The MATHUSLA Experiment

Steven Robertson
Institute of Particle Physics, Canada
and
University of Alberta

steven.robertson@ualberta.ca

The International Joint Workshop on the Standard Model and Beyond 2024
UNSW, Sydney, Australia
Dec 9-13, 2024

INSTITUTE OF
PARTICLE
PHYSICS

UNIVERSITY OF
ALBERTA

Outline

- Why Long-Lived Particles?
- MATHUSLA concept
- MATHSULA-40 detector design
- Ongoing research and development activities
- Expected physics reach
- Prospects

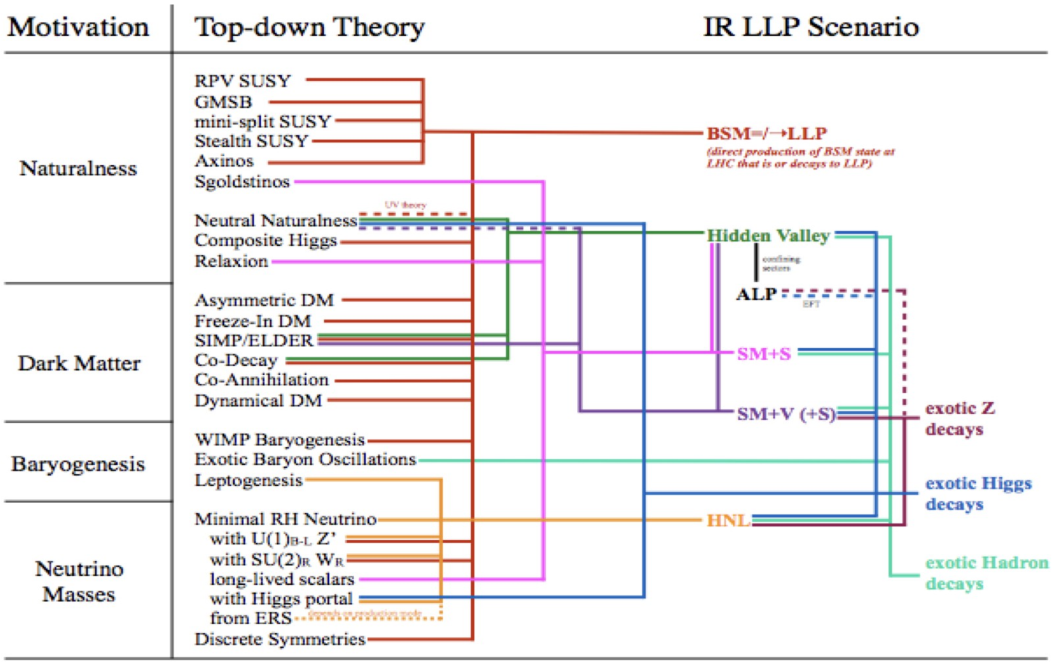
Long-lived particles

Particles have long lifetimes due to inaccessibility of states into which they can readily decay (i.e. due to kinematics and/or couplings)

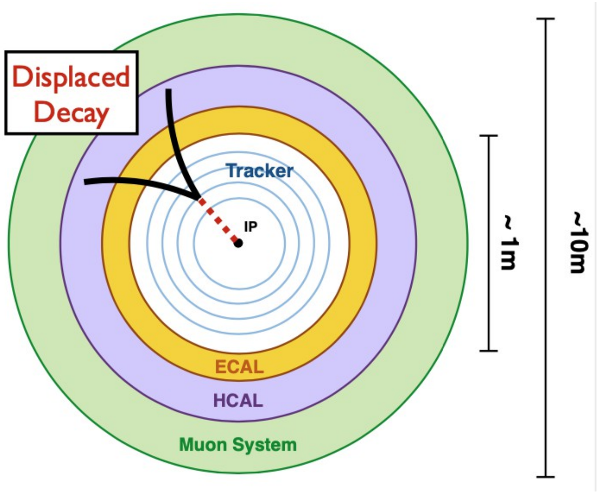
- Examples exist already within the SM, e.g. muons $\tau_\mu \sim 2.2\ \mu s$
- Big Bang nucleosynthesis limit on long-lived new particles is ~0.1s ($c\tau \sim 10^7$ m)

Various theories of beyond-SM physics (e.g. supersymmetry) "naturally" include particles that can be long lived:

→ Reasonable to expect that beyond-SM particles may also have long lifetimes, particularly if they are light or have "feeble" couplings to the SM



Searching for LLPs



Neutral long-lived particles (LLPs) cannot be directly detected in experiments

- Instead, the SM decay daughters must be detected and the LLP reconstructed based on the displaced decay vertex
- If the decay length $c\tau$ is too long, the decay can occur outside of the detector fiducial volume
- "Missing energy" searches are possible, but these signatures can be challenging due to resolution, background, and trigger issues

LLP searches have been identified by the [HL-]LHC community as a growing priority

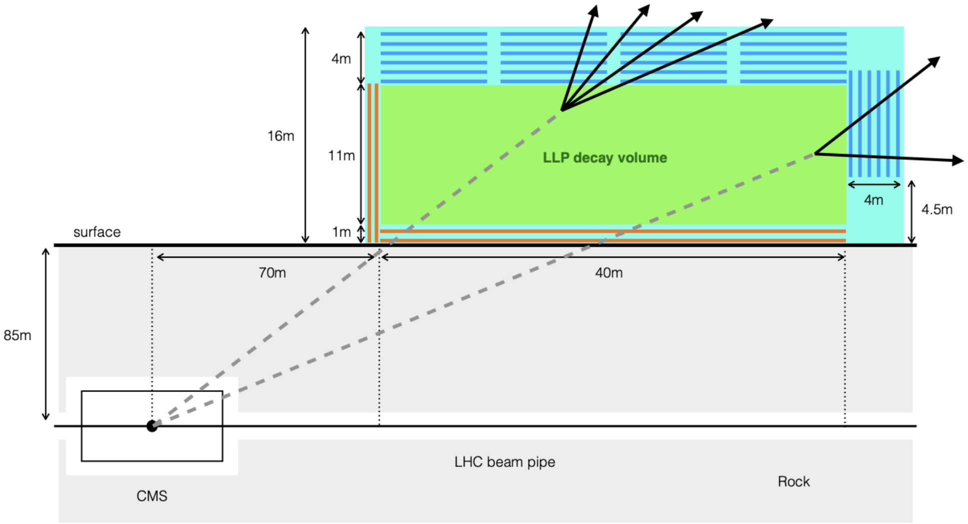
- High centre of mass energy gives access to heavy states that may be coupled to LLPs (e.g. Higgs)
- Very high luminosity (HL-LHC)

However, the LHC could be making LLPs that are effectively invisible to its main detectors

Concept

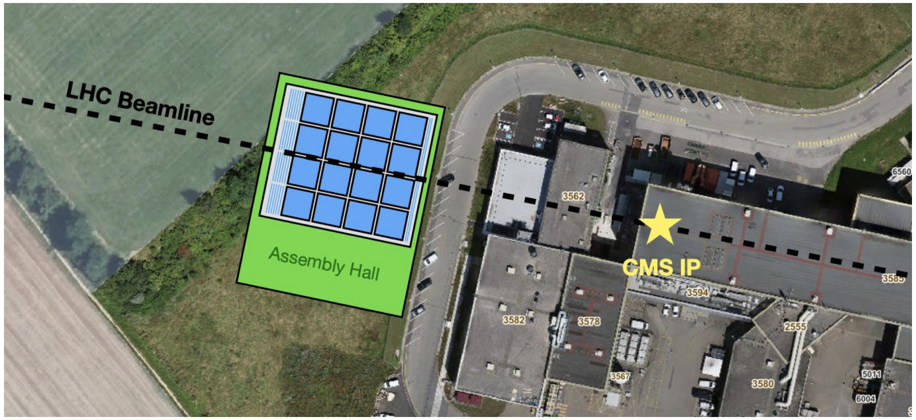
Proposal for a large LLP detector on the surface adjacent to one of the LHC interaction regions (CMS)

- 40m x 40m x 16m instrumented decay volume to detect decay daughters of LLPs produced by LHC interactions
- Array of 16 10m x 10m modules composed of 6 layers of tracking detectors, plus 2 layers of floor “veto” detectors
- Back wall tracking layers to improve tracking acceptance



Track multiplicity of potential signals depends on the LLP mass

- Reconstruct 4D decay vertices of upward-going LLPs
- Use timing and hit position information to reject LHC and cosmic ray backgrounds

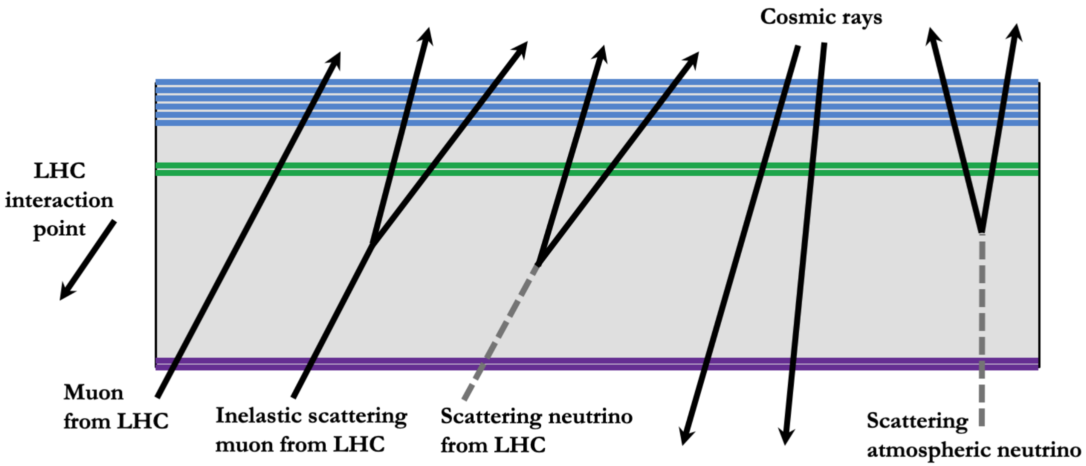


Original (100m x 100m x 25m) MATHUSLA proposal recently re-scoped for cost reasons (new design referred to as “MATHUSLA-40”)

