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

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ATLAS EXPERIMENT

Motivation

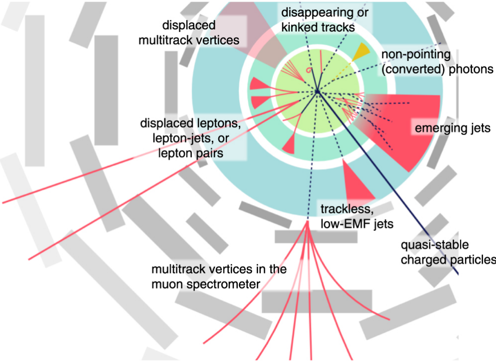
- BSM models: SUSY, heavy neutral leptons (HNLs), dark sector, ... predict new **long-lived particles** (LLPs).
- The reasons behind the long lifetimes are – approximate symmetries, small couplings, and availability of suppressed phase space for decays.
- Deviating from the customary searches in the *prompt* scheme, the BSM LLPs offer tremendous possibilities for discovering New Physics at particle colliders.
- However, searching for the LLPs is **challenging** because of
  - their *unusual* experimental signatures.
  - (atypical signatures, and hence) atypical backgrounds.
- **Decisive factors**: ionization, decay length, energy deposits, and displacements.

  $\Rightarrow$ Requirement of *dedicated* methods and tools.
- **Signatures discussed:**

  Exotics – displaced jets in the muon spectrometer, light long-lived neutral particles;

  SUSY – displaced leptons, stopped LLPs.

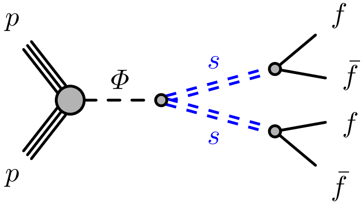
Courtesy: Heather Russell



Displaced jets in the muon spectrometer (MS) - I

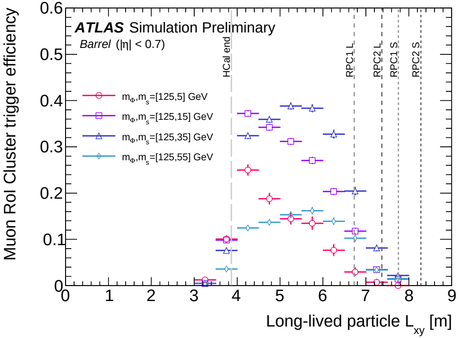
ATLAS-CONF-2021-032

- MS is useful for its coverage of an extensive range of LLP lifetimes.
- Decay of LLPs with a pair of displaced vertices (DVs) into hadronic jets in the ATLAS MS.
- Results interpreted by a scalar portal model:
  - Φ: SM-like Higgs or, lower-/higher-mass scalar boson.
  - S: long-lived hidden sector (pseudo-)scalar (LLP).



- Requirement of two MS DVs.
- The muon Region of Interest (RoI) cluster High Level Trigger (HLT): JINST 8 (2013) P07015

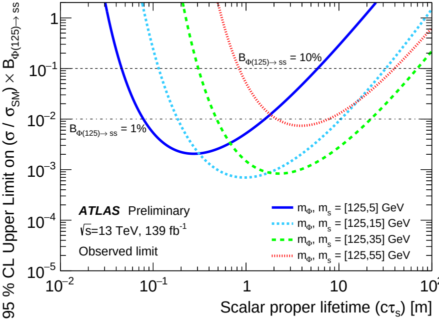
  $\Rightarrow$ a cluster of 3 (4) muon RoIs within an $\Delta R = 0.4$ around the level 1 (L1) object in the barrel (endcaps).
- A dedicated algorithm to reconstruct DVs in the muon spectrometer: JINST 9 (2014) P02001.

