SEARCHING FOR LONG-LIVED PARTICLES WITH THE ATLAS MUON SPECTROMETER

AUDREY KVAM ON BEHALF OF THE ATLAS COLLABORATION

UNIVERSITY OF WASHINGTON

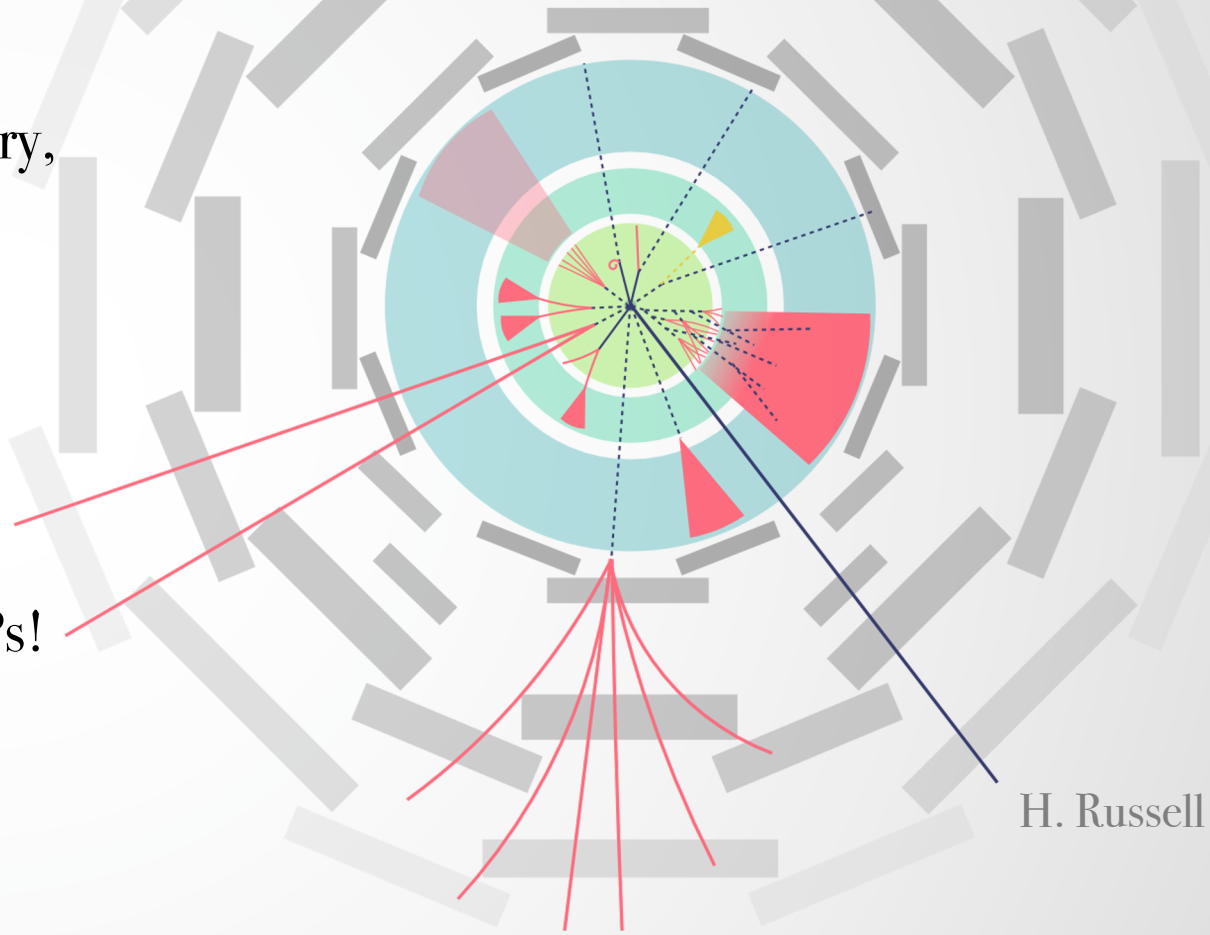
Long-lived particles (LLPs) at the LHC

Many BSM theories addressing open questions such as dark matter, neutrino mass, matter-antimatter asymmetry, the hierarchy problem, etc, either allow or explicitly predict neutral *long-lived particles*

Constraint from Big Bang Nucleosynthesis puts upper bound on lifetime at $c\tau \lesssim 10^7$–10^8 m

The LHC is an excellent place to search for neutral LLPs!

- High energy
- Large statistics
- Provides known point of origin for neutral LLP