Backgrounds

Primary physics target (high multiplicity DV) is essentially background-free

- Secondary physics target of low-mass, low multiplicity LLP decays have backgrounds that need to be carefully studied



LHC muons:

- Muons with E > 40 GeV can penetrate rock shielding, but do not generally form vertices
- Delta rays and rare decays can be rejected based on vertex topology

GeV-scale atmospheric neutrinos:

- Scattering within the decay volume result in a few events per year
- Can be effectively vetoed using time-of-flight track measurements

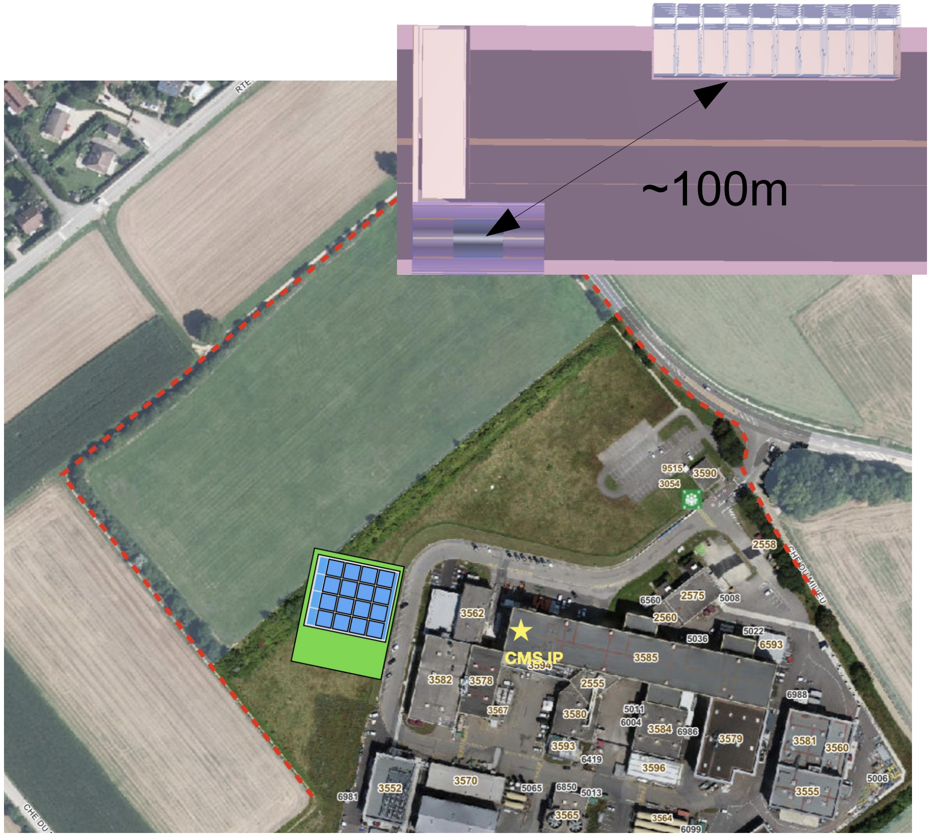
Cosmic rays:

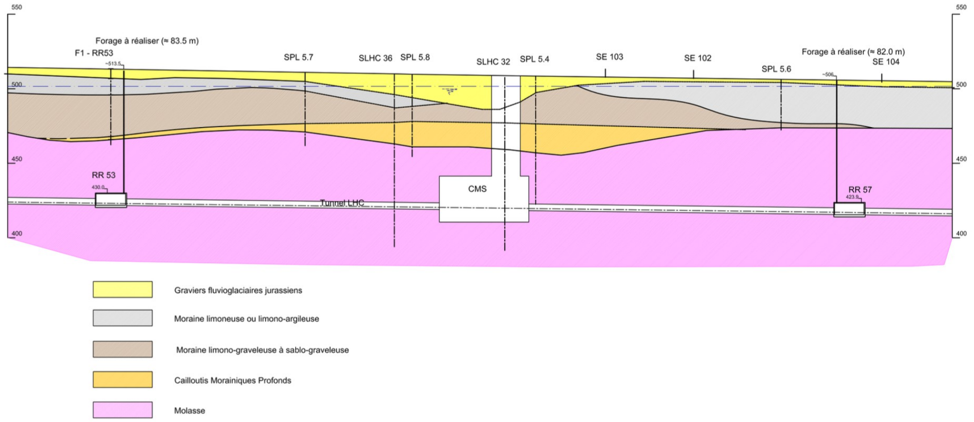
- ~300 kHz flux to entire detector; rejected by directionality (timing) and topology
- Cosmic ray nucleons can undergo inelastic backscatter in detector floor
- Results in O(100) non-relativistic K_S^0 (over life of experiment) traveling into MATHUSLA volume and decaying into charged particles that could reach the ceiling trackers.
- Can be characterized with beam off, and distinctive low momentum signature

Location

An appropriate site is available adjacent to the CMS surface buildings at CERN Point 5 (Cessy, France)

- CERN owned land, green-field site (currently leased as farmland)
- MATHUSLA decay volume would be located ~100m “as the mole digs” from the CMS IP.
- Substantial shielding from LHC, particularly for LHC muons





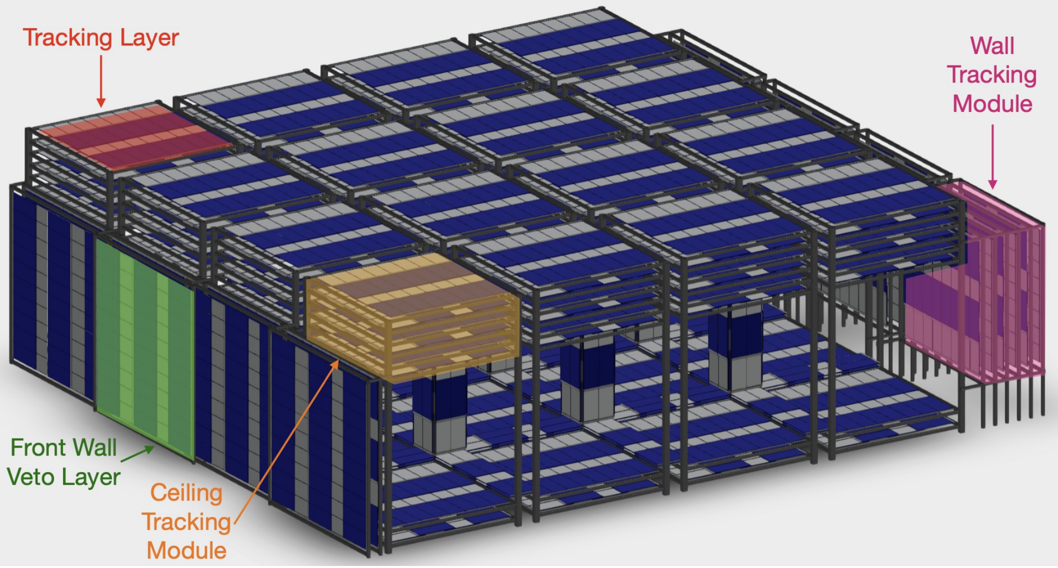
Local ordinances restrict roof height to 17m for the surface building, limiting vertical extent of detector

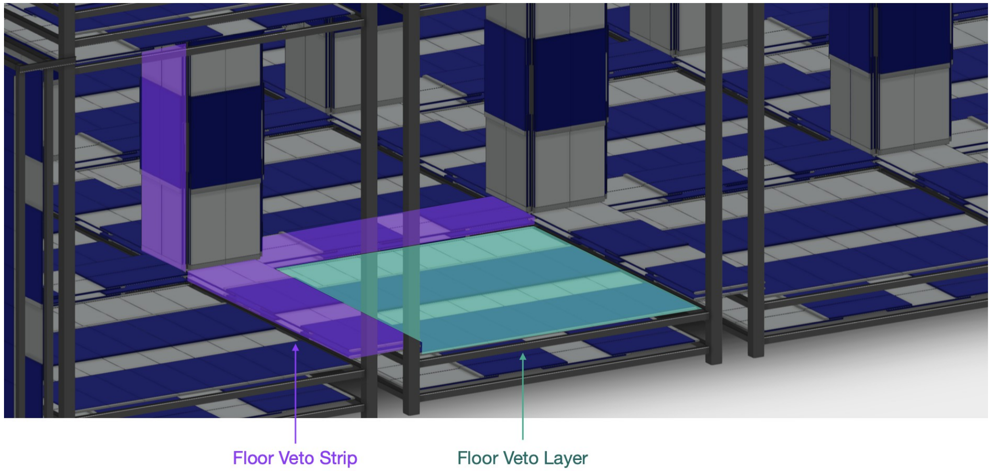
- excavation possible, but expensive

Detector concept

40m x 40m array of 16 "towers" of low-cost plastic scintillator bars

- floor and forward "veto" layers to reject punch-through LHC muons and CR back-scatters
- scintillator panels surround support columns to veto interactions in material