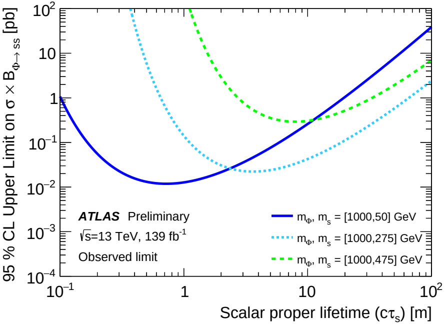


Displaced jets in the muon spectrometer (MS) - II

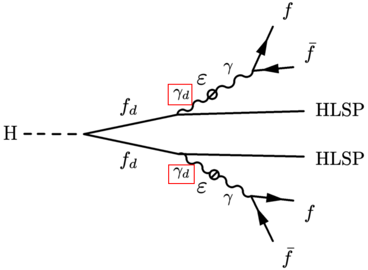
ATLAS-CONF-2021-032

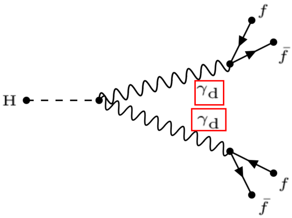
- To assure that the two MS DVs and/or two muon-RoI clusters do not come from the same background activity, the two MS DVs are separated by $\Delta R \geq 1.0$.
- Main source of background: hadronic or electromagnetic showers not contained in the calorimeter volume (*punch-through jets*).
- Expected number of events: $\mathbf{0.32} \pm \mathbf{0.05}$.
- Observed number of events in data: **0**.
- Exclusion limits set on the S production cross-section as a function of its proper lifetime for $m_\Phi = 125$ GeV and $m_\Phi \neq 125$ GeV.



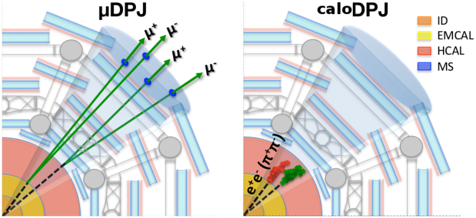


- Search for dark photons (γ_d) in MeV-GeV mass range.
- Benchmark models: Falkowski–Ruderman–Volansky–Zupan (FRVZ) model and Hidden Abelian Higgs Model (HAHM).
- γ_d: the mean lifetime (τ) $\propto 1/\epsilon^2$.

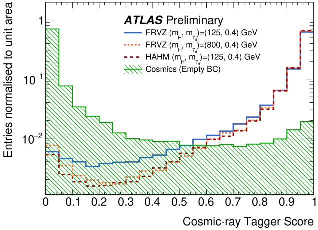




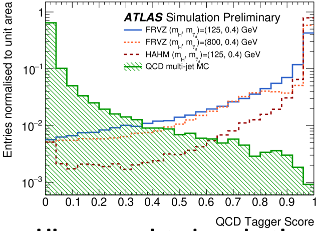
- Small mass → large Lorentz boosts → *collimated* fermions in a jet-like structure.
  ⇒ Dark photon jets (DPJs).
- Muonic dark photon jets (μDPJs).
- Calorimeter dark photon jets – electrons, quarks (caloDPJs).



- μDPJs:
  - Main background: cosmic-ray muons.
  - Dense Neural Network (DNN) cosmic-ray muon tagger
    $\Rightarrow$ 90% rejection.



- caloDPJs:
  - Main background: QCD jets.
  - Convolutional Neural Network QCD tagger
    $\Rightarrow \sim$ 94% rejection.
  - Other background: beam-induced background (BIB).
  - Dedicated per–jet tagger (BIB tagger)
    $\Rightarrow$ 68% rejection.



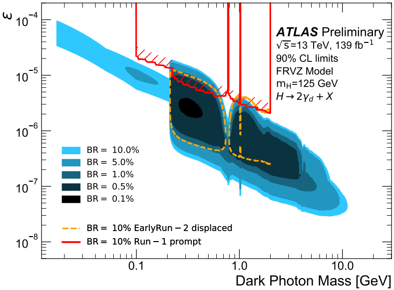
Two search categories: gluon fusion (ggF) and W boson Higgs associated productions (WH).

