MATHUSLA status update

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on behalf of the MATHUSLA Collaboration

13 LHC LLP workshop
22 June 2023

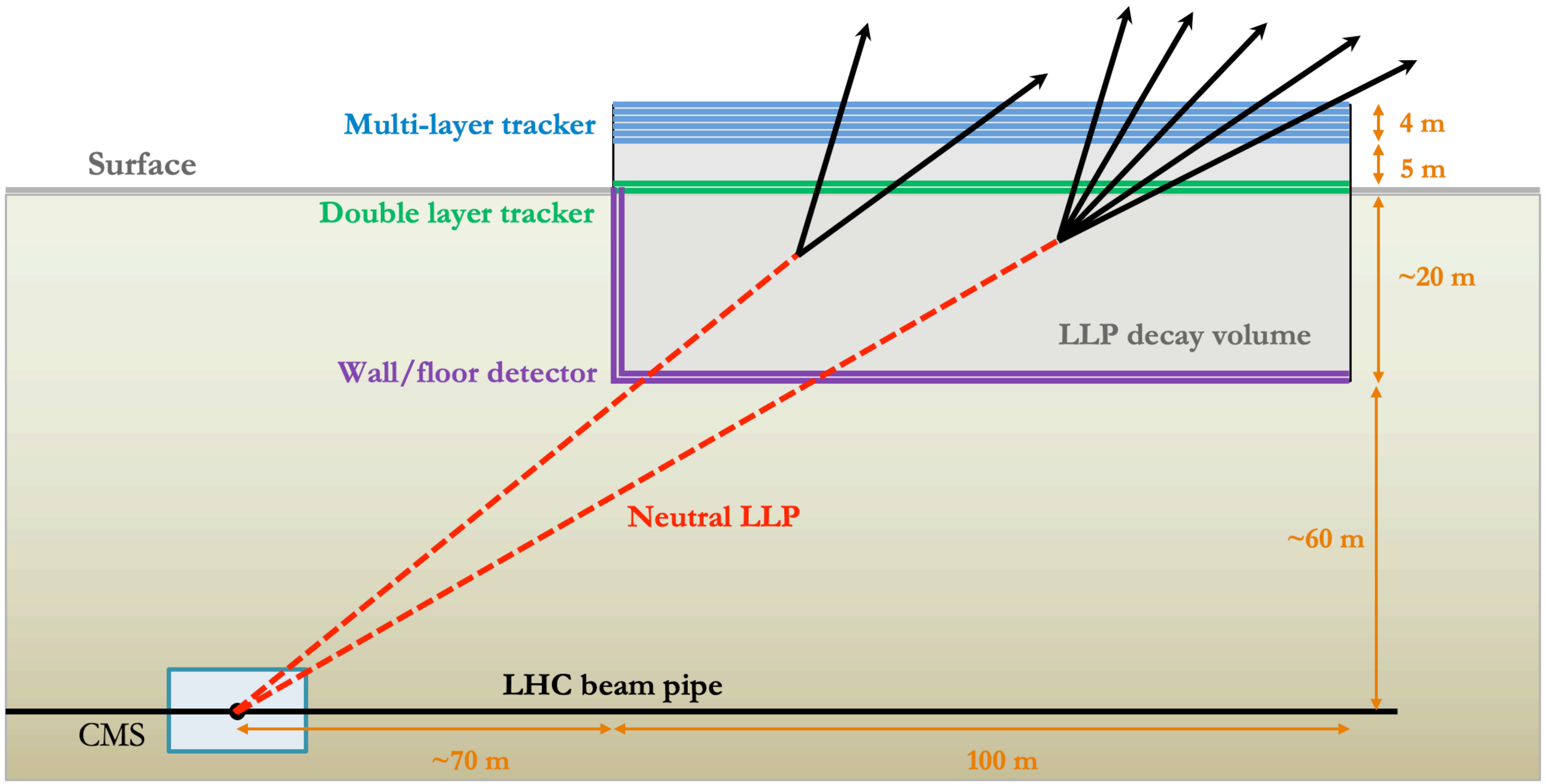
MATHUSLA concept

Updated LHCC LoI: https://arxiv.org/abs/2009.01693

MAsive Timing Hodoscope for Ultra Stable neutraL pArticles

- Proposed LHC auxiliary transverse LLP Detector
- Target: ultra long-lived particles, to have sensitivity to lifetimes up to 0.1s (BBN limit)

- To be placed on the surface **above CMS**
- To take data **during the entire HL-LHC** operation



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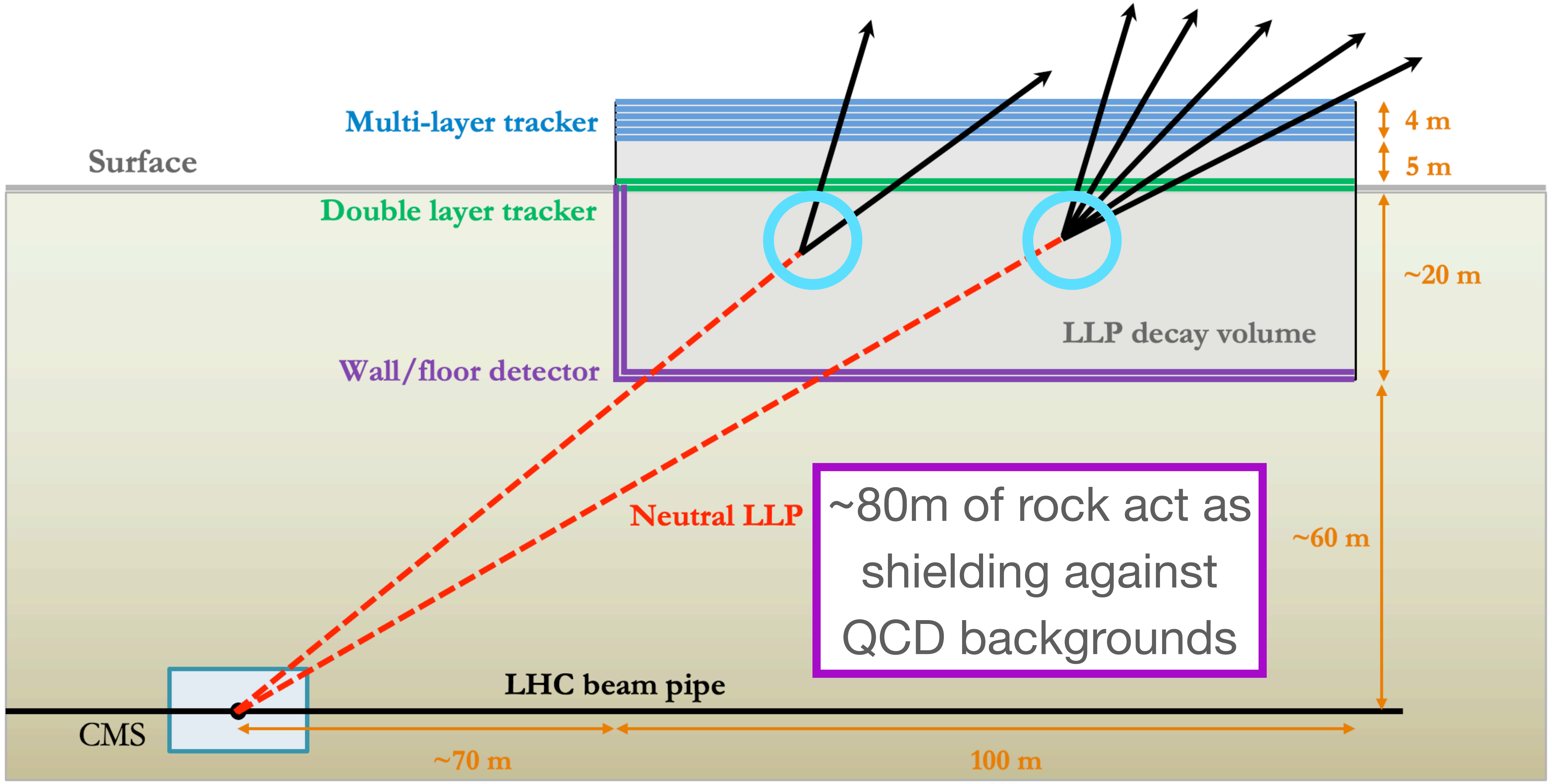
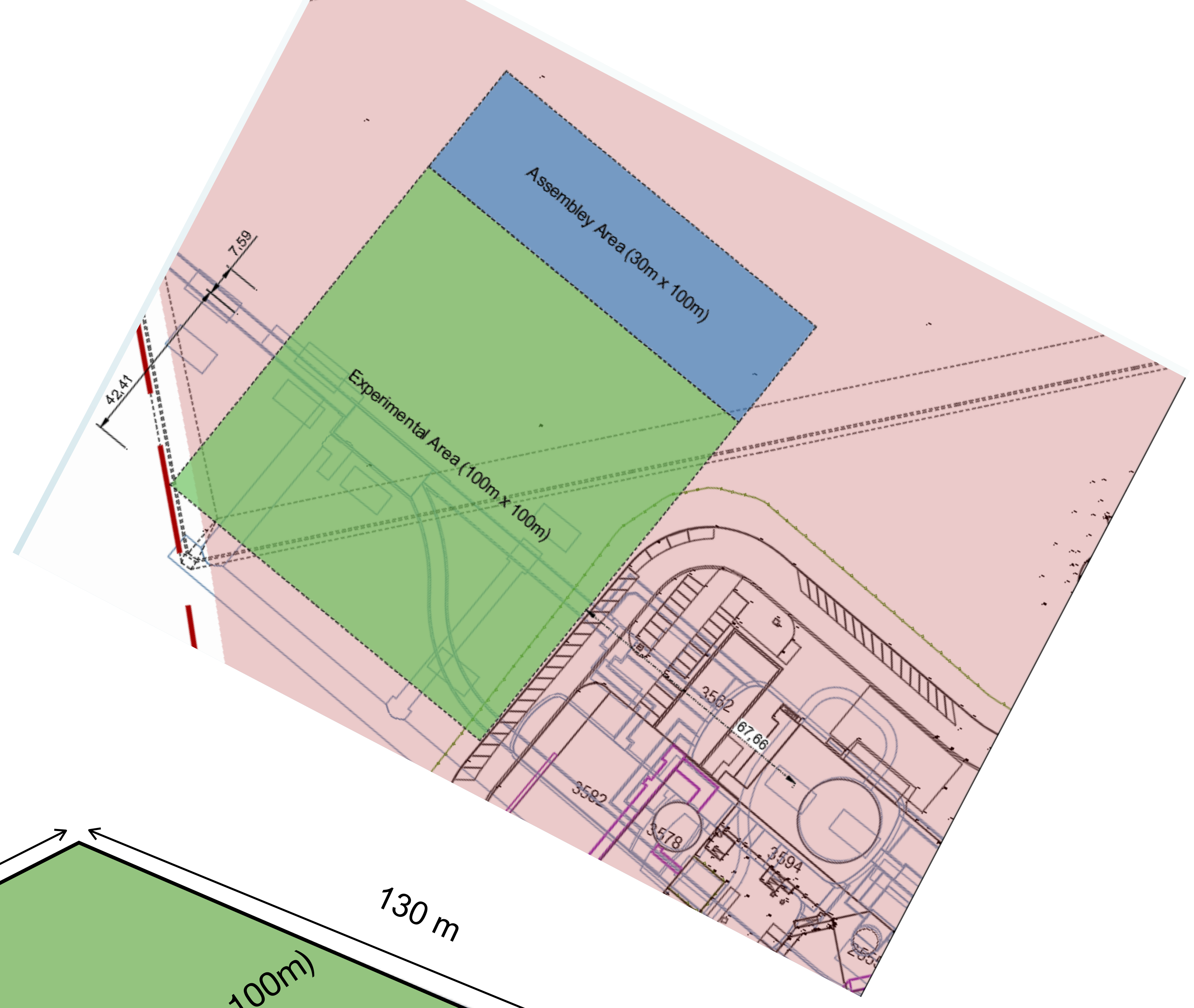
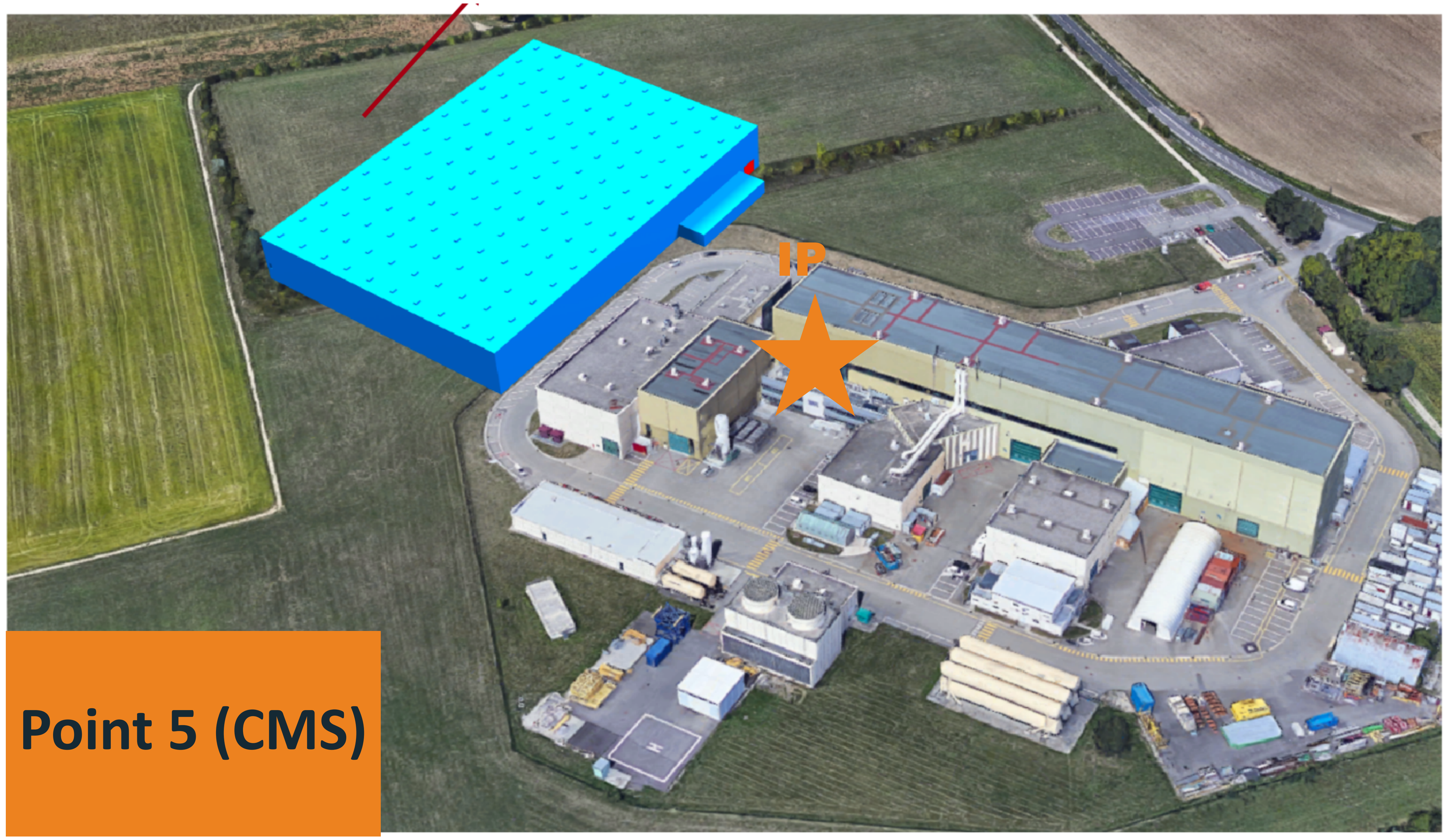


