MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL Particles

A New Detector to Probe the Lifetime Frontier

IPP TOWN HALL, 16 JULY 2020

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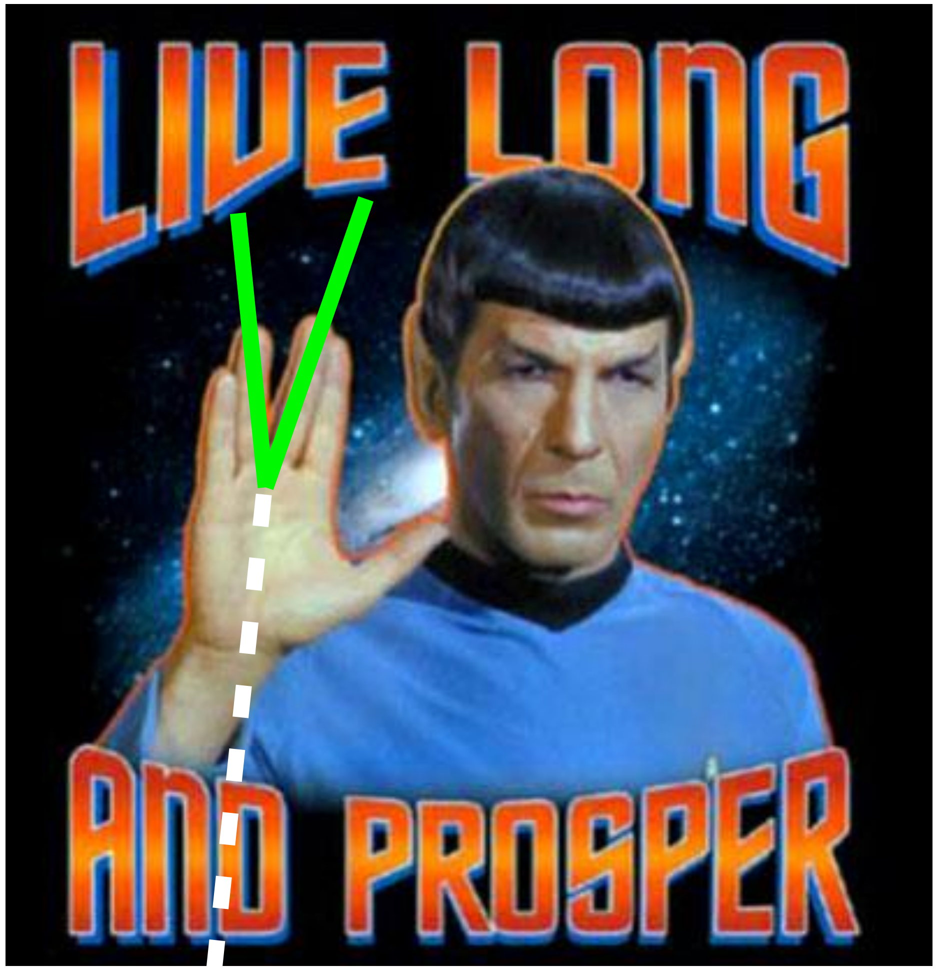
Live Long and Prosper

Maybe our BSM searches for prompt high-p_T objects have been looking in the wrong place?

We know Long-Lived Particles (LLPs) occur in the SM.

"Bottom-up" point of view:
Mechanisms that lead to tiny decay widths in SM can also produce LLPs in BSM theories.

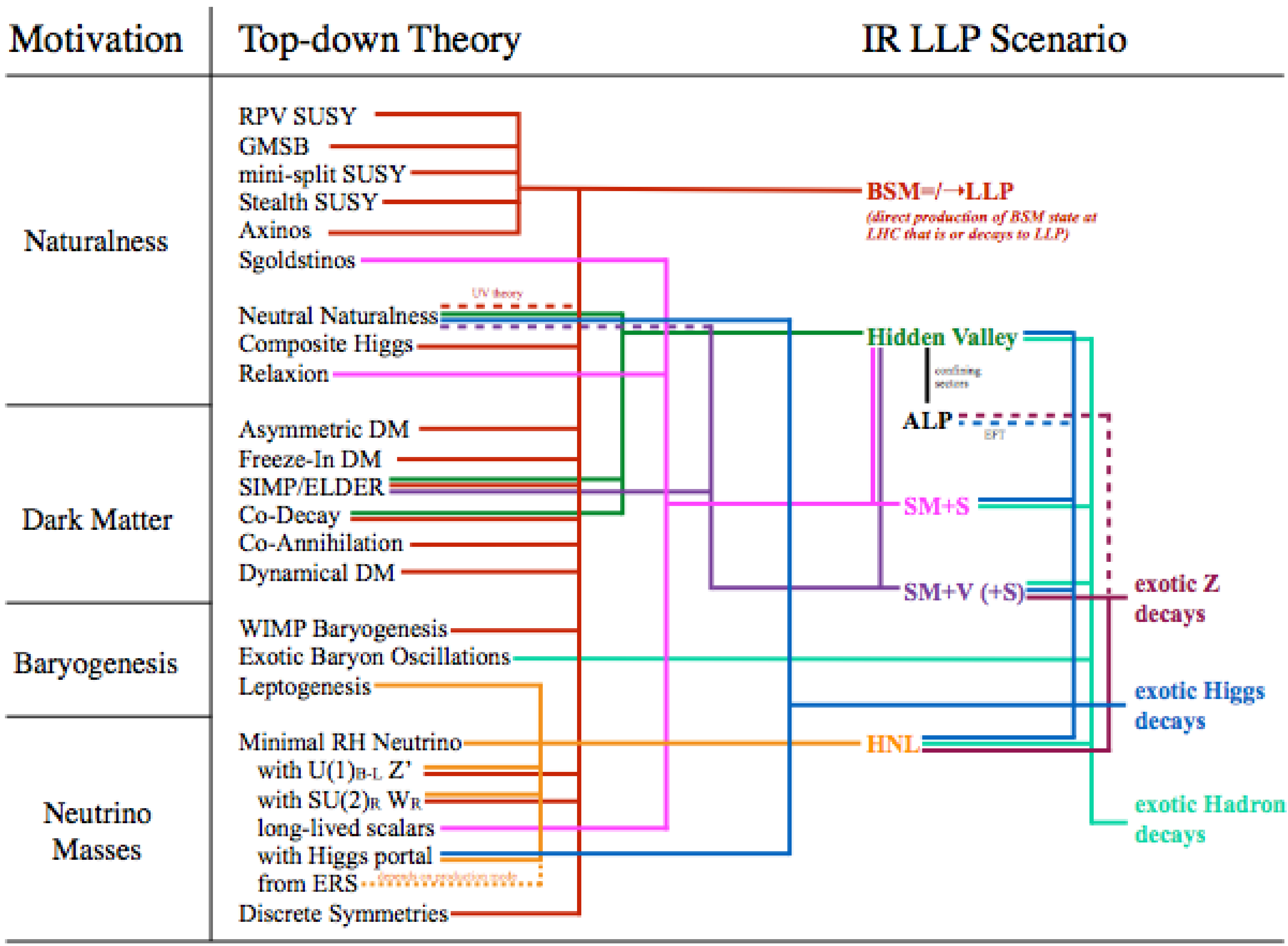


"Top-down" point of view:
BSM LLPs can solve fundamental mysteries such as DM

Outline

- Motivation: Exploring The Lifetime Frontier
- MATHUSLA: Basic Detector Concept
- LLP Identification & Sensitivity
- Cosmic Ray Telescope
- Detector Design
- Schedule & Outlook Through 2027
- Canadian Involvement & HQP

Motivation for LLPs



Most of these scenarios are still poorly constrained at LHC

The Lifetime Frontier

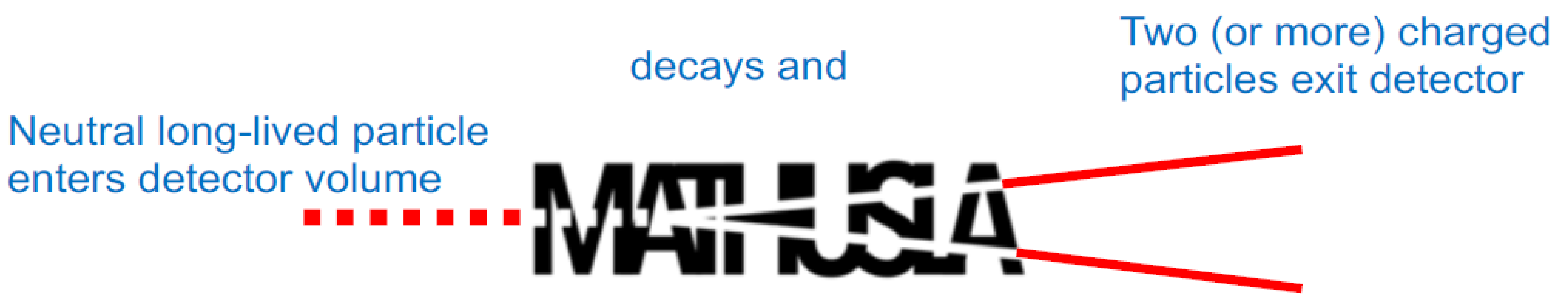
The problem of long lifetimes: LHC could be making LLPs invisible to its detectors!

