Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

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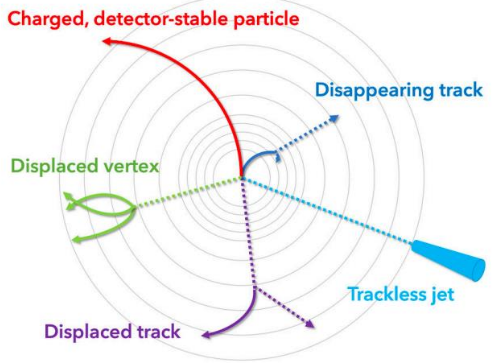
On behalf of the ATLAS Collaboration

PIC2024 Oct 23rd, 2024

Introduction

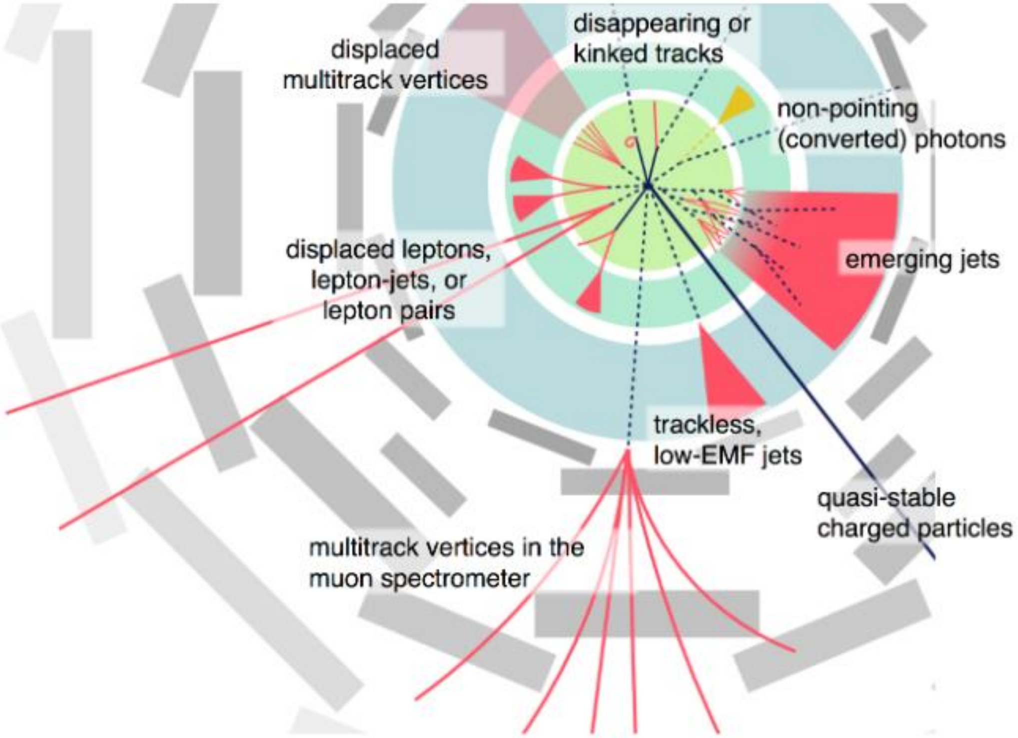
- After the discovery of the Higgs, there are many Beyond Standard Model (BSM) theories trying to explain the problems Standard Model cannot answer (dark matter, antimatter, gravity…)
  - Many of them predict particles with decays suppressed by weak coupling constants, small mass differences between particles, or heavy mediators.
    -> Acquire large lifetimes, becoming long-lived particles (LLPs).
- ATLAS experiment at LHC have many searches for BSM phenomena.
  - LLP search: Search for new particle at life-time frontier
    - Distinctive signature → Zero or low SM background
    - Sensitivity gain promised with accumulating luminosity
    - Unconventional / Dedicated reconstruction + trigger
    - Instrumental backgrounds: Beam-induced backgrounds, Cosmic rays, Fake, etc.



Signatures of LLPs

- LLPs can have unusual experimental signatures:
  - Tracks with unusual ionization and propagation properties
  - Small, localized deposits of energy inside of the calorimeters without associated tracks
  - Stopped particles (SPs) that decay out of time with collisions
  - Displaced vertices (DV) in the inner detector (ID) or muon spectrometer (MS)
  - Disappearing, appearing, and kinked tracks.
- The standard reconstruction algorithms may reject events or objects containing LLPs precisely.
- Dedicated searches are needed to uncover LLP signals.

