Searches for unconventional signatures with the ATLAS detector at 13 TeV

LHCP2018

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R. Kopeliansky, Indiana University

On behalf of the ATLAS collaboration

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  - Question of stableness
  - Search requirements
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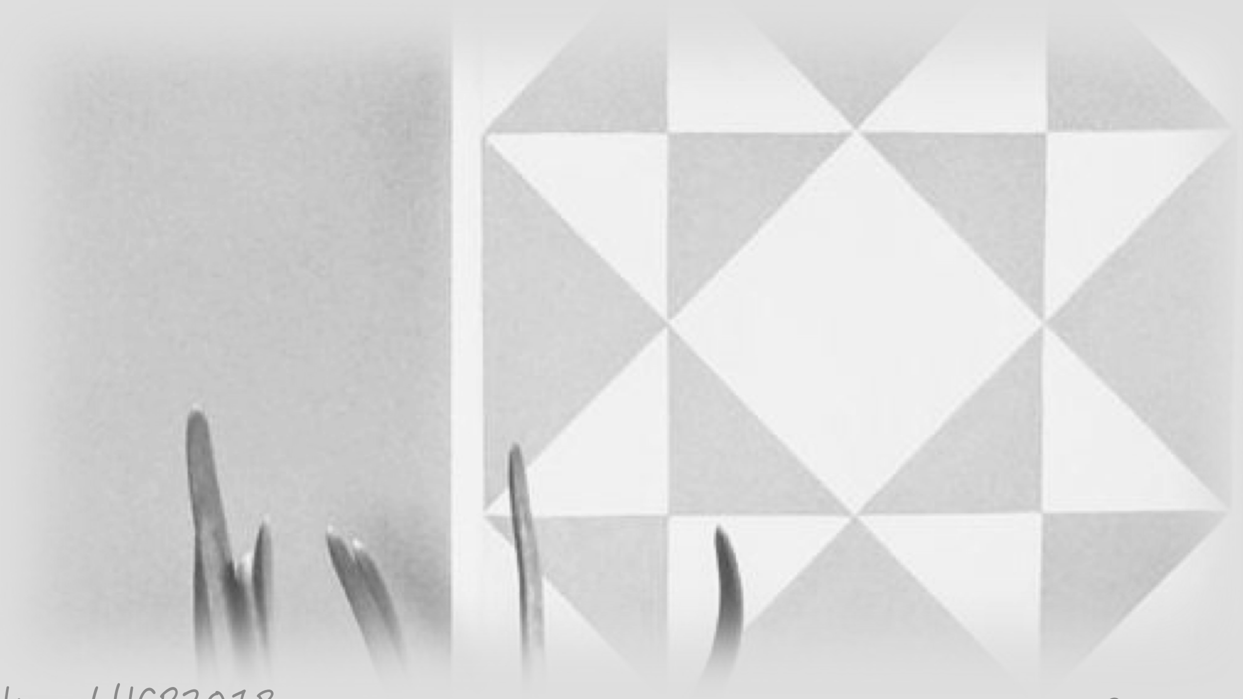
  - Displacement-ness
  - Displaced jets in the calorimeter
  - Displaced lepton-jets
- Summary



Unconventional-ism

Definition of Unconventional-ism

Unconventional final-state usually refers to unique detector signatures

- Mostly refers to physics beyond the standard model (BSM)
- Many scenarios include new particles with relatively long life-time, enabling direct measurements
- Final states can include BSM particles
- The new particle interactions with the detector can differ from interactions involving SM particles
  - Can be massive and therefore are expected to travel at low velocities ($\beta < 1$)
  - If electrically charged, the new particle is expected to be highly ionizing ($\frac{dE}{dx} > \frac{dE}{dx}_{MIP}$)

Question of Stableness

- A particle is considered as long-lived (LLP) if it has a long-enough lifetime to be measured directly by the detector

- Two types of long-lived particles:
  - Meta-stable
    - Decays inside the detector volume
    - The decay location is usually unknown and hence a range of lifetimes will be studied
  - Stable
    - pass through the detector without decaying

- Detector signature:
  - Electrically charged LLPs will leave signal in all detector stations
  - If neutral, depending on the LLP lifetime, either large reconstructed E_T^{miss} or unusual vertex locations will appear
  - Strongly interacting LLPs might flip their electric charge while interacting with the detector medium
  - In most cases the background sources are cavern/instrumental noise and badly reconstructed objects

