SEARCHING FOR LONG-LIVED AXION-LIKE PARTICLES WITH THE ATLAS EXPERIMENT

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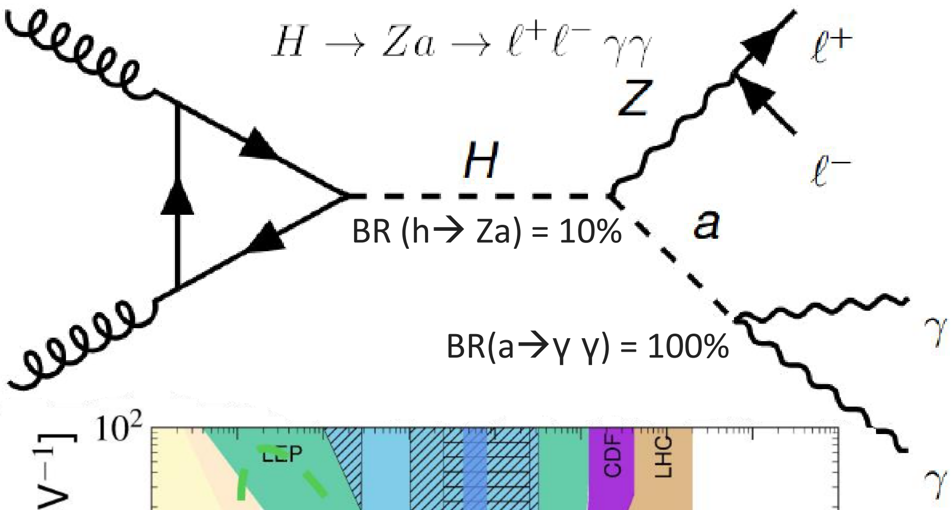
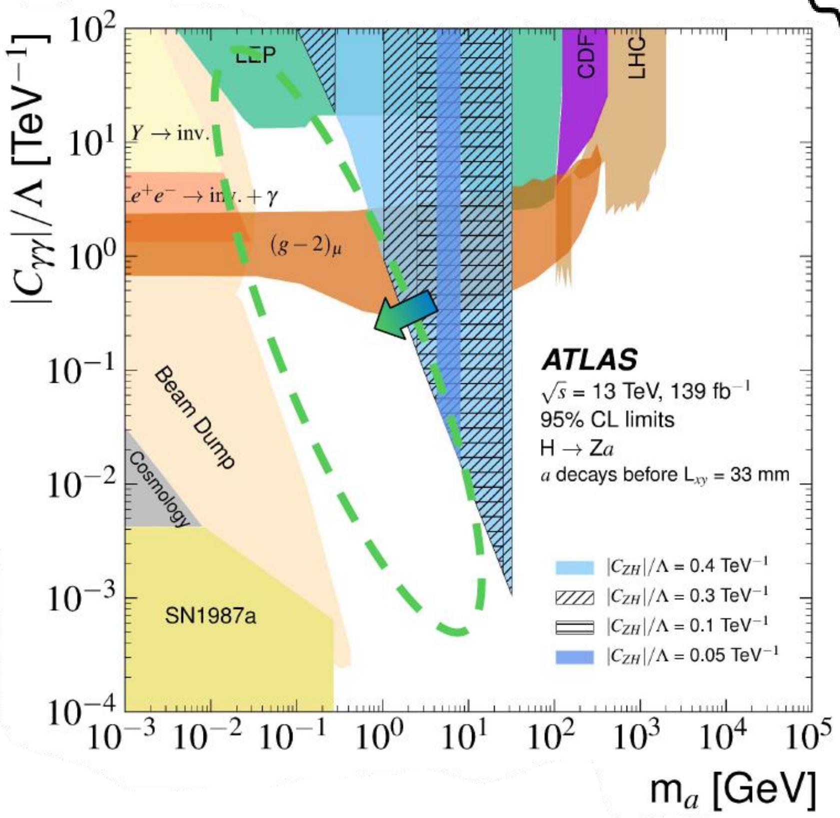
ATLAS EXPERIMENT

INTRODUCTION

- We know the Standard Model to be incomplete, and axion-like particles (ALPs) are part of many BSM theories that introduce dark matter
- We are searching for long-lived ALPs produced in exotic Higgs decays, using a partial Run 3 dataset of 159.4 fb^{-1}
- The ALP is assumed to decay to photons with a branching ratio of 100%
- This is a follow-up on the Run 2 analysis searching for a promptly decaying ALP





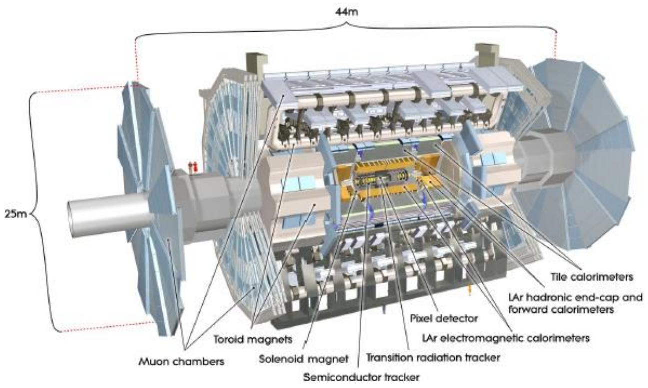
SIGNATURE

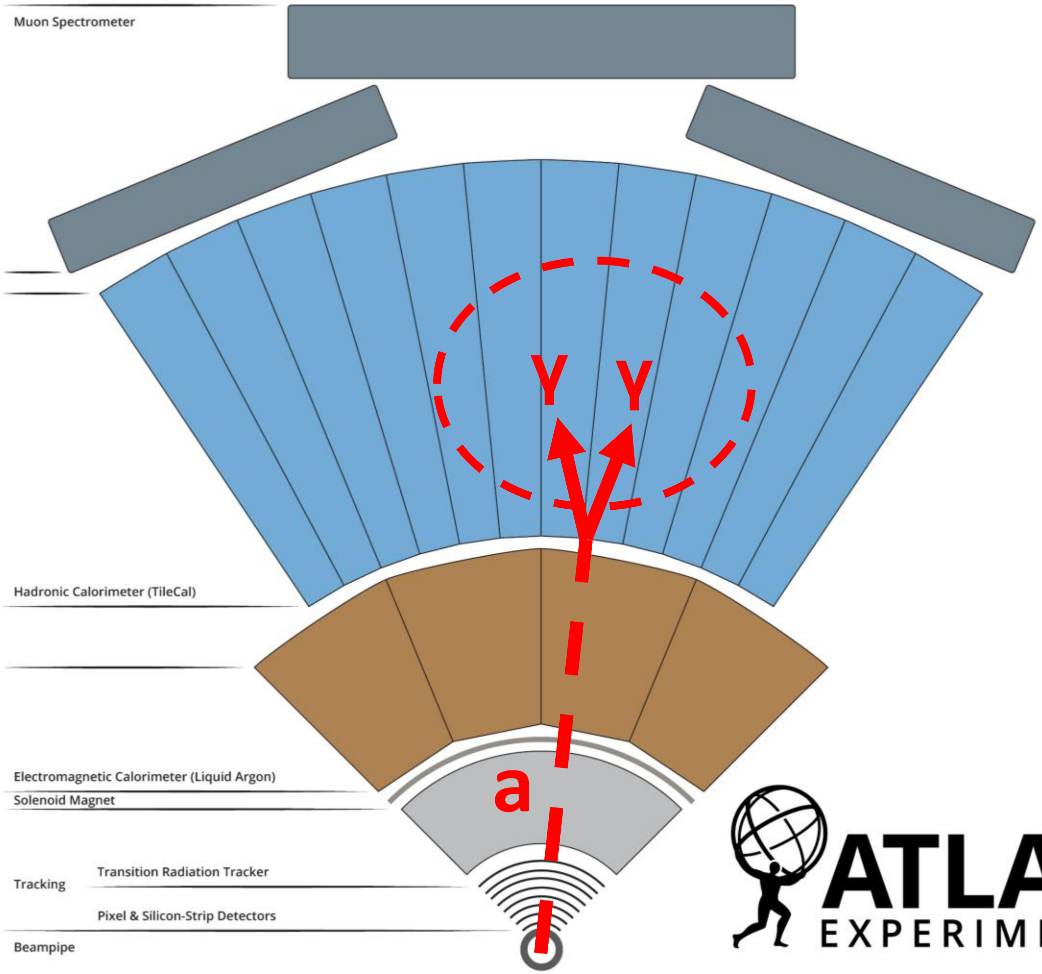
- By considering longer lifetime ALPs, we are able to investigate weaker couplings between ALPs and photons

