Searches for Ultra Long-Lived Particles with MATHUSLA

MI ANNUAL MEETING

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Outline

An Update to the Letter of Intent for MATHUSLA: Search for Long-Lived Particles at the HL-LHC (arXiv:2009.01693)

Recent Progress and Next Steps for the MATHUSLA LLP Detector [SNOWMASS] (arXiv:2203.08126)

- Basic Concept
    - Backgrounds
    - Identifying LLPs
- LLP Sensitivity
- Cosmic Ray Telescope
- Detector Design
    - Geometry simulations
    - Trackers
    - DAQ
    - Vertex Reconstruction
- Simulations for rate estimates
- Test stands

Basic Concept

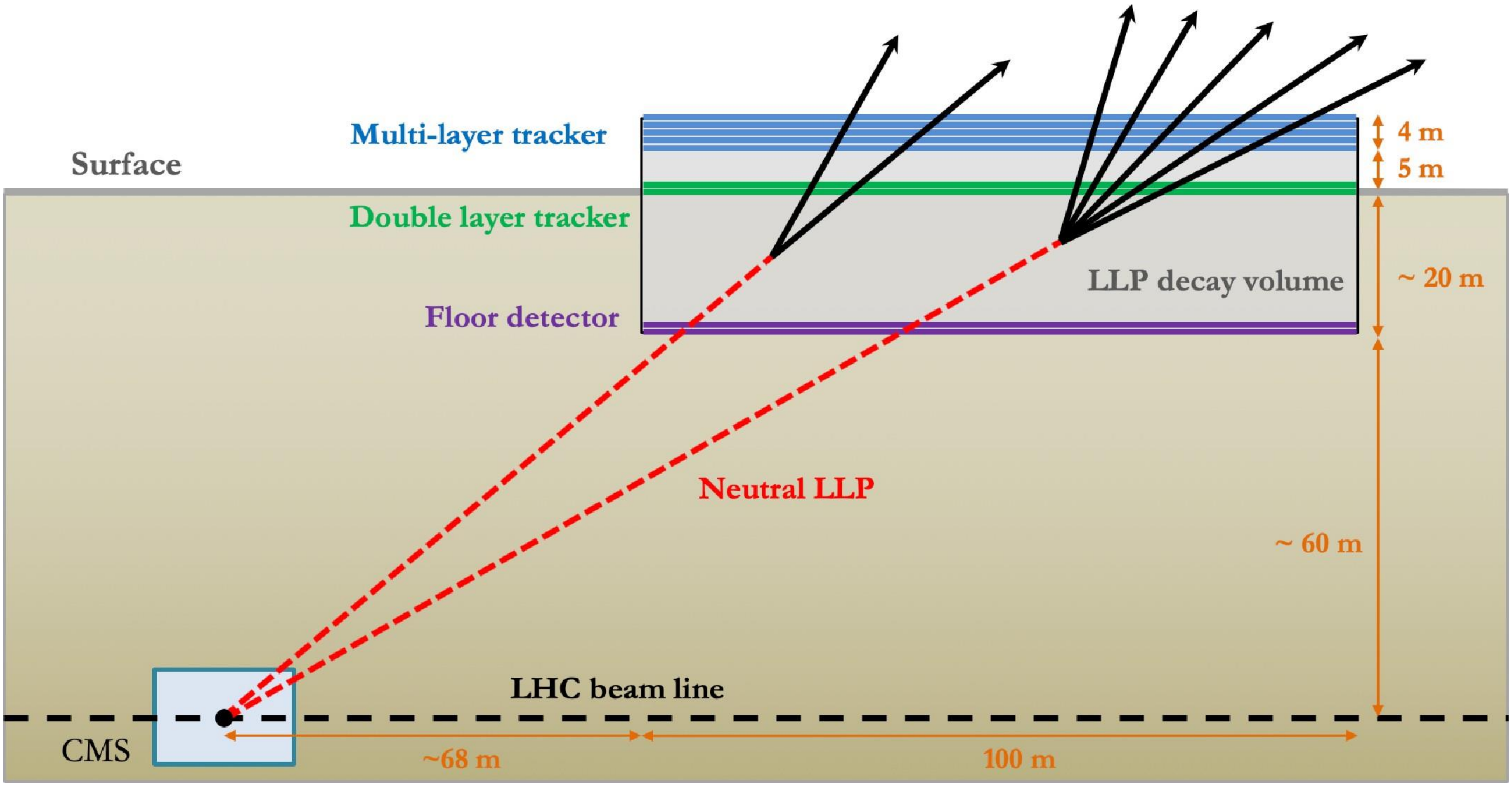
MAssive **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** P**A**rticles

An External LLP Detector for HL-LHC

- Dedicated detector **sensitive to neutral long-lived particles that have lifetime up to the Big Bang Nucleosynthesis** (BBN) limit (10^7 – 10^8 m)
- Proposed **large area surface detector located above CMS** with **robust tracking** and **background rejection**

- ❖ Can run standalone or "combined" to CMS
- ❖ Construction & operation will not interfere with any other LHC experiments

An External LLP Detector for HL-LHC

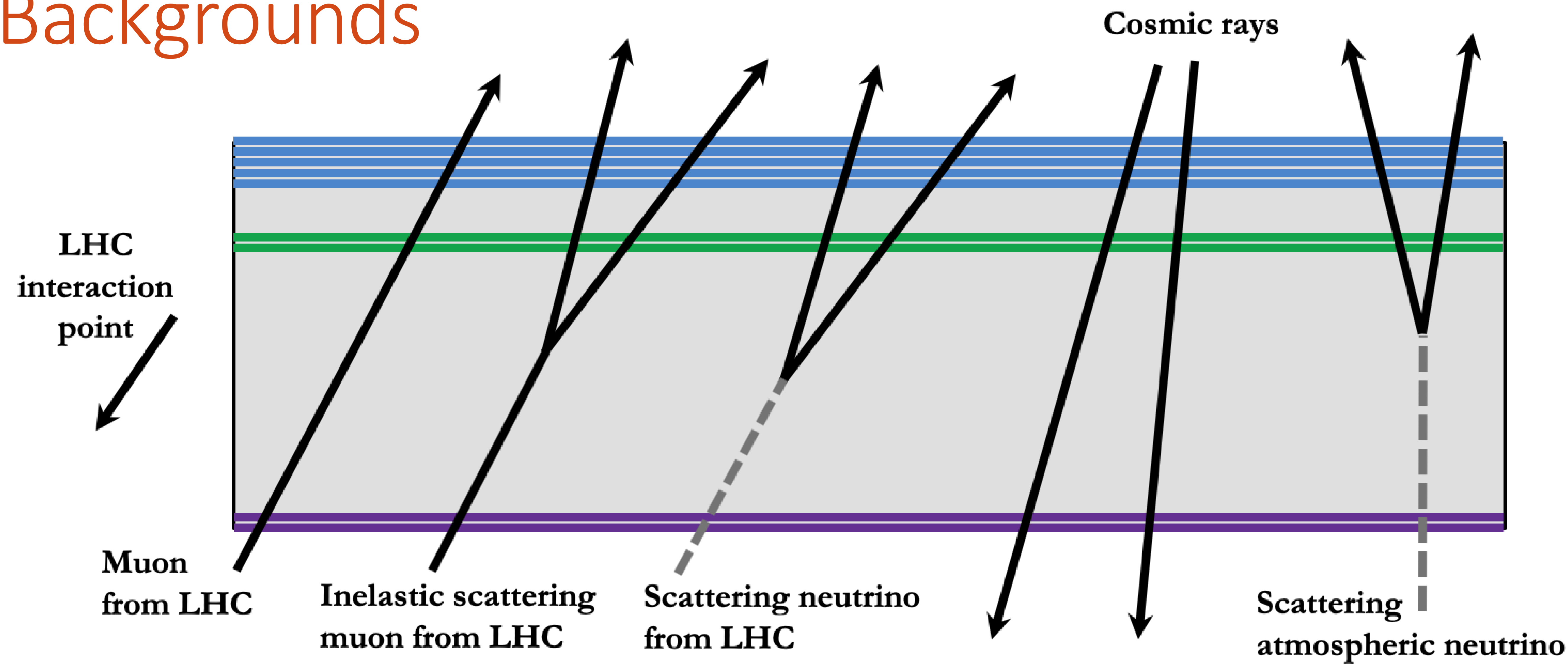


NOT TO SCALE

~100m x 100m x 25m decay volume

Displacement from IP: ~70m horizontally, 60m vertically

Backgrounds

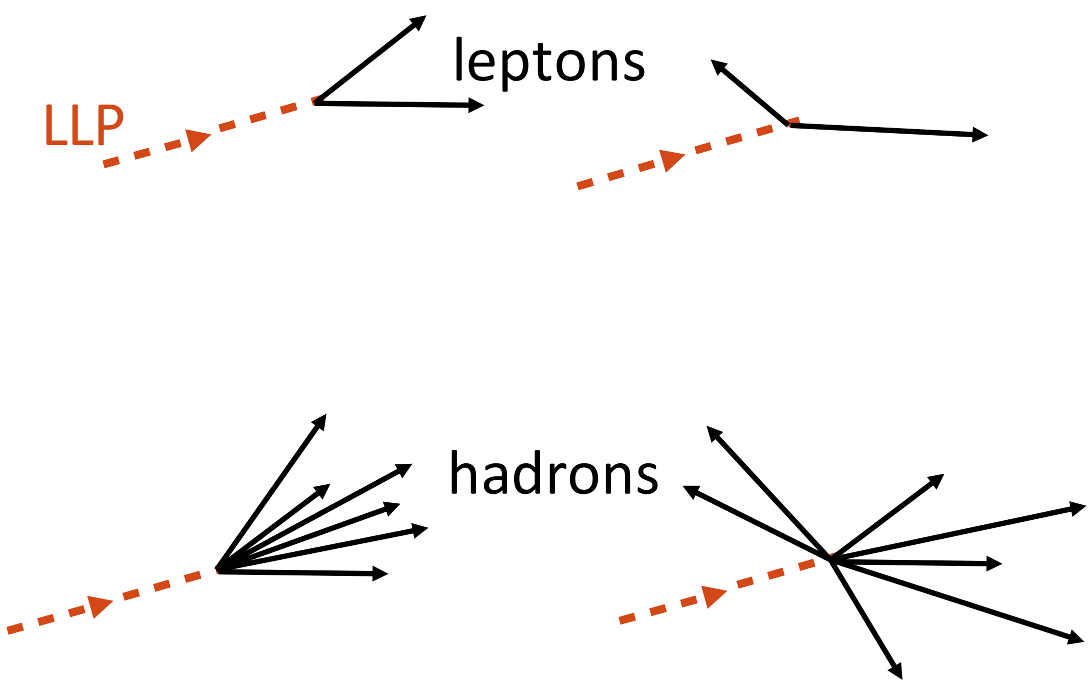


LLP displaced vertex (DV) signal has to satisfy many stringent geometrical and timing requirements ("4D vertexing" with cm/ns precision)

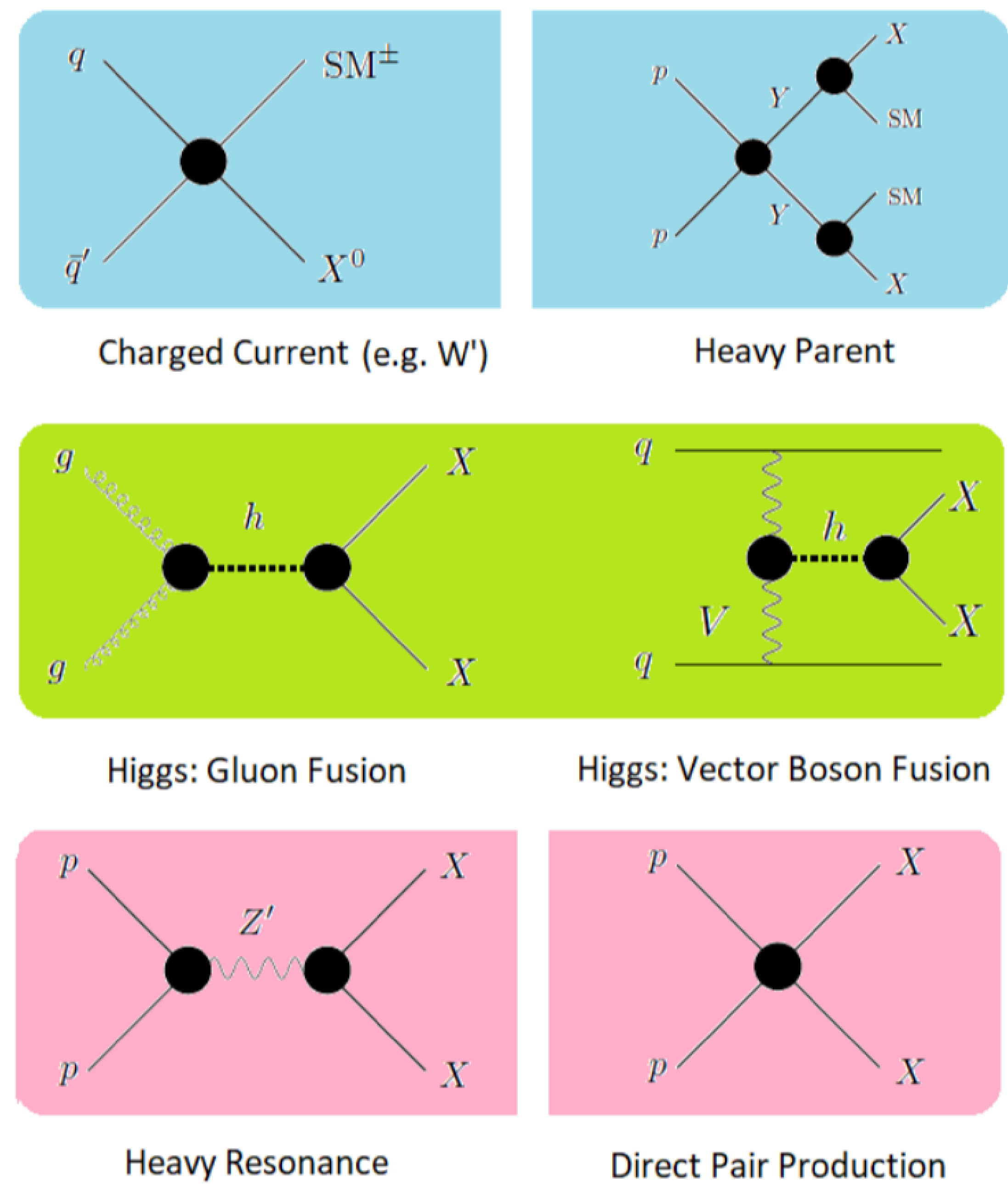
These requirements, plus a few extra geometry & timing cuts, provide "near-zero background" (< 1 event per year) for neutral LLP decays!

Identifying LLPs

MATHUSLA can't measure particle momentum or energy, but:
track geometry → measure of LLP boost event-by-event



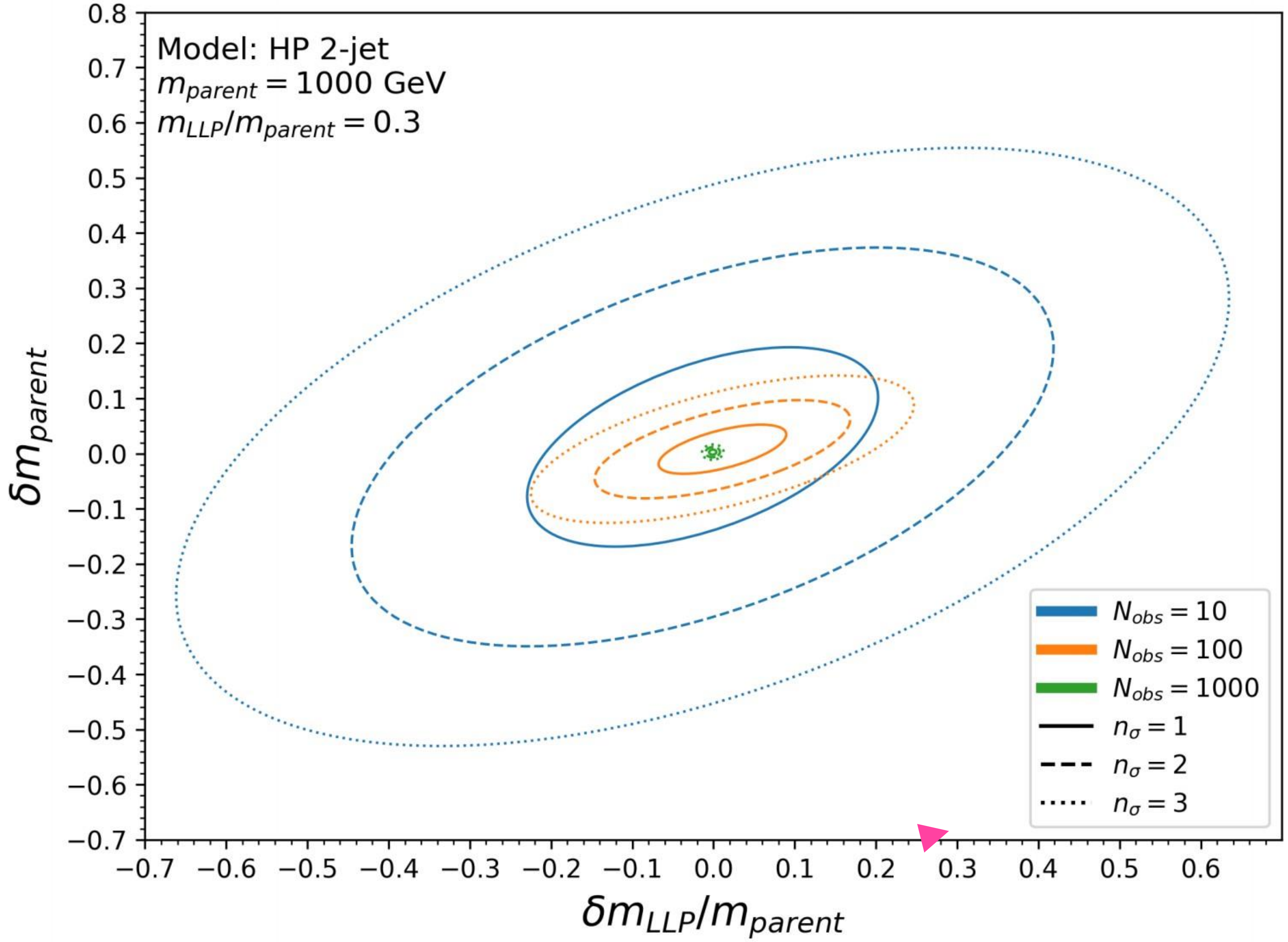
Incorporate MATHUSLA into CMS L1 Trigger
Correlate event info off-line → determine LLP production mode



Identifying LLPs

If production mode is known: Boost distribution → LLP mass
If LLP mass is known: Track multiplicity → LLP decay mode

MATHUSLA + CMS analysis will reveal model parameters (parent mass, LLP mass) with just ~100 observed LLP events!



