Searches for Ultra Long-Lived Particles with

MATHUSLA

SEARCHING FOR LONG-LIVED PARTICLES AT THE LHC AND BEYOND: EIGHTH WORKSHOP OF THE LHC LLP COMMUNITY

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Outline

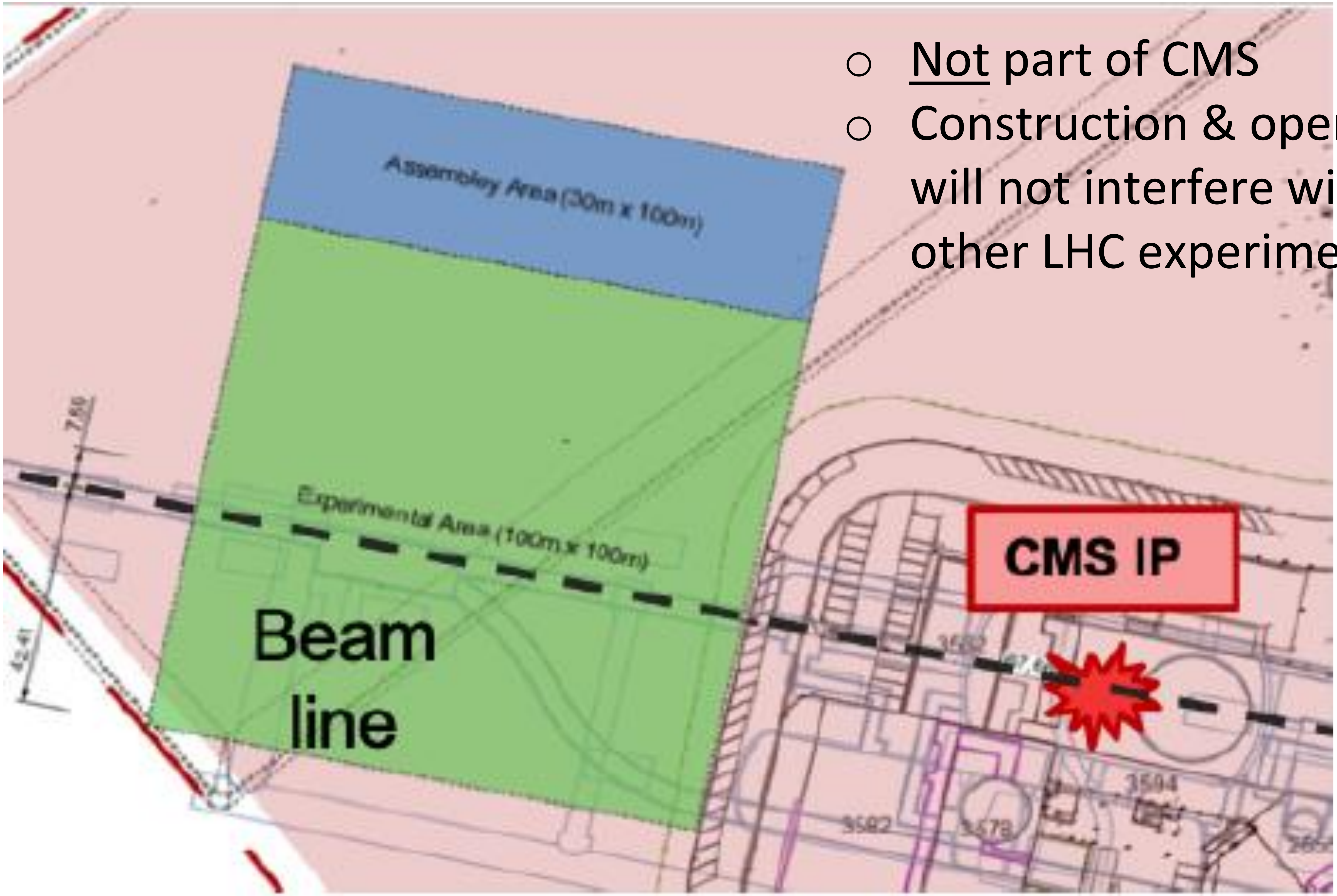
- Basic Concept
  - Backgrounds
  - Identifying LLPs
- LLP Sensitivity
- Cosmic Ray Telescope
- Detector Design

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

Basic Concept

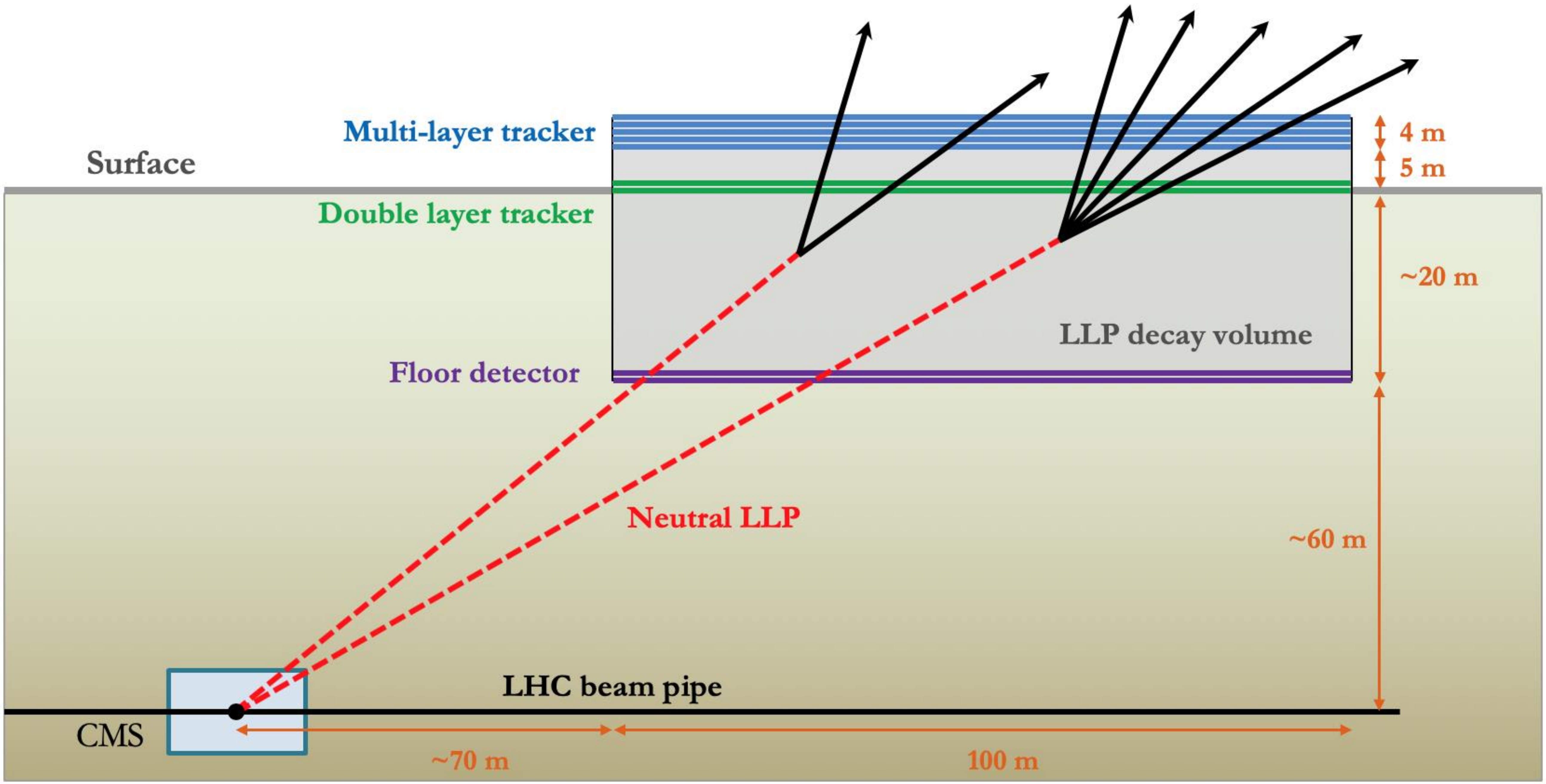
MAssive **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** P**A**rticles

An External LLP Detector for HL-LHC



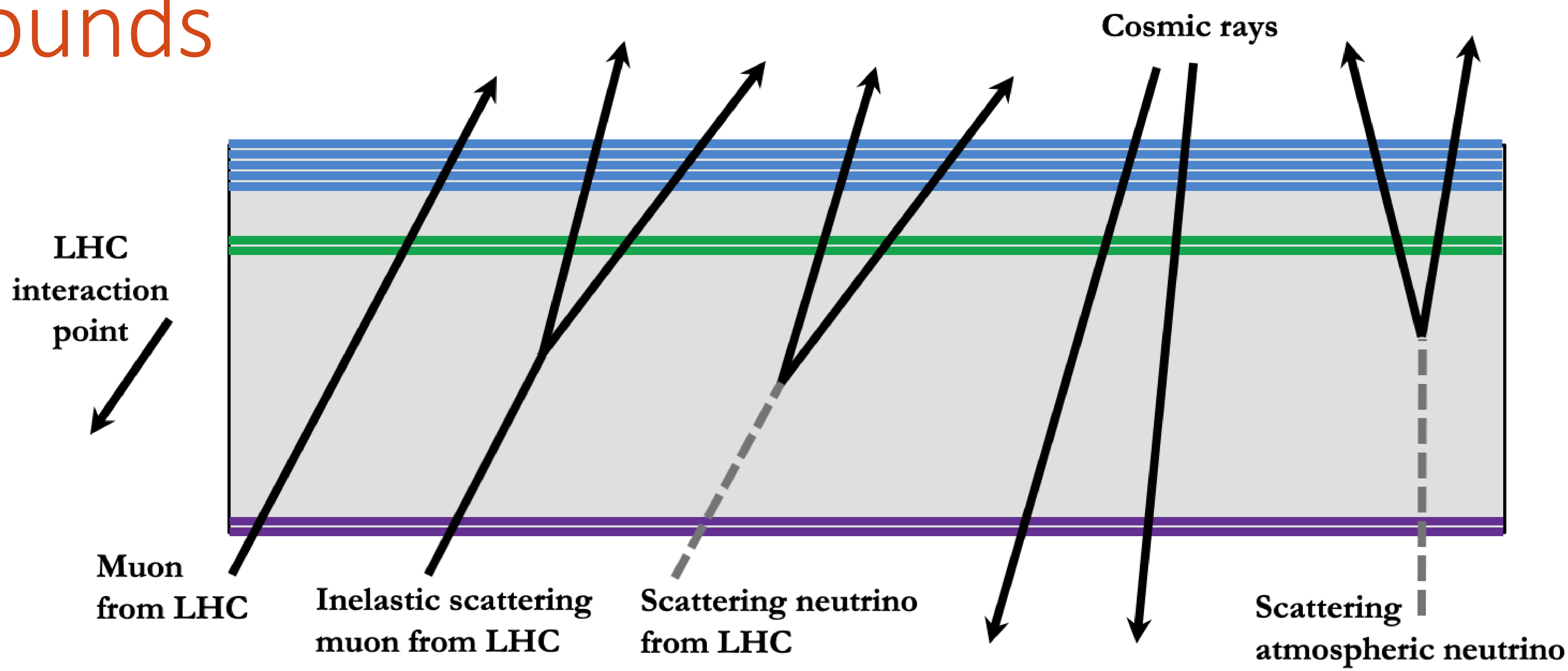
- Not part of CMS
- Construction & operation will not interfere with any other LHC experiments

An External LLP Detector for HL-LHC



Optimized detector geometry & location (“MATHUSLA@CMS”) provides similar reach as original proposal (“MATHUSLA200”), with detector area 100m x 100m instead of 200m x 200m

Backgrounds



LLP displaced vertex 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, veto all backgrounds!