$$g_{a\gamma\gamma} \approx 1.0 \times 10^{-4} \left(\frac{1\,\mathrm{GeV}}{m_a}\right)^{3/2} \left(\frac{1\,\mathrm{mm}}{c\tau}\right)^{1/2} \mathrm{GeV}^{-1}$$

- The main difficulty arises from reconstructing the photons, since they are displaced

- For long-lived ALPs, photons can be produced in the HCAL, where they will not pass the standard ATLAS photon reconstruction – reconstructed as a jet





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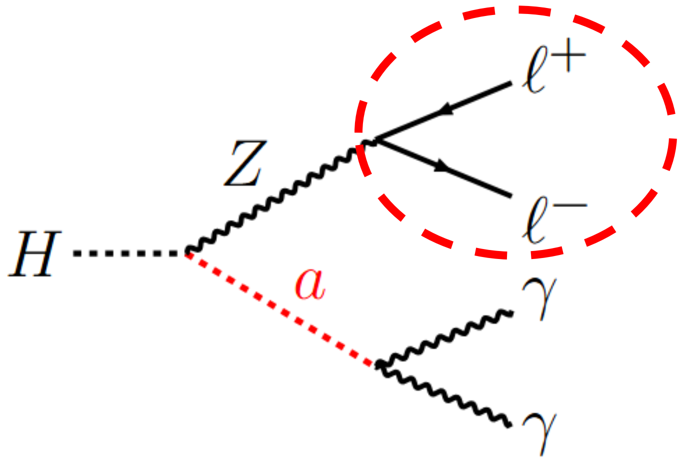
SIGNAL PHENOMENOLOGY



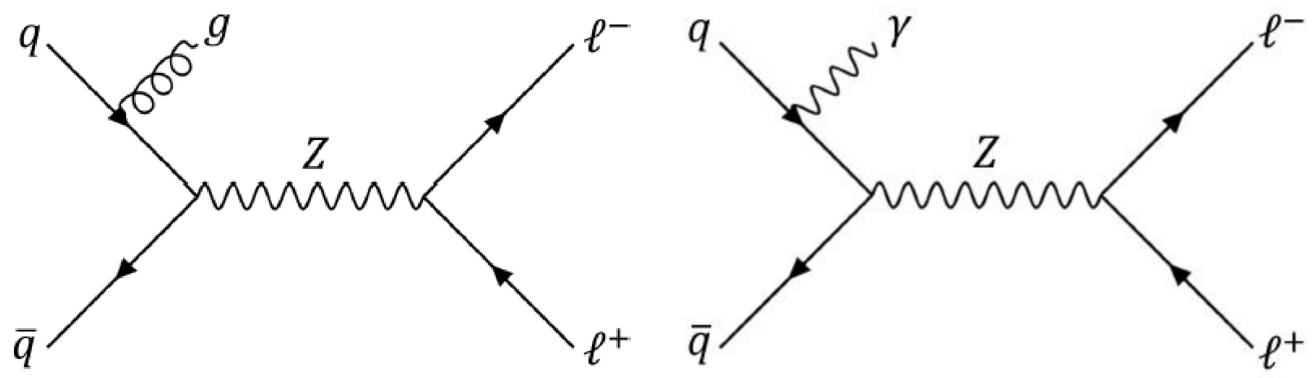
- Every event that we consider is required to have oppositely charged electrons or muons
- There are geometric and kinematic requirements on the leptons, such as their invariant mass being in a window around the Z mass

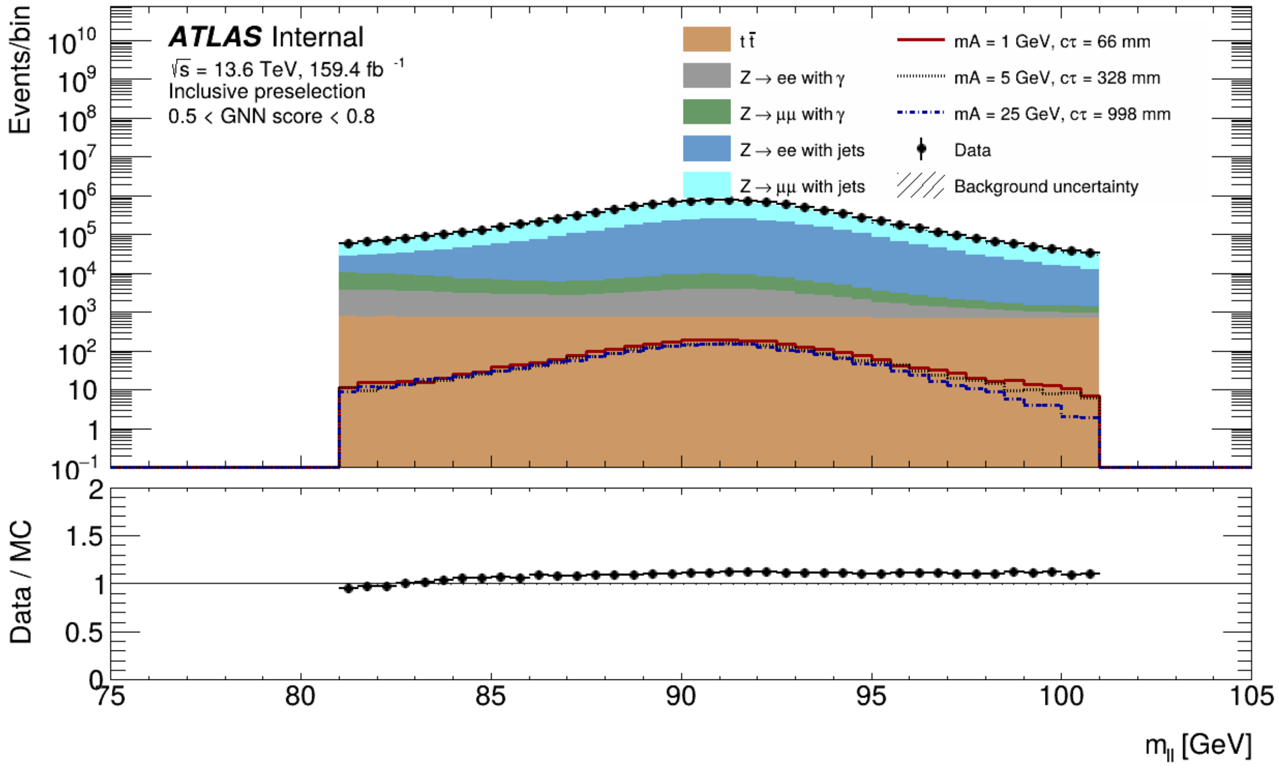
Variable	Pre-selection condition
Leading lepton p_T	> 27 GeV
Sub-leading lepton p_T	> 20 GeV
Di-lepton ΔR	> 0.2
Di-lepton invariant mass	81 GeV $\leq m_{ll} \leq$ 101 GeV
Di-lepton p_T	≥ 10 GeV

