Searches for boosted resonances in hadronic final states

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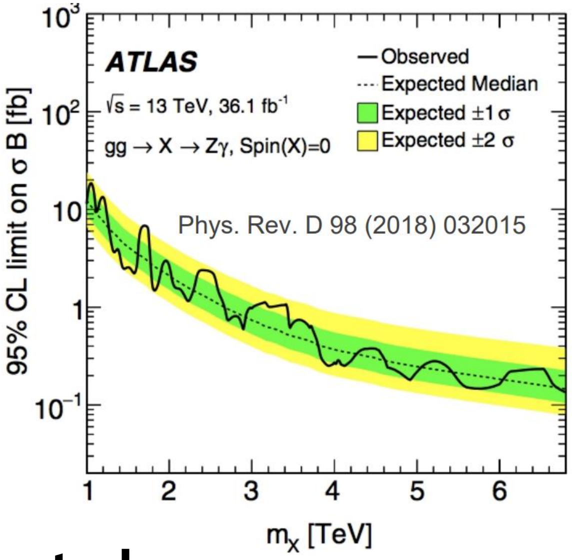
ATLAS EXPERIMENT

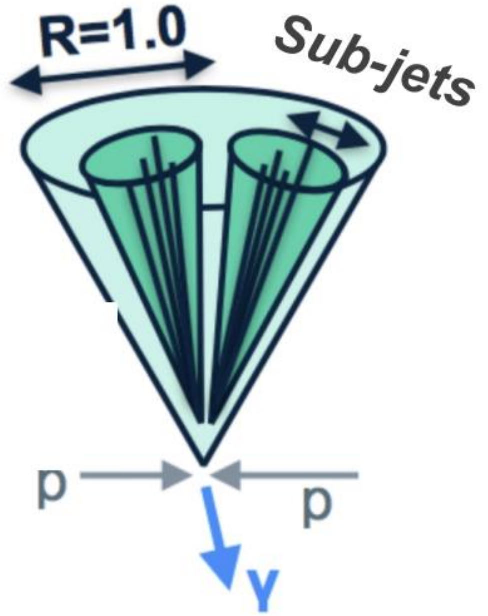
Introduction

- Many extensions to the Standard Model (SM) predict new particles decaying into two bosons
  - Heavy Vector Triplet (HVT), Two-Higgs-Doublet Model (2HDM), etc.
  - Important signatures for new physics search
- Boosted hadronic decays are essential channels for these searches
  - Large signal branching fraction
  - More sensitive to heavy particle
  - Jet substructure and jet performance crucial for various di-boson searches
  - Heavy resonance require excellent V-tagging and H-tagging in boosted scenarios
- This talk:
  - Highlight new technique – unsupervised learning
  - Recent results in the boosted di-boson search (only for hadronic channel)
    - $W+\gamma, Z+\gamma$
    - $XH \rightarrow qqbb$
    - $SH \rightarrow bb\gamma\gamma$

$W\gamma$ and $Z\gamma$

- Generic search for any BSM heavy particle decaying to $V+\gamma$, where V decay hadronically
- Various signal hypotheses explored
  - spin=0/2 $X \to Z\gamma$
  - spin=1 $X \to W\gamma$





Improvements w.r.t. precious study:

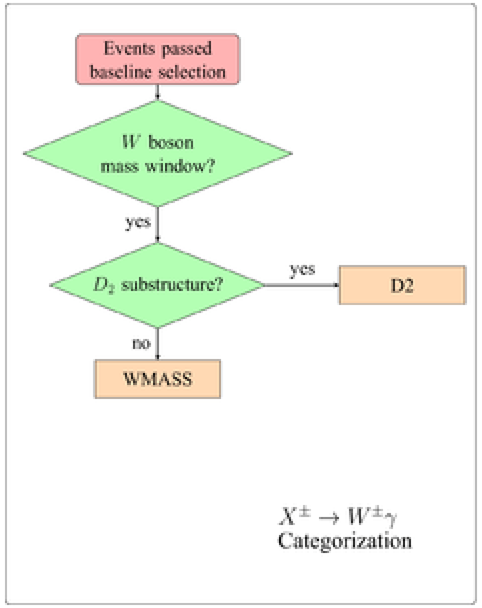
- Increase total luminosity to 139/fb
- New large-radius jet definition, new sub-jet reconstruction method
- Better W/Z boson tagger and b-tagger
- Re-optimized selections
- Sensitivity has been **improved by a factor of 2** in high mass region

