A Proposed Detector for Long-Lived Particles at High-Luminosity LHC

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Outline

- Motivation: Long-lived particles (LLP) at HL-LHC
- MATHUSLA experiment
  - Experiment concept
  - Simulation and reconstruction
  - Signals and backgrounds
  - Sensitivity
  - Detector design and R&D
- Summary & Outlook

Motivation: Long-lived particle at LHC

The fundamental mysteries (DM, hierarchy, neutrino masses, …) require the existence of physics **Beyond the Standard Model (BSM), which motivates undiscovered neutral LLPs that are invisible to LHC detectors**

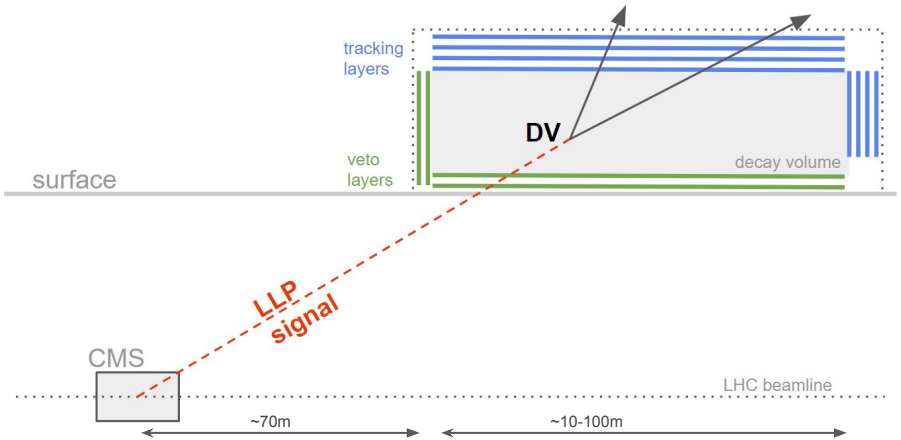
1. **BSM neutral LLPs** are highly theoretically motivated
   - **Top down**: LLPs naturally arises in various BSM theories
   - **Bottom up**: LLPs occur in the SM (e.g. muons), and can occur via similar mechanisms in BSM theories
2. **Hard to detect in LHC main detectors**
   - Most LLPs escape the detector if $c\tau >>$ *detector size (~10m)*
   - Tiny fraction of LLPs that decay in the detector get swamped by backgrounds

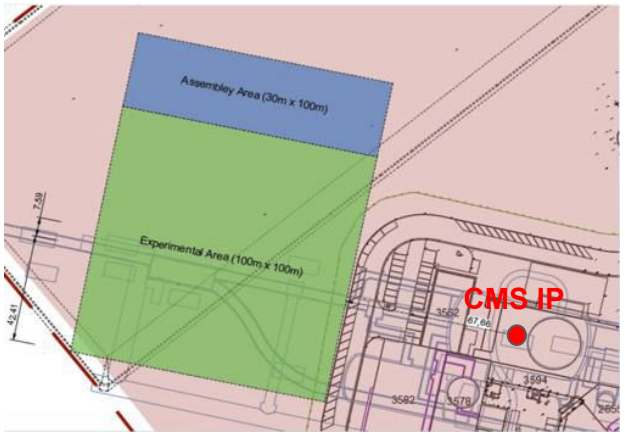
MATHUSLA concept

MAssive Timing Hodoscope for Ultra Stable neutraL pArticles

Proposed external LLP detector for HL-LHC

- Surface detector located above CMS
- **Large decay volume filled with air** with scintillator layers for tracking
  - LLPs decaying inside MATHUSLA are reconstructed as **displaced vertices** (DV)
- Target for LLPs with lifetime up to the Big Bang Nucleosynthesis (BBN) limit (10^7–10^8m)