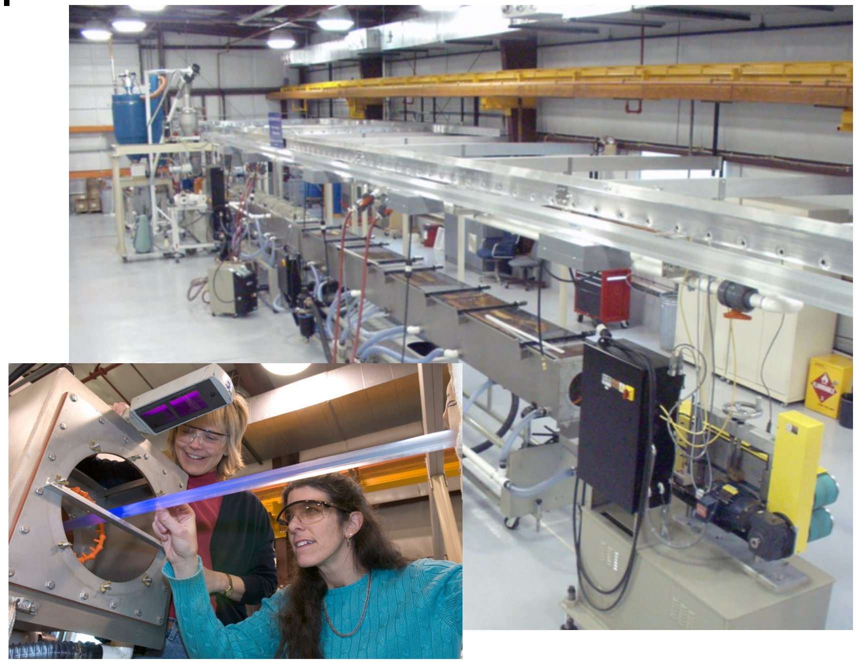
- Detector access possible via catwalks between towers
- Removable floor scintillator panels to access floor walkways
- Serviced by (low profile) overhead rail crane and/or floor-lifts

Extruded plastic scintillator

Extruded scintillator based on commercial polystyrene pellets with added dopants

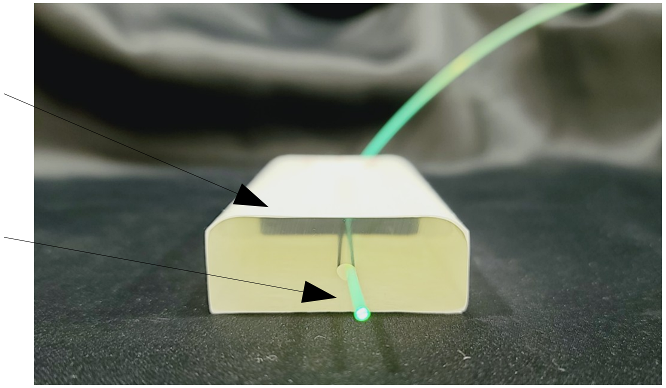
- MUCH cheaper than “cast” scintillator
- Intrinsic light yield comparable to cast scintillator, but poorer optical quality (i.e. attenuation length O(10cm))
- wavelength shifting optical fibre used to bring signals to photodetectors

Fermilab extrusion facility



Extruded plastic scintillator is primary detector element

Light brought to the bar ends via blue-green wavelength shifting optical fiber (WLSF)

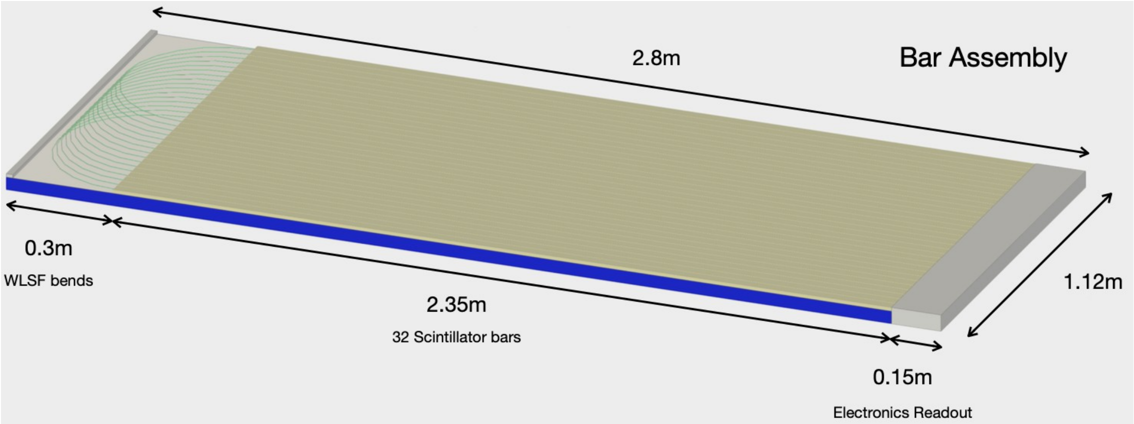


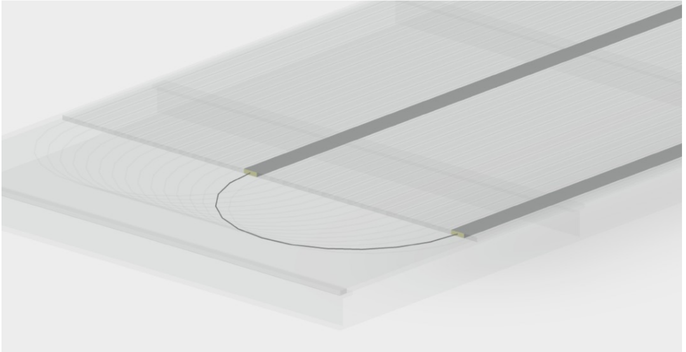
- **Primary dopant:** ~1% PPO
  2,5-diphenyloxazole
- **Secondary dopant:** ~0.02% POPOP
  (wavelength shifter)
  1,4-bis(5-phenylxazole-2-yl)benzene
- TiO_2 reflective coating co-extruded
- Various profiles can be extruded, with hole(s) for inserting WLSF

Bar modules

Very simple detector technology based on extruded plastic scintillator

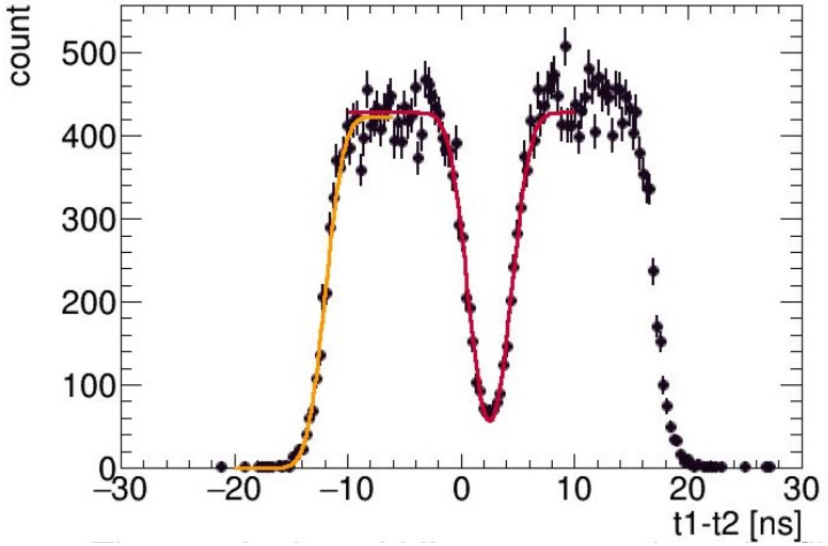
- 3.5cm x 1cm x 2.35m extruded scintillator bars, threaded with 1.5mm WLSF





32 bars per module:

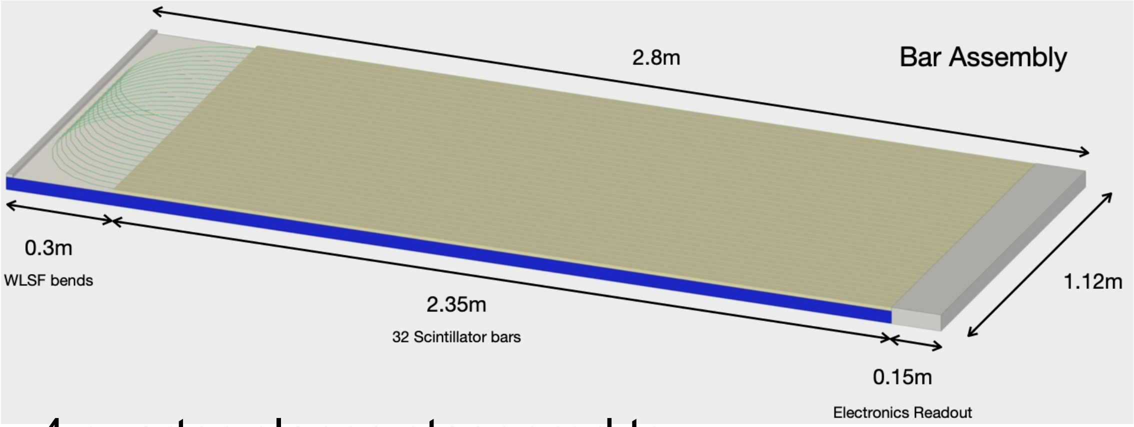
- ~5m WLSF looped through two bars, with SiPMs on both ends
- Absolute and differential timing from the two end of each fibre
- Electronic readout only on one side of bar assembly



