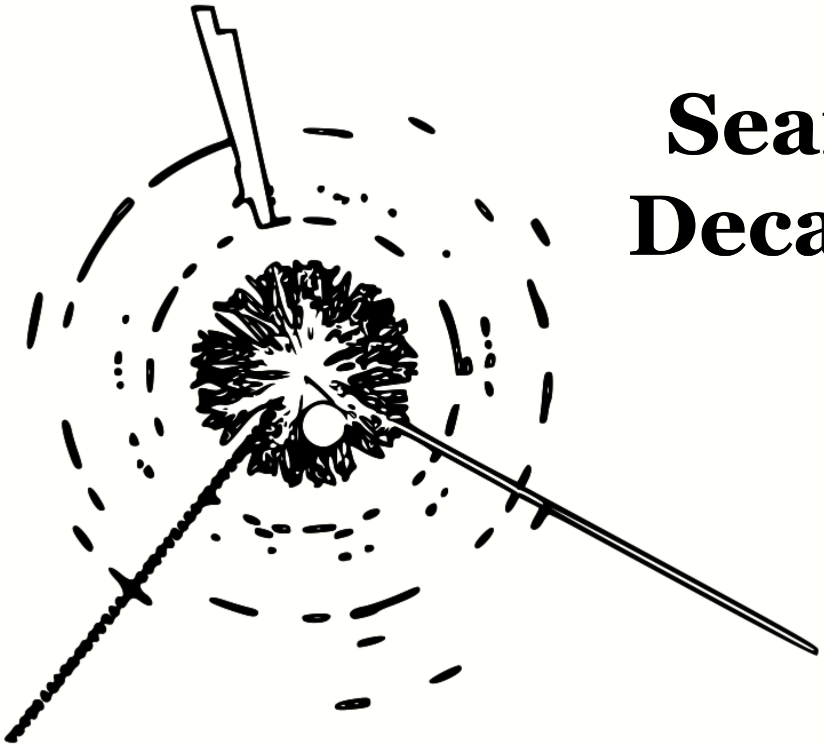

Searches for Resonances Decaying to Pairs of Heavy Bosons in ATLAS

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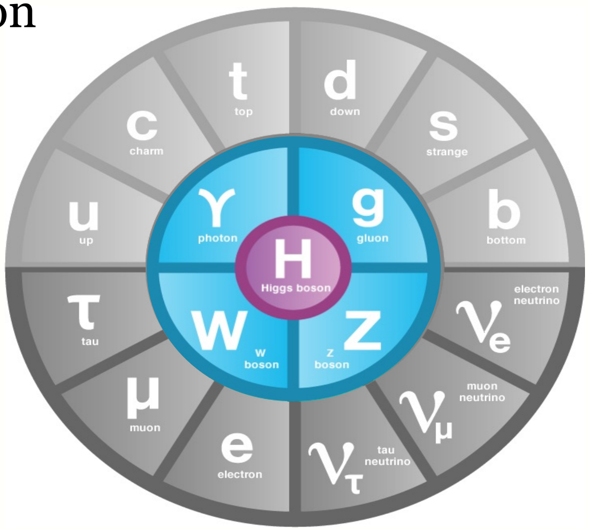
ATLAS EXPERIMENT

Introduction

- The Standard Model (SM) of particle physics has been extensively developed and tested over the last decades
- **Beyond the Standard Model (BSM)** theories have been predicted heavy resonances to decay to SM bosons
  - **Extended Higgs sector:** 2HDM, Georgi-Machacek (GM)
  - **Seesaw model (type II)**
  - **Extra Dimensions:** Spin-2 graviton, Spin-0 radion
  - **Simplified Model:** Heavy Vector Triplets (HVT)

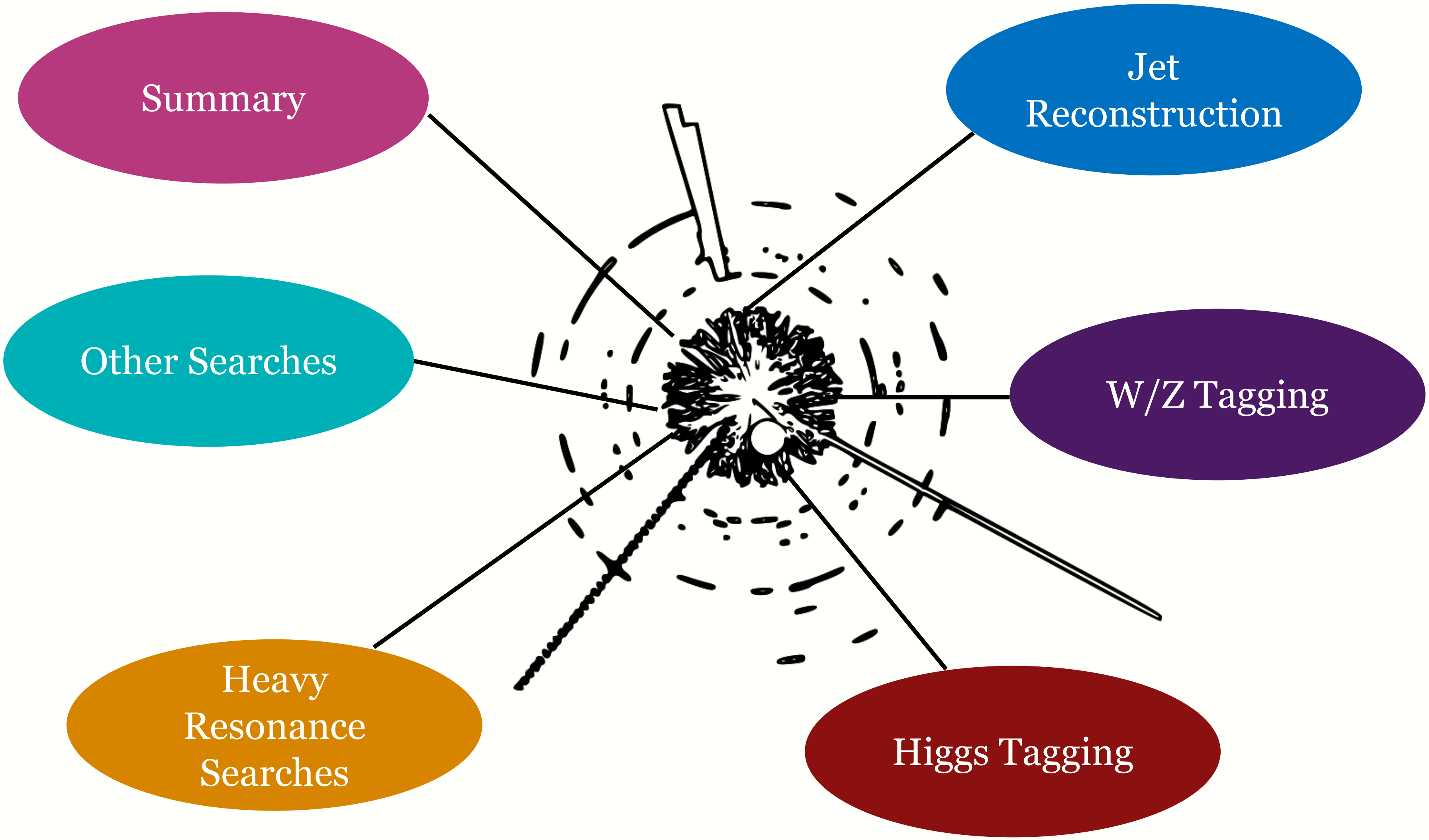
This talk presents:

- Summary of **jet reconstruction and boson tagging techniques** used to probe hadronically decaying final states
- Analyses presented use the **full Run-2 dataset** and contain **heavy bosons in the final state**

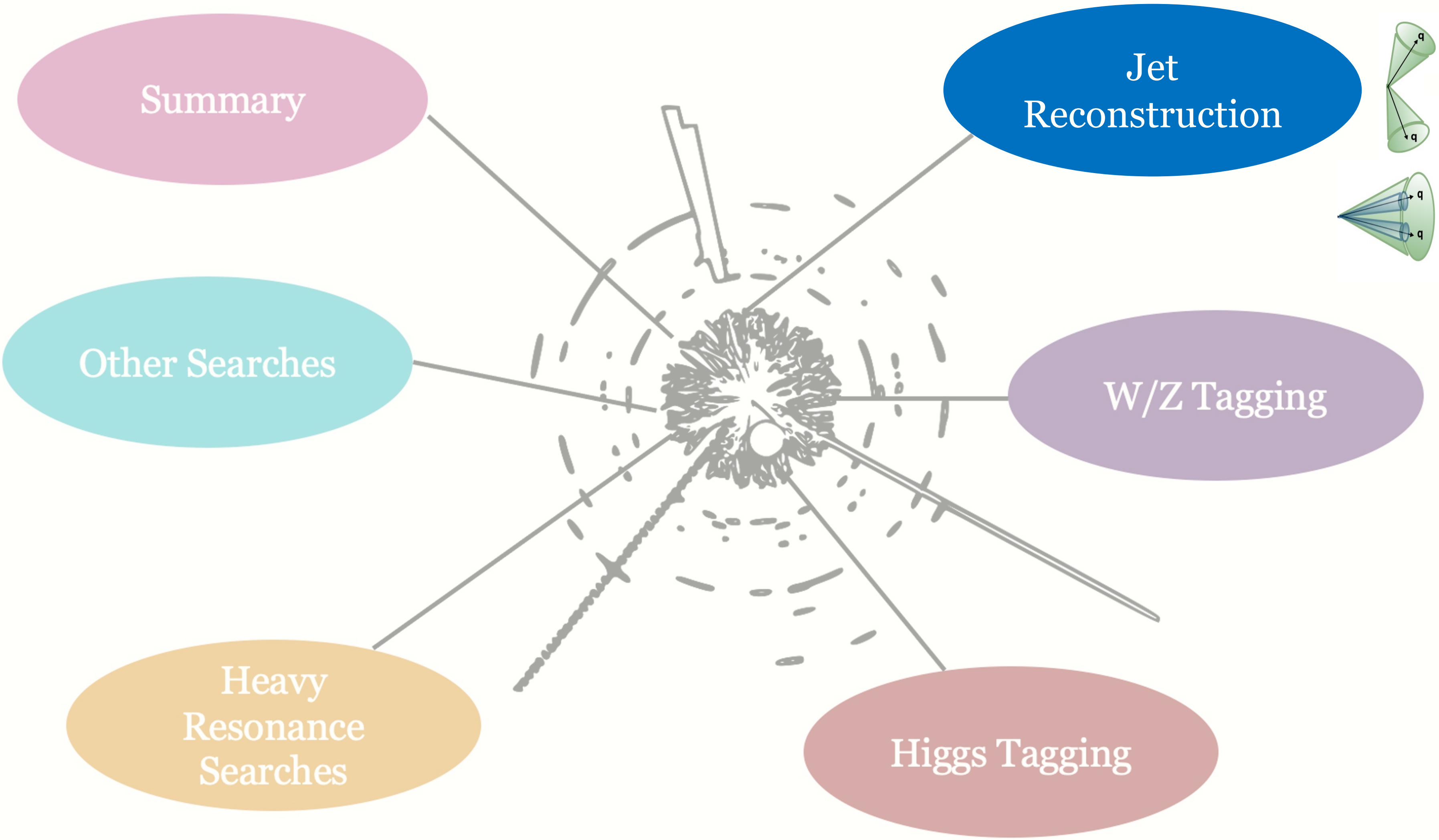


BSM models predicted to decay to SM bosons (γ, W, Z, H)

Setting the stage

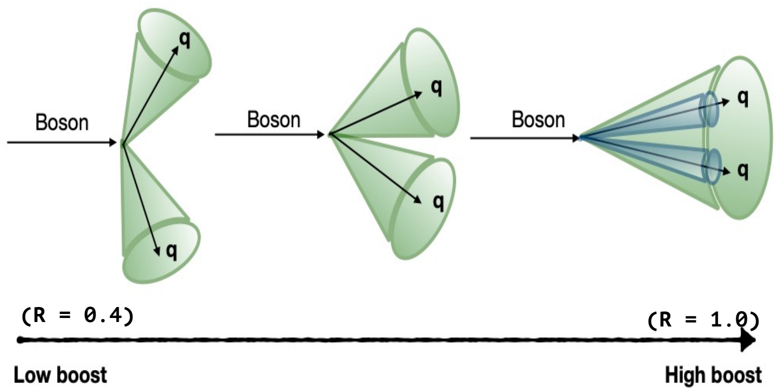


Setting the stage



Summary of Jet Reconstruction Techniques

What is a Jet?



Left: a slow W, Z or H-boson decaying to a pair of quarks, **each resulting in a jet**

Right: At high momentum "boost", the two jets merge into **one single, wide jet** with sub-structure corresponding to the two original quarks

Event data processing → **Particle reconstruction** → **Jet clustering** → **Pile-up mitigation/Grooming**

Event data processing: Converted to a format for analysis, e.g., reconstructed tracks and energy deposits

Particle reconstruction: Individual particles are reconstructed using information from detector subsystems

Jet clustering: Group reconstructed particles into jets based on their momenta and spatial separation in the detector.

Pile-up mitigation/Grooming: Reduce overlap of events / refine the substructure of components to help improve the sensitivity

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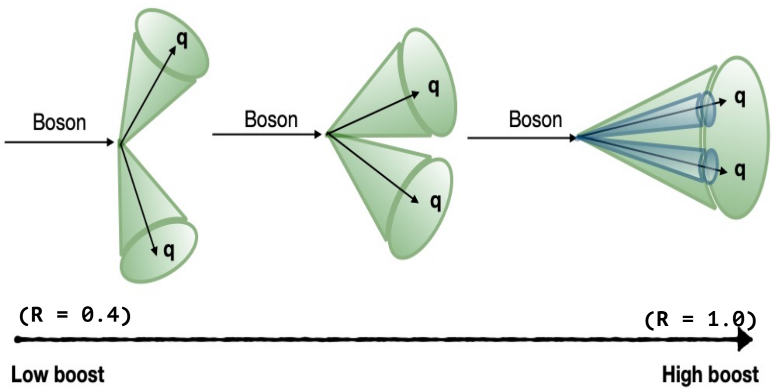
Summary of Jet Reconstruction Techniques

What is a Jet?