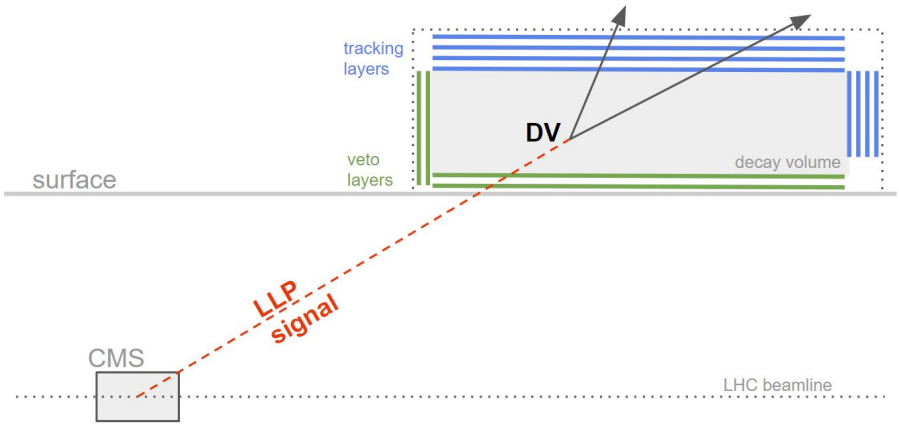


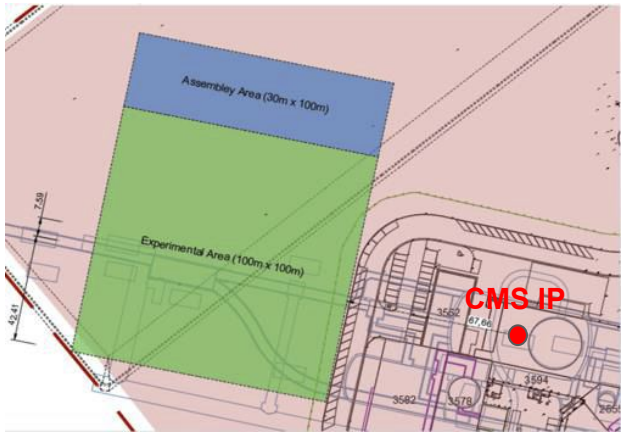


MATHUSLA concept

MATHULSA solves the challenges of LLP detection in LHC main detectors

- Two to three **orders more sensitive** to longer lifetime (Further away from IP)
- Aiming for **~zero background** analysis (~100 m of rock shielding)

