Current Status: MATHUSLA40

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On behalf of the MATHUSLA collaboration

Summary up front

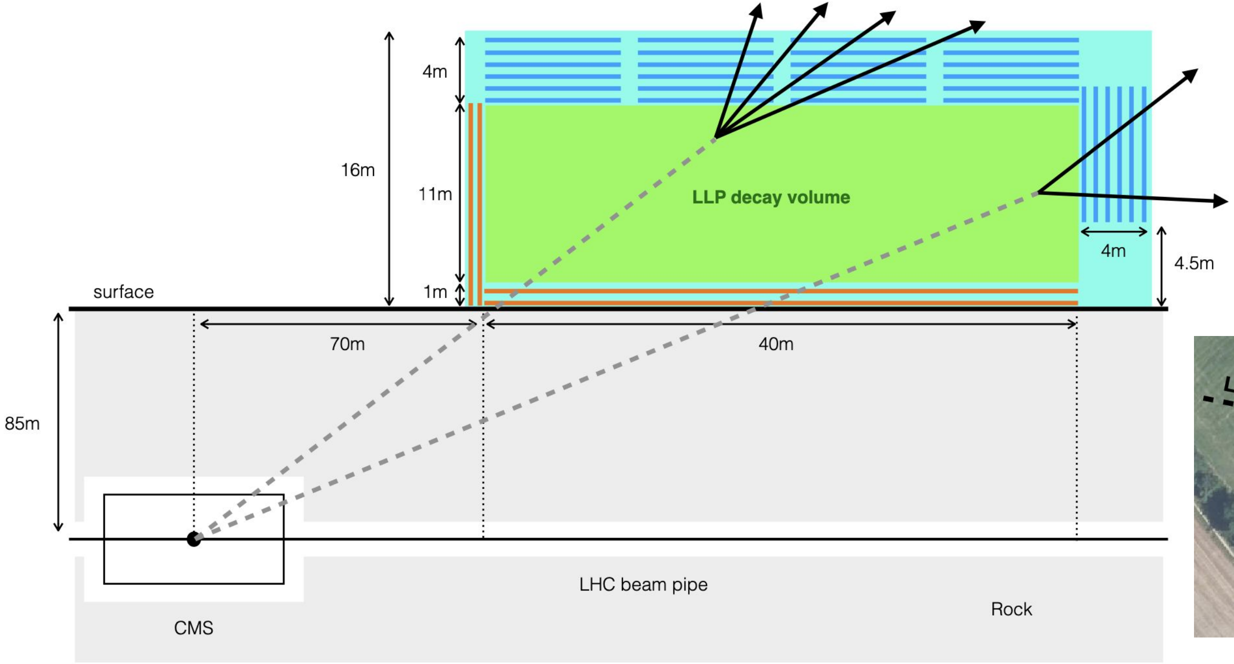
If you’re roughly familiar with public info on the MATHUSLA proposal, here are the most important upshots:

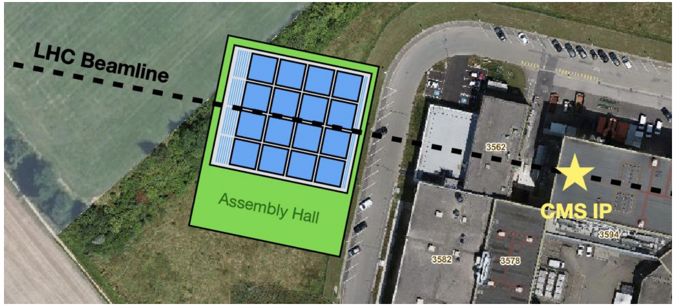
- We’ve **resized** the detector from 100m to **40m: “MATHUSLA40”** Reduces detector/infrastructure cost to make approval/funding more likely.
  - **Cost ***aim*** (USD): ~ 20-30M detector, ≲ 10M infrastructure, but still being finalized**
- Lots of **R&D** has been happening to get us to conceptual design stage.
- **Full GEANT simulations with realistic reconstruction** are almost complete, to demonstrate zero- or low-background LLP search capability.
- A **CDR** for the 40m proposal is mostly complete, with some finishing touches needed on the simulations and civil engineering. (We can share the draft.)

MATHUSLA40 Detector Overview & Design

Main Physics motivation: discover O(10-100GeV) LLPs with near-zero BG.