- Big Bang Nucleosynthesis limit on lifetime is all the way up at ~ 0.1s ($c\tau \sim 10^7$-10^8 m)
- Most LLPs with lifetime >> detector size **escape the detector**
- **LLP searches are now being elevated to the top of the LHC search program**, but tiny rate of decays in detector mean searches become very vulnerable to even small backgrounds
- Novel LLP searches specifically highlighted in "Major Developments" section of 2020 Update of the European Strategy for Particle Physics

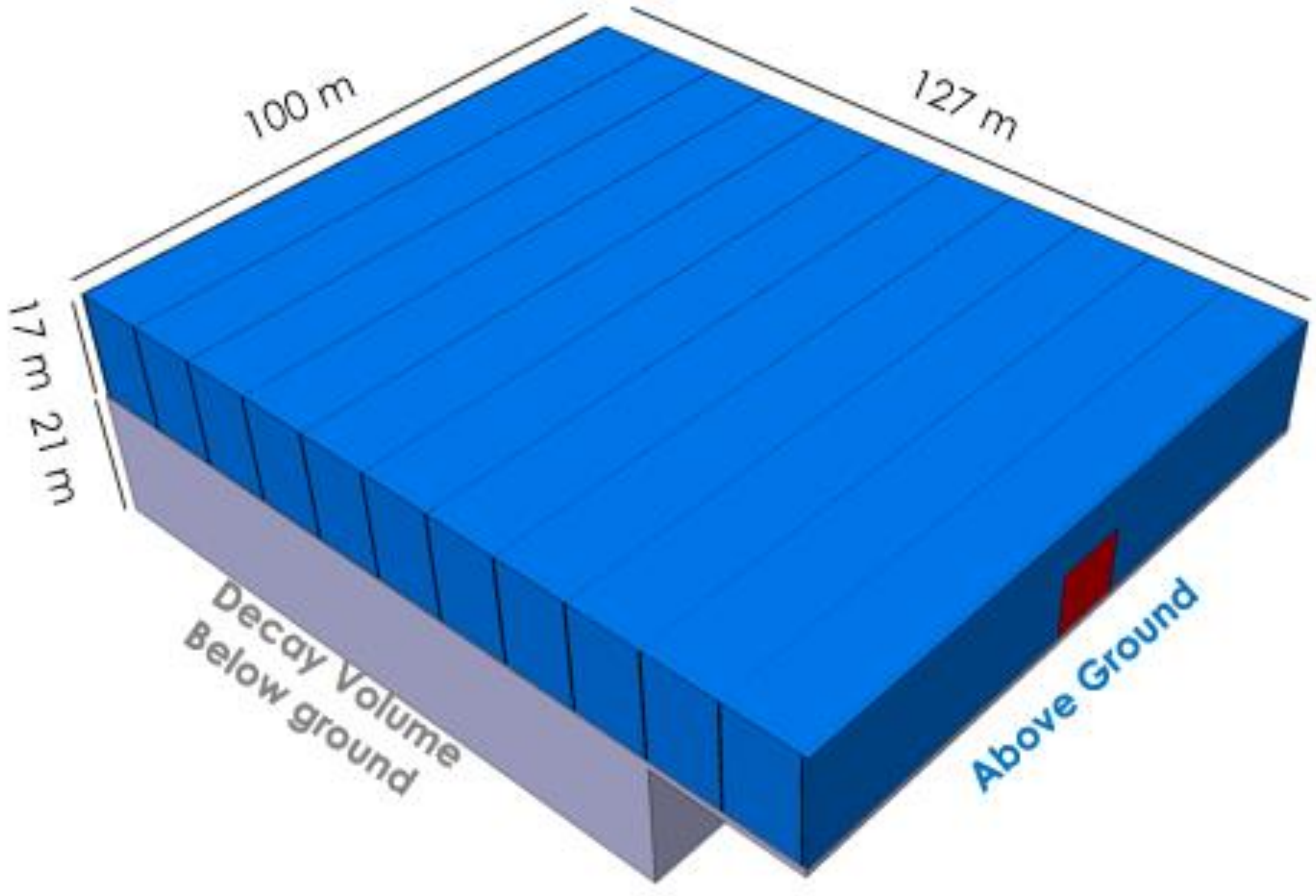
MATHUSLA Detector Concept

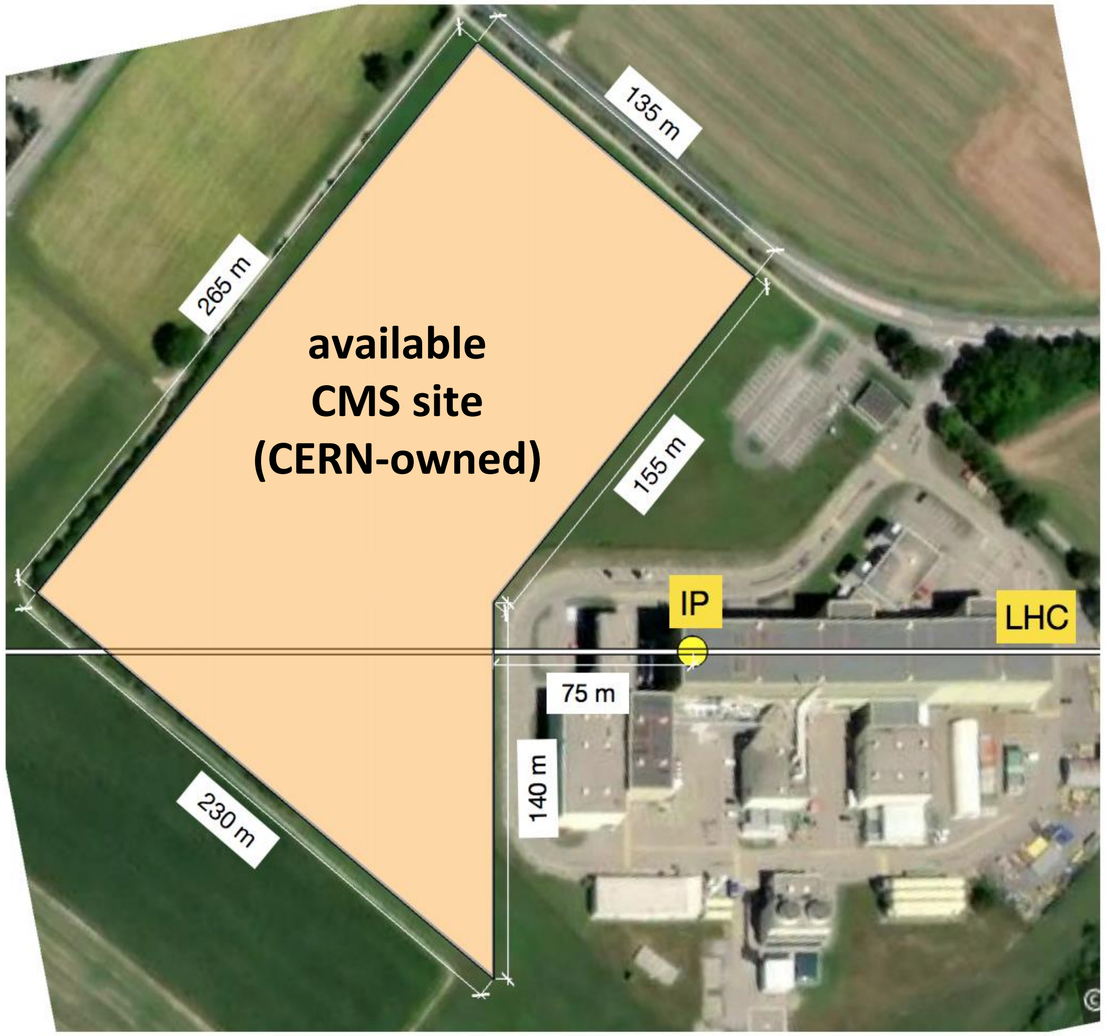
Detector on surface above LHC main detector would use O(100 m) of rock to range out SM particles from LHC collisions. Requirements:

- Large volume for good acceptance of LLPs from IP
- Good timing resolution to distinguish downward-going cosmic rays and atmospheric neutrinos from upward-going particles
- Robust tracking for vertex reconstruction to identify decays of neutral LLPs to charged objects



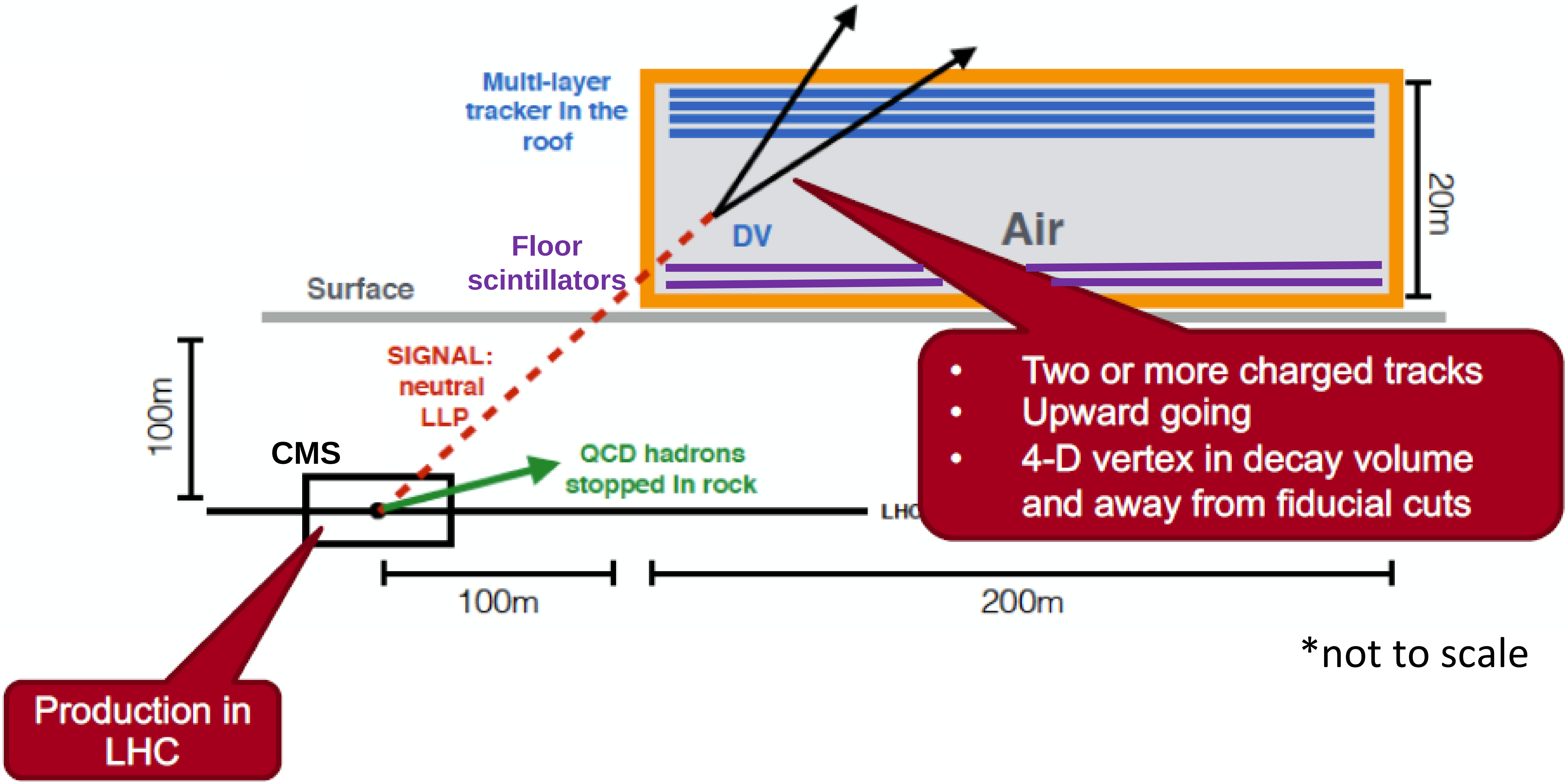
An external LLP detector for HL-LHC





- <u>Not</u> part of CMS
- Construction & operation will not interfere with any other LHC experiments

An external LLP detector for HL-LHC



*not to scale

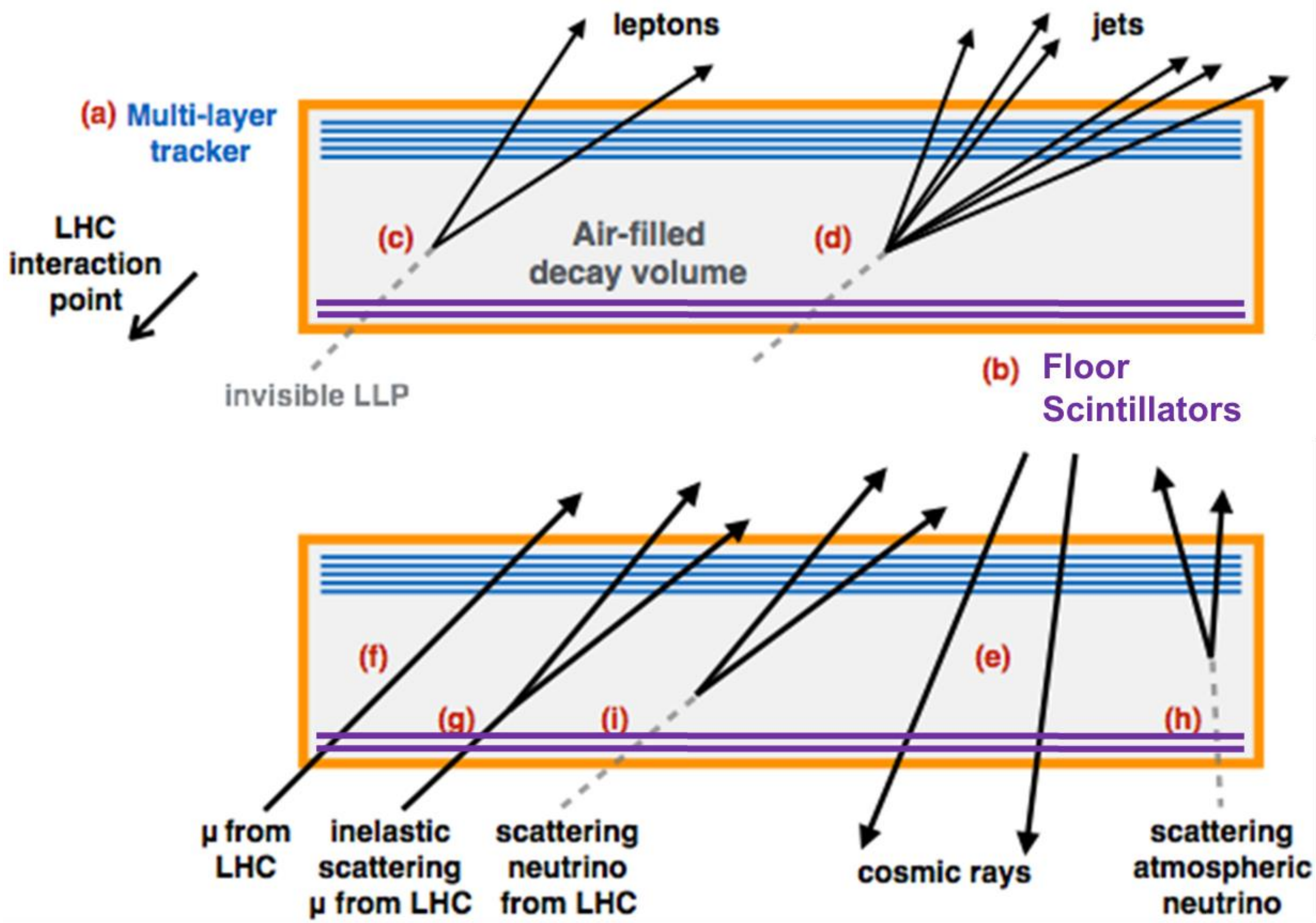
MATHUSLA Collaboration

mathusla.web.cern.ch

- Comprehensive white papers on the importance of LLP searches at MATHUSLA in particular (arXiv:1806.07396) and the LHC in general (arXiv:1903.04497)
- Submitted Letter of Intent to LHCC (arXiv:1811.00927)
- Operated a test stand on the surface above ATLAS in 2018; analysis of results (arXiv:2005.02018) demonstrates good understanding of background sources and detector issues
- Next step in becoming a CERN-approved experiment: Technical Design Report submission (expected early 2021)
- Proto-collaboration includes members at institutions in 8 countries
  - Canadians currently represent ~10%

