Searches for resonances decaying to pairs of heavy bosons in ATLAS

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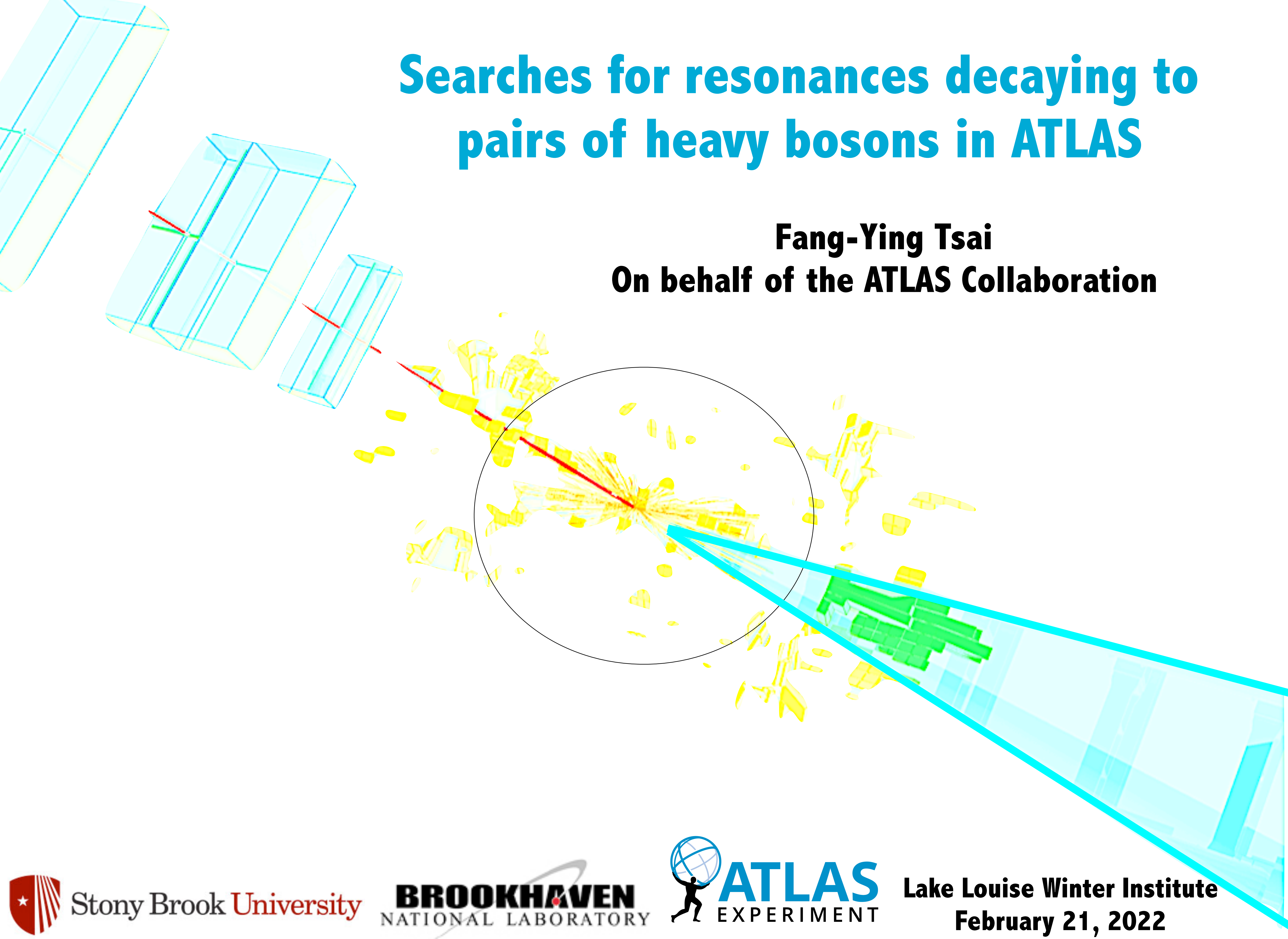
On behalf of the ATLAS Collaboration



Stony Brook University
BROOKHAVEN NATIONAL LABORATORY
ATLAS EXPERIMENT

Lake Louise Winter Institute
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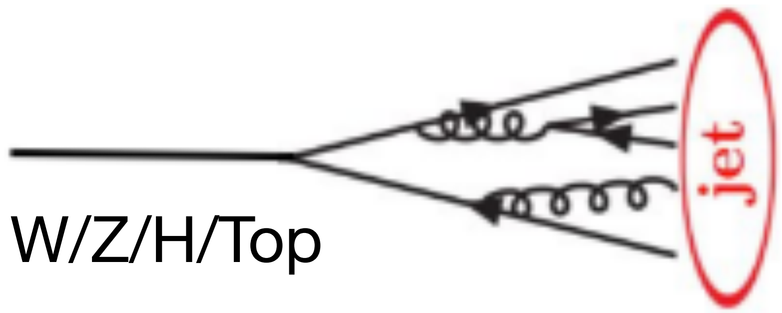
Outline

- Sensitivity to search for new heavy particles is significantly enhanced with respect to Run 1.
- Identification of hadronic decays of heavy bosons is a key component to searches for new physics.
  - Higher sensitivity than fully leptonic final states.
  - The collimated decay products of new heavy particles can be reconstructed via a single large-radius jet.
    - This talk will focus on large-R (R=1.0) jets.
      Large-R (R=1.0) jets are used in ATLAS for the purpose of W/Z/H/Top tagging.

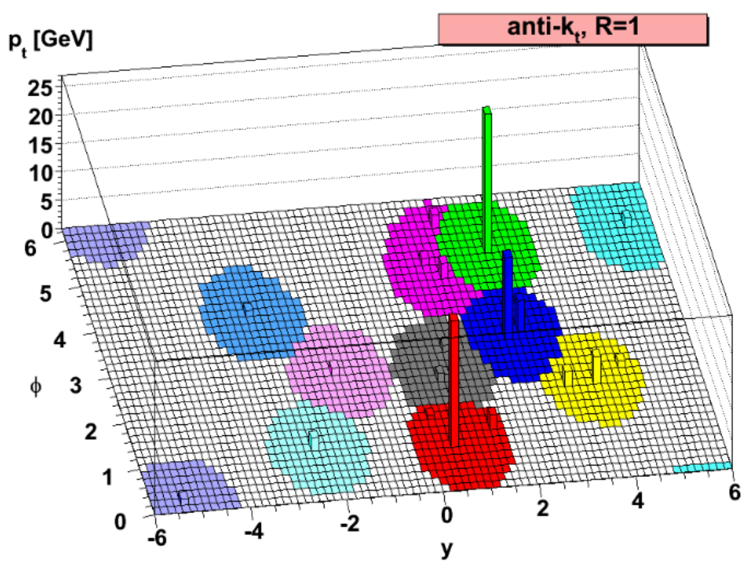
$\Delta R \gtrsim 2m/p_T$



- Heavy boson searches using the Track-CaloCluster (TCC) technique
  - Search for high-mass Wγ and Zγ resonances.
  - Search for heavy resonances decaying into a W and a Higgs boson.
- Tagging into the future
  - Hadronic object tagging using Unified Flow Object jets (UFO).
  - Future tagging improvements.

Intro to Jets & their inputs

- Jets represent the energy flow from the hadronization of a quark or gluon in a detector.
- Large-R jets are used for boosted topologies, with various jet inputs.
  - Topo-cluster jets: large-R jets calibrated to the hadronic scale,
  - Track-CaloCluster jets (TCC),
  - Unified Flow Object jets (UFO): combine Particle Flow Object jets (PFOs inputs are small-radius jets) and TCC.
- Anti-kt algorithm is the default jet clustering algorithm in ATLAS.
- Remove the effects of pile-up through jet grooming (soft drop, trimming, etc.). This affects the jet constituents, and thus the clustering structure of the jet is changed.
- Energy and mass of the reconstructed jets need to be calibrated.
  - MC-based energy and mass calibration, in-situ.



Track-Calo-Clusters (TCC)

ATL-PHYS-PUB-2017-015

- Start from clusters as calorimeters have better resolution at high p_T than the inner detector.
- Improve angular resolution of high p_T particles by using tracker spatial coordinates information (η and Φ) to resolve structure within clusters.

match tracks to cluster → build 4-vector → unmatched topo = neutral objects
(calo pt, tracker η, tracker Φ, calo mass) e.g. TCC①