H. Russell

There are many LLP searches currently being performed in ATLAS, CMS, LHCb…

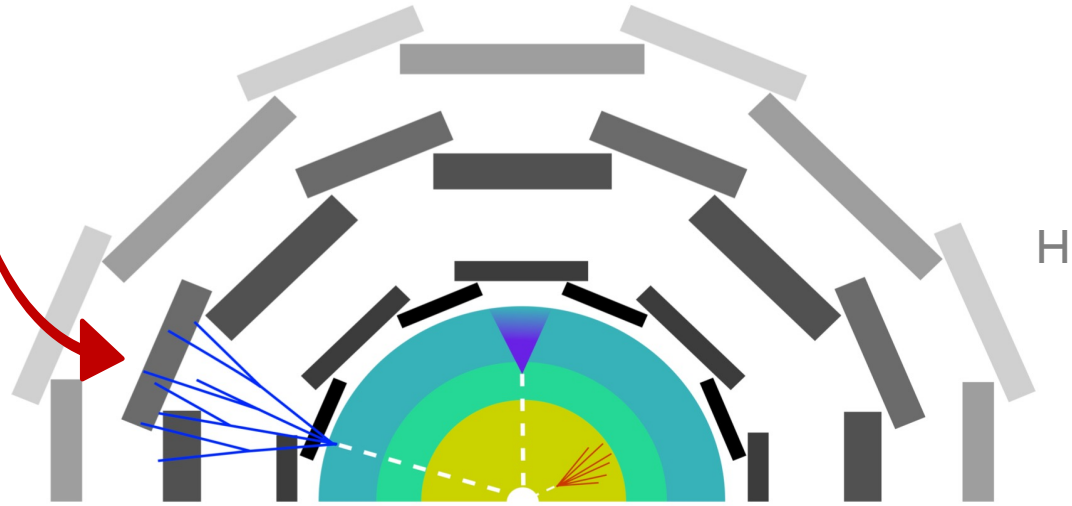
Search for events with a pair of displaced vertices from neutral long-lived particles decaying to hadronic jets in the ATLAS muon spectrometer in pp collisions at $\sqrt{s} = 13$ TeV

ATLAS-CONF-2021-032/

DETECTOR SIGNATURE:
Displaced vertex in muon spectrometer with no activity preceding it in inner detector or calorimeters

- Interpret our results in terms of benchmark model
- Complementary analyses are performed in other regions of ATLAS

MS is great place to search for LLPs:
- Large volume
- Good tracking capabilities
- Calorimeters provide shielding
- Sensitive to long lifetimes



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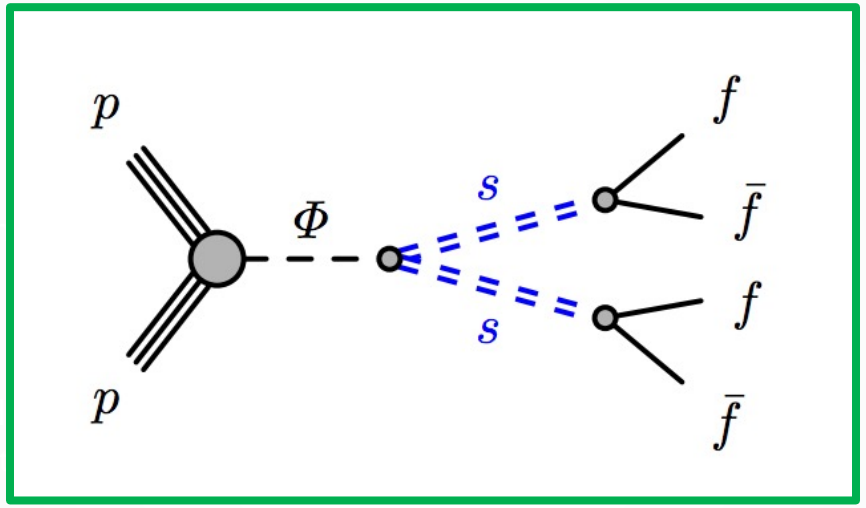
Benchmark model



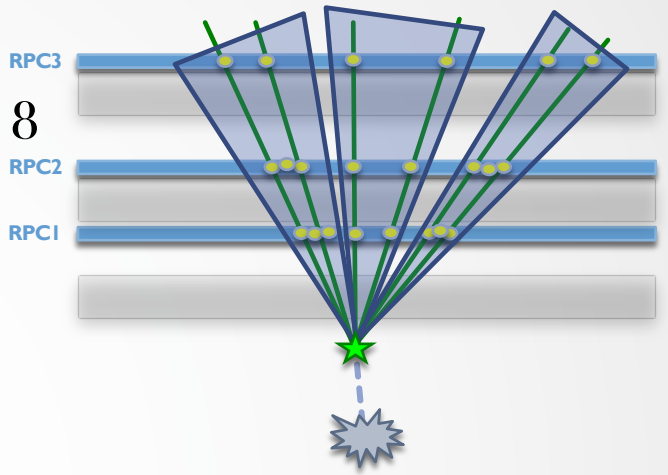
HSS Model

Signature in the detector: the long-lived particles are pair-produced before decaying to fermions, with no other associated activity