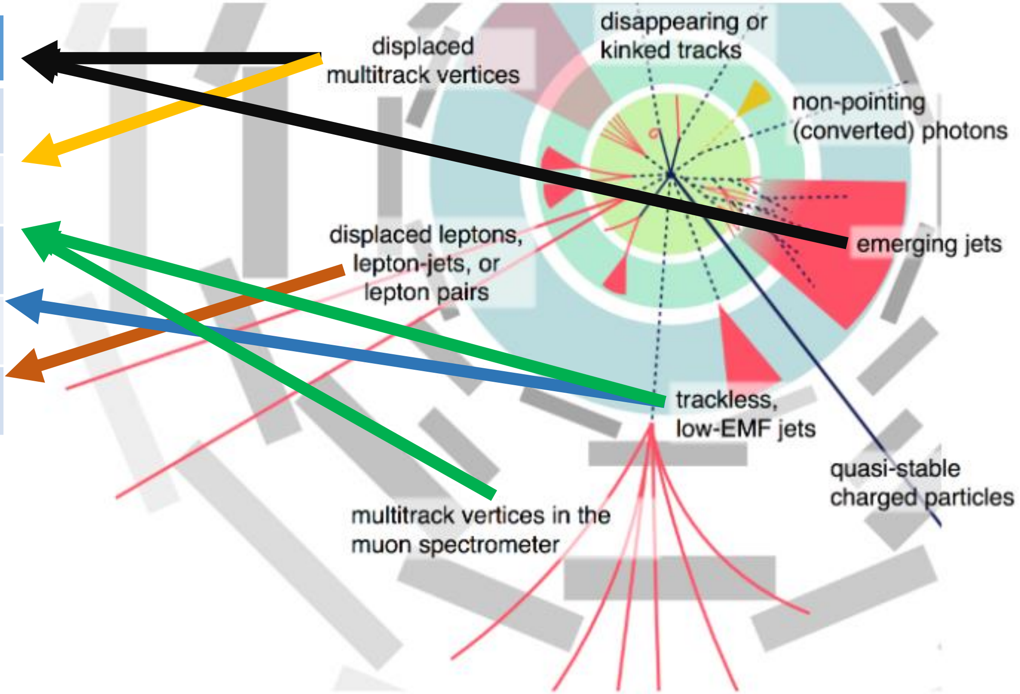
LLP signatures



Overview

LLP signatures

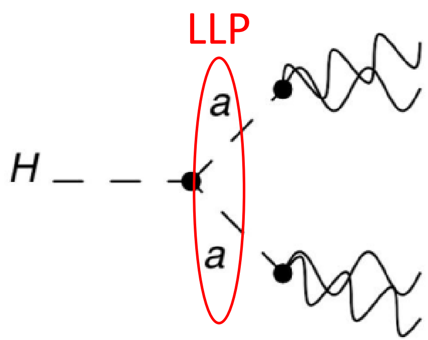
	LLP signatures	Reference
Run 2	Displaced vertices with collinear photons	2312.03306
Run 2	Displaced vertices from hadronic LLPs	2403.15332
Run 2	Displaced dark photon jets	2311.18298
Run 2	Neutral LLPs + leptons or jets	2407.09183
Run 2 + Run 3	Displaced leptons	CONF-2024-011



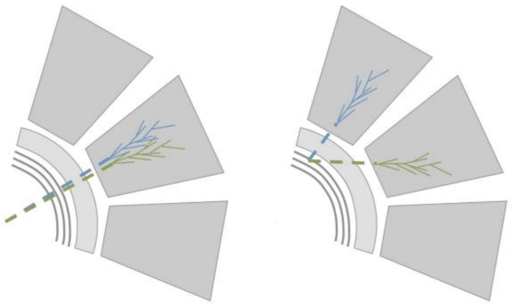
Displaced vertices with collinear photons

[2312.03306]

- Decay Chain: $H \rightarrow aa \rightarrow 4\gamma$
  - Axion-like particles (ALPs) decay within the calorimeter
- Range:
  - ALP mass: 0.1 GeV < m_a < 60 GeV
  - ALP-photon couplings: 10^{-5} < $C_{a\gamma\gamma}$ < 1
- 4-Photon final state
  - Opening angle of photons determined by ALP mass
  - Number of reconstructed photons:
    - 4: fully reconstructed
    - 2,3: merged or missing photons
    - 0,1: not usable
- Main background:
  - QCD Multi-photon Events.
  - Higgs Boson Decays: $H \rightarrow \gamma\gamma$.



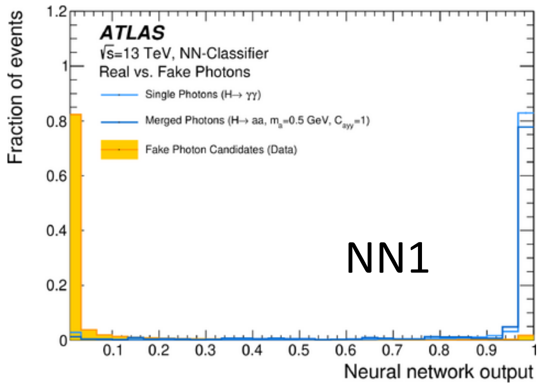
$H \rightarrow aa \rightarrow 4\gamma$

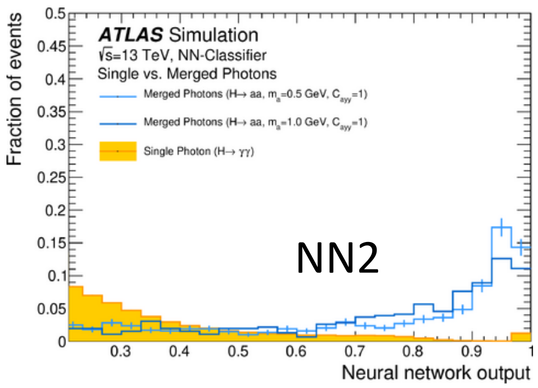


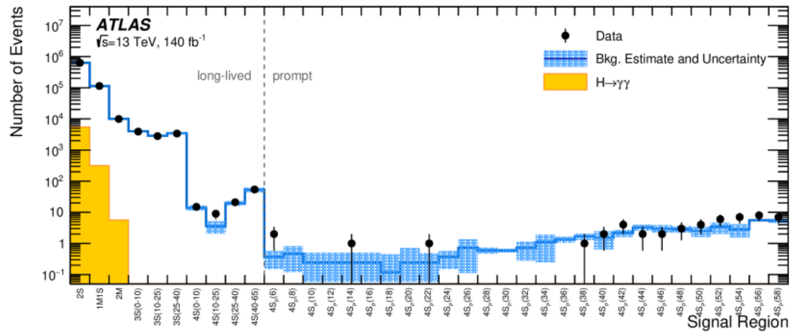
Merged photons shower

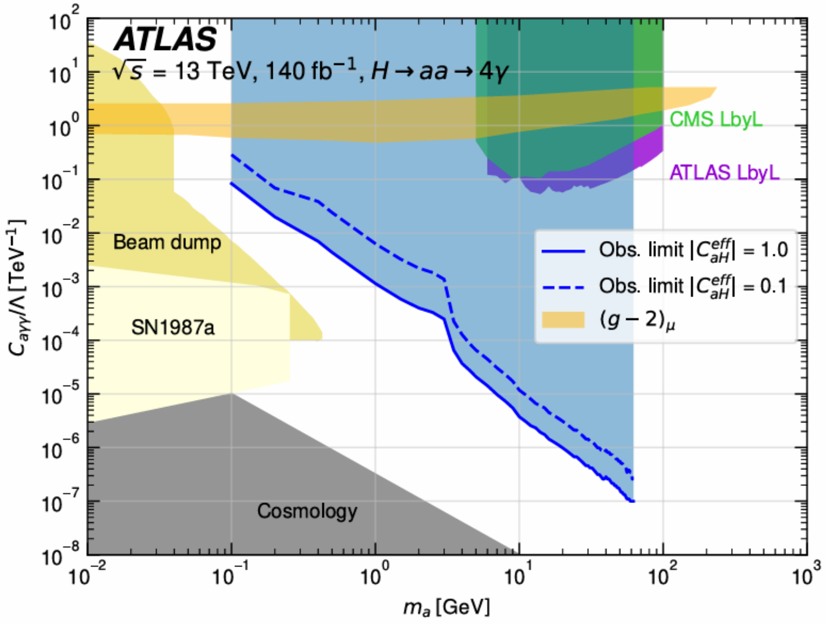
2 well separated photons shower

Displaced vertices with collinear photons







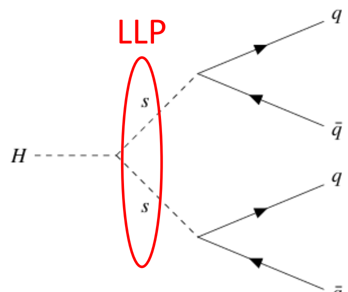


- 2 NN are trained to identify merged photons
  - NN1: Signal photons vs. multi jet bkg.
  - NN2: Single vs. merged photons.
- A Data-driven sideband method is used to estimate background.
- Result：
  - No Excess Observed: Good agreement between observed and expected results.
  - Exclusion Limits:
    - Set in the ALP mass-coupling parameter space
    - Limits on $C_{a\gamma\gamma}$ derived using template fitting.

