Tackling Technological Challenges for the MATHUSLA Detector: Searching for Long-Lived Particles at High-Luminosity LHC

TRIUMF SCIENCE WEEK

JULY 2024

MIRIAM DIAMOND

ASSISTANT PROFESSOR

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

UNIVERSITY OF TORONTO

Canadian MATHUSLA Team

UVic

Faculty
Heather Russell

Postdoc
Caleb Miller

Undergrads
Branden Aitken
Sarah Alshamaily

UofA

Faculty
Steven Robertson

UofT

Faculty
Miriam Diamond
David Curtin

Postdoc
Runze (Tom) Ren

Grad Students
Jared Barron
Caleb Gemmel
Gabriel Owh
Andrija Rasovic
Zhihan Yuan

Undergrads
Alex Lau

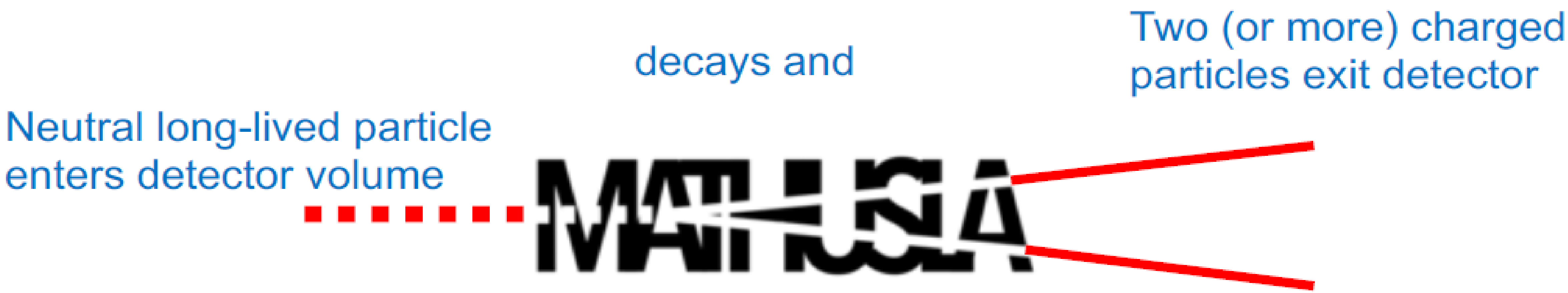
Outline

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
  - Simulations for Precise Rate Estimates
- Detector Design
- Technological Challenges
  - Trackers: Scintillator Bars, Fibers, SiPMs
  - Test Stands
  - DAQ & Front-End Electronics

Basic Concept



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

Motivation

Fundamental mysteries (DM, hierarchy, neutrino masses, …) require physics **Beyond the Standard Model (BSM)**

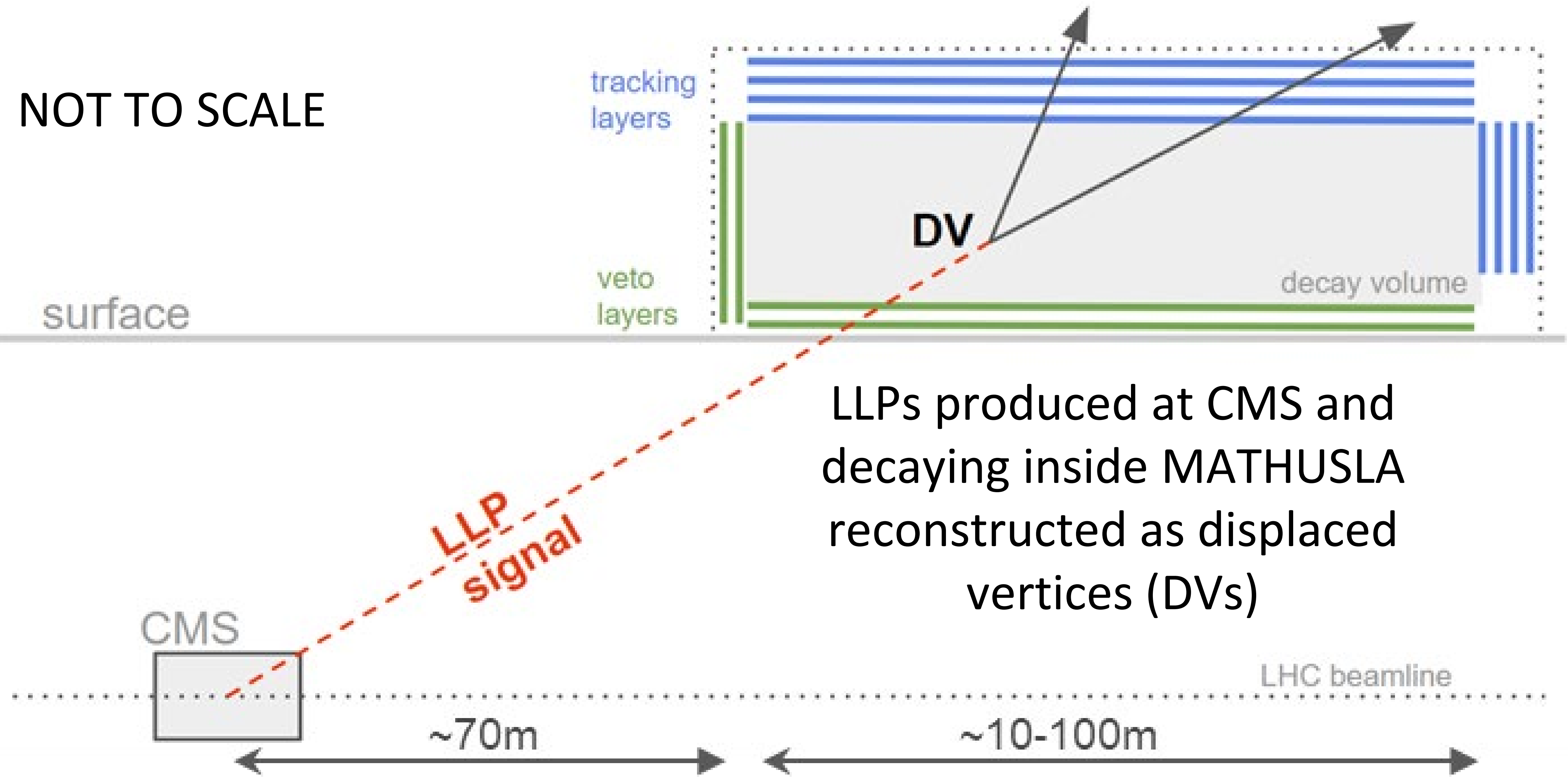
Undiscovered neutral Long Lived Particles (LLPs) that are invisible to LHC detectors ?

1. **BSM neutral LLPs** highly theoretically motivated
   - **Top down**: naturally arise in various BSM frameworks
   - **Bottom up**: LLPs occur in SM (e.g. muons), and can be incorporated via similar mechanisms in BSM models
2. **Hard to spot in LHC main detectors**
   - Most escape ATLAS / CMS if *$c\tau$ >> detector size (~10m)*
   - The tiny fraction that decay within detector get swamped by backgrounds

An External LLP Detector for HL-LHC

- **100-1000x more sensitive than main detectors** for **neutral LLPs** with lifetime up to the Big Bang Nucleosynthesis limit ($10^7 - 10^8$ m)
- Proposed **large-area surface detector** located **above CMS**
- Air-filled decay volume with scintillator layers for tracking

NOT TO SCALE

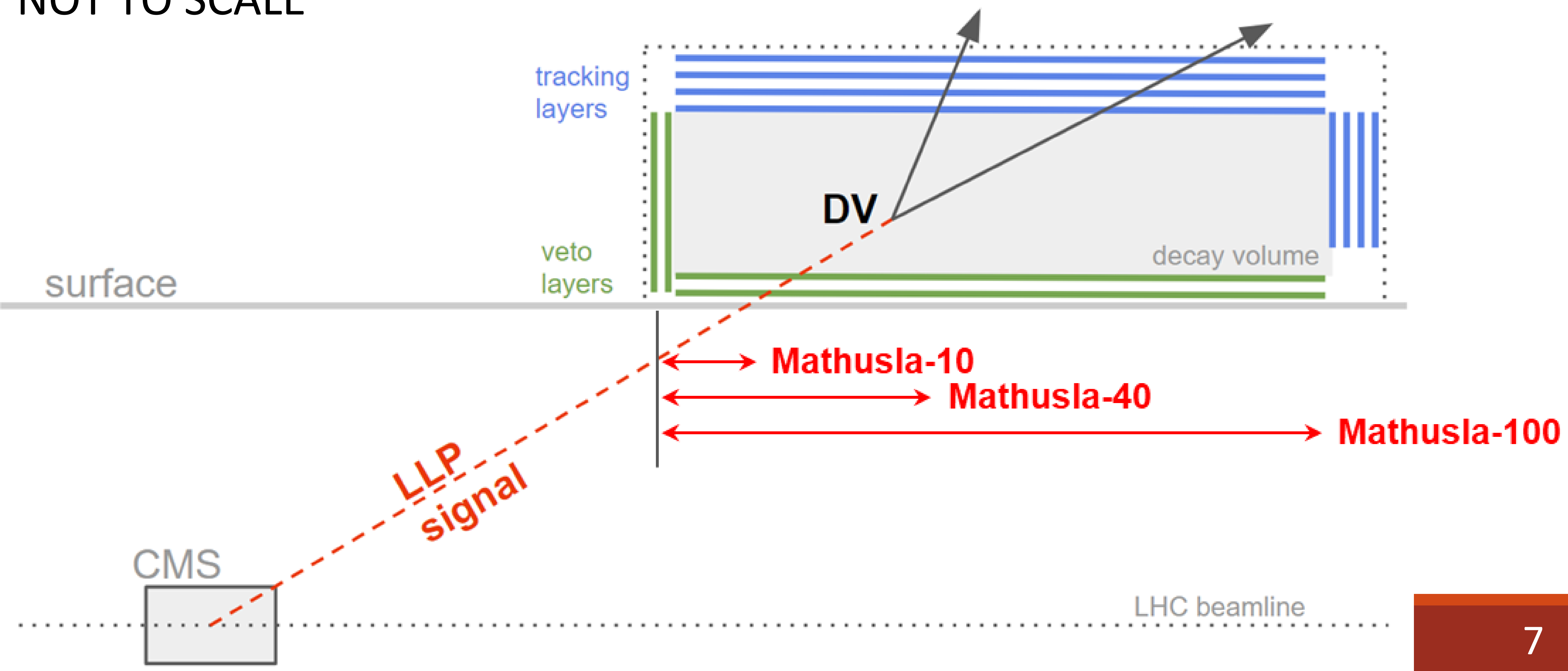


LLPs produced at CMS and decaying inside MATHUSLA reconstructed as displaced vertices (DVs)

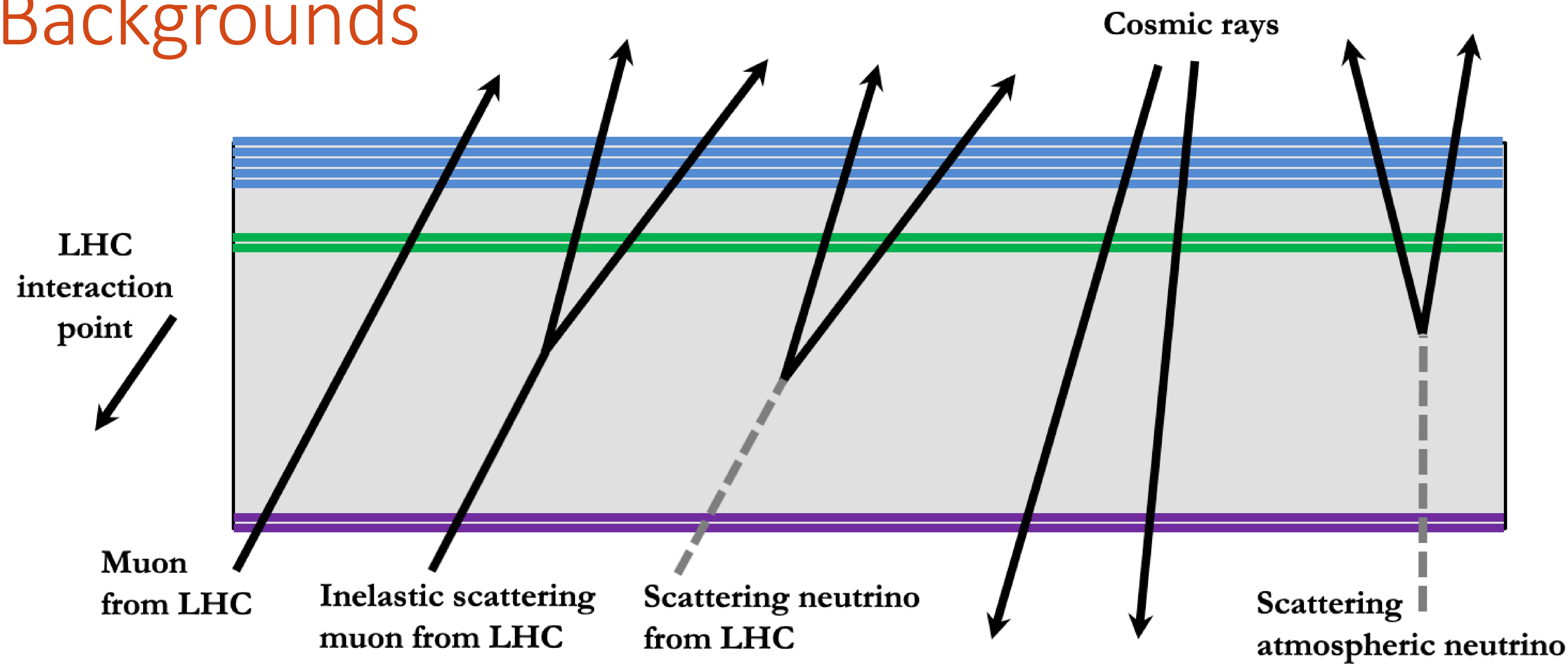
An External LLP Detector for HL-LHC

- Aiming for **~zero background** analysis
- Can run standalone, or “combined” to CMS
- Will not interfere with any other LHC experiments
- Staged construction & commission: independent 10m^2 modules

NOT TO SCALE



Backgrounds

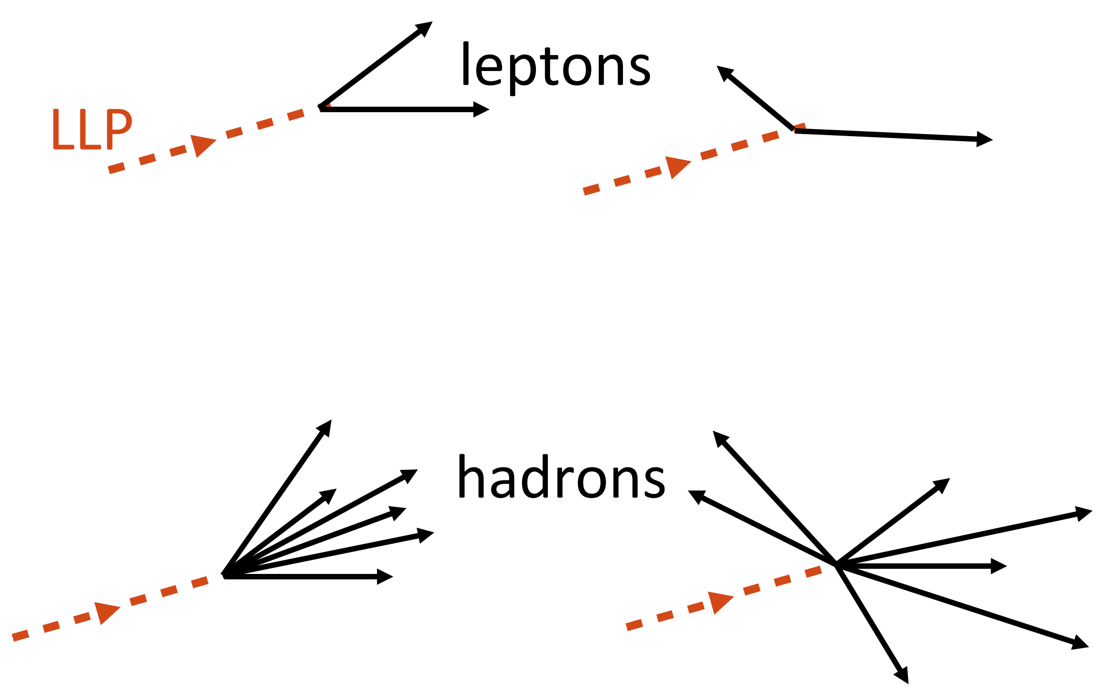


LLP DV signal must satisfy many stringent geometrical & timing requirements ("4D vertexing" with cm/ns precision)

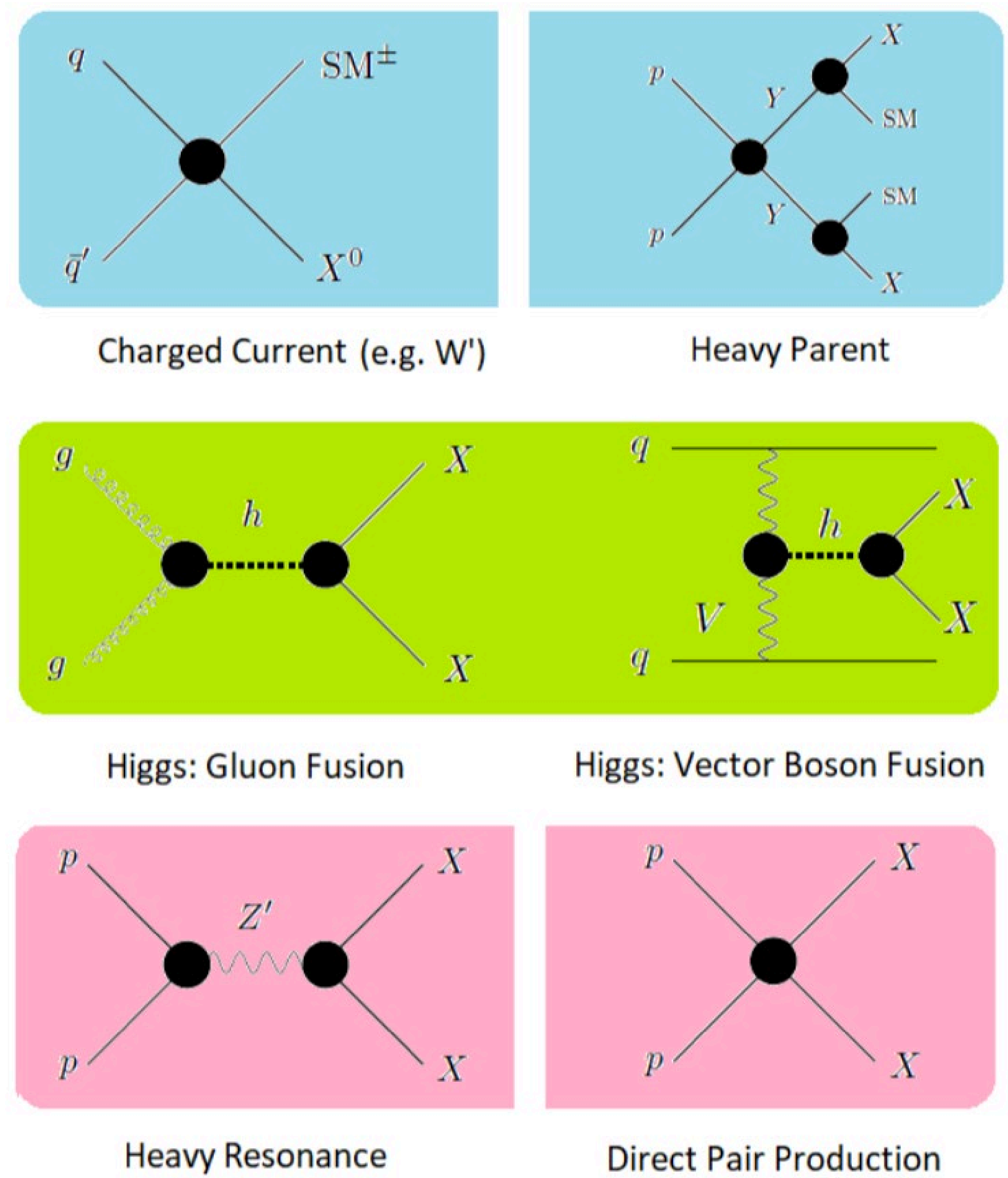
Add a few extra cuts for "~zero background" (< 1 event/yr)