→ **Instrument $(40\text{m})^2$ LLP decay volume with ceiling/wall trackers and vetos**

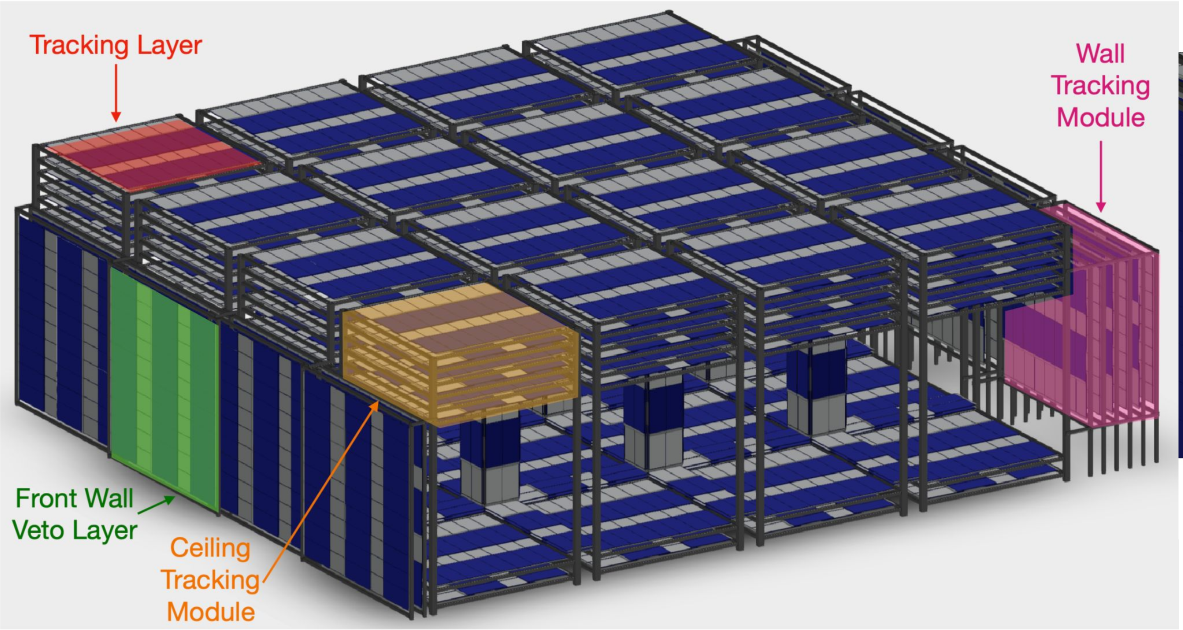


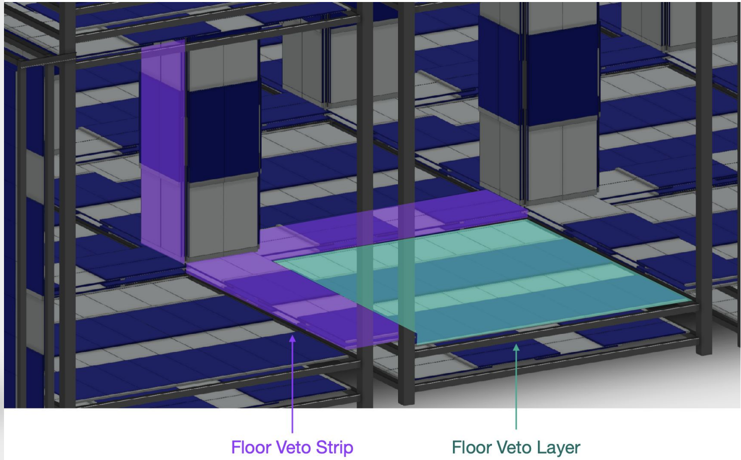


MATHUSLA40 Detector Engineering Concept

Each **tower module** has 6 tracking layers in ceiling and 2 floor veto layers.

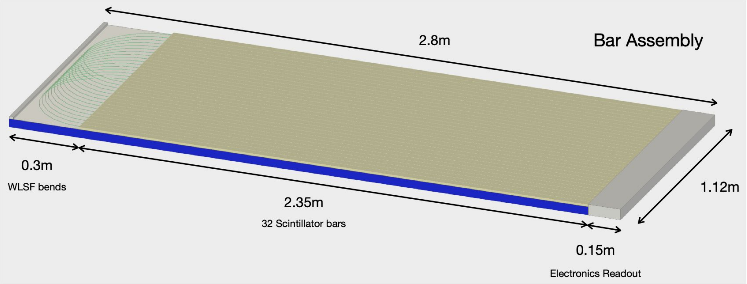
16 of those in 4x4 grid + wall trackers + front wall veto + detectors to cover gaps & vertical supports to make floor veto hermetic.