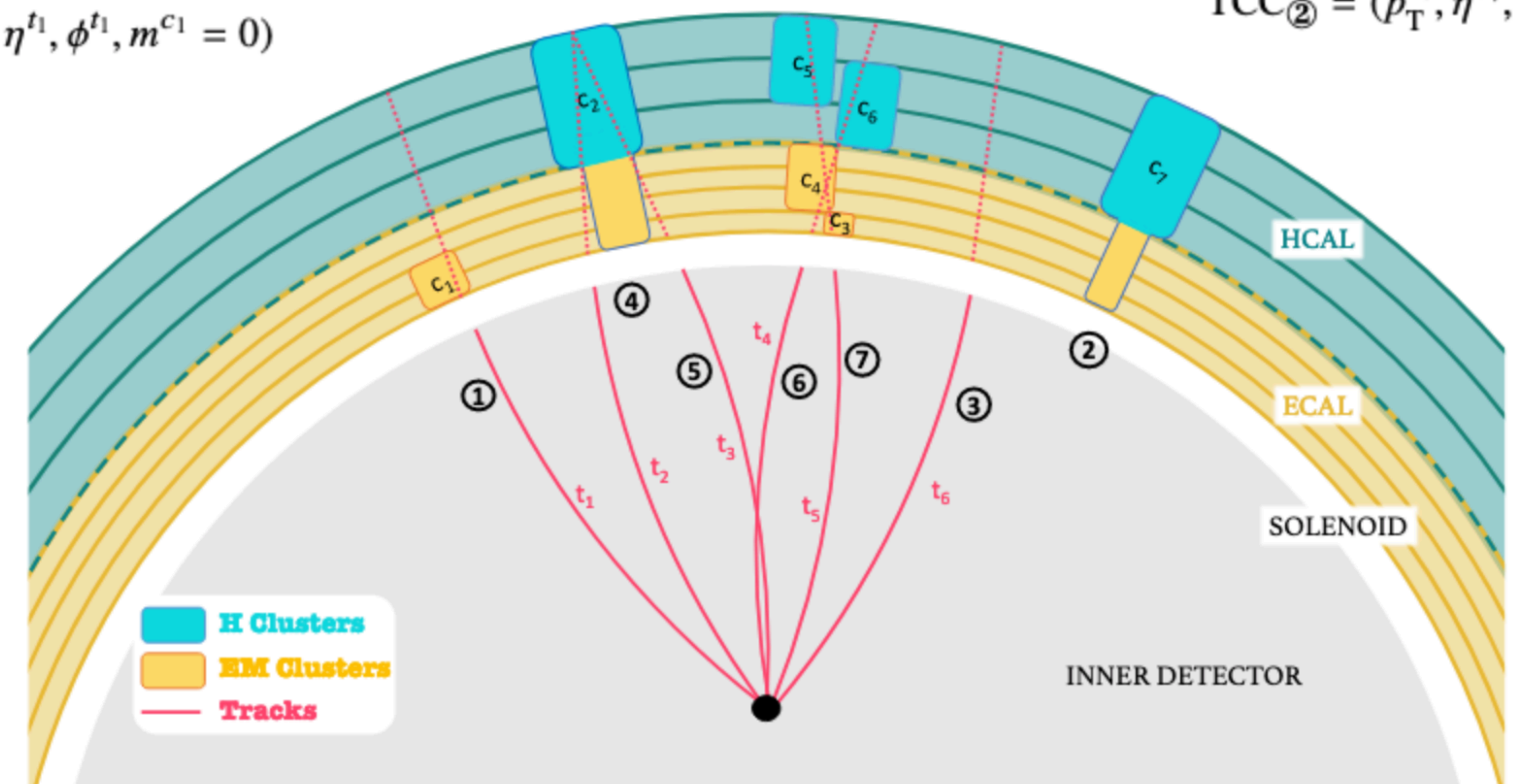
$$\mathrm{TCC}_{④} = \left(p_T^{c_2}\frac{p_T^{t_2}}{p_T\,[\mathbf{p}^{t_2}+\mathbf{p}^{t_3}]}, \eta^{t_2}, \phi^{t_2}, m^{c_2}\frac{p_T^{t_2}}{p_T\,[\mathbf{p}^{t_2}+\mathbf{p}^{t_3}]} = 0\right)$$

$$\mathrm{TCC}_{⑤} = \left(p_T^{c_2}\frac{p_T^{t_3}}{p_T\,[\mathbf{p}^{t_2}+\mathbf{p}^{t_3}]}, \eta^{t_3}, \phi^{t_3}, m^{c_2}\frac{p_T^{t_3}}{p_T\,[\mathbf{p}^{t_2}+\mathbf{p}^{t_3}]} = 0\right)$$

track p_T is used to determine shared fraction of calo clusters

$$\mathrm{TCC}_{①} = (p_T^{c_1}, \eta^{t_1}, \phi^{t_1}, m^{c_1} = 0)$$

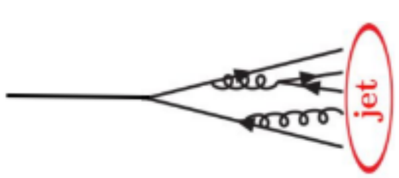
$$\mathrm{TCC}_{②} = (p_T^{c_7}, \eta^{c_7}, \phi^{c_7}, m^{c_7} = 0)$$



Boosted boson tagging using TCC jets

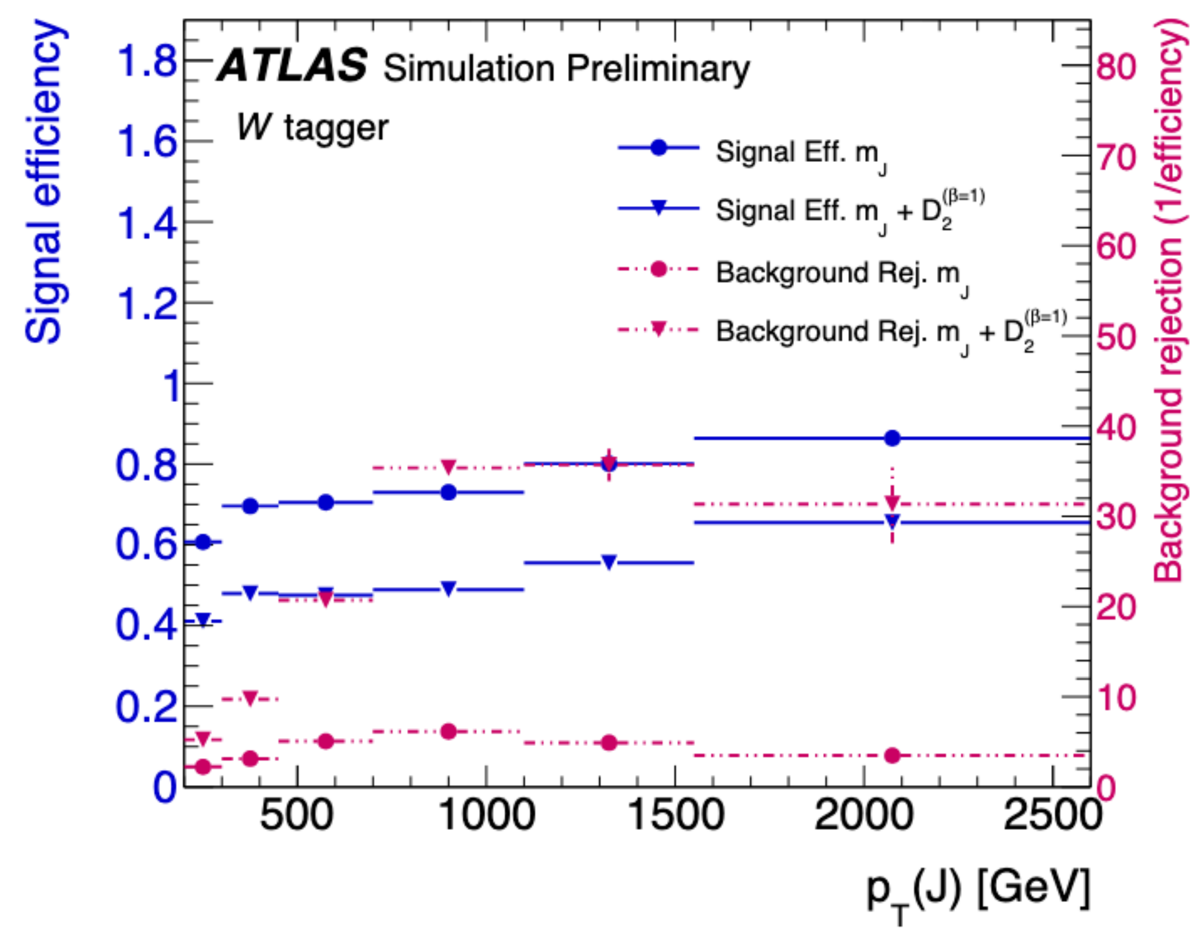
ATL-PHYS-PUB-2020-008

- Sources of hadronic decays of massive particles:
  - Diboson resonances are searched for in the semi-leptonic (ℓvqq/ ℓℓqq/ vvqq) as well as in the fully hadronic final states.
- Significant background jet contributions due to V+jets, multijets, γ+jets production.
- Boosted boson tagging is used to reduce these backgrounds.
  - Cut based W/Z taggers:
    - mass window(m_J),
    - two-prong substructure (D_2), describes how the energy is distributed inside the jet.



    - the number of tracks to the jet (n_{trk}, mainly for reducing multijets in the fully hadronic decays.)

Signal jet efficiency at high pT increased by ~20% compared to purely calo based.



H→bb tagging & efficiency correction

ATL-PHYS-PUB-2021-035

- b-tagging plays a crucial role for searches for boosted Higgs boson production.

$$\sum (p_{\mathrm{T}}^{\mathrm{track}})^2 = \max .$$

- Variable-radius (VR) track-jets are used to reconstruct b-jets.
  - R → $R_{\mathrm{eff}}(p_{\mathrm{T}}) = \rho/p_{\mathrm{T}}$. ρ = 30 GeV. R_{min} = 0.02 and R_{max} = 0.4