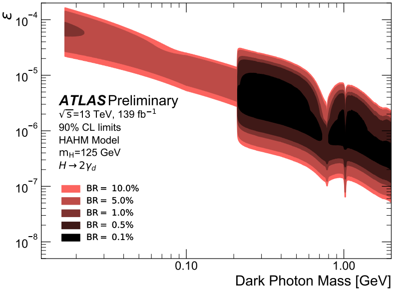
- ggF:
  - Dedicated MS-based triggers (tri-muon, muon-narrow scan), and calorimeter trigger (hadronic).
  - Channels: 2 μDPJs (2μ), 2 caloDPJs (2c), 1 μDPJ + 1 caloDPJ (c + μ).
  - Backgrounds: rare QCD events, multi-jet production, cosmic-ray muons.
- WH:
  - Single electron or muon triggers.
  - Channels: 1 caloDPJ (c), 2 caloDPJs (2c), 1 μDPJ + 1 caloDPJ (c + μ).
  - Backgrounds: W+jets.

Light long-lived neutral particles - III

- Data-driven background estimation via ABCD method.
  $\Rightarrow$ Background prediction in agreement within 1σ deviation.

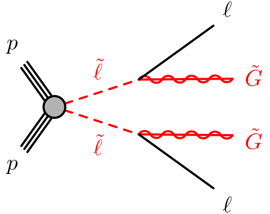
Selection	Search channel	CRB	CRC	CRD	SR expected	SR observed
ggF	2μ	55	61	389	317 ± 47	269
	c+μ	169	471	301	108 ± 13	110
	2c	97	1113	12146	1055 ± 82	1045
WH	c	1850	3011	155	93 ± 12	103
	c+μ	30	49	31	19 ± 8	20
	2c	79	155	27	14 ± 5	15



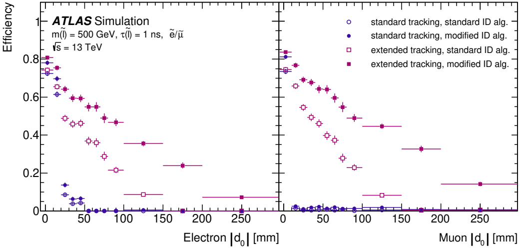


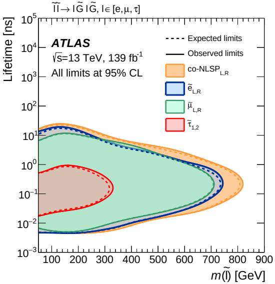
Sensitivity reached BR($H \rightarrow 2\gamma_d + X$) = 0.1% for the first time.

- Pair-produced sleptons ($\tilde{\ell}$) decay into an invisible gravitino ($\tilde{G}$) and a charged lepton of the parent slepton flavor.

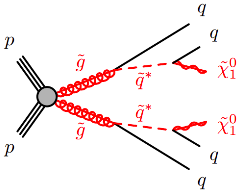


- Std. tracking ($|d_0| < 10$ mm) + extended tracking ($|d_0| < 300$ mm); Lepton: $p_T > 65$ GeV.
- **Displaced leptons w/ no visible decay vertex are also covered.**
- Main backgrounds: fake leptons, *out-of-time* cosmic-ray muons.
- Predicted events: 0.46 ± 0.10 (SR-ee), $0.007^{+0.019}_{-0.007}$ (SR-$e\mu$), and $0.11^{+0.20}_{-0.11}$ (SR-$\mu\mu$). **No dilepton events are observed.**

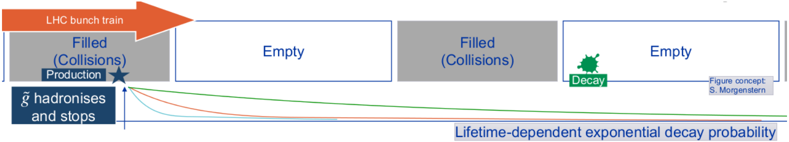




Stopped LLPs - I



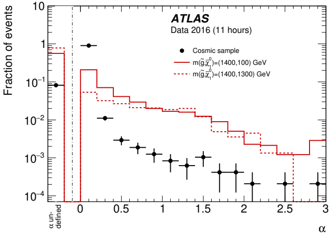
- A search for LLPs, which have come to rest within the ATLAS detector
  - $\Rightarrow$ high-p_T jets,
  - $\Rightarrow$ large *out-of-time* energy deposits in calorimeters.
- Benchmark model: long-lived gluinos ($\tilde{g}$) from the split-SUSY model: $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$.