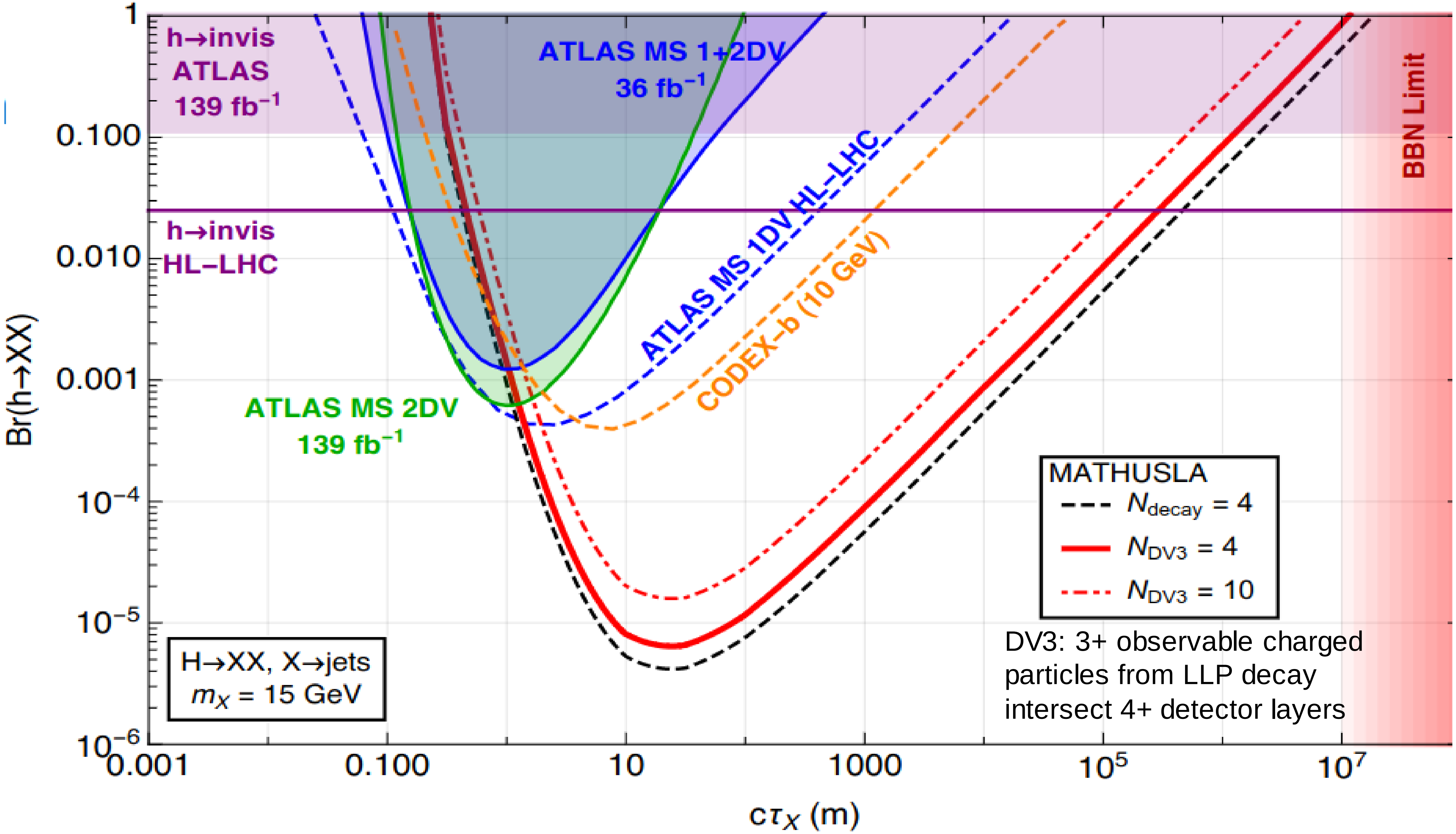
LLP Sensitivity

More benchmark models can be found in **Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report** arXiv:1901.09966

LLP Sensitivity: Weak- to TeV- Scale

Up to 1000x better sensitivity than LHC main detectors

e.g. hadronically-decaying LLPs in exotic Higgs decay



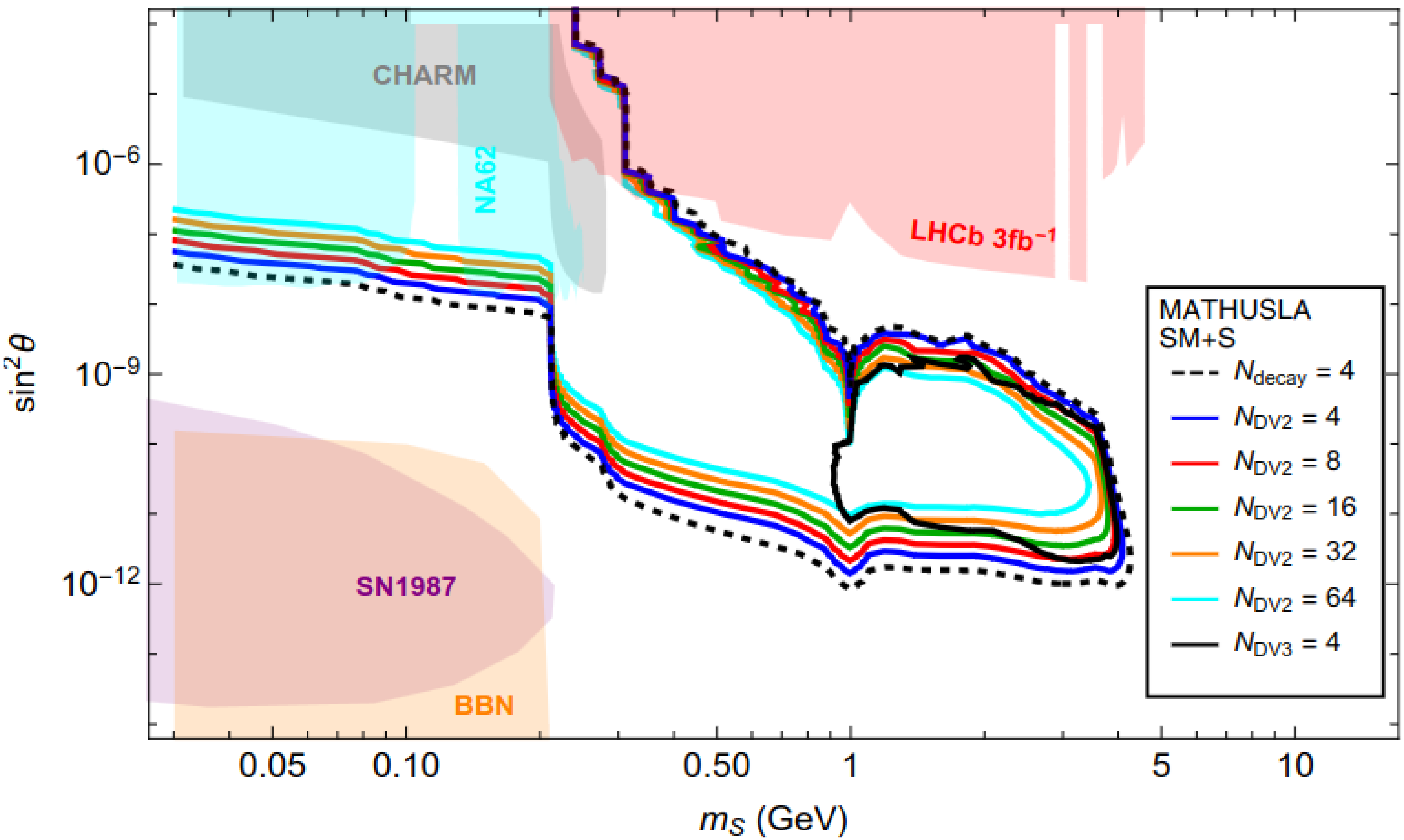
Any LLP production process with σ > fb can give signal in MATHUSLA

arXiv:2001.04750

LLP Sensitivity: GeV-Scale

For scenarios where the long-lifetime limit (>100m) is accessible, MATHUSLA is complementary to other planned experiments

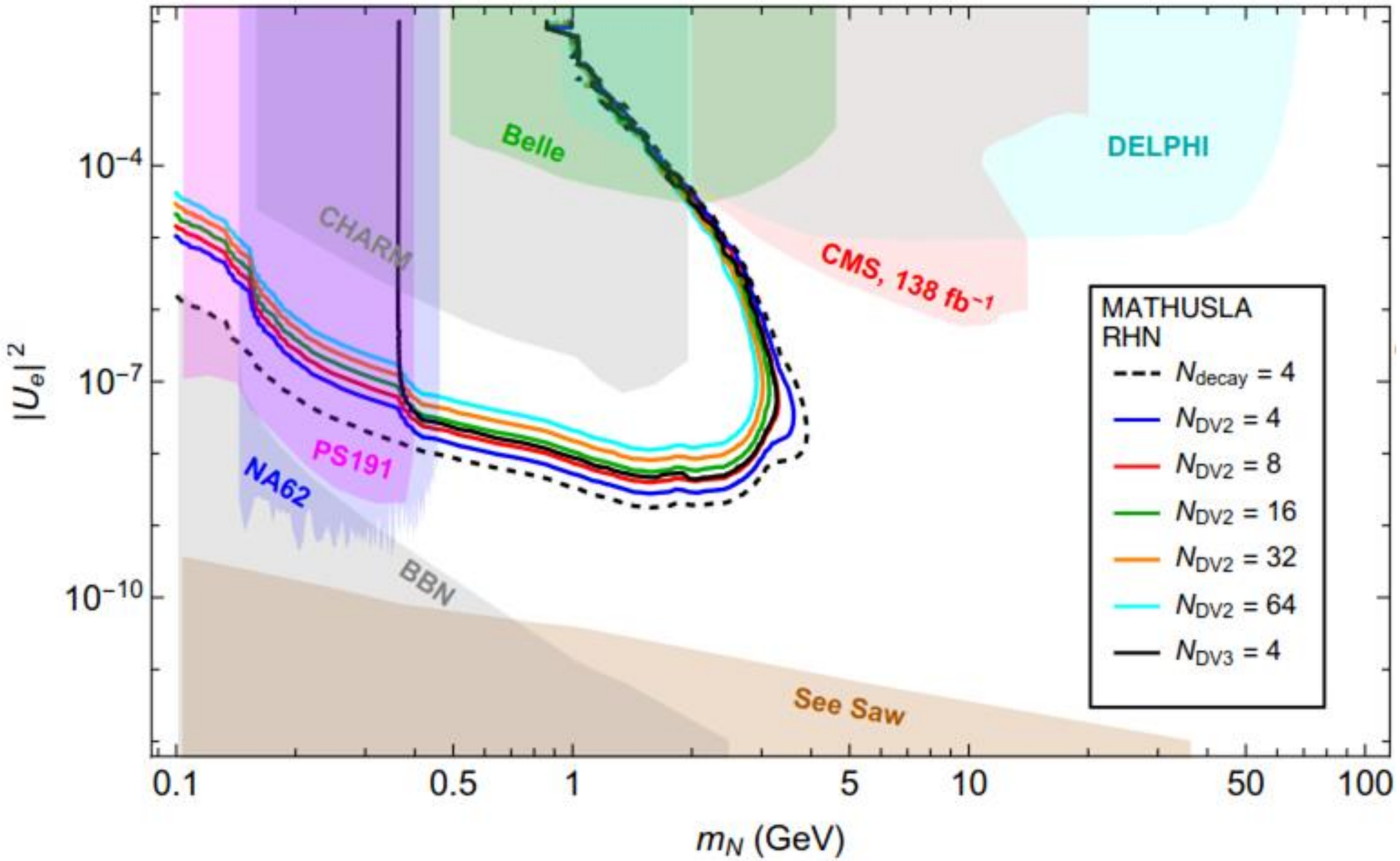
e.g. singlet dark scalar S, mixing angle θ with SM Higgs



LLP Sensitivity: GeV-Scale

Reach for heavy neutral leptons

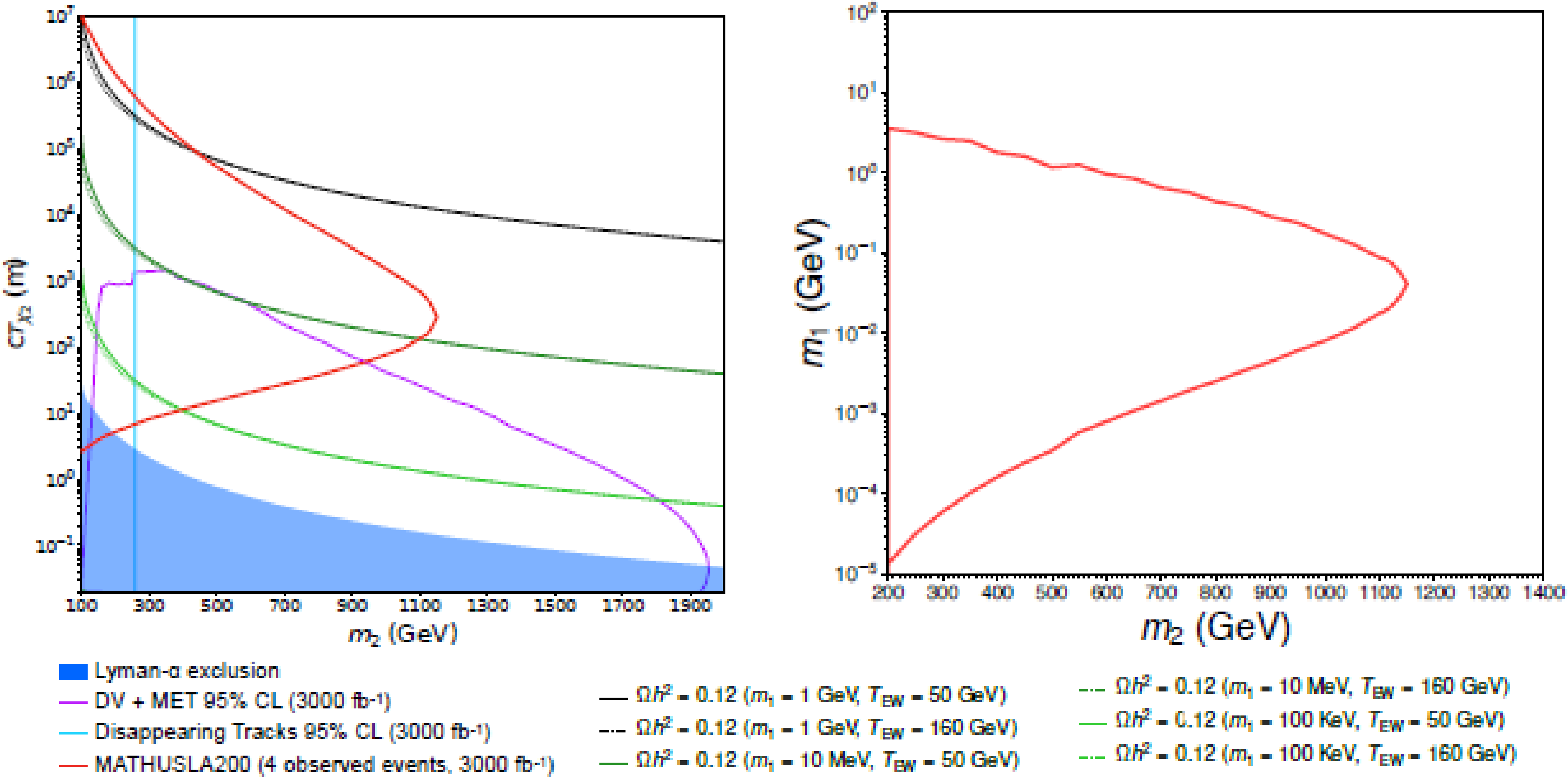
e.g. sterile neutrino N, whose largest mixing angle U_e is with υ_e