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- **Event data processing**: Converted to a format for analysis, e.g., reconstructed tracks and energy deposits
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Focus on this techniques today

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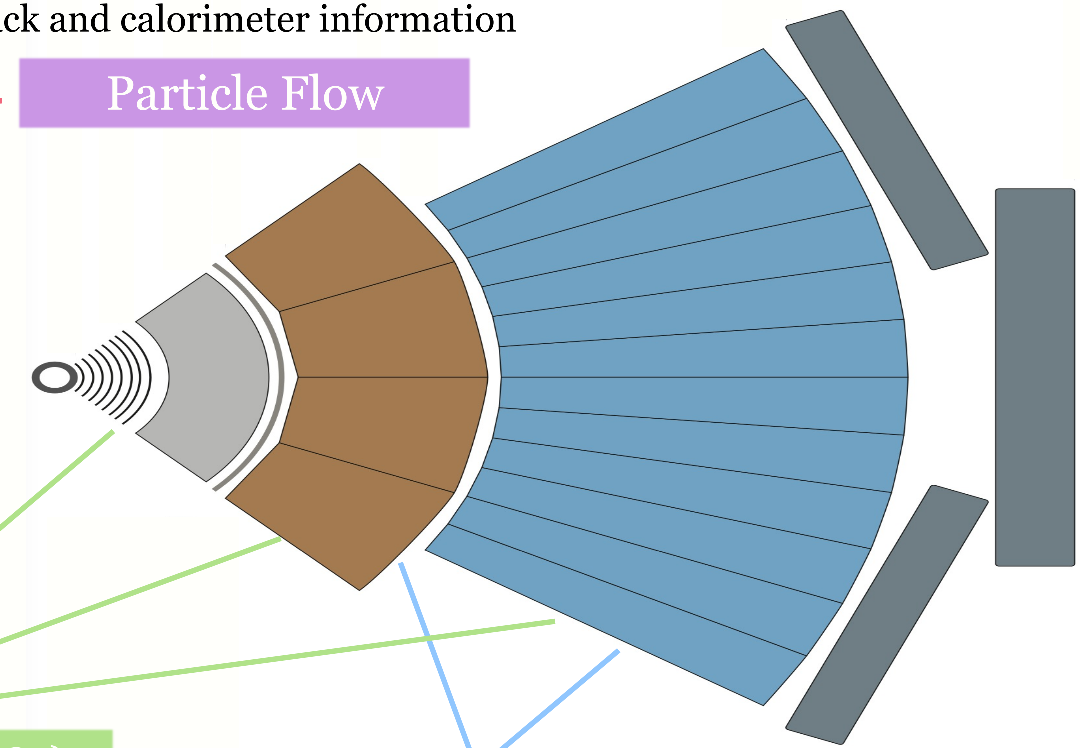
Summary of Jet Reconstruction Techniques

These reconstruction algorithms are used in combination with jet clustering algorithms (e.g., Anti-k_T)

Improves stability and jet energy and mass resolution by combining track and calorimeter information

Particle Flow



Unified Flow Objects (UFO)

Combination of Particle Flow and TCCs Objects to achieve optimal overall performance across the full kinematic range. Best performance

Track – CaloClusters (TCCs)

Combines calorimeter- and inner-detector information. Optimized for jet substructure reconstruction performance in high-p_T jets

Topological Clusters

- Most common in ATLAS
- Calorimeter-based technique that groups adjacent cells with significant energy deposits

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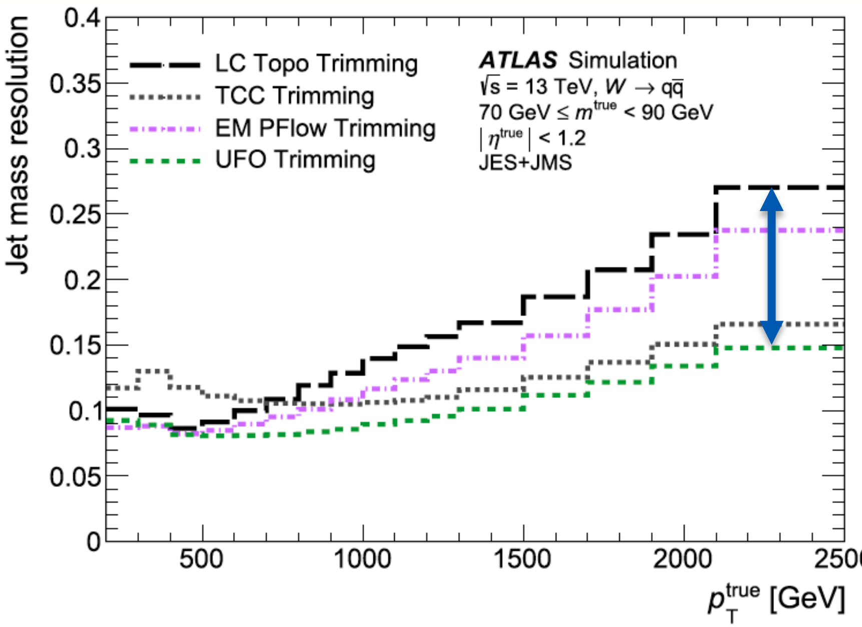
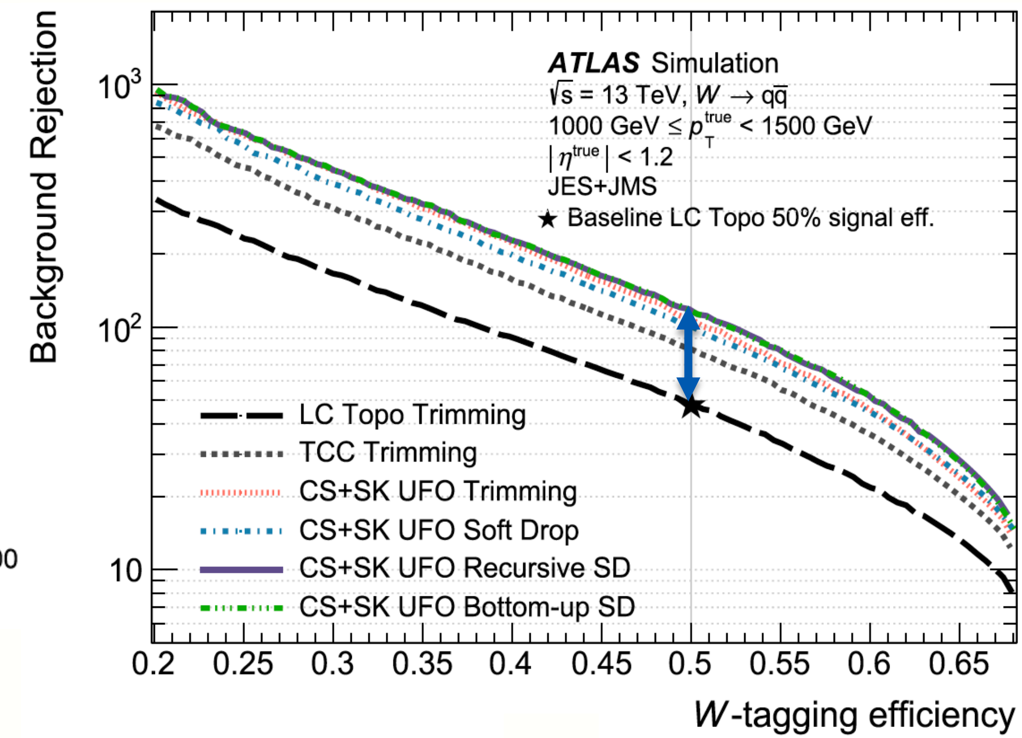
Performance of Jet Reconstruction Techniques



UFO jets provide an **improved jet mass resolution** with up to **45% improvement compared to Baseline (LC Topo Trimming)** at high p_T

$$\text{Improvement} = \frac{\text{new value} - \text{baseline value}}{\text{baseline value}} * 100\%$$



UFO inputs can **increase the background rejection** of jet taggers by up to **120% compared to Baseline (LC Topo Trimming) for a simple W-tagger** at 50% signal efficiency

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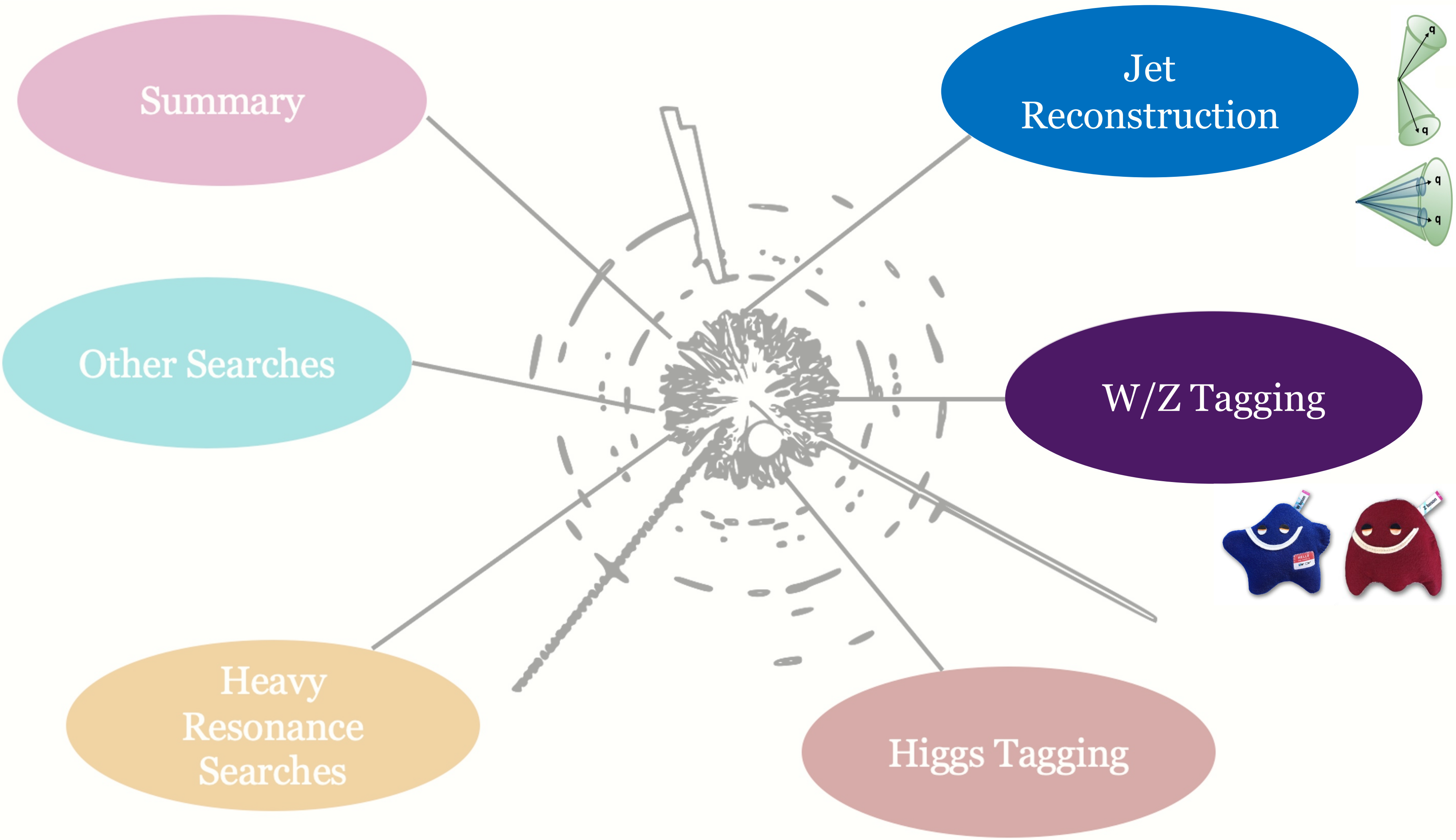
Setting the stage

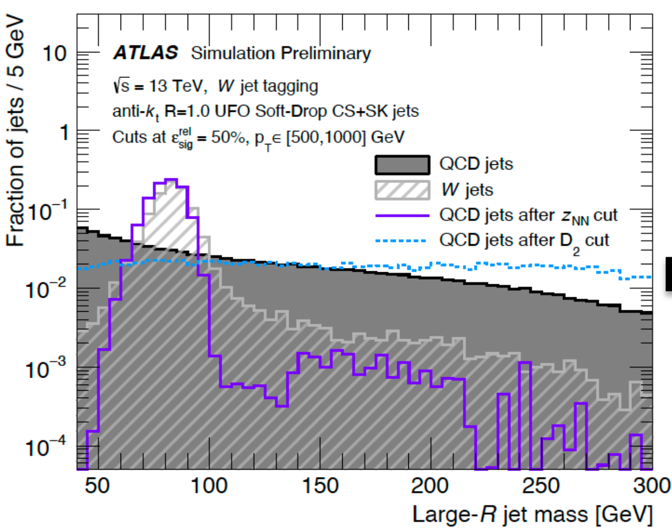


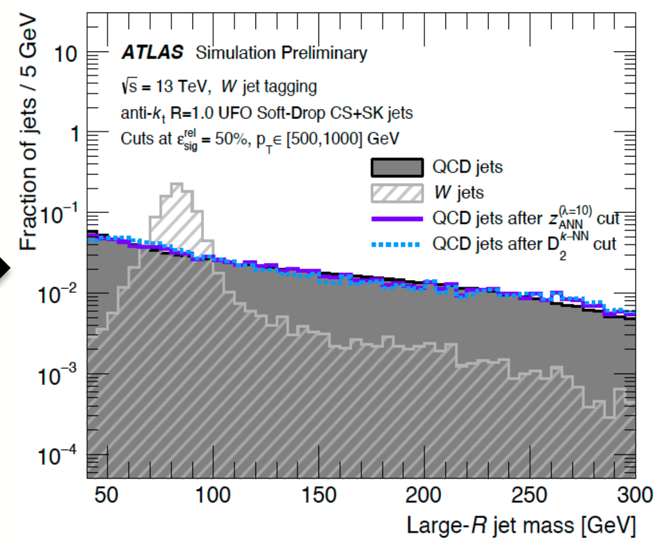
Summary of W/Z taggers

Approach	Highlights
Cut-based tagger (m_J, $D_2^{\beta=1.0}$, n_{trk})	Based on rectangular cuts on substructure variables. Optimized for 50% WP
Deep Neural Network-based tagger	Substructure variables trained to separate **W-jets from bkg-jets**. Improved wrt. LCTopo jet DNN tagger by a factor of 2 to 4
Mass-decorrelated taggers	Two approaches in decorrelating jet mass (m_J): • Optimal Cut on D_2 using k-NN • Adding an "adversary" neural network (ANN) to compete with the DNN-based tagger

Variable	Description	Reference
D_2, C_2	Energy correlation ratios	[30]
τ_{21}	N-subjettiness	[41]
R_2^{FW}	Fox-Wolfram moment	[42]
$\mathcal{P}$	Planar flow	[43]
a_3	Angularity	[44]
A	Aplanarity	[45]
Z_{cut}, $\sqrt{d_{12}}$	Splitting scales	[33, 46]
$Kt\Delta R$	k_t-subjet ΔR	[47]

