MATHUSLA

メトセラ

Methuselah lived 900 years
Who calls that livin'
When no gal will give in
To no man what's 900 years

It ain't necessarily so
The things that you're liable
To read in the Bible,
It ain't necessarily so.

MATHUSLA メトセラ

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

Extending the LHC LLP horizon with large but simple apparatus

July 2024

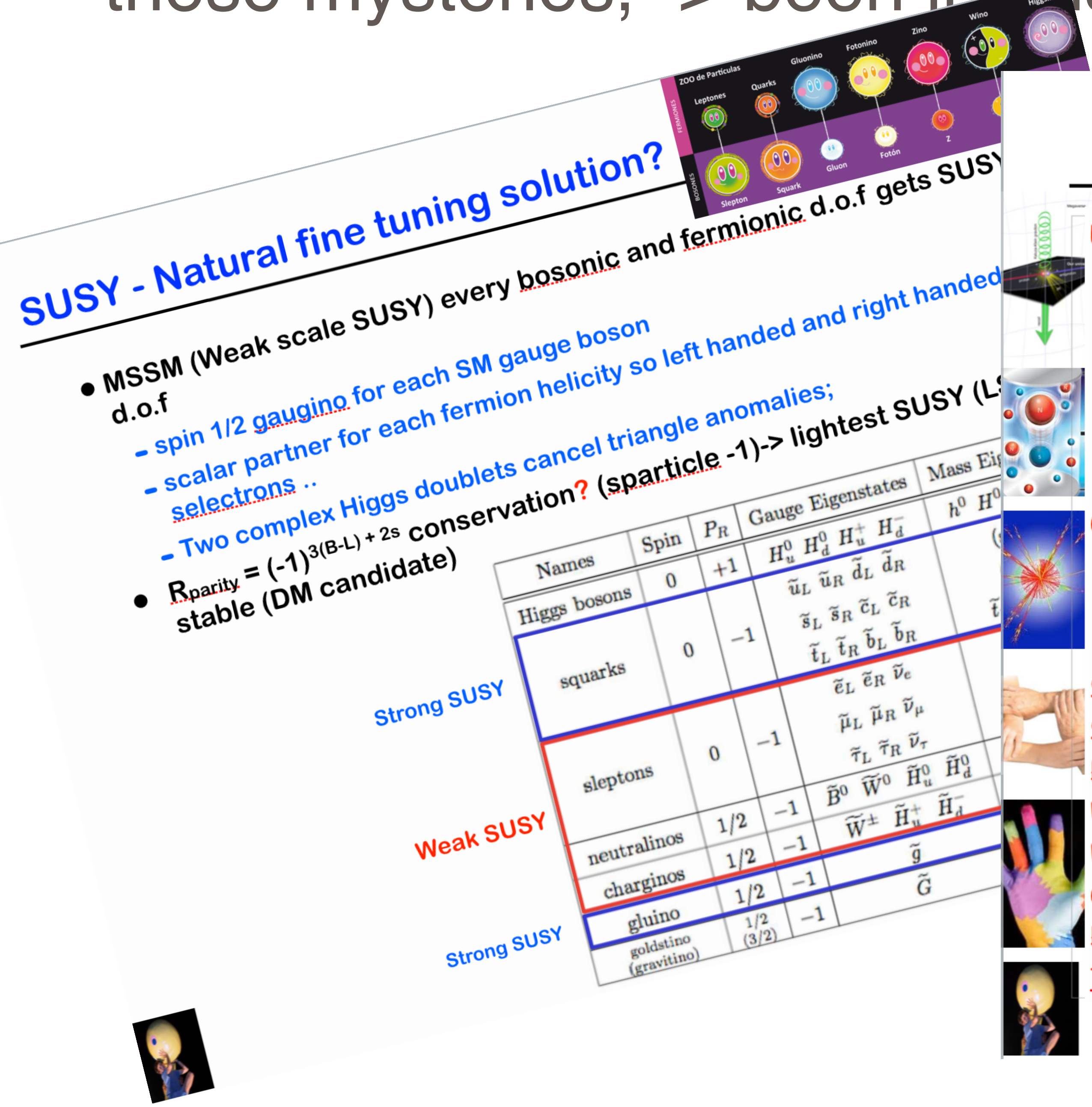
Erez Etzion, on behalf of the MATHUSLA team

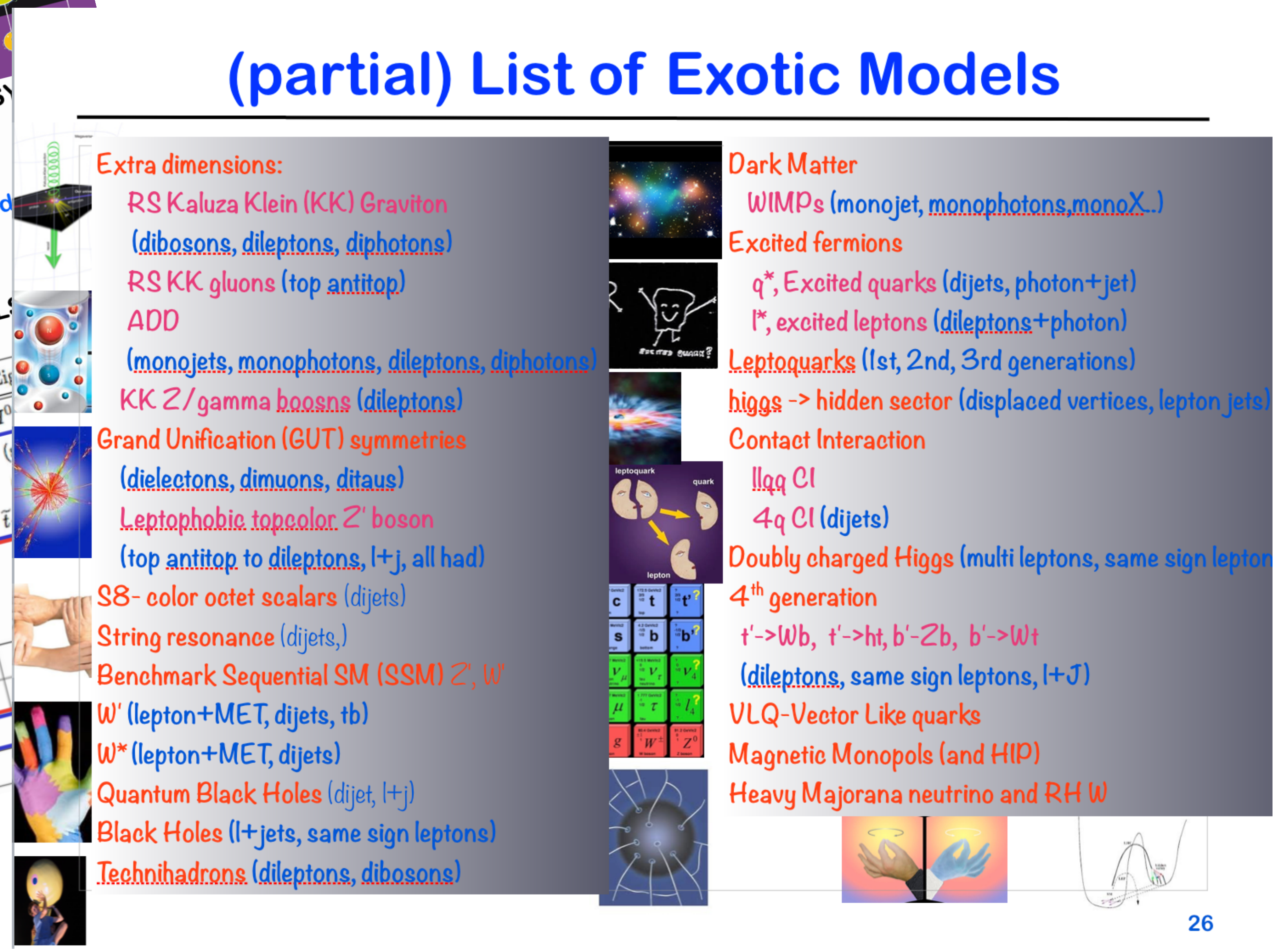
UNIVERSITY OF TORONTO

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

SM and beyond..

- BSM motivations: Hierarchy problem, Baryogenesis (Matter/Anti matter asymmetry) Dark Matter, Neutrinos..
- Several well-established theoretical frameworks which can solve these mysteries, -> been intensively searched for.





SM and beyond..

- BSM motivations: Hierarchy problem, Baryogenesis (Matter/Anti matter asymmetry) Dark Matter, Neutrinos..
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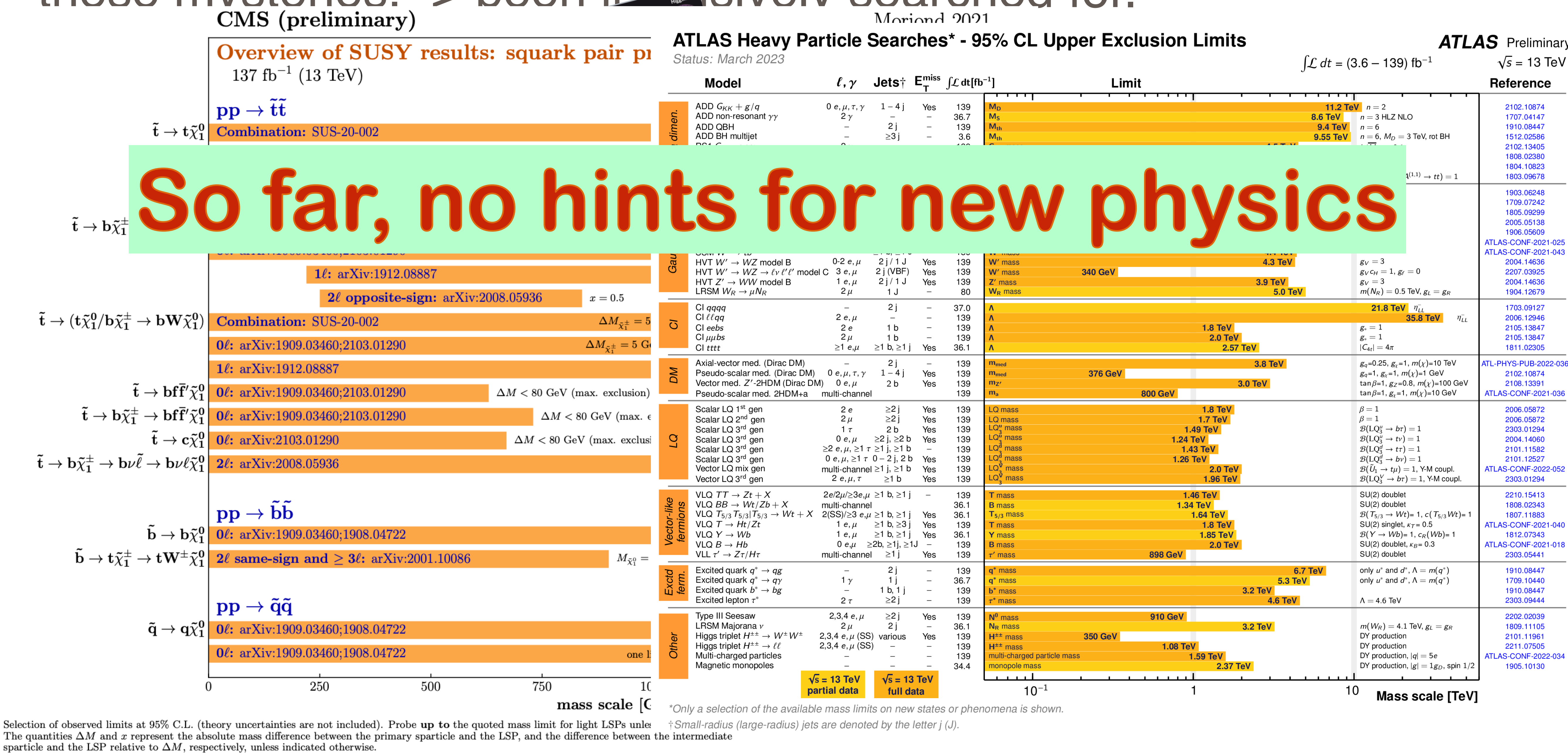


So far, no hints for new physics

Hidden sectors?