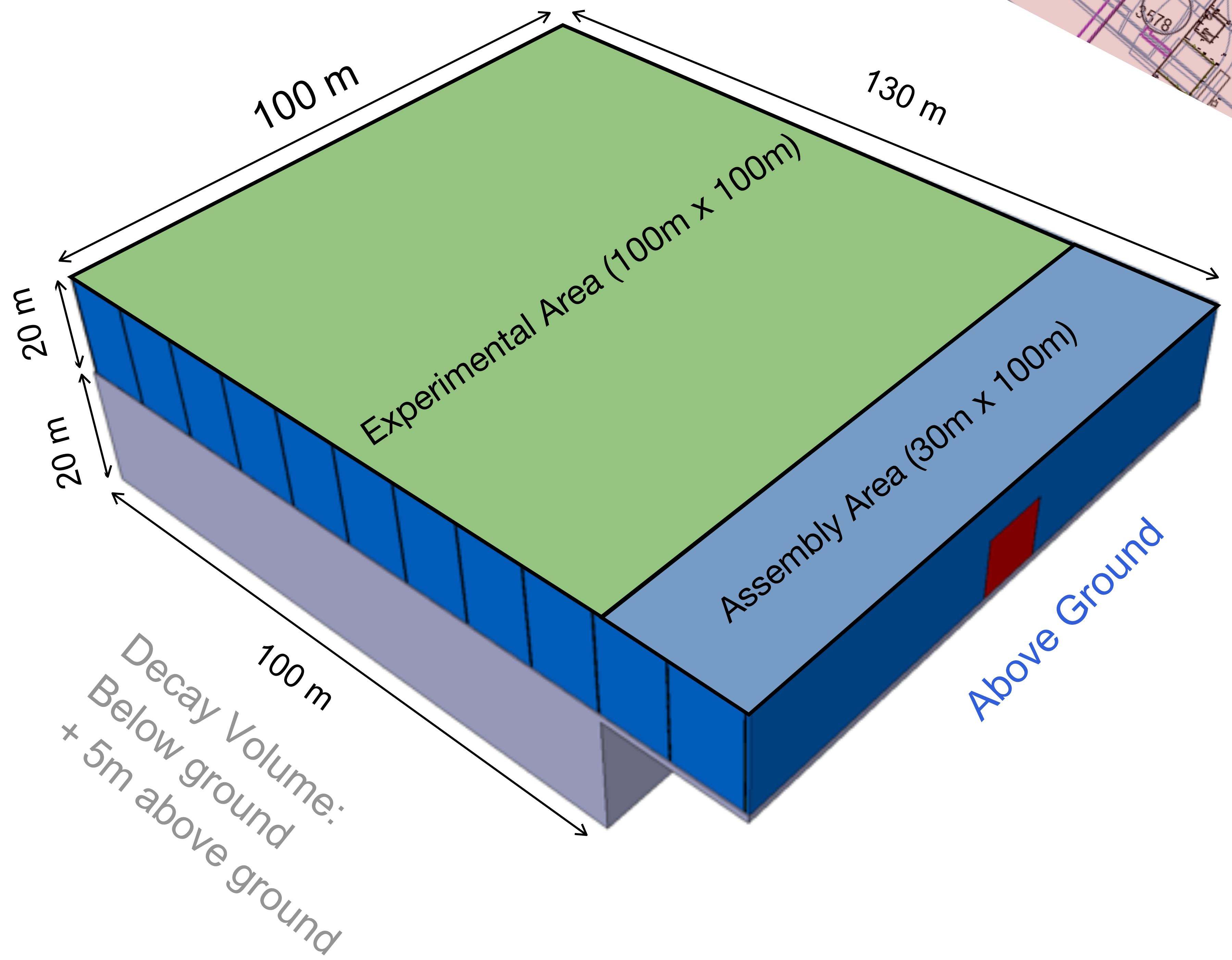
- Large air decay volume with:
  - walls and floor scintillator layers to flag LHC muons
  - several layers of scintillators for tracking
  - Scintillator timing separates upward tracks from LLP decays from downward cosmic rays
  - LLPs decaying inside MATHUSLA are reconstructed as **displaced vertices** (robust tracking)

