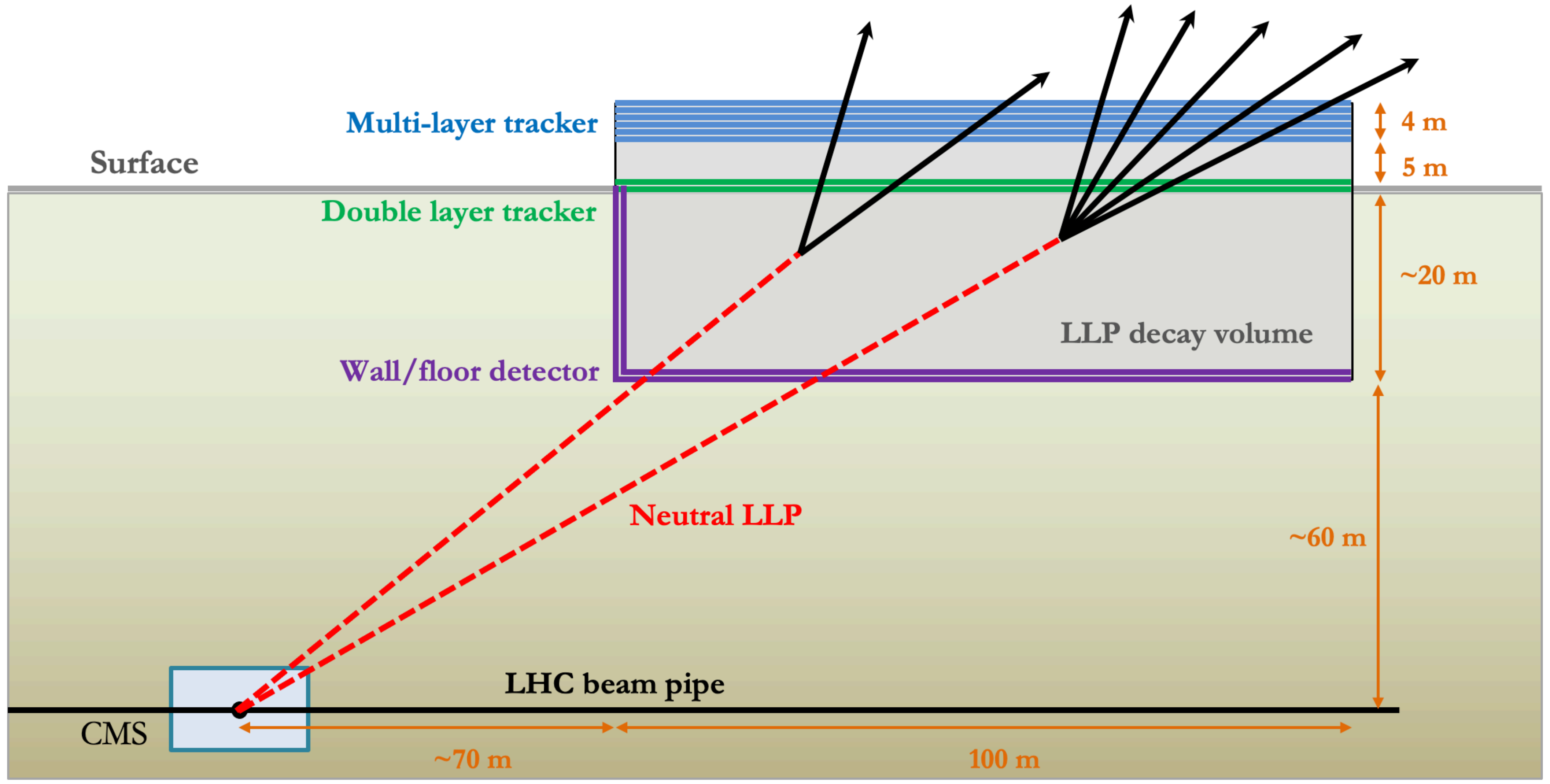
MATHUSLA LLP Detector Proposal: Current Status and Prospects

FNAL LPC Topic of the Week Seminar

26 Sep 2023

David Curtin

UNIVERSITY OF TORONTO



mathusla-experiment.web.cern.ch

Outline

1. Physics Motivation
2. MATHUSLA Detector Concept
3. **Synergies with CMS**
4. Detector Design
5. DAQ/Trigger/Computing
6. Civil Engineering
7. Cost Estimates
8. Schedule Goal
9. Some Ongoing Efforts
10. **Next Steps**

1. Physics Motivation

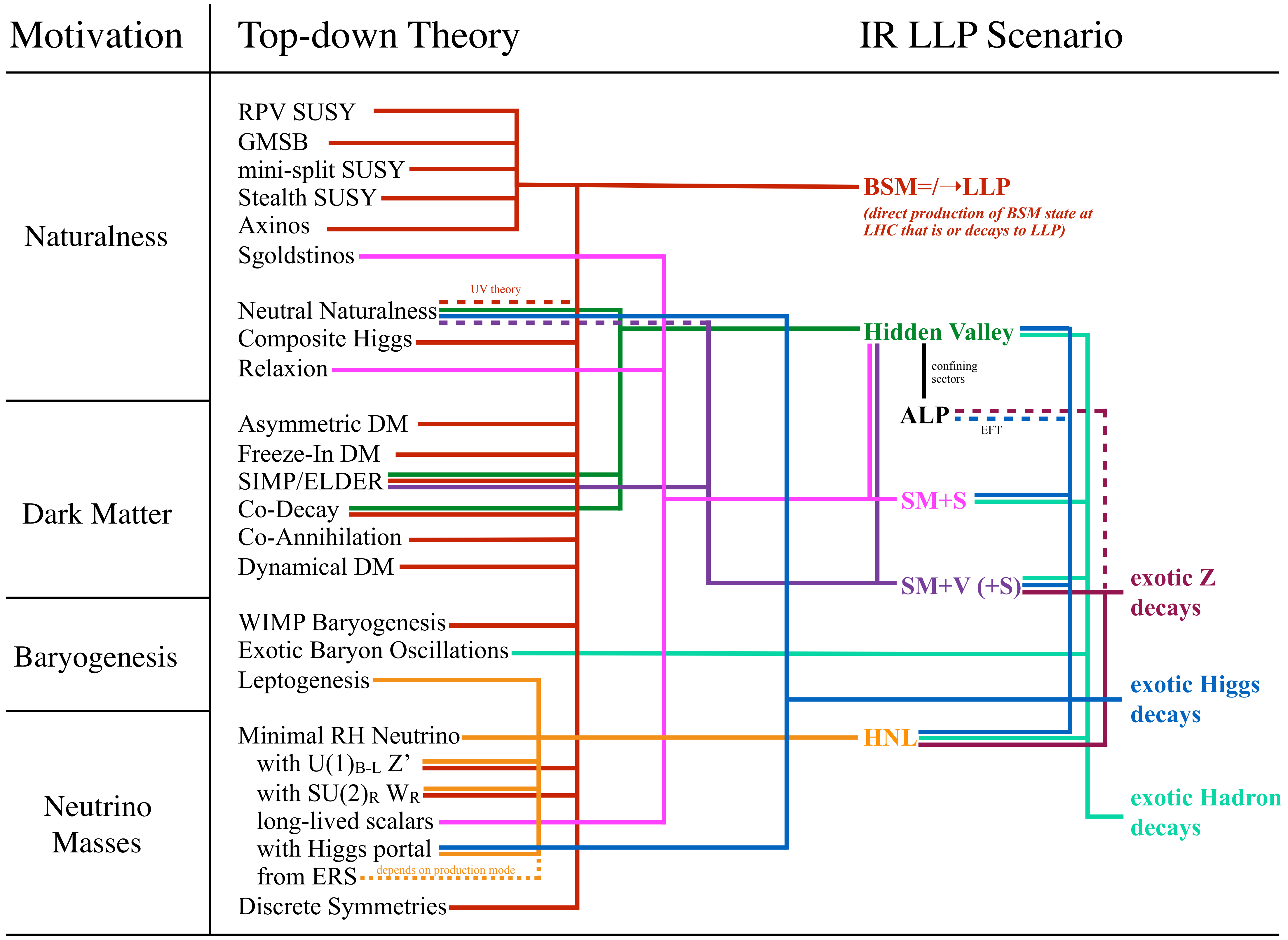
Physics Motivation

- Long-Lived Particles (LLPs) are a completely generic signature of new physics.
- Could solve any of the *Major Mysteries*™.
- Lifetime is essentially a free parameter, up to BBN limit of ~ 0.1 second.
- For lifetimes >> meter, decays in main LHC detectors become very **RARE**

  → backgrounds and triggers become crucial bottlenecks

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

1806.07396



Physics Targets

We identify two classes of LLP signals that are main detector blind-spots in the long-lifetime limit

(i.e. single-DV search has low trigger acceptance and significant main detector background)

1. **Primary physics target: O(10-100 GeV) LLPs that decay hadronically**
   High theoretical motivation, e.g. from exotic Higgs decays.

2. **Secondary physics target: O(GeV) LLPs, any decay mode**
   e.g. from light scalar or RHN LLPs. Small final state multiplicity and low energy scale (produced in B/D decays), theoretically ubiquitous.

2. MATHUSLA Detector Concept

Collaboration and Current Status

- Spokesperson: **Henry Lubatti** (University of Washington)
- Management: **David Curtin** (University of Toronto), **Erez Etzion** (Tel Aviv), **Henry Lubatti** (University of Washington), **Charlie Young** (SLAC)
- Submitted LOI to LHCC 1811.00927, 2009.01693
- Operated test stand in ATLAS hall 2005.02018
- Inputs to Snowmass, European Strategy, …
- Conducted significant simulation, detector design and R&D efforts for CDR, which is in final editing stages.

mathusla-experiment.web.cern.ch/

Conceptual Design Report for the MATHUSLA Long-Lived Particle Detector near CMS.

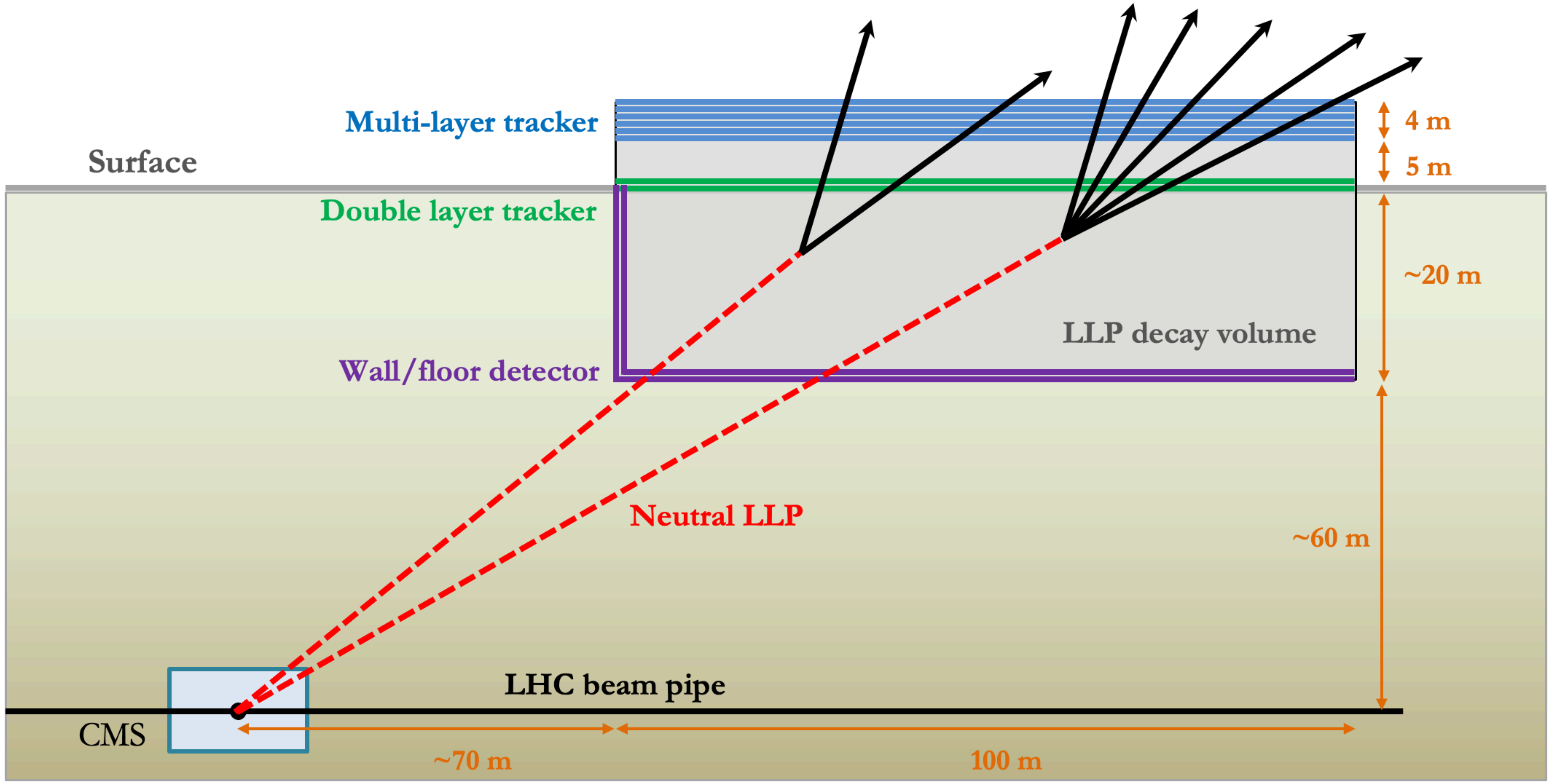
Contents

Draft

Draft

I'll give a preview of CDR material and comment on other ongoing efforts within the collaboration.

MATHUSLA Detector



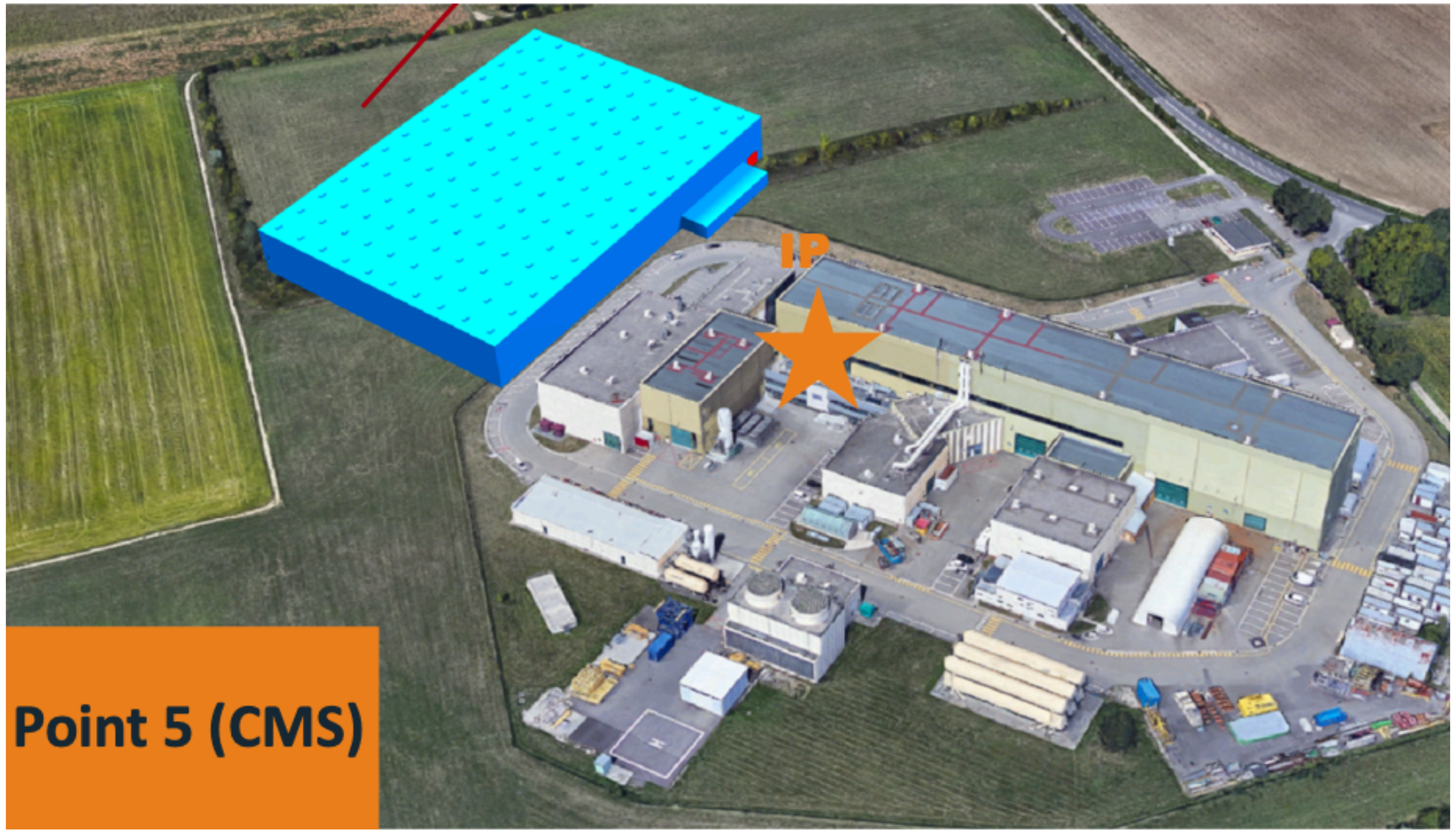
Basic idea: a roughly 100m-footprint empty building next to CMS, with trackers in the roof to reconstruct LLP decays produced in LHC collisions ~ 100m away.

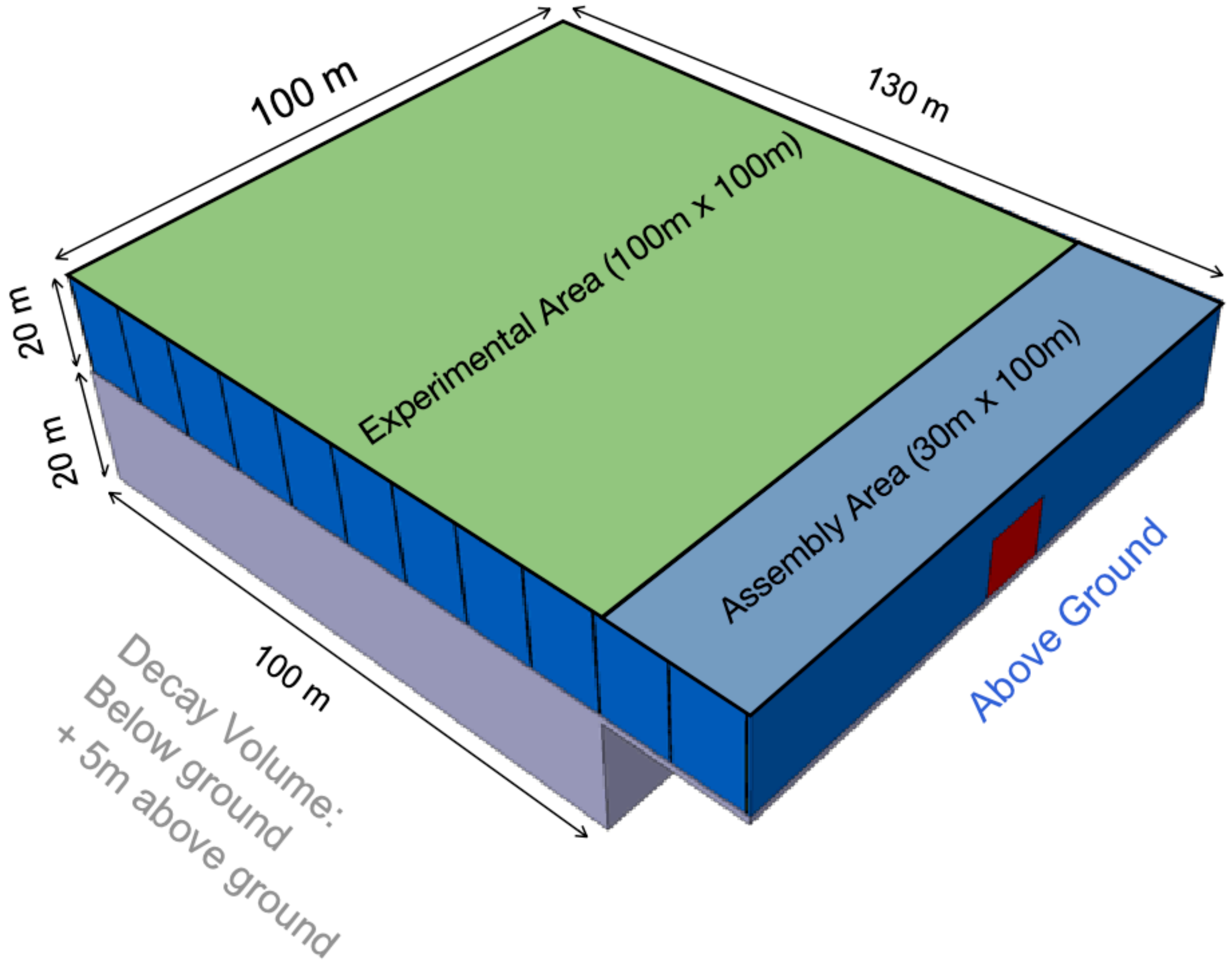
Wall/floor detector provides additional veto capabilities for LHC muons.

Chou, DC, Lubatti 1606.06298

MATHUSLA at P5

Proposed building to house MATHUSLA on CERN owned lands at P5



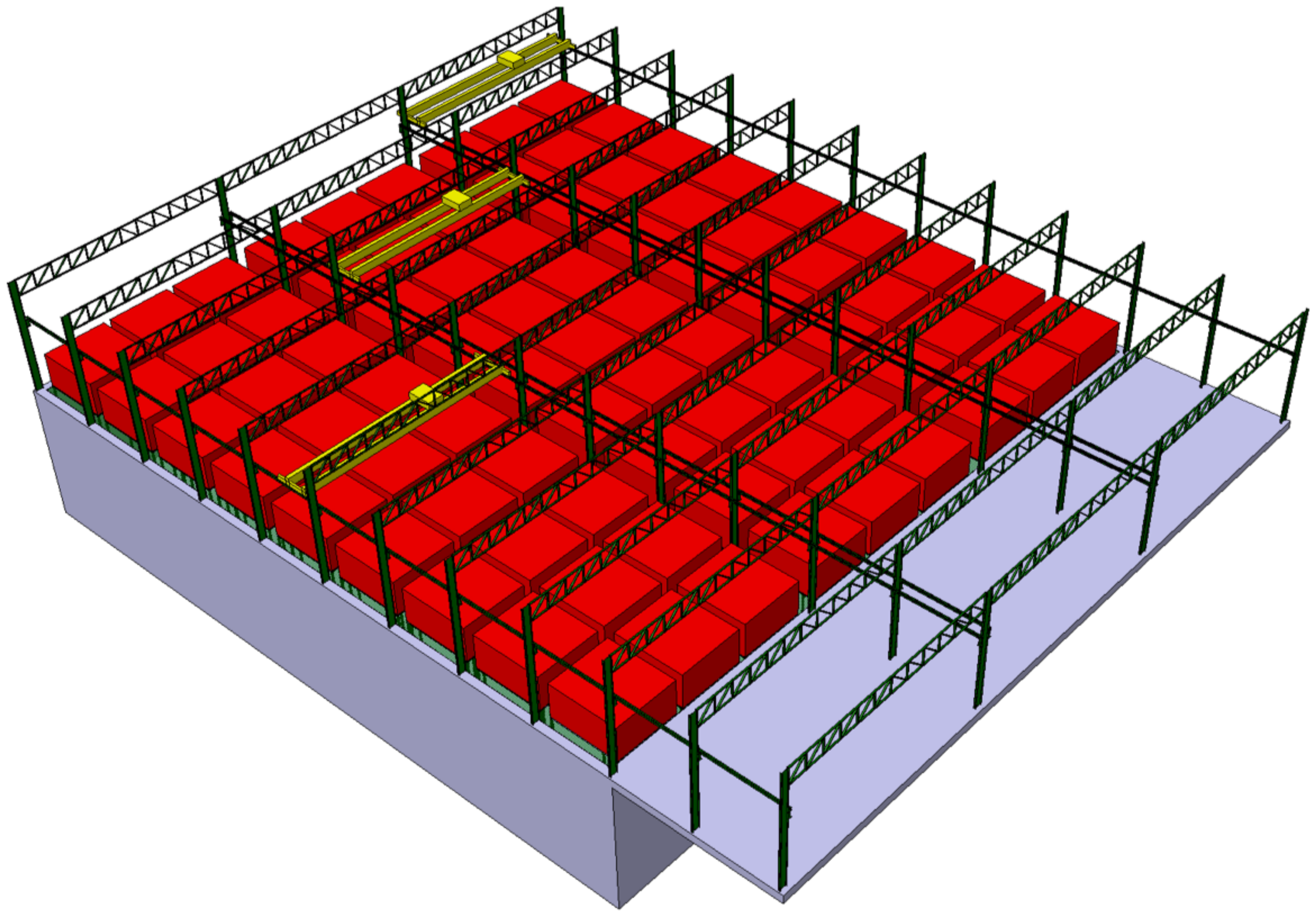


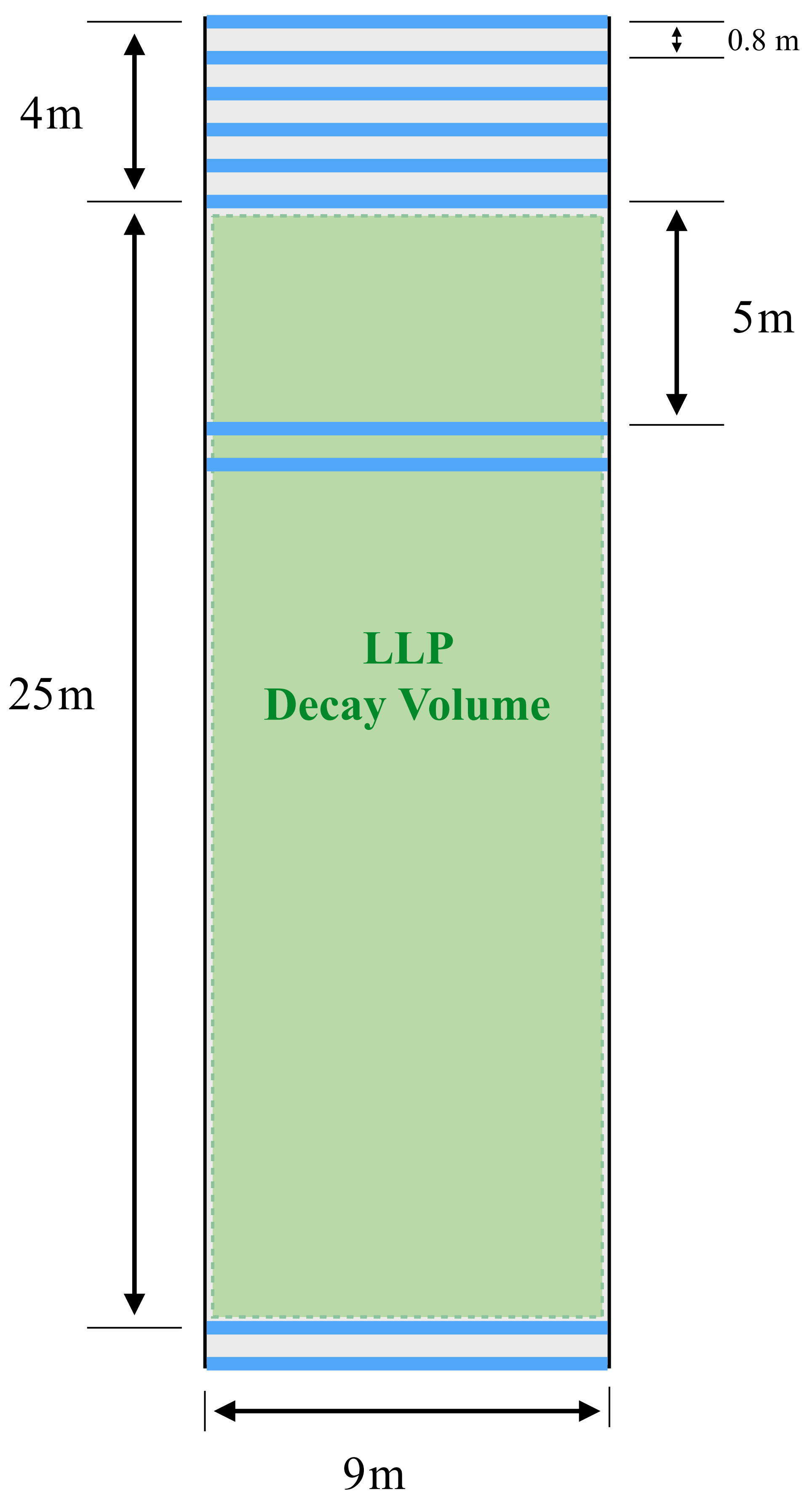
Layout restricted by existing structures based current concept and engineering requirements.