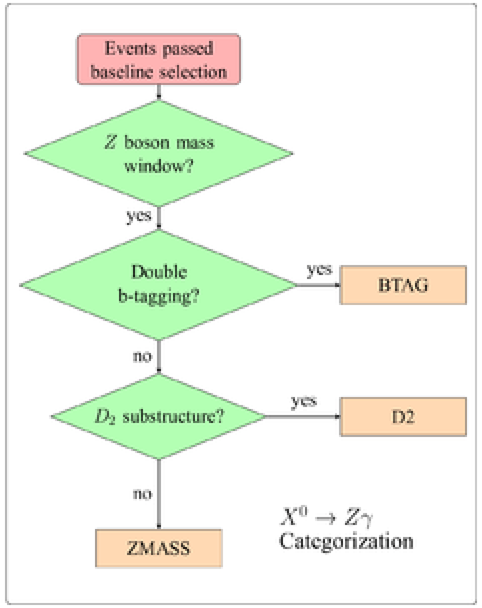
Physics objects:
1 high energy photon
1 large-Radius jet (fatjet)

Event selections and categorizations

Baseline selection
- Trigger: photon with pT>140 GeV
- Tight-Isolated Photon: pT>200 GeV, |η|<1.37
- Large-R jet (R=1.0 TrackCaloClusters jets): pT>200 GeV, |η|<2.0
- VR subjet reconstruction method for b-tagging

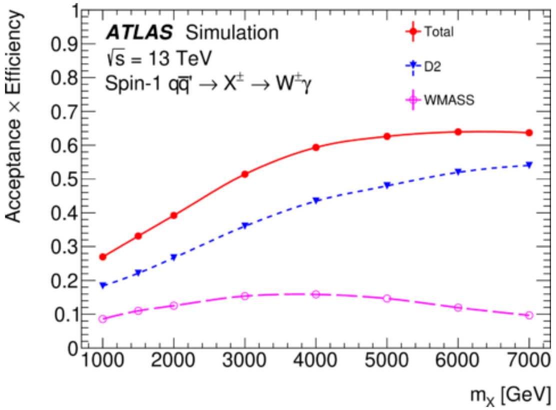
Categorization
- Boson tagger based on **jet mass** and **D2** (energy correlation) and sub-jet b-tagging info
- Additional optimizations for pT of the photon and jet are performed for different categories

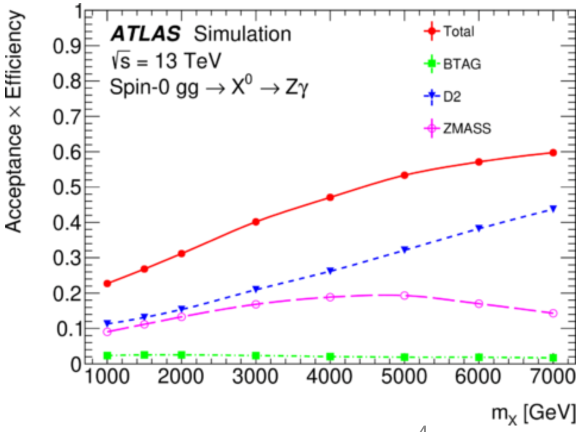




TrackCaloClusters Jet (optimized for high-pT jet)

At high pT:
- Calorimeter provides good energy resolution, but p oor granularity.
- Tracker provides good angular resolution, but degr aded pT resolution.