Variables used for DNN based tagger





Decorrelating jet mass with D2 significantly improves distribution of bkg jet vs. W-jets

ATL-PHYS-PUB-2021-029, ATL-PHYS-PUB-2020-017, ATL-PHYS-PUB-2018-014

Performance of W/Z taggers

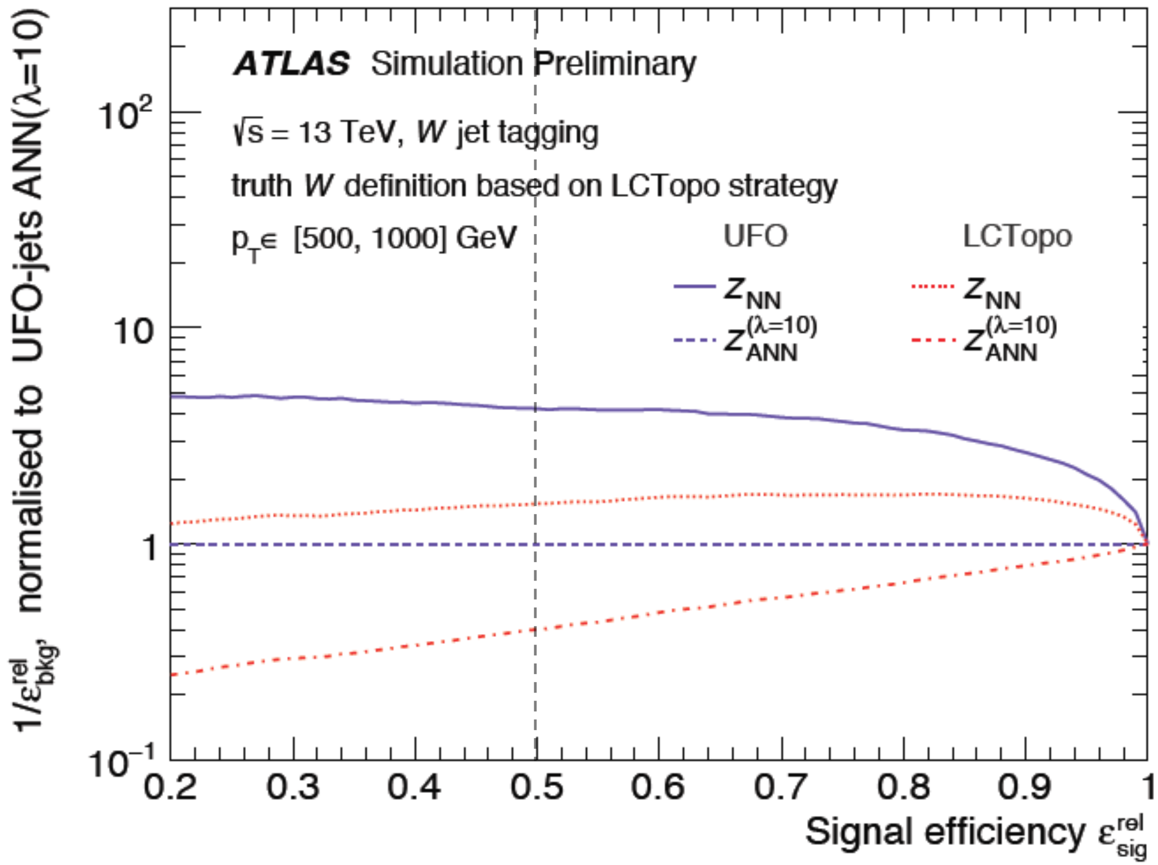
Test 1: Performance of UFO Jets vs. LCTopo Jets for DNN and ANN

Uses the same truth labeling and selection cuts for comparison

y-axis: precision of the background rate estimation (normalized to $Z_{ANN}^{(\lambda=10)}$)

x-axis: relative signal efficiency

Improved by a factor of ~ 3 for both the low and high-pT range for the DNN taggers, and a factor of ~ 2.5 for the ANN taggers.



ATL-PHYS-PUB-2021-029, ATL-PHYS-PUB-2020-017, ATL-PHYS-PUB-2018-014

Performance of W/Z taggers

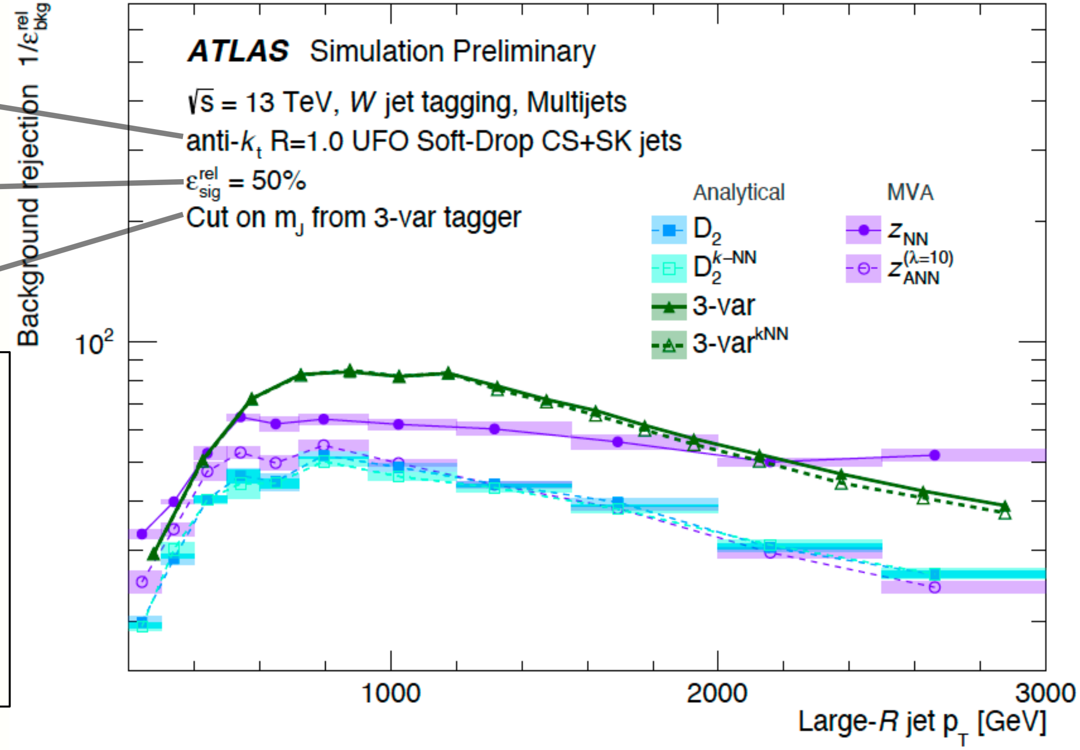
Test 2: Performance of mass cut, DNN, and mass-decorrelated approach using UFO Jet Inputs

Jet reconstruction, cluster, and grooming algorithm used

Signal efficiency WP

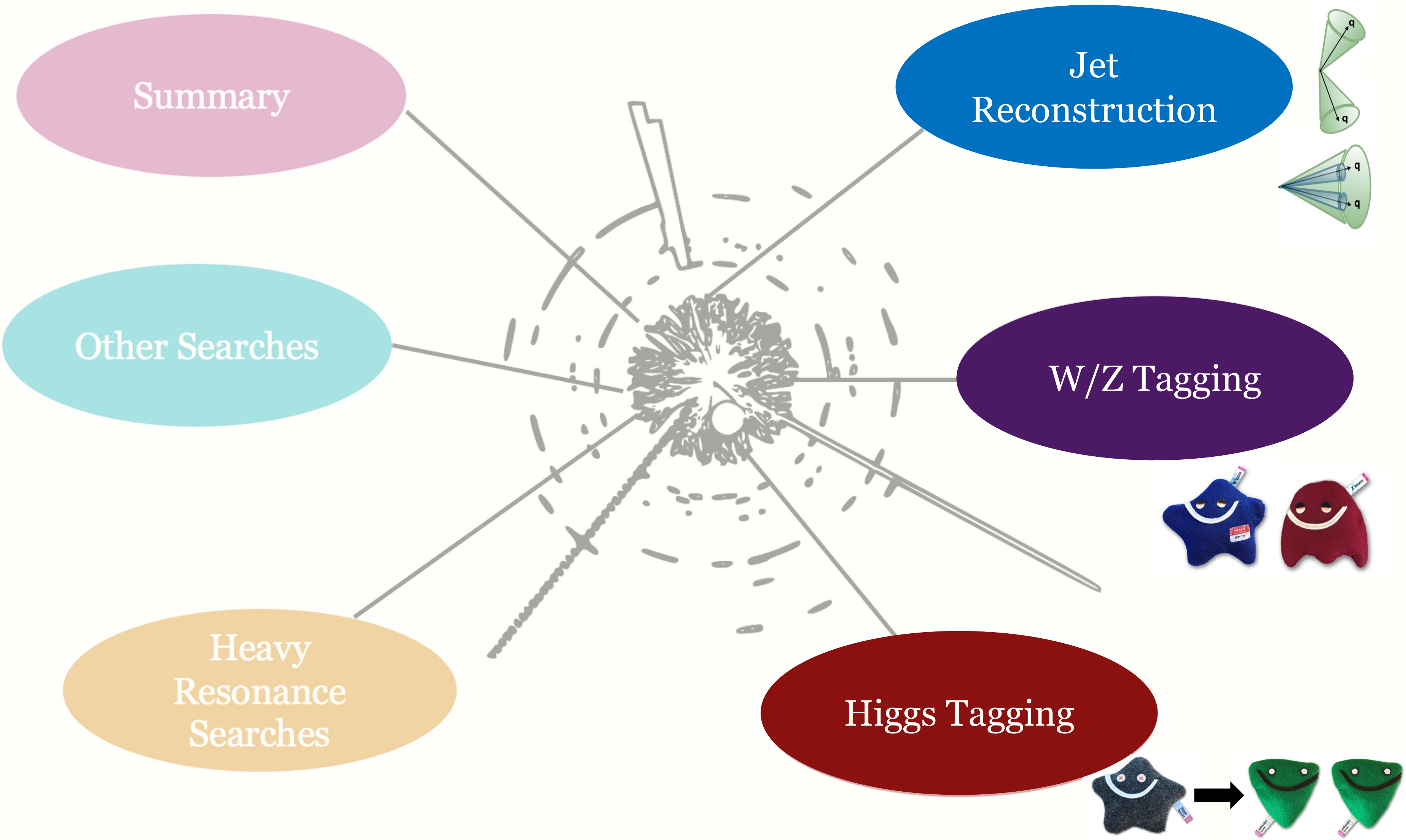
Mass window cut applied on jets

$3-var$: m_J, $D_2^{\beta=1.0}$, n_{trk}
$3-var^{k-NN}$: 3-var tagger using k-nearest neighbors (k-NN)
D_2: D_2-cut based tagger
D_2^{k-NN}: D_2-cut based tagger with k-NN
z_{NN}: D_2-cut based tagger
$z_{NN}^{\lambda=10}$: D_2-cut based tagger with k-NN



- The performance of the $3-var$ tagger is almost equivalent to the $3-var^{kNN}$ tagger
- The bkg-jet rejections of the 3-var taggers are slightly better than the DNN tagger, while the DNN tagger is significantly better than D_2 -only and D_2^{k-NN}
- n_{trk} not used in MVA training: could improve DNN and ANN taggers in the future

Setting the stage



Summary Higgs ($H \rightarrow b\bar{b}$) Tagging

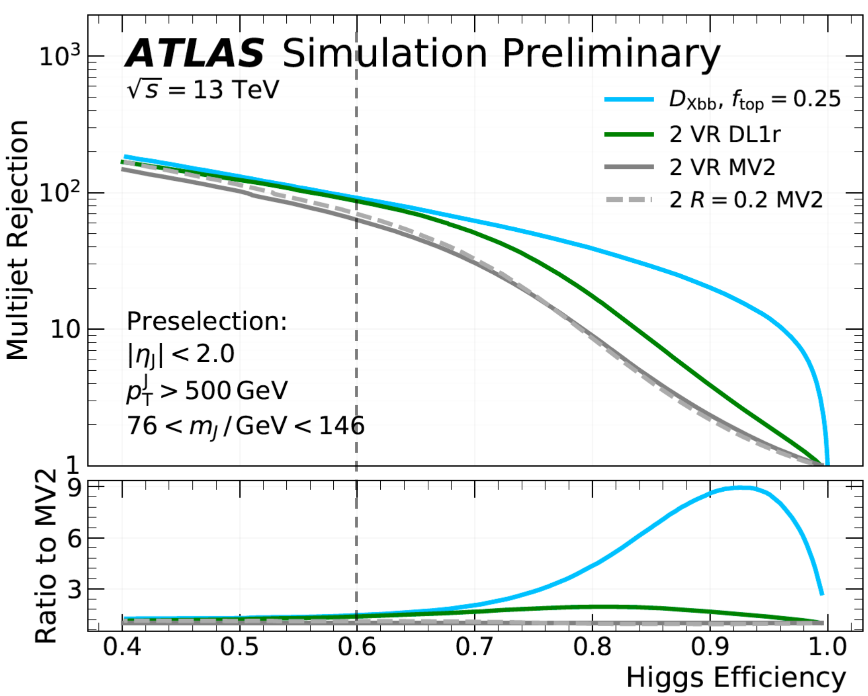
$H \rightarrow b\bar{b}$ has the highest branching ratio and are crucial for improving sensitivity to BSM searches

3 key-ingredients for b-jet identification:

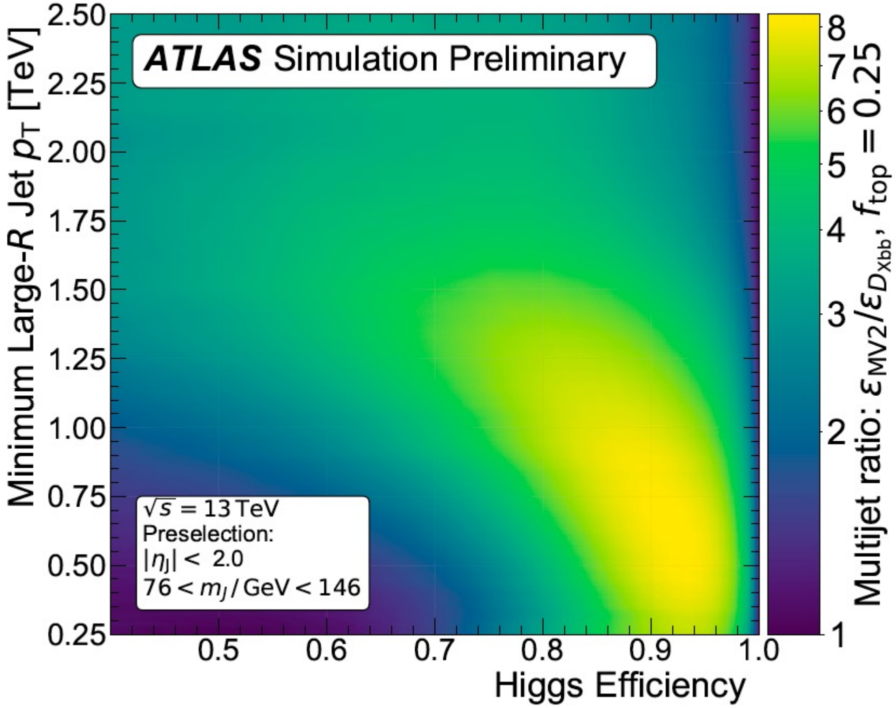
- Inner Detector Tracks: tracks can be identified and distinguished from other tracks in the detector. (p_T > 500 MeV are considered)
- Primary Vertex: Reference point for tracks and vertex displacement calculation
- Hadronic Jets: b-quarks produce more massive jets (higher p_T), can impose cuts to identify jets that are likely to have originated from b-quarks.