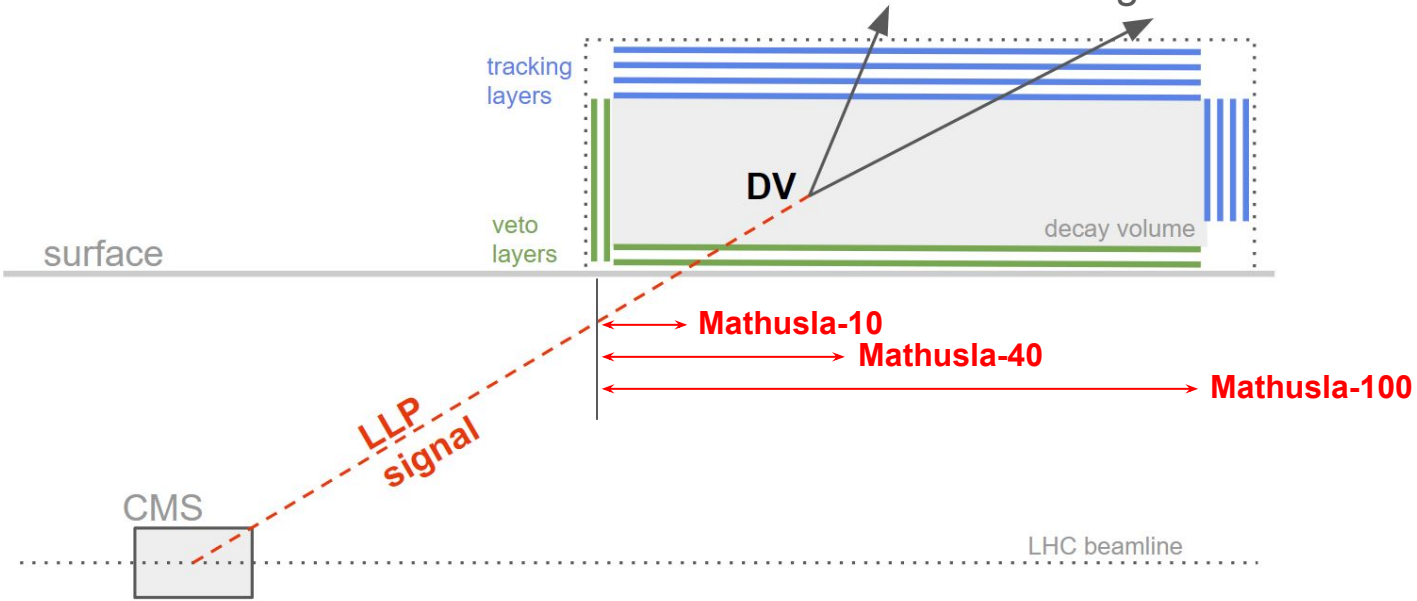




MATHUSLA concept

Staged construction & commission

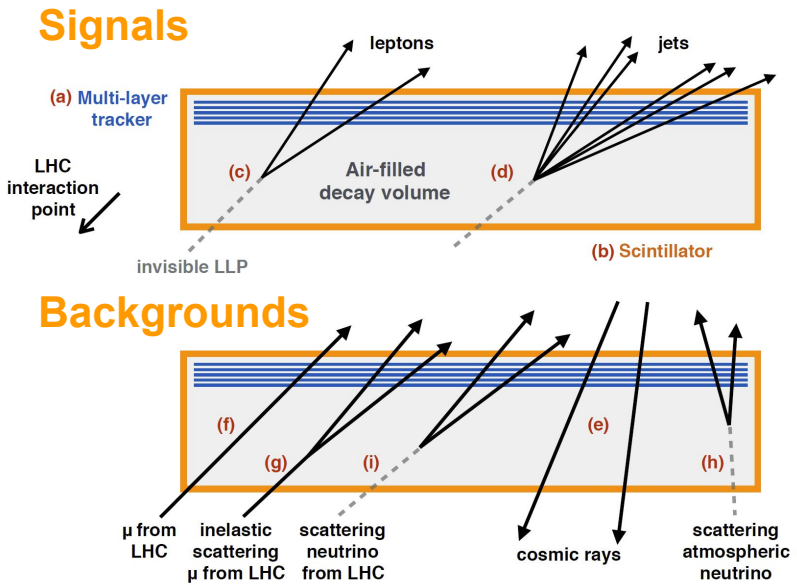
- Scintillator layers are grouped into vertical tower modules with ~10m^2 each. A module can be constructed on the side while the other modules are taking data.



Detecting LLPs – Signal and Background

Signal: displaced vertices from LLPs decaying inside MATHUSLA. Integration into CMS trigger system will associate MATHUSLA LLP candidate events with CMS detector activity.

Near-zero backgrounds for neutral LLP decays can be achieved by geometry & timing cuts.

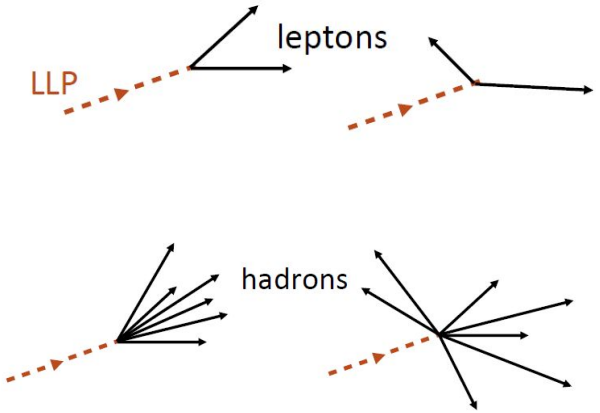


Detecting LLPs – Signal

MATHUSLA can't measure particle momentum or energy, but can measure LLP boost through track geometry.

Identifying LLPs:

- MATHUSLA Standalone: Determination of LLP decay mode and boost with assumptions of production mode.
- MATHUSLA+CMS: This allows further determination of LLP production mode, mass range and spin.