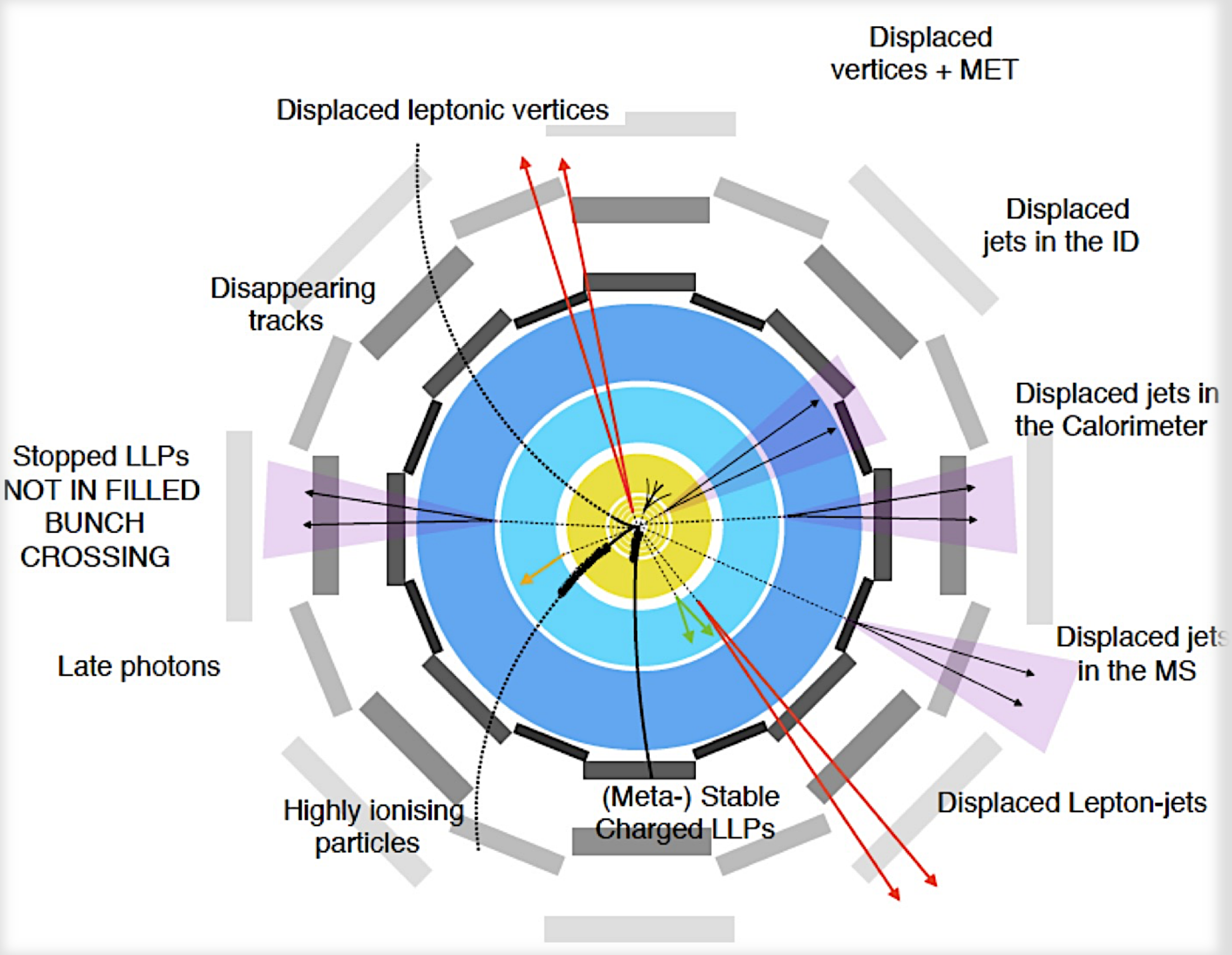
Search Requirements

Usually requires unconventional analysis methods

- Detector-signature driven search
- Standard triggers are not designed for unusual objects
- Self-made object reconstructions is required
- Requires non-standard analysis strategies and tools
    - Custom made MC simulations
    - Background estimation is usually data driven

Searches

ATLAS Unconventional Signature Searches

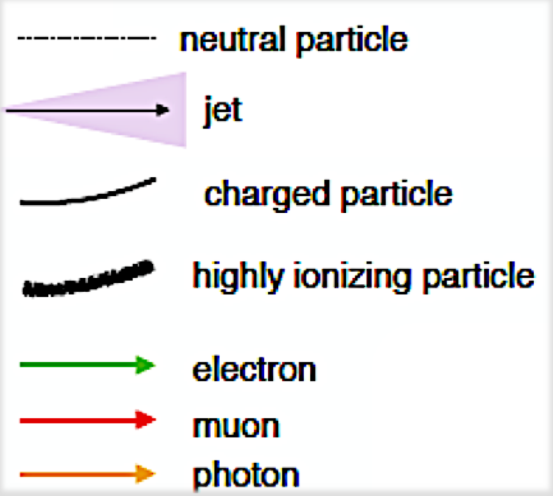


EXOTIC Searches

- Public Results: LINK

SUSY Searches

- Public Results: LINK



© Many thanks to the talented artist: **Emma Torro**, University of Washington

Displacement-ness

'Displaced Vertices':