Approach	Highlights
MV2	Boosted Decision Tree (BDT)-based algorithm. Advantageous for less expensive computations
DL1/DL1r	Deep Neural Networks (DNN)-based algorithm. Outperforms MV2 in some cases
X_{bb} (FFNN-based)	Feed Forward Neural Network (FFNN)-based algorithm. Uses large-R jet kinematic properties (p_T, η), and flavor information of up to three associated variable-radius (VR) track-jets.

Performance Higgs ($H \rightarrow b\bar{b}$) Tagging



Multi-jet rejection for $D_{X_{bb}}$ at ε_{sig}^{rel}= 60% is 1.4 times better than MV2 tagger and relatively similar performance with DL1r tagger

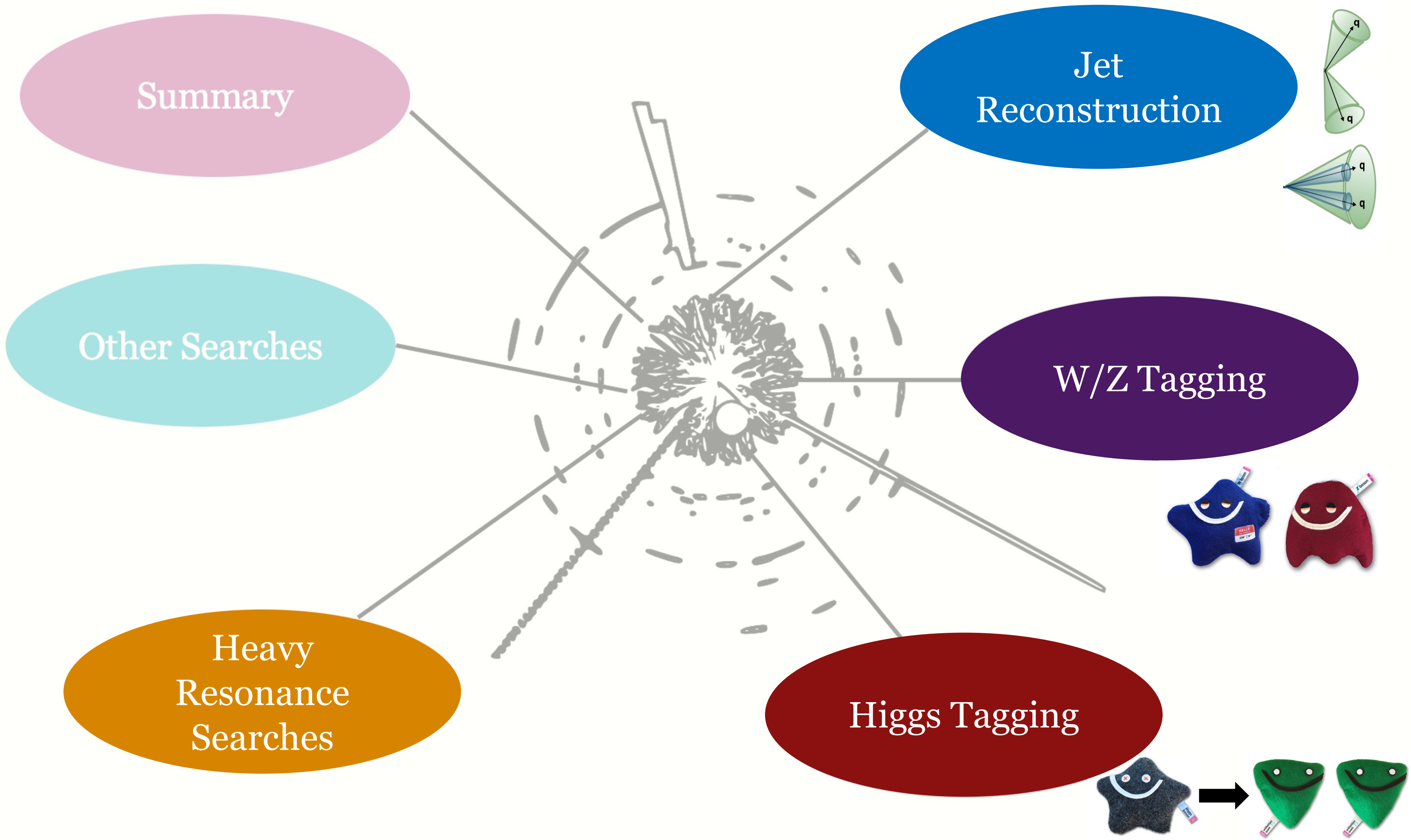


Z-axis: yield_baseline/yield_new_tagger

- Compare rejection power: when numerator is greater than denominator, that means improvement

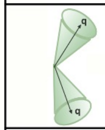
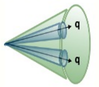
$D_{X_{bb}}$ becomes more significant at higher p_T

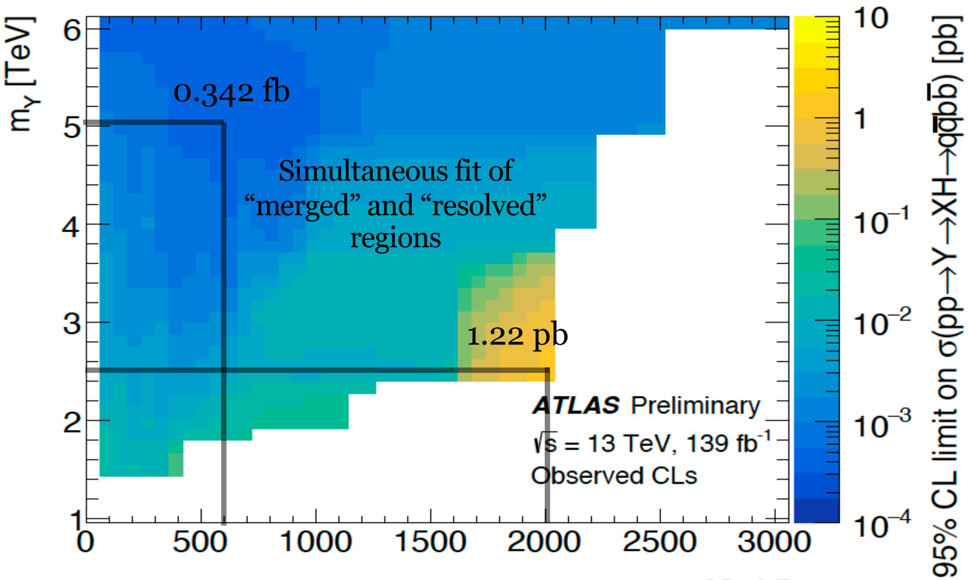
Setting the stage

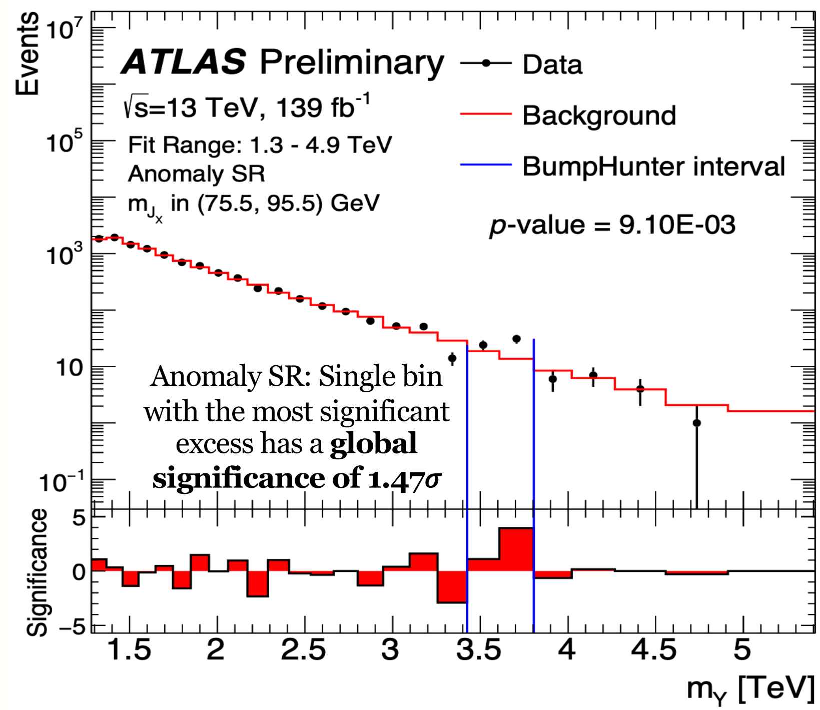


Search for Y→X + Higgs → $q\bar{q}b\bar{b}$

- Search for a **heavy resonance Y** decaying to a SM Higgs ($b\bar{b}$) and **another particle X** ($q\bar{q}$)
- **Novel anomaly detection** based on jet-level score for tagging boosted X **(Anomaly SR)**
  - Additional "resolved" and "merged" regions to improve reconstruction of less boosted X
- **HVT model** used as **benchmark** for cross section upper limits

	Reconstruction
	Two resolved small-R jets: Particle Flow + Anti-k_T algorithms
	One boosted large-R jet: Track-CaloCluster (TCC) + Anti-k_T + trimming algorithms
	X_{bb} Double Tagging Algorithm





ATLAS-CONF-2022-045

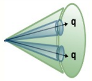
Generic Search for a Heavy Higgs boson (VH)

- Search for heavy Higgs boson produced in VH channel with same-sign di-lepton final state

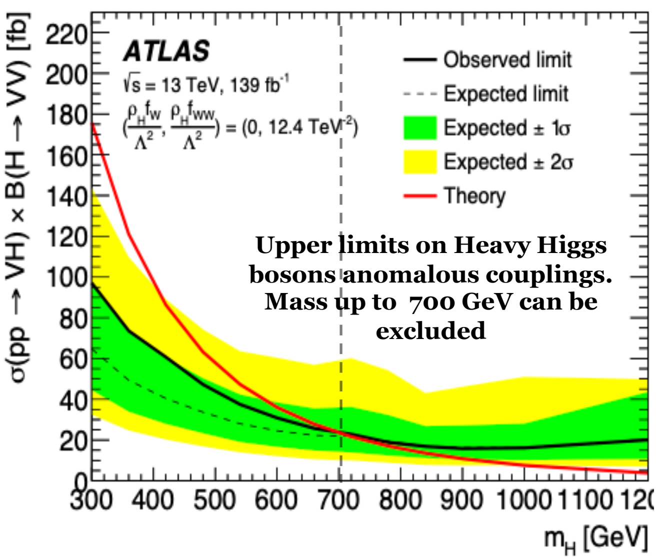
$$W^{\pm}H \rightarrow W^{\pm}\, W^{\pm}\, W^{\mp} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu q q$$

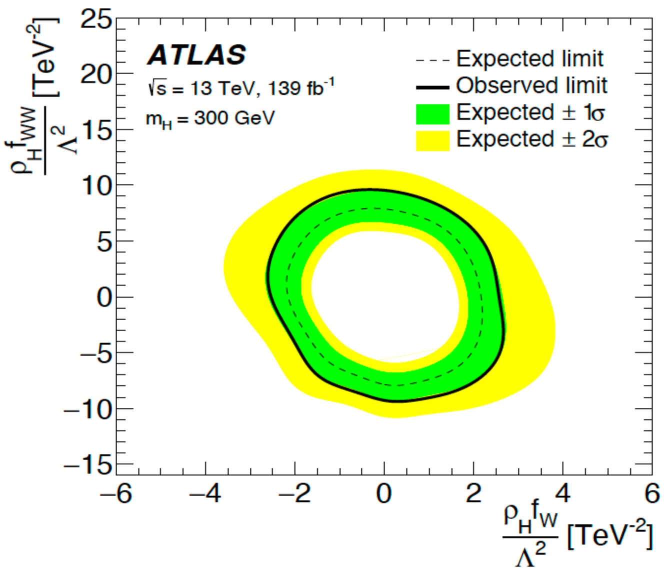
(H is heavy Higgs not the SM Higgs *h*)

- Highest signal sensitivity among other VH decay channels
- Sizeable Branching Fraction for $H \rightarrow W^{\pm}\, W^{\mp}$ decay

	Reconstruction
	Two resolved small-R jets: Particle Flow + Anti-k_T algorithms
	One boosted large-R jet: Topological Cluster + Anti-k_T + trimming algorithms
	For boosted large-R jets: Cut-based tagger using jet mass (m_J), energy correlation ratio ($D_2^{\beta=1.0}$), and number of tracks (n_{trk}) at 80% WP
	DL1r algorithm based on a Feed-Forward NN at 85% WP