Tower assemblies

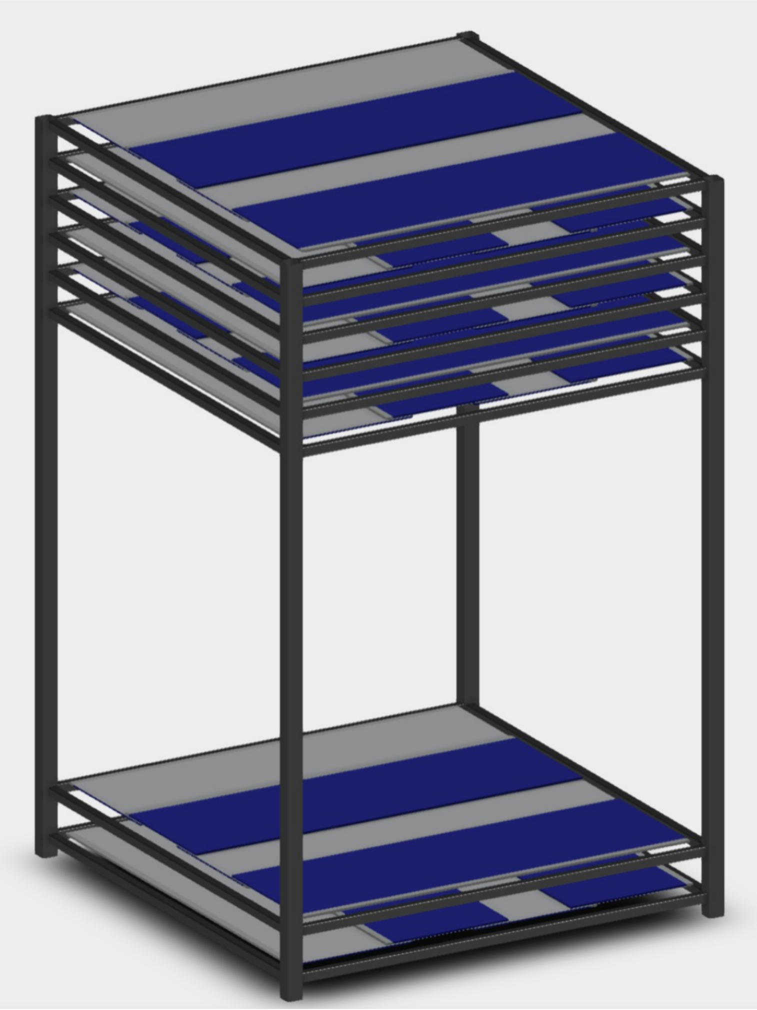
Bar modules can be mechanically connected edge-wise to create quarter-planes of ~9m x 2.35m of active detector area

- 8 bar modules per quarter-plane



- 4 quarter-planes staggered to provide full plane coverage:

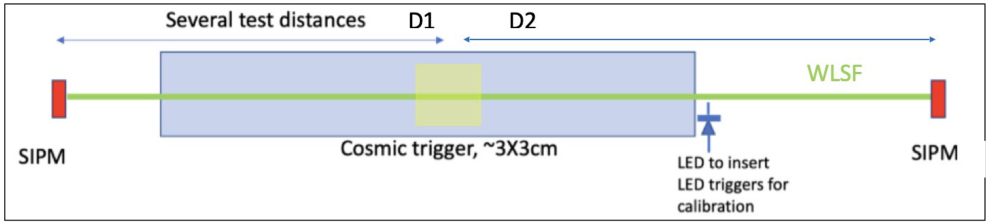
- tracking planes alternate bar orientation in x-y



Performance

Large detector volume means material costs are a limiting factor, hence desirable to use:

- smallest number of electronic readout channels (i.e. widest/longest scintillator bars)
- thinnest feasible scintillator bars
- smallest diameter WLSF



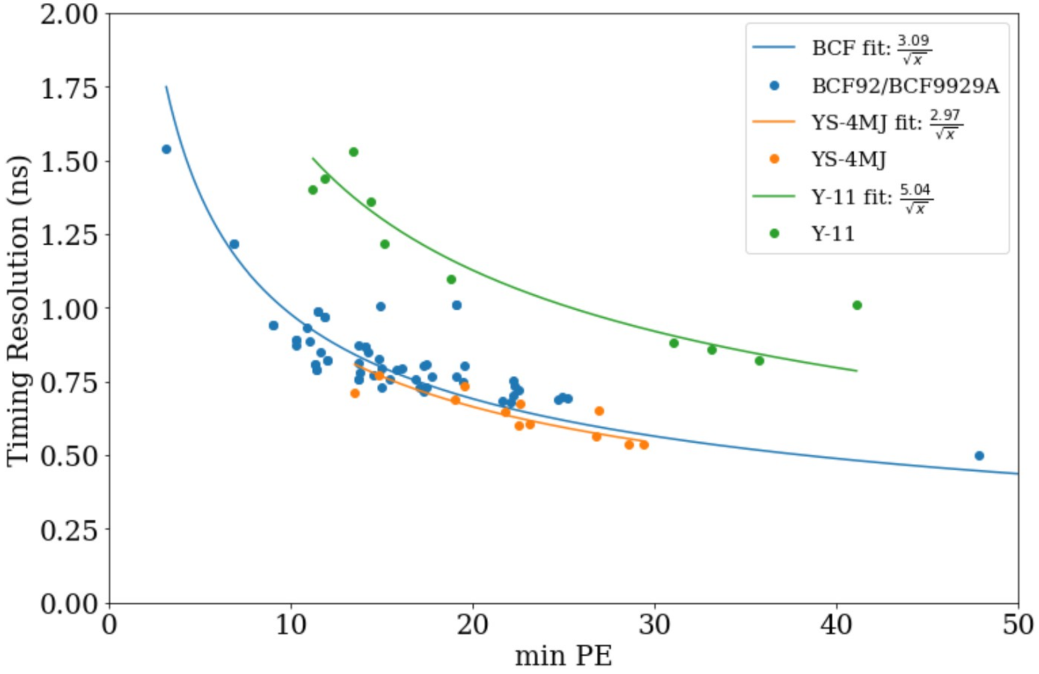


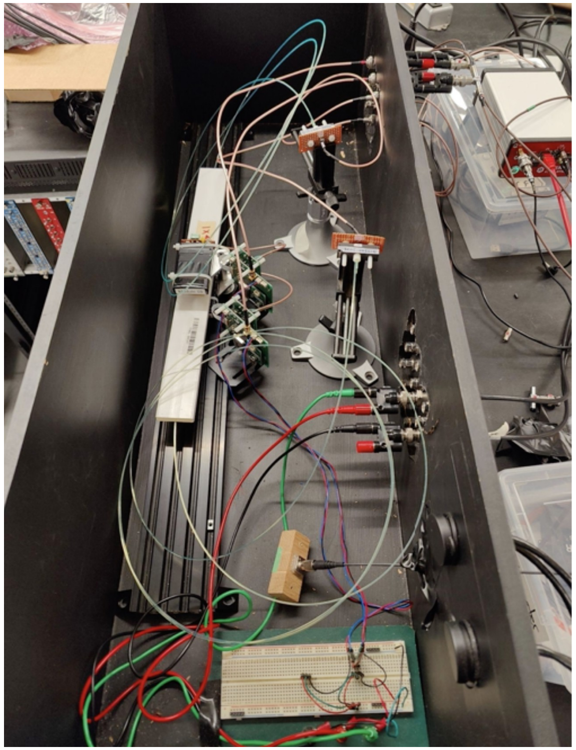
Photo-electrons detected by SiPM

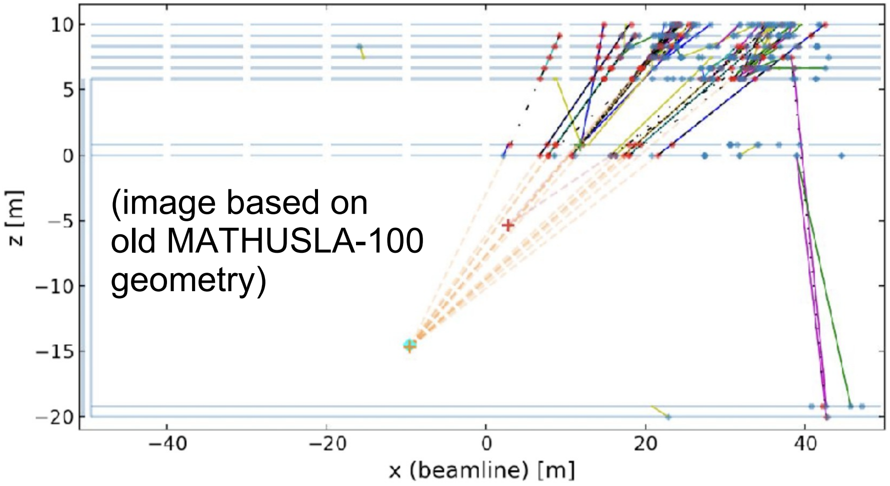
Hit efficiency and timing are key performance metrics:

- **Light yield**
- WLSF based on K-27 fluor (e.g. Y-11) are not fast enough, given the typical light yield in the MATHUSLA design

Ongoing R&D activities

- Studies of new WLSF formulations with higher yield, shorter decay times and longer attenuation lengths
  - Light yield impacts timing resolution (not efficiency), and reduces material costs
- Cost/performance optimization for SiPMs
  - SiPM performance not a limiting factor
  - Define QA/QC criteria