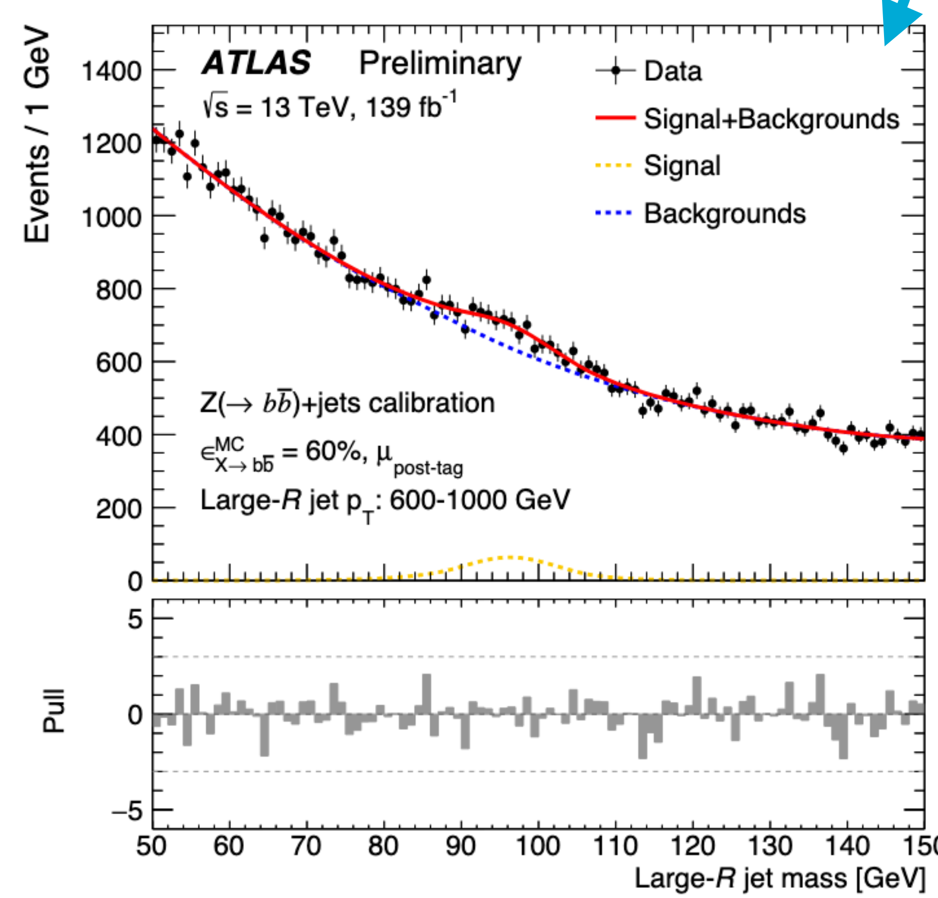
- Tagger is based on a neural network: using the large-R jet p_{T} ,η and the flavor tagging information that can identify VR track jets containing single b-hadrons as inputs.

$$\mu_{\mathrm{pre-tag}} = \frac{N_{\ell\ell}^{\mathrm{data}} - N_{\mathrm{bkg},\ell\ell}^{\mathrm{MC}}}{N_{Z\rightarrow\ell^+\ell^-}^{\mathrm{MC}}}$$

- A good modeling of signal and background processes is observed in the analysis within the uncertainties.
  - Measure a data-to-simulation scale factor ($\mu_{\mathrm{post\text{-}tag}}/\mu_{\mathrm{pre\text{-}tag}}$).
  - The top-jet mis-tag scale factor is considered.

- **First calibration of the Higgs boson tagger is available now.**

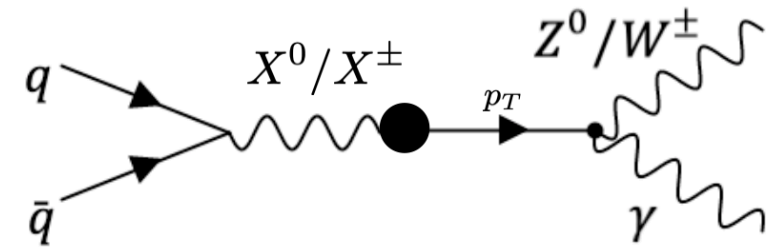
$\mu_{\mathrm{post\text{-}tag}}$: binned likelihood fit:

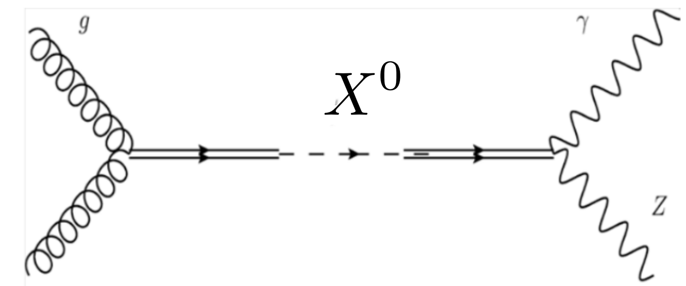


Search for high-mass Wγ and Zγ resonances

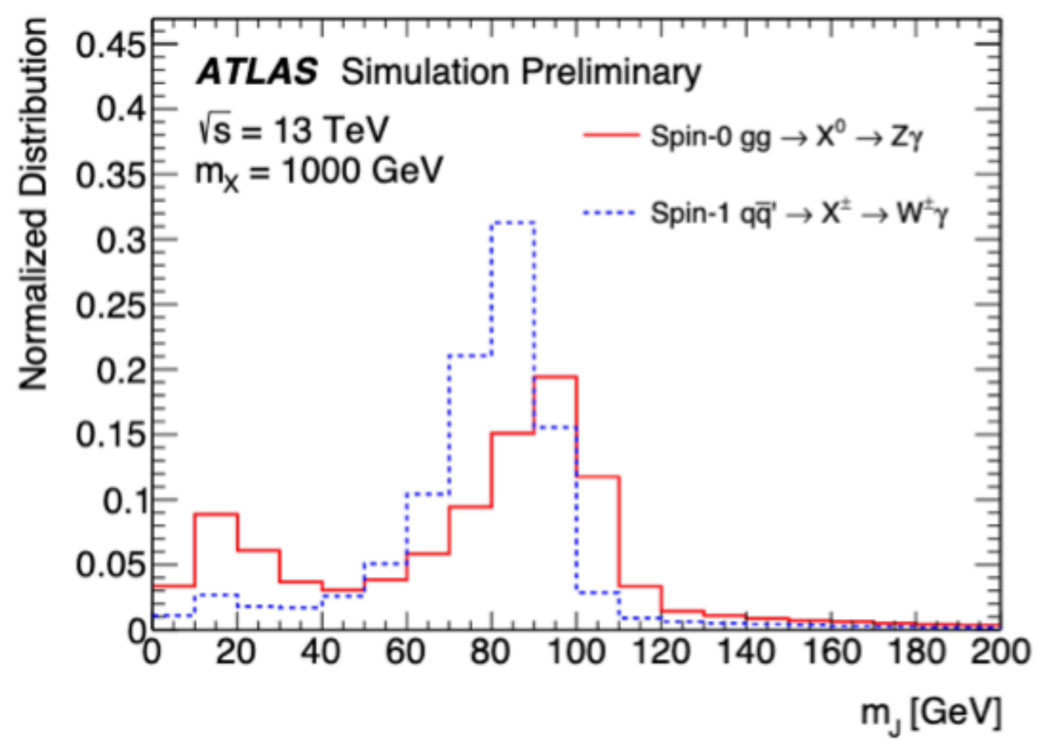
ATLAS-CONF-2021-041

- Narrow resonances decaying to final states of W/Z + γ in the boosted hadronic channel.
- Consider several signal scenarios: Spin-0 Zγ, spin=2 Zγ, Spin-1 Wγ
- Probe resonance masses in a range from 1TeV to 6.8TeV.
- The cut based W/Z taggers are based on: jet mass, two-prong structure.





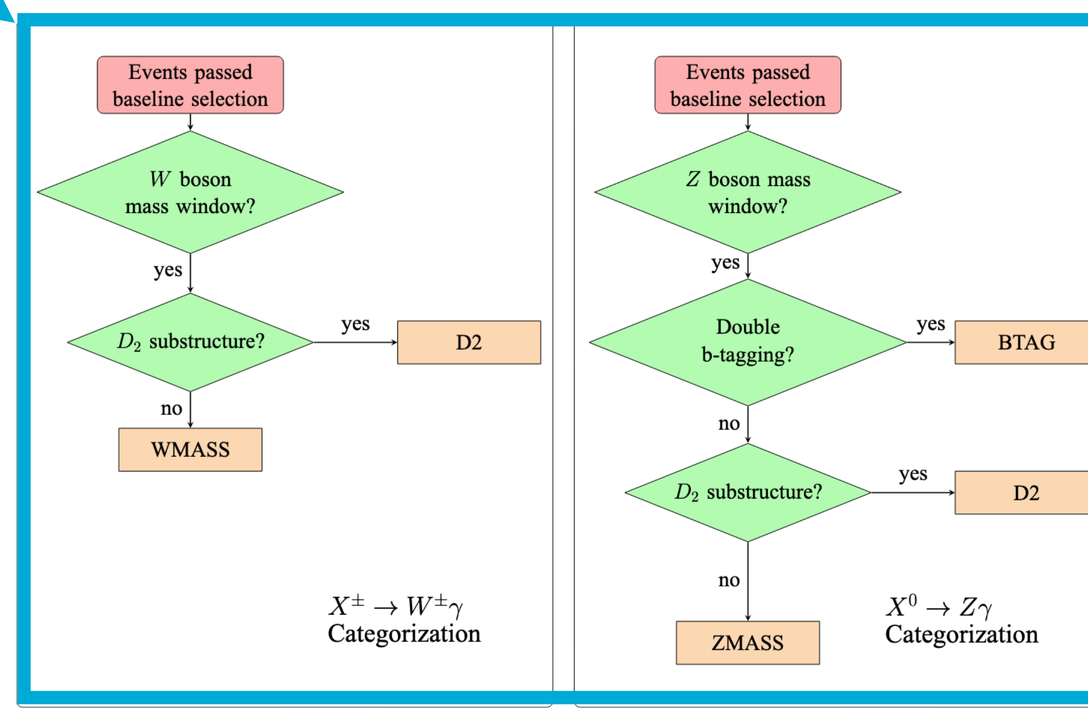
jet mass is calculated from TCC jet 4-vectors