Identifying LLPs

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



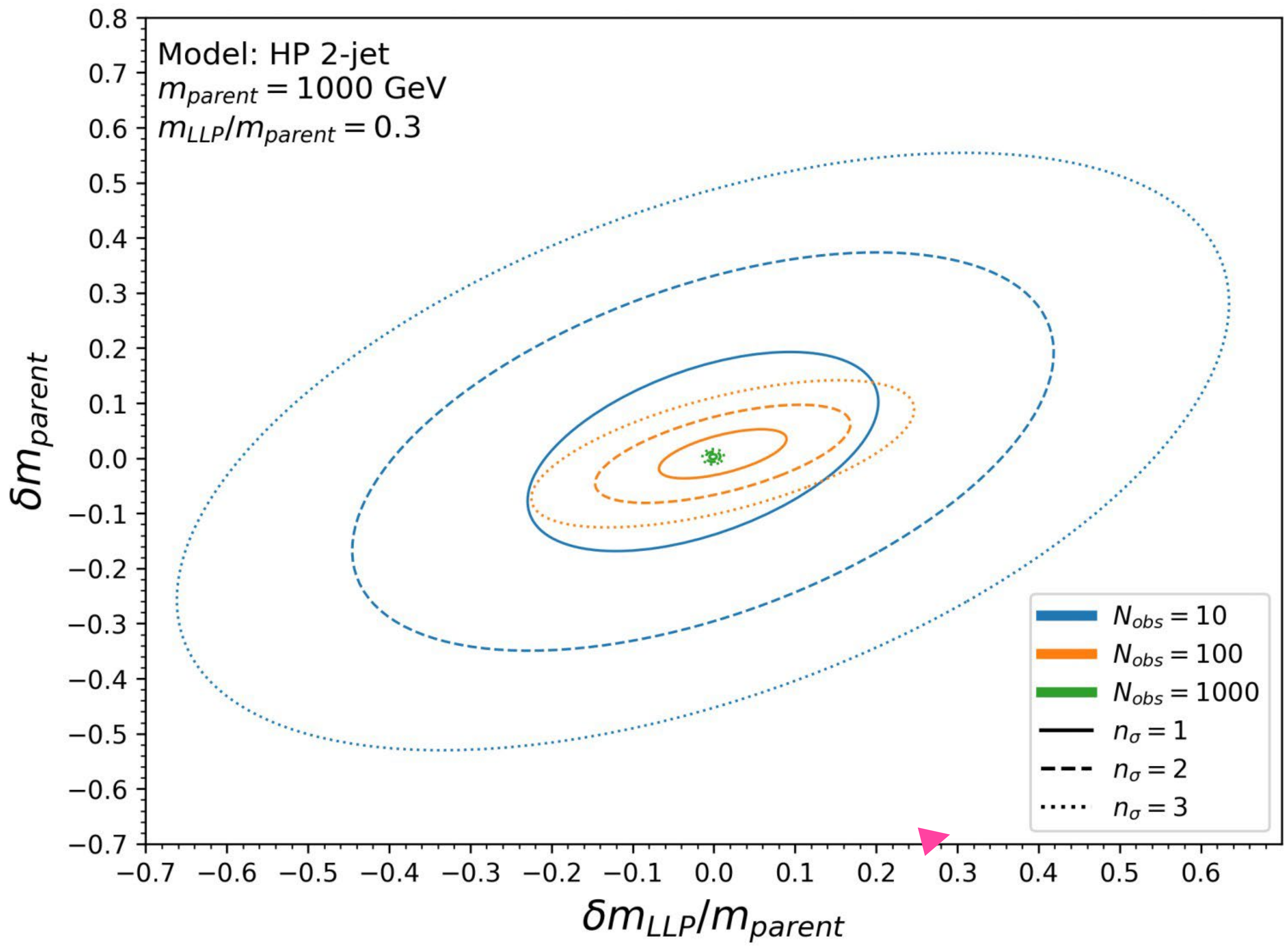
Incorporate MATHUSLA into CMS L1 Trigger
Correlate event info off-line → determine LLP production mode



Identifying LLPs

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

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



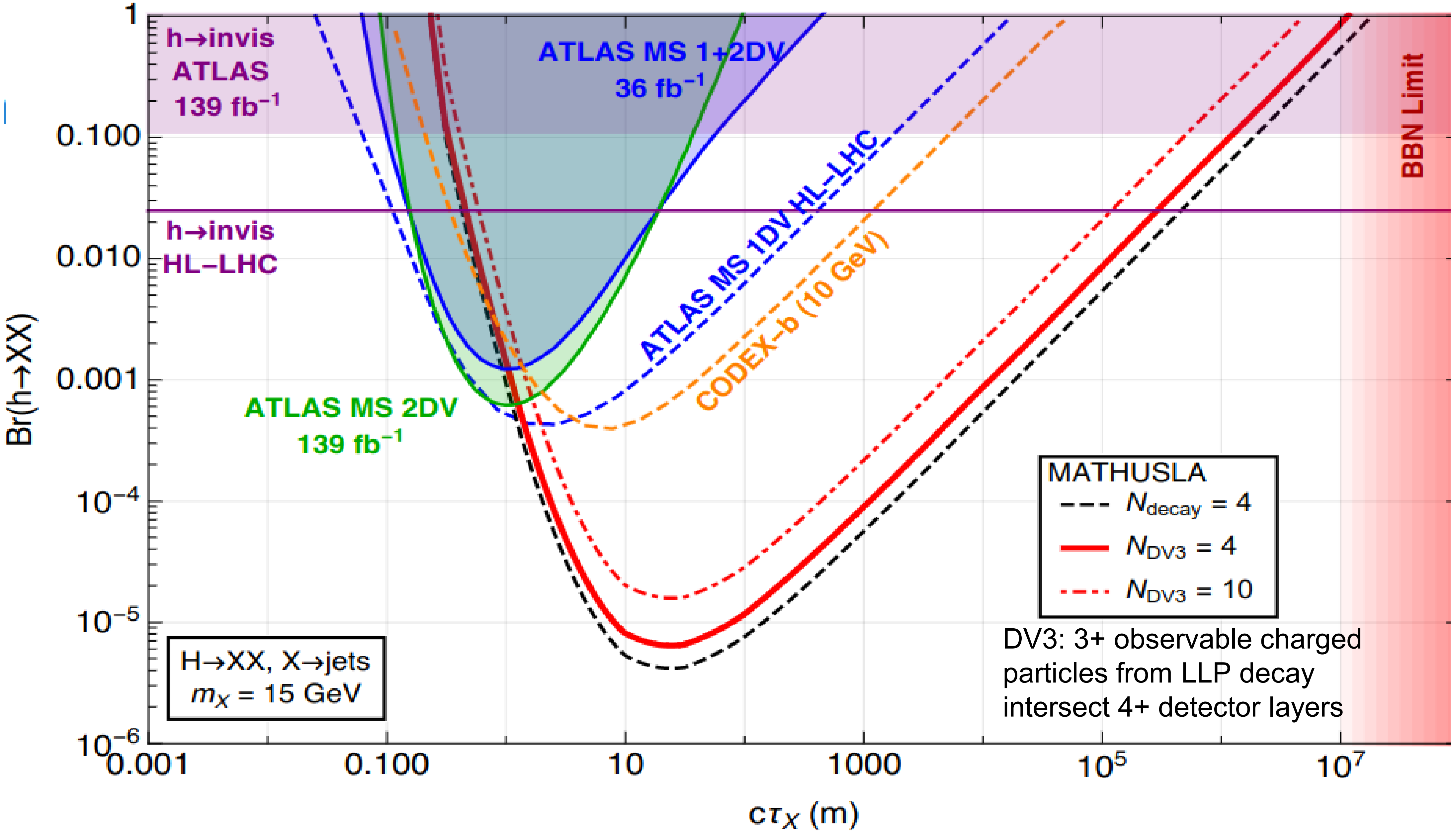
arXiv:2007.05538 , 1809.01683

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

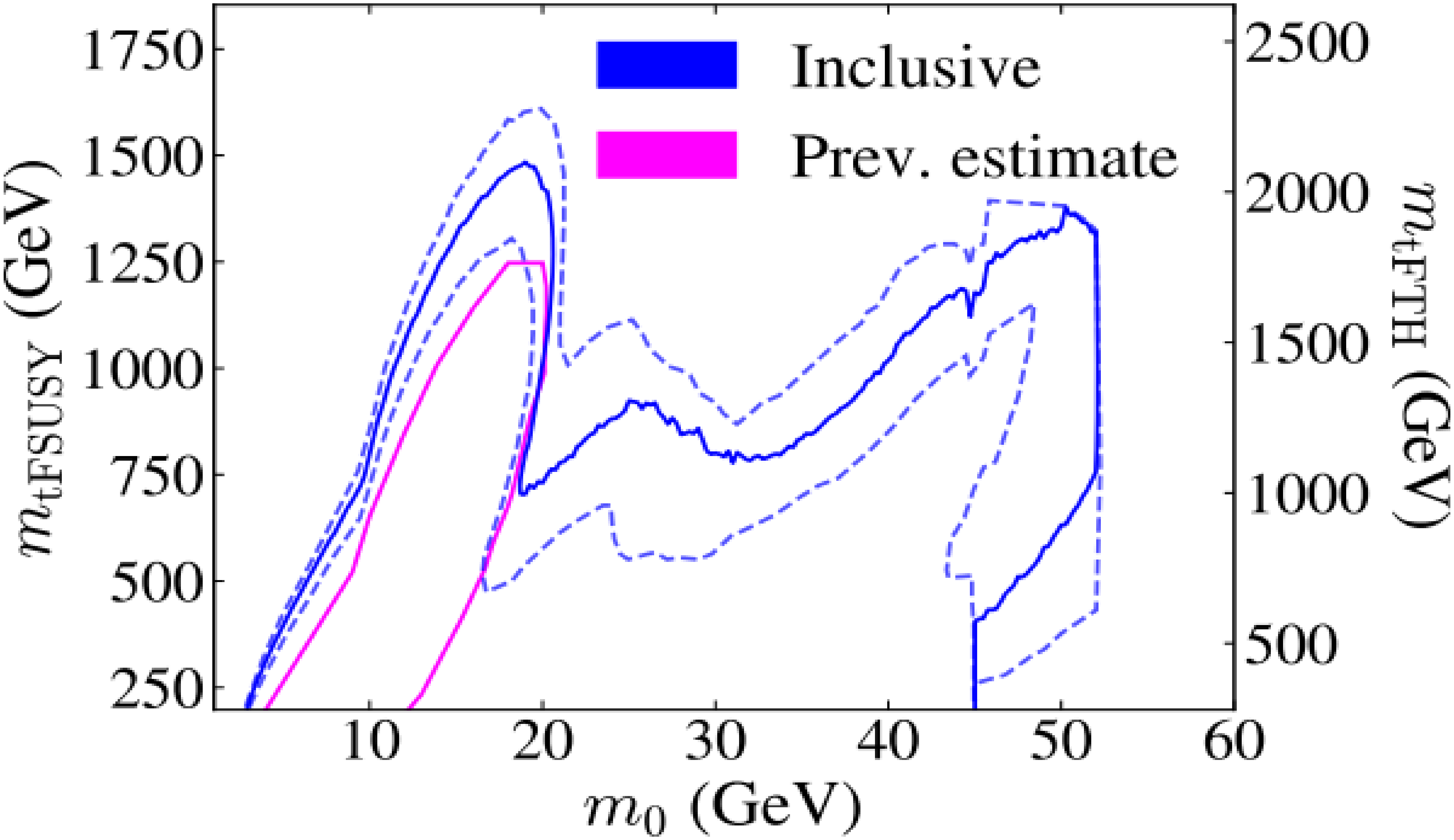
Primary physics case: hadronically-decaying LLPs, ~10-1000 GeV (e.g. in exotic Higgs decays)



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

LLP Sensitivity: Weak- to TeV- Scale

Dark glueballs: wide sensitivity found with recently-improved modeling (e.g. in neutral naturalness / SUSY models)

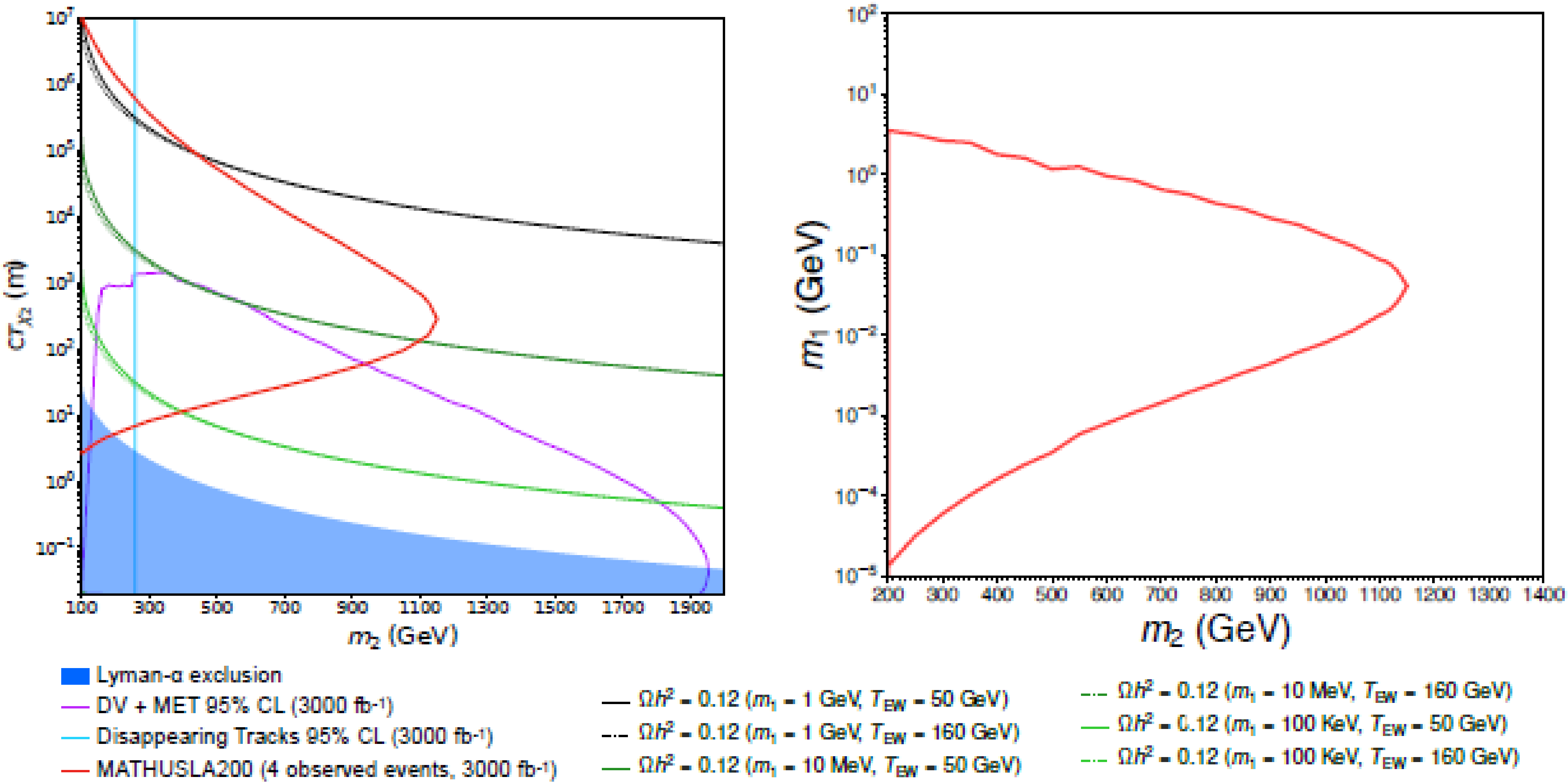


arXiv:2310.13731

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)



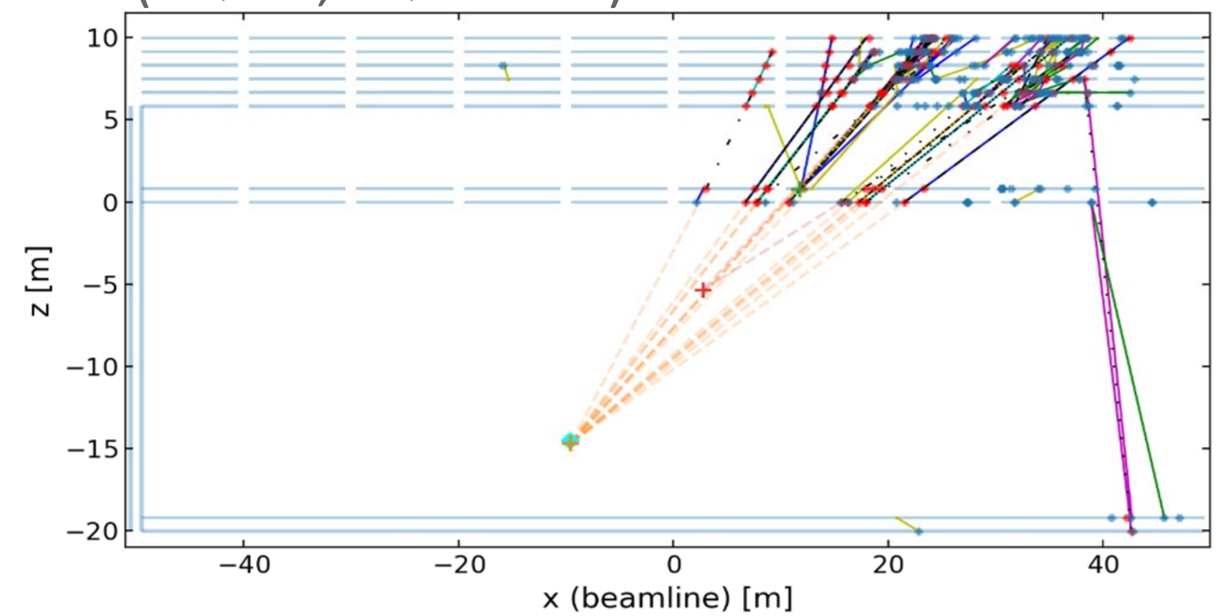
Simulation & Reconstruction for Precise Rate Estimates

Simulation: two packages

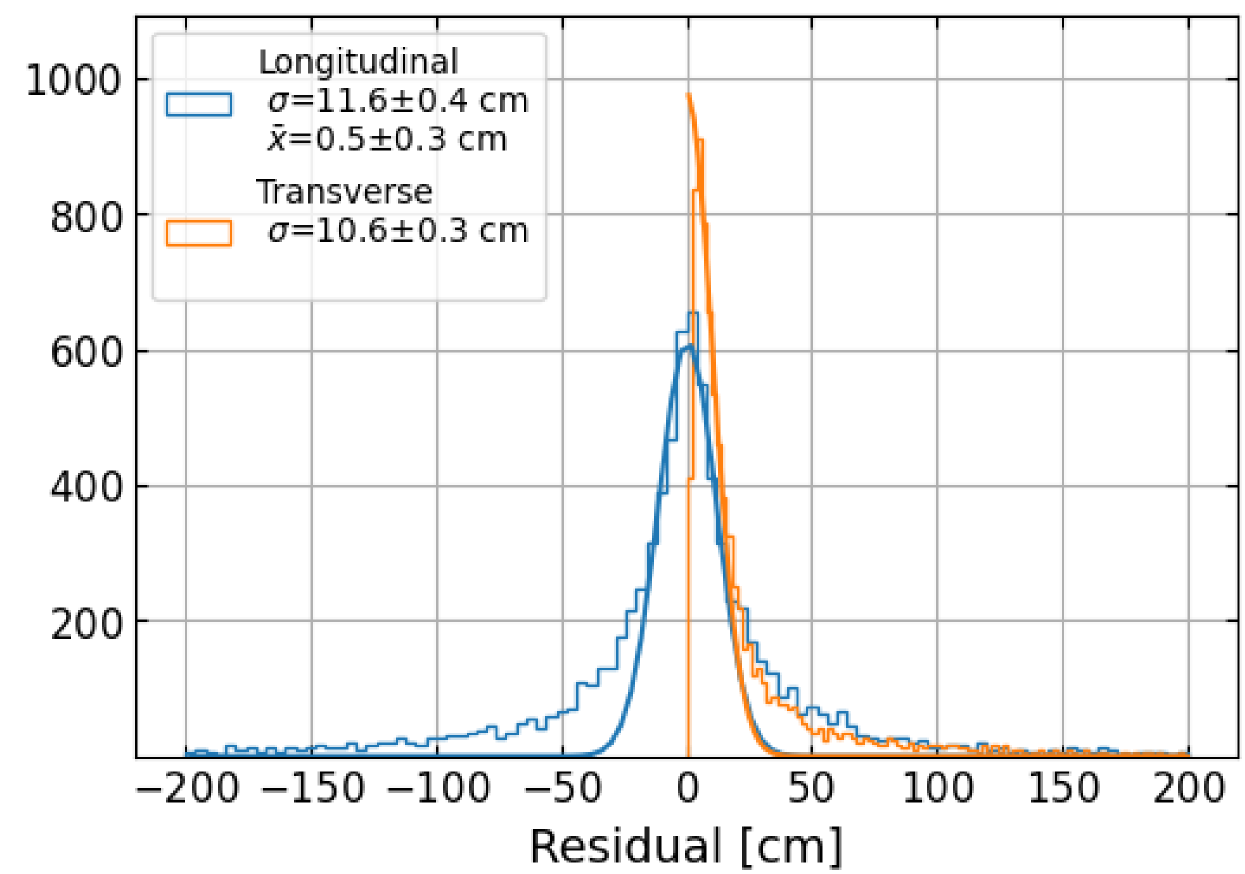
- **FastSim**, geometry-only detector simulation, used in the sensitivity studies shown previously
- **Full Geant4 simulation** underway, for more precise background rate projections

Reconstruction: Kalman filter-based track and vertexing, same for simulated as planned for real data

Simulated hadronically-decaying LLP (H→XX, X→b bbar)