MATHUSLA at P5

- Proposed building to house MATHUSLA on CERN owned lands at P5



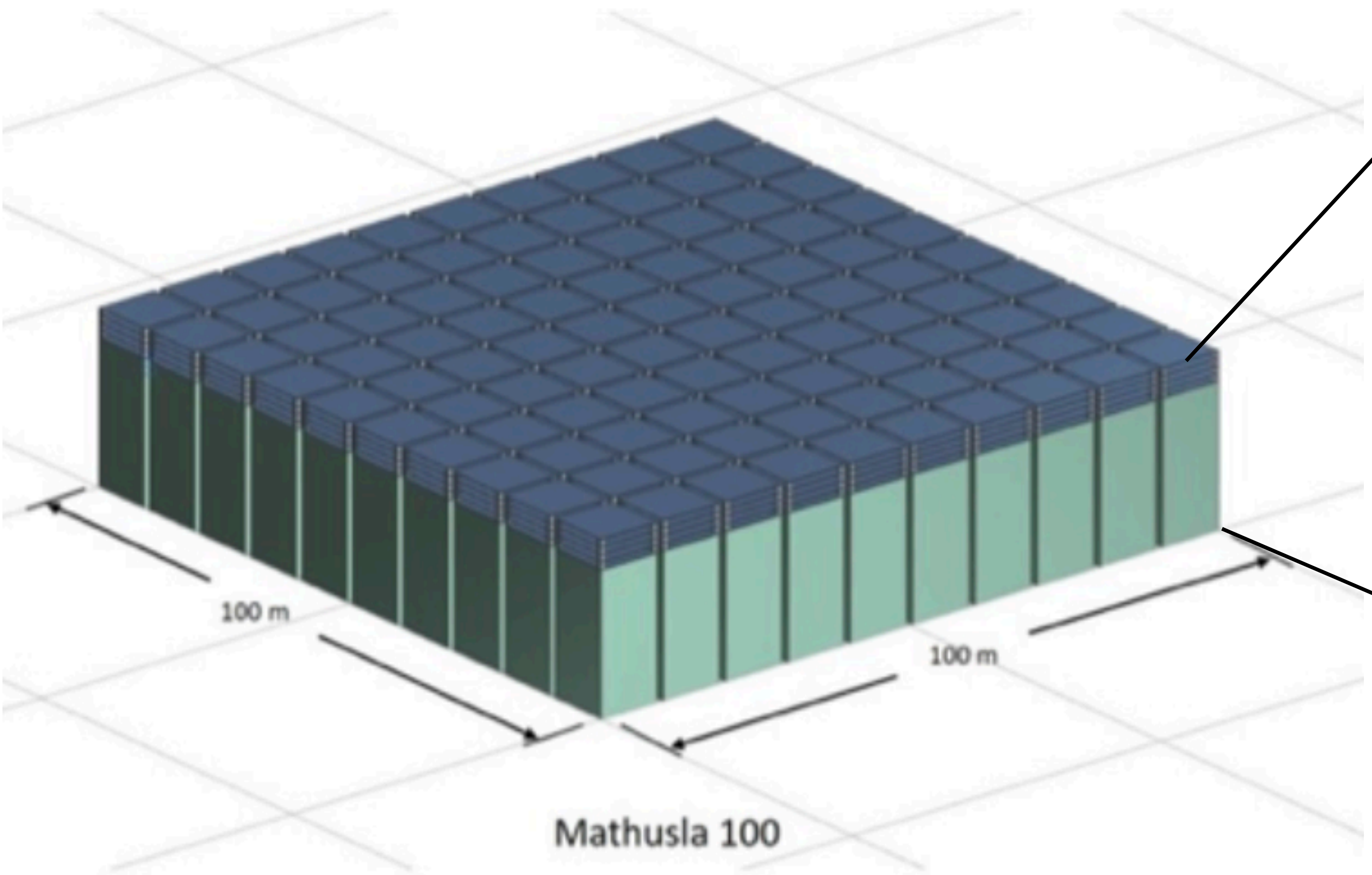


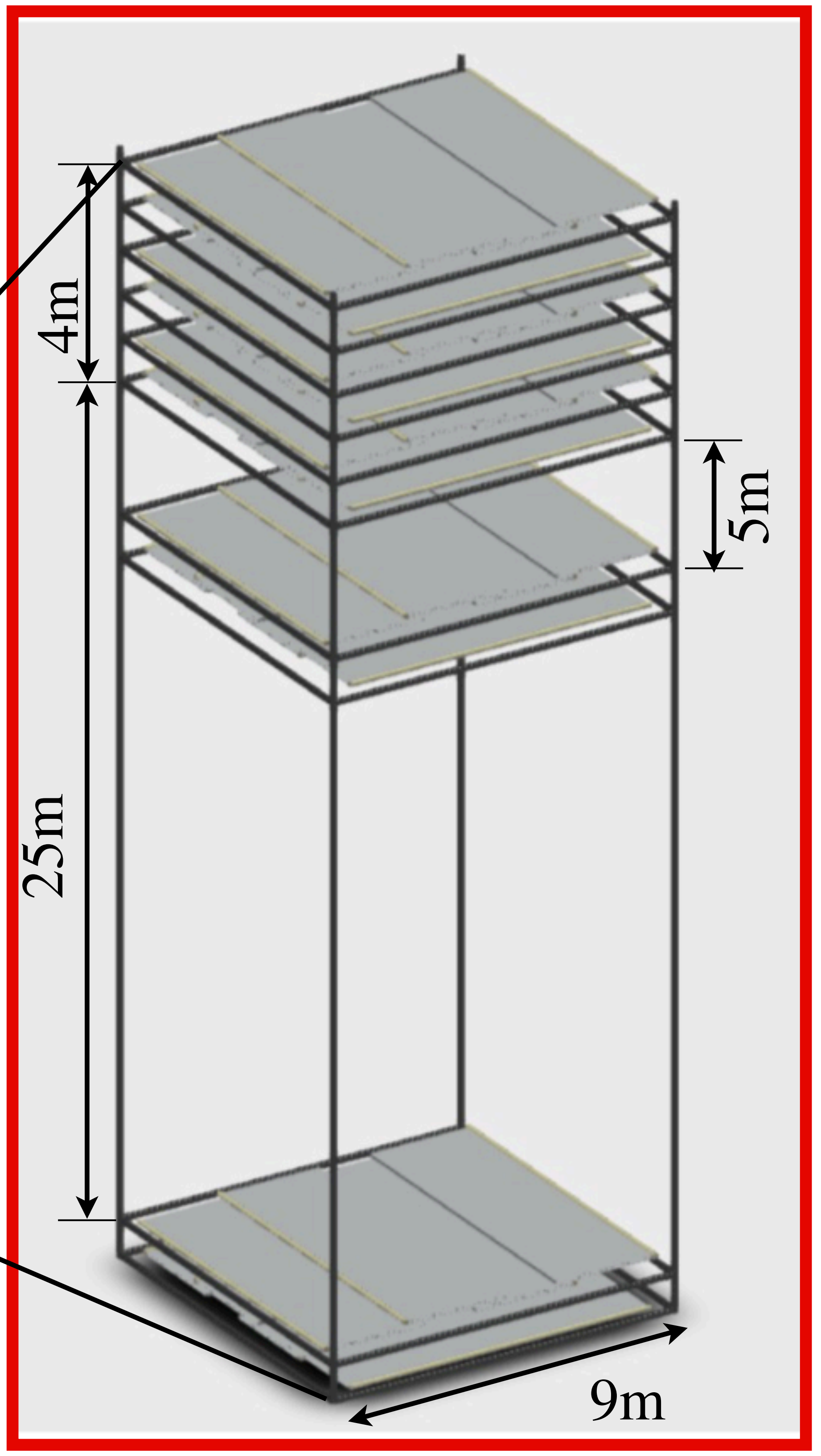


- Layout restricted by existing structures based on current concept and engineering requirements
- Building at the surface extends ~20m below ground

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

Detector Plane layout

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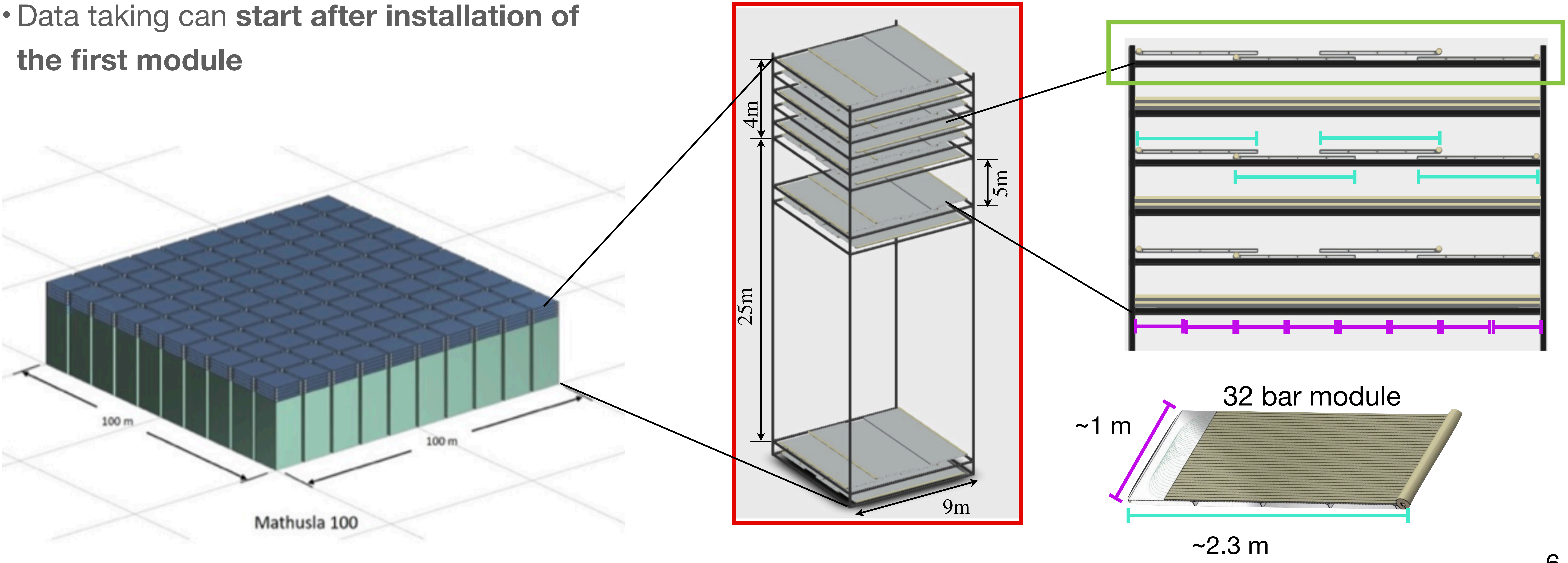
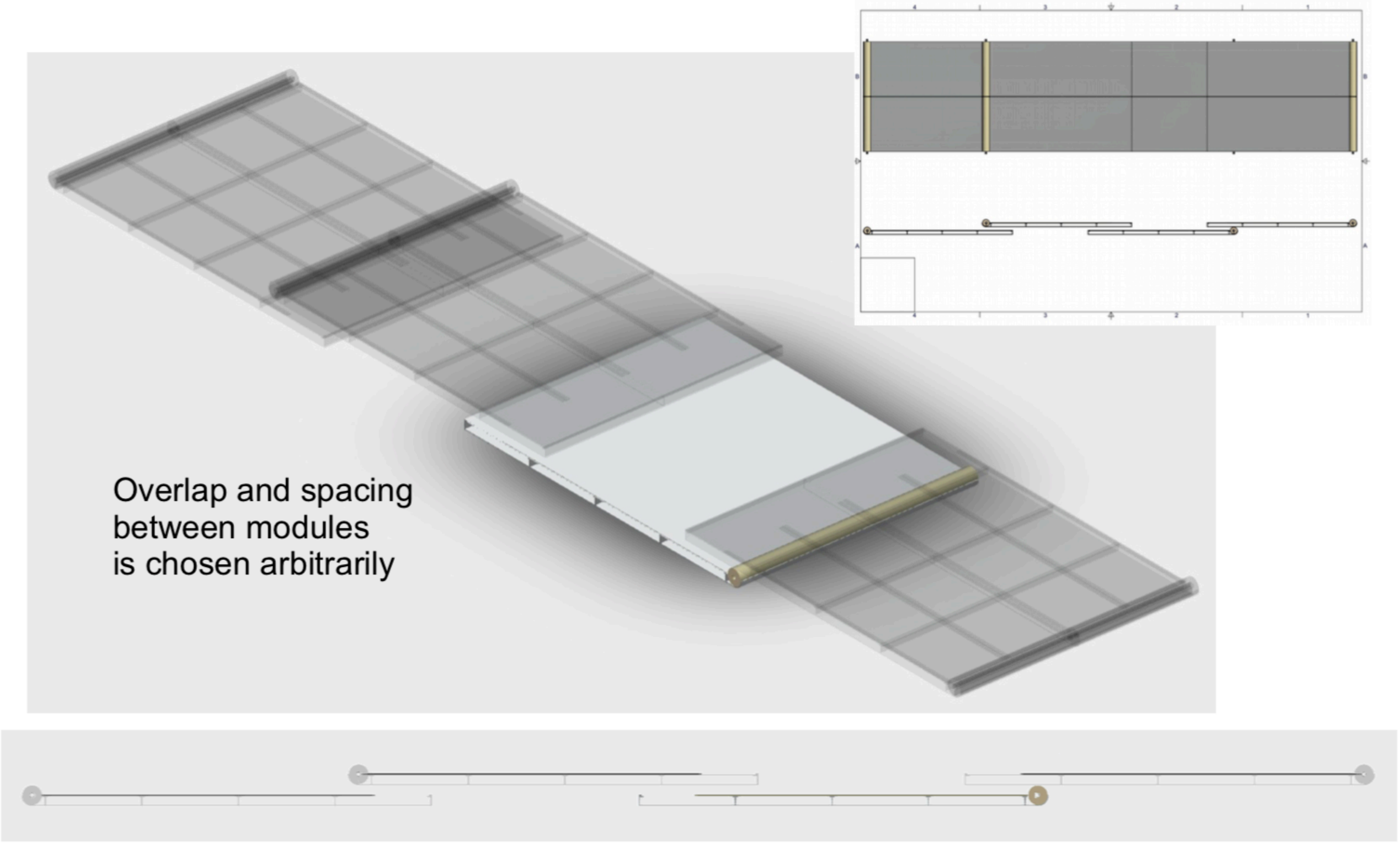
- Each tracking layer is formed by 4 sub-planes consisting of 8 adjacent modules
- Each module contains 32 scintillator bars