Simulation and reconstruction

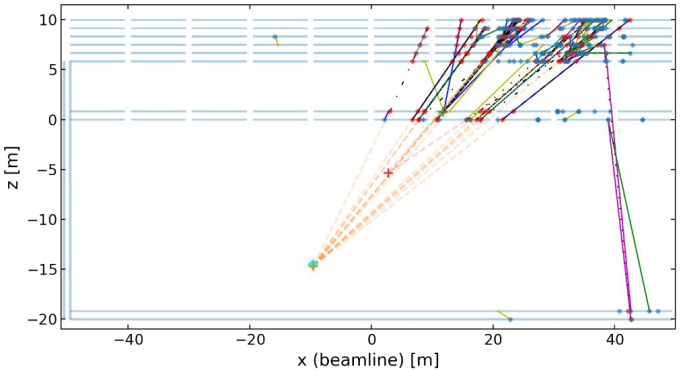
Simulation: two packages are developed

- **FastSim**, geometry-only detector simulation, used in the sensitivity study on page 10
- **Full Geant4 simulation**
  - The sensitivity study using full simulation is underway.

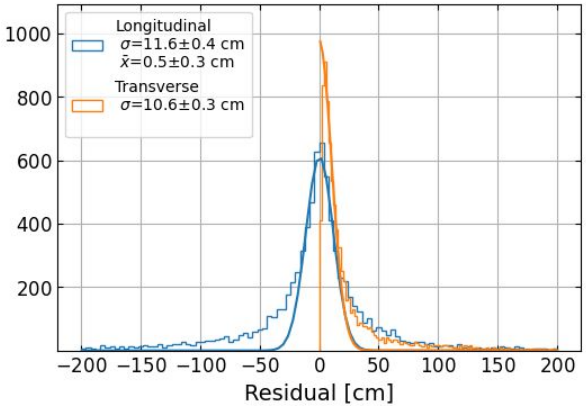
Reconstruction:

- Kalman filter based track and vertex reconstruction

Example of a simulated adronically decaying LLP event (H→XX, X→bbbar)



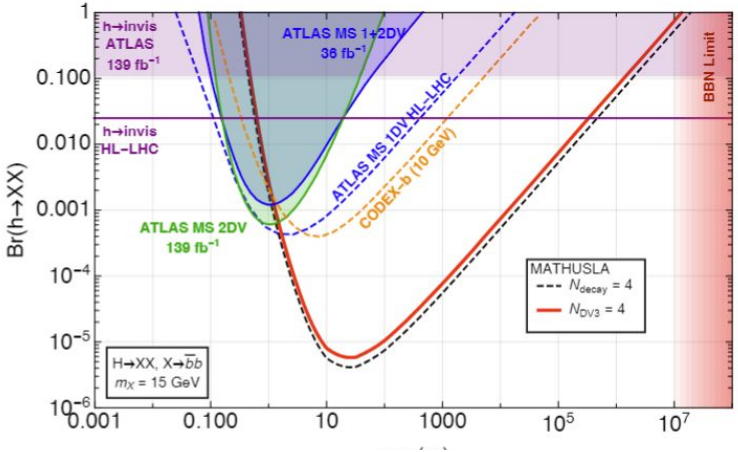
Reconstructed vertex resolution

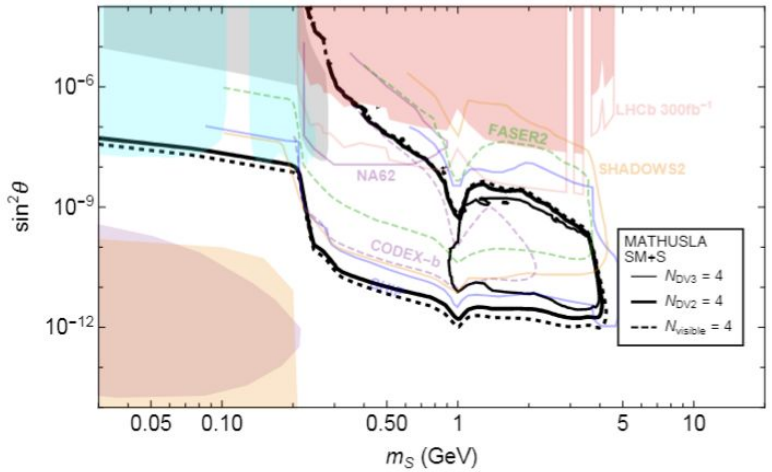


Sensitivity

Primary physics case: hadronically decaying O(10-100 GeV) LLPs.
e.g., LLPs in exotic Higgs decays.