Building blocks

Everything is made out of identical **‘bar assemblies’**: 32 scintillator bars + WLS fibers + SiPMs + readout in a 2.8m x 1.12m structurally self-supporting flatpack.



^ bar assembly (BA)

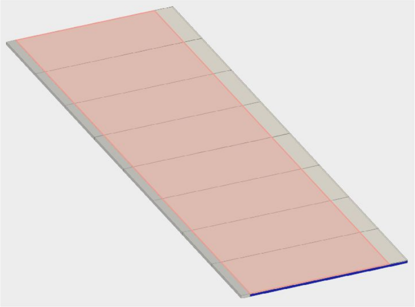
(a) 8 BA = 1 sublayer

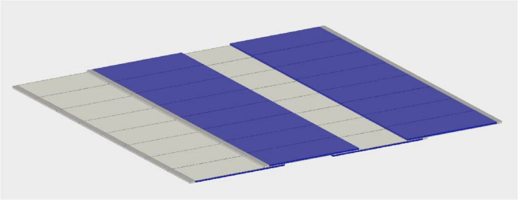
(b, c) 4 sublayers = 1 layer

(d) 6 ceiling + 1 floor layer =

1 tower module

(note alternating orientation)


(a)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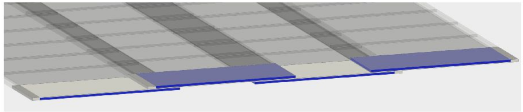
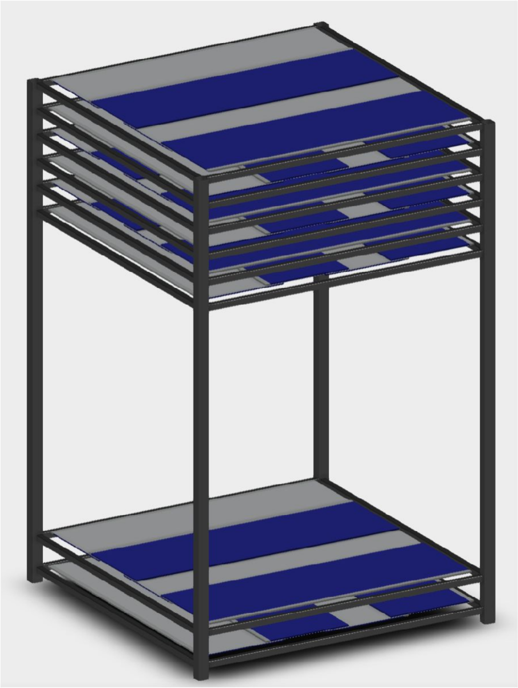

(c)

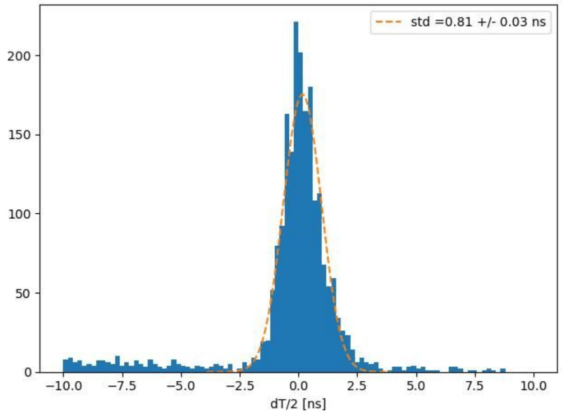

(d)

Tracking resolution

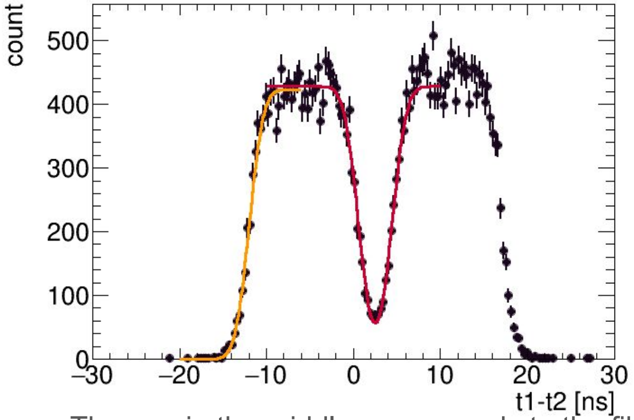
Scintillator bars provide ~cm resolution transverse to bar direction, and O(10cm) resolution along bar direction. Timing resolution is ~ 1ns.

