On the Origin of Long-Lived Particles

Jared Barron, David Curtin

jared.barron@mail.utoronto.ca

Department of Physics, University of Toronto

Based on arxiv:2007.05538

Abstract

MATHUSLA is a proposed large-volume displaced vertex (DV) detector, situated on the surface above CMS and designed to search for long-lived particles (LLPs) produced at the HL-LHC. We show that a discovery of LLPs at MATHUSLA would not only prove the existence of BSM physics, it would also uncover the theoretical origin of the LLPs, despite the fact that MATHUSLA gathers no energy or momentum information on the LLP decay products. Our analysis is simple and robust, making it easily generalizable to include more complex LLP scenarios, and our methods are applicable to LLP decays discovered in ATLAS, CMS, LHCb, or other external detectors. In the event of an LLP detection, MATHUSLA can act as a Level-1 trigger for the main detector, guaranteeing that the LLP production event is read out at CMS. We perform an LLP simplified model analysis to show that combining information from the MATHUSLA and CMS detectors would allow the LLP production mode topology to be determined with as few as 100 observed LLP decays. Underlying theory parameters, like the LLP and parent particle masses, can also be measured with ≈ 10% precision. Together with information on the LLP decay mode from the geometric properties of the observed DV, it is clear that MATHUSLA and CMS together will be able to characterize any newly discovered physics in great detail..

MATHUSLA

- The proposed MATHUSLA detector is a large-volume surface detector, to be placed near CMS [3-4].
- The goal is to instrument a large volume to search for displaced vertex (DV) decays of ultra long-lived particles produced at the LHC, focusing on decay lengths $c\tau > 100$ m.
- MATHUSLA will be equipped with an internal trigger system for LLPs.
- The trigger rate will be low enough that the MATHUSLA trigger can also act as a Level-1 burst-trigger for CMS: If the upwards tracks originate from the decay of an LLP, there is a range of < 10 candidate LHC bunch crossings that are very likely to include the production event at CMS.
- MATHUSLA can measure the velocity of LLPs from the geometry of their decays [5].

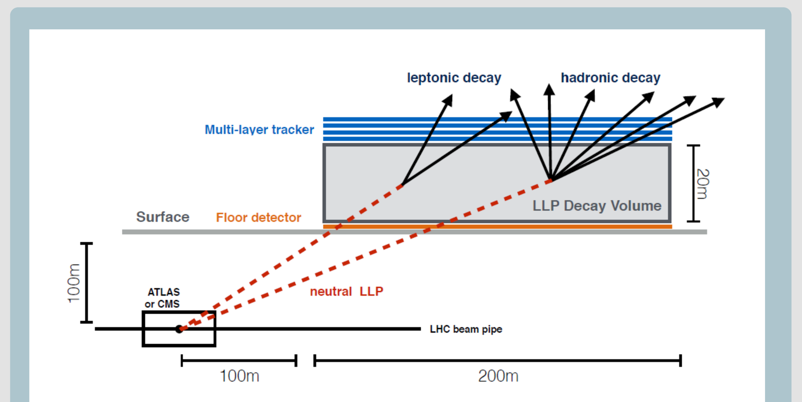

Figure 1: Schematic illustration of MATHUSLA, using the 200m benchmark geometry.

LLP Simplified Models

- We simulate LLPs produced under a variety of simplified model production modes [1,7-10].
- This set of simplified models is meant to cover a wide range of well-motivated LLP production scenarios while remaining agnostic of the underlying mechanism generating the particles' long lifetimes.