Building at the surface extends ~20m below ground

with thanks to Emma Torro Pastor for the slide

Modular Design





Modular design,
~ 10x10 modules,
~ $(9m)^2$ each

Each module has
6+2 tracking layers
+ floor detector

Physics Reach

2308.05860

Most recent estimates based on careful simulations of three benchmark models.

All assume zero background, but do take into account geometric acceptance of detector to LLP final states, requiring 2+ tracks with 4+ hits each for vertex reconstruction. **Should be very close to real sensitivity.**

Careful simulation of 3 benchmark physics models:

Primary Physics Target

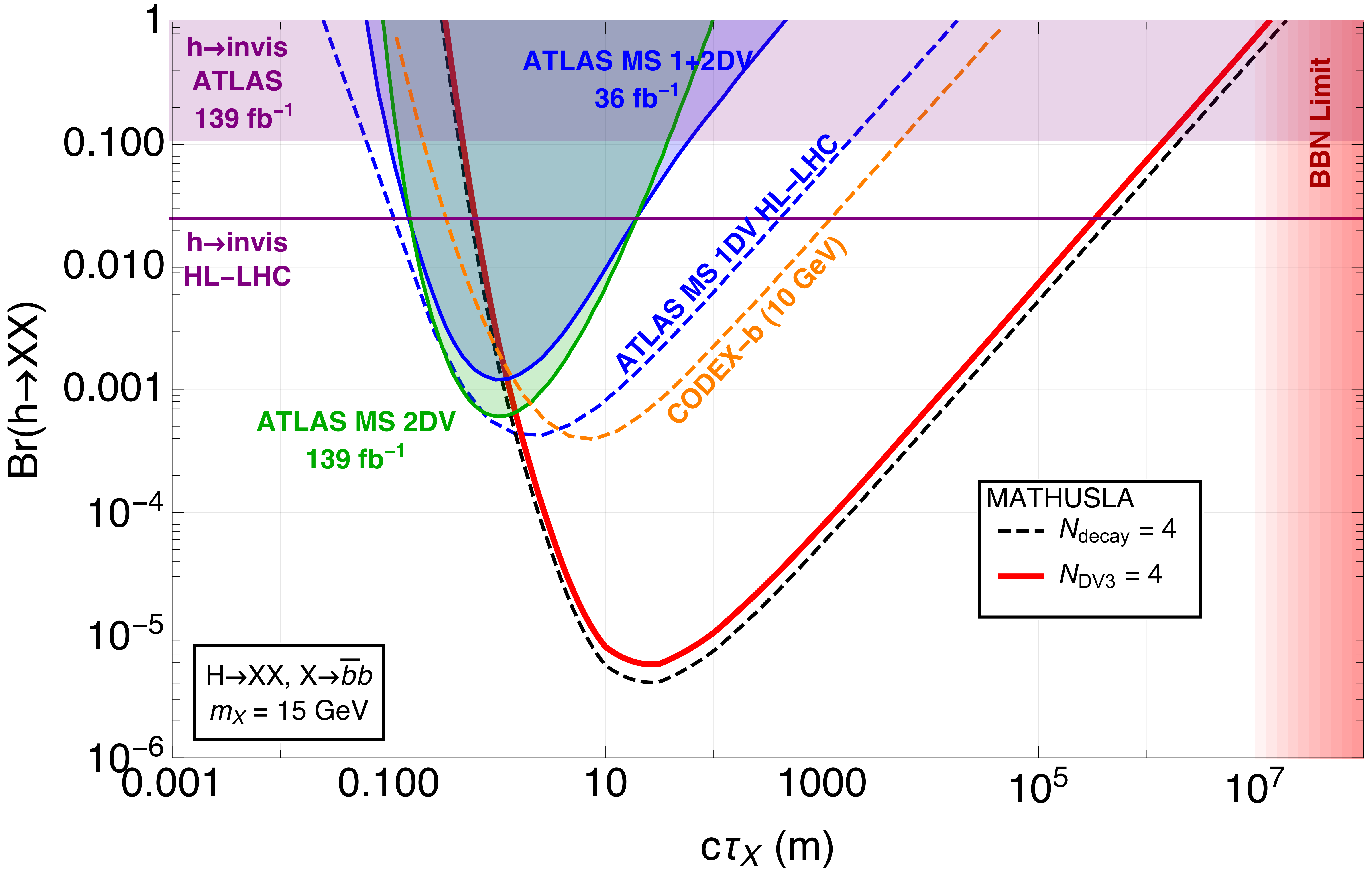
1) Exotic Higgs Decays $h \to XX \ , \quad X \to \bar{b}b \text{ or } jj$

Secondary Physics Target

2a) SM + S (GeV-scale light scalar LLP mixed with Higgs)

2b) RHN (GeV-scale Right-Handed Neutrino LLPs with small active-neutrino mixing)

Exotic Higgs Decays



Addendum: in updates, here will show for comparison CMS EXO-21-008 single DV search in muon system

MATHUSLA has near-unity geometric acceptance for high-multiplicity hadronic LLP decays

Most sensitive main detector search in long-lifetime regime is 1DV search in muon system. 1605.02742

MATHUSLA 3 orders of magnitude more sensitive than main detectors.

Also 2+ orders of magnitude more sensitive than CODEX-b

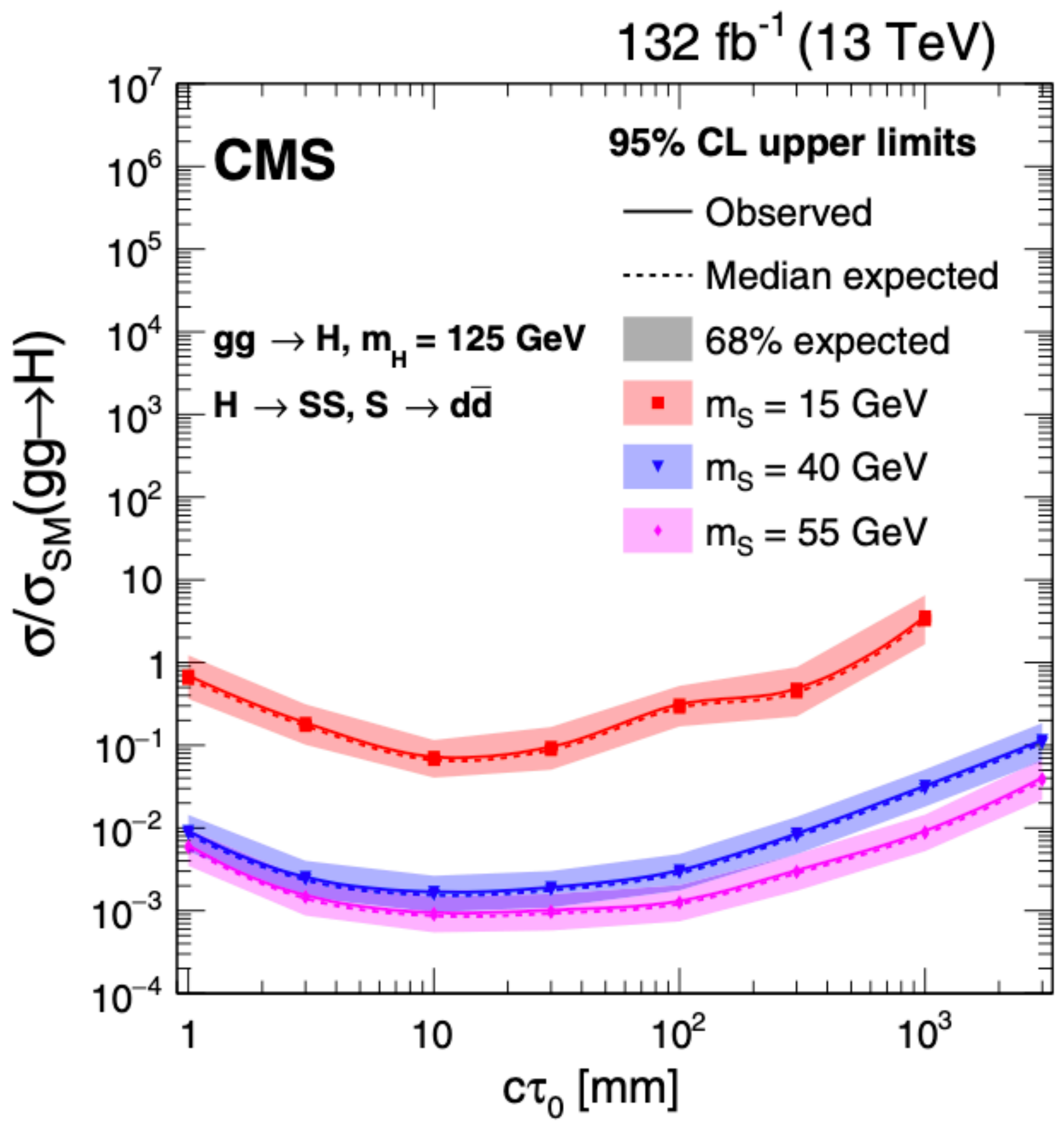
Comparison with ATLAS/CMS

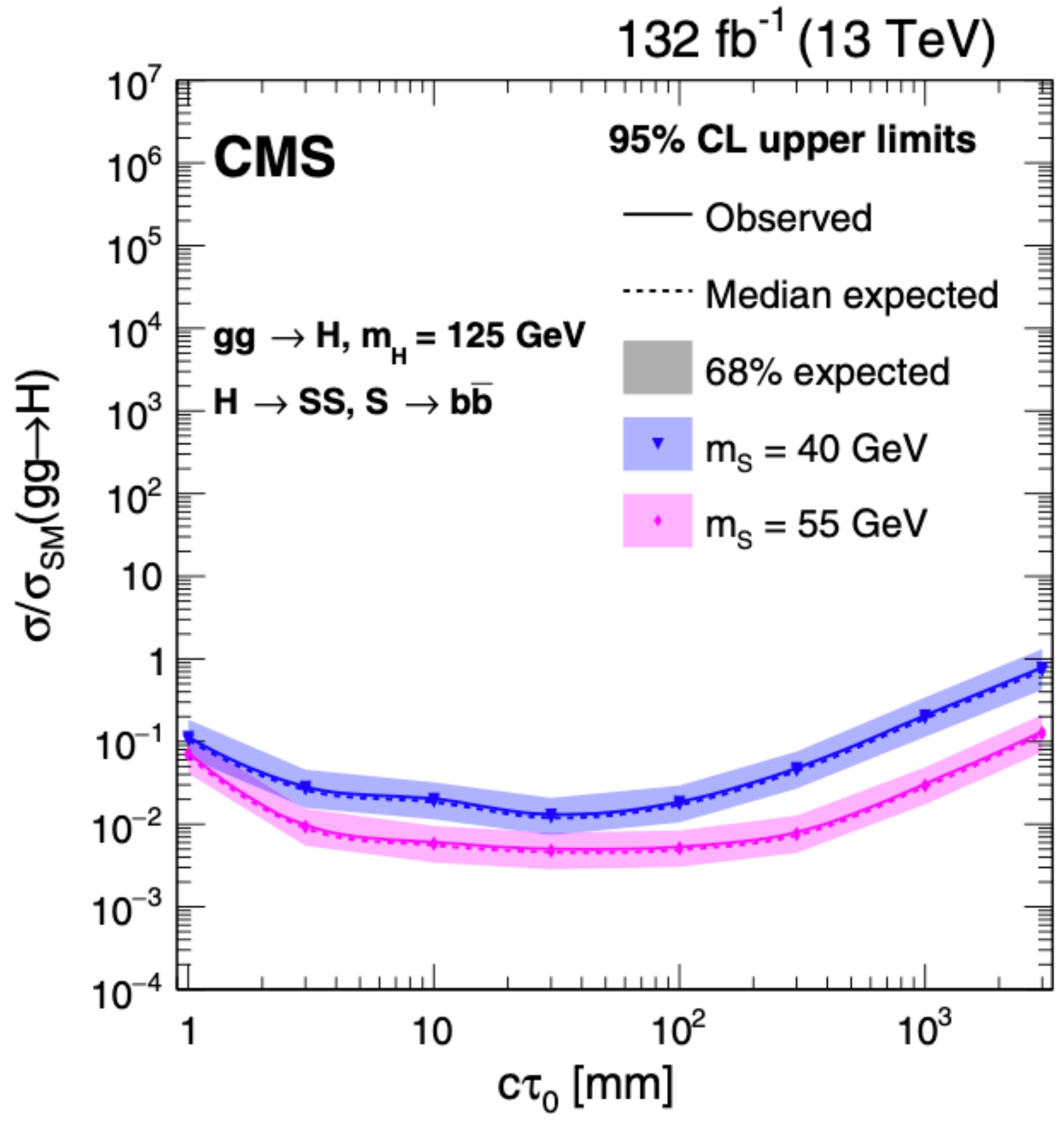
In the long-lifetime regime, only searches that can pick up a SINGLE DV are sensitive.

Most sensitive reliable projection based on **ATLAS 1DV-search in muon system**. Key advantage: MS acts as L1 trigger.

CMS has powerful displaced dijet search, but currently requires L1 $H_T \gtrsim 500\ \mathrm{GeV}$ trigger seed, very low acceptance for exotic Higgs decays.

Even optimistic scaling to HL-LHC and assuming various analysis improvements, MATHUSLA has $10^2 - 10^4 \times$ more sensitivity, depending on LLP mass.





HL-LHC main detector upgrades?

Difficult to estimate, but it's an uphill battle due to busy HL-LHC environment.

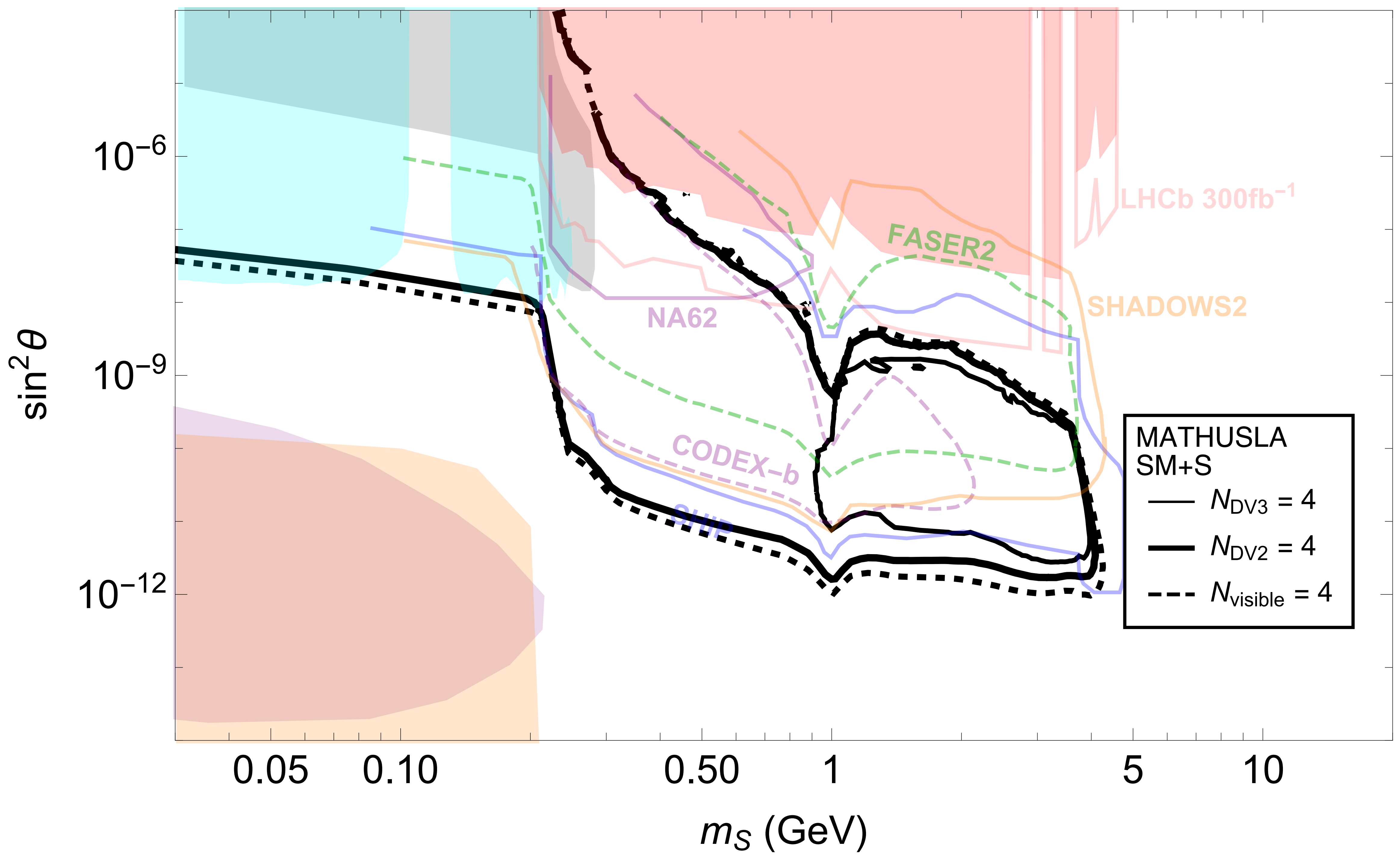
Could imagine CMS-displaced-dijet style search with different L1 seed, e.g. isolated lepton for VH production.

> **CMS Tracker and MATHUSLA have similar geometric acceptance for LLP decays in long-lifetime regime, but VH production has 1/200 rate penalty.**

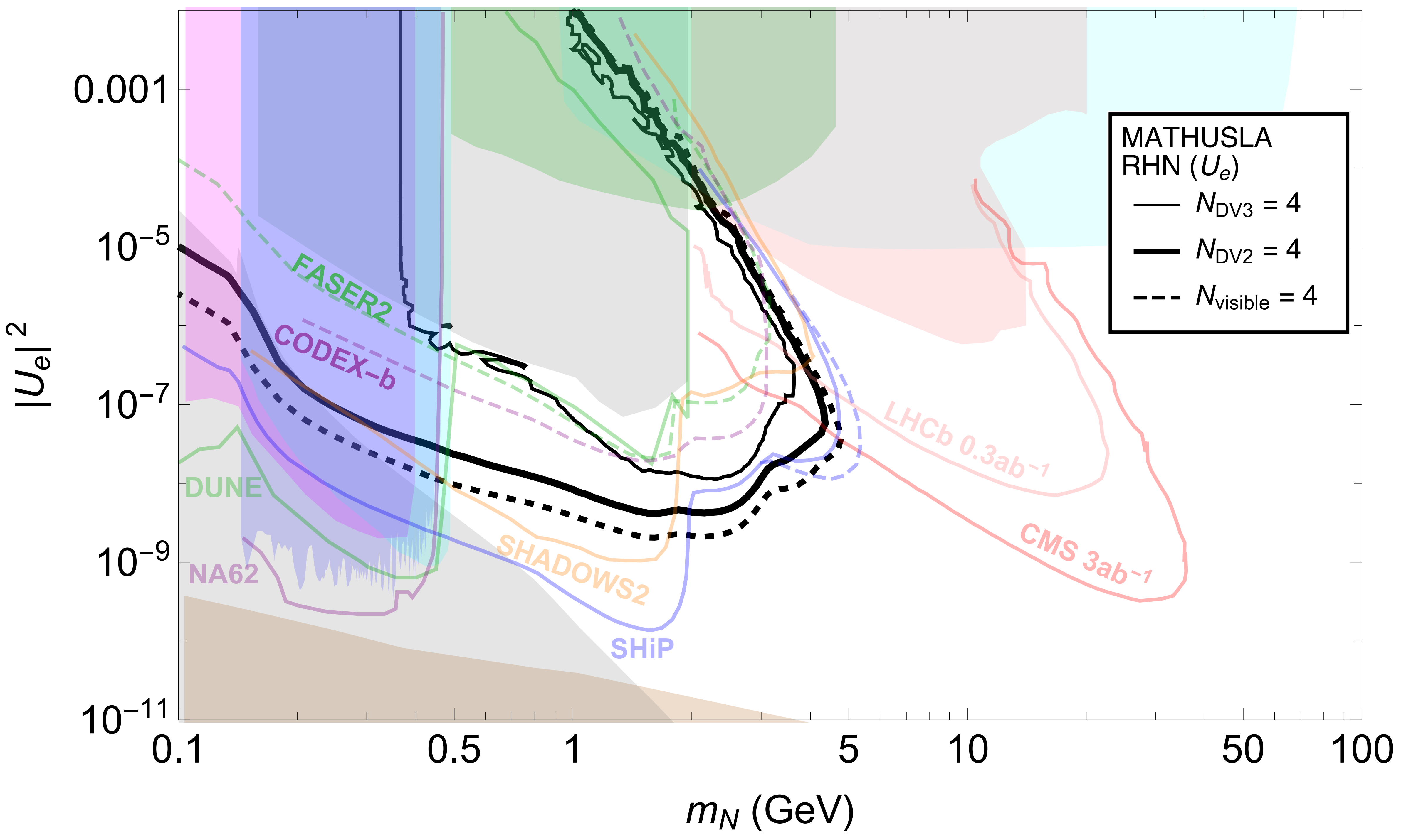
*More speculative: L1 tracking/vertexing/timing upgrades? To be competitive with MATHUSLA, would have to catch order-1 fraction of **all** $h \to XX$ events where one X decays to hadrons in tracker. Seems challenging?*

GeV-Scale LLPs

LLP Scalars



LLP RHN mixing with ν_e



Upshot:
MATHUSLA explores orders of magnitude of new parameter space, extending reach of various other intensity-frontier proposals like FASER or SHADOWS.

Backgrounds

There are NO backgrounds for the primary physics target, which is O(10) charged hadrons generating a high-multiplicity displaced vertex.

There are some backgrounds we have to carefully understand for the secondary physics target of O(GeV) LLP decays, most of which only result in 2 tracks.

Backgrounds: Cosmic Rays

Dominant source of particle flux on MATHUSLA, about 2 MHz on whole detector.

CR's themselves are NOT actually a LLP background, cm & ns tracking resolution easily distinguishes up vs down tracks, and CRs don't form a vertex.

However, CR Nucleons can undergo inelastic backscatter in detector floor.

Over whole life of detector, results in **O(1000) non-relativistic K_L^0's traveling into MATHUSLA volume** and decay into charged particles that could reach the ceiling trackers. In principle, this is a background for **secondary** physics target.

⇒ This BG can be precisely measured and characterized when LHC beam is off

⇒ Extreme low momentum of final states (< 400 MeV), very wide opening angle, and other features should allow this to be vetoed to manageable or even negligible level. (Studies ongoing)

Backgrounds: Atmospheric Neutrinos

Isotropic atmospheric neutrinos (E ~ GeV) can scatter off air or detector material, generating a vertex.

