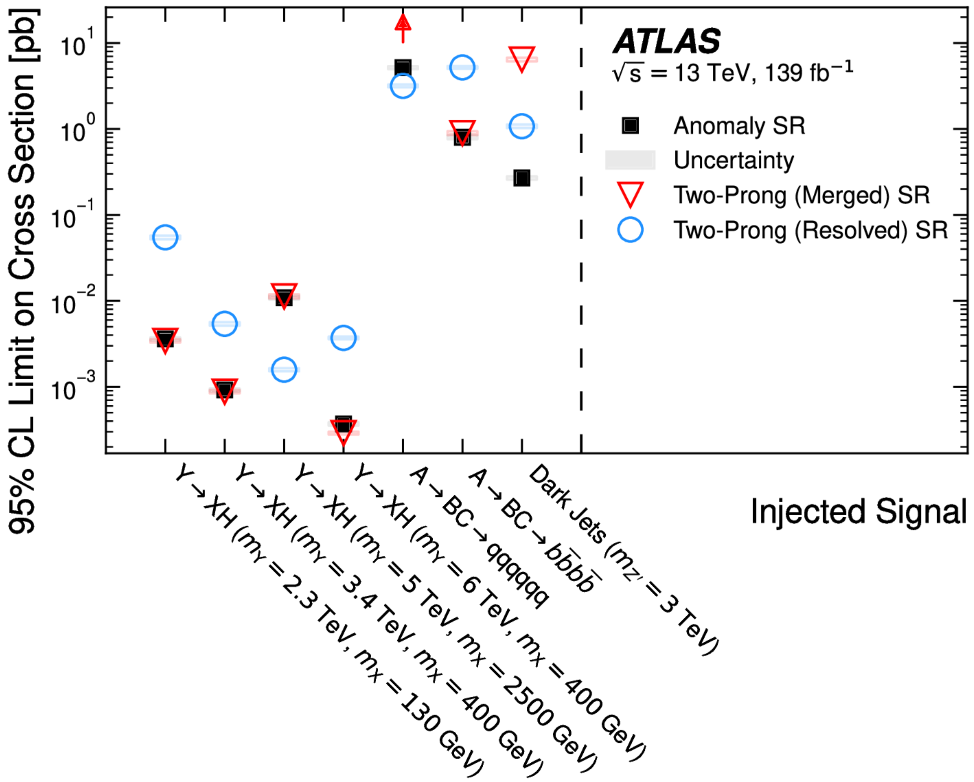






Results





- No significant excesses observed over SM prediction are observed using either AD approach or using more standard event selections

- AD method tested on a range of signals and compared to signal regions designed specifically for those signatures and showed comparable results in most cases. When tested on a different type of model (Dark jets), Anomaly SR greatly outperforms other standard regions – **Anomaly Detection allows for much more model independent searches**

Transformer Neural Networks for Identifying Boosted Higgs Bosons decaying into bb and cc in ATLAS

ATL-PHYS-PUB-2023-021

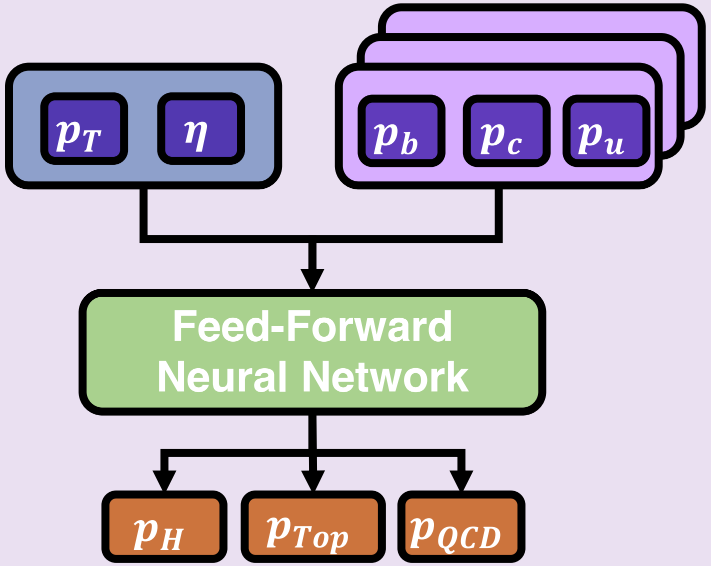
Boosted Higgs Tagging

- **GN2X** is a transformer based Xbb tagger that replaces the previous subjet based model used within ATLAS (previous version used in the anomaly detection and VBF HH4b analyses shown here)