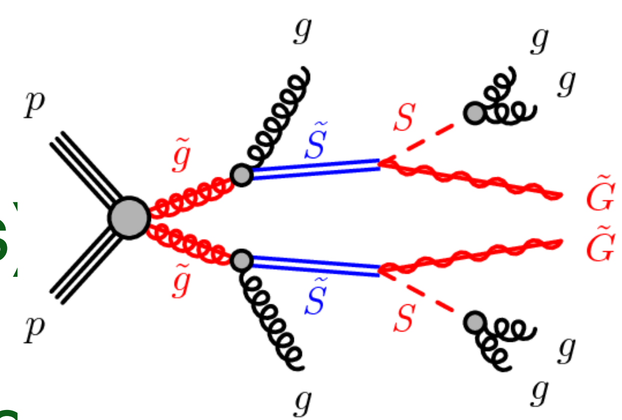
- SUSY, BSM .. most of these models assume fairly minimal structure.
- Look for particles with significant couplings to SM.
  - Hints for Physics beyond SM have not been found yet.
    - Where is it hiding?
- Many SM extensions (Hidden Valley, stealth SUSY etc..) include **Neutral**, **long-lived** O (*mm*) up to O $(10^{\#}m)$ particles with **small** effective **couplings** to the SM.
- No explicit constraints to the decay time
- Examples:
  - Heavy mediator (Z' / W'..)
  - Photon portal
  - Higgs Portal

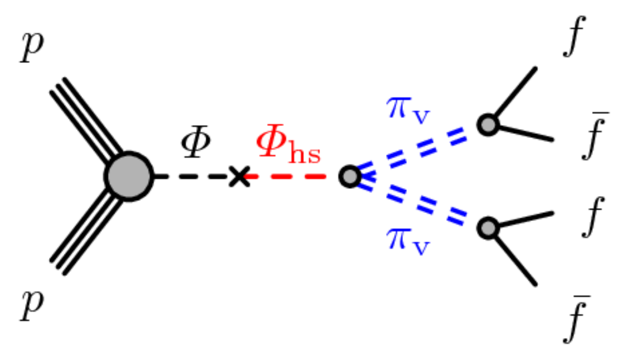
Long Lifetimes are typical!

A hidden gauge boson that mixes SM with hidden BSM

Searches for LLP at LHC

- ATLAS/CMS are large detectors however:
  - The detectors & analyses target IP events.
  - LLP may have a large QCD background
  - Limited by geometrical acceptance, particles lifetimes
- Signatures are model dependent:
  - **Production process** -> cross section (rate)
  - **Decay coupling** -> particles lifetimes
  - Can come with **associate objects** (leptons or jets) typical in many SUSY models or **alone** like in Scalar decaying into a pair of long-lived particles each decaying into SM pair.
  - Most searches focused on **two DV** or DV and with **associated object**



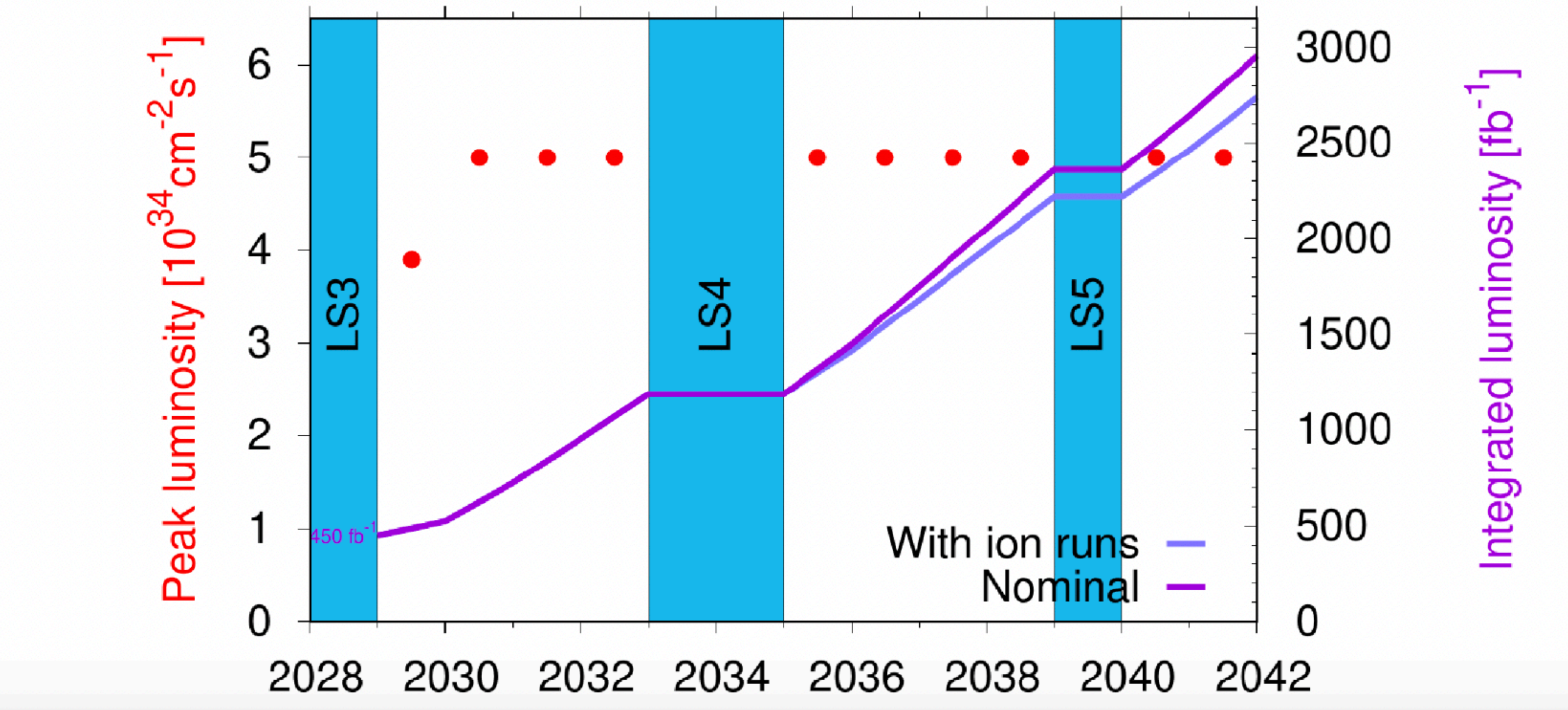


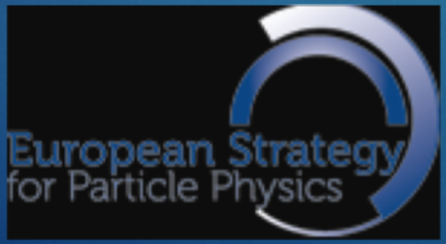
Accessing the hidden sectors

- The nontrivial signature could be why we haven't seen any hint yet..
    - Can be turned to an advantage …
- With dedicated searches, these signatures could allow a small number of events for discovery!
- New mindset:
    - Dedicated analyses, new triggers /tracking..
    - **New experiments?**
    - Large QCD Backgrounds limit LHC detector searches – need LHC "Background-free" detector
    - =>FASER, Codex-B, ANUBIS, SHiP..

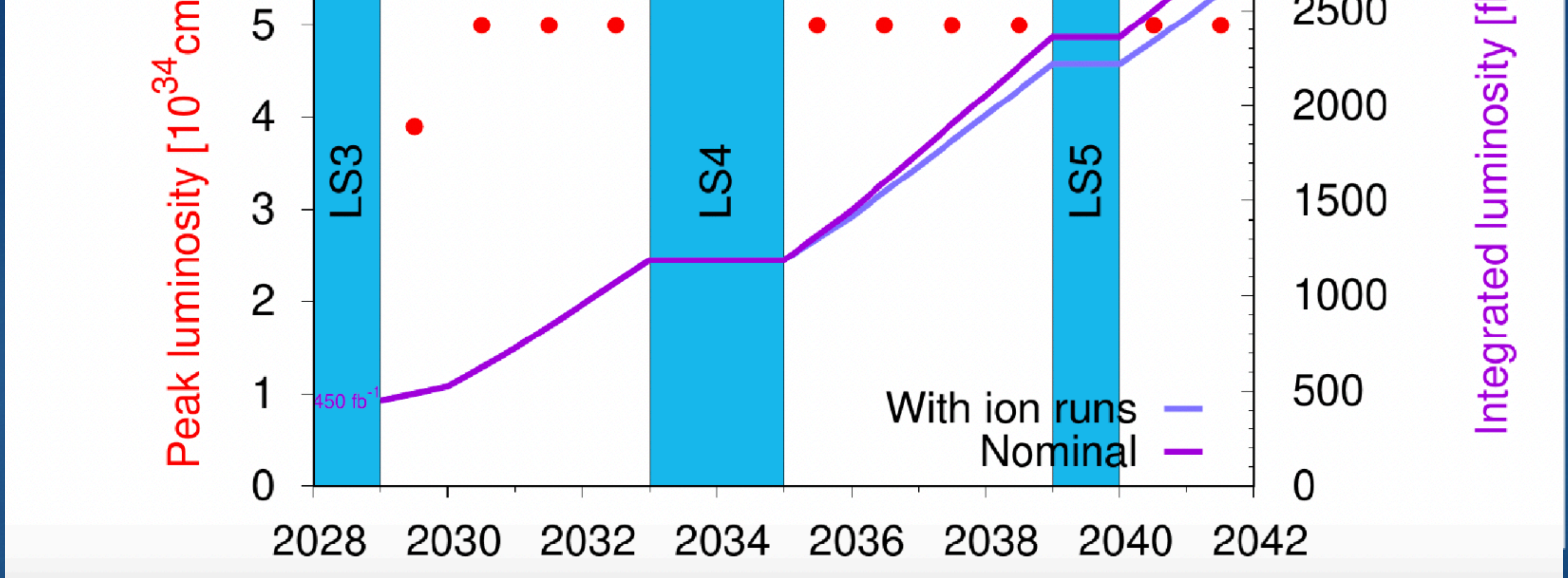
Overview of the challenge

In the nominal plan $\sim 3000\ fb^{-1}$ should be delived during the HL-LHC.