This satisfies our physics requirements of good displaced vertex reconstruction with O(10cm) position resolution, and “perfectly” distinguishing upwards-traveling from downwards-traveling tracks.

Toronto Test Stand Data:



0.81 ns timing resolution achieved



The gap in the middle corresponds to the fiber between two bars.

Fabrication

Scintillator can be fabricated at the NICADD Fermilab extrusion facility at FNAL. MATHUSLA40 needs ~300 tons of scintillator, taking up ~ 9 months of capacity.

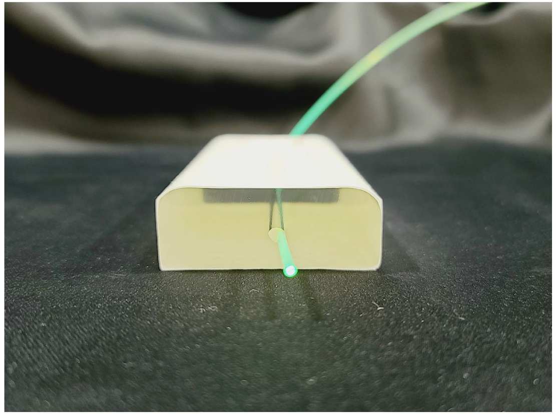


Figure 13. A scintillator bar extrusion as made at Fermilab. A white co-extruded cladding and a central co-extruded hole can be seen. Through the hole is a WLSF. Fiber ends will be instrumented with SiPMs.

Figure 14. The scintillator extrusion facility at Fermilab.

We developed plans for production of BAs in university labs. These would be shipped to CERN and assembled into tracking planes to be installed in the detector structure.

Silicon Photomultipliers and Wavelength Shifting Fibers

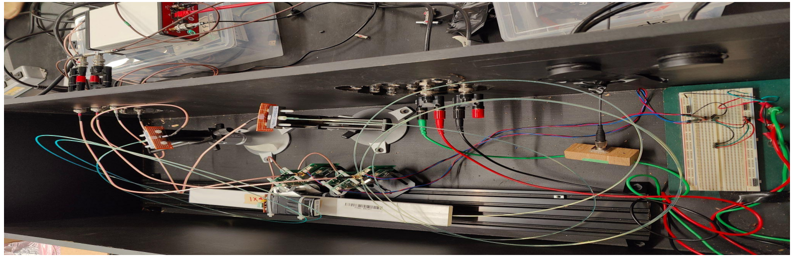
Various component options being explored as part of R&D.

Hamamatsu S14160 or S13360 series SiPMs and Saint Gobain BCF-92XL WLSFs are current main contenders.

SiPM gain dependence on temperature would necessitate applying temperature correction to overvoltage.

Each fiber loops through two bars, with both readout ends on same side of BA
Dark-box setups have studied different vendors/models for: response time, light yield / attenuation, light leakage, fiber stress, dark counts

Toronto dark-box



DAQ & Trigger

MATHUSLA40 is a relatively low-rate detector by particle physics standards, entirely dominated by cosmics (~300 kHz on full 40m detector). DAQ and trigger designs based on very well-understood principles for reliability and scalability.

The entire MATHUSLA40 detector outputs about 0.6 Tb/day. Readily available storage devices can buffer one or more days of hits.

A fast L1 trigger looks for upwards-traveling track candidates, prompting readout of all hits within 0.5 μs of L1 timestamp → save to permanent storage.

This trigger is fast enough that supplying a L1 trigger signal to CMS is possible, to save LLP production event to disk. Scouting data would allow a much broader range of collisions to be saved, guaranteeing at least some information on production event even for slow LLPs.

Civil Engineering

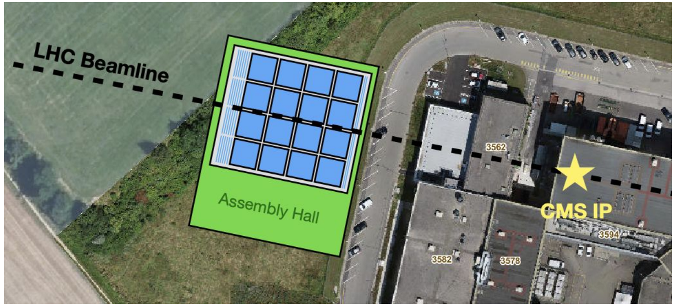
MATHUSLA40 needs a fairly simple experimental hall with ~ 50m x 70m footprint.

