Diagnosing Hidden Sectors with MATHUSLA and HL-LHC

(MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles)

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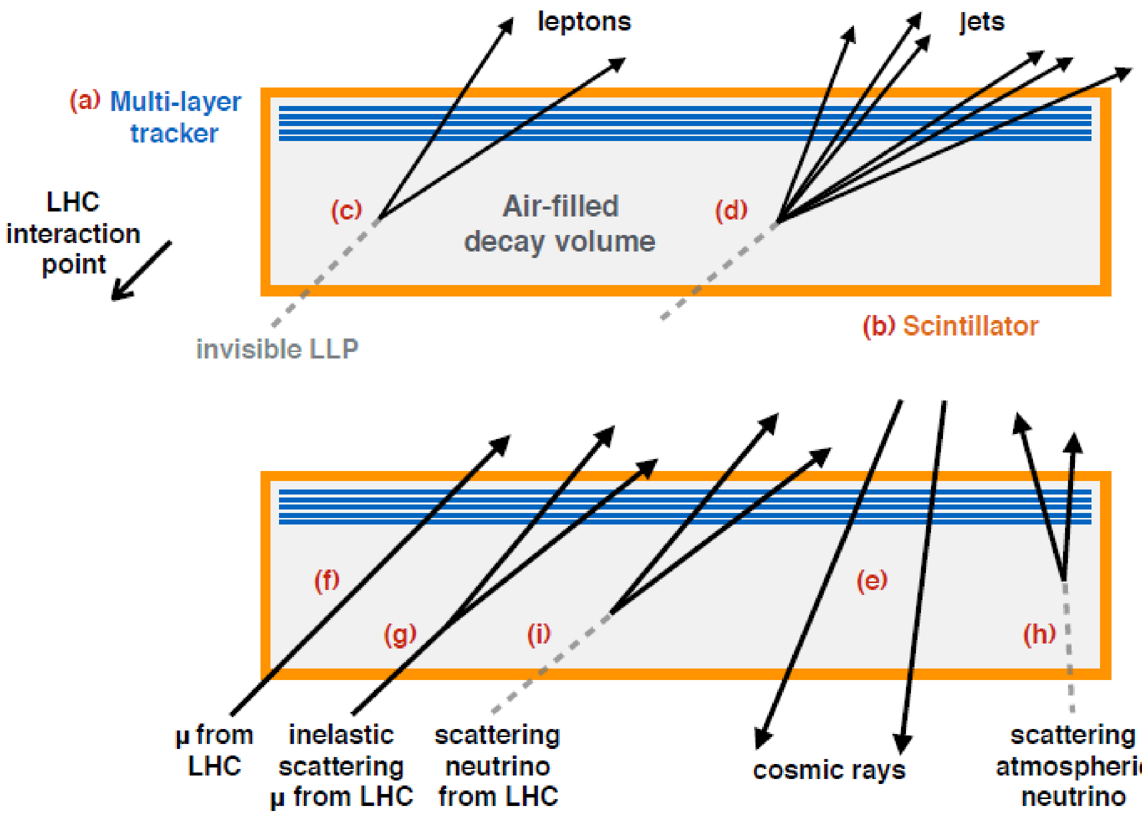
Based on work in progress with David Curtin

Background: Long-lived Particles (LLPs)

- Dark matter, baryon asymmetry, the hierarchy problem, and neutrino masses all point to BSM physics.
- The LHC has not yet yielded any observations of BSM particles.
- The LHC was designed to search for heavy particles that promptly decay to visible SM final states.
- There are a variety of BSM models that motivate the search for long-lived BSM particles.
- LLP searches in ATLAS/CMS are difficult in the long lifetime regime because of low acceptance.