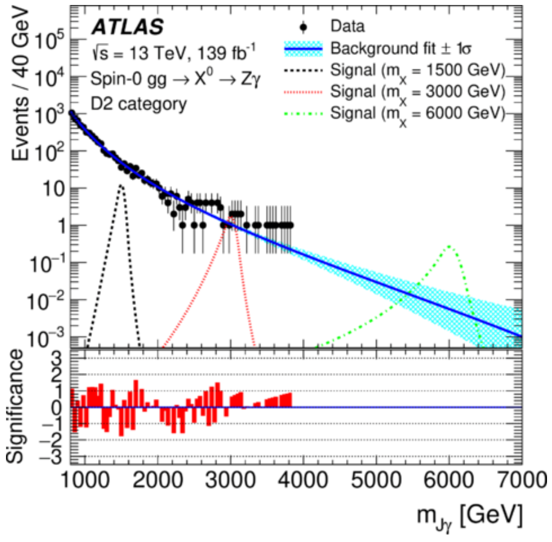


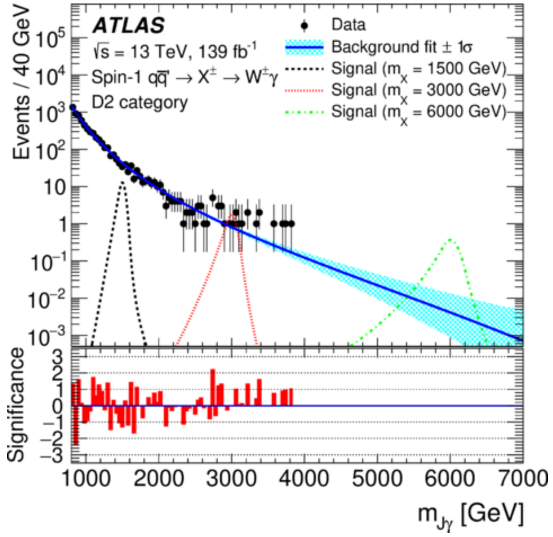


Results

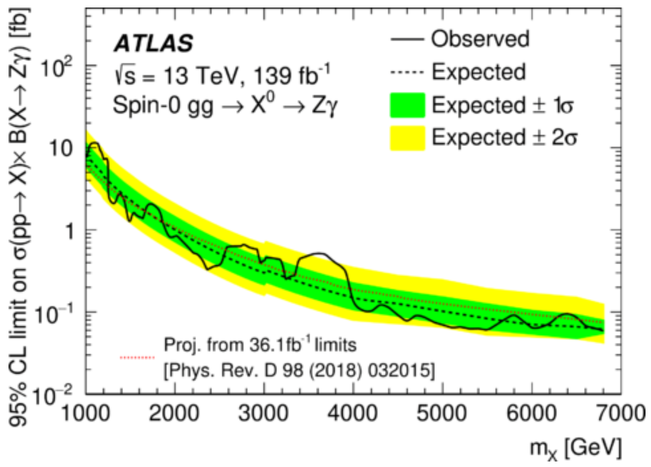
- Di-jet function with floating number of parameters is used for background estimation
- Uncertainty on this background modeling is covered by the spurious signal test results

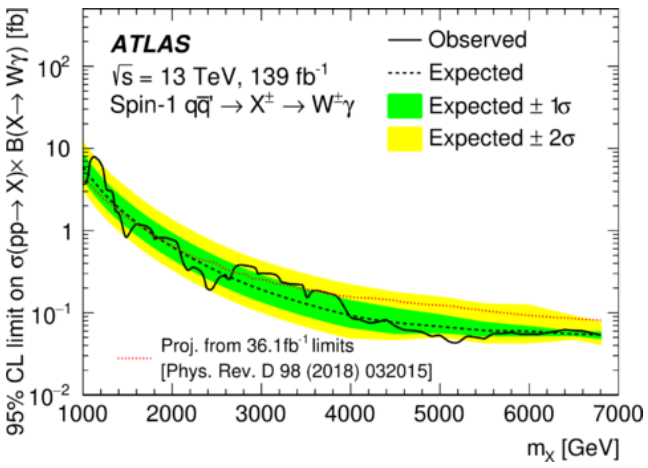
$$\mathcal{B}(m_{J\gamma}; \boldsymbol{p}) = (1-x)^{p_1} x^{p_2+p_3\log(x)},$$





- No significant excess observed from the full run-2 data
- Depending on the signal hypothesis, 95% CL upper limits are set with respect to the boson mass and signal channels.





PRD.108.052009

$Y \to XH \to qqbb$

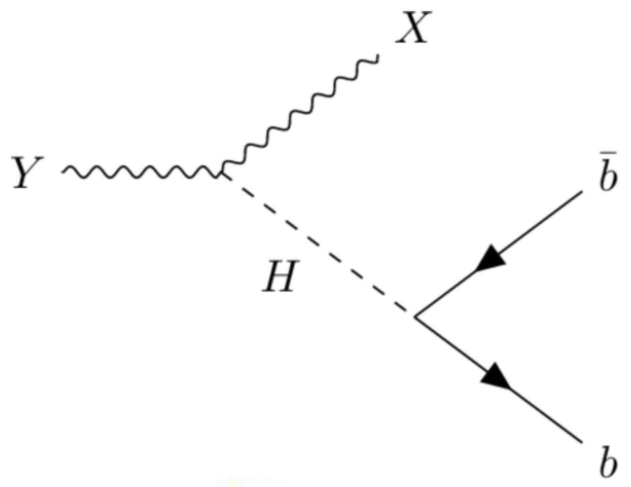
Search for two new particles:

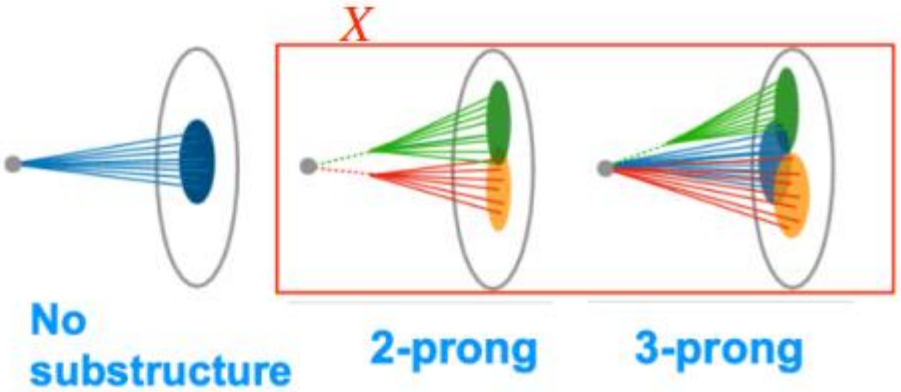
- A heavy particle Y ([1-6] TeV)
- Y reconstructed with a SM Higgs ($H \to bb$) and another BSM particle X ($X \to qq$)