LLP Identification with MATHUSLA

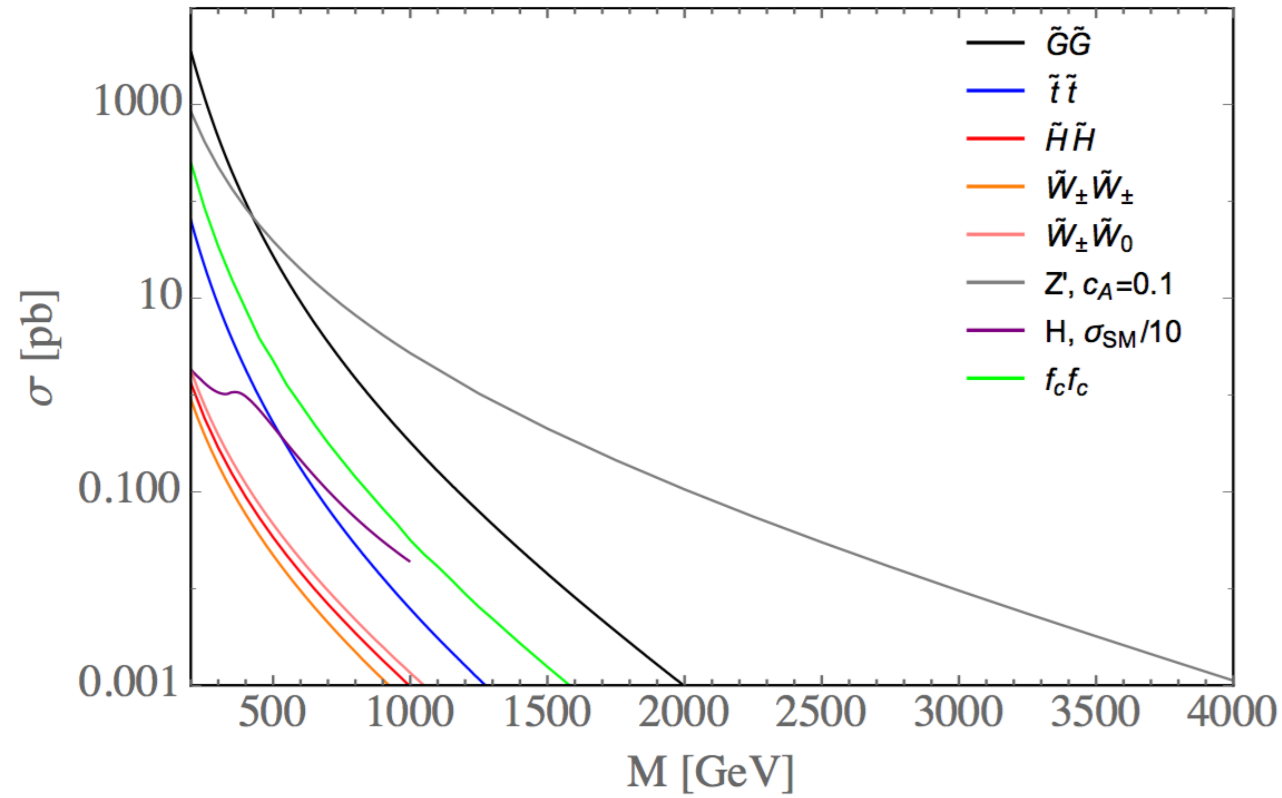
- Strict geometry & timing cuts will achieve near-zero backgrounds for neutral LLP decays!
- Integration into CMS trigger system will associate CMS detector activity with MATHUSLA LLP candidate events



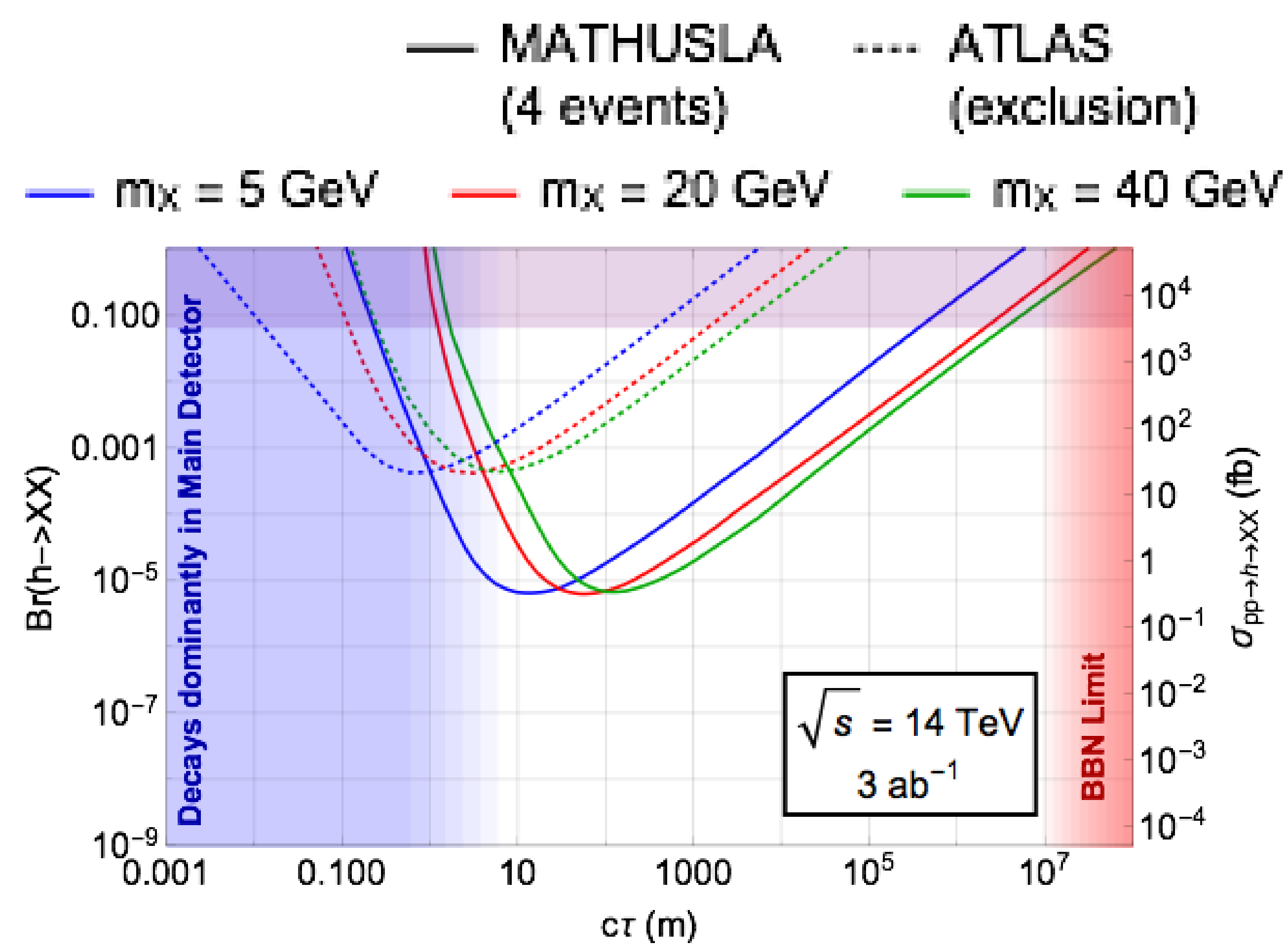
- MATHUSLA standalone: Determination of LLP decay mode and boost
- MATHUSLA + CMS: Also LLP production mode, mass range and spin