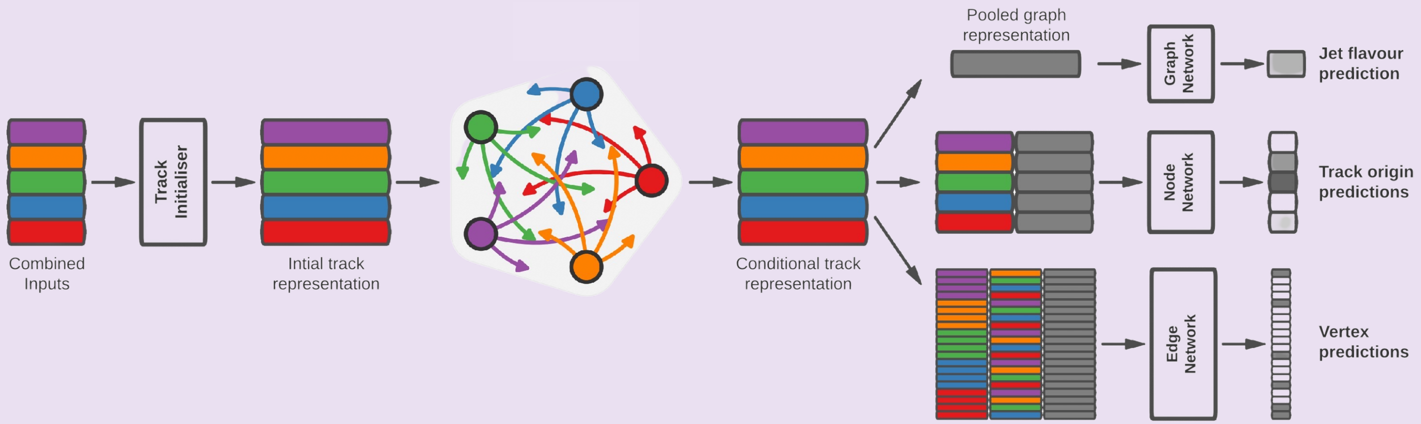
- Trained to discriminate between boosted H → bb, H → cc, hadronic top and QCD jets, previous model did not include H → cc as a category