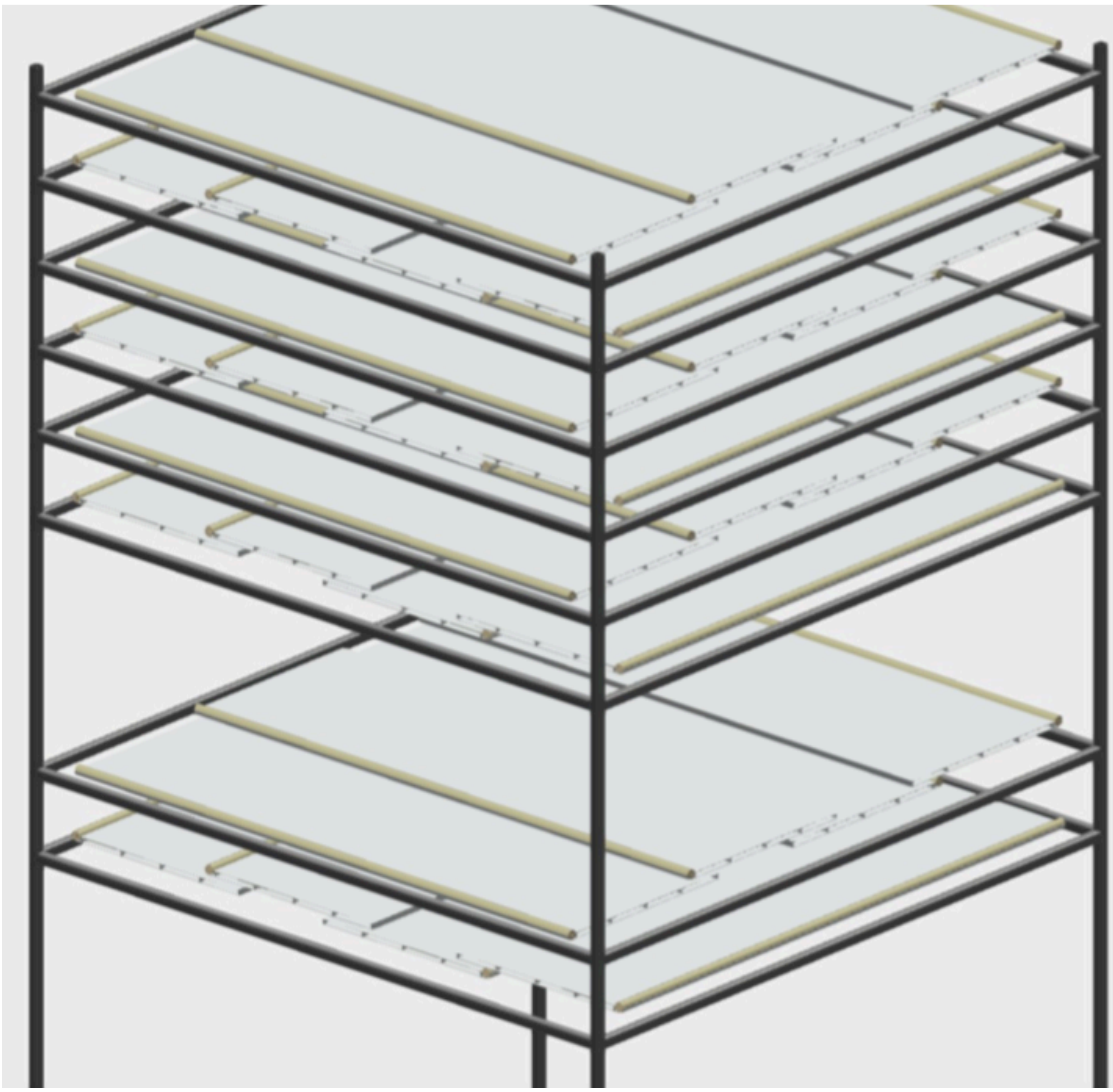


Detector Plane layout

- 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



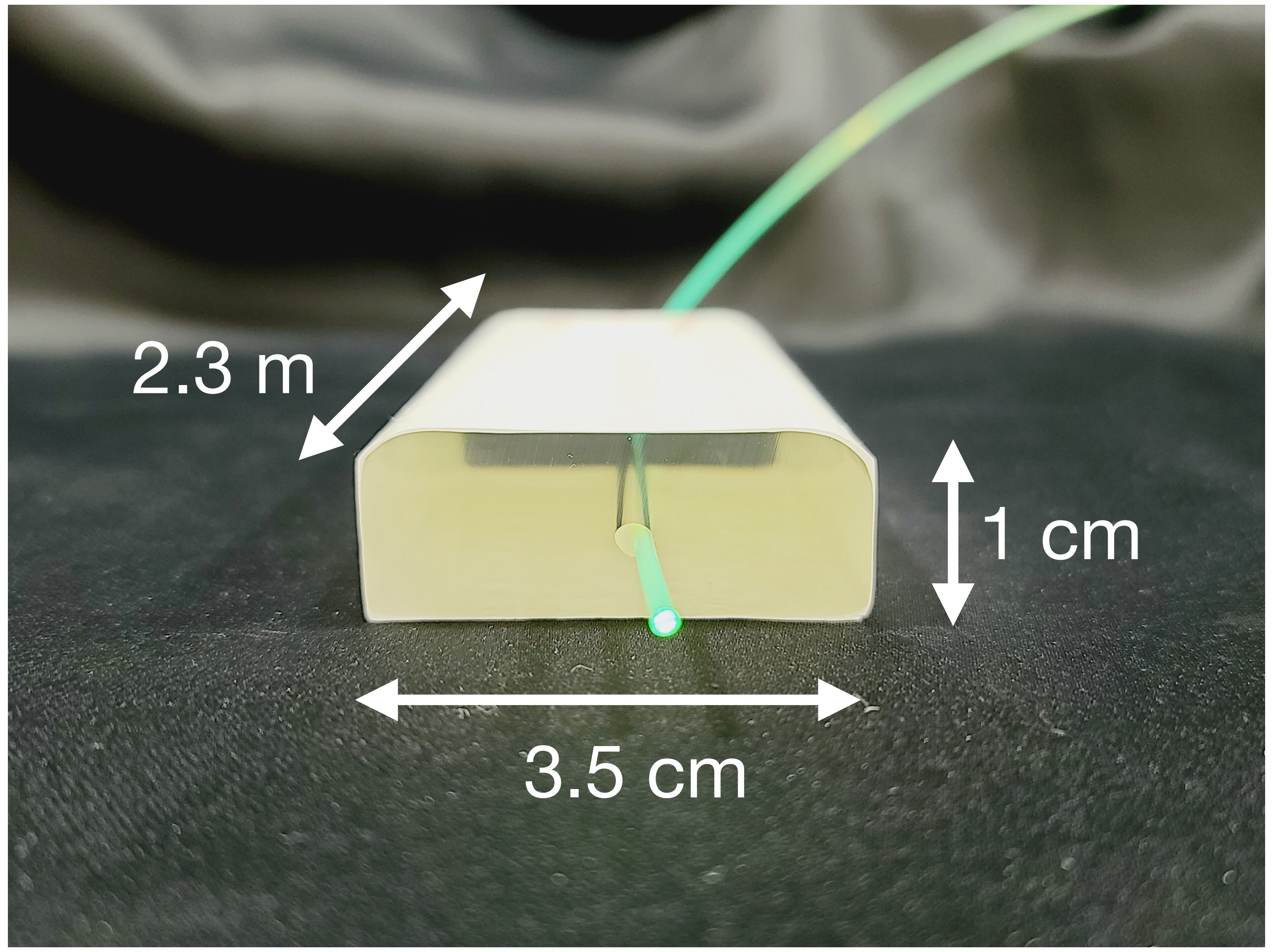
Scintillators / SiPMs R&D

- 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
  - …

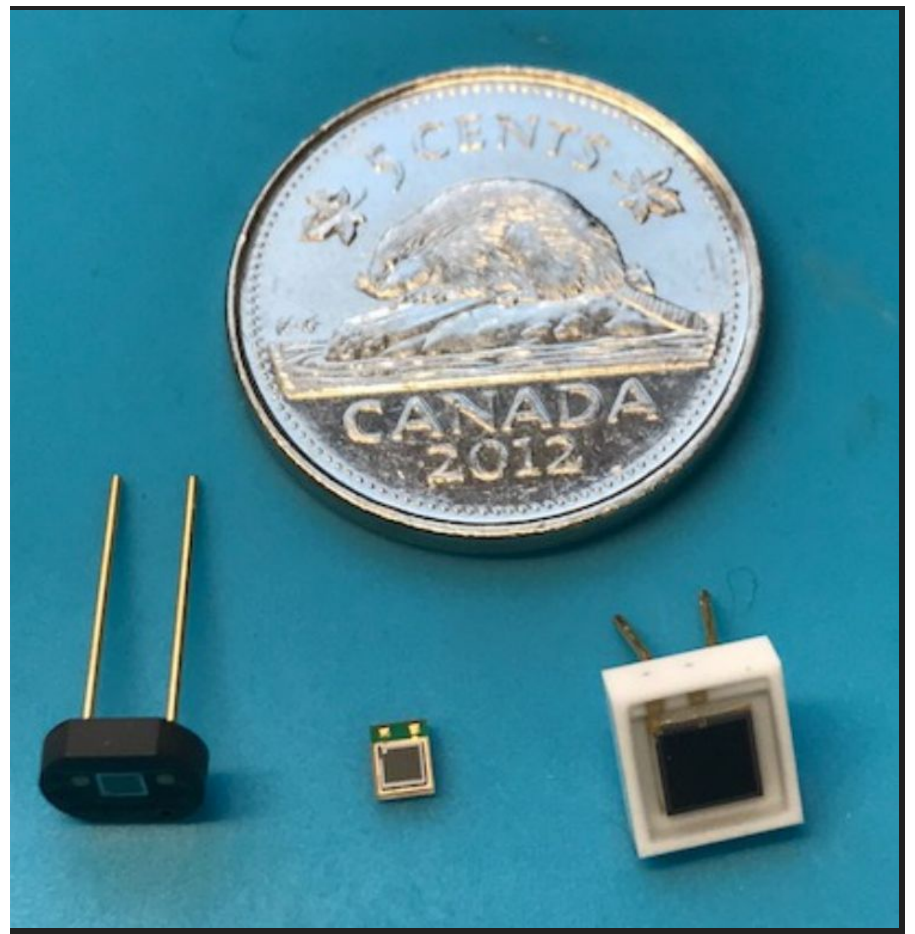
- Critical features for detector design
  - Separate downward from upward going tracks
  - Reject low beta particles from neutrinos