Secondary physics case: GeV-scale LLPs.
e.g, scalar LLPs in the SM+S model



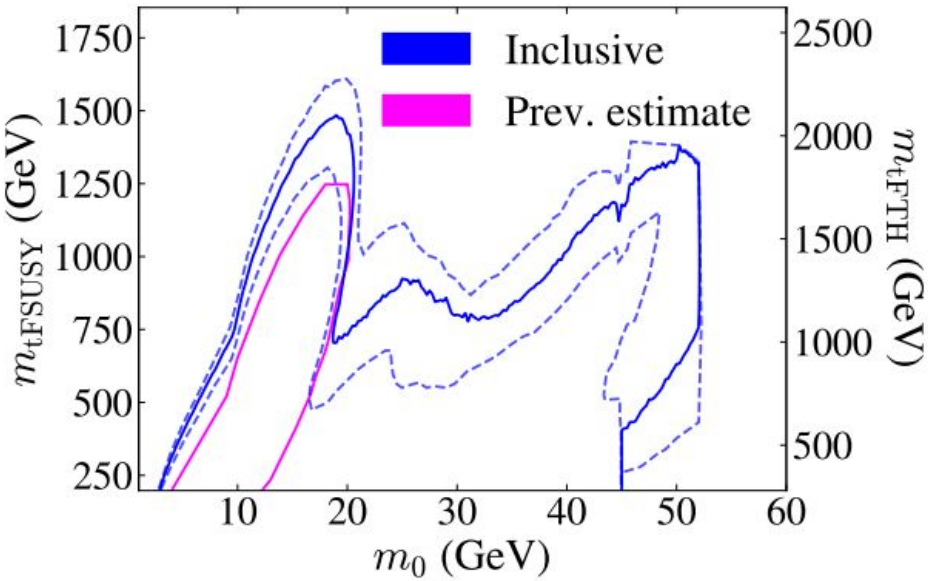


- Up to 1000x better sensitivity
- Assuming 100m x 100m x 20m decay volume (**Mathusla-100**). Sensitivity scales roughly with area. The smaller design (MATHUSLA-40) has reduced reach by up to one order of magnitude.

Sensitivity

Sensitivity estimation improved with better modelling: arxiv:2310.13731

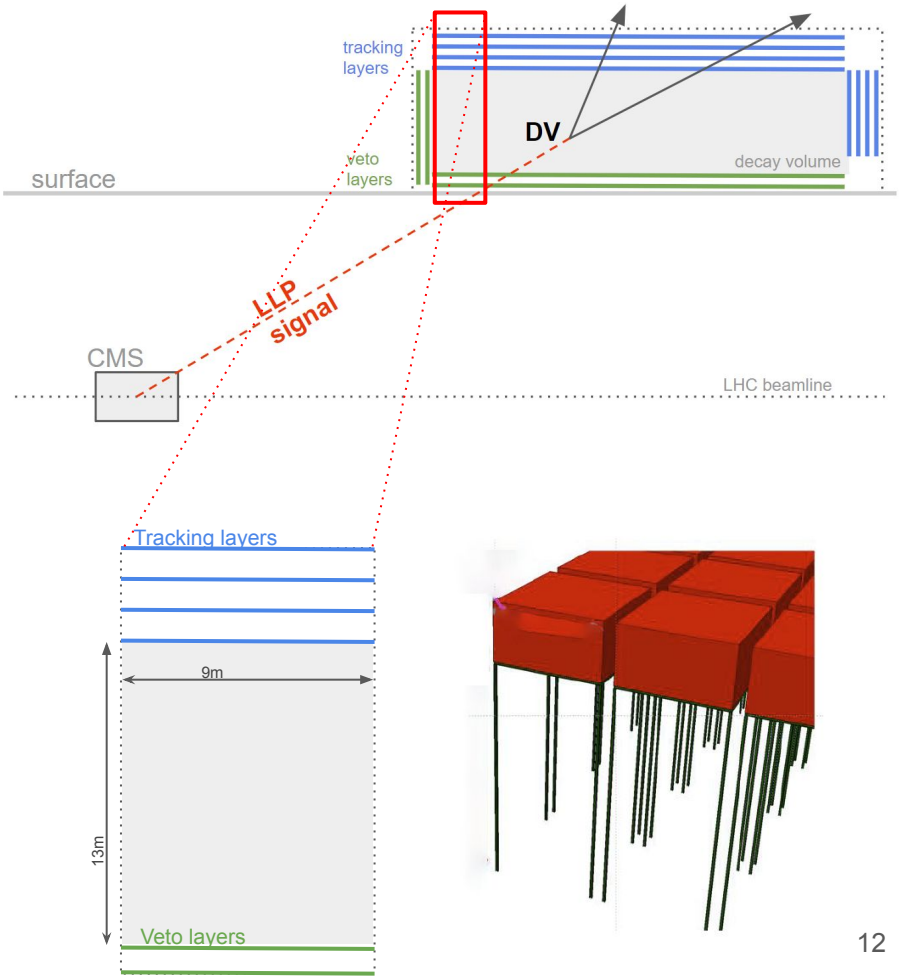
Model: dark glueballs produced in exotic Higgs decays. MATHUSLA sensitivity estimates for neutral naturalness presented in 1806.07396 is updated.