"Europe's top priority should be the exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030"



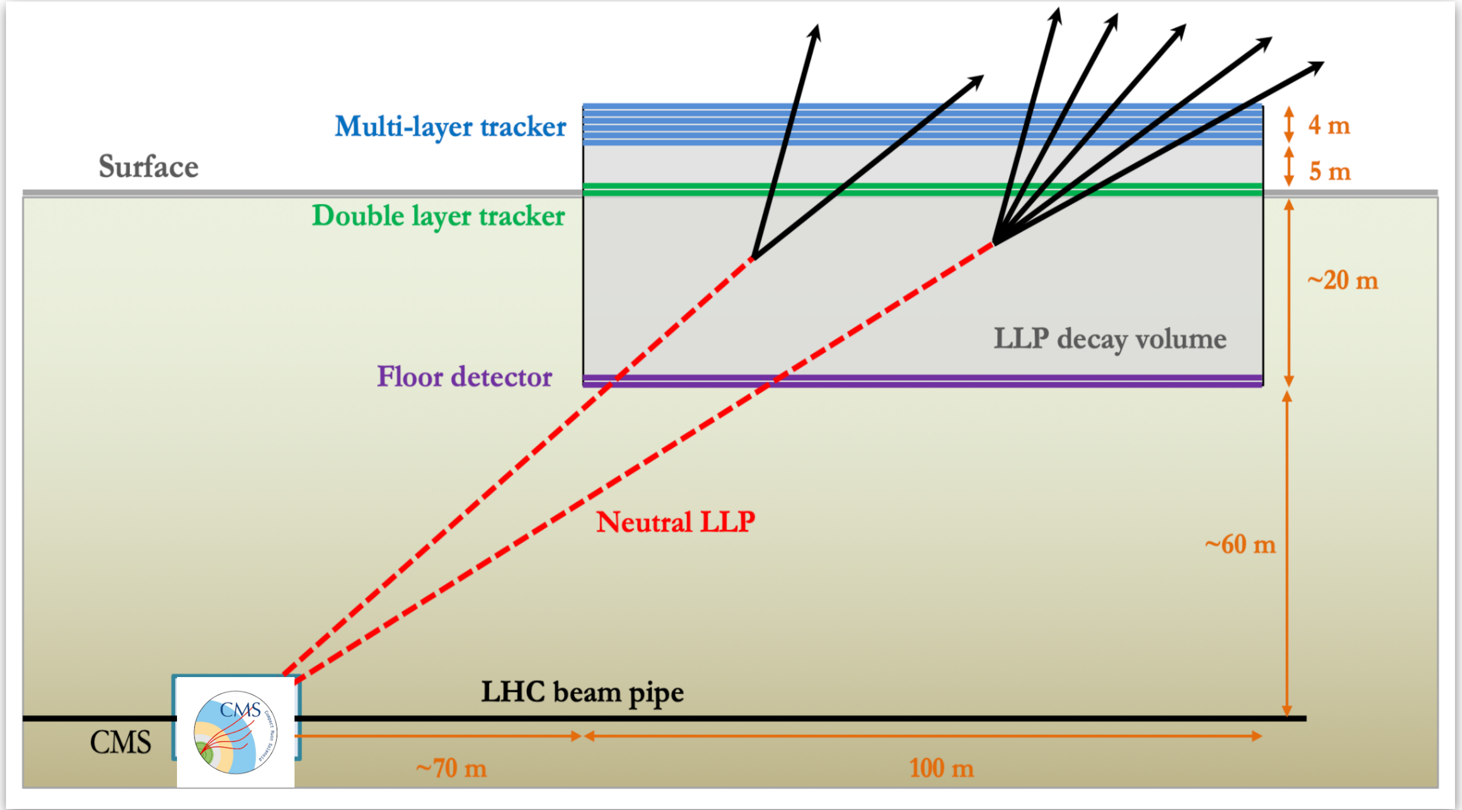
European Strategy for Particle Physics

*"Europe's **top priority** should be the **exploitation** of the **full potential of the LHC**, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030"*

- By ~2040 plan to collect **~3ab^{-1}** of data!
- Will require very significant (not cheap..) upgrades to the machine and the detectors
- **Huge statistics** (>10^8 Higgs bosons! …)
- However, **lifetime frontier** is still somewhat limited by the fixed **size of the detectors**

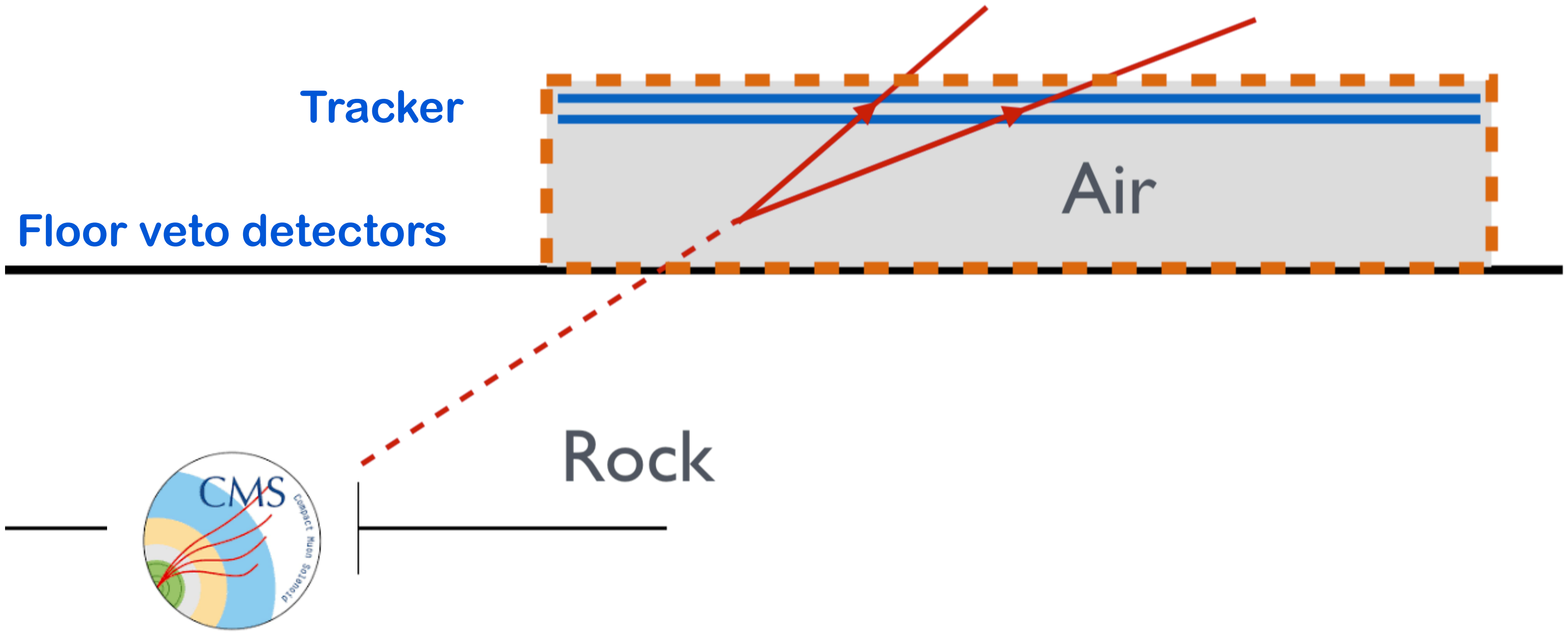
- Assume ULLPs are produced in exotic Higgs decays with Br > 10%
- Assume a lifetime near the Big Bang nucleosynthesis (BBN) limit: $c\tau \sim 10^7$m
- The LHC makes a lot of Higgs bosons…
- A few of these LLPs will decay in ATLAS or CMS!
- Detection requires:
  - High production rate but also **Tiny** BG rate
    - Dedicated detector sensitive to neutral LLP with lifetimes up to the BBN limit for HL-LHC
    - A large-volume, air-filled detector above ATLAS or CMS

Extension to the detectors for HL-LHC



- Large surface detector (~100 above the IP and displaced vertically)
- Air decay volume H~20 m along the ULLP direction
- Geometrical acceptance of a few percent allow a few ULLP events during the HL-LHC run
- Use simple and cheap detection technology
- Robust tracking and excellent BG rejection
- Floor detectors to reject interactions occurring near the surface

The signal characteristic

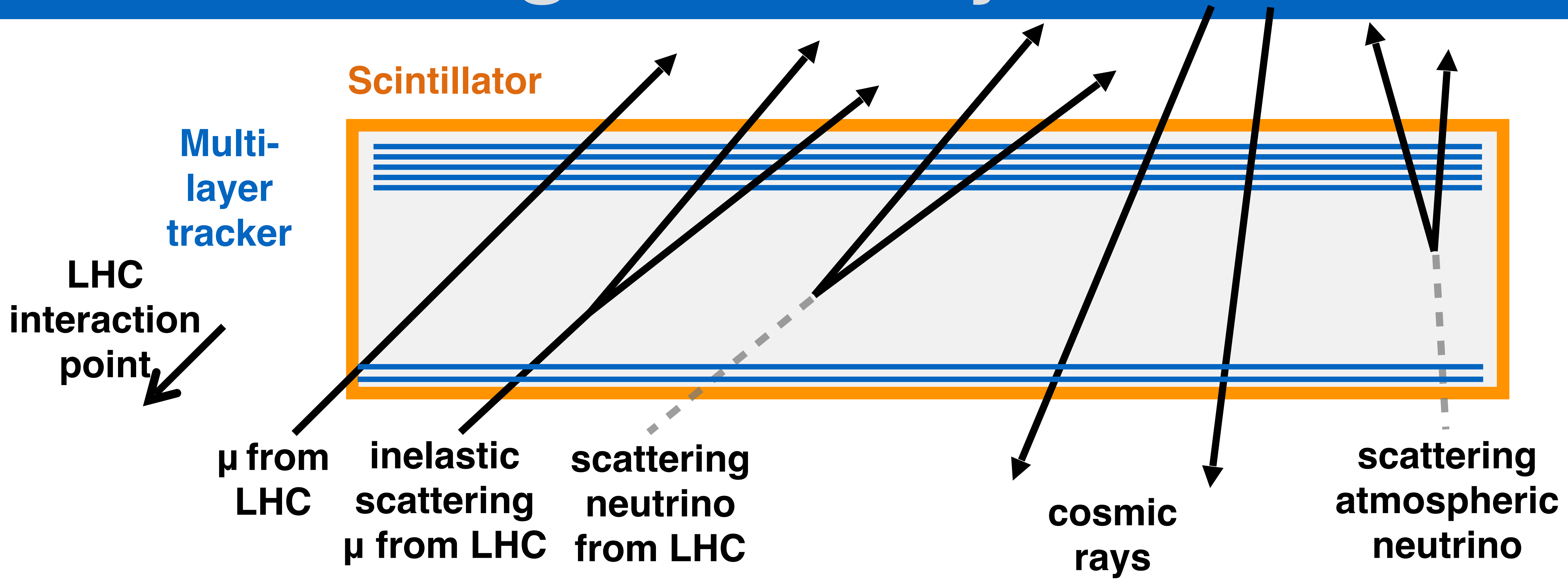


- Searching for upward going vertex in the detector volume
  - LLP may decay to jets or lepton pair, signal requires >= two
  - Particles reaching the ground should be relativistically boosted
  - The tracks come from common vertex
  - The vertex within a cone from the CMS IP
    - Material could help with particle ID (but induce other BG)
  - Use a veto based on the bottom scintillators