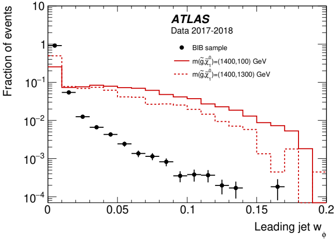
[Courtesy: Louie Dartmoor Corpe.]

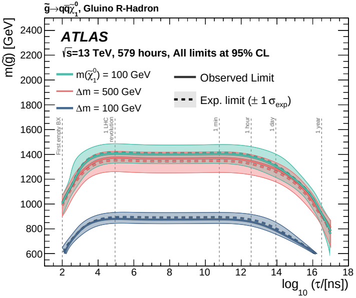
- The sensitivity of stopped LLP searches depends on:
  - integrated luminosity,
  - *live time* – total time during which the trigger selects and accepts signal events in the empty bunch crossings (BXs).
- 2017 data $\Rightarrow$ 49.0 fb^{-1}, 298 hrs empty-BX live time.
- 2018 data $\Rightarrow$ 62.1 fb^{-1}, 281 hrs empty-BX live time.
- Main backgrounds: cosmic-ray muons, beam-induced background (BIB).

- **Cosmic-ray muon background**:
  - Estimated via a *cosmic sample* – taken w/o beam in the LHC during 2016.
  - α: closest distance between the leading-jet and cosmic muon segment pair.
  - Background rejection: $\alpha > 0.2$.



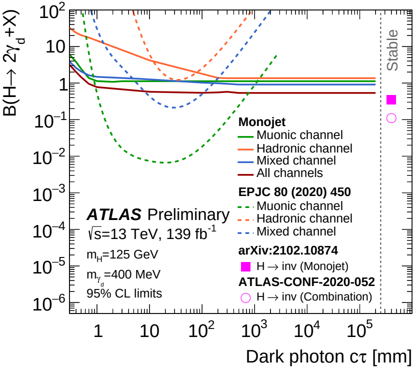
- **Beam-induced background**:
  - The sample is from unpaired BX data during 2017-18.
  - w_ϕ: jet width in the ϕ-plane.
  - Background rejection: $w_\phi > 0.02$.

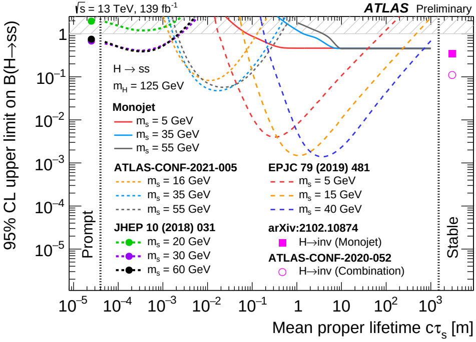




- The signal regions are binned by leading-jet p_T $\Rightarrow$ limits extraction and extrapolation.
- Gluino masses up to 1.4 TeV are excluded for gluino lifetimes of 10^{-5} to 10^{3} s.

- RECAST (Request Efficiency Computation for Alternative Signal Theories) framework ⇒ a robust method that uses “old” search results to produce “new” limits.





FRVZ: exclusion contours w/ γ_d lifetime and branching fraction.

Muonic: both $\gamma_d \to \mu^+\mu^-$.

Hadronic: both $\gamma_d \to e^+e^-$ or light hadrons.

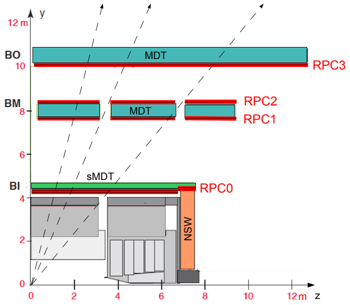
Mixed: one $\gamma_d \to \mu^+\mu^-$ and another $\gamma_d \to e^+e^-$ or light hadrons.