Detector design

Large scale tracker with veto layers

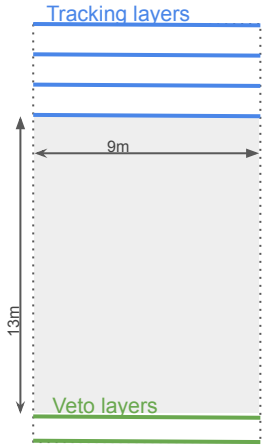
- **Modular** design facilitates staged construction & commission
  - 1 module: MATHUSLA-10
  - 16 modules: MATHUSLA-40
- Each tower module covers **9x9 m area**, with two veto layers and four tracking layers. The height of decay volume is limited by the CERN building height.
- Floor **veto layer** will be made hermetic by having additional tracker plane between modules. Wall veto layers will be constructed separately.



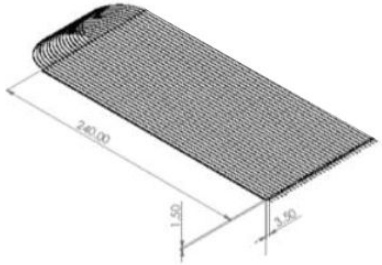
Detector design

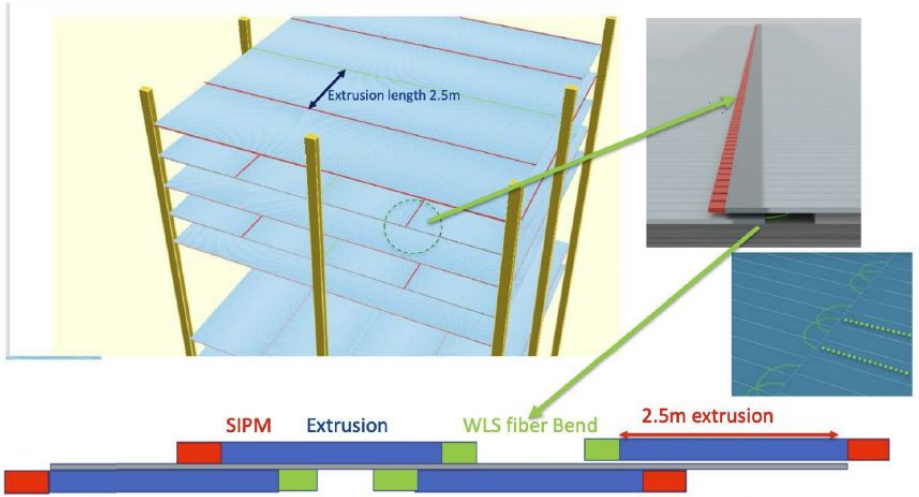
Large scale tracker with veto layers

- Also **modular within the** module:
  A module is made with tracker layers, which consist of **bar assemblies** that can be manufactured in lab.