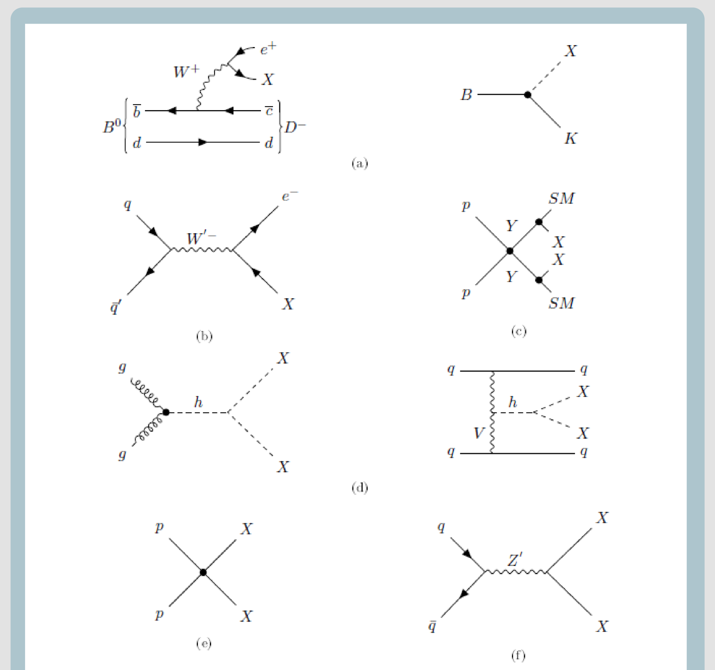

Figure 3: Schematic Feynman diagrams for the models we consider. (a): Exotic B-meson decay (**BB**), with heavy neutral lepton and scalar LLPs. (b): Charged Current (**CC**). (c): Heavy Parent (**HP**). (d): Exotic Higgs Decay (**HIG**) with gluon fusion and vector boson fusion production channels. (e): Direct Pair Production (**DPP**). (f): Heavy Resonance (**RES**).

Model Classification

- Our goal is to identify the production mode of a sample of observed LLPs, from the list of simplified models already described.
- We assume that MATHUSLA observes N_{obs}= 10, 100 or 1000 LLP decays, all resulting from the same single production topology.
- Sample-level variables describing characteristics of the entire observed LLP dataset, like fraction of events with some number of jets above some p_T in CMS, are used to classify the production mode.
- Using characteristic features of each production mode, we find that simple cuts in sample-level observables can be used to achieve ≈ 90% probability of correct model classification for all but small corners of BSM particle parameter space with 100 observed events, and 98% with 1000 observed events. For the BB, CC, and HP models, >90% probabilities of correct classification can be achieved with only $N_{obs} = 10$ events.

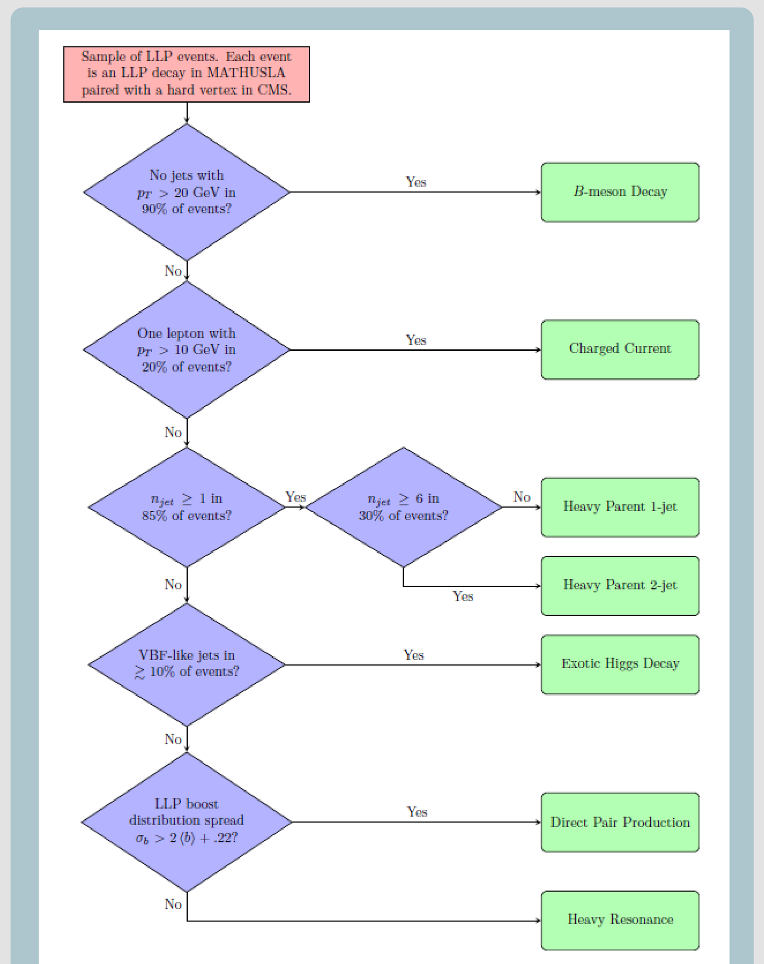

Figure 4: Summary of our hierarchical LLP production mode classification algorithm.