Sensitivity for LLP detection

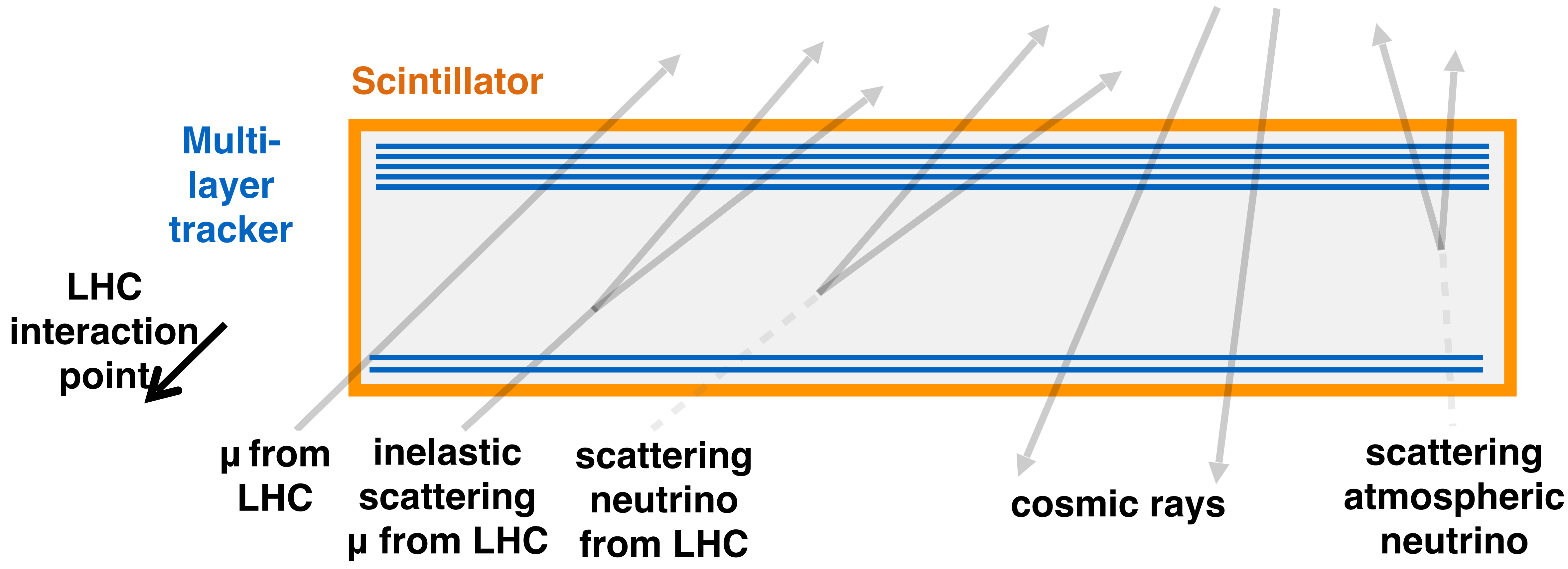
- Characterization of the signals:
  - Clean vertex of lepton pair
  - Vertex with two energetic jets, large angular separation
  - LLP decay length upto 10^8 m..
- Signal sensitivity
  - Geometrical acceptance
  - Detector efficiency
  - Decay volume .vs. the LLP decay length
  - Background rejection

Background Rejection



- Cosmic muon rate of about 10^6 Hz
- LHC collision backgrounds
- Upward atmospheric neutrinos that interact in air decay volume
- non-collision backgrounds

Background Rejection



- Attempt to use geometry and timing of the DV to veto all sources of BG
- Reach close to zero background !
- Study CR / non LHC background and atmospheric neutrino during no beam time

Documentation

- **White paper** *[1806.07396v2 [hep-ph]]*
- **Letter of Intent** [arXiv:1811.00927]
- **Several progress reports**

arXiv:2203.08126], [arXiv:2009.01693], [arXiv:1901.04040], PoS **ICRC2023** (2023) 510, PoS **EPS-HEP2019** (2020) 572,, Nucl.Instrum.Meth.A **936** (2019) 507,, JINST **14** (2019) C05015, , PoS **ALPS2018** (2018) 033, EPJ Web Conf. **182** (2018) 02004, , PoS **EPS-HEP2017** (2017) 772. .....

- **CDR soon**


arXiv:1806.07396v2 [hep-ph] 5 Mar 2019

CERN-TH-2018-142
CP3-Origins-2018-023 DNRF90
FERMILAB-PUB-18-264-T
IFT-UAM-CSIC-18-060
IPMU18-0109
KIAS-P18052
LCTP-18-17
TTP18-022
ULB-TH/18-09
UMD-PP-018-04
YITP-SB-18-16

Long-Lived Particles at the Energy Frontier:
The MATHUSLA Physics Case

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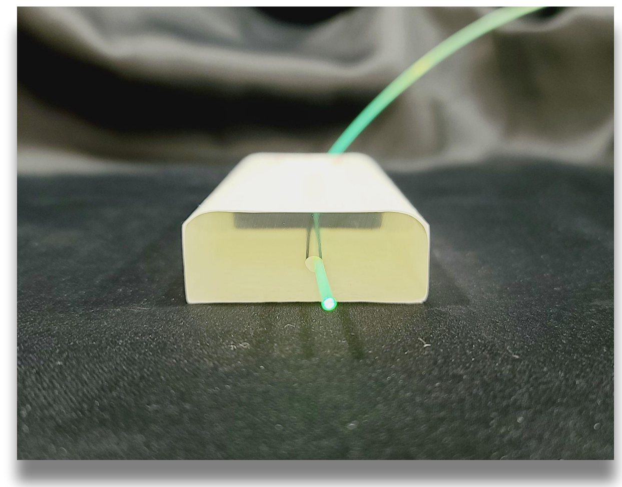
Technology

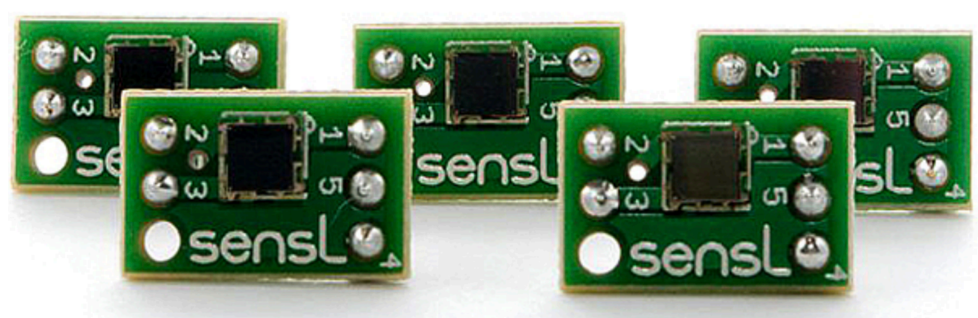
Extruded Scintilators

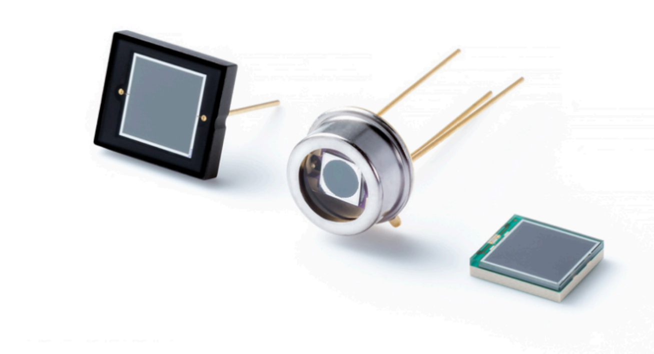
arXiv:2005.02018 (Test stand)
arXiv:2009.01693 (update LoI)
arXiv:2203.08126 (Snowmass22)

- A cheaper method to produce plastic scintillators is extrusion. Studies at Fermilab (FERMILAB-PUB-05-344) show they reach ~75% of the light yield of BC408, or similar to Kuraray SCSN-81.
- Insert WLS fibers into holes prepared during extrusion to increase the light yield.
- Used before by MINOS , Mu2e, MINERVA and D0

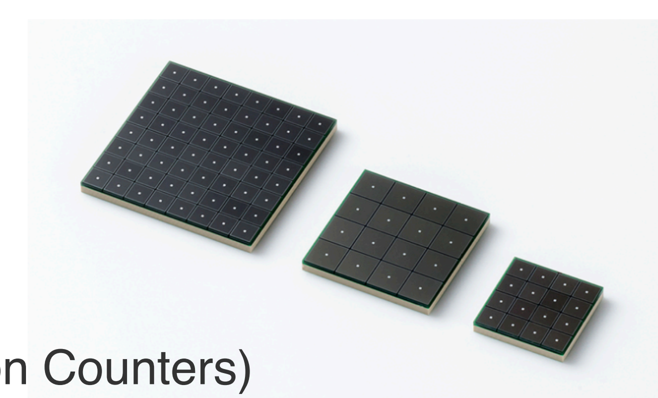


Light readout





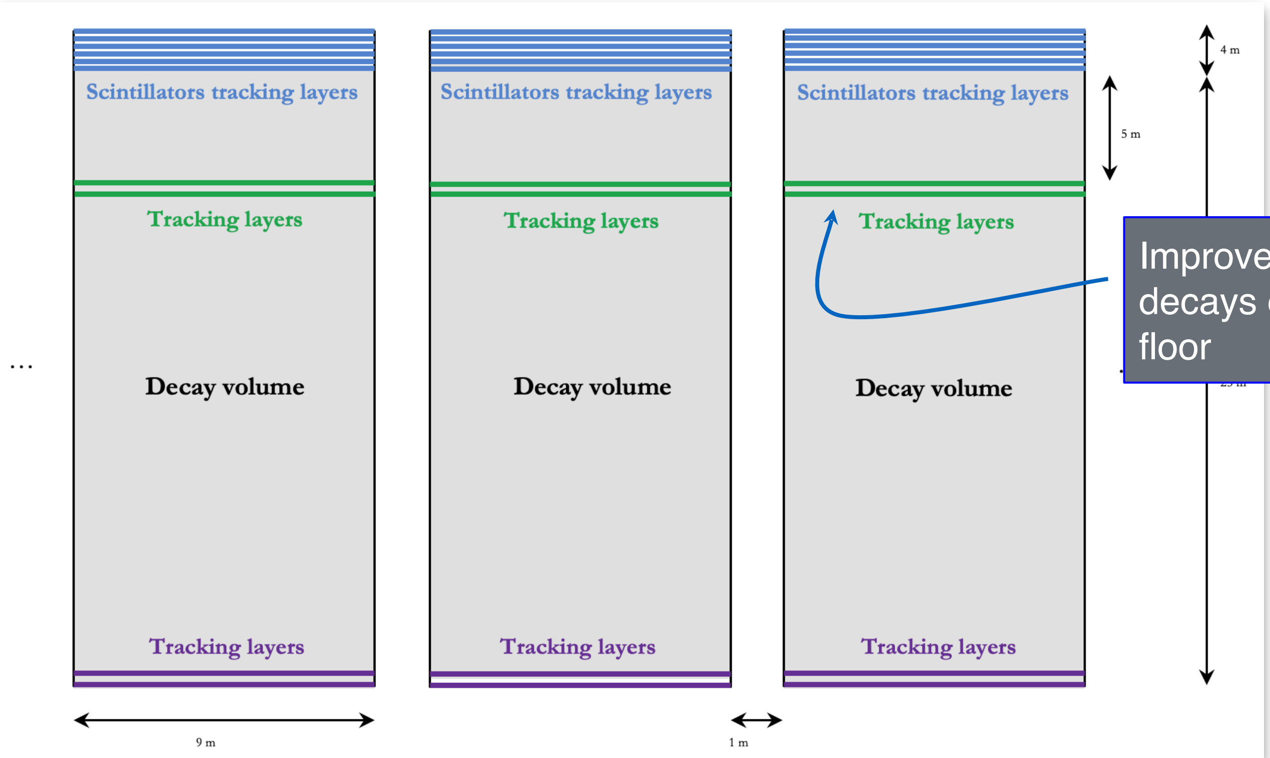
- SiPM – low cost, high-performance alternative.
- Bias voltage ~30-35V
- Sensors are available in several sizes (1-6mm)
- Single units and arrays



MPPCs (Multi-Pixel Photon Counters)