Analysis sensitive to wide arrange of possible decays of particle

- **Two-prong** decay ($X \to qq$) as benchmark
- Many other decay topologies checked: three-prong, displaced vertices (heavy-flavour), dark jets (patterns of missing and visible energy)
- Sensitive to wide range of mass: [50, 3000] GeV

Y Reconstructed with two large-R jets -> TrackCaloCluster (TCC) Jets

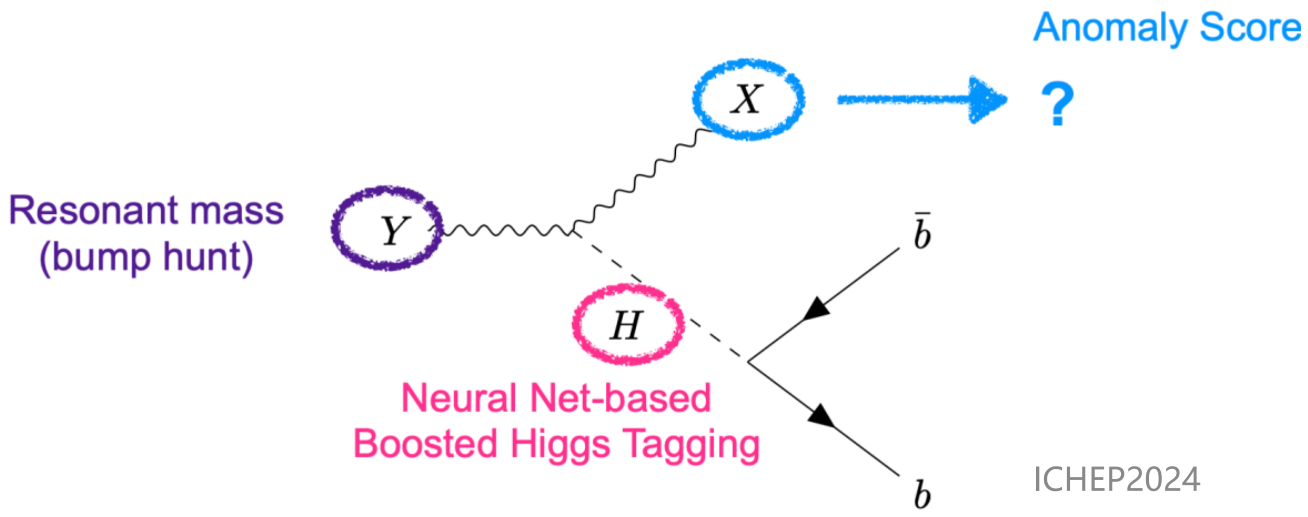


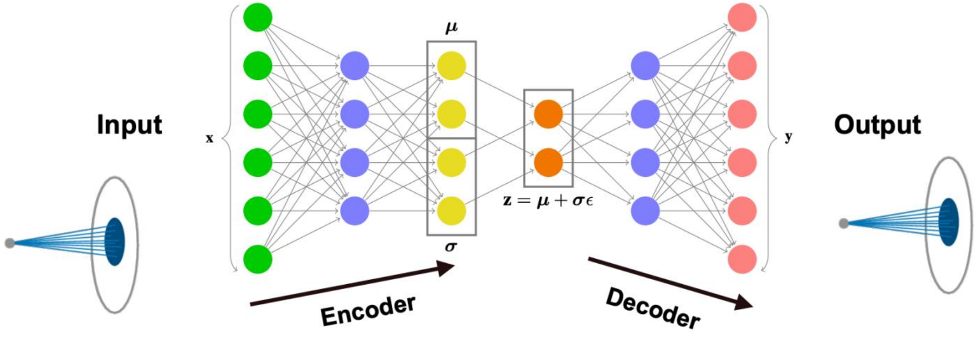


Anomalous X tagging

Many ML approaches used including unsupervised technique

- Per-jet anomaly score to perform model-independent tagging of anomalous X candidate jets
  - Jet-level anomaly score given by a **variational recurrent neural network (VRNN)** consist of a **variational autoencoder (VAE)**
  - **Unsupervised training** over jets in data modeled as sequence of kt-ordered constituent 4-vectors
  - Define anomaly score (AS) per jet as a function of VRNN loss
- Neural net-based tagging of boosted H→ bb topology
- DNN-based (density ratio estimation) reweighting procedure for data-driven background estimation



