# Searching for long-lived particles with the ATLAS muon spectrometer

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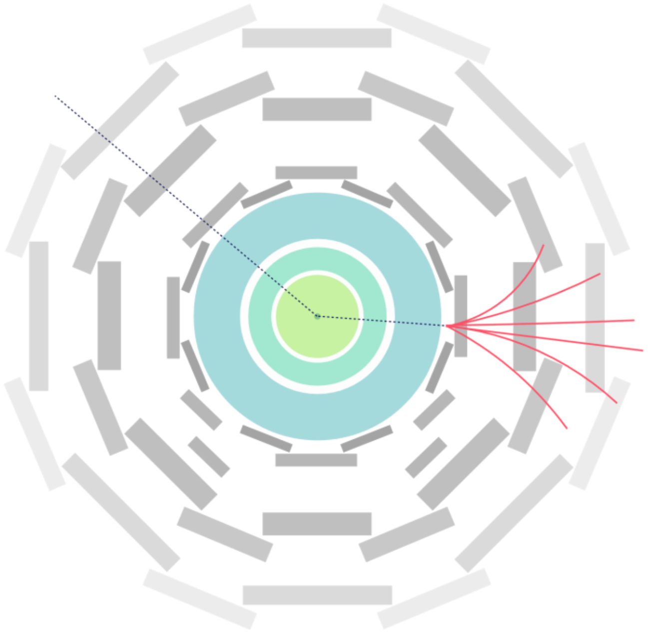
IOP HEPP 2025, Cambridge

# Introduction



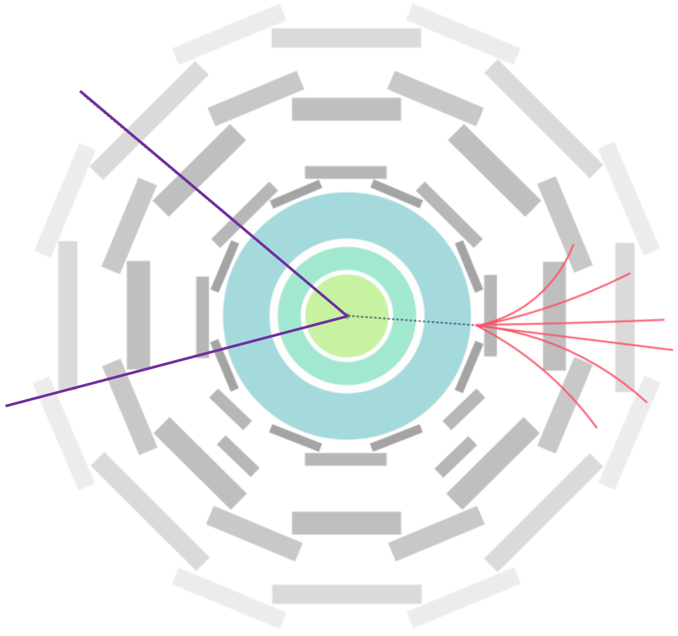
- Long-lived particles (LLPs) are common in dark matter models and BSM in general.
  - Lifetime is a free parameter.

- The large size and precise tracking capabilities of the ATLAS muon spectrometer (MS) makes it a powerful tool for searching for LLPs with very long lifetimes.
  - Complimentary to searches for LLPs with shorter lifetimes in the ATLAS inner-detector (PRL 133 (2024) 161803) and calorimeter (JHEP 11 (2024) 036).

- Previous searches for neutral LLPs in the MS probed models featuring pair-production of LLPs that decay to hadronic jets, particularly Higgs/scalar portal scenarios.
  - Hadronic decays of LLPs are reconstructed as displaced vertices (DVs) in the MS.
  - Previous searches for 1DV and 2DVs (Phys. Rev. D 99, 052005 (2019), Phys. Rev. D 106, 032005 (2022)).
  - Ongoing search for 1DV - triggered by activity in MS.

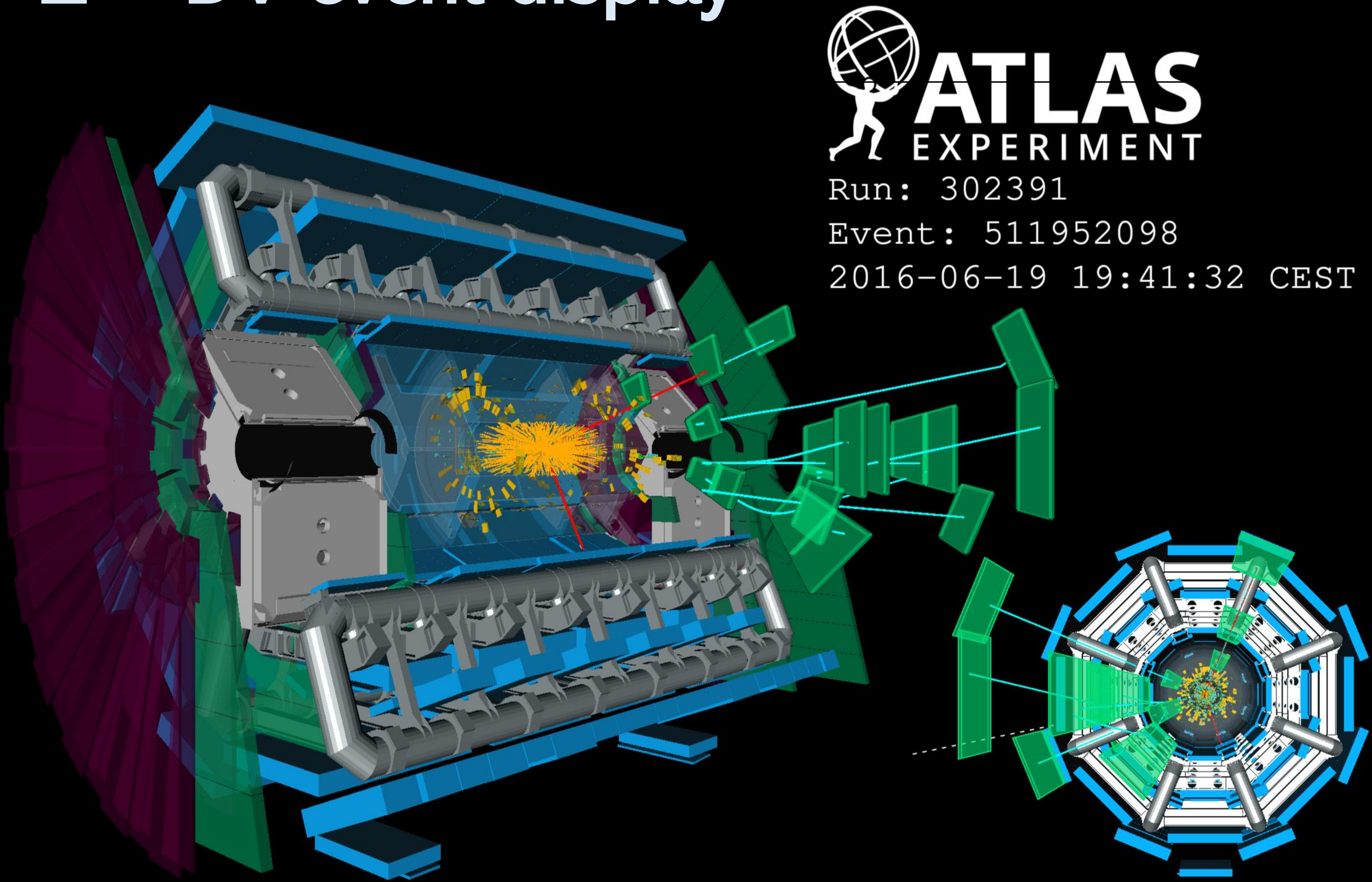
- Some models hypothesise single-LLP production, such as axion-like particles (ALPs) produced in association with a prompt $Z$ boson.

# Analysis strategy



- Search for events with a prompt $Z$ boson and 1DV in the MS.
- Target leptonic decay modes of the $Z$ boson.
  - Efficient triggering.
  - Background suppression.
- Main background from $Z$ + punch-through jets.
  - Non-collision background (cosmic rays and beam-induced) considered negligible.
- Signal selection
  - Baseline event selection: trigger, event and DV quality, MS fiducial volume.
  - Signal selection: $E_T^{miss}$ > 40 GeV, isolation criteria to reject punch-through jets.
  - Signal/background discrimination using neural nets (NNs).
- Data-driven background estimation method.
- Extrapolate signal efficiencies across a wide range of LLP lifetimes and set limits on $\sigma \times B$.

# Z + DV event display




Muons

Standalone MS tracks

Inner detector tracks

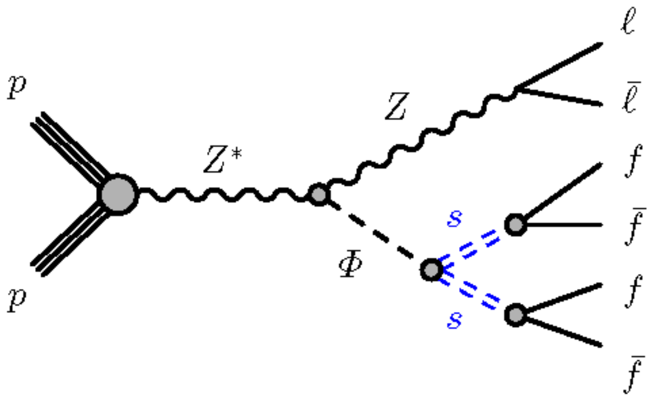
$E_T^{miss}$

Calorimeter clusters

# Signal models

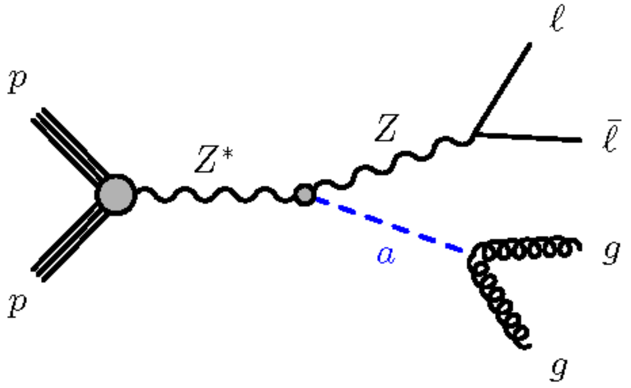
**Scalar portal**

- A mediator $\phi$ is radiated from a $Z$ boson and decays to a pair of dark sector scalars.
- The scalars can be long-lived and decay to SM fermions via a Yukawa coupling.
- $\phi$ can be the Higgs boson or a new massive particle.