  - **4D tracking and vertexing** to reduce fakes/combinatorics

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



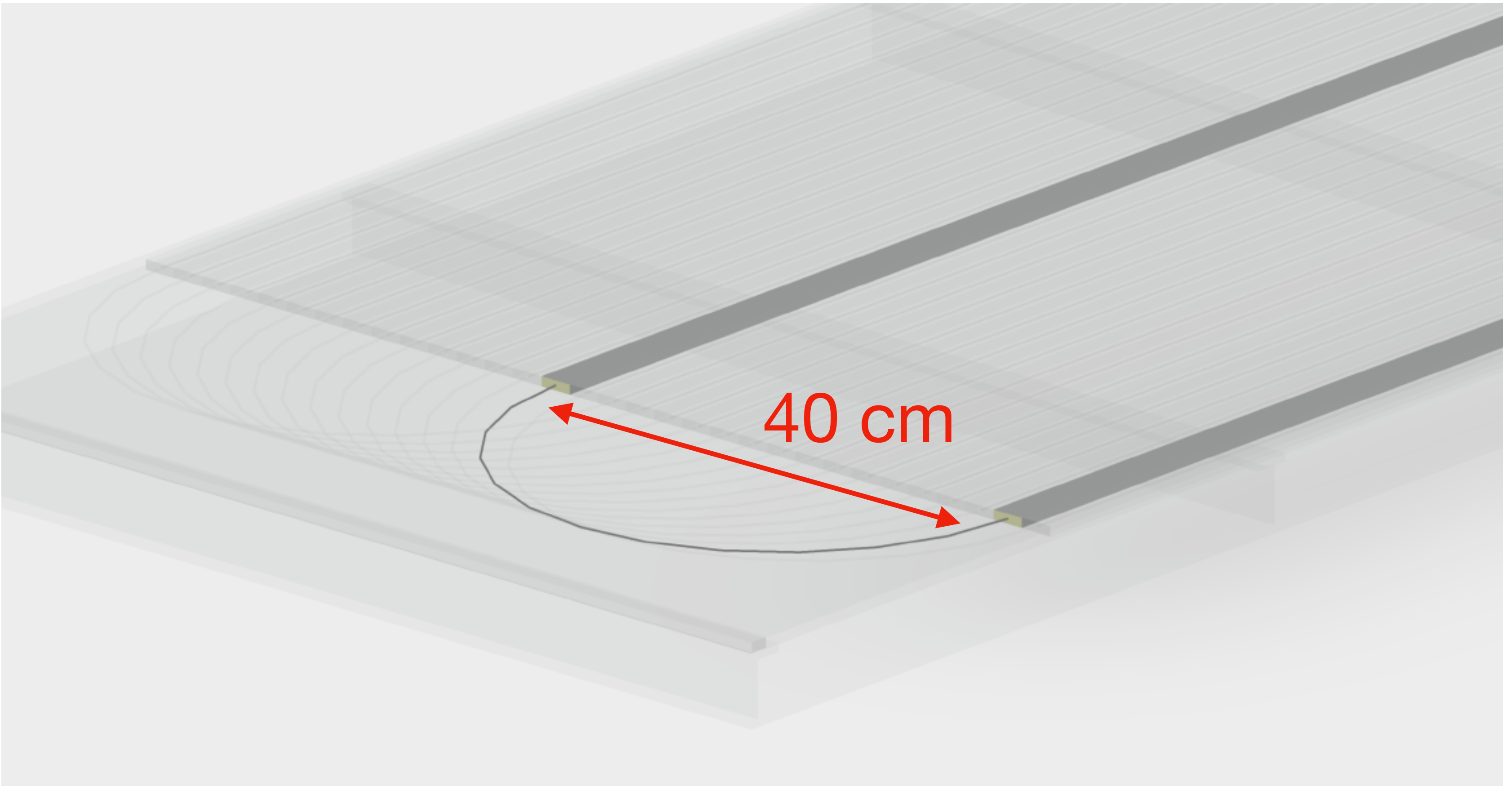
Example SiPMs that have been tested

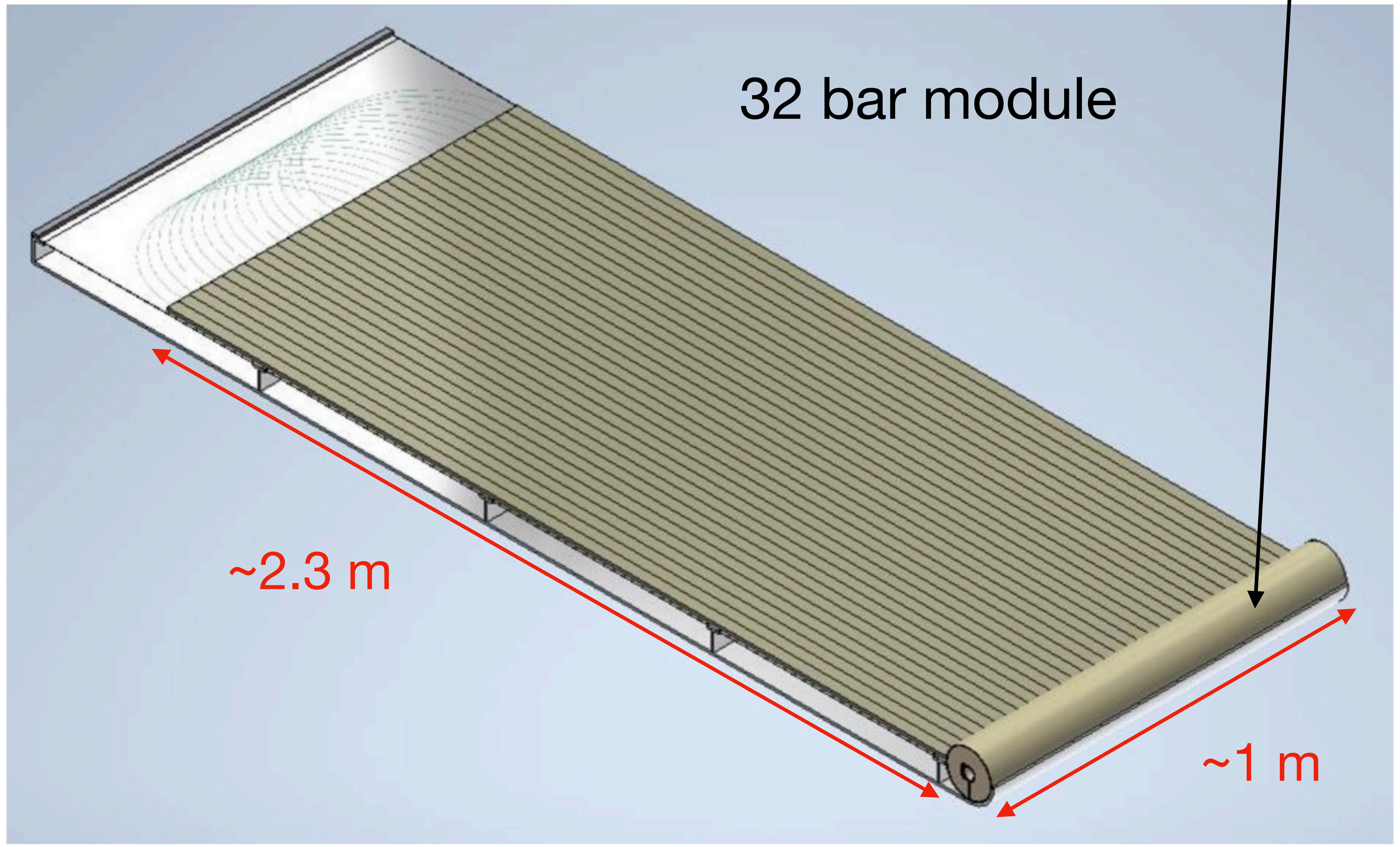
Detector Plane layout

- 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

Detector Plane layout

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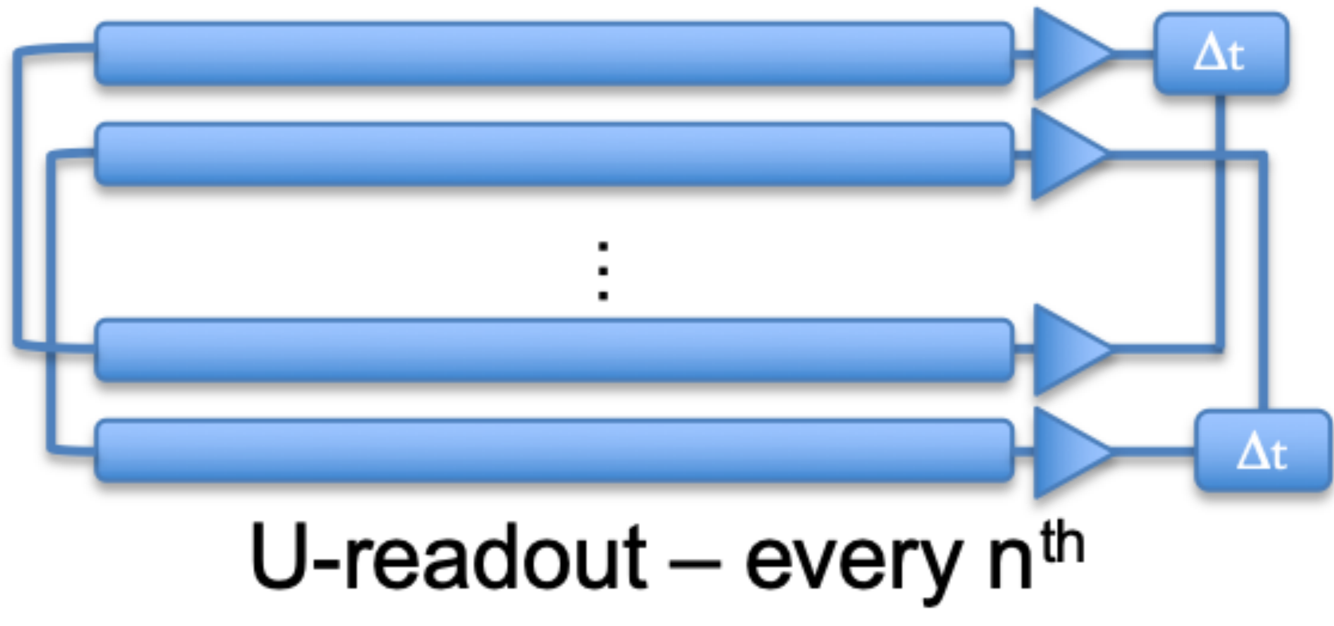

