MATHUSLA

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

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McDonald Institute

UNIVERSITY OF TORONTO

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
- **Teststand at UofT**
- 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**

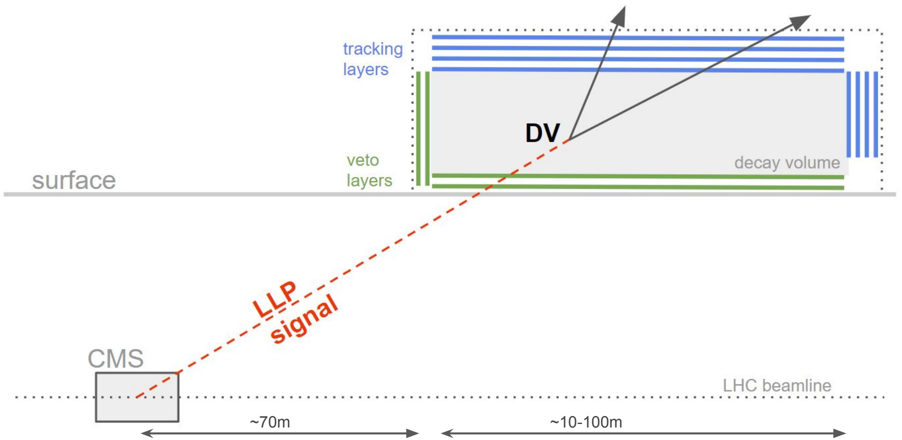
1. **BSM neutral LLPs** are highly theoretically motivated
    - **Top down**: LLPs naturally arises in various BSM theories
    - **Bottom up**: LLPs occur in the SM (e.g. muons), and can occur via similar mechanisms in BSM theories
2. **Hard to detect in LHC main detectors**
    - Most LLPs escape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

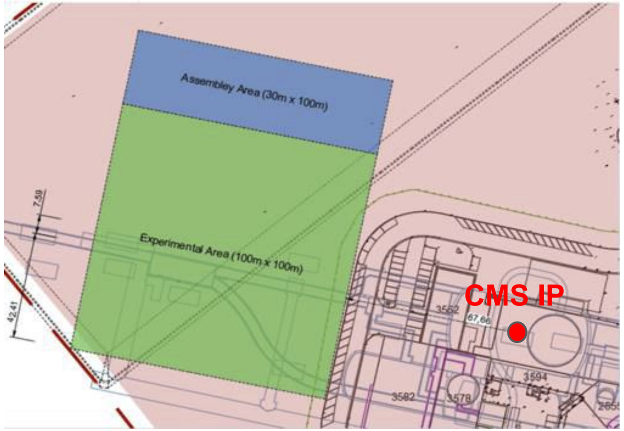
MATHUSLA concept

MAssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

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)

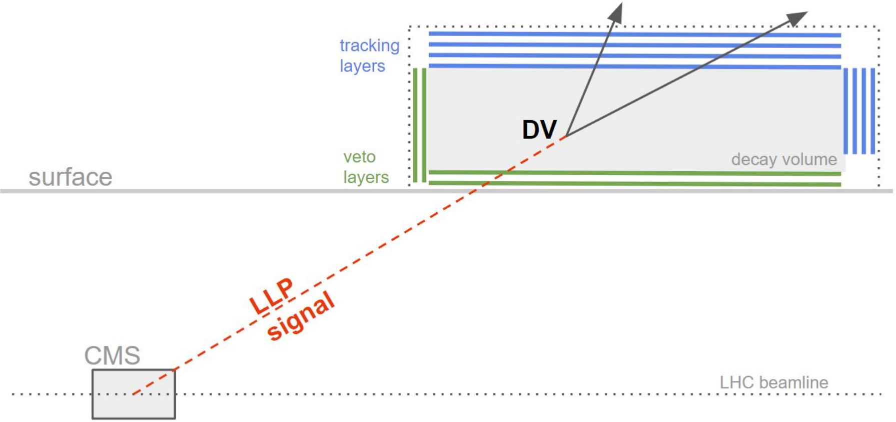


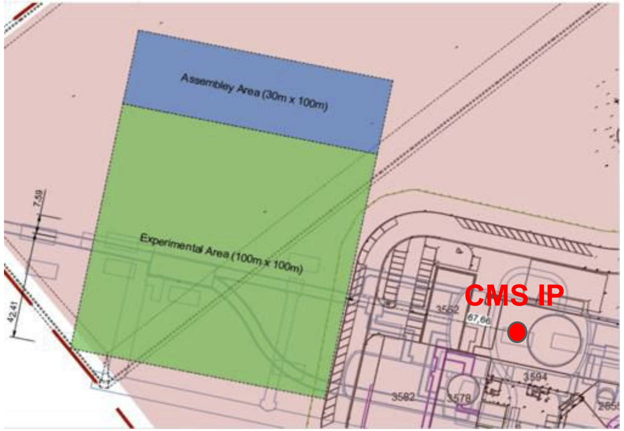


MATHUSLA concept

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)