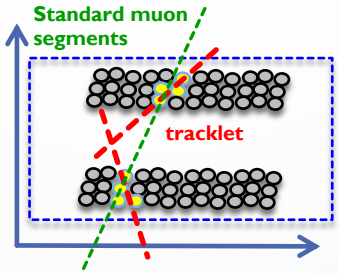
MC signal mass points

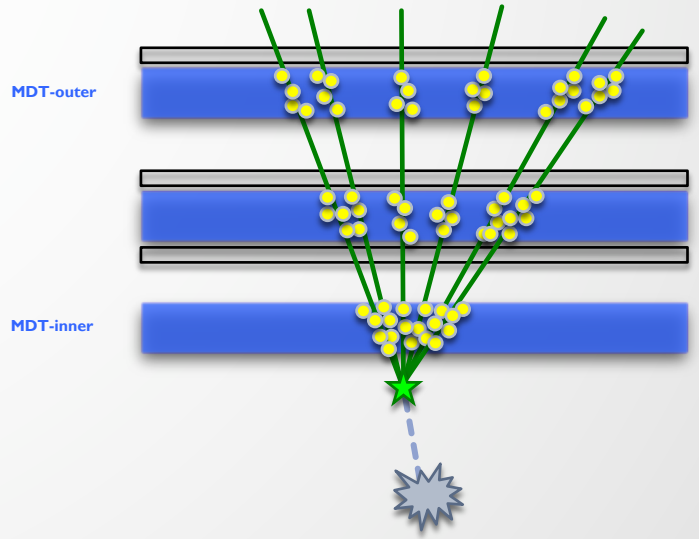
m_Φ [GeV]	m_s [GeV]	Proper lifetime [m]
125	5	0.127, 0.411
	15	0.580
	35	1.310, 2.630
	55	1.050, 5.320
60	5	0.217
	15	0.661
200	50	1.255
400	100	1.608
600	50	0.590
	150	1.840, 3.309
	275	4.288
1000	50	0.406
	275	2.399, 4.328
	475	6.039

Trigger and MS Vertex Reconstruction



- MS has a dedicated trigger, the **muon RoI cluster trigger** (2013 JINST 8 P07015), selecting events with a cluster of at least 3 (4) RoIs in the barrel (endcaps) in a ΔR cone of 0.4 around L1_2MU10
  - Using RPC for the barrel and TGC for the endcaps
- MS has a dedicated **vertex algorithm** (2014 JINST 9 P02001) reconstructing vertices with at least 3 (4) tracklets in the barrel (endcaps)
- Takes advantage from the multilayer separation in an MDT chamber
  - Tracklets are more background robust
  - NB: standard ATLAS muon segments are straight lines between two multi layers





- Two different vertex algorithms for the barrel and the endcaps (negligible magnetic field in the endcaps)

Signal event selection

Event passes Muon RoI Cluster trigger.
Event has a PV with at least two tracks with $p_{\mathrm{T}} > 500$ MeV.
Event has at least two MS DVs.
MS DV is matched to the triggering muon-RoI cluster (ΔR(DV, RoI cluster) < 0.4). In the case of two muon-RoI clusters, the second vertex must be matched to the second cluster.
$300 \leq n_{\mathrm{MDT}} < 3000$

Barrel	*Endcaps*
MS DV with $\lvert\eta_{\mathrm{vx}}\rvert < 0.7$	MS DV with $1.3 < \lvert\eta_{\mathrm{vx}}\rvert < 2.5$
MS DV with $3\,\mathrm{m} < L_{xy} < 8\,\mathrm{m}$	MS DV with $L_{xy} < 10\,\mathrm{m}$ and $5\,\mathrm{m} < \lvert L_z\rvert < 15\,\mathrm{m}$
$n_{\mathrm{RPC}} \geq 250$	$n_{\mathrm{TGC}} \geq 250$

Isolation requirements	Barrel	Endcaps
High-p_{T} track isolation ($p_T > 5$ GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Low-p_{T} track isolation ($\Sigma p_{\mathrm{T}}(\Delta R < 0.2)$)	$\Sigma p_{\mathrm{T}} < 10$ GeV	$\Sigma p_{\mathrm{T}} < 10$ GeV
Jet isolation	$\Delta R > 0.3$	$\Delta R > 0.6$

Background estimation

Looking for 2 DV in the MS, isolated from any track or jet (an MS vertex is mainly created by punch-through jets)

✓ Very small bkg by requiring 2 DV but lower sensitivity to longer lifetimes

We use the same data-driven background estimation method as in the 2015-2016 analysis that also takes into account residual bkg (e.g. BIB) that cannot be properly simulated in MC

To estimate the bkg we need to quantify the frequency the vertex algorithm reconstructs isolated vertices in non-signal events. We use events with:

- one isolated MS vertex which pass the Muon RoI cluster trigger in the main stream
- one isolated MS vertex which pass zero-bias trigger → compute the fake-vertex probability ($P^{Vx}_{noMStrig}$)

Expected background is given by:

$$N_{2Vx} = N^{1cl} \cdot P^{Vx}_{noMStrig} + N^{2cl}_{1UMBcl} \cdot P^{Vx}_{Bcl} + N^{2cl}_{1UMEcl} \cdot P^{Vx}_{Ecl}$$