 $H \rightarrow Zh$ decay negligible in this analysis

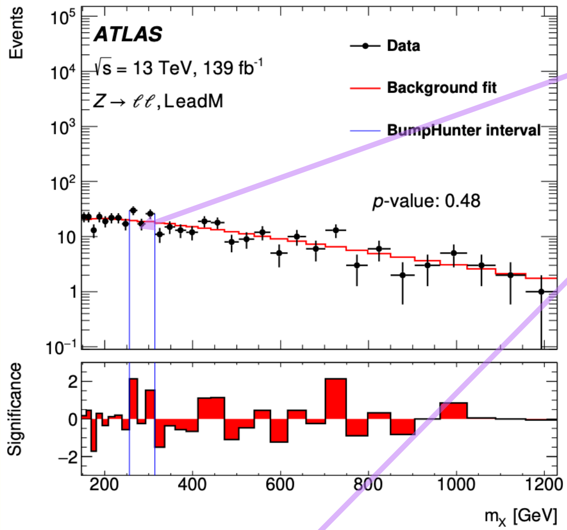


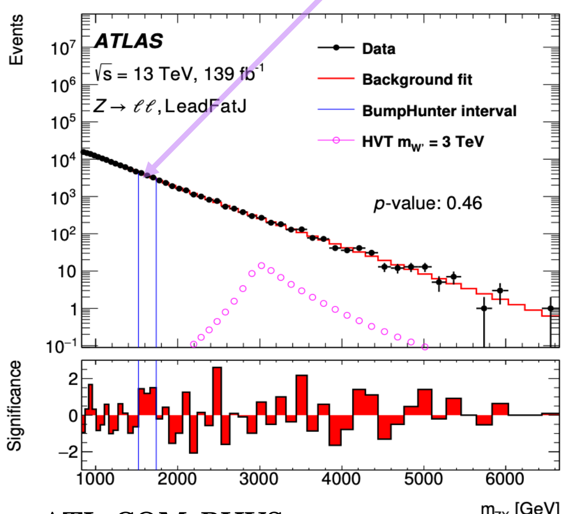


Upper limits derived as a function of **Heavy Higgs mass** and **coupling strengths to vector boson**

Exclusion Contours show observed result is consistent with the expected result within 1 sigma uncertainty

Generic Search for Heavy Z boson decays

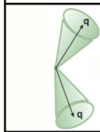
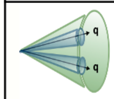




ATL-COM-PHYS-2022-071

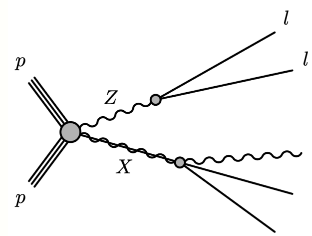
Largest Excess:
m_X spectrum: 280 GeV in the LeadM category

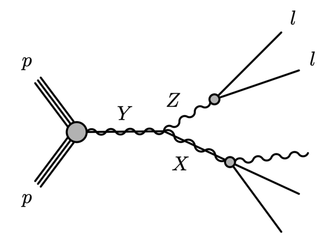
m_{ZX} spectrum: 1.6TeV in the LeadFatJ category

	Reconstruction
	Two resolved small-R jets: Particle Flow + Anti-k_T algorithms
	One boosted large-R jet: Topological Cluster + Anti-k_T + trimming algorithms
	DL1r algorithm based on a Feed-Forward NN at 85% WP

- Generic resonance search for boosted leptonically decaying Z bosons

$$p\bar{p} \rightarrow Z + X$$
$$p\bar{p} \rightarrow Y \rightarrow Z + X$$





- Six mutual exclusive categories for X: e, μ, γ, b-jet, small(large)-R jet
- X (m_X) or Y (m_{ZX}) spectra probed for local excesses from 200 GeV to 6 TeV
- Gaussian-shaped signals and HVT as benchmarks

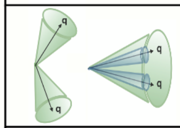
Search for Heavy Resonance Decaying to W/Z + Higgs

- Search for new resonances decaying into a Z or W boson and a SM Higgs boson

$$\mathbf{W'/Z' \rightarrow W/Z + h}$$

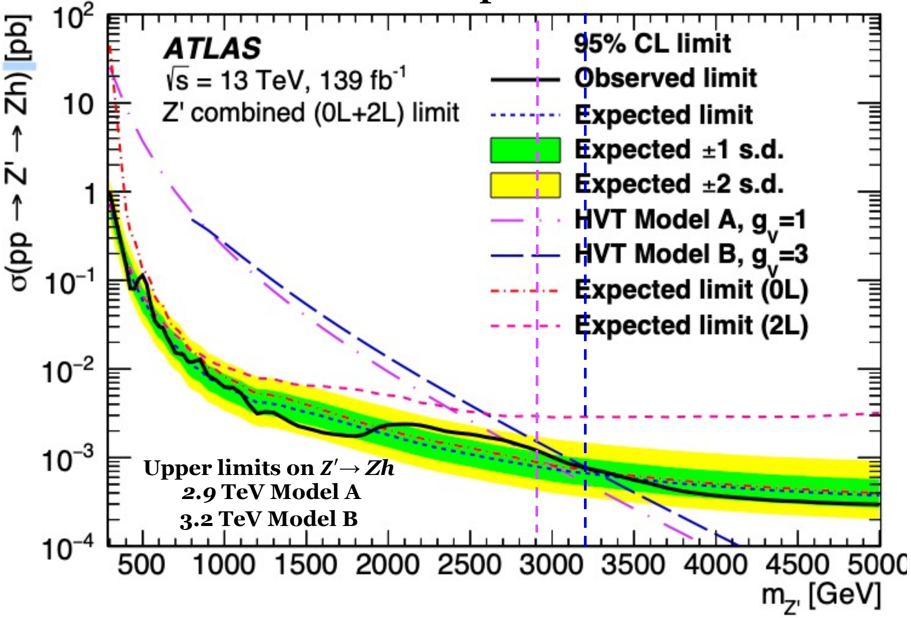
$$(\boldsymbol{W/Z \rightarrow \ell\nu / \ell\ell / \nu\nu} + \boldsymbol{h \rightarrow b\bar{b}})$$

$$\boldsymbol{A(+b\bar{b}) \rightarrow Z + h\ (Z \rightarrow \ell\ell / \nu\nu} + \boldsymbol{h \rightarrow b\bar{b})}$$

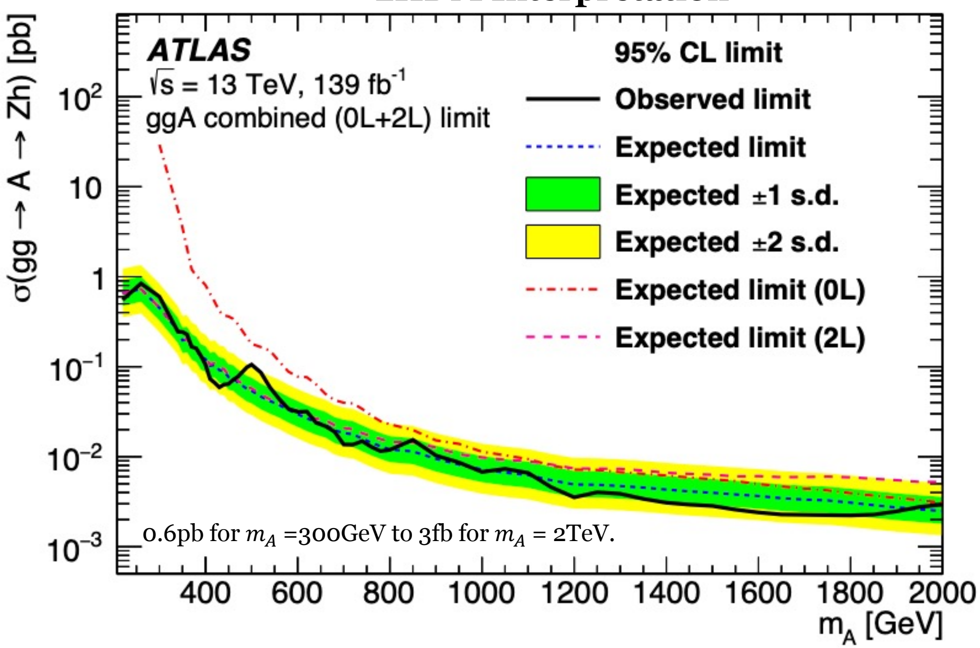
	Reconstruction
	Track-CaloCluster (TCC) + Anti-k_T + trimming algorithms (R = 0.4 to R = 1.0)
	MV2c10 b-tagging algorithm

- Interpretations using HVT and 2HDM

HVT Interpretation



2HDM Interpretation



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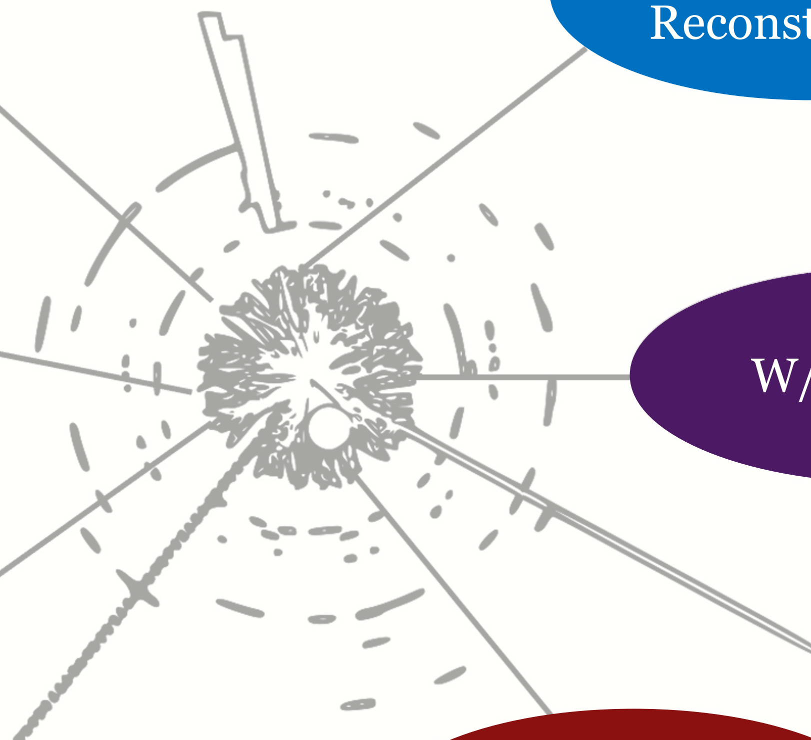
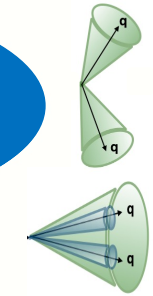
Setting the stage



Summary

Jet Reconstruction



Other Searches

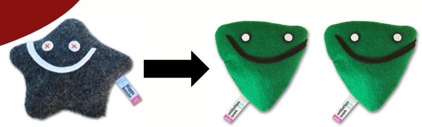
ZZ, WW, WZ

$HH \rightarrow b\bar{b}\gamma\gamma, b\bar{b}\tau^{+}\tau^{-}, 4b$

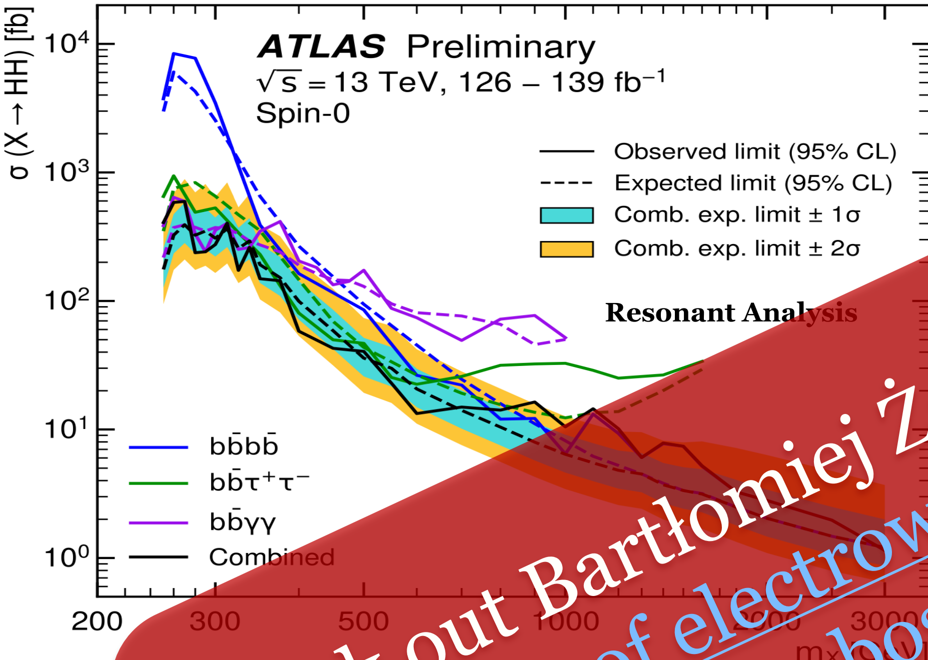
W/Z Tagging

Heavy Resonance Searches

Higgs Tagging



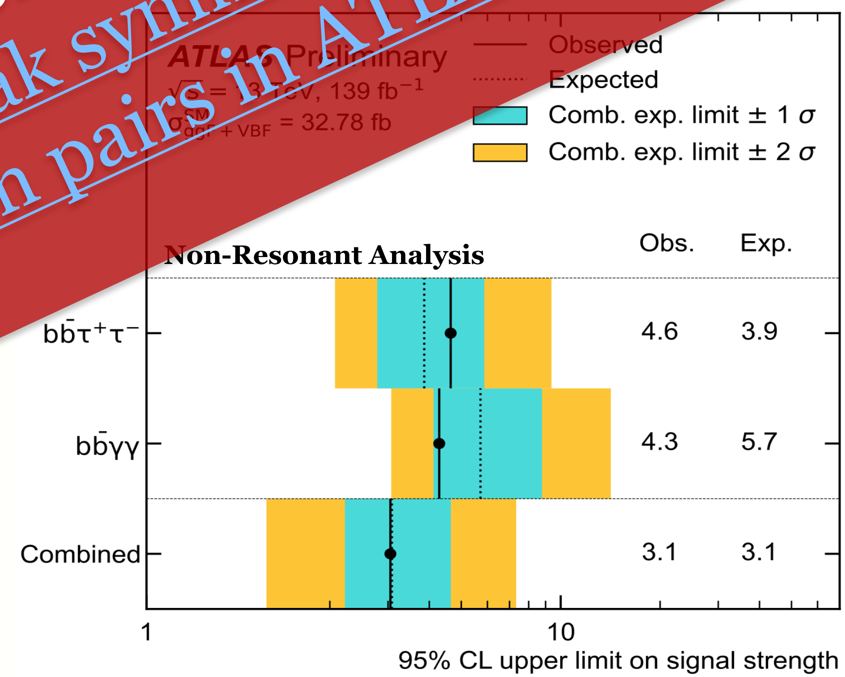
Combination of Searches Higgs boson Pairs



Combination of searches for non-resonant and resonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ decay channels

- The obs. (exp.) combined 95% C.L. on the SM HH cross-section and signal strength is 92 fb (92 fb) and 3.1 (3.1) respectively