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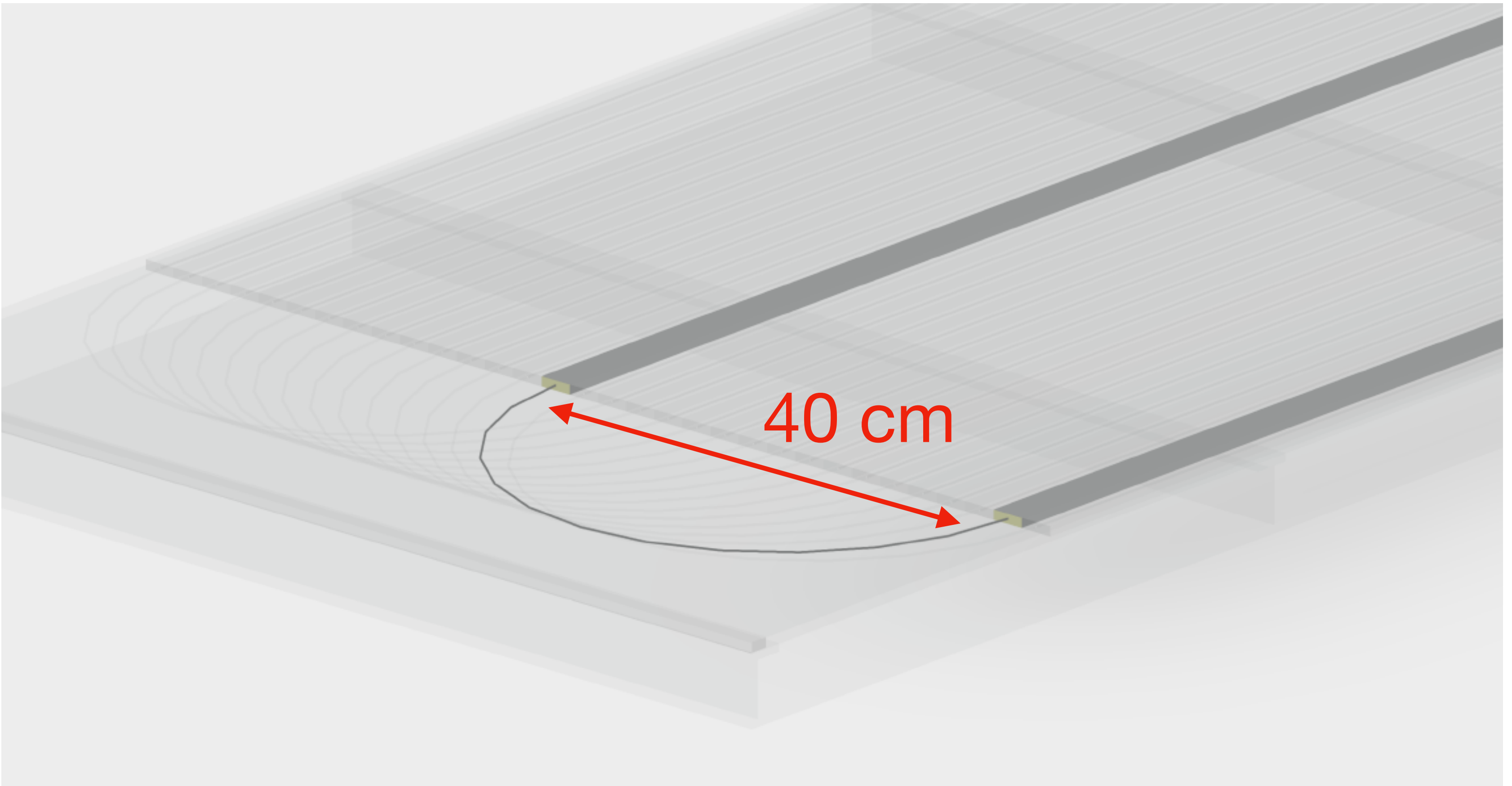
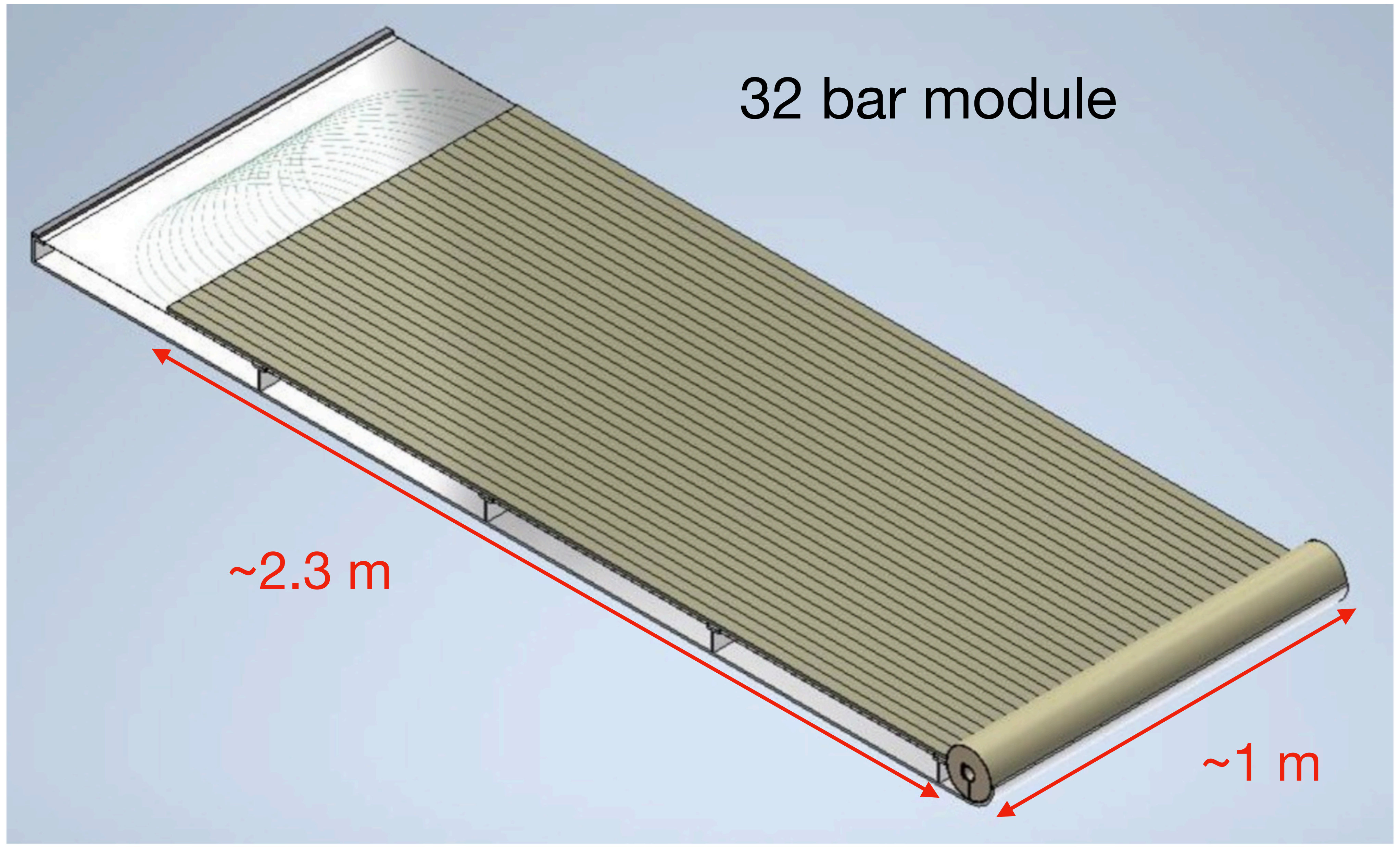




- Time difference between light pulses at the ends of the WLS fibre: complementary coordinate measurement in each scintillating layer

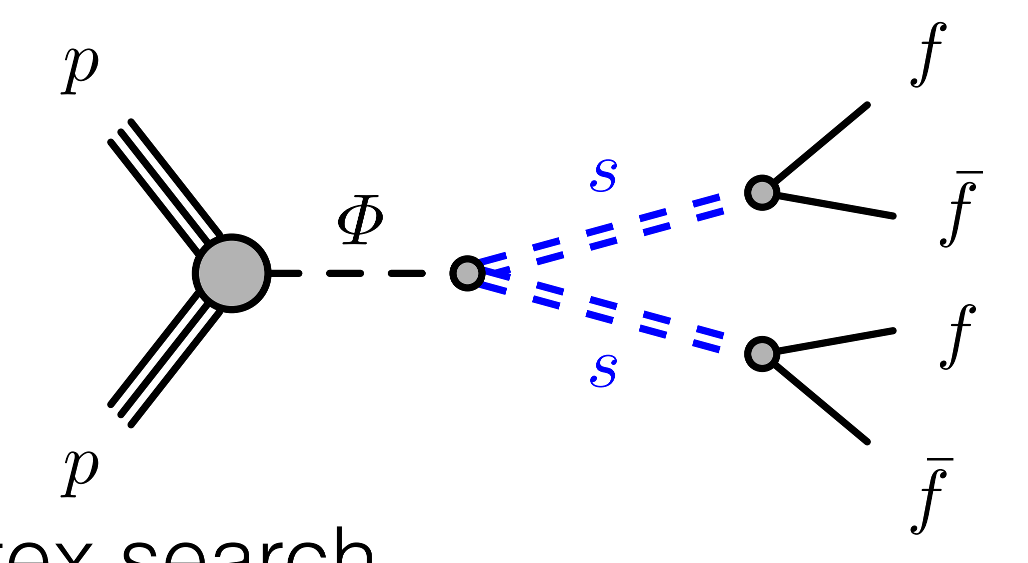
- Separation of extrusions to satisfy minimum bend radius of the fiber