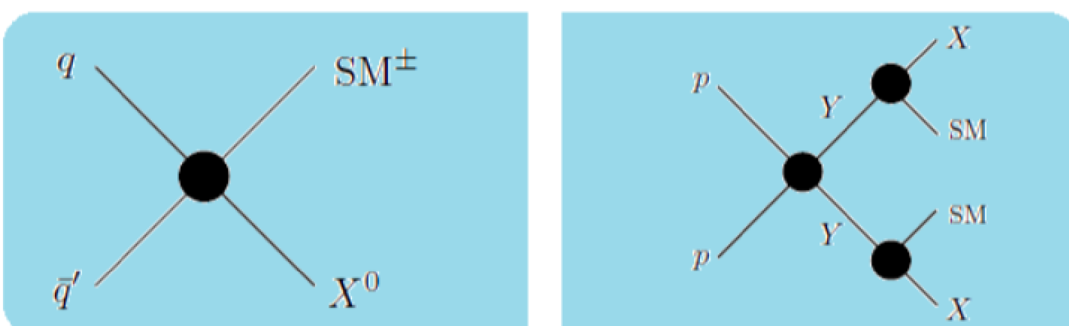
Recent refined estimates for MATHUSLA@CMS confirm earlier MATHUSLA200 estimates: near-zero backgrounds (< 1 event per year) for neutral LLP decays

Backgrounds: Recent Refined Estimates

- Cosmic rays
  - Calibrations performed using Test Stand measurements (taken above ATLAS IP in 2018) arXiv: 2005.02018
  - Simulations performed using PARMA 4.0 + GEANT4
  - Downward-track rate ~2MHz over the entire detector, distinguished from LLPs using timing cuts
  - Upward-tracks produced through inelastic backscatter from CRs that hit the floor, or through decay of stopped muons in floor
- Rare decays of muons originating from HL-LHC collisions
  - Muons coming mostly from W and bbar production, simulated using MadGraph & Pythia8
  - GEANT4 model now includes CMS cavern & surrounding rock layers
- Charged particles from neutrino scattering in decay volume
  - Simulations performed using GENIE
  - Neutrinos from HL-LHC collisions: estimated using LHC minimum-bias samples
  - Neutrinos from CR interactions in atmosphere: estimated using flux measurements from Frejus experiment

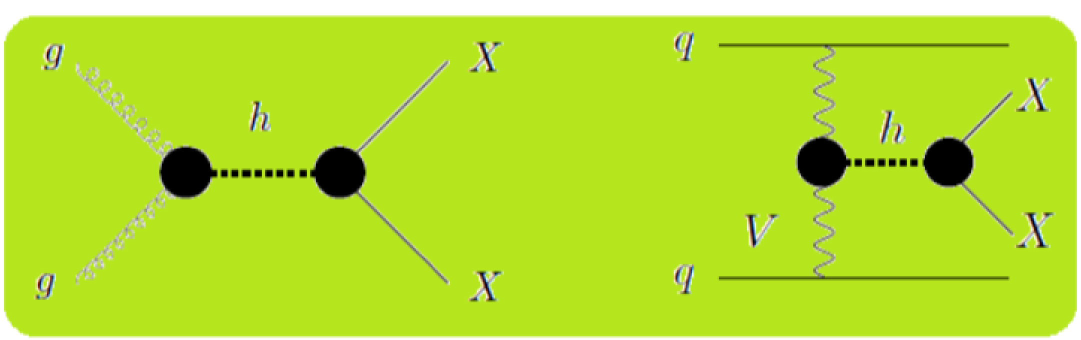
Identifying LLPs

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



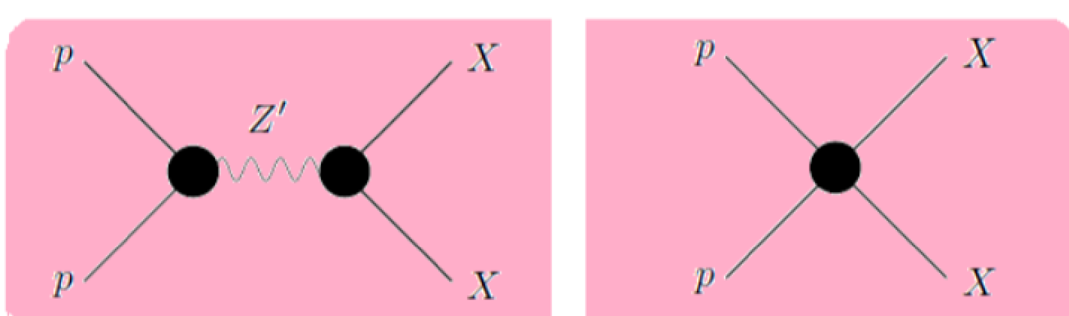
Charged Current (e.g. W')