- Leptonic Z decays are selected using single and di-lepton triggers, alongside a dedicated set of requirements on the leptons

BACKGROUNDS

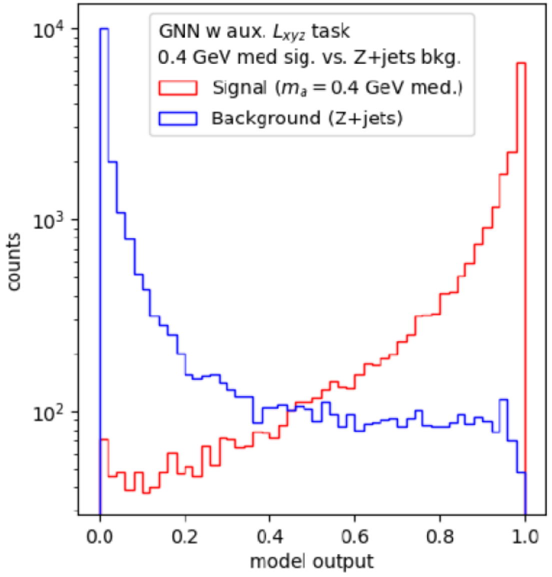
- Some SM processes can mimic the final state, so we need simulations of backgrounds to compare to data
- The dominant backgrounds are Z + jets (blue), and Z + γ (green + grey)
- t-tbar (brown) are also included, and di-boson backgrounds were also investigated, but were found to be negligible
- To distinguish between background and signal events, we need to identify the differences between the jets

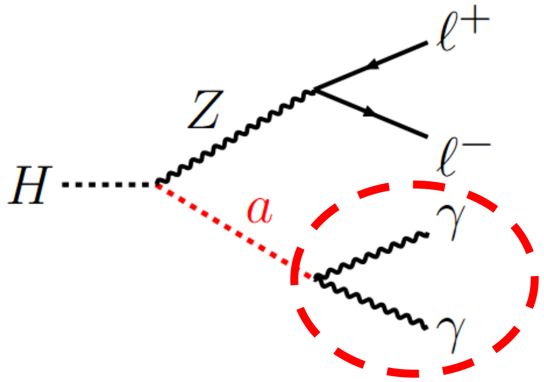


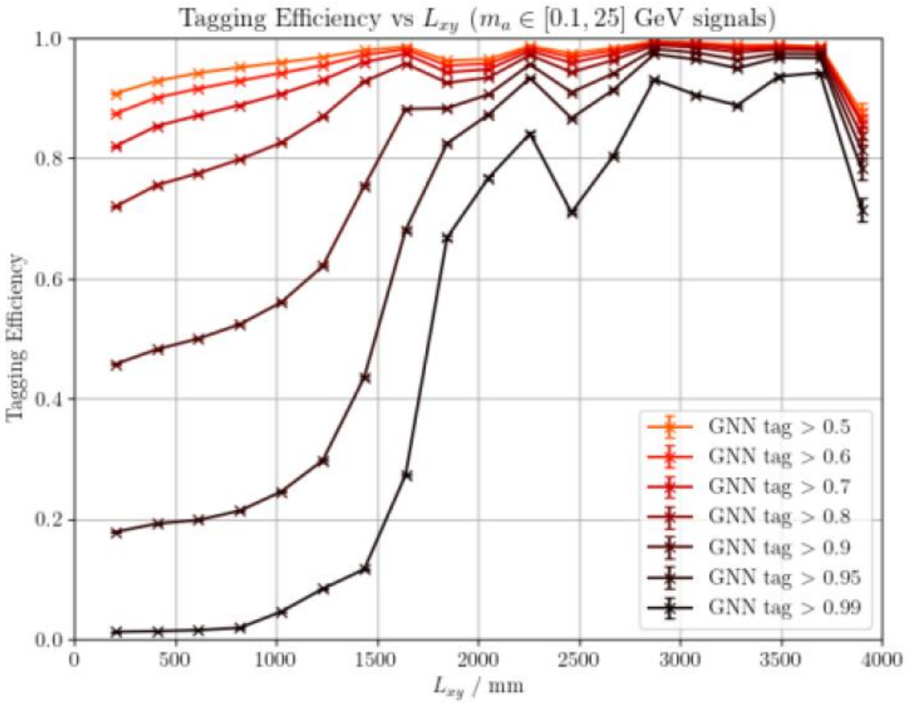


ALP IDENTIFICATION

- We use a Graph Neural Network (GNN) to identify jets and give them a score of how much they look like an ALP jet
- It is optimised in searching for photons that are displaced between 2m and 4m



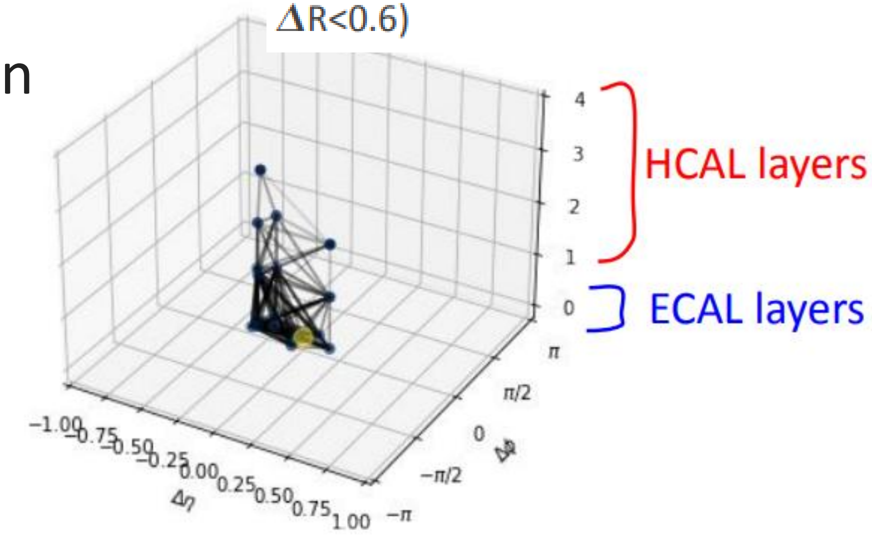




Node⟶ [E, η, ϕ, l] of energy deposits (l = calo sampling layer)

Edge ⟶ ΔR between nodes (if ΔR<0.6)