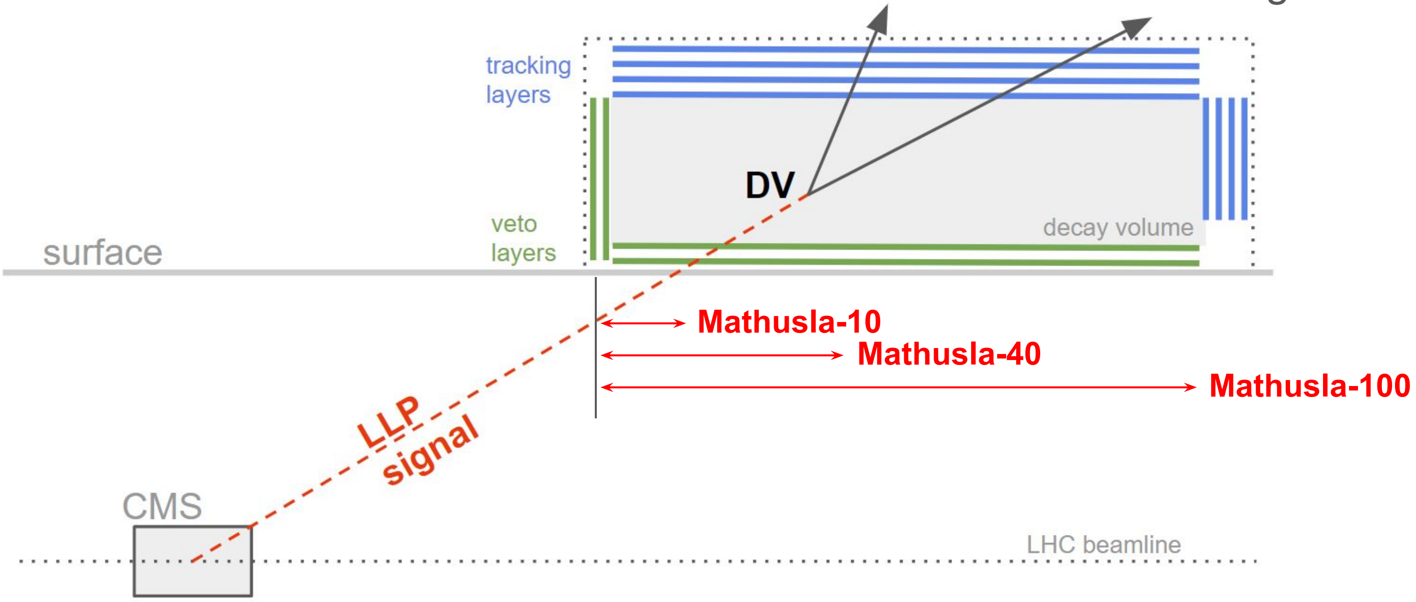




MATHUSLA concept

Staged construction & commission

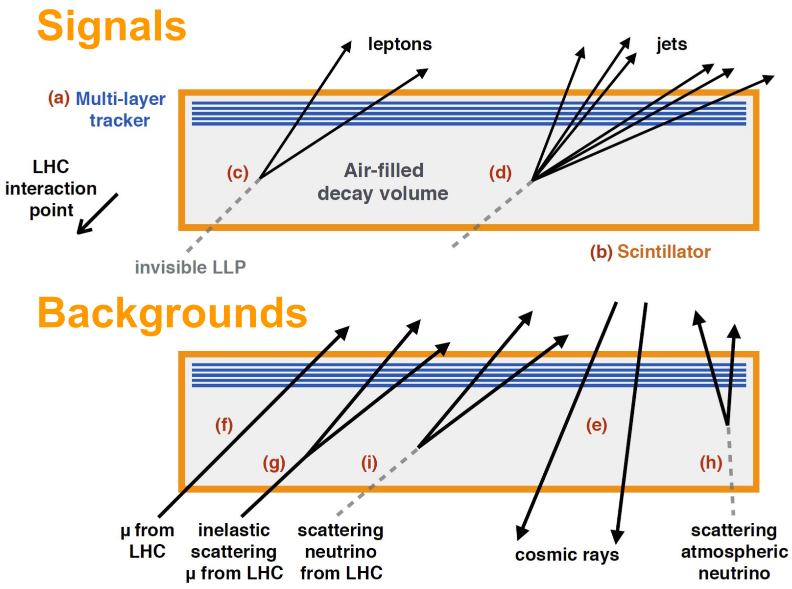
- Scintillator layers are grouped into vertical tower modules with ~10m*10m each. A module can be constructed on the side while the other modules are taking data.



