Searches for Ultra Long-Lived Particles with

MATHUSLA

IPP 50TH ANNIVERSARY SYMPOSIUM

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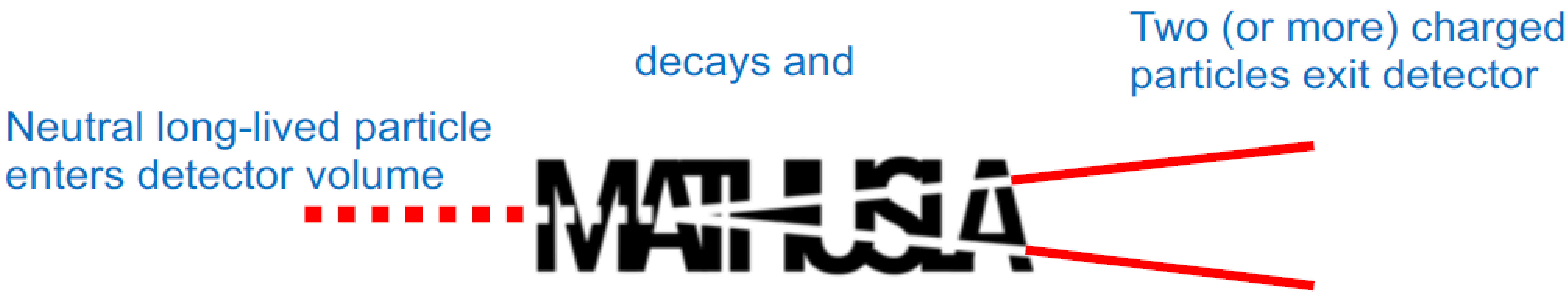
Outline

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
  - Trackers
  - DAQ
  - Vertex reconstruction

Basic Concept



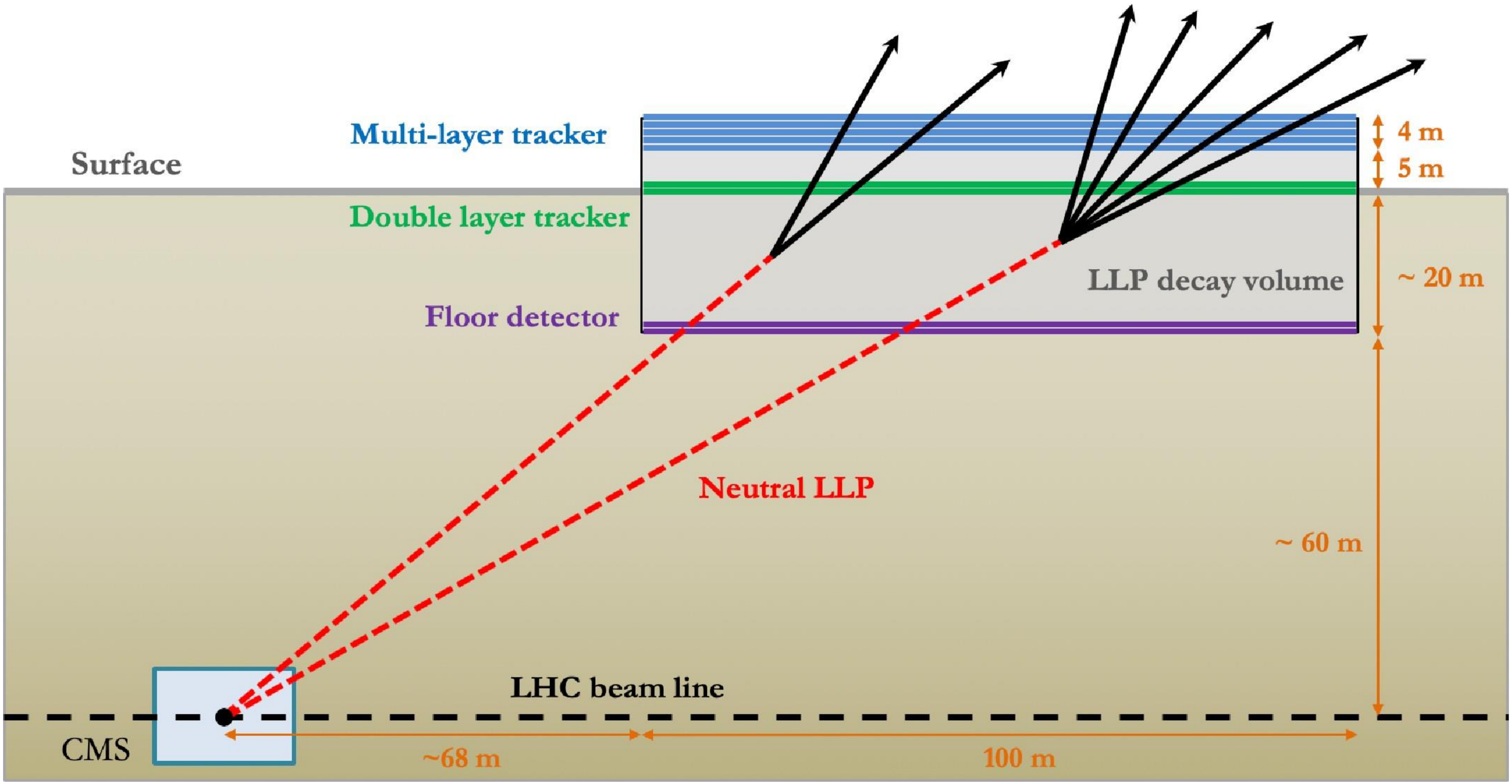
MAssive **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** P**A**rticles

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

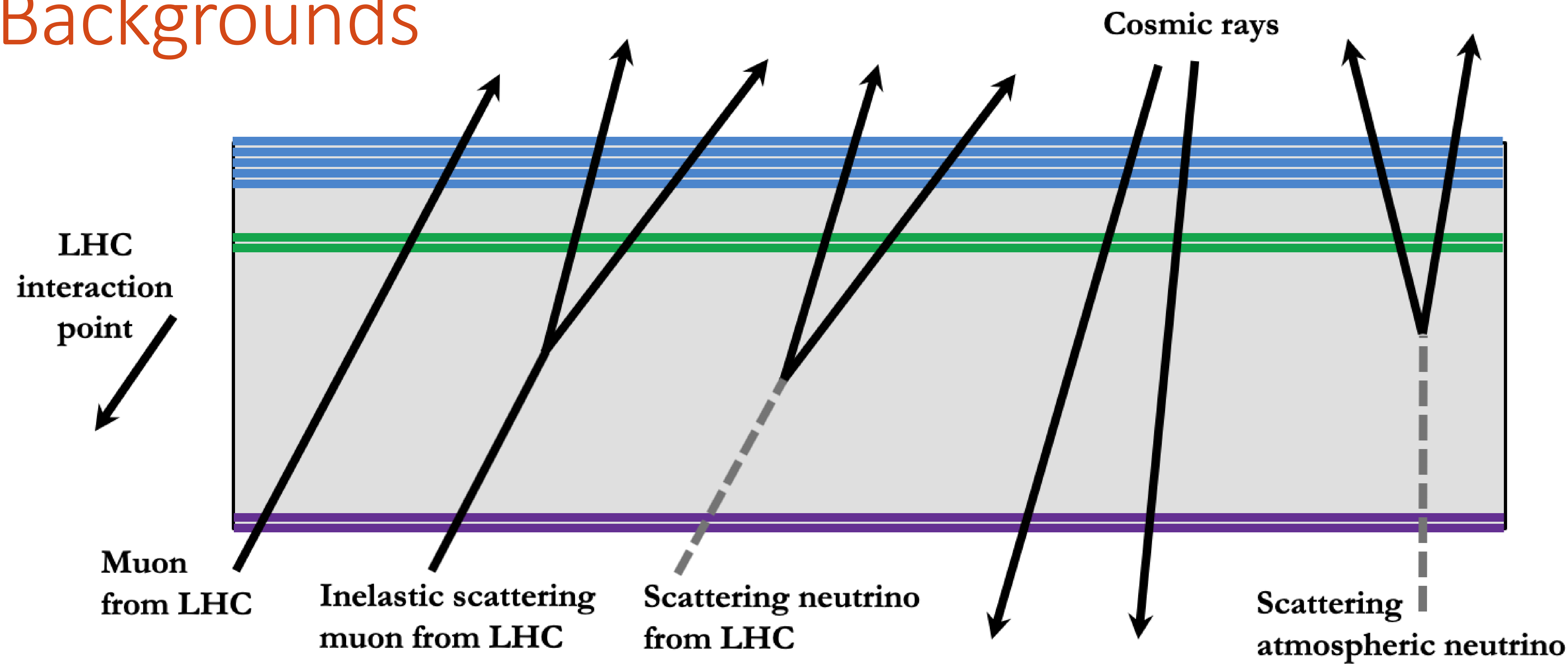


NOT TO SCALE

~100m x 100m x 25m decay volume

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

Backgrounds

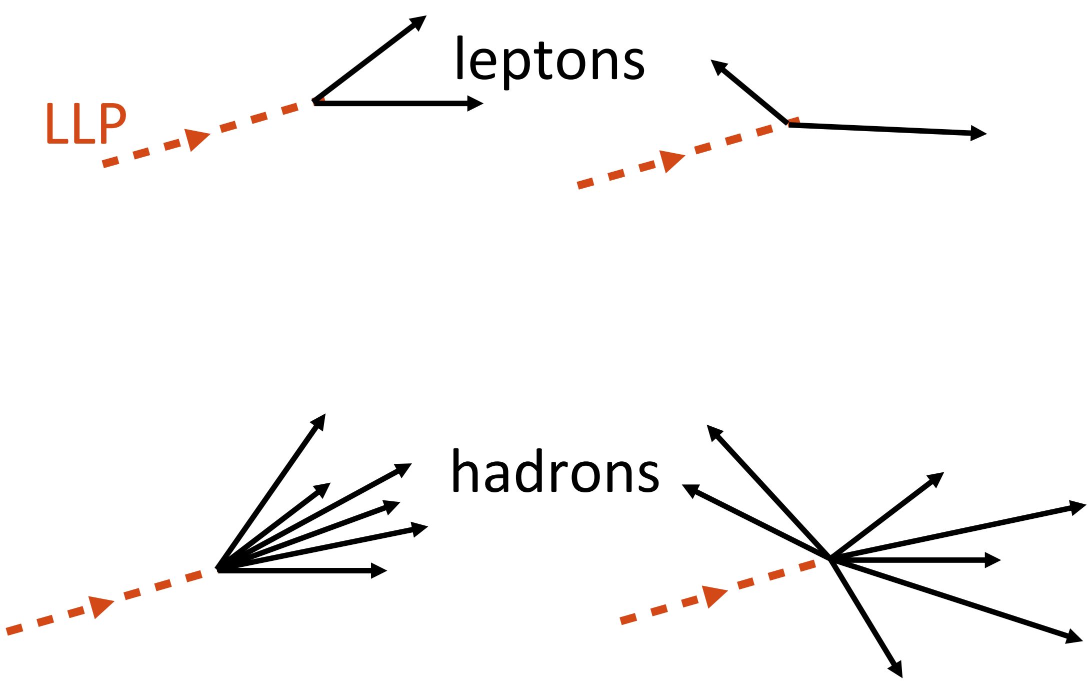


LLP displaced vertex (DV) signal has to satisfy many stringent geometrical and timing requirements (“4D vertexing” with cm/ns precision)

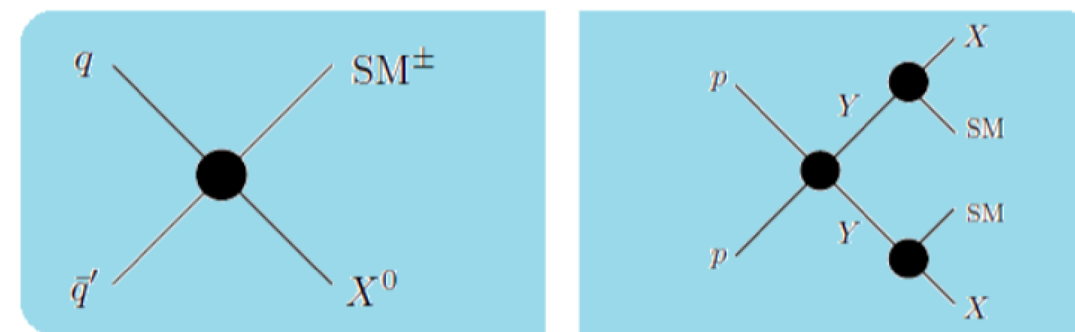
These requirements, plus a few extra geometry & timing cuts, provide “near-zero background” (< 1 event per year) for neutral LLP decays!