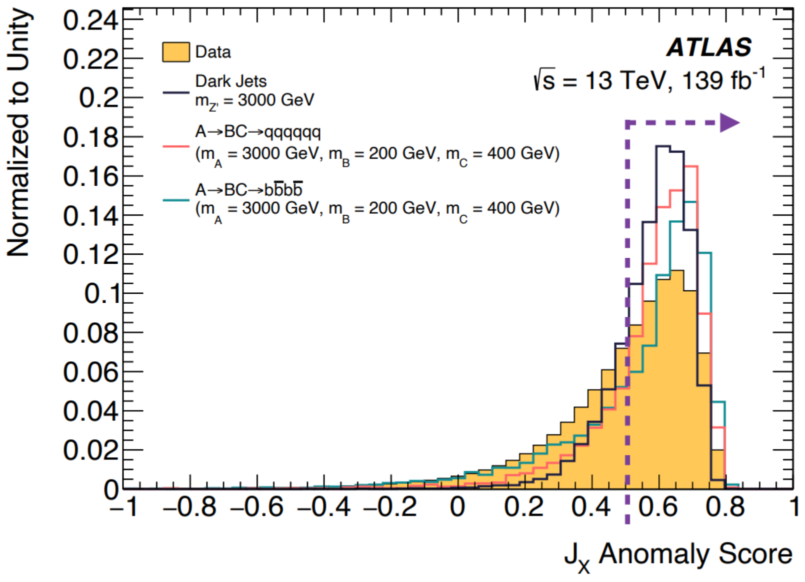


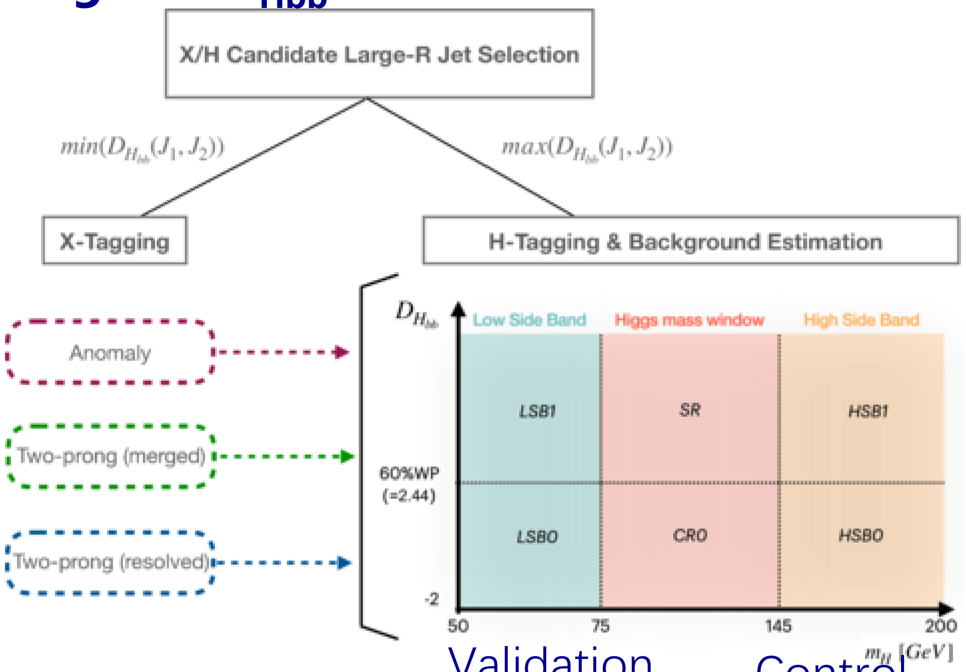
Anomalous X tagging

- Trained using jets from full Run-2 dataset
- Test model-independence by studying AS discrimination performance on 4 jet topologies:
  - 2-prong, 3-prong, heavy flavor, and dark jets

$$D_{H_{bb}} = \ln \frac{P_{\text{Higgs}}}{f_{\text{top}} \cdot P_{\text{top}} + (1 - f_{\text{top}}) \cdot P_{\text{multijet}}}$$

- Large-R jet trigger: J1(pT) > 500 GeV and mJJ > 1.3 TeV
- Ambiguity resolution: Higgs defined as the jet with **highest D_{Hbb} score**
- X-tagging: Anomaly **score >0.5**
- Higgs tagging: D_{Hbb} > 2.44