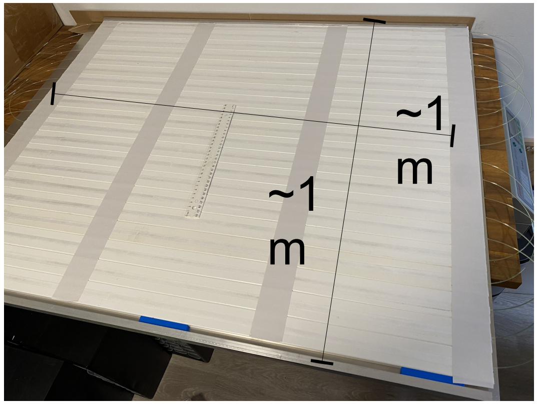


(image based on old MATHUSLA-100 geometry)

- Detailed GEANT4 simulation studies with robust pattern recognition/ track finding (Kalman filter) and vertexing

"Global" performance optimization of extrusion, WLSF and SiPMs still to be performed (detailed technical design)

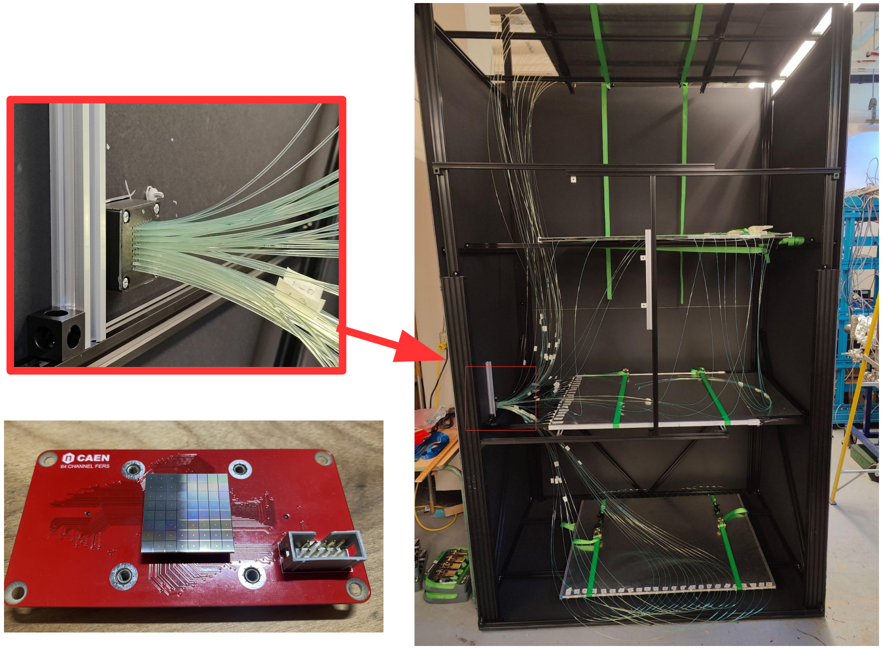
Tracking test-stands



Ongoing testing of prototype scintillator bar modules in two large cosmic ray hodoscopes

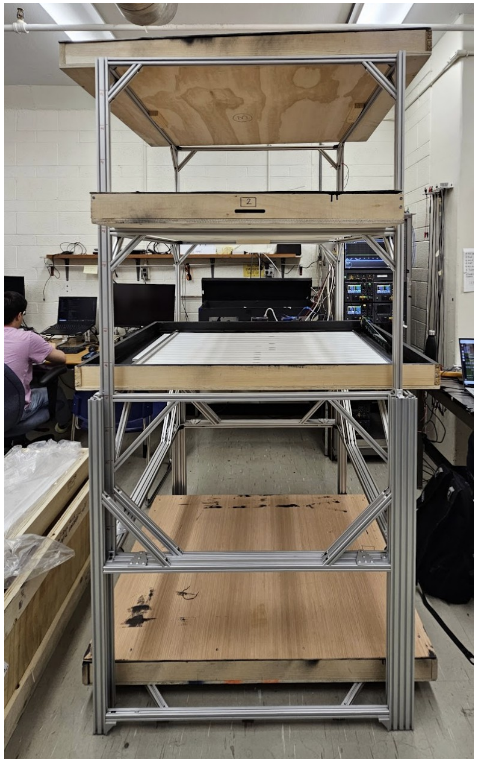
- Tracking with four-layer x-y arrays with looped WLSF and 80cm layer spacing
- Scintillator bars, fiber and SiPMs with close to MATHUSLA nominal specifications

UVic: Full-length (~5m) WLSF routed to single 64-SiPM array with CAEN readout system



UofT: Individual SiPMs mounted on front face of scintillator bars

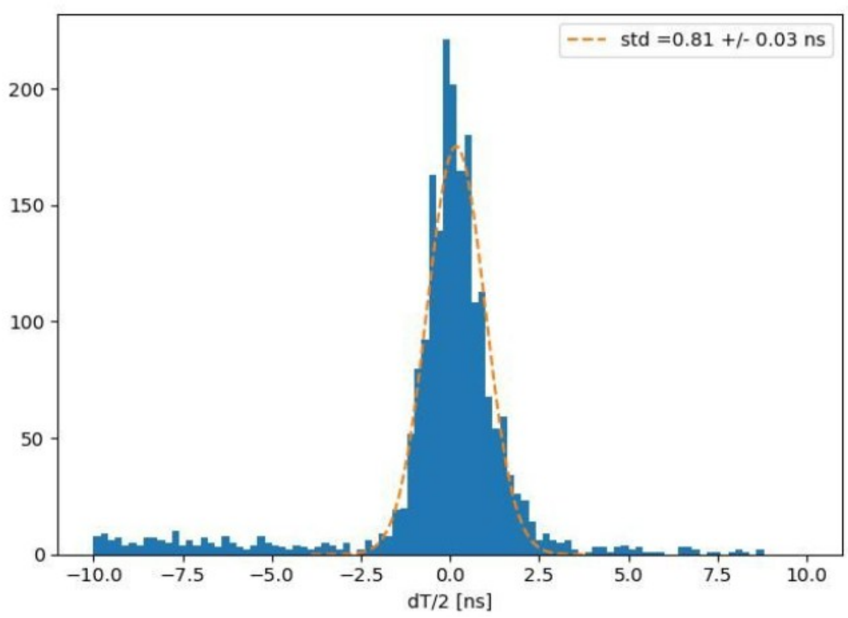
- Custom preamps mounted on bar module
- More similar to final MATHUSLA design, but different WLSF configuration



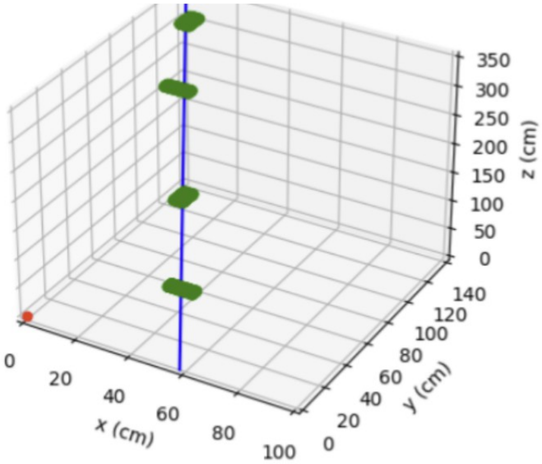
Tracking test-stands

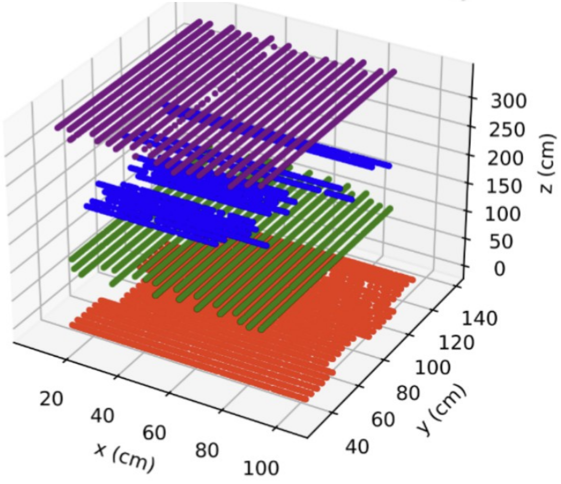
Recent milestones:

- MATHUSLA benchmark 1ns timing performance achieved using FNAL 4cm x 1cm extrusion and 1.5mm St. Gobain BCF-92XL fibre
- O(10cm) position resolution from timing