Heavy Parent



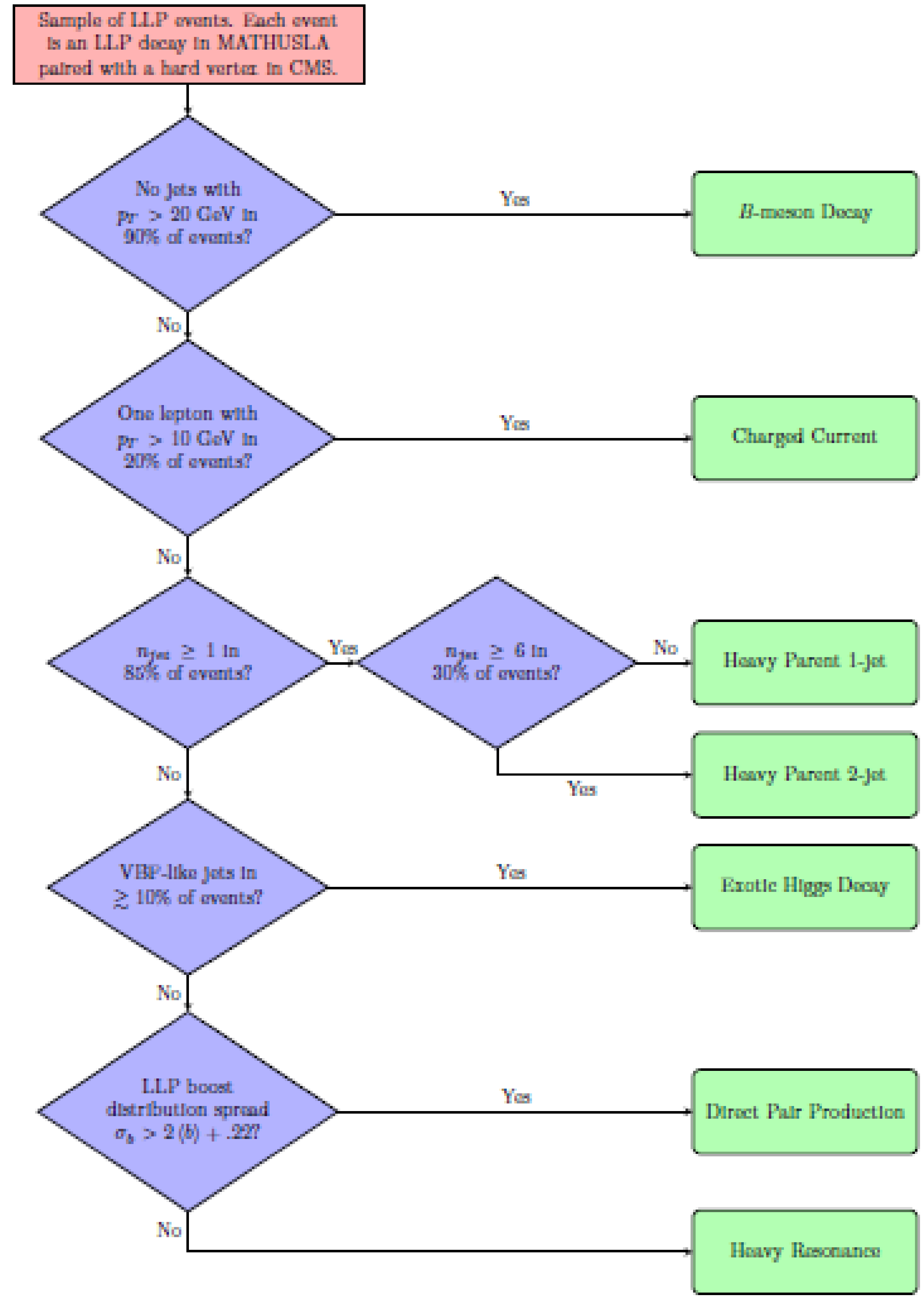
Higgs: Gluon Fusion

Higgs: Vector Boson Fusion



Heavy Resonance

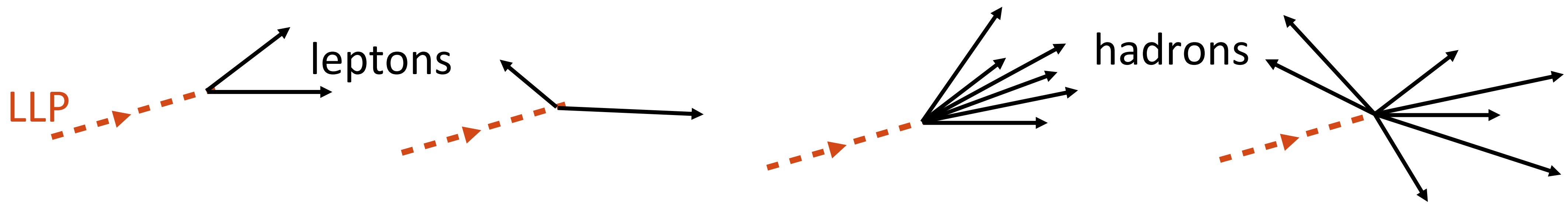
Direct Pair Production



Identifying LLPs

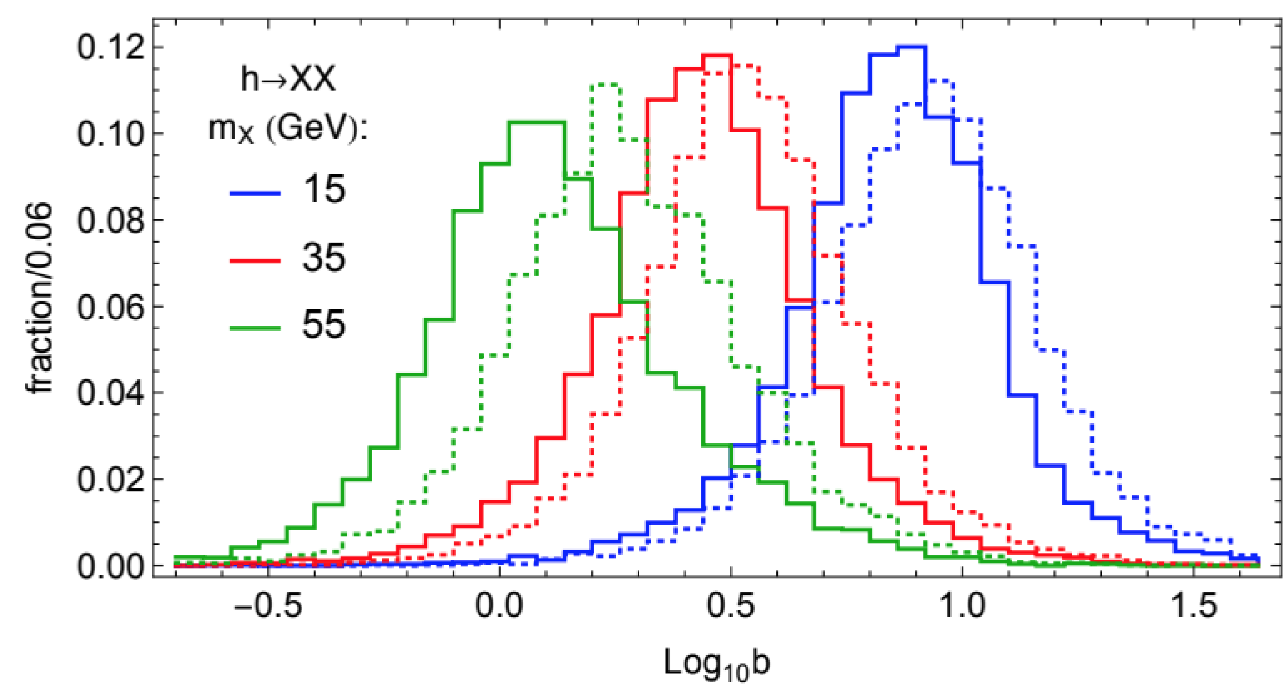
MATHUSLA can’t measure particle momentum or energy, but:

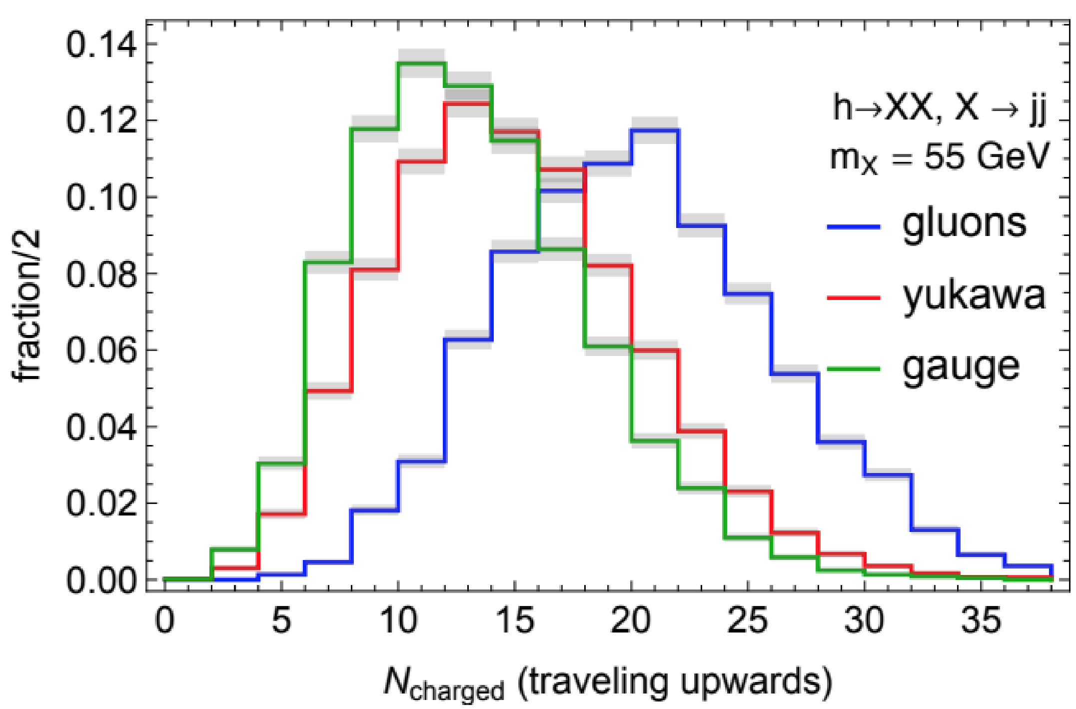
track geometry → measure of LLP boost event-by-event!



If production mode is known:

Boost distribution → LLP mass





If LLP mass is known:

Track multiplicity → LLP decay mode

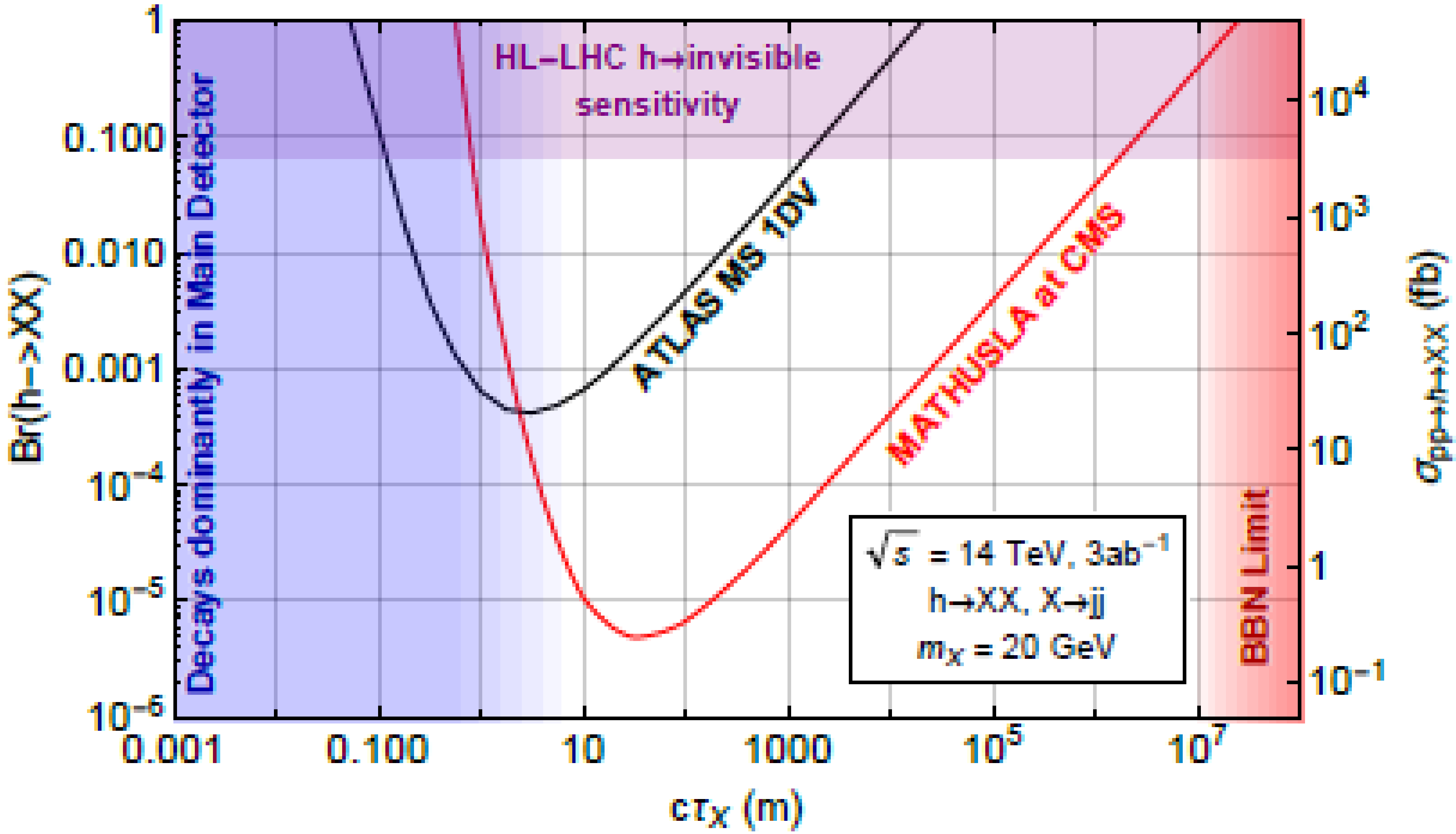
LLP Sensitivity

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

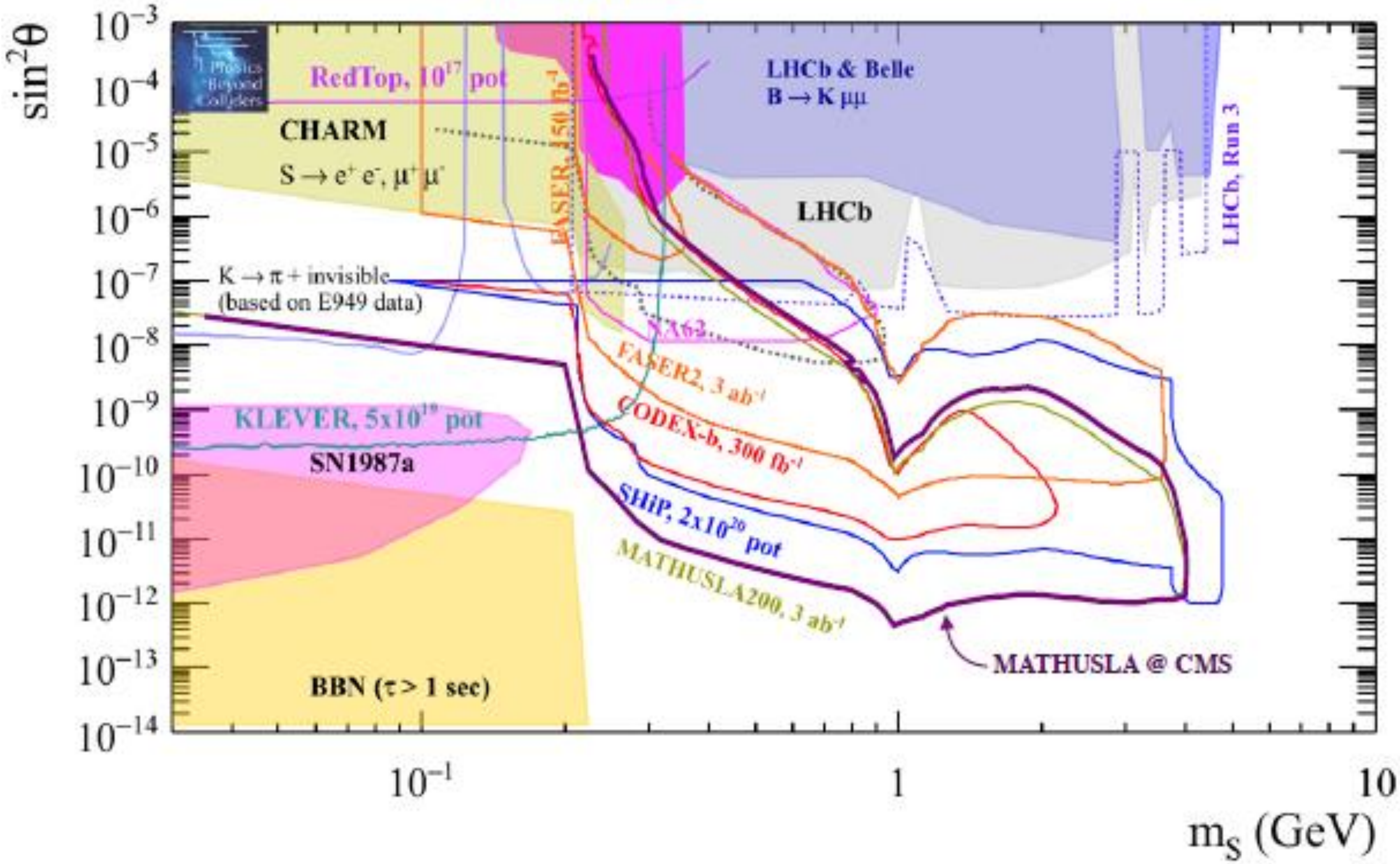


Any LLP production process with σ > fb can give signal in MATHUSLA

LLP Sensitivity: GeV-Scale

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

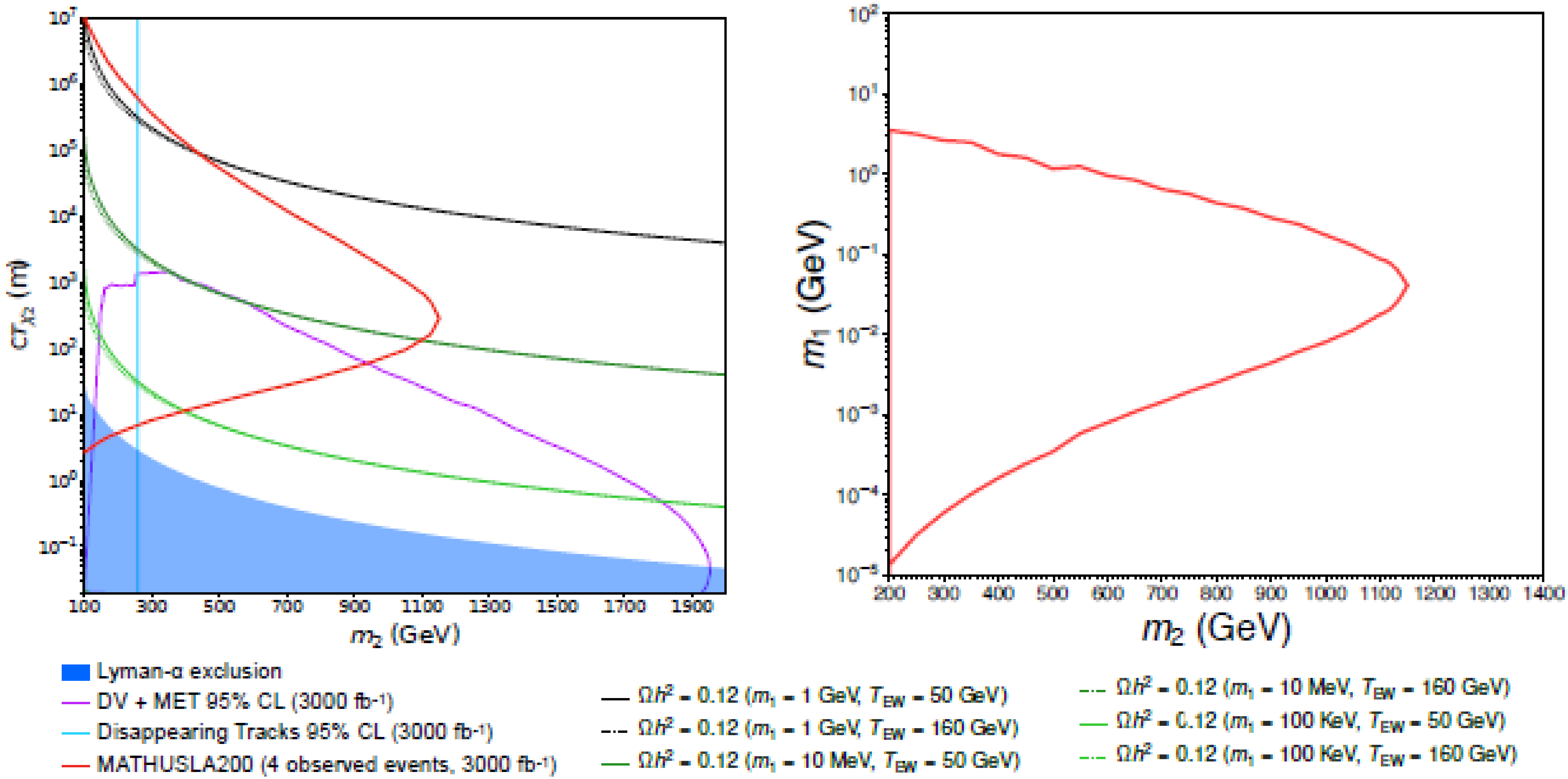
e.g. singlet dark scalar S, mixing angle θ with SM Higgs