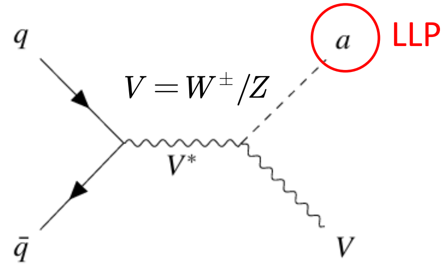
Displaced vertices in the ATLAS inner detector

[2403.15332]

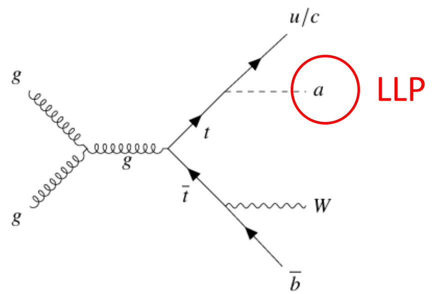
- Benchmark model:
  - Exotic Higgs decay
    - SM Final state: $4u$, $4b$ ($4c$ for 5 GeV)
    - Production modes considered: ZH, WH, VBF
  - ALP produced in association with a SM vector boson
    - Final states: gg
    - Production modes considered: Za, Wa
  - Exotic top decay
    - Final states: cc, gg
    - Production modes considered: tt
- Range
  - 5 GeV < m_H < 55 GeV
  - 1 mm < $c\tau$ < 1000 mm
- Signal features:
  - Displaced jets: ≥2 hadronic jets originate from ≥1 displaced vertices
  - Displaced vertices (DVs): secondary vertices reconstructed with displacements up to 300 mm.



Exotic Higgs decay



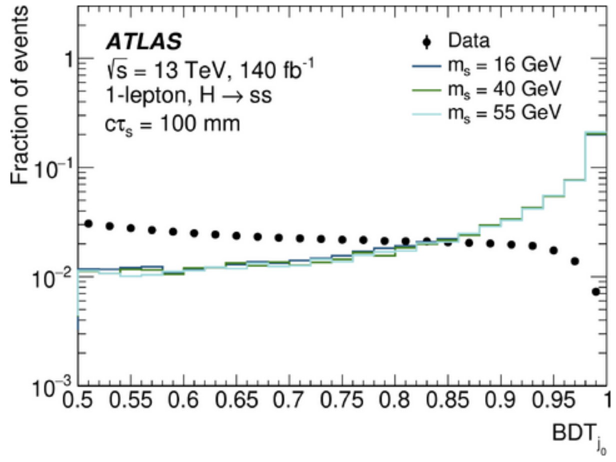
ALP decay

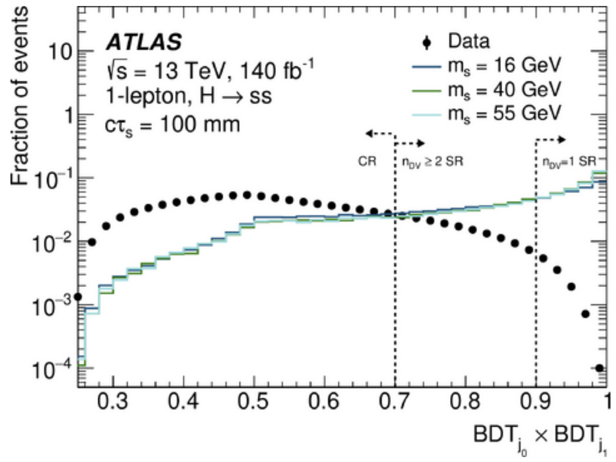


Exotic top decay

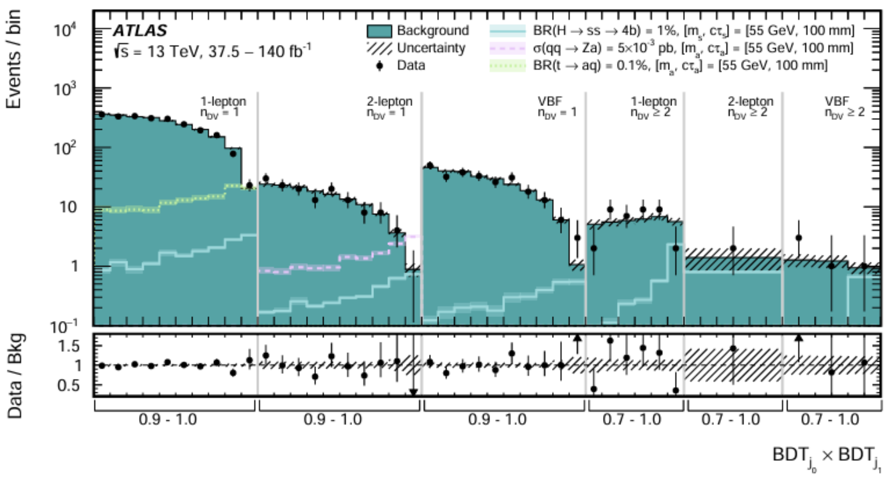
Displaced vertices in the ATLAS inner detector