Number of non-signal events passing 2Vx criteria

Number of non-signal events with 1 cluster and 2 vertices

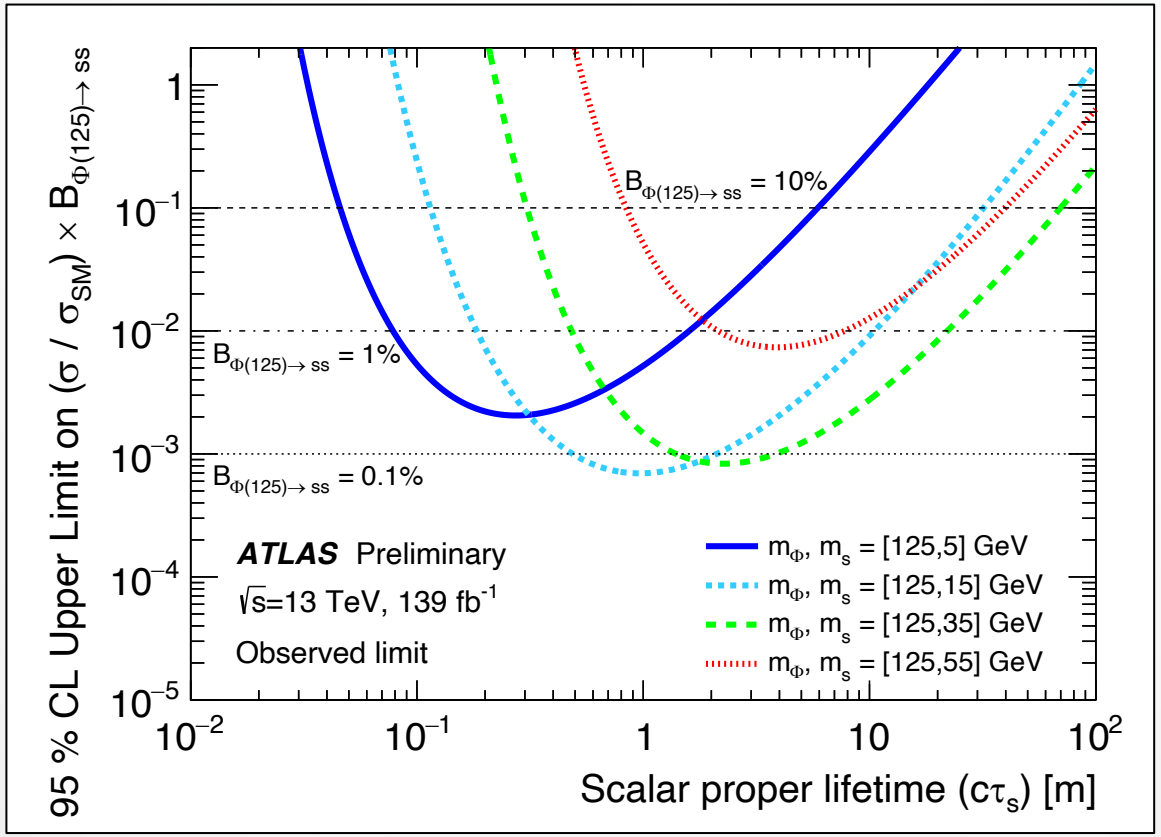
Number of non-signal events with 2 clusters and 2 vertices – this term was 0 in 2015-2016 because the probability of having 2 clusters in an event is very small