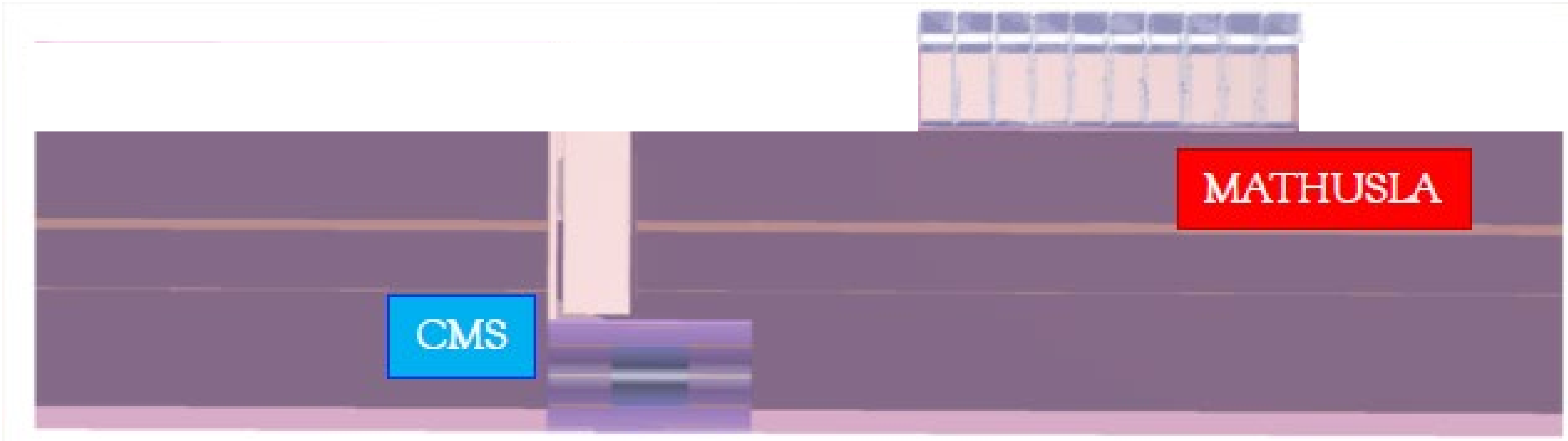


Reconstructed vertex resolution



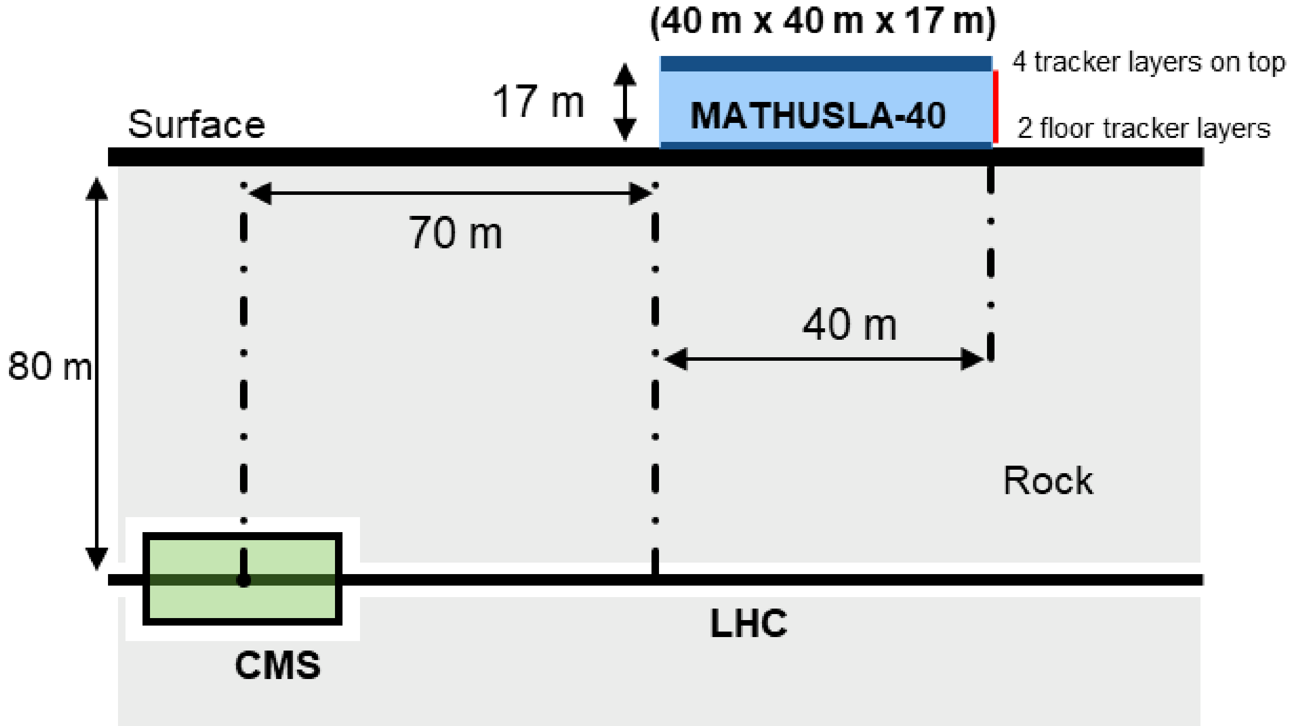
Simulation & Reconstruction for Precise Rate Estimates

- Full Geant4 simulation: includes cavern, access shaft, CMS, rock, detector
  - Rock model from a geological survey

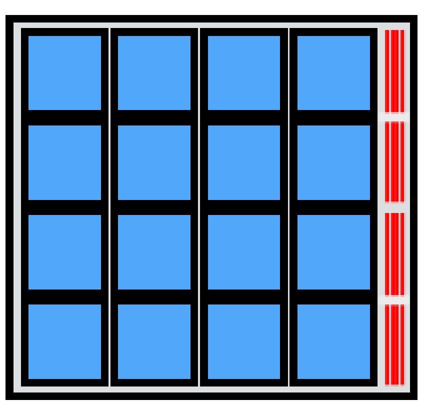


- Backgrounds under detailed study:
  - Upward-going muons from collisions (Pythia8)
  - Backscatter (to upward-going V^0) from cosmic rays (Parma)
  - Neutrino interactions (Genie3)
- Quantifying the background rejection power of the high-coverage floor veto, [partially]- instrumented walls

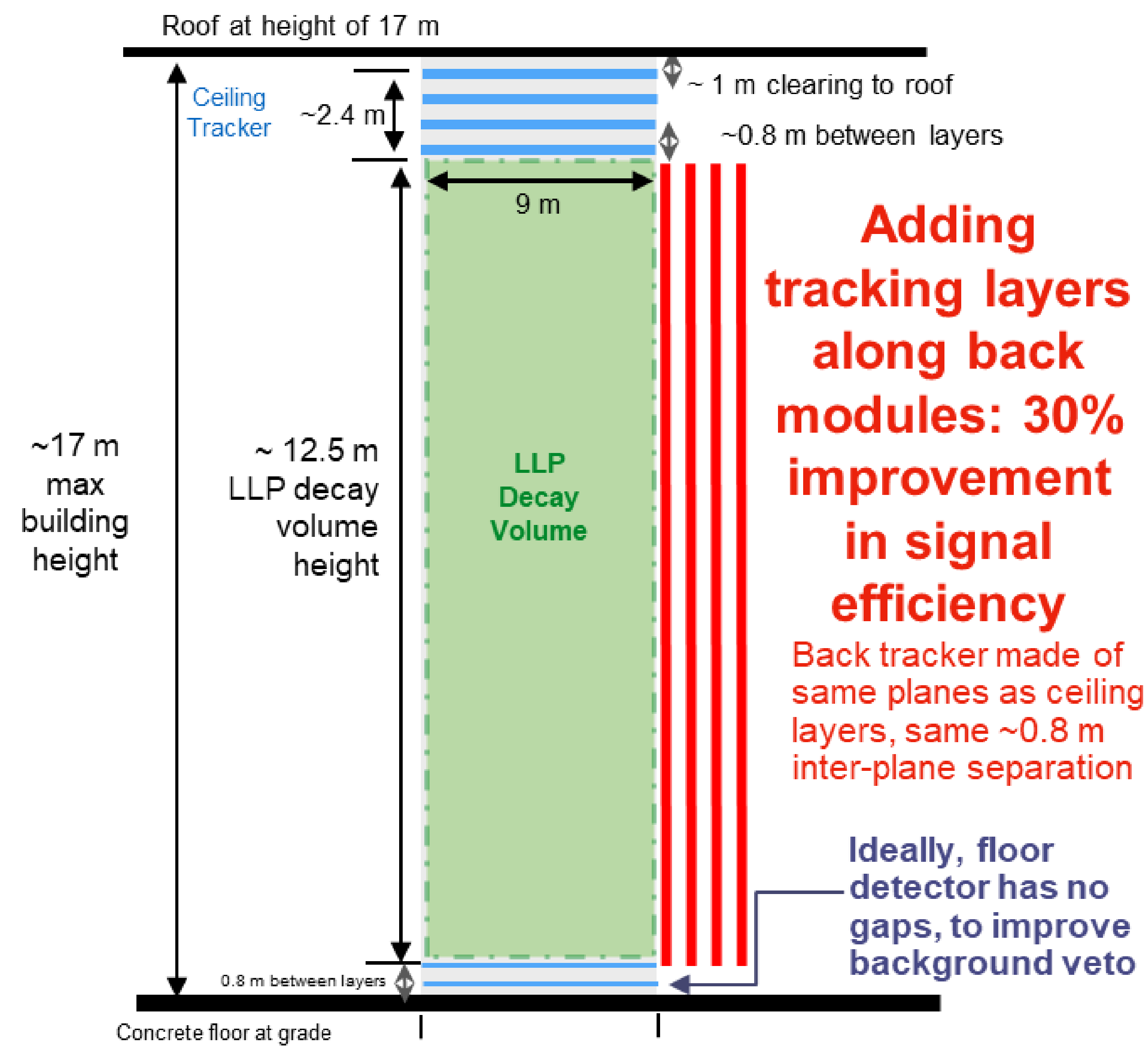
Simulation & Reconstruction for Precise Rate Estimates



Side view with CMS



Cross-section of MATHUSLA: 4 x 4 grid of 9 m x 9 m modules, ~1 m gap between modules



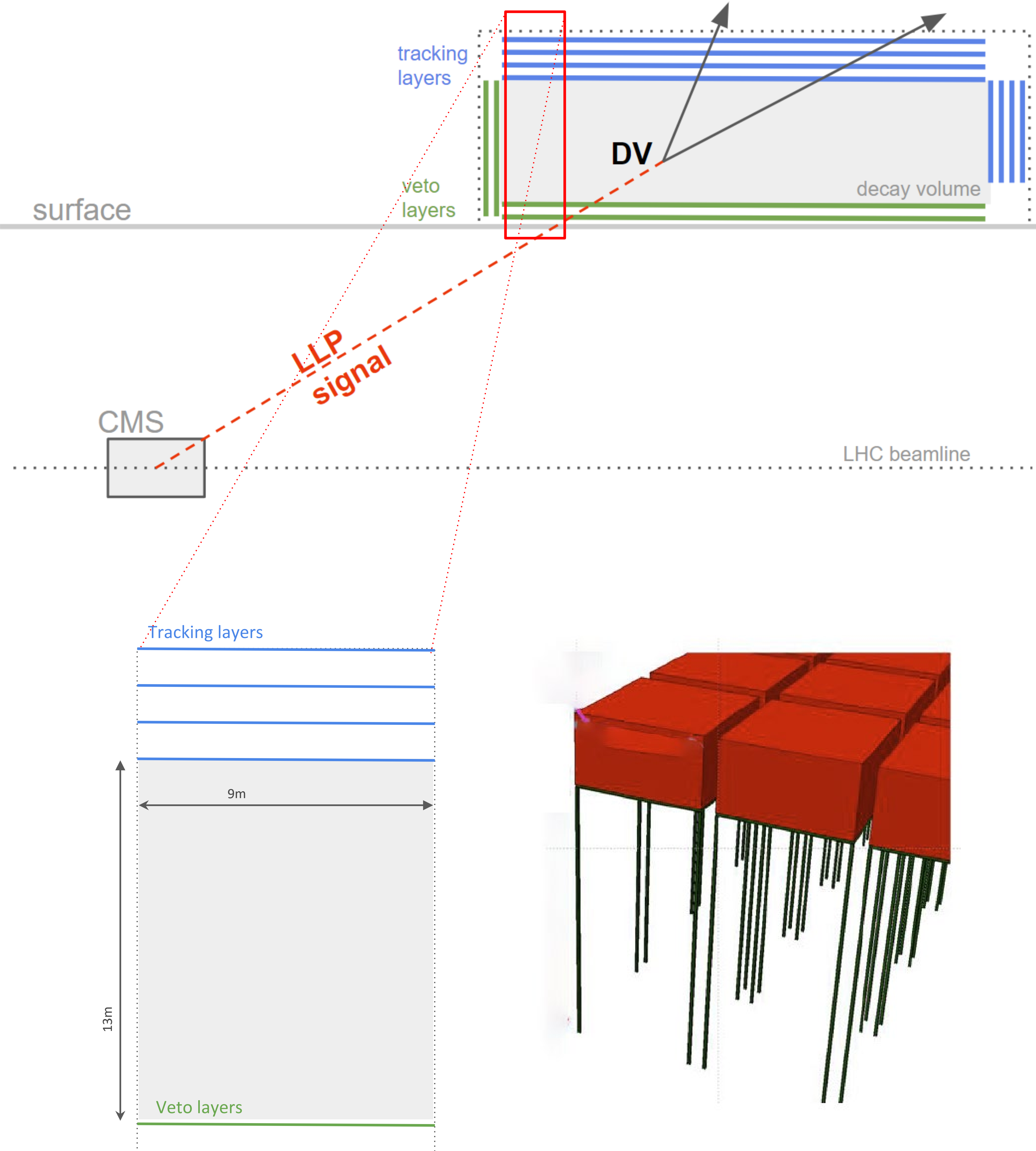
Vertical structure detail (not showing any mechanical supports etc) for a single 9 m x 9 m sensor module

Detector Design

Detector Layout

Large scale tracker with veto layers

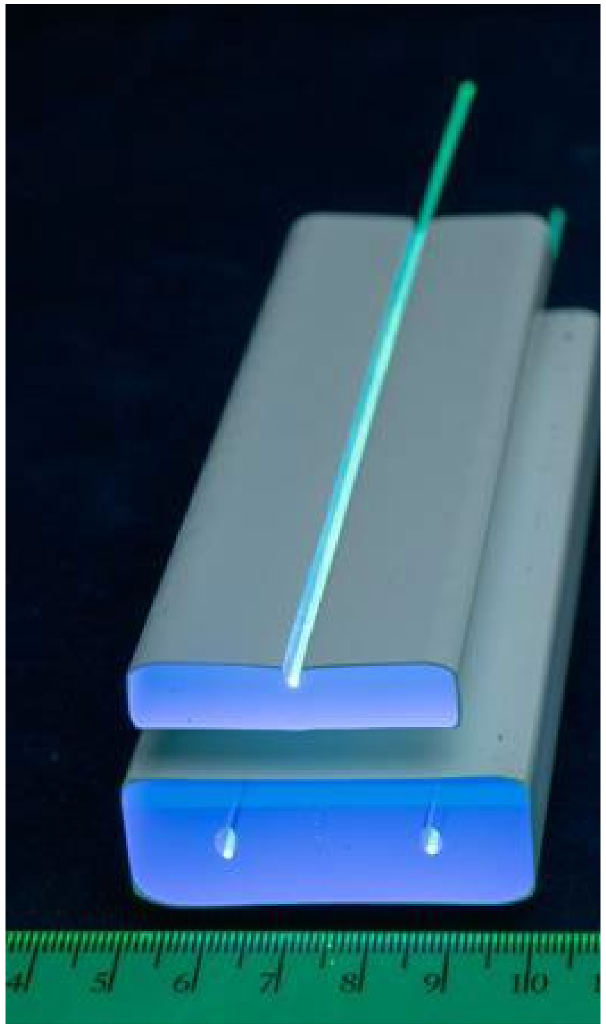
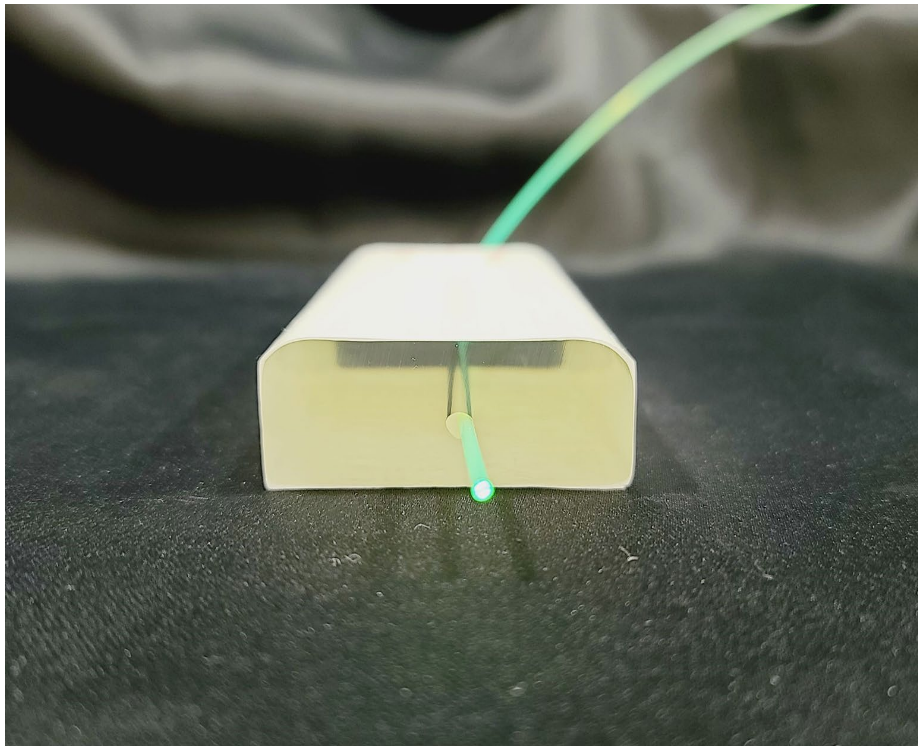
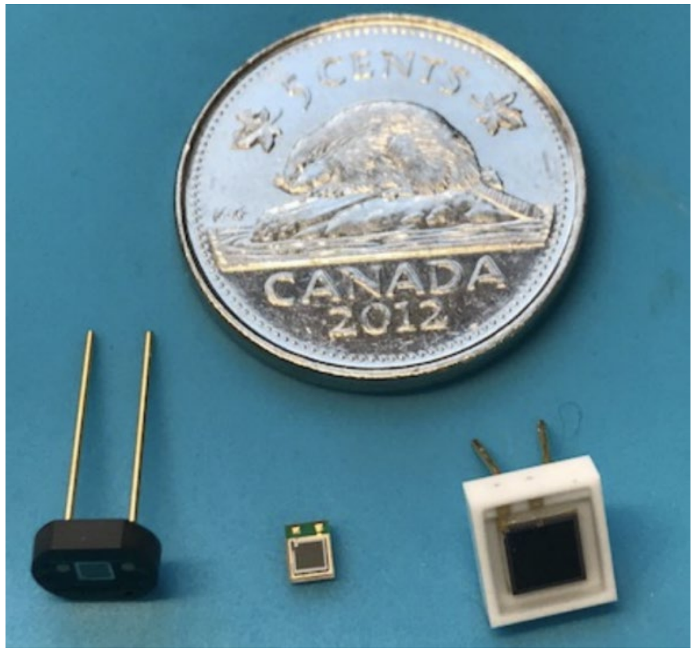
- Each tower module **9x9 m area**
- 2 veto layers, 4 or 5 tracking layers
- Height of decay volume limited by the CERN building height rules
- Floor **veto layer** hermetic (using additional tracker plane between modules)
- Wall veto layers constructed separately



Tracker Layers

Composed of extruded scintillator bars with WLSFs (wavelength-shifting fibers) coupled to SiPMs (Silicon Photo Multipliers)

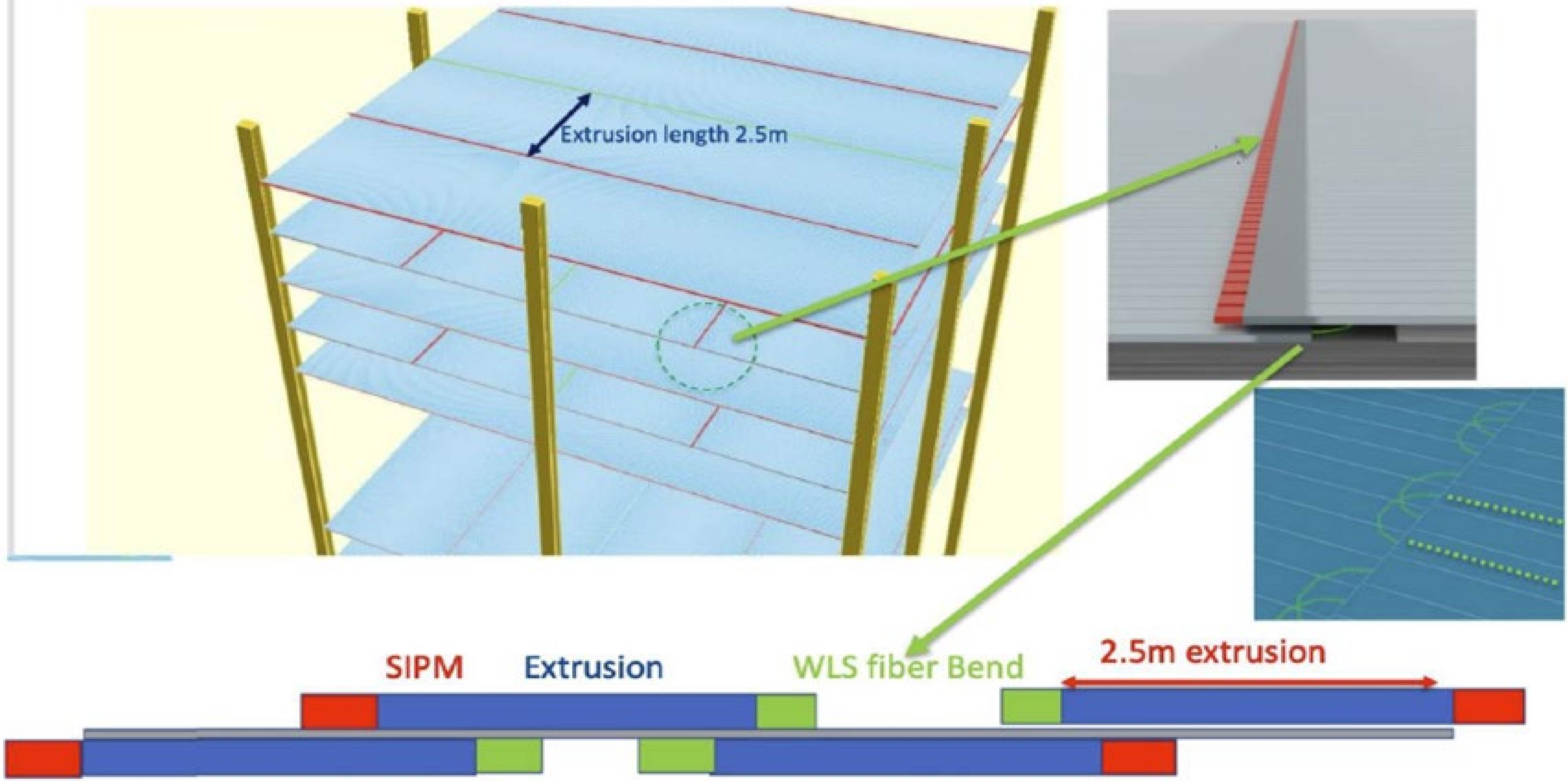
- Bar extrusion facilities in FNAL used for several experiments (e.g. Belle muon trigger upgrade, Mu2e)