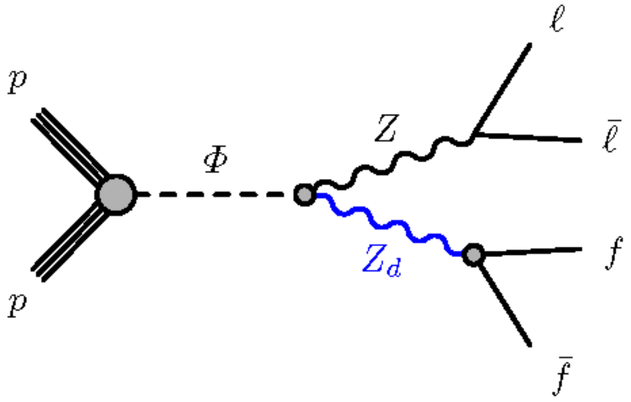

**Axion-like particles (ALPs)**

- ALPs are radiated from a $Z$ boson.
- Many previous searches for ALPs assumed coupling to photons. ALPs in this model are photophobic and decay to gluons.

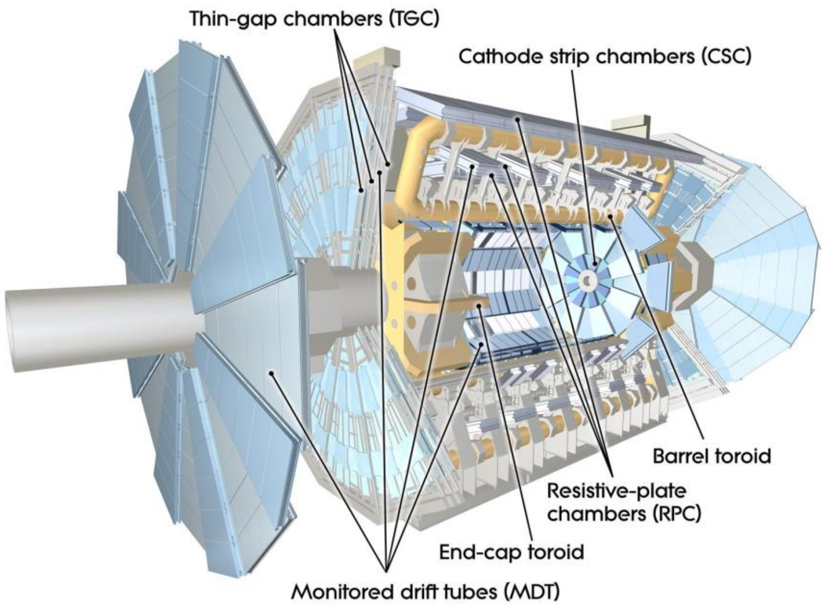


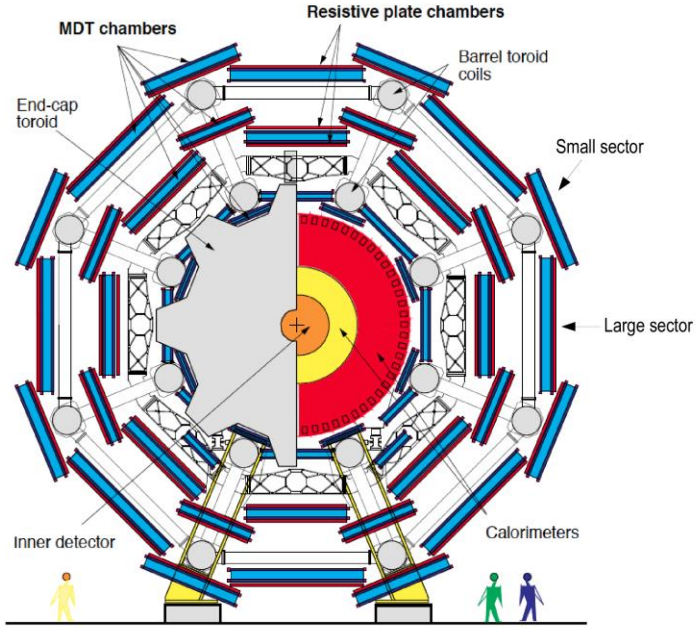

**Dark Photon**

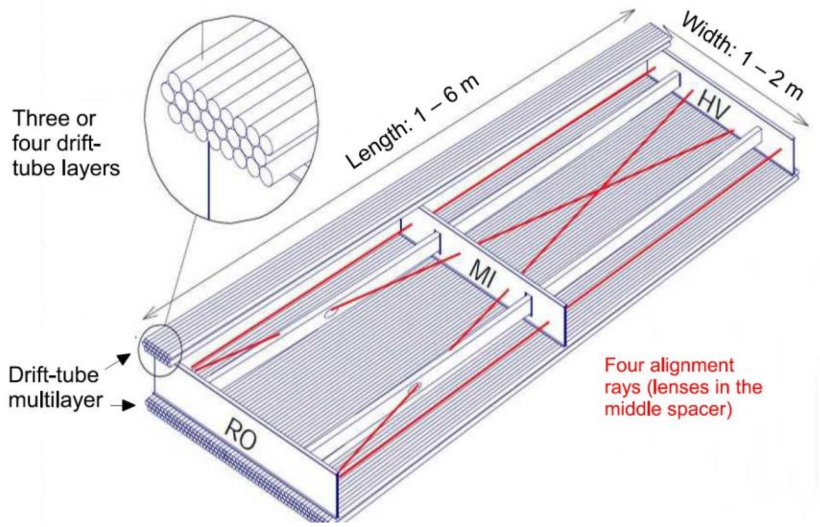
- A mediator $\phi$ decays into a $Z$ and long-lived dark photon $Z_d$ that decays to SM fermions.
- $\phi$ can be the Higgs boson or a new massive particle.



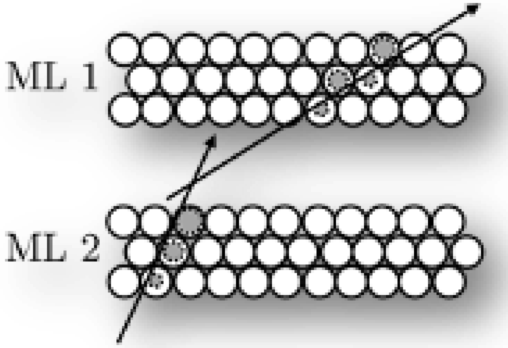
# The ATLAS muon spectrometer



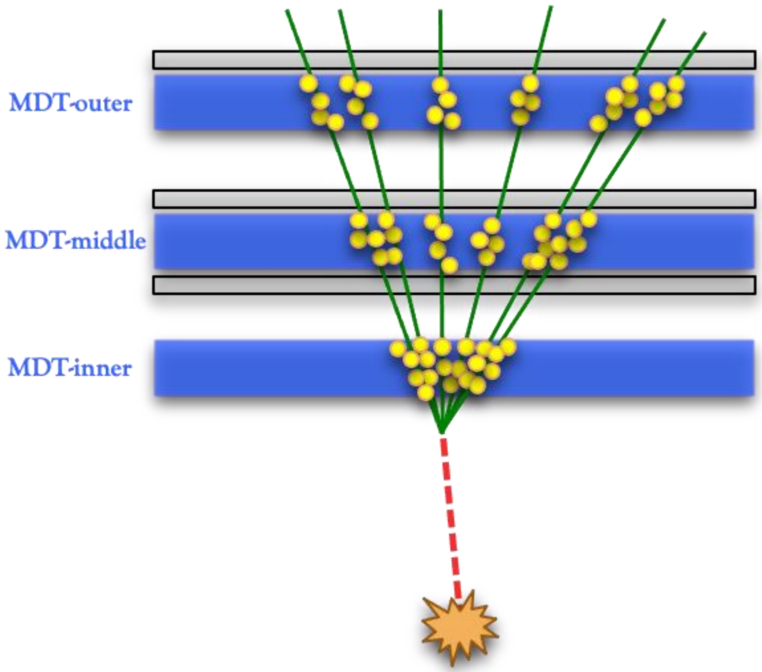




- 3 tracking layers immersed in toroidal magnetic field.
- Monitored drift tubes (MDTs) for precision tracking
  - Chambers comprised of 2 “multilayers” (MLs) that consist of 3-4 tube layers.
  - Straight-line fit of hits in tube layers of a ML is called a “segment”.
- Fast triggering
  - Resistive plate chambers (RPCs) in barrel.
  - Thin-gap chambers (TGCs) in endcap.
- Calorimeter suppresses backgrounds.