$\mathbf{N_{obs} = 10}$:

Truth \ Result	BB	CC	HP 1-jet	HP 2-jet	HIG	DPP	RES
BB (4570)	$98.4^{+0.3}_{-0.4}$	0	0	0	0	$1.4^{+0.4}_{-0.3}$	$0.2^{+0.2}_{-0.1}$
CC (20920)	$4.0^{+0.3}_{-0.3}$	$93.5^{+0.3}_{-0.3}$	$0.004^{+.017}_{-.004}$	0	$0.03^{+0.03}_{-0.02}$	$2.2^{+0.2}_{-0.2}$	$0.2^{+0.1}_{-0.1}$
HP 1-jet (26510)	$0.1^{+0.04}_{-0.03}$	0	$81.8^{+0.5}_{-0.5}$	$9.2^{+0.4}_{-0.3}$	$1.3^{+0.1}_{-0.1}$	$5.7^{+0.3}_{-0.3}$	$2.0^{+0.2}_{-0.2}$
HP 2-jet (12360)	0	0	$19.9^{+0.7}_{-0.7}$	$78.8^{+0.7}_{-0.7}$	$0.5^{+0.1}_{-0.1}$	$0.8^{+0.2}_{-0.1}$	$0.1^{+0.1}_{-0.0}$
HIG (28550)	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.03}_{-0.02}$	$9.5^{+0.3}_{-0.3}$	0	$36.1^{+0.6}_{-0.6}$	$29.4^{+0.5}_{-0.5}$	$24.9^{+0.5}_{-0.5}$
DPP (29120)	$0.01^{+0.02}_{-0.01}$	0	$17.5^{+0.4}_{-0.4}$	0	$12.3^{+0.4}_{-0.4}$	$48.0^{+0.6}_{-0.6}$	$22.2^{+0.5}_{-0.5}$
RES NW (40160)	$4.7^{+0.2}_{-0.2}$	0	$7.6^{+0.3}_{-0.3}$	0	$14.0^{+0.3}_{-0.3}$	$3.0^{+0.2}_{-0.2}$	$70.7^{+0.4}_{-0.4}$
RES HW (23100)	$3.9^{+0.3}_{-0.2}$	0	$6.6^{+0.3}_{-0.3}$	0	$14.9^{+0.5}_{-0.5}$	$11.4^{+0.4}_{-0.4}$	$63.1^{+0.6}_{-0.6}$

$\mathbf{N_{obs} = 100}$:

Truth \ Result	BB	CC	HP 1-jet	HP 2-jet	HIG	DPP	RES
BB (457)	$100.0^{+0.0}_{-0.5}$	0	0	0	0	0	0
CC (2092)	0	$97.6^{+0.6}_{-0.7}$	0	0	0	$2.4^{+0.7}_{-0.6}$	0
HP 1-jet (2651)	0	0	$90.5^{+1.1}_{-1.2}$	$0.9^{+0.4}_{-0.3}$	$1.0^{+0.4}_{-0.3}$	$7.3^{+1.0}_{-0.9}$	$0.3^{+0.3}_{-0.2}$
HP 2-jet (1236)	0	0	$16.0^{+2.1}_{-2.0}$	$83.5^{+2.0}_{-2.1}$	$0.4^{+0.5}_{-0.2}$	$0.1^{+0.3}_{-0.1}$	0
HIG (2855)	0	0	0	0	$90.4^{+1.0}_{-1.1}$	$7.4^{+1.0}_{-0.9}$	$2.2^{+0.6}_{-0.5}$
DPP (2912)	0	0	$0.1^{+0.2}_{-0.1}$	0	$1.6^{+0.5}_{-0.4}$	$97.9^{+0.5}_{-0.6}$	$0.4^{+0.3}_{-0.2}$
RES NW (4016)	0	0	0	0	$4.8^{+0.7}_{-0.6}$	$1.9^{+0.5}_{-0.4}$	$93.3^{+0.7}_{-0.8}$
RES HW (2310)	0	0	0	0	$6.3^{+1.0}_{-0.9}$	$8.0^{+1.2}_{-1.1}$	$85.7^{+1.4}_{-1.5}$

$\mathbf{N_{obs} = 1000}$:

Truth \ Result	BB	CC	HP 1-jet	HP 2-jet	HIG	DPP	RES
BB (40)	$100.0^{+0.0}_{-6.0}$	0	0	0	0	0	0
CC (191)	0	$97.6^{+1.5}_{-3.0}$	0	0	0	$2.4^{+3.0}_{-1.5}$	0
HP 1-jet (246)	0	0	$92.7^{+2.8}_{-3.8}$	0	0	$7.3^{+3.8}_{-2.8}$	0
HP 2-jet (112)	0	0	$15.0^{+7.5}_{-5.7}$	$85.0^{+5.7}_{-7.5}$	0	0	0
HIG (282)	0	0	0	0	$100.0^{+0.0}_{-0.9}$	0	0
DPP (274)	0	0	0	0	0	$100.0^{+0.0}_{-0.9}$	0
RES NW (390)	0	0	0	0	0	$1.7^{+1.7}_{-0.9}$	$98.3^{+0.9}_{-1.7}$
RES HW (219)	0	0	0	0	$0.3^{+1.5}_{-0.2}$	$5.7^{+3.7}_{-2.5}$	$94.0^{+2.6}_{-3.7}$