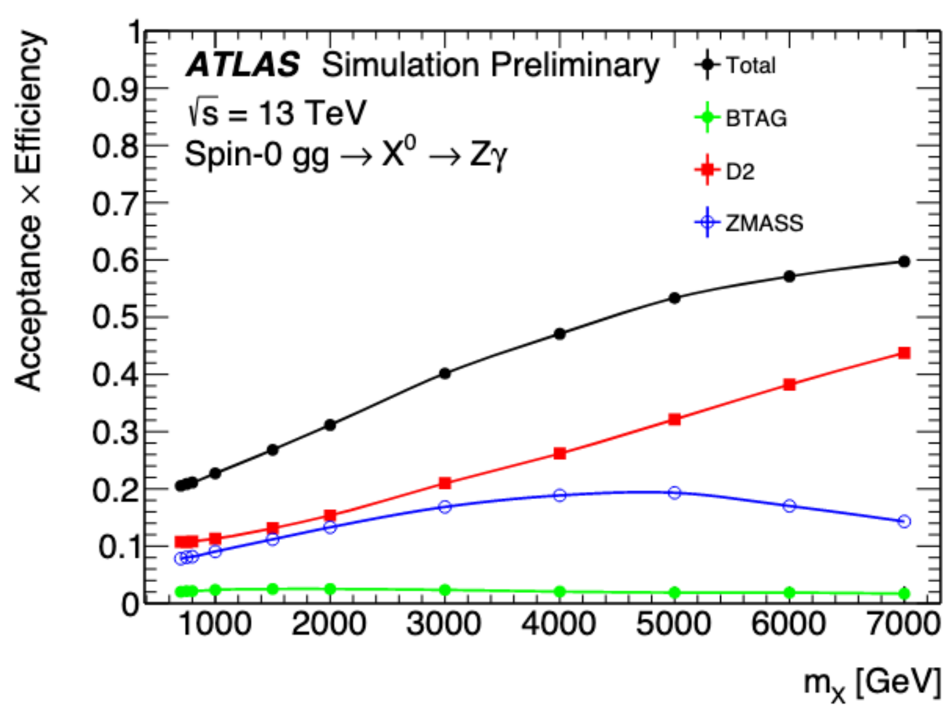


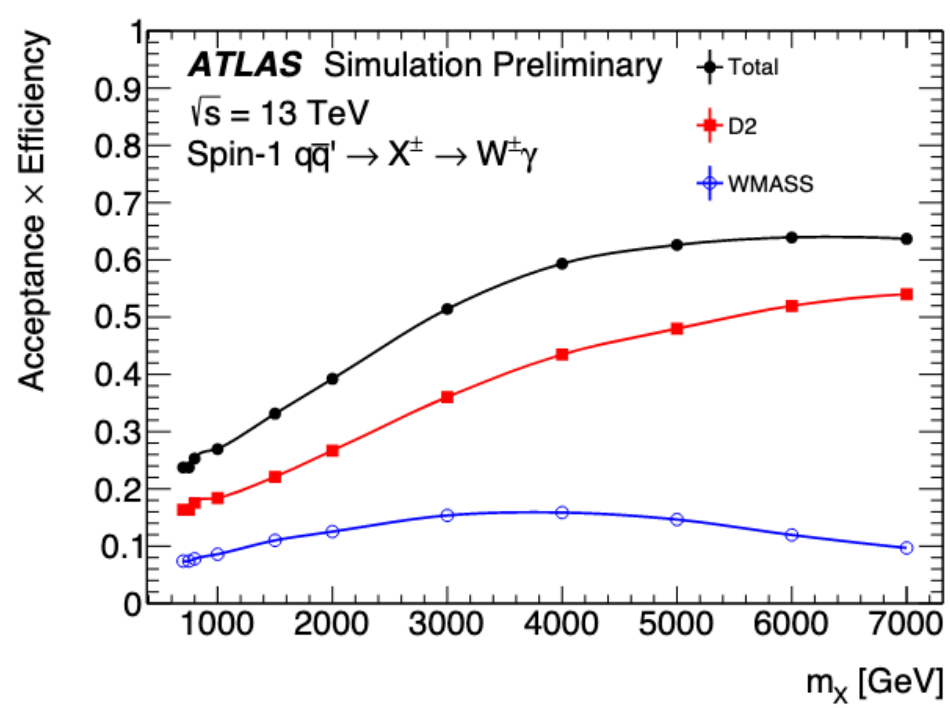
- Sensitivity to boosted Z bosons can be enhanced by applying b-tagging on VR track jets.

Search for high-mass Wγ and Zγ resonances

- The categories of the Wγ and Zγ events:
- Signal selection efficiencies increase as a function of the resonance mass.
  - BTAG category has the smallest efficiency but the highest signal purity.
  - Above 4TeV, the collimation of the constituents is so strong that the two-prong structure can no longer be resolved via the D2 cut.
  - γ+jet background is strongly suppressed when applying a W/Z tagger.

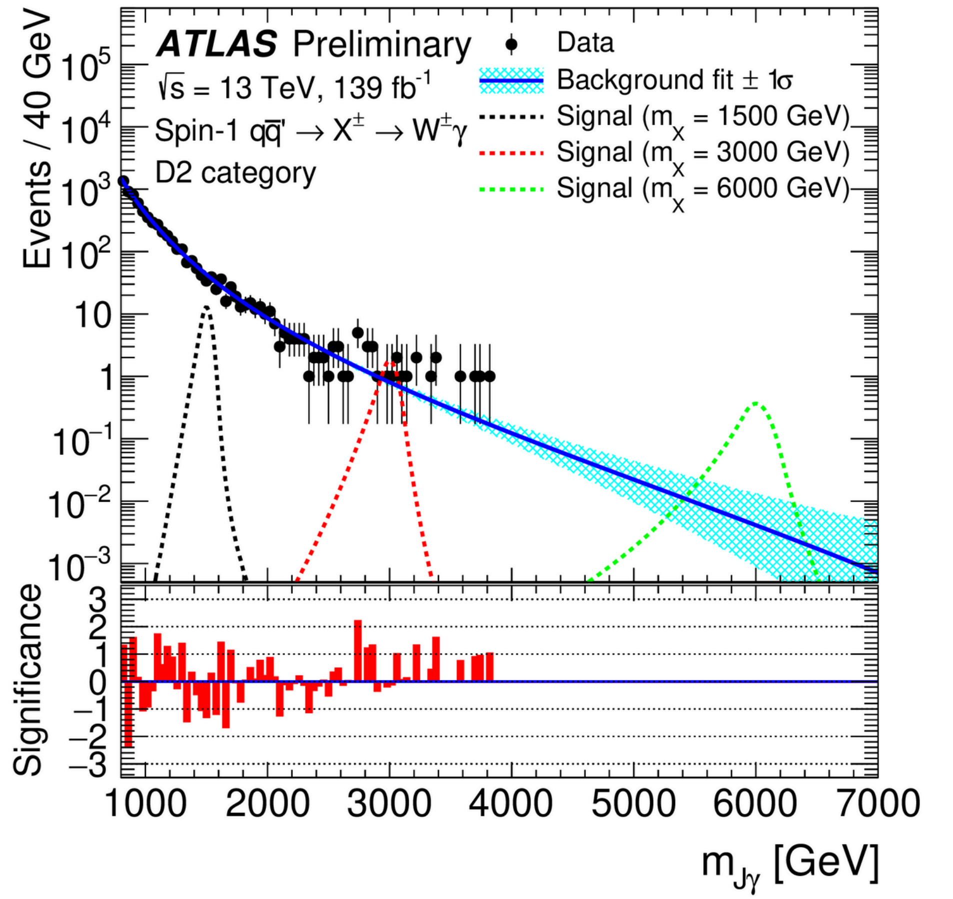




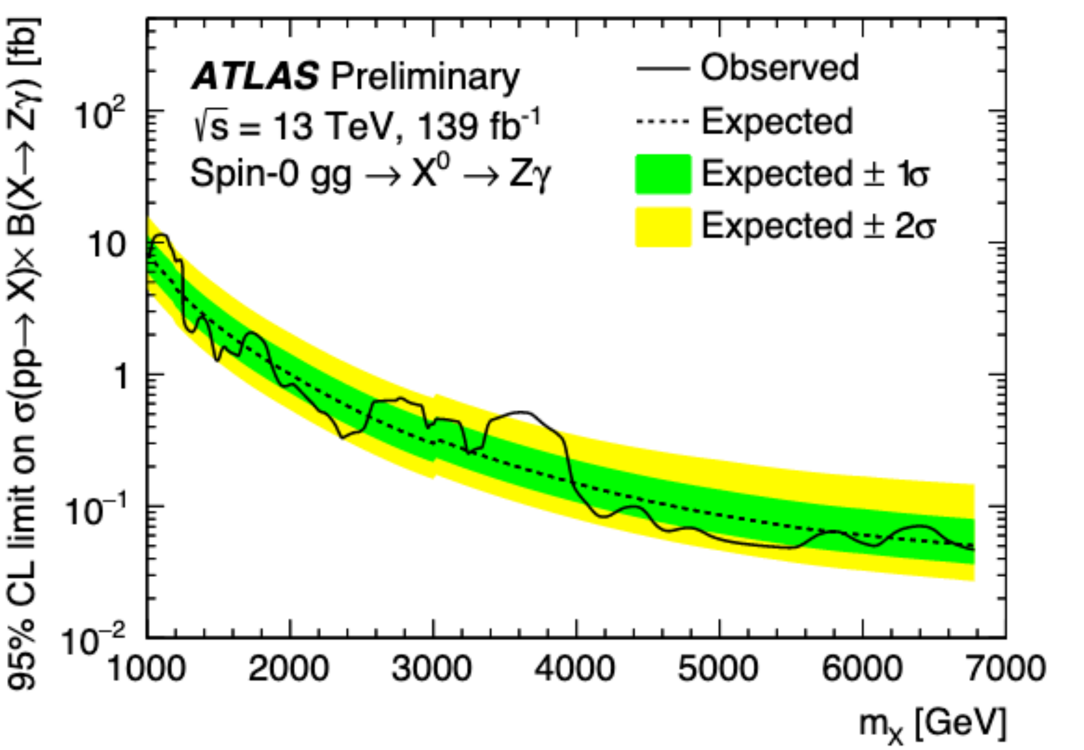


Search for high-mass Wγ and Zγ resonances

- Apply a binned maximum-likelihood fit to the $m_{J\gamma}$ distribution in different categories.
  - BSM signal is modeled with a double-sided crystal ball (DSCB) function.
  - SM Backgrounds (γ+jets, W/Z+γ) are estimated through a background fit function.