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

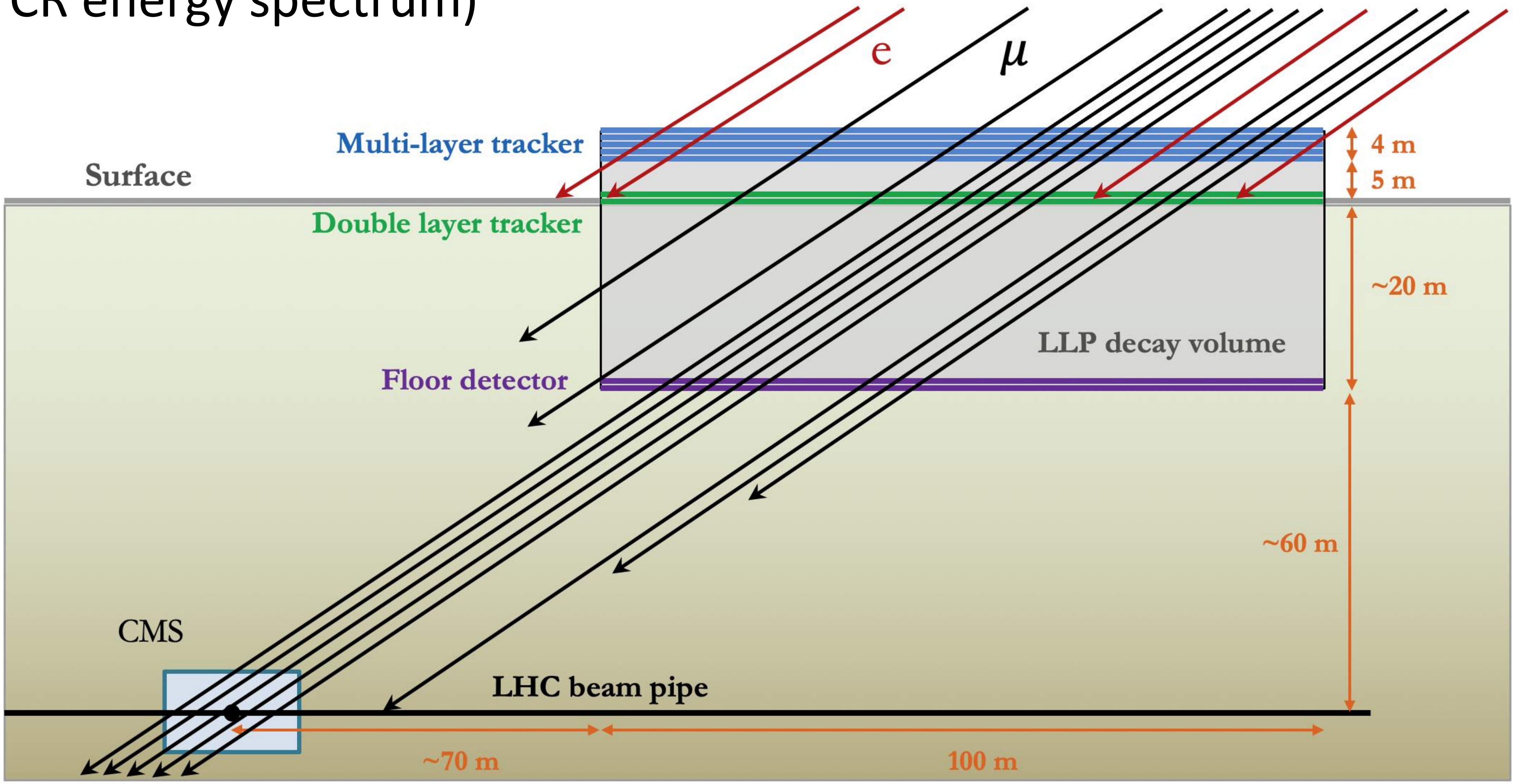


Cosmic Ray Telescope

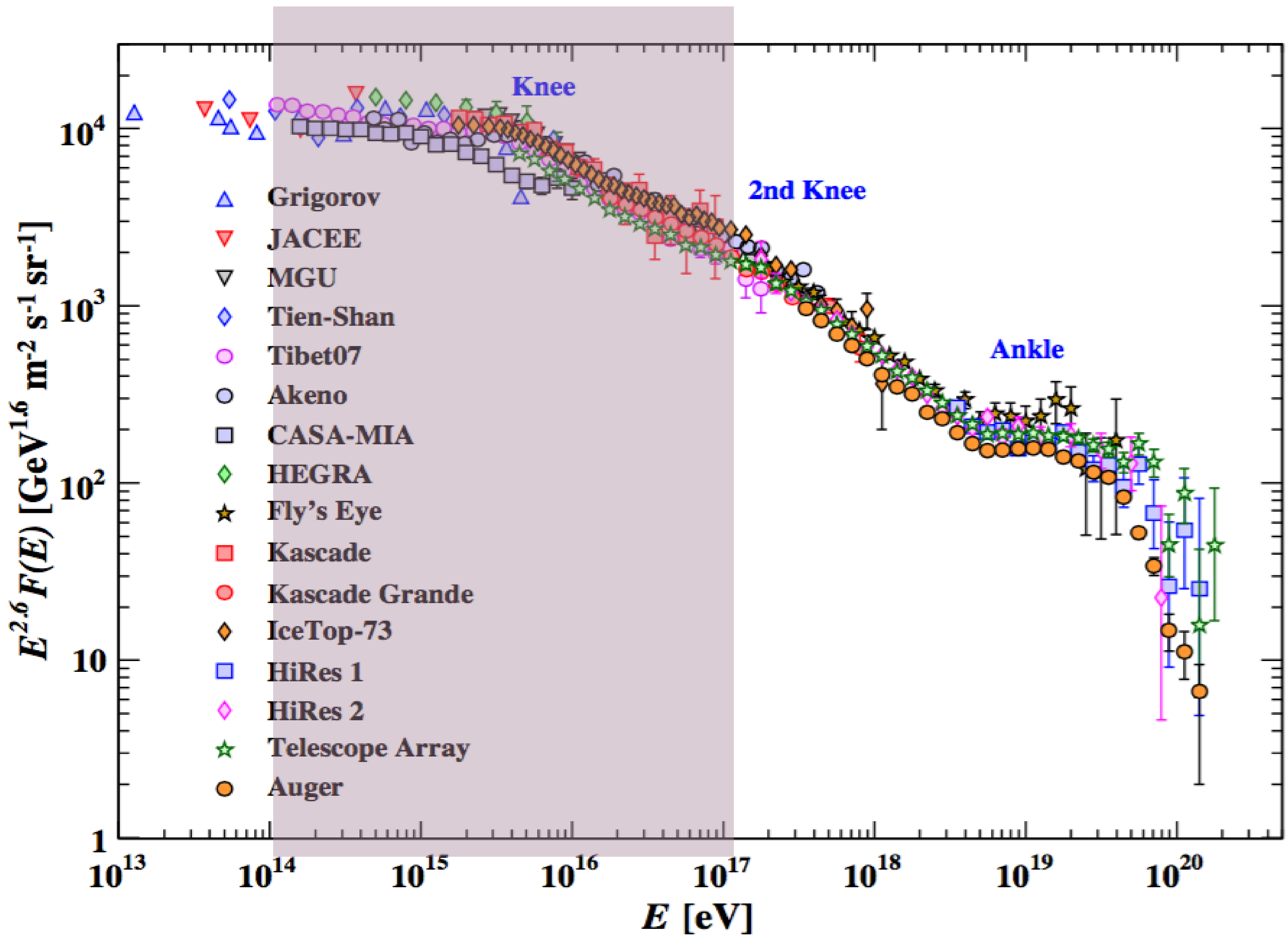
MATHUSLA as a Cosmic Ray Telescope

“Guaranteed Physics Return”

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



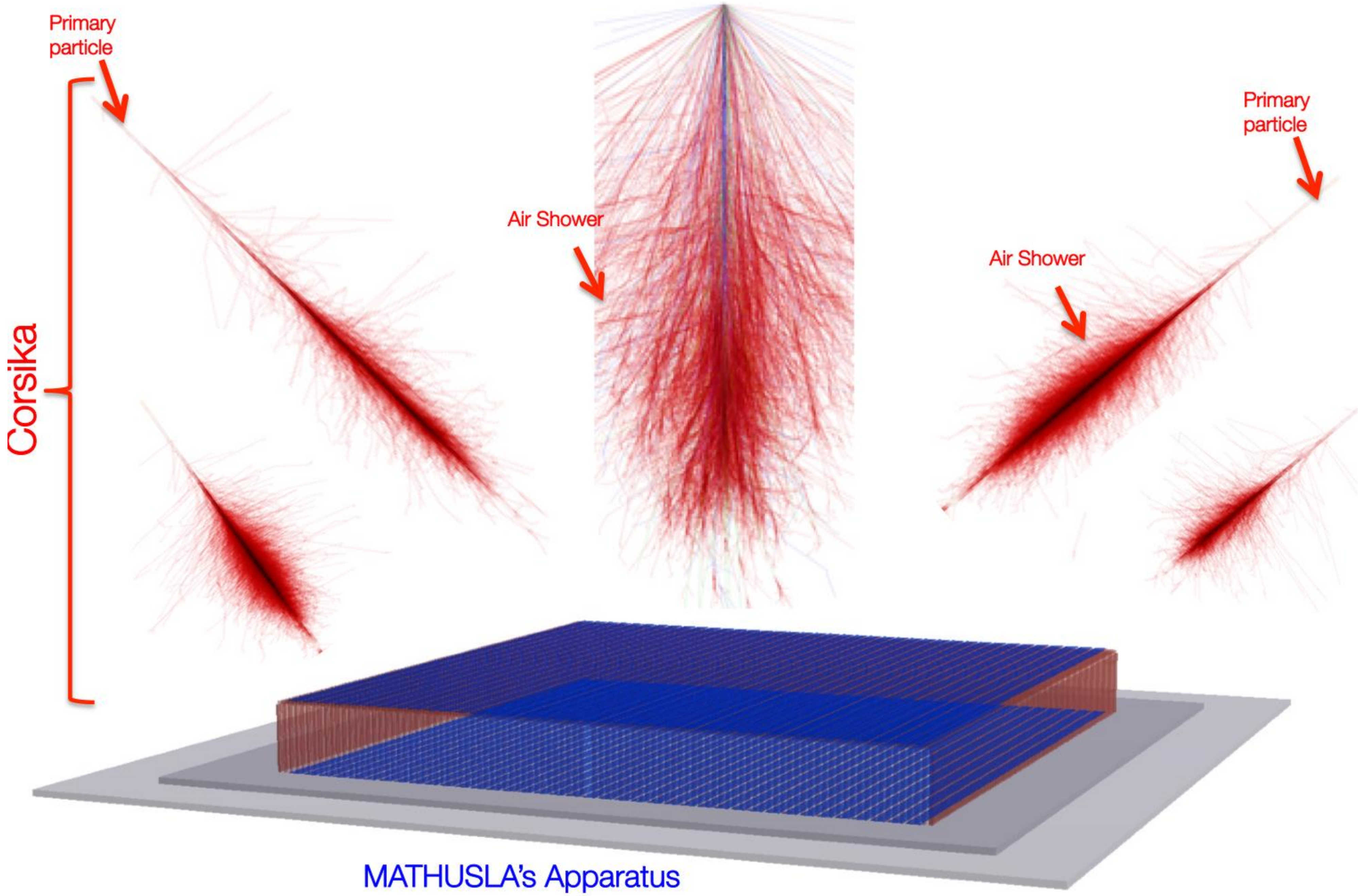
MATHUSLA as a Cosmic Ray Telescope



Paper describing potential contributions to CR physics nearly completed. This effort is being led by the Mexico MATHUSLA team