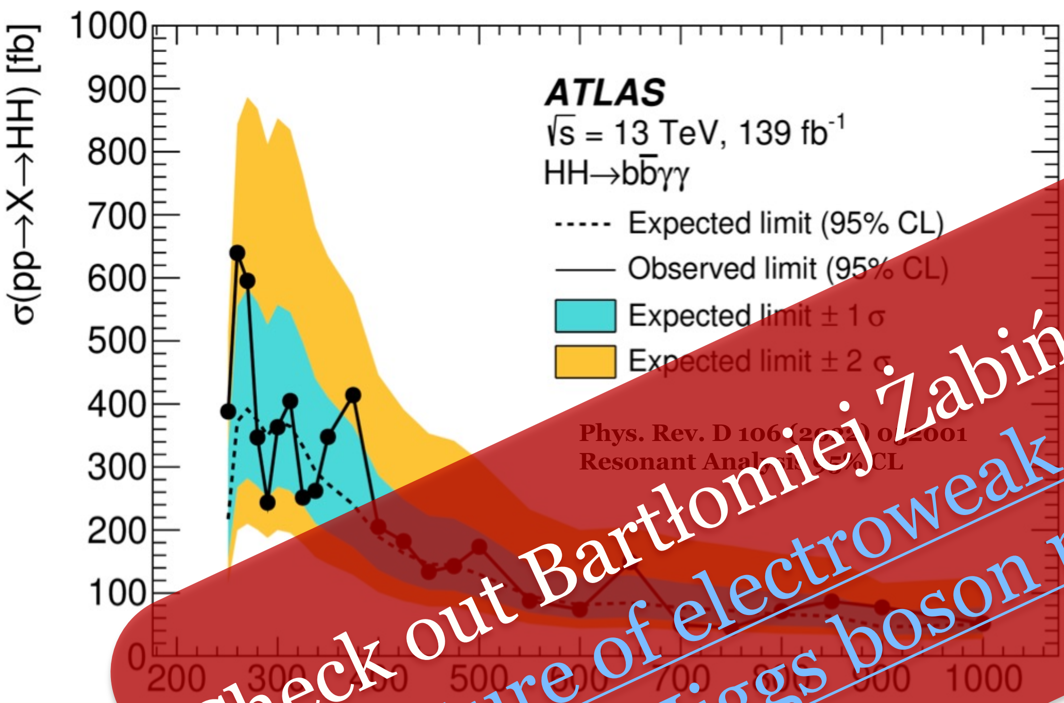
Check out Bartłomiej Żabiński's Talk: Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

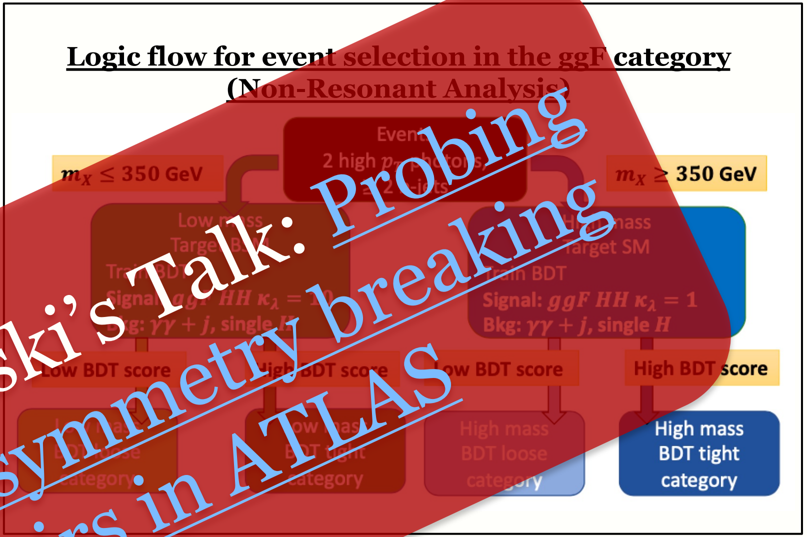


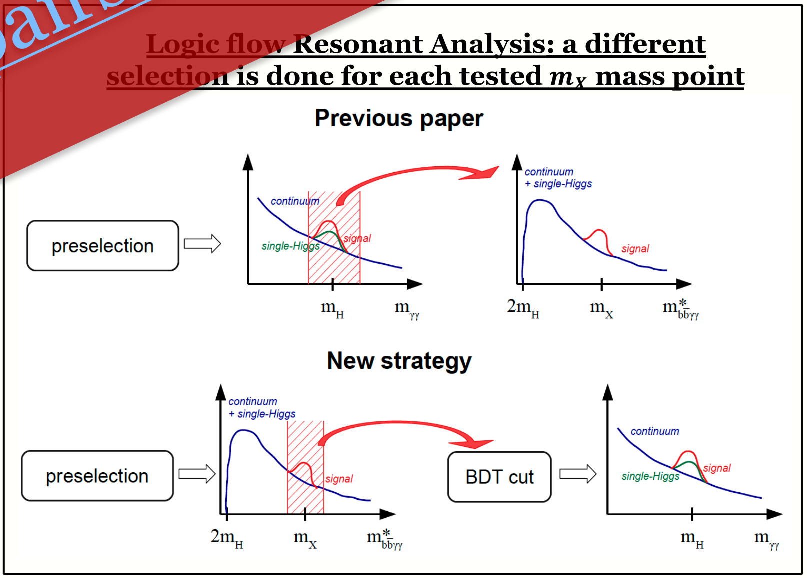
- Resonant HH searches target a heavy spin-0 scalar X
- $b\bar{b}\gamma\gamma$ is the most sensitive at low m_X, the $b\bar{b}\tau^+\tau^-$ is the most sensitive in the 400–800 GeV range, and $b\bar{b}b\bar{b}$ dominates for high m_X
- Local (global) significance for m_X = 1.1 TeV is 3.2σ (2.1 σ)

ATLAS-CONF-2021-052

Search for $HH \rightarrow b\bar{b}\gamma\gamma$



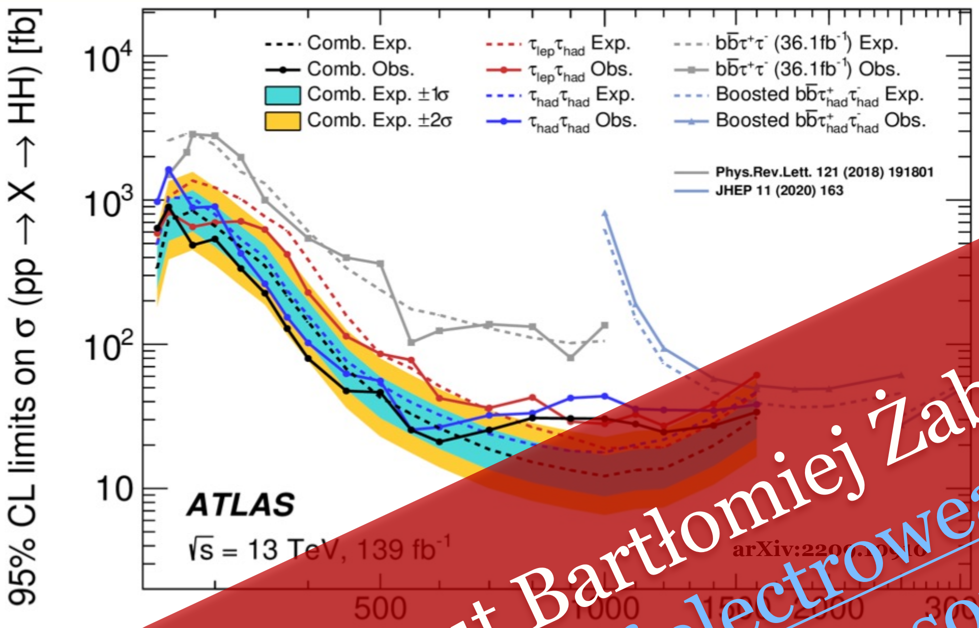




- Non-Resonant: obs. (exp.) upper limit at 95% C.L. on the signal strength of 4.2 (5.7) times the SM.
- Resonant: obs. (exp.) upper limits vary between 640–44 fb (391–46 fb) in the range 251 GeV ≤ m_X ≤ 1000 GeV

Check out Bartłomiej Żabiński's Talk: Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

Search for $HH \to b\bar{b}\tau^+\tau^-$



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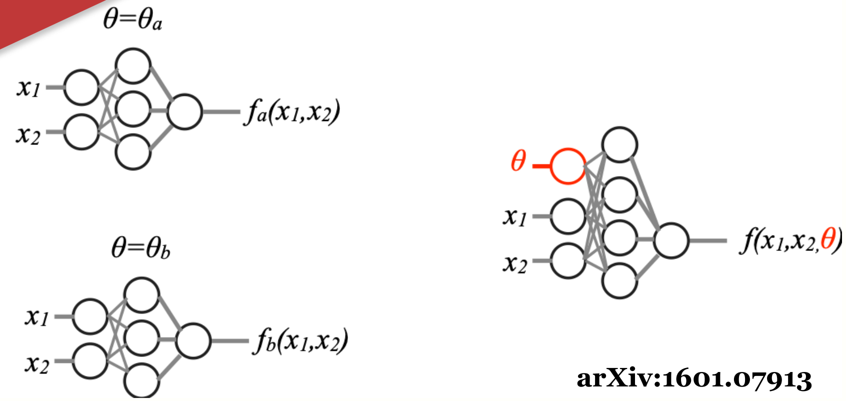
- Search is categorized into $\tau^+_{\text{lep}}\tau^+_{\text{had}}$ and $\tau^+_{\text{had}}\tau^+_{\text{had}}$ analyses
- $\tau^+_{\text{lep}}\tau^+_{\text{had}}$ further divided into SLT (Single Lepton Trigger) and LTT (Lepton Tau Trigger) channels
- Multivariate Analysis:
  - Non-resonant: BDT
  - Resonant: PNN (Parametric Neural Networks)

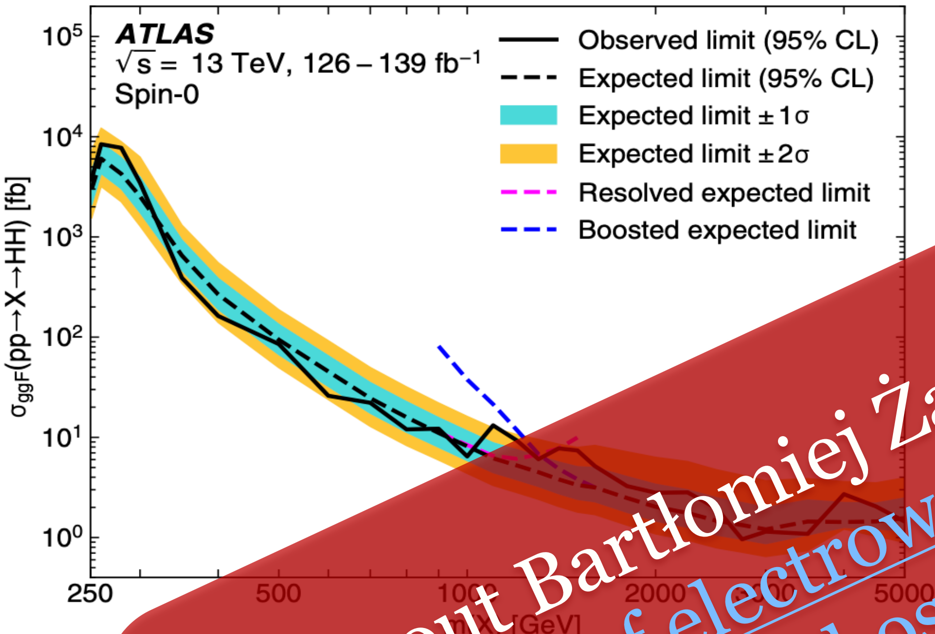
PNNs used to parameterized resonance mass



arXiv:1601.07913

- Non-Resonant obs. (exp.) upper limit at 95% C.L. on the signal strength of 4.7 ($3.9^{+1.5}_{-1.1}$) times the SM.
- Resonant obs. (exp.) upper limits vary between 21 – 900 fb (12–840 fb) depending on the mass of narrow scalar resonance
- Excess observed at Resonance mass of 1 TeV with a local (global) significance of 3.1σ (2.0 σ)

Search for $HH \rightarrow b\bar{b}b\bar{b}$ Boosted + Resolved

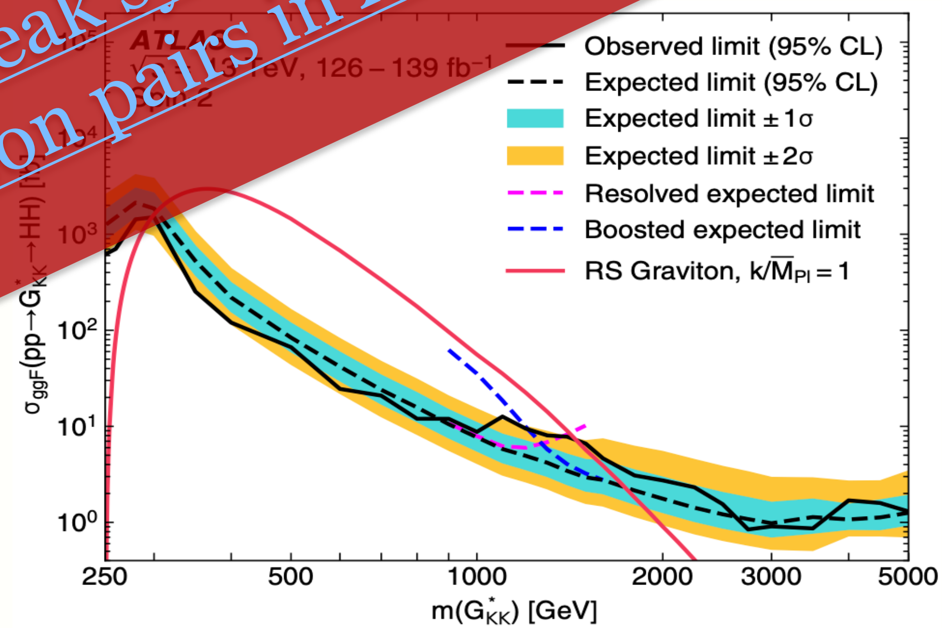


Largest BR for HH searches with 34%

Resolved channel (4 b-jets):
- ML –based jet pairing algorithm
- NN based background reweighting
- Search covers 251 < m_X < 1.5 TeV

Boosted channel (2 large-R jets):
- VR track jets for b-tagging at high m_X
- Search covers 900 < m_X < 5 TeV