Identifying LLPs

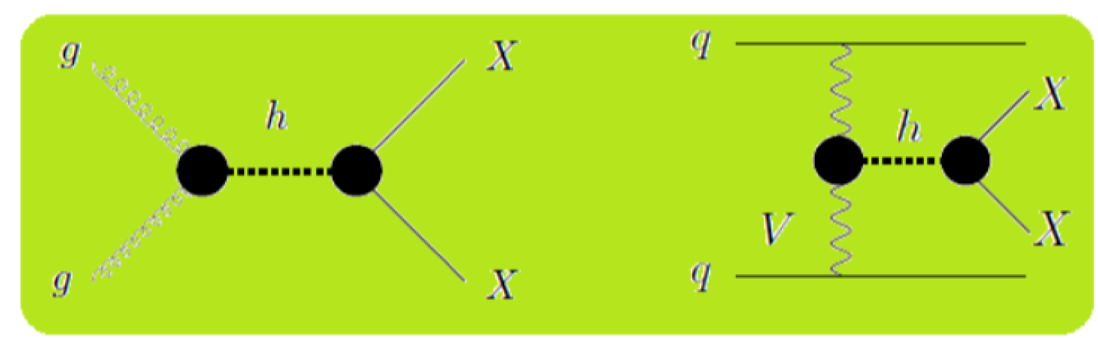
MATHUSLA can't measure particle momentum or energy, but:
track geometry → measure of LLP boost event-by-event



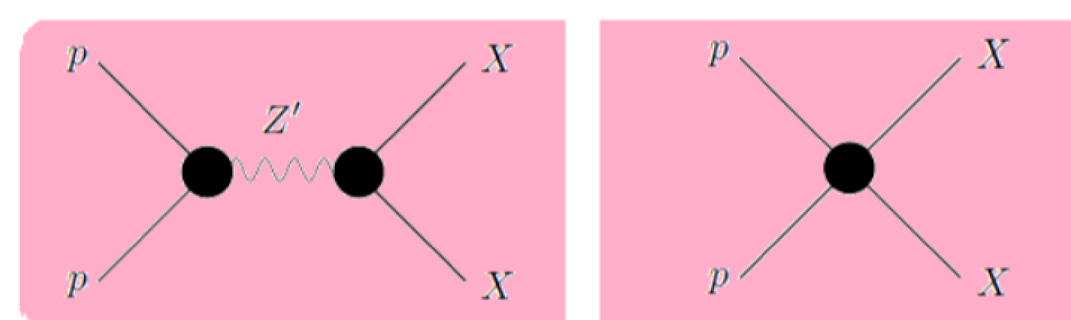
Incorporate MATHUSLA into CMS L1 Trigger
Correlate event info off-line → determine LLP production mode



Charged Current (e.g. W')   Heavy Parent



Higgs: Gluon Fusion   Higgs: Vector Boson Fusion

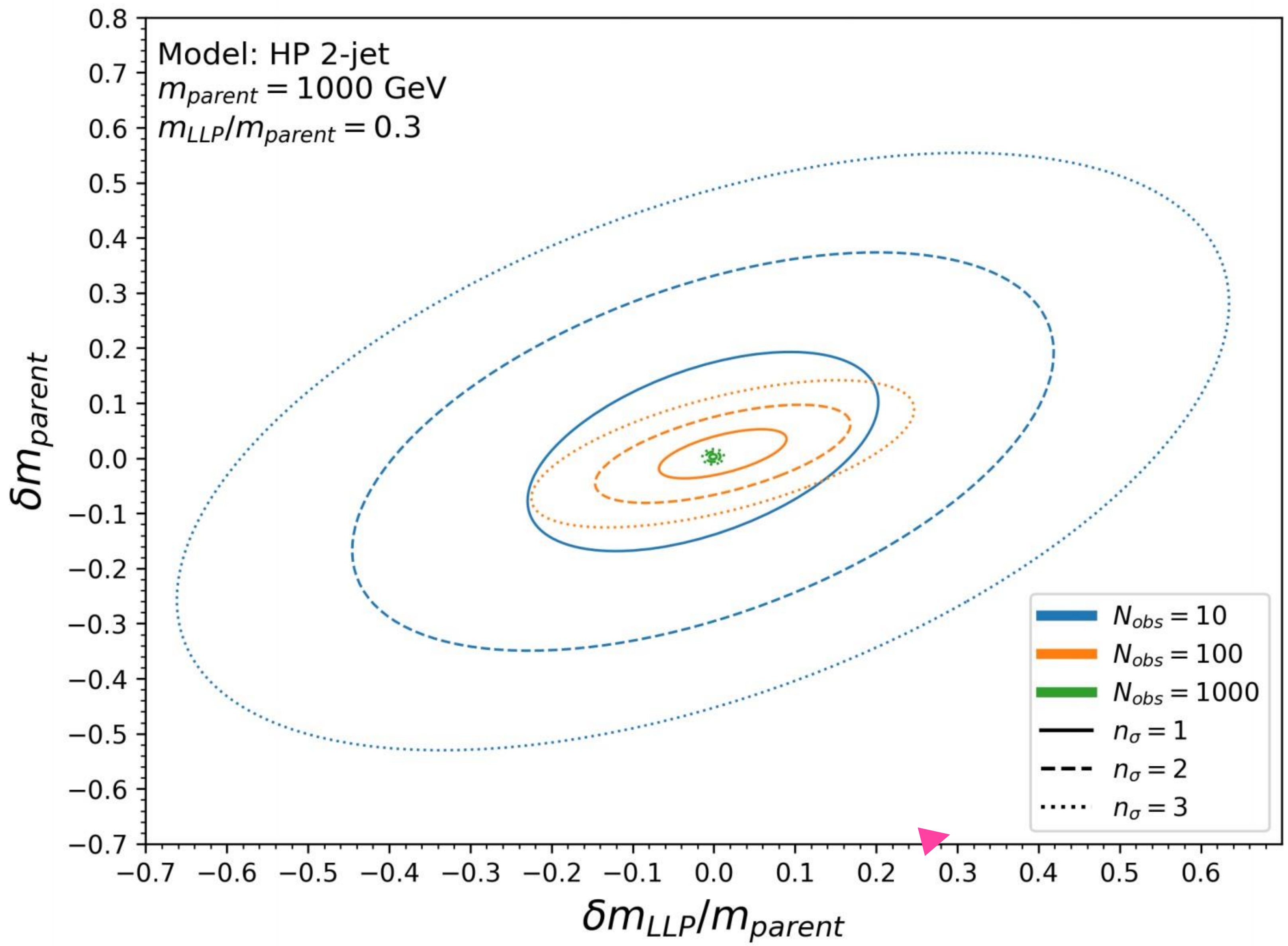


Heavy Resonance   Direct Pair Production

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!