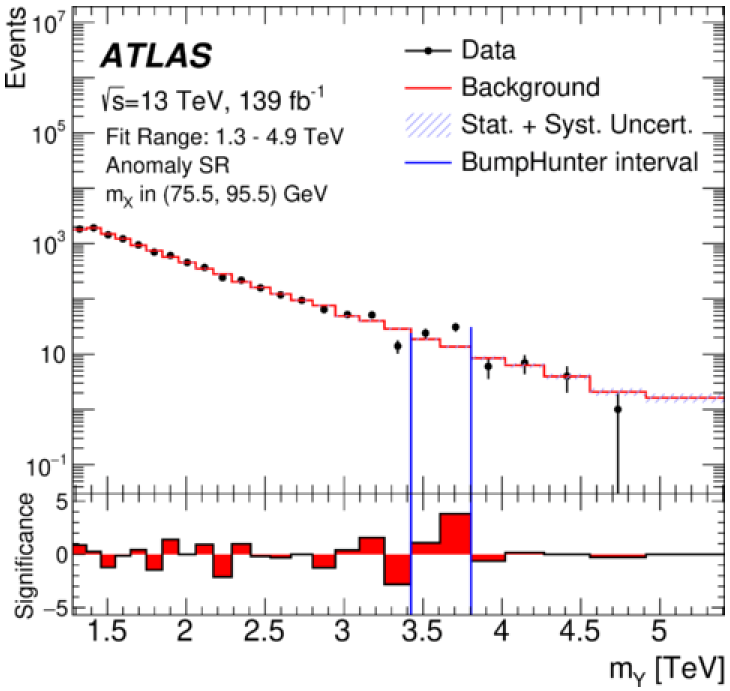


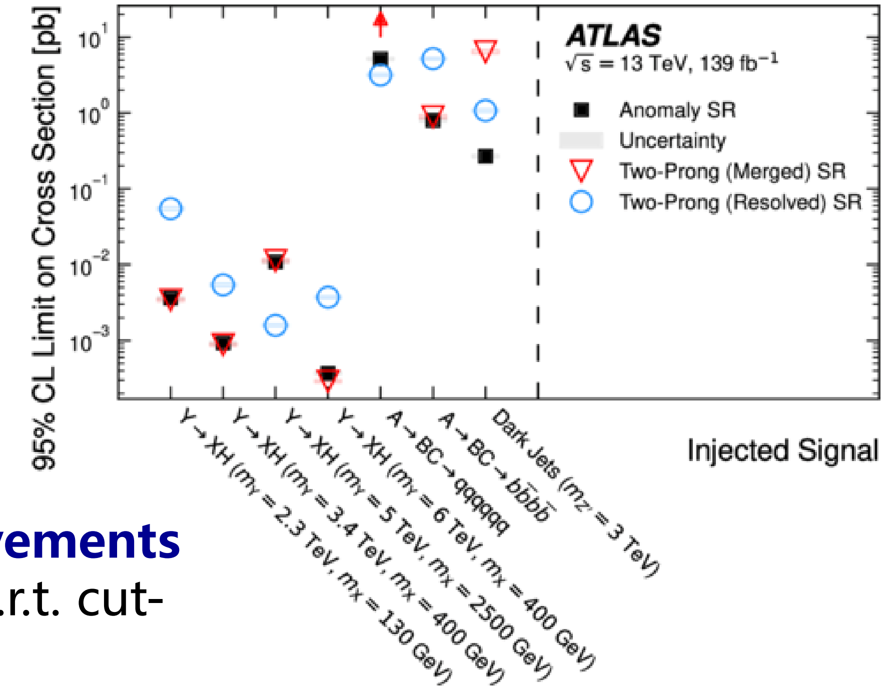
Validation region

Control region

Results

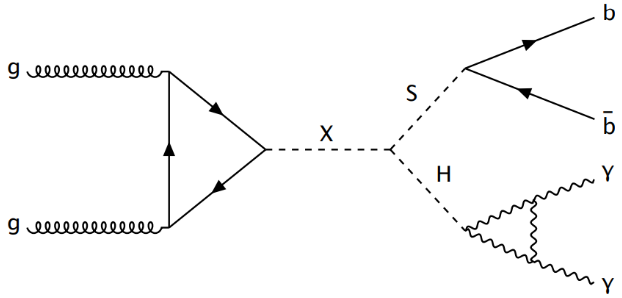
- Calculated p-values across all mY and mX bins in the anomaly signal region
- The lowest observed p-value corresponds to the bin with $mY \in [3608, 3805]$ GeV and $mX \in [75.5, 95.5]$ GeV
- Compatibility p -value of < 0.001, **1.4σ** global significance in BumpHunter