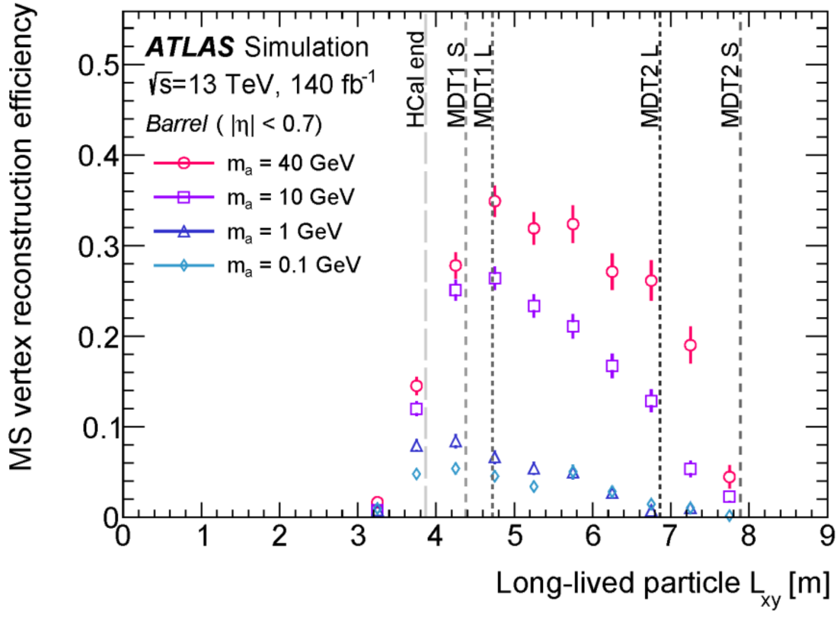


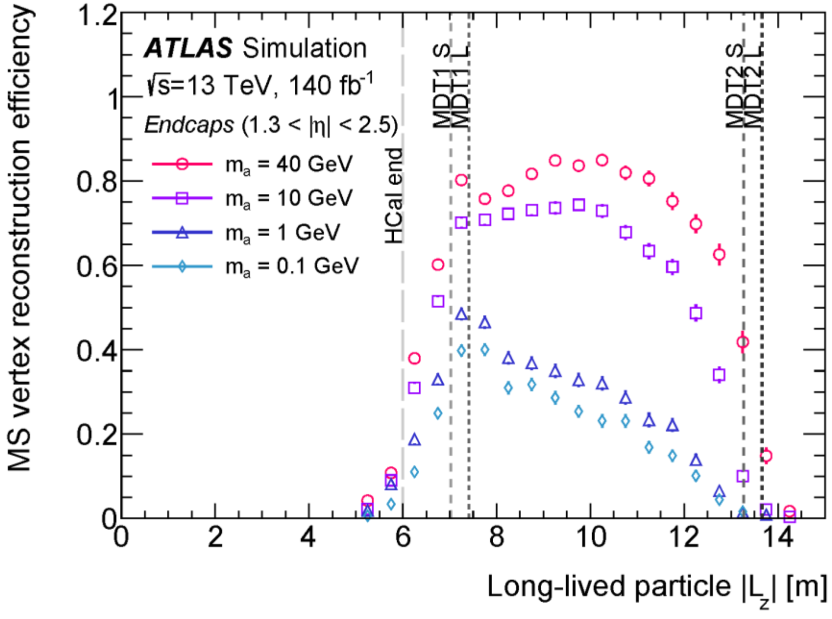
# Displaced vertex reconstruction

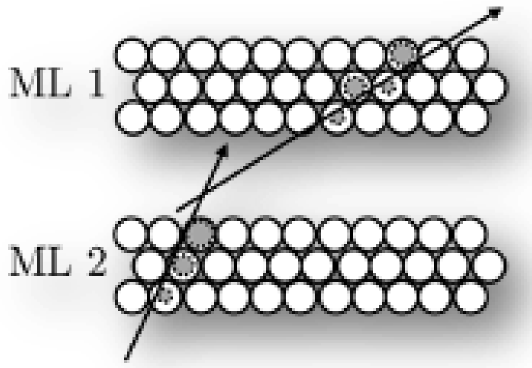



- Segments in adjacent MDT MLs are combined to form "tracklets".
- Tracklets are fitted to vertices using two different vertex algorithms (JINST 9 (2014) P02001) for the barrel and the endcaps since magnetic field is negligible in endcaps.

Truth-matched DVs that pass baseline and signal selections.



# Background estimation method

- Jets that penetrate the calorimeter are not well modelled in Monte Carlo. Therefore, a data-driven background estimation method is implemented.

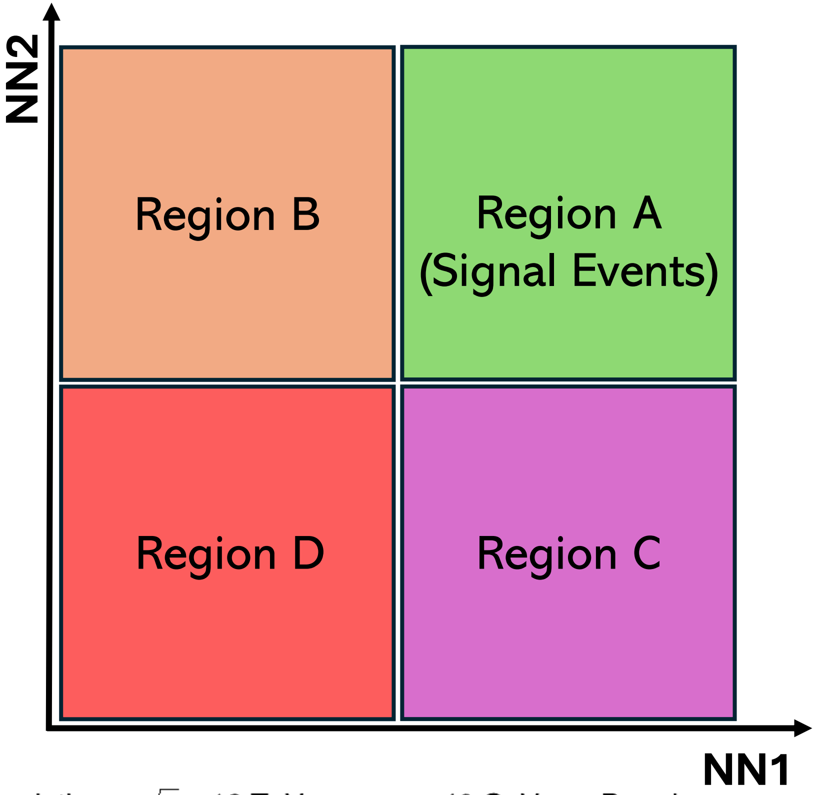
- Two uncorrelated variables can be used to construct an **ABCD plane**, where the number of events in each region are related by:

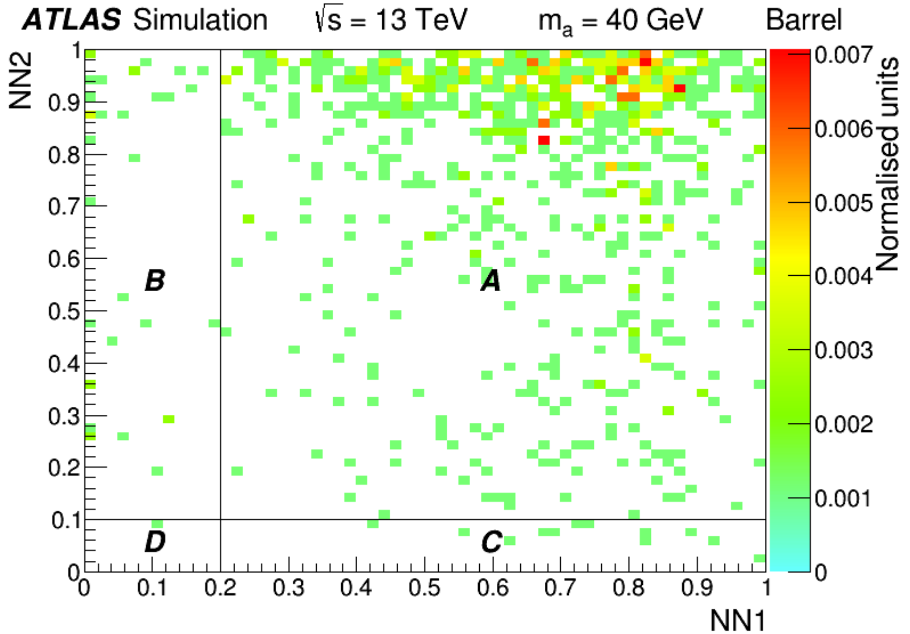
$$\frac{N_A}{N_C} = \frac{N_B}{N_D}$$

- **Forming an ABCD plane from two NN scores**, which discriminate signal from background, expected number of background events in region A is:

$$N_A^{expected} = \frac{N_B\, N_C}{N_D}$$

- **NN1: Isolation and background features.**
- **NN2: DV-related features.**



# Background estimation – validation

Define two background-dominated validation regions:

**MET VR**

- 10 GeV < $E_T^{miss}$ < 40 GeV

**γ+Jet VR**

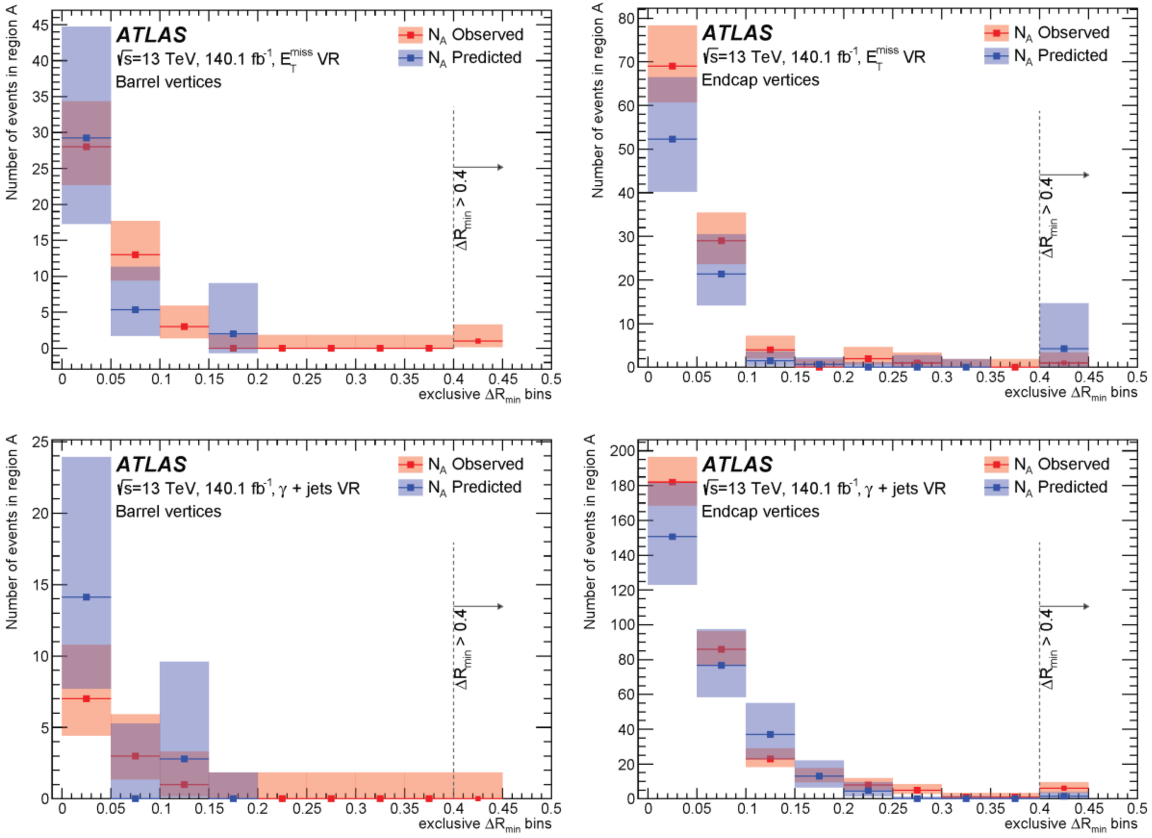
- Pass single or di-photon trigger
- Loose ID and isolation
- photon $p_T$ > 20 GeV
- $E_T^{miss}$ > 10 GeV