MATHUSLA

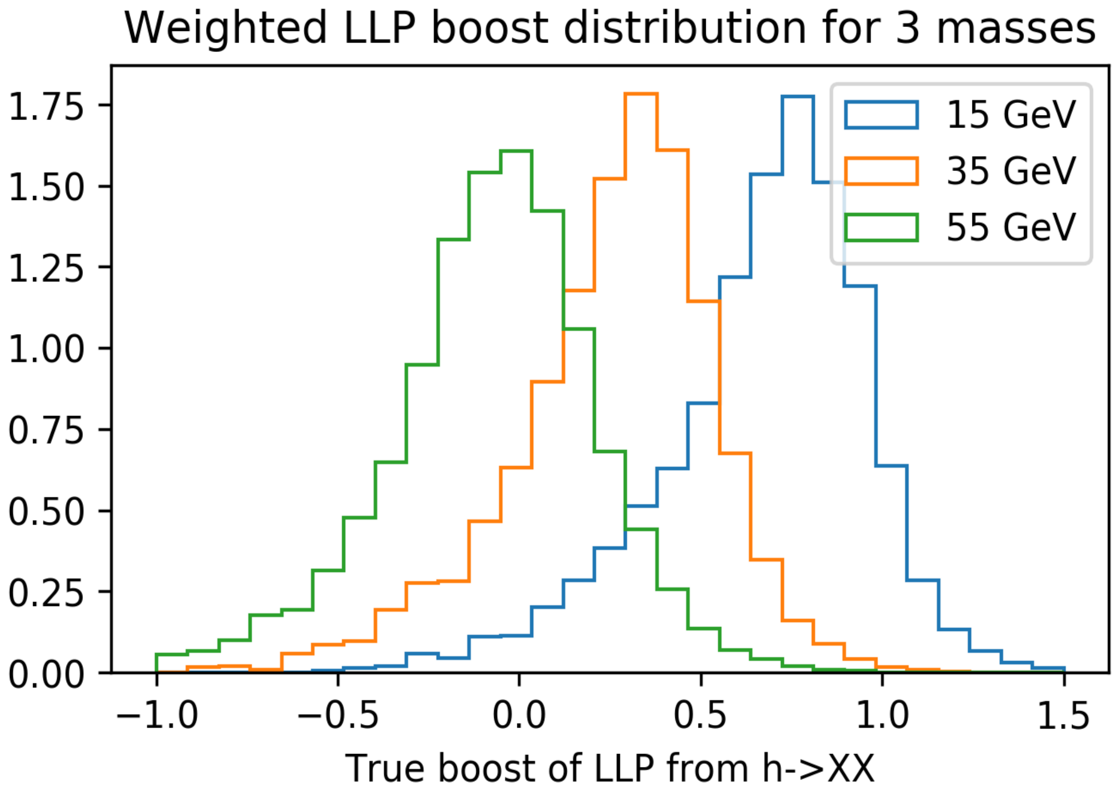
- MATHUSLA is a proposed large-volume displaced vertex detector, to be located on the surface above CMS.
  Chou, Curtin and Lubatti, 1606.06298
  Alpigiani et al., 1811.00927
- Its purpose is to detect neutral, ultra long-lived particles with decay lengths up to $O(10^7 \text{ m})$.
- Search for displaced vertex events originating from LHC interaction point.
- Near zero background allows for sensitivity several orders of magnitude greater than ATLAS/CMS.



Top: LLP decay signal.
Bottom: Main backgrounds.
Alpigiani et al. 1811.00927

Determining LLP Mass with MATHUSLA

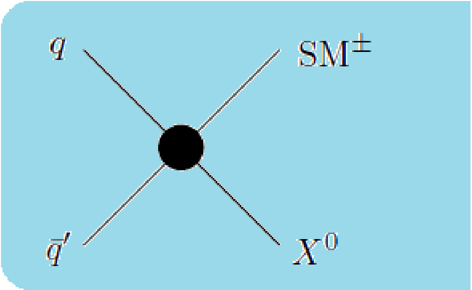
- One of the most well-motivated models of LLP production is by exotic Higgs decay.
- Under this production mode at the HL-LHC, the distribution of LLP boosts is highly correlated with the LLP mass, providing a method to easily evaluate LLP mass.
- Boost $b = \gamma v = |\vec{p}|/m$.
- Using the geometric information MATHUSLA collects, it is possible to determine the velocity of the long-lived particle, and therefore estimate its mass.



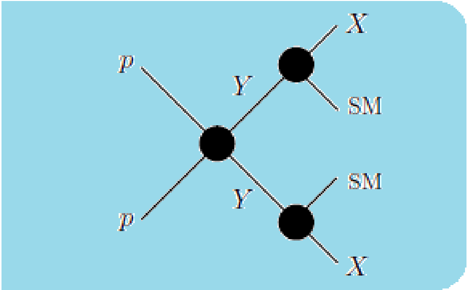
Curtin & Peskin, 1705.06327

LLP Production: Simplified Models

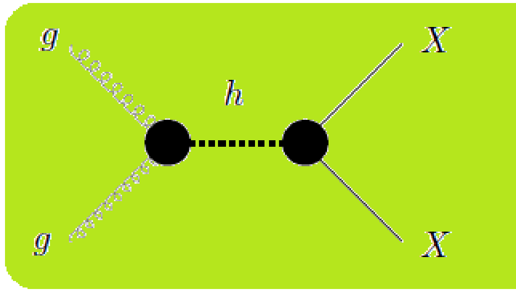
- Exotic Higgs decay is not the only scenario for LLP production.
- Simplified models/LLP production topologies from LHC-LLP whitepaper.
- LLP velocity from MATHUSLA identifies production event in HL-LHC.
- Assuming MATHUSLA triggers CMS, can we use MATHUSLA + HL-LHC main detector (CMS) information to identify LLP production mode and BSM particle masses?