Maximum building height above grade is limited to 17m by local regulations.

Current detector height is 15m. Main outstanding question is how to accommodate ceiling crane system for detector installation.

A ceiling-mounted, underhung bridge crane system with ultra-low headroom hoists + a few meters of excavation to lower floor to create ceiling clearance **<u>may</u>** be a viable and cost-effective solution.

<u>STILL BEING INVESTIGATED!</u>



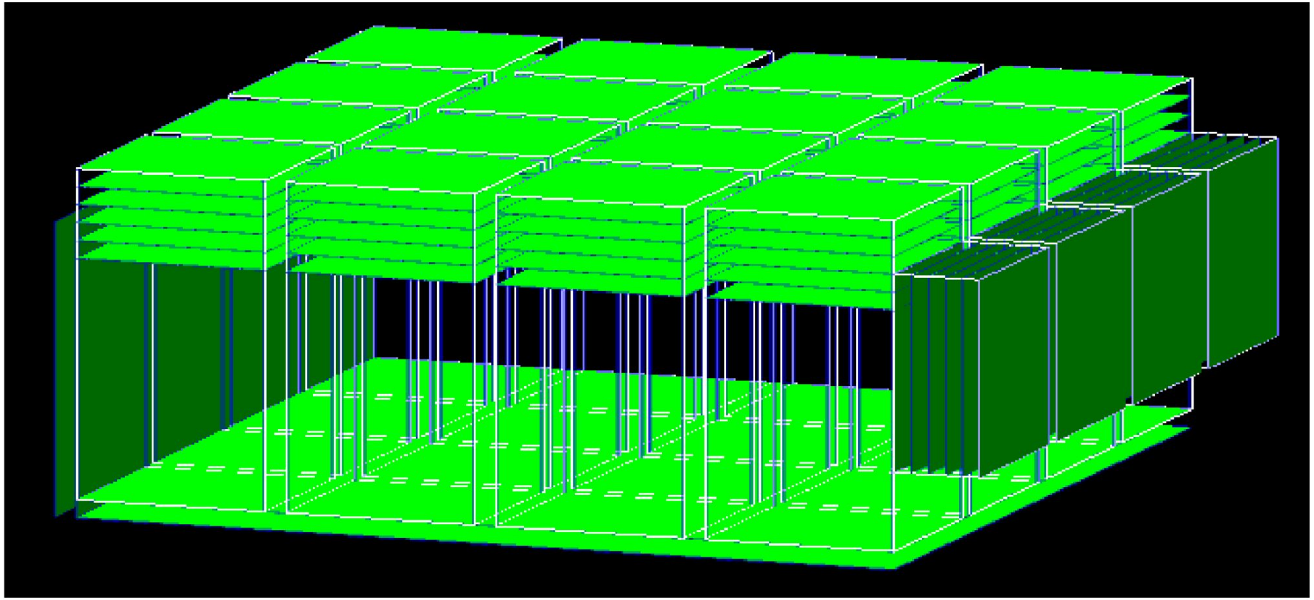
Simulations

Signal model: h -> XX LLP, with X decaying hadronically (bb, but gg etc similar)

Backgrounds in order of severity:

- **Inelastic interactions** from cosmic rays, most importantly protons and neutrons.
  - Use PARMA to generate unweighted (weighted) 1/37 (1/962) exposure above (below) 2.65 GeV for protons
  - Neutron investigation still wrapping up.
- **LHC muons**: use MadGraph + Pythia for EW & bb production, propagate through rock to detector in GEANT4
  - p_T > 35-40 GeV required to reach detector.
  - Surprise: deflection by O(10^O) in the rock is typical.
- **Atmospheric neutrinos**: simulate interaction with detector material, support structure and air in GENIE, place corresponding interaction sites in GEANT4 detector sim.