- The GNN is trained on signal samples with different mass ALPs, using Calorimeter Clusters for each jet



SIGNAL REGION

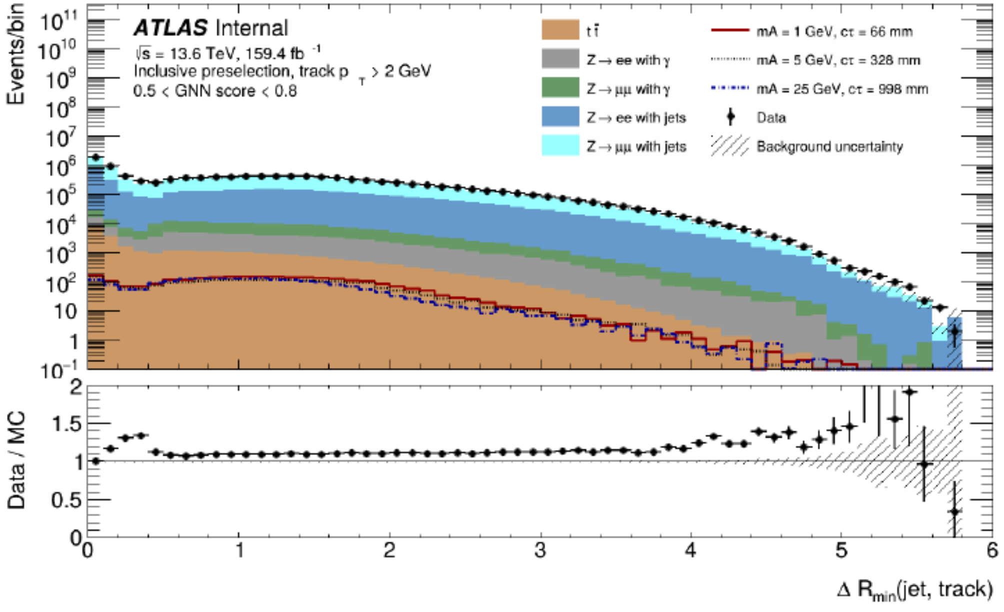
- To give the highest chance of making a discovery, we need to search a region of the ALP parameter space that gives the greatest significance

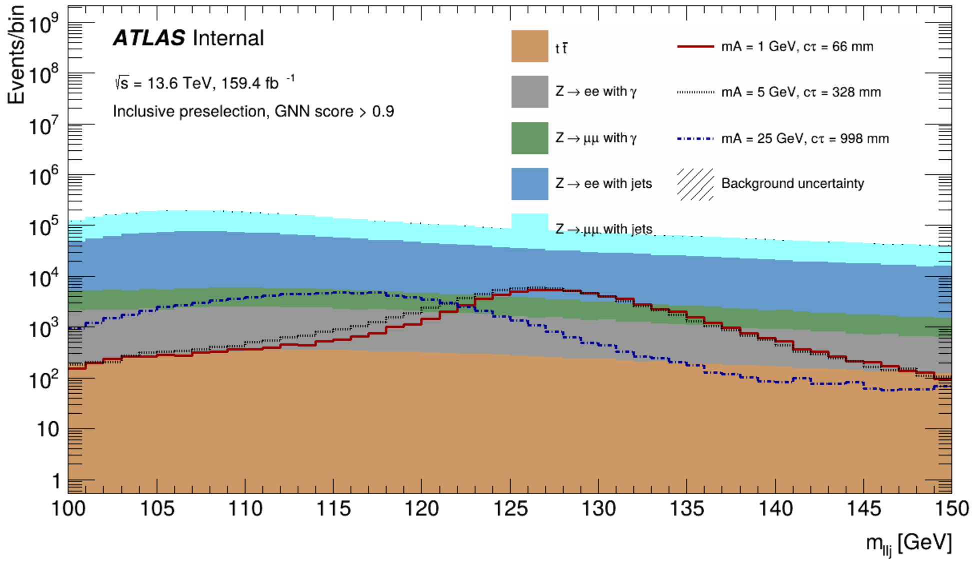
- Using kinematic and geometric variables (such as ΔR, the angular separation) to distinguish between signal and background, and requiring the jet with the highest GNN score to be above 0.9

- We are using the GNN score and invariant mass of the di-lepton + jet as discriminating variables

Selection	Background	Signal	Asimov Z_A (20% syst. unc.)
Preselection	70.53×10^6	18,225	0.0013
Leading jet GNN score ≥ 0.90	7.16×10^6	8,930	0.0062
$105 < m_{llj} < 145$ GeV	4.14×10^6	8,364	0.0101
$\Delta R_{\min} > 0.2$, track $p_T > 2$ GeV	2.21×10^6	6,281	0.0142

- An event-based Boosted Decision Tree (BDT) is being developed to improve these significances



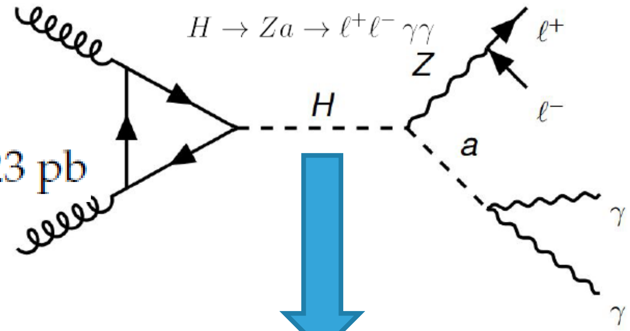


VBF SIGNAL REGION

- Two main Higgs production mechanisms at the LHC: gluon-gluon fusion (ggF) and vector boson fusion (VBF)

ggF

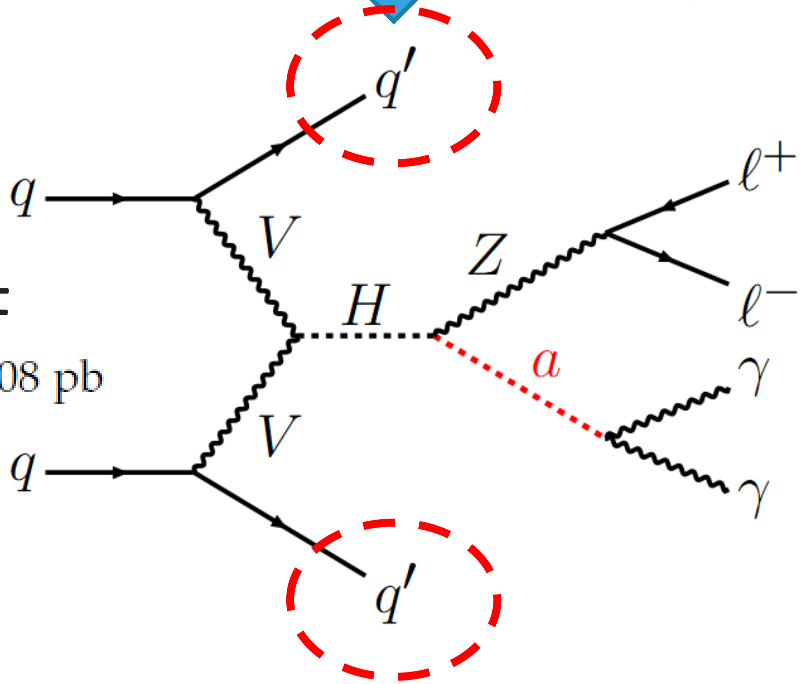
$\sigma_{\text{ggF}} = 52.23 \text{ pb}$