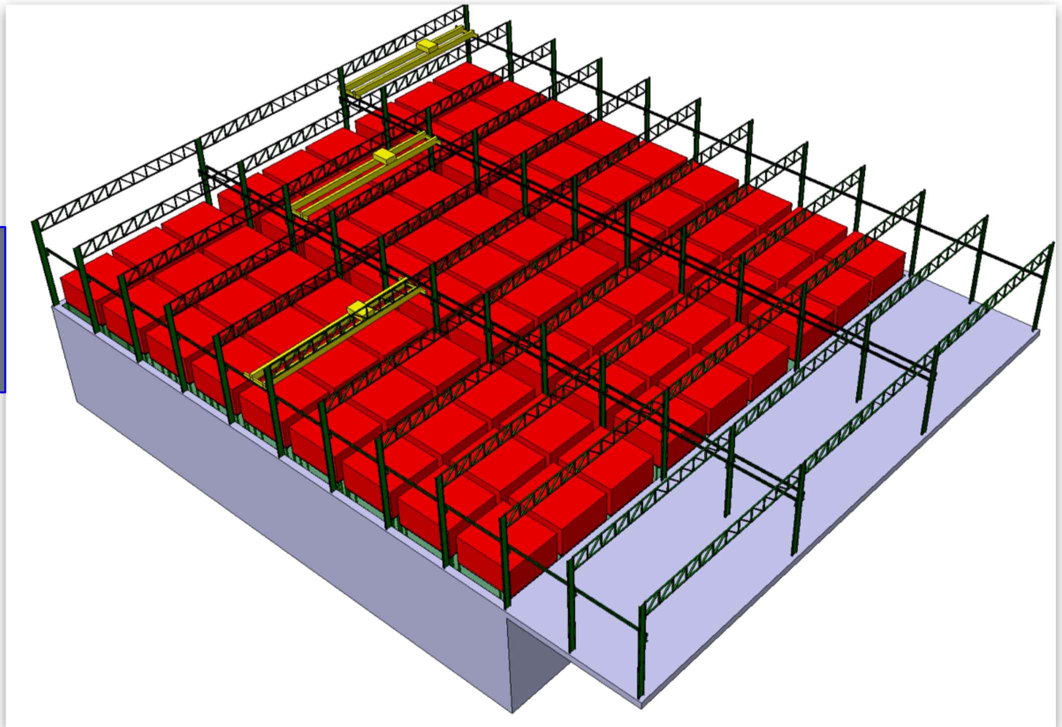
Detector structure

arXiv:2005.02018 (Test stand)
arXiv:2009.01693 (update LoI)
arXiv:2203.08126 (Snowmass22)

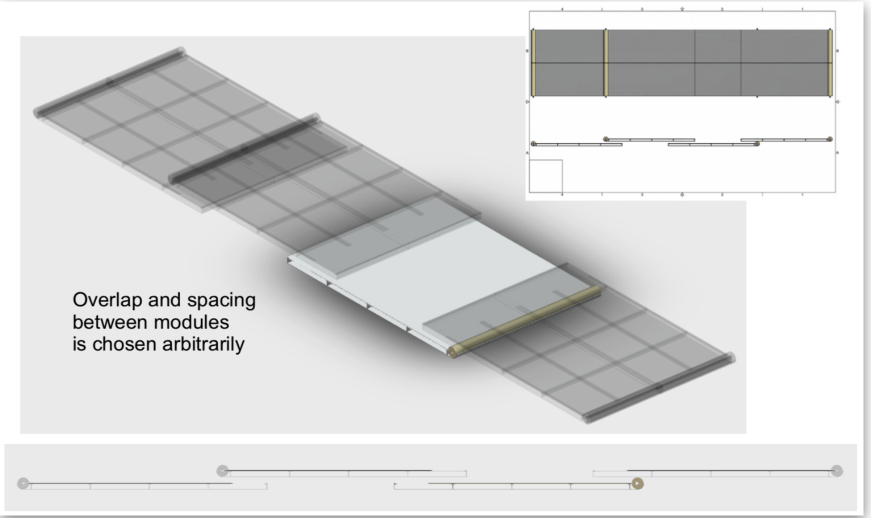


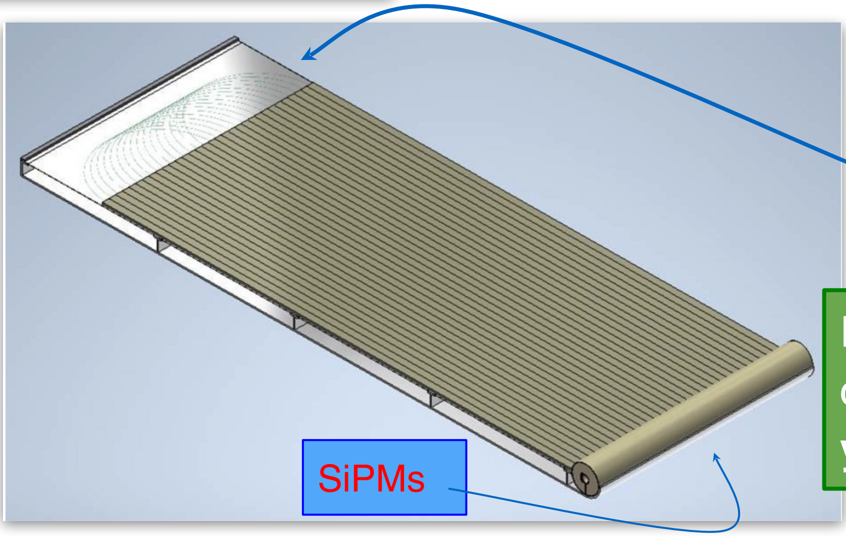
9 m x 9 m modules

Improve vertex reco for decays close to the floor



Detector + assembling



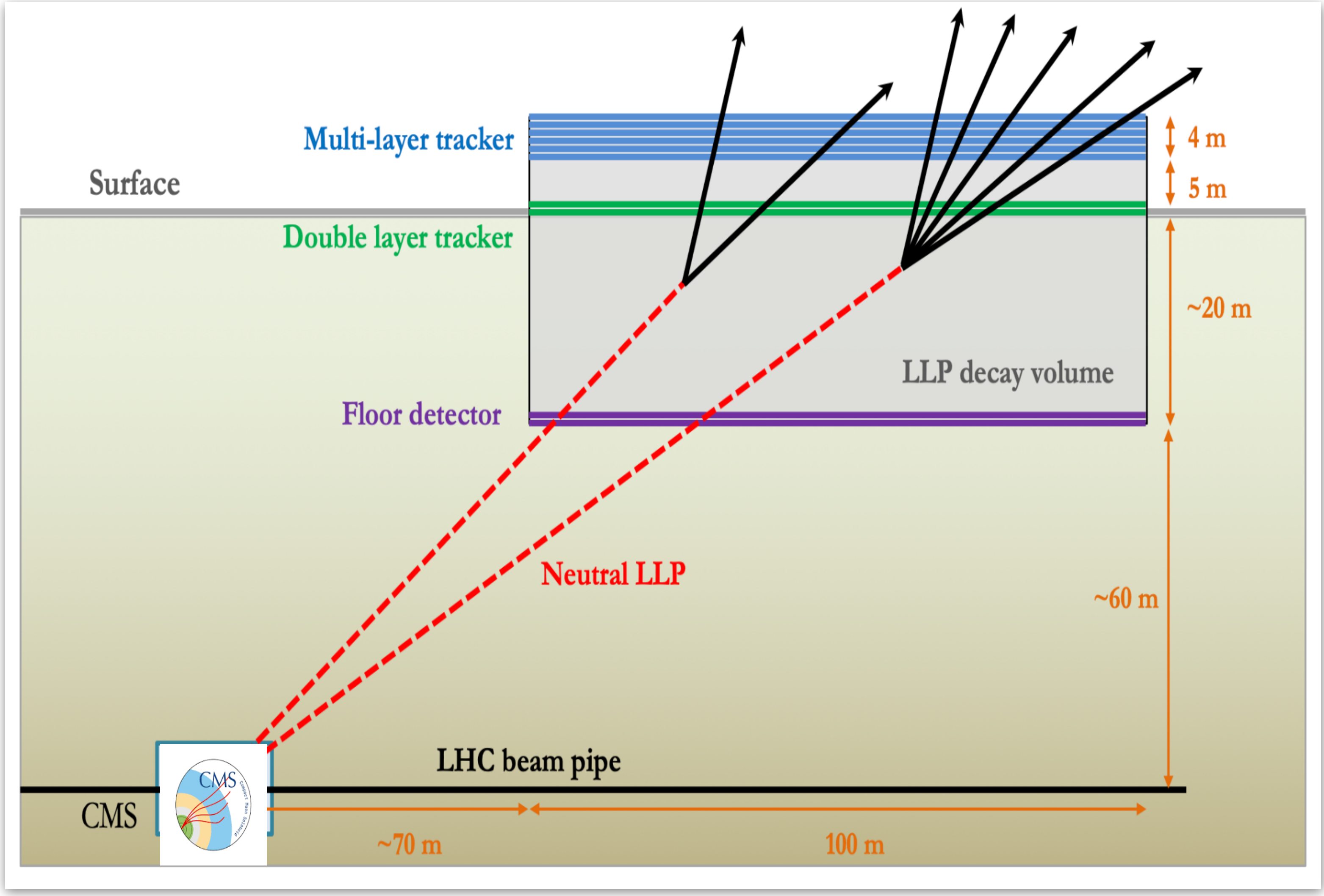


U-readout:
two bars connected at one end (every N-bars). Info read by SiPM only on one side of the bar

Reached timing resolution of **~0.54 ns** (i.e. 9 cm RMS position resolution) **Worst case light-yield: 29 PE**