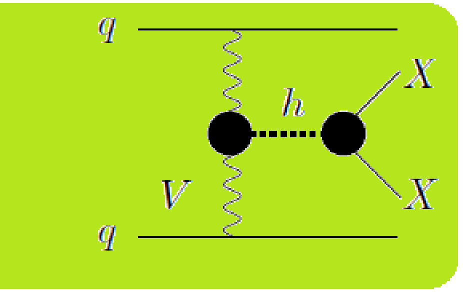
Charged Current (e.g. W')



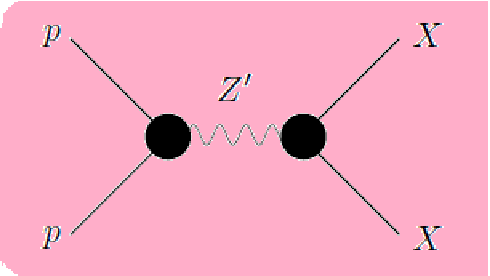
Heavy Parent



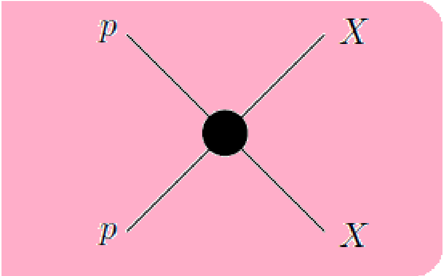
Higgs: Gluon Fusion



Higgs: Vector Boson Fusion



Heavy Resonance



Direct Pair Production

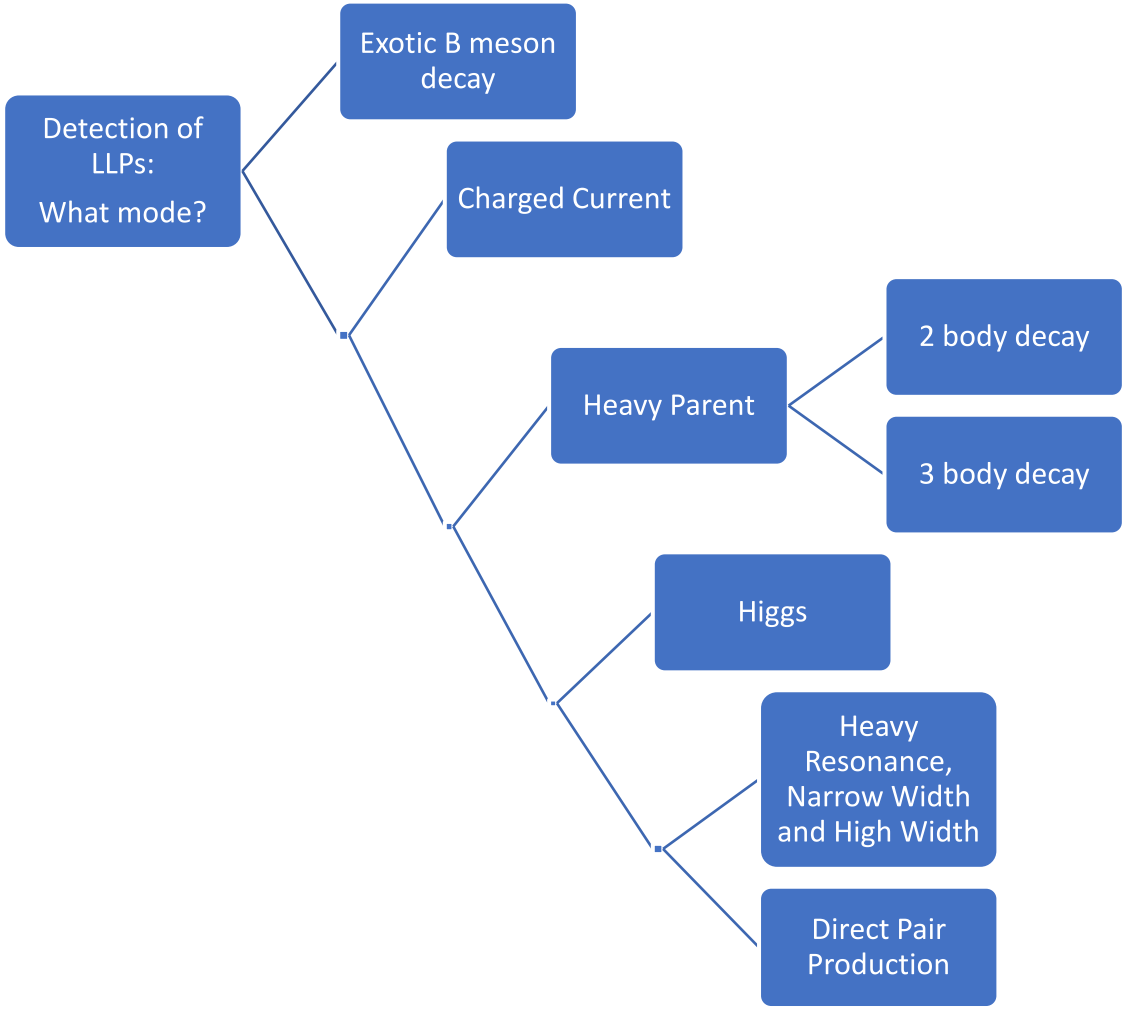
(Also exotic meson decay)