Expected background events, full Run 2 = 0.32 ± 0.05

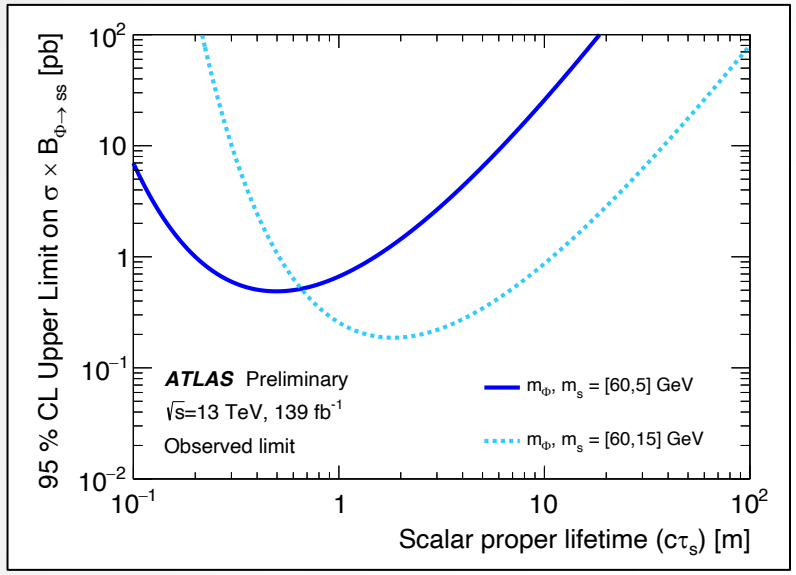
Limits

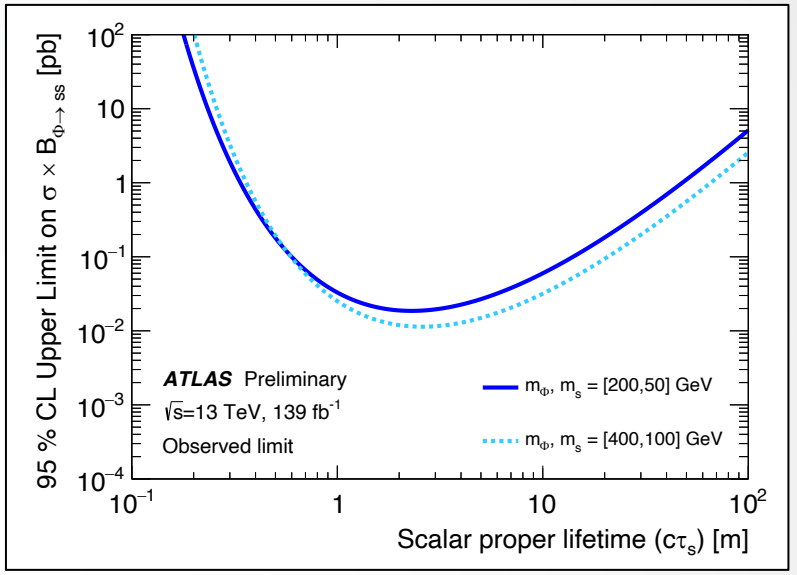
0 events observed

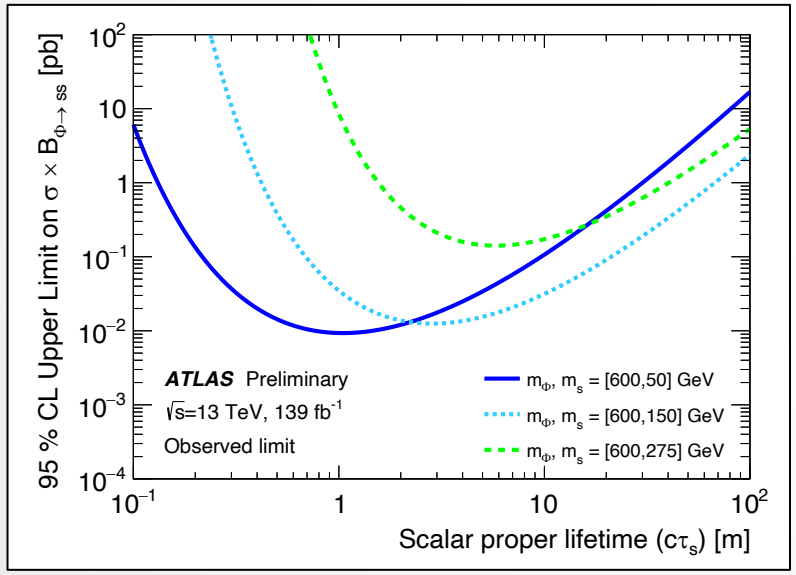
Using the CLs procedure, we set limits from the two-vertex search on production cross section times branching fraction for all mass points

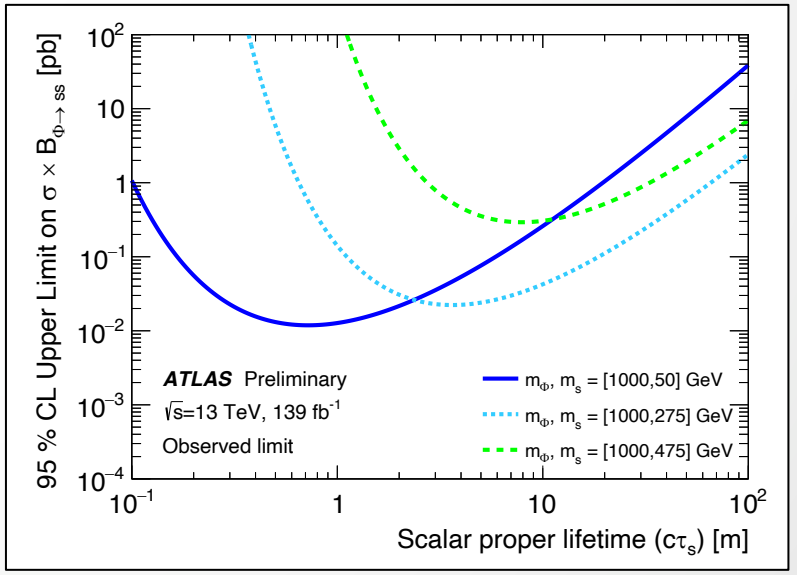


Limits


95 % CL Upper Limit on σ × B_Φ→ss [pb]
ATLAS Preliminary
√s=13 TeV, 139 fb-1
Observed limit
mΦ, ms = [60,5] GeV
mΦ, ms = [60,15] GeV
Scalar proper lifetime (cτs) [m]


95 % CL Upper Limit on σ × B_Φ→ss [pb]
ATLAS Preliminary
√s=13 TeV, 139 fb-1
Observed limit
mΦ, ms = [200,50] GeV
mΦ, ms = [400,100] GeV
Scalar proper lifetime (cτs) [m]


95 % CL Upper Limit on σ × B_Φ→ss [pb]
ATLAS Preliminary
√s=13 TeV, 139 fb-1
Observed limit
mΦ, ms = [600,50] GeV
mΦ, ms = [600,150] GeV
mΦ, ms = [600,275] GeV
Scalar proper lifetime (cτs) [m]


95 % CL Upper Limit on σ × B_Φ→ss [pb]
ATLAS Preliminary
√s=13 TeV, 139 fb-1
Observed limit
mΦ, ms = [1000,50] GeV
mΦ, ms = [1000,275] GeV
mΦ, ms = [1000,475] GeV
Scalar proper lifetime (cτs) [m]