| VR | A | B×C/D | B | C | D |
|---|---|---|---|---|---|
| $E_T^{miss}$ Barrel | 4 | $16 \pm ^{43}_{18}$ (stat.) | 2 | 8 | 1 |
| $E_T^{miss}$ Endcaps | 8 | $6 \pm ^{4}_{3}$ (stat.) | 5 | 43 | 38 |
| $\gamma$+Jets Barrel | 1 | $3 \pm ^{7}_{3}$ (stat.) | 18 | 1 | 6 |
| $\gamma$+Jets Endcaps | 57 | $44 \pm ^{13}_{11}$ (stat.) | 30 | 82 | 56 |

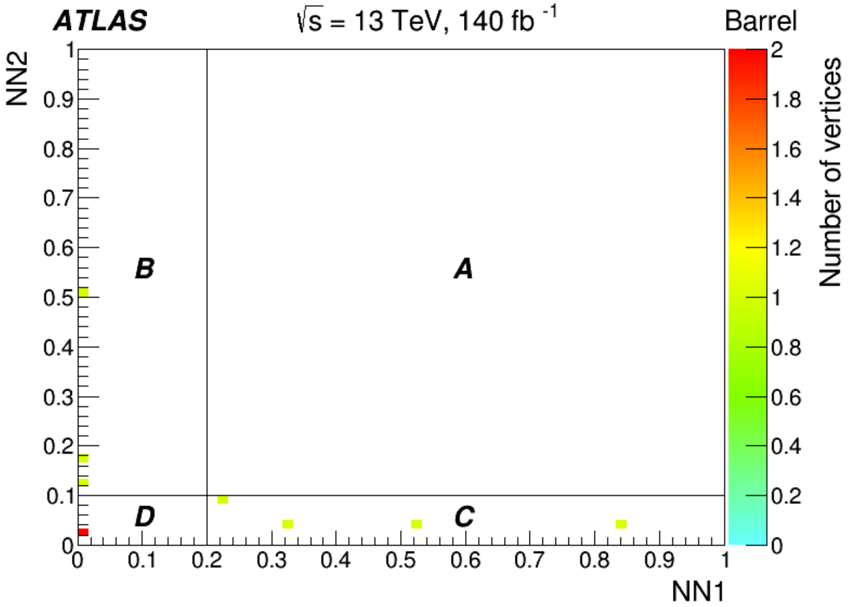
**Observed events consistent with predictions.**

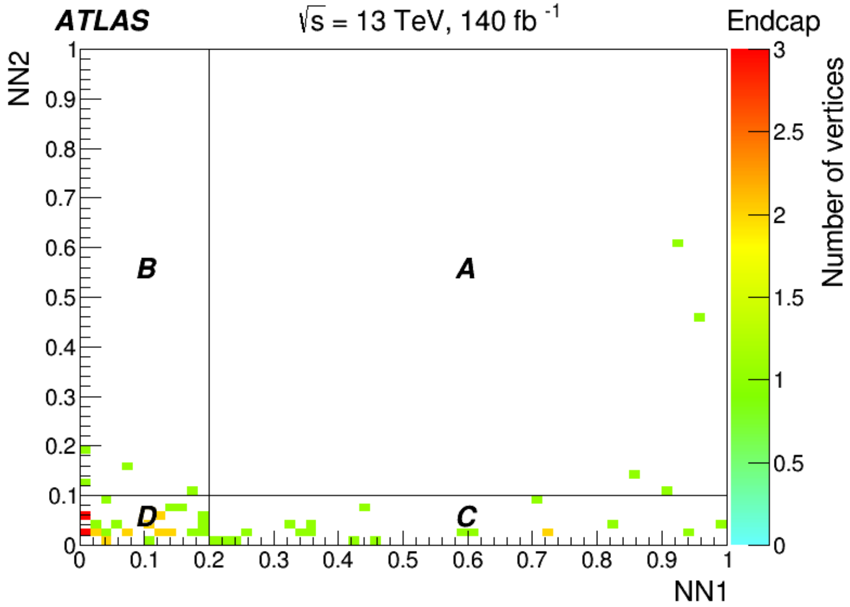
Divide VRs into regions of $\Delta R_{min}$(DV,jet/high-pT track) to check for systematic trends.

- No trend observed and the statistical error in the prediction dominates - **no systematic is assigned**.



# Background estimation – results



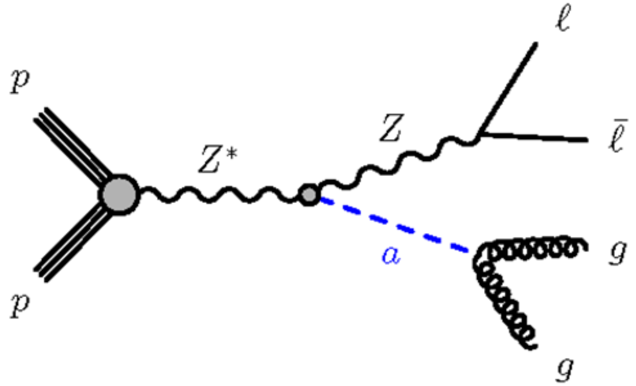




| SR | A | B×C/D | B | C | D |
|---|---|---|---|---|---|
| Barrel | 0 | $6 \pm ^{11}_{6}$ (stat.) | 3 | 4 | 2 |
| Endcaps | 4 | $2 \pm ^{2}_{1}$ (stat.) | 4 | 19 | 31 |

**Observed events in region A consistent with predicted SM background.**

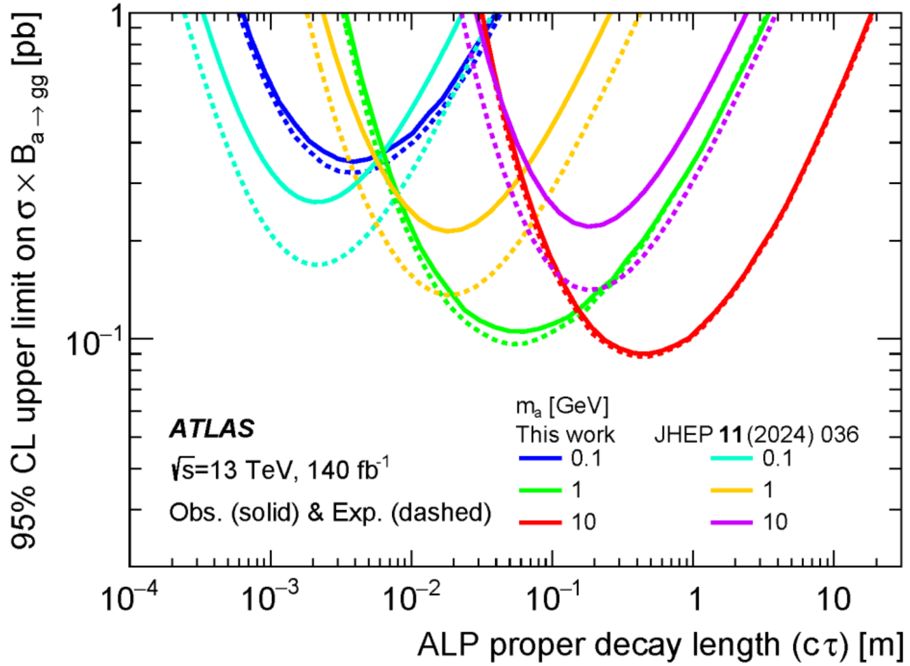
**No new physics found.**

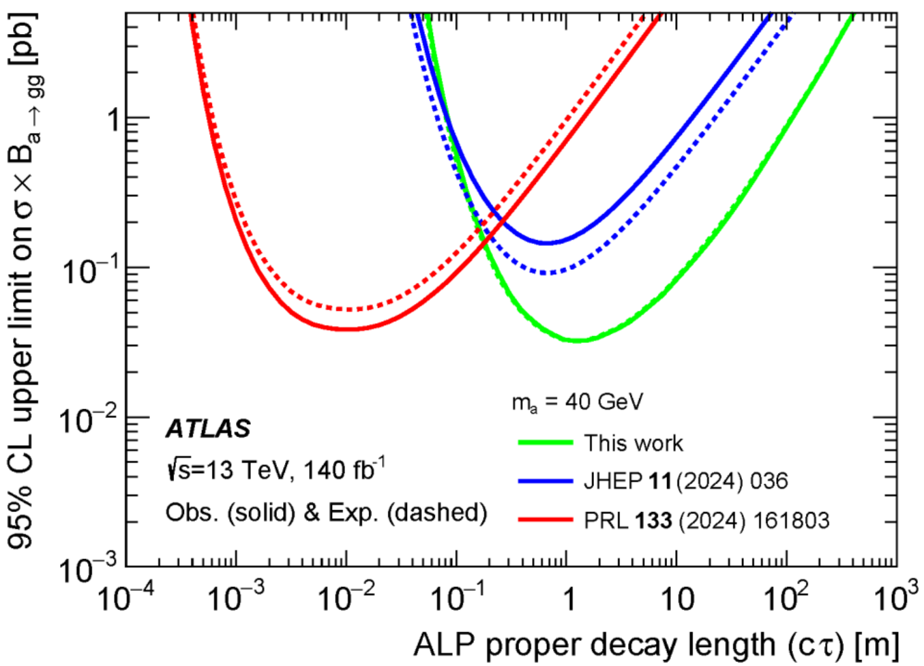
# Results – ALPs



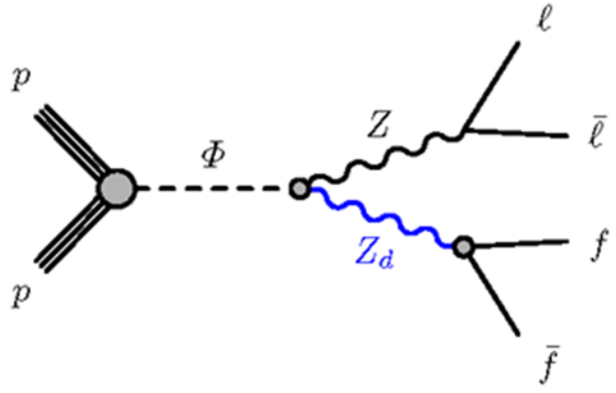

Previous searches for ALPS:
- ATLAS inner detector (PRL 133 (2024) 161803)
- ATLAS calorimeter (JHEP 11 (2024) 036)