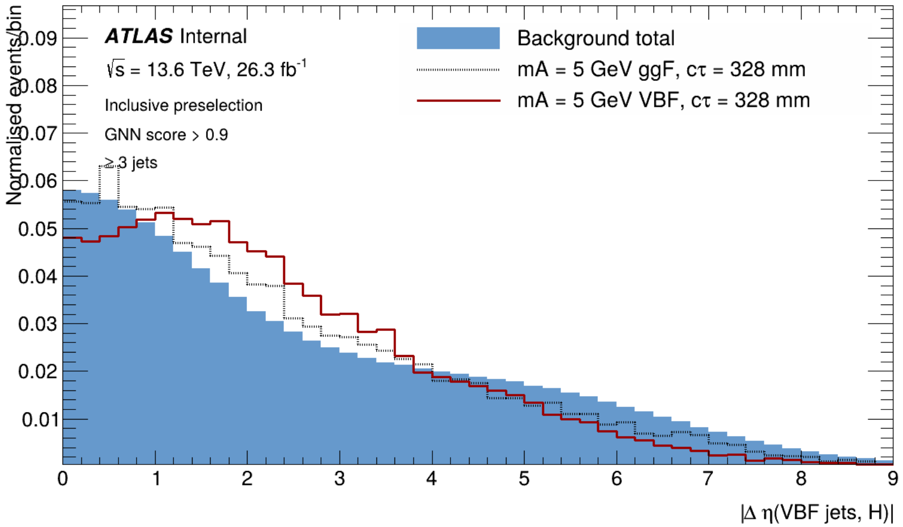


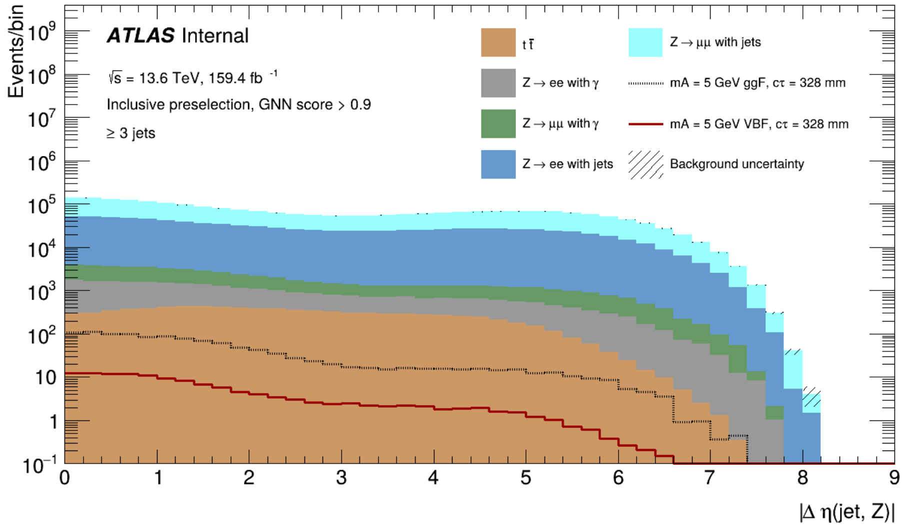
- Main distinction between ggF and VBF are the two extra jets, which can be used to define a signal region

VBF

$\sigma_{\text{VBF}} = 4.08 \text{ pb}$





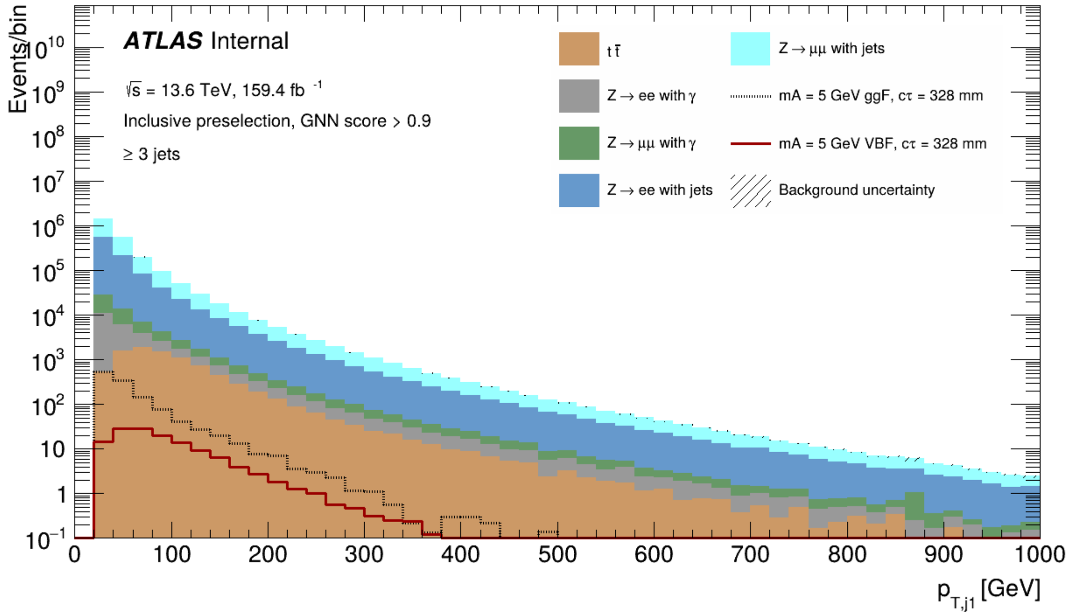


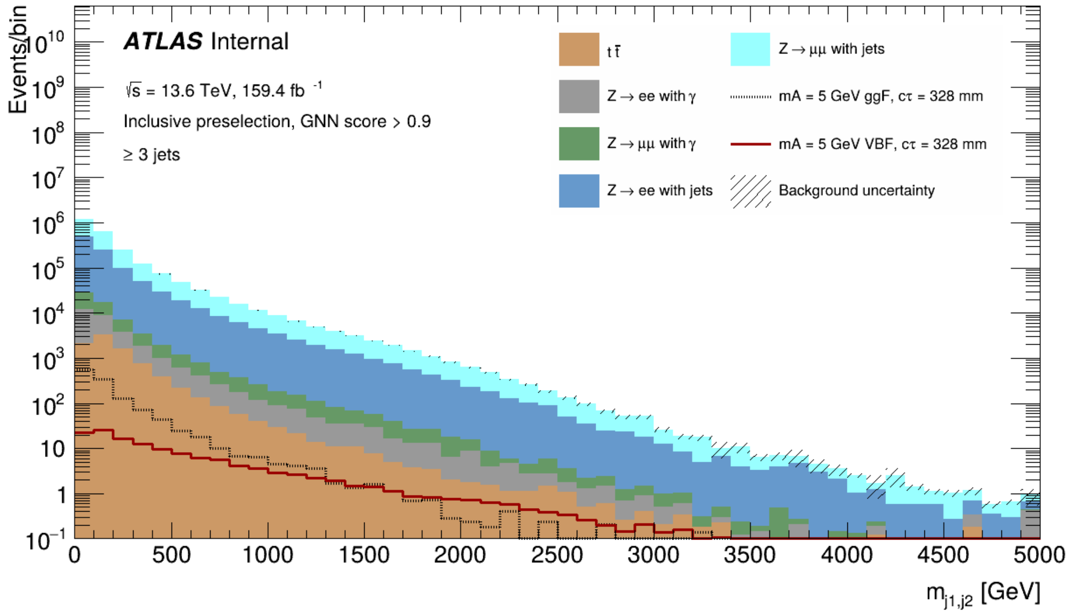
VBF SIGNAL REGION

- The two VBF jets are likely to be produced in the forwards direction of the detector, have a high p_T, and a very high invariant mass