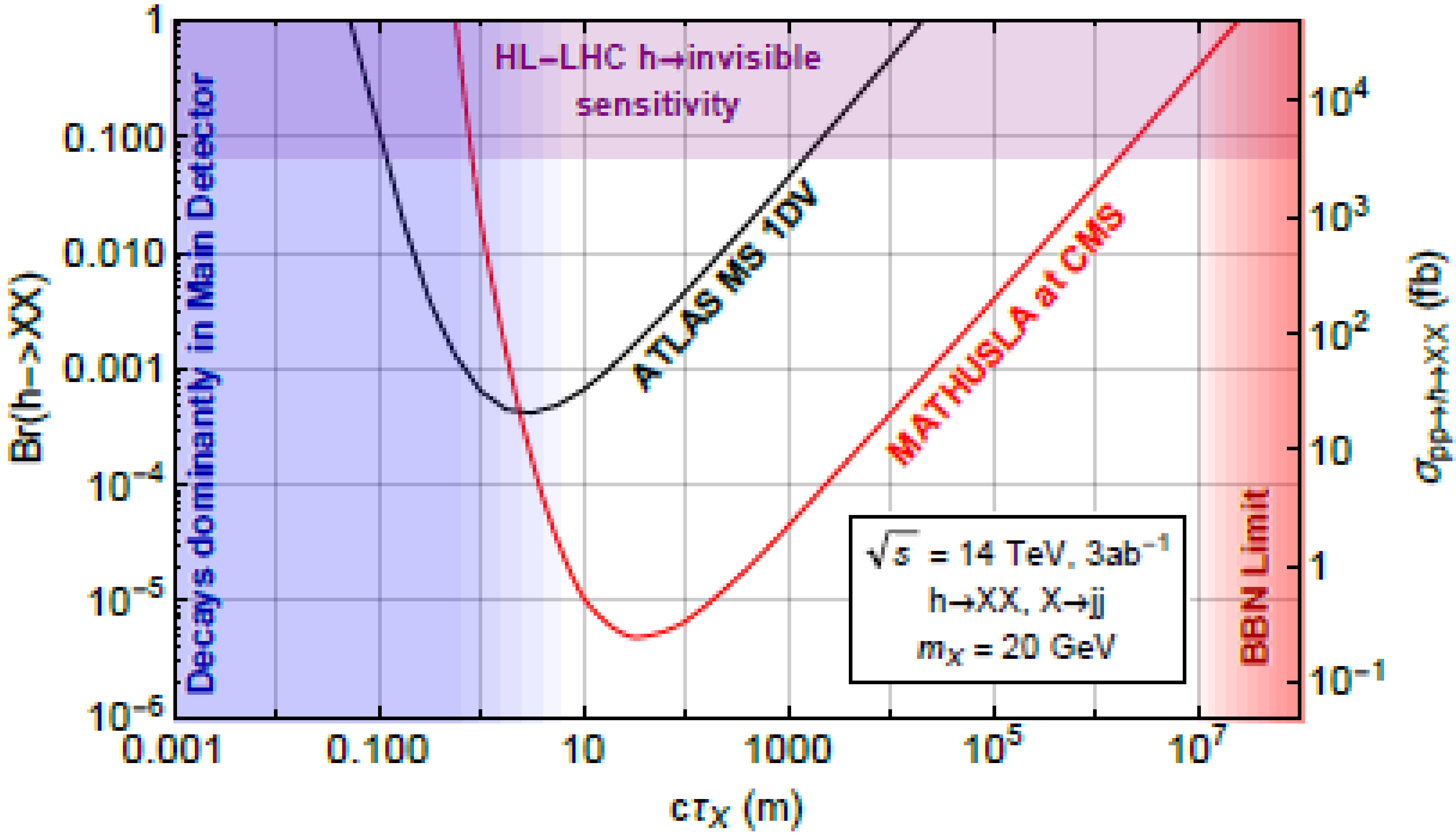
LLP Sensitivity

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

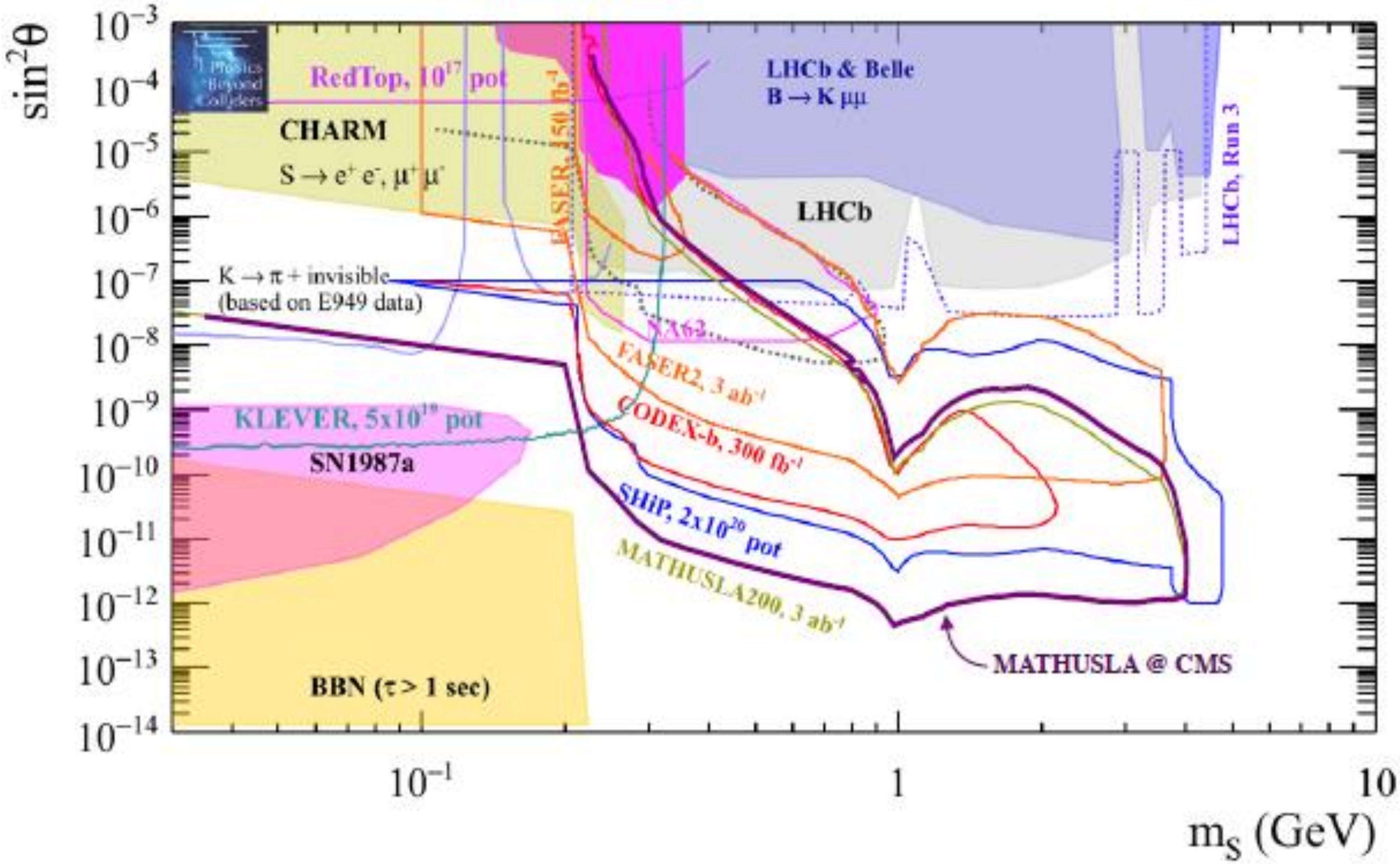


Any LLP production process with σ > fb can give signal in MATHUSLA

LLP Sensitivity: GeV-Scale

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

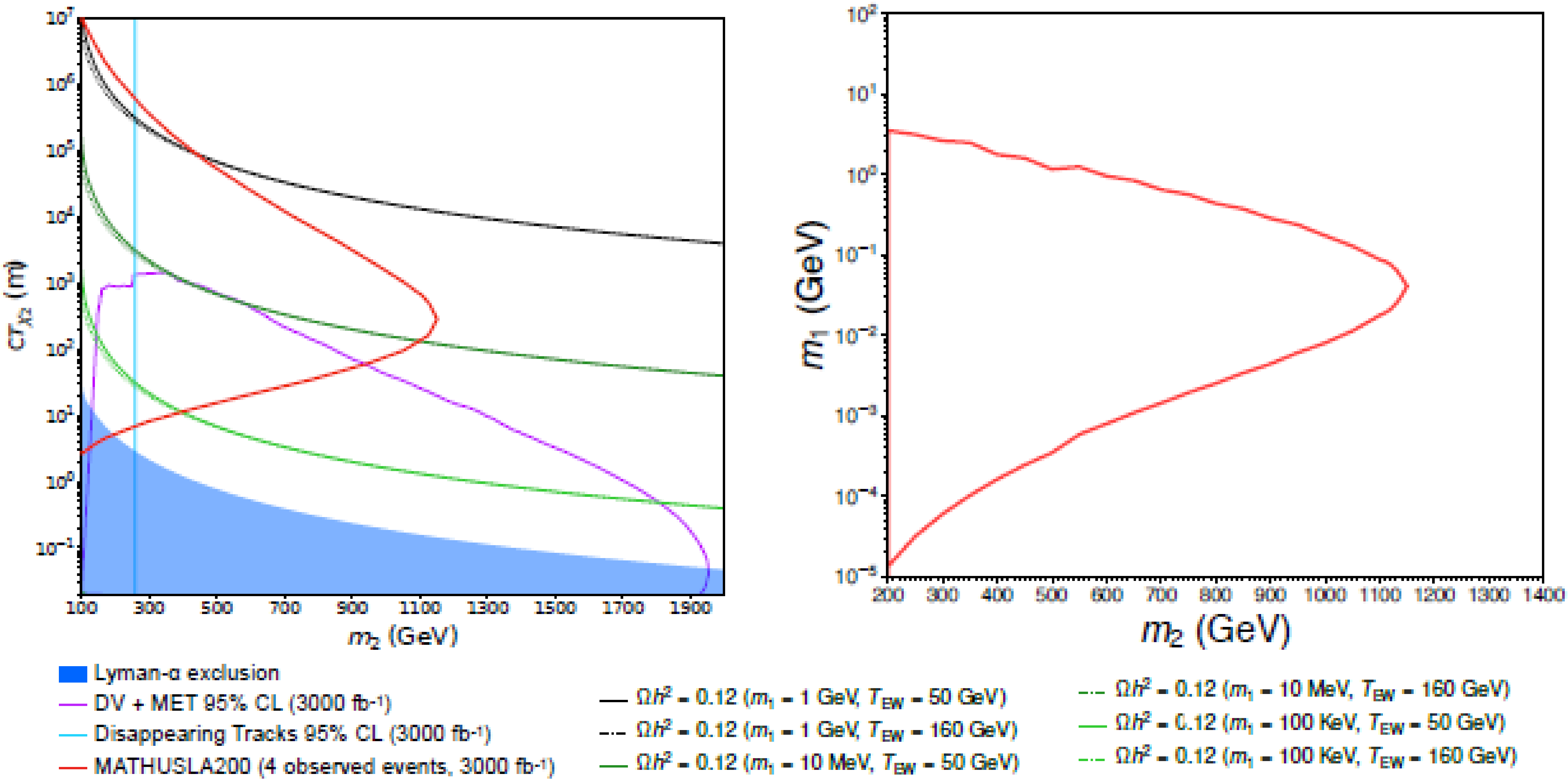
e.g. singlet dark scalar S, mixing angle θ with SM Higgs



LLP Sensitivity: DM

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

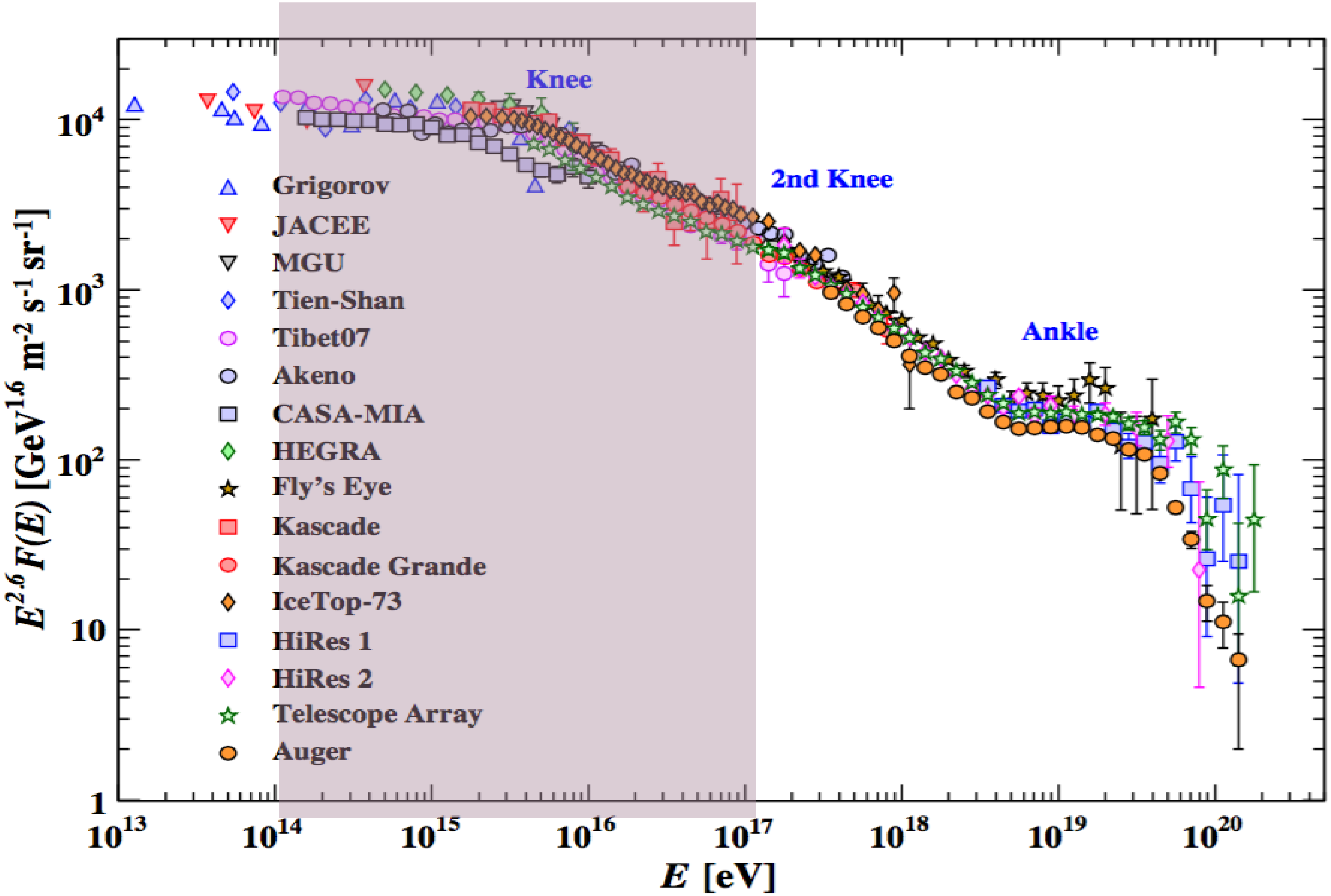
e.g. Freeze-In Dark Matter: BSM mass eigenstates χ_1 (DM) and χ_2 (LLP), where χ_2 was in thermal equilibrium with primordial plasma



Cosmic Ray Telescope

MATHUSLA as a Cosmic Ray Telescope

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



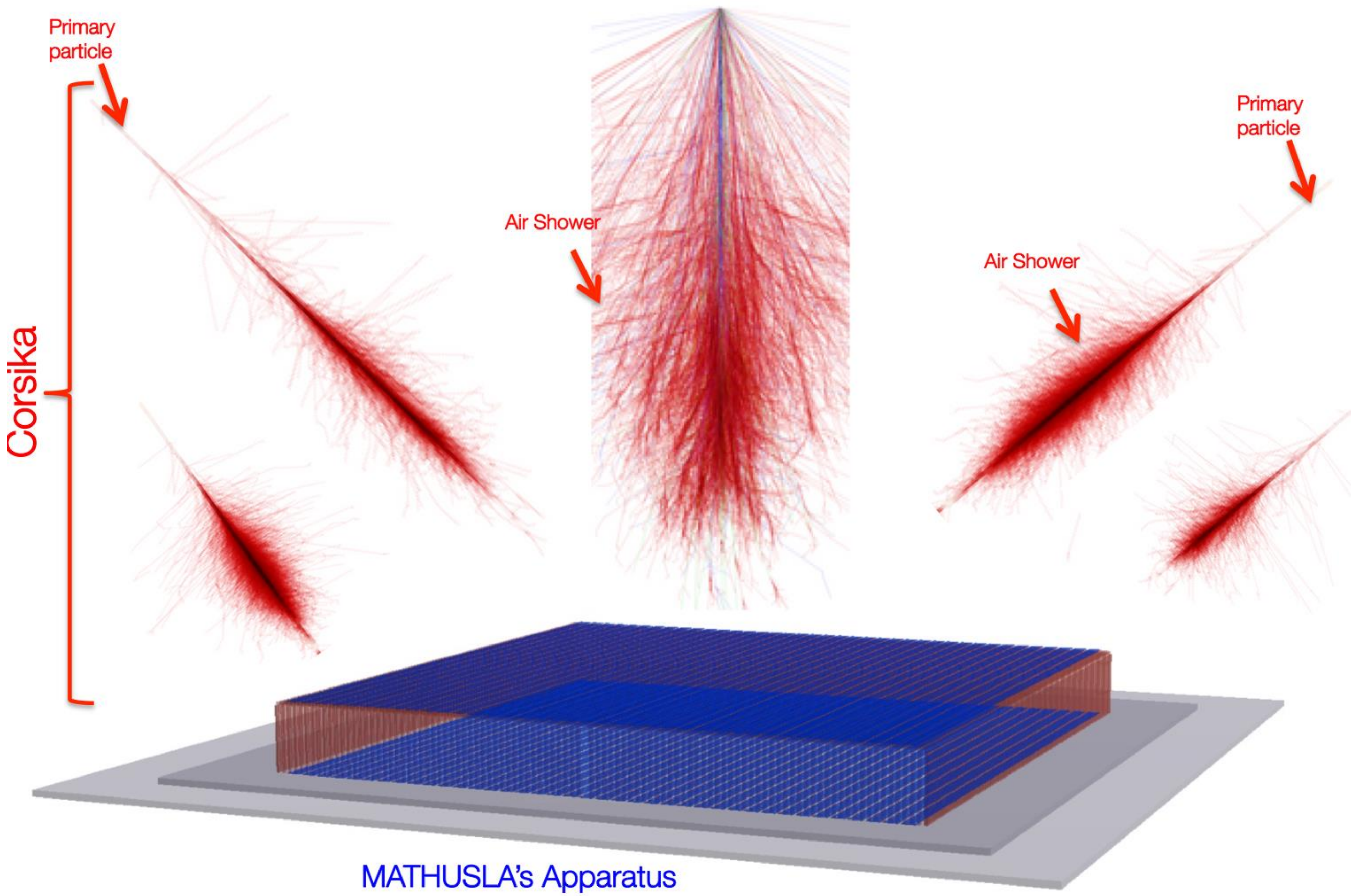
CR physics reach would be greatly enhanced by adding an analog RPC layer, due to scintillator saturation effects