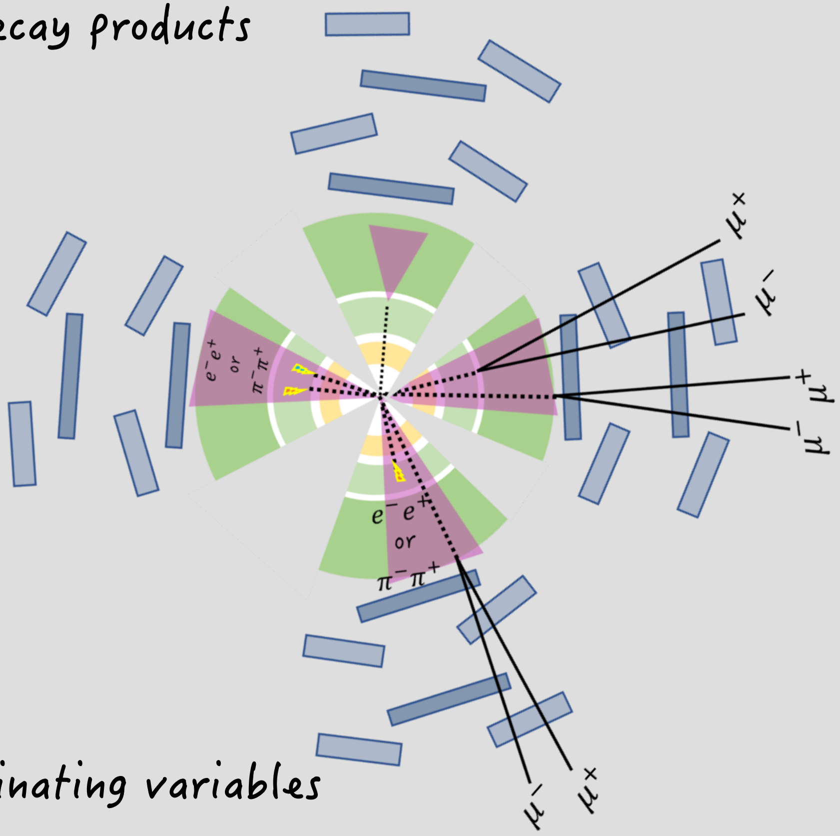
- Some BSM models consider a possible production of a neutral metastable particle
- Depending on the LLP's lifetime a decay is expected inside the detector
- Signal 'appears' inside one of the detector stations
- No trail leading to the Interaction-Point (IP) from the decay location, only decay products

Searches presented:

- Displaced jets
- Displaced Lepton-Jets (LJs)

Common:

- Neutral LLP decays inside the detector
- Background sources of multi-jet production, and Non-Collision Bkg (NCB)
  - NCB – (Cosmic-μ and beam halo (Beam Induced Bkg (BIB)))
- Public results based on data sample of ~3 fb^{-1} (2015)
- Background estimation based on data-driven ABCD method with two discriminating variables



Displaced Jets in the Calorimeter – 1/3

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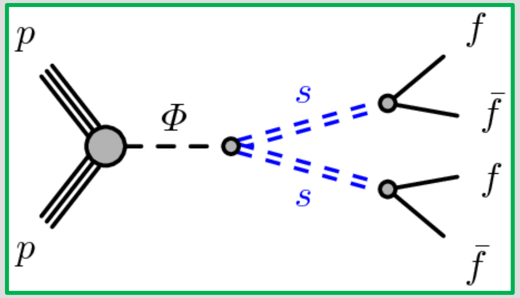
Scenario

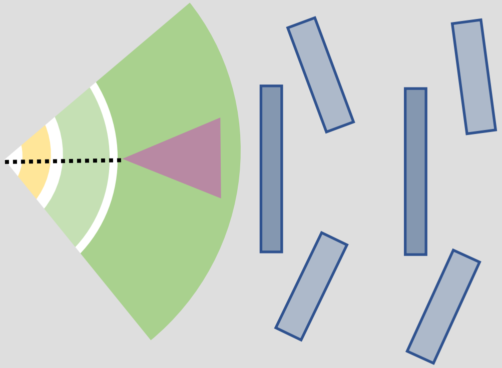
- Hidden Sectors (HS) containing a new sector weakly coupled to the SM via a communicator particle
- The HS particles may decay to SM particles via the communicator