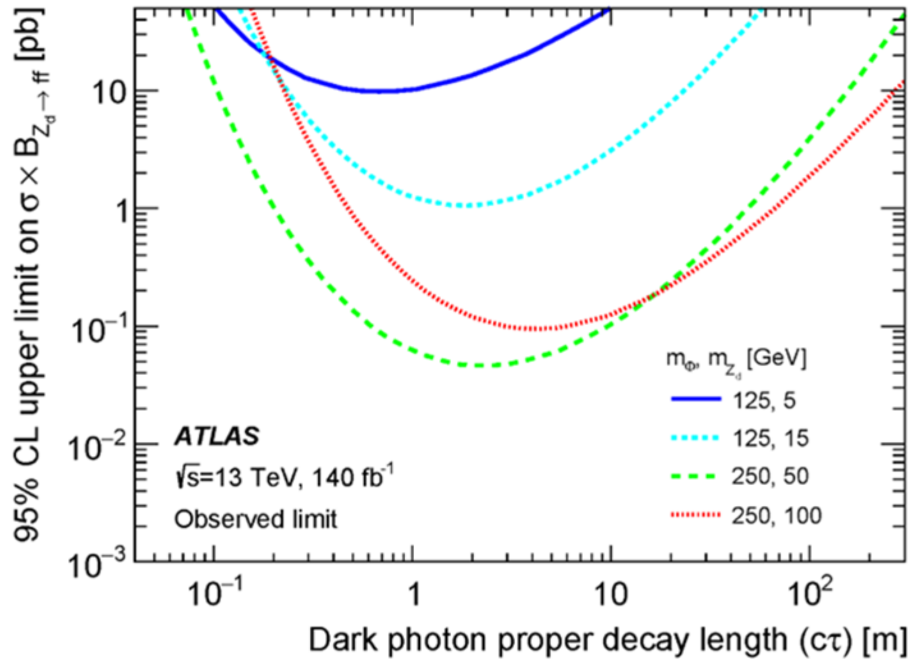
This work: **most stringent limits on photophobic ALPS with $c\tau > \mathcal{O}(10\ \text{cm})$**