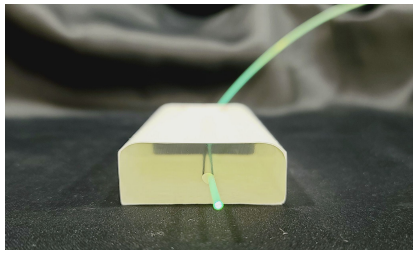
Bar assembly, 1.1m*2.7m



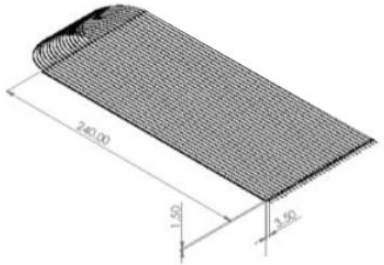


Detector design – Bar assembly

Extruded **scintillator bars** with **wavelength-shifting fibers** coupled to **silicon photomultipliers.**



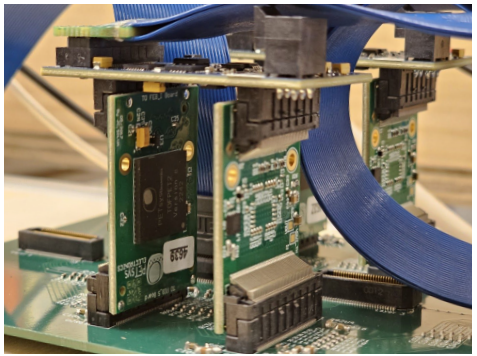
Bar assembly, 1.1m*2.7m

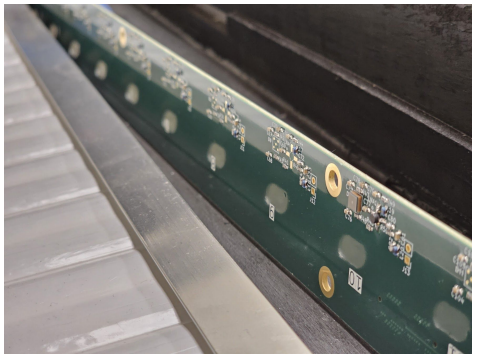


- **4D hit information** (x,y,z,t)
- **Optimized for cost** due to the large volume:
  - Each fiber loops through two bars
  - Read out on both ends. Position along the bar is derived from time difference.
- **Design requirement**:
  - **1 ns timing resolution.**
    - crucial for distinguishing upward/downward track to reject cosmic background
    - equivalent to 14 cm positional resolution

Detector design – data acquisition

Using commercial ASIC developed for PET scan with custom frontend.





ASIC: TOFPET2

- 64 channels of timing/energy readout per ASIC
- 40 Mevent/s throughput

Frontend:

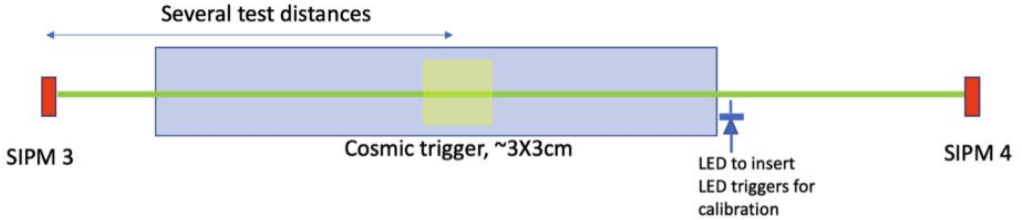
- Custom made preamplifier to keep the signal to noise ratio

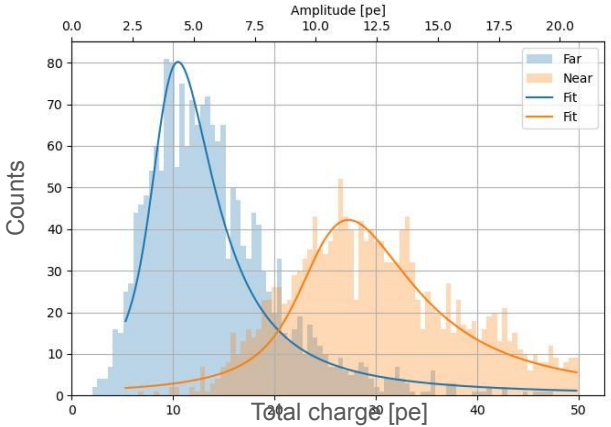
Trigger:

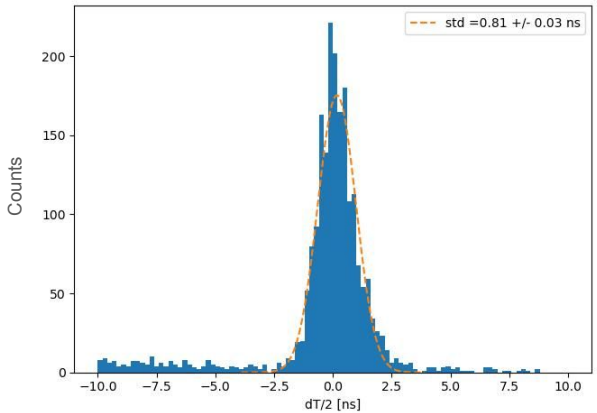
- **Trigger to CMS**: FPGA fast vertex reconstruction to meet CMS L1 latency budget
- **MATHUSLA alone**: software trigger that finds precise vertex and selects data from buffer for permanent storage

R&D efforts

- **Characterization** of scintillator, SiPM and WLS fiber shows that selected parts meet our design requirements.



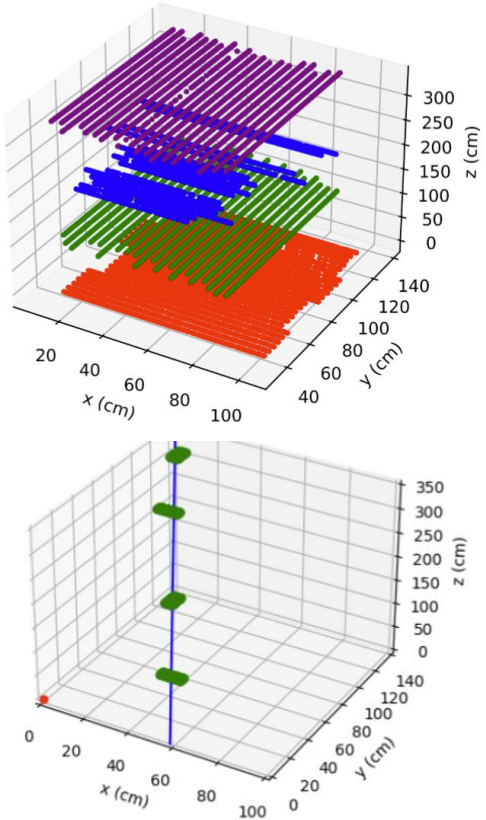




0.81 ns timing resolution achieved

R&D efforts

- **Two test stands** are constructed at *Uni Victoria* and *Uni Toronto*. Both are about 1m^2 with 4 layers



Cosmic ray events in the UVic MATHUSLA prototype, and a reconstructed muon track passing through all four layers

Summary

- **MATHUSLA can greatly improve the reach and versatility to probe LLP at HL-LHC**
- **Significant progress and ongoing efforts:**
  - Scintillator/fiber/SiPM characterization
  - DAQ and frontend design
  - Simulations of rare backgrounds
  - Track & vertex reconstruction software
- **Status and outlook**:
  - Lab-scale prototypes are being tested
  - Preparing for the production of a full-scale (9m*9m) “Tower0” demonstrator
  - The goal is to have the “Tower0” ready at the start of HL-LHC run

MATHUSLA collaboration

New collaborators welcome!

Canadian groups:

PI
- David Curtin (UToronto)
- Miriam Diamond (UToronto)
- Heather Russell (UVic)
- Steven Robertson (McGill)

Postdoc
- Caleb Miller, Tom Ren

Student
- Gabriel Owh, Alex Lau, Caleb Gemmell, Andrija Rasovic, Zhihan Yuan…

References

- MATHUSLA webpage: https://mathusla-experiment.web.cern.ch/
- MATHUSLA LHCC letter of intent: arXiv:1811.00927, 2009.01693
- MATHUSLA Physics Case: arXiv:1806.07396

- LLP decays in MATHUSLA: arXiv:2308.05860
- Analysis of Long Lived Particle Decays with the MATHUSLA Detector: https://arxiv.org/abs/1705.06327
- On the Origin of Long-Lived Particles: https://arxiv.org/abs/2007.05538
- Recent Progress and Next Steps for the MATHUSLA LLP Detector: https://arxiv.org/abs/2203.08126