- **A simplified HS model** in which the SM sector and hidden sector are connected via a **heavy neutral boson Φ**
- The Φ decays to two long-lived neutral scalars **S**: $\boldsymbol{\Phi \rightarrow SS}$
- The neutral scalar **S** decays to a pair of SM fermions: $\boldsymbol{S \rightarrow f\bar{f}}$

Detector signature

- The neutral LLPs will decay in the hadronic calorimeter
- Results in a-typical jet (mainly $b\bar{b}$ -quarks):
  - No tracks in the ID
  - No energy deposit in the electromagnetic calorimeter
- Final state of two displaced jets



Displaced Jets in the Calorimeter – 2/3

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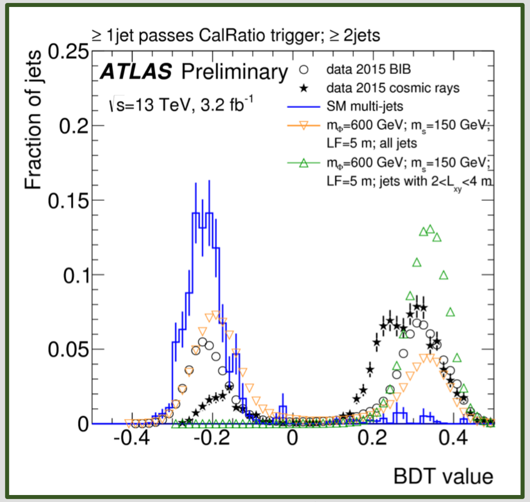
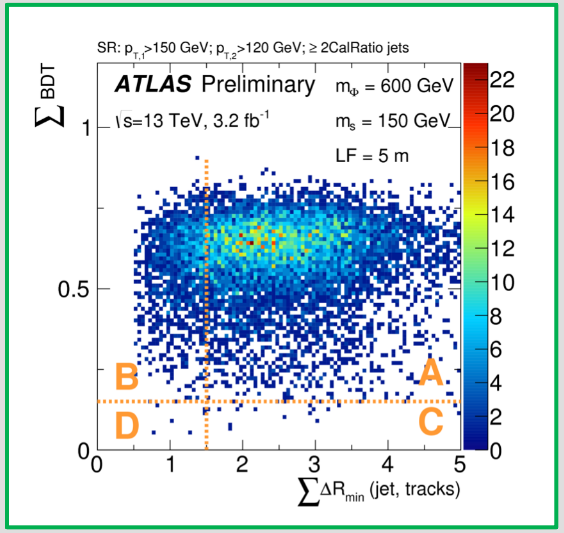
Analysis Strategy

- LLP decay products are less separated when the decay occurs in the HCal resulting in a narrow jet
  - High 'CaloRatio-jet' – $(\frac{E_{HCal}}{E_{EM}})$
  - No ID tracks
- MC simulations:
  - Heavy boson: $m_{\Phi} = 400\ GeV\ \rightarrow 1\ TeV$
  - Neutral scalars: $m_S = 50\ \rightarrow 400\ GeV$
- Trigger selection: signature-driven trigger: 'CalRatio'
- Offline selection:
  - BIB removal algorithm
  - Boosted Decision Tree (BDT)

    and p_T cuts:
    - $p_T > 150\ GeV, BDT > 2.0$
    - $p_T > 120\ GeV, BDT > -0.2$



- Background rejection:
  - BDT value should be within $-3ns < t < 15ns$
  - Rejection of soft NCB jets $p_T > 50\ GeV$
  - $\Delta\phi(jet_1^{CaloRatio}, jet_2^{CaloRatio}) > 0.75\ rad$
- Background estimation using a data-driven ABCD method:
  - $\sum \Delta R_{min}$ (jet, tracks)
  - $\sum BDT$



Displaced Jets in the Calorimeter – 3/3

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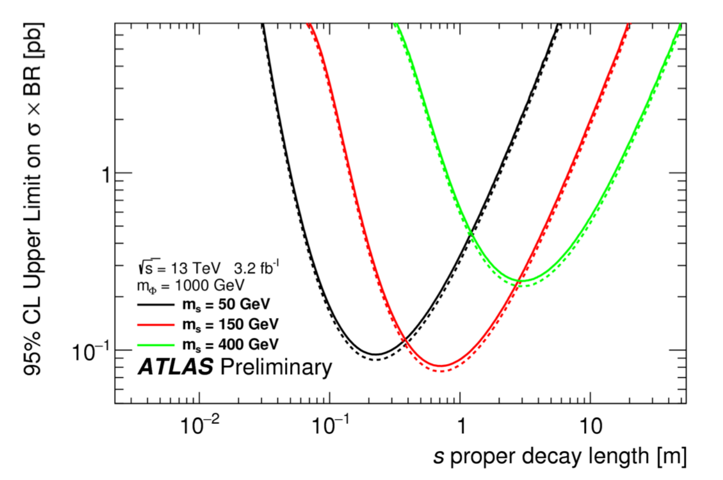
Results