LLP Sensitivity: DM

Scenarios where LLP → DM + SM decay is the only way to see the DM

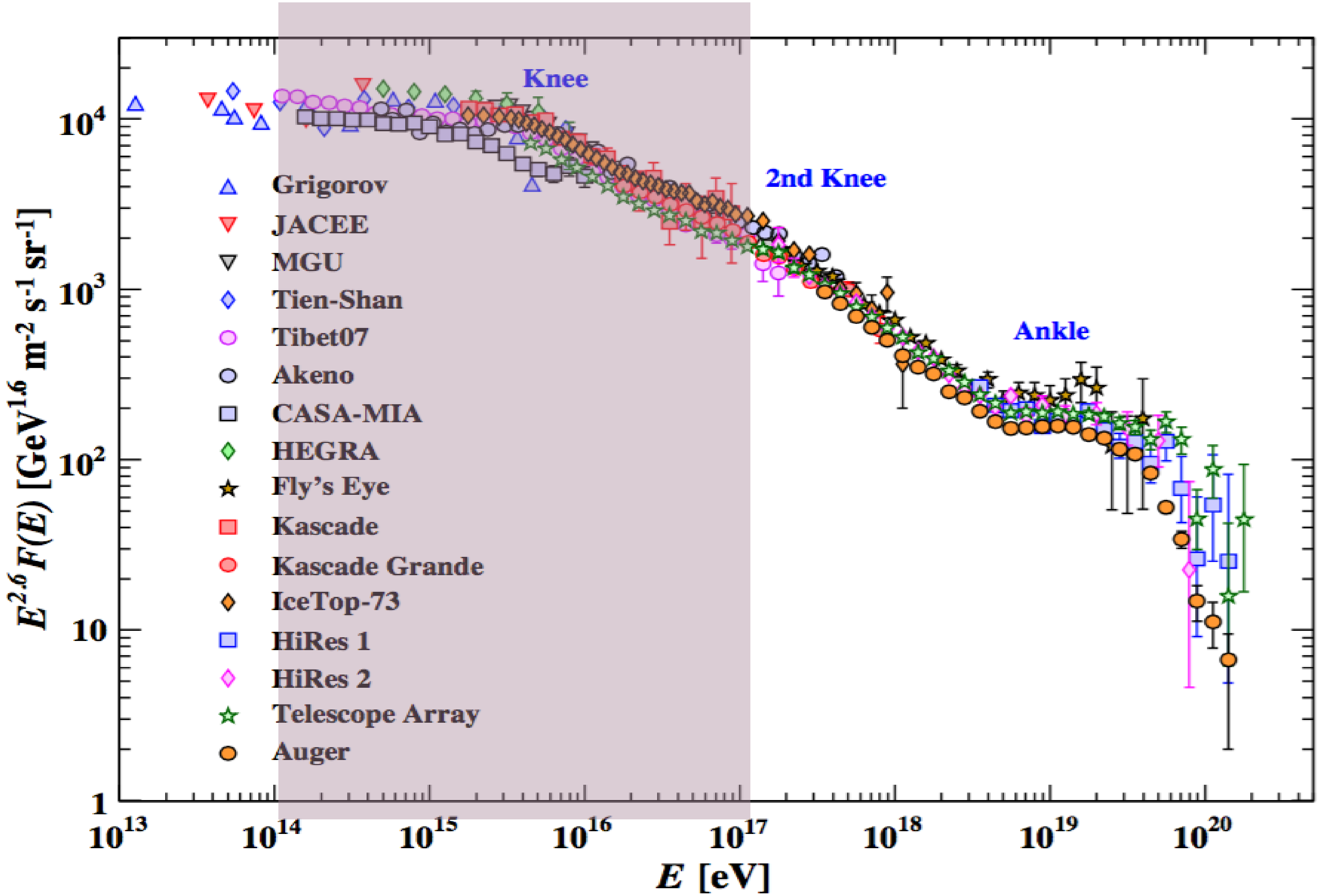
e.g. Freeze-In Dark Matter: BSM mass eigenstates χ_1 (DM) and χ_2 (LLP), where χ_2 was in thermal equilibrium with primordial plasma



Cosmic Ray Telescope

MATHUSLA as a Cosmic Ray Telescope

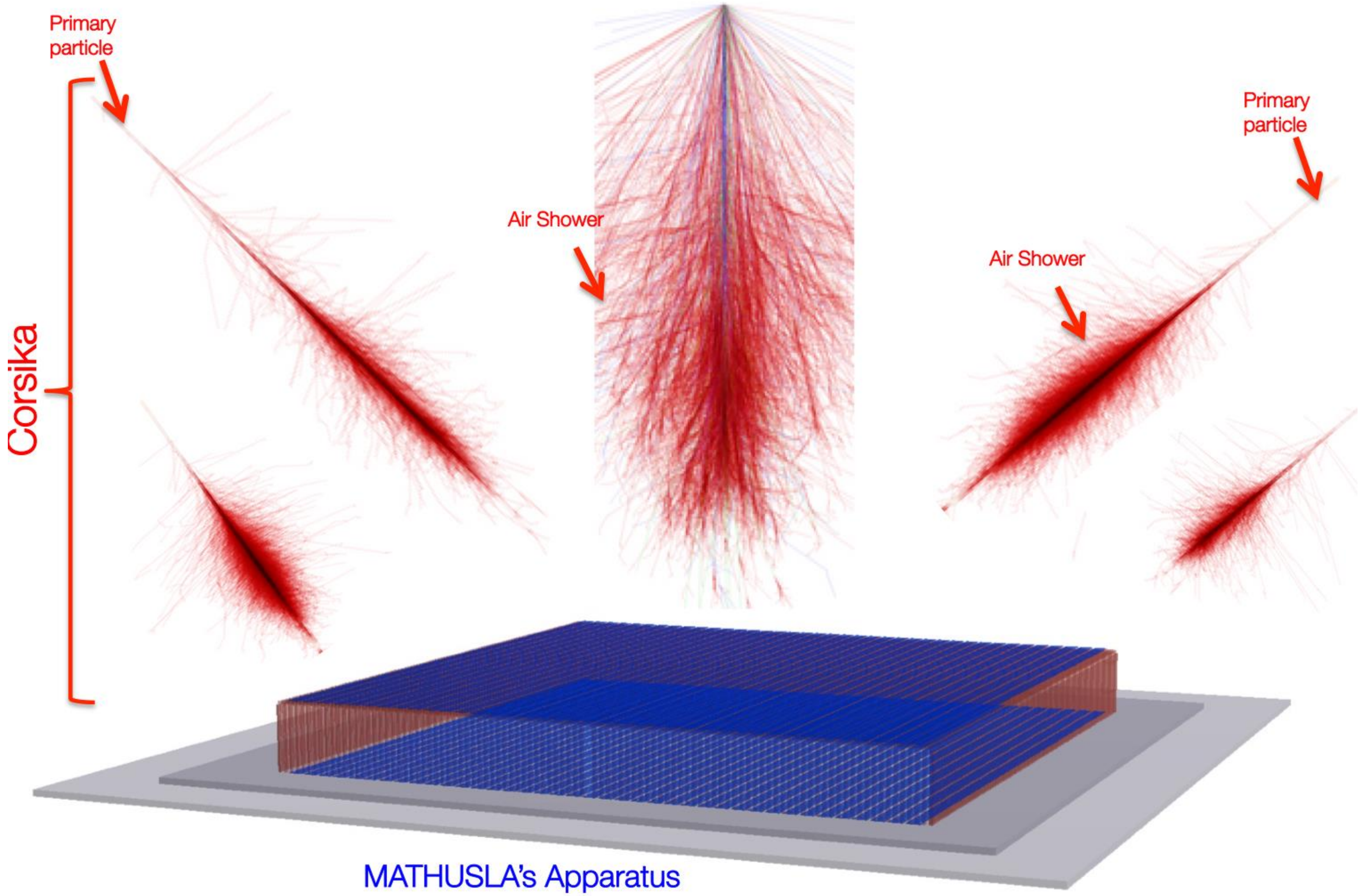
Relevant abilities in CR experimental ecosystem (precise resolution, directionality, large-area coverage, interesting region CR energy spectrum)



https://indico.cern.ch/event/980853/contributions/4361206/attachments/2251261/3819144/CRMathusla_LLP_25May2021_JC.pdf

MATHUSLA as a Cosmic Ray Telescope

Reconstruction of shower core, direction, total # charged particles, slope of radial particle density distribution



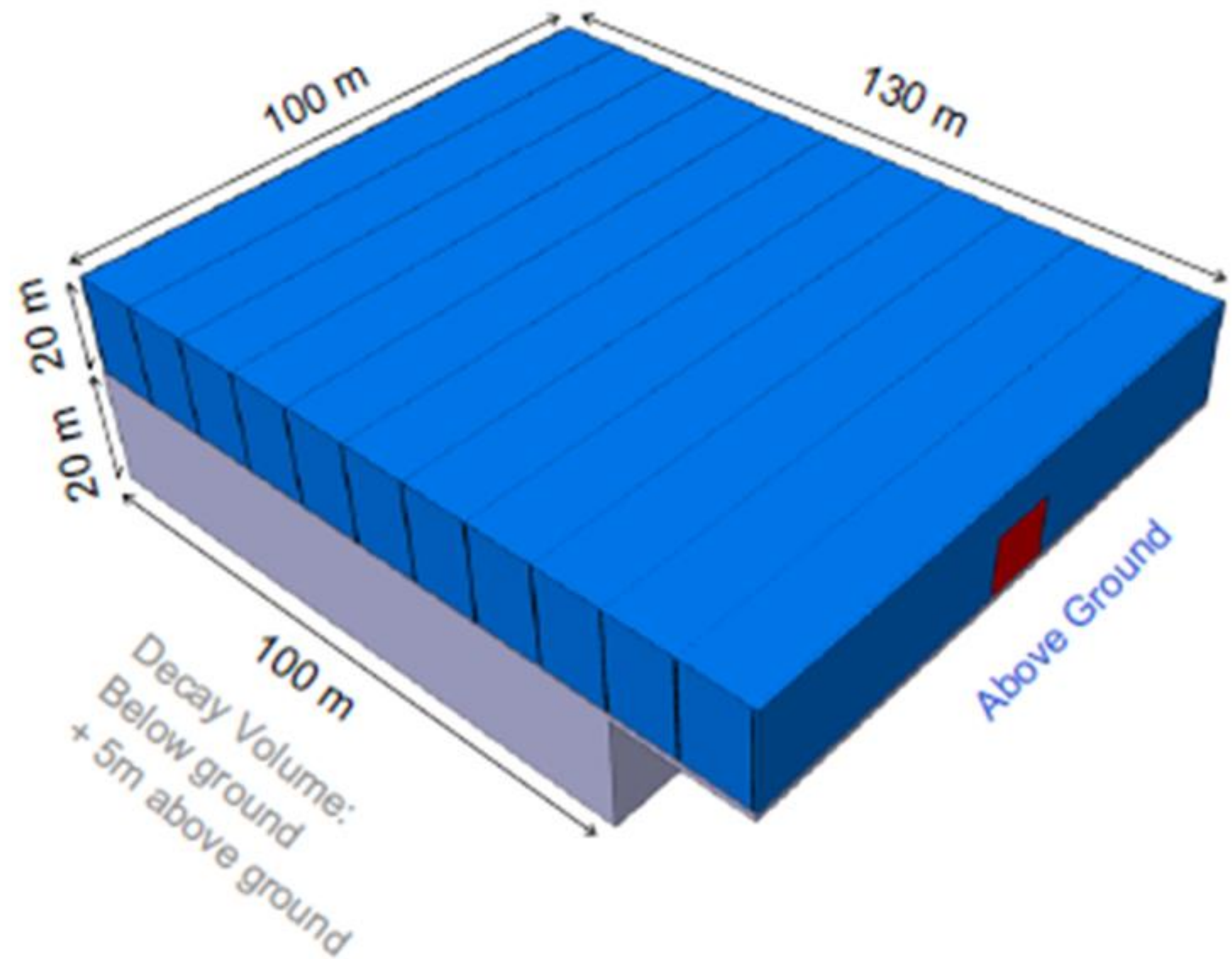
MC simulations using CORSIKA (https://www.iap.kit.edu/corsika/)

Detector Design

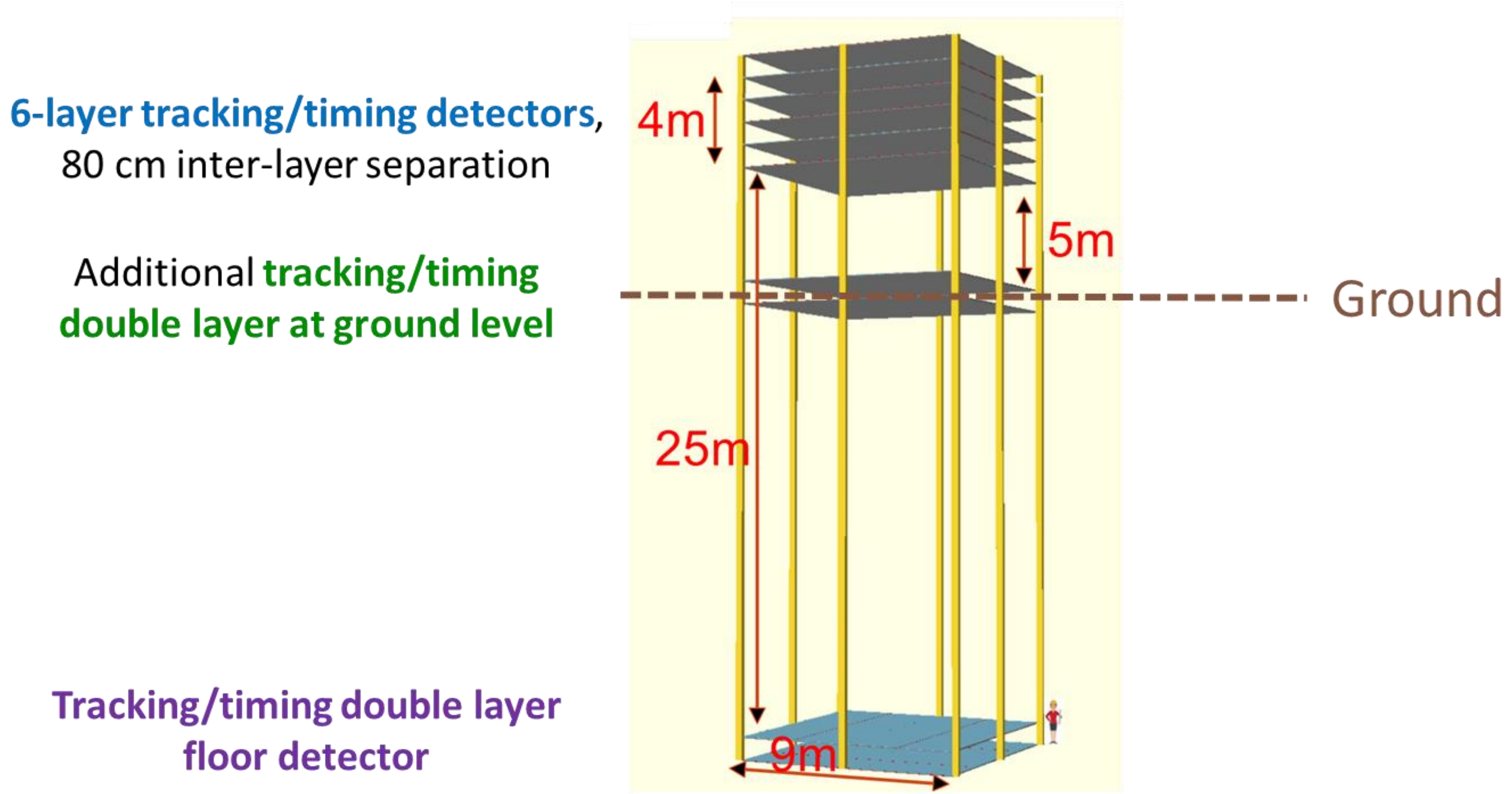
Detector Design

- Worked with Civil Engineers to define **building and layout of MATHUSLA at P5**
- Layout **restricted by existing structures** based on concept and engineering requirements

- Decay volume ~100 x 100 x 25 m^3
- Modular design



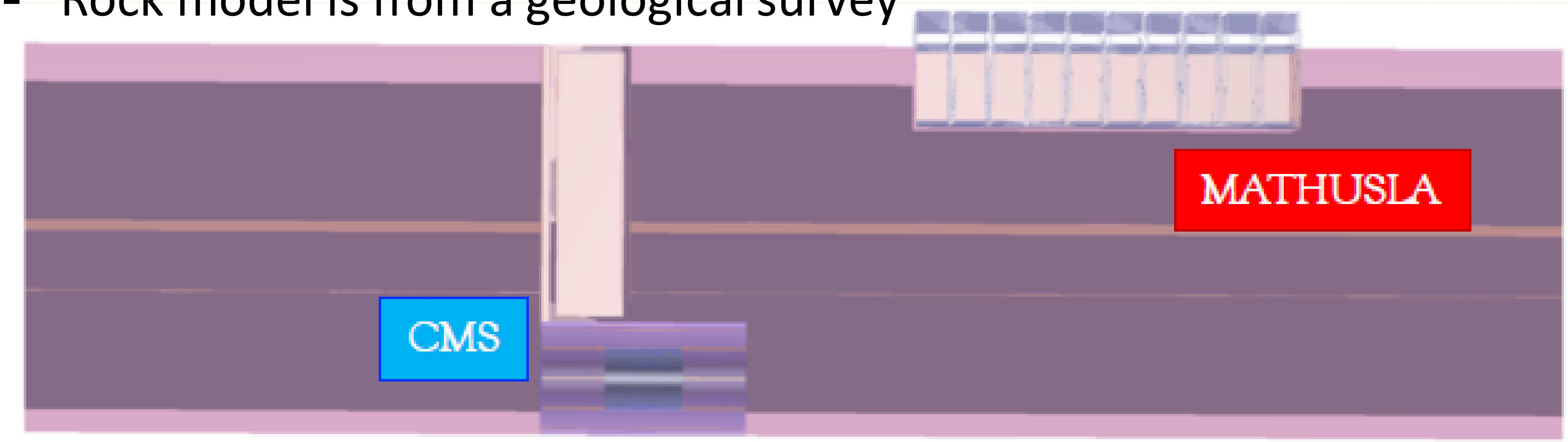
Detector Design



- Total ~ **25 m height for decay volume**
- Individual detector units each **9 x 9 x 30 m^3**

Geometry Simulations

- Cavern, access shaft, CMS, rock, and detector all modeled in GEANT4
  - Rock model is from a geological survey