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.

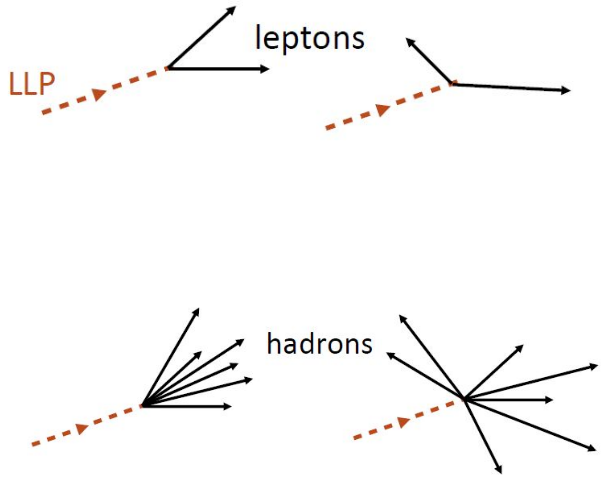


Detecting LLPs – Signal

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

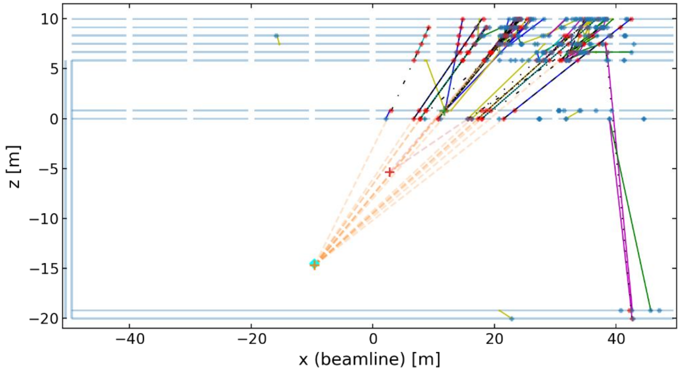
Simulation: two packages are developed

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

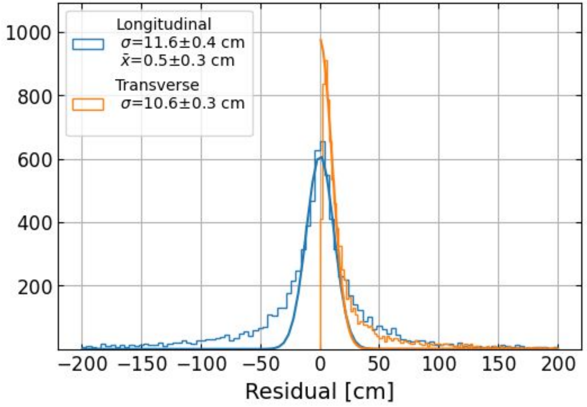
Reconstruction:

- Kalman filter based track and vertex reconstruction

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

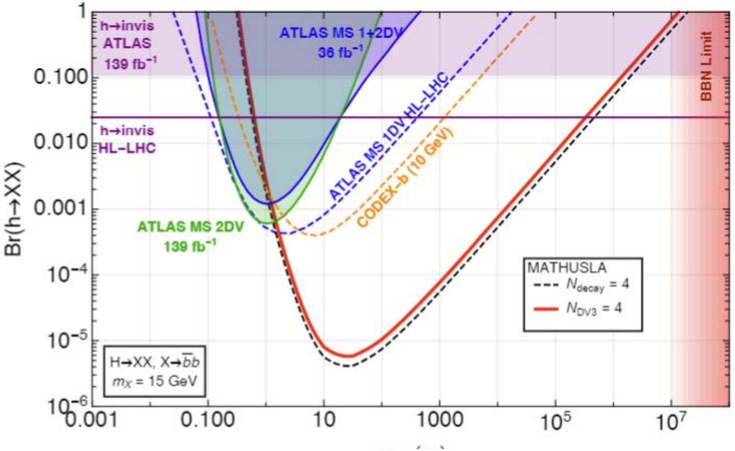


Reconstructed vertex resolution

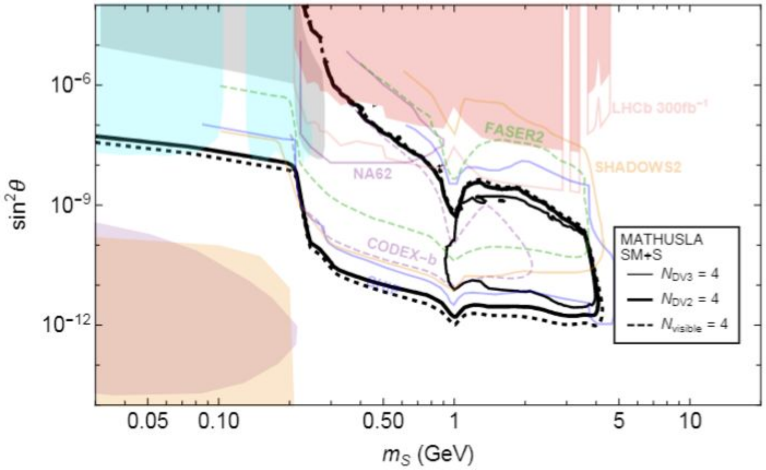


Sensitivity

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

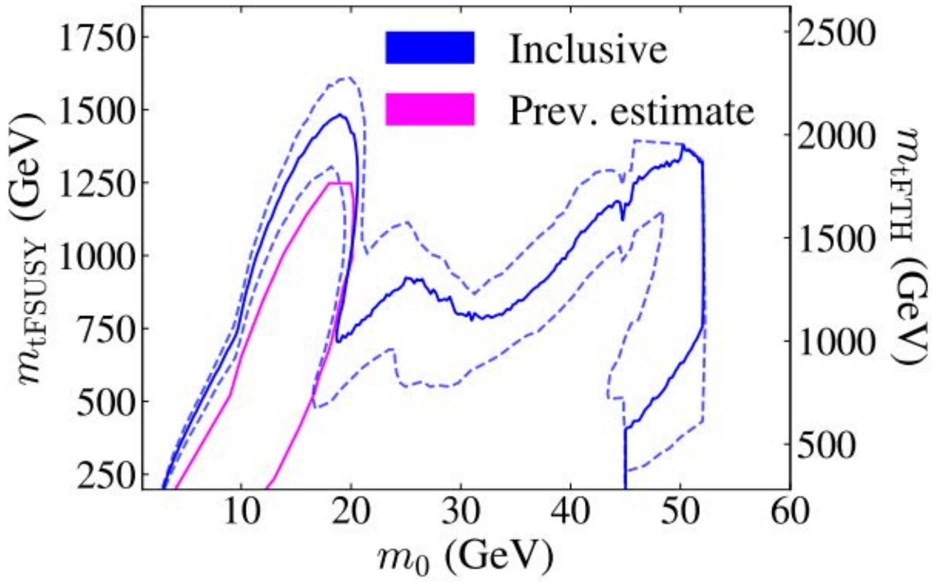


- Up to 1000x better sensitivity
- Assuming 100m x 100m x 20m decay volume (**Mathusla-100**). Sensitivity scales roughly with area. The smaller design (MATHUSLA-40) has reduced reach by up to one order of magnitude.

Sensitivity

Sensitivity estimation improved with better modelling: arxiv:2310.13731

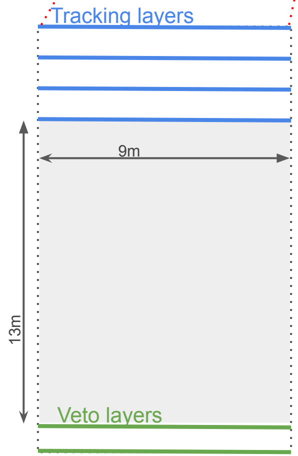
Model: dark glueballs produced in exotic Higgs decays. MATHUSLA sensitivity estimates for neutral naturalness presented in 1806.07396 is updated.

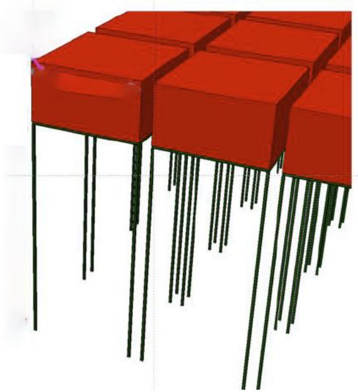


Detector design

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.