MATHUSLA as a Cosmic Ray Telescope

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

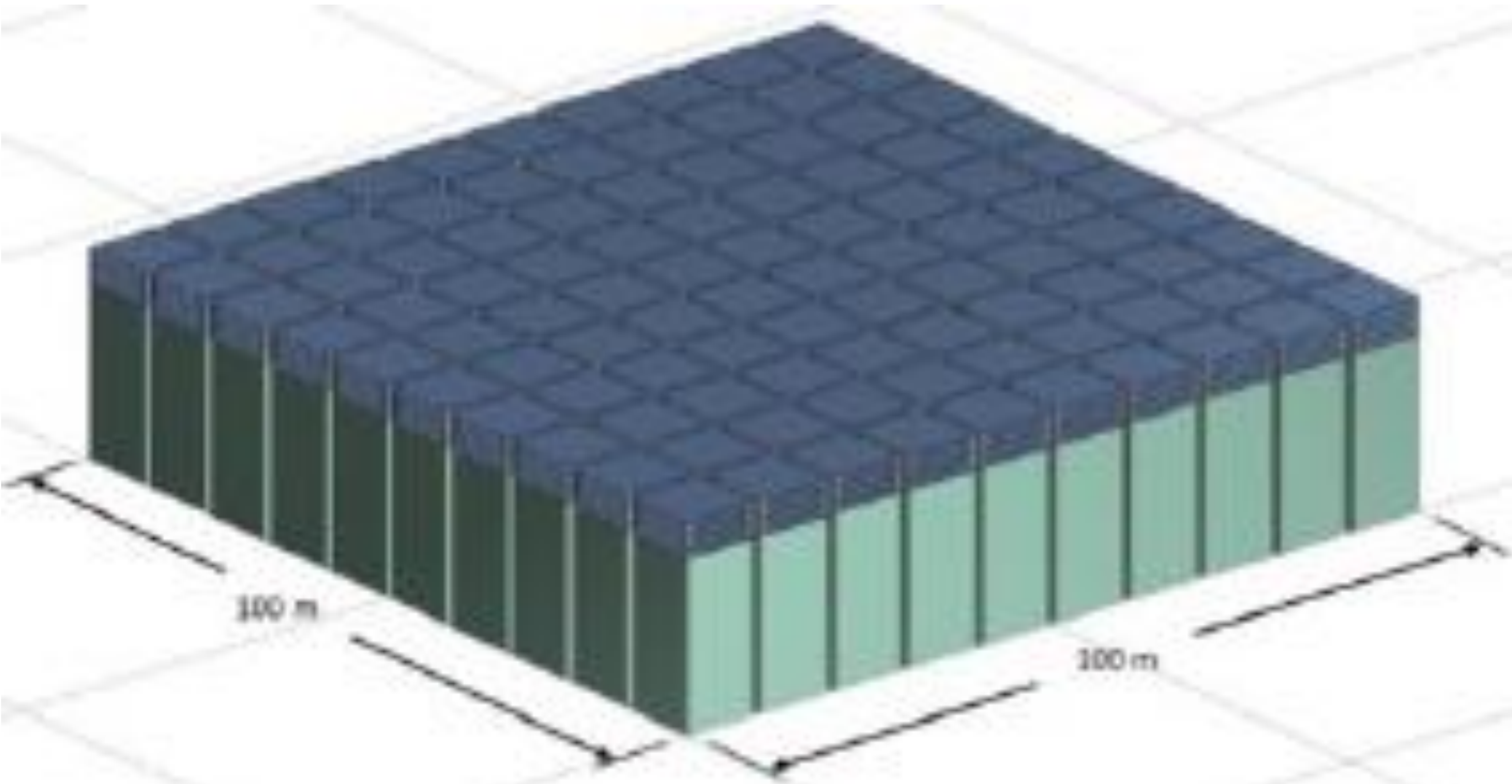


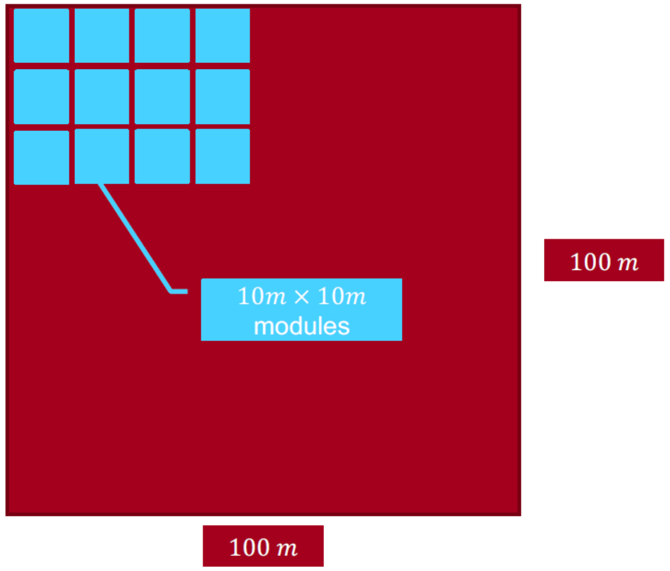
MC simulations using CORSIKA (https://www.iap.kit.edu/corsika/)