Cosmic ray muon track reconstructed in UVic test stand





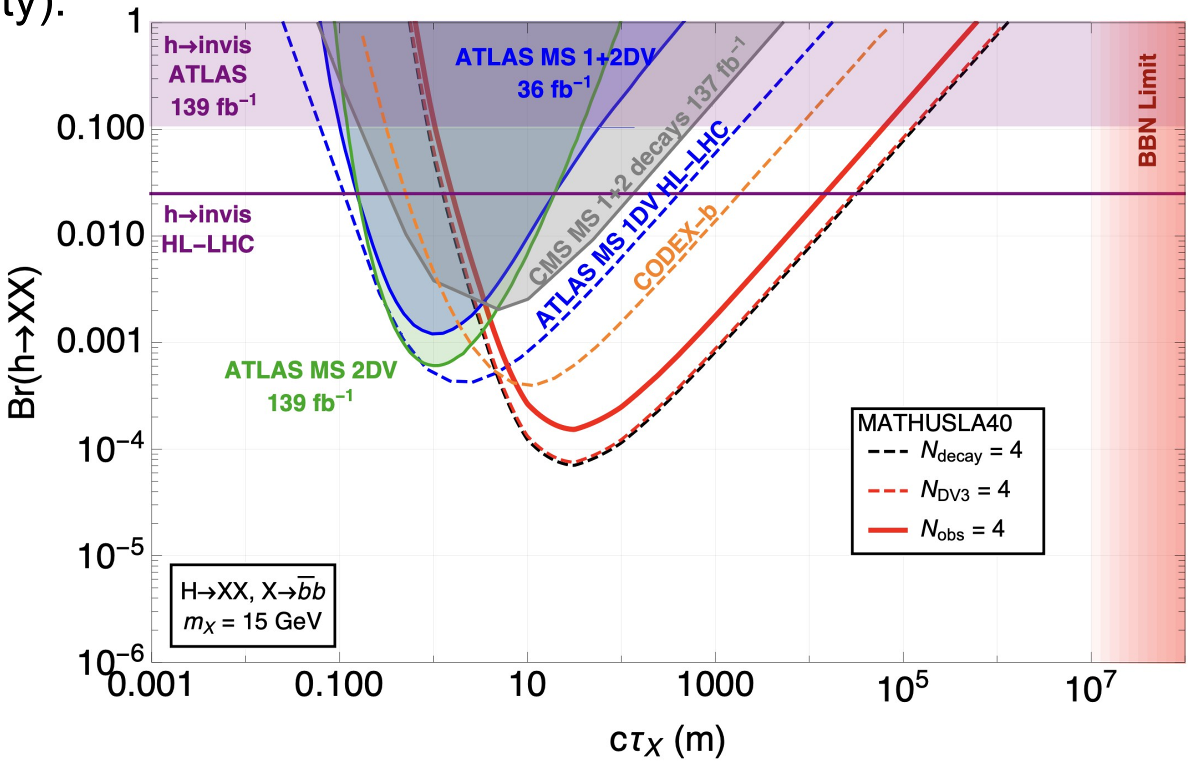
Cosmic ray muon hit positions in scintillator bars

- Work ongoing to characterize tracking parameters (i.e. residuals) in UVic test stand

New physics sensitivity

MATHUSLA-40 Benchmark analysis: $h \rightarrow XX$ LLP, with $X \rightarrow \text{hadrons}$

- Backgrounds (in order of severity):
  - Cosmic ray inelastic interactions, (most importantly protons and neutrons): simulated using PARMA
  - LHC muons: MadGraph + Pythia for EW & bb production, propagate through rock to detector in GEANT4
  - Atmospheric neutrinos: simulate interaction with detector material, support structure and air in GENIE



- LHC muons and atmospheric neutrinos can be completely eliminated by signal selection cuts, with typical signal efficiency ~ 50%

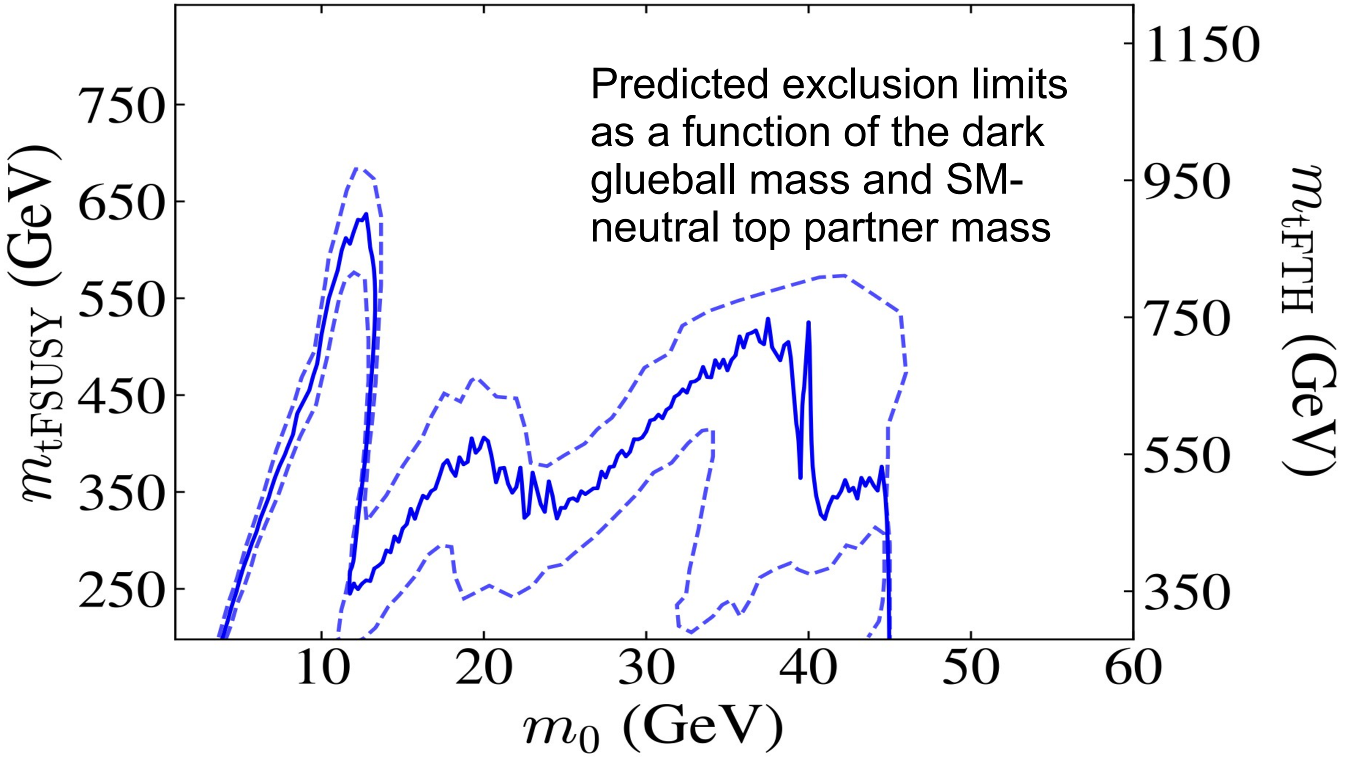
► MATHUSLA-40 would significantly extend HL-LHC reach for LLPs

New physics sensitivity

Dark glueballs produced in exotic Higgs decays:

- LLP signal arising from the production of all meta-stable dark glueball species

MATHUSLA effectively probes neutral naturalness solutions of the little hierarchy problem across the entire motivated TeV-range of neutral top partner masses

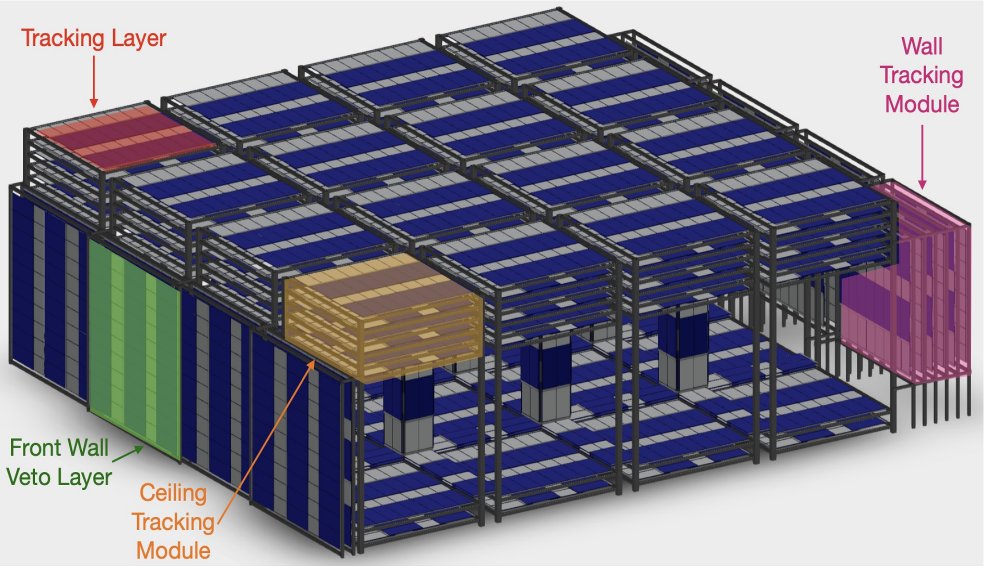


Predicted exclusion limits as a function of the dark glueball mass and SM-neutral top partner mass

Additional scenarios studied based on original MATHUSLA-100 concept

- To be updated using new geometry and simulation framework

Prospects



Updated Conceptual Design Report for MATHUSLA-40 detector is almost finalized

- Hopefully, will be publicly available soon!

- Detailed GEANT4 simulation of realistic MATHUSLA-40 detector
- Full physics simulations with robust and realistic background estimates for benchmark physics models
- Detector R&D ongoing using large test stands in Canada; have demonstrated required performance capabilities

Extra material

References

John Paul Chou, David Curtin, and H.J. Lubatti. New detectors to explore the lifetime frontier. Physics Letters B, 767:29–36, Apr 2017.

Cristiano Alpigiani et al. A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS, 2018, arXiv:1811.00927.

David Curtin and Michael E. Peskin. Analysis of long-lived particle decays with the MATHUSLA detector. Physical Review D, 97(1), Jan 2018.

David Curtin et al. Long-lived particles at the energy frontier: the MATHUSLA physics case. Reports on Progress in Physics, 82(11):116201, Oct 2019.

Imran Alkhatib. Geometric Optimization of the MATHUSLA Detector, 2019, arXiv:1909.05896.