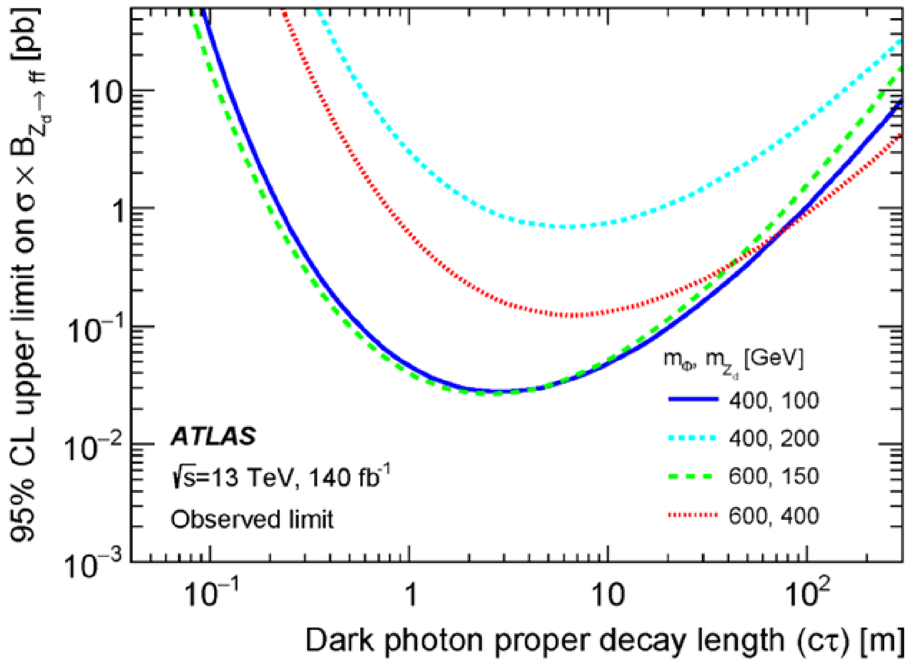


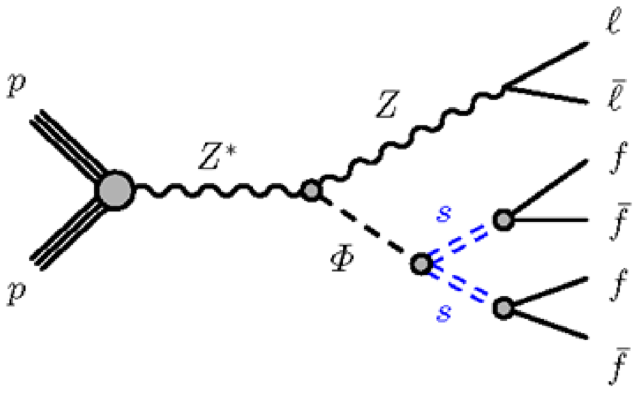
# Results – dark photon

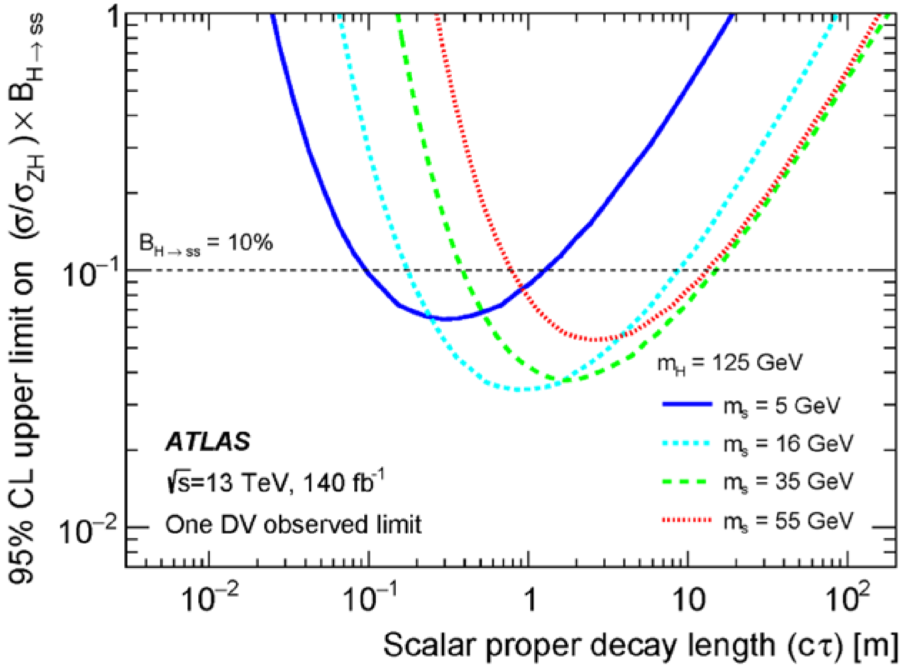


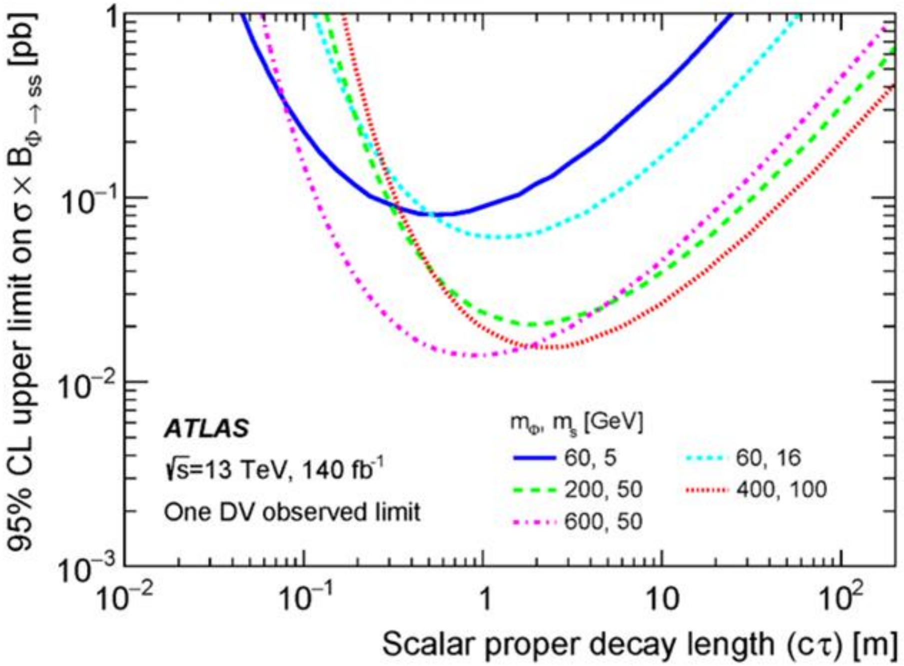



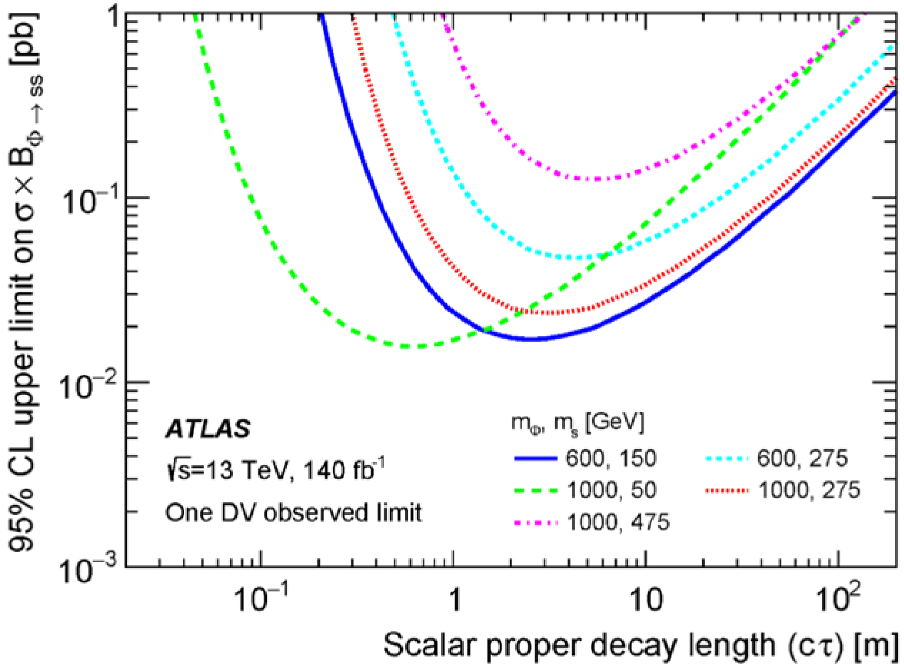



# Results – scalar portal



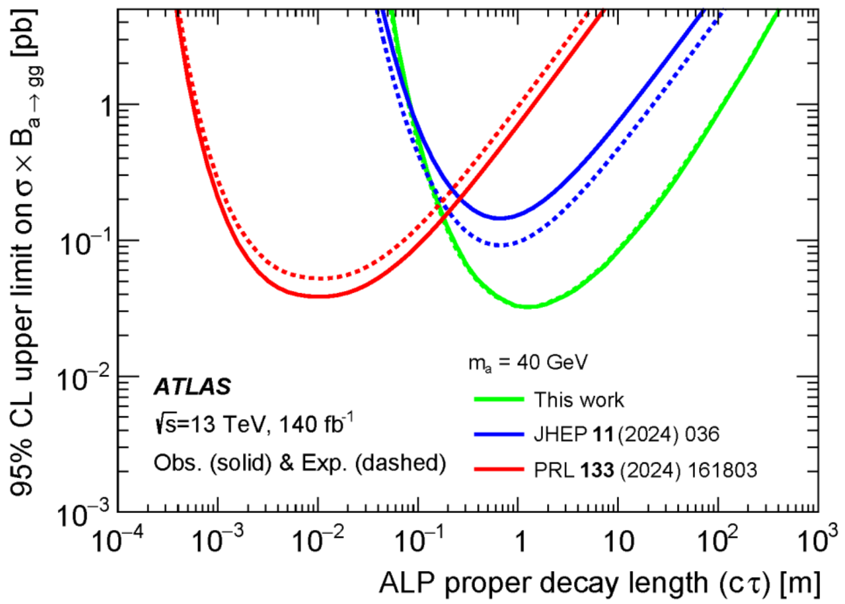



# Summary and outlook

- Stringent ATLAS limits on long-lived scalars, ALPs, and dark photons radiated from a $Z$ boson.
- Run 3 and beyond: searches will benefit from larger datasets, detector upgrades and improvements in DV reconstruction.
- Auxiliary experiments such as ANUBIS and Faser will increase sensitivity at longer lifetimes.

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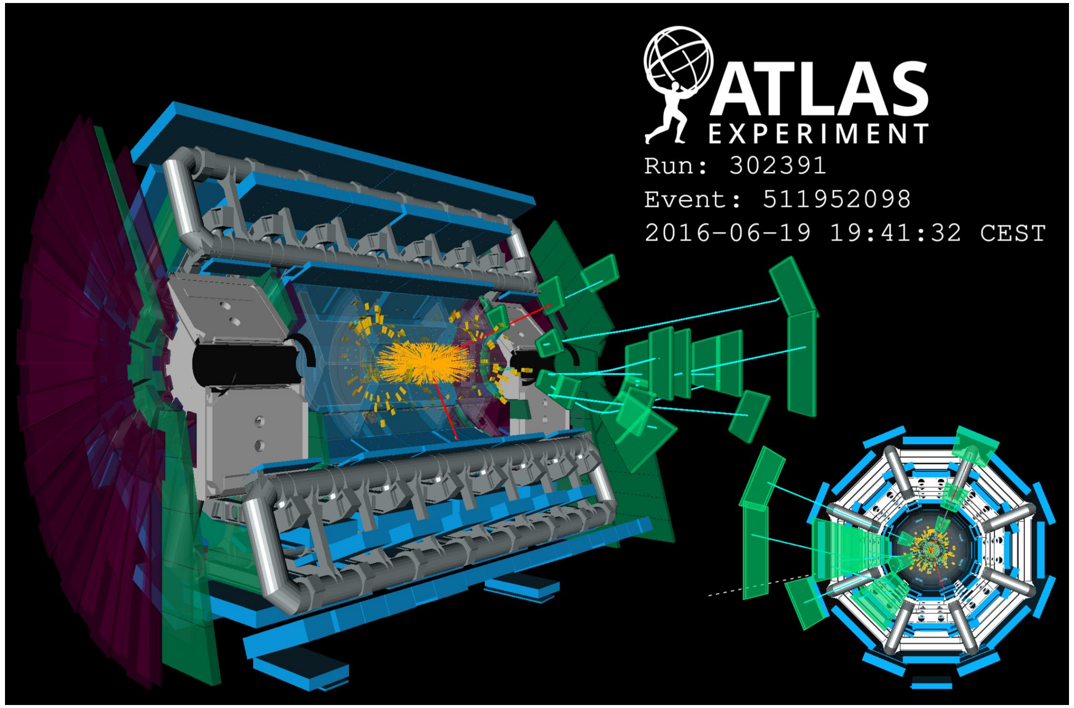


# Backup

# Signal samples

| Model | $m_\Phi$ [GeV ] | $m_s$ [GeV ] | Proper decay length [m] |
|---|---|---|---|
| Scalar portal | 125 | 5 | 0.127, 0.411 |
| | | 16 | 0.580 |
| | | 35 | 1.310, 2.630 |
| | | 55 | 1.050, 5.320 |
| | 60 | 5 | 0.217 |
| | | 16 | 0.661 |
| | 200 | 50 | 1.255 |
| | 400 | 100 | 1.608 |
| | 600 | 50 | 0.590 |
| | | 150 | 1.840, 3.309 |
| | | 275 | 4.288 |
| | 1000 | 50 | 0.406 |
| | | 275 | 2.399, 4.328 |
| | | 475 | 6.039 |

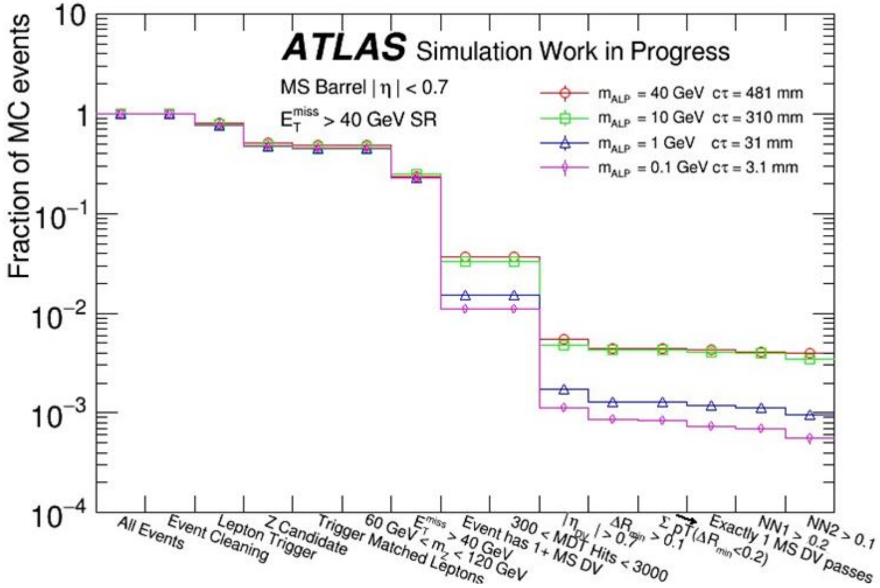
| Model | $m_\chi$ [GeV ] | $\chi$ decay channel | Proper decay length [m] |
|---|---|---|---|
| Higgs portal baryogenesis | 10 | $\tau^+\tau^-\nu_\ell$ , $c\,b\,s$ , $\nu\,b\,\bar{b}$ | 0.920 |
| | 55 | | 5.550 |
| | 100 | | 3.500 |

| | $m_a$ [GeV ] | $C_{\tilde{G}}$ | Proper decay length [m] |
|---|---|---|---|
| $Z$+ALP | 0.1 | $10^{-2}$ | 0.003 |
| | | $5\times10^{-3}$ | 0.012 |
| | 1 | $10^{-4}$ | 0.031 |
| | 10 | $3.2\times10^{-6}$ | 0.030 |
| | | $10^{-6}$ | 0.310 |
| | | $7.5\times10^{-7}$ | 0.551 |
| | 40 | $10^{-7}$ | 0.481 |

| Model | $m_\Phi$ [GeV ] | $m_s$ [GeV ] | Proper decay length [m] |
|---|---|---|---|
| $Z$+Scalar portal | 125 | 5 | 0.100, 0.300 |
| | | 16 | 0.300 |
| | | 35 | 0.750, 2.500 |
| | | 55 | 3.500, 1.000 |
| | 60 | 5 | 0.12 |
| | | 15 | 0.25 |
| | 200 | 50 | 1.25 |
| | | 80 | 2.00 |
| | 400 | 100 | 1.25 |
| | | 175 | 2.50 |
| | 600 | 50 | 0.40 |
| | | 150 | 1.50, 3.50 |
| | | 275 | 2.50 |
| | 1000 | 50 | 0.30 |
| | | 275 | 1.50, 3.50 |
| | | 475 | 4.50 |

| Model | $m_\Phi$ [GeV ] | $m_{Z_d}$ [GeV ] | Proper decay length [m] |
|---|---|---|---|
| Dark Photon | 125 | 5 | 0.60 |
| | | 15 | 1.60, 3.00 |
| | 250 | 50 | 1.60 |
| | | 100 | 3.40 |
| | 400 | 100 | 1.60 |
| | | 200 | 4.00 |
| | 600 | 150 | 1.60, 4.00 |
| | | 400 | 4.00 |