Alimena et al. 1903.04497

Simulation

- Used the MadGraph 5 event generator to simulate large samples of events for each simplified model at the HL-LHC.
- Showering and hadronization with Pythia 8, CMS detector simulation with Delphes.
- No detector simulation for MATHUSLA. Want to factor out the dependence on the LLP decay.
- Produced events for a variety of masses for each simplified model.
- Will demonstrate how a simple decision tree can identify simplified model responsible for LLP production.

Classification



Classification Strategy

- Cuts on sample-level variables were used to define the classification algorithm.
- Pseudo-data samples of 10, 100 and 1000 events from each model were run through the classifier. Each sample was assigned to one of the simplified models.
- The variables chosen to cut on took advantage of the differences between the physical processes in each simplified model.
- These included the fraction of events with a hard lepton, the fraction of events with jets satisfying particular kinematic constraints, and width of the detected LLP boost distribution.

Classification Results

- The fraction of pseudo-data samples classified correctly was averaged over the simulated parameter space of each simplified model.
- >90% accuracy can be achieved with only 100 events.
- For the CC and HP models, the incorrectly classified samples have $m_{parent} < 100$ GeV.

N_{obs} /Model	BB	CC	HP	HIG	DPP	RES
10	98	94	91	36	48	71
100	100	98	91	90	98	93
1000	100	98	93	100	100	98

Percentage of samples correctly classified for each model

Parameter Estimation Strategy

- We assume correct model classification.
- We performed a maximum likelihood fit on pseudo-data samples to estimate the LLP mass and, if applicable, parent particle mass.
- For one-parameter models, the LLP boost was used to estimate m_{LLP}.
- For two-parameter models, the LLP boost was used to estimate m_{LLP}/m_{parent}.
- For models with associated SM objects from the LLP production process, kinematic variables combining the information from MATHUSLA and CMS were used to estimate m_{parent}.

Parameter Estimation Results

- Due to computing constraints, the precision of model parameter estimation was carried out for a limited number of selected BSM particle masses.
- For the heavy parent, charged current, and Higgs decay models, the LLP and (if applicable) parent particle best-fit mass distributions have precision $\frac{\sigma}{\mu} \approx 0.05$ at $N_{obs} = 100$.
- For the exotic B decay and direct pair production models, the LLP best-fit mass distributions have $\frac{\sigma}{\mu} \approx 0.1$ at $N_{obs} = 100$.
- For the heavy resonance model, $\frac{m_{LLP}}{m_{parent}}$ can be estimated with 10% precision at $N_{obs} = 100$, but estimating m_{parent} requires $N_{obs} \approx 1000$.

Conclusions

- With 100 observed LLPs correctly identified with their production events, the production topology can be accurately classified from among the simplified models described with >90% probability.
- With the same number of events, the LLP mass (or parent mass and LLP/parent mass ratio if applicable) can be estimated with $\approx 5 - 20\%$ precision in many cases, depending on the model and true mass values.
- Using MATHUSLA to trigger CMS can greatly increase our ability to diagnose the nature of new physics at MATHUSLA.

References

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