Whitepaper describing potential contributions to CR physics nearly completed, led by the Mexico MATHUSLA team

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



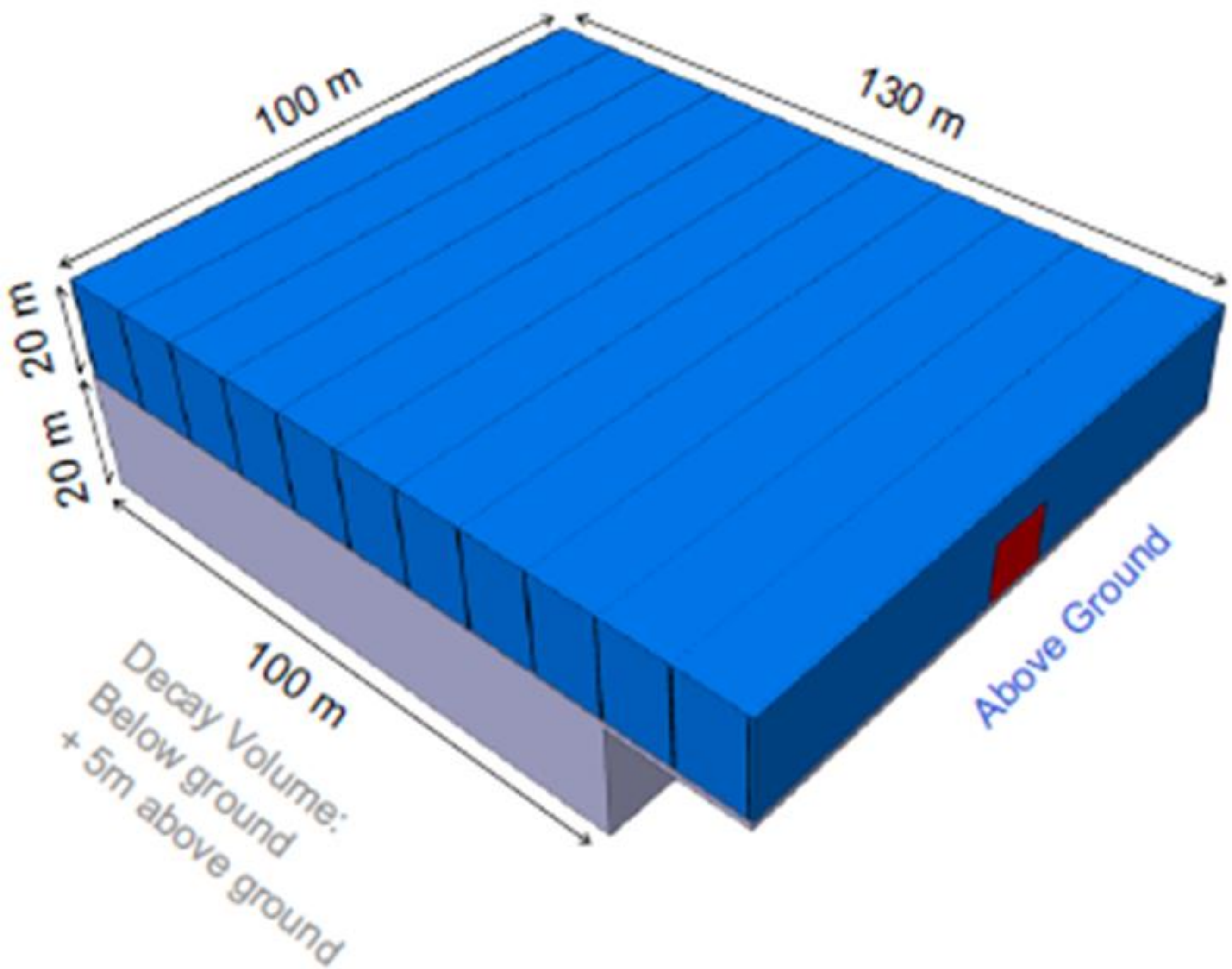
MC simulations using CORSIKA (https://www.iap.kit.edu/corsika/)

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

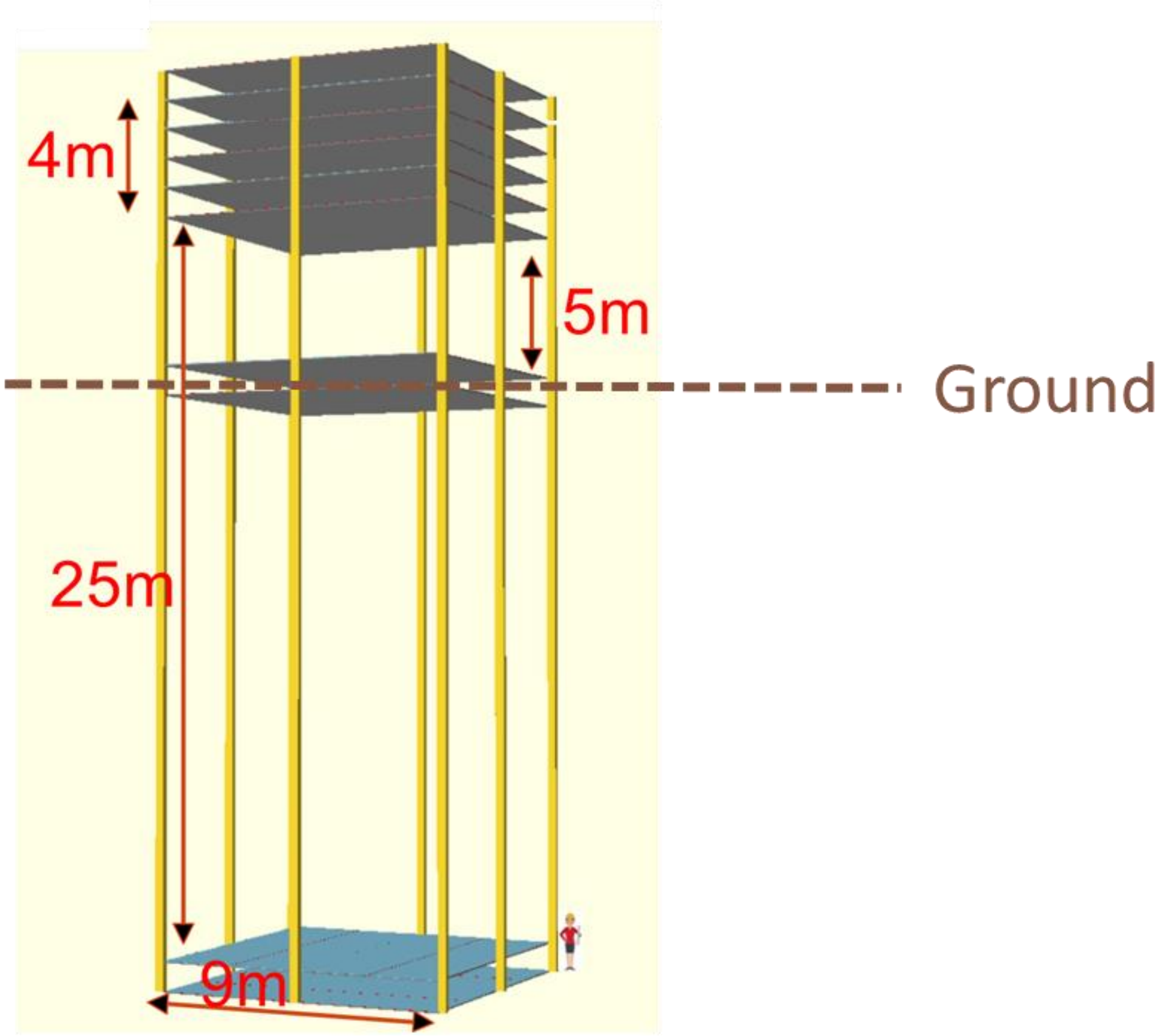


Detector Design

6-layer tracking/timing detectors, 80 cm inter-layer separation

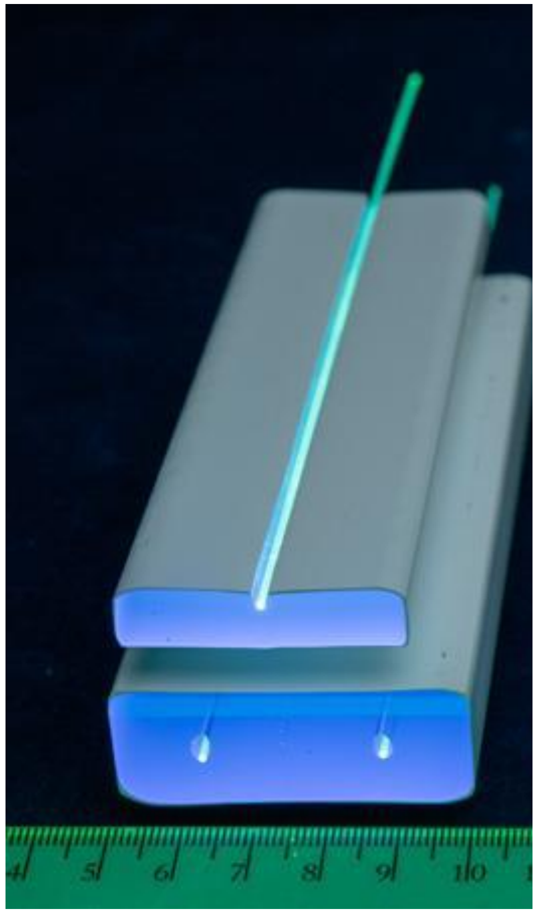
Additional tracking/timing double layer at ground level

Tracking/timing double layer floor detector



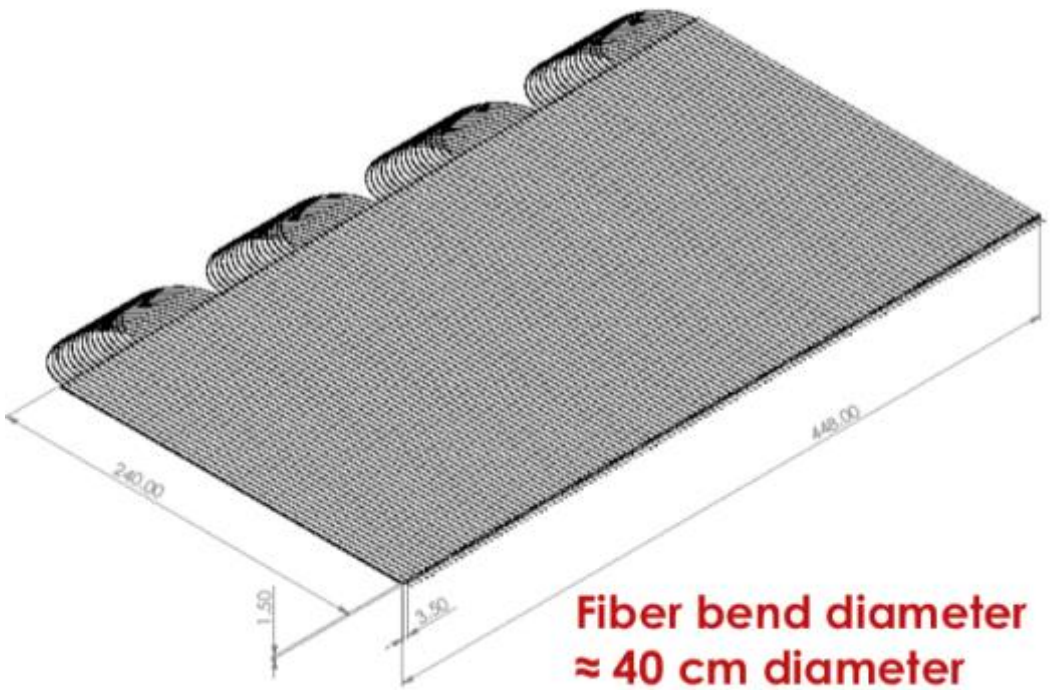
- Total ~ **25 m height for decay volume**
- Individual detector units each **9 x 9 x 30 m^3**