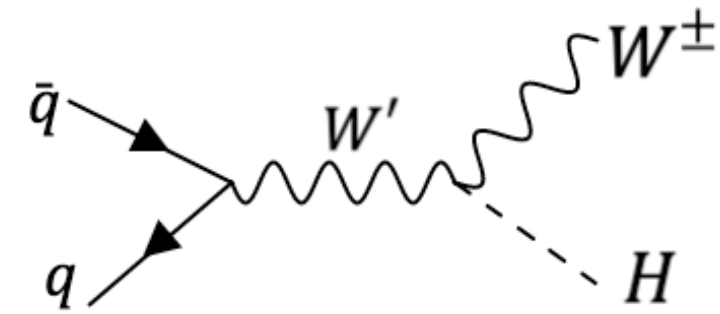
- No significant deviation was found.
  - Limits are improved from 0.1 fb (36 fb^{-1}) to 0.05 fb at high p_T regions: VR tracks and TCC jets are used.

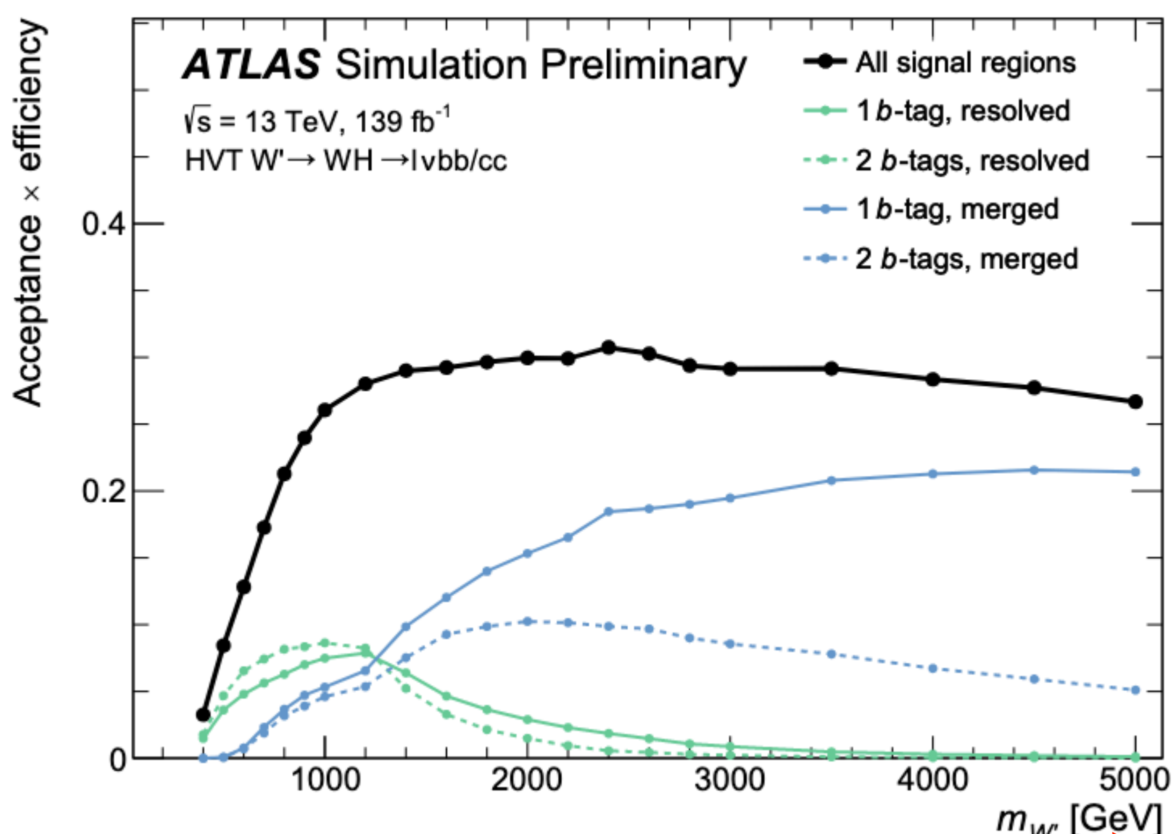


Search for heavy resonances decaying into a W and a Higgs boson

ATLAS-CONF-2021-026)

- New heavy vector bosons decaying to final states of a W(→ℓν) and a SM Higgs boson (→bb).
- Interpretation: Heavy Vector Triplet (HVT)
  - Model A: the branching fraction to fermions and gauge bosons are comparable.
  - Model B: Fermionic couplings are suppressed.
- Probe mass range between 400 GeV and 5 TeV.



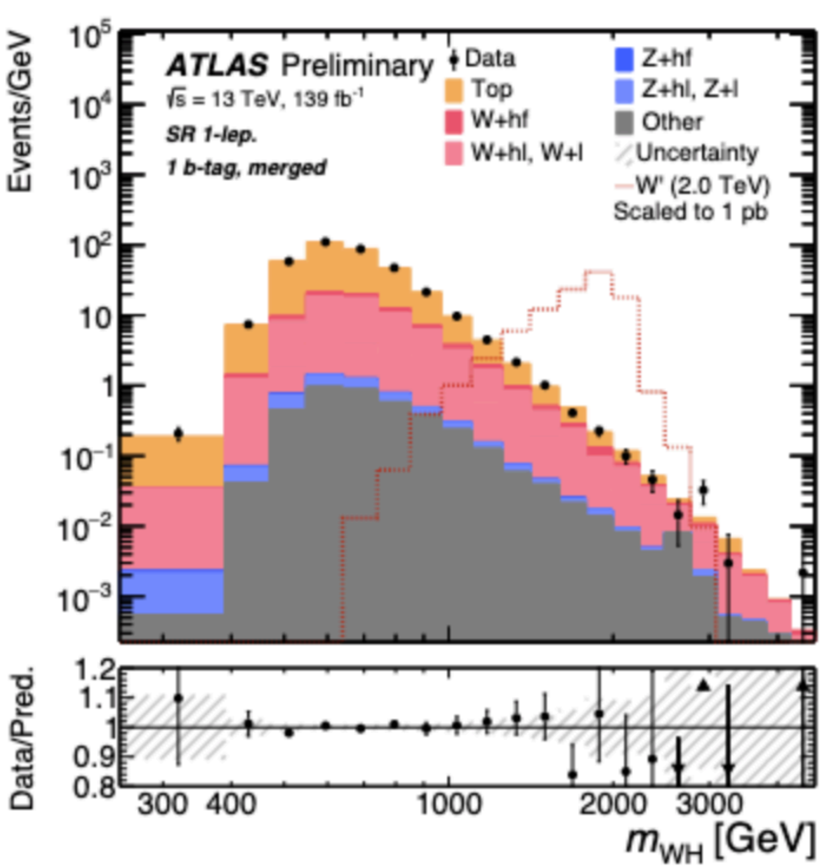


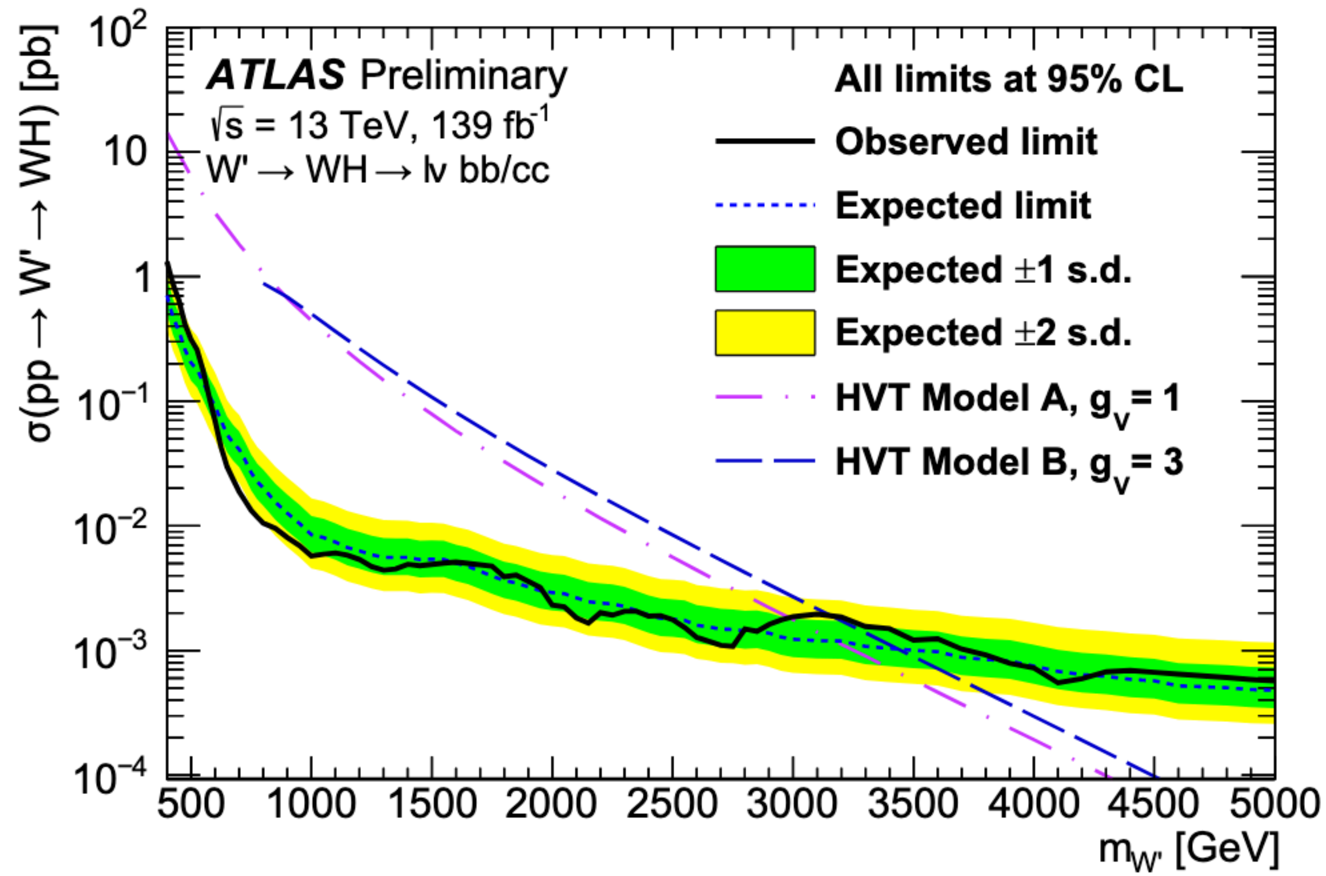
The merged categories become more efficient.