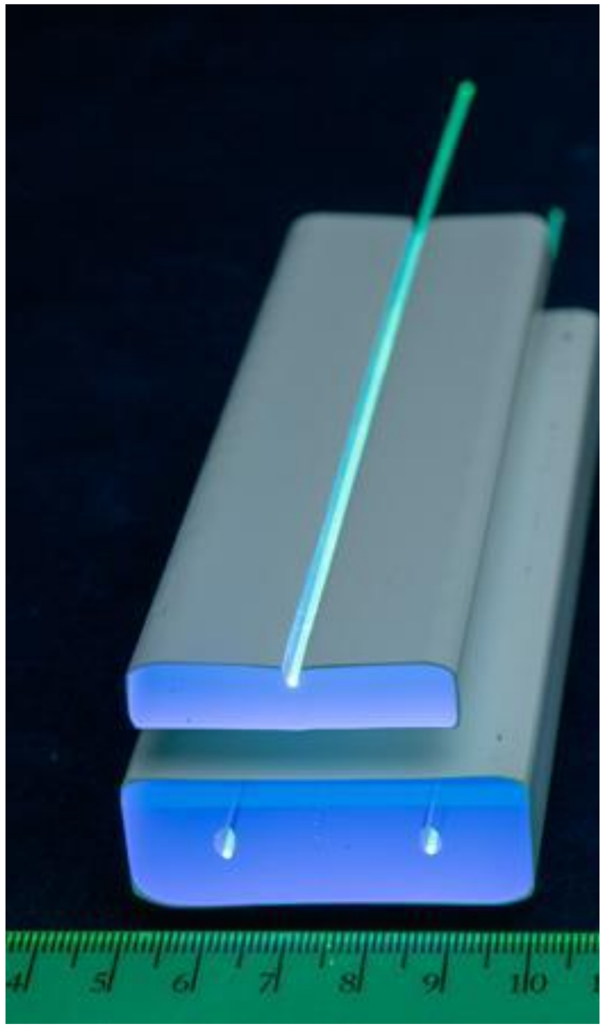


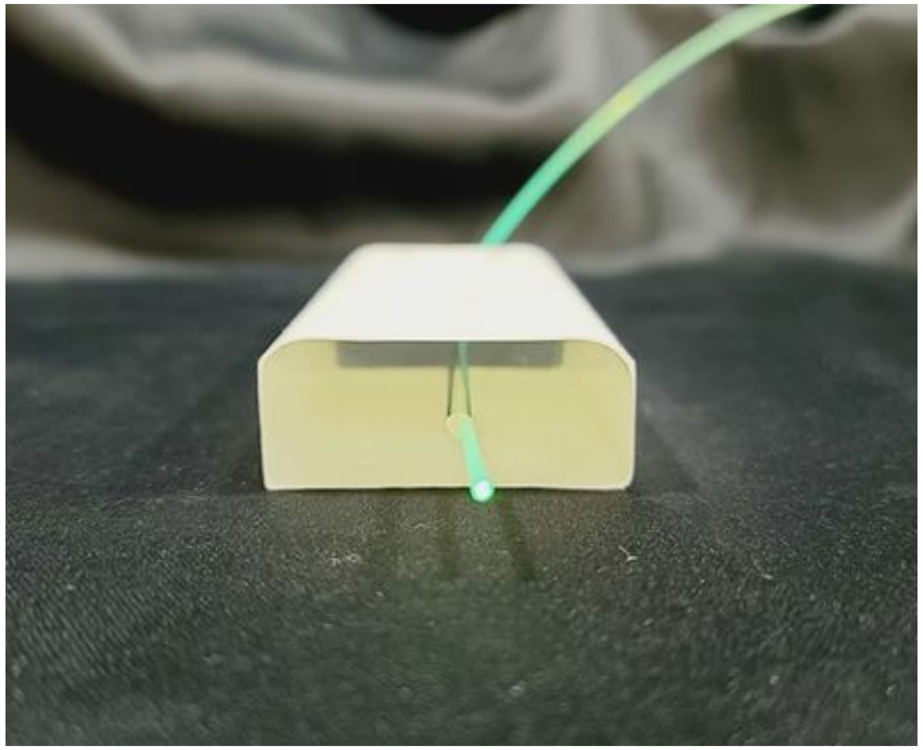
- Backgrounds under detailed study:
  - Upward-going muons from collisions (Pythia8)
  - Backscatter (to upwards going V^0) from downward-going cosmic rays (Parma)
  - Neutrino interactions (Genie3)
- Exploring background rejection power of adding a high-coverage floor veto, [partially]- instrumented walls

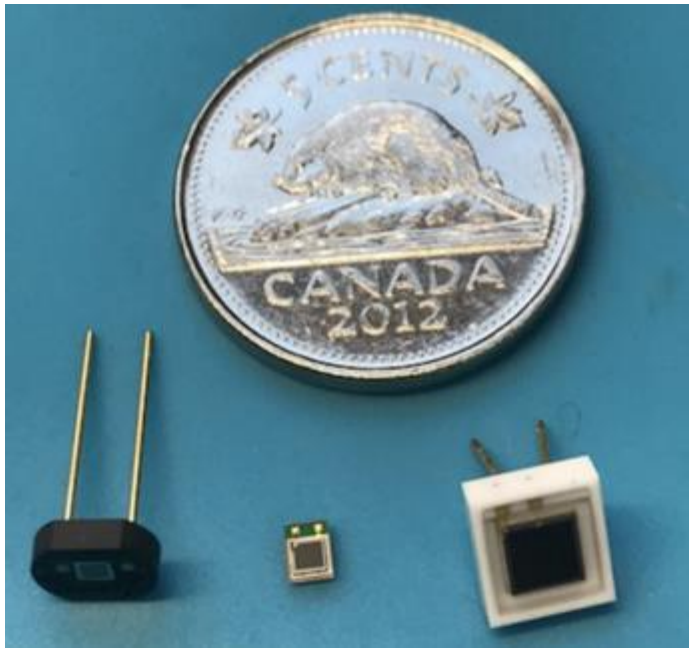
Trackers

Tracker layers: Composed of extruded scintillator bars with WLSFs (wavelength-shifting fibers) coupled to SiPMs (Silicon Photomultipliers)

- Extrusion facilities in FNAL used for several experiments (e.g. Belle muon trigger upgrade, Mu2e)

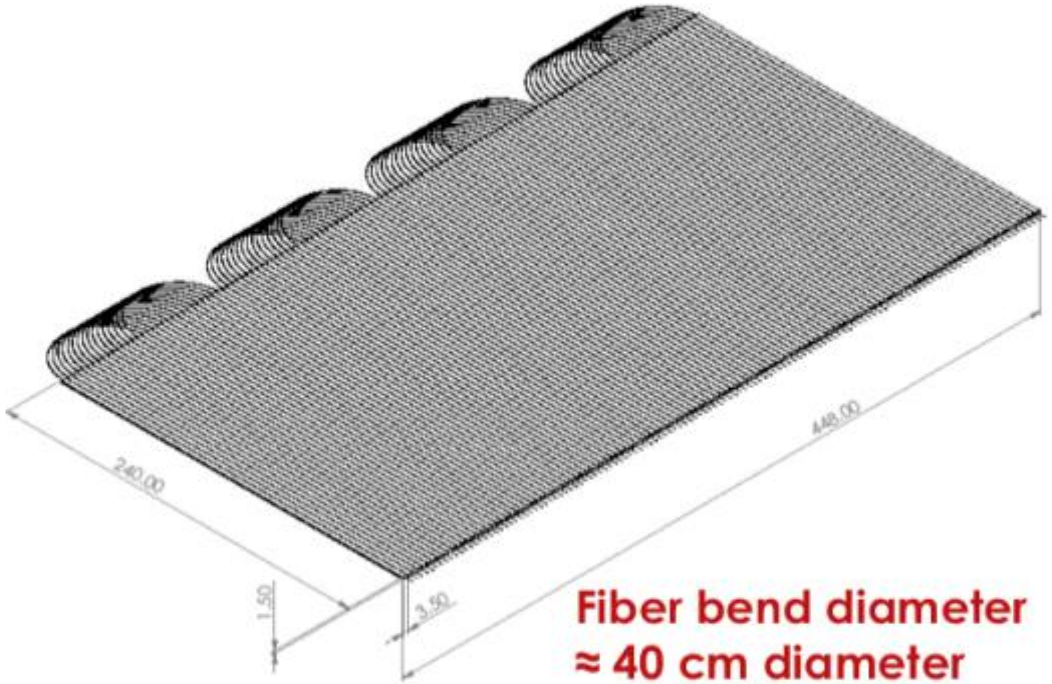






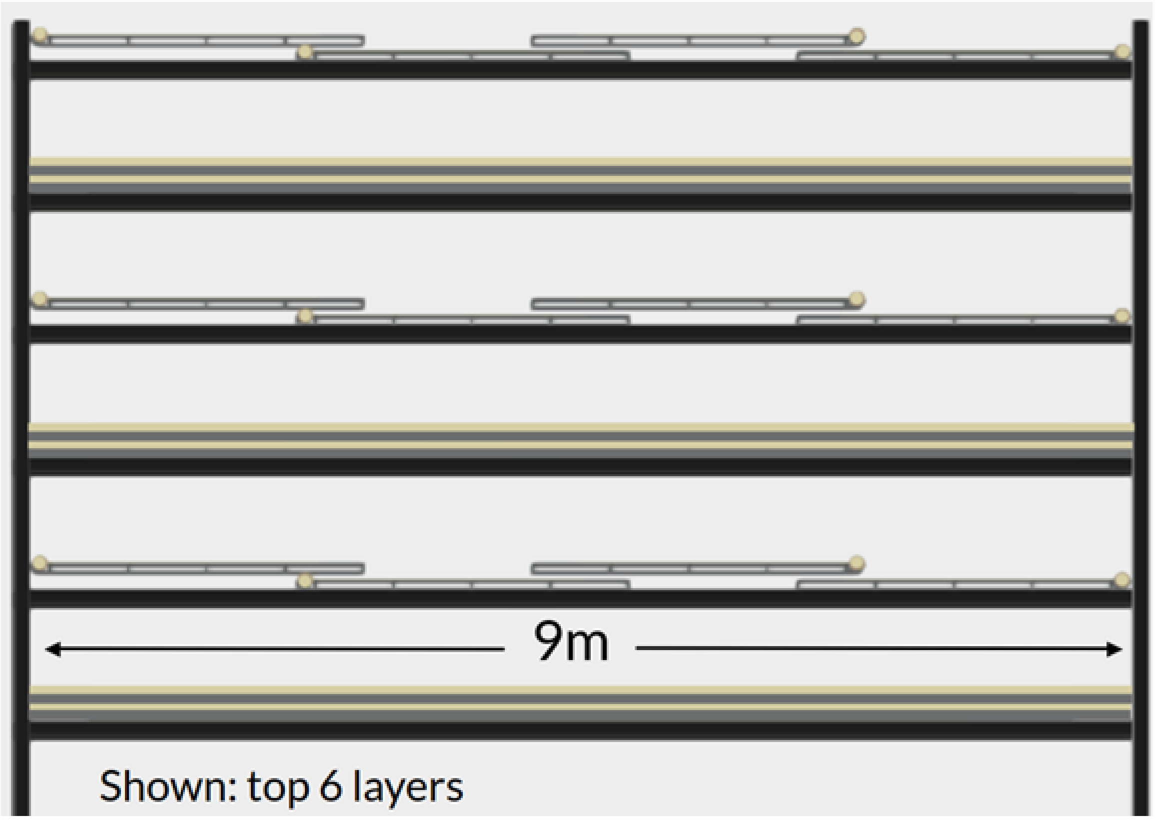
Trackers

MRS engineering support for layout



Considering readout at both ends of each scintillator bar, or looped fiber for readout at one end

- Transverse resolution depends on bar width
- Δt between two ends gives longitudinal resolution

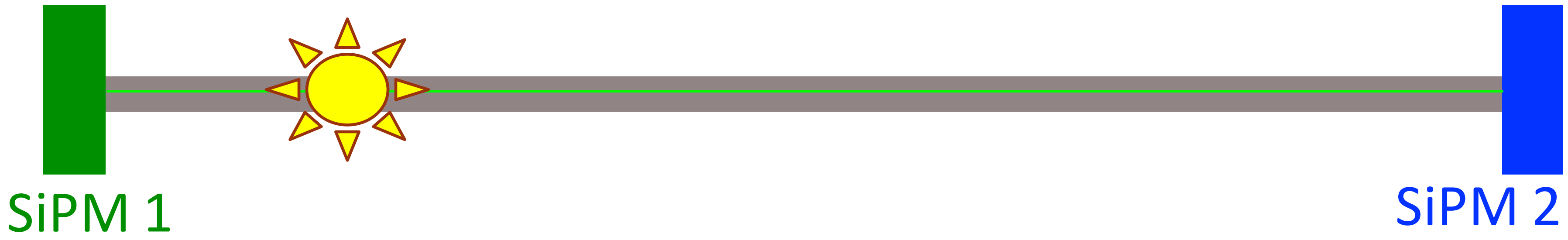


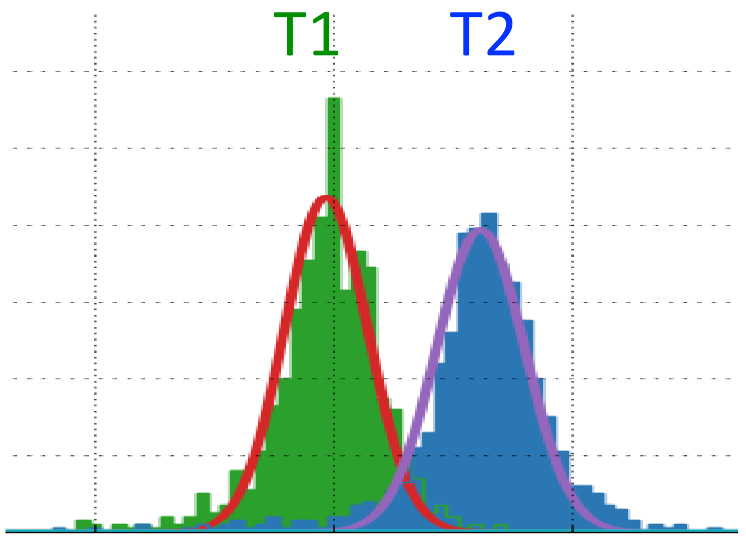
Nominal layer design: 256 bars, each 2.5 m long

- Each layer segmented into 4 sheets of bars
- Overlapping sheets, and alternating layer orientation, ensures no gaps in coverage

Trackers

To reconstruct hit position along scintillator bar: use difference in arrival time between separate measurements at two ends





or

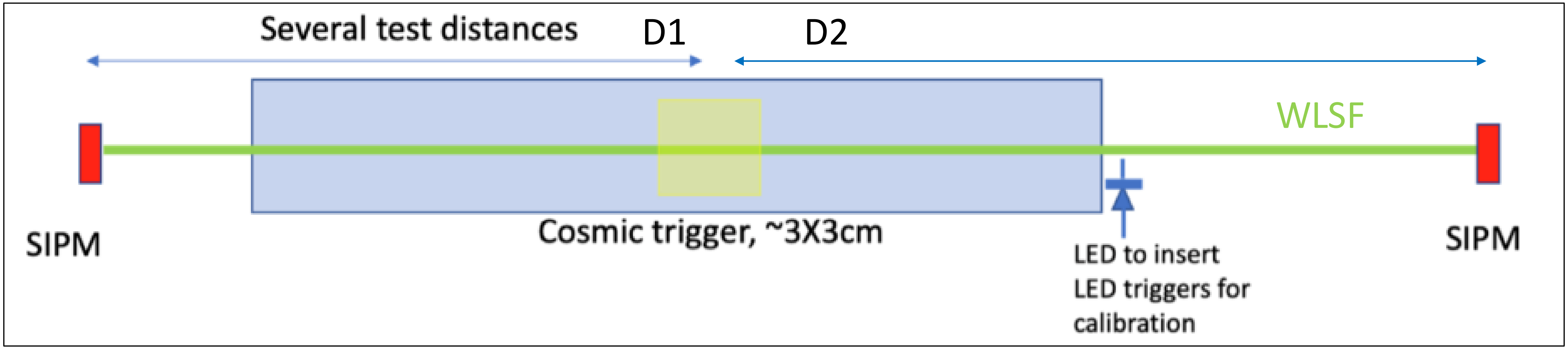
Target timing resolution ~1 ns

Trackers

Precise timing resolution is a critical feature of the detector design

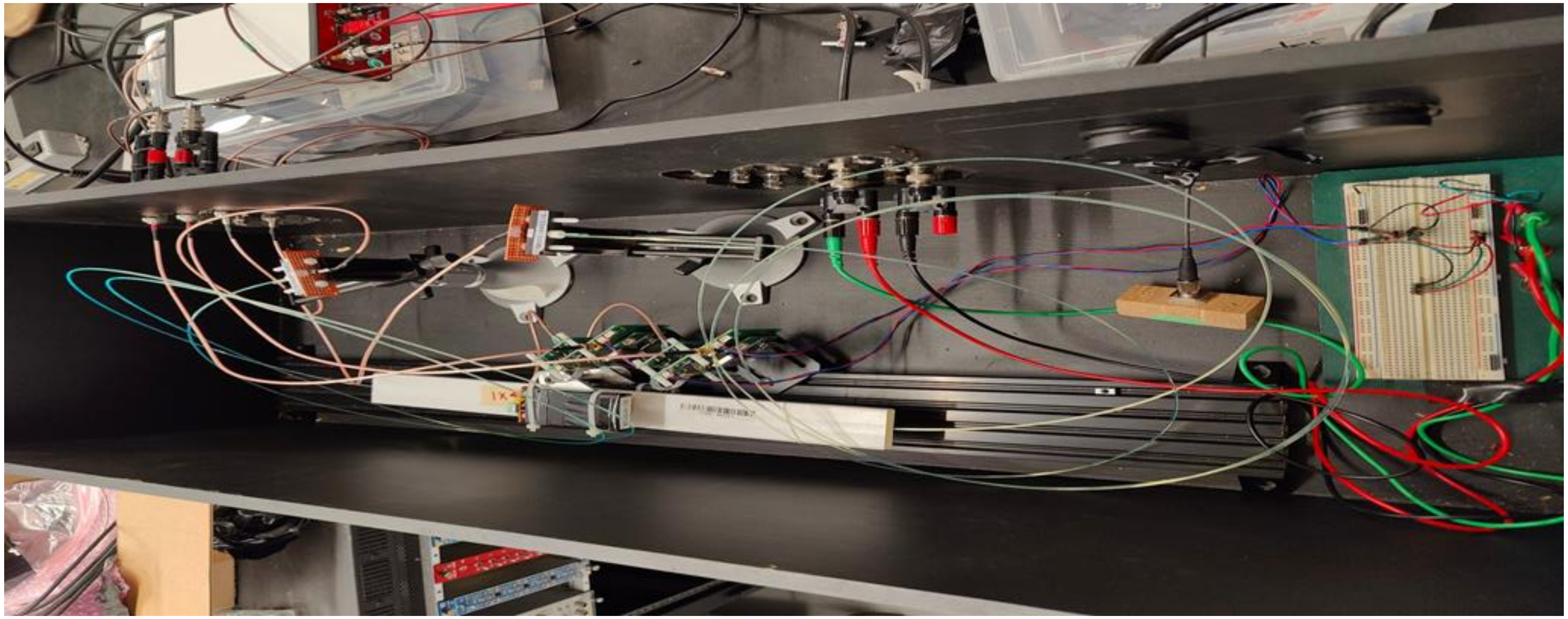
- Separates downward- from upward-going tracks
- Rejects low-β particles from neutrino quasi-inelastic scattering
- “4D” tracking and vertexing reduces fakes/combinatorics