- The number of predicted background events (18.4±6.3(stat)±6.6(syst)) is within 1σ of the observed events (24)
- Limits were set on **σ×BR** of the signal as a function of the proper lifetime of the LLP:

	$m_s = 50$ GeV	$m_s = 100$ GeV	$m_s = 150$ GeV	$m_s = 400$ GeV
	Decay length range excluded at 95% CL for $\sigma\times$ BR = 1 pb			
$m_\Phi = 400$ GeV	(0.20, 2.4) m	(0.52, 4.6) m	–	–
$m_\Phi = 600$ GeV	(0.09, 2.7) m	–	(0.38, 8.2) m	–
$m_\Phi = 1$ TeV	(0.05, 2.0) m	–	(0.14, 7.2) m	(0.78, 16) m



- For $m_\Phi = 1\,TeV$, a decay-length range of $0.05\,m \rightarrow 16\,m$ is excluded (assuming 1 pb Xsec and 100% BR)

Experiment	8 TeV $c\tau$(m)	13 TeV $c\tau$ (m)
ATLAS	$0.14 \leq c\tau \leq 8.32$ Physics Letters B 743 (2015) 15-34 arXiv:1501.04020	$0.05 \leq c\tau \leq 16$
CMS	$0.01 \leq c\tau \leq 3.5$ Phys. Rev. D 91 (2015) 012007 arXiv:1411.6530	-

Displaced Lepton-Jets (LJs) – 1/4

ATLAS-CONF-2016-042

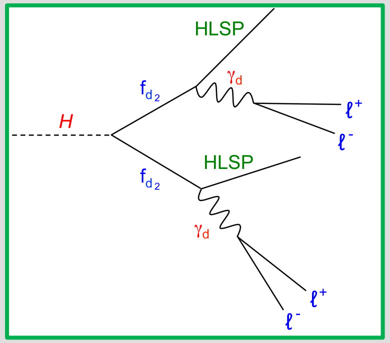
Scenario

- Light hidden photon γ_d mixed kinetically with SM photon
- Expected small mass and hence produced boosted and long-lived
- The γ_d lifetime depends on the kinetic mixing parameter
- At its lightest state the γ_d will decay to SM particles, mainly leptons & mesons

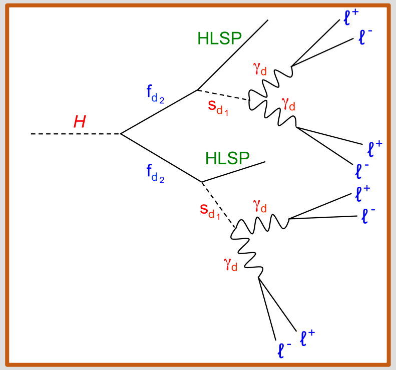
Two FRVZ models used as benchmarks:

In both the hidden sector is communicating with the SM sector through the Higgs portal:

The Higgs boson decays to a pair of hidden fermions f_{d2}



the dark fermion f_{d2} decays to a γ_d and a Hidden-Lightest-Stable-Particle f_{d1} (HLSP)



the dark fermion f_{d2} decays to a dark scalar s_{d1} and an HLSP
then the s_{d1} decays to pairs of dark photons

Displaced Lepton-Jets (LJs) – 2/4

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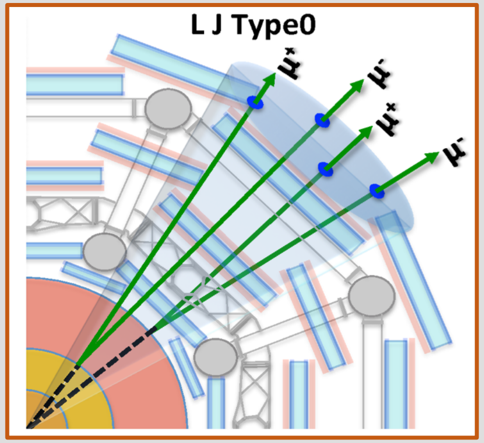
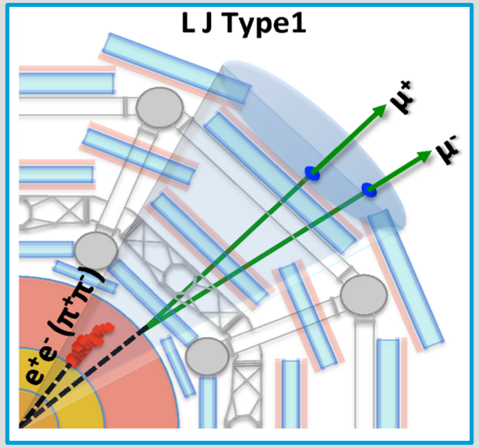
Detector Signature