Trackers



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

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

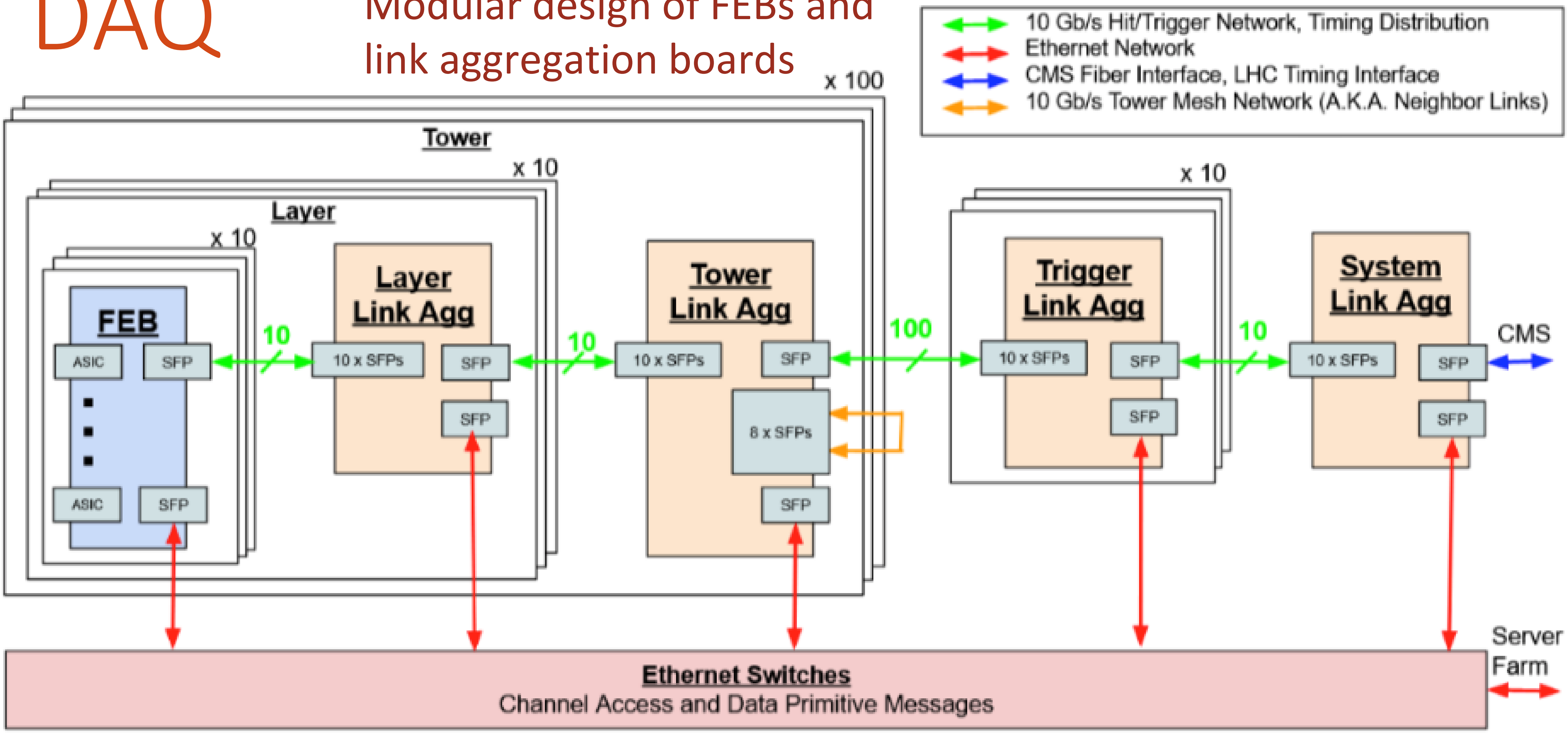


Considering readout at both ends of each scintillator bar, or looped fiber for readout at one end

- Transverse resolution depends on bar width: need ~cm precision
- Δt between two ends gives longitudinal resolution: need sub-ns precision

DAQ

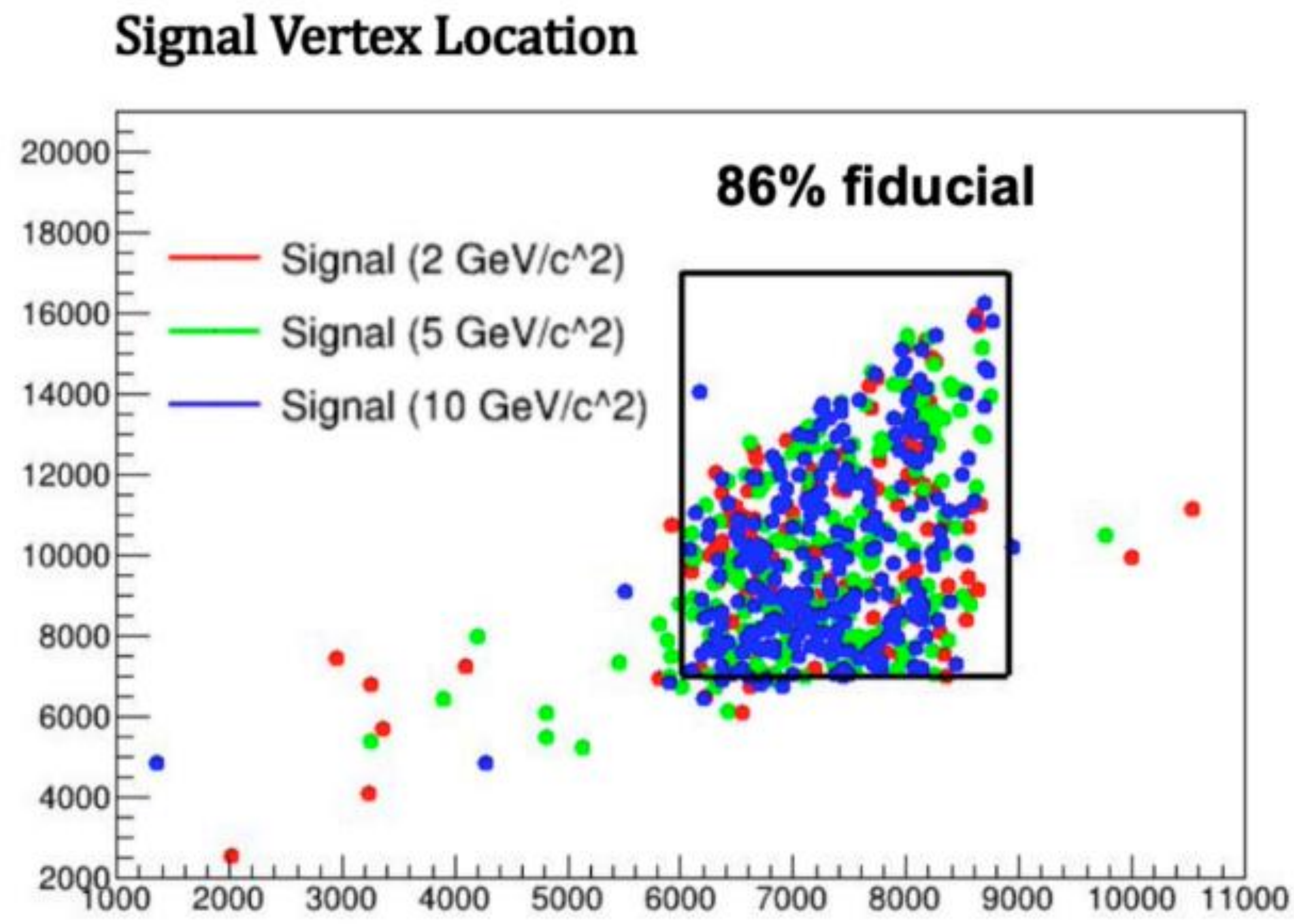
Modular design of FEBs and link aggregation boards



- **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**

Track & 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



The MATHUSLA Collaboration

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

Canadian MATHUSLA Team

Now NSERC funded!

- **Steven Robertson (McGill)**
- **Heather Russell (UVic)**
- **Miriam Diamond (UToronto)**
- **David Curtin (UToronto)**

- **HQP:**
  - **2 post-docs coming soon!**
  - **Several current & former MSc & undergrad students, and now recruiting more!**

Conclusions

- MATHUSLA is a planned external LLP detector for the HL-LHC that can probe deep into LLP parameter space in a variety of Beyond the Standard Model scenarios
  - Including many DM models
- Significant recent progress and ongoing efforts
  - DAQ design
  - Detector plane layout
  - Scintillator/fiber/ SiPM characterization
  - Simulations of rare backgrounds
  - Track & vertex reconstruction software
  - Cosmic ray studies – including physics case for addition of RPC layer
- Aiming to produce TDR by Fall 2022, followed by prototype module and full detector for HL-LHC
- New collaborators always welcome!

References

Alpigiani et al. Recent Progress and Next Steps for the MATHUSLA LLP Detector”. Proceedings of the US Community Study on the Future of Particle Physics (Snowmass), March 2022, arXiv:2203.08126.

John Paul Chou, David Curtin, and H.J. Lubatti. New detectors to explore the lifetime frontier. Physics Letters B, 767:29–36, Apr 2017, arXiv: 1606.06298.

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, arXiv:1806.07396.

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

Henry Lubatti et al. MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LHC, 2019, arXiv:1901.04040.

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

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.

M. Alidra et al. The MATHUSLA Test Stand. NIMA, 985:164661, 2021, arXiv:2005.02018.

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

Background Simulations

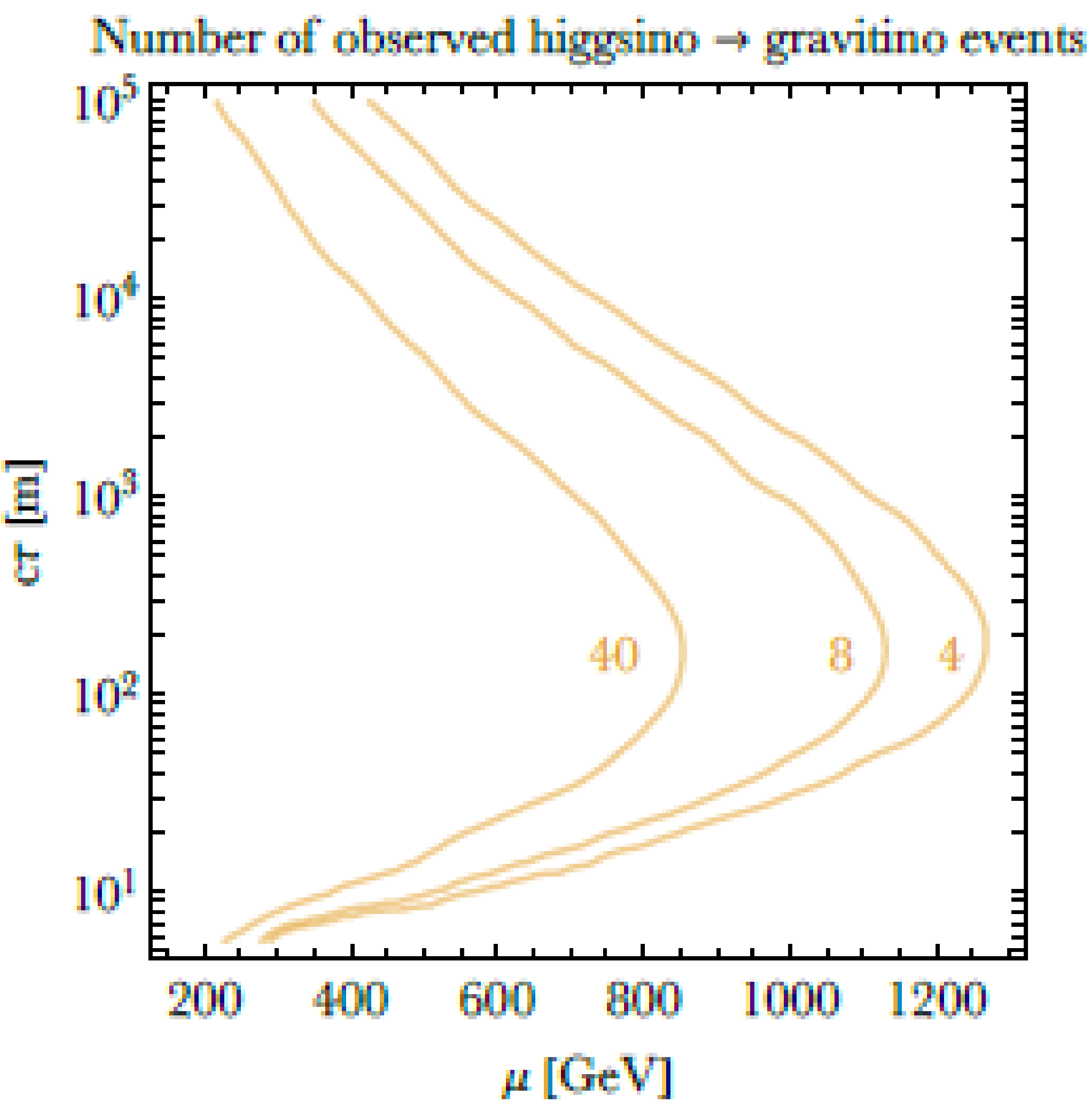
- Cavern, access shaft, CMS, rock, and detector all modeled in GEANT4
  - Rock model is from a geological survey