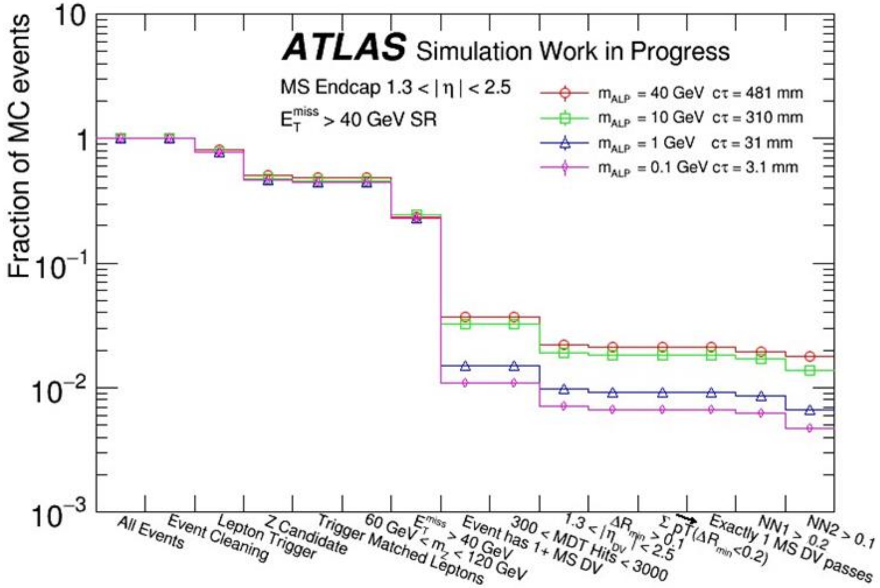
# Event selection




## Baseline event selection

| | |
|---|---|
| Event passes data quality requirements and Lepton triggers | |
| Event has a PV with at least two tracks with $p_{\mathrm{T}} > 500$ MeV | |
| Event has at least one DV | |
| Exactly one opposite-sign, same-flavor lepton pair, invariant mass >60 GeV and <120 GeV<br>No additional leptons not used in the pair | |
| $300 \leq n_{\mathrm{MDT}} < 3000$ | |

| *Barrel* | *Endcaps* |
|---|---|
| DV with $\lvert\eta_{\mathrm{vx}}\rvert < 0.7$ | DV with $1.3 < \lvert\eta_{\mathrm{vx}}\rvert < 2.5$ |
| DV with $3\,\mathrm{m} < L_{xy} < 8\,\mathrm{m}$ | DV with $L_{xy} < 10\,\mathrm{m}$, $5\,\mathrm{m} < \lvert L_z\rvert < 15\,\mathrm{m}$ |




## Signal selection

| Selection | Barrel | Endcaps |
|---|---|---|
| Event $E^{T}_{\mathrm{miss}}$ | > 40 GeV | |
| Isolation from high-$p_{\mathrm{T}}$ tracks ($p_{\mathrm{T}} > 5$ GeV)<br>Isolation from low-$p_{\mathrm{T}}$ tracks ($\Sigma p_{\mathrm{T}}(\Delta R < 0.2)$)<br>Isolation from jets | $\Delta R > 0.1$<br>$\Sigma p_{\mathrm{T}} < 5$ GeV<br>$\Delta R > 0.1$ | $\Delta R > 0.1$<br>$\Sigma p_{\mathrm{T}} < 5$ GeV<br>$\Delta R > 0.1$ |
| NN1, NN2 | > 0.2, 0.1 | > 0.2, 0.1 |

# Neural net

A multilayer perceptron is used to find variables with strong background discrimination power.

- Used sequential model provided by Keras and Tensorflow.
- NN consists of 2 hidden layers with 128 neurons and uses ReLU as activation function.
- Output layer has 1 node and uses Sigmoid function as activation function (NN output $\in [0,1]$).
- Training on background-enriched region with $H_T^{miss} < 40$ GeV.
- Combination of signal MCs with $m_\phi$ = 60, 125, 1000 GeV.
- Separate training for barrel and endcaps.

**Two sets of features used as inputs to get two NN scores**

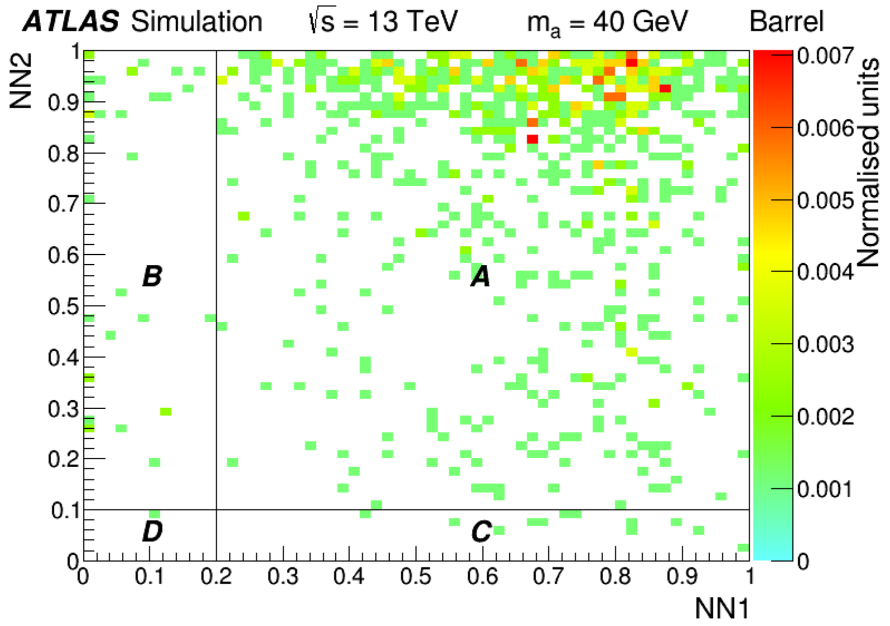
NN1: isolation and residual background features

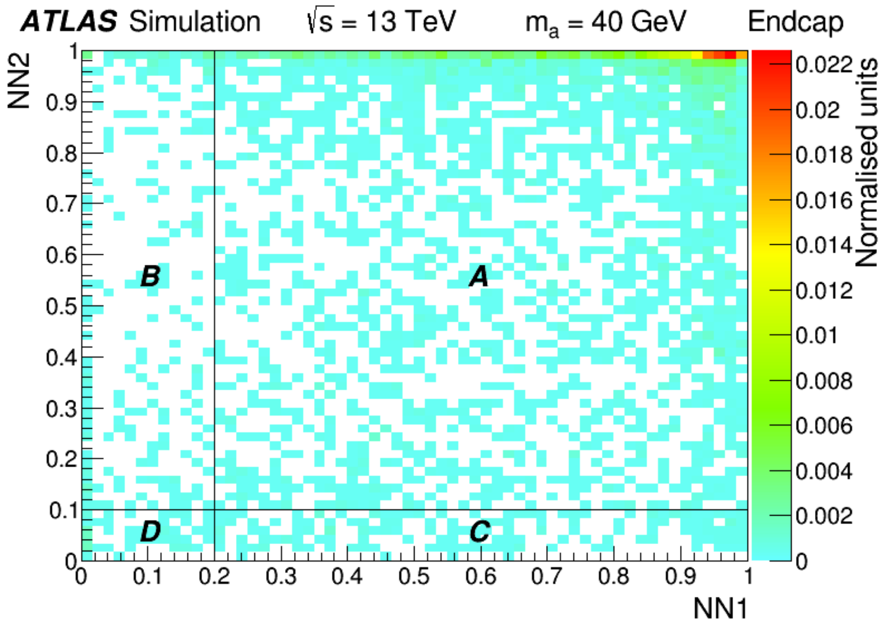
- Scalar sum of $p_T$ for all high-$p_T$ (> 5 GeV) tracks
- Total, average, RMS and maximum energy of all calorimeter clusters satisfying $\Delta R$(DV,cluster) < 0.4
- Calorimeter cluster energy at each ECal and HCal sampling layer satisfying $\Delta R$(DV,cluster) < 0.4
- $\Delta R$ of the high-$p_T$ (> 5 GeV) track or jet closest to the DV
- Low-$p_T$ track isolation
- Ratio of the number of muon segments in the inner and middle MDT station

NN2: DV related features

- Average and RMS $\Delta R$(DV, tracklets)
- Average and RMS $\Delta R$(DV, segments)
- $n_{MDT} + n_{RPC/TGC}$ associated to the DV
- Number of tracklets satisfying $\Delta R$(DV,tracklet) < 0.4
- $\Delta\phi(\mathrm{DV}, E_T^{miss})$
- Average, RMS and maximum time of arrival of the particle depositing the energy in the calorimeter clusters satisfying $\Delta R$(DV,cluster) < 0.4