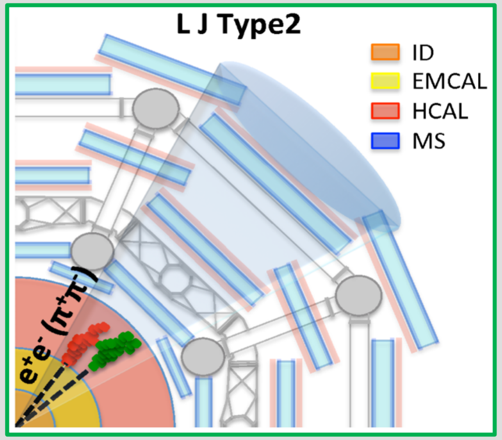
- The γ_Ds are expected to decay two LJs, produced back-to-back in the azimuthal plane
- LJs are defined and classified according to the muon/jet content found within a cone of opening: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$



Muons only – at least two muons, no jets



Muons + jet – at least two muons and only one jet



Jets only – no muons, jets only

Displaced Lepton-Jets (LJs) – 3/4

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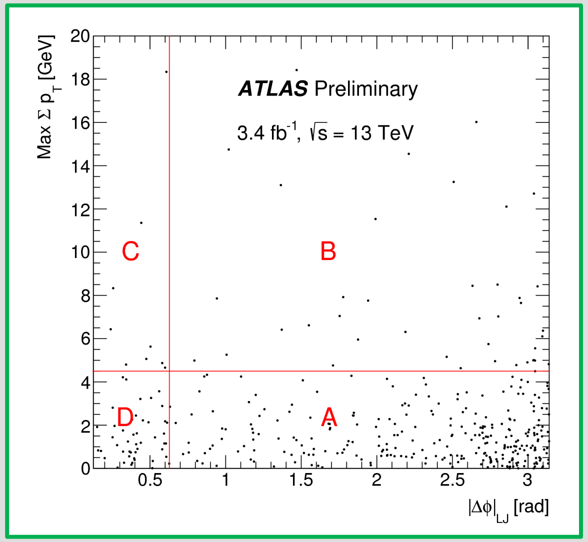
Analysis Strategy

- Searching for long-lived neutral particles decaying into collimated jets of light-leptons and mesons
- MC simulations:
  - 2 or 4 γ_D
  - $m_{\gamma_D} = 0.4\ GeV$
  - $m_H = 125, 800\ GeV$
- Trigger selection - 'OR' combinations:
  - Narrow-scan – scan for μ object in a narrow cone
  - Tri-muon MS only – events with at least 3- μs with no ID info
  - CalRatio – isolated jets with low energy deposition in the EMcal
- Background rejection:

LJ type	Selection requirement	Requirement description
Type 0/1	z_0 limits	an impact parameter $\lvert z_0\rvert < 280$ mm for both muons of the LJ
Type 1/2	jet timing Δt_{Calo}	remove jets outside the $\pm$ 4 ns time window
Type2	tile-gap scint.	max energy in tile-gap scintillators $\leq 10\%$ of the jet energy
Type2	EM fraction	EM fraction of the jet < 0.1
Type2	jet width	$W < 0.058$
Type2	JVT	JVT variable ≤ 0.56
Type2	BIB	use BIB tagging to remove fake jets from beam-halo muons
Type 0/1	no-CB	all muons of the LJ to be non-combined ("no-CB")

- Offline selection:
  - Two LJ objects passed the Bkg. Rejection
  - ID-track isolation + $\Delta\phi$ between the two LJs
- Background estimation using a data-driven ABCD method:
  - $\max\sum p_T \leq 4.5\ GeV$
  - $\lvert\Delta\phi\rvert_{LJ} \geq 0.628\ rad$