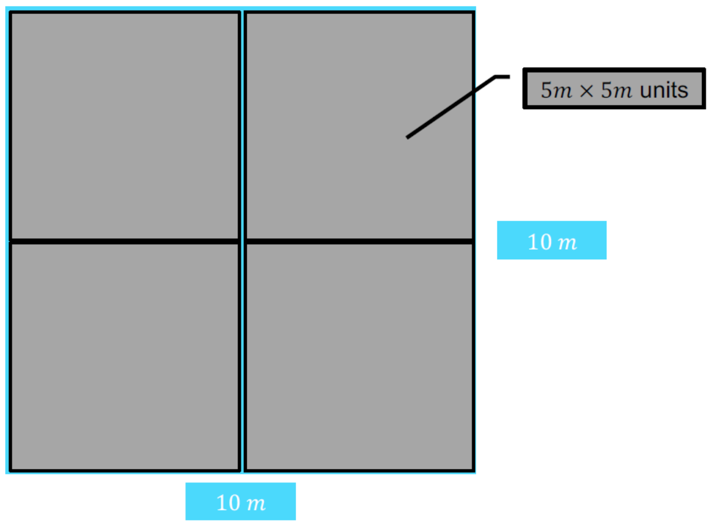
Detector Design

Detector Design

Modular design facilitates staged construction and commissioning



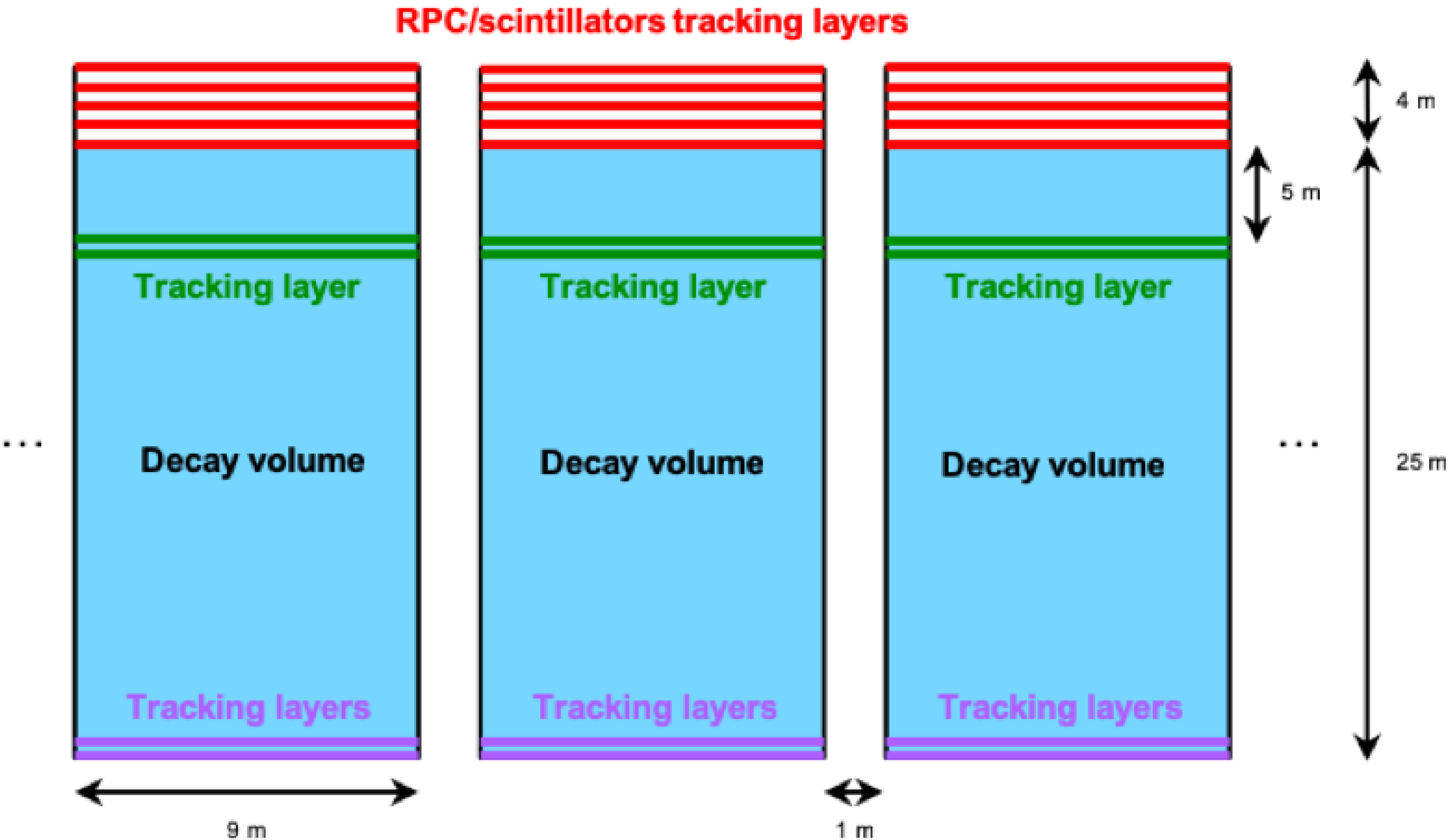




100 Modules in $100m \times 100m$ Footprint

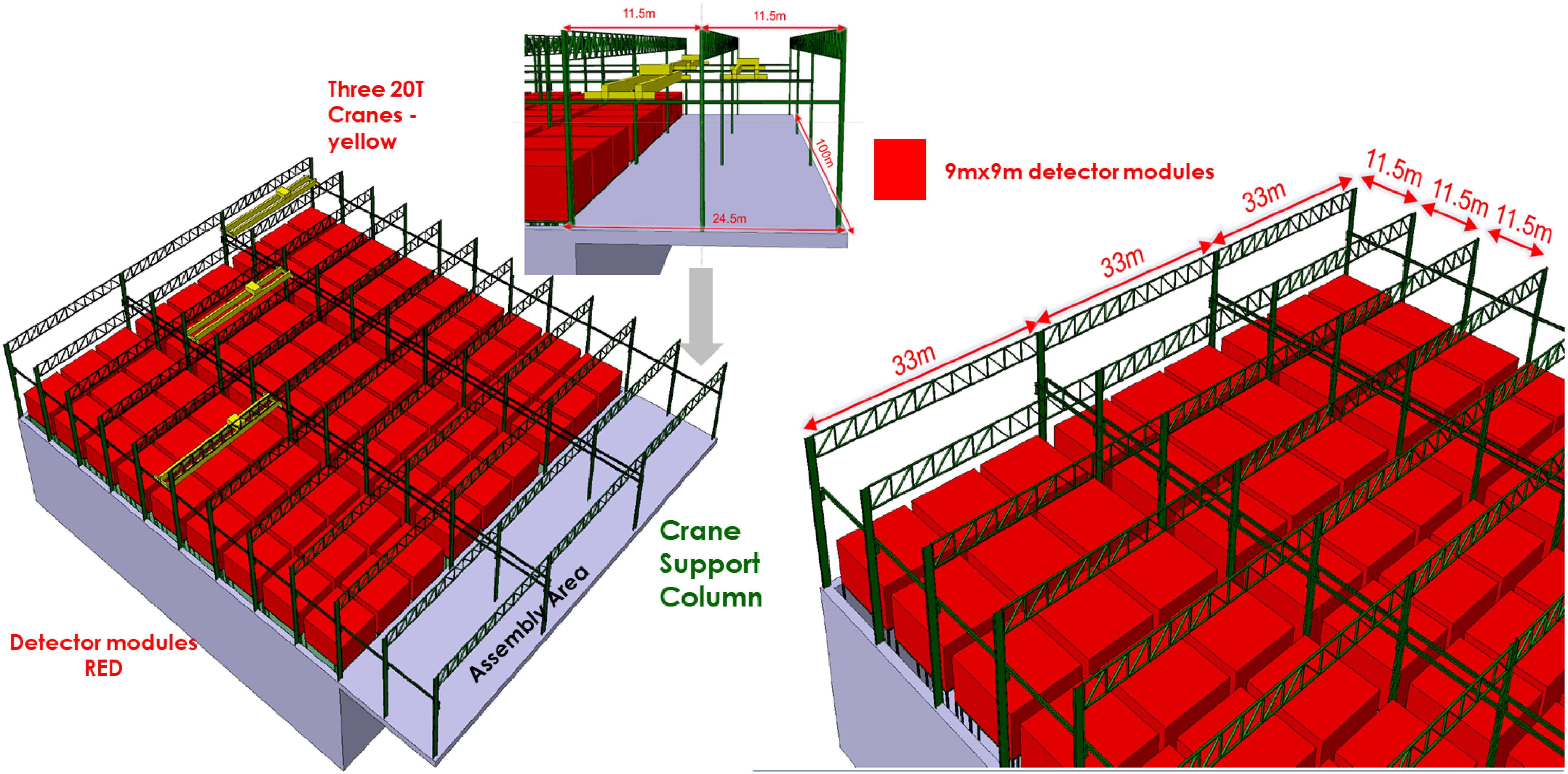
4 Detector Units per Module Plane

Detector Design



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

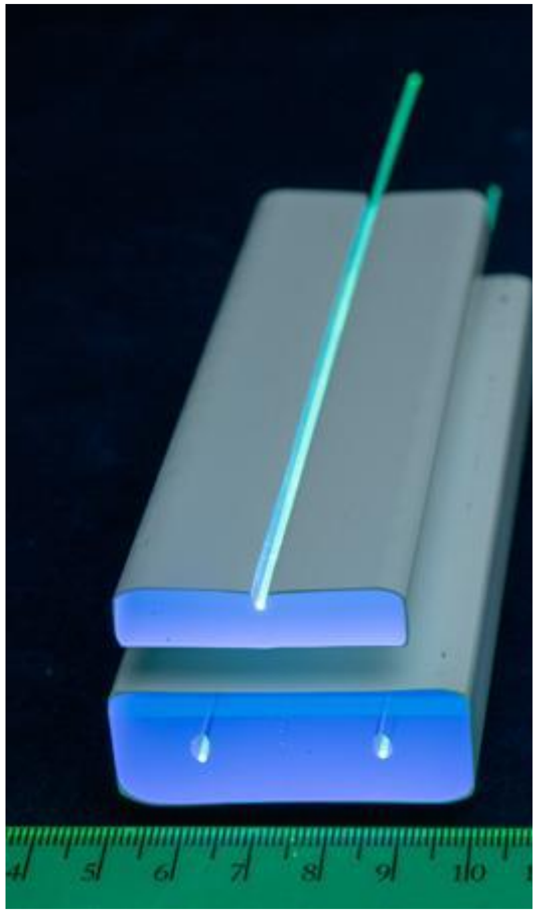
Detector Design



Trackers

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

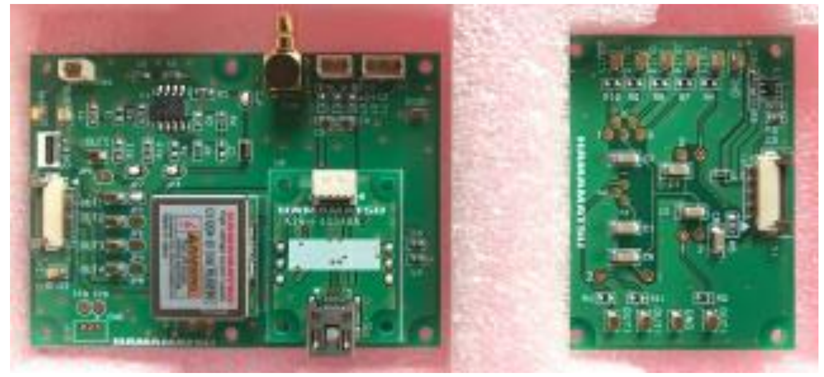
- Extrusion facilities in FNAL used for several experiments (e.g. Belle muon trigger upgrade, Mu2e)
- Possibility of adding Resistive Plate Chamber layers

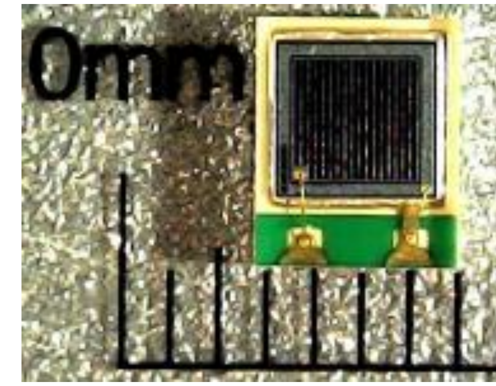


Each scintillator bar ~ 5m x 4cm x 2cm, with readout at both ends

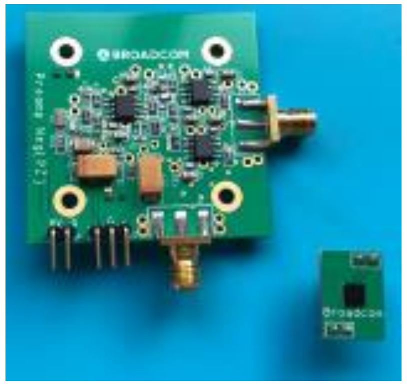
- Transverse resolution $\sigma \approx 1$ cm
- Δt between two ends gives longitudinal resolution: need sub-ns precision

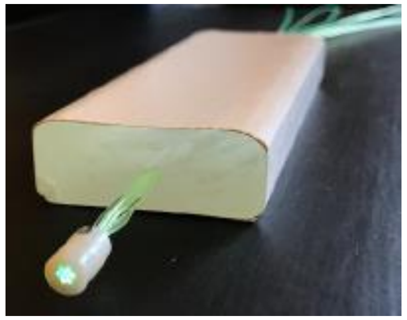
Trackers

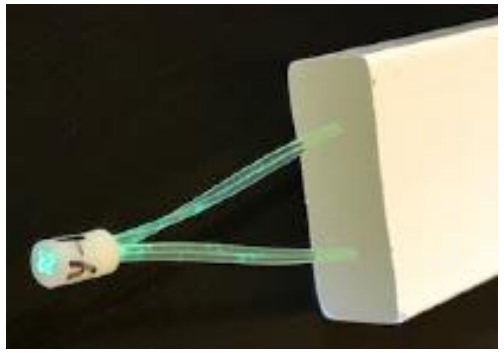


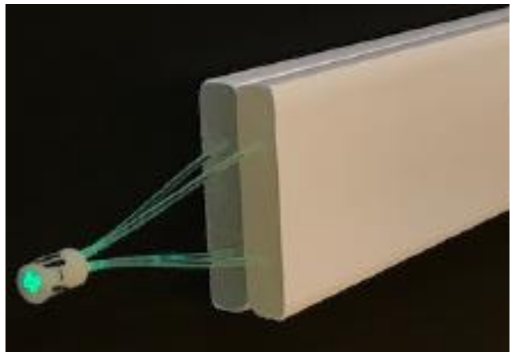


- R&D goal: determine optimal combination of SiPM + wavelength shifting fiber for time resolution, and optimal configuration for light-collection efficiency & readout
  - Teams at CERN, Fermilab, U. Oklahoma, U. Washington, McGill & U. Toronto (work is suffering delays from COVID-19)
- Evaluating SiPM models from different manufacturers
  - Broadcom, ON-Semiconductor, Hamamatsu, Ketek
- Evaluating different wavelength-shifting fibers
  - Saint-Gobain, Kuraray
- Trying different numbers of fibers per hole, holes per scintillator block, and scintillator blocks per layer

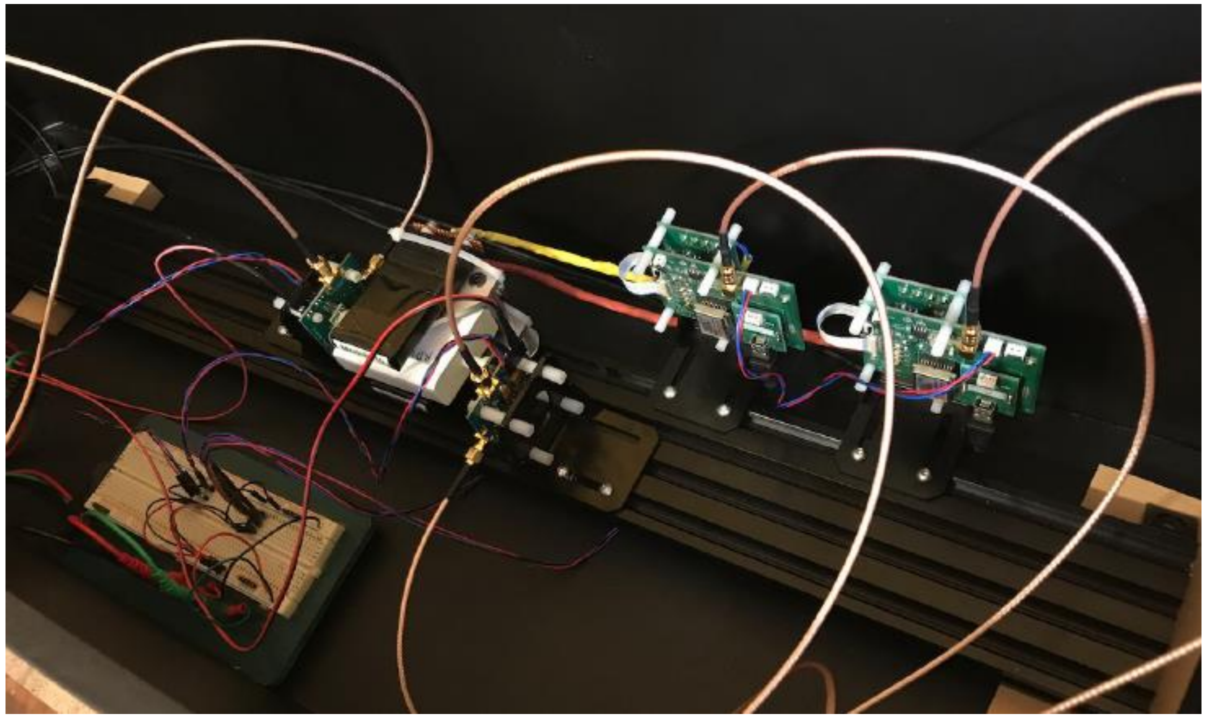








Readout & Trigger



- Readout: ~700,000 channels
  - Does not require sophisticated ASIC
  - Currently performing preliminary SPICE simulations for readout circuits
  - Goal for front-end: $1/channel
- Collect all detector hits with no trigger selection
  - Separately record trigger data and move it to central trigger processor
- Want to associate trigger with CMS bunch crossings
  - MATHUSLA will have ~9 μs to form trigger and get the data to CMS Level-1 trigger
- Trigger rate $\sim$ 2 MHz
- Trigger unit: 3 x 3 modules
  - ~1 MB/s (~30 TB/year) per module