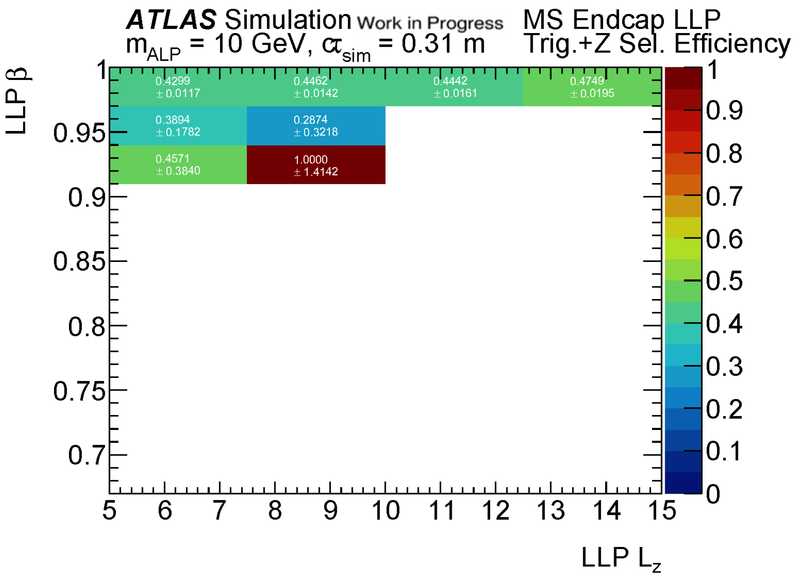
# ABCD planes – signal Monte Carlo

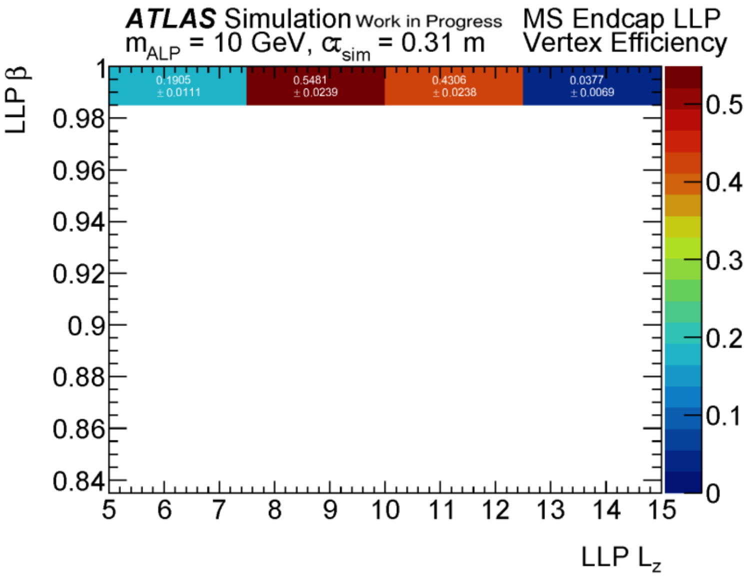


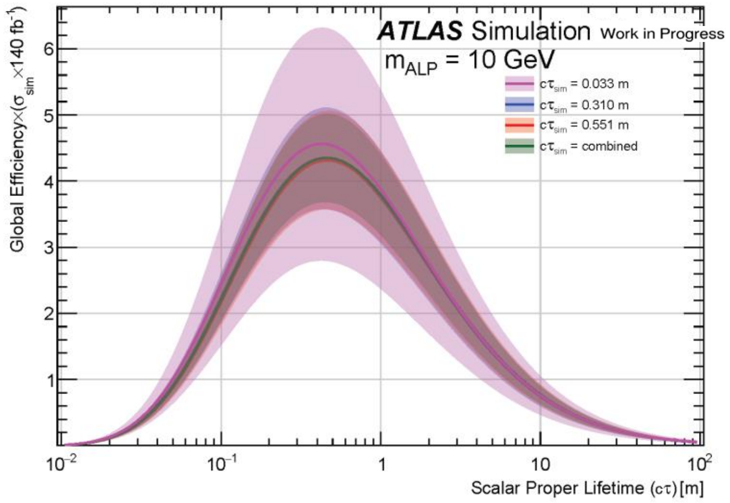



# Lifetime extrapolation

- Toy MC method based on the LLP boost and decay position to extrapolate efficiencies at various lifetimes
- Extract trigger and DV reconstruction efficiencies from MC samples generated at specific proper lifetimes
- Toys use truth kinematic information of the LLP.
- Method validated using additional lifetimes generated for some MC samples.
- Assign a systematic based on scaling toy samples to the original full-sim efficiencies.
- Extrapolation systematic varies between 1.9% and 30%.

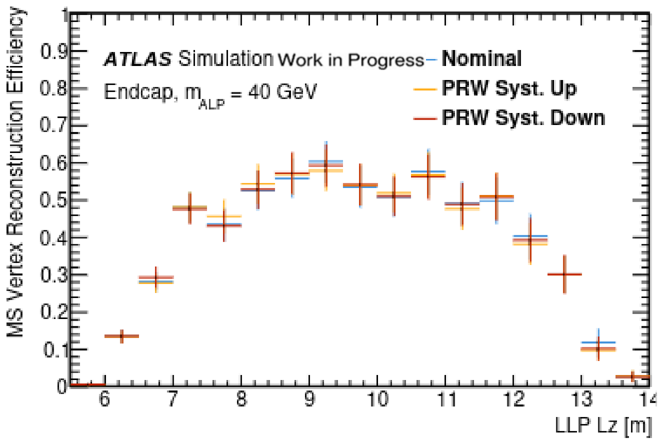


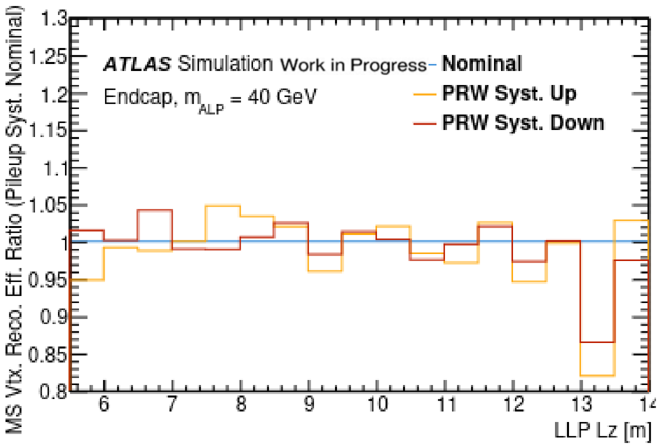



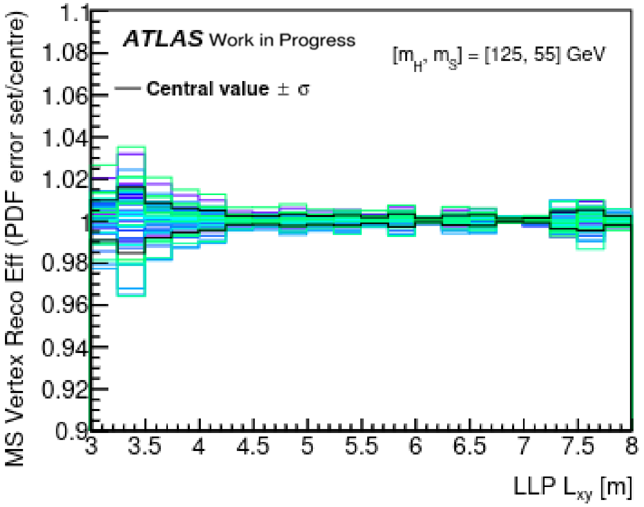



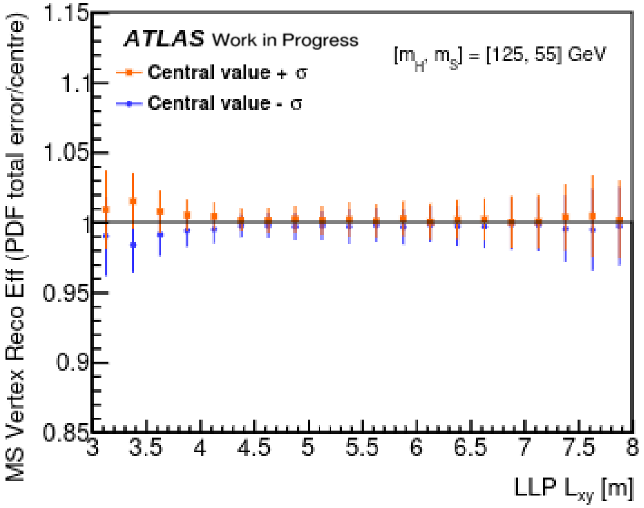
# Systematics - pileup and PDF

- For pileup, re-weight <μ> by one std. deviation up and down, assess impact on trigger and DV reconstruction efficiency.
- For PDF uncertainties, calculate std. deviation of trigger and reconstruction efficiency for 100 different PDF tunes.
- For both pileup and PDFs, first verify that there are no systematic trends in the LLP decay position.
- Apply final systematics as global uncertainties for all LLP decay positions separately for the trigger and vertex reconstruction.
  - PDF Uncertainty: **0.03% - 0.2%**
  - Pileup Uncertainty: **0.4% - 3.1%**



# Systematics

- NLO Re-weighting: Compare 125 mediator NLO MadGraph predictions to next-to-next-to-leading-order (NNLO) accuracy in QCD using Powheg Box v2
- Uncertainty on the signal efficiency ranging from 0.1% to 4%
- Luminosity uncertainty of 0.8% from LUCID-2 measurements
- Uncertainty in lepton measurements estimated by varying lepton systematics by one up- and down- std. dev. according to ATLAS CP recommendations.

| Systematic Variation | $m_{ALP}$ = 0.1 GeV % | $m_{ALP}$ = 1 GeV % | $m_{ALP}$ = 10 GeV % | $m_{ALP}$ = 40 GeV % |
|---|---|---|---|---|
| Electron Barrel Trigger and Z Selection | 0.19 | 0.19 | 0.25 | 0.17 |
| Electron Endcap Trigger and Z Selection | 0.19 | 0.19 | 0.25 | 0.17 |
| Muon Barrel Trigger and Z Selection | 0.26 | 0.21 | 0.43 | 0.38 |
| Muon Endcap Trigger and Z Selection | 0.88 | 0.89 | 0.94 | 0.80 |
| Electron Barrel Vertex Reco. | 0.39 | 0.30 | 0.12 | 0.06 |
| Electron Endcap Vertex Reco. | 0.07 | 0.08 | 0.04 | 0.04 |
| Muon Barrel Vertex Reco. | 1.96 | 1.15 | 0.26 | 0.37 |
| Muon Endcap Vertex Reco. | 0.11 | 0.25 | 0.03 | 0.05 |