Each tracking layer has 16 "bar assemblies"
32 x 2.35m long bars

CDR Design



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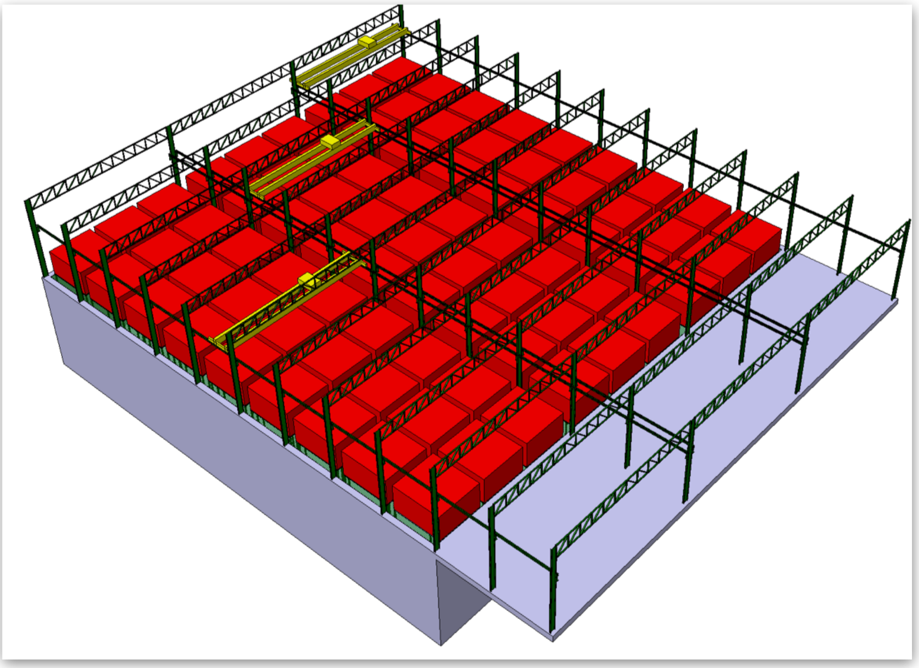
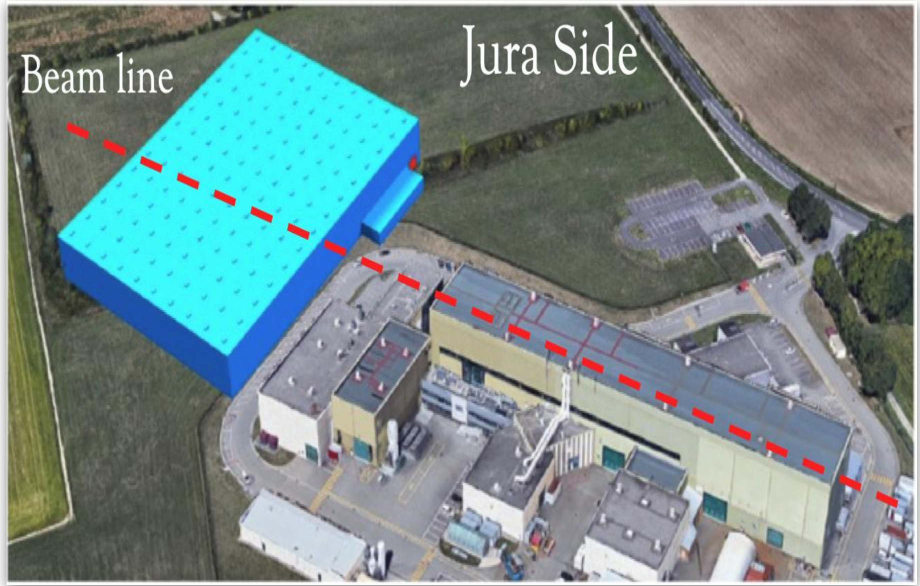
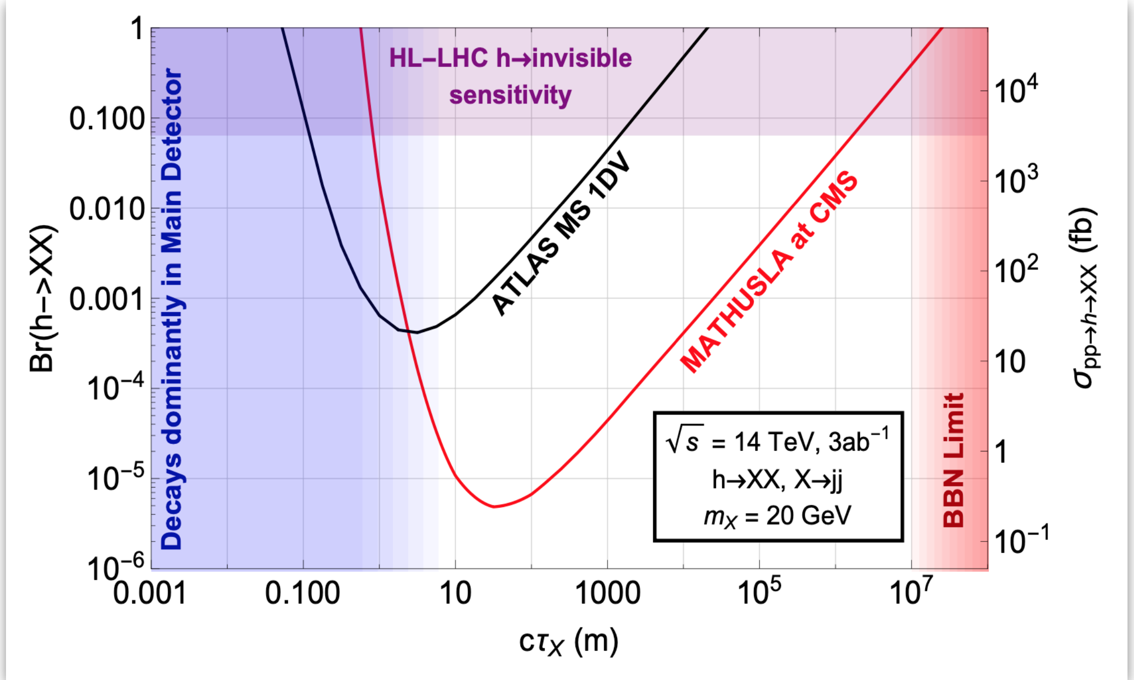


Modular structure

100 modules x (9 x 9 m²)
-> ~20m decay volume underground (building code prominence max. 17 m)
→ above CMS (empty, CERN-owned land)



Reach for new physics



- For shorter lifetimes ATLAS & CMS are more sensitive
- MATHUSLA has similar acceptance as ATLAS and CMS for large lifetimes. For σ(pp→h→XX) extends the sensitivity by ~1000 and even more for the DM searches when compared to mono-X searches.
- MATHUSLA reaches superior sensitivity due to the ATLAS / CMS trigger limitations and background rejection

Descoping

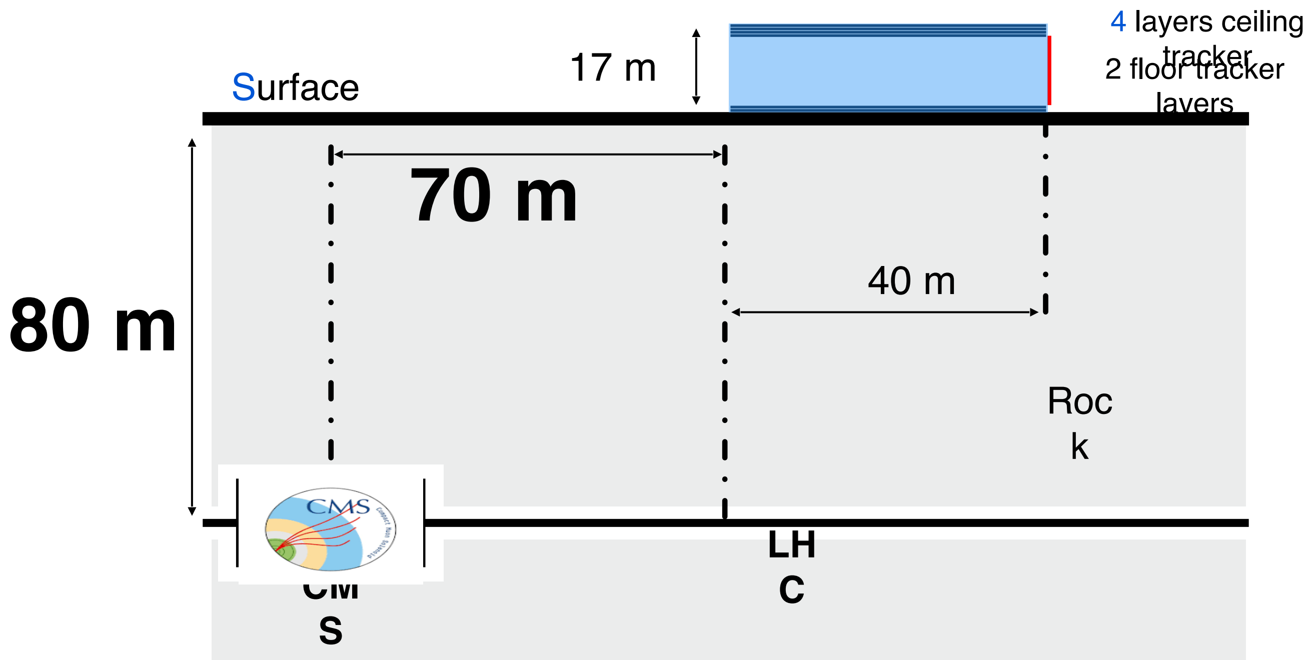
- P5 confirmed that **"auxiliary experiments like CODEX-b and MATHUSLA can extend the sensitivity to BSM particle lifetime in Higgs decays by several orders of magnitude"**. However, it did not recommend DOE to fund MATHUSLA in its full 100 m x 100 m scale and proposed it will compete in the portfolio for the smaller scale Agile projects

$$\text{Sensitivity} \propto \text{Volume} \text{ while } \text{Cost} \propto \text{Area}$$

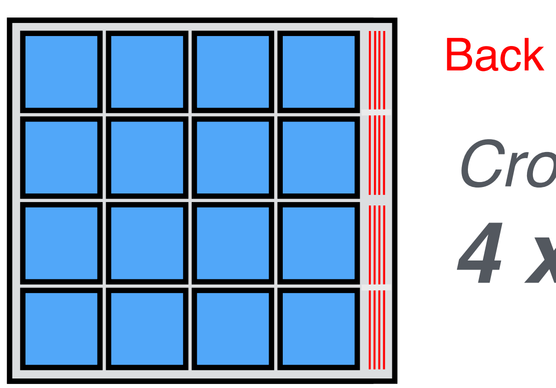
- MATHUSLA can still significantly contribute to the LLP searches (hadronic decays in the 10-100 GeV range) with a reduced size
  - Need to rescope the detector to make it affordable
- Investigating the possibility of housing a smaller-scale MATHUSLA-like detector in existing buildings near ATLAS and CMS
  - Still ongoing discussion (expected more concrete conclusions in the coming months)

Updated design

40 m x 40 m x 17 m



Side view

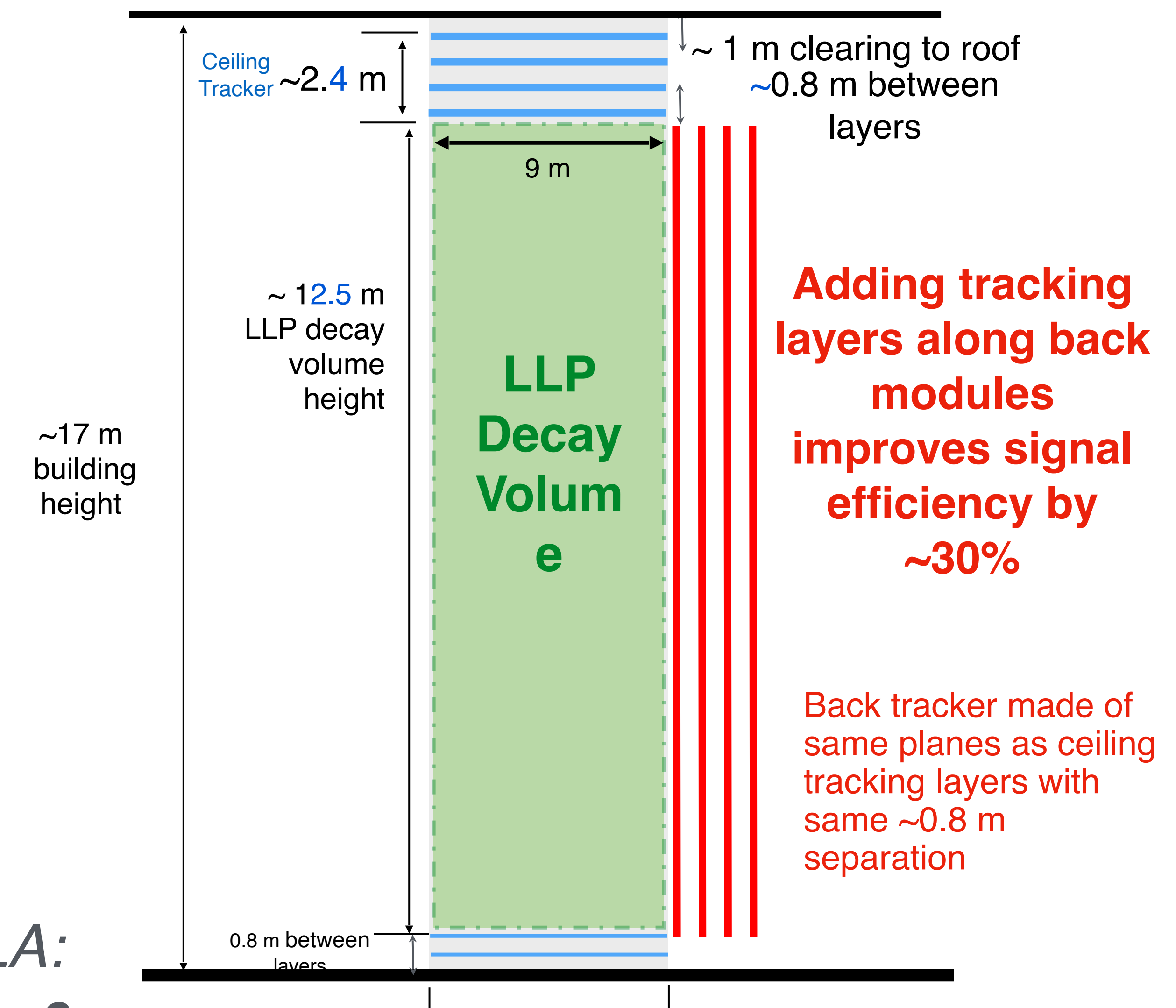


Cross-section of MATHUSLA:

4 x 4 grid of 9 x 9 m²

modules

*with ~**1 m** gap*



9 x 9 m² module Vertical structure

Proposed new geometry (prel.)