Variable	VBF SR
N_{jet}	≥ 3
GNN score	> 0.9
$\lvert\eta_{j_1}\rvert$, $\lvert\eta_{j_2}\rvert$	> 1
$\eta_{j_1} * \eta_{j_2}$	< 0
$p_T^{j_1}$	> 100 GeV
$p_T^{j_2}$	> 40 GeV
m_{j_1,j_2}	> 2000 GeV

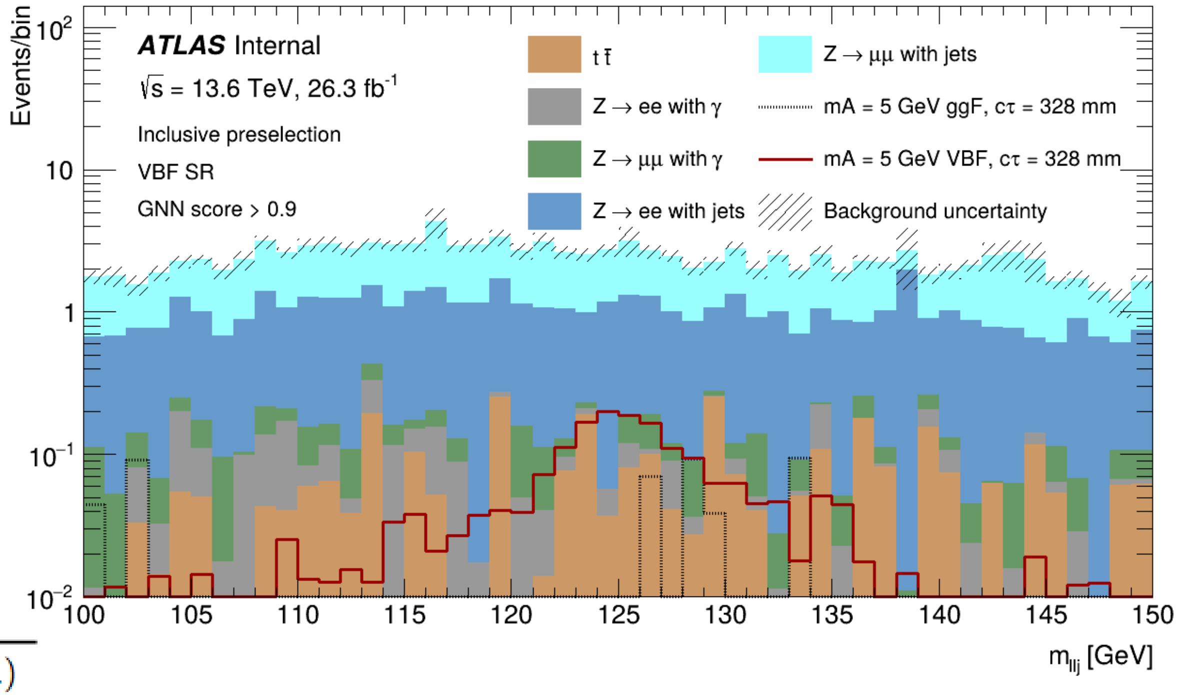
- These cuts have been optimized to enhance the VBF signal, scanning each parameter individually





VBF SIGNAL REGION

- After optimisation, the red VBF signal dominates the black ggF signal
- However, the background still dominates, more work is needed to further reduce the background