References

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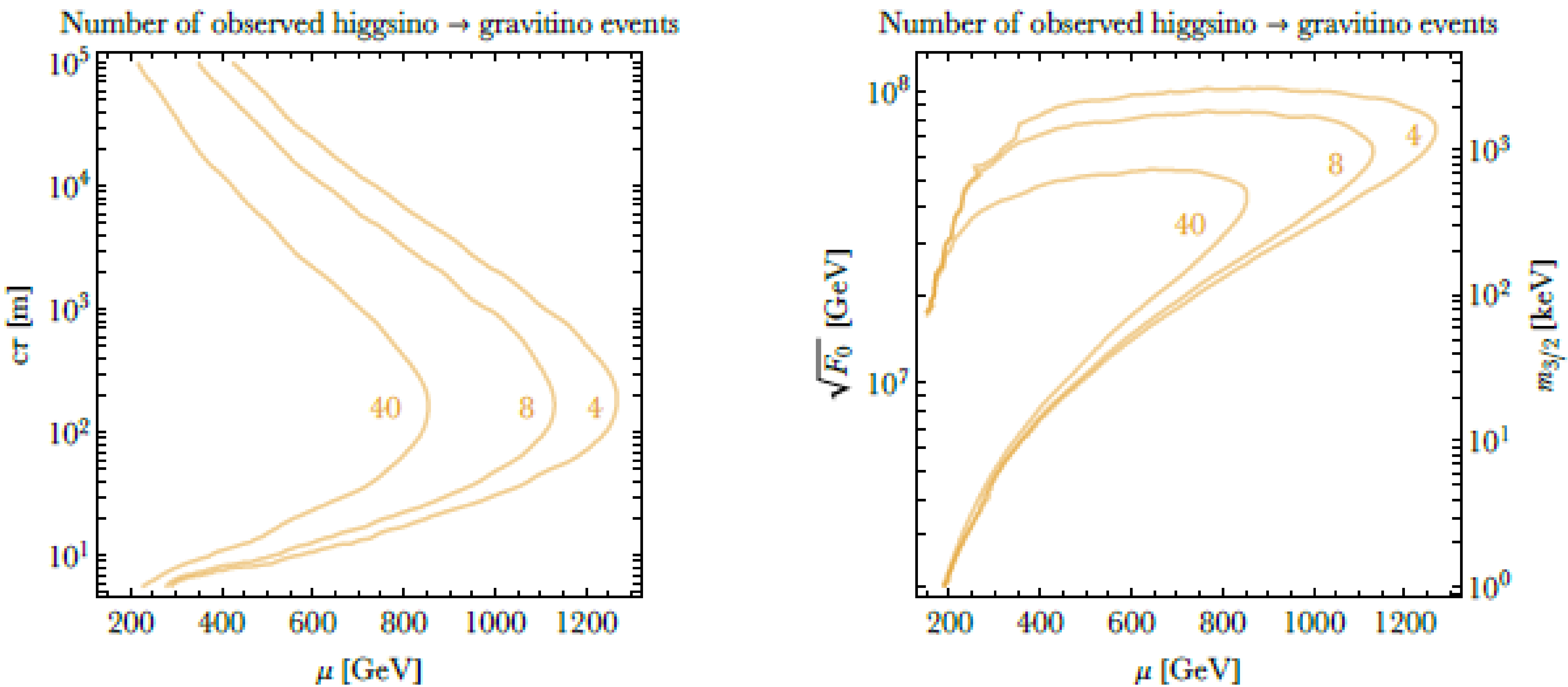
BACKUP

LLP Sensitivity: TeV-Scale

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

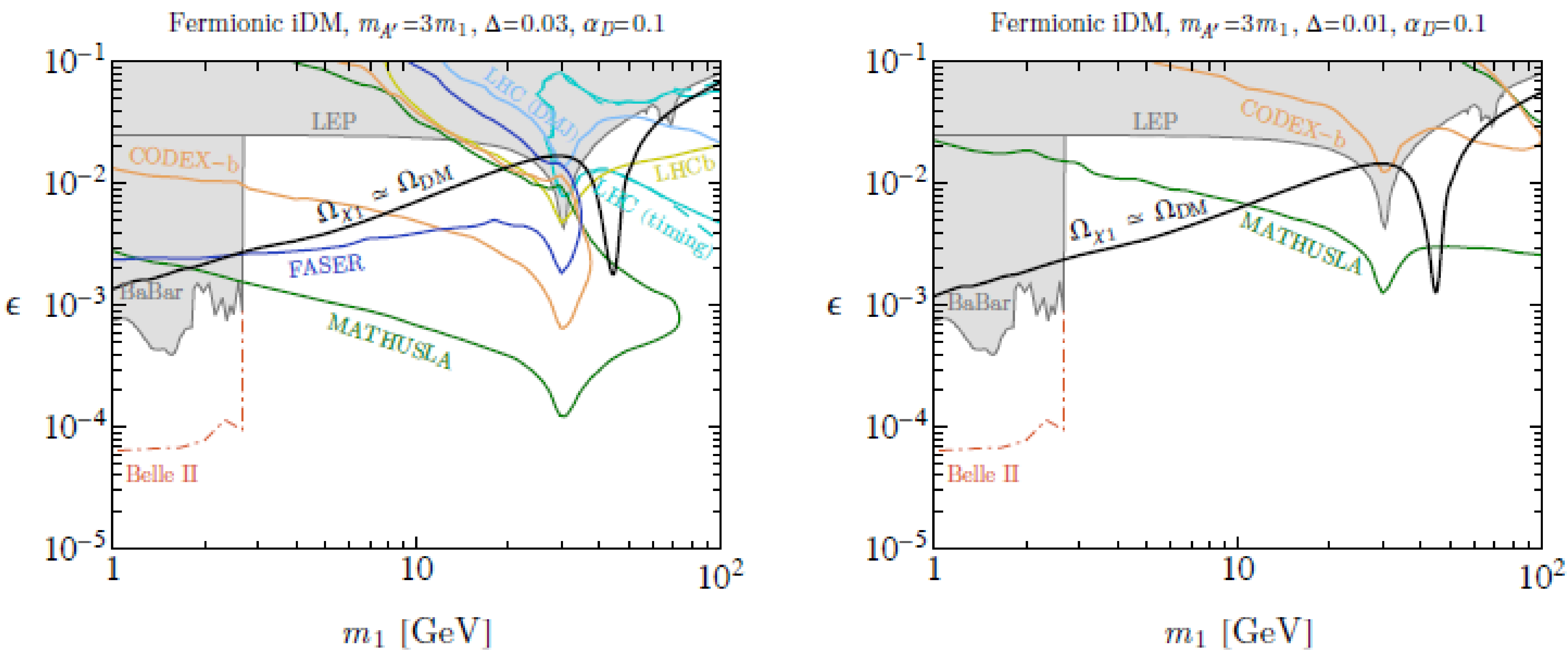
e.g. meta-stable Higgsinos



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



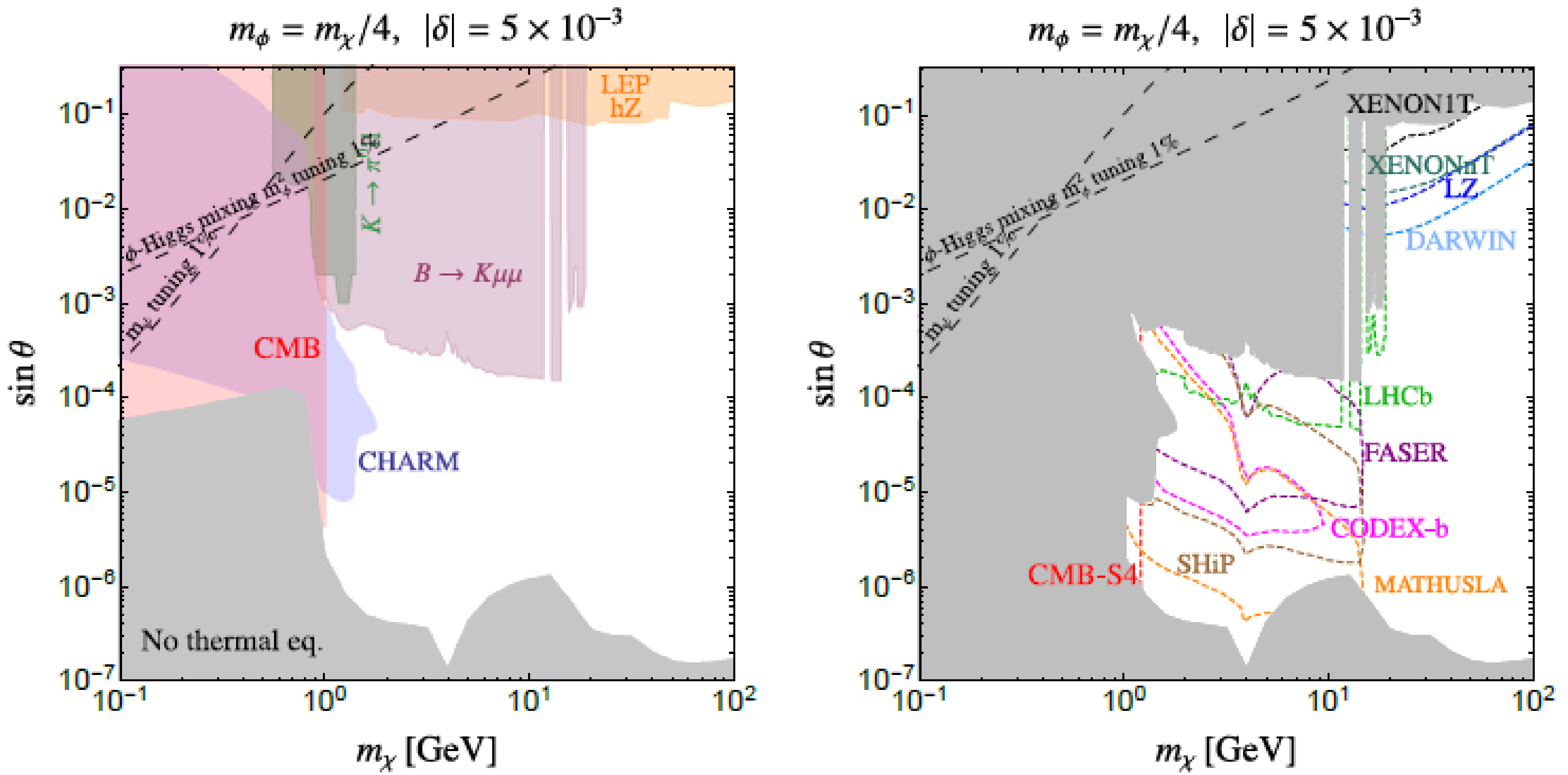
Black curve: thermal o-annihilations $\chi_2\chi_1 \to A' \to f\bar{f}$ yield observed DM relic density

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