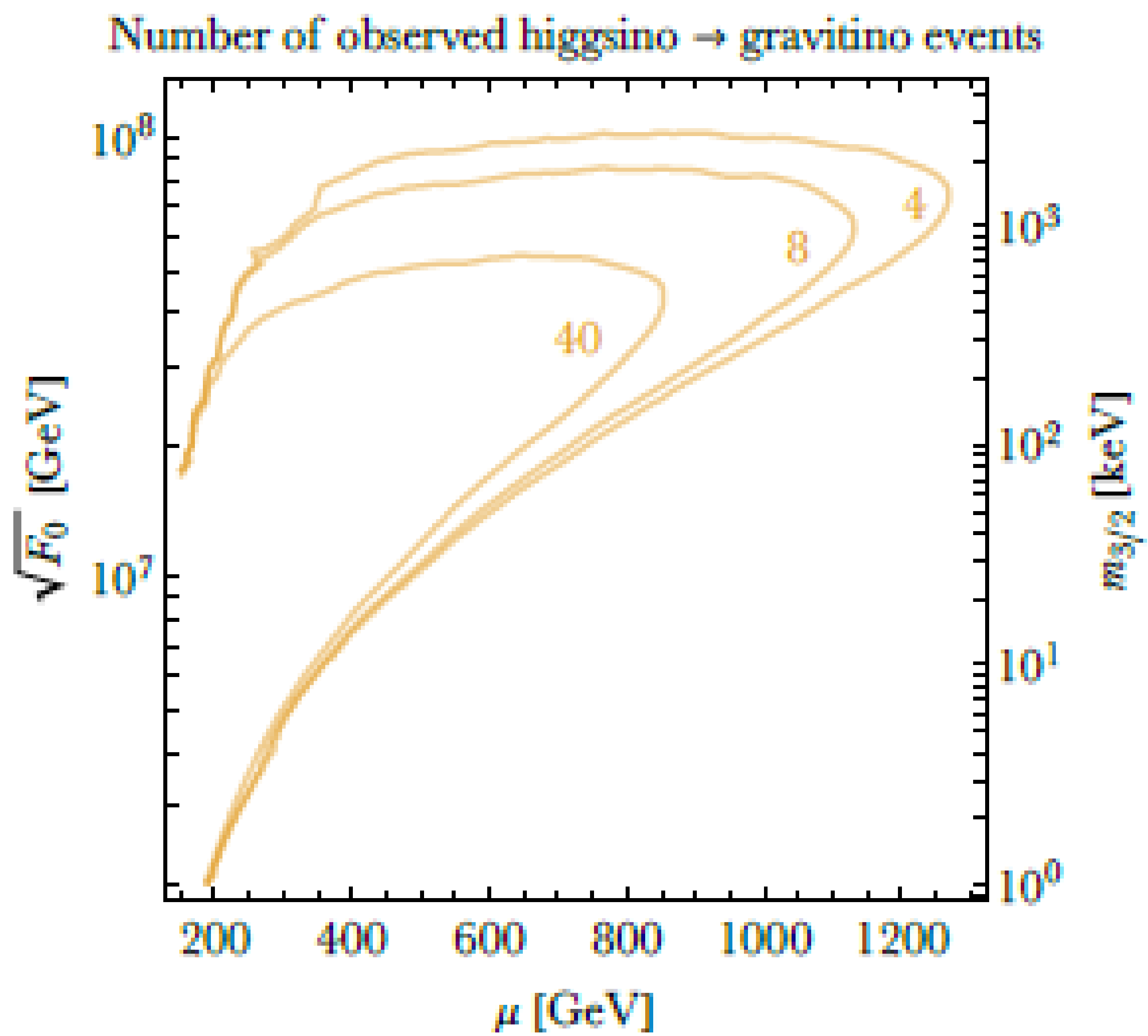
- Backgrounds under detailed study:
  - Upward-going muons from collisions (Pythia8)
  - Backscatter (to upwards going V^0) from downward-going cosmic rays (Parma)
  - Neutrino interactions (Genie3)
- Backgrounds rejected with a high-coverage floor veto + topological constraints on the vertices

LLP Sensitivity: TeV-Scale

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

e.g. meta-stable Higgsinos

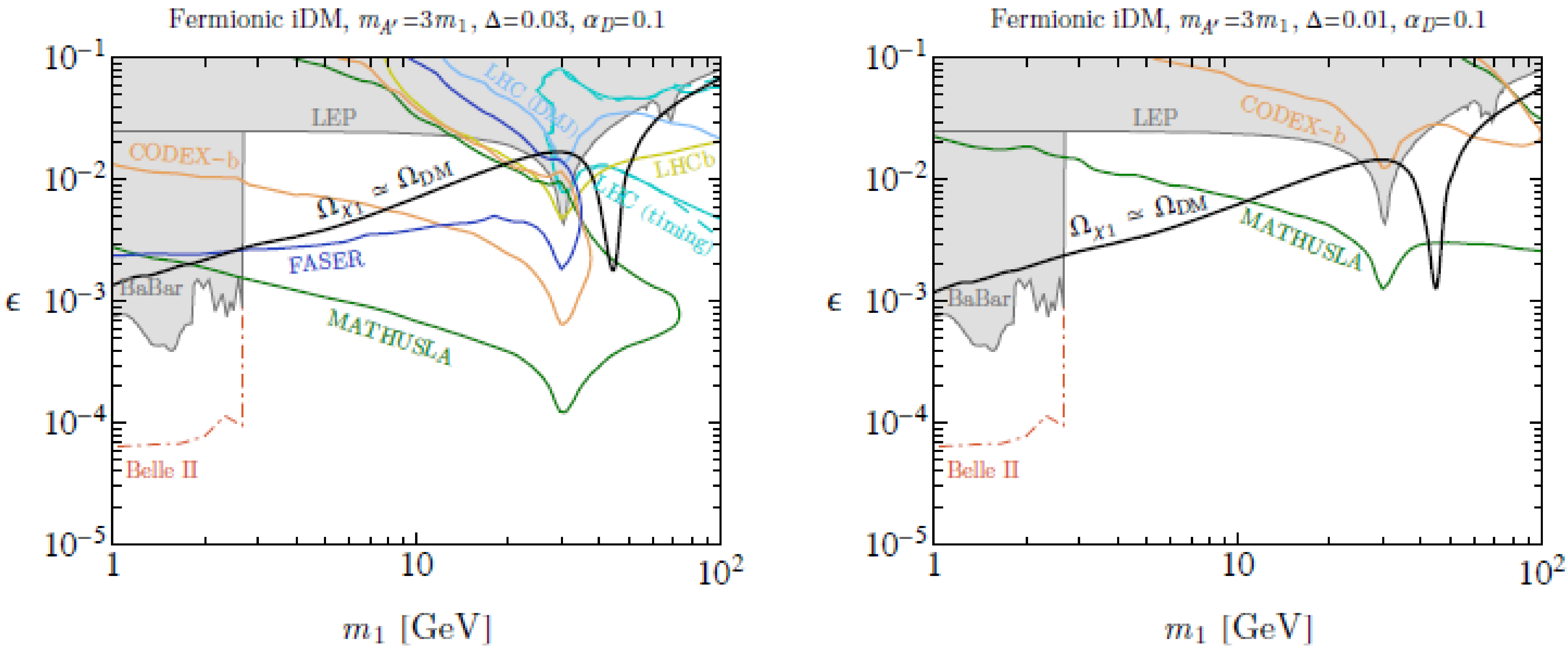




LLP Sensitivity: DM

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



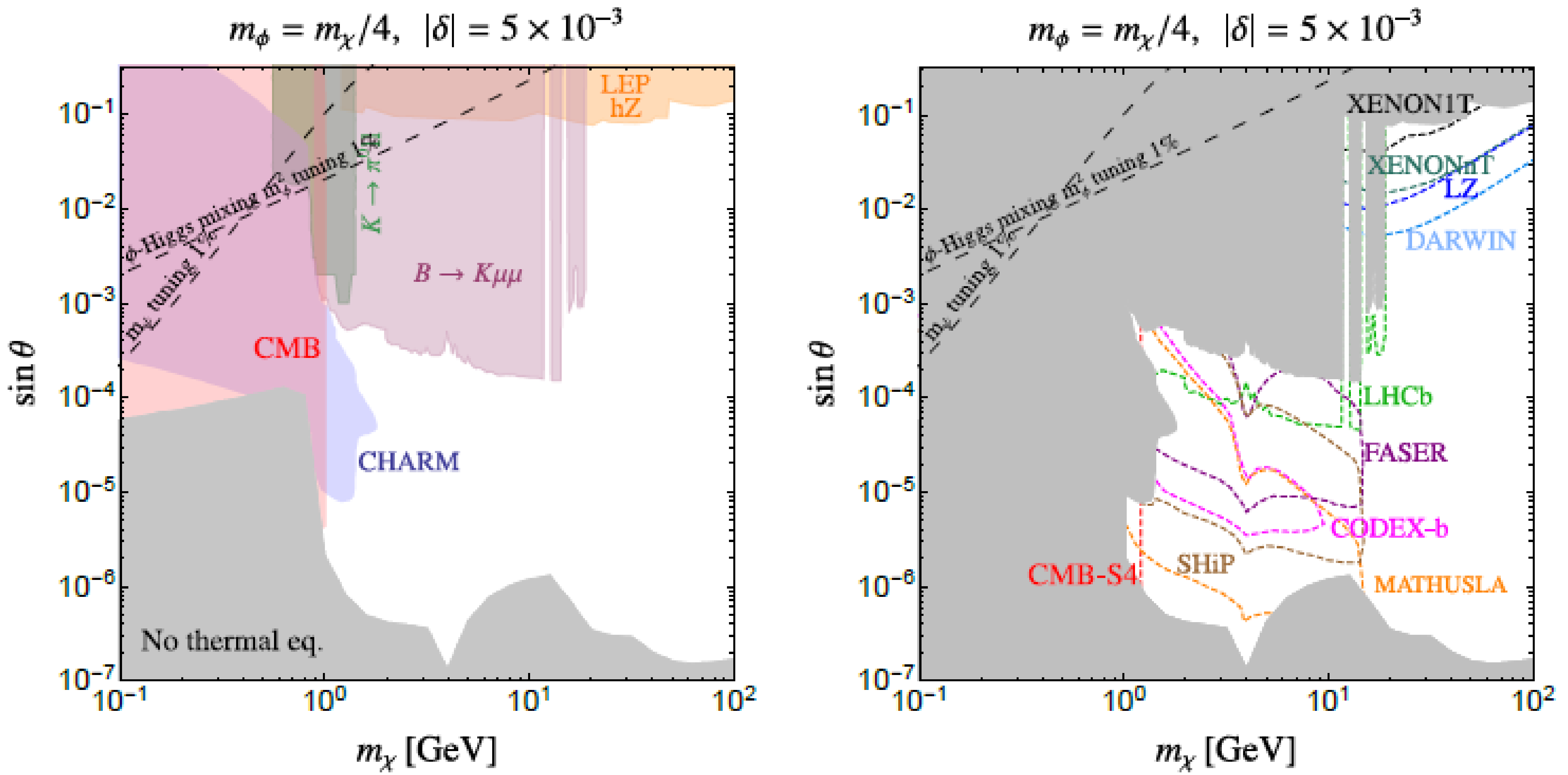
Black curve: thermal o-annihilations $\chi_2\chi_1 \to A' \to f\bar{f}$ yield observed DM relic density