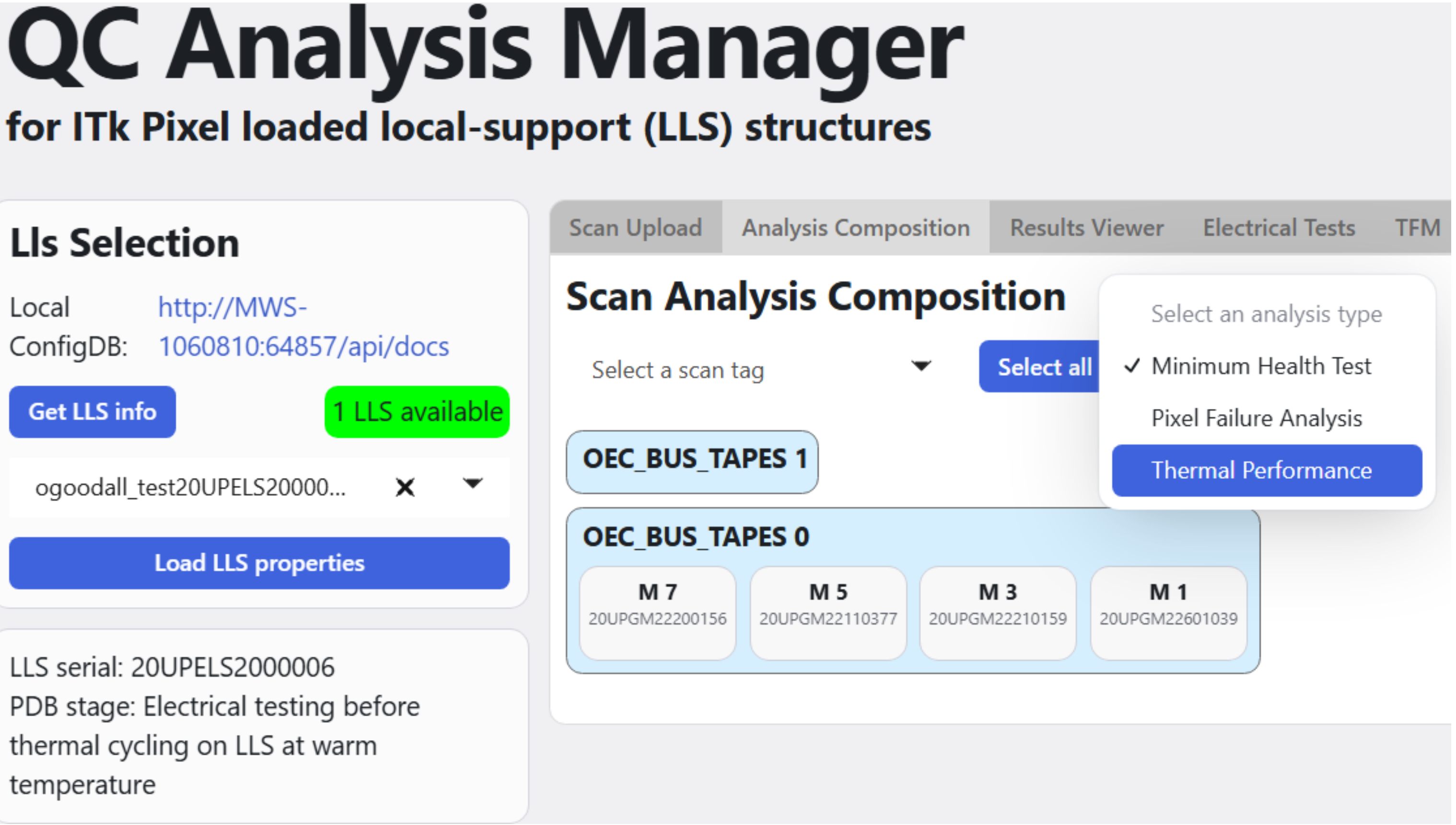


Selection	Background	Signal	Asimov Z_A (20% syst. unc.)
Preselection	72.10×10^6	18,963	0.0013
$n_{jet} \geq 3$	35.72×10^6	12,072	0.0017
$105 < m_{llj} < 145$ GeV	16.87×10^6	8,561	0.0025
GNN score ≥ 0.90	5.64×10^6	5,940	0.0053
$\lvert\eta_{j1,2}\rvert > 1.0$	2.75×10^6	2,952	0.0054
$\eta_{j1} \cdot \eta_{j2} < 0$	1.24×10^6	1,462	0.0059
$p_T^{j1} > 100$ GeV	33,080	178	0.0270
$p_T^{j2} > 40$ GeV	17,934	115	0.0320
$m_{j1,j2} > 2000$ GeV	632	13	0.1012

- Work is being done to develop a BDT to more efficiently optimise a larger set of parameters

QUALIFICATION TASK

- I have been working on the ATLAS Inner Tracker upgrade (ITk), particularly loaded local supports
- Developing a framework to allow analysis tests to be run (quality control for thermal performance, IV etc.)
- Producing a GUI to implement and view tests and results



CONCLUSIONS

- The search for long-lived ALPs decaying in displaced photons is on-going using partial Run 3 data
- I have been working on an independent framework to cross check selections and data-MC agreement, investigating event selections for the inclusive analysis and developing a dedicated signal region for VBF production of the Higgs
- Various selections have been tested to improve the sensitivity, maximising the significance, and exploiting a GNN to identify jets most likely from displaced photon decays
- More work is required to further reduce SM backgrounds
  - The team has developed an event-based BDT to do so, now under study for both inclusive and VBF-dedicated region
- Going on LTA to CERN from October!

BACKUP

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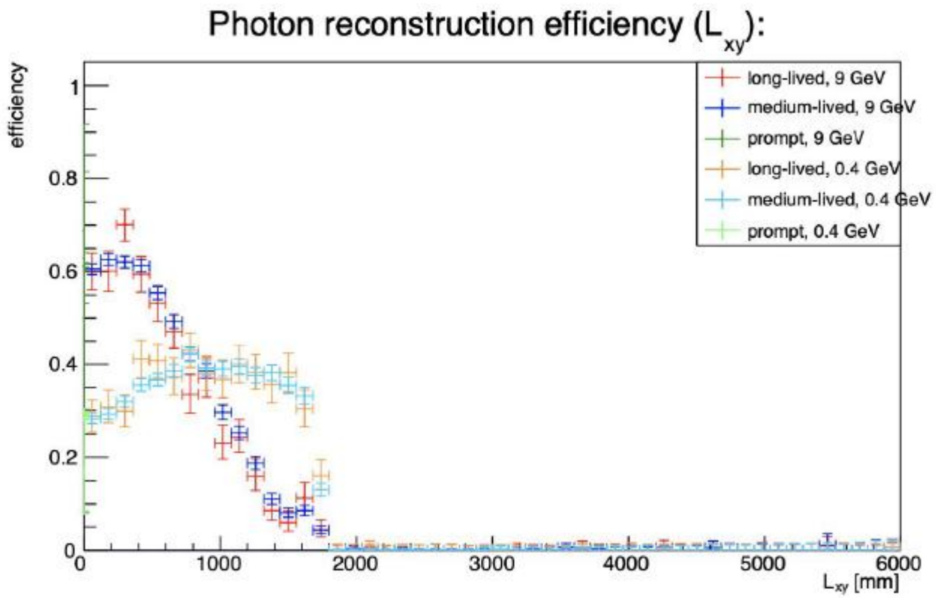
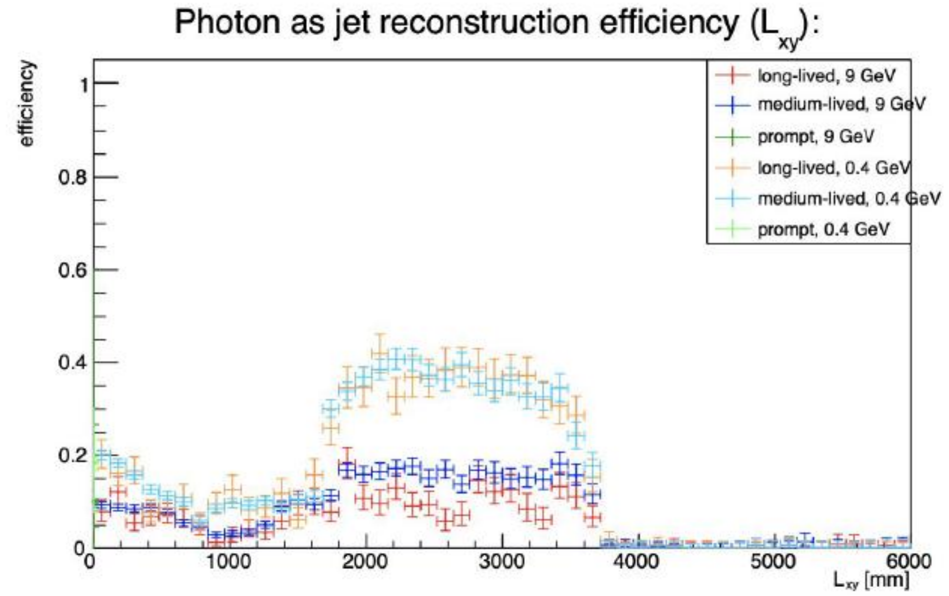
PHOTON RECONSTRUCTION