LLP Sensitivity

- Sensitivity to any LLP production process with σ > fb

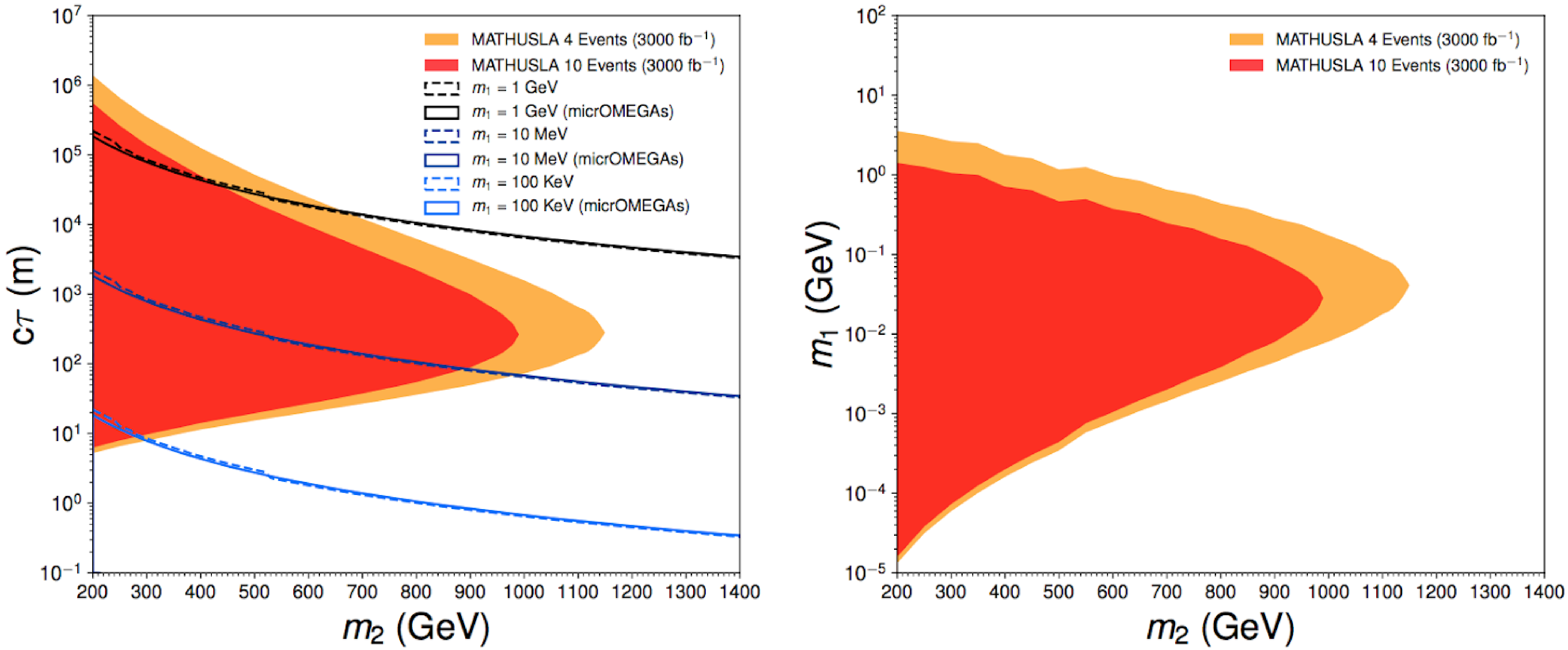


- Can probe scales from >TeV all the way down to GeV
- Scenarios include:
  - Exotic Higgs decay (up to 1000x better sensitivity than LHC main detectors)
  - Heavy sterile neutrinos
  - Dark photons
  - Axions



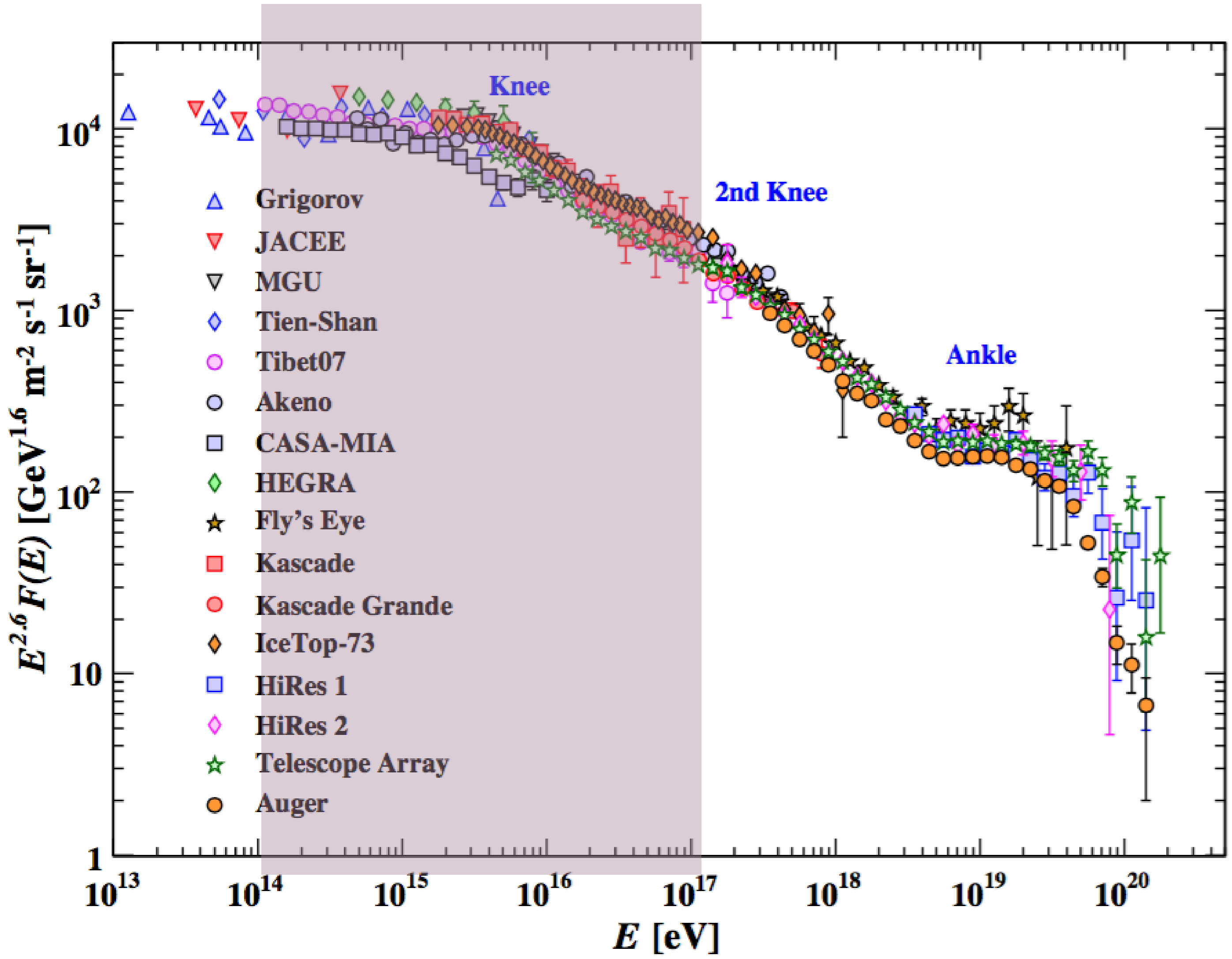
LLP Sensitivity

- Scenarios where LLP → DM + SM decay is the only way to see the DM
- e.g. model with BSM (χ_1, χ_2) where DM candidate χ_1 is very difficult to see due to low mass and possibly very small coupling. We look for LLP χ_2 which eventually decays to χ_1