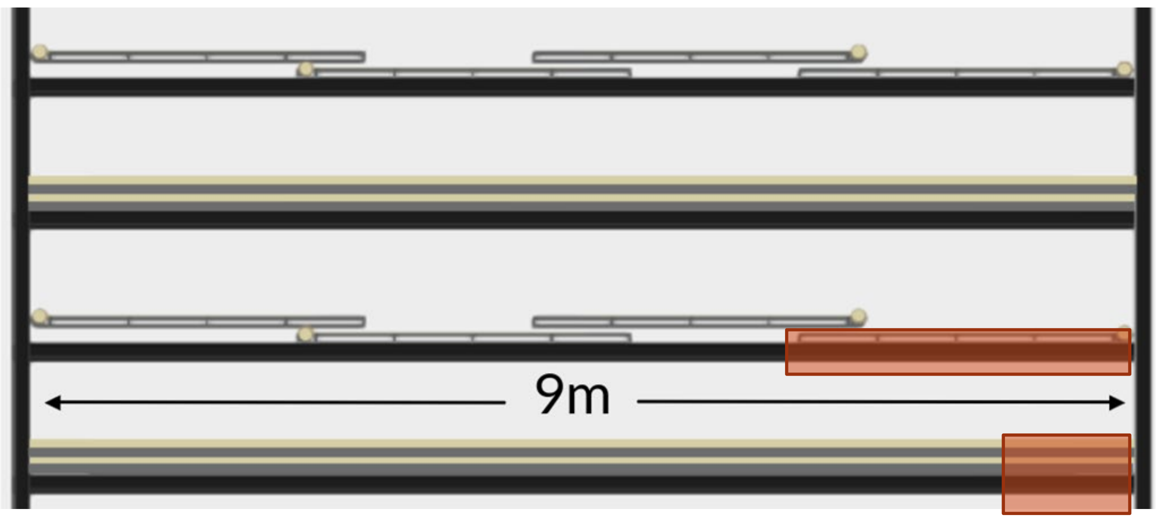
Tracker Layers

Nominal layer design: 256 bars, each 2.7 m long

- Each layer segmented into 4 sheets of bars, made from “bar assemblies” 1.1 m wide that can be manufactured in the lab
- Overlapping sheets, alternating layer orientation: no gaps in coverage

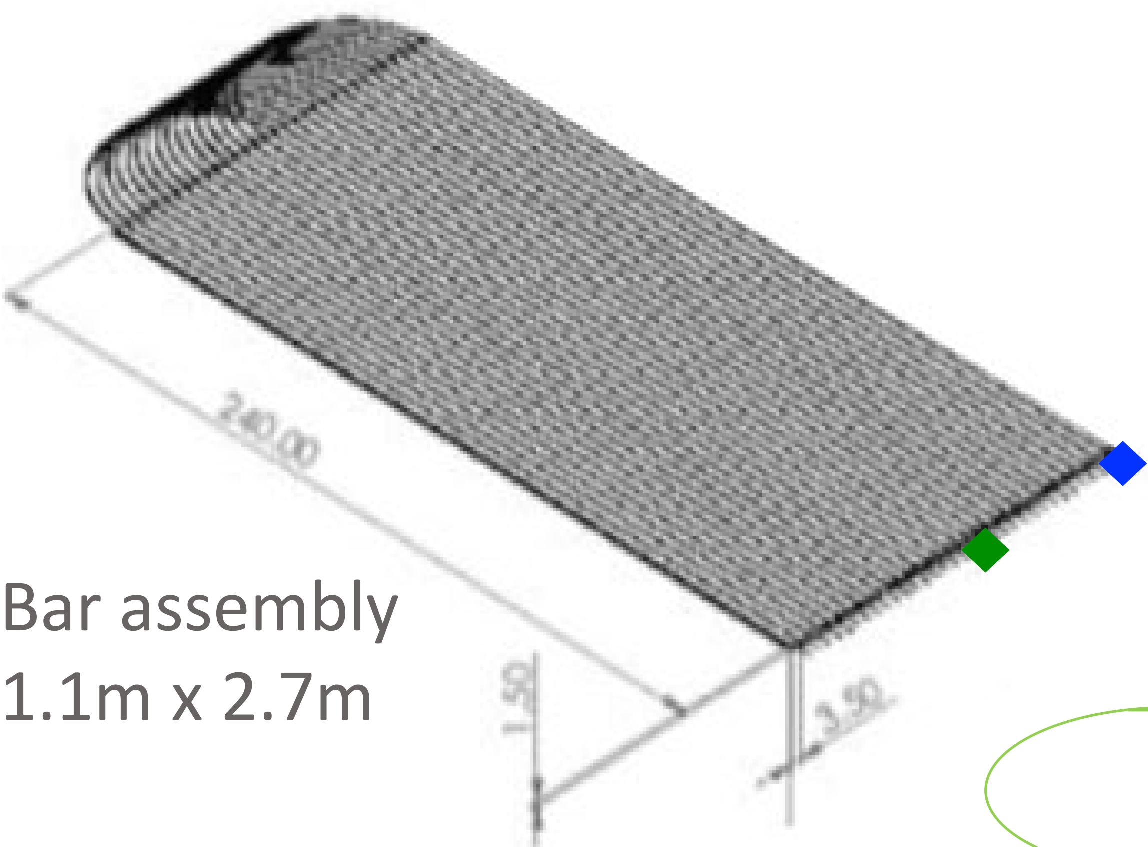


Tracker Layers

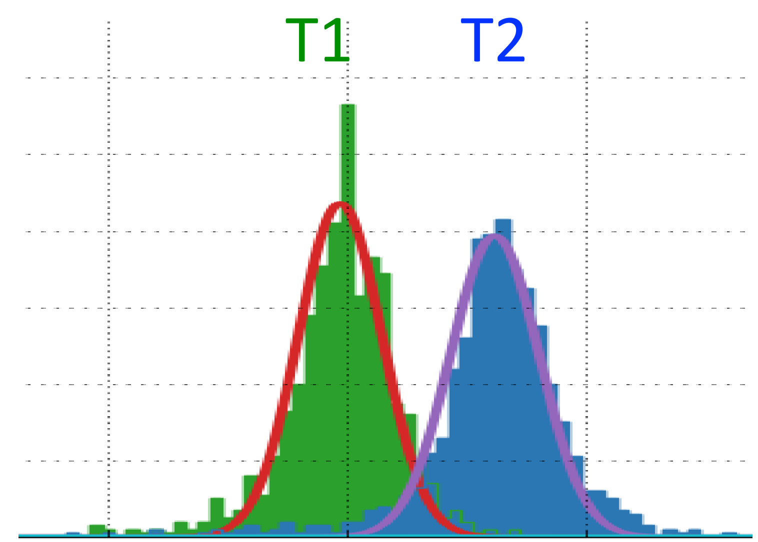


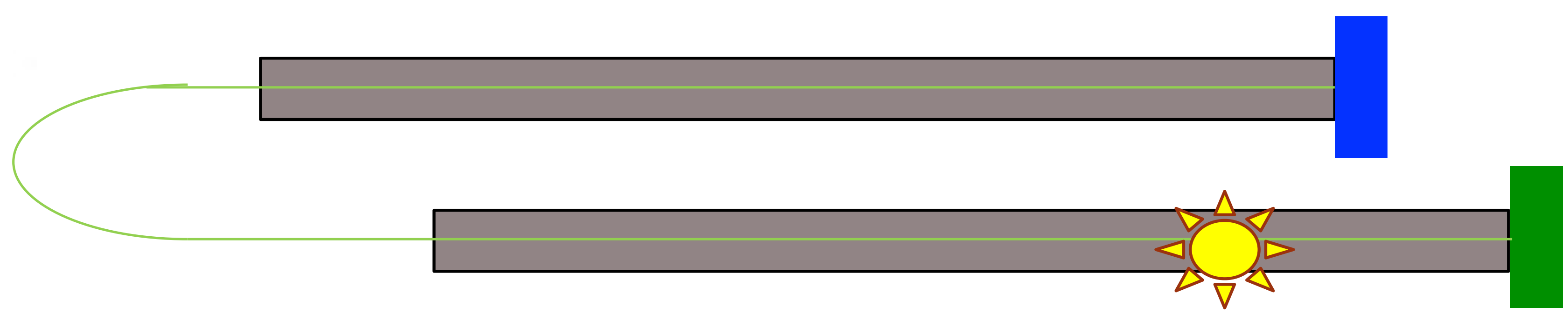
Each fiber loops through 2 bars, readout at both end

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



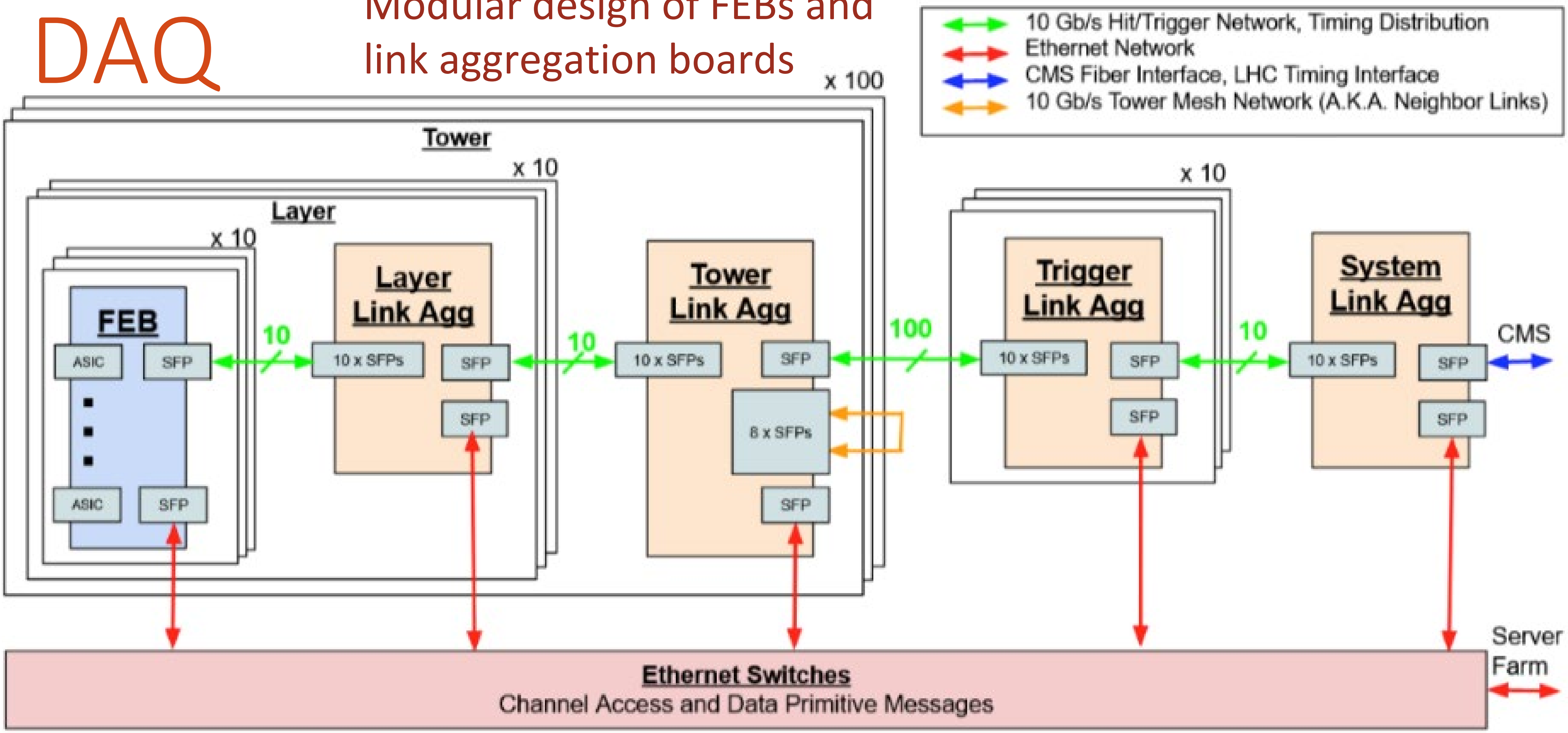
Bar assembly
1.1m x 2.7m





DAQ

Modular design of FEBs and link aggregation boards

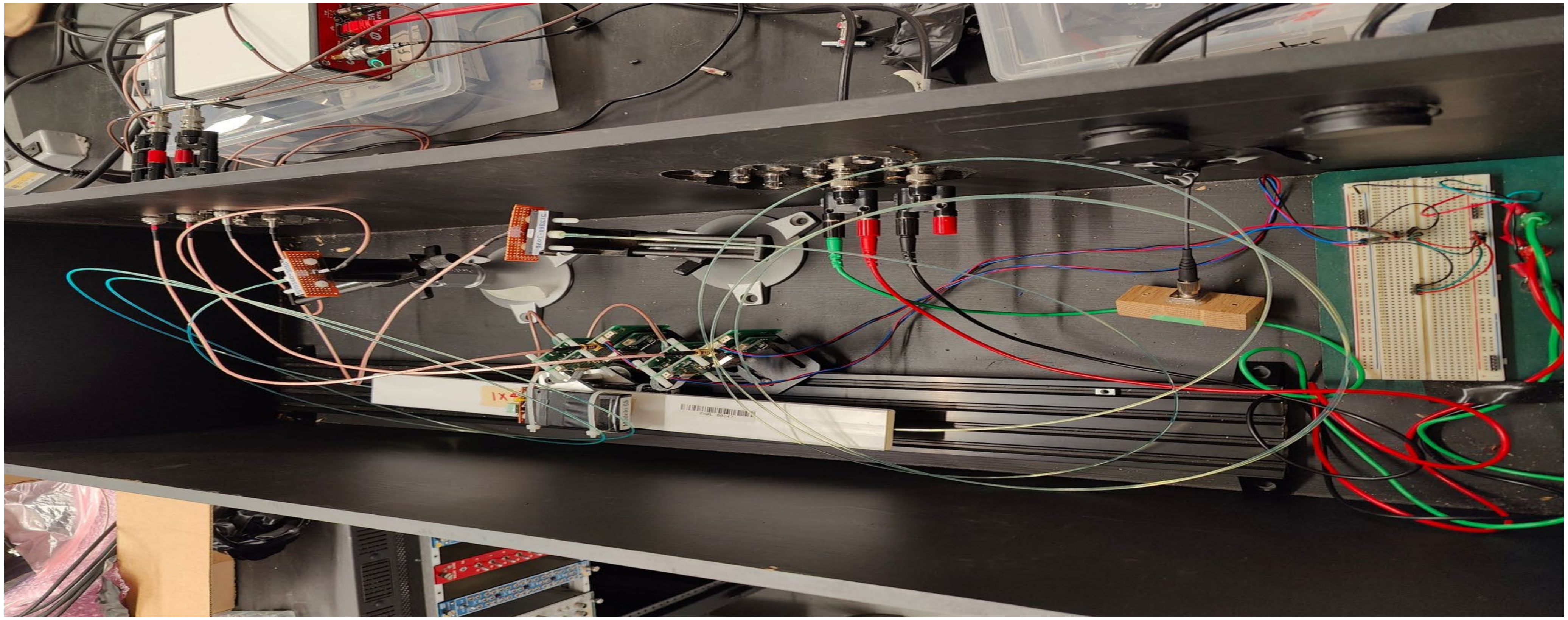


- **MATHUSLA Trigger**
  - Tower agg module triggers on upward-going **tracks** within 3x3 tower volume
  - Selects data from buffer for permanent storage
- **Trigger to CMS**
  - Upward-going **vertex** forms trigger to CMS
  - Trigger latency estimates appear compatible with CMS L1 latency budget
-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

Technological Challenges

Scintillator + WLSF + SiPM

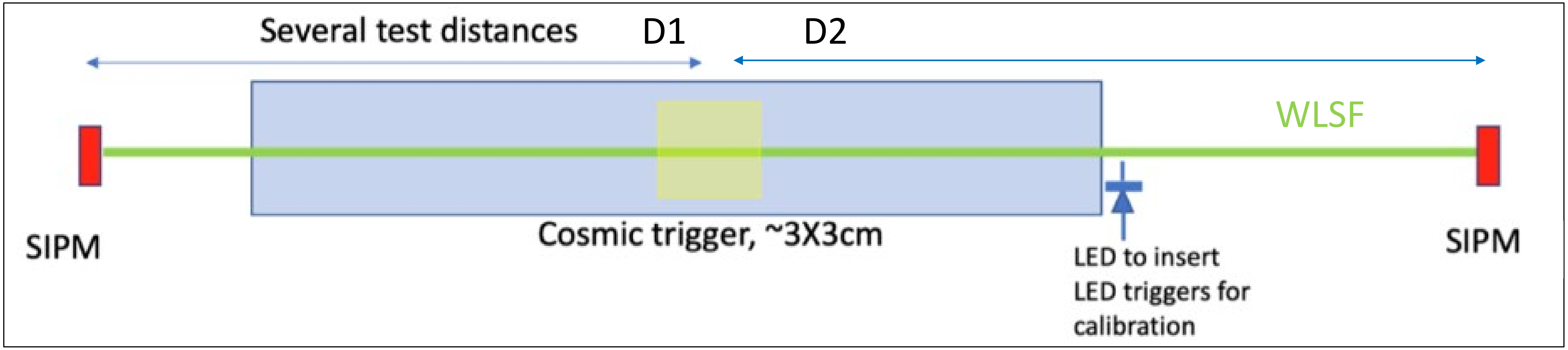
- Dark-box setups at UToronto & UVic have studied different vendors/models of scintillator, WLSF, SiPM:
  - **Optimizing timing (position) resolution**
  - Light yield
  - Light leakage and fiber stress
  - Temperature effects, e.g. on SiPM dark current