- Events require 1 lepton and missing transfer momentum (MET), 2 or 3 central small-R jets with 1 or 2 b-tags.
- Both resolved (small-R) and merged (large-R) jets are studied.
- TCC large-R jets and VR track-jets improve the analysis sensitivity for high resonance masses.

Search for heavy resonances decaying into a W and a Higgs boson

- Apply a binned maximum-likelihood fit to the m_{WH} distribution in 4 orthogonal signal regions.
  - the normalization of the following backgrounds are floating in the fit: W + (bb, cc, cb), W + (bl, cl), Top
  - the normalization of other backgrounds may vary within their uncertainties.
- No significant excess over the background prediction is observed.
- The upper limits range from 1.3 pb to 0.56 fb.
- Limits are improved by a factor 4 for large mVH values due to the introduction of VR track jets.
- W' resonances are excluded for mass values up to 2.95 TeV (3.15 TeV) for the HVT model A (B).





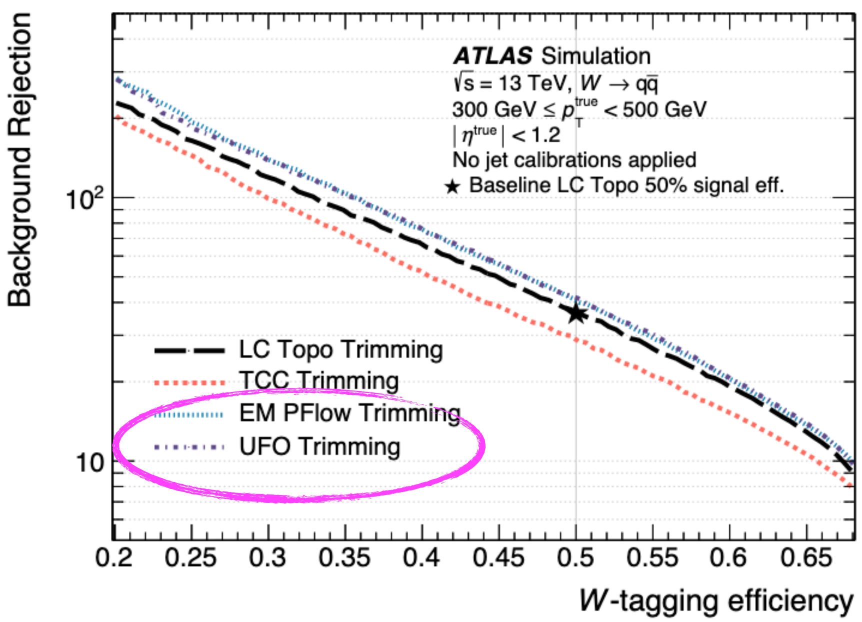
W/Z tagging techniques using UFO jets

JETM-2018-06

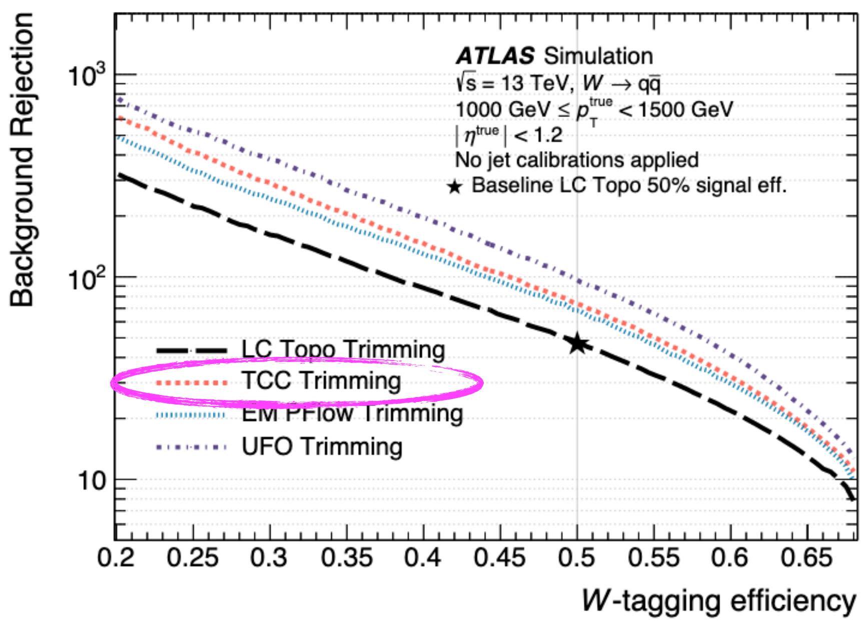
- UFO jets merge PFO and TCC inputs to obtain better performance across a wider p_T spectrum.
  - TCC improves tagging performance at high p_T but it is more sensitive to pileup resulting in poor performance at low p_T ranges.
  - PFlow algorithm is more robust to pileup because it starts from tracks and subtracts the expected energy deposit by charged tracks matched to the clusters.

- UFO jets increase the background rejection in a wide p_T range.

