Recent results on LLPs from displaced vertices in ATLAS

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Displaced vertices

LLPs are predicted by various BSM theories, including supersymmetry, hidden sectors, and dark matter models:

- mass scale is unknown and are very difficult to probe at particle colliders, often lead to unconventional signatures!
- complement traditional searches for prompt decays by providing sensitivity to different lifetimes and decay modes
- the challenge of detecting LLPs drives the development of innovative tracking and detection techniques

\[ \kappa H^2 S^2 + \mu H^2 S \]

Higgs portal and mixing with ‘dark’ scalars

For scalar masses above 10 GeV \( \rightarrow \) bb decay mode favoured

**Dedicated searches**

- in calorimeter: \( 0.1 \leq c\tau \leq 10 \text{m} \)
- in muon system: \( c\tau \leq 100 \text{m} \)

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**JHEP 11 (2021) 229**

**ATLAS** Preliminary

- \( \sqrt{s} = 13 \text{ TeV} \)
- \( m_{H^\pm} = 125 \text{ GeV} \)

- \( m_{H^\pm} = 15 \text{ GeV} \)
- \( m_{H^\pm} = 35 \text{ GeV} \)
- \( m_{H^\pm} = 55 \text{ GeV} \)

**EPJC 79 (2019) 481**

**ZH,H->4b analysis**

Displacement in ID

- **Prompt search**
  - (no displaced techniques)
  - \( 50 \mu m \leq c\tau \leq 2 \text{mm} \)

- **Mean proper lifetime** \( {c\tau}_a \text{ [m]} \)
ATLAS search for displaced vertices

Search for exotic decays of the Higgs boson to pairs of long-lived neutral particles in the inner detector:

• Trigger on VH/VBF Higgs production to probe small lifetimes $\text{ctau} < 100\text{mm}$ and small masses $> 5\text{ GeV}$

• First ATLAS search to exploit the improved Large Radius Tracking algorithm: O(10) improvement over previous search with same dataset

• First collider search to probe long lived axion-like particle (ALP) in $V a$ non-photon decays and exotic top decay benchmarks

Submitted to PRL: arXiv:2403.15332
ATLAS has a **new** special tracking iteration, the **Large Radius Tracking (LRT)**, which has now been made available for **every event** (in legacy Run-2 it was applied to O(10\%) of the events)

- Run on unused hits with LLP focused tracking cuts
- Optimised for neutral LLP decays
- Huge gain in CPU time and disk space consumption allows to run LRT in ATLAS reconstruction workflow for every event

Extends ATLAS standard tracking:
- \(d_0\): 5 mm \(\rightarrow\) 300 mm
- \(z_0\): 200 mm \(\rightarrow\) 500 mm

**x5** significance impact on displaced vertex searches!!

**x10** fakes reduction w/ LRT
most challenging background for light LLPs in the ID

**Huge increase in processing performance**
Reduced event-time reconstruction and event size output

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Analysis overview

Signature is characterised by the presence of two or more displaced jets that do not originate at the PV

Three search regions, targeting ZH, WH, and VBF production modes:

• Events with at least 2 displaced jets and at least 1 matched displaced vertex

• Signal (SR) and control region (CR) based on BDT discriminant output and number of DVs

• Data-driven background estimation of the hadronic jets main background, based on per-jet vertex matching probability maps

• Material veto used to reject secondary vertices from material interactions

![Number of displaced vertices (nDV)](image)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1} \)

1-lepton, \( H \rightarrow ss \)

\( c \tau_s = 100 \text{ mm} \)

- Data
  - \( m_s = 16 \text{ GeV} \)
  - \( m_s = 40 \text{ GeV} \)
  - \( m_s = 55 \text{ GeV} \)

**Prompt vs displaced jet BDT tagger trained on track variables associated to the jet**
Displaced DVs and jets

The reconstructed DVs are required to uniquely match the displaced jets in the event.

**ATLAS Simulation**

- $\sqrt{s} = 13$ TeV
- $m_{a,s} = 55$ GeV

- $H \rightarrow ss \rightarrow 4b$
- $H \rightarrow ss \rightarrow 4u$
- $qq \rightarrow Za$
- $t \rightarrow ac$

**ATLAS**

- $\sqrt{s} = 13$ TeV, $140$ fb$^{-1}$
- 1-lepton, $H \rightarrow ss \rightarrow 4b$

- Data
- $m_s = 16$ GeV
- $m_s = 40$ GeV
- $m_s = 55$ GeV
- $c\tau_s = 100$ mm

**Efficiency of the displaced vertex reconstruction algorithm**

**Ratio of DV mass and the max distance between tracks**
Exploit the control regions to parametrise the background by deriving a per-jet probability map which quantifies the likelihood that a given jet is matched to a DV as a function of:

- BDT score
- pT
- Jet b-tagging score

Per-event probability is then computed from a multinomial distribution based on the jets in the event:

\[
P(1 \text{ DV})_{\text{event}} = \sum_{i=1}^{n_{\text{jet}}} P(1 \text{ DV}|j_i)_{\text{jet}} \times \prod_{k \neq i} (1 - P(1 \text{ DV}|j_k)_{\text{jet}})\]

\[
P(2 \text{ DV})_{\text{event}} = 1 - P(1 \text{ DV})_{\text{event}} - P(0 \text{ DV})_{\text{event}}
\]

Applied as per-event weight to predict background distribution in 1DV and 2DV SRs
Results

No excess over background estimate observed
Results

No excess over background estimate observed

Axion-like particle $t\rightarrow aq$ production

Neutral long-lived scalar

Axion-like particle $Z_a$ production
Observed limits

**Neutral long-lived scalar**

**Axion-like particle \( Z_a \) production**

**Axion-like particle \( t \rightarrow aq \) production**
Observed limits

Neutral long-lived scalar

Limits on BR(H → ss) are most stringent to date for ms < 40 GeV and 1 < ct < 100 mm

Axion-like particle Za production

First ATLAS limits on long-lived ALP decaying to gluons

Axion-like particle t→aq production

First collider search to present limits on BR(t → aq) and long-lived photo-phobic ALP production

Submitted to PRL: arXiv:2403.15332
The big picture

x10 improvement wrt previous ATLAS limit on same dataset!

Large coverage in mass vs ctau phase space
Conclusions

• New Large Radius Tracking in ATLAS opens up new possibilities for searches involving displaced vertices, enhancing existing searches and enabling new ones

• The first new LRT ATLAS search for displaced vertices in the Inner Detector has been presented, more LRT analyses will come out very soon… stay tuned!

• Great effort in developing new tools and strategies to improve identification and reconstruction of long-lived particles pushing the detectors beyond their limits

• Run-3 and HL-LHC programmes offer a unique opportunity to plan, innovate and create new unconventional searches yet to be explored