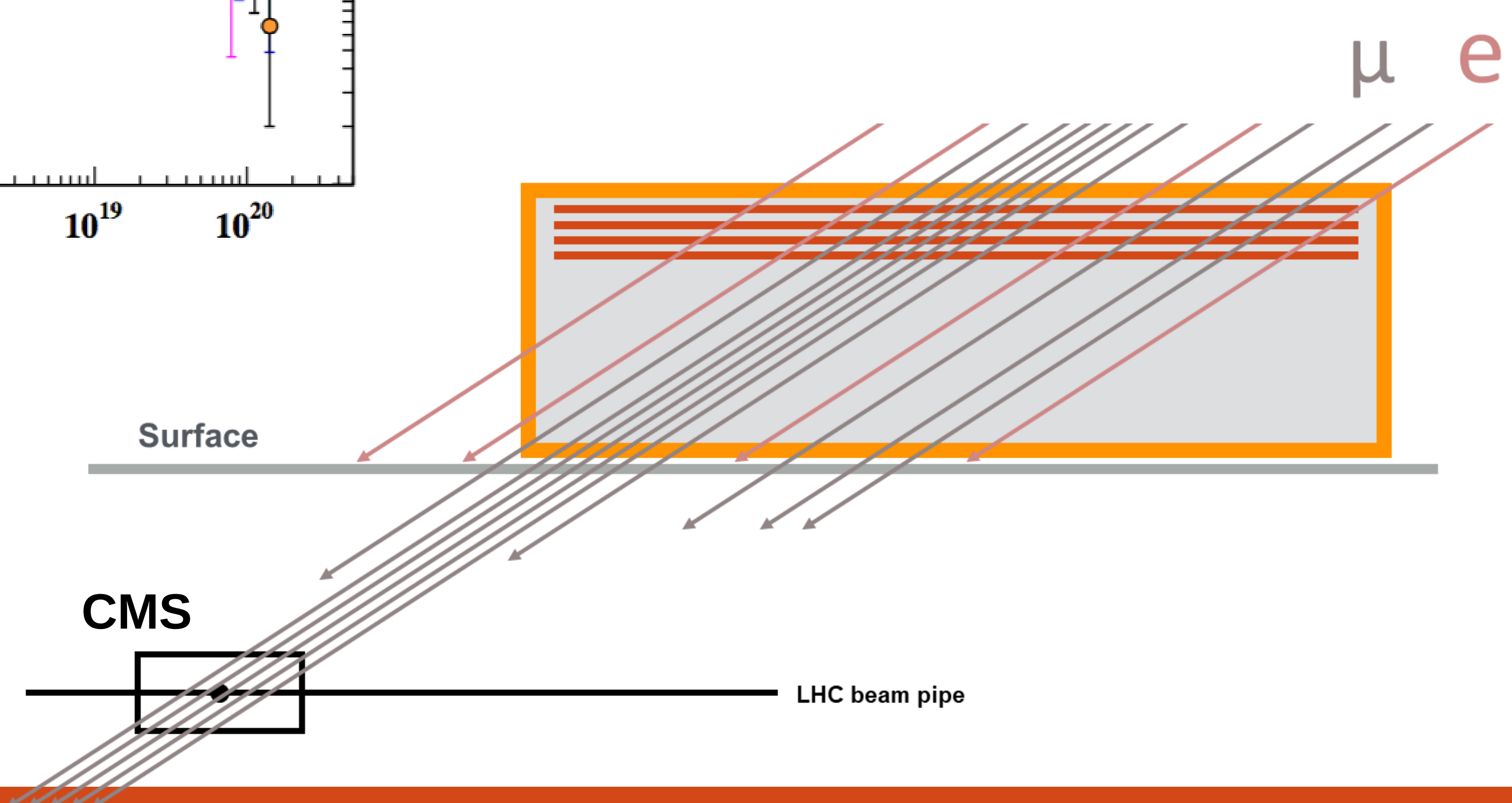
(lines yield observed DM relic density)

MATHUSLA as a Cosmic Ray Telescope



"Guaranteed Physics Return"

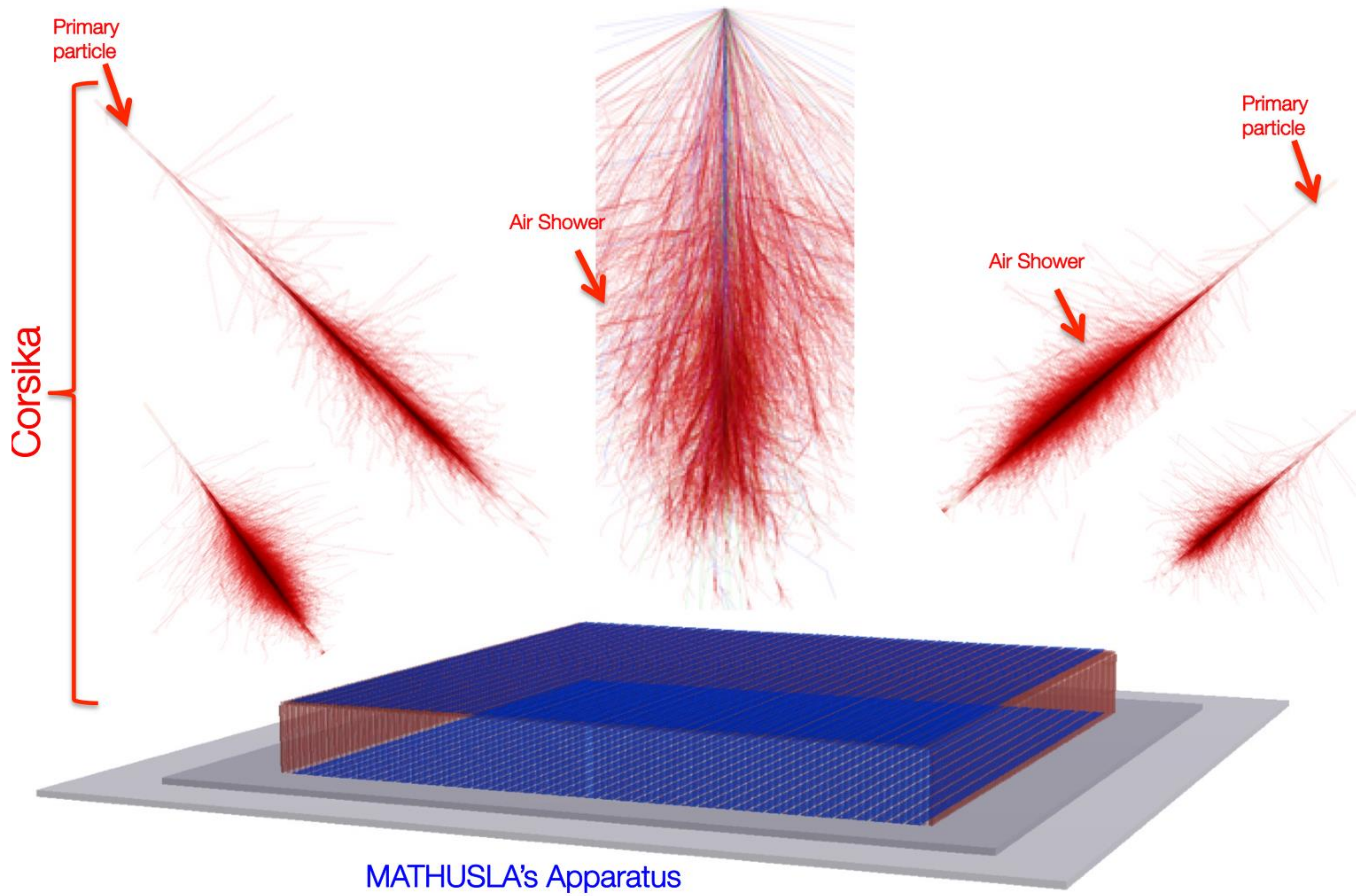
Unique abilities in CR experimental ecosystem (precise resolution, directionality, large-area coverage)



Probes highly interesting region of CR spectrum

MATHUSLA as a Cosmic Ray Telescope

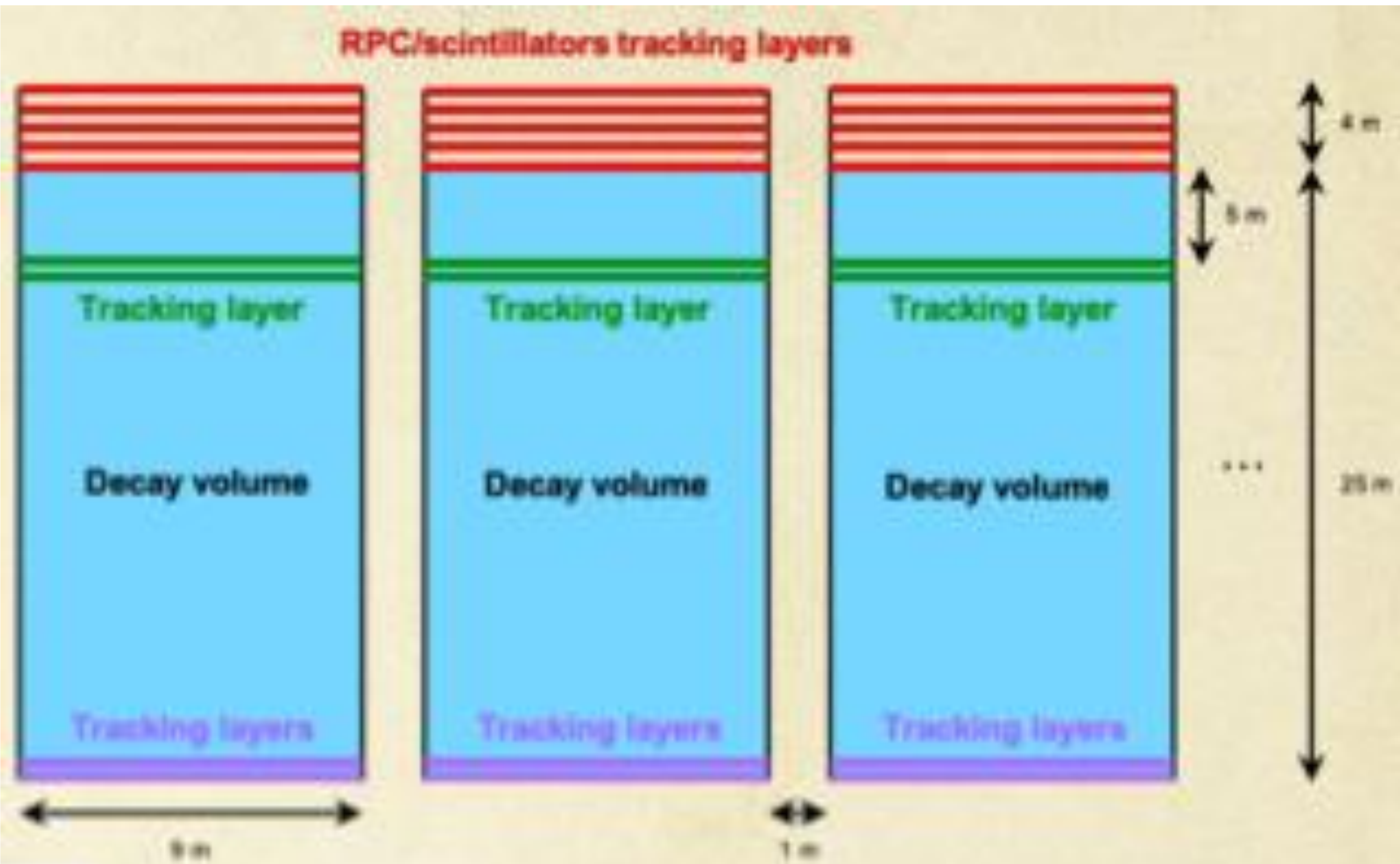
Standalone: reconstruction of shower core, direction, total # charged particles, slope of radial particle density distribution