Displaced Lepton-Jets (LJs) – 4/4

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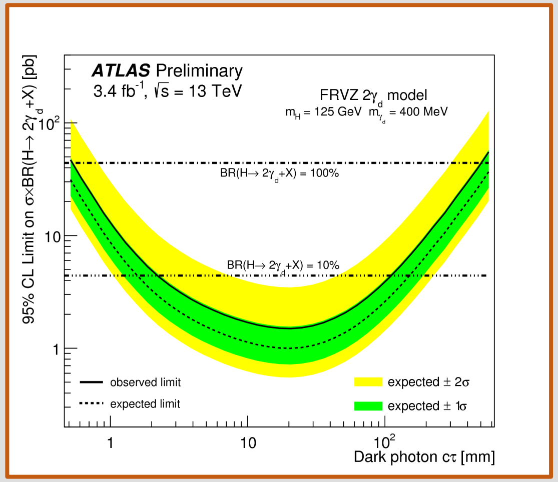
Results

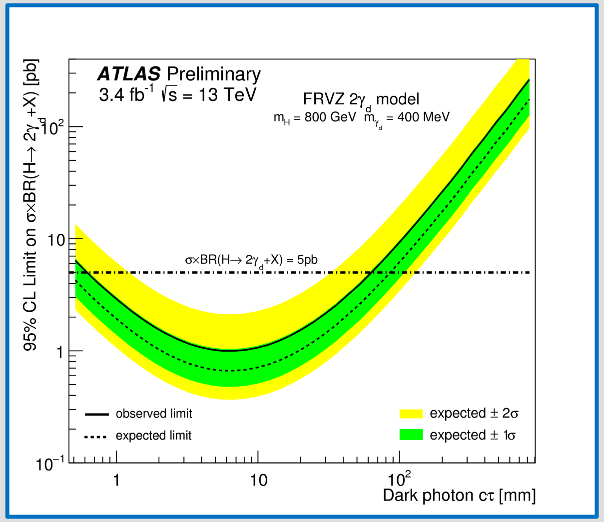
- Consistency between the observed data (285) and expected background (231±12(stat)±62(syst))
- Upper-limits were set on (non-)SM Higgs decays to LJs:



For SM ggf H production Xsec with $m_{\gamma_D} = 0.4\ GeV$

The BR was found to be lower than 10% for H with $m_H = 125\ GeV$ decaying to γ_d

- $H \to 2\gamma_d + X$ for γ_d with $2.2\ \mathrm{mm} \le c\tau \le 111.3\ mm$
- $H \to 4\gamma_d + X$ for γ_d with $3.8\ \mathrm{mm} \le c\tau \le 163\ mm$



For production XSec σ×BR of 5.0pb with $m_H = 800\ GeV$ decaying to γ_d:

- $H \to 2\gamma_d + X$ for γ_d with $0.6\ \mathrm{mm} \le c\tau \le 63\ mm$
- $H \to 4\gamma_d + X$ for γ_d with $0.8\ \mathrm{mm} \le c\tau \le 186\ mm$

m_H (GeV)	8 TeV	13 TeV
125	$14 \le c\tau \le 140$ JHEP11(2014)088 arXiv:1409.0746	$2.2 \le c\tau \le 163$
800	-	$0.6 \le c\tau \le 63$

Summary

Summary

- Many BSM models predict unconventional detector signatures
  - Custom analysis techniques are designed & used to achieve sensitivity to these final-states
- ATLAS Exotic meta-stable search results presented were based on 13 TeV data
  - No evidence for the existence of new physics was found
    - Higher limits were set at 95% CL on the new particles decay-length
- Other unconventional signature searches are ongoing
  - For some, results will be published already this summer
- LLP triggers are being updated/designed for phase-1/2 upgrade to address more scenarios (displaced ID vertices, MS-Only objects, slow-particles…)
  - Improved technology that allows running more sophisticated algorithms

Backup

Displaced Lepton-Jets (LJs)

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- MC simulations:

Benchmark model	m_{H} [GeV]	$m_{\mathrm{f}_{\mathrm{d}_2}}$ [GeV]	m_{HLSP} [GeV]	$m_{\mathrm{s}_{\mathrm{d}_1}}$ [GeV]	$m_{\gamma_{\mathrm{d}}}$ [GeV]	$c\tau_{\gamma_{\mathrm{d}}}$ [mm]	Branching Ratio $\gamma_{\mathrm{d}} \to ee$	Branching Ratio $\gamma_{\mathrm{d}} \to \mu\mu$	Branching Ratio $\gamma_{\mathrm{d}} \to \pi\pi$
2 γ_{d}	125	5.0	2.0	-	0.4	47.0	45%	45%	10%
4 γ_{d}	125	5.0	2.0	2.0	0.4	82.40	45%	45%	10%
2 γ_{d}	800	5.0	2.0	-	0.4	11.76	45%	45%	10%
4 γ_{d}	800	5.0	2.0	2.0	0.4	21.04	45%	45%	10%

- Results of the ABCD Bkg. Est.:

Category	Observed events	Expected background
All events	285	231 ± 12 (stat) $\pm$ 62 (syst)
Type2–Type2 excluded	46	31.8 ± 3.8 (stat) $\pm$ 8.6 (syst)
Type2–Type2 only	239	241 ± 41(stat) $\pm$ 65(syst)

- Expected number of LJ-pairs after full set of selection criteria:

Category	$m_{\mathrm{H}} = 125$ GeV Higgs $\to 2\gamma_{\mathrm{d}} + X$	$m_{\mathrm{H}} = 125$ GeV Higgs $\to 4\gamma_{\mathrm{d}} + X$	$m_{\mathrm{H}} = 800$ GeV Higgs $\to 2\gamma_{\mathrm{d}} + X$	$m_{\mathrm{H}} = 800$ GeV Higgs $\to 4\gamma_{\mathrm{d}} + X$
All events	113 ± 2	96 ± 2	53.0 ± 0.6	112 ± 1
Type2–Type2 excluded	111 ± 2	96 ± 2	43.0 ± 0.5	109 ± 1
Type2–Type2	2.0 ± 0.5	0.34 ± 0.10	10.0 ± 0.3	3.2 ± 0.2

- Ranges of γ_d lifetime ($c\tau$) excluded at 95% CL:

FRVZ model	m_{H} (GeV)	Excluded $c\tau$ [mm]
Higgs $\to 2\gamma_{\mathrm{d}} + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\to 4\gamma_{\mathrm{d}} + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\to 2\gamma_{\mathrm{d}} + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\to 4\gamma_{\mathrm{d}} + X$	800	$0.8 \leq c\tau \leq 186$

Displaced Jets in the Calorimeter

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- MC simulations:

m_Φ [GeV]	m_s [GeV]	LF=5 m		LF=9 m	
		$c\tau$ [m]	Events	$c\tau$ [m]	Events
400	50	0.700	400k	1.26	200k
	100	1.46	400k	2.64	200k
600	50	0.520	400k	0.960	200k
	150	1.72	400k	3.14	200k
1000	50	0.380	400k	0.670	200k
	150	1.17	400k	2.11	200k
	400	3.96	400k	7.20	200k

- Offline selection:

Requirement	Data main	SM multi-jets MC	$m_\phi = 600$ GeV; $m_s = 150$ GeV	Data BIB	Data cosmic rays
Events passing the trigger	548600 ± 740	404000 ± 27000	25.7%	100%	100%
≥ 2 clean jets	421800 ± 650	197000 ± 19000	22.1%	38.3%	21%
$\text{jet}_{1,2}^{\text{CalRatio}}$ clean	23860 ± 150	900 ± 440	7.21%	6.67%	7.28%
$\Delta\phi > 0.75$	17590 ± 130	600 ± 350	6.85%	0.86%	3.38%
$-3 < \text{time} < 15$	16180 ± 130	600 ± 350	6.84%	0.35%	1.10%
$H_T^{\text{miss}}/H_T < 0.3$	14880 ± 120	600 ± 350	6.09%	0.30%	0.25%
$\sum \Delta R_{\min} > 0.5$	9500 ± 97	500 ± 330	6.08%	0.14%	0.25%
BDT value($\text{jet}_1^{\text{CalRatio}}$) > 0.2	8190 ± 91	500 ± 330	5.95%	0.09%	0.25%
BDT value($\text{jet}_2^{\text{CalRatio}}$) > -0.2	4890 ± 70	300 ± 260	5.93%	0.06%	0.25%
$p_{T,1} > 150$ GeV	330 ± 18	0 ± 0	5.31%	0.005%	0%
$p_{T,2} > 120$ GeV	110 ± 10	0 ± 0	4.27%	0.001%	0%
region A:					
$\sum \Delta R_{\min} > 1.5$	60 ± 8.0	0 ± 0	3.73%	0%	0%
$\sum \text{BDT} > 0.15$	24 ± 4.9	0 ± 0	3.57%	0%	0%

- Estimated number of events in the Signal-Region using the ABCD method:

Region	A	B	C	D	Estimated $A = BC/D$
SR : $p_{T,1} > 150$ GeV; $p_{T,2} > 120$ GeV :					
$\sum$ BDT boundary $= 0.15$	24	16	39	34	18.0 ± 6.3
VR : $p_{T,1} > 140$ GeV; 80 GeV $< p_{T,2} < 120$ GeV:					
$\sum$ BDT boundary $= 0.2$	15	14	84	77	15.3 ± 4.7
$\sum$ BDT boundary $= 0.15$	42	38	57	53	40 ± 10
$\sum$ BDT boundary $= 0.1$	72	64	27	27	60 ± 19