Low p_T ranges



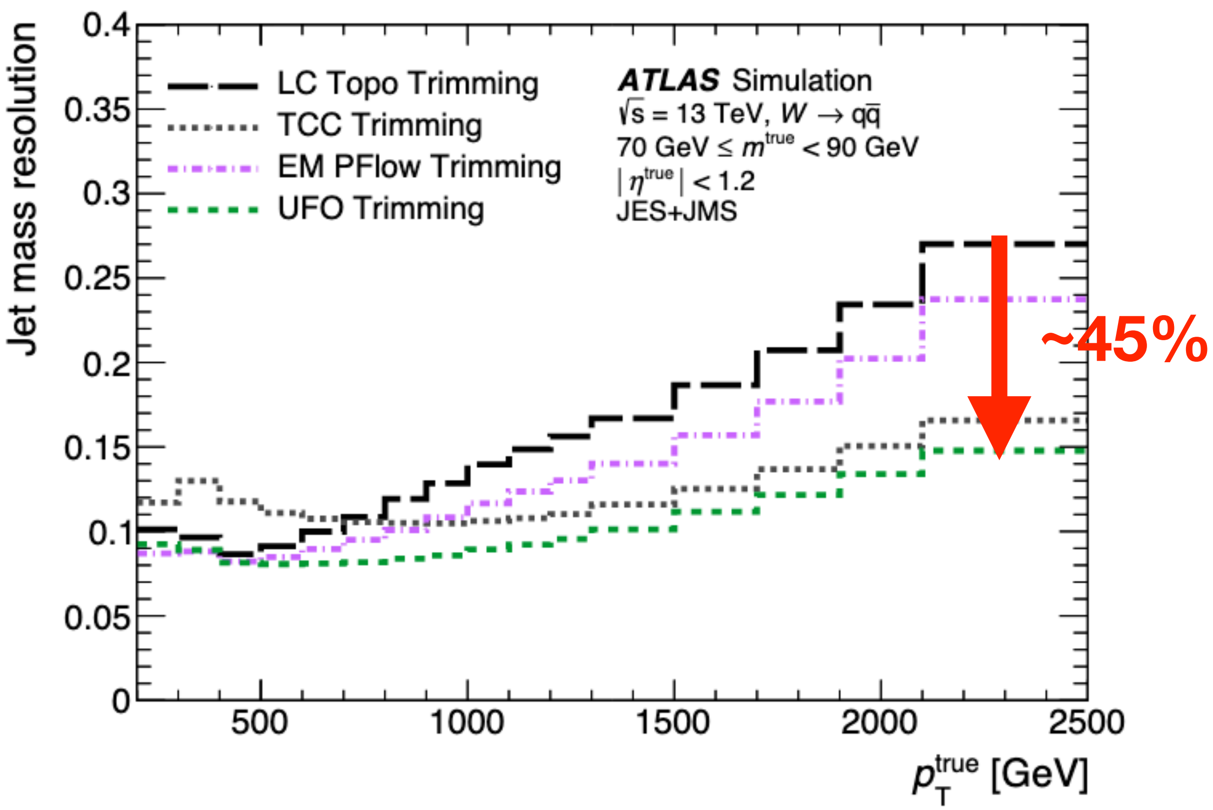
High p_T ranges

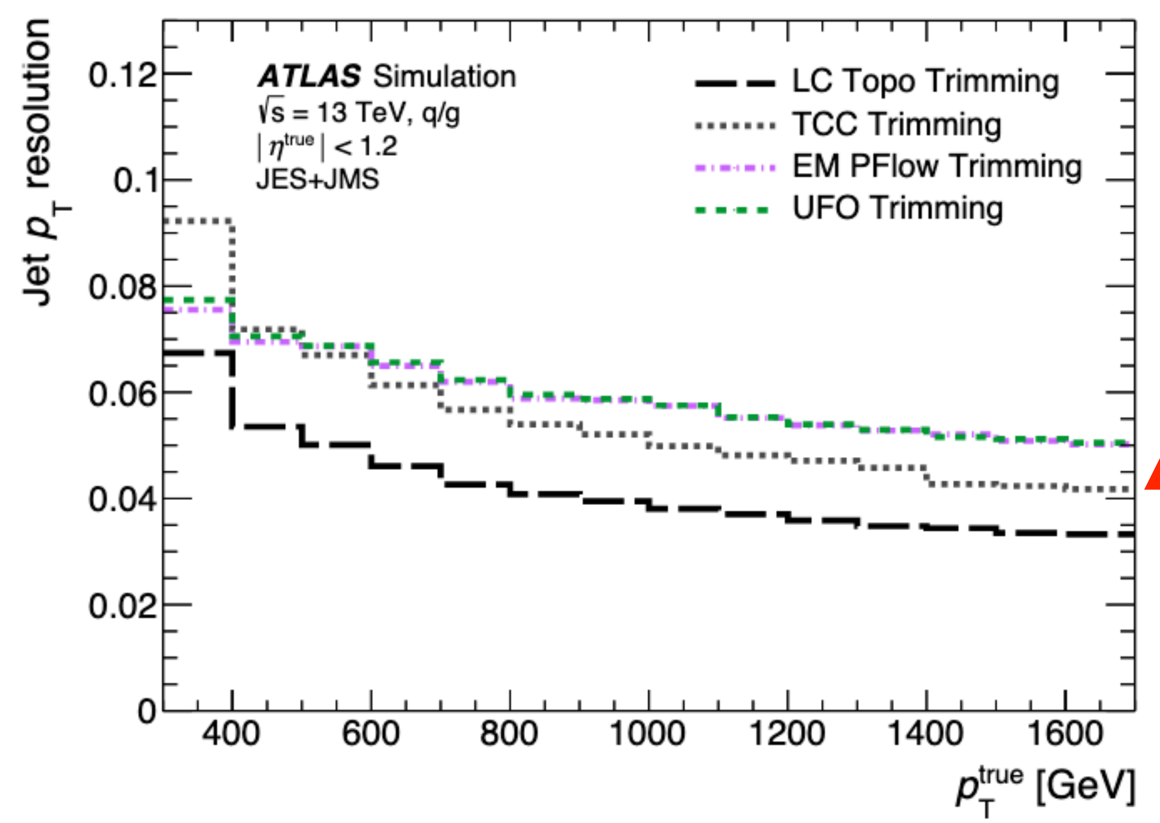


UFO jets for future tagging improvements

JETM-2018-06

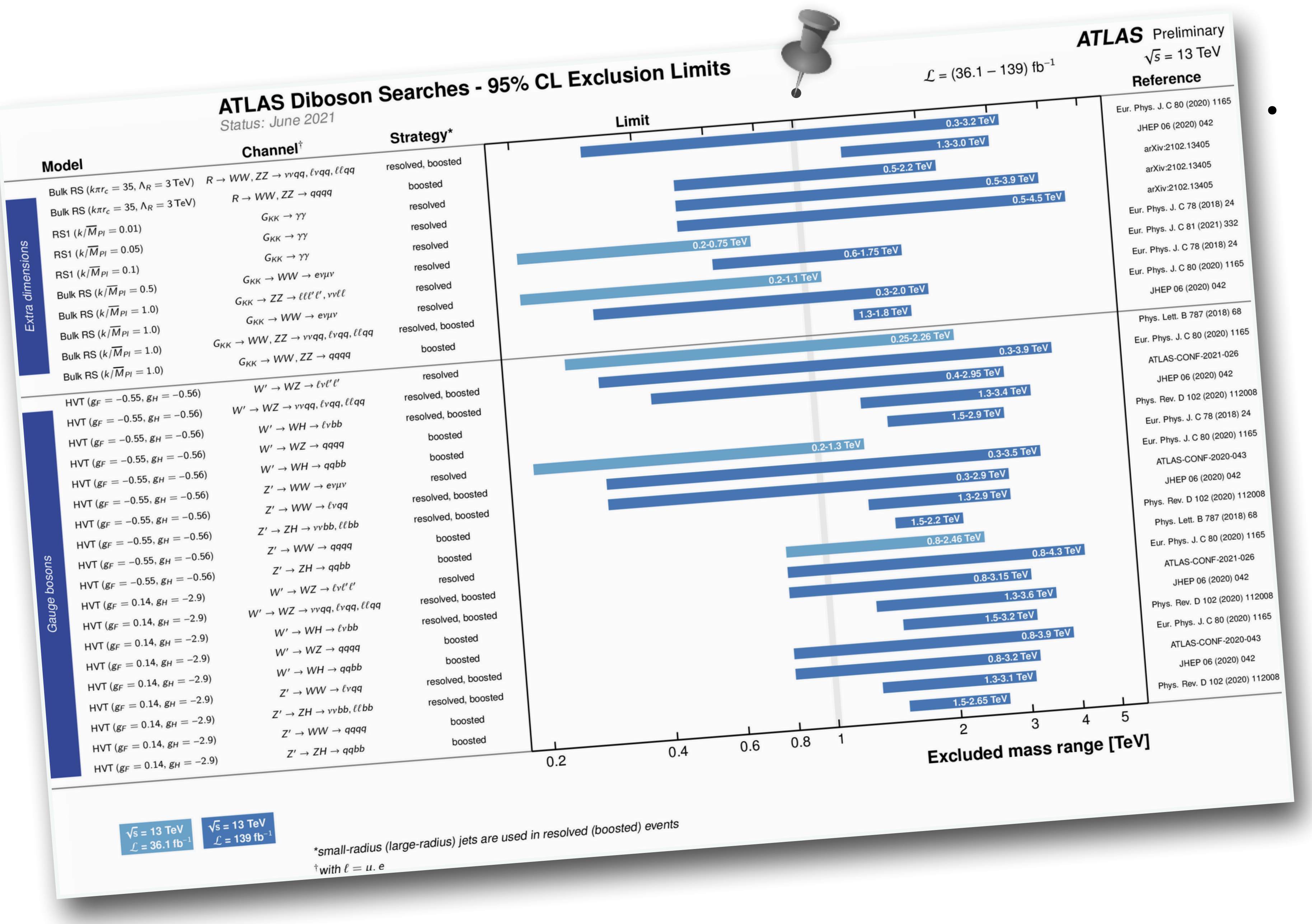
- UFO jets improve the jet mass resolution with up to a 45% at high p_T with respect to topo jets.
- p_T resolution of the UFO jets is worse than the p_T resolution of topocluster-based jets as different energy scales are used. (Using all hadronic scales for UFOs is planned!)





Summary

- The novel ATLAS jet reconstruction and tagging techniques provide significant improvements to searches for new heavy particles.
  - e.g., Improved jet reconstruction enhances sensitivities, improved taggers reduce backgrounds, etc.



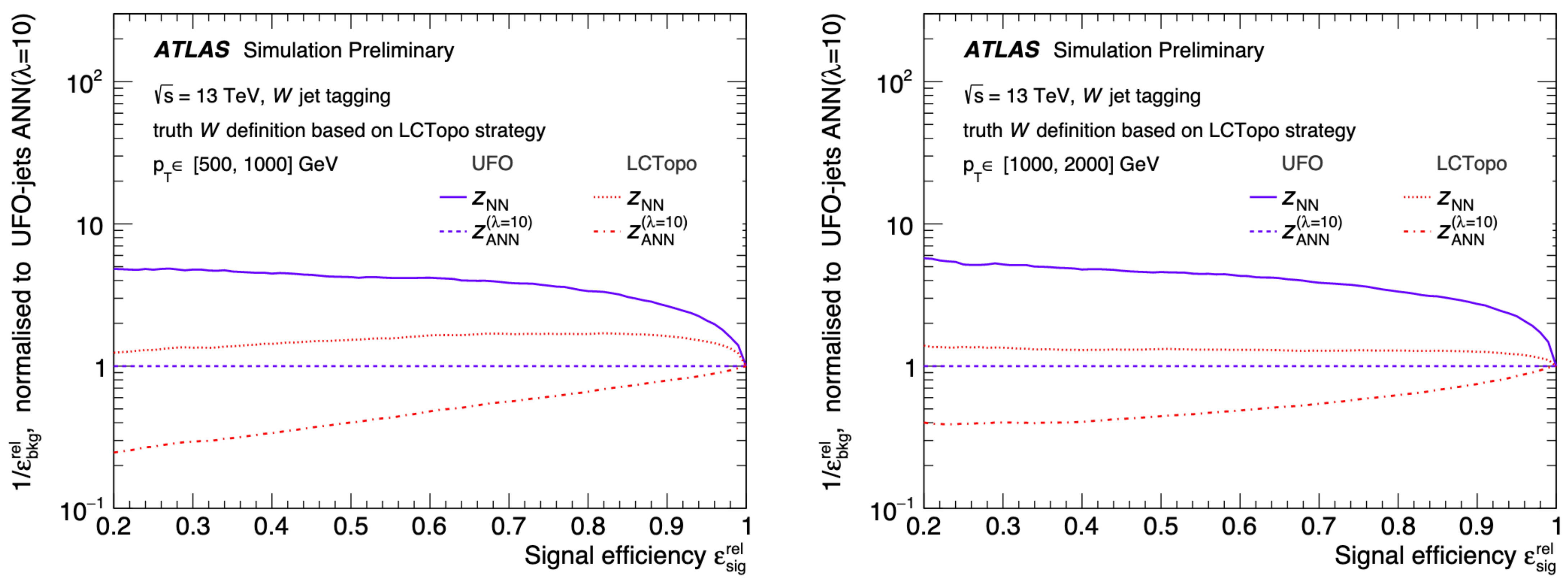
- Two heavy bosons searches using TCC jets have been shown.
  - Lot of heavy resonance searches are ongoing in ATLAS!