Slightly Simplified MATHUSLA40 GEANT Geometry

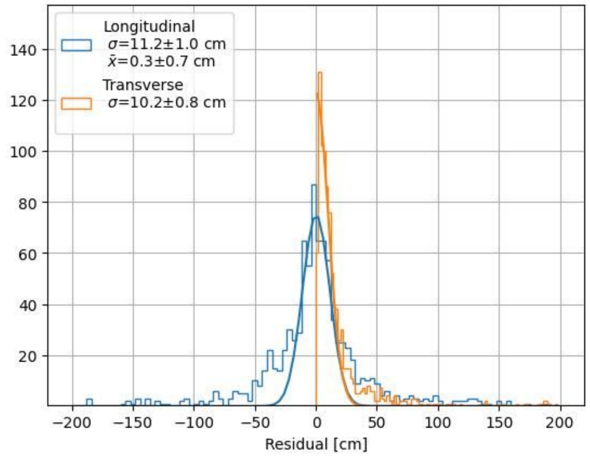


Default is 6 layers, 95% hit efficiency. Include ambient CRs + noise rate of 0.1*CR. Setting noise rate = cosmic rate makes little difference, and we investigate different number of layers and hit efficiency to evaluate robustness of design.

Reconstruction

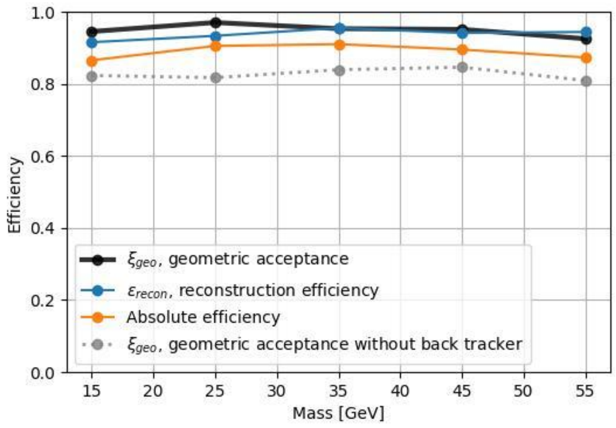
Track reconstruction based on Kalman Filter, vertex reconstruction uses least-squares fit.

- Efficiency verified on single track, two-track vertex and multi-track vertex
- Vertex resolution on primary physics case (m_X = 25 GeV) is ~10 cm for both longitudinal and transverse directions.



Reconstruction is done on six different configuration

- Number of tracking layers: 4, 5, 6
    - 3 hits are required to form a track for 4 layer
    - 4 hits are required to form a track for 5 and 6 layer
- Detector efficiency: 90% or 95%
- **Benchmark: 6 layers with 95% efficiency**



(slide by Tom Ren)

Background veto strategies

- Material vetos for vertices in sensor/structural material
- Reject vertices with many hits BEFORE vertex in time
- Reject vertices with slow ($\beta \lesssim 0.83$) tracks
- Reject vertices that can be associated with muon hits in floor/wall veto
- Reject tiny vertex opening angles ($\lesssim 0.2$ rad)
- Reject vertices close to inward-traveling track
- Reject vertices that point very different direction from CMS IP
- Reject vertices with lots of random hits in vetos
- Require 3 or more tracks per vertex, and/or high number of hits with spacetime distance ~ 0 to vertex.

MATHUSLA40 Benchmark analysis

Final numbers still being finalized. But important upshots:

- LHC muons and atmospheric neutrinos are completely eliminated by various cuts, <<< 1 event over MATHUSLA exposure
- CR protons take more work, but we end up with < 1 event over MATHUSLA exposure
  - Caveat: since simulation statistic is < full exposure, this was estimated using various ABCD type methods. Will obviously have to be verified with even higher statistics simulation or something clever.
- CR neutron analysis still being finalized.
- Current status of signal efficiency ~ 50%

MATHUSLA40 Physics Sensitivity

MATHUSLA40 still extends HL-LHC reach far beyond main detector projections.