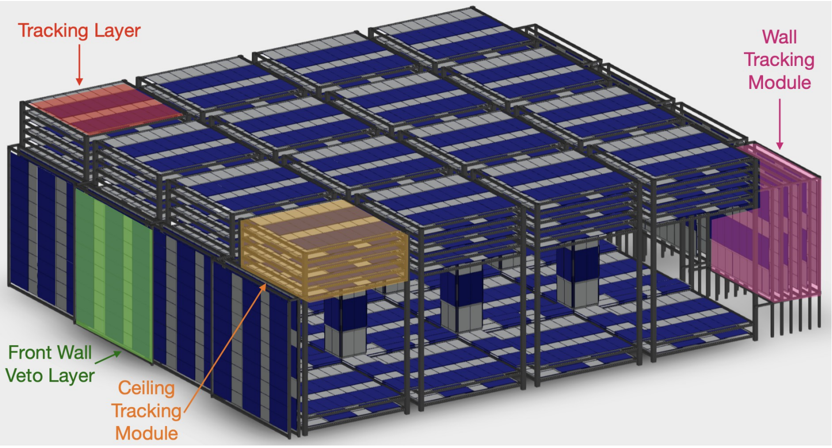
Cristiano Alpigiani. Exploring the lifetime and cosmic frontier with the MATHUSLA detector, 2020, arXiv: 2006.00788.

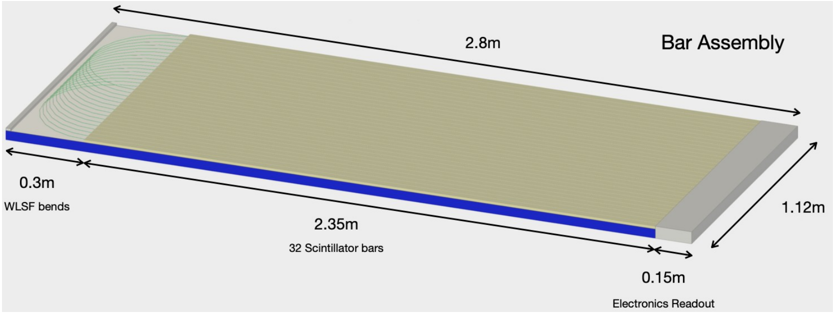
M. Alidra et al. The MATHUSLA Test Stand, 2020, arXiv:2005.02018.

Jared Barron and David Curtin, On the Origin of Long-Lived Particles, 2020, arXiv:2007.05538.

Cristiano Alpigiani et al. An Update to the Letter of Intent for MATHUSLA: Search for Long-Lived Particles at the HL-LHC, 2020, arXiv:2009.01693.

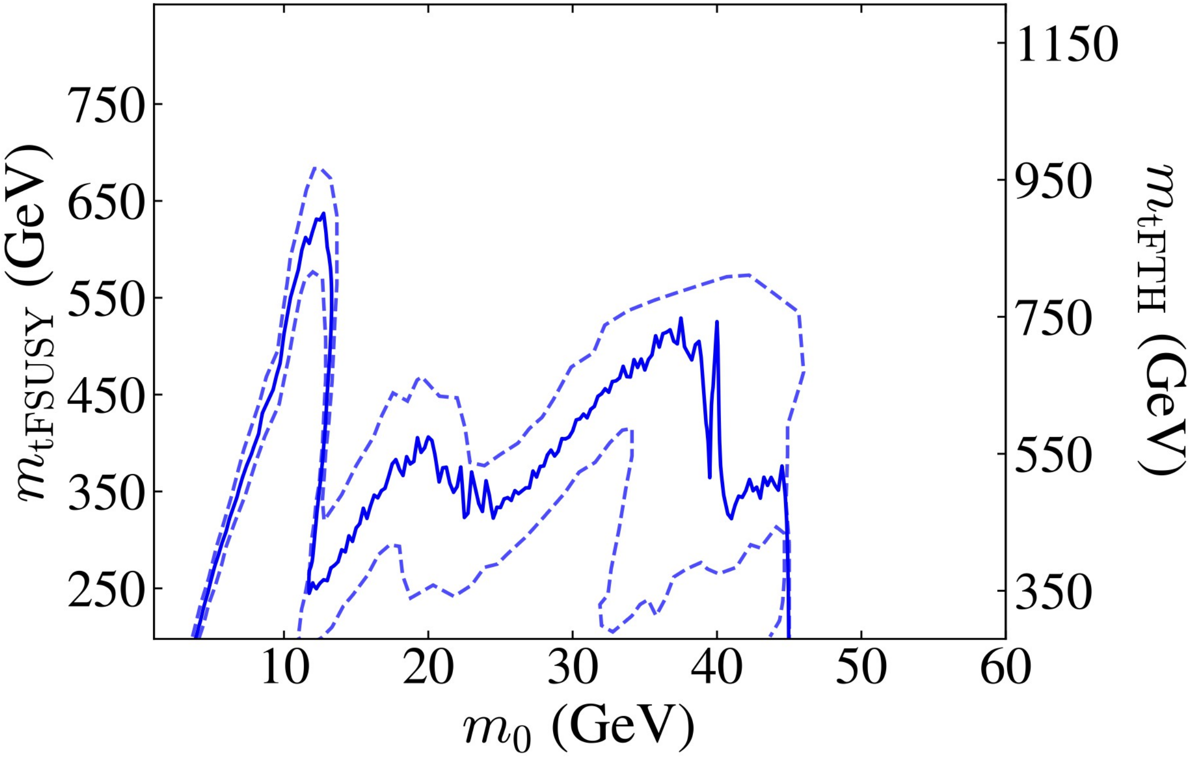
Detector specifications





Distance from CMS IP	86-97m vertical, 70-110m horizontal along beam axis.
Detector footprint	40 m × 45 m
Decay volume	$\sim$ 40 m × 40 m × 11 m
Number of tracking modules	20 total: a grid of 4 × 4 tower modules each has a ceiling tracking module, and 4 wall tracking modules are mounted on the rear wall.
Tracking module Dimensions	9 m × 9 m, height $\sim$ 4 m
Tracking layers	6 in ceiling (top 4m, 0.8m apart) and 6 in rear wall (starting $\sim$ 4.5m above the floor, also 0.8m apart).
Hermetic wall detector	Double layer in wall facing IP to detect LHC muons.
Hermetic floor detector	2 floor veto layers at heights 0.5m and 1m in each of the 16 tower modules, 24 (9 m × 2.8 m) floor veto strips to cover gaps between tower modules, and 9 column detectors each utilizing 4 vertical floor veto strips to cover the vertical support columns.
Detector technology	Extruded plastic scintillator bars, 3.5 cm wide, 1 cm thick, 2.35 m long, arranged in alternating orientations with each vertical tracking layer. Bars are threaded with wavelength-shifting fibers connected to SiPMs.
Number of bar assemblies	6224, 32 channels each
Number of Channels	$\sim 2 \times 10^5$ SiPMs
Tracking resolution	$\sim$ 1 ns timing resolution; $\sim$ 1 cm (15 cm) along transverse (longitudinal) direction of scintillator bar.
Trigger	3 × 3 groups of tracking modules perform simplified tracking/vertexing to trigger on upwards-traveling tracks and vertices. Corresponding time stamps flag regions of MATHUSLA datastream for full reconstruction and permanent storage. MATHUSLA can also send hardware trigger signal to CMS to record LLP production event.
Data rate	Each tracking module and section of floor veto detector detector associated with each tower module produces $\lesssim$ 0.6 TB/day. (The front wall veto detector data rate is a small addition.) Less than 0.1% of full detector data will be selected for permanent storage using a trigger system, corresponding to about 8 TB/year.

Neutral Naturalness



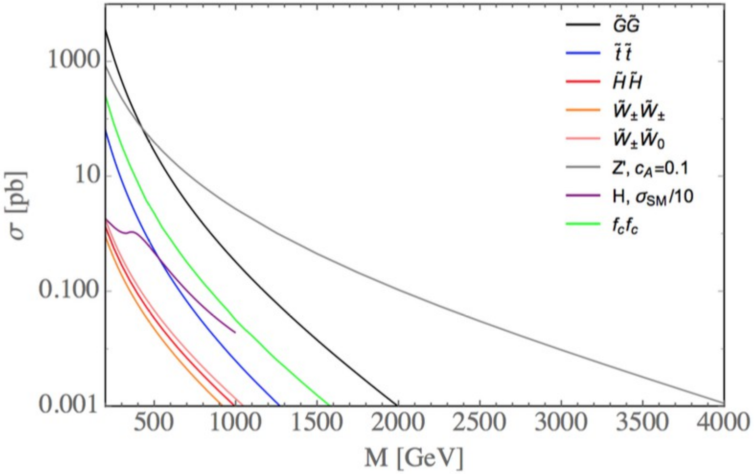
Reach of the 40m MATHUSLA design in a simplified parameter space of Neutral Naturalness, generated using the dark glueball Monte Carlo from [18]. Dark glueballs, the lightest of which has mass m0, are produced in exotic Higgs decays which undergo dark Lund-String hadronization. The effective higgs coupling to dark gluons, which also allows glueballs to decay, is generated by neutral top partners in the Folded SUSY [46] and Fraternal Twin Higgs [16] models, with masses indicated on the horizontal axes. The solid blue curve shows the reach for 8 decays in the MATHUSLA decay volume, corresponding to the exclusion limit for 50% reconstruction efficiency expected for near-background-free searches. The dashed curves represent theoretical uncertainties in this reach from unknown aspects of non-perturbative dark Nf = 0 QCD.