Table 4: Breakdown of the Production Mode Classifier output, for pseudo-data samples with 10, 100 or 1000 events, averaged over all LLP and parent particle masses simulated for each model. Entries in row i, column j show the percentage of samples from model i classified as model j. 95% confidence intervals are shown for non-zero classification accuracies, accounting only for statistical uncertainty due to the limited number of samples tested. The number of samples tested for each model is listed in brackets in the first column.

Parameter Estimation

- The second task for which we would like to estimate the prospective capabilities of MATHUSLA and CMS is the measurement of the properties of the newly discovered BSM particles.
- We assume the LLP production mode has been correctly identified.
- We find estimators for m_{LLP}, or $\frac{m_{LLP}}{m_{parent}}$ and m_{parent} if applicable and perform maximum likelihood estimation on simulated samples with given N_{obs} to find the best-fit masses.
- The spread of best-fit masses gives an estimate of MATHUSLA's precision for BSM particle mass measurements.
- The LLP boost is highly (inversely) correlated with m_{LLP} in models with one BSM mass, and correlated with m_{LLP}/m_{parent} in models with two BSM particles.
- For the Charged Current, Heavy Parent, and Heavy Resonance models, where there is a parent particle with an unknown mass, another observable using information from the main detector is required.
- For the Charged Current model, the transverse momentum of the associated lepton is correlated with m_{parent}.
- For the Heavy Parent model, the scalar sum of jet transverse momentum H_T is correlated with m_{parent}.
- For the Heavy Resonance model, the number of jets with $p_T > 20$ GeV is correlated with m_{parent}.

Model	x_1	x_2	N_{obs}	$\frac{m_{LLP}}{m_{parent}}$ or m_{LLP} precision	m_{parent} precision
B decay	$\log_{10}(b_{LLP})$	-	10	$0.3-0.7$	-
			100	$0.1-0.2$	
			1000	$\lesssim 0.05$	
Charged Current		p_T^ℓ	10	0.1	0.1
			100	0.05	0.02
			1000	0.01	0.01
Heavy Parent		H_T	10	0.2	0.2
			100	0.05	0.05
			1000	0.01	0.01
Exotic Higgs decay		-	10	0.15	-
			100	0.05	
			1000	0.01	
Direct Pair Production		-	10	$0.3-0.5$	-
			100	$0.1-0.2$	
			1000	$.03-.07$	
Heavy Resonance (narrow)		n_{jet}	10	0.07	
			100	0.02	
			1000	0.01	0.15
Heavy Resonance (wide)		n_{jet}	10	0.12	
			100	0.05	
			1000	0.02	0.15

Table 5: Summary of parameter estimation performance for all of the simplified models we consider. The variables x_1, x_2 chosen to estimate BSM particle masses are listed. The precisions shown are the characteristic standard deviation/mean of best-fit masses for benchmark BSM particle masses that are approximately representative for each model.

Conclusion

Many well-motivated scenarios for BSM physics include long-lived particles, and it is important that the experimental search program for long-lived particles continue to be developed and expanded. The proposed MATHUSLA detector represents a vital part of that program, able to probe parameter space inaccessible by any other experiment. Allowing MATHUSLA to act as a Level-1 Trigger for CMS is required to take full advantage of both detectors' potential.

For heavy LLPs, an accurate diagnosis at the simplified model level can be achieved > 90% of the time with only 100 observed events, ≈ 98% of the time with 1000 observed events. Similar performance is possible for lighter LLPs, except for the Heavy Parent and Charged Current models with squeezed spectra $m_{LLP} \sim m_{parent} < 100$ GeV, where classification fails because the associated objects being used to identify the production mode become too soft. With similar statistics, the underlying parameters of the simplified model, like LLP and parent particle mass, can be measured with ~ 10% precision or better in most cases.

This performance is achieved with extremely simple cuts and analyses using robust, physically motivated features of LLP production events. Further work is sure to improve on our demonstrated classification accuracy and measurement precision. Our methods are applicable not just to MATHUSLA and CMS, but also to other external LLP detector proposals, or even LLPs discovered using LHC main detectors alone. This emphasizes not only the great discovery potential of new LHC detectors like MATHUSLA [3], CODEX-b [11] or FASER [12], but also shows that in the event of a discovery, however it took place, the origin of Long-Lived Particles can be uncovered in great detail.

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