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,

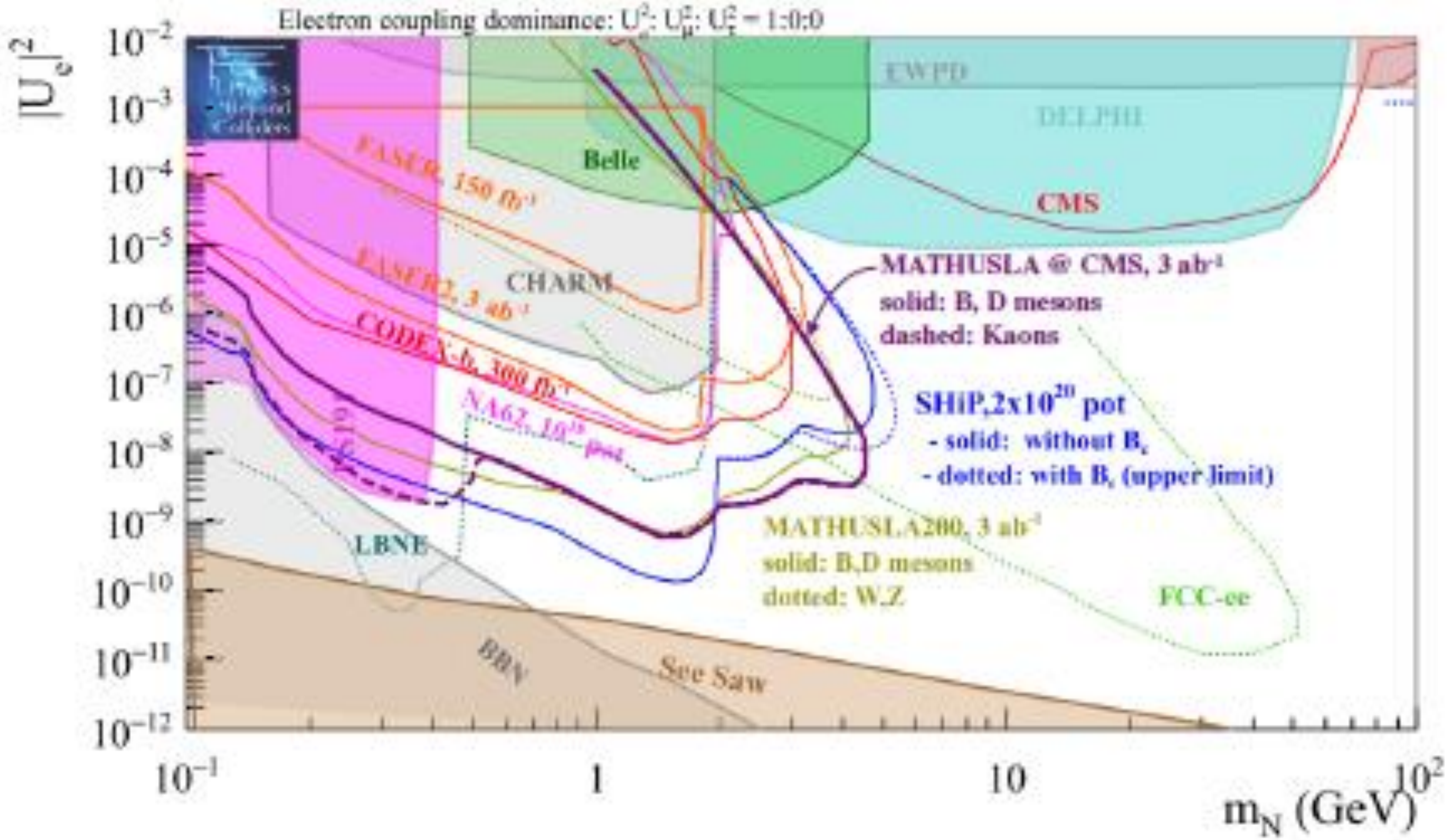
$\chi\,\chi_2 \rightarrow \phi\phi$ where scalar ϕ has mixing angle θ with SM Higgs



LLP Sensitivity: GeV-Scale

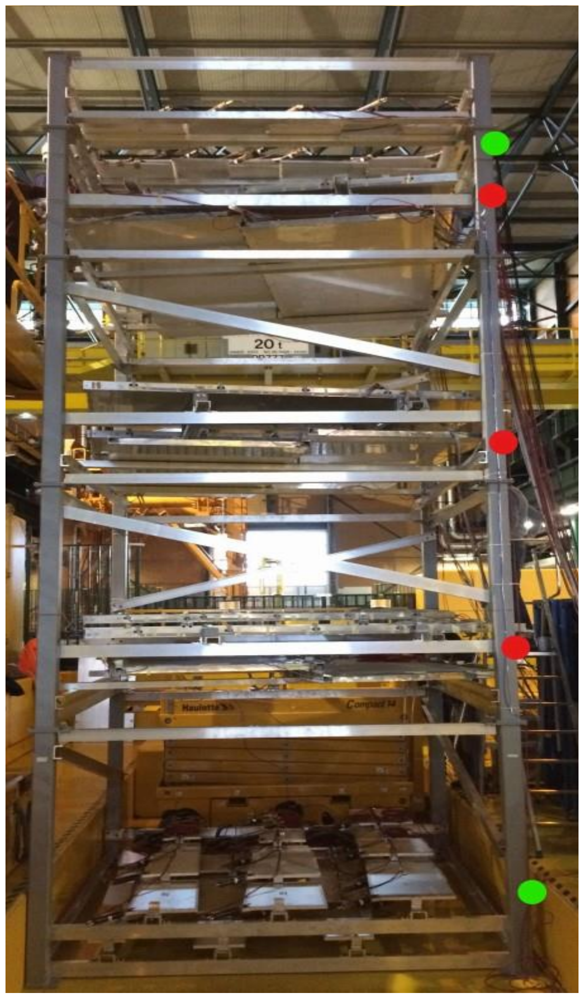
For heavy neutral leptons, reach is similar to SHiP

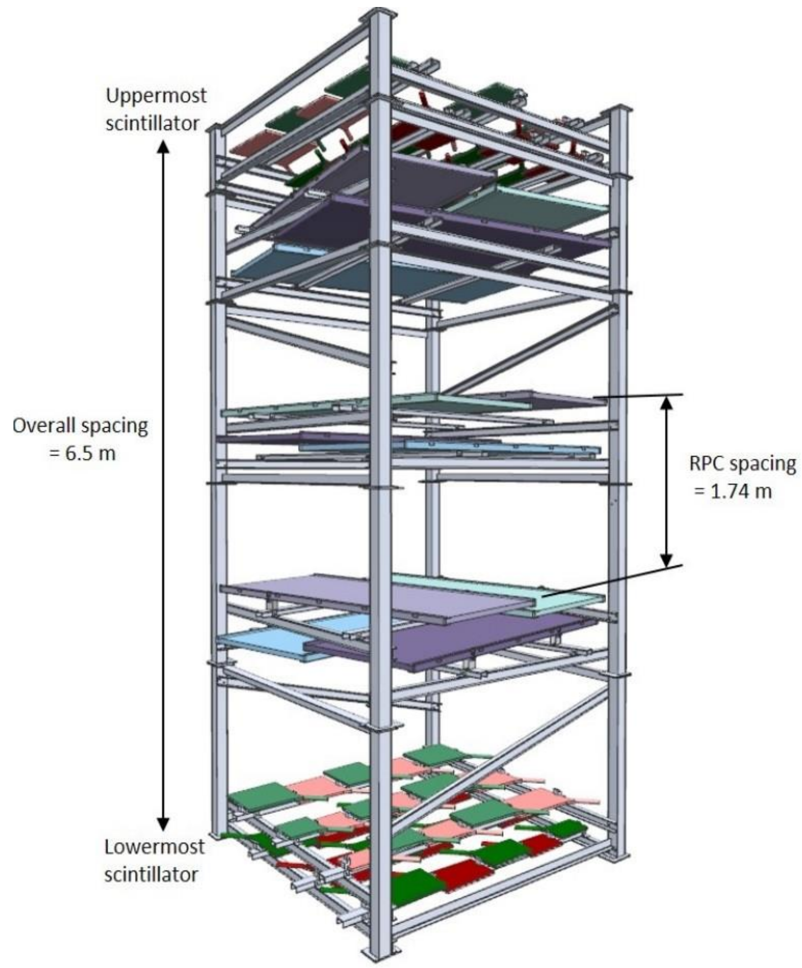
e.g. sterile neutrino N predominantly mixing with electron-neutrino