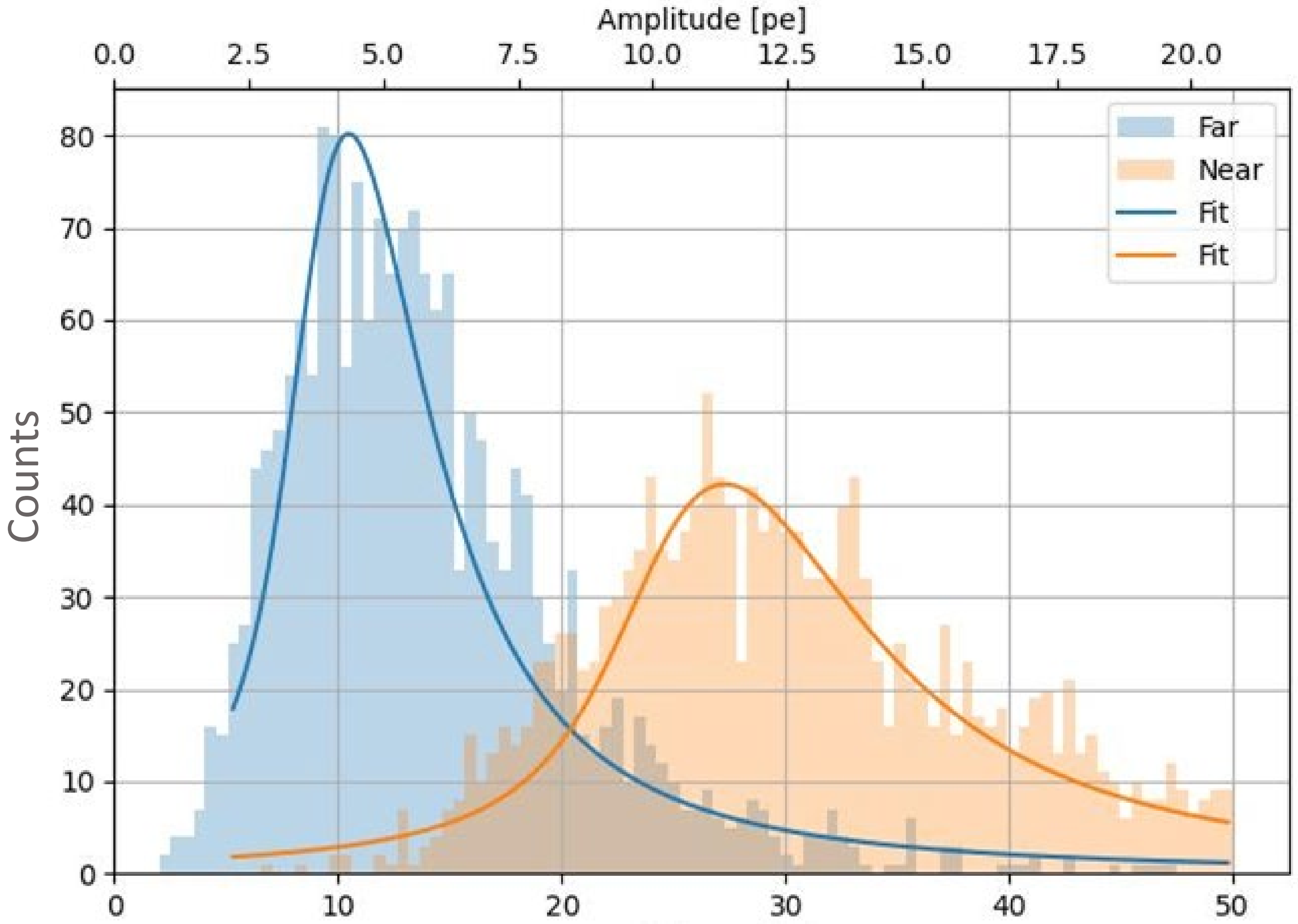
Scintillator + WLSF + SiPM Timing

Precise timing is critical

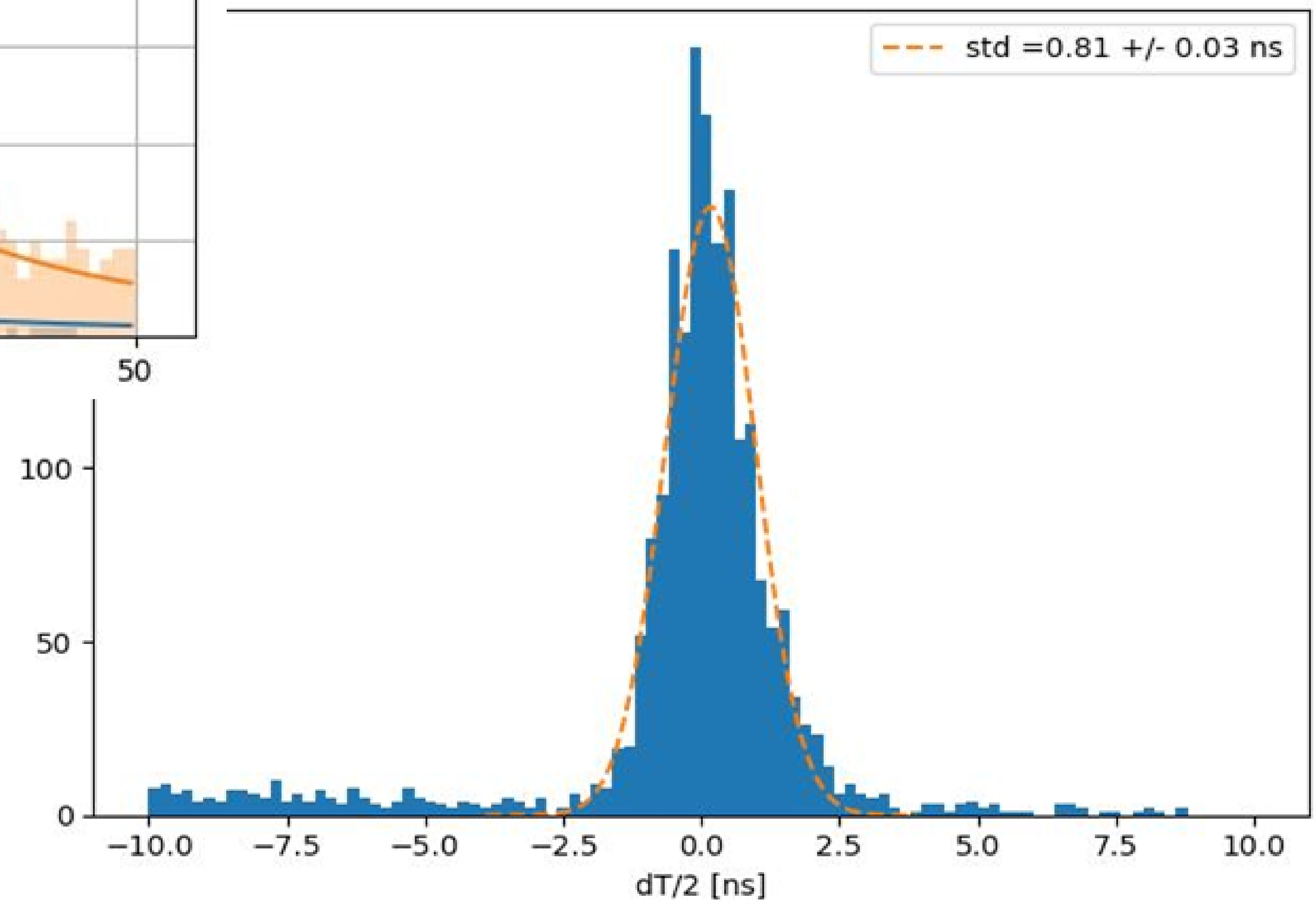
- Separates downward- from upward-going tracks
- Rejects low-β particles from neutrino quasi-inelastic scattering
- “4D” tracking and vertexing reduces fakes/combinatorics



Scintillator + WLSF + SiPM Timing



0.81 ns timing resolution
(cosmic ray muon,
Saint-Gobain BCF92XL fiber,
Hamamatsu S14160-3050HS SiPM,
1 cm thick scintillator bar)

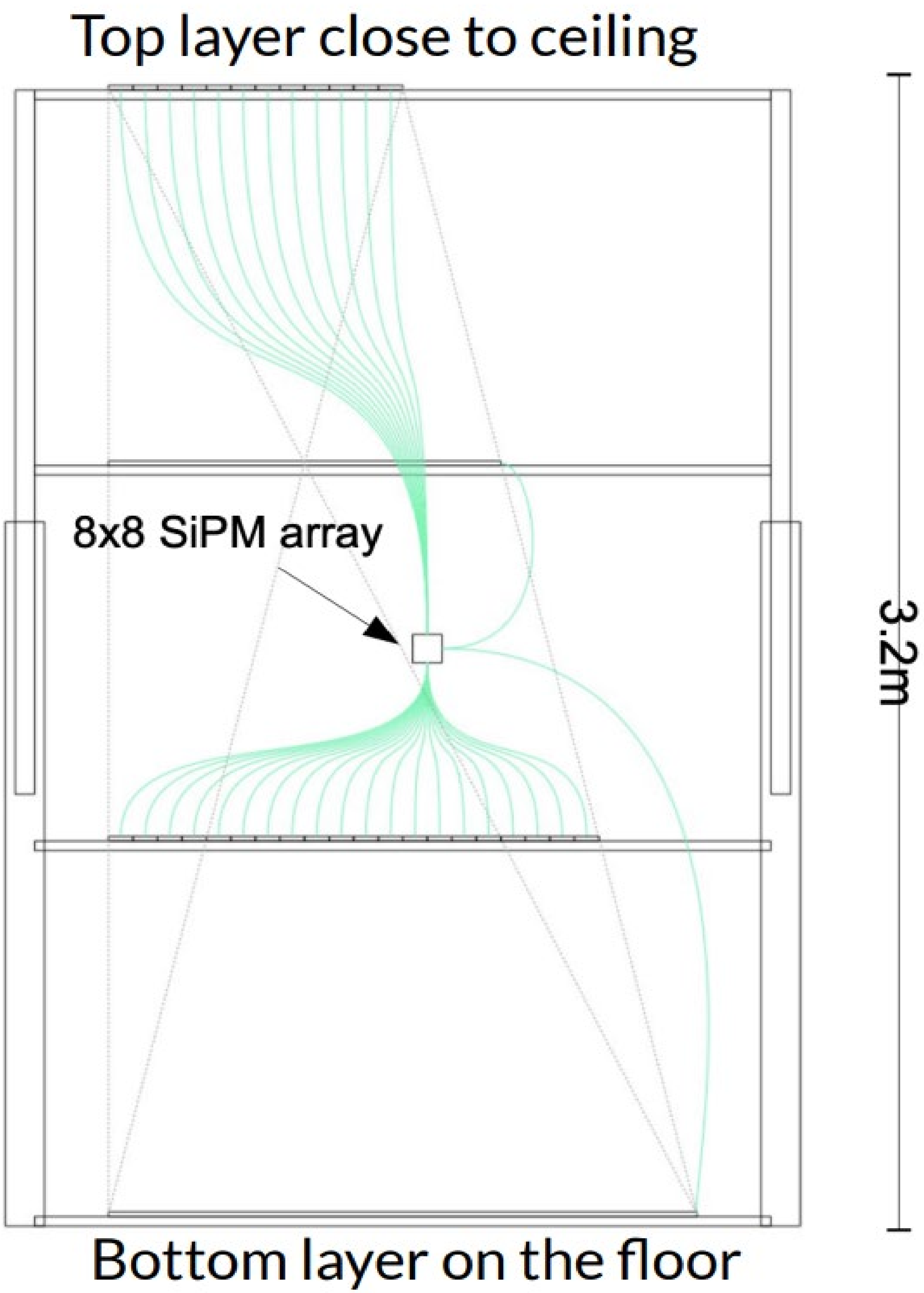


Fiber type is important: e.g.
Kuraray is too slow,
Saint-Gobain BCF92 has too
much attenuation

Test Stand @ UVic

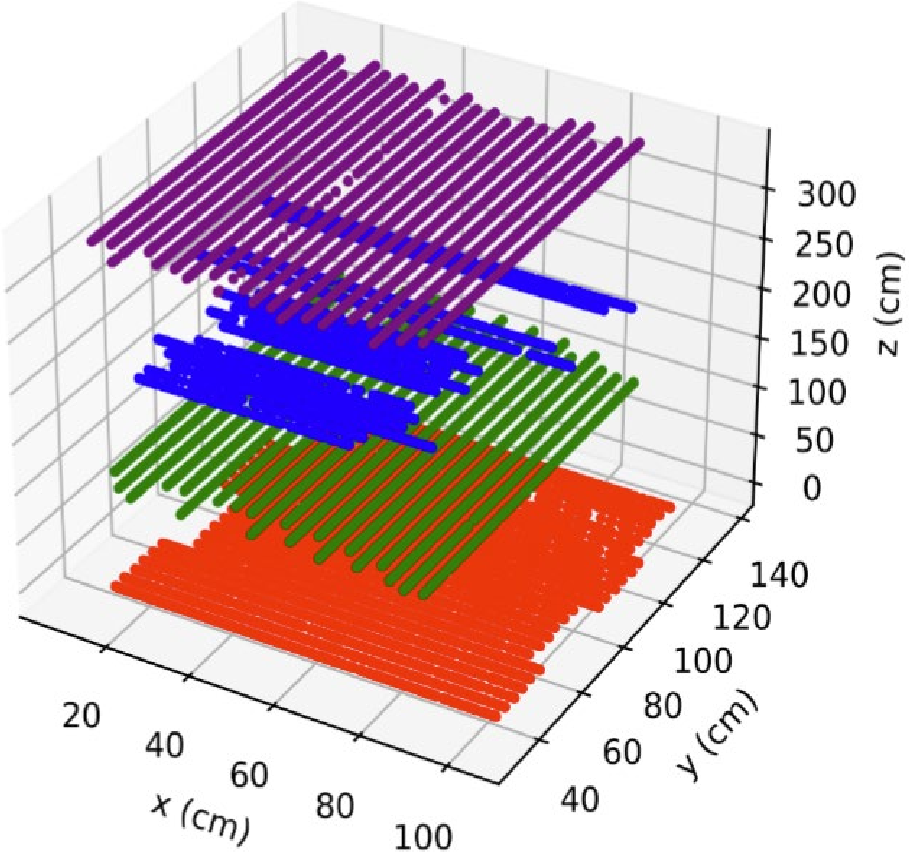
64-channel “mini-module” of 4 layers, ~1m x 1.5m each

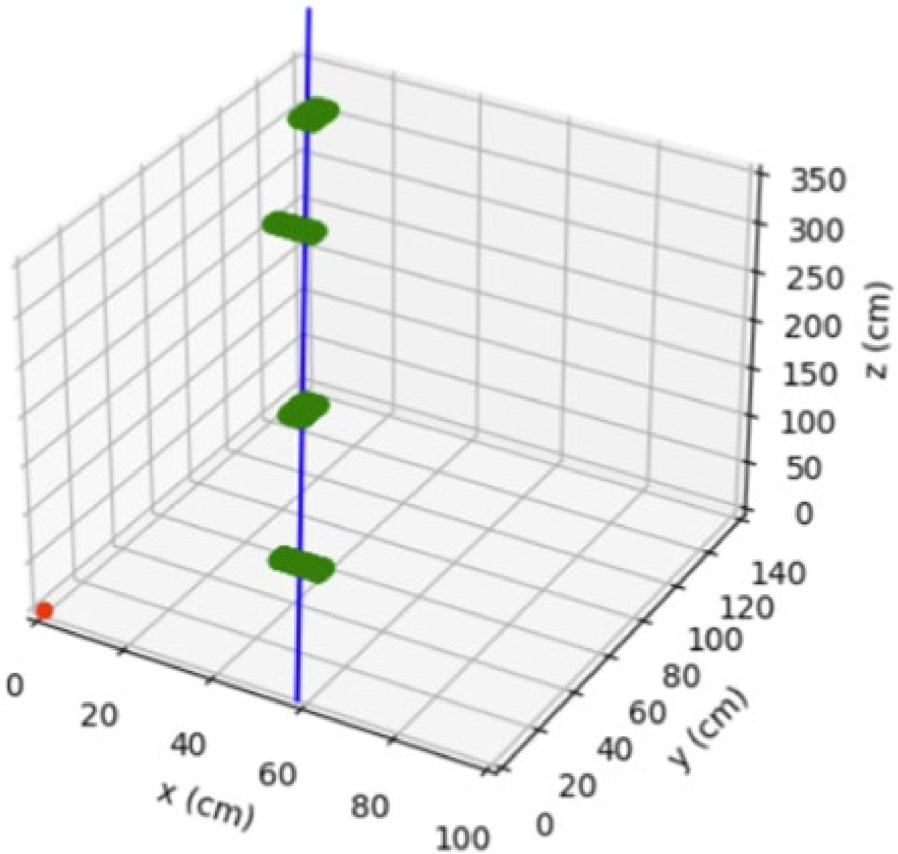
- Mechanical structure options
- Basic track reconstruction with cosmics (validation, performance)
- Basic triggering
- Hit efficiencies, effects of gaps between bars
- Comparisons with simulations



Test Stand @ UVic

Cosmic ray events





Reconstructed muon track passing through all 4 layers

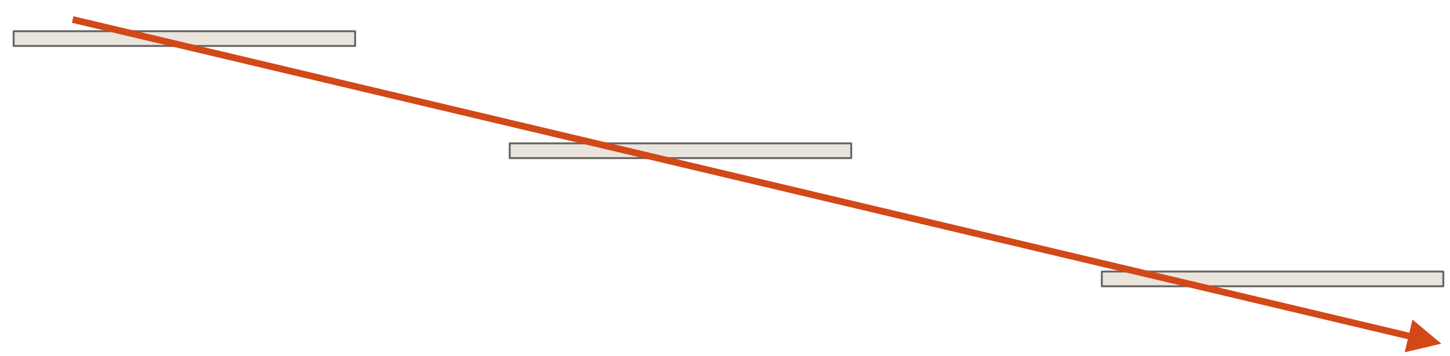
Test Stand @ UofT

120-channel "mini-module" of 4 layers, ~1m x 1m each
More advanced features include:

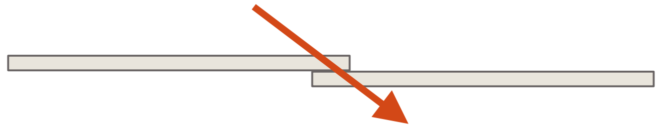
- PCBs (with pre-amps) to carry SiPM signals to readout boards
- Compression-fitting mounting apparatus to keep each SiPM in place
- Layers [re]moveable and height-adjustable individually

Potential studies include:

- PCB design optimization
- "Large angle" tracking



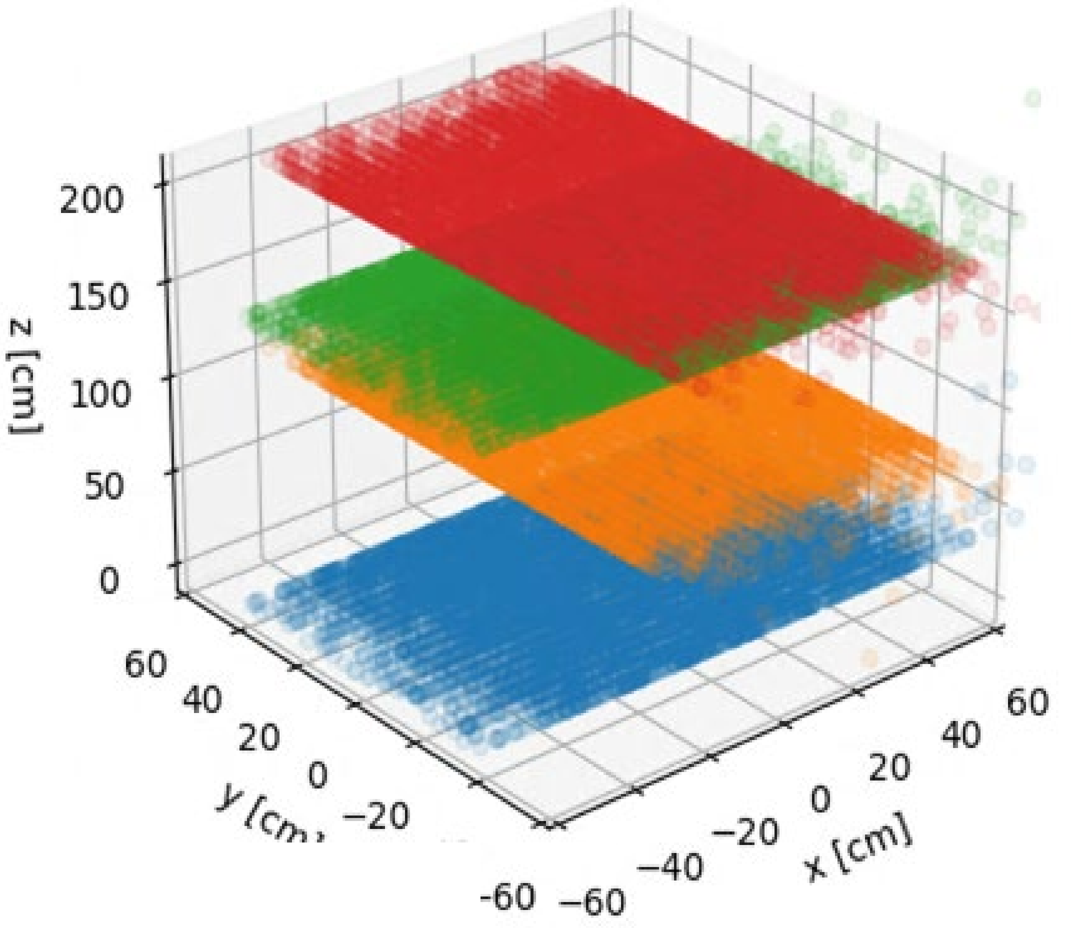
- Modelling interfaces between modules

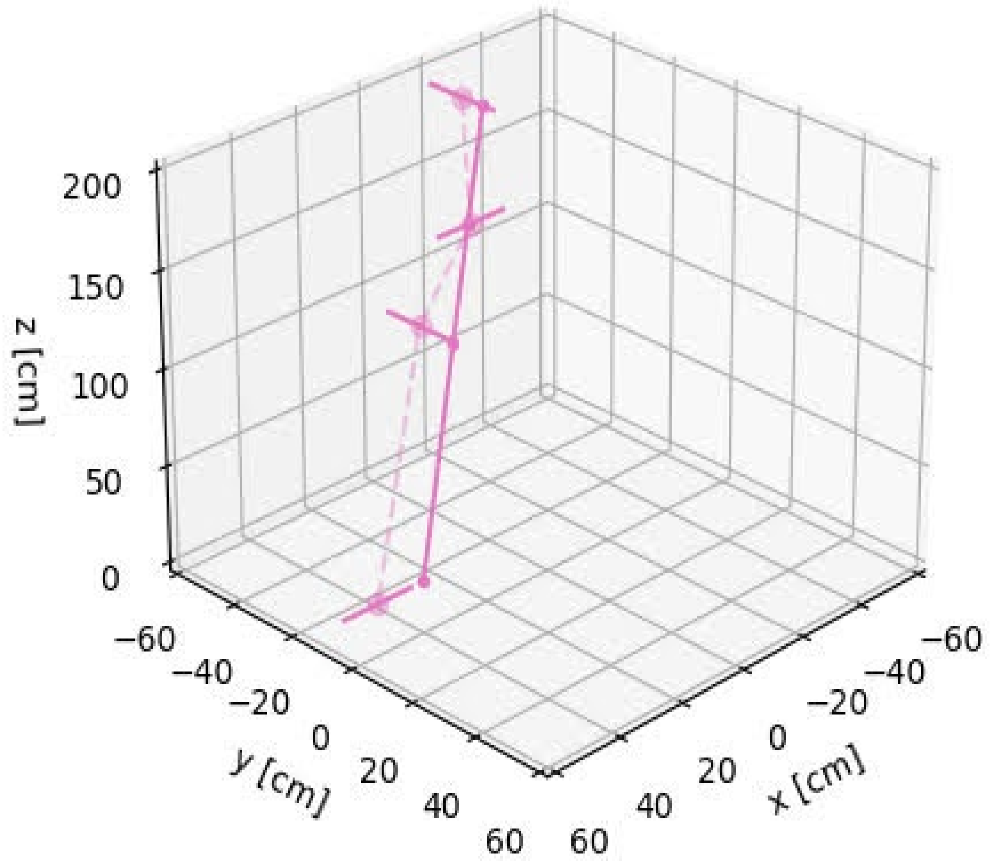


30

Test Stand @ UofT

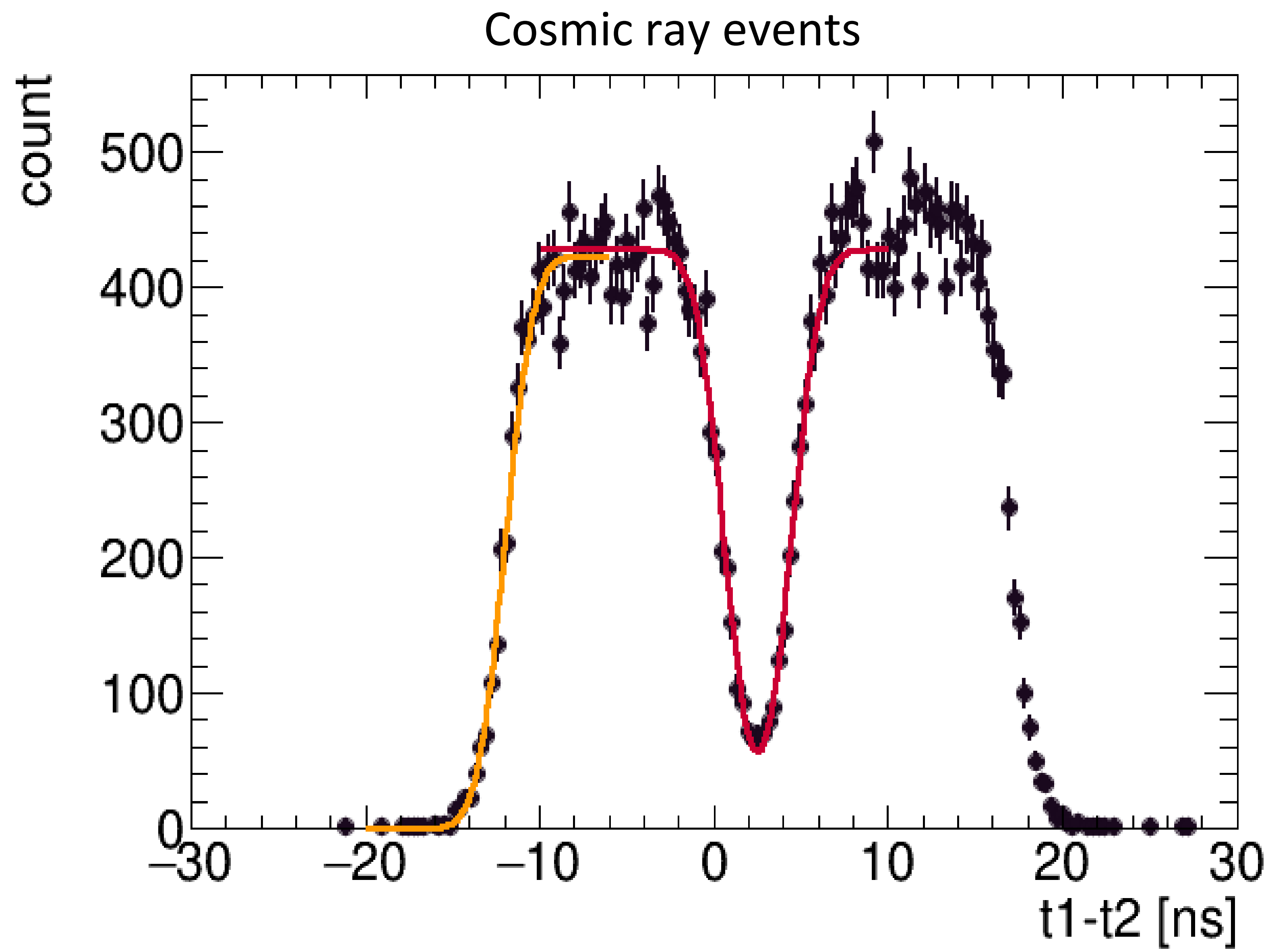
Cosmic ray events

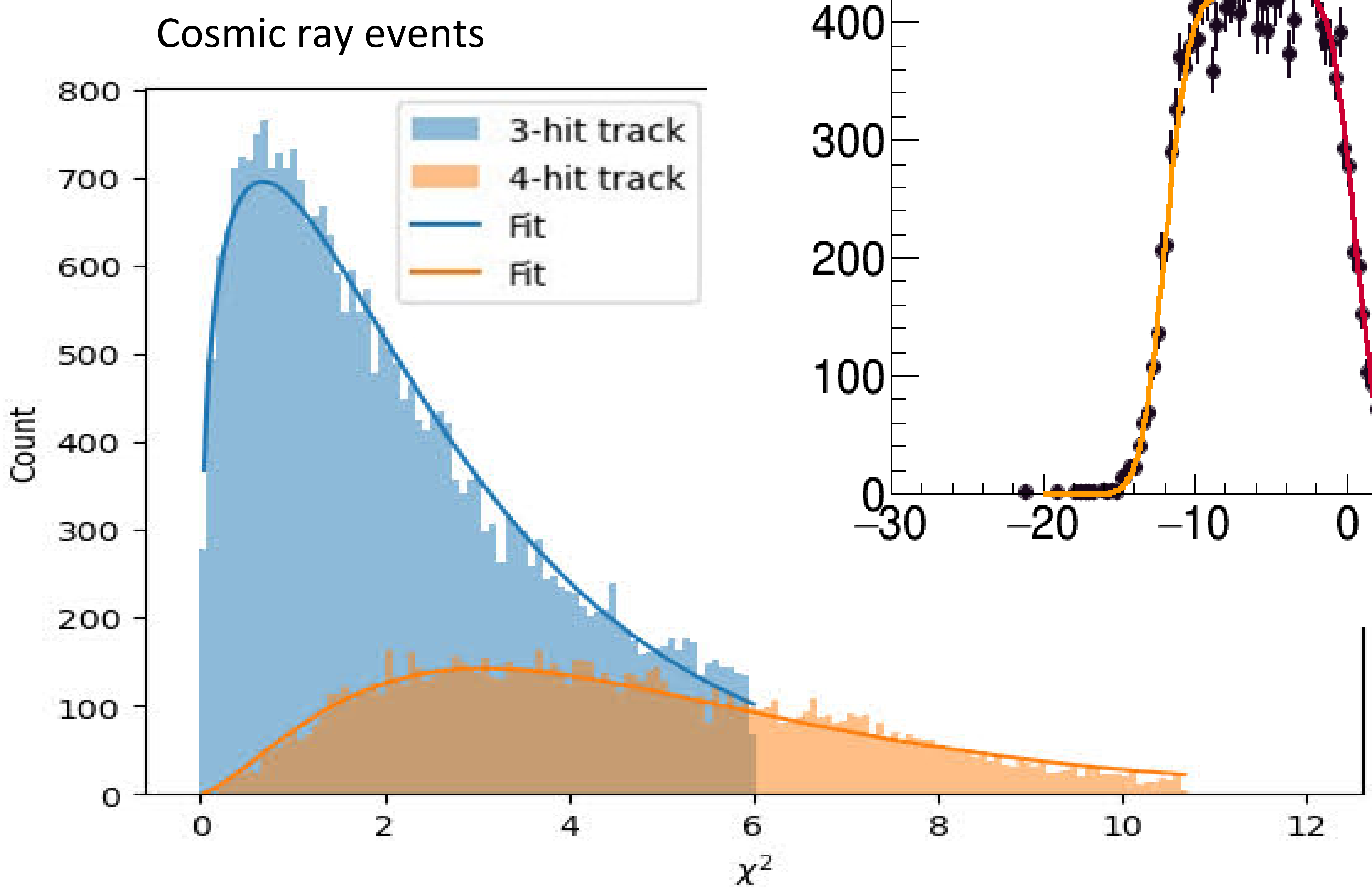




Reconstructed muon track passing through all 4 layers

Test Stand @ UofT





ASICs: Off-the-shelf with internal charge & time readout

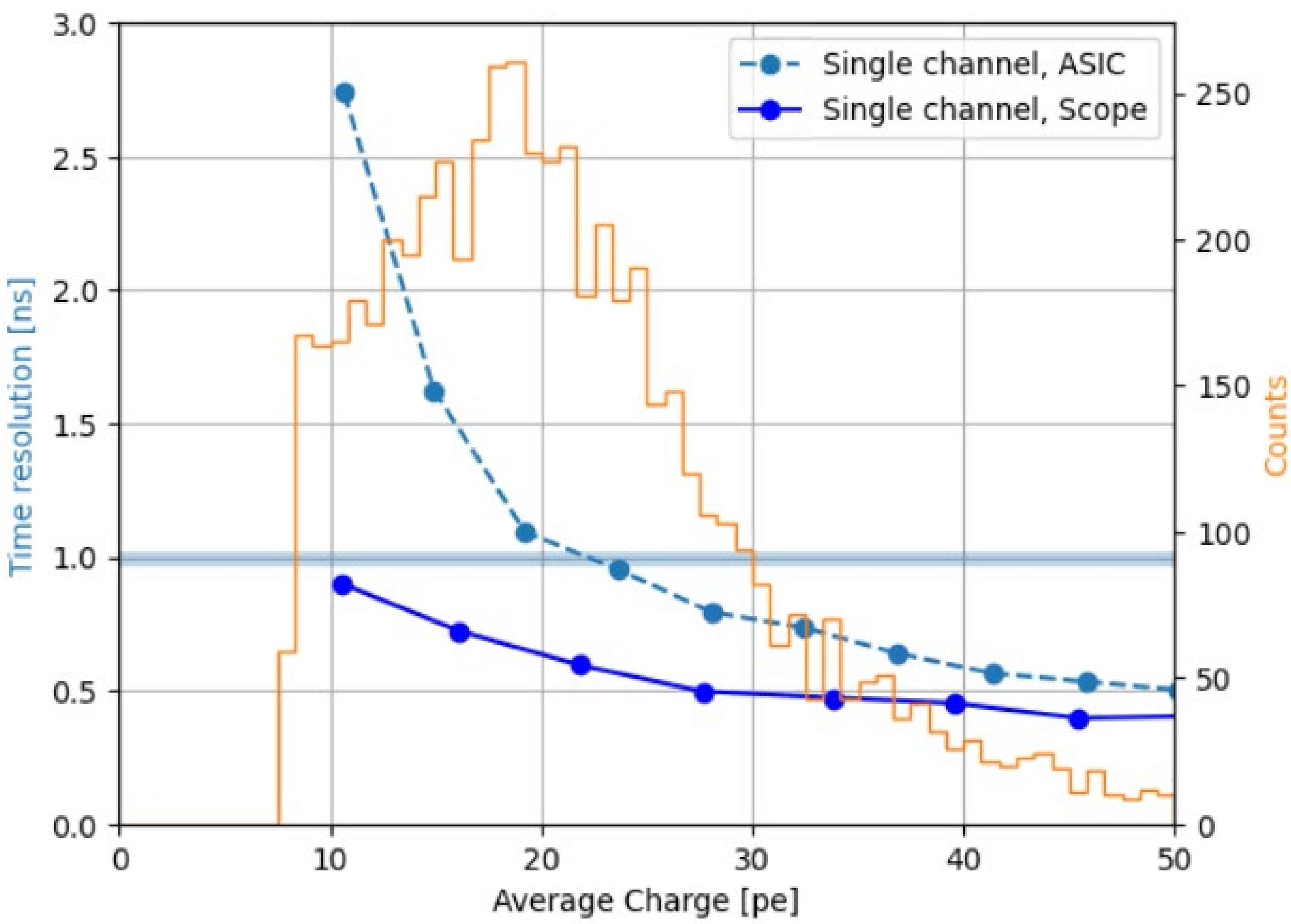
	TOFPET 2	PETIROC 2
Channels	64	32
Coinc. timing resolution[1] [ps]	41 ps tested (28 ps specified)	50 ps tested[2] (53 ps specified)
Energy resolution	bad, larger than 1 pe	good, can see single pe
Max throughput	**500 kHz per channel**, 32 MHz total, each event only digitizes the triggering channel	**40k frames/s**, each frame digitizes all channels. Need external coincidence/veto algorithm to prevent saturating the ASIC throughput.
Trigger configurations	2 time trigger + 1 charge trigger	1 time trigger + 1 charge trigger
Trigger logic controlled by	**ASIC** ASIC uses the second time/charge trigger to veto the low level time trigger	**External FPGA** FPGA takes the trigger output from the ASCI and decide whether to start the event or veto it.

- Timing resolution measured with ideal pulses (rising edge < 1ns)
- PETIROC2 timing resolution degrades much faster than TOFPET2 when pulse has rising edge slower than 20 mV/ns, due to ASIC internal clock leakage

ASICs: Off-the-shelf with internal charge & time readout

Hidden problem with PETIROC2: specified timing resolution can only be achieved with very fast slew rate on rising edge (> 20 mV/ns)

- Why? It's internal to the ASIC: clock leakage from digital domain, which can only be suppressed when signal is fast
- Not significant issue for apparatus where SiPM couples **directly** to scintillators
- But has great effect when **using WLSF**, which adds a second time constant that slows the rising edge



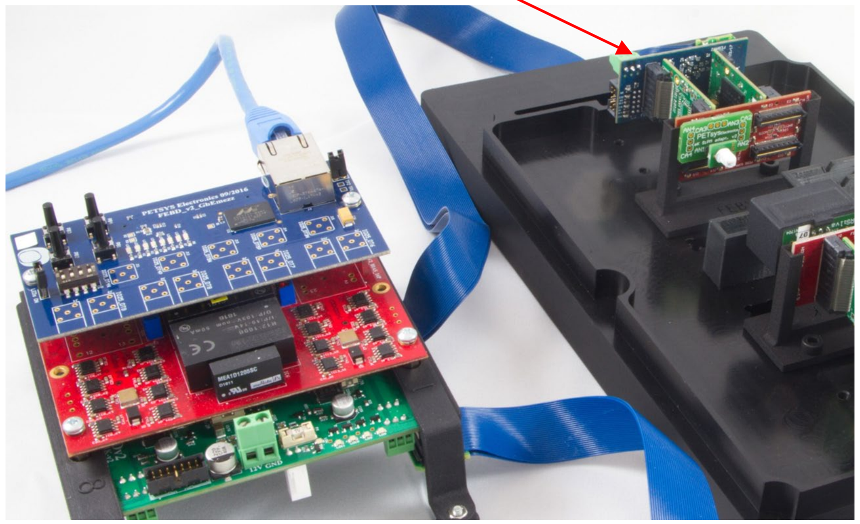
- SiPM must be mounted very close to ASIC, or using fast preamp, to obtain fast slew rate
- Still impossible to have fast enough rising edge for small signal with tens of PE

ASICs: Off-the-shelf with internal charge & time readout

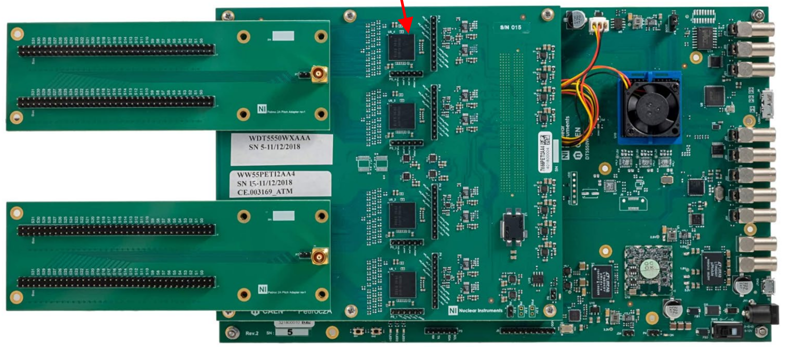
"Evaluation kits" for both ASICs provide basic functionality:

- HV supply
- ASIC control
- Data readout

TOFPET2



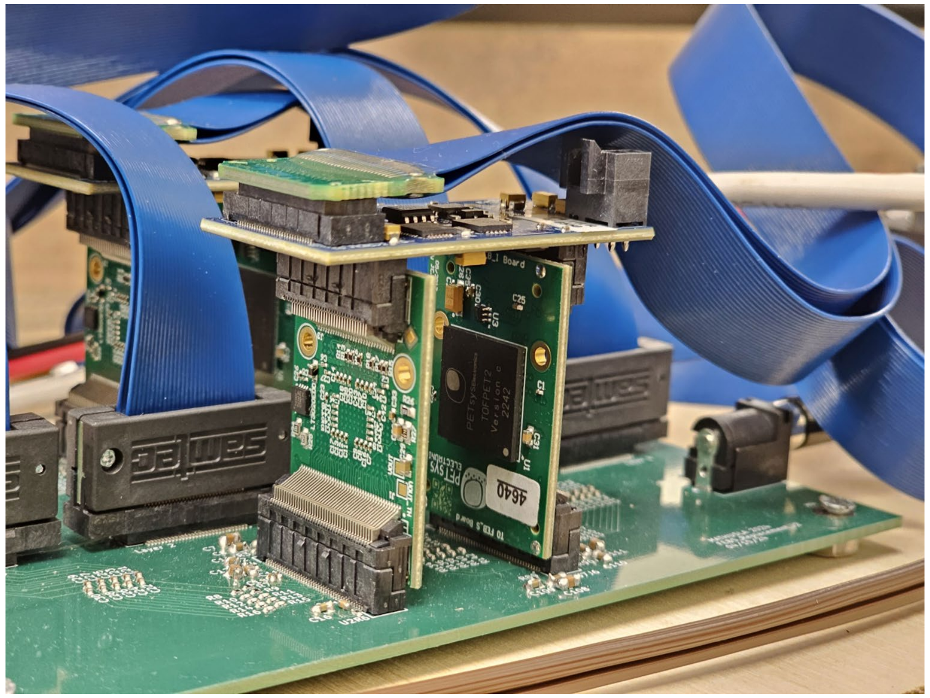
PETIROC2



Firmware	Proprietary	Open source
Connectivity	* 16 ASICs (1024 channels) * ASIC mounted on a small board, **connected to FPGA board with ribbon coax cable**	* 4 ASICs (128 channels) * ASIC on **a mezzanine board** of the FPGA board
Trigger conditioning	* **Dark current rejection** on ASIC * **HW coinc**. exists, but only between two ASIC groups. Channel to channel coincidence needs custom firmware.	* Dark current rejection and HW coincidence **not possible with the shipped firmware**, but can be implemented by developing custom firmware

- TOFPET2 evaluation kit works better directly "out of the box"
- Both can fully meet our requirements (dark current rejection to trigger at low threshold, hardware coincidence) if we do some firmware development

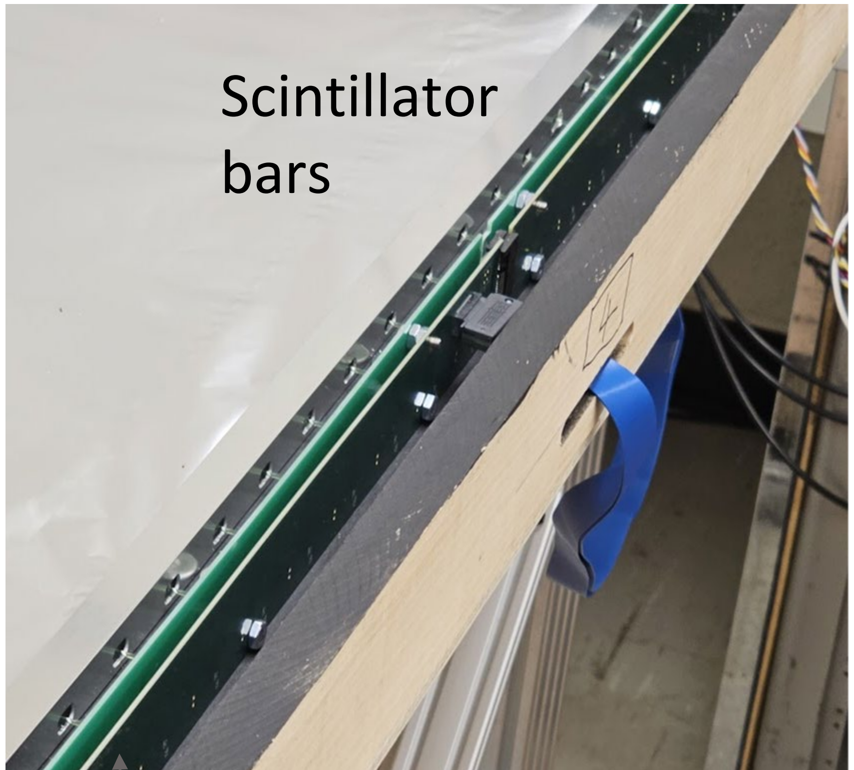
ASICs: Off-the-shelf with internal charge & time readout