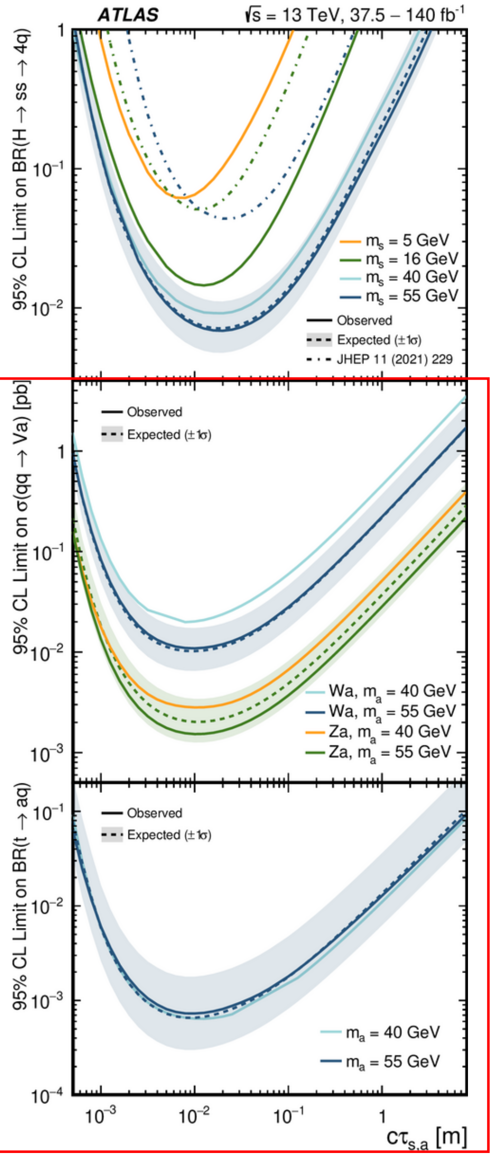
- Main background:
  - SM hadronic jets
- Per-jet BDT is trained to identify prompt and displaced jets.
  - Trained on simulated $t\bar{t}$, W+jets, Z+jets + signal
- In signal DVs are excepted to be correlated to displaced jets.
  - DVs are matched to a jet with BDT score > 0.5
- 3 search regions, targeting ZH, WH and VBF production modes.
- Search regions are divided into control (CR), and signal regions (SR) based on event-level discriminant “BDT_{j0} x BDT_{j1}” (from highest scoring jets) and number of DVs (n_{DV})





Displaced vertices in the ATLAS inner detector





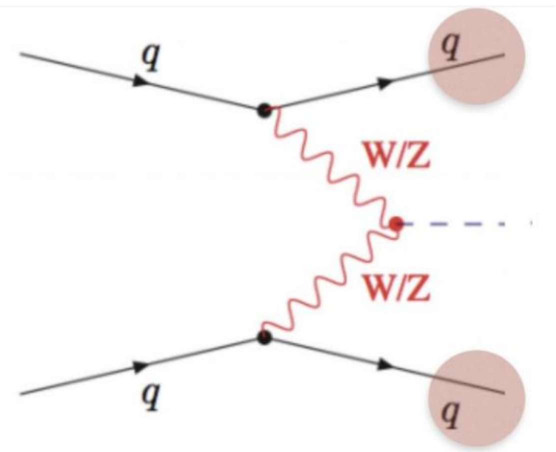
- Data-Driven Background Estimation:
  - Predict background from P(jet matched to DV) in CR → per-event weights applied in SR
- Exclusion Limits:
  - No significant excess of signal events observed.
  - Limits on BR($H \rightarrow ss$) are most stringent to date for m_s < 40 GeV and 1 mm < $c\tau_s$ < 100 mm

First limits on ALPs with photon coupling suppressed at LHC!

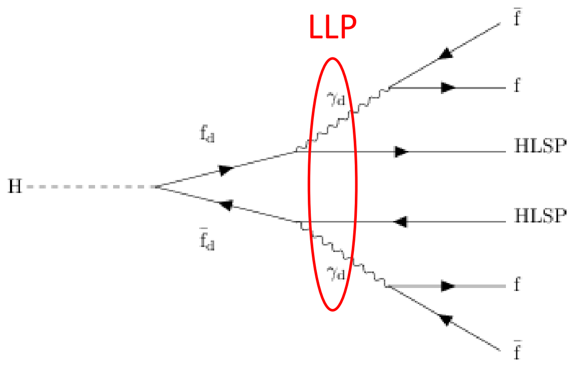
Displaced Dark Photon Jets VBF Production

[2311.18298]

- The Falkowski Ruderman-Volansky-Zupan (FRVZ) benchmark model
  - $H \rightarrow 2\gamma_d + X$ via **Higgs & vector portals**
  - SM final states ($\gamma_d \rightarrow \ell^+\ell^-/qq$) + MET signature
- Small coupling ε: long-lived γ_d
  - $10^{-6} < \varepsilon < 10^{-5}$
- With $m_{\gamma_d} \ll m_H$: collimated decay
  - $2m_e < m_{\gamma_d} \leq 15$ GeV
- Investigate VBF production mode
- Signal features: Displaced Dark Photon Jets (Displaced DPJs)
  - 2 channels: muonic DPJ (μDPJ), calorimeter DPJ (caloDPJ)



VBF production



FRVZ decay

Displaced Dark Photon Jets VBF Production

- Displaced signature
  - Sensitive to γ_d decays after pixel detector
- Main backgrounds:
  - QCD hadronic jets
  - Non-collisional: cosmic rays & beam-induced (BIB)

- CNN is trained to reject cosmic contamination, BIB & QCD multi-jet.
- ABCD method is used to do the Data-driven background estimation

μDPJ

$\gamma_d \to \mu^+\mu^-$

Targeting decays outside ID acceptance

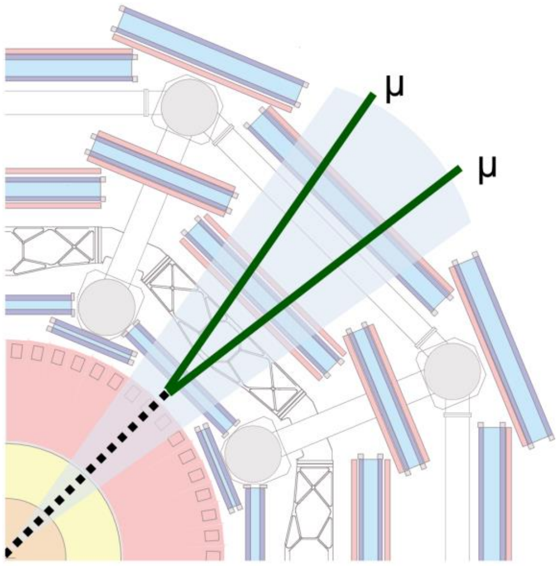
Pair of close-by MS tracks with no matching tracks in the ID