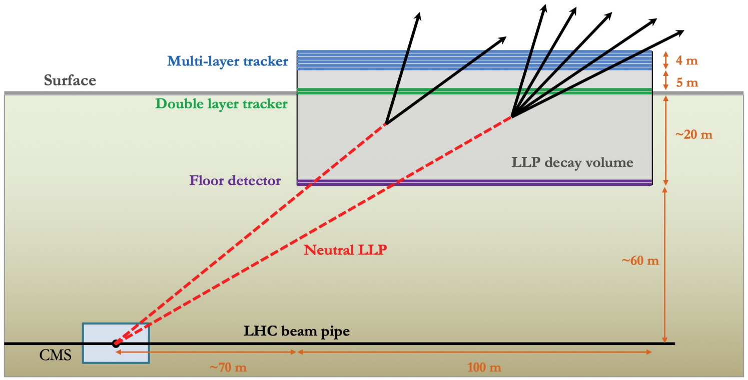
Physics objectives

MATHUSLA can search for two general categories of physics signatures:

- Hadronically decaying LLPs ranging from a few GeV to TeV scale
  - High multiplicity final states are relatively easy to vertex and distinguish from backgrounds
  - Factor of 1000 improvement over LHC for LLPs with mass < ~100GeV *(LHC searches background limited and are difficult to trigger)*
- LLPs with mass less than a few GeV (any decay mode)
  - Typically low multiplicity (i.e. 2 tracks) final states
  - Sensitivity **very dependent on detector geometry and performance** due to both signal efficiency and background rejection requirements

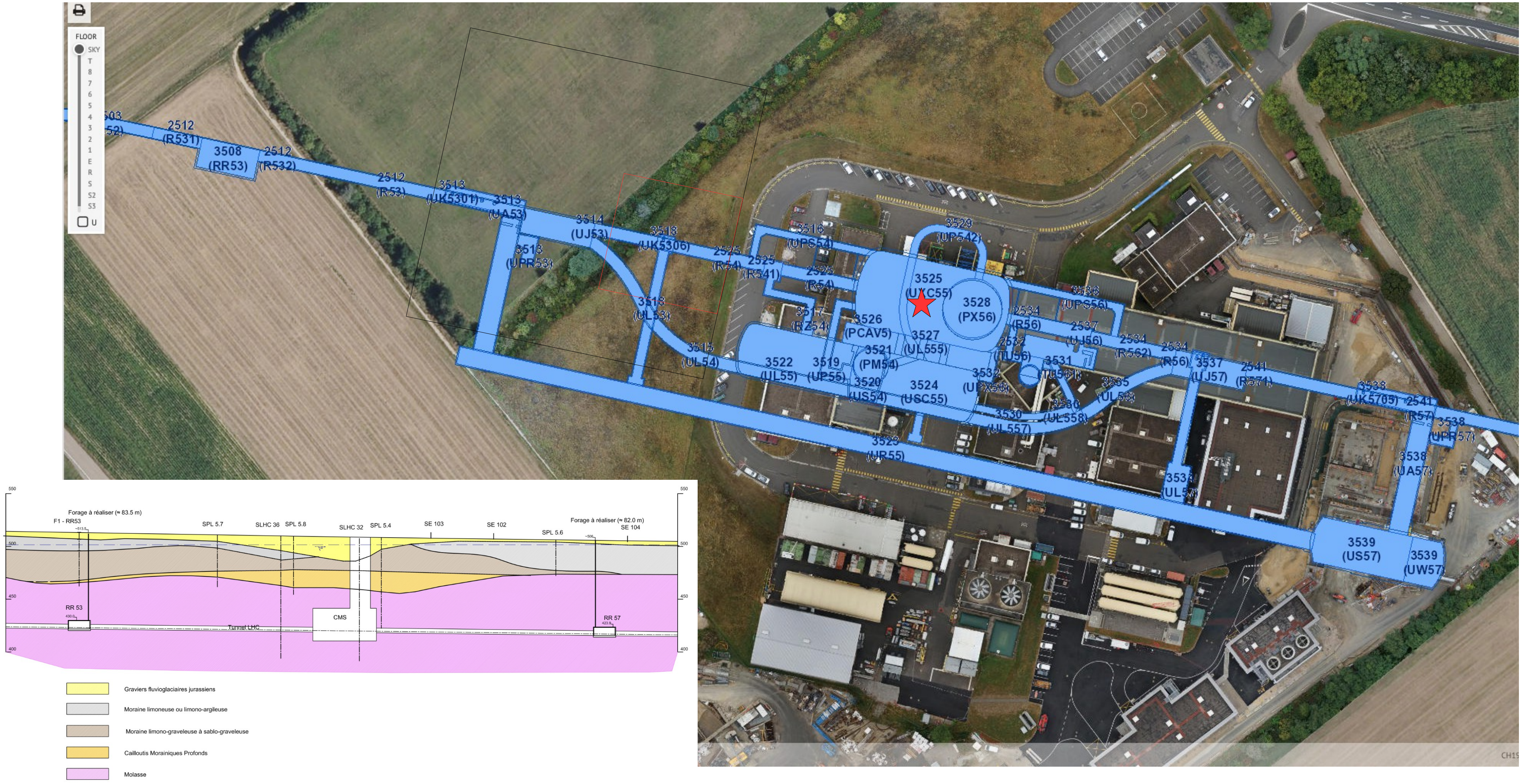
Any production process with σ>1fb can give a signal. Sensitivity to multi-TeV scales:





Second category provides the main benchmarks for detector design

Location



🟨 Graviers fluvioglaciaires jurassiens

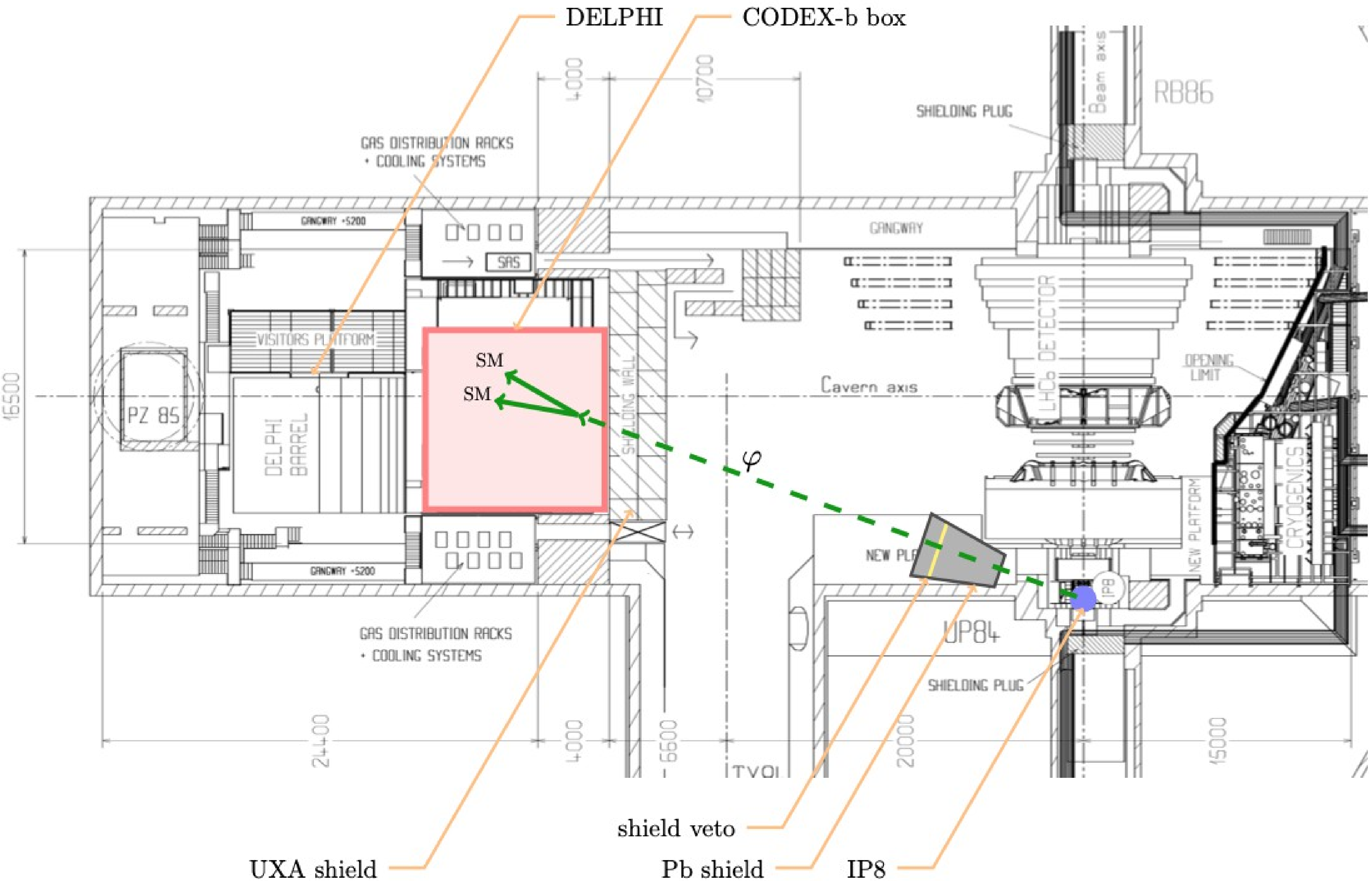
⬜ Moraine limoneuse ou limono-argileuse

🟫 Moraine limono-graveleuse à sablo-graveleuse

🟧 Cailloutis Morainiques Profonds

🟪 Molasse

CODEX-b


DELPHI
CODEX-b box
4000
10700
GAS DISTRIBUTION RACKS + COOLING SYSTEMS
RB86
Beam axis
SHIELDING PLUG
GANGWAY
GANGWAY +5200
SAS
VISITORS PLATFORM
16500
PZ 85
DELPHI BARREL
SM
SM
SHIELDING WALL
Cavern axis
LHCb DETECTOR
OPENING LIMIT
φ
NEW PLATFORM
CRYOGENICS
IP8
UP84
24400
4000
6600
20000
15000
TVOI
shield veto
UXA shield
Pb shield
IP8