Ongoing characterization studies using **small dark-box setups** indicate 1 ns timing resolution goal is achievable



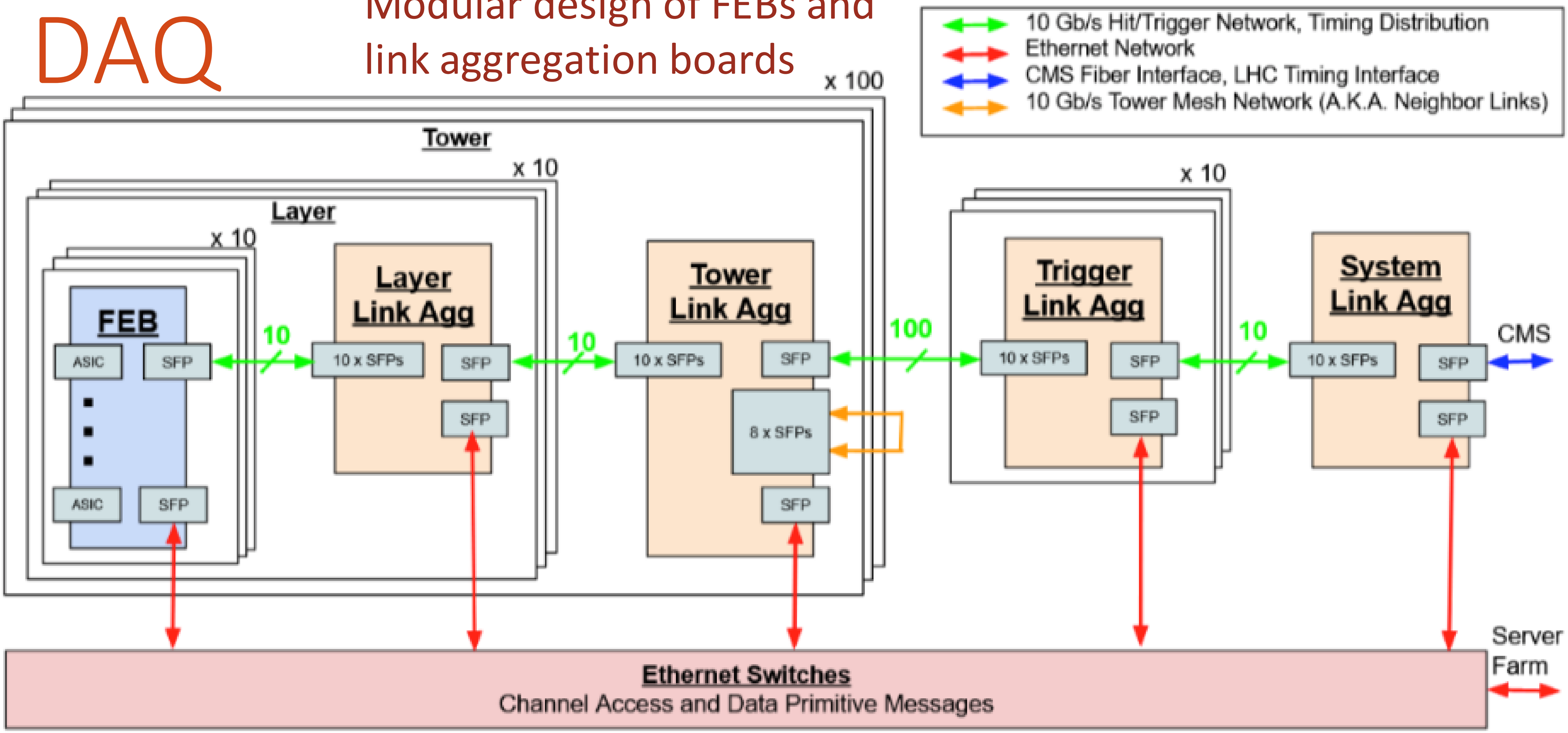
Trackers

- Currently under investigation in dark-box setups at UToronto & UVic with different vendors/models of scintillator, WLSF, SiPM:
  - Optimizing timing (position) resolution
  - Light yield
  - Light leakage and fiber stress
  - Temperature effects, e.g. on SiPM dark current



DAQ

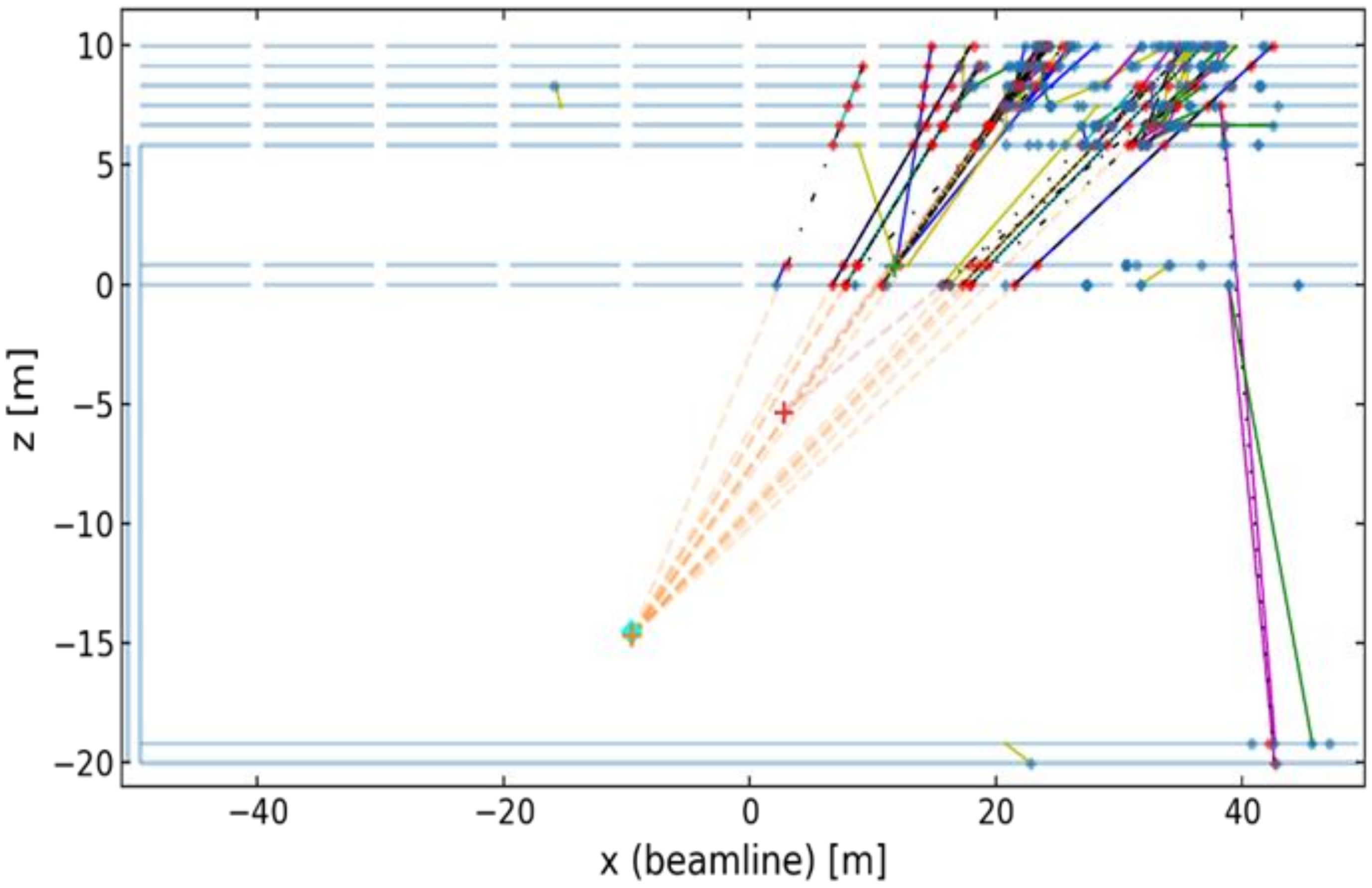
Modular design of FEBs and link aggregation boards



- **MATHUSLA Trigger**
  - Tower agg module triggers on upward-going **tracks** within 3x3 tower volume
  - Selects data from buffer for permanent storage
- **Trigger to CMS**
  - Upward-going **vertex** forms trigger to CMS
  - Trigger latency estimates appear compatible with CMS L1 latency budget
- **Data rate well within COTS servers**

Vertex Reconstruction

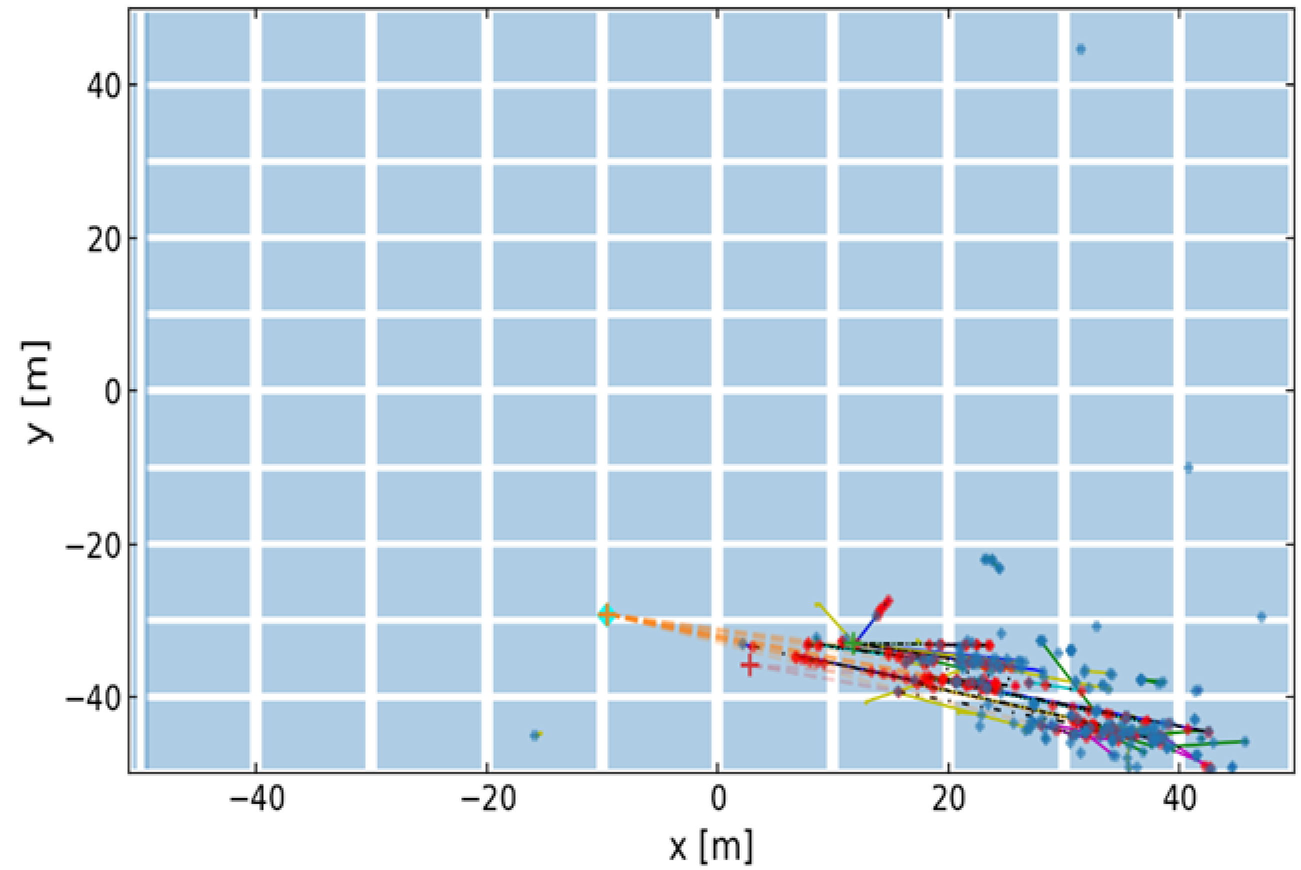
Implementation of **custom tracking algorithms** (based on Kalman filtering) + **"4D" vertex formation**, to achieve high LLP reconstruction efficiency for low-multiplicity LLP final states in MATHUSLA's unique environment