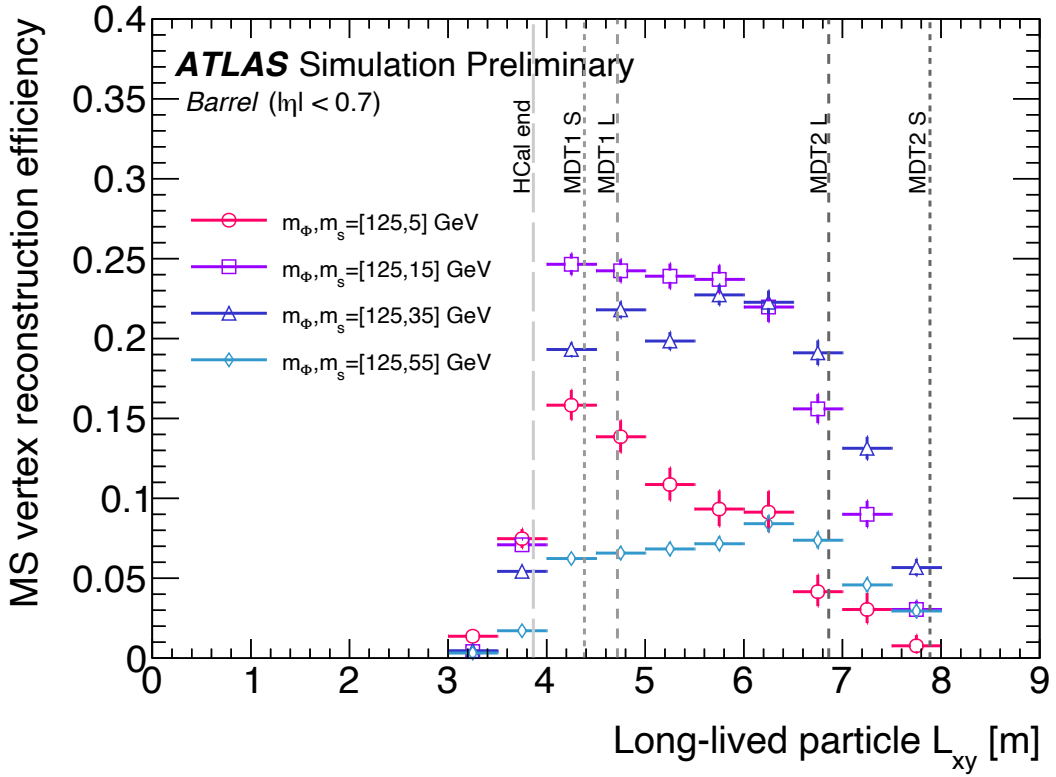
Conclusion

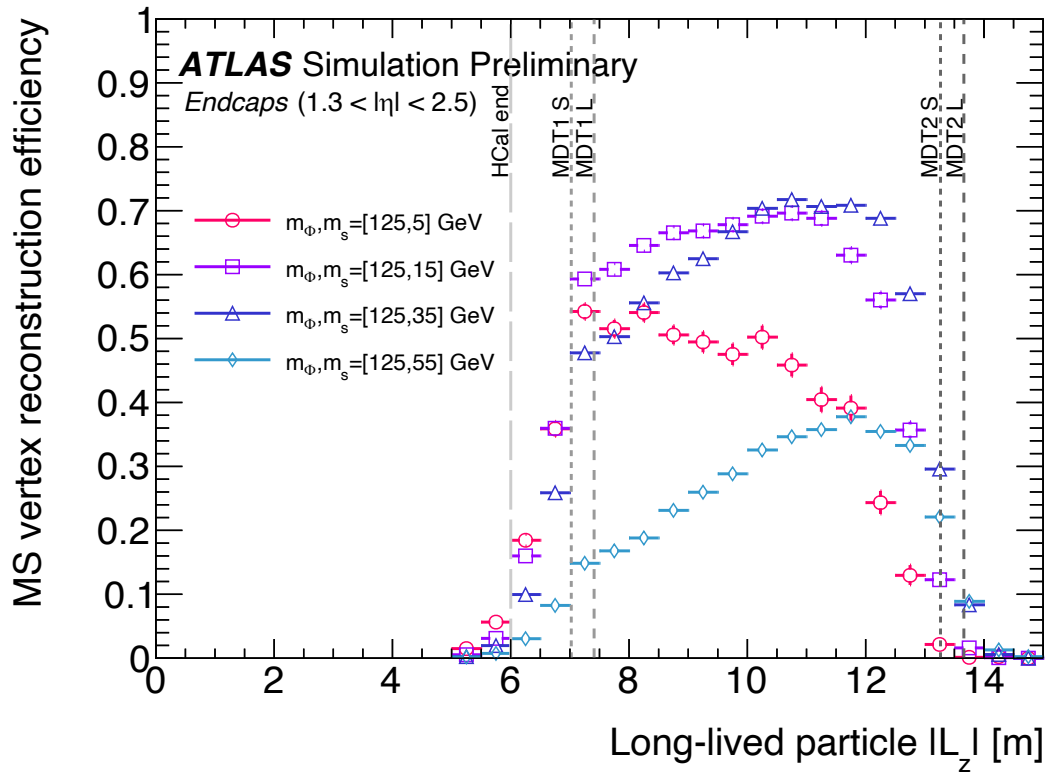
- Results from the search for two displaced vertices from long-lived particles decaying to hadronic jets in the ATLAS muon spectrometer were presented at EPS as a CONF note
- We are converting to a paper now, aiming for Phys Rev D (where the 2015-2016 results were published)
- The analysis team is working on the one-vertex search with full Run 2 data; when this is complete those results will be combined with the two-vertex results

THANK YOU FOR LISTENING!