Trigger and data acquisition

- Naturally shielded from IP, so hit rates are dominated by cosmic rays
- Plan to use commodity hardware for trigger and data acquisition
  - Stream all hits to a buffer storage
  - Relevant hits selected for permanent storage
    - Kind of high-level trigger with hours of trigger latency

- Able to trigger CMS readout!
  - Allows matching to full event information
    - Can check prompt activity and missing transverse momentum in CMS collision
  - Challenging due to tight CMS L1 latency with their Phase-2 trigger upgrade
  - Feasibility has been confirmed in detailed study
    - Trigger is defined by identification of upward going decay vertex using 4D tracking
    - Necessary to include particle transit times from IP, signal propagation time in MATHUSLA, trigger algorithm time, and signal transmission time back to CMS
    - Resource usage reasonable with current generation FPGAs

Expected sensitivity

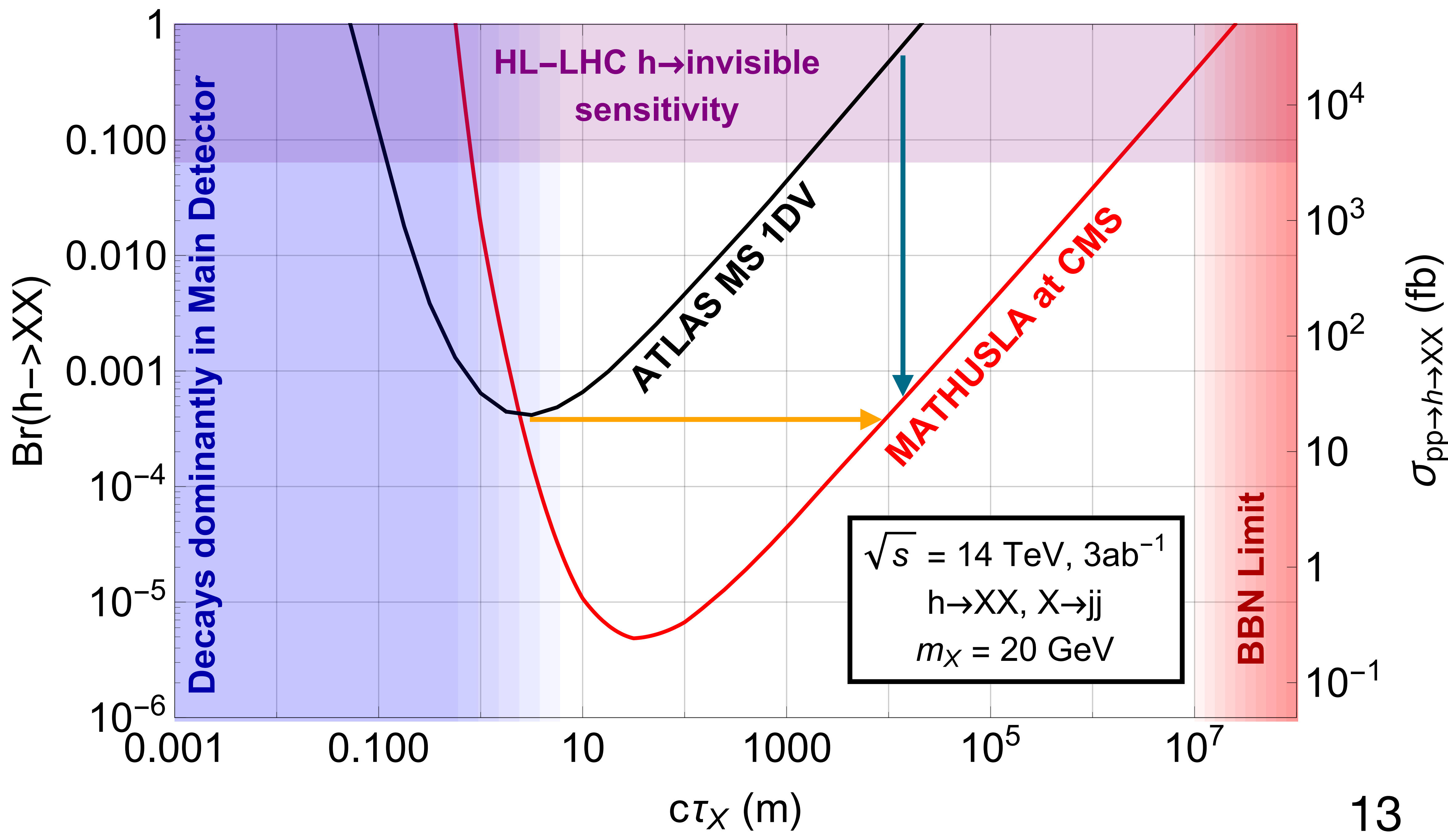


- Great background rejection to ~zero thanks to:
  - Rock shielding: punch-through jets in ATLAS (CMS) background is the limiting factor for the mu-vertex search
    - In MATHUSLA this is eliminated in the rock
    - ~zero QCD background
  - Good space-time resolution: rejection of 1.7MHz from cosmic μ
  - Robust tracking: rejection of 10Hz from LHC μ
- **Background hypotheses confirmed** with the Test Stand

- Primary physics case: hadronically decaying O(10-100 GeV) LLPs
  - Example: exotics Higgs decays in Hidden sector H→ ss

Absence of collision backgrounds allow MATHUSLA for a good gain wrt best ATLAS expected result:

- 3 orders of magnitude in ctau
- 3 orders of magnitude in sensitivity



Expected sensitivity

- Secondary physics case: GeV-scale LLPs from B, D meson decays

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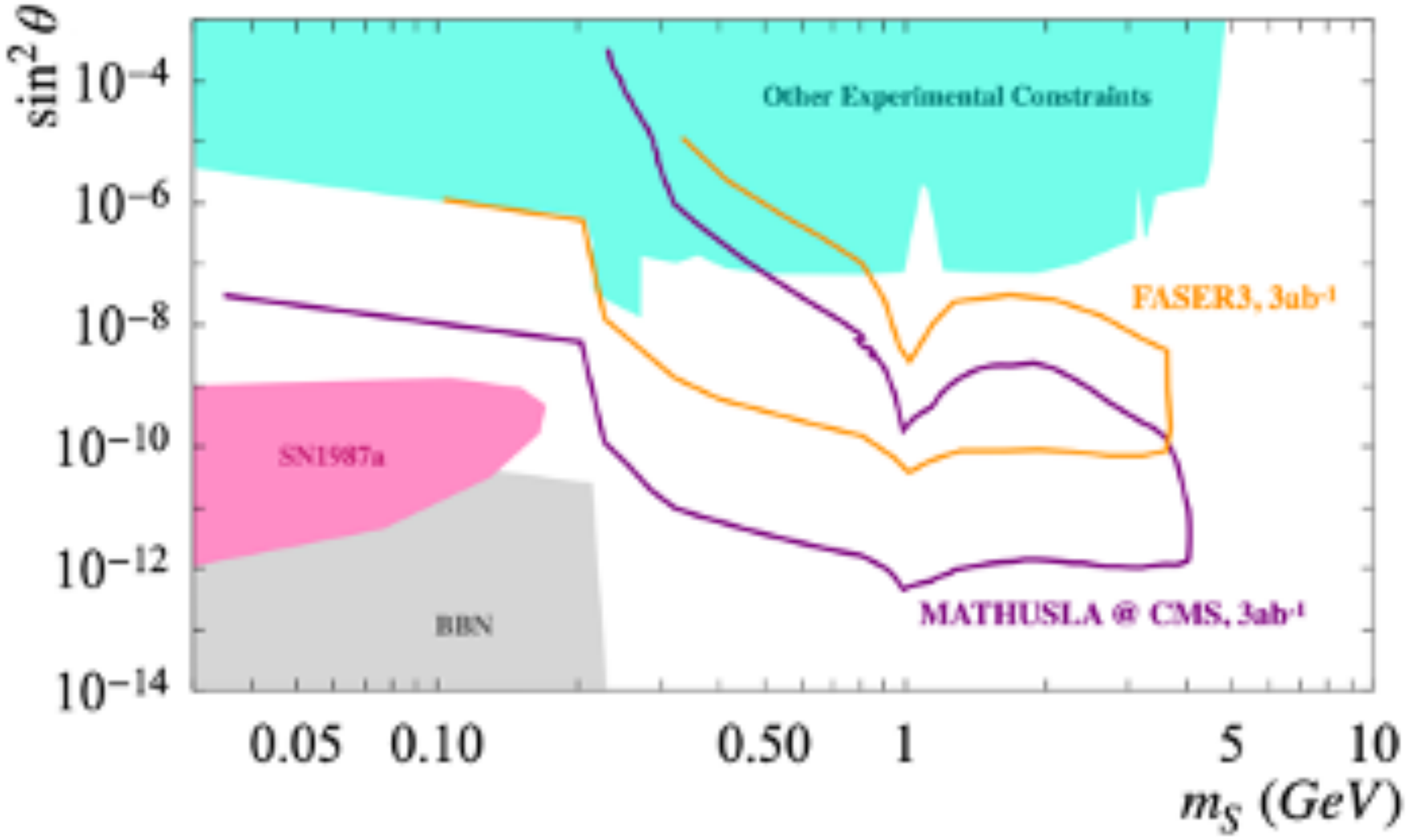