e.g. scalar LLP X

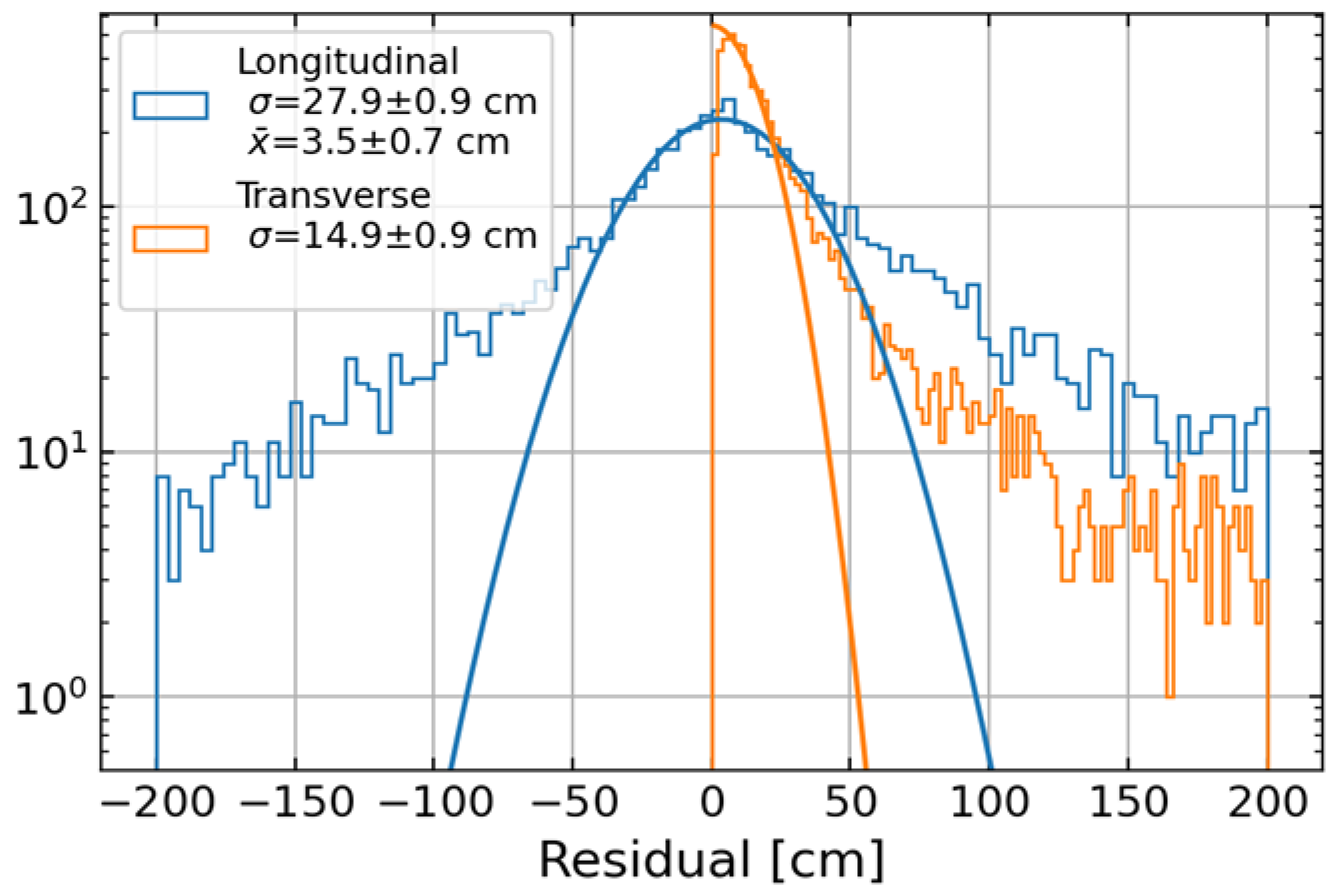
$pp \to h \to XX,\ \ X \to bb$

$m_x = 20$ GeV, $c\tau_x = 1000$ m



Vertex Reconstruction

Validated using GEANT4 simulated events

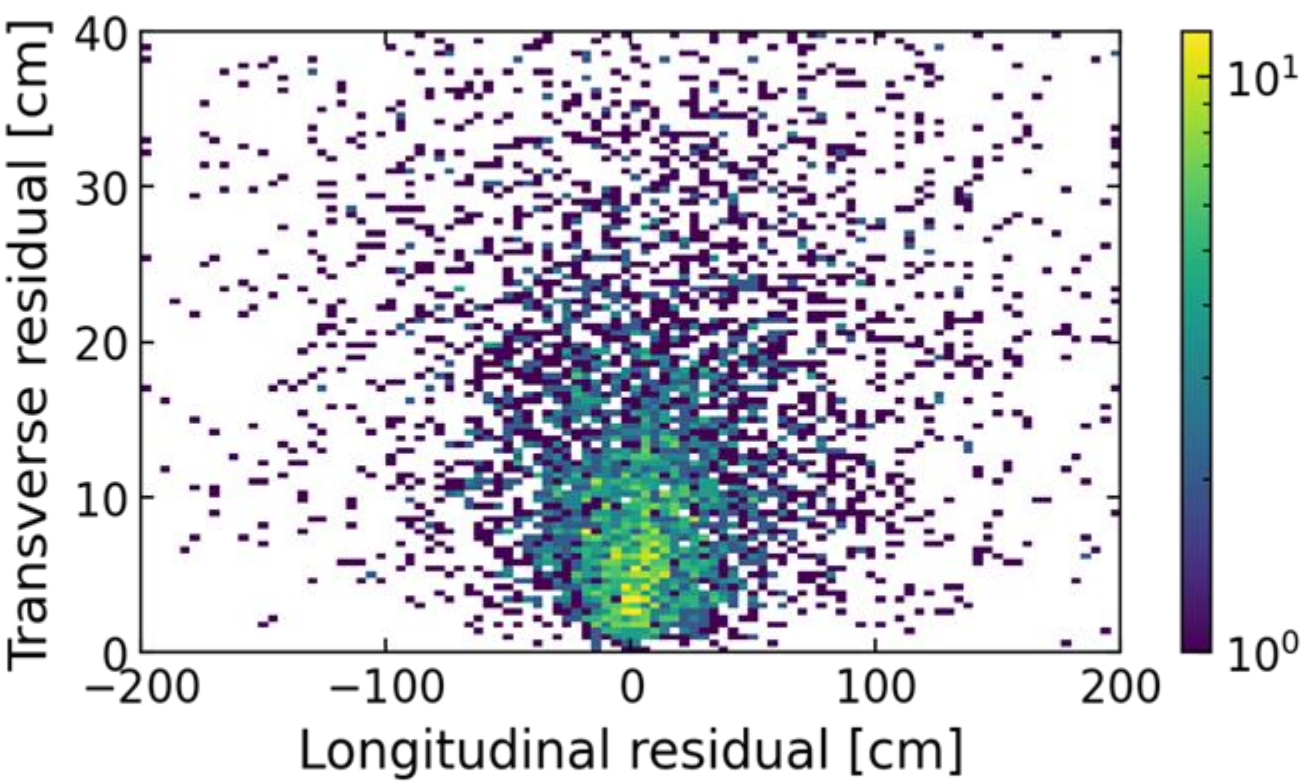


e.g. scalar LLP X

$pp \to h \to XX,\ X \to bb$

m_X = 20 GeV, $c\tau_X$ = 1000 m

10000 events simulated
Geometric acceptance 73%
Vertex identification efficiency 98%

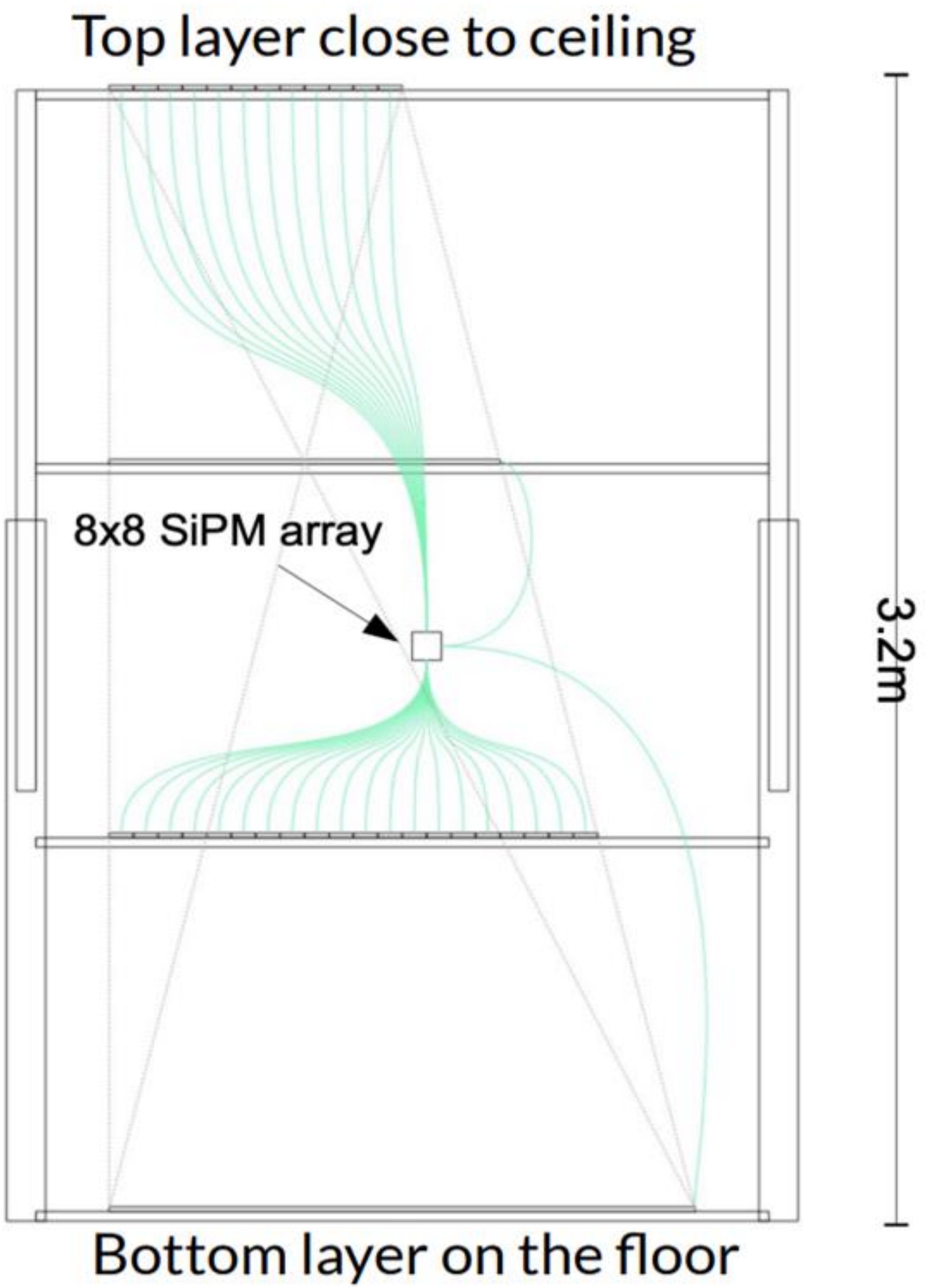


Test Stand @ UVic

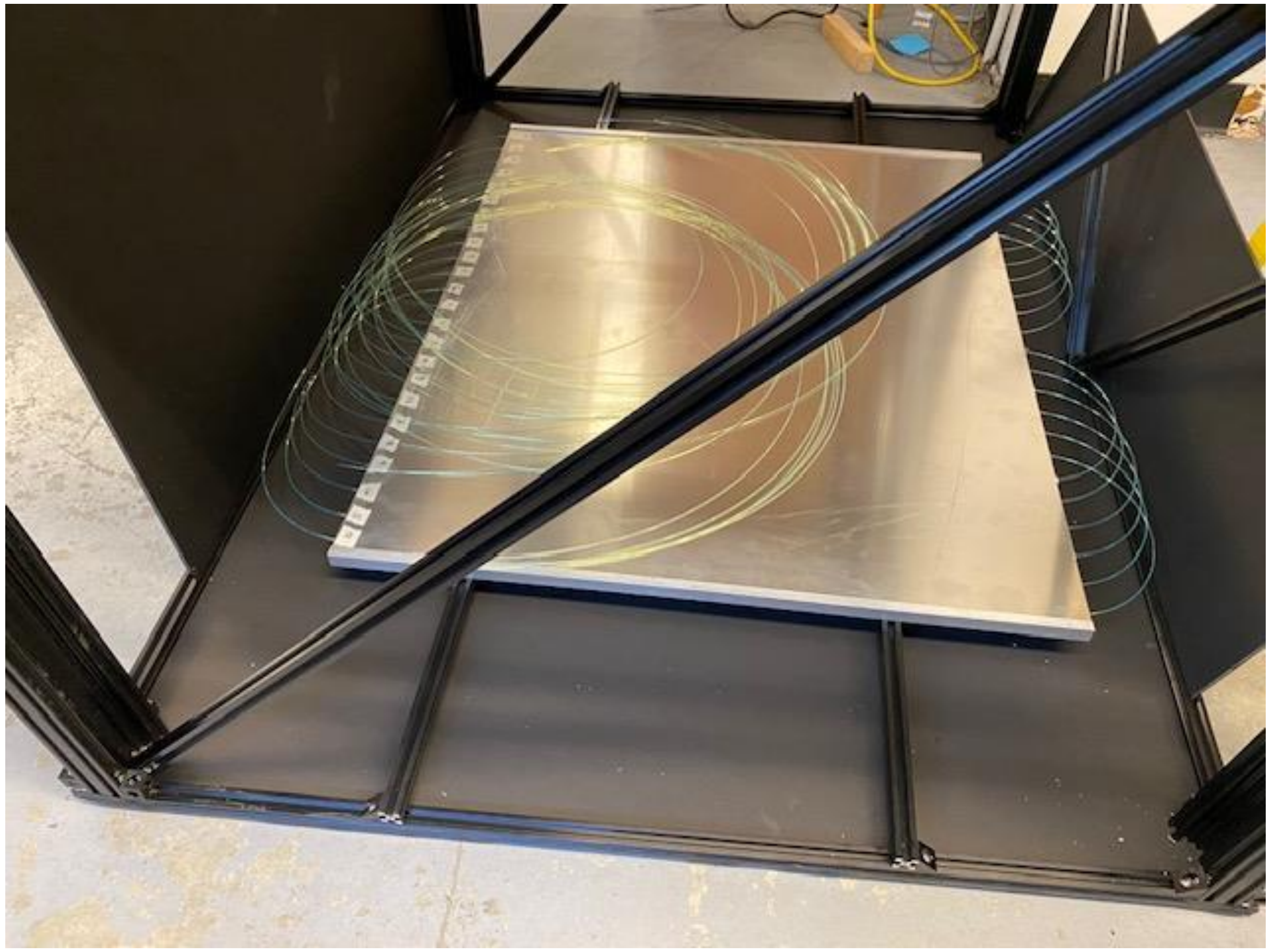
Constructing 64-channel “mini-module” of 4 layers, ~1m x 1.5m each

Potential studies include:

- Mechanical structure
- Basic track reconstruction with cosmics (validation, performance)
- Basic triggering
- Hit efficiencies, effects of gaps between bars
- Comparisons with simulations



Test Stand @ UVic



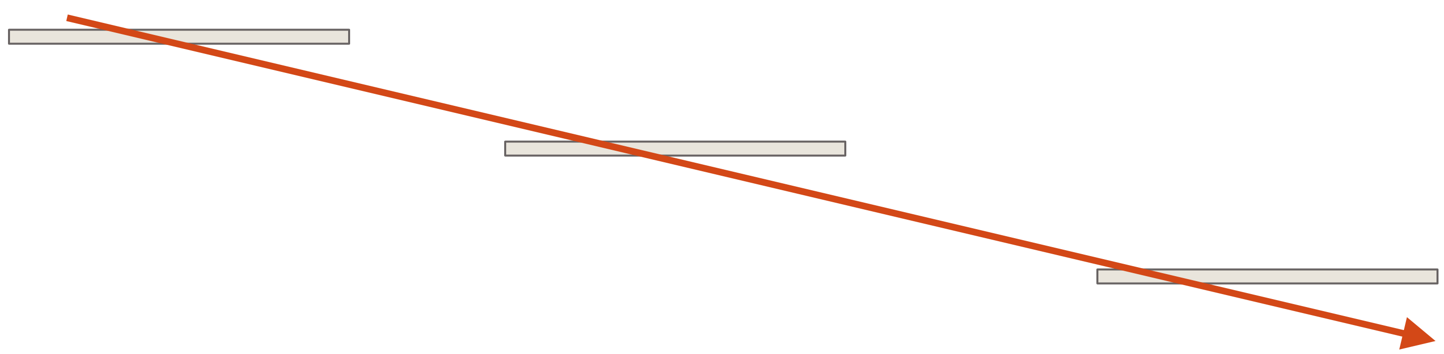
Test Stand @ UToronto

Constructing 120-channel “mini-module” of 5 layers, ~1m x 1m each
More advanced features include:

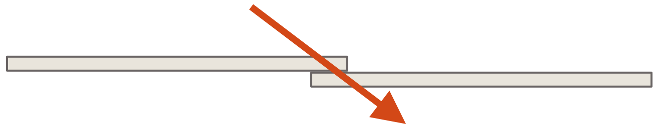
- PCBs (with pre-amps) to carry SiPM signals to readout boards
- Compression-fitting mounting apparatus to keep each SiPM in place
- Layers [re]moveable and height-adjustable individually

Potential studies include:

- PCB design optimization
- “Large angle” tracking



- Modelling interfaces between modules



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The MATHUSLA Collaboration

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Tsinghua University 1911

Institute of High Energy Physics
Chinese Academy of Sciences

The University of Arizona

University of Washington 1861

https://mathusla-experiment.web.cern.ch/

Conclusions

- MATHUSLA is a planned external LLP detector for the HL-LHC that can probe deep into LLP parameter space in a variety of BSM scenarios
- Canadian groups highly active in multiple aspects
  - Sensitivity projections for various BSM models
  - Detector simulations of rare backgrounds
  - Layout of tracker layers
  - Scintillator/fiber/SiPM characterizations
  - Vertex reconstruction software
  - Test stands
- Excellent training-ground for HQP
- Conceptual Design Report to be published soon, followed by prototype module and full detector for HL-LHC
- New collaborators always welcome!

References

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BACKUP

LLPs at the [HL-]LHC

Seeking to go Beyond the Standard Model (BSM) motivates the possibility of so-far-undiscovered LLPs

- "**Top-down**": Various BSM theories (e.g. supersymmetry) constructed to explain the "fundamental mysteries" naturally include new LLPs
- "**Bottom-up**": LLPs occur in the SM (e.g. muons), and can occur via similar mechanisms when adding new particles to the model

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

- **If the LLP has c · lifetime >> detector size, most escape the detector**
- **Even LLPs that decay in the detector, but a significant distance away from the Interaction Point, are difficult to spot**
- **If the LLPs decay in the detector with only a tiny rate, they get swamped by backgrounds**

Backgrounds

- Cosmic rays
  - Calibrations performed using Test Stand measurements (taken above ATLAS IP in 2018) arXiv: 2005.02018
  - Downward-going events ~3 x 10^{14} over entire HL-LHC run, distinguished from LLPs using timing cuts
  - Upward-going events ~2 x 10^{10} : inelastic backscatter from CRs hitting the floor, or decay of stopped muons in floor. Only tiny fraction (estimates underway) produce fake DV, via decay to 3 charged tracks
  - Rare production of K^0_L harder to estimate; work underway on veto strategies
- Rare decays of muons originating from HL-LHC collisions
  - Upward-going events ~2 x 10^8 , mostly from W and bbar production
  - Work underway for optimal rejection strategies
- Charged particles from neutrino scattering in decay volume
  - Neutrinos from HL-LHC collisions << 1 "fake" DV/year
  - Atmospheric neutrinos ~30 "fake" DV/year, reduced to < 1 with cuts

Backgrounds: Recent Refined Estimates

- Cosmic rays
  - Calibrations performed using Test Stand measurements (taken above ATLAS IP in 2018) arXiv: 2005.02018
  - Simulated using PARMA 4.0 + GEANT4
  - Downward-going events ~3 x 10^{14} over entire HL-LHC run, distinguished from LLPs using timing cuts
  - Upward-going events ~2 x 10^{10} , produced through inelastic backscatter from CRs that hit the floor, or through decay of stopped muons in floor. Tiny fraction can produce fake DV, via decay to 3 charged tracks
  - Rare production of K^0_L harder to estimate; veto strategies are available. Currently working on precise estimates and studying rejection