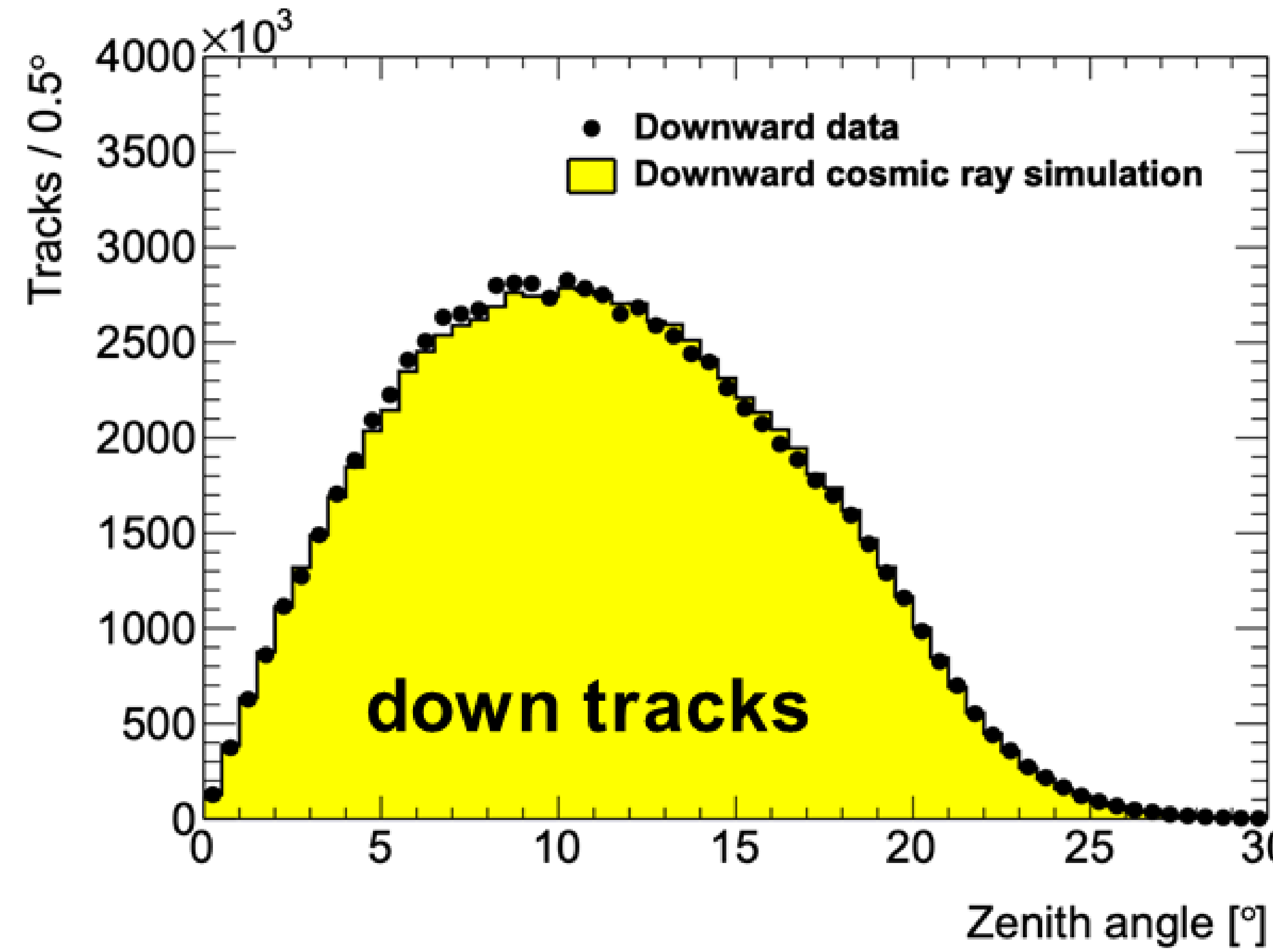


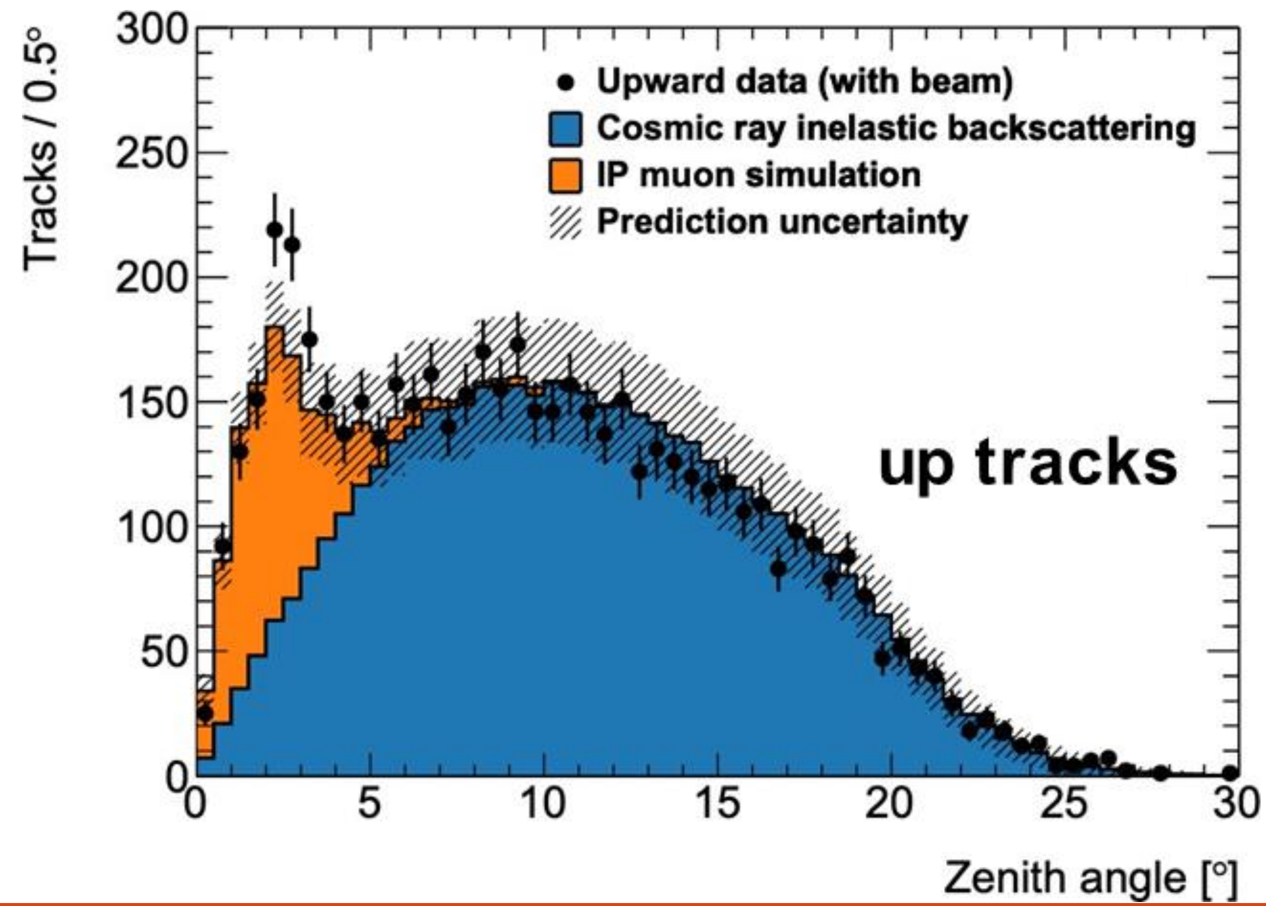
MATHUSLA Test Stand

Operated above ATLAS in 2018







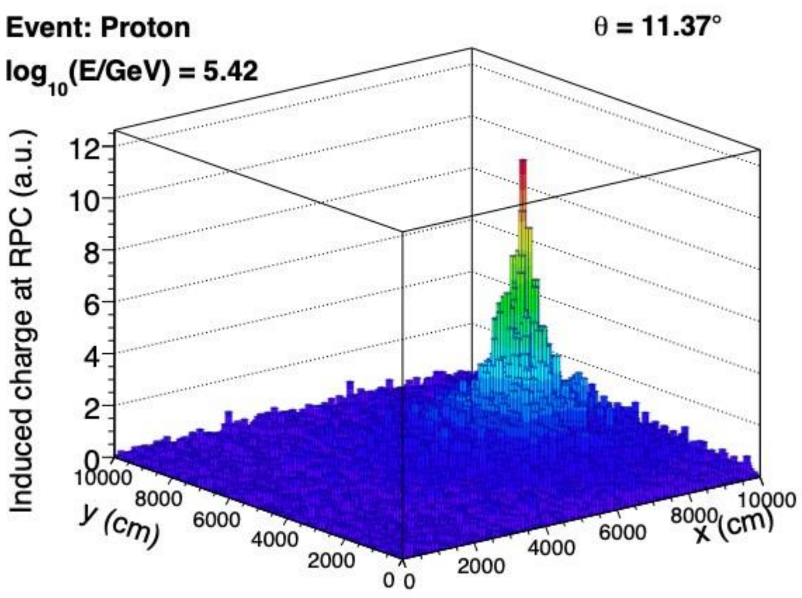


Downward cosmic rays, upward LHC muons and upward CR backscatter well described by simulations

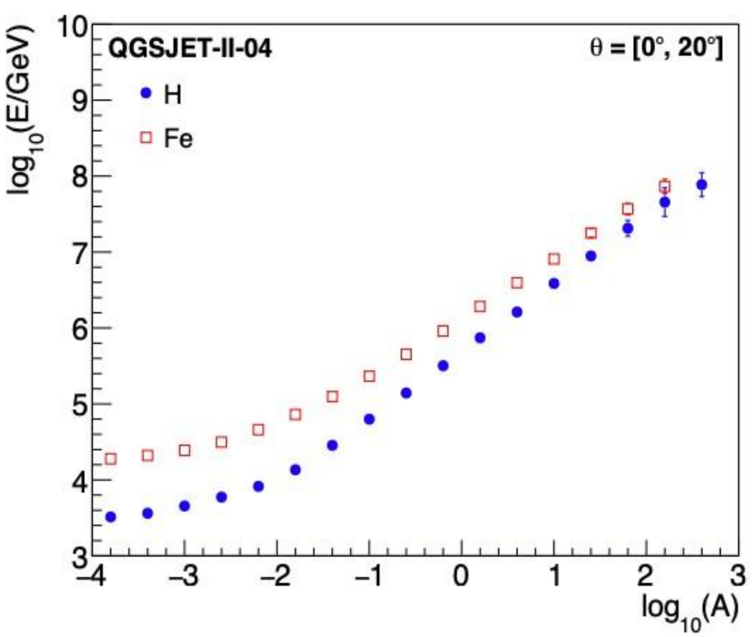
MATHUSLA as a Cosmic Ray Telescope

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

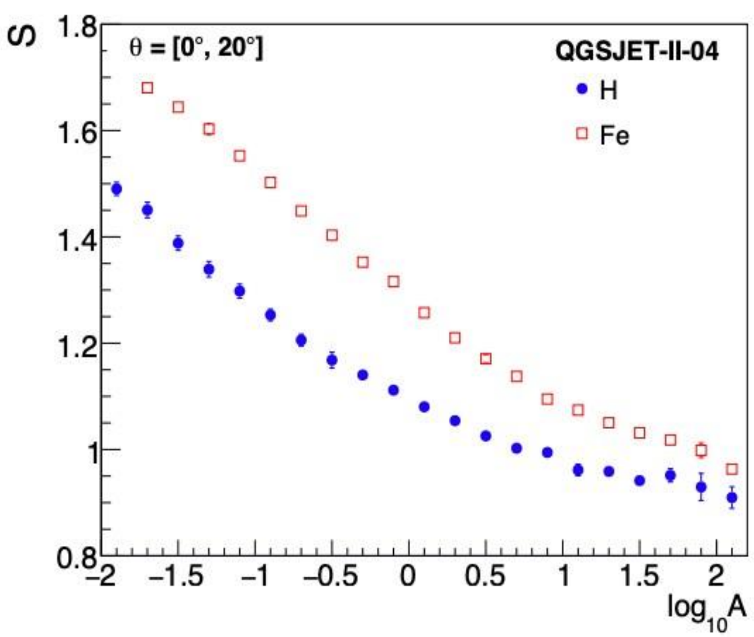
Charge density at the RPC



Amplitude of lateral distribution (LD)



Shower age (slope of LD) vs amplitude



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

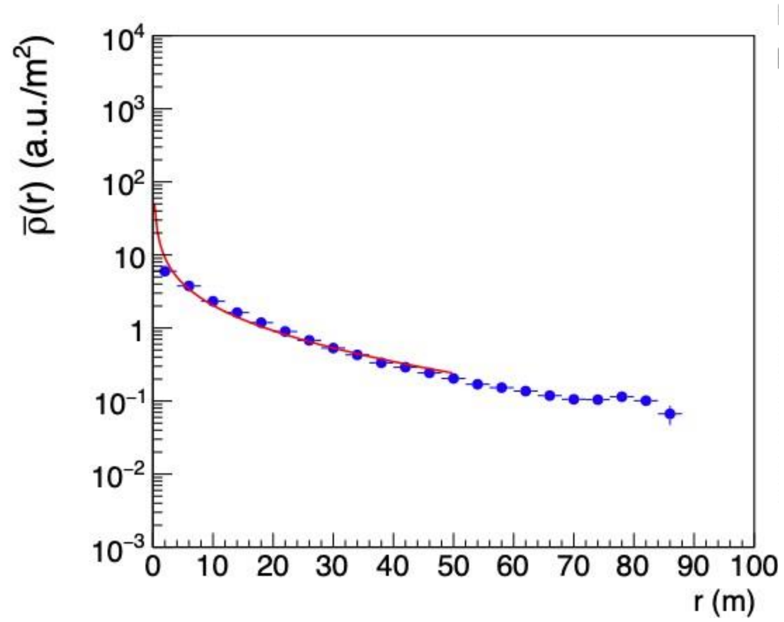
—> **It could provide energy scale**

- 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.**

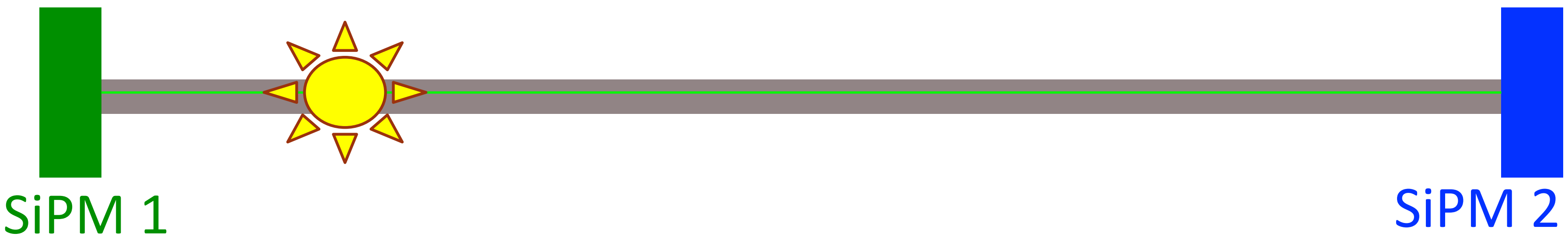
Lateral charge density at RPC

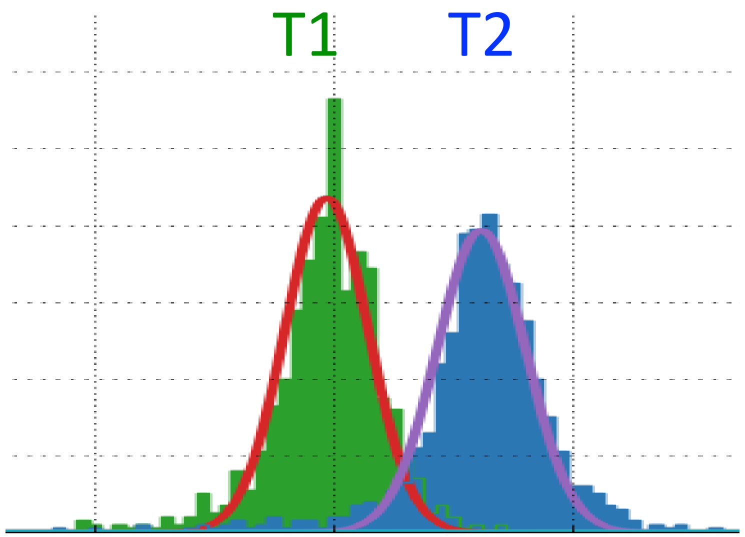


https://indico.cern.ch/event/980853/contributions/4361206/attachments/2251261/3819144/CRMathusla_LLP_25May2021_JC.pdf

Trackers

- To reconstruct hit position along scintillator bar: use difference in arrival time between separate measurements at two ends
  - Target timing resolution ~1 ns





- **Critical feature of the detector design**
  - **Separates downward- from upward-going tracks**
  - **Rejects low-β particles from neutrino QIS**
  - **4D tracking and vertexing reduces fakes/combinatorics**
- Currently under investigation:
  - Different vendors/models of scintillator, WLSF, SiPM
  - Dark current and SiPM cooling
  - Geometry optimisation: bar dimensions, number & thickness of fibers per bar, etc.

Hardware Timing & Testing

Ongoing characterization studies using **small lab setups and GEANT4 simulations** indicate resolution goal is achievable