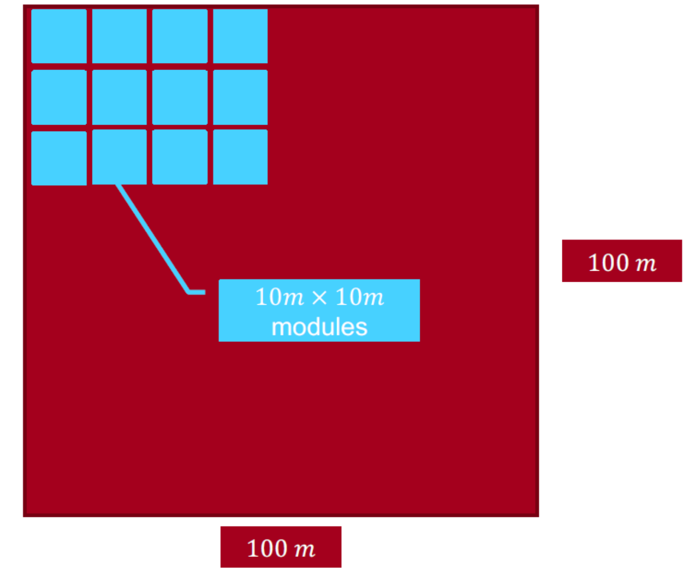
+ CMS: analysis of muon bundles traversing both detectors, probing heavy primary CR spectra and astrophysical acceleration mechanisms