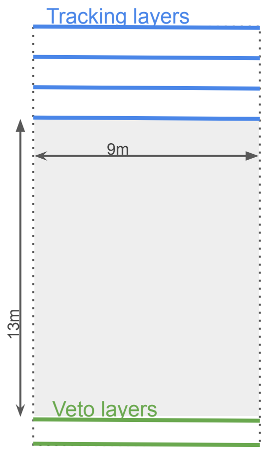




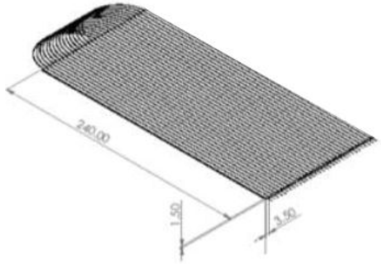
Detector design

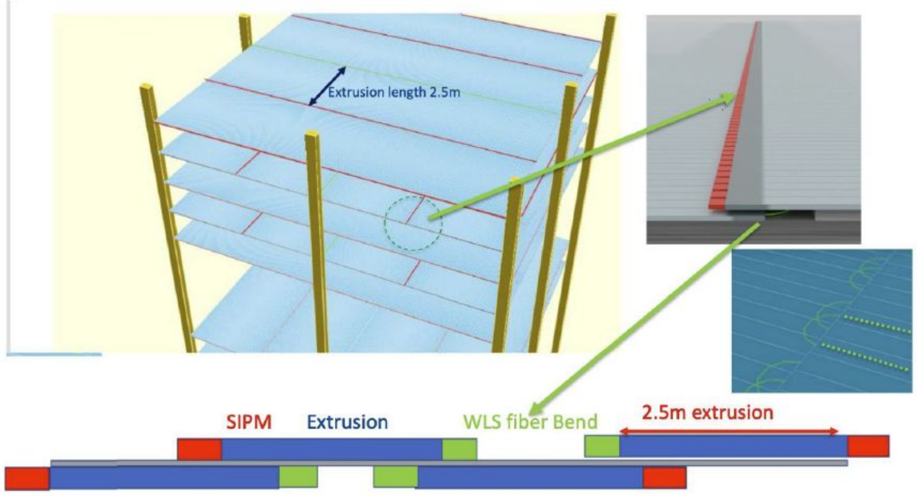
Large scale tracker with veto layers

- 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



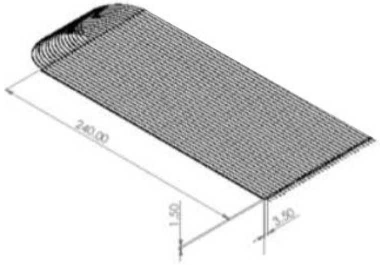


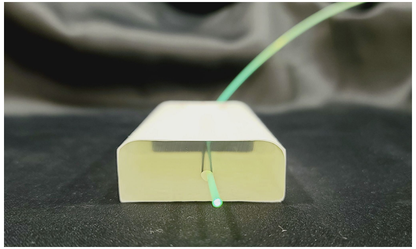
Detector design – bar assembly

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

- **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

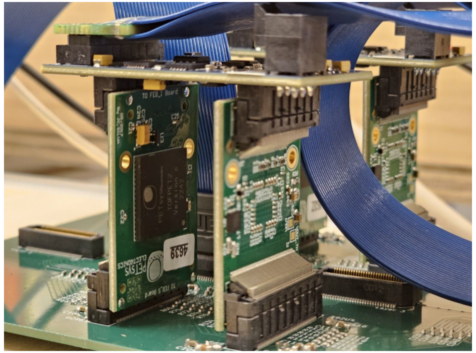
Bar assembly, 1.1m*2.7m

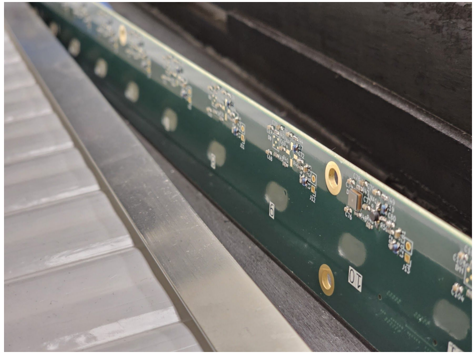




Detector design – data acquisition

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