Backgrounds: Recent Refined Estimates

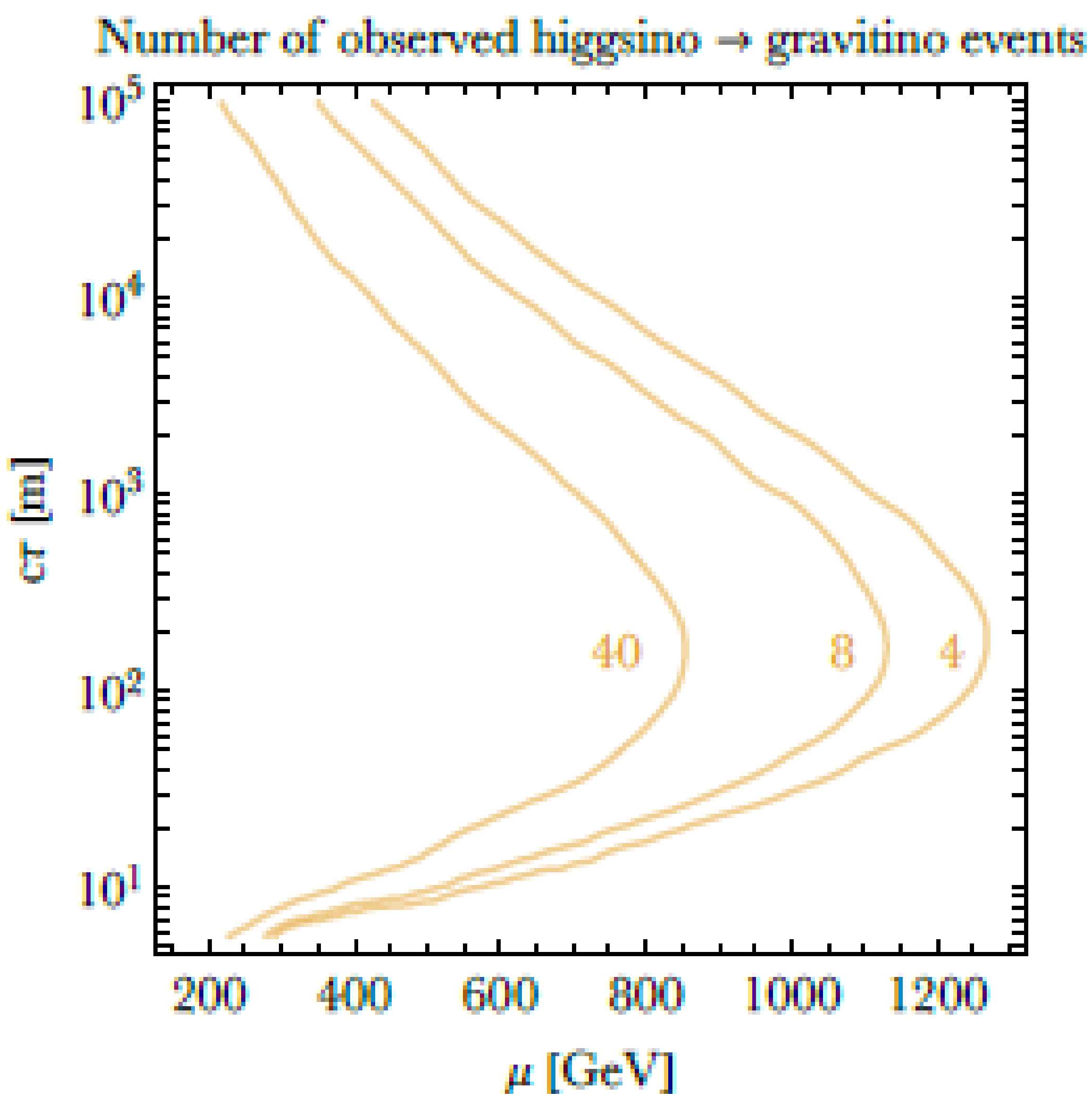
- Rare decays of muons originating from HL-LHC collisions
  - Expect ~2 x 10^8 upward-going muons over entire HL-LHC run, mostly from W and bbar production
  - Simulated using MadGraph & Pythia8
  - Full study underway to demonstrate optimal rejection while maintaining high LLP signal efficiency; test-bed for custom tracking algorithms in unique MATHUSLA environment

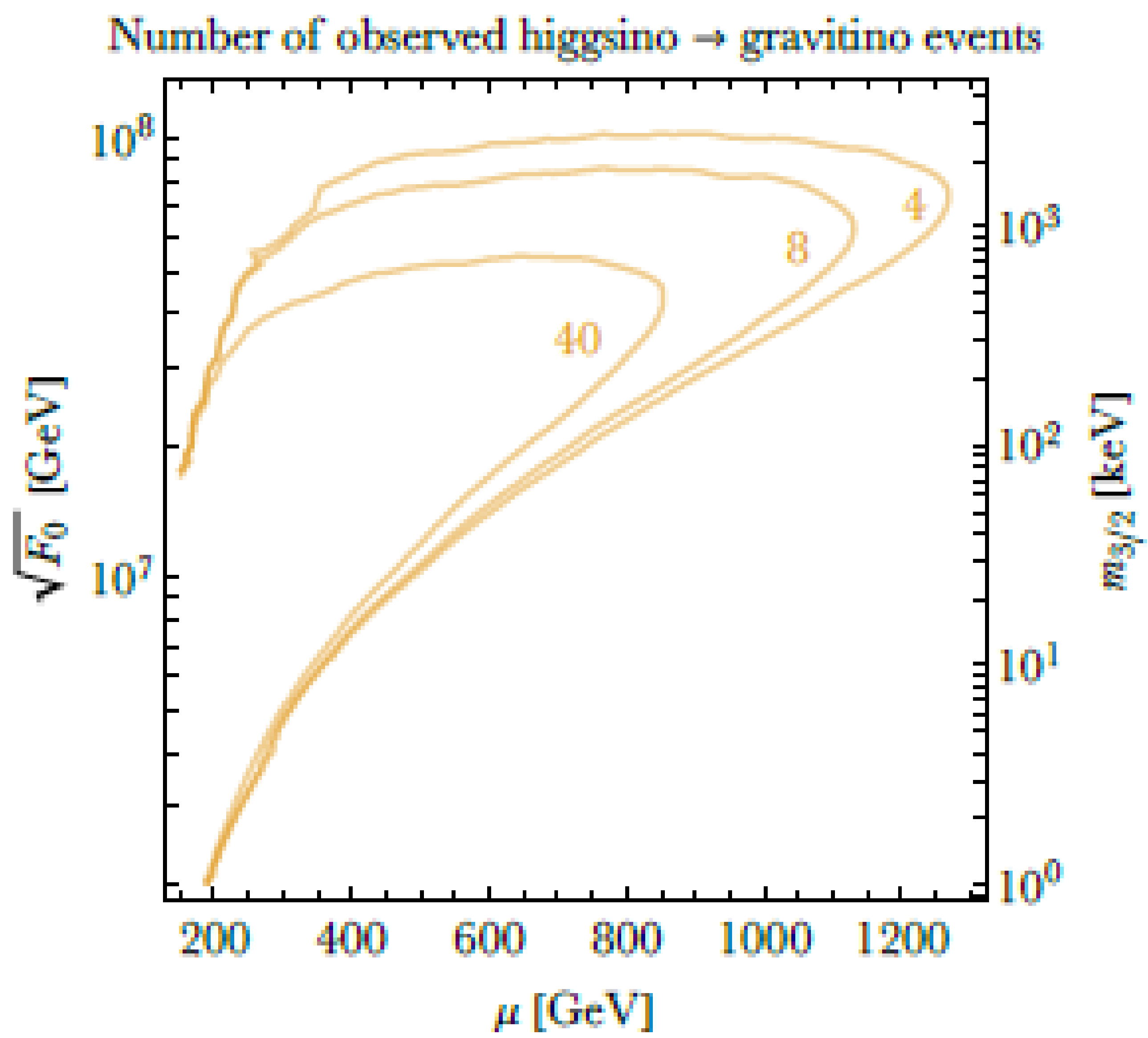
- Charged particles from neutrino scattering in decay volume
  - Simulated using GENIE
  - Neutrinos from HL-LHC collisions: using LHC minimum-bias samples, estimate << 1 “fake” DV/year
  - Atmospheric neutrinos: using flux measurements from Frejus experiment, estimate ~30 “fake” DV/year, reduced to < 1 with cuts

LLP Sensitivity: TeV-Scale

Any LLP production process with σ > fb can give signal.

e.g. meta-stable Higgsinos

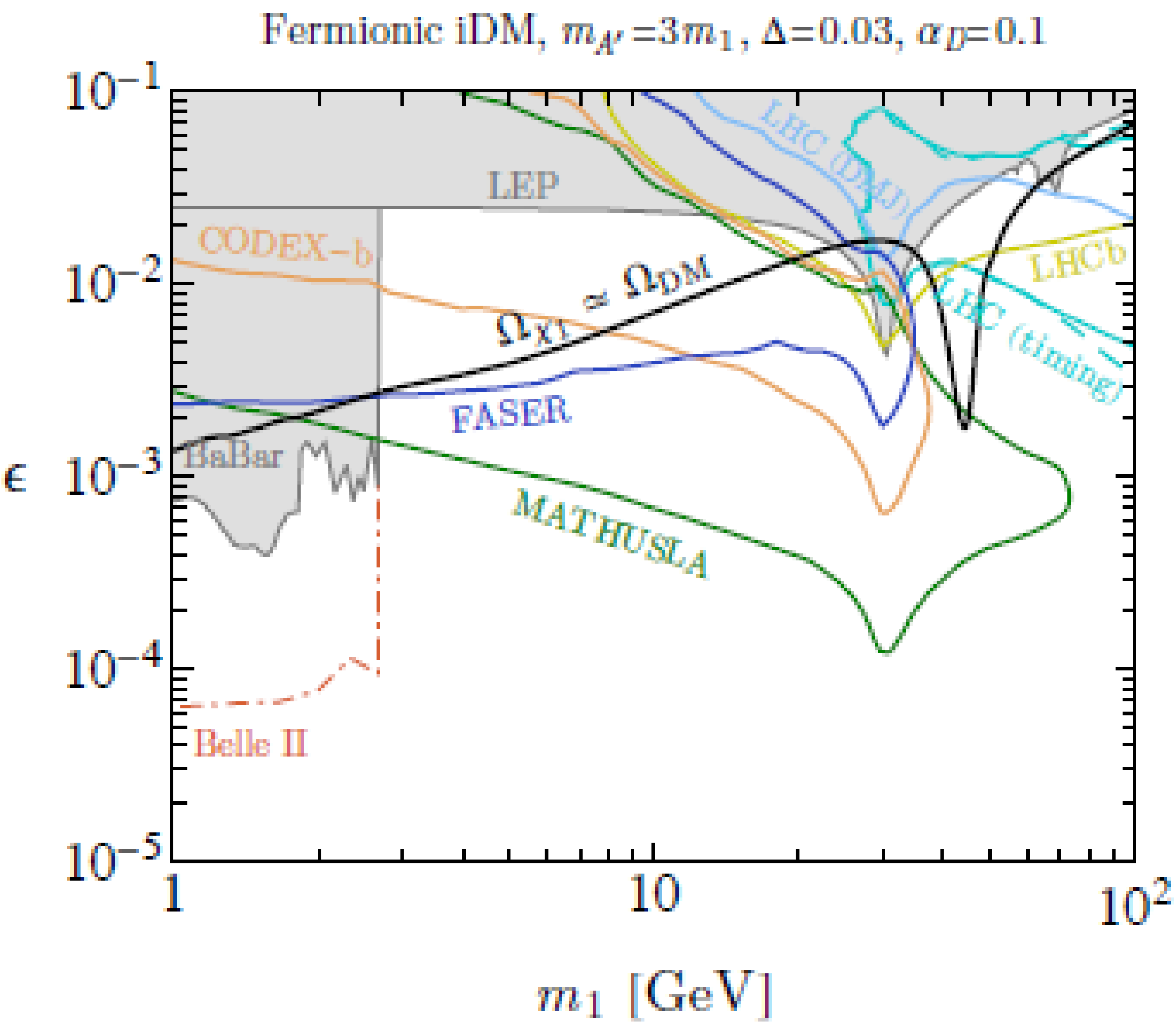


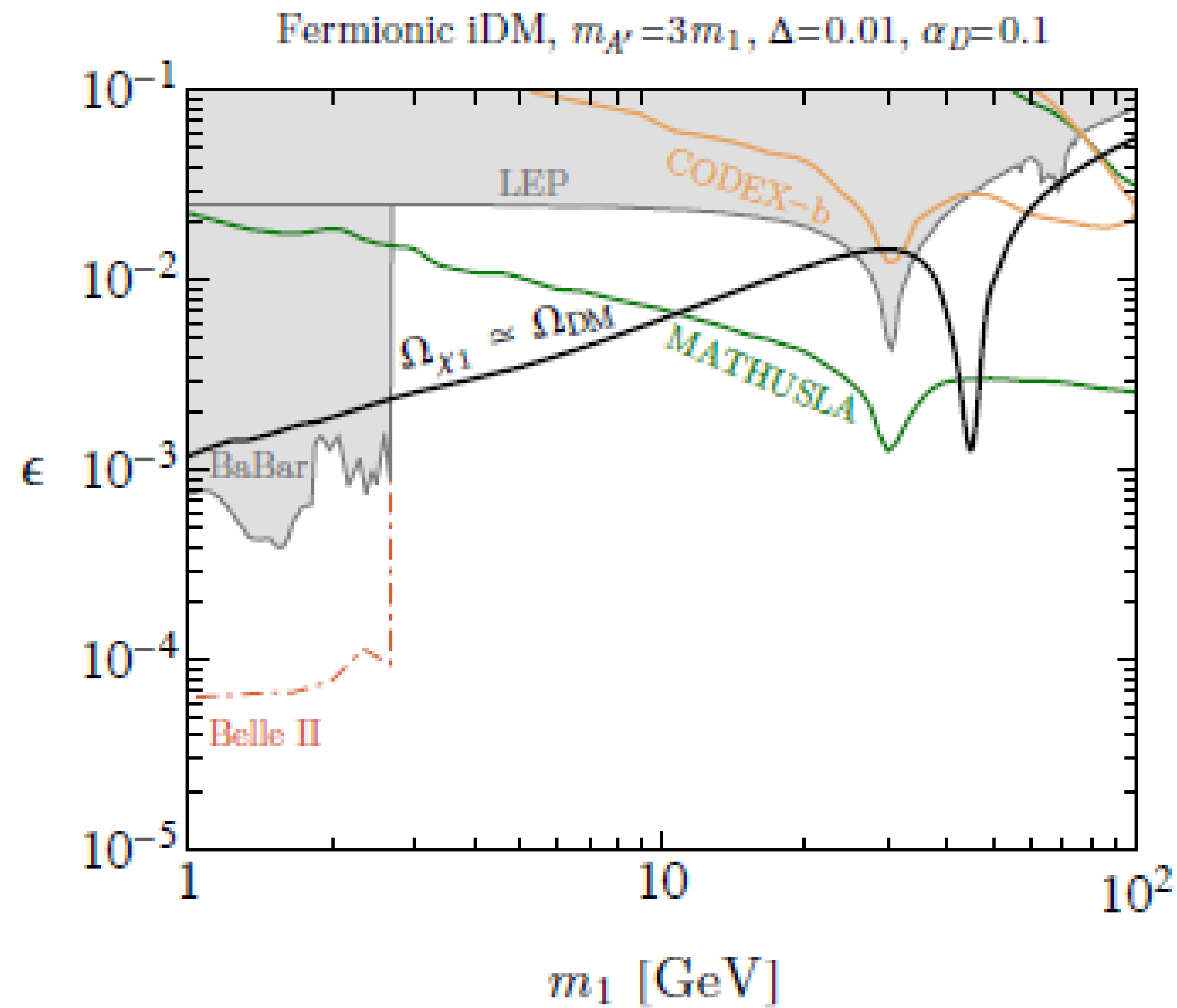


LLP Sensitivity: DM

Scenarios where LLP → DM + SM decay is the only way to see the DM

e.g. Inelastic Dark Matter: BSM mass eigenstates χ_1 (DM) and χ_2 (LLP) with mass splitting Δ, dark photon A' with mixing ϵ with SM photon





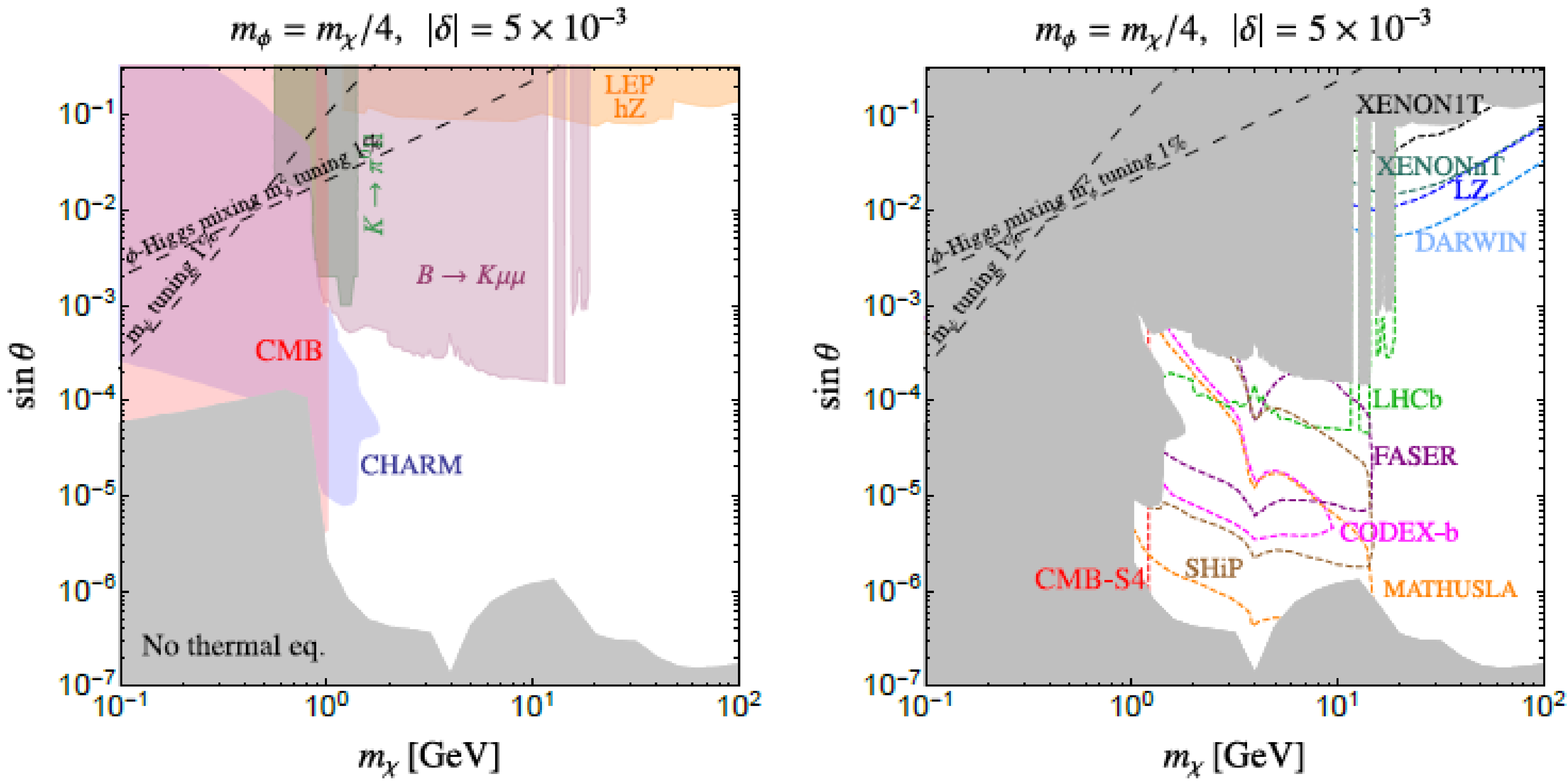
Black curve: thermal o-annihilations $\chi_2\chi_1 \to A' \to f\bar{f}$ yield observed DM relic density