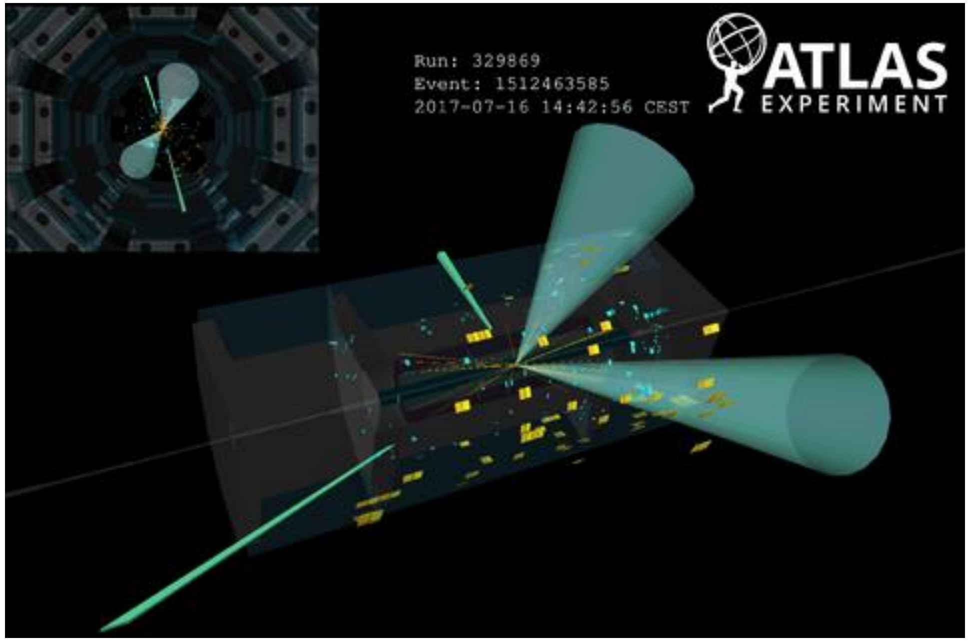


~x10 Improvements for dark jet w.r.t. cut-based results arXiv:2404.12915

$X \rightarrow SH \rightarrow bb\gamma\gamma$

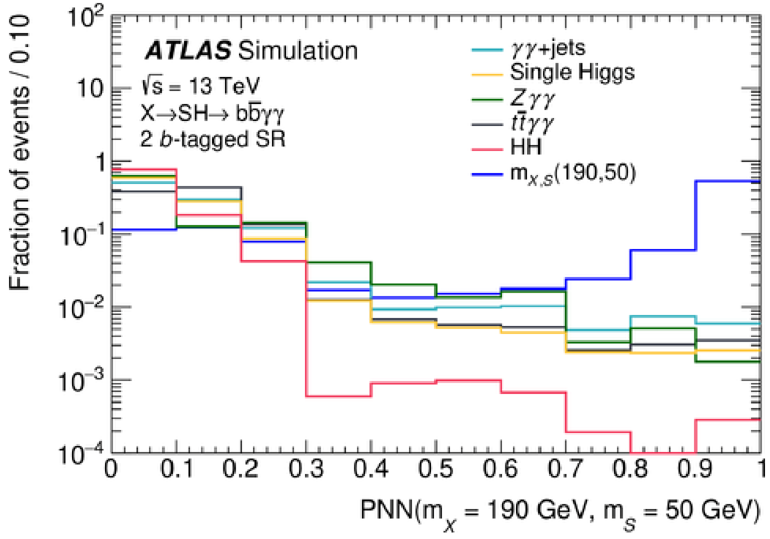


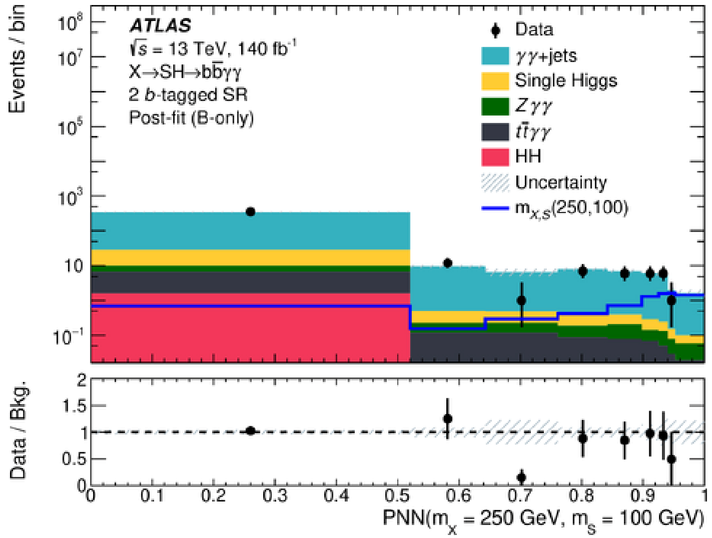
- Many BSM models predict an extended Higgs sector:
  - The 125 GeV observed boson is one of the states
- This search is for two additional scalars X and S
  - Assume mX > mS + mH
  - Complex 2-Higgs doublet model
  - Next-to-Minimal Supersymmetric SM
- $H \rightarrow \gamma\gamma$ and $S \rightarrow bb$
  - Highest sensitivity to light X and S bosons
  - 170 > mX > 1000 GeV
  - 15 < mS < 500 GeV
- Full Run2 data
- **Resolved and boosted $S \rightarrow bb$**
  - **One or two b-tagged jets**