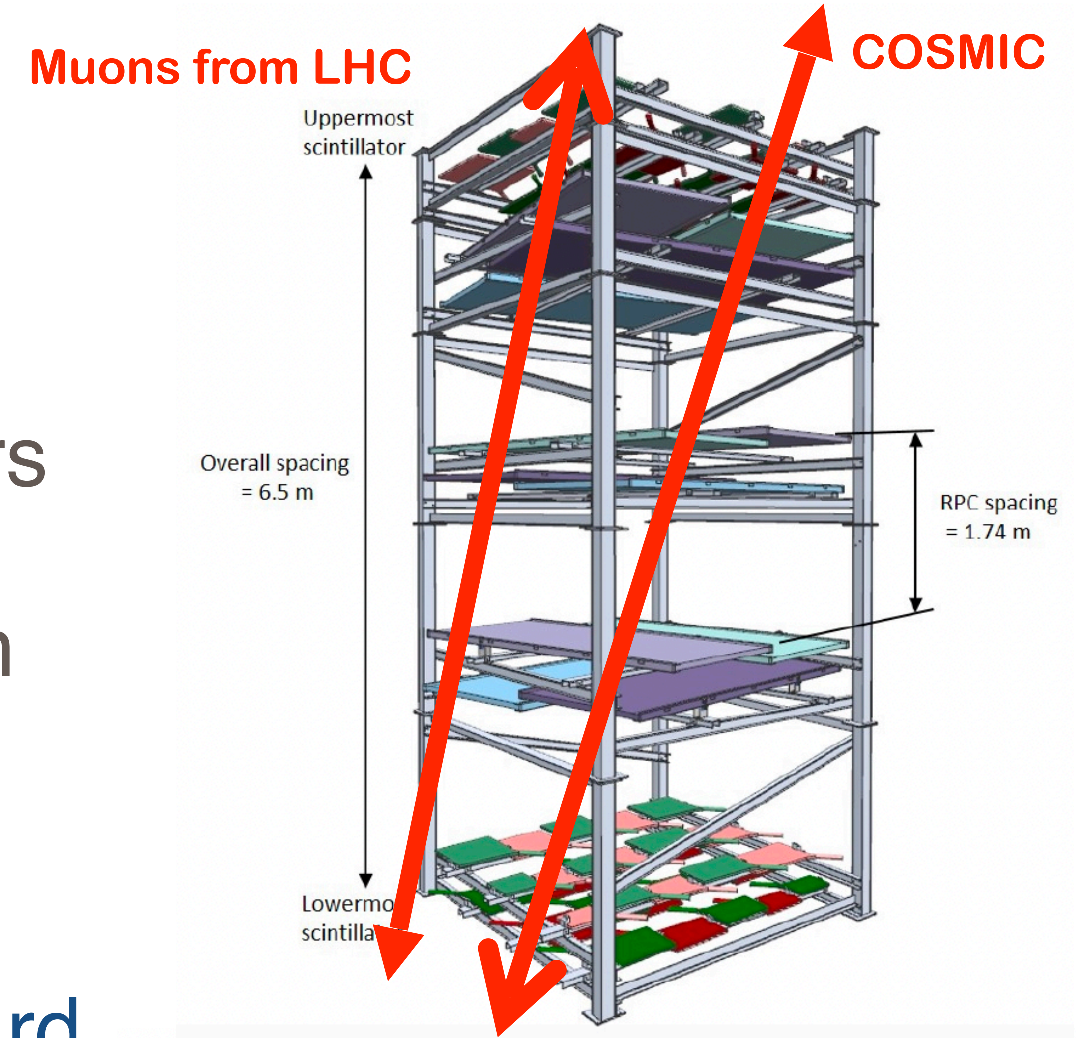
Goal to reduce both infrastructure and detector costs to roughly 1/10 of original design

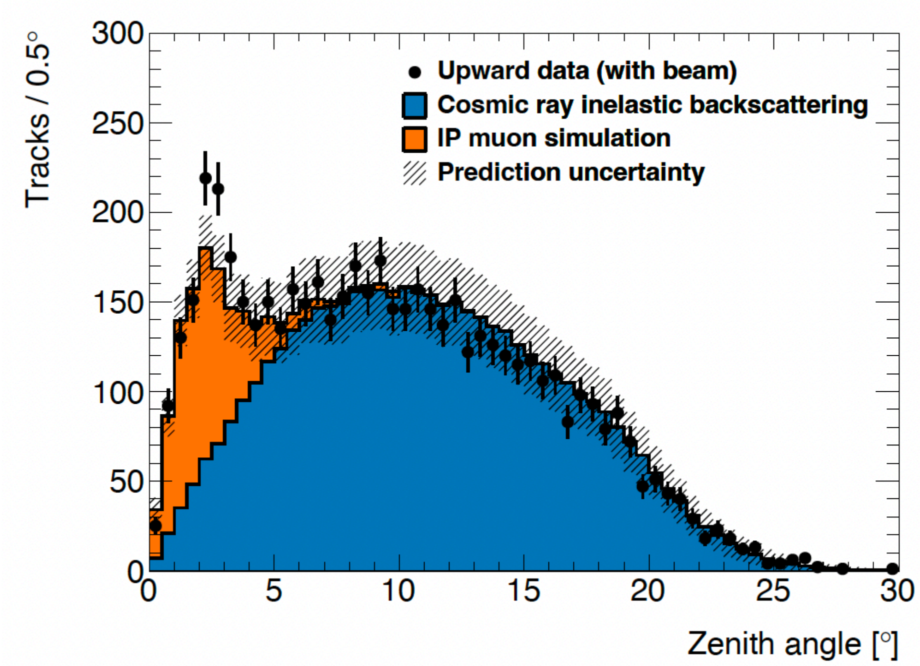
Attribute	Pre-P5 benchmark	New proposal	Comment
Position	Near CMS	Same	Centered at beamline
Area	100 m x 100 m	40 m x 40 m	
Excavation	About 20	NONE	Huge reduction in infrastructure costs
Modularity	9x9 m^2, 1 m gap	The same? TBC	
# of layers	6 (ceiling) + 2 (mid)	4 (ceiling) - TBC	GEANT studies ongoing
Vertical layer	2 floor, 2 mid, 6 ceiling	2 floor, 4 ceiling (mid TBC)	GEANT studies ongoing
Installation	Crane assemblies above tracker	Under engineering studies	H=17m constraints by building height at CMS, no excavation
Height	25 m	~12 m	
Decay volume	250,000 m^3	~20,000 m^3	1/10 the signal sensitivity as 100 x 100 ? (TBC)

Test stand above ATLAS

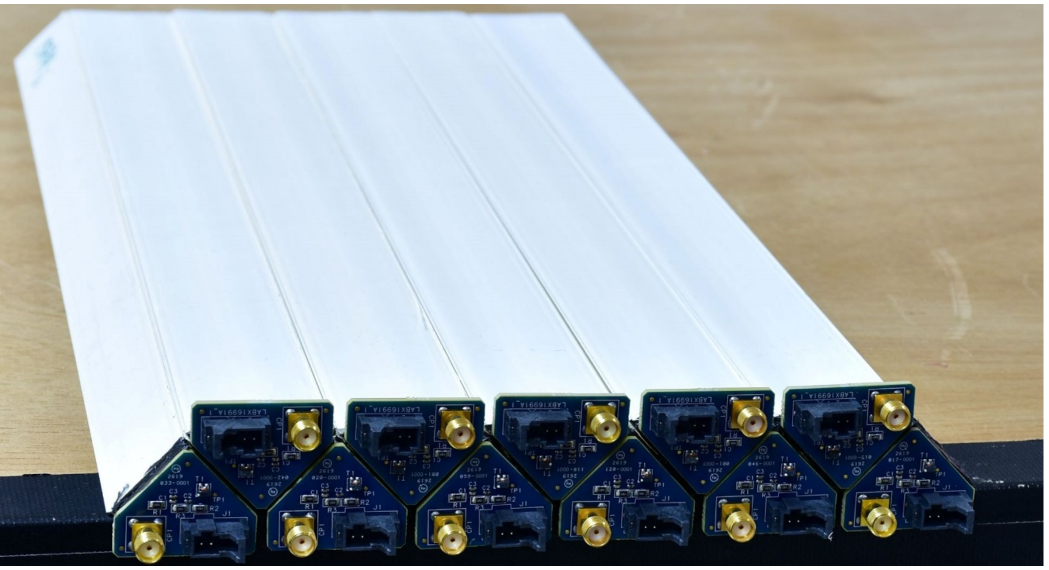
arXiv:2005.02018 (Test stand)

- Two layers of scintillators used for trigger
- RPC arranged in six 2.50 x 2.80 m² layers for tracking
- Took Cosmic data (LHC off) and data with LHC on
- Upward tracks (identified by timing) come from:
  - 1. LHC (consistent with expected upward muons penetrating through the ground).
  - 2. Inelastic backscattering CR.
- The test results confirmed the background assumptions in the MATHUSLA proposal.