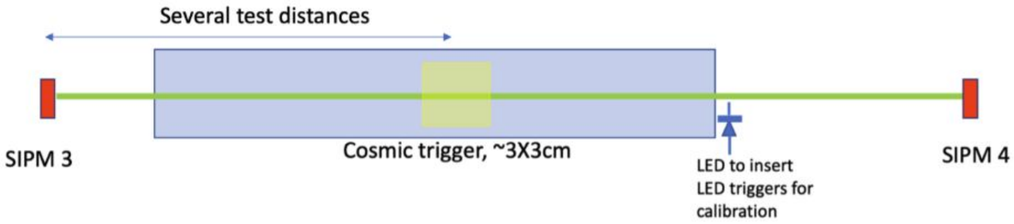
Trigger:

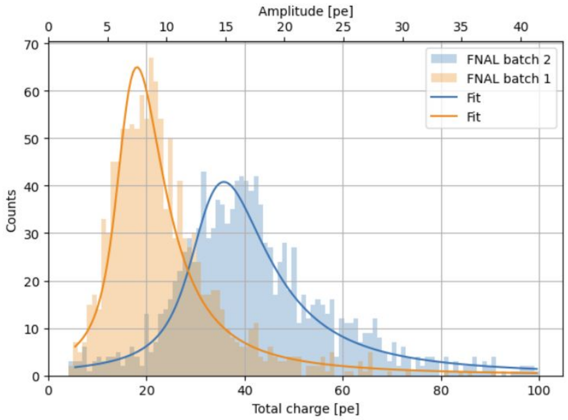
- **Trigger to CMS**: FPGA fast vertex reconstruction to meet CMS L1 latency budget
- **MATHUSLA alone**: software trigger that finds precise vertex and selects data from buffer for permanent storage

R&D efforts

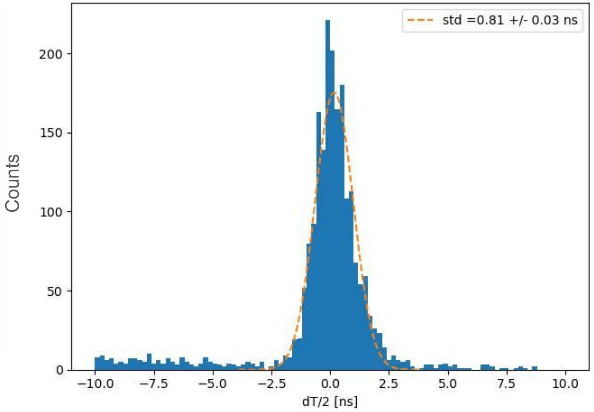
Characterization of scintillator, SiPM and WLS fiber shows that selected parts meet our design requirements.

Using cosmic muons,
- **Light yield:** 42 pe
- **Timing resolution**: 0.8 ns





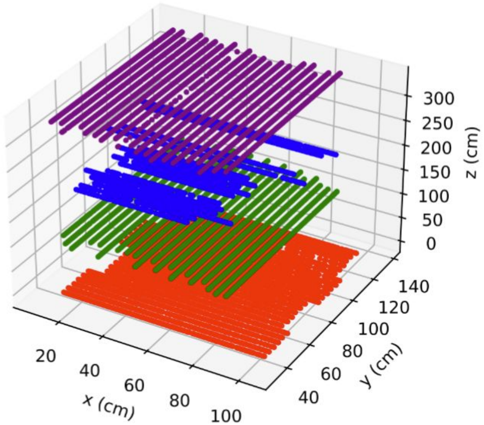
~42 pe average light output from cosmic muon