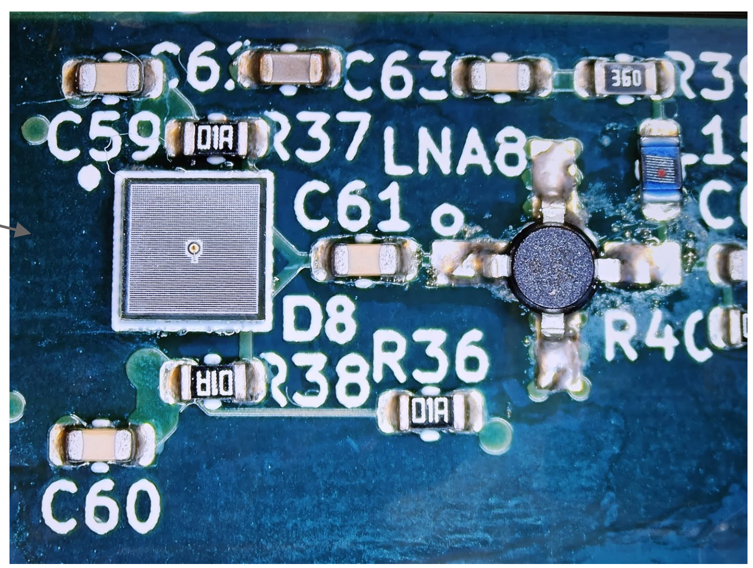
Using TOFPET kit in test stand

- Kit comes with 4 ASICs
- We made an adapter board to connect ASICs to detector

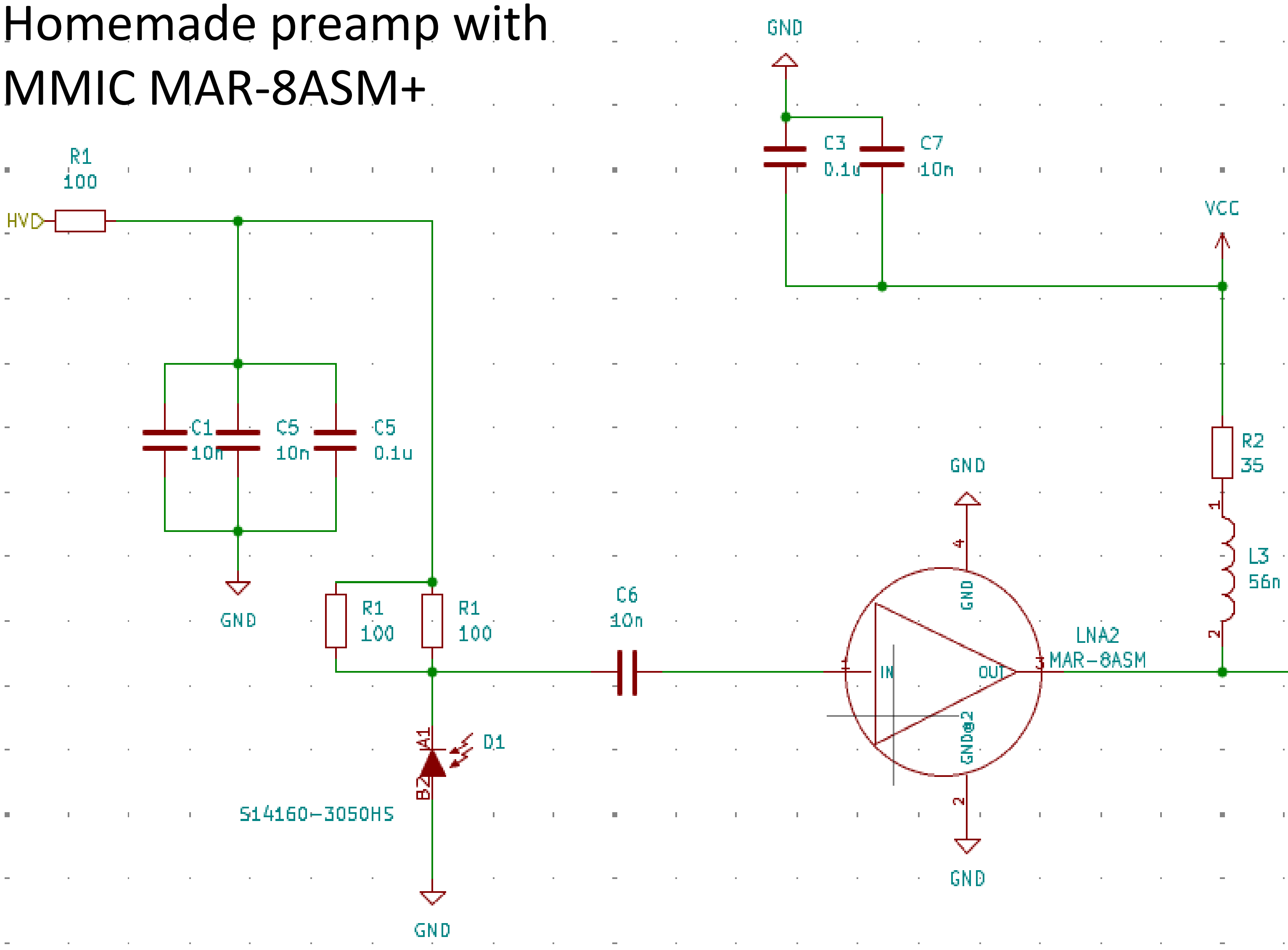
Front-end electronics for each channel



SiPM +
preamp



Homemade preamp with
MMIC MAR-8ASM+



The MATHUSLA Collaboration

STANFORD

KIT
Karlsruher Institut für Technologie

UHH
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

UNIVERSITY OF TORONTO

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

Fermilab

Virginia Tech

BOSTON UNIVERSITY

NISER

UNIVERSITY OF OXFORD

TEL AVIV UNIVERSITY

UNACH Universidad Autónoma de Chiapas

SLAC NATIONAL ACCELERATOR LABORATORY

CAL STATE EAST BAY

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Università di Roma Tor Vergata

INFN Istituto Nazionale di Fisica Nucleare
Sezione di Bari

cnrs IN2P3

UNIVERSIDAD NACIONAL DE LA PLATA

UNIVERSITÀ DEL SALENTO

CERN

Institute of High Energy Physics
Chinese Academy of Sciences

THE UNIVERSITY OF ARIZONA

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

Conclusions

- MATHUSLA, as a large-area dedicated LLP detector for HL-LHC, poses several technological challenges that we've demonstrated we can meet
- Still have ongoing efforts for optimization and lowering costs, especially for front-end electronics & DAQ
- Status and outlook:
  - Two test-stands (~1m x 1m, 4 layers) operational in Canadian labs
  - Submitting CFI proposal for building 9m x 9m "MATHUSLA-10", to serve as demonstrator and first full module in staged construction/commissioning: Canada is taking the lead!
  - Aiming to have MATHUSLA-10 installed above CMS for start of HL-LHC run

References

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.

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.

David Curtin and Jaipratap Singh Grewal. LLP decays in MATHUSLA, 2023, arXiv:2308.05860.

BACKUP

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

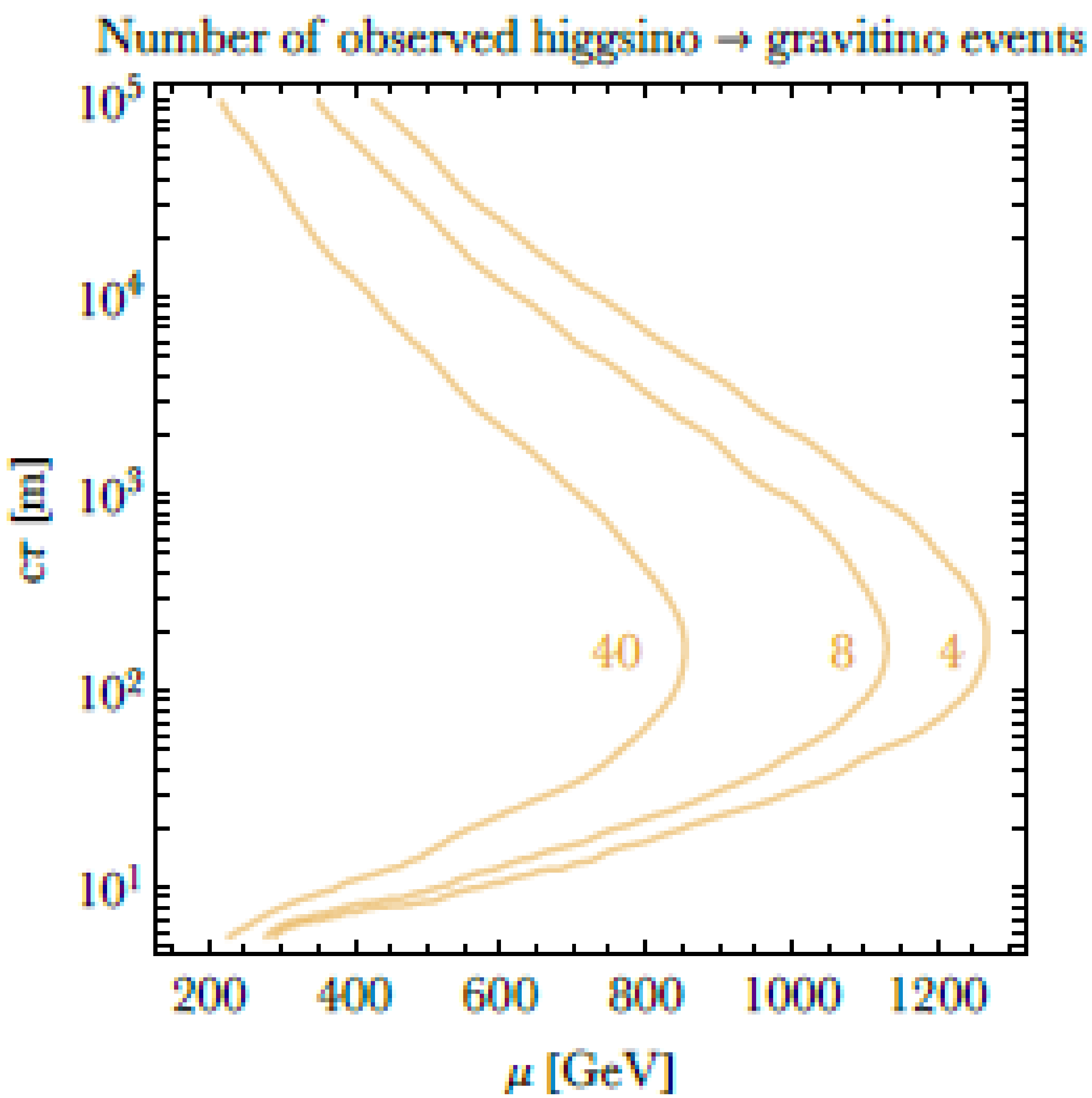
- Rare decays of muons originating from HL-LHC collisions
  - Expect ~2 x 10^8 upward-going muons over entire HL-LHC run, mostly from W and bbar production
  - Simulated using MadGraph & Pythia8
  - Full study underway to demonstrate optimal rejection while maintaining high LLP signal efficiency; test-bed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

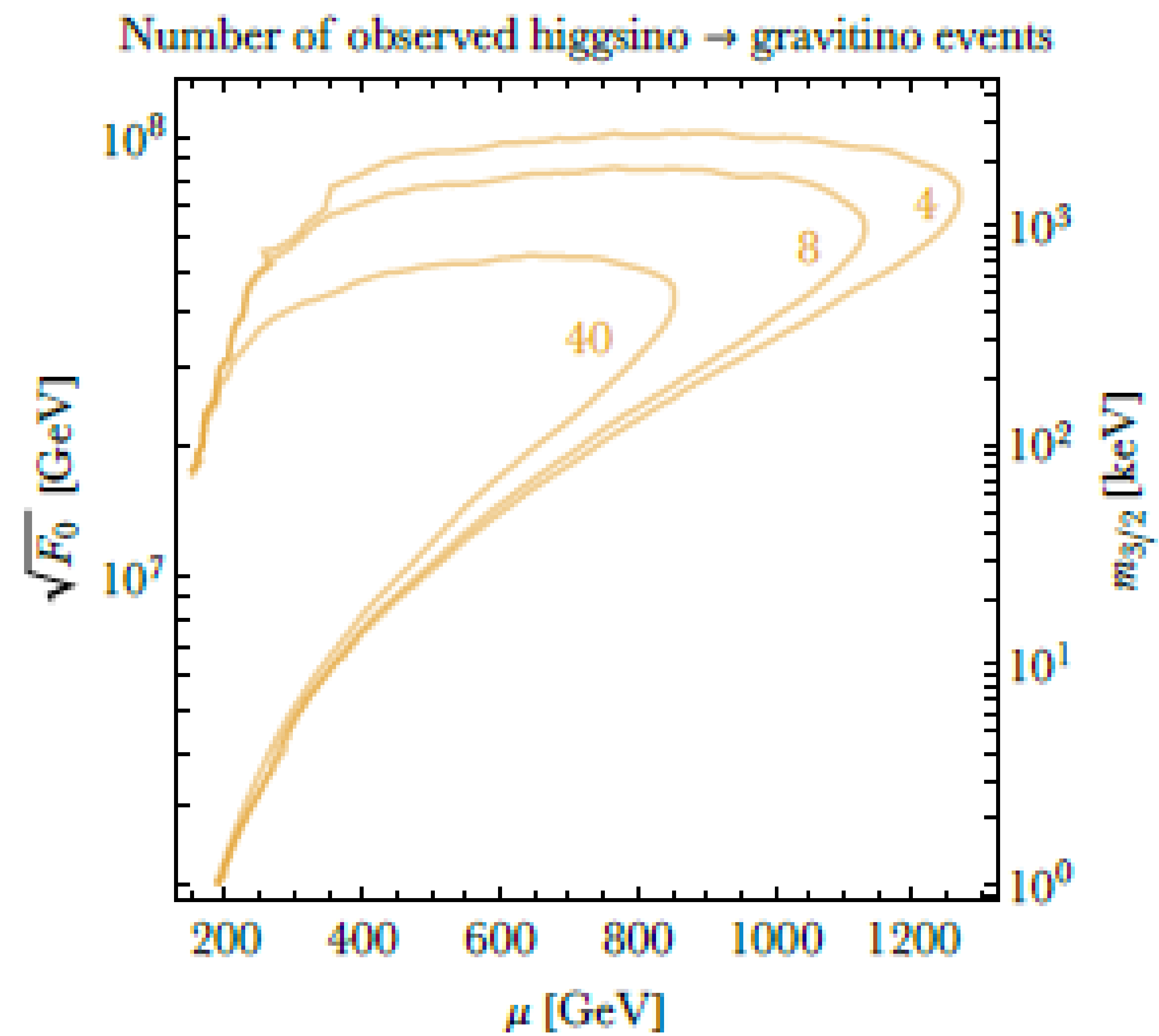
- Charged particles from neutrino scattering in decay volume
  - Simulated using GENIE
  - Neutrinos from HL-LHC collisions: using LHC minimum-bias samples, estimate << 1 "fake" DV/year
  - Atmospheric neutrinos: using flux measurements from Frejus experiment, estimate ~30 "fake" DV/year, reduced to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

LLP Sensitivity: TeV-Scale

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

e.g. meta-stable Higgsinos

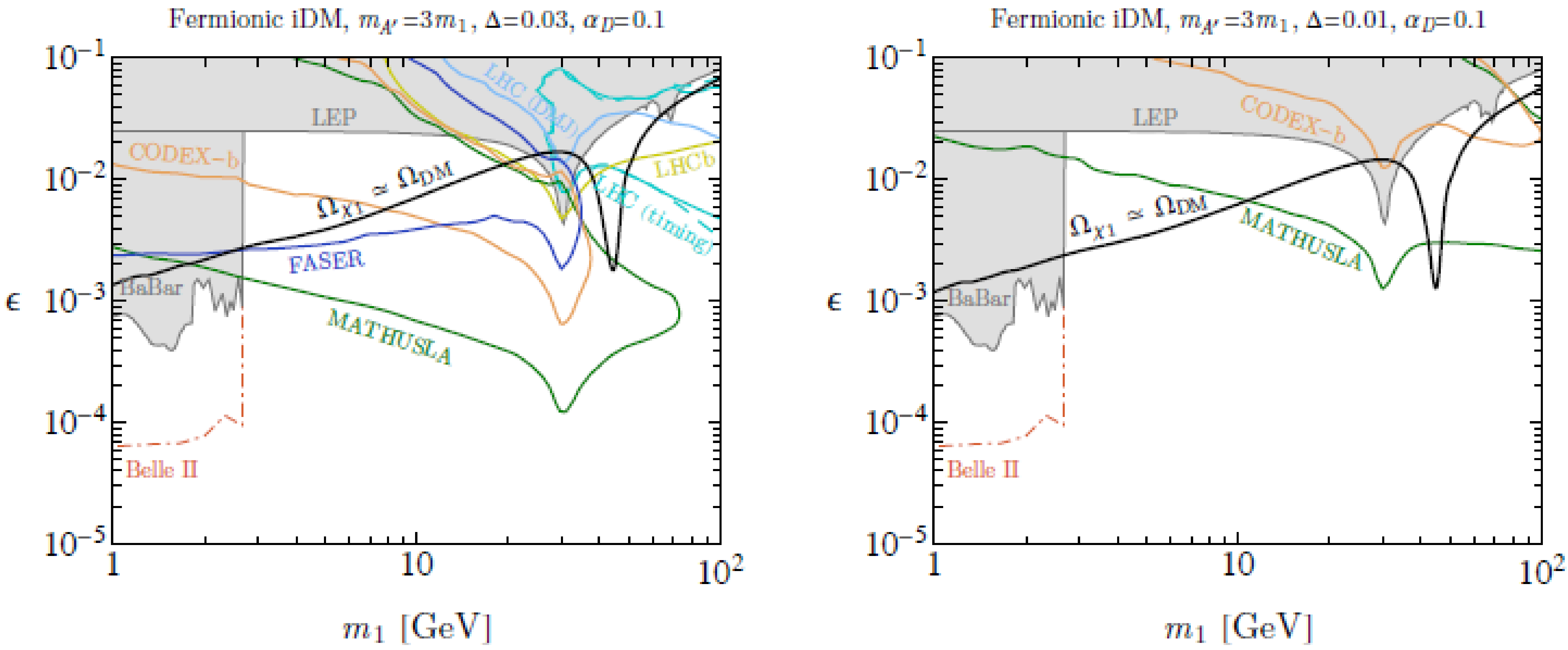




LLP Sensitivity: DM

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



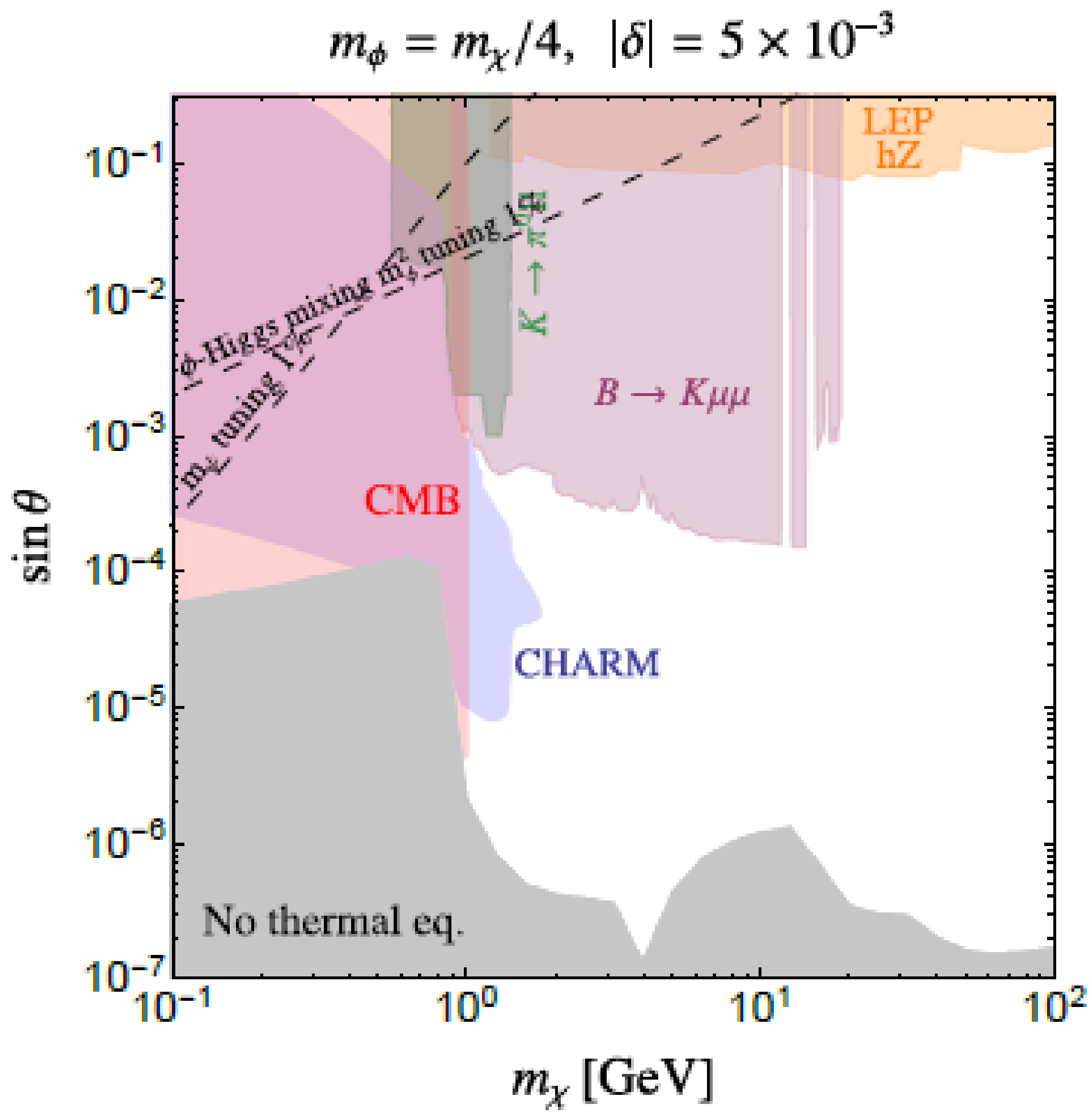
Black curve: thermal o-annihilations $\chi_2\chi_1 \rightarrow A' \rightarrow f\bar{f}$ yield observed DM relic density