- Includes auxiliary tasks to perform vertex and track origin prediction

Previous DNN Model

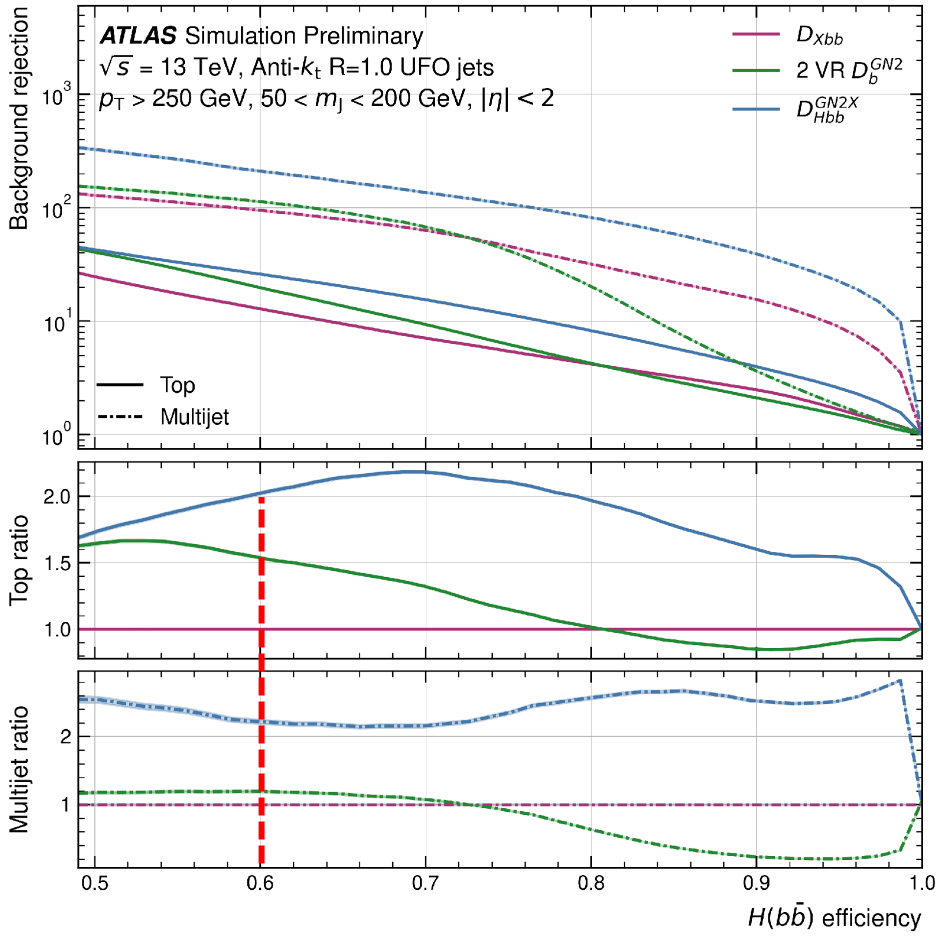


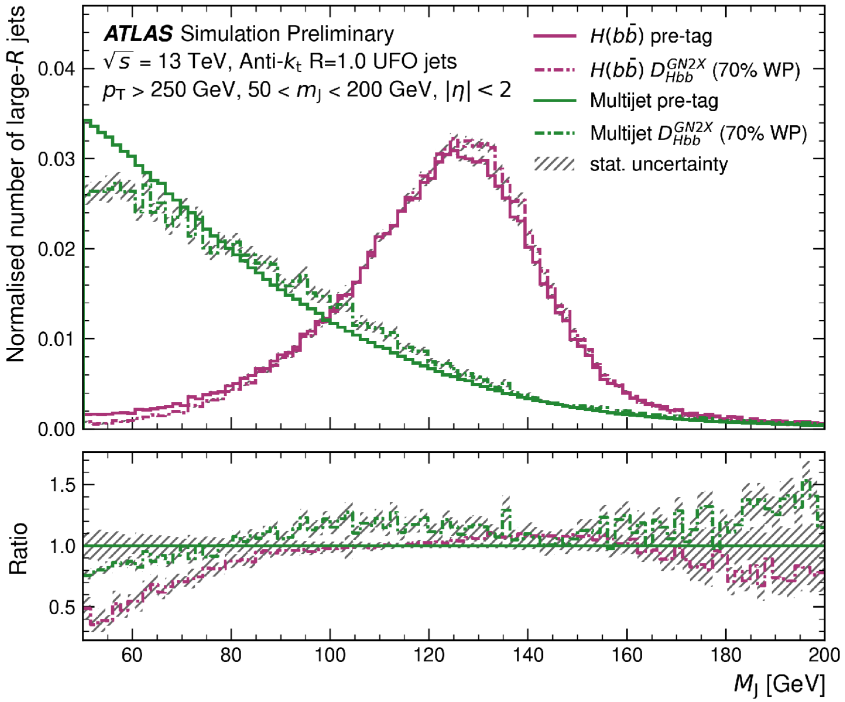
New Transformer Model



Simulation Performance

- At a 60% signal efficiency, GN2X achieves more than doubles the top and QCD rejection
- Trained on modified Higgs sample with increased decay width to reduce background mass sculpting – keeps sculpting to within 20% in bulk of distribution
- Calibration efforts underway, future boosted Higgs searches with hadronic decays will greatly benefit from new model





Summary

- ATLAS has significant program dedicated to probing decays from heavy resonances
- Many improvements in results driven by novel approaches to analyses and tools used to better identify objects used within them
- New techniques are continually being developed and tested to allow us to perform even better results with the new Run 3 data that is currently incoming!

Thank You For Listening