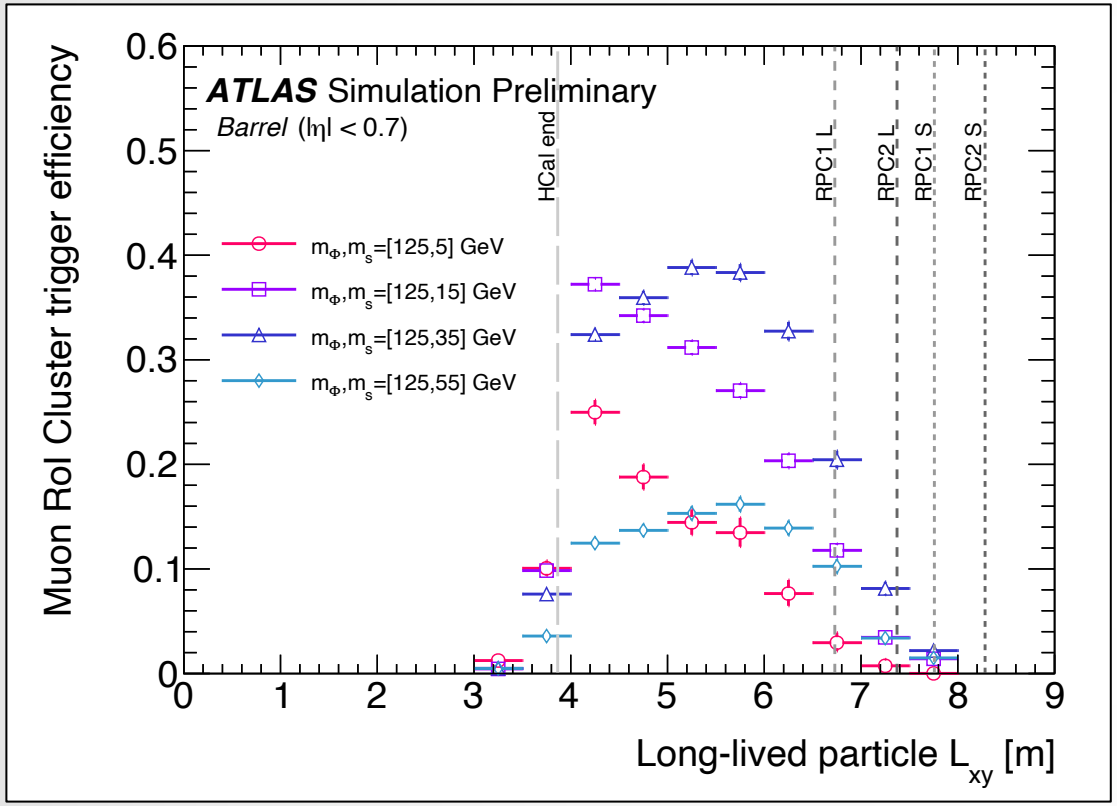
BACKUP

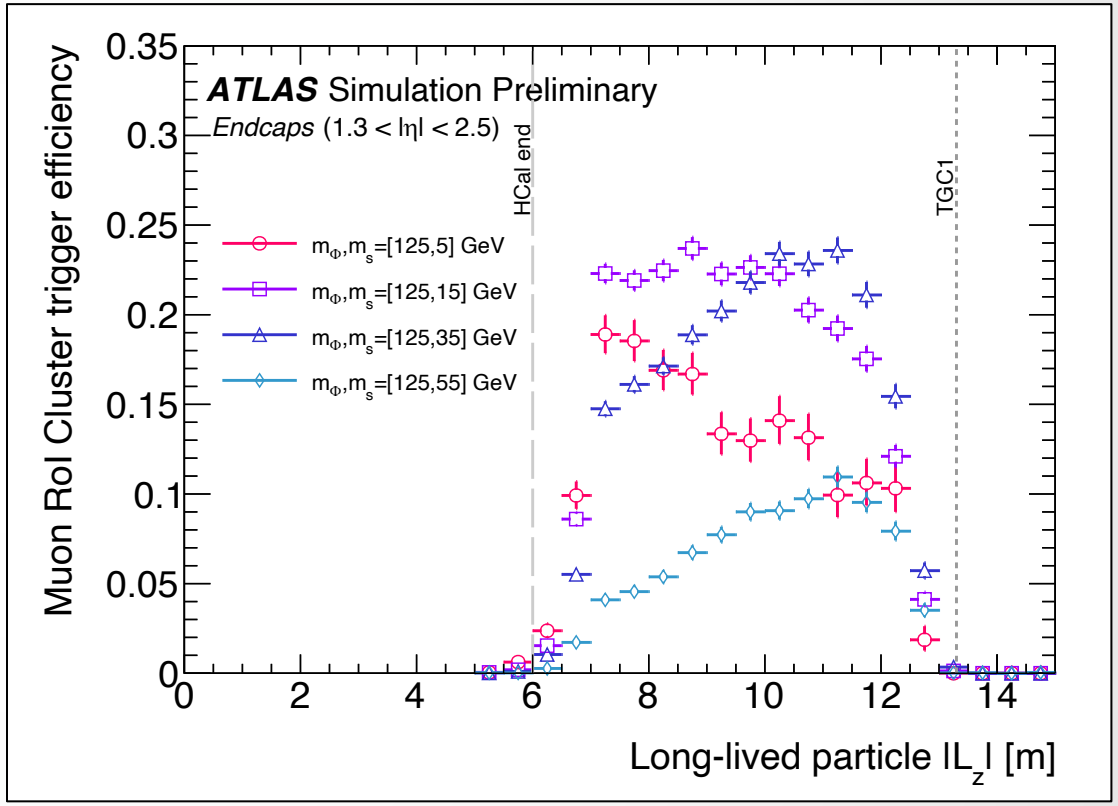
Vertex reconstruction efficiency





Trigger efficiency





[1]https://arxiv.org/abs/1305.2284

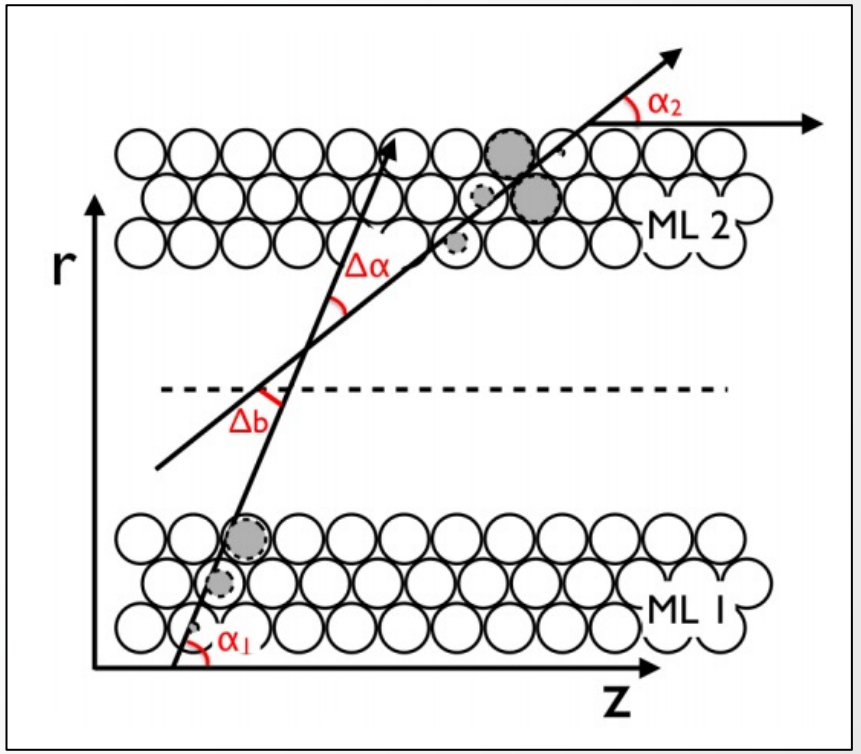
Muon spectrometer vertex reconstruction algorithm

This algorithm takes advantage of the spatial separation between MDT multilayers.

Straight line segments are formed from MDT hits within a single multilayer. Segments between multilayer 1 and multilayer 2 are then combined to form *tracklets*.

Tracklets are extrapolated back to reconstruct the displaced vertex.

This reconstruction algorithm is only used for LLP searches!



https://arxiv.org/abs/1311.7070

Background estimation

Stream	Quantity	Value
ZeroBias	N[Events]	115707416 ± 10757
	N[1Vx]	$46^{+7.33}_{-6.27}$
	$\rightarrow P^{\mathrm{Vx}}_{\mathrm{noMStrig}}$	$(4.06 \pm 0.59) \times 10^{-7}$
Muon RoI Cluster	$N^{1\mathrm{cl}}$	674775 ± 821
	$N^{2\mathrm{cl}}_{1\mathrm{UMBcl}}$	$3^{+2.43}_{-1.17}$
	$N^{2\mathrm{cl}}_{1\mathrm{UMEcl}}$	$0^{+1.35}_{-0.00}$
	N[1BClu]	38509130 ± 6206
	N[1BCluVx]	124648 ± 353
	$\rightarrow P^{\mathrm{Vx}}_{\mathrm{Bcl}}$	$(3.24 \pm 0.009) \times 10^{-3}$
	N[1EClu]	15598939 ± 3950
	N[1ECluVx]	550127 ± 742