caloDPJ

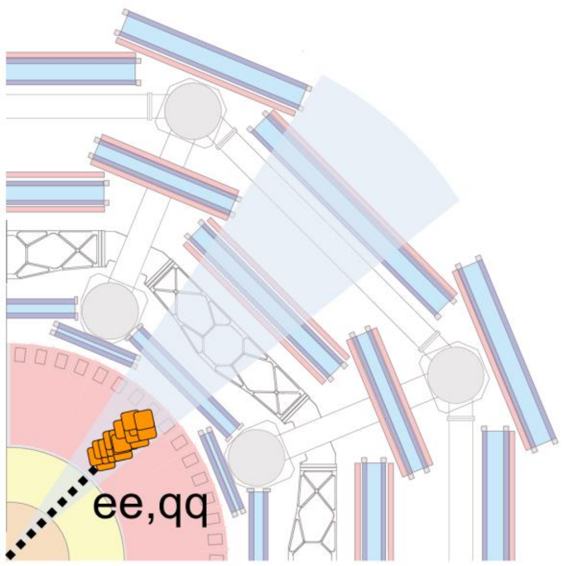
$\gamma_d \to e^+e^-/qq$

Targeting decays in HCAL

Low EM fraction jets with no matching MS tracks



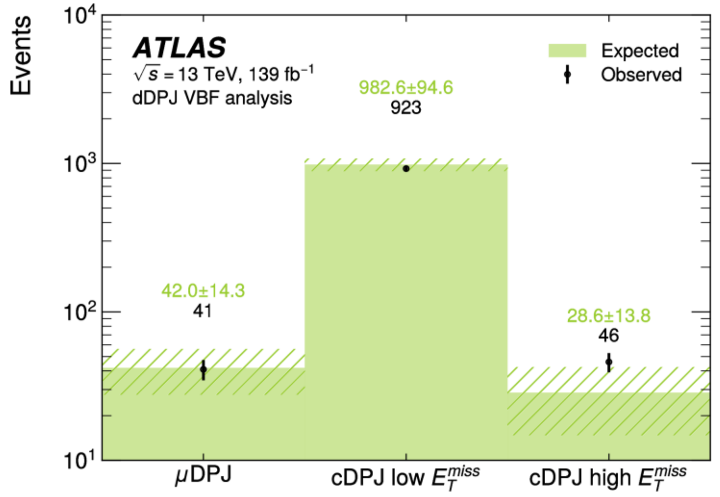
muonic DPJ

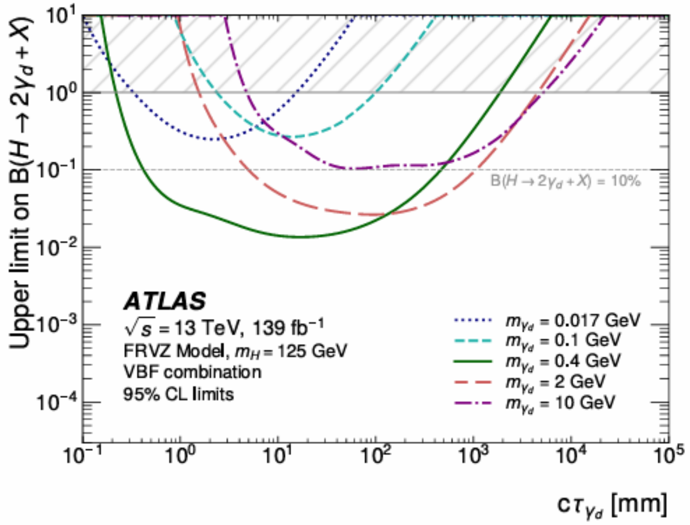


calorimeter DPJ

Displaced Dark Photon Jets VBF Production

- No new physics observed
- Good agreement between observed and expected in SRs
  - caloDPJ high E_T^{miss} SR shows slight disagreement with observed yield; around 1σ above expectation
- Set limits on BR($H \longrightarrow 2\gamma_d + X$) as a function of $c\tau$
  - Using lifetime reweighting algorithm to extrapolate signal efficiencies at different $c\tau_{\gamma_d}$ values

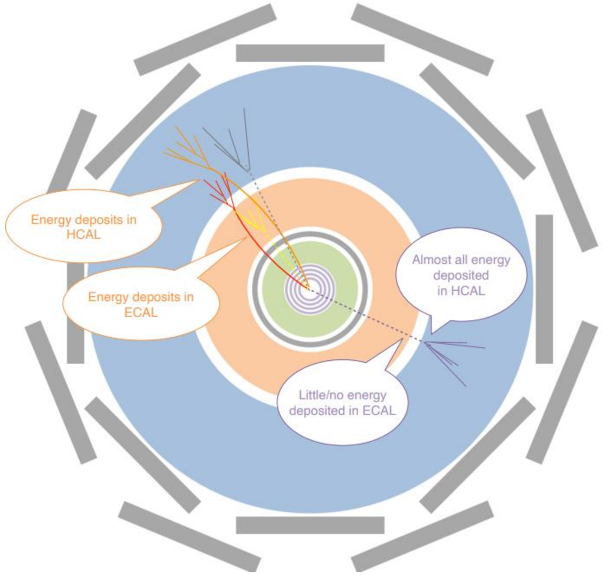


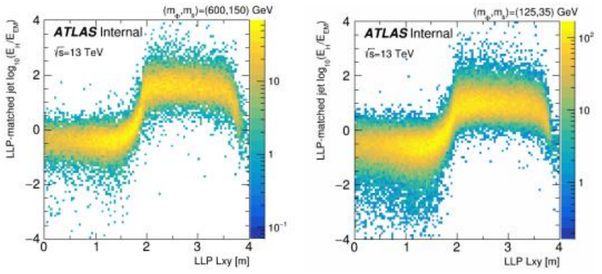


Hadronic LLPs + Leptons/Jets

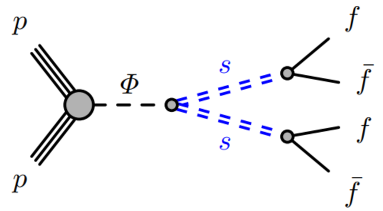
[2407.09183]

- Benchmark model:
  - Hidden sector(HS) model:
    - Φ can be produced in association with a vector boson (W/Z) decaying to leptons.
  - Axion-like particles (ALPs) model
  - Dark photon (Z_d) model
- Signal features:
  - CalRatio jets (CalR): jets from LLP decaying after the 1st HCAL layer
    - Trackless and narrower
    - High E_H/E_{EM} (The ratio of energy deposited in the HCAL to the energy deposited in the ECAL, the so-called CalRatio).
- 3 analysis channels with different final status:
  - CalR + 2 jets: 1 CalRatio jet and 2 prompt jets
  - CalR + W/Z: ≥ 1 CalRatio jets and ≥ 1 leptons from W/Z bosons

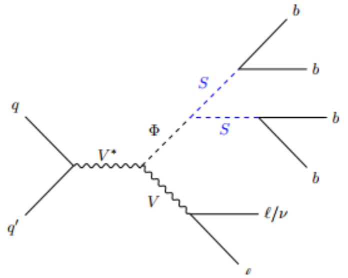




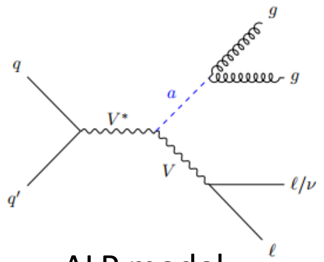
Particles with higher lifetime have higher E_H/E_{EM}