Requiring 2+ charged particles yields about 30 events per year.

Can be vetoed with time-of-flight track measurements, since one of the tracks must be a non-relativistic proton with $\beta < 0.8$, to << 1 event per year.

Backgrounds: LHC Muons

Muons with initial energy $\gtrsim$ 40 GeV are able to penetrate the rock shielding and reach the MATHUSLA detector volume.

Vast majority of muons do not constitute LLP background, do not form a vertex.

Muons produce Delta Rays, but their narrow vertices, if reconstructed, can be rejected. Can also be vetoed with floor/wall detectors, and optionally with offline information from CMS muon system.

Detailed studies ongoing, depends on exact track/vertex resolutions, but should be manageable.

3. Synergies with CMS

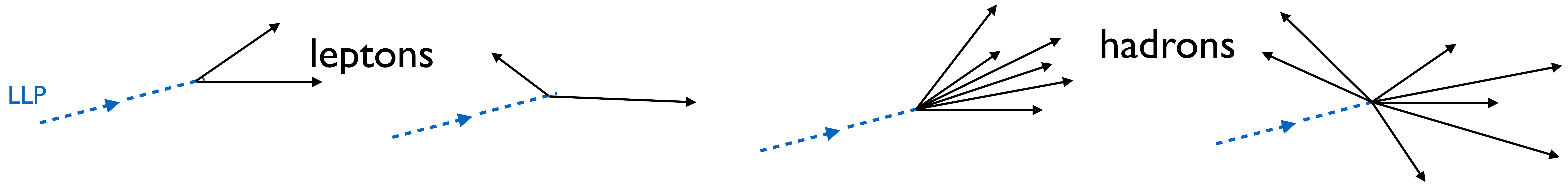
Properties of LLP Decays

MATHUSLA only has tracks, no energy or momentum measurement.

Even so, you can learn significant information about the observed LLP decay

Multiplicity ↔ Decay Mode (leptonic or low-mass vs jets)

Relative Track Directions ↔ LLP boost $b = |\vec{p}|/m$ 1705.06327



Track Orientation ↔ presence of missing energy 1809.01683 2007.05538

Correlated CMS-MATHUSLA Analysis?

If you know the production mode, the boost distribution reveals the LLP mass.

Learning the production mode requires 4π information from the main detector for the LLP production events.

Given time-of-flight, production event can be identified to within a few bunch crossings.

Could then perform correlated analysis off-line with info from both CMS and MATHUSLA.

→ Problem: one reason we're building MATHUSLA is that these LLP production events don't make it past main detector L1 triggers.

→ Solution: MATHUSLA COULD SUPPLY AN L1 TRIGGER SIGNAL TO CMS, to ensure LLP production events are recorded!

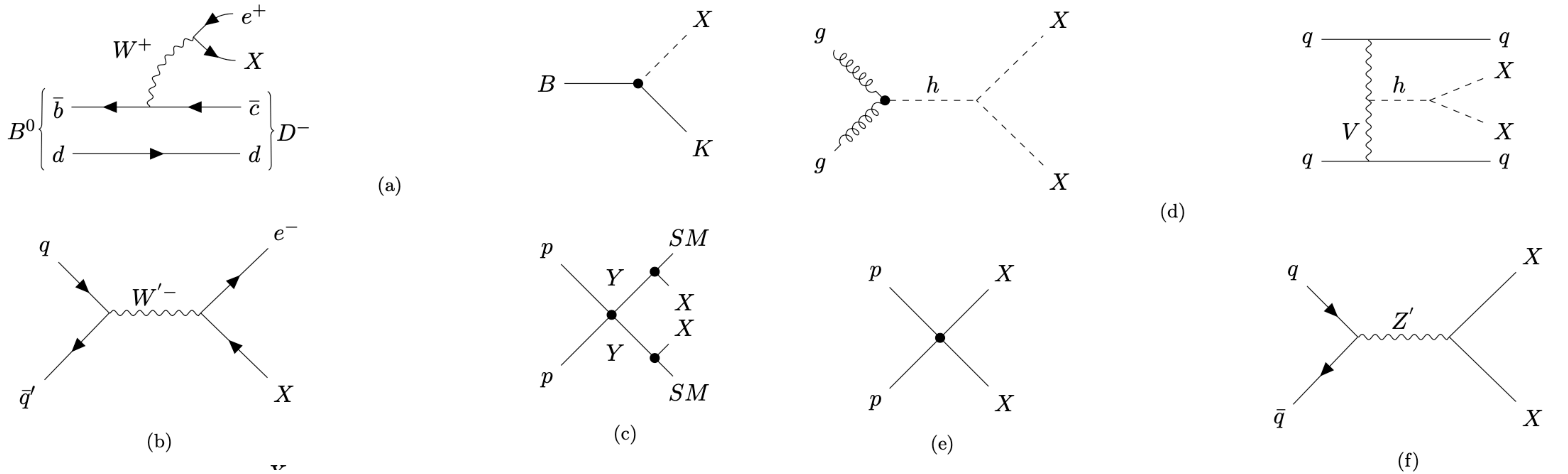
2007.05538

Diagnosing the dark sector with CMS + MATHUSLA

What could you do if MATHUSLA ensured CMS recorded LLP production events?

Step 1: Diagnosing LLP Production Mode

Have to make *some* assumptions, so adopt LLP simplified model library:



2007.05538

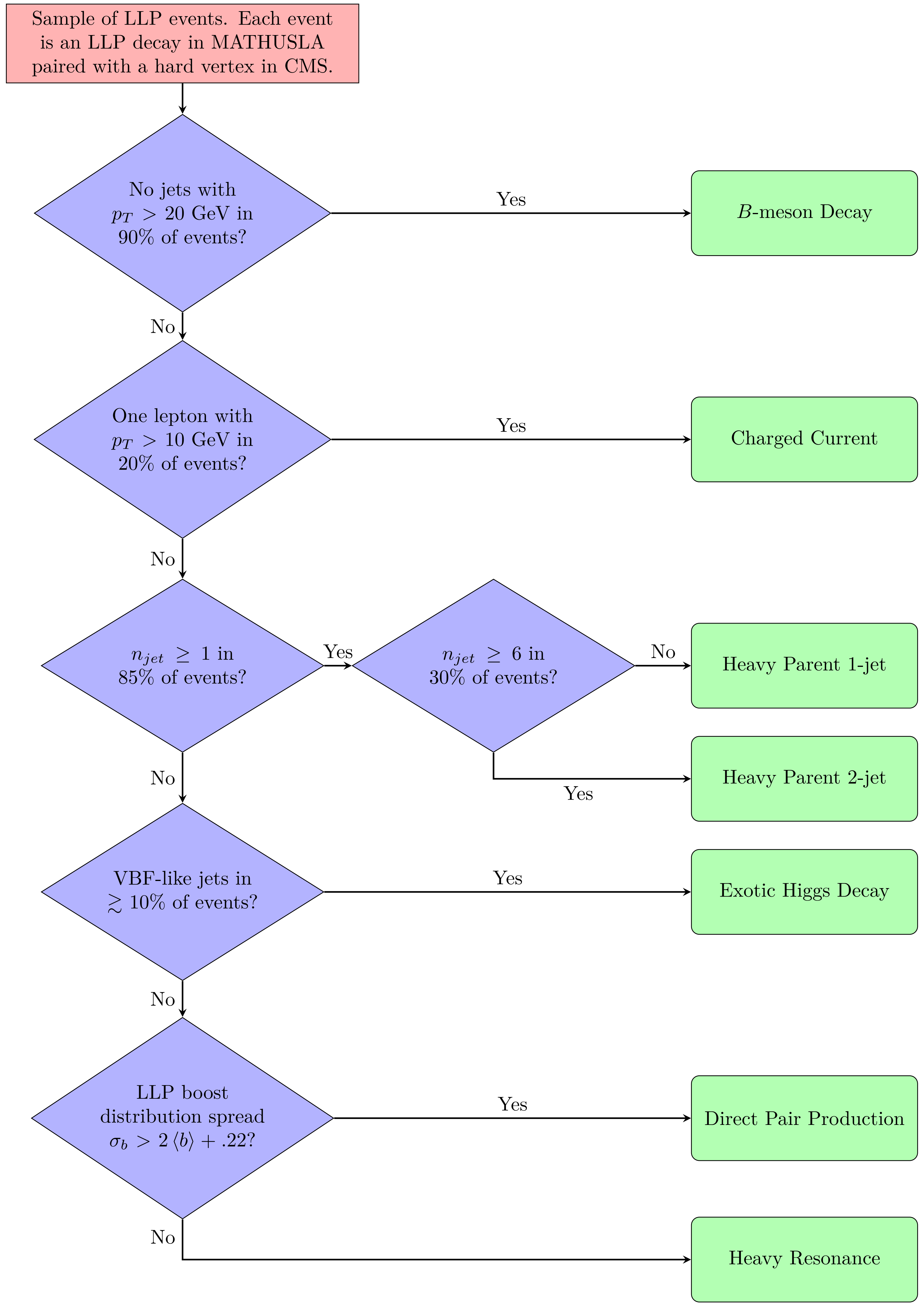
Diagnosing the dark sector with CMS + MATHUSLA

Treat events as (CMS, MATHUSLA) doublets, and perform simple decision-tree based on jet pT, lepton and jet and VBF-jet multiplicity, and shape of LLP boost distribution.

Can diagnose production mode with O(10) events!

N_{obs}	10	100	1000
B-decay (BB)	98	100	100
Charged Current (CC)	94	98	98
Heavy Parent (HP)	91	92	93
Higgs Decay (HIG)	36	91	100
Direct Pair Production (DPP)	48	98	100
Resonance, narrow-width (RES NW)	71	93	98
Resonance, high-width (RES HW)	63	86	94

Classification Accuracy (%)



2007.05538

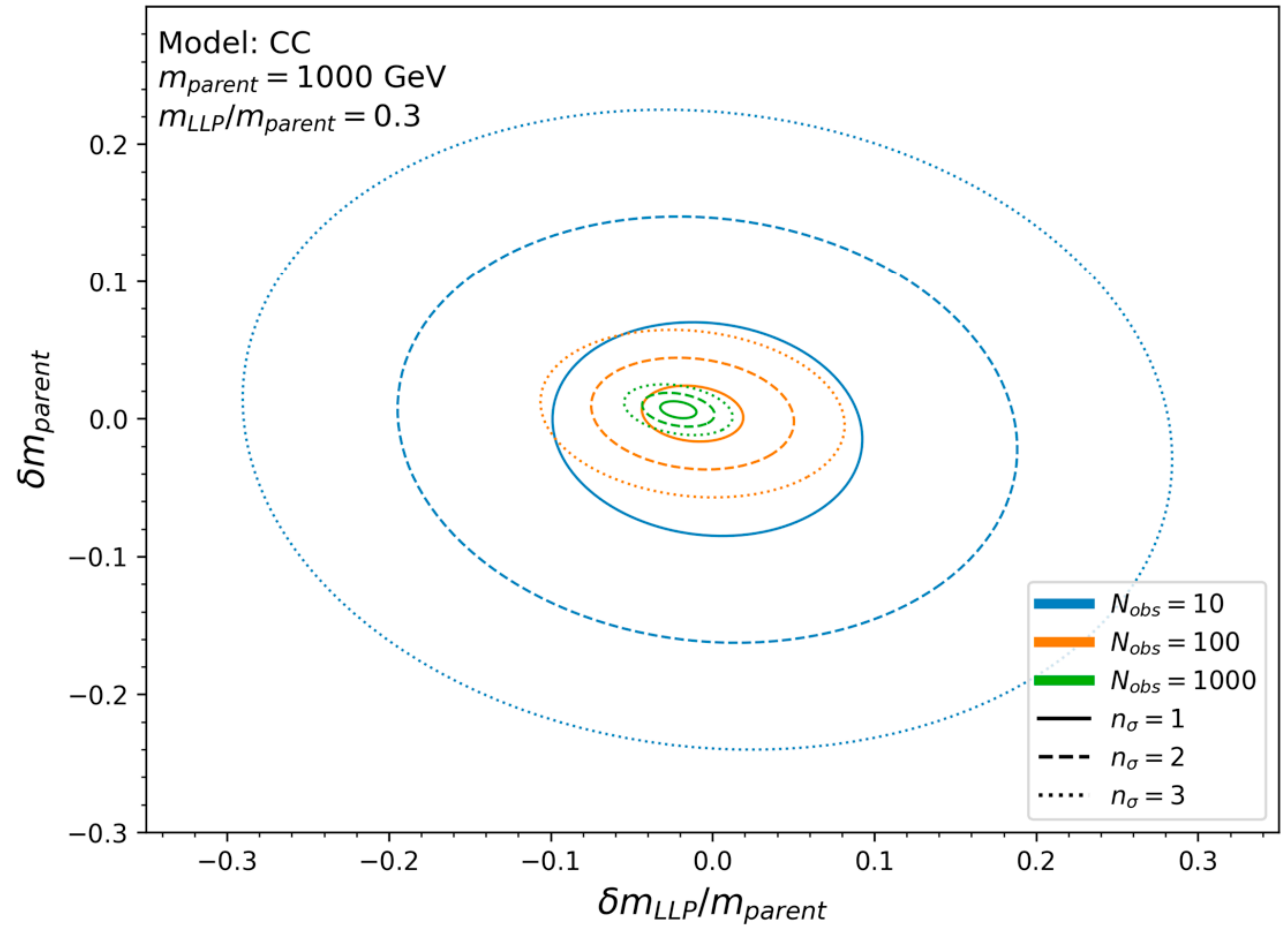
Diagnosing the dark sector with CMS + MATHUSLA

Step 2: Determining New Physics Parameters

Once you decided on a production mode, it's not too surprising that you can measure (fit) its parameters like LLP mass and parent particle mass.

We found that O(100) events are sufficient to measure new particle masses at 10%-level.

This is obviously just a theory-level analysis. Would be interesting to make it realistic!



2007.05538

Bonus Content

There are dark sector scenarios that are hard to trigger on for CMS, but produce shower of LLPs with hierarchically varying lifetimes.

Could see LLP decay in MATHUSLA, then discover more LLPs in CMS data.

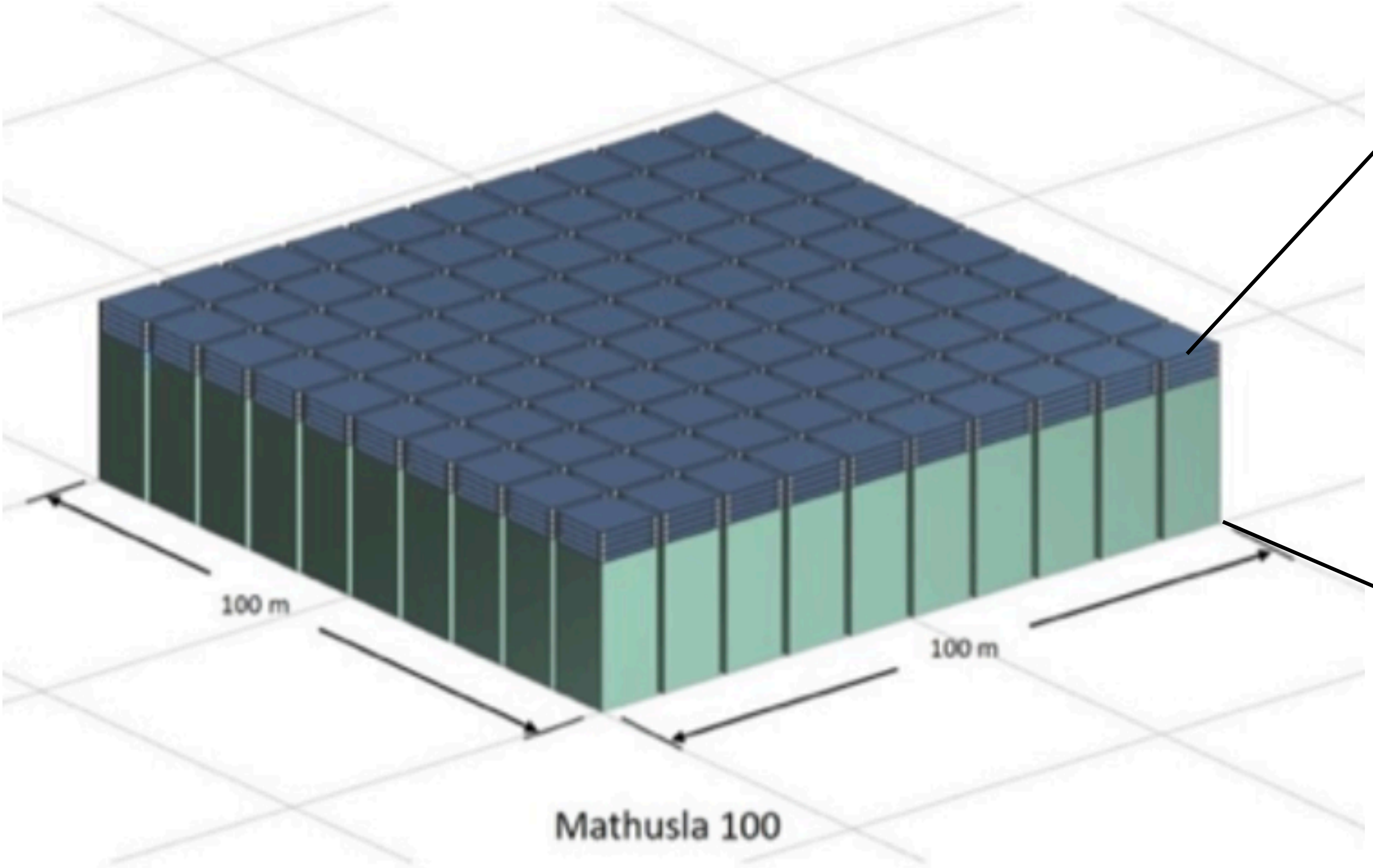
This would open up precision-diagnostics of non-perturbative dark sectors, made possible by unique ‘lever arm’ (two detectors at different length scales).

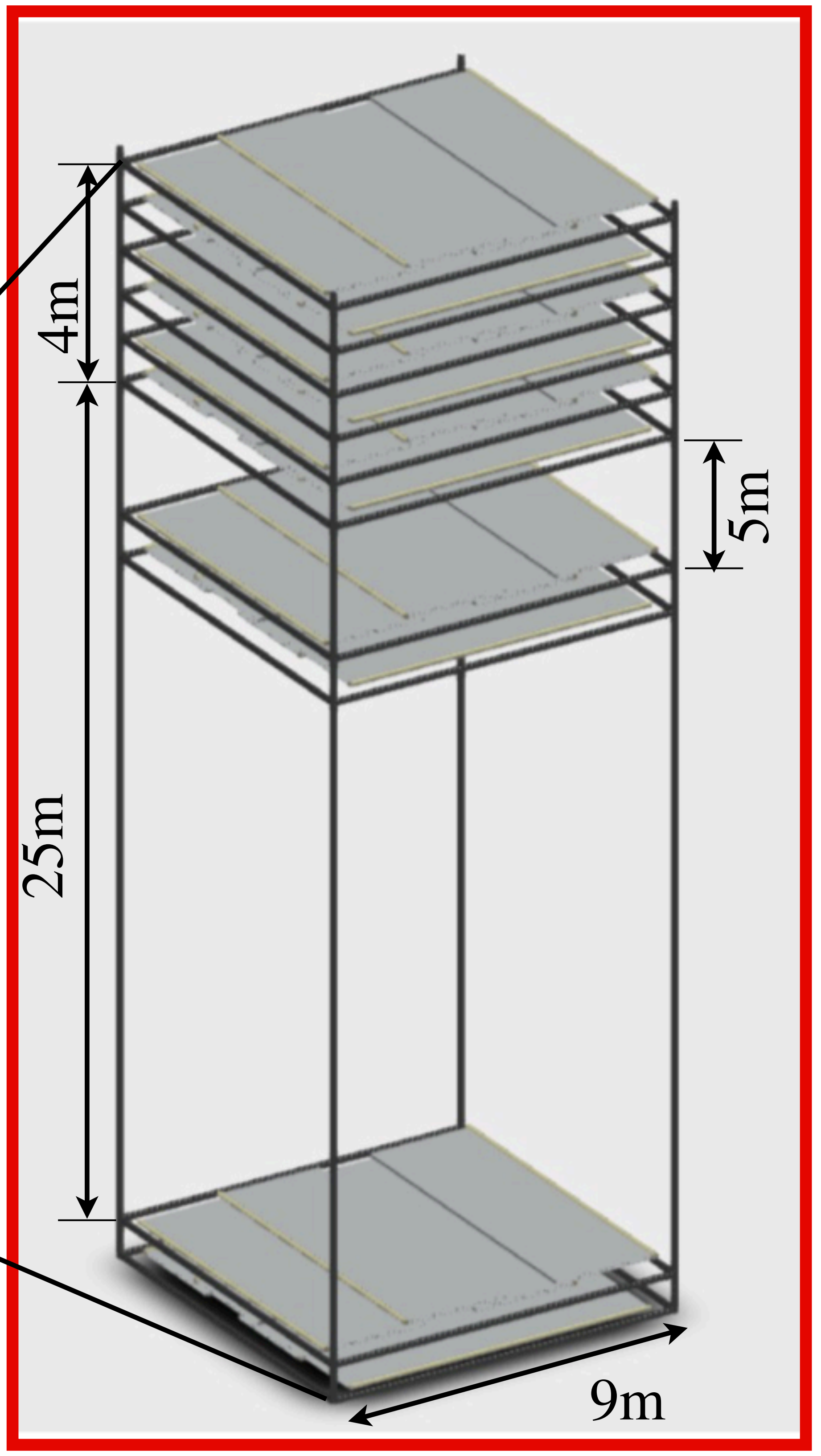
4. Detector Design

For technical questions, you can also chat with your local MATHUSLA collaboration member **Jim Freeman**

Detector Plane layout

- Decay volume ~100 x 100 x 25 m^3
- Modular design (100 modules of 9 x 9 x 30 m^3)
  - Assembly time line not governed rigidly by HL-LHC beam schedule
  - Data taking can **start after installation of the first module**





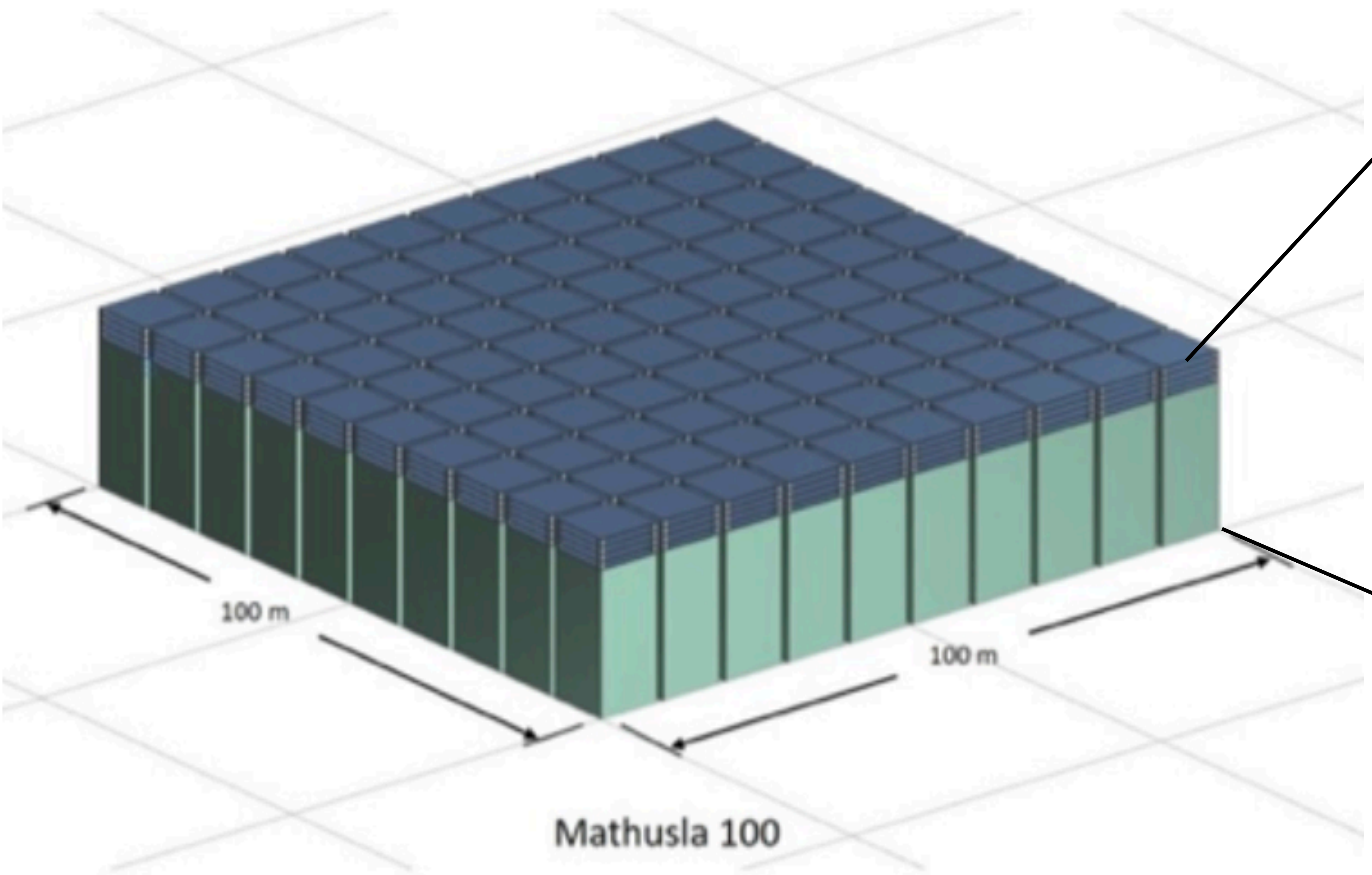
- 6 layers of tracking / timing detector
  - 80 cm between planes
- Additional double layer 5 m below
- Double layer floor detector to veto charged particles from the LHC