Backups

Advanced W/Z tagging techniques for UFO jets

ATL-PHYS-PUB-2021-029

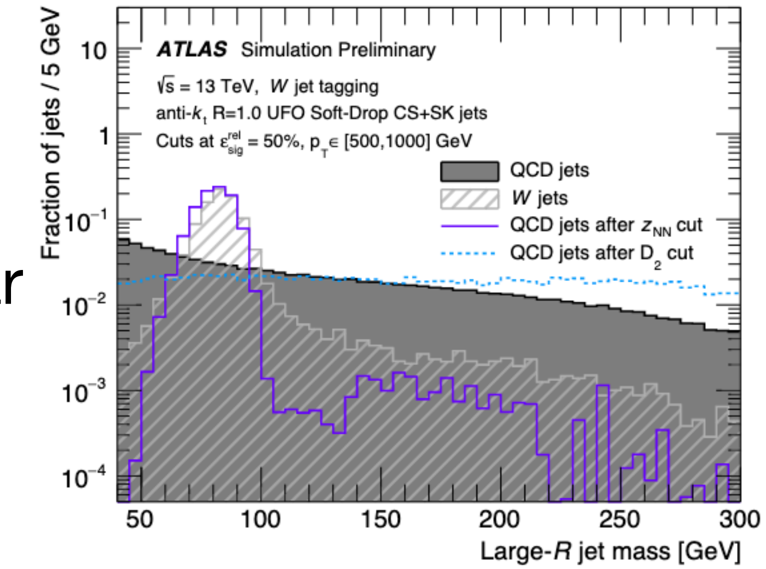
- W/Z tagger optimizations
  - Cut-based tagger (3-var tagger): m_J , D_2 and n_{trk}.
  - Deep neural network tagger.
    - Mass-decorrelated taggers.
  - Adversarial Neural Network.

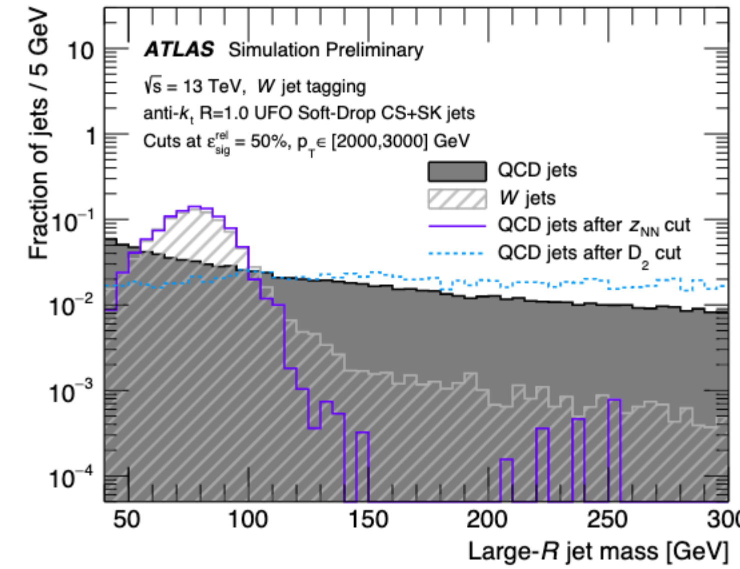


Analytical mass decorrelation

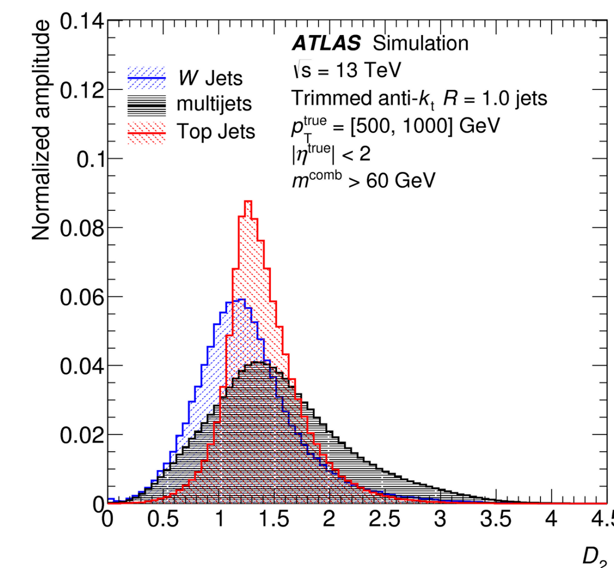
ATL-PHYS-PUB-2021-029

- Cuts on the DNN score yielding a background jets shape quite similar to the W-jets.





- D_2 : the ratio of the energy correlation functions of the jet constituents. The correlation functions are described by the angular separation of the jet constituents and its p_T.
  - Separation 3-prong from top jets and 2-prong decays of W jets. arXiv:1903.02942v2



- 2-dimensional regression fit using k-nearest neighbor (k-NN)

$D_2^{k\text{-NN}} = D_2 - D_{8\%}$

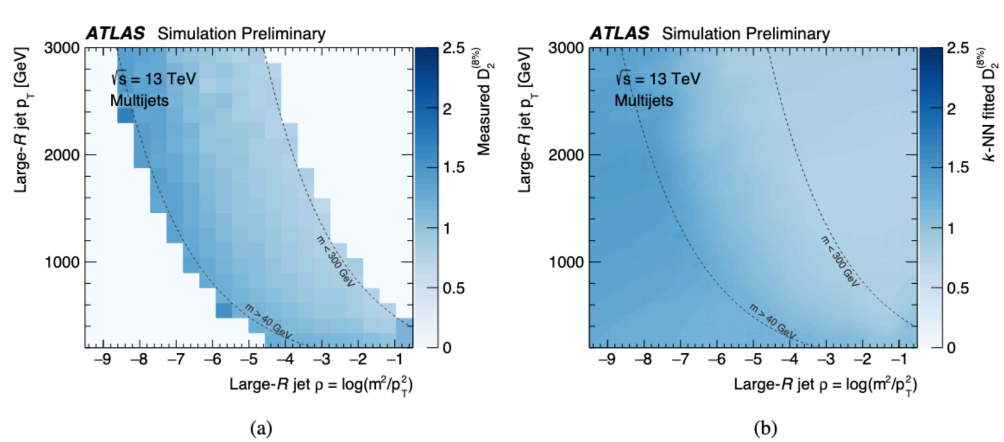
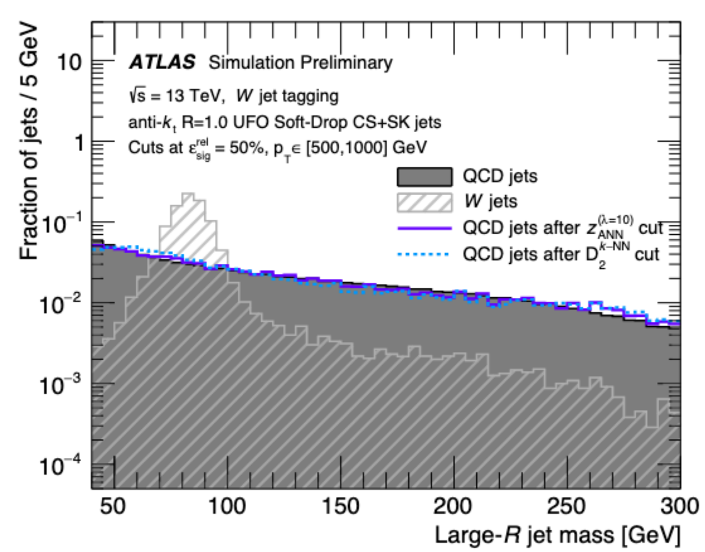
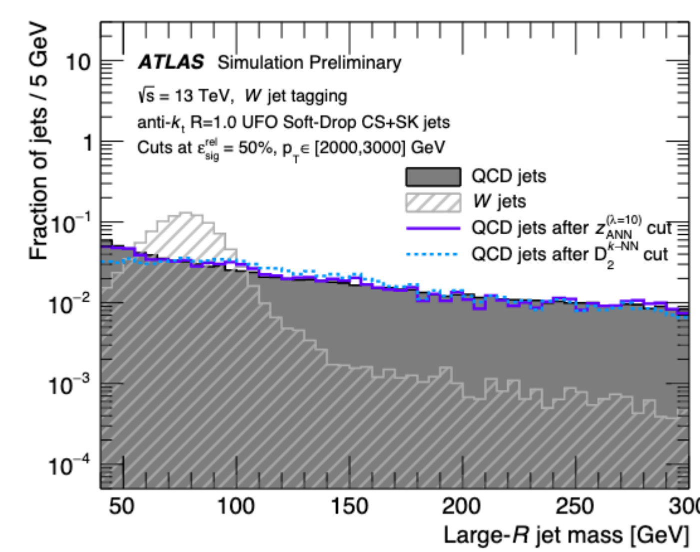


Figure 4: Optimal cut on D_2 to achieve $\epsilon_{\text{bkg}}^{\text{rel}} = 8\%$ as a function of ρ and p_T (a) before and (b) after the k-NN fit.





Search for heavy resonances decaying into a W and a Higgs boson

Table 2: A list of the signal and control regions included in the analysis.

Region	signal regions	control regions
	Resolved	
b-tags	1, 2 b-tag	1, 2 b-tag
Mass window	$110 < m_{jj} < 140$ GeV	$50 < m_{jj} < 110$ GeV || $140 < m_{jj} < 200$ GeV
	Merged	
b-tags	1, 2 b-tag	1, 2 b-tag
Mass window	$75 < m_J < 145$ GeV	$50 < m_J < 75$ GeV || $145 < m_J < 200$ GeV

Table 3: Topological and kinematic selections for each category as described in the text for the resolved and merged categories. (†) indicates the selection for the muons while the non indexed value is for electrons.

Variable	Resolved	Merged
Number of jets	≥2 central small-R jets	≥1 large-R jet ≥ 2 VR track jets (matched to leading large-R jet)
Leading jet p_{T} [GeV]	> 45	> 250
m_{jj}/m_J [GeV]	110–140	75–145
Leading lepton p_{T} [GeV]	> 27	> 27
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$> 80\ (40^{\dagger})$	> 100
$p_{\mathrm{T},W}$ [GeV]	$> \max\left[150,\ 710 - (3.3 \times 10^5\ \mathrm{GeV})/m_{WH}\right]$	$> \max\left[150,\ 394 \cdot \ln(m_{WH}/(1\ \mathrm{GeV})) - 2350\right]$
$m_{\mathrm{T},W}$ [GeV]	< 300	