- Both channels use **DL1r b-tagging algorithm**
- Excess observed at Resonance mass of 1.1 TeV with a local (global) significance of 2.3σ and 2.5σ (0.4σ and 0.6σ) for spin-0 and spin-2 models respectively



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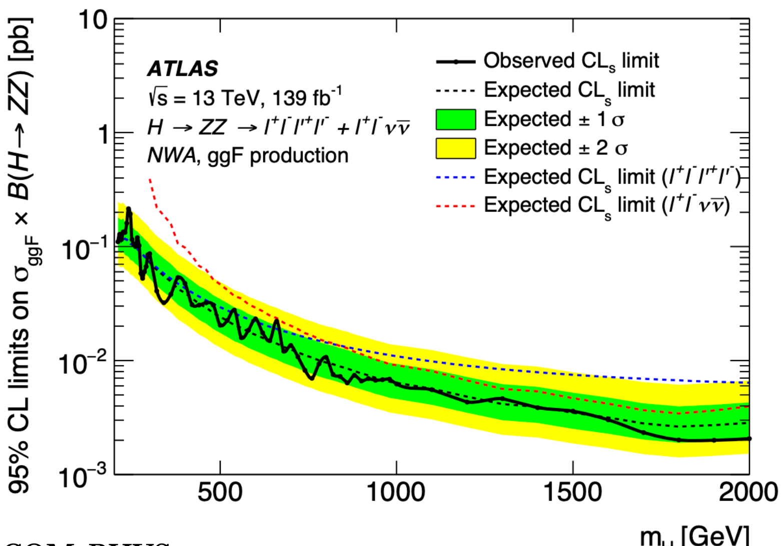
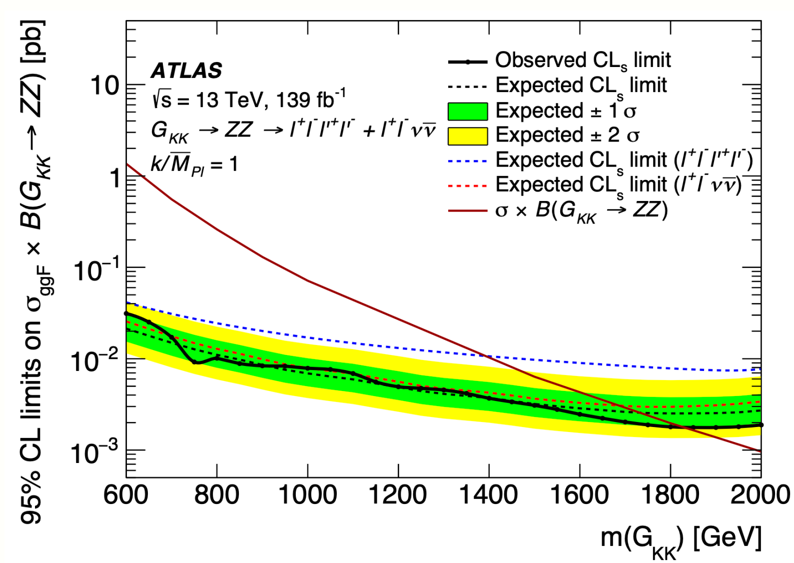
Search for BSM $H \rightarrow ZZ \rightarrow 4\ell + \ell\ell\nu\nu$

- Combined search for high mass resonance in the $4\ell + \ell\ell\nu\nu$ channels
- Jet reconstruction using the **particle flow algorithm**
- m_T distribution used for VBF enriched signals
- Mass range search extended to 2 TeV
- Interpreted from spin-0 (NWA) and spin-2 resonances (Randall-Sundrum)
- Expected 95%CL upper limit reduced by ~40% in comparison to previous analysis
  - ggF: 215 fb at $m_H = 240$ GeV to 2.0 fb at $m_H = 1900$ GeV (decreased by 20-28%)
  - VBF: 87 fb at $m_H = 255$ GeV to 1.5 fb at $m_H = 1800$ GeV (decreased by 27-43%)

$$m_{\mathrm{T}} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\,\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$





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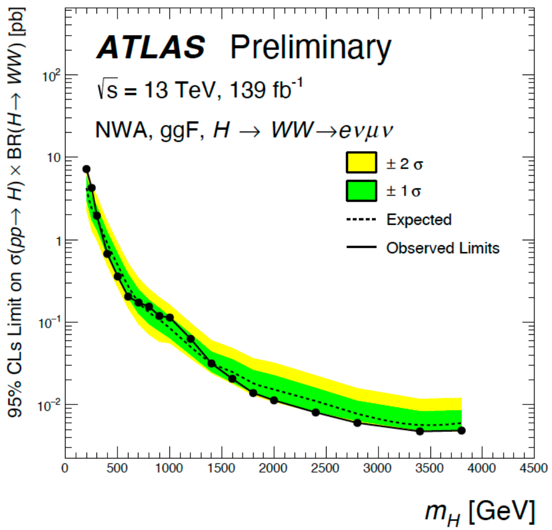
Search for WW → $e\nu\mu\nu$



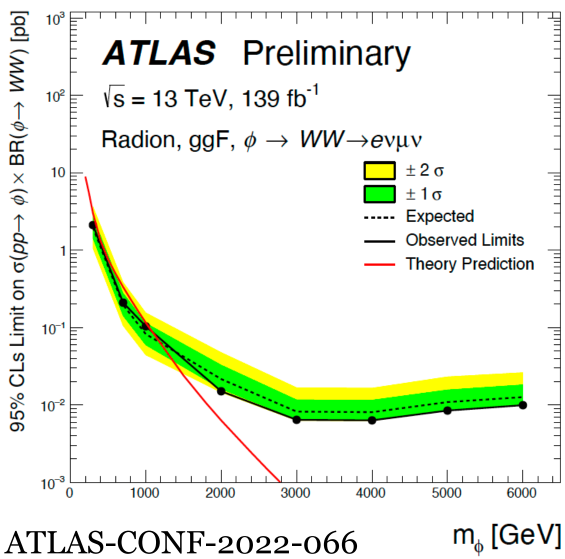
- Jet inclusive signal category via ggF targeting heavy resonances (R)
- Five models: three scalar and two to non-scalar resonance
- Mass range search from 600 GeV to 6 TeV
- Summary of 95% CL exclusions (**σ** × BR (R → WW)), only for ggF

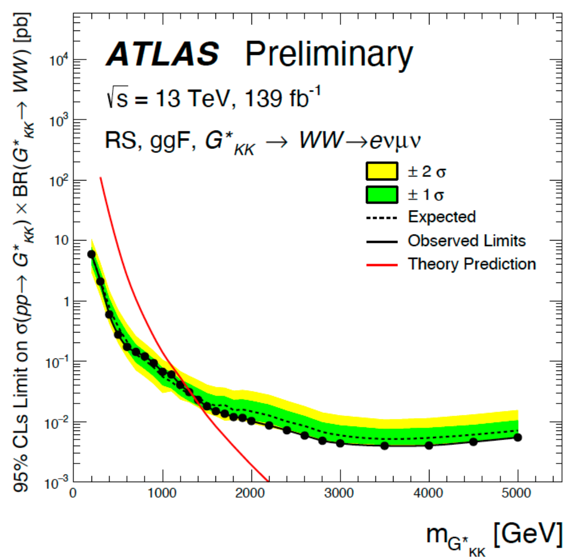
NWA: above 7.2 pb and 0.0048 pb at m_H = 200 GeV and 3.8 TeV

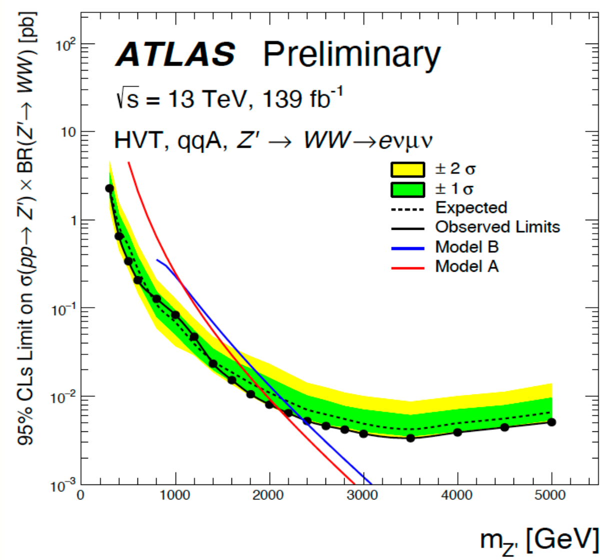
Radion: above 2.1 pb and 0.01 pb at m_H = 300 GeV and 6 TeV

RS: above 5.9 pb and 0.0055 pb at m_H = 200 GeV and 5 TeV

HVT: above 2.3 pb and 0.0039 pb at m_H = 300 GeV and 4 TeV

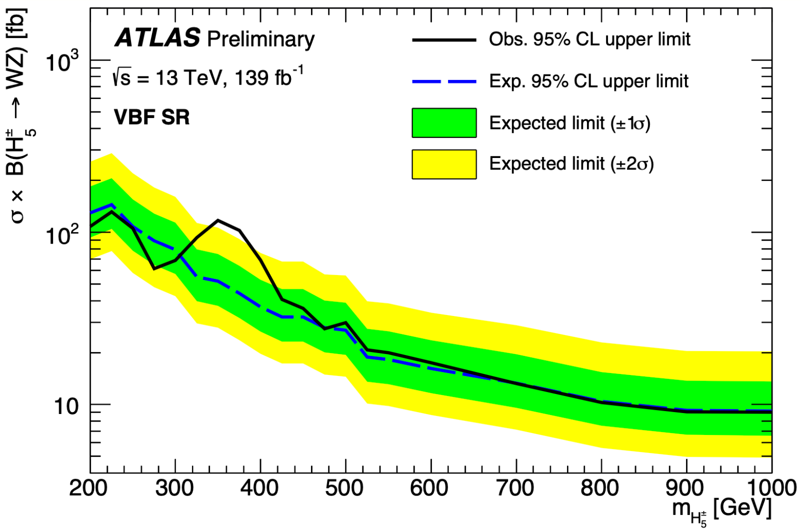




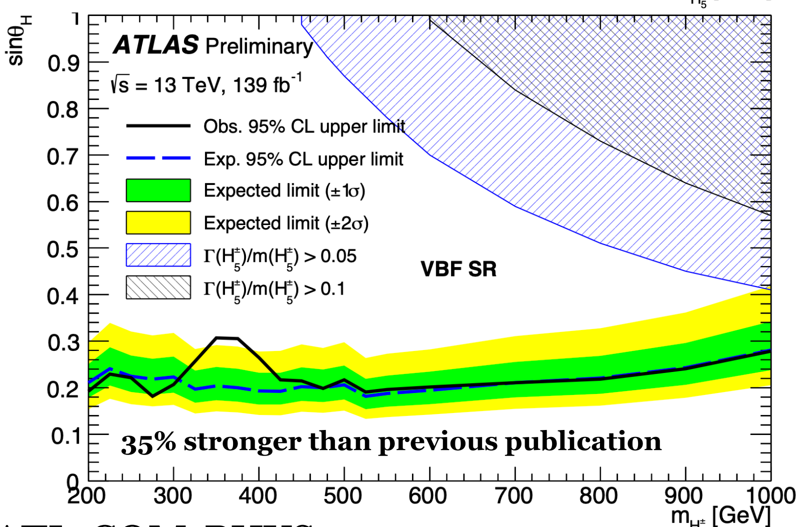


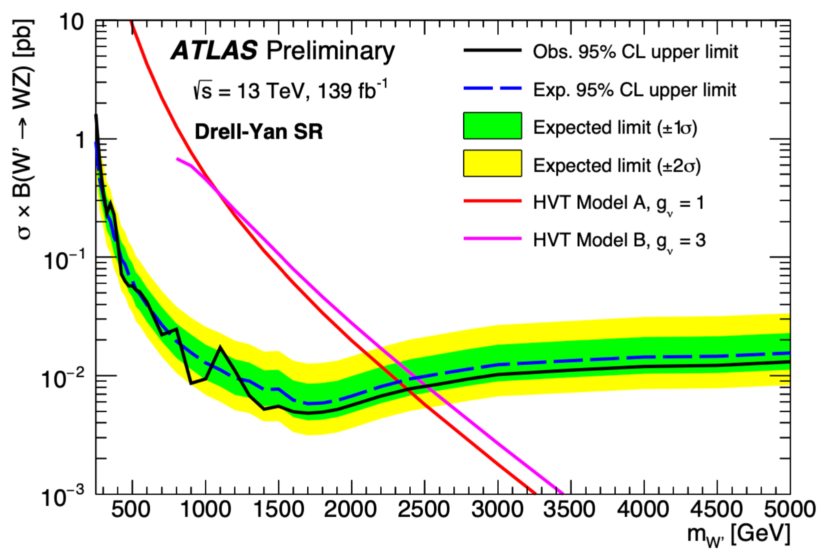
ATLAS-CONF-2022-066

Search for WZ $\rightarrow \ell\nu\ell\ell$



- Search for WZ resonance produced via the Drell–Yan process or vector-boson fusion (VBF)
- Newly implemented ANN for VBF signal
- HVT and Georgi–Machacek (GM) used as benchmark for Drell-Yan and **VBF regions**
- $\sin\theta_H > 0.3$ are excluded for 200 GeV and 2 TeV
- Local excess at resonance mass of 375 GeV. Local significance for W' or $H_5^{\pm}$ are $2.5\boldsymbol{\sigma}$ and $2.8\boldsymbol{\sigma}$





ATL-COM-PHYS-2022-032

Search for Z/W + HH Production (VHH + VVHH)

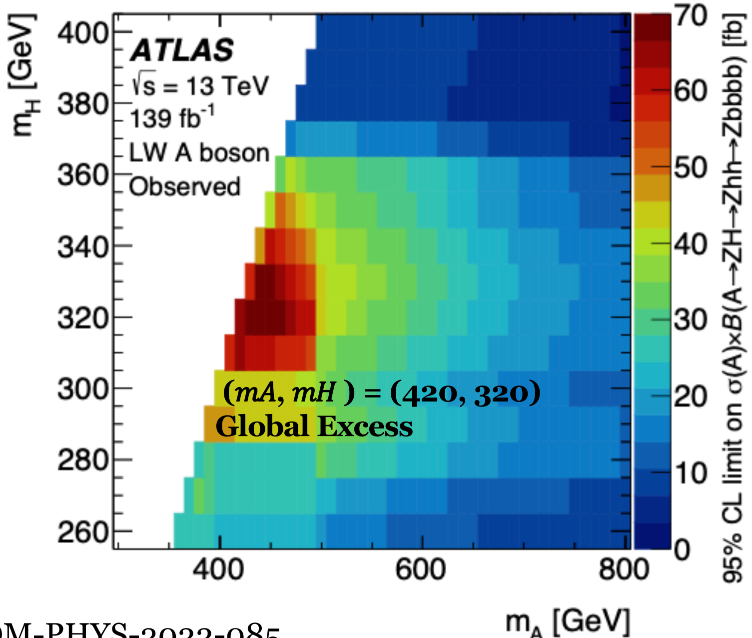
- Search for Higgs boson pairs in association with a vector boson (Vhh, V=Z/W)