	$\rightarrow P^{\mathrm{Vx}}_{\mathrm{Ecl}}$	$(3.53 \pm 0.005) \times 10^{-2}$

Background estimation

Calculation of expected background is data-driven, using events with one isolated MS vertex which pass either the Muon RoI cluster trigger or zero-bias trigger. Expected background is given by:

$$N_{2\mathrm{Vx}} = N^{1\mathrm{cl}} \cdot P^{\mathrm{Vx}}_{\mathrm{noMStrig}} + N^{2\mathrm{cl}}_{1\mathrm{UMBcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Bcl}} + N^{2\mathrm{cl}}_{1\mathrm{UMEcl}} \cdot P^{\mathrm{Vx}}_{\mathrm{Ecl}}$$

Number of non-signal events passing 2Vx criteria

Number of non-signal events with 1 cluster and 2 vertices

Number of non-signal events with 2 clusters and 2 vertices

A "zero-bias trigger" fires on the bunch crossing that occurs one LHC revolution after a luminosity trigger. It is recorded during the same period as the signal trigger, so it contains background events with the correct run conditions. It selects events in proportion to the instantaneous luminosity.

Systematic uncertainties

Systematic uncertainties are evaluated for

- Muon RoI Cluster Trigger scale factors
- MS vertex reconstruction mismodelling
- PDF used in MC simulation
- Pileup
- Jet energy scale
- Lifetime extrapolation procedure
- Background estimation procedure for the ABCD plane