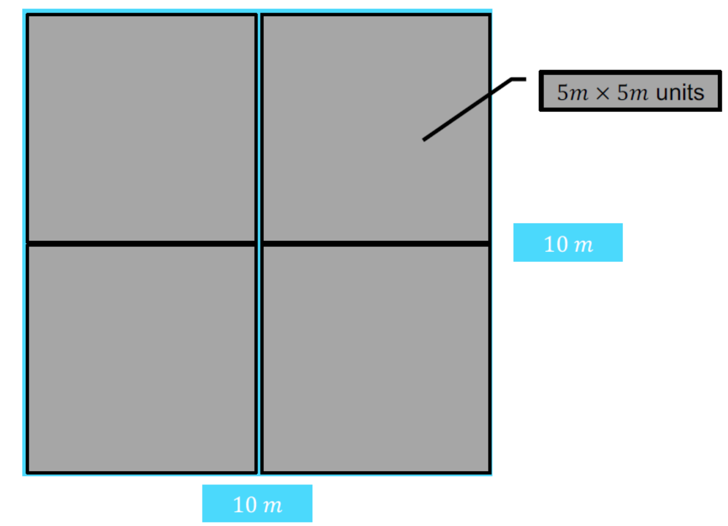
Detector Design

Modular design facilitates staged construction and commissioning



Each module has 5 tracking layers on top + 2 floor layers + 2 mid-level layers



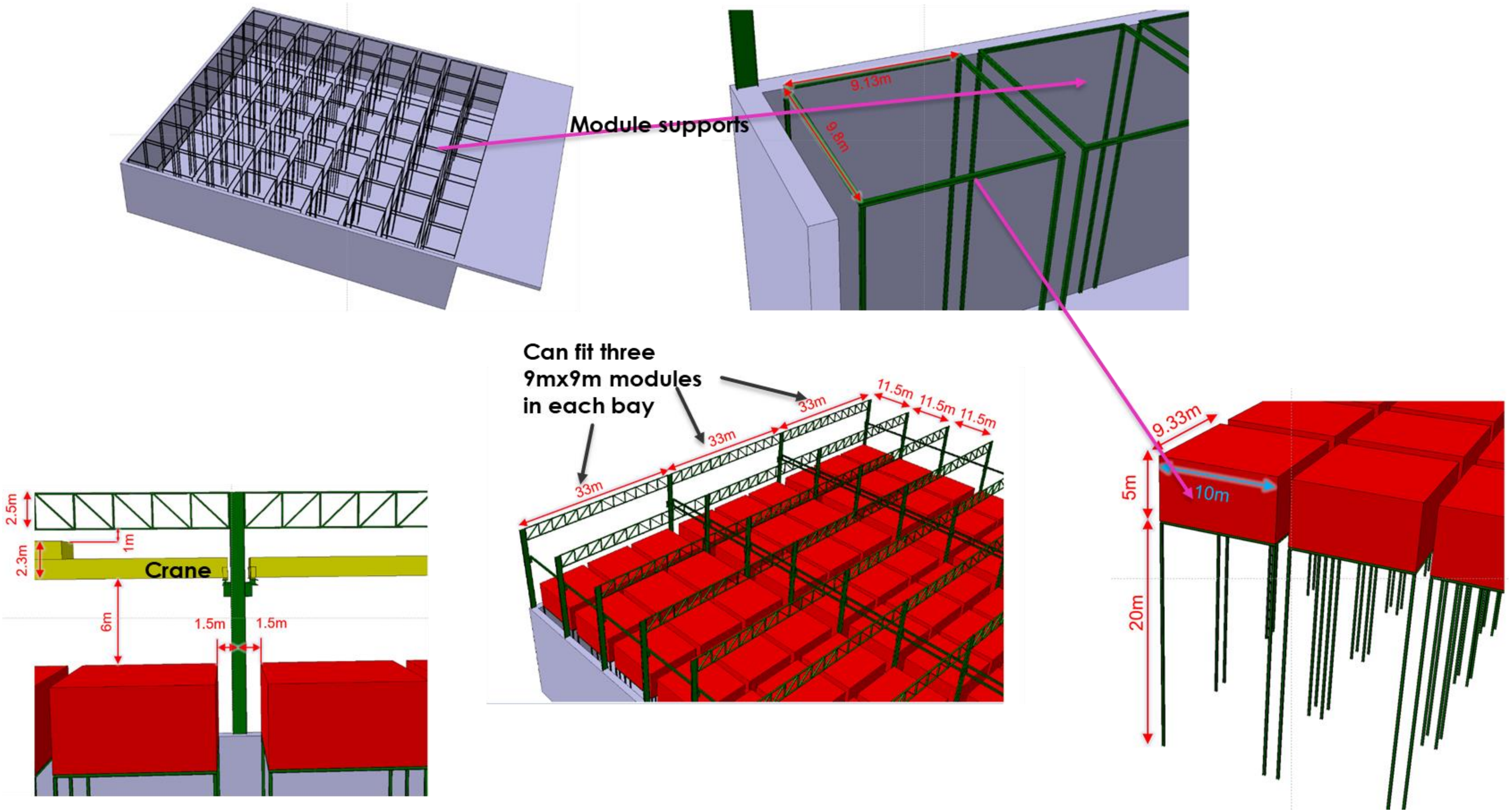


100 Modules in $\mathbf{100m \times 100m}$ Footprint

4 Detector Units per Module Plane

Detector Design

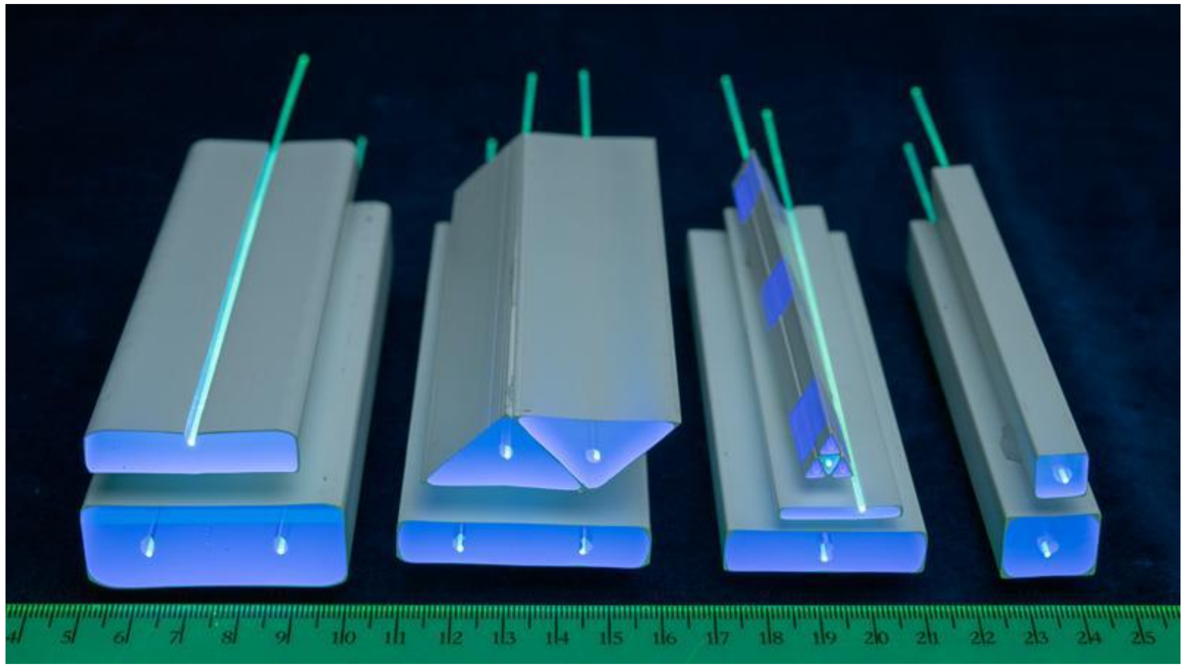
Engineering concept developed in collaboration with CERN engineers



Trackers, Readout & Trigger

Tracker layers: Composed of extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers

- FNAL extrusion facilities have produced bars for several existing experiments
- Possibility of adding Resistive Plate Chamber layers



Each scintillator bar ~ 5m x 4cm x 2cm, with readout at both ends

- Transverse resolution $\sigma \approx 1$ cm
- Δt between two ends gives longitudinal resolution: need sub-ns precision

Collect all hits with no trigger selection; separately record trigger data and associate it with CMS bunch crossings

- Cosmic ray rate ~2MHz

Project Schedule & Outlook

Project phases:

i) Optimization of scintillators, electronics, and DAQ, using small numbers of proto-type mini-units in individual researchers' laboratories (pre-2027)

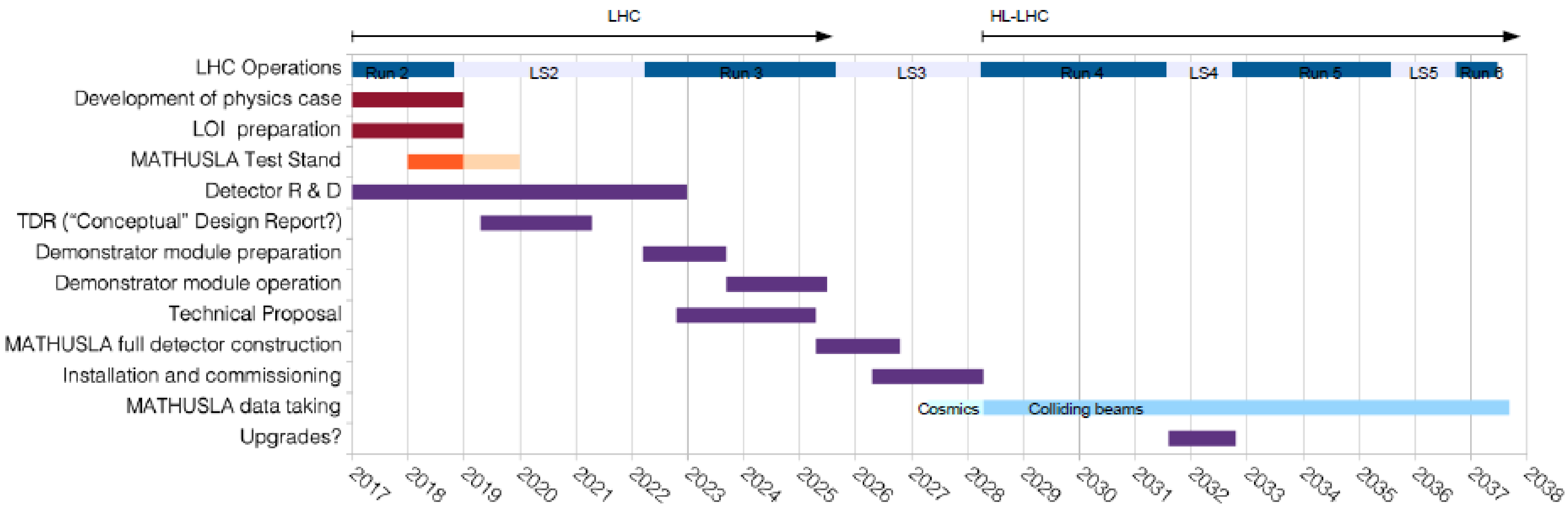
ii) Construction of first full ("Demonstrator") unit on-site (later part of LHC Run 3)

iii) Construction of full-size detector around the Demonstrator unit (LHC LS 3)

iv) Data collection & analysis from full-size detector (HL-LHC Run 4, 2028-2036)

As a surface detector, accessible regardless of LHC running conditions. Construction not tightly tied to HL-LHC schedule, except for overall goal of maximizing integrated luminosity

Project Schedule & Outlook



Canadian Group

- Curtin group: key role in pheno calculations and preliminary simulations that have informed the basic detector design
  - Will provide increasingly precise reach & background estimates as detailed detector parameters are determined
  - Will assist with interpretation of early Demonstrator data, which will already probe some interesting models
- Diamond, Robertson: constructing and assessing prototype mini-units to optimize scintillator bar geometry, fiber & SiPM models, timing electronics, DAQ
  - Some hardware funding included in Diamond's CFI JELF award
  - Will participate in Demonstrator construction, commissioning, and data analysis
- McKeen, Morrissey, Stolarski: co-authors of experiment proposal, contributed to physics case & sensitivity studies

Canadian Group

Will aim for significant contribution and leadership role in construction and commissioning of the Demonstrator, and ultimately the full detector

- NSERC SAPES project proposal, for detector R&D, planned for fall 2020
  - May also make modest (<$100k) funding request to NSERC RTI and/or McDonald Institute
- Modest MRS support for electronics (James Botte currently assisting Diamond at ~0.1 FTE level)
- Future CFI request(s) anticipated for Demonstrator and full detector hardware (2022/2023)
- Modest computing needs could be satisfied on one major platform + mirror (ComputeCanada or elsewhere), or distributed among multiple member institutions’ small clusters
- Strong complementarity with experimental and theoretical projects in Canada doing dark/hidden sector particle studies (e.g. ATLAS, Belle II)
- Similar SiPM R&D efforts also exist on nEXO / LoLX, Hyper-K, etc.

HQP

- Rough estimate: ~6 - 8 grad students + 2 postdocs trained on MATHUSLA through 2027, if no additional Canadian PIs join
- HQP training will ramp up next year, with NSERC grant

Unique opportunities for students & post-docs!

- Training on diverse aspects of a "small" experiment (simulations, hardware, DAQ, data analysis, …) in multiple stages of its lifetime (planning, prototyping & optimization, operations, …)
- Since detector is modular, and accessible during data taking, students can continuously interact with it hands-on throughout its lifetime
- All the usual benefits of working on a CERN project, with detector sub-units still available in local labs

Conclusions

Exploration of the Lifetime Frontier will be central to the future of the HL-LHC program to discover new physics

MATHUSLA will probe deep into the LLP lifetime parameter space for a wide range of masses

Unique opportunity for Canada to assume a key role at the Lifetime Frontier!