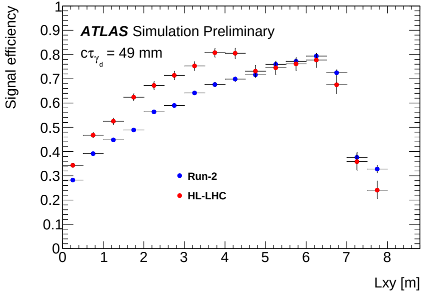
Exclusion contours on B$(H \to ss)$.

Mean proper lifetimes greater than 0.5 (10) m for $m_S = 5$ (55) GeV can be excluded at 95% CL with branching fraction values larger than 50%.

I. Dark photons @HL-LHC

- Dark photons (γ_d) decaying to displaced muon jets at High Luminosity LHC (HL-LHC).
- Benchmark model: FRVZ model – production of dark photons via dark fermions.
- HL-LHC $\Rightarrow \sqrt{s} = 14$ TeV; pile-up $(<\mu>) = 200$; $\mathcal{L}_{\text{Total}} = 3000$ fb^{-1}.
- **Upgrades for HL-LHC:**
  - Muon spectrometer (MS) in the barrel region ($|\eta| < 1.0$):
    RPC0 – the new layer.
    $\Rightarrow$ Increase in the acceptance from 75% to 95%.
  - The new L0 muon trigger:
    a coincidence of hits in RPC layers within a $\Delta\eta \times \Delta\phi$ window.
    $\Rightarrow$ Better efficiency at a moderate rate for low threshold single-muon triggers.

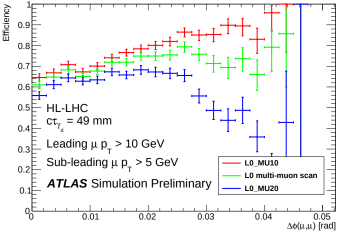


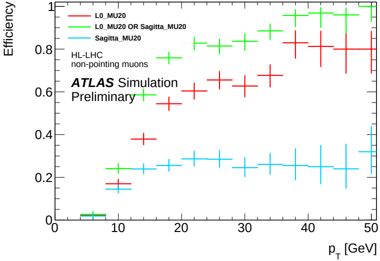


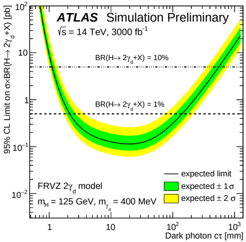
II. Dark photons @HL-LHC

ATL-PHYS-PUB-2019-002

- **Two new proposed triggers** are studied for hidden sector scenarios:
  - **The L0 multi-muon scan trigger**: to improve trigger efficiency for close-by muon pairs.
    $\Rightarrow$ Improvement up to 7% w.r.t the baseline $p_T = 20$ GeV selection.
  - **The L0 sagitta muon trigger**: to trigger on displaced non-pointing muons.
    $\Rightarrow \sim 20\%$ improvement in efficiency by *adding* the new trigger.







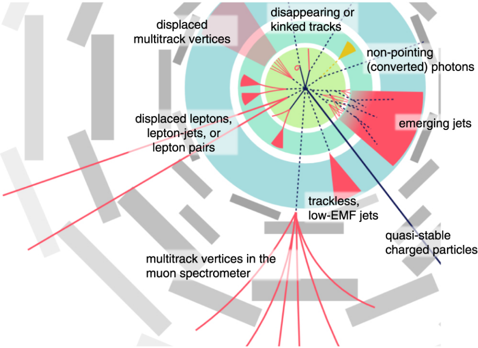
Excluded $c\tau$ [mm] muonic-muonic	HL-LHC	HL-LHC w/ L0 muon-scan
$\mathcal{B}(H \to 2\gamma_d + X) = 10\%$	$0.97 \leq c\tau \leq 553$	$0.97 \leq c\tau \leq 597$
$\mathcal{B}(H \to 2\gamma_d + X) = 1\%$	$2.18 \leq c\tau \leq 142$	$2.13 \leq c\tau \leq 148$

Extrapolation of Run 2 results to HL-LHC by assuming $\mathcal{L}_{\text{Total}}$ 3000 fb^{-1}, and a scale factor which takes into account $\sqrt{s} = 13$ TeV to $\sqrt{s} = 14$ TeV change as well as $< \mu >= 200$.