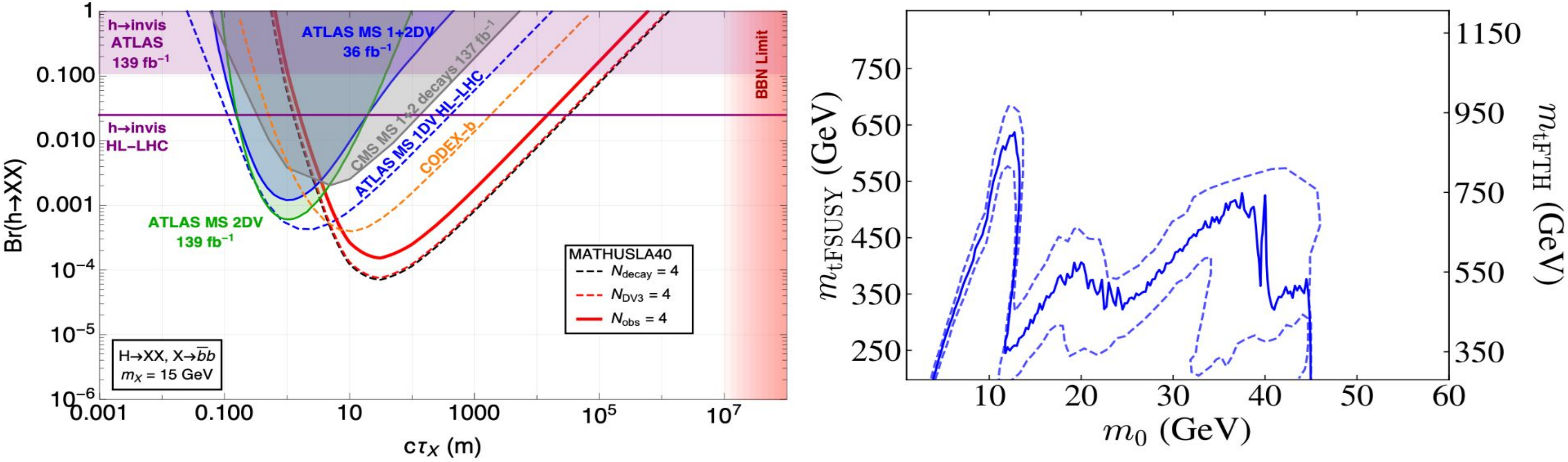


Figure 1: Left: Reach of the 40m MATHUSLA design (solid red), including realistic experimental efficiencies for a zero-background search, vs ATLAS, CMS, and the idealized reach of CODEX-b. Right: Corresponding MATHUSLA sensitivity to dark glueballs (mass m_0) for different neutral top partner masses, using latest simulations with dark-Lund-String fragmentation [13].

Ongoing Collaboration Activities

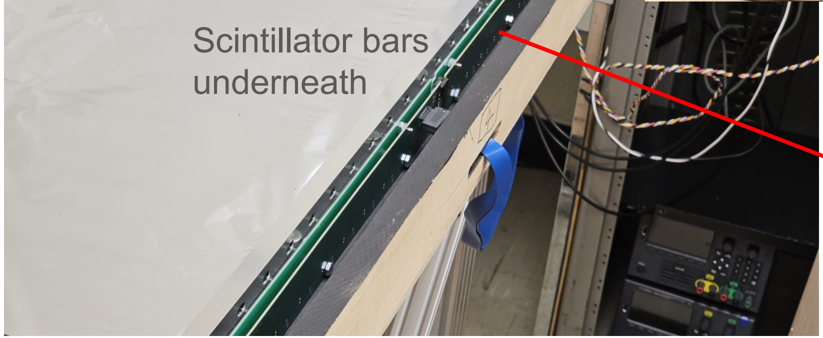
Apart from finishing the CDR (out standing civ eng + sims):

- R&D at the Toronto and Victoria test stands answered basic questions on bar, fiber and SiPM choice & performance. Ongoing work:
  - SiPM characterization, optimization and model selection
  - Characterization and quality control for the WLSFs
  - Optimization of the SiPM-WLSF coupling
  - Full development of the front-end readout system.
  - Full calibration system design
- Plan to develop simulations further
  - Implement fully realistic detector sensor geometry, especially for floor veto
  - Full statistics for CR p,n background is very challenging, but ultimately necessary
- Work with PBC to refine our proposal and justify its physics motivation
- Plan to solicit approval from the LHCC in 2025