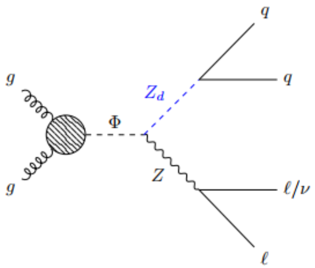
Benchmark HS model



HS model association with a vector boson



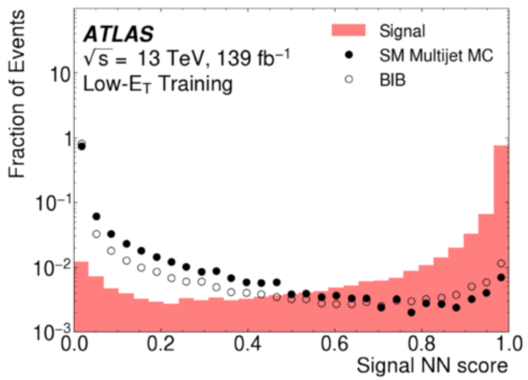
ALP model

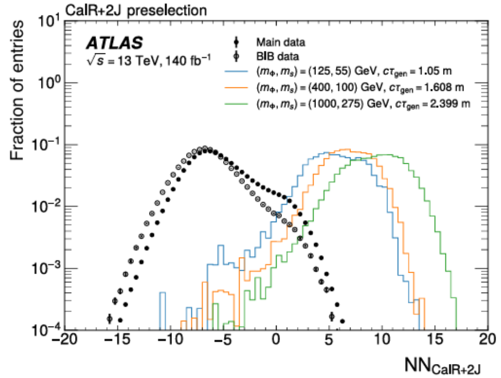


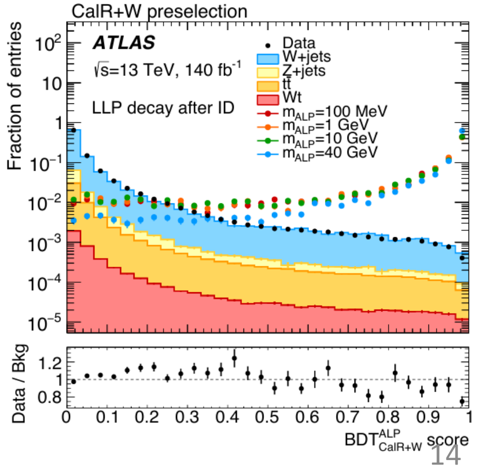
Dark photon model

Hadronic LLPs + Leptons/Jets

- Main background:
  - CalRatio jet + 2 prompt jets:
    - SM multijets
    - Non-collisional: cosmic rays & beam-induced (BIB)
  - CalRatio jet + W/Z :
    - SM processes involving vector bosons produced with jets
    - single- or pair-production of top quarks
- A NN is trained to identify CalRatio jets, qcd jets and BIB jets.
- Additional NN/BDTs are used to separate signal and bkg events.
- Use a ABCD method to do the data-driven background estimation







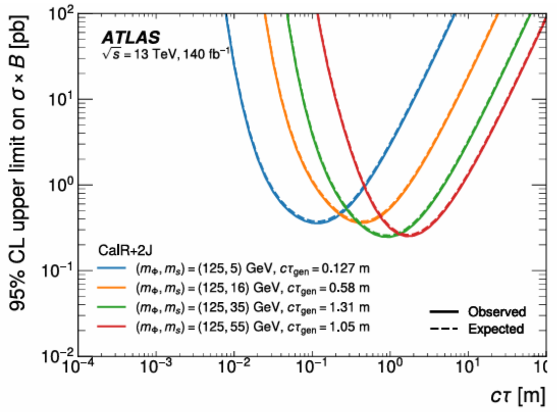
Hadronic LLPs + Leptons/Jets

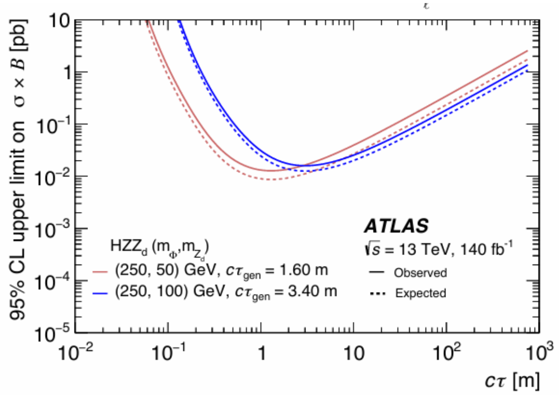
- No significant excess is observed
- Hidden sector (HS) model:

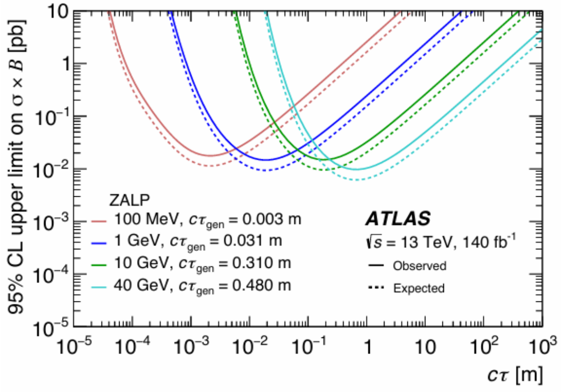
  3x improvement for BR($H \rightarrow ss \rightarrow 4b$) with respect to previous search [JHEP06(2022)005]
- Dark photon (Z_d) model:

  $\sigma > 0.1$ pb for Z_d with $c\tau \in$ 0.1mm – 10m (10x improvement with respect to previous search [PRL122(2019)151801].)
- Axion-like particles (ALPs) model:

  Photo-phobic ALP $\sigma > 0.1$ pb excluded for $c\tau \in$ 0.1 mm – 10 m

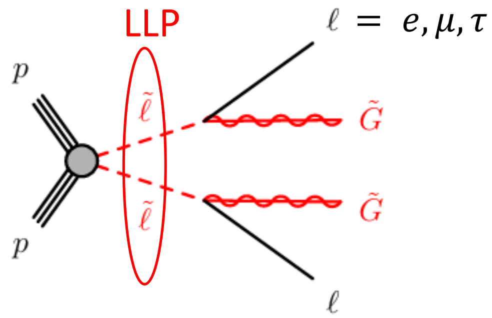






Displaced leptons

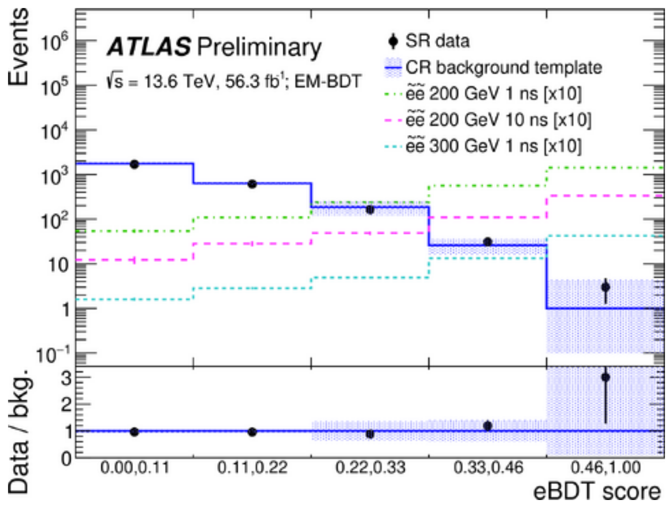
[ATLAS-CONF-2024-011]

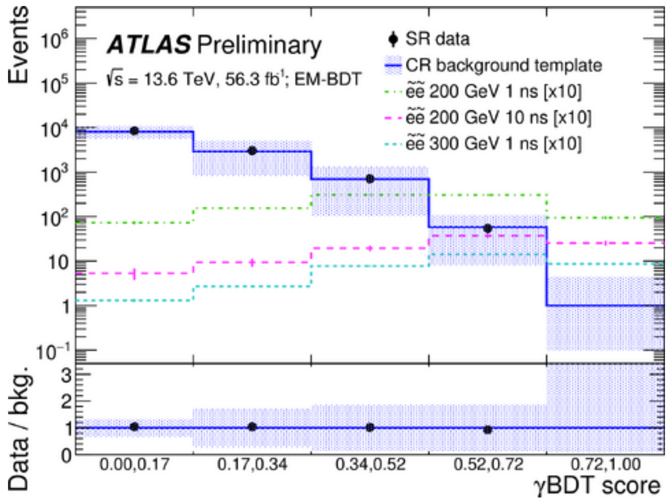


- Benchmark: Gauge-Mediated Supersymmetry Breaking (GMSB)
  - Lightest SUSY particle (LSP): nearly massless gravitino.
  - Next-to-Lightest SUSY particle (NLSP): long-lived slepton (selectron, smuon, stau).
  - LLPs produce displaced electrons or muons through slepton decay.
- Signal features:
  - Displaced pairs of SM leptons
    - Reconstruct e/μ using standard and LRT tracks
    - Can look in $1e$, $e\gamma$, $\gamma\gamma$, where one decay is outside ATLAS or displaced e recorded as γ.
- Final status:
  - ee, $e\mu$, $\mu\mu$ for Run 2 and Run 3
  - $1e$, $e\gamma$, $\gamma\gamma$ for Run 3

Displaced leptons

- Main background:
  - Heavy-flavor hadrons (FHF)
  - cosmic rays
- Liquid Argon (LAr) Calorimeter precision timing is exploited to target LLPs.
  - O(200ps) resolution for energetic e/γ (limited by beamspread)
  - Enough to resolve “late” e/γ from LLP decays against prompt SM background
- ABCD method is used to do the Data-driven background estimation
- For Run 3 data, 2 BDTs are trained to find displaced electrons misidentified as photons due to their displacement and lack of tracks.
  - eBDT: Identifies displaced electrons.
  - γBDT: Identifies displaced electrons misreconstructed as photons