Wrap-up

- Utilizing Run 2 data, the ATLAS LLP searches have covered various signatures from diverse lifetimes.
  - Disappearing-track signature (**more recently from SUSY**): arXiv:2201.02472 [hep-ex].
- Analysis techniques and triggering strategies have been devised.
- The RECAST framework allows for high fidelity re-interpretations of the already published results.
- The HL-LHC is expected to probe higher sensitivities.
- The outcomes from these searches are anticipated to facilitate future discoveries at the LHC and beyond.

Courtesy: Heather Russell



Backup

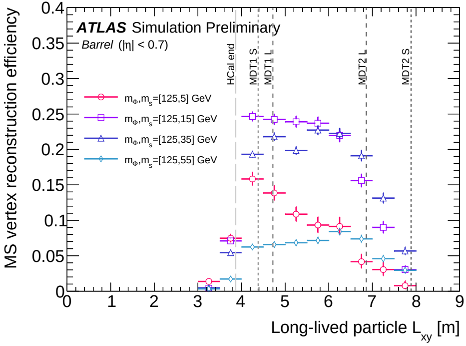
Displaced jets in the muon spectrometer (MS)

ATLAS-CONF-2021-032

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 one MS DV
MS DV matched to the triggering muon-RoI cluster ($\Delta R(\mathrm{DV}, \mathrm{RoI\ cluster}) < 0.4$). In the case of two muon-RoI clusters, the second vertex should be matched to the second cluster.
$300 \leq n_{\mathrm{MDT}} < 3000$

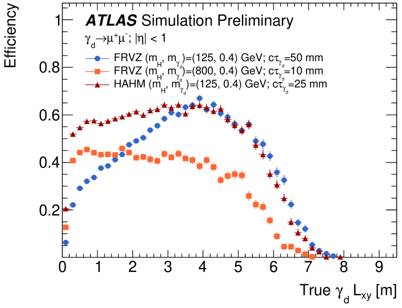
Barrel	*Endcaps*
MS DV with $\lvert\eta_{\mathrm{vx}}\rvert < 0.7$	MS DV with $1.3 < \lvert\eta_{\mathrm{vx}}\rvert < 2.5$
MS DV with $3\,\mathrm{m} < L_{xy} < 8\,\mathrm{m}$	MS DV with $L_{xy} < 10\,\mathrm{m}$ and $5\,\mathrm{m} < \lvert L_z\rvert < 15\,\mathrm{m}$
$n_{\mathrm{RPC}} \geq 250$	$n_{\mathrm{TGC}}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

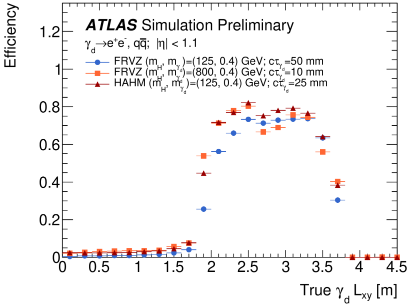
Isolation requirements	Barrel	Endcaps
High-p_{T} track isolation ($p_T > 5$ GeV)	$\Delta R > 0.3$	$\Delta R > 0.6$
Low-p_{T} track isolation ($\Sigma p_{\mathrm{T}}(\Delta R < 0.2)$)	$\Sigma p_{\mathrm{T}} < 10$ GeV	$\Sigma p_{\mathrm{T}} < 10$ GeV
Jet isolation	$\Delta R > 0.3$	$\Delta R > 0.6$