Analysis flow

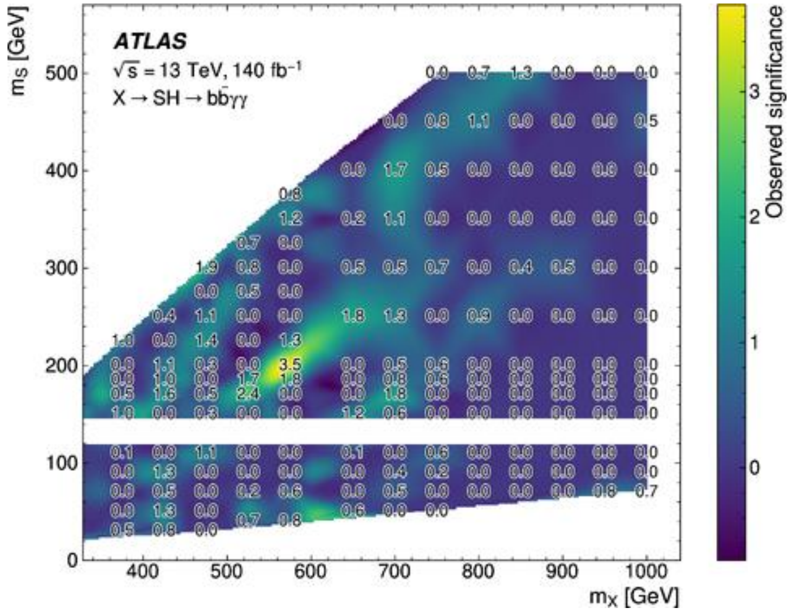
- Two different selections defined
  - 2 b -tagged where 2 b-jets can be resolved
  - 1 b -tagged where S is boosted so only 1 large-R jet
- For each a **parameterized neural network (PNN)** is trained to discriminate signal from background
- The PNN learns the mass dependence of signal kinematics -> only one model for the whole mass grids
- To further exploit the parametrization we interpolate signal to intermediate mass grid points

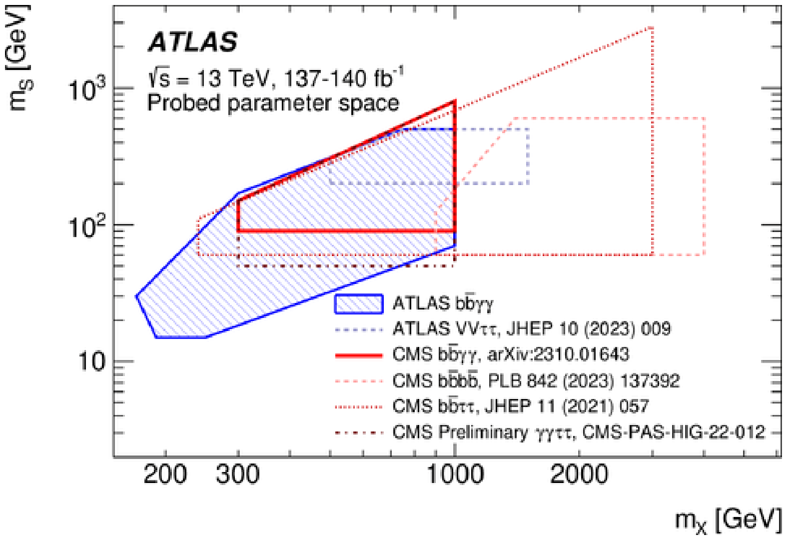




Results

- No significant excess observed vs SM expectation found
- Limits on cross sections times BR from 39 fb at mX = 170 GeV to 0.09 fb at 1000 GeV
- Largest excess at (mX , mS) = (575, 200) GeV, corresponding to local (global) significance of **3.5 (2.3) σ**
- First ever limits on these models in low mass region of **mX < 240 GeV and mS < 60 GeV**





Summary

- Many studies at ATLAS to search for heavy particle using boosted objects
- **Many new approaches and techniques!**
  - **Tagging, unsupervised learning …**
- A successful application of unsupervised machine learning for anomaly detection $Y \to XH \to qqbb$
  - A powerful way to cast a wide net in the search for new physics
- Run3 is on-going, more data will come, stay tune

Many other heavy resonance searches covering different BSM scenarios in the talks by Hector , Andrea and Vakhtang .

Thanks for your attention.

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abstract

Many extensions to the Standard Model predict new particles decaying into two bosons (W, Z, photon) making these important signatures in the search for new physics. Searches for such diboson resonances have been performed in different final states and novel analysis techniques, including unsupervised learning, are also used to extract new features from the data. This talk summarises such recent ATLAS searches with Run 2 data collected at the LHC and explains the experimental methods used, including vector-boson-tagging techniques.