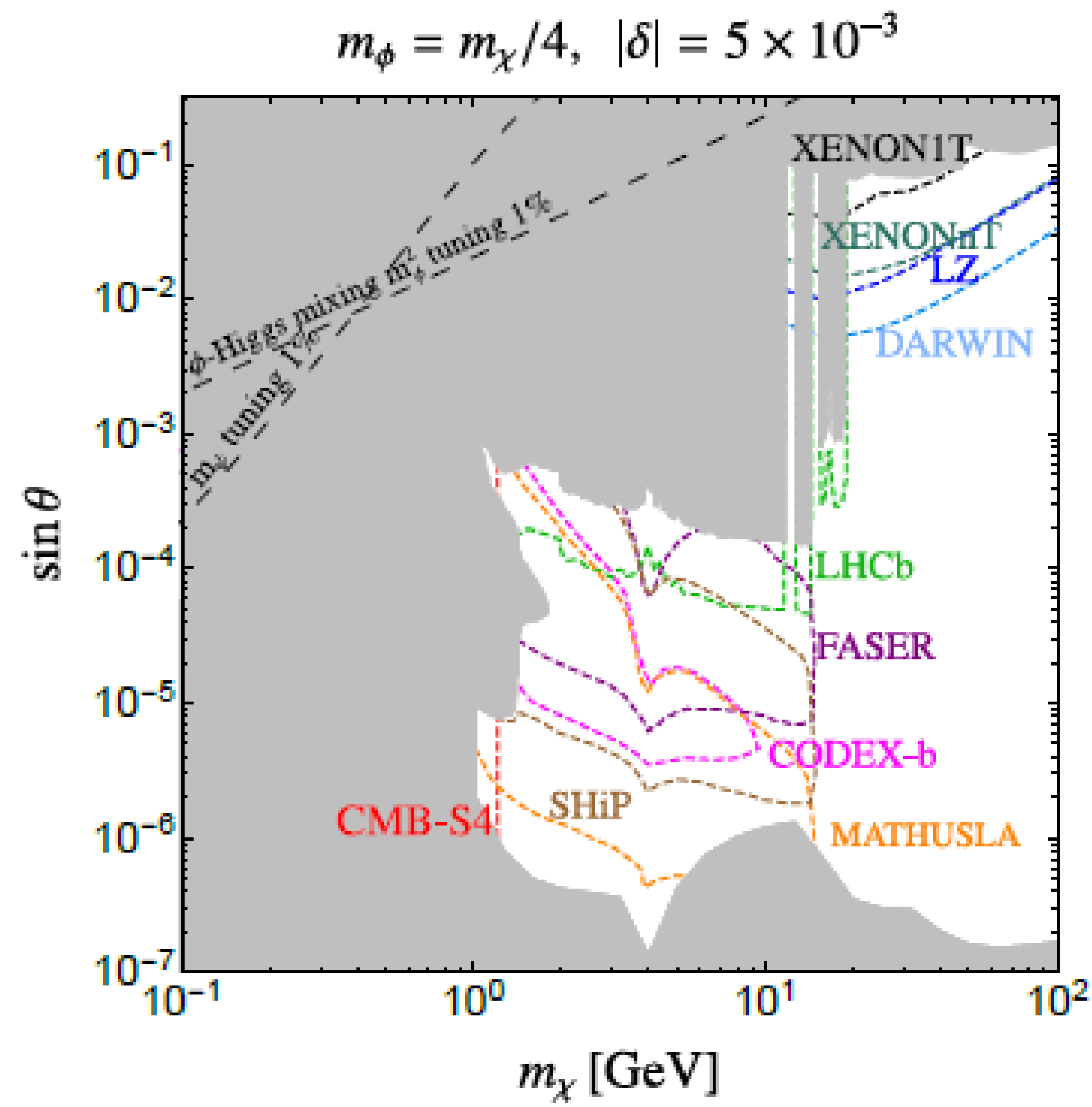
LLP Sensitivity: DM

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

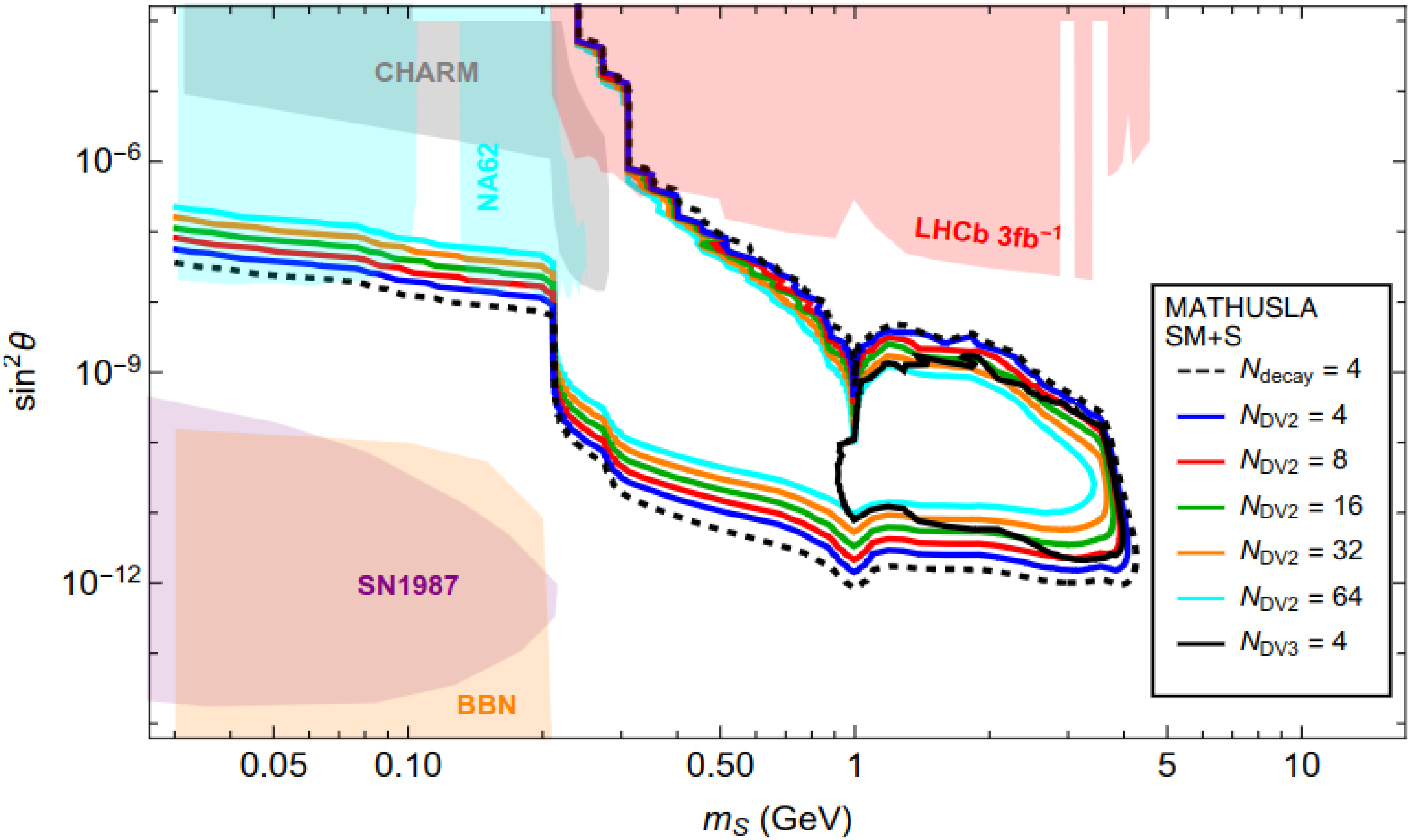




LLP Sensitivity: GeV-Scale

Secondary physics case: complementarity to other planned experiments in scenarios with accessible long-lifetime limit (>100m)

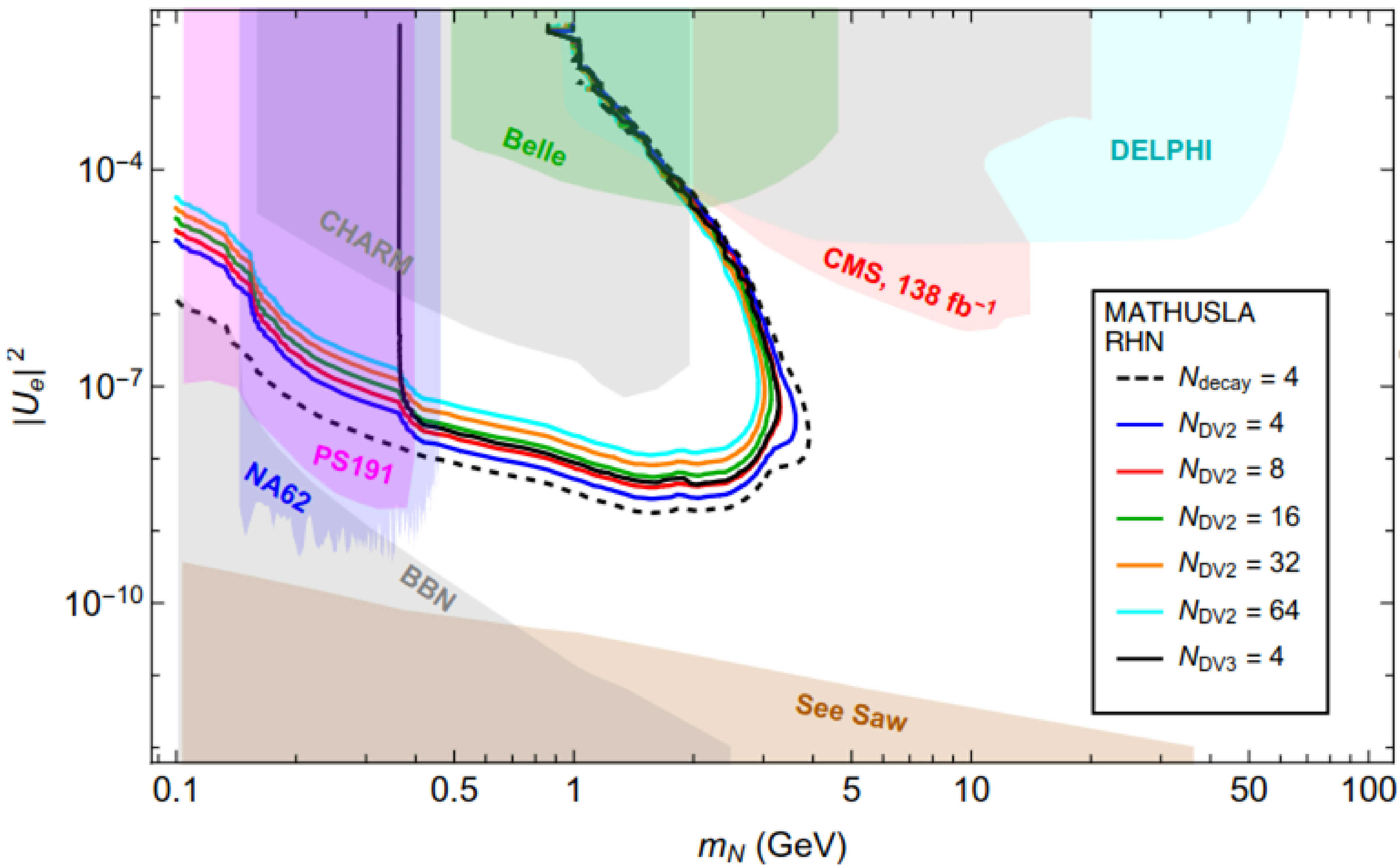
e.g. singlet dark scalar S, mixing angle θ with SM Higgs



LLP Sensitivity: GeV-Scale

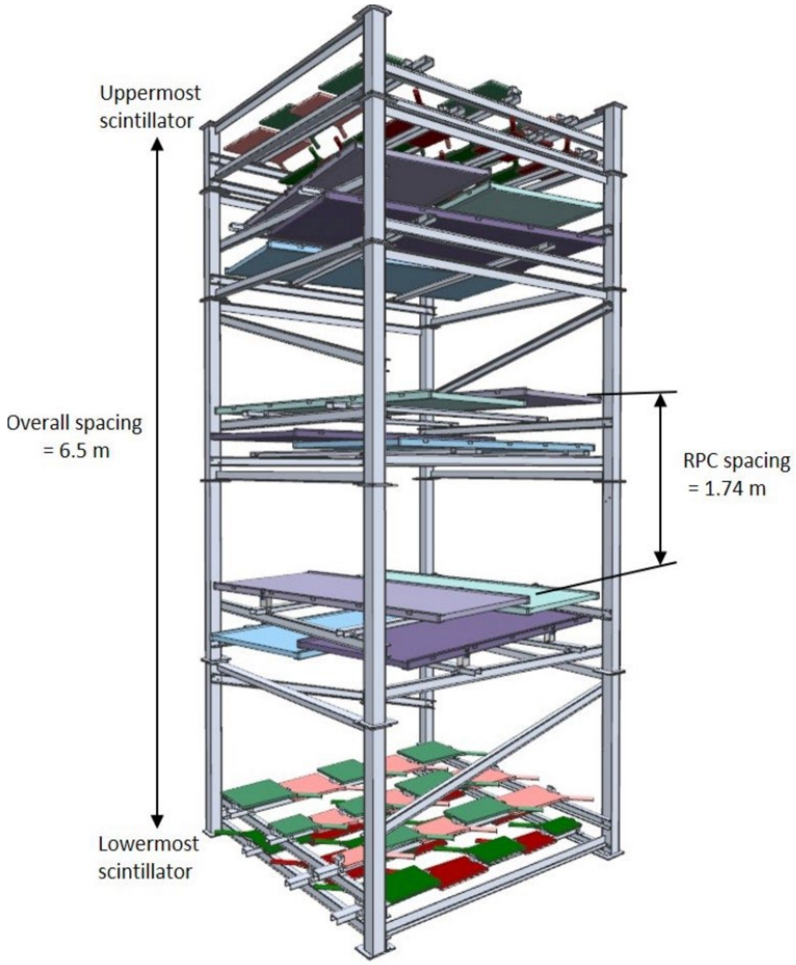
Secondary physics case: heavy neutral leptons

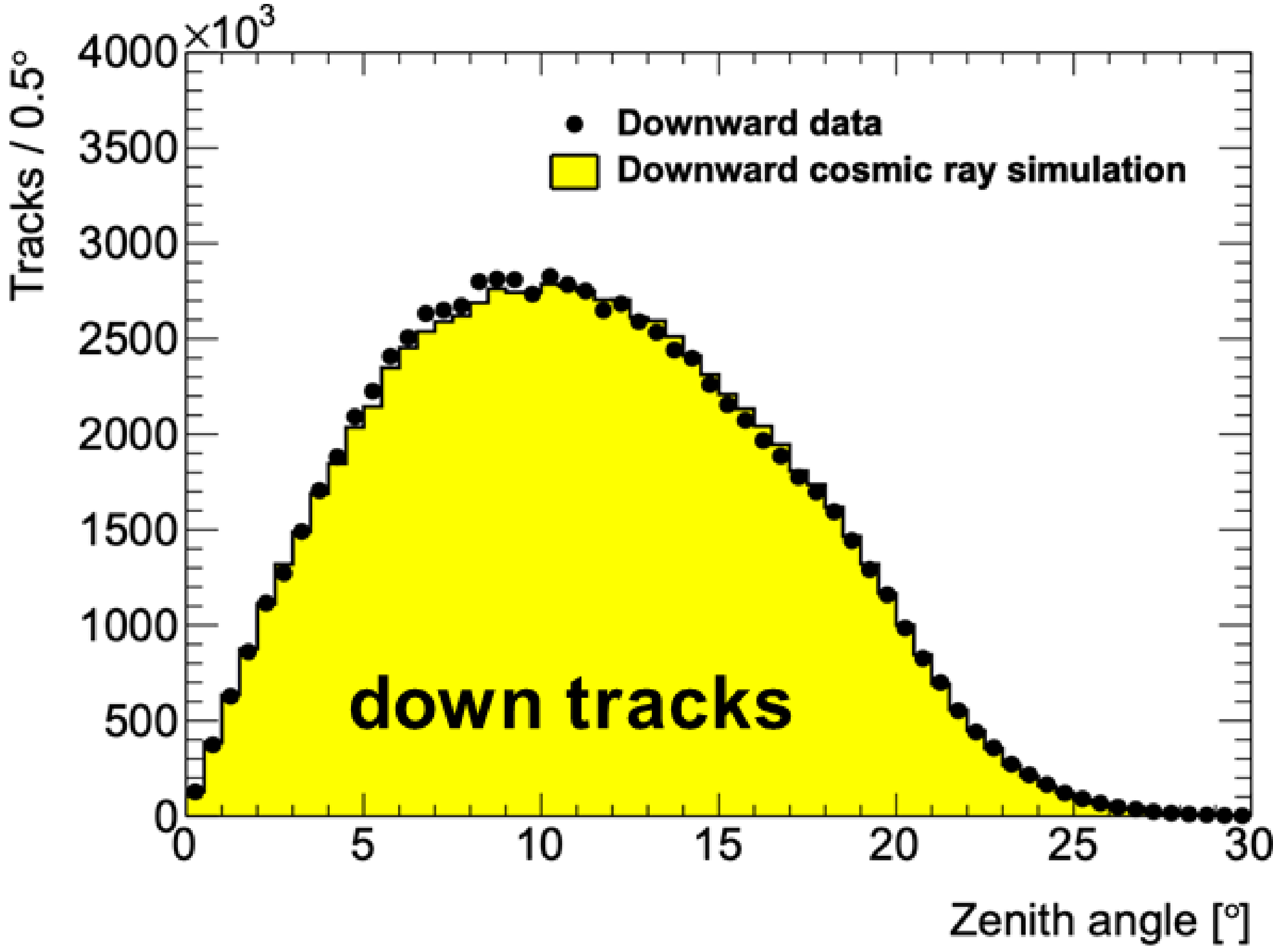
e.g. sterile neutrino N, whose largest mixing angle U_e is with υ_e

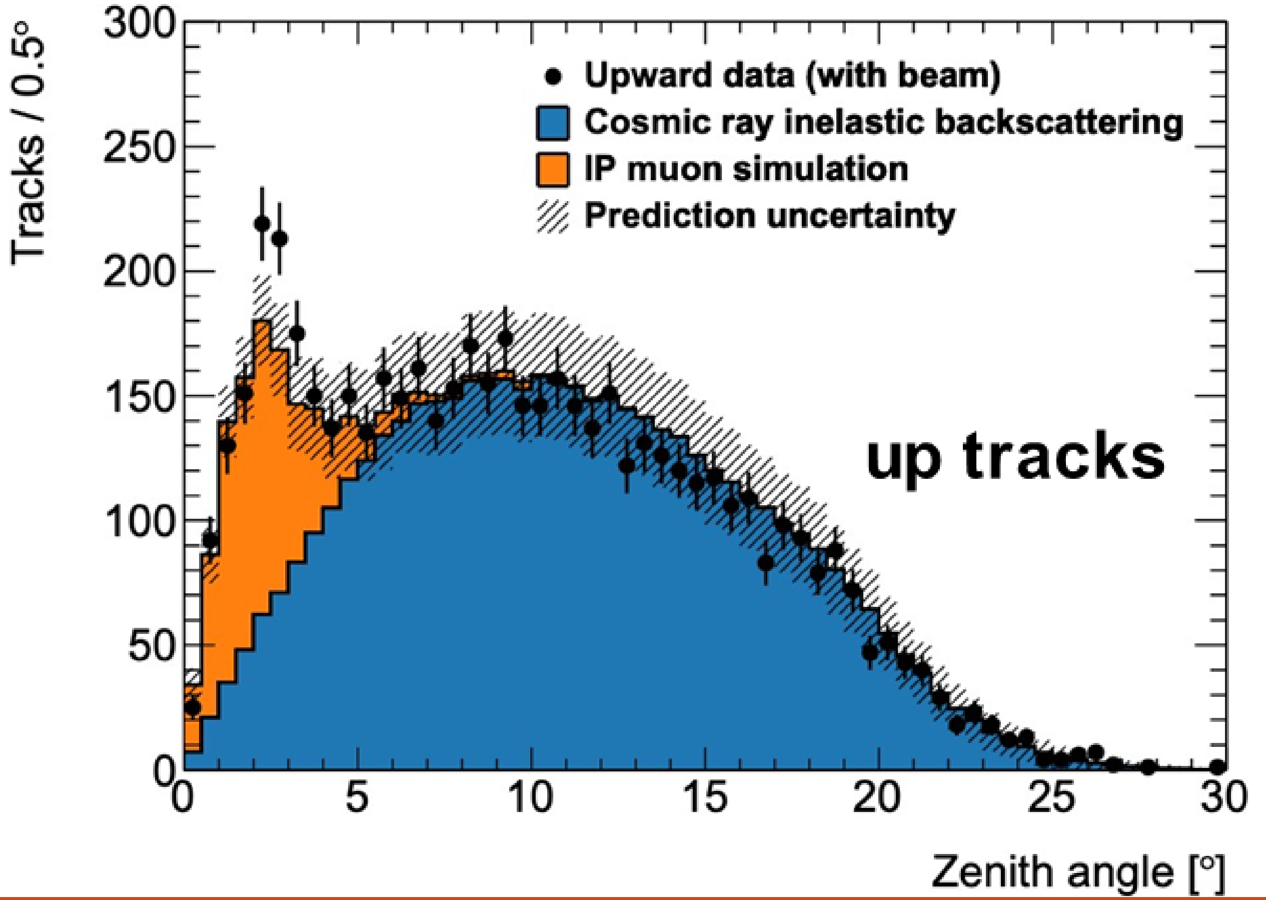


MATHUSLA Test Stand

Operated above ATLAS in 2018







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