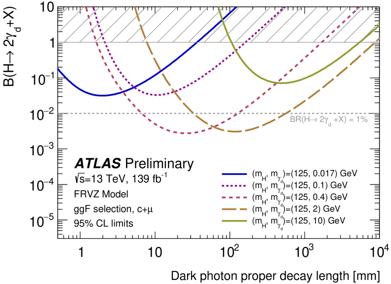


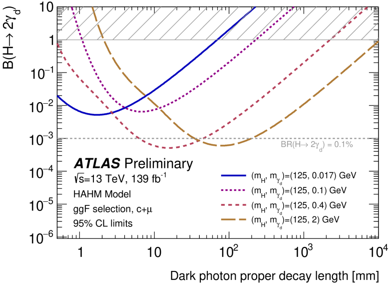
$\Phi(125) \to ss$ m_s [GeV]	Excluded $c\tau_s$ range for s [m] B = 1%	B = 10%
5	0.08–1.6	0.04–5.9
15	0.18–10.8	0.11–32.9
35	0.48–22.6	0.30–71.3
55	2.1–7.8	0.84–40.2

Light long-lived neutral particles









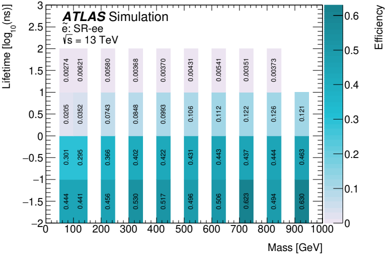
Displaced leptons

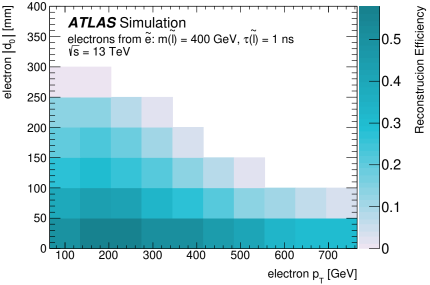
Phys. Rev. Lett. 127 (2021) 051802

	VR-ee-fake	VR-ee-heavy-flavor	VR-$e\mu$-fake	VR-$e\mu$-heavy-flavor
Estimate	1356 ± 49	23.5 ± 1.9	$1.9^{+1.8}_{-1.0}$	$0.38^{+0.37}_{-0.32}$
Observed	1440	26	2	1

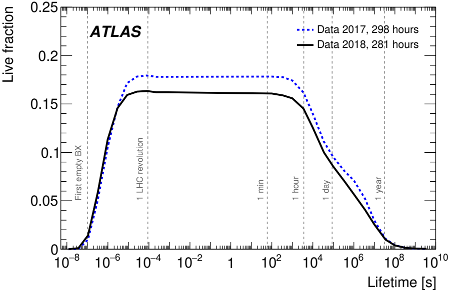
Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + heavy-flavor	0.46 ± 0.10	$< 10^{-4}$	$0.007^{+0.019}_{-0.007}$
Cosmic-ray muons	–	$0.11^{+0.20}_{-0.11}$	–
Expected background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

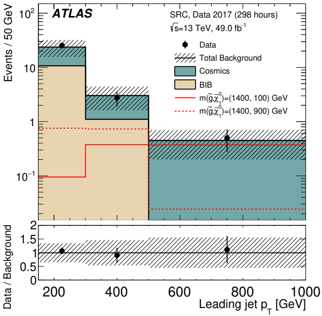
Signal channel	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	S^{95}_{obs}
SR-ee	0	0.46 ± 0.10	0.02	3.0
SR-$\mu\mu$	0	$0.11^{+0.20}_{-0.11}$	0.02	3.0
SR-$e\mu$	0	$0.007^{+0.019}_{-0.007}$	0.02	3.0