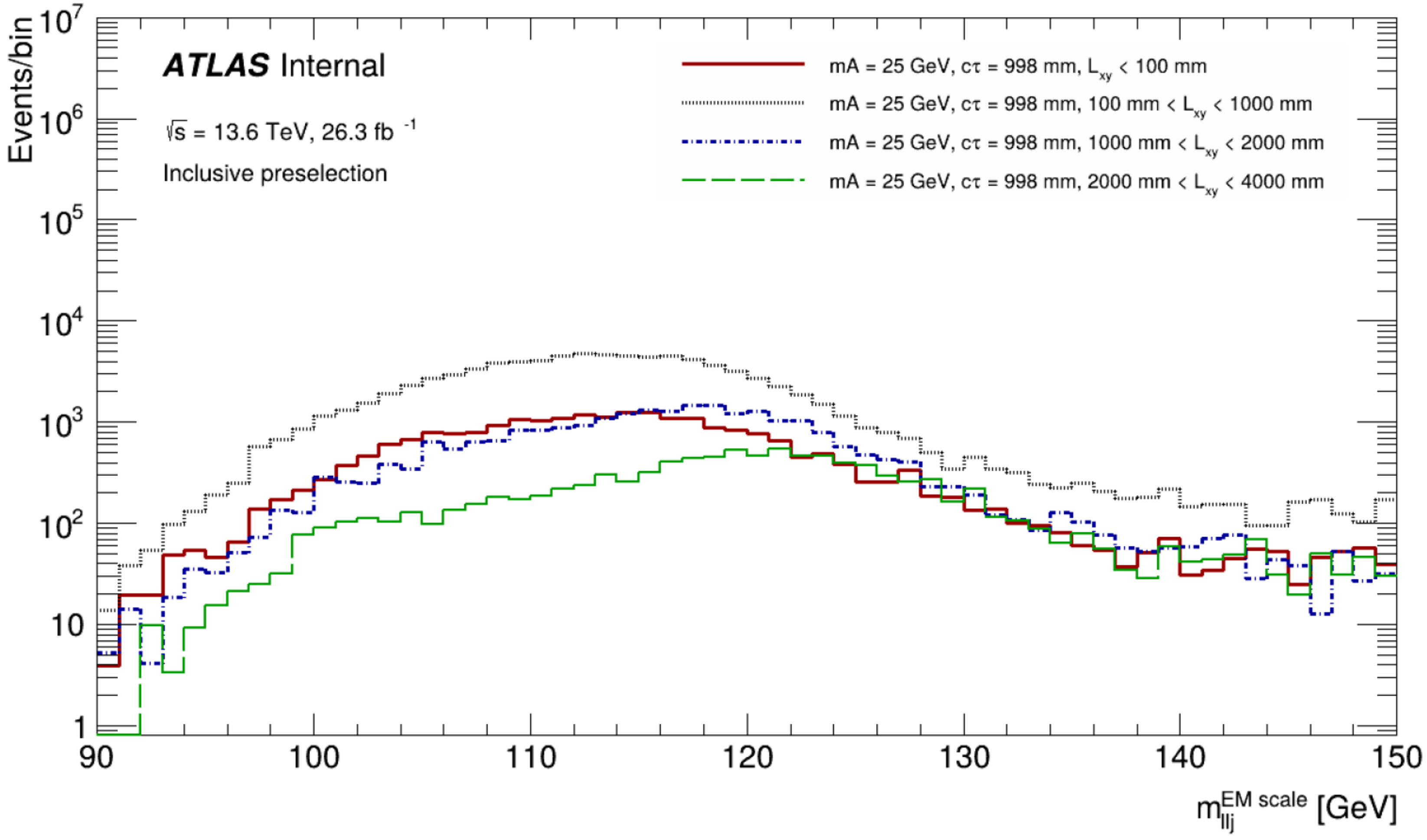
GRAPH VARIABLES

- Energy of the leading cluster
- Total energy of the sub–leading clusters
- Number of clusters
- Number of edges
- Global max distance between two clusters in the same layer
- "Depth" (n layers between inner and outermost populated layer)
- Index of layer containing highest E cluster
- Largest distance and average distance (Delta R) to highest E cluster (capture
- asymmetries?) "where is center of jet with/without leading cluster in relative
- coordinates?"
- Number of populated/empty layers
- Number of non-consecutively populated layers (i.e. count number of empty layers in between non-empty layers)
- Edge density (n edges/(n nodes(n nodes-1)/2))

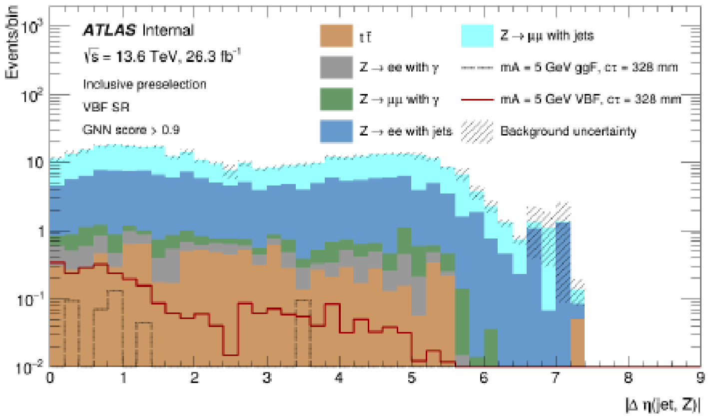
Layerwise variables:

- Number of clusters per layer
- Total energy per layer
- Largest widths per layer (separately in eta, phi and Delta R)

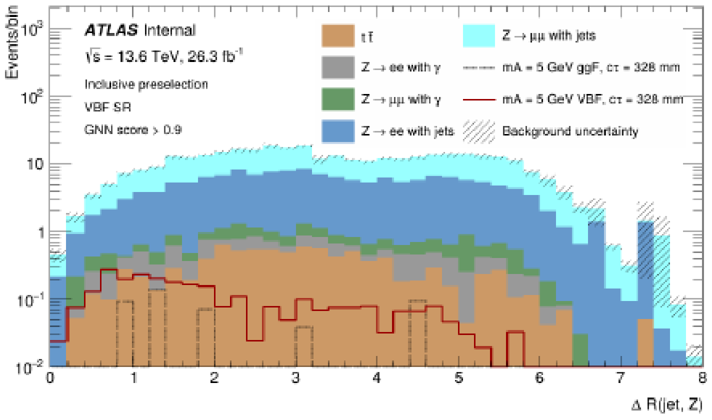
HEAVY SIGNAL SAMPLE



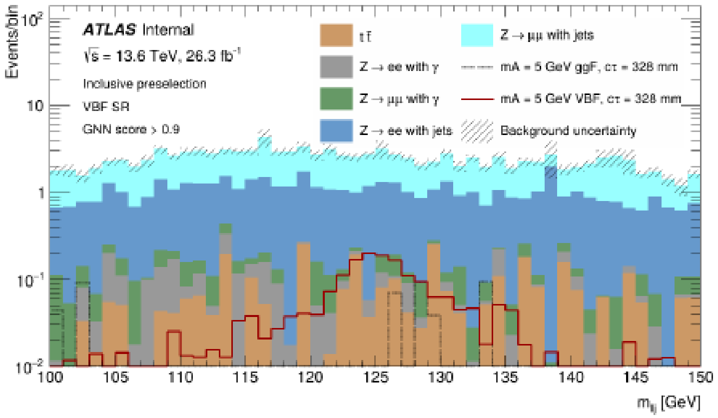
MORE VBF VARIABLES



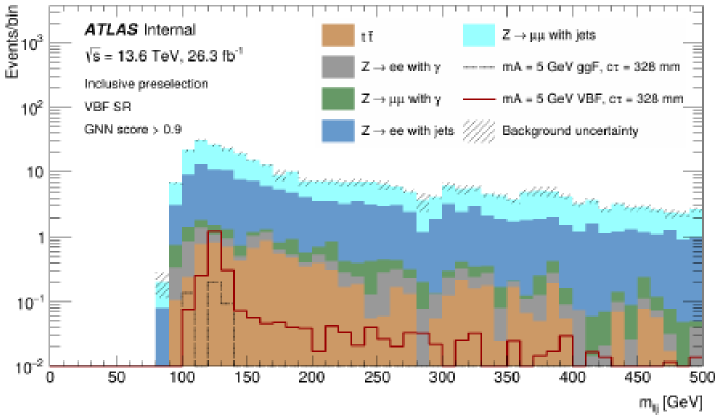
(a) $\Delta\eta(jet, Z)$, VBF SR



(b) $\Delta R(jet, Z)$, VBF SR



(c) m_{ljj} peak, VBF SR



(d) m_{llj}, VBF SR