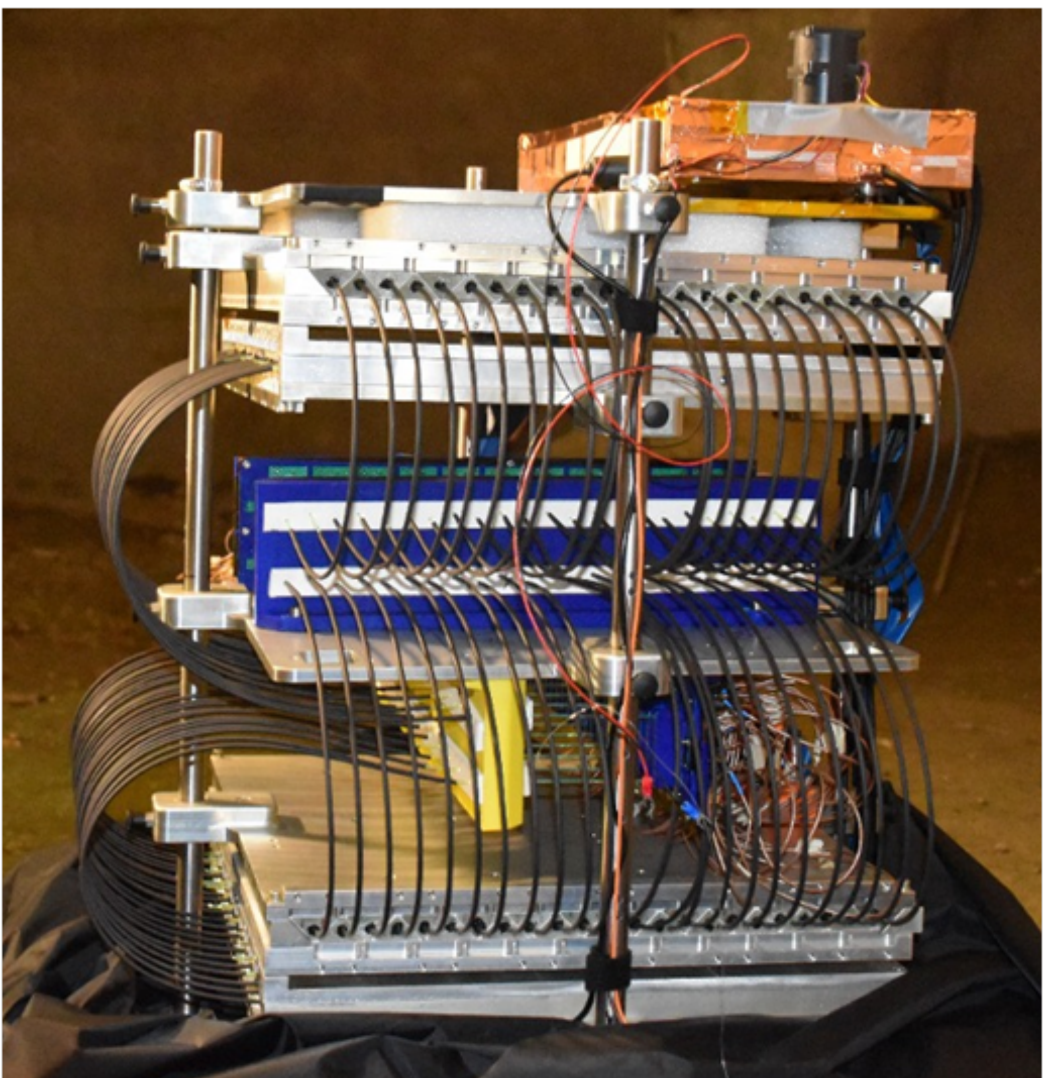
Muon tomography



NIM-A 1042 (2022) 167412

An early demonstrator of MATHUSLA is used as an underground detector. It uses cosmic ray muons, penetrating through the ground, for 3D imaging in the City of David Archeological site

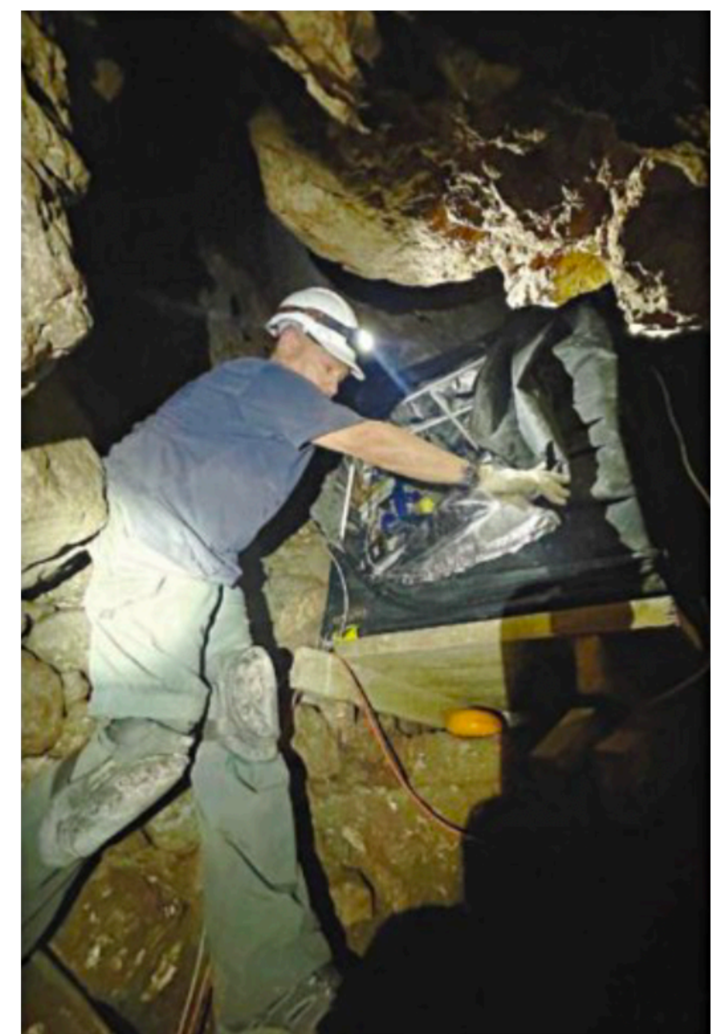
Scintillating bars



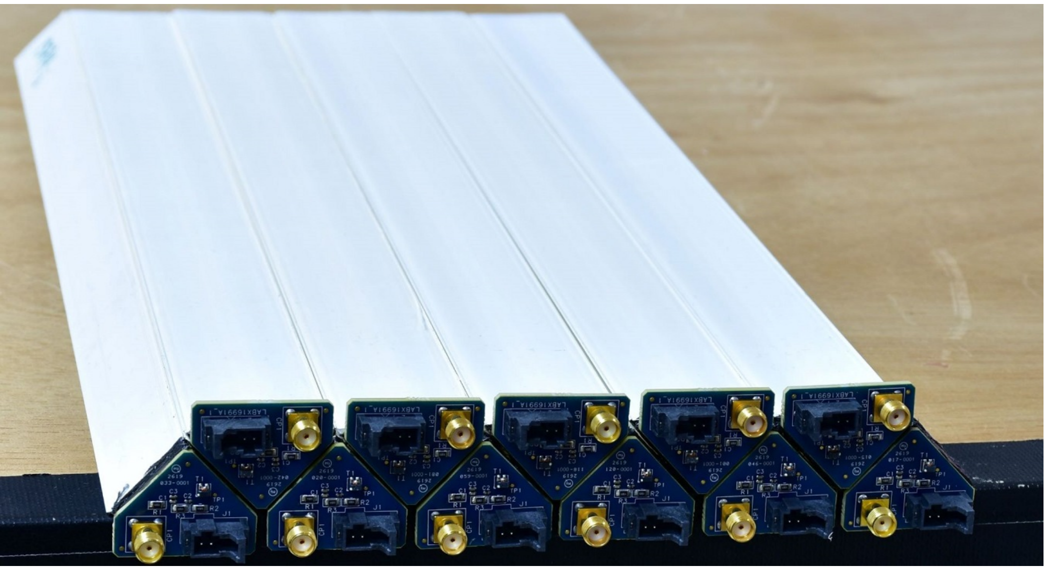
Four tracking layers demonstrator

Extruded scint. FNAL
WLS BCF91A
SiPM Sensel 30035
DAQ CAEN DT5550W

The detector underground



Muon tomography



Scintillating bars

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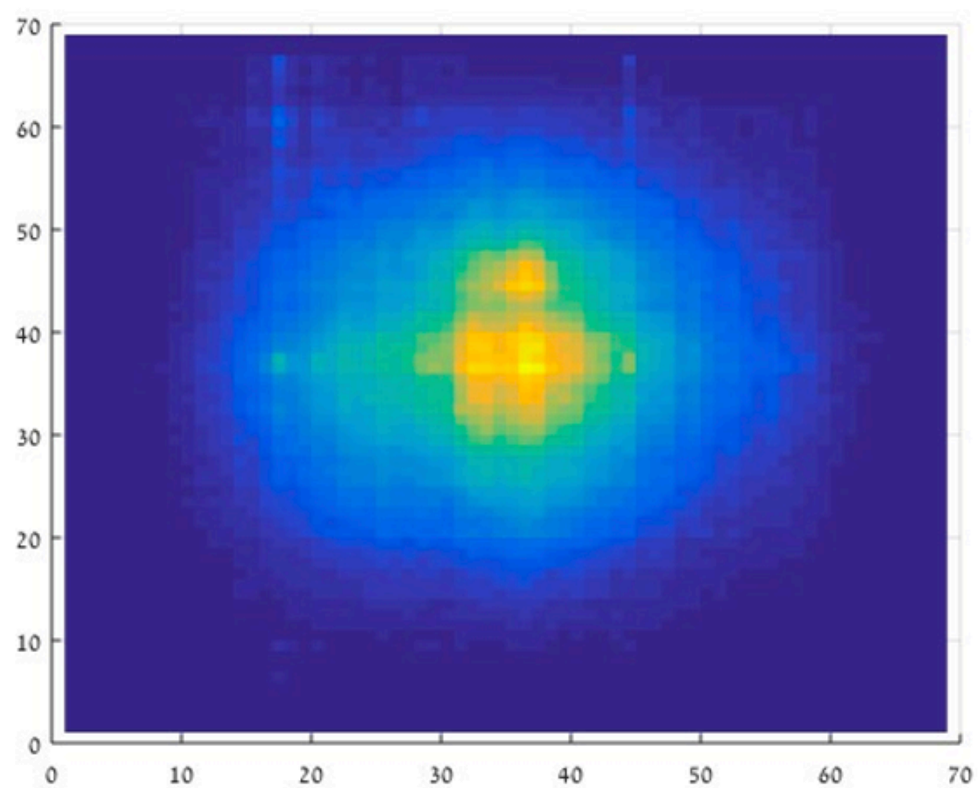
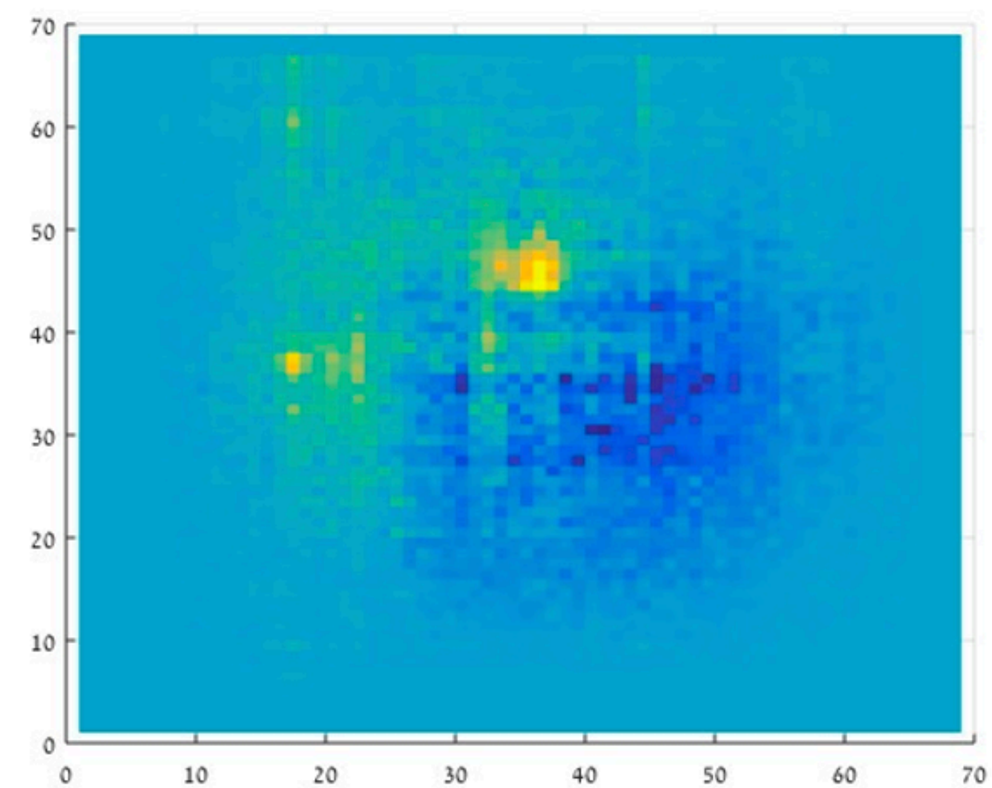
Raw data