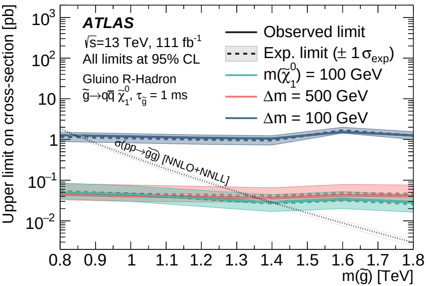




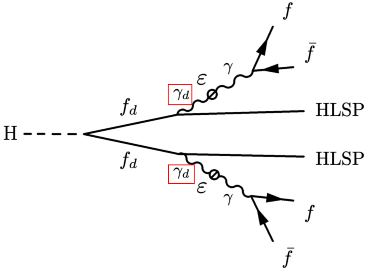
Data sample (purpose)	Bunch structure	Trigger requirements	Offline requirements
Search sample	Empty	HLT jet $p_T > 55$ GeV HLT $E_T^{miss} > 50$ GeV HLT jet $\|\eta\| < 2.4$	Leading jet $p_T > 90$ GeV Leading jet $\|\eta\| < 2.4$
Cosmic sample	–	L1 jet $p_T > 12$ GeV	Leading jet $p_T > 90$ GeV Leading jet $\|\eta\| < 2.4$
Beam-induced background sample	Unpaired	L1 jet $p_T > 12$ GeV or L1 jet $p_T > 50$ GeV	Leading jet $p_T > 90$ GeV Leading jet $\|\eta\| < 2.4$
Cavern background sample	Empty	Random	–

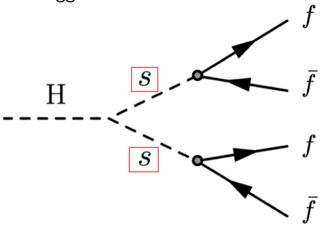




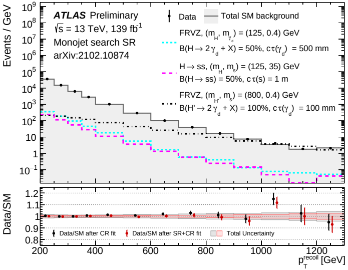


- The *dark sector* is constrained with the monojet signature using RECAST.
- The **new** searches:
  - FRVZ model: production of dark photons (γ_d) from the Higgs boson. HLSP: Hidden Lightest Stable Particle.
  - Exotic Higgs decays into scalar particles (S).





- The **old** monojet search. A binned likelihood fit is performed exploiting the p_T^{recoil} distributions of the several regions.



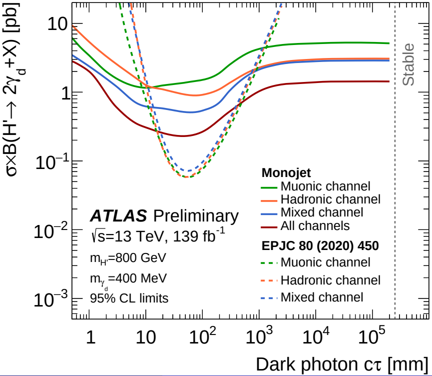
Monojet re-interpretation - II

ATL-PHYS-PUB-2021-020

Model 1		Model 2	
m_H	125 GeV	$m_{H'}$	800 GeV
$c\tau_d$	5, 50, 500 mm	$c\tau_d$	10, 100 mm
Common parameters			
m_{γ_d}	400 MeV		
m_{f_d}	5 GeV		
m_{HLSP}	2 GeV		

$m_{\mathrm{H}}(m_{\mathrm{H'}})$ GeV	m_s [GeV]	$c\tau_s$ [mm]
125	5	223, 411
125	35	1310, 2630
125	55	1050, 5320

Source of uncertainty and impact on the prefit signal yields (%)	
FRVZ model, m_H = 125 GeV, m_{γ_d} = 400 MeV, $c\tau_d$ = 500 mm	
Jet energy scale	1.8 – 2.4
Jet energy resolution	1.0 – 2.1
Jet quark/gluon composition and response	0.9 – 2.8
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	1.2 – 2.6
Hss model, m_H = 125 GeV, m_s = 5 GeV, $c\tau_s$ = 411 mm	
Jet energy scale	1.7 – 2.3
Jet energy resolution	1.0 – 3.3
Jet quark/gluon composition and response	0.7 – 3.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.1 – 2.9



Dark photons @HL-LHC

ATL-PHYS-PUB-2019-002