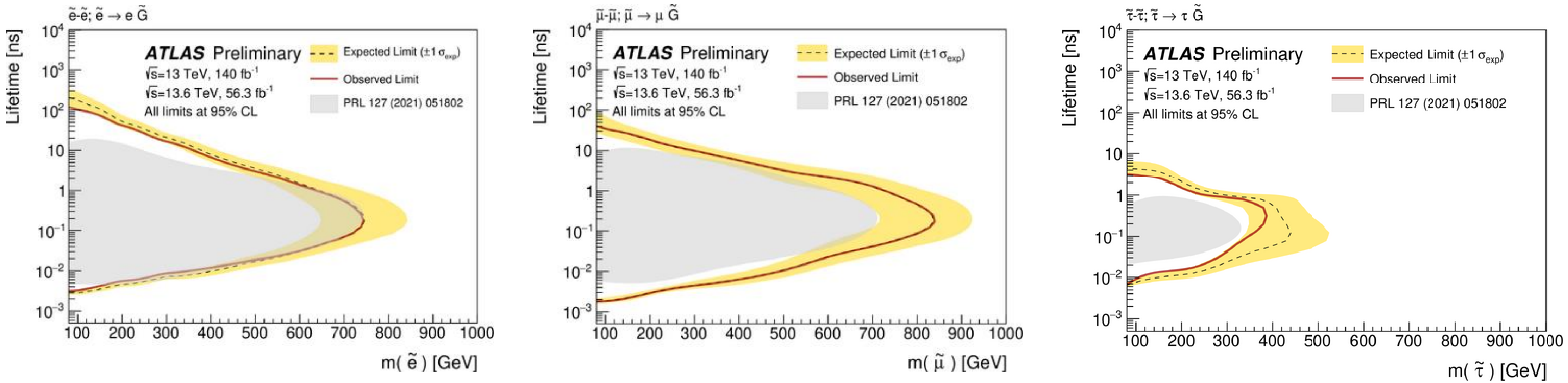




Displaced leptons

New sensitivity for long-lived decays to electrons from BDT

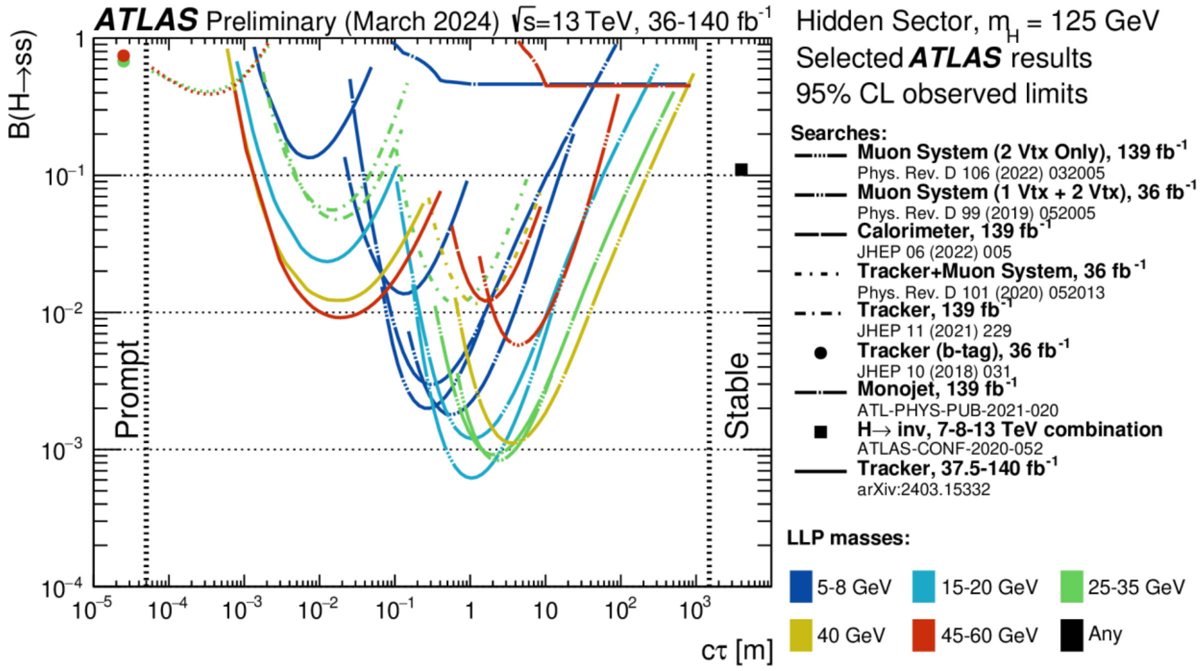
~5x for selectrons,~3x for staus



- First ATLAS Search Result at $\sqrt{s}$= 13.6 TeV, no significant deviation from SM expectation
- Largest local significance 2.2σ in LRT-enriched ee final state (1 event observed, $0.0016^{+0.0029}_{-0.0016}$ expected)
- Adding early Run 3 data + new triggers improves sensitivity w.r.t. previous search [PRL 127 051802]
  - Smuon limits for μμ final states only – gains here driven by Run 3 LRT triggers
  - BDT region probes new final states, allows exclusion at higher lifetimes

Summary

- In ATLAS, Many LLP searches are trying to search for BSM physics, both for Run 2 and Run 3.[ATLAS Public Results]
- The LLP could escape “standard” search methods.
  - Dedicated searches are needed.
- By now, no significant excess is observed for LLP.
- More exciting results expected from Run 3.
- LLP searches are expected to gain search sensitivity in HL-LHC.

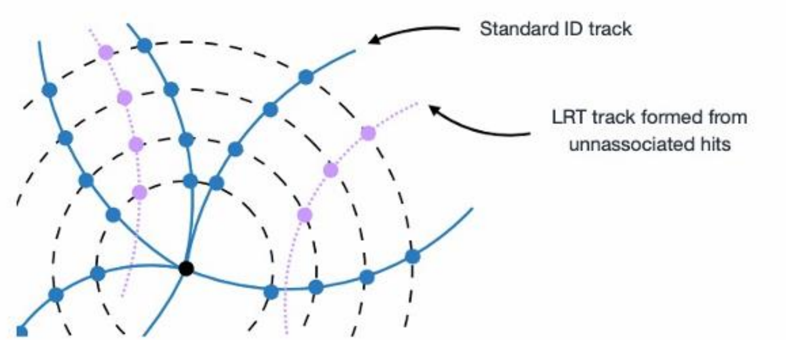


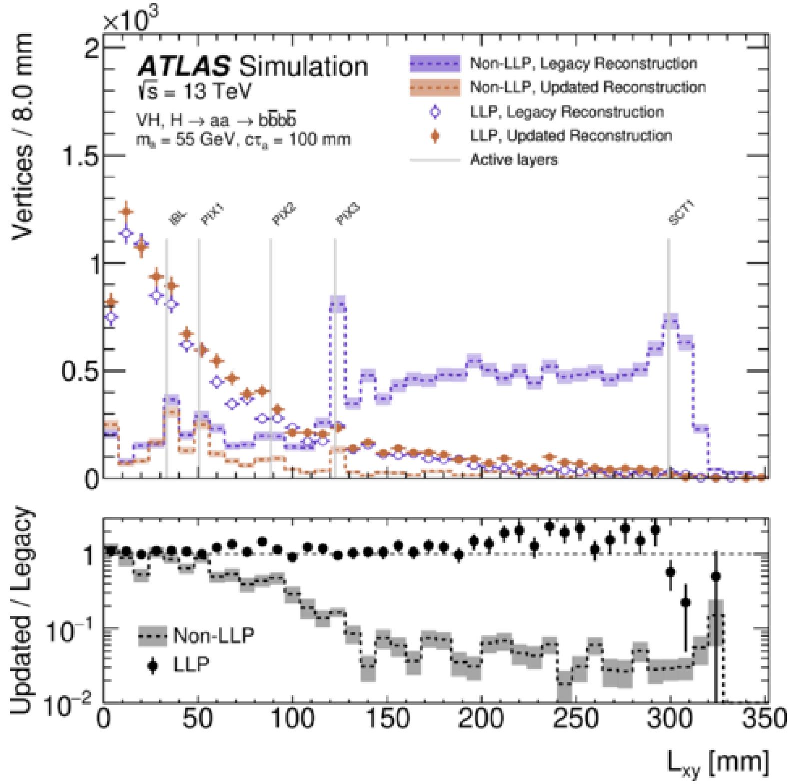
Backup

Special Reconstruction: Large Radius Tracking

- Standard track reconstruction in ATLAS designed for tracks pointing back to Primary Vertex (PV)
- Large Radius Tracking (LRT) – additional tracking pass on unused hits after initial tracking pass, relaxing some requirements (e.g. impact parameters)
- Difficult computational problem – high pileup, many random hits in the tracker

- Improvements in LRT [IDTR-2021-03]
  - Run on all events, rather than prev. ~10%
  - In Run 2: can now look at LRT with full dataset!
  - In Run 3: [new LRT triggers] increase sensitivity to LLP decays!





Displaced vertices with collinear photons

5 signal categories, events assigned in this order:

- **4S**: At least 1 tight ID γ, all remaining γ loose ID
- **3S**: 3 tight ID photons
- **2M**: 2 merged photons, no additional loose ID γ
- **1M1S**: Exactly 1 merged and 1 loose ID γ
- **2S**: 2 tight ID γ, no additional loose ID γ
- **4Sp**: At least 3 tight ID γ, all remaining γ loose ID