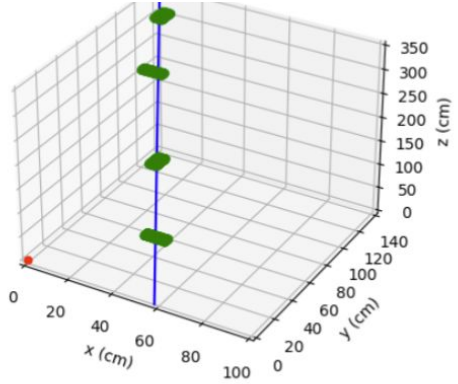


0.81 ns timing resolution achieved

R&D efforts

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



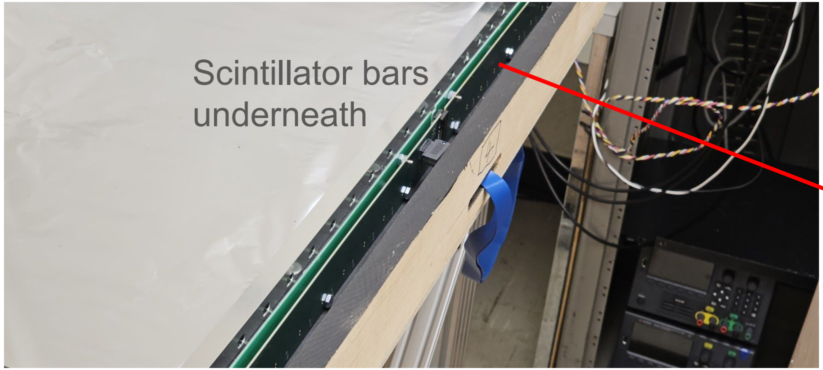


Cosmic ray events in the UVic MATHUSLA prototype, and a reconstructed muon track passing through all four layers

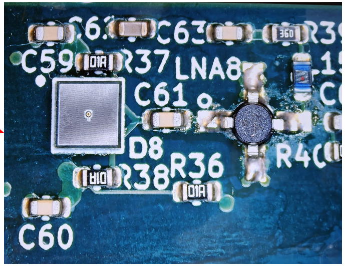
UofT test stand

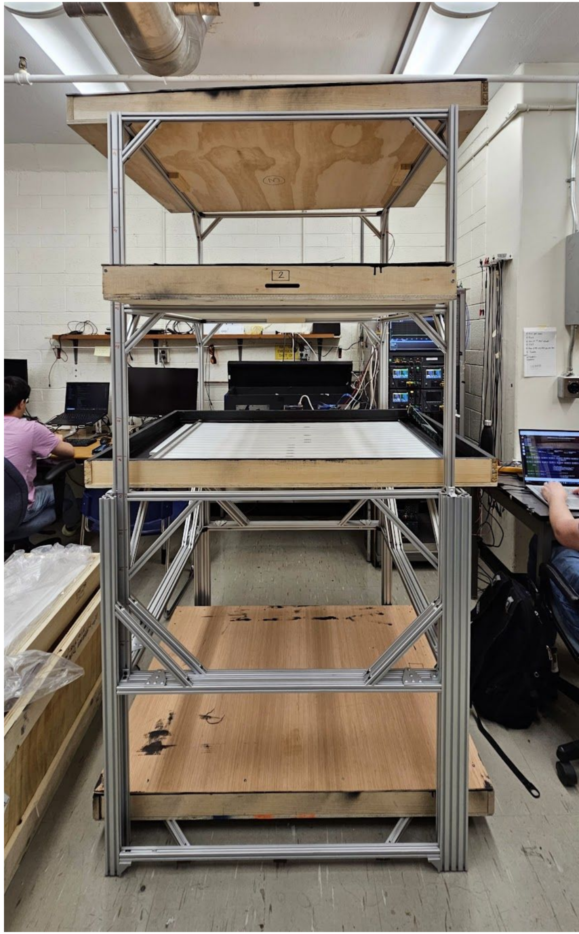
- **SiPM**: Hamamatsu S14160-3050, 3 mm
- **Preamp**: Custom made using MAR-8ASM+
  - 20 channels per board
- **Scintillator**: Fermilab extruded, 1cm*4cm*1m
- **WLS Fiber**: BCF-92 XL, 1.5 mm diameter

Light yield and timing resolution showed on page 16.