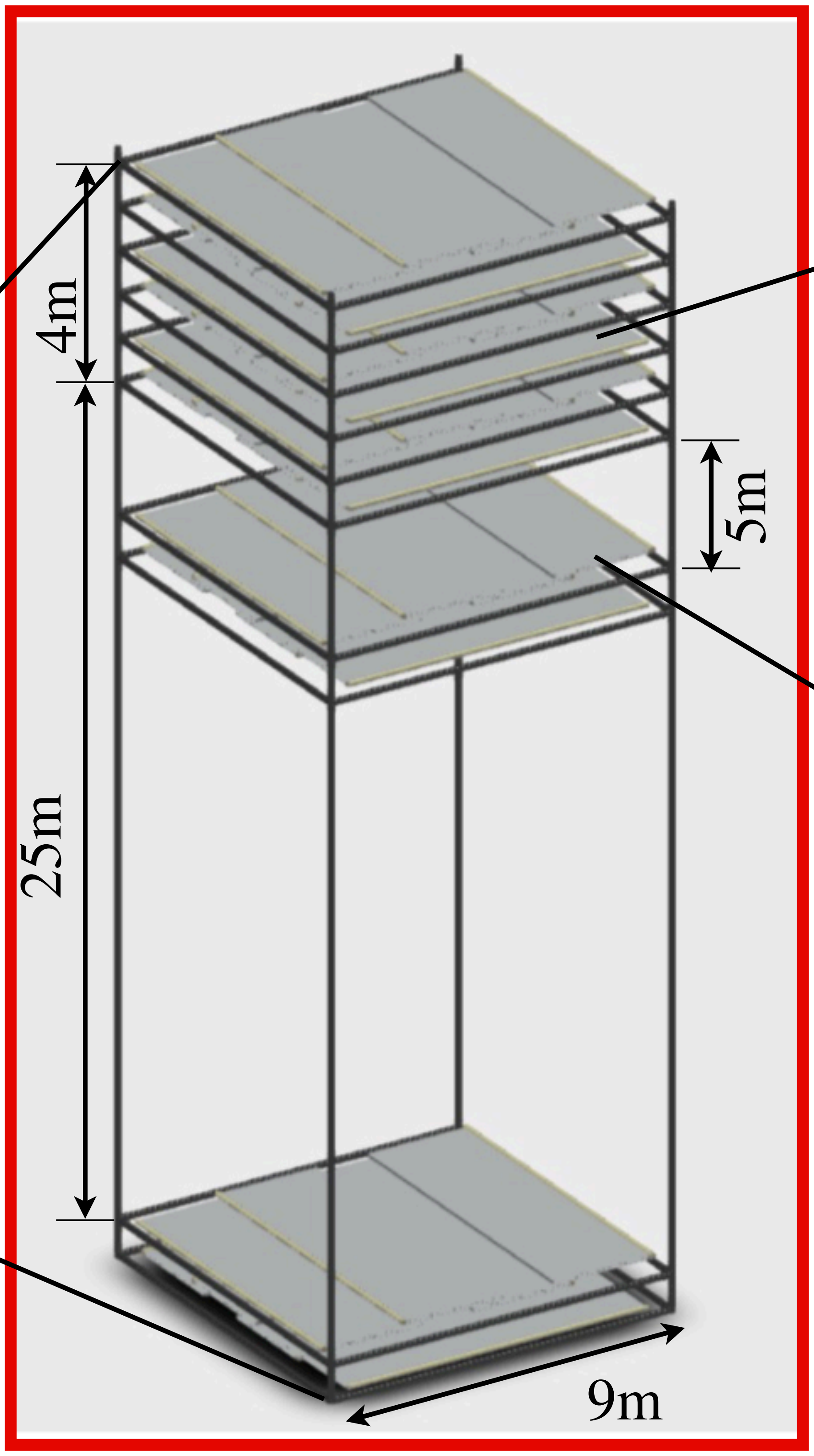
with thanks to Emma Torro Pastor for the slide

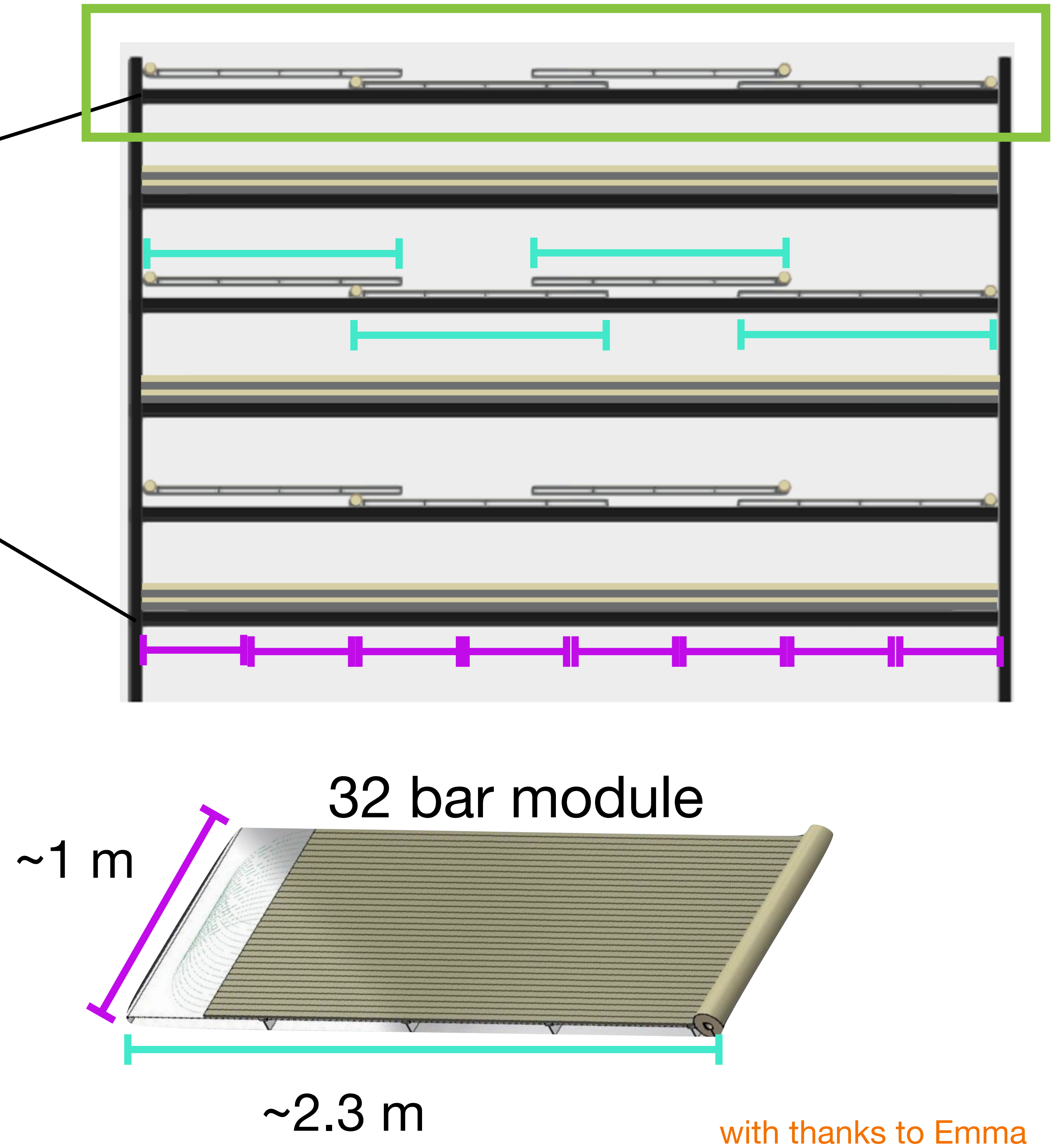
Detector Plane layout

- Decay volume ~100 x 100 x 25 m³
- Modular design (100 modules of 9 x 9 x 30 m³)
  - Assembly time line not governed rigidly by HL-LHC beam schedule
  - Data taking can **start after installation of the first module**

- Each tracking layer is formed by 4 sub-planes consisting of 8 adjacent modules
- Each module contains 32 scintillator bars





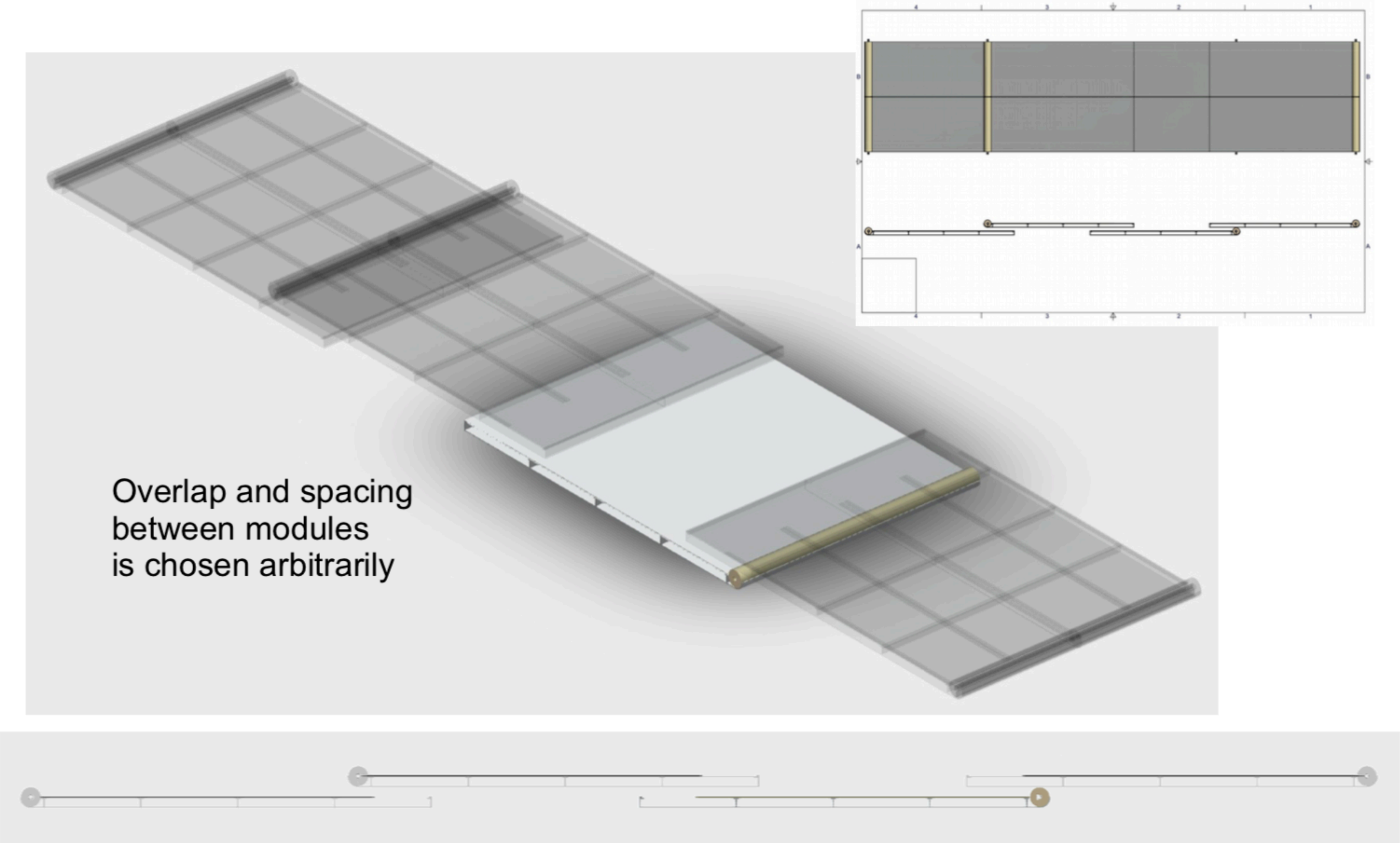


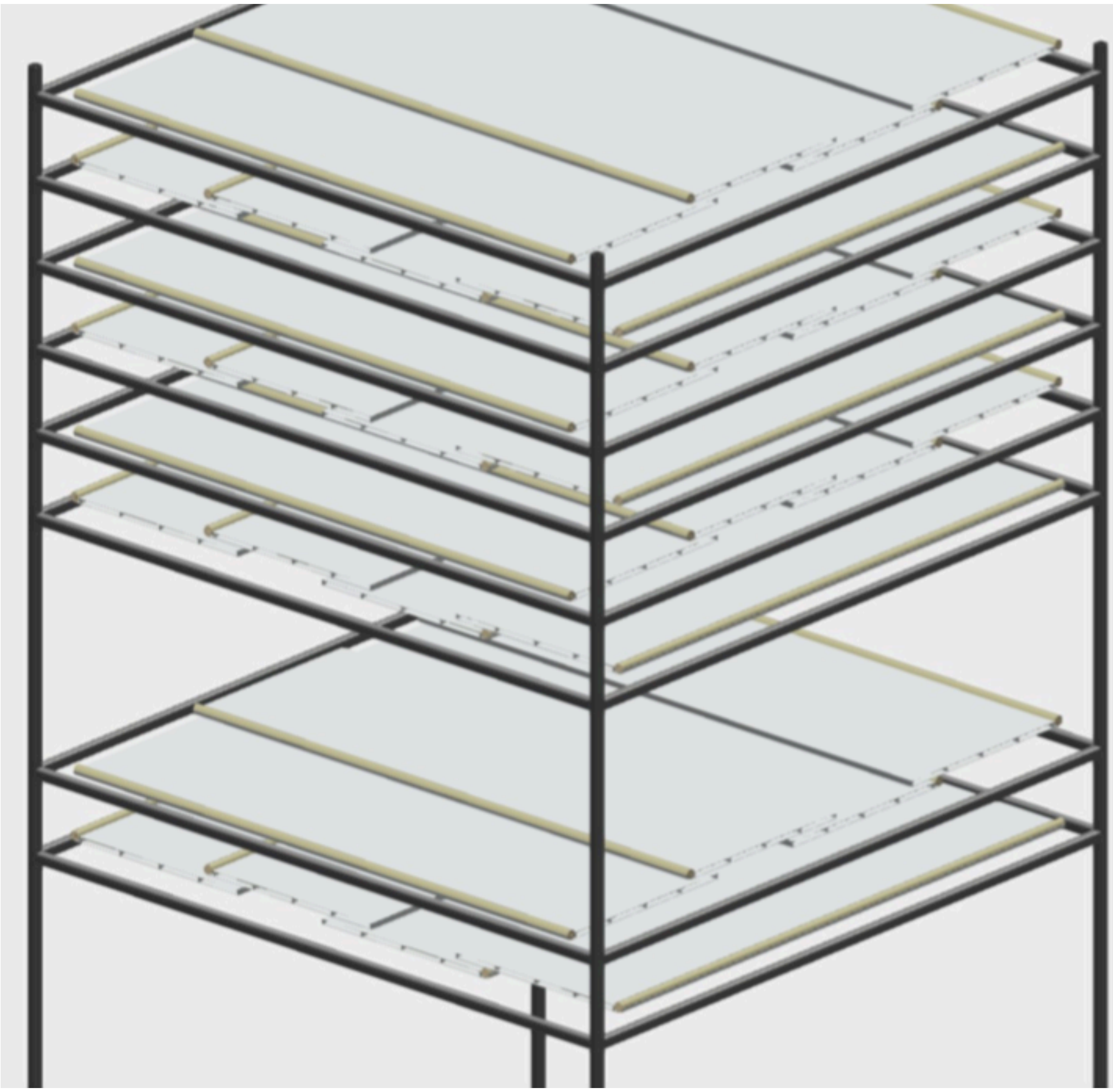
with thanks to Emma Torro Pastor for the slide

Detector Plane layout

- Each scintillator layer made of 4 sub-planes (2.3 m x 2.25 m) to cover (9 m x 9 m) with overlaps

- Extrusions rotated by 90 degrees for alternating scintillating layers that gives X-Y segmentation





with thanks to Emma
Torro Pastor for the slide

Scintillators / SiPMs R&D

- Bar modules are extruded scintillators
- Scintillator extrusions would be fabricated at Fermilab
- Extruded scintillators from Fermilab widely used:
  - Mu2e cosmic ray veto
  - MINERVA
  - Belle-2
  - …

Could be extruded here at Fermilab!

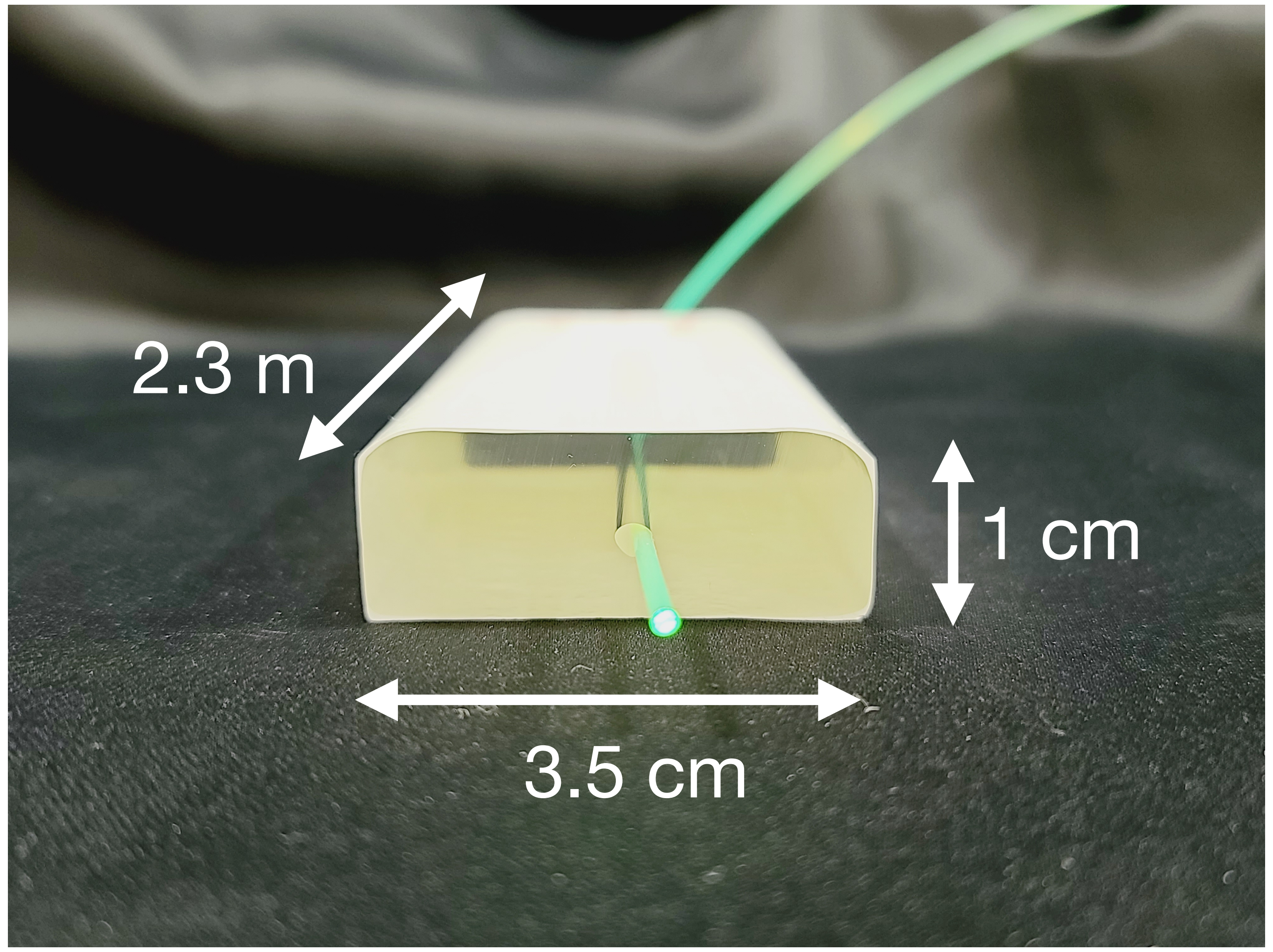
- Critical features for detector design
  - Separate downward from upward going tracks
  - Reject low beta particles from neutrinos
  - **4D tracking and vertexing** to reduce fakes/combinatorics

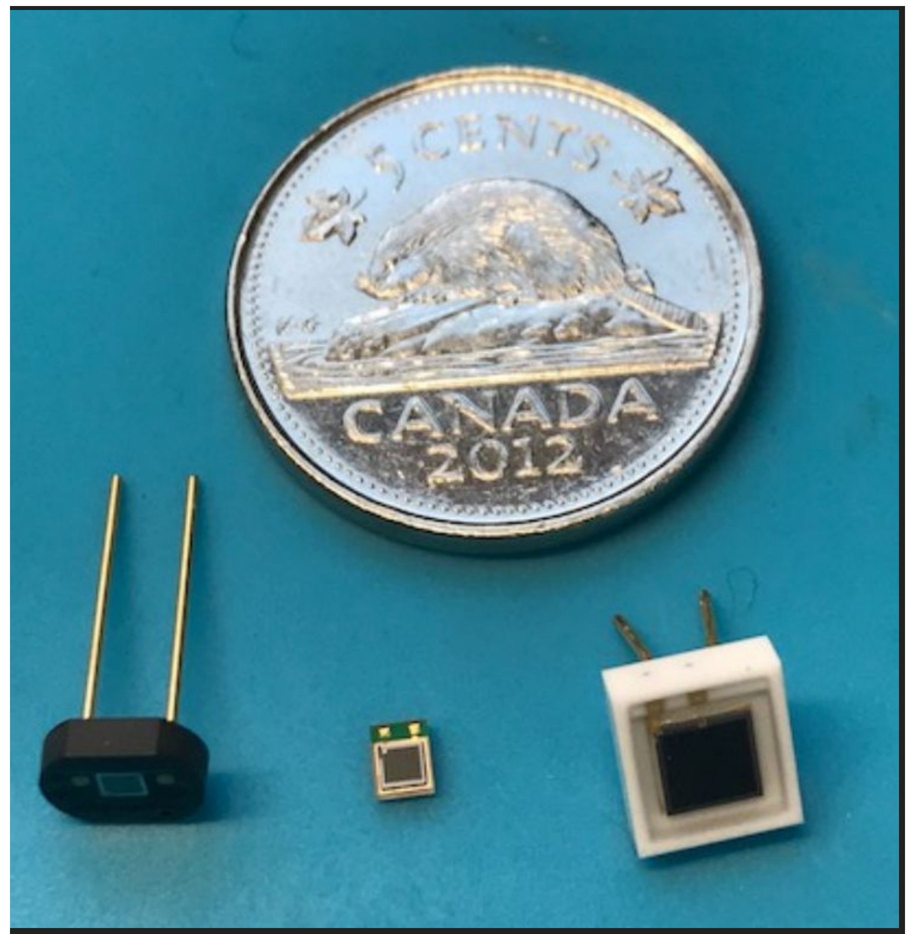
Cost is a major design consideration

with thanks to Emma Torro Pastor for the slide

Scintillators / SiPMs R&D

- Extruded scintillators have a ~25 cm attenuation length
  - Light is carried through a wavelength-shifting (WLS) fibre running through the bar
  - Detected by silicon PMs (SiPMs) on both ends of the fibre
- Good resolution both in time and space:
  - Timing hit resolution is ~1ns (corresponds to ~15cm along the bar)
  - Transverse hit resolution is ~1cm
- Lab tests of multiple WLS fibres show these resolutions are achievable
- Currently testing a number of SiPMs performance





Example SiPMs that have been tested

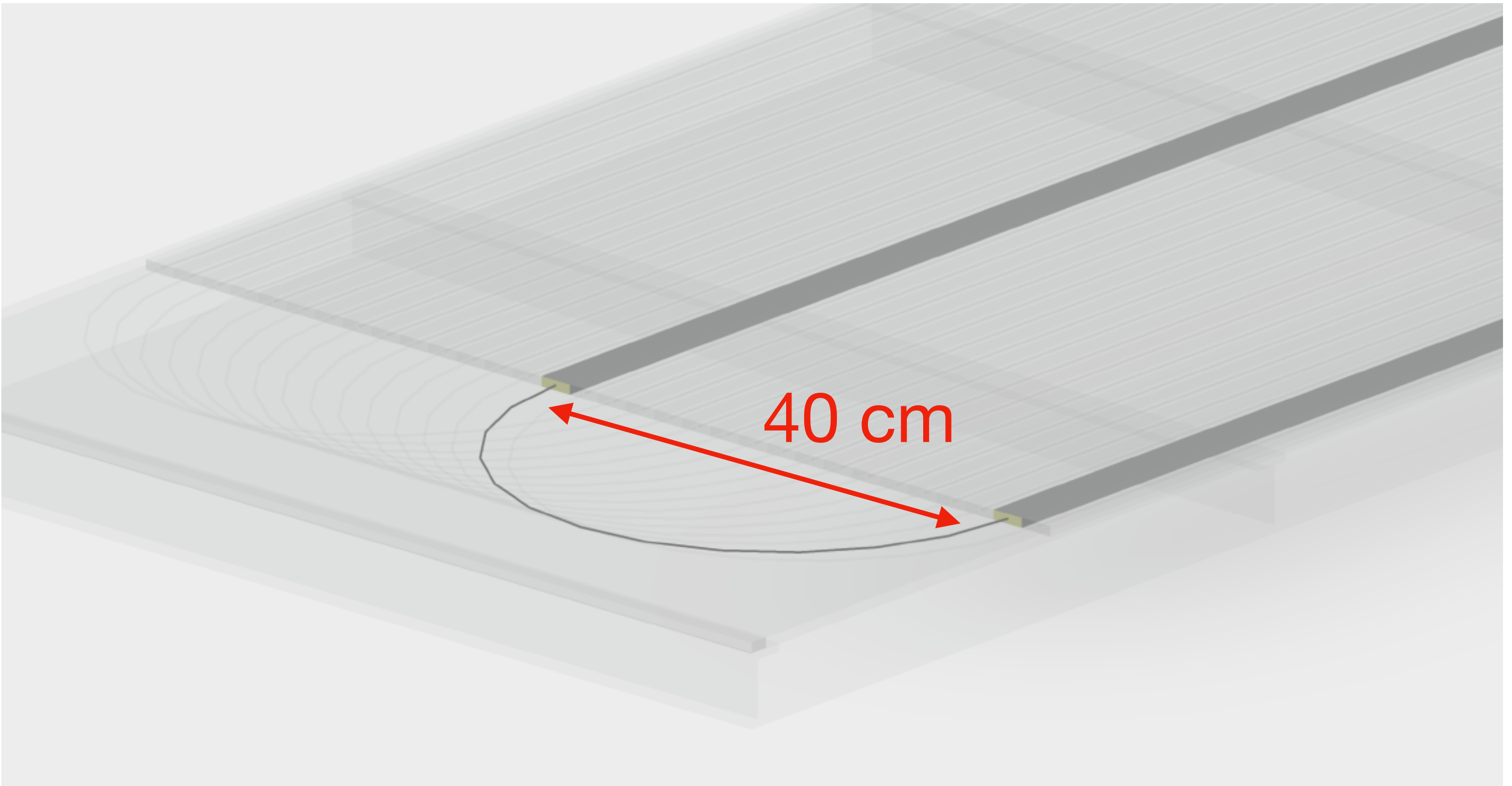
with thanks to Emma Torro Pastor for the slide