LLP Sensitivity: DM

Scenarios where DM model requires existence of LLP, but LLP signature does not involve the DM particle directly

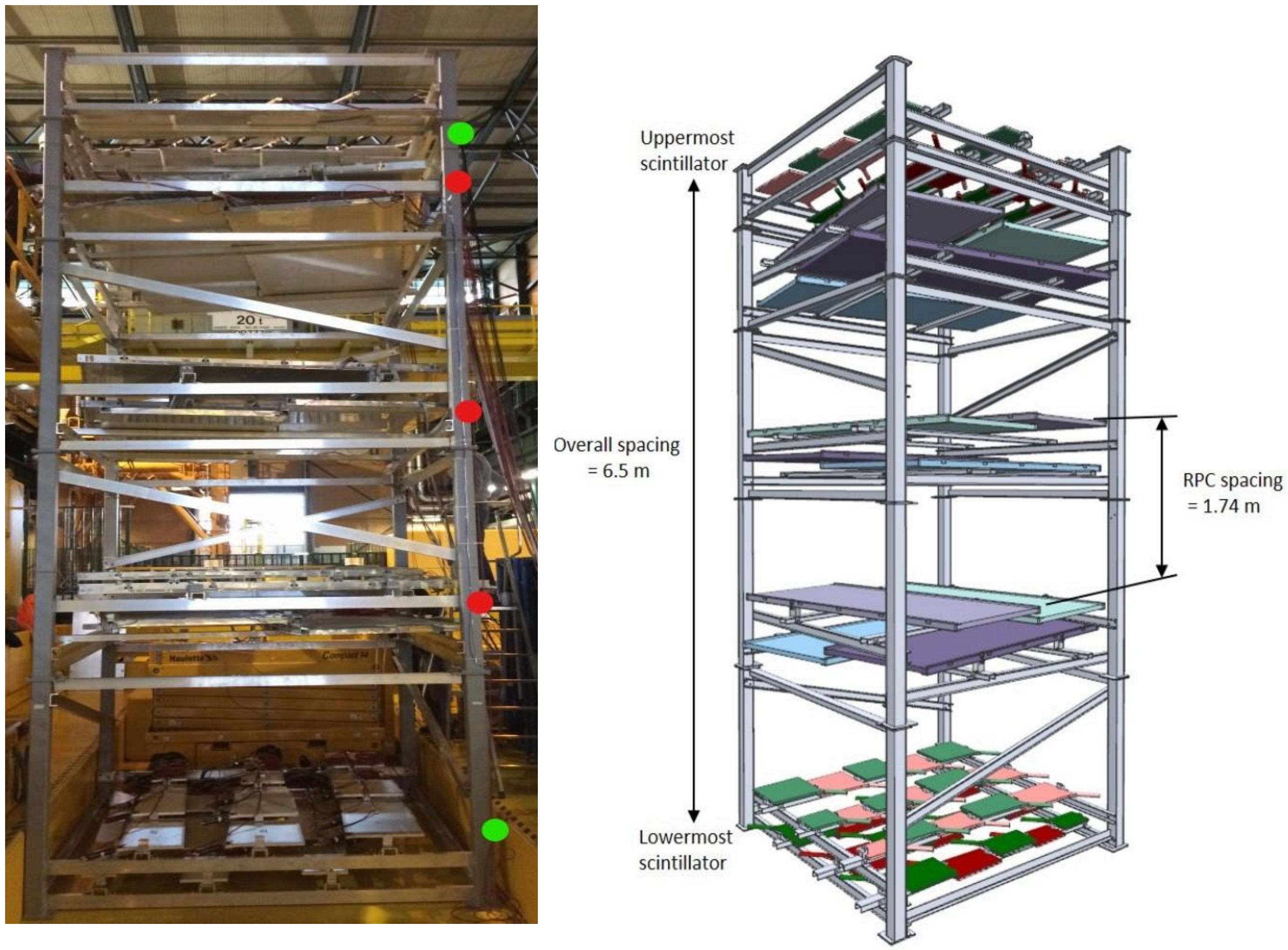
e.g. Co-Annihilating DM: BSM χ and χ_2 with mass splitting δ,

$\chi\,\chi_2 \rightarrow \phi\phi$ where scalar ϕ has mixing angle θ with SM Higgs

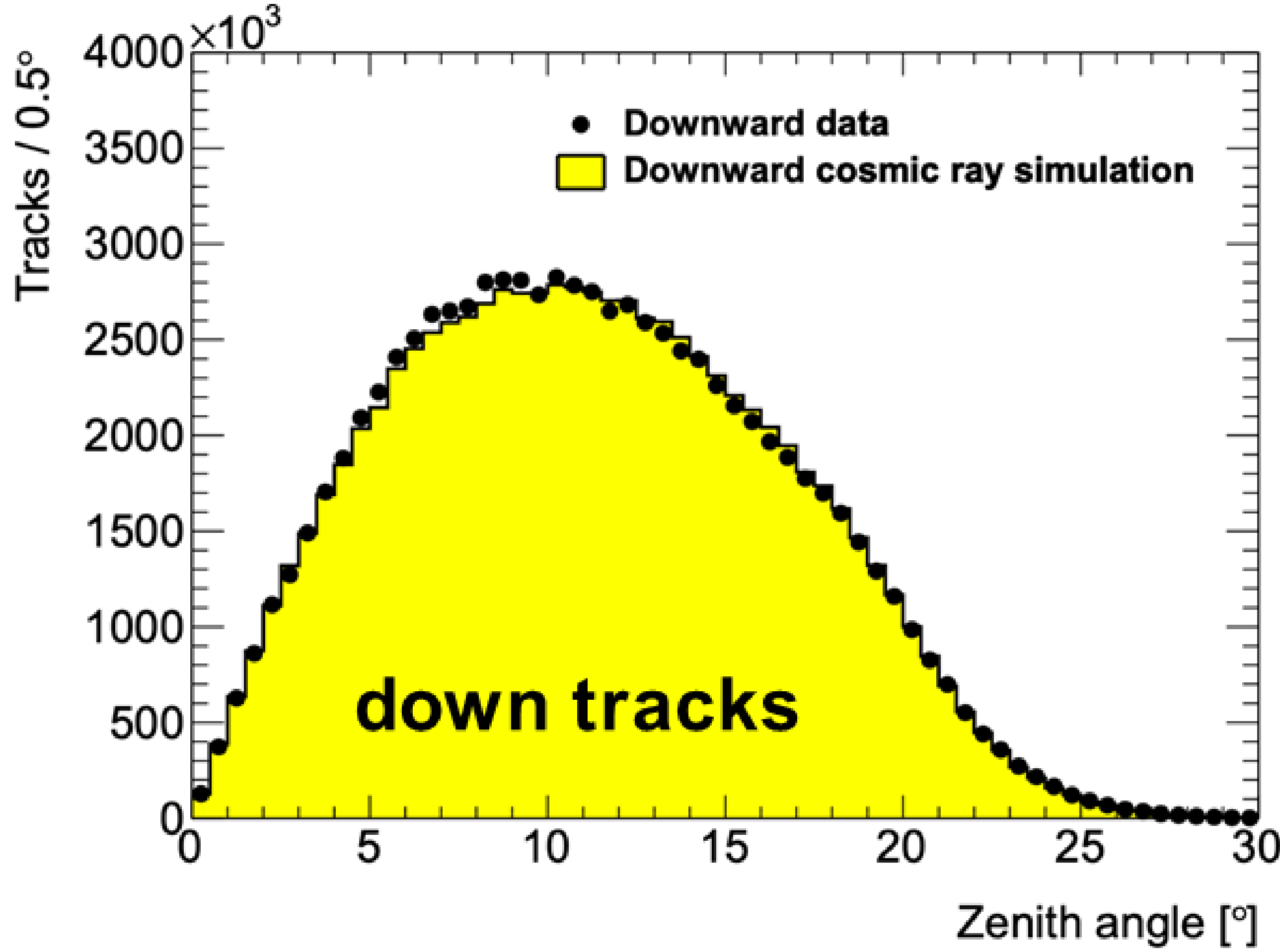


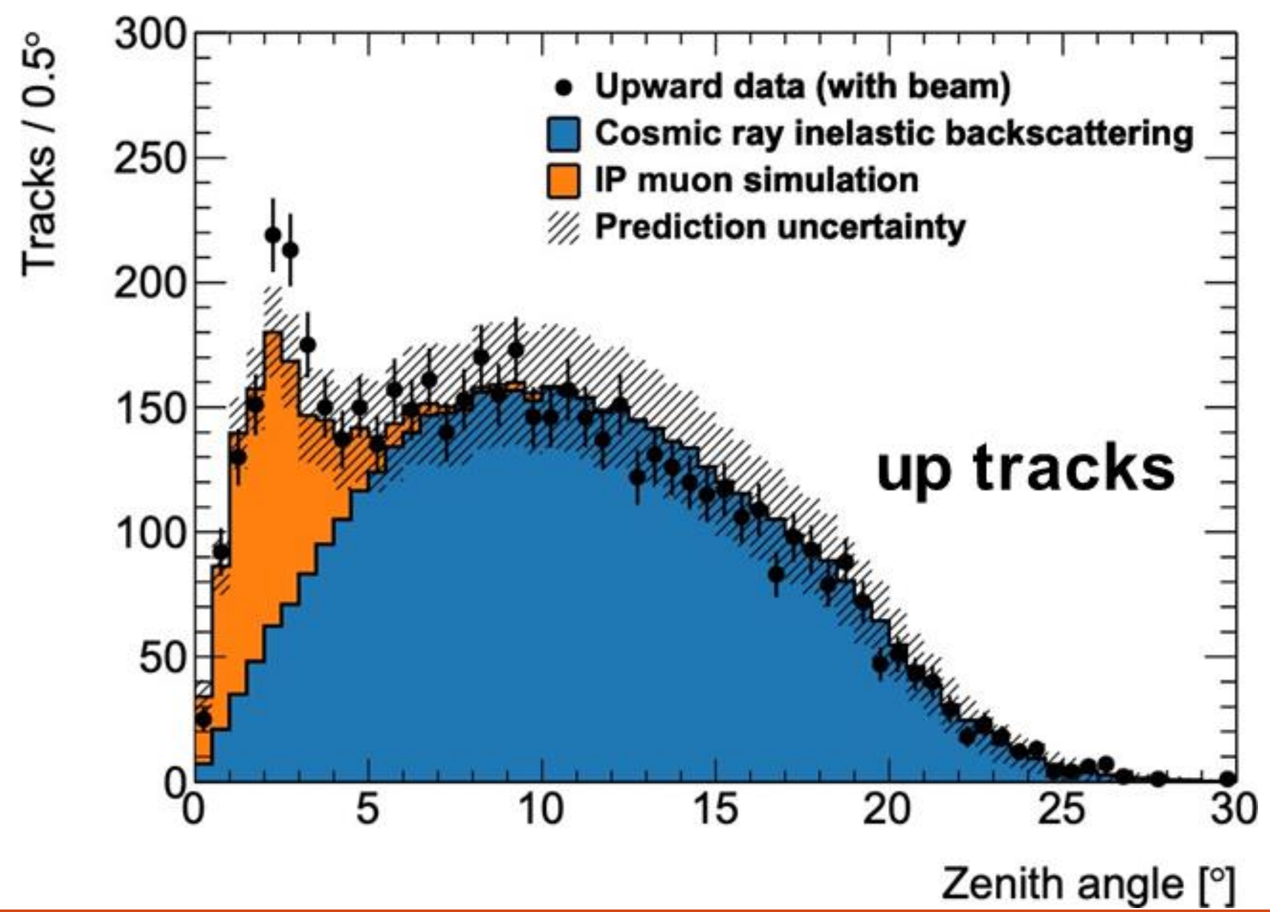
MATHUSLA Test Stand

Operated above ATLAS in 2018



Downward cosmic rays, upward LHC muons and upward CR backscatter well described by simulations

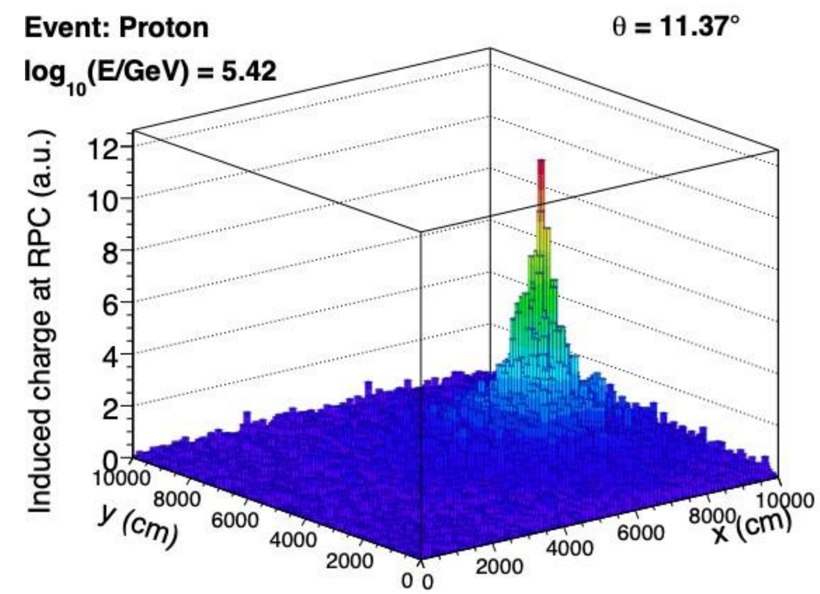




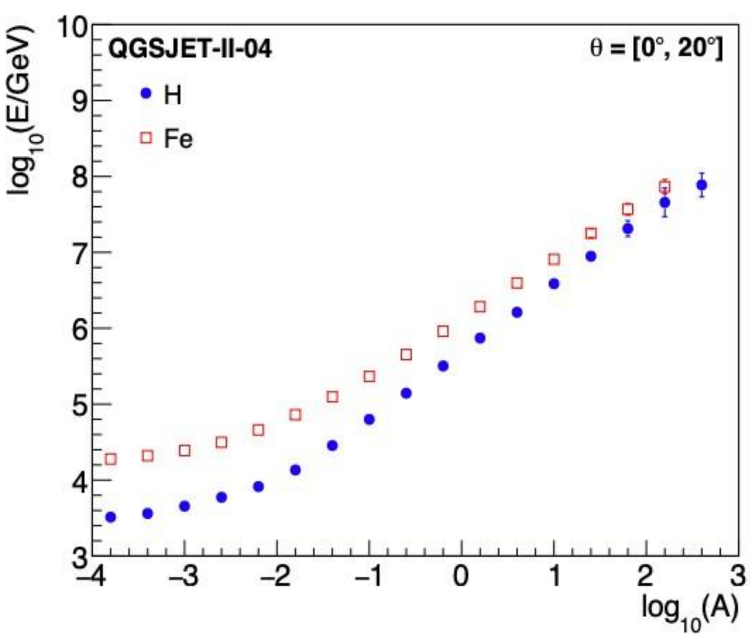
MATHUSLA as a Cosmic Ray Telescope

CR physics reach would be greatly enhanced by adding an analog RPC layer, due to scintillator saturation effects

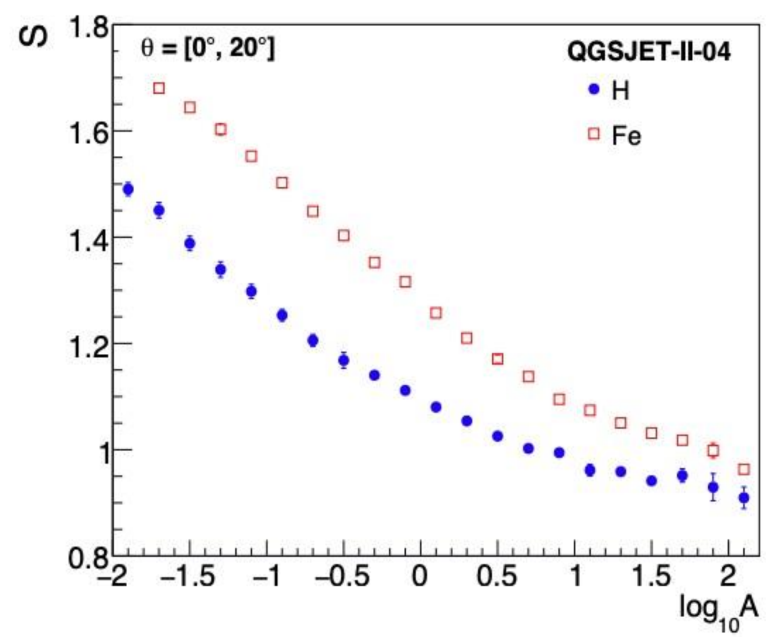
Charge density at the RPC



Amplitude of lateral distribution (LD)



Shower age (slope of LD) vs amplitude



- In region of maximum efficiency linear dependence of logE with logA.

—> **It could provide energy scale**

- Shower age shows sensitivity to primary composition.

—> **Useful for composition studies**

- RPC allows to **extend CR** energy and composition **studies above E = 10^{15} eV.**

Lateral charge density at RPC