SiPM + preamp

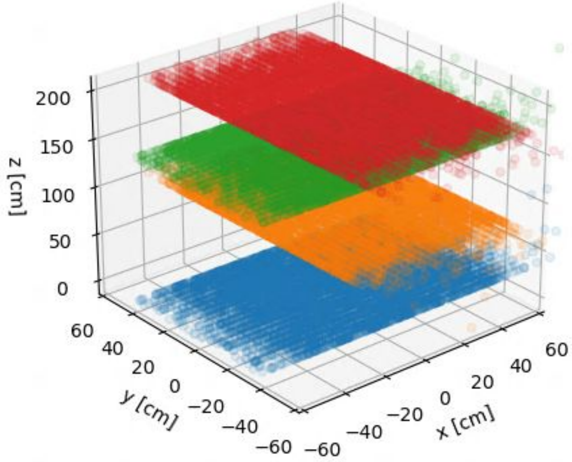


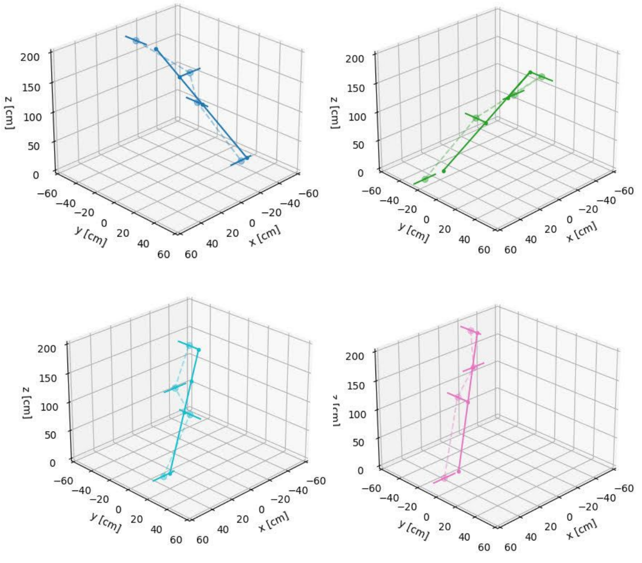


UofT test stand

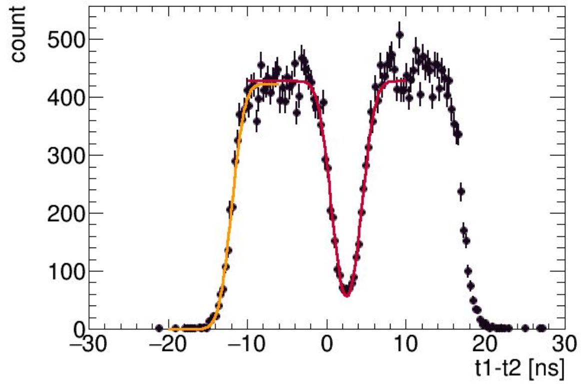
Cosmic muons measured by the test stand:

- Triggering on any two hits within 25 ns
- Kalman filter based track/vertx reconstruction.





Credit: Alex Lau



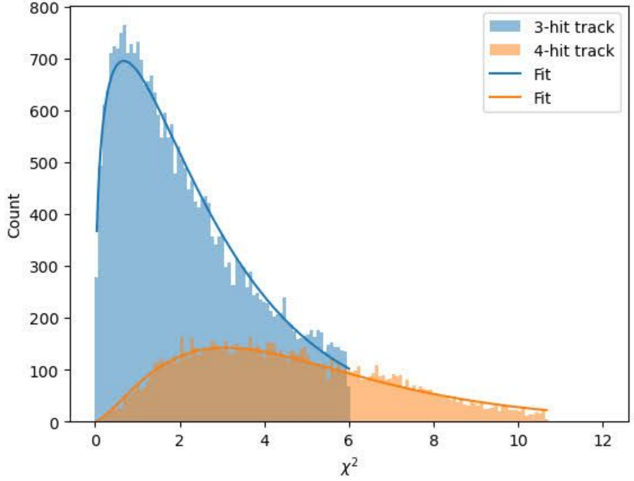
Position along the bar is measured by time difference. The gap in the middle corresponds to the fiber between two bars.

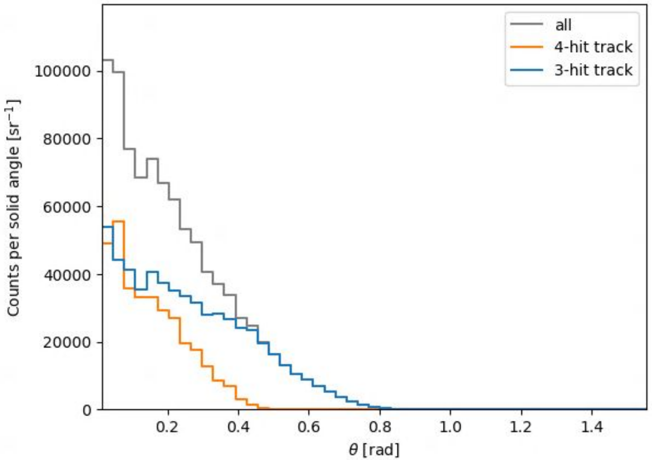
UofT test stand

Cosmic muons measured by the test stand:

- **Event rate**:
  - 38.5 k/hour (measured, after track reconstruction.)
  - 43.8 k/hour (simulation with PARMA cosmic generator + Geant4)
  - **Efficiency: 88%** for detector plus reconstruction (very preliminary)

Credit: Alex Lau





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