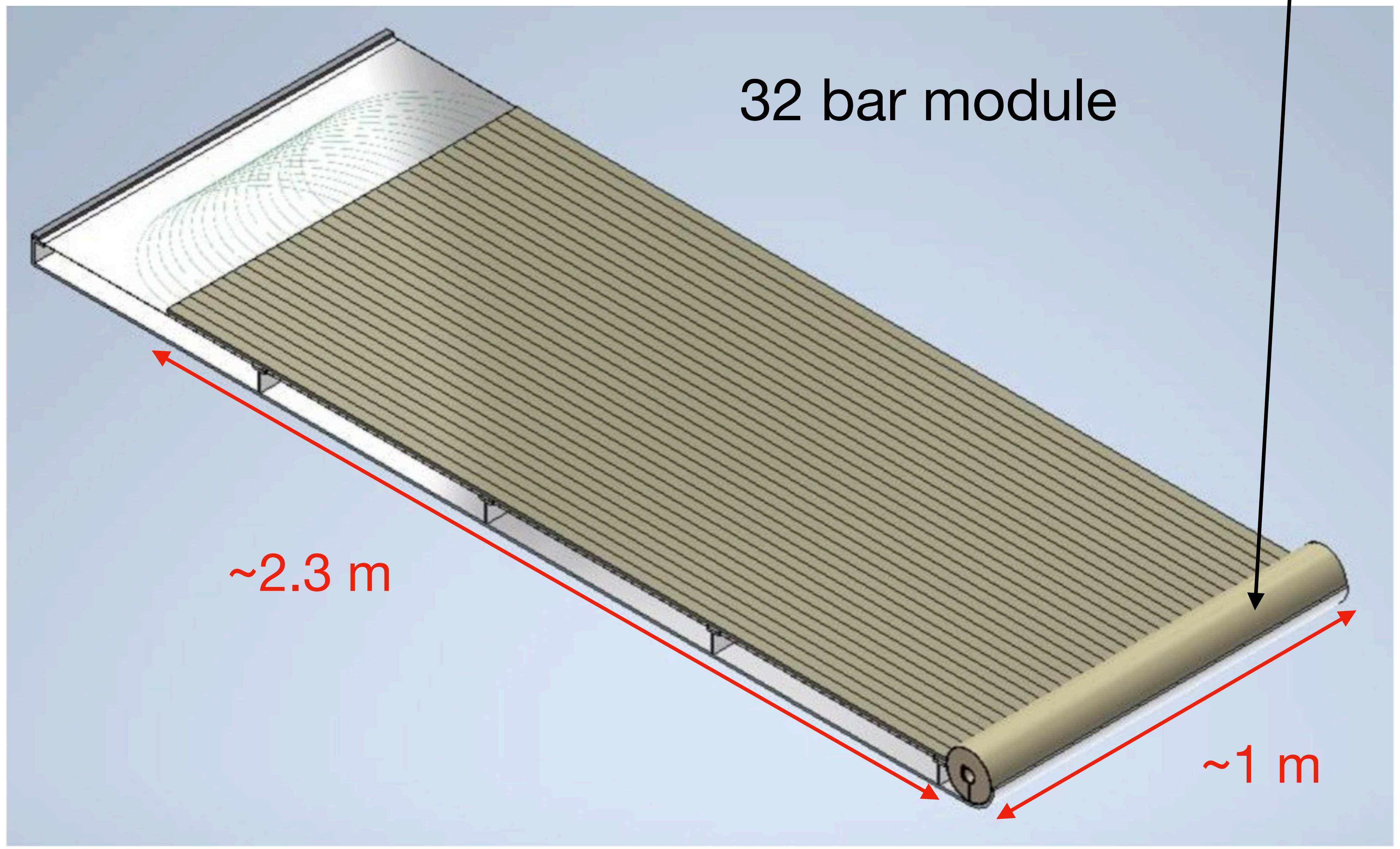
Detector Plane layout

- Extruded scintillator bars with WLSF connected to SiPMs
  - low operating voltage (~30 V), low sensitive to temperature and pressure variations
- Extruded bars 2.3m x 3.5 cm x 1 cm
- All SiPM connections on one side of the layer
  - Unit with 2 x (32 bars in ~2.3 m x ~1 m)

- Cylindrical region: SiPMs, connections to electronics, and cooling for temperature stabilization

- Layout of a detector unit with U-readout





- All SiPMs on the same side simplifies DAQ readout
- But require protective cover on WLS fibres / more delicate assembly

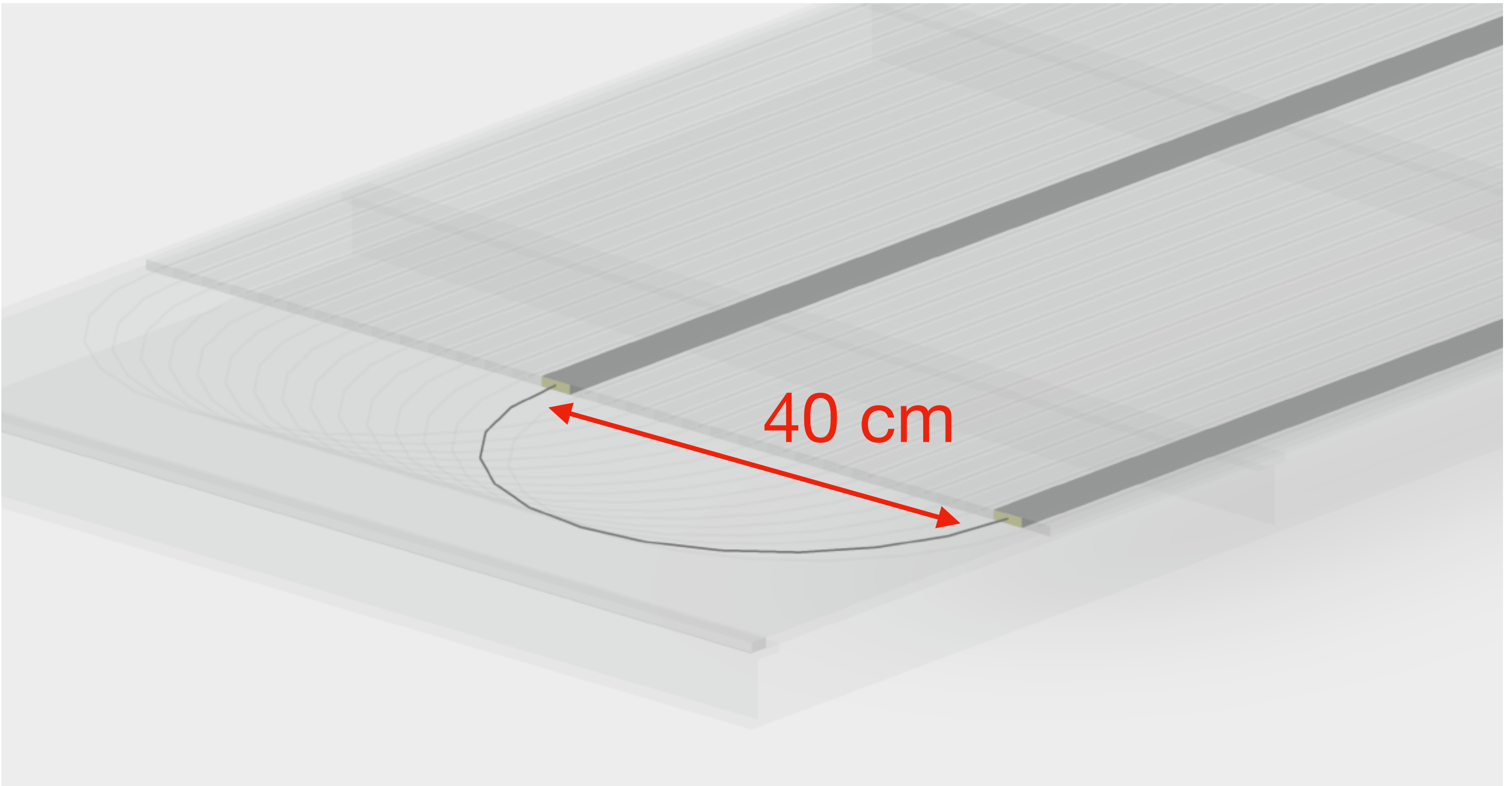
- Separation of extrusions to satisfy minimum bend radius of the fiber

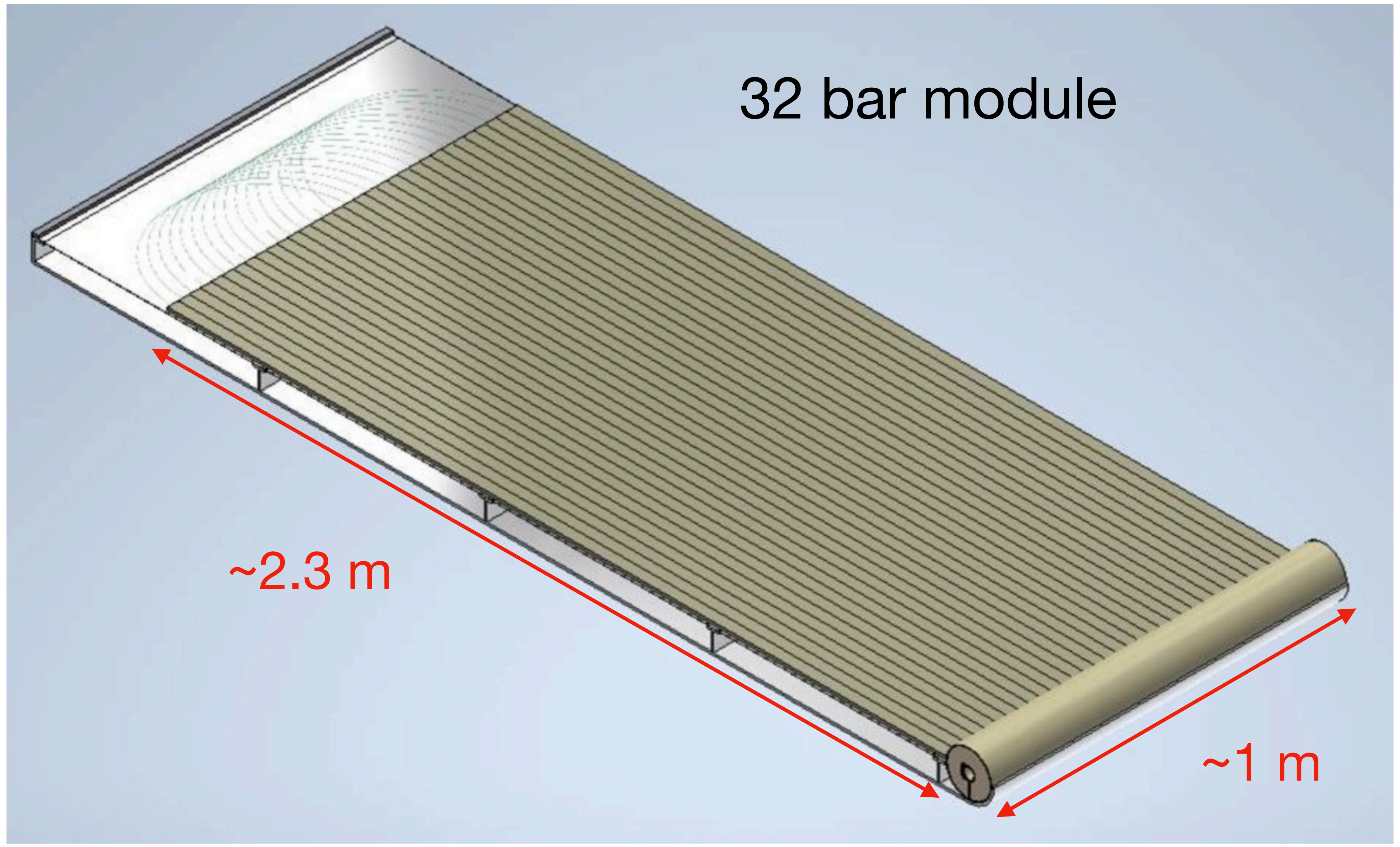
with thanks to Emma Torro Pastor for the slide

Detector Plane layout

- Extruded scintillator bars with WLSF connected to SiPMs
  - low operating voltage (~30 V), low sensitive to temperature and pressure variations
- Extruded bars 2.3m x 3.5 cm x 1 cm
- All SiPM connections on one side of the layer
  - Unit with 2 x (32 bars in ~2.3 m x 1 m)

- Layout of a detector unit with U-readout



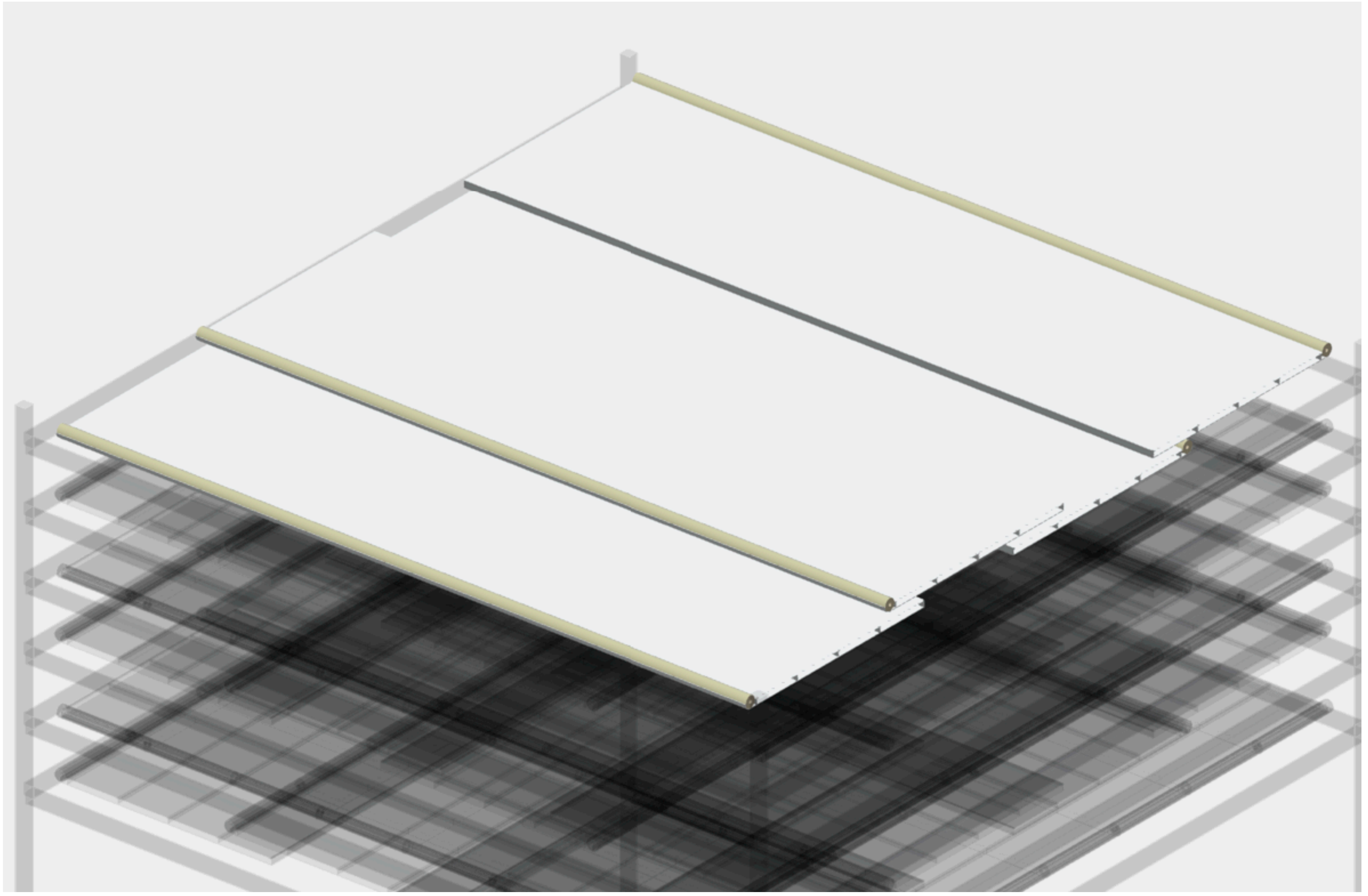


- Time difference between light pulses at the ends of the WLS fibre: complementary coordinate measurement in each scintillating layer

- Separation of extrusions to satisfy minimum bend radius of the fiber

with thanks to Emma Torro Pastor for the slide

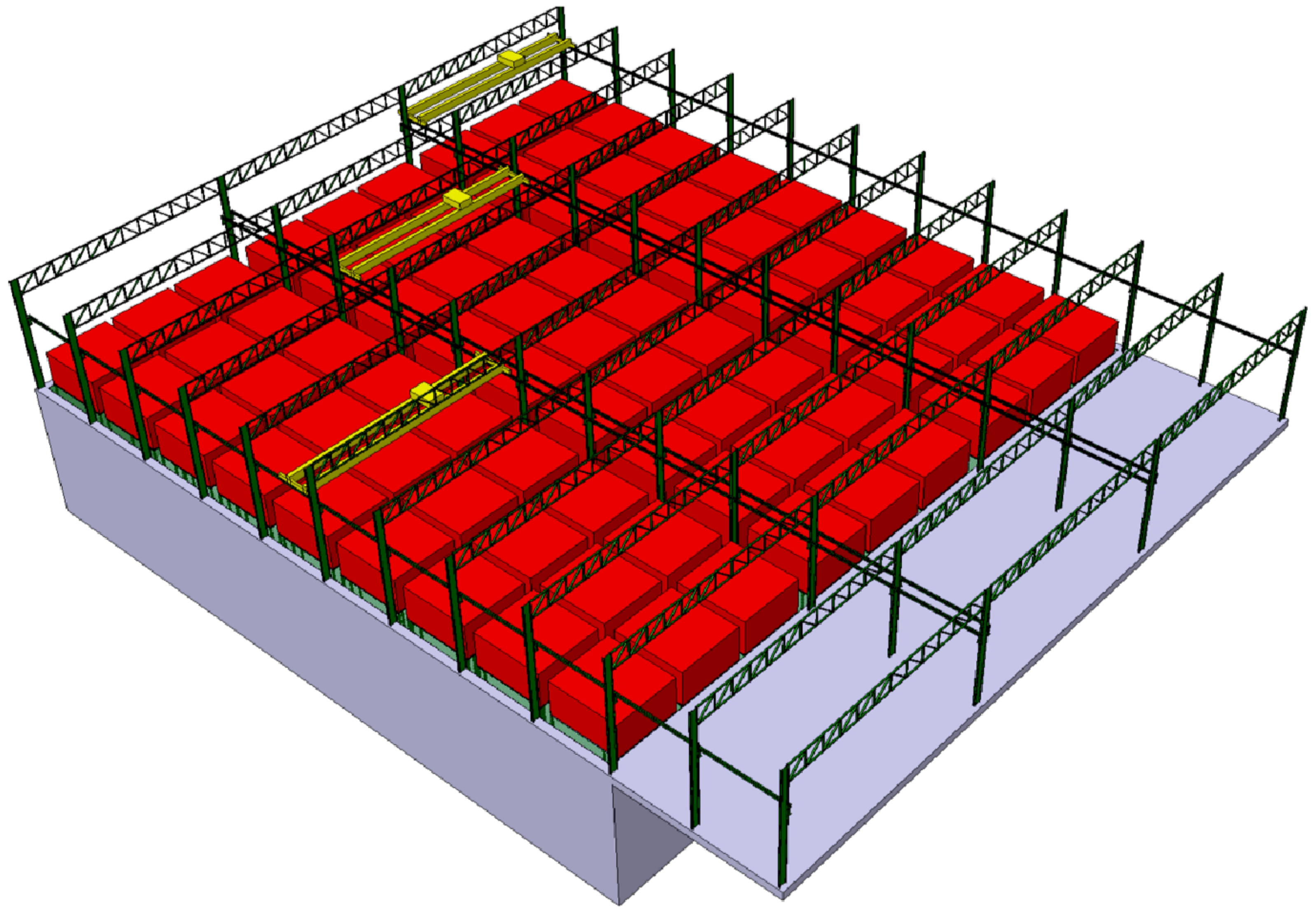
Structural Support

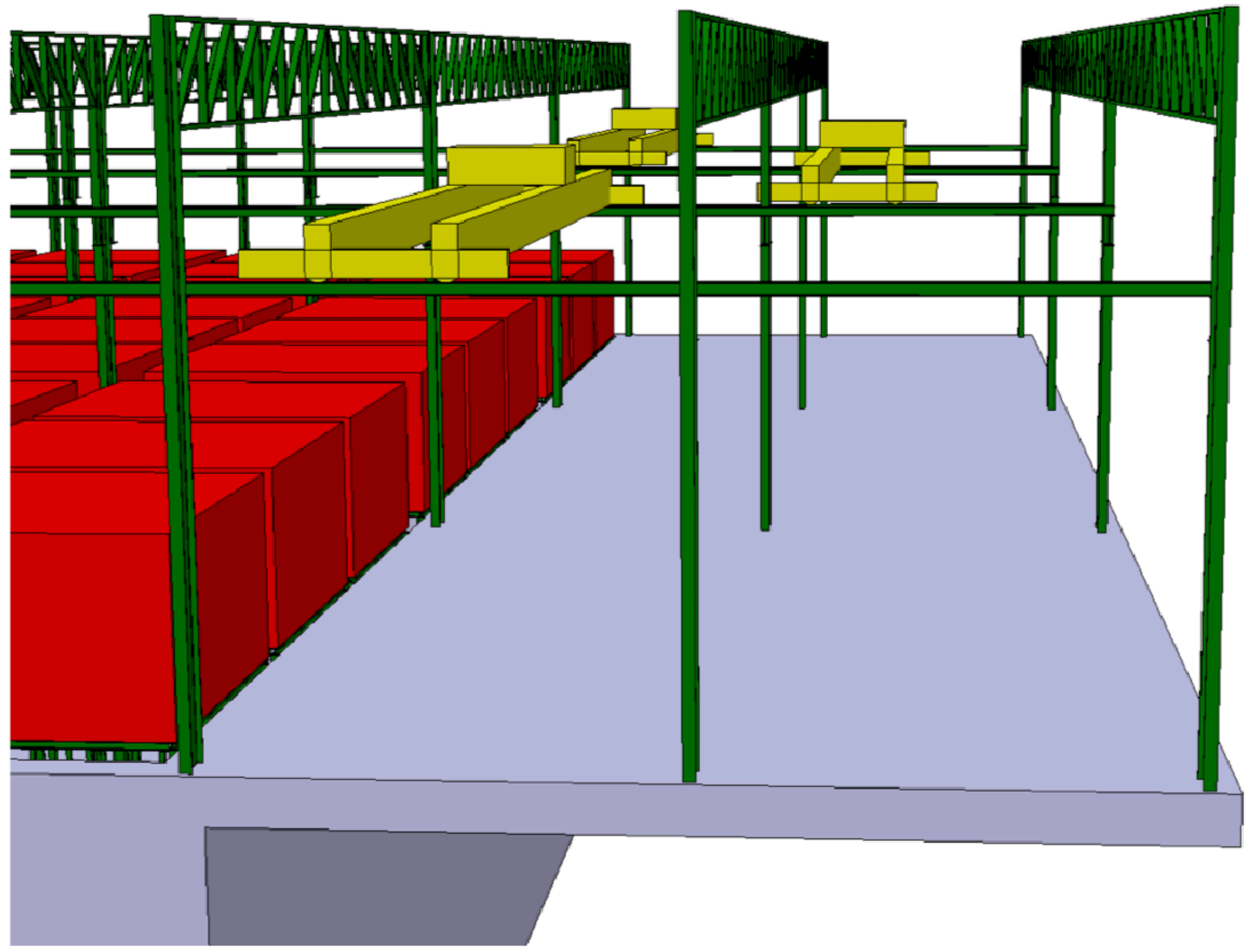


Four 8-panel detector sheets make one 9x9m detector layer.

Scintillator planes are tiled on a aluminum hex panel strongback, with pickup points for crane lifting and installation.

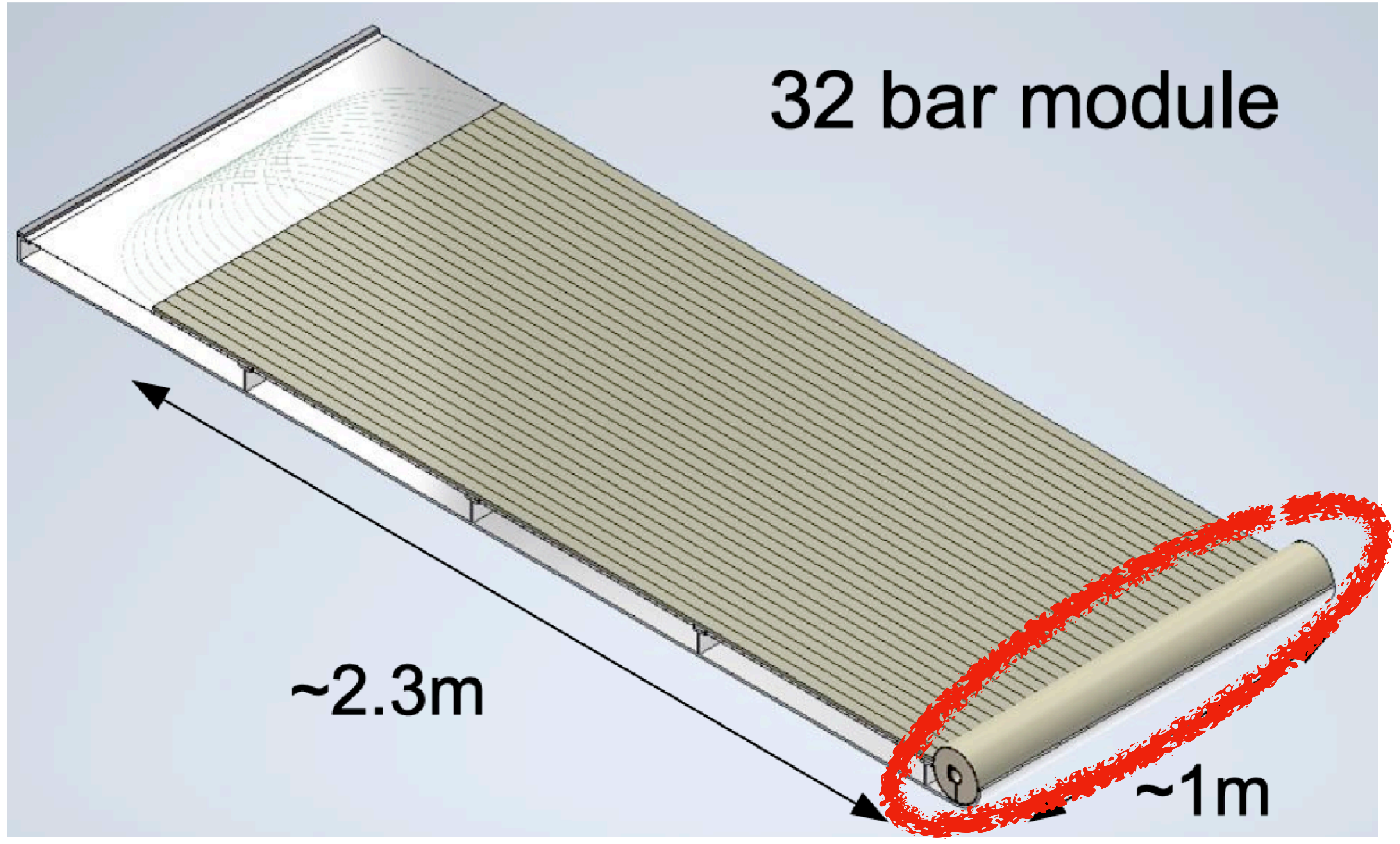
Three 20T cranes shown in yellow



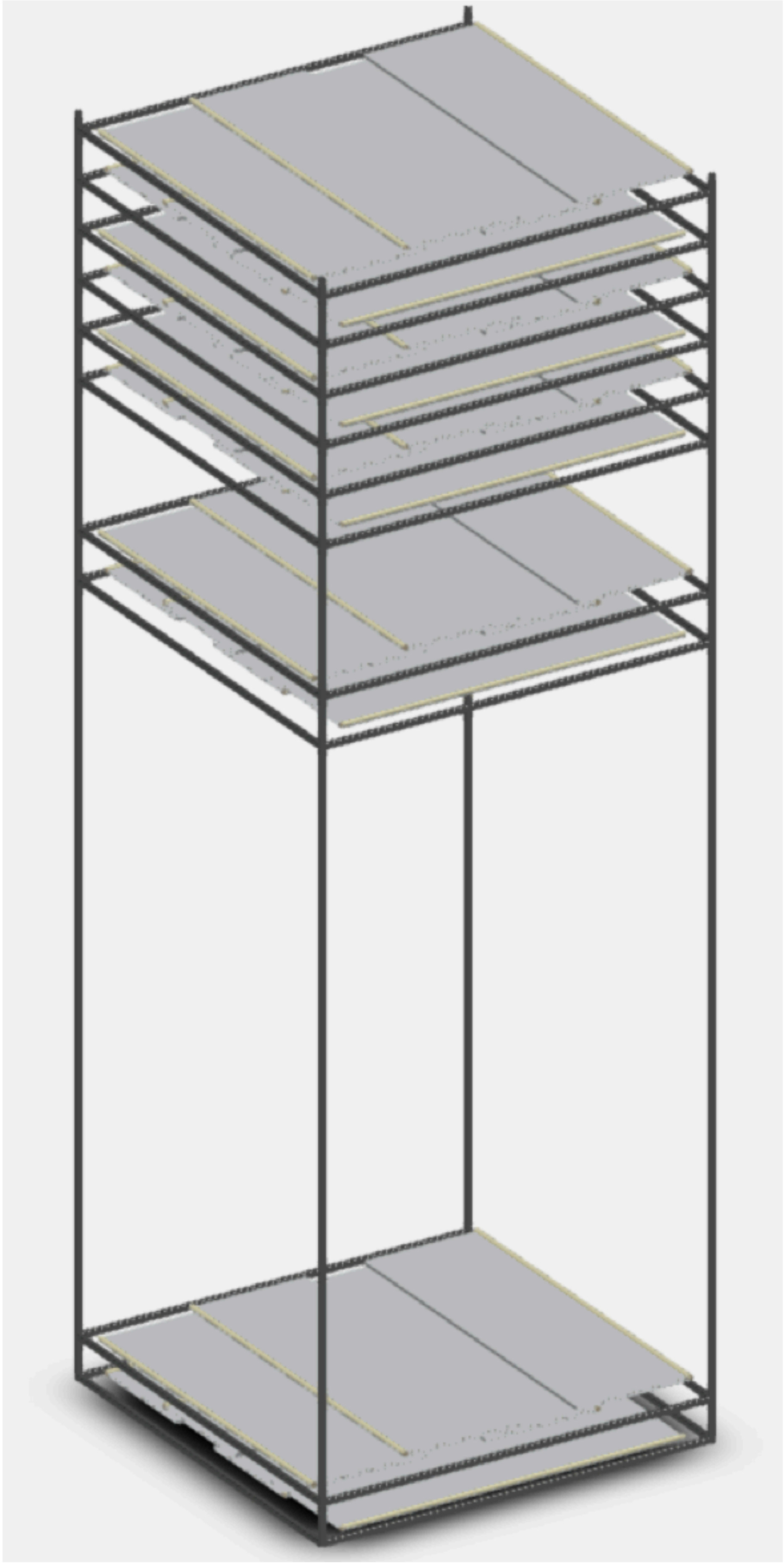


5. DAQ / Trigger / Computing

Front-End + Aggregator



Front-end ASIC attached to each SiPM have two comparators to detect hits (coincidences of two SiPM signals).



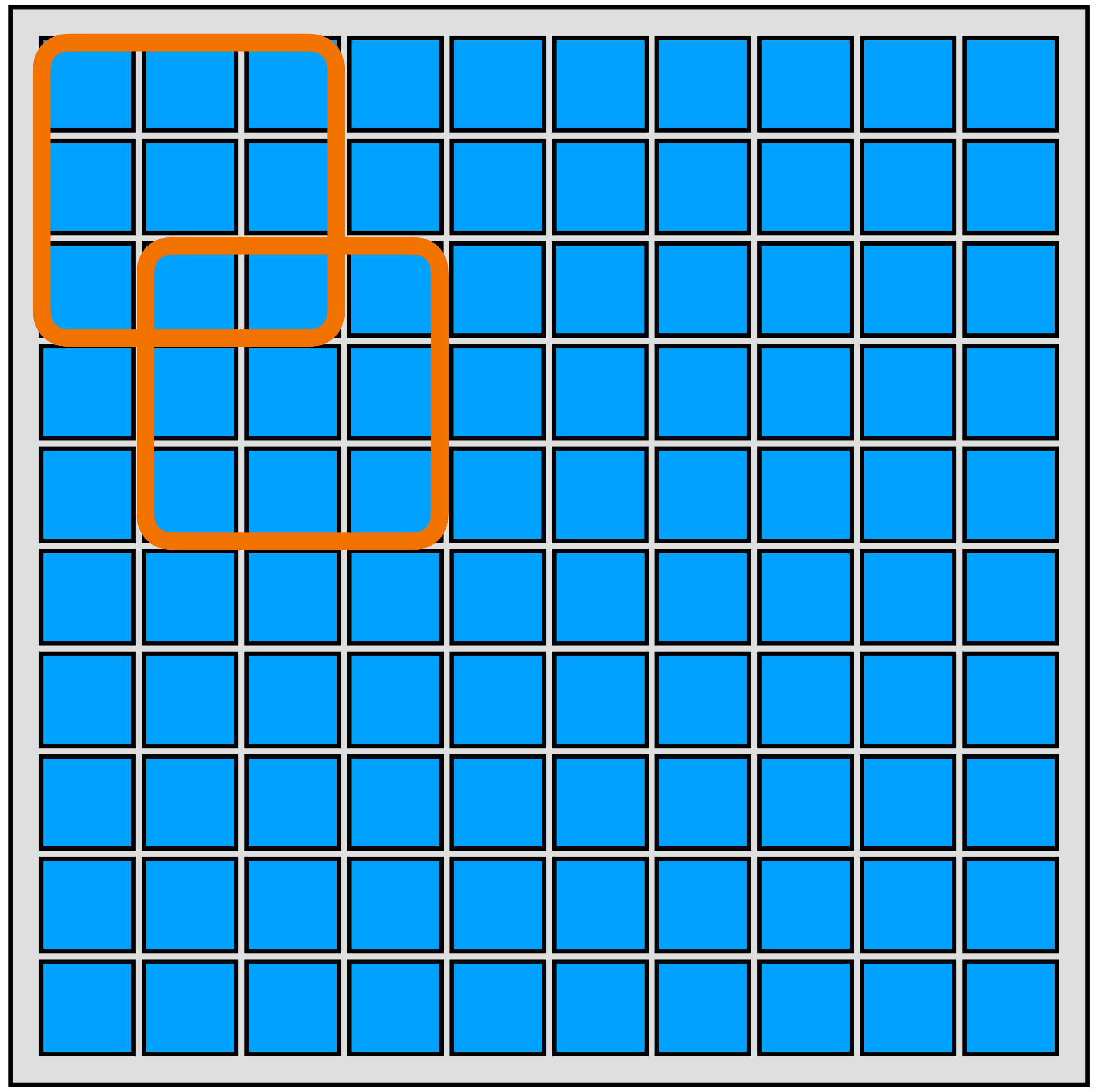
Signals from ASICs transmitted to successive FPGAs that **aggregate hit data for each sensor and ultimately the whole detector module.**

DAQ & Trigger

All hits are read out and stored in a disk buffer, one for each detector module.
Data rates low enough to allow for commodity hardware in DAQ.

CR + dark count ~ 14 MB/s/module, or ~1TB/day/module.

Each 3x3 group of modules employs a local L1 trigger system using large FPGAs.



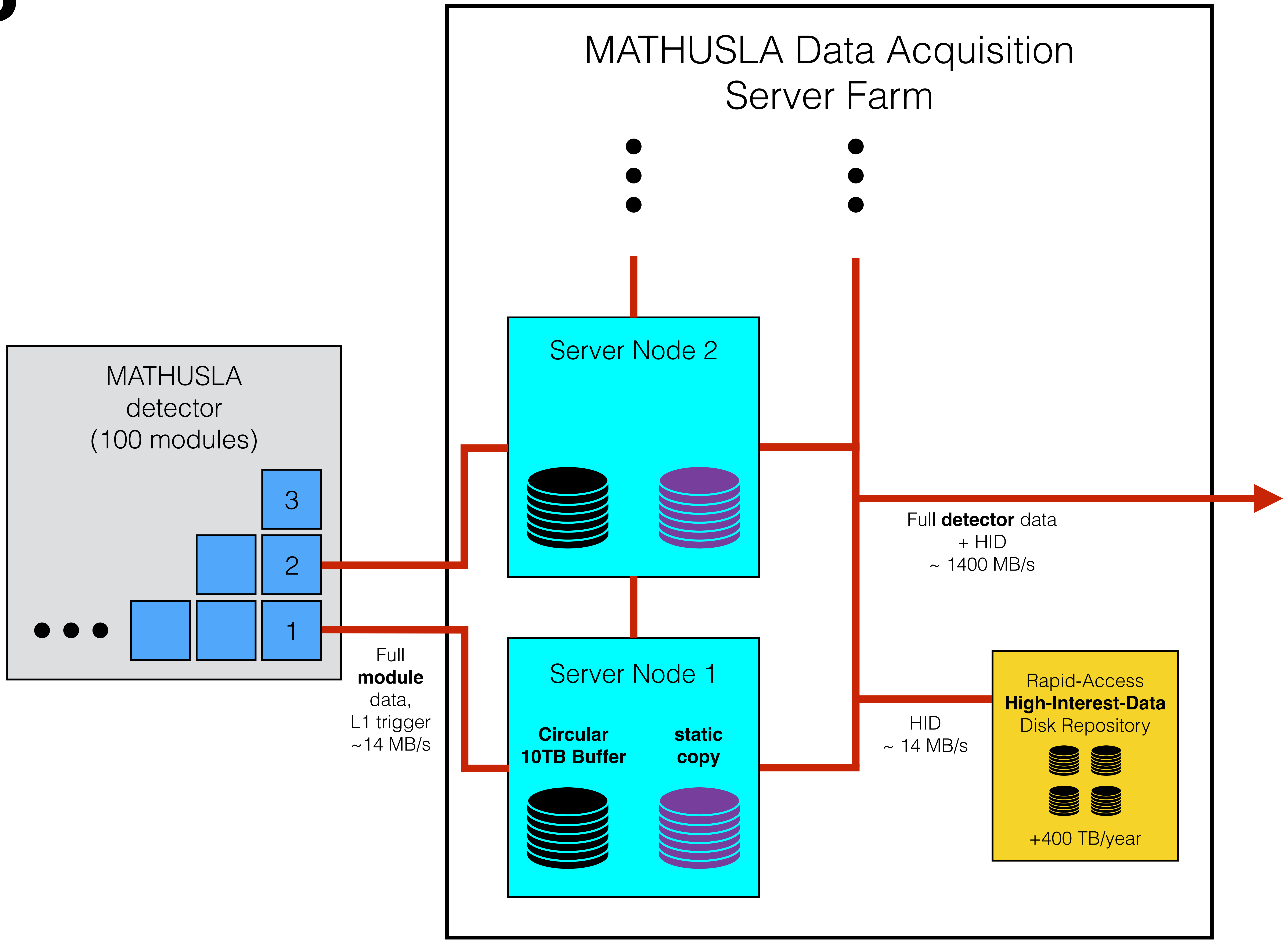
Each 3x3 group does simplified local track-finding, can then trigger on upward going tracks and simplified vertices.

Trigger time-stamps attached to data stream for reconstruction using full detector data in high-level trigger (HLT).

Computing

MATHSLA's server farm maintains **circular disk buffers** of full hit data for each module, and **HLT** runs full recon within μs time-window of trigger timestamps.

About 1% of raw detector + recon data around trigger timestamps is stored as **High Interest Data** (HID) for future analysis.



We are **investigating possibility** of long-term storage for **full** detector data (every hit).

(Help welcome)

Supplying L1 Trigger Signal to CMS

Correlated analysis of **MATHUSLA + CMS events** for **LLP production + decay info** can reveal **detailed information about the newly discovered physics**.

Feasibility has been confirmed in detailed study:

CMS L1 trigger latency requirement ~ 9μs with their Phase-2 trigger upgrade.

Detailed accounting of all latencies (signal transit & aggregation times) and prototype of L1 MATHUSLA track finding indicates this can be accomplished in the required time.

Based on consultation with CMS experts, plan is for MATHUSLA to provide stream of L1T signals to request range of several bunch crossings to be recorded, to capture range of slow or relativistic LLPs.

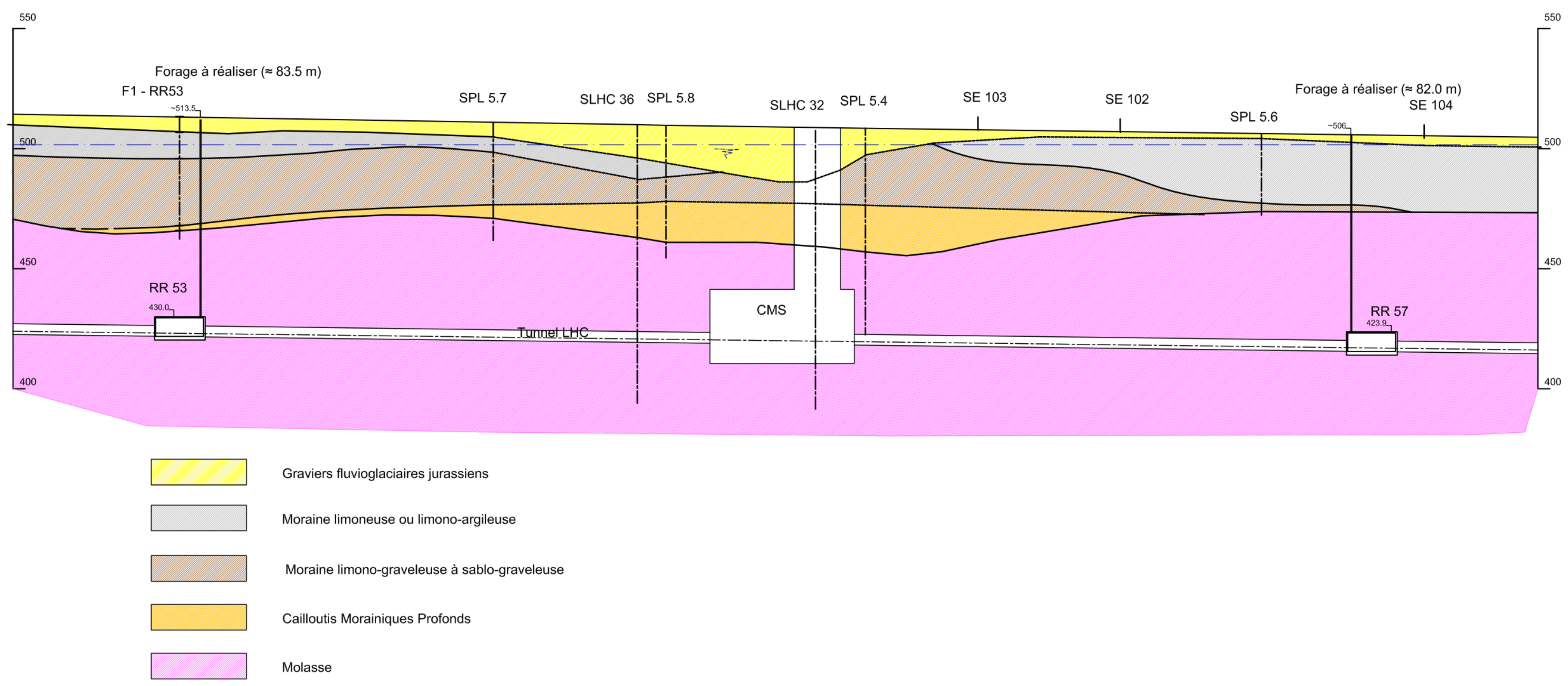
The resulting increase in net trigger rate for CMS will be *negligible*.

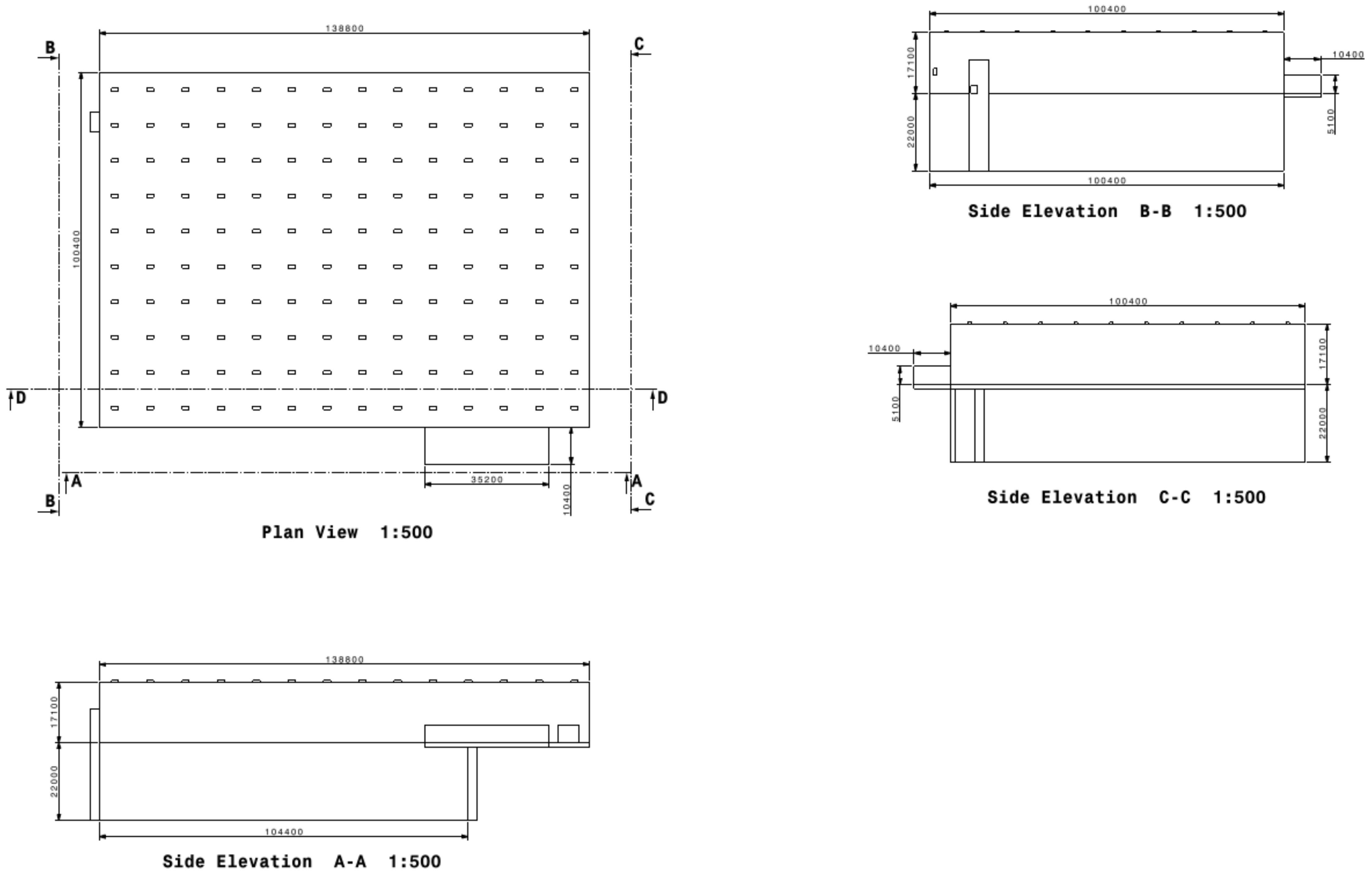
6. Civil Engineering

Civil Engineering

MATHUSLA is very ‘civil-engineering heavy’ as a detector, due to its technological simplicity and importance of its large, empty LLP decay volume.

CERN Civil Engineers supplied conceptual design of facility and internal cost estimates to CERN for construction.

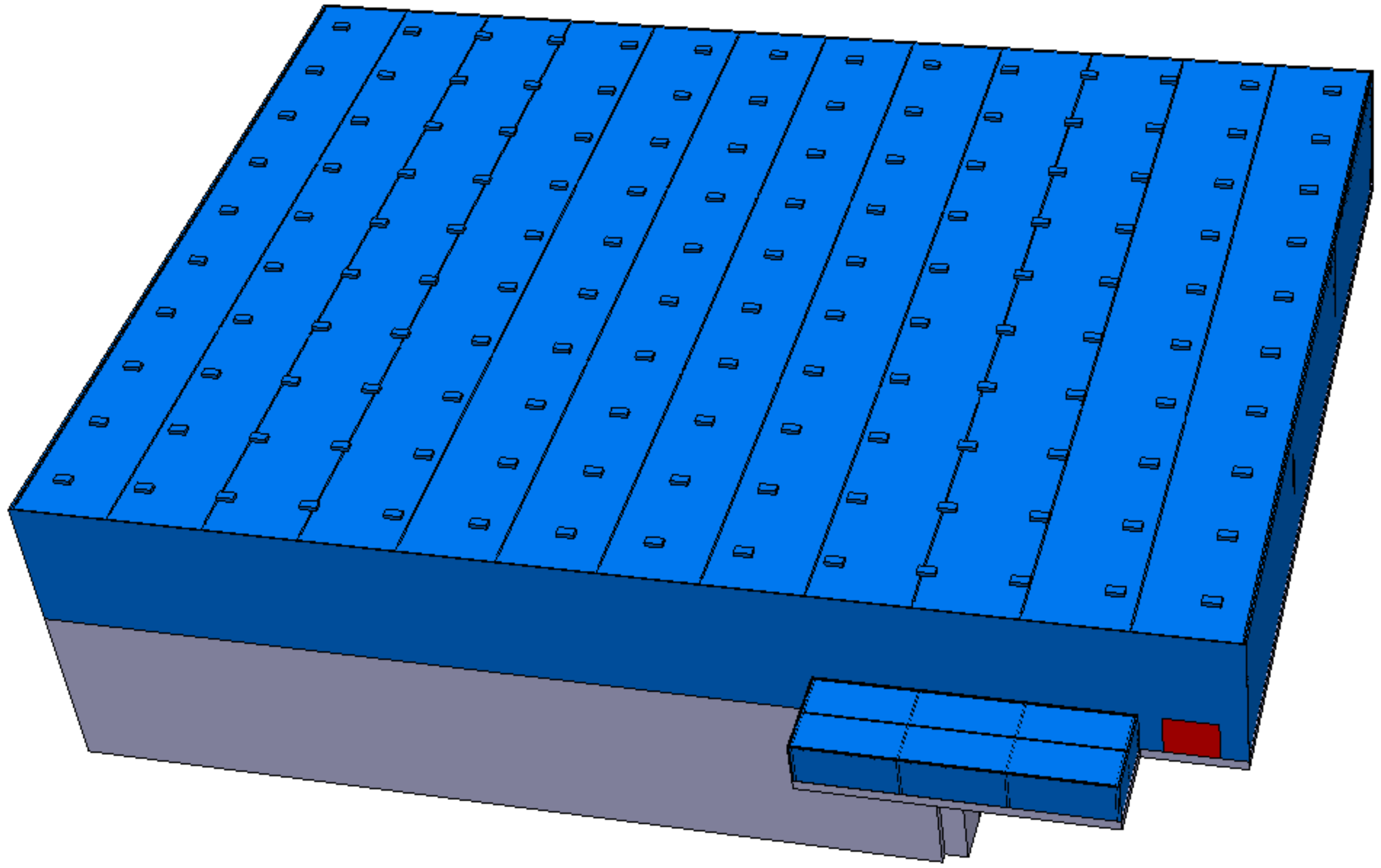


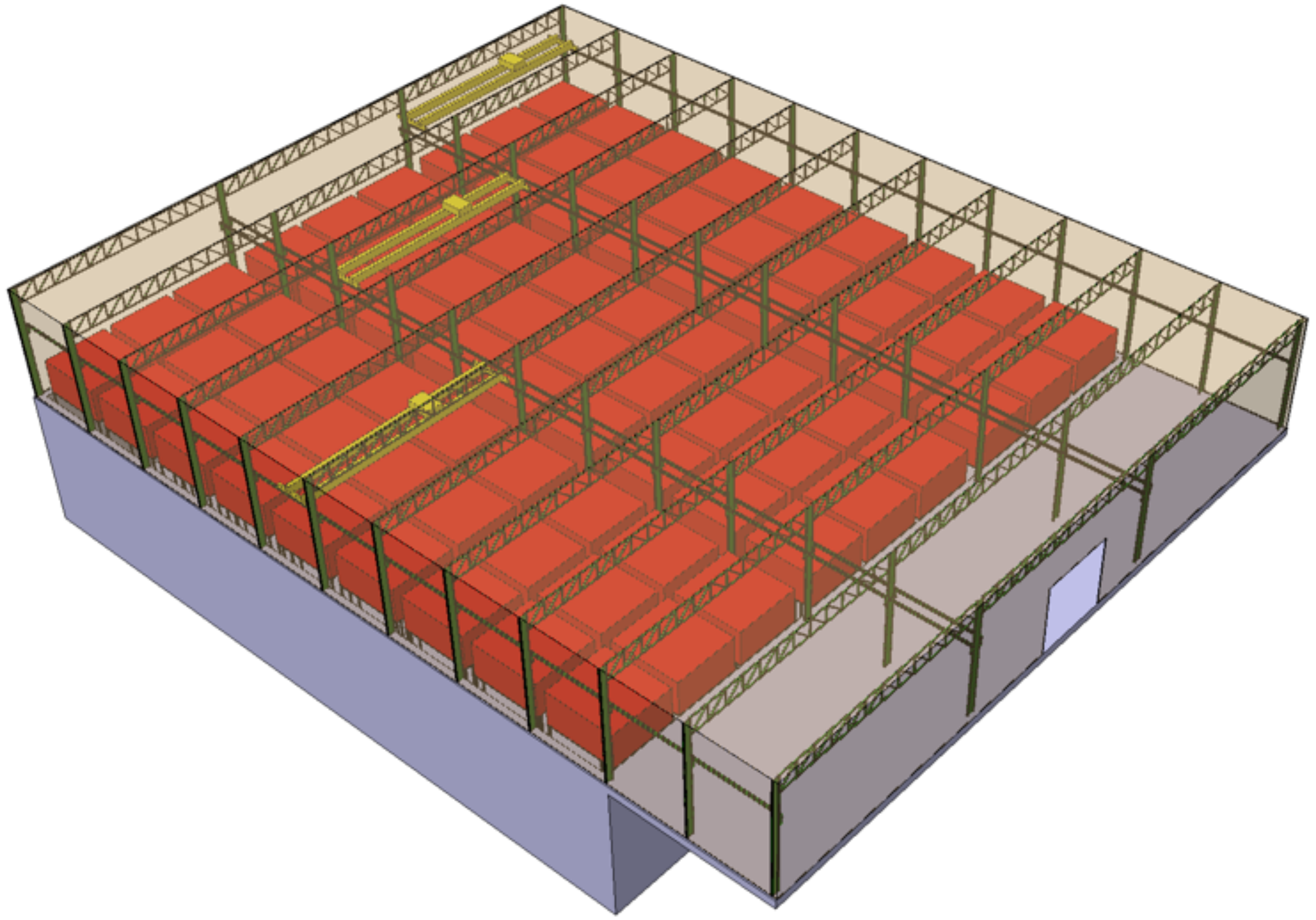


Civil Engineering

MATHUSLA is very ‘civil-engineering heavy’ as a detector, due to its technological simplicity and importance of its large, empty LLP decay volume.

CERN Civil Engineers supplied conceptual design of facility and internal cost estimates to CERN for construction.





7. Cost Estimates

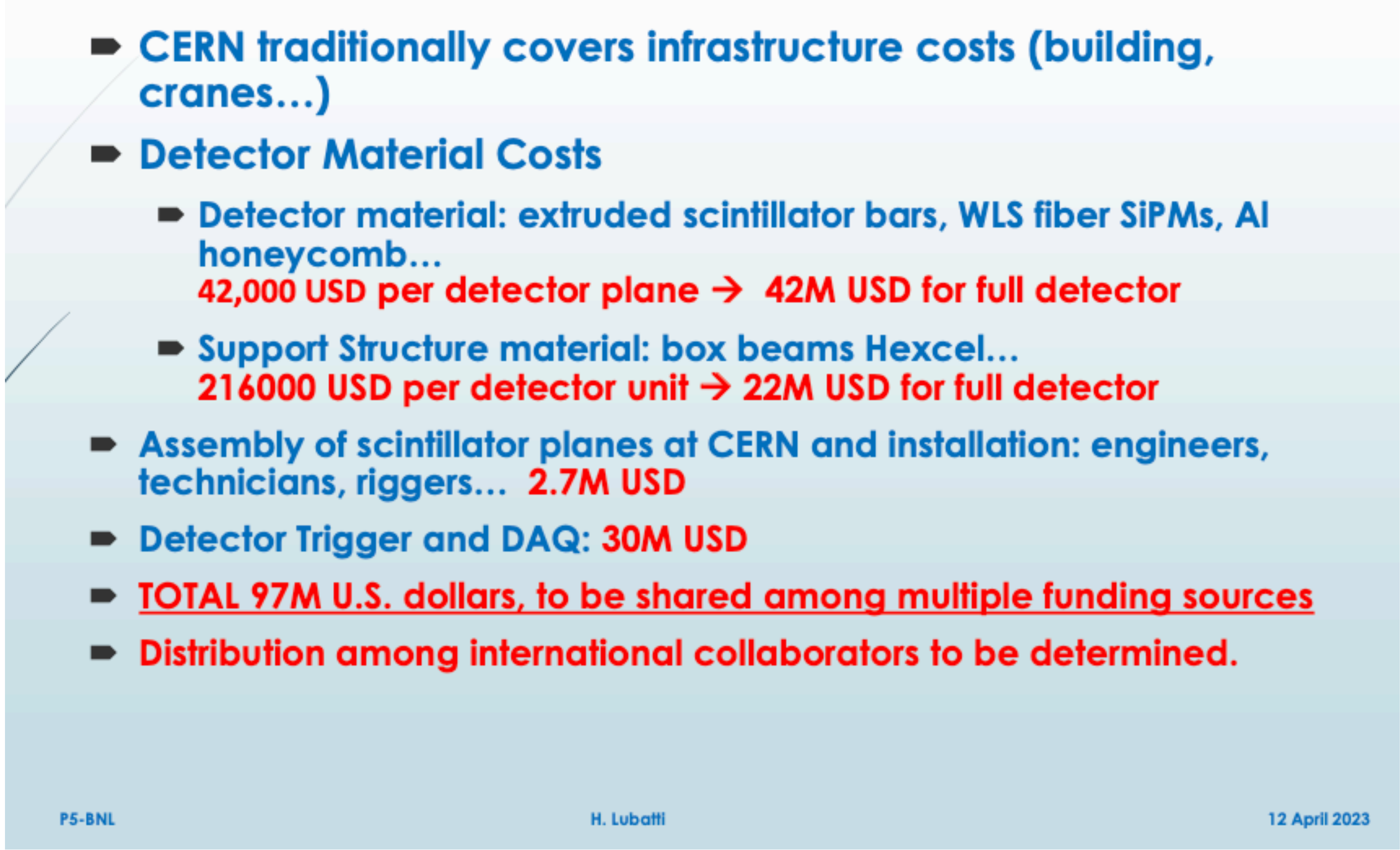
Cost Estimates

See slide from Henry Lubatti's P5 presentation in April 2023:

Infrastructure costs traditionally covered by CERN.

~100M USD for 100-module full detector.

Distributed amongst multiple funding sources in international collaboration.



8. Schedule Goal

Schedule Goal

- Ready for HL-LHC collisions.
- Staged installation beginning about 2.5 years before HL-LCH pp collisions.
  - Installation of one 9x9 m^2 unit O(1-week)
  - Can begin data taking when a few modules are installed.

9. Some Ongoing Efforts

Light Yield Studies (Fermilab)

Test Stand (U VIC)

Test Stand (Toronto)

Detailed Simulations

Fermilab: Improving Light Yield

Jim Freeman IPRD23

Improve reflectivity of cladding around scintillator extrusion to improve light yield (LY).

2% improvement → 30% more light.

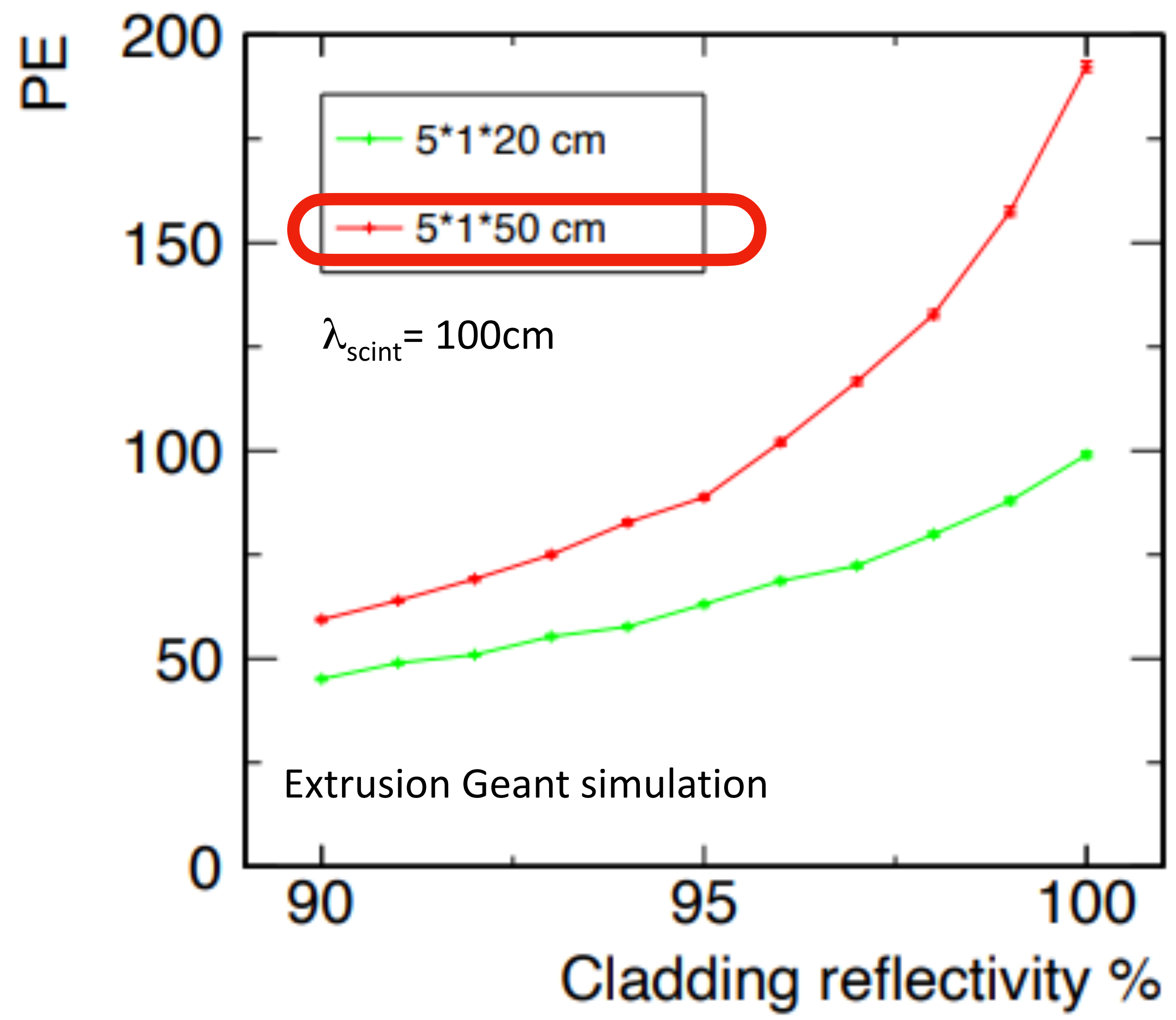
Could reduce MATHUSLA scintillator requirement by 30%.

Yucun Xie (UMD) doing GEANT Sims to study effect of different reflectivity cladding on extrusion.

Looking at new materials better than TiO2 for coating the scintillator.

Cladding:

Light yield vs reflectivity. Clear that improved reflectivity of cladding can have big effect on LY



Wrapper:

Measurement of LY for different wrappers around extrusion. Can make big improvement.

Table 5. Light yield relative to TiO_2 co-extruded cladding

Wrapper	Relative Light Yield
TiO_2 coextruded cladding	1.0
Tyvek	1.08
ESR	1.46
Black wrapper	0.24

with thanks to Jim Freeman for the slide

University of Victoria

Constructing a 64 channel “mini-MATHUSLA”

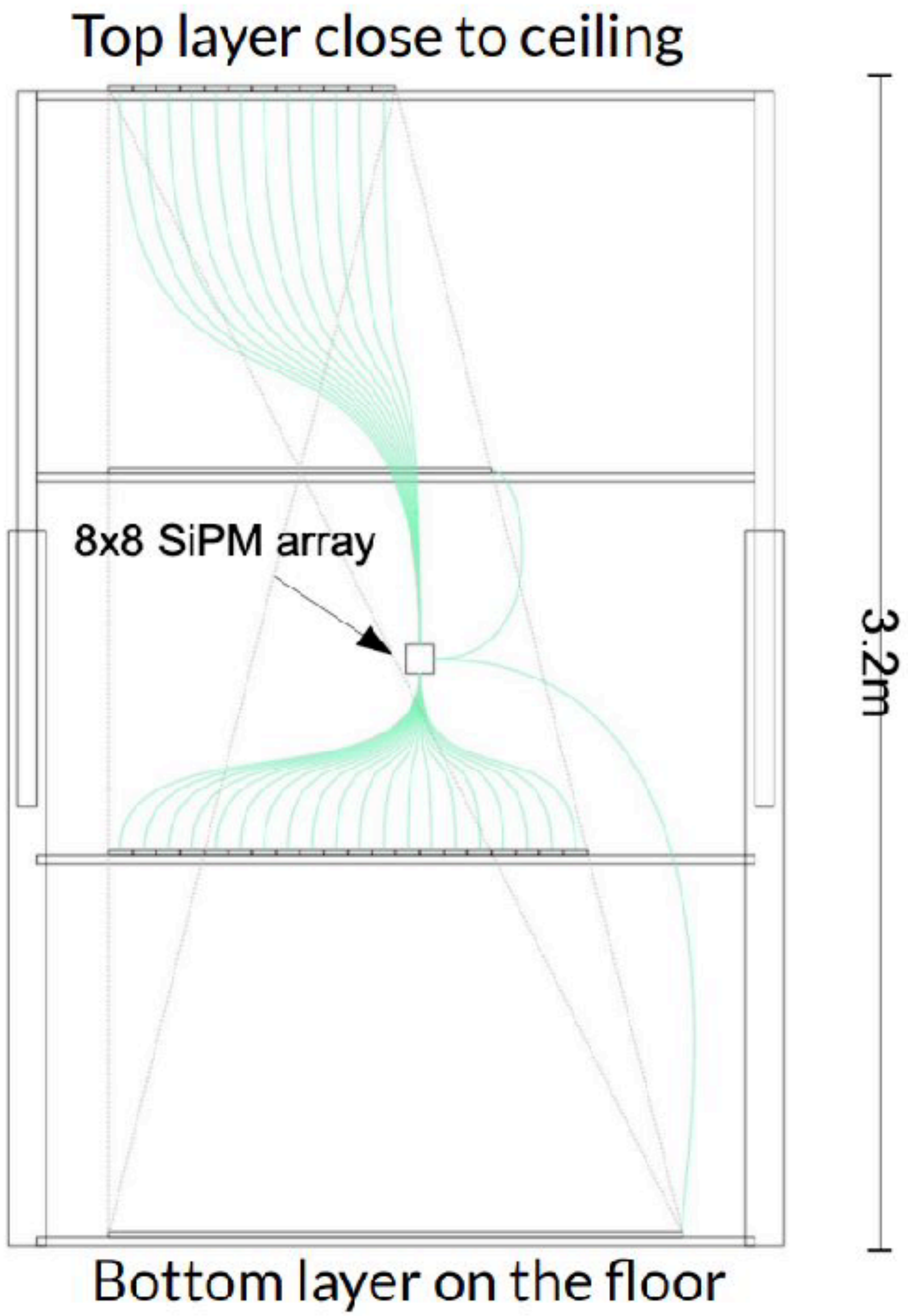
Four layers of ~1m x 1.5m sheets of scintillator

Replicate MATHULSA layers to study cosmic signals, validate the simulation, quantify environmental effects, etc…

Faculty: Heather Russell

Postdoc: Caleb Miller

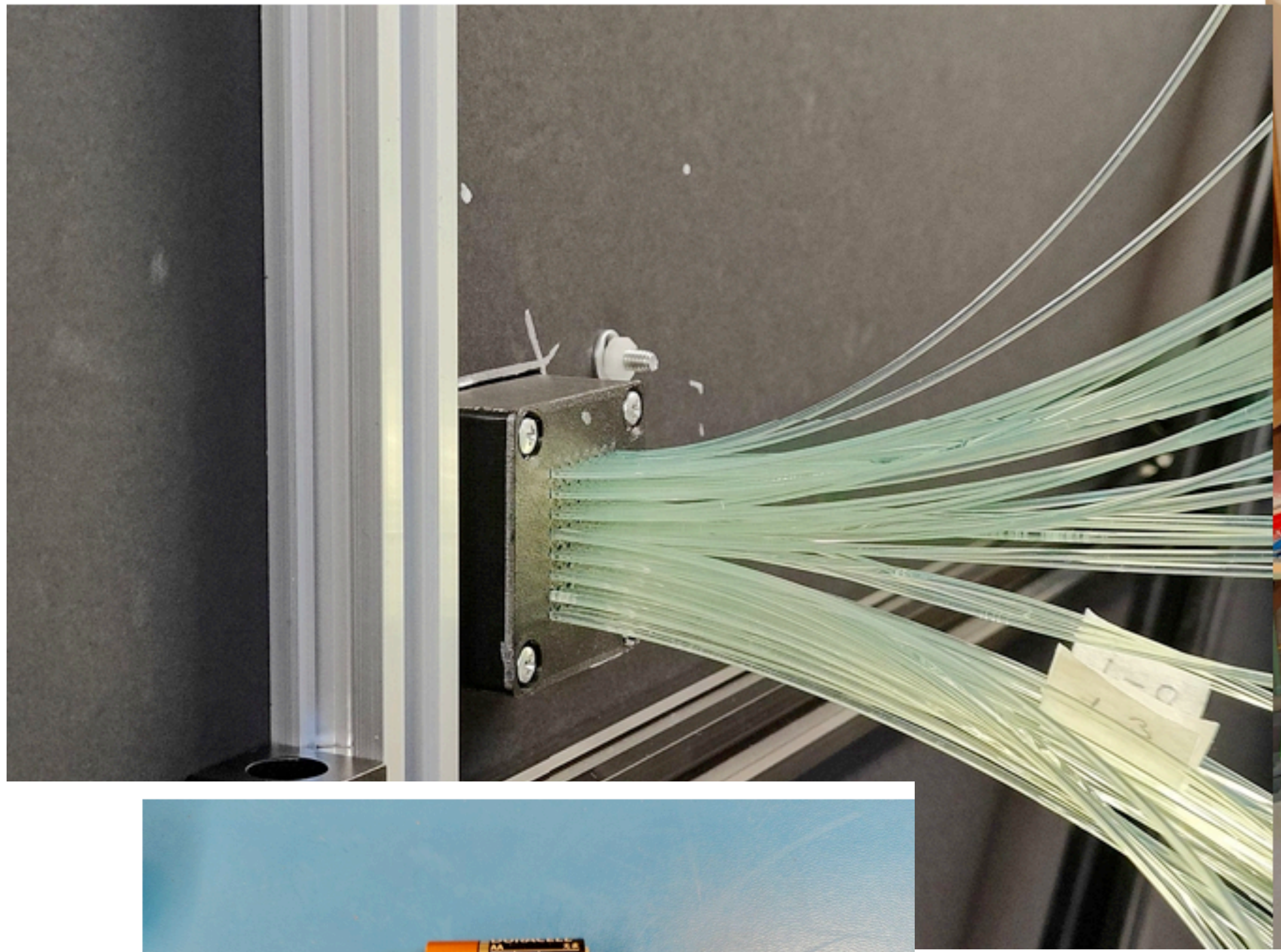
Summer students: Branden Aitken, Sarah Alshamaily



with thanks to Caleb Miller for the slide

University of Victoria

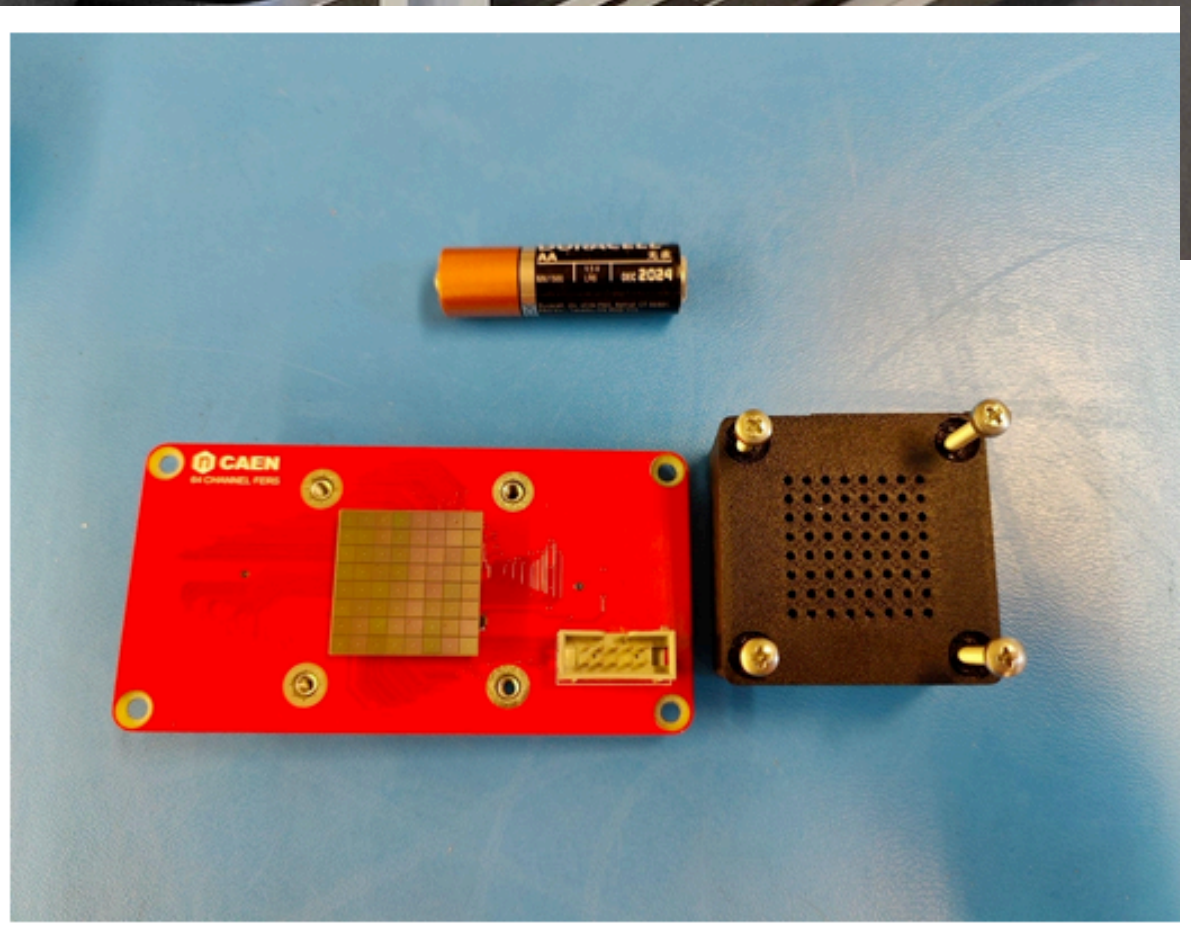
Fibre routing



64-Channel Hamamatsu S13361-3050AE-08

Custom 3D printed light shield

Darkbox tests show no light leakage between channels



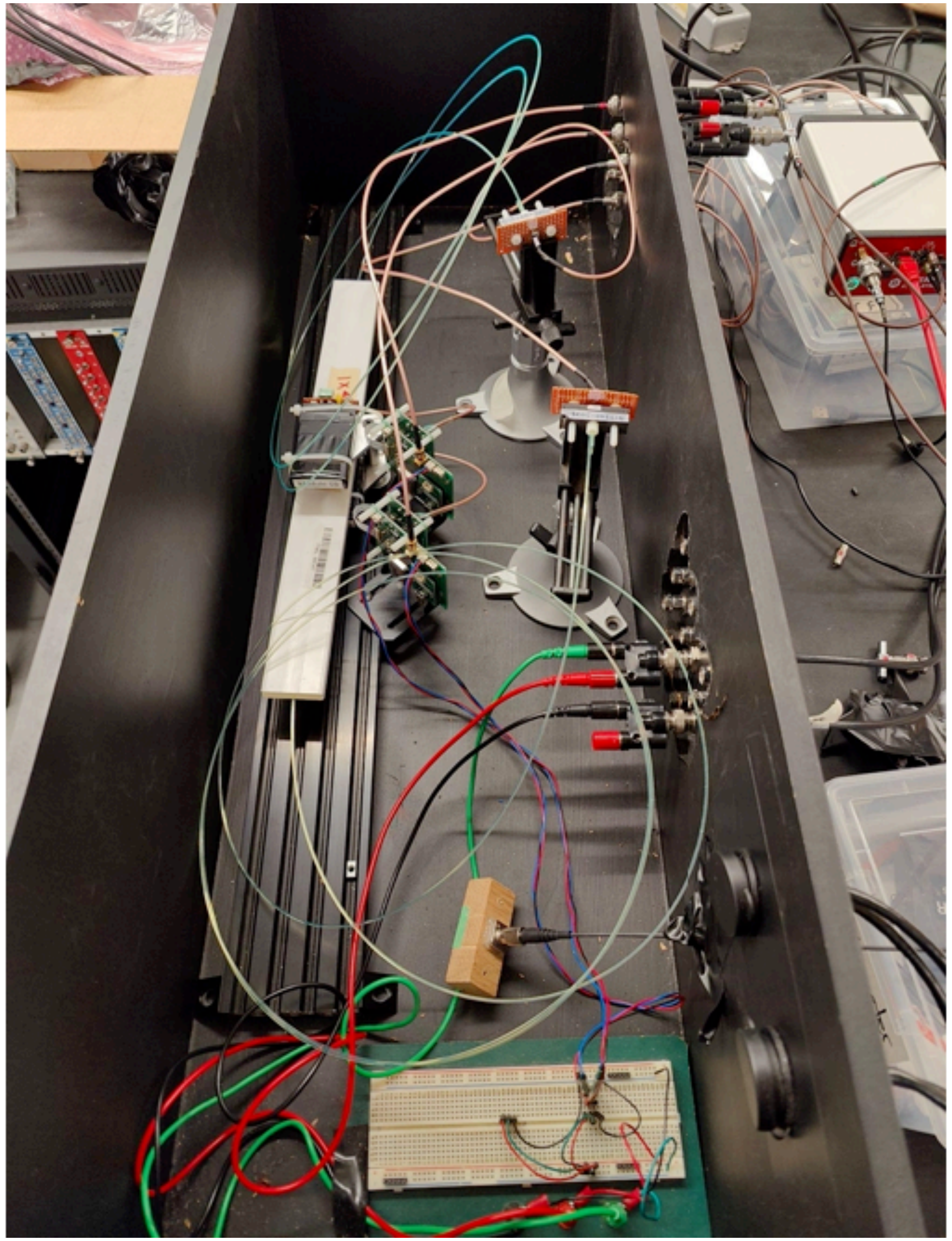
with thanks to Caleb Miller for the slide

University of Victoria

Darkbox used to test performance of various parts

Two summer students, Branden Aitken and Sarah Alshamaily, working on various projects while we construct the test stand

- Timing/position resolution
- Light yield
- Light leakage and fibre stress
- Temperature effects

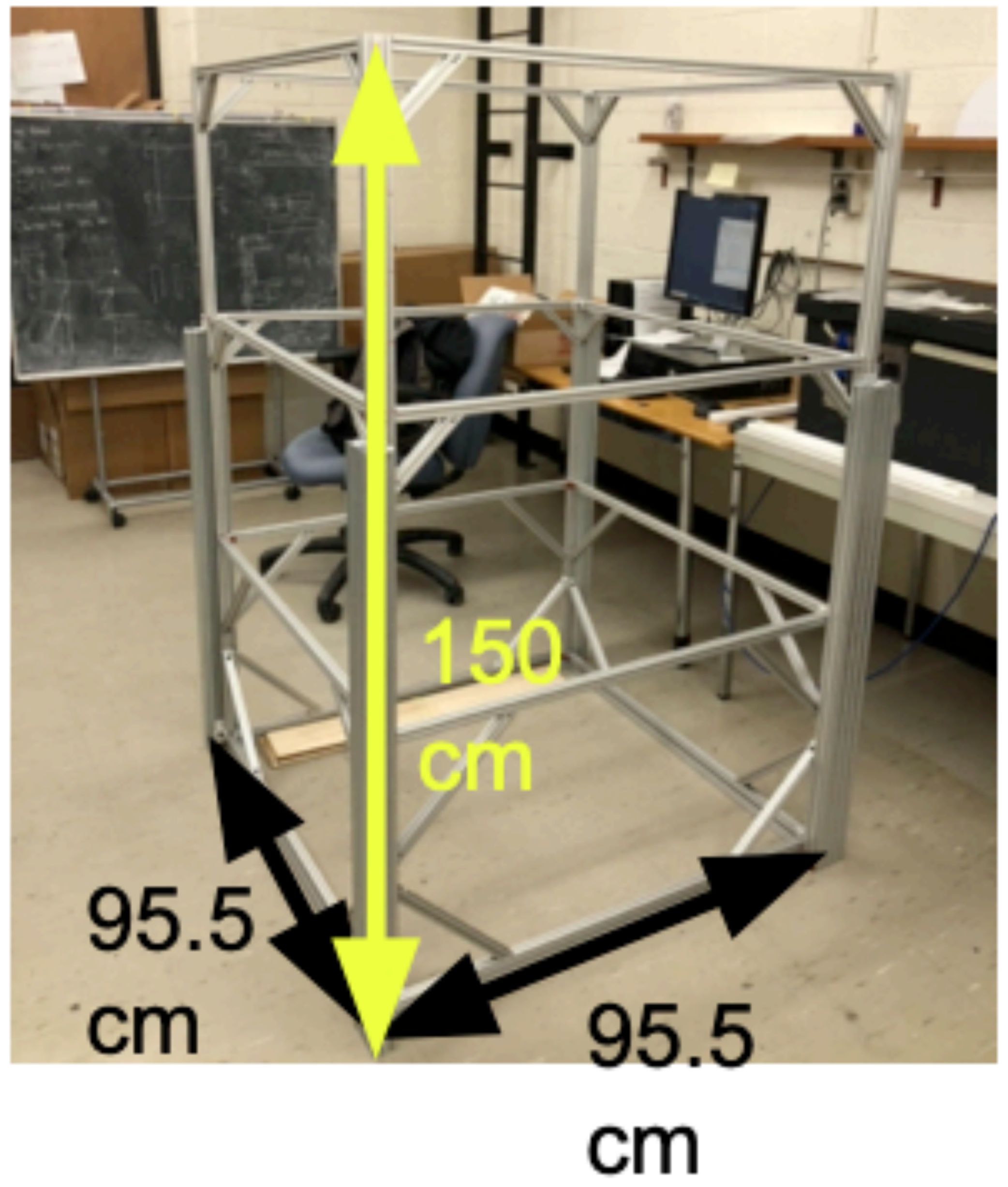


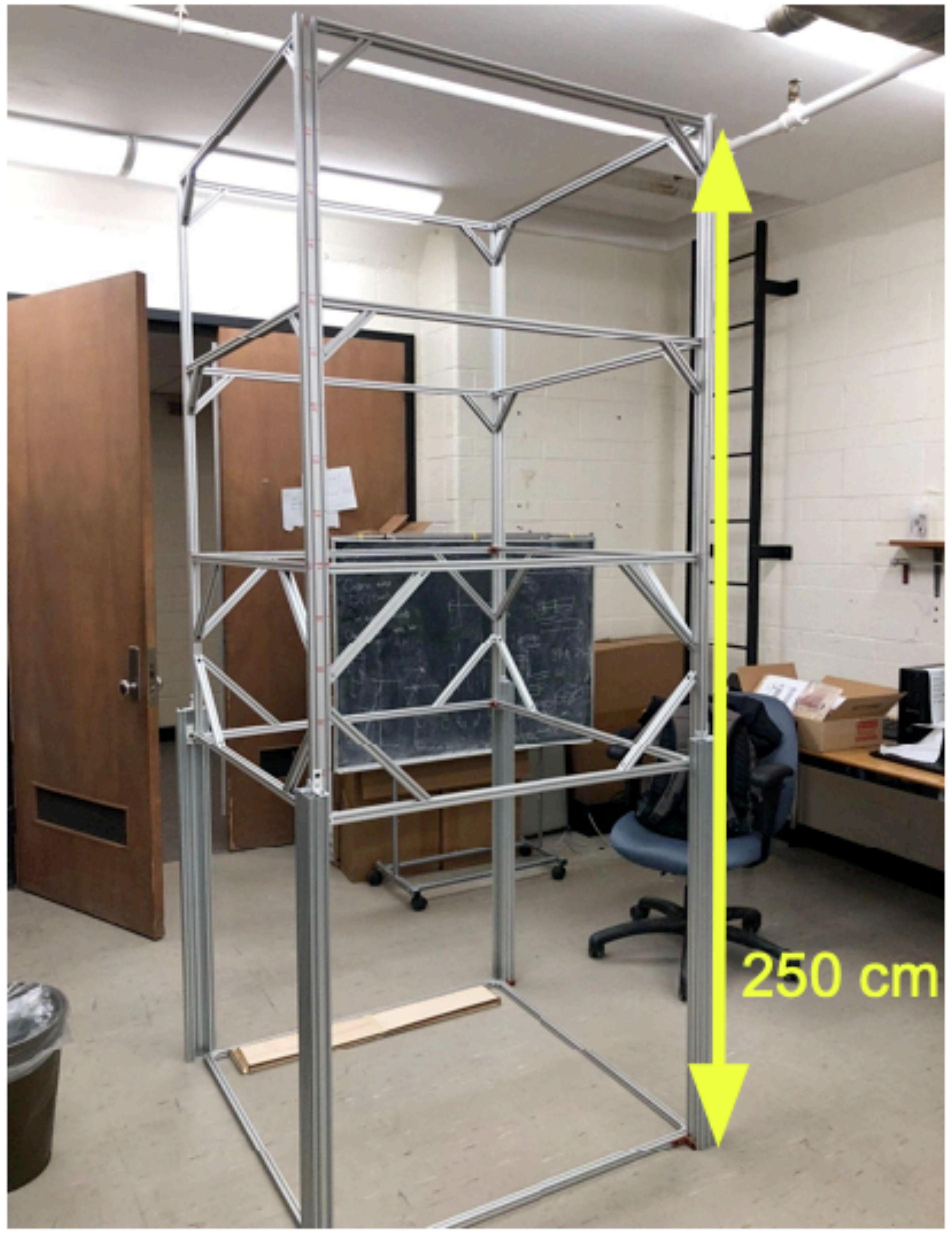
with thanks to Caleb Miller for the slide

University of Toronto

The Toronto team is also constructing a test stand

- Extendable frame
- Up to 5 layers





Faculty: Miriam Diamond

grad: Gabriel Owh

undergrad: Alex Lau

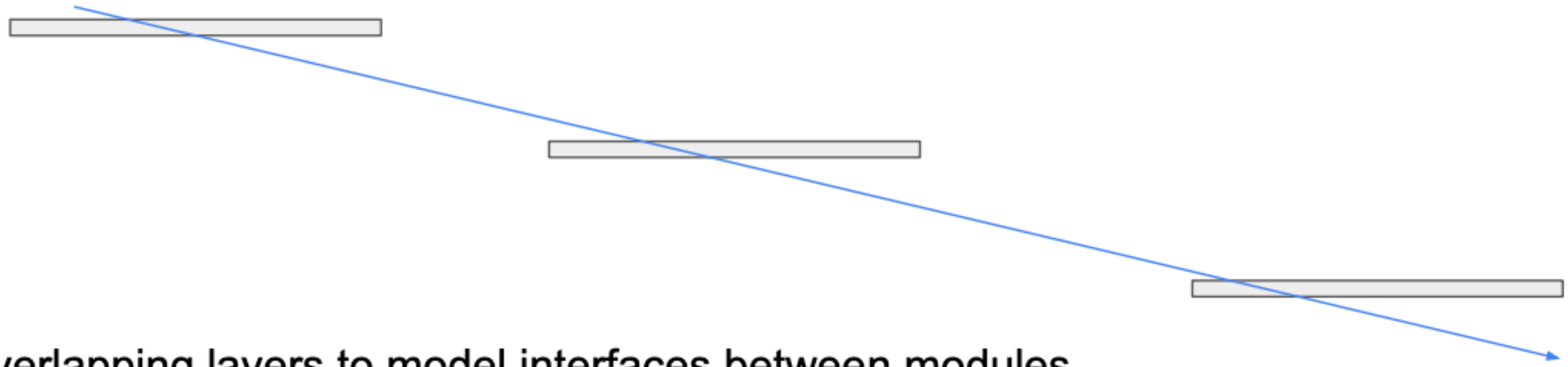
summer students: Yongqi Wang and Jason Yuan.

with thanks to Caleb Miller for the slide

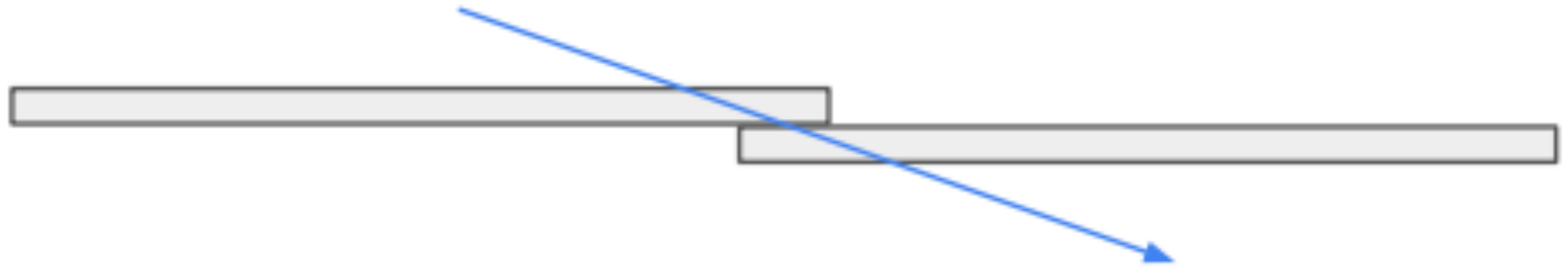
University of Toronto

Planned studies:

- PCB design & fabrication issues (noise, robustness, etc.)
- DAQ readout issues (multi-channel time-of-flight measurements, etc.)
- "Large angle" tracking



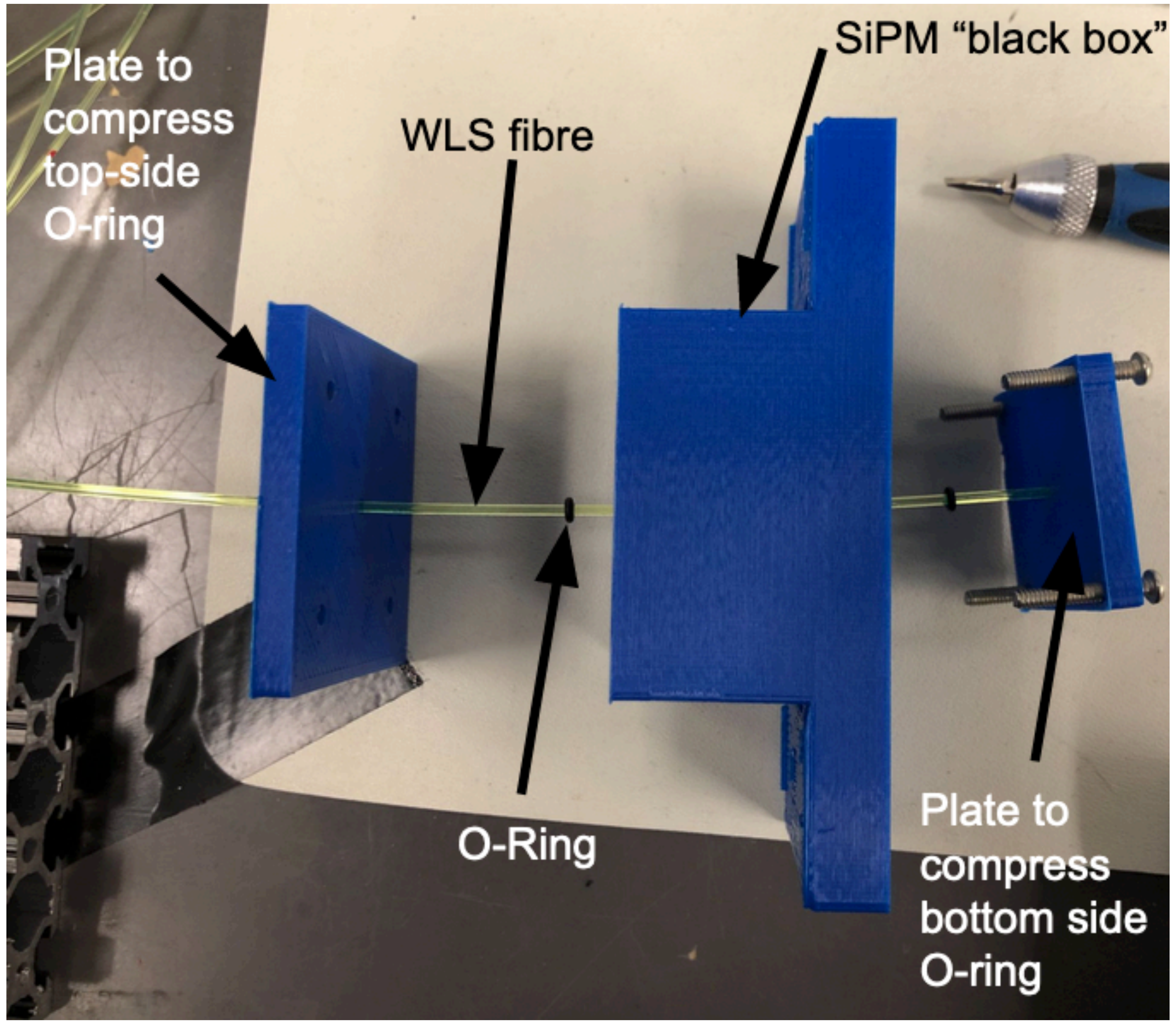
- Overlapping layers to model interfaces between modules



with thanks to Caleb Miller for the slide

University of Toronto

2 dark boxes to test schemes of attaching WLSFs to SiPMs at ends of bars, and carry the signals from the SiPMs to a front-end board.



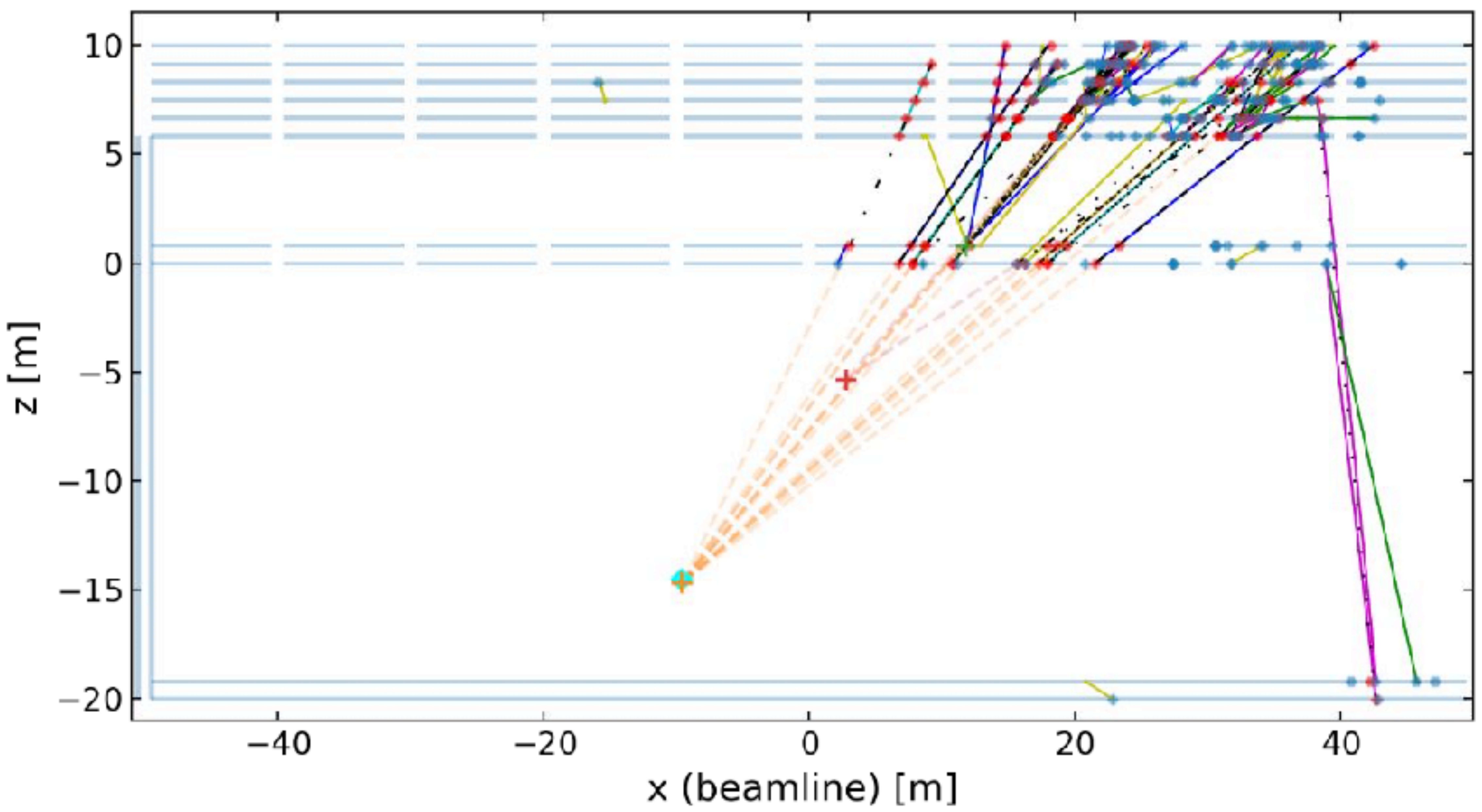
with thanks to Caleb Miller for the slide

Detailed Simulation Studies

Full GEANT simulations of MATHUSLA detector + CMS IP + rock.

Developed robust pattern recognition/ track finding (Kalman filter) and vertexing.

Reconstruction efficiencies of > 90% for tracks and vertices that are in geometric acceptance.



Faculty: Miriam Diamond, David Curtin, Emma Torró Pastor

Postdoc: Runze Tom Ren

Grad students: Jaipratap Grewal, Gabriel Owh, Abdulrahman Mohamed, Victoria Sánchez, Mariia Didenko

Summer Students: Simran Hiranandi, Haider Abbas

Detailed Simulation Studies

Currently simulating background contribution from LHC muons and K_L^0 from cosmic backscatter.

For LHC muons, rejection will depend on track/vertex finding resolution, and utilization of floor/wall detectors to tag muon tracks.

For K_L^0, simulations are challenging due to low production rate, but physics issues mostly worked out to get first rate estimates. Integration with realistic reconstruction and veto studies in progress.

10. Next Steps

Next Steps

MATHUSLA CDR will be completed in coming weeks, and presented to CERN LHCC for CERN approval.

This is a big step that will facilitate securing major funding.

Immediate next goals:

- **Detailed TDR**
- **Production of full-size prototype detector module.**

Great opportunities for new (CMS) collaborators!

How can you get involved?

- Detailed **simulation studies**, in particular correlated CMS-MATHUSLA analyses. *(Realistic LLP diagnosis)*
- We need **computing experts** to flesh out MATHUSLA's **data storage strategy**. *(Can we store every hit in MATHUSLA, and if yes, how?)*
- In coming years, we will lock down details of **Scintillator/SiPM** for MATHUSLA detector modules. Implementing these at **at scale** makes **QAQC** a high priority. Coming up with a plan, defining priorities etc would benefit from Fermilab/CMS expertise.
- For **DAQ/Electronics** we have high-level design and feasibility studies, but need **detailed design and implementation**
- Very high priority but difficult to get: **Systems Engineer** to finalize high-level design of MATHUSLA detector.