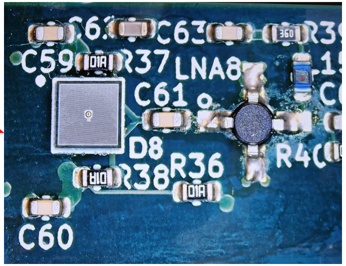
Backup

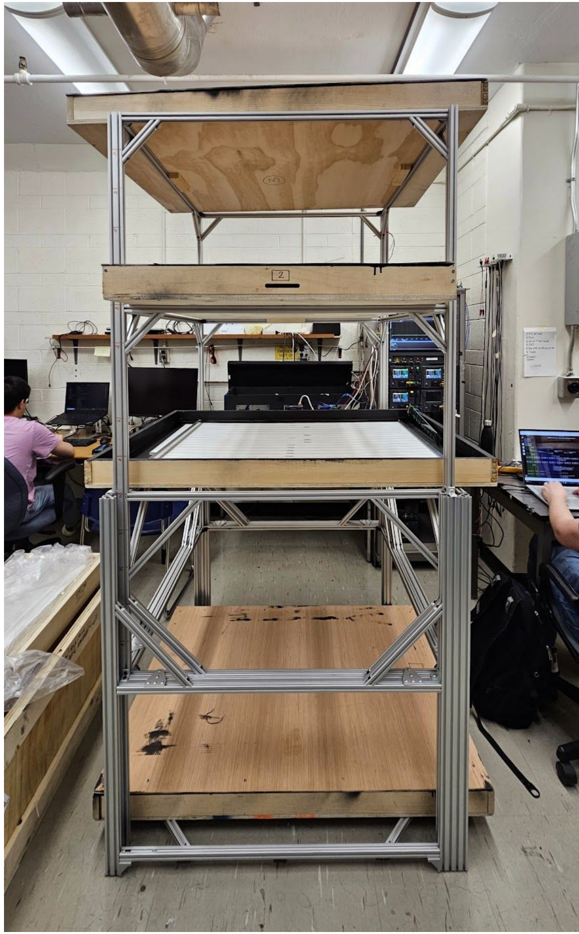
UofT test stand

- **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-92XL, 1.5 mm diameter



Scintillator bars underneath

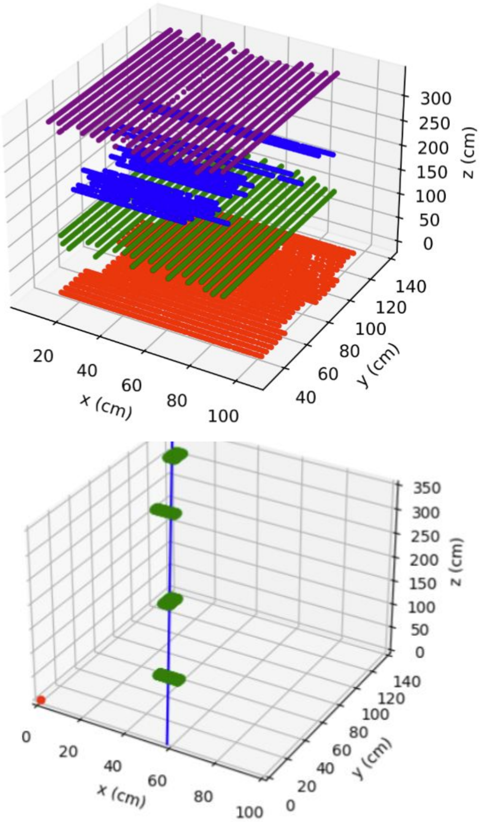




SiPM + preamp

R&D efforts

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

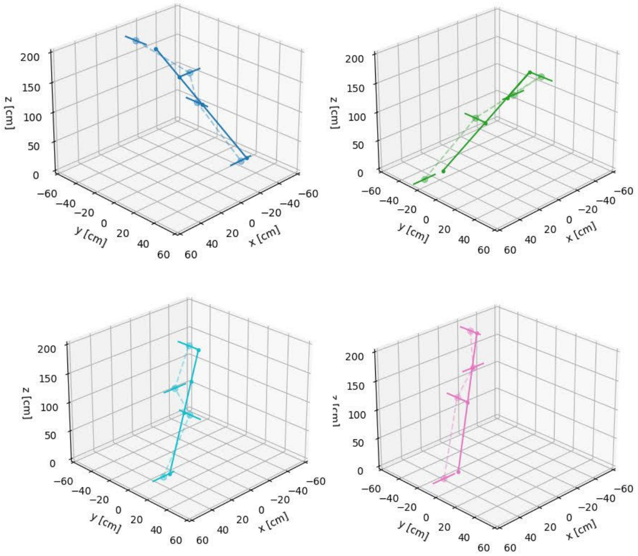


Cosmic ray events in the UVic MATHUSLA prototype, and a reconstructed muon track passing through all four layers

Cosmic muons

Cosmic muons measured by the test stand:

- Triggering on any two hits within 25 ns
- Reconstructed with the same code used for simulation



Credit: Alex Lau