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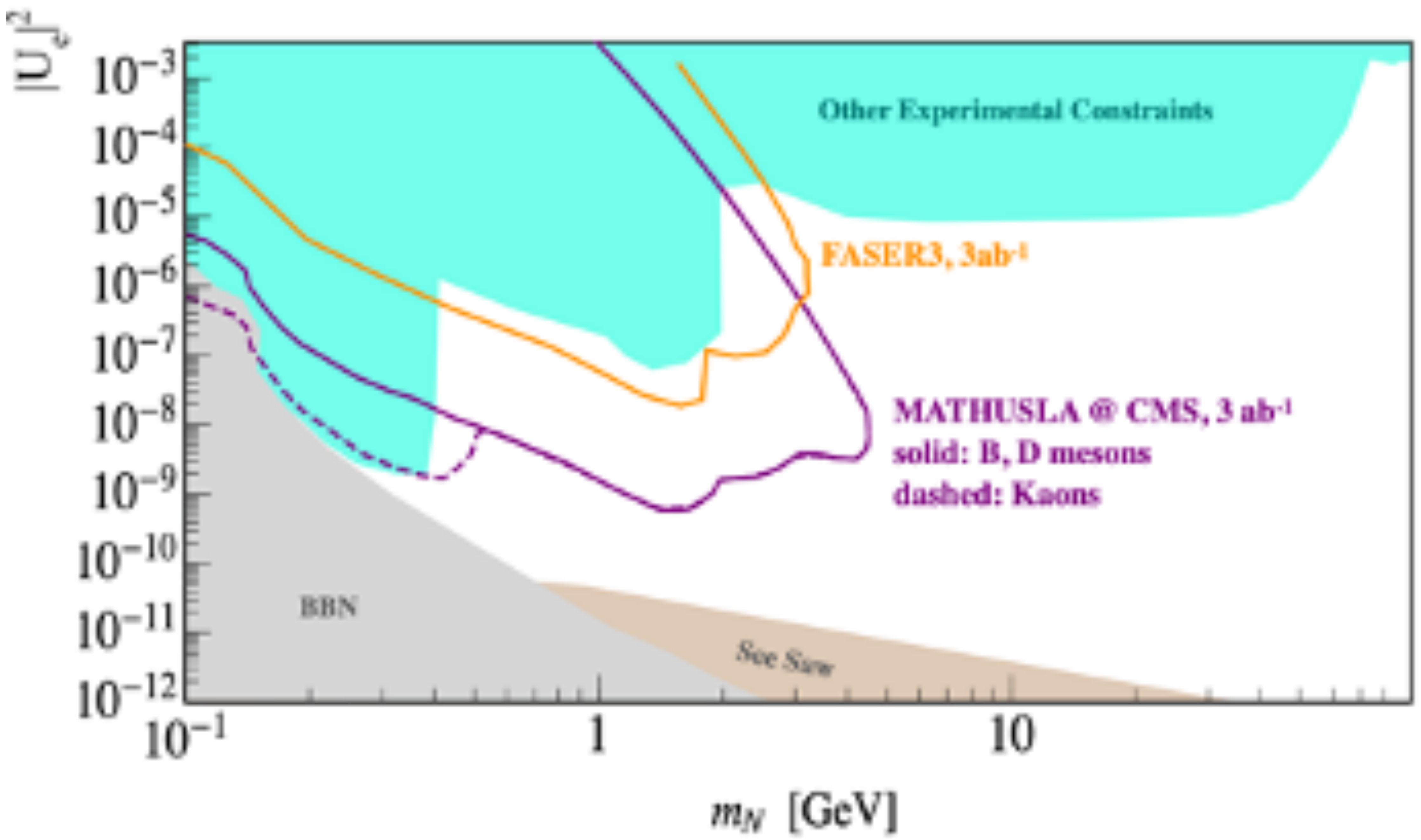

- Greatly extends the discovery potential to smaller angles
- Significant complementarity with FASER, which probes similar masses but shorter lifetimes

Status and outlook

- Current status:
  - Detector technology has been studied extensively
  - Small lab-scale prototype units are under construction
  - Conceptual design report (CDR) in preparation

- Looking ahead:
  - Full detector construction can be installed in stages (per detector unit)
    - Installation of one 9m x 9m unit O(1 week)
    - Can begin taking data before all units are installed
  - Goal is to be ready for the start of HL-LHC running

Documentation

Auxiliary LHC detectors are widely supported in Snowmass study and European Strategy Update.

- Web: https://mathusla-experiment.web.cern.ch
- Original idea: J.P. Chou, D. Curtin, H. Lubatti arXiv 1606.06298
- Mathusla physics case - theory white paper arXiv 1806.07396
- LHCC Letter of Intent arXiv 1811.00927
- Input to **European Strategy** for Particle Physics arXiv 1901.04040
- Updated LHCC Letter of Intent: arXiv 2009.01693
- MATHUSLA Test Stand: NIMA 985 (2021) 164661
- **Snowmass** White Paper: https://arxiv.org/abs/2203.08126

MATHUSLA Collaboration

Backup

Expected sensitivity

- Secondary physics case: GeV-scale LLPs from B, D meson decays

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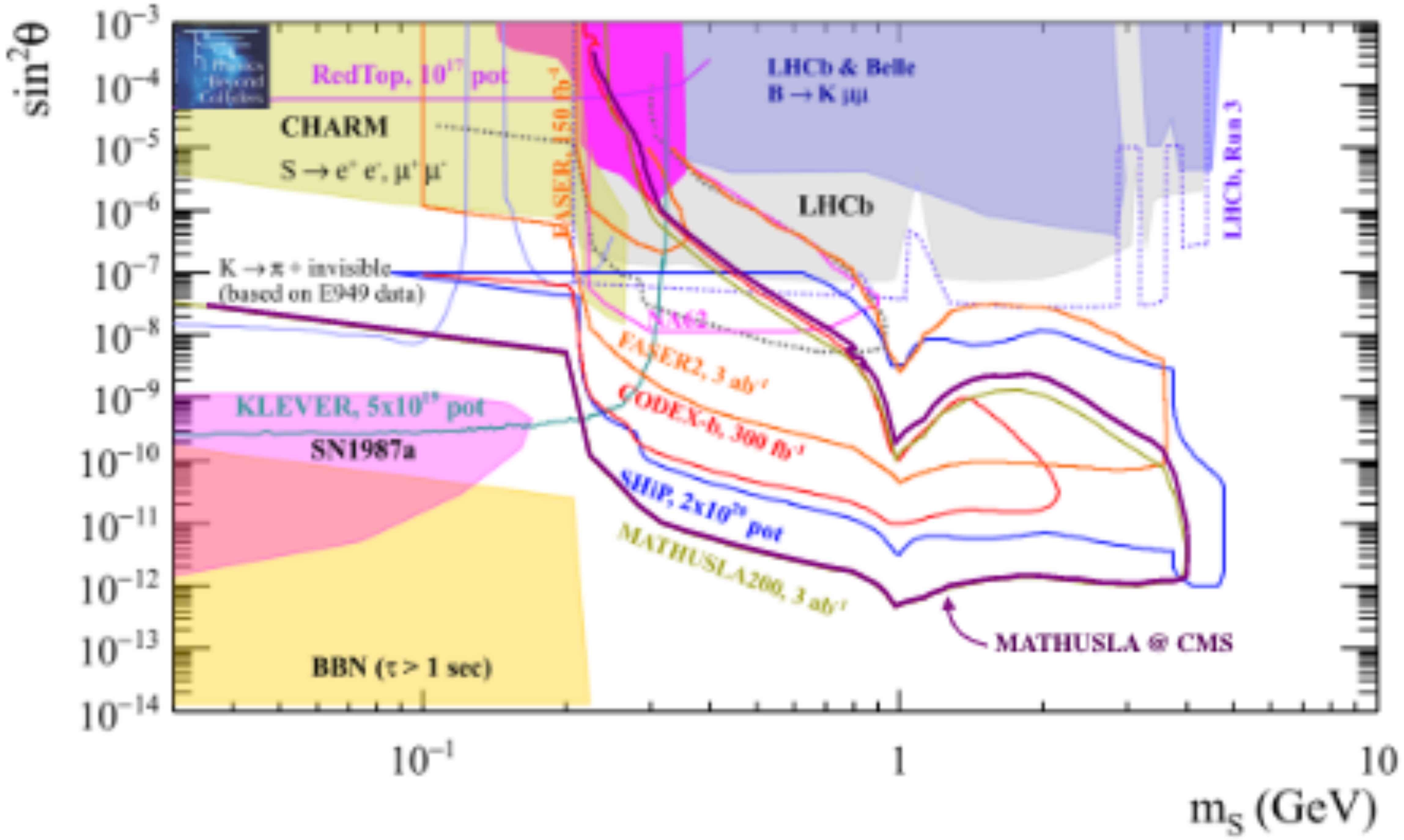

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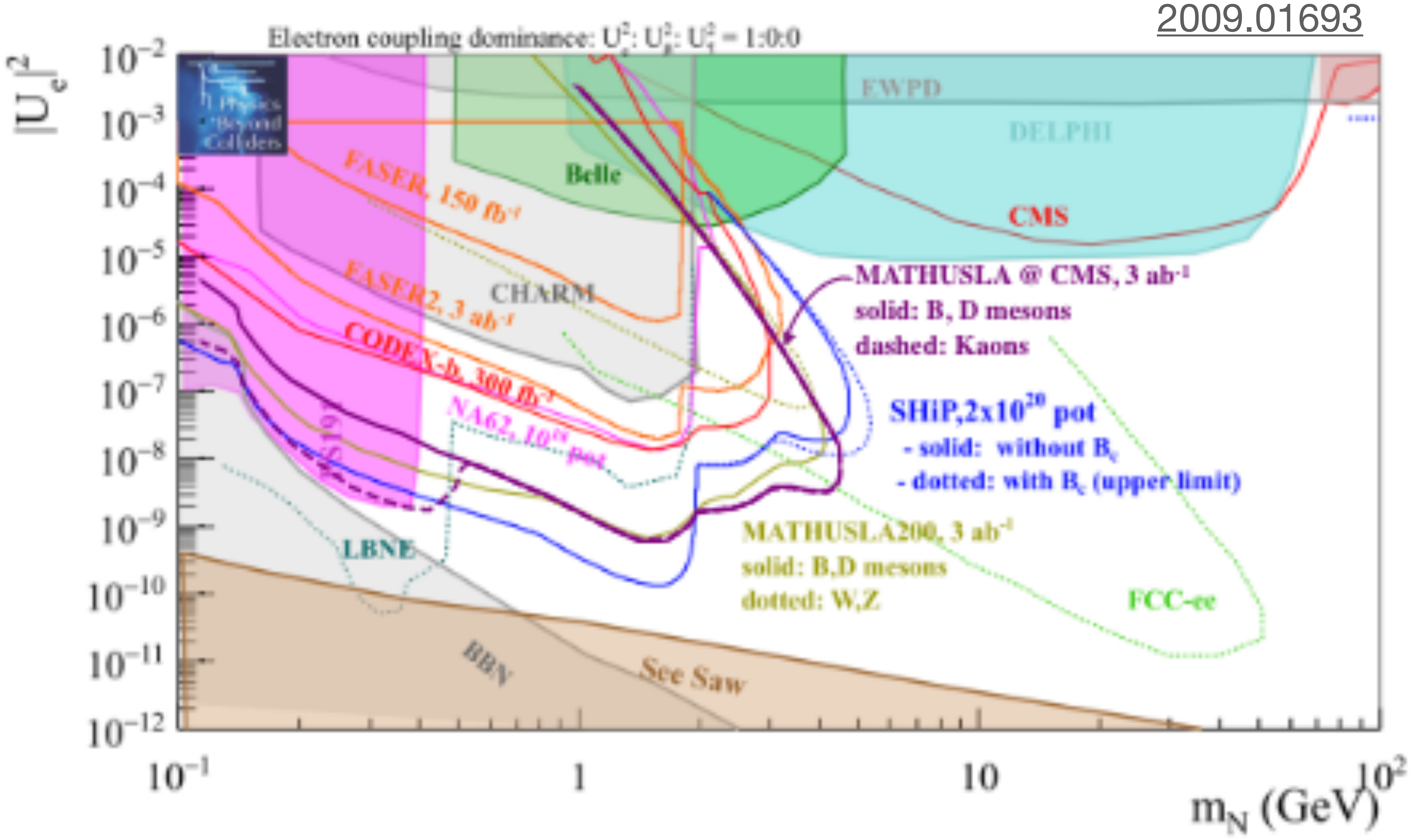

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