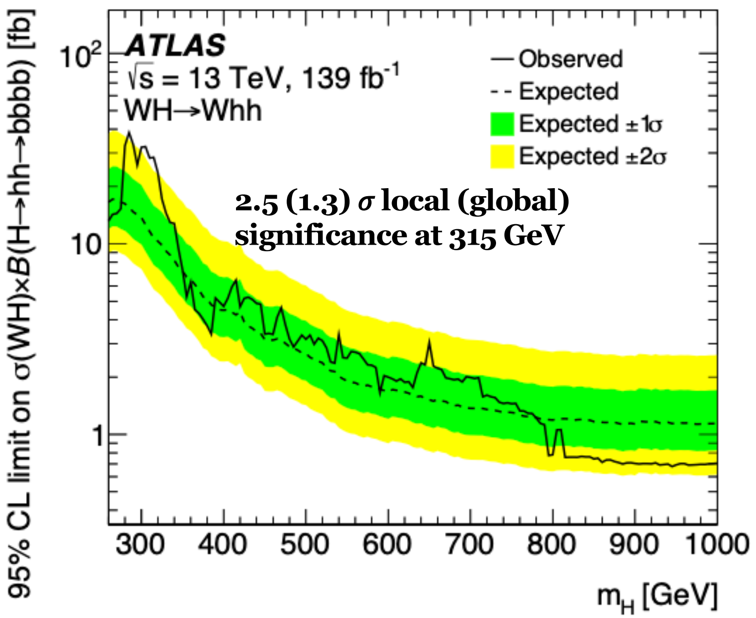
$$\mathbf{W/Z\,hh} \rightarrow \boldsymbol{W/Z} \rightarrow \boldsymbol{\ell\nu\,/\,\ell\ell\,/\,\nu\nu} + \boldsymbol{hh} \rightarrow \boldsymbol{b\bar{b}b\bar{b}}$$

- Studies the Higgs self coupling and quartic VVHH
- VH (Higgstrahlung) and $A \rightarrow ZH$ (2HDM) BSM scenarios considered for resonant analysis
- Jets reconstructed using **Particle Flow algorithm** and **DL1r algorithm for b-tagging**

Resonant:

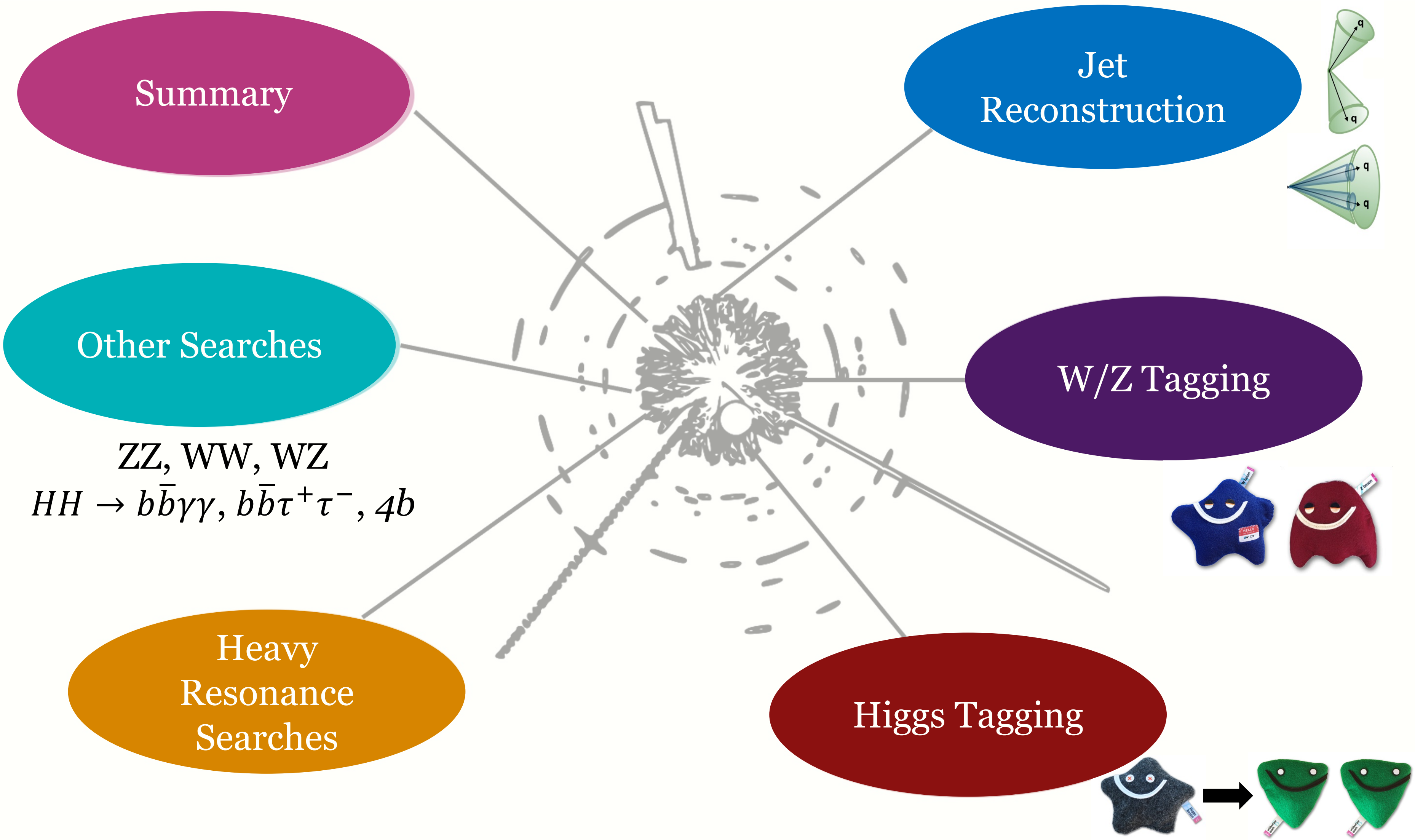
Global excess observed in LW $A \rightarrow ZH \rightarrow Zhh$, where local (global) sig is 3.8$\boldsymbol{\sigma}$ (2.8$\boldsymbol{\sigma}$)





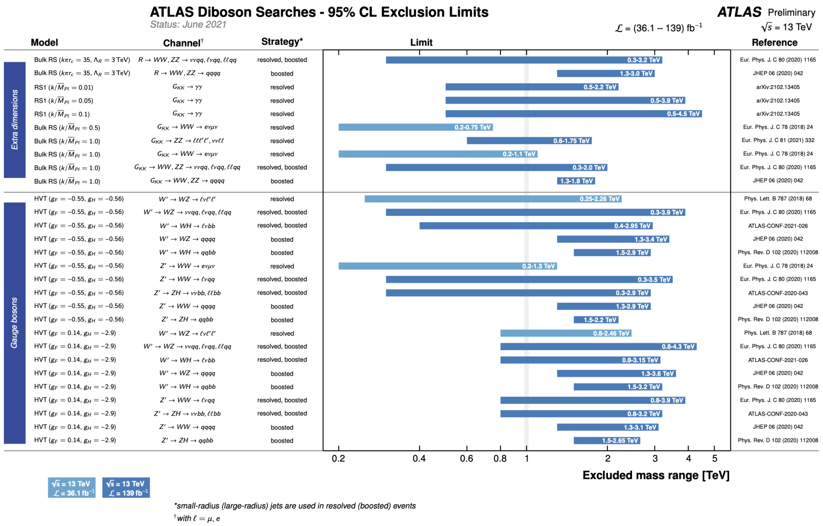
ATL-COM-PHYS-2022-085

Setting the stage



Summary

- A summary of up-and-coming Jet Reconstruction techniques, H/W/Z tagging algorithms
- These algorithms are essential to the search for BSM heavy resonance searches
- An overview of the many ATLAS Run-2 searches with boson final states which uses some of these new and developed algorithms
- More developments for Run-3



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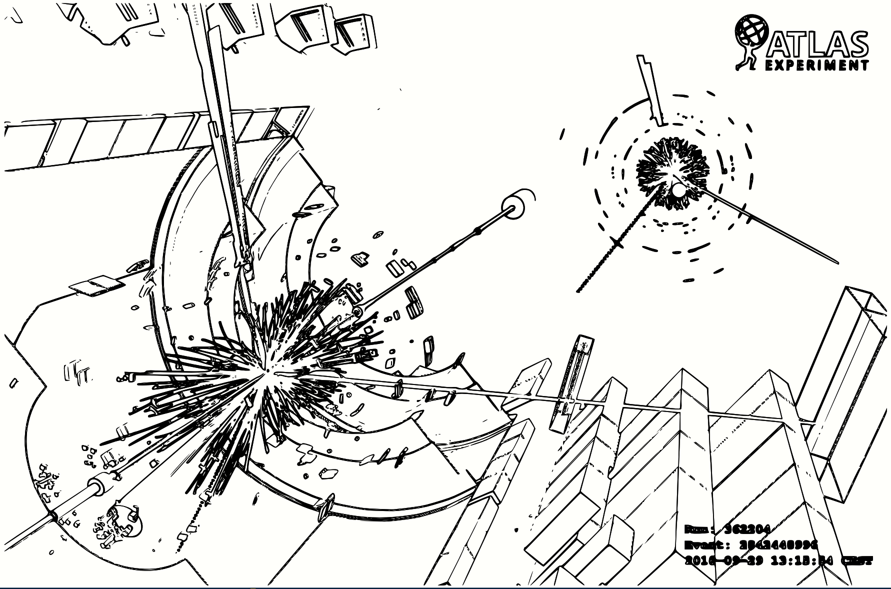
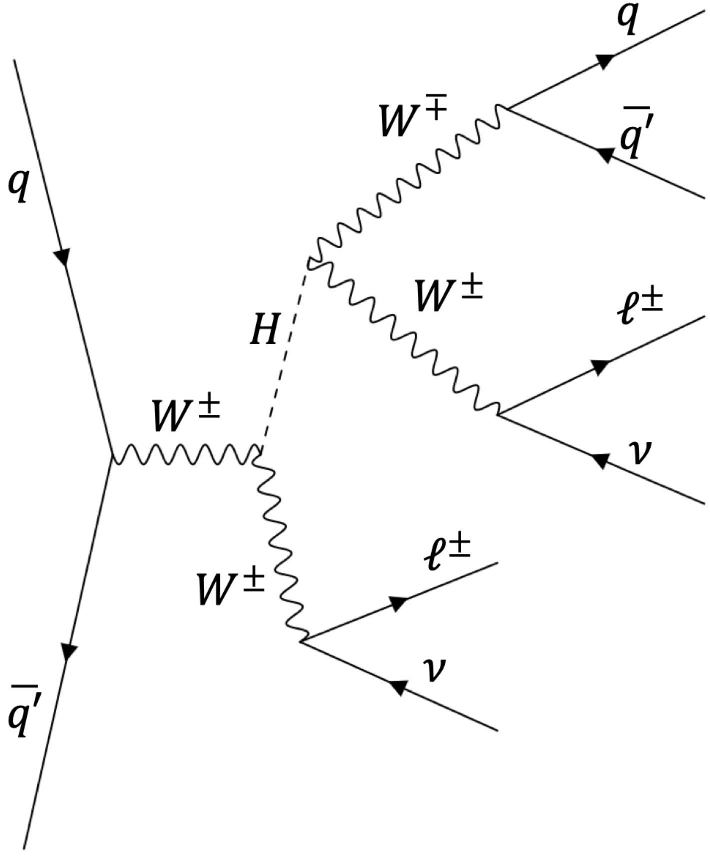
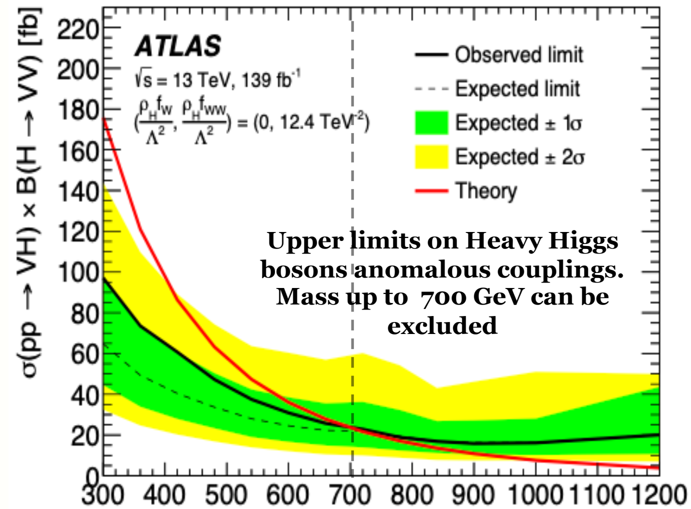
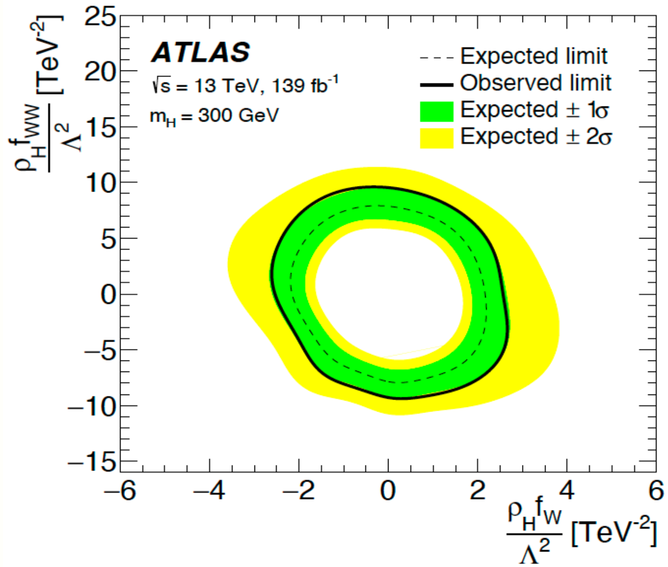


Thank you!

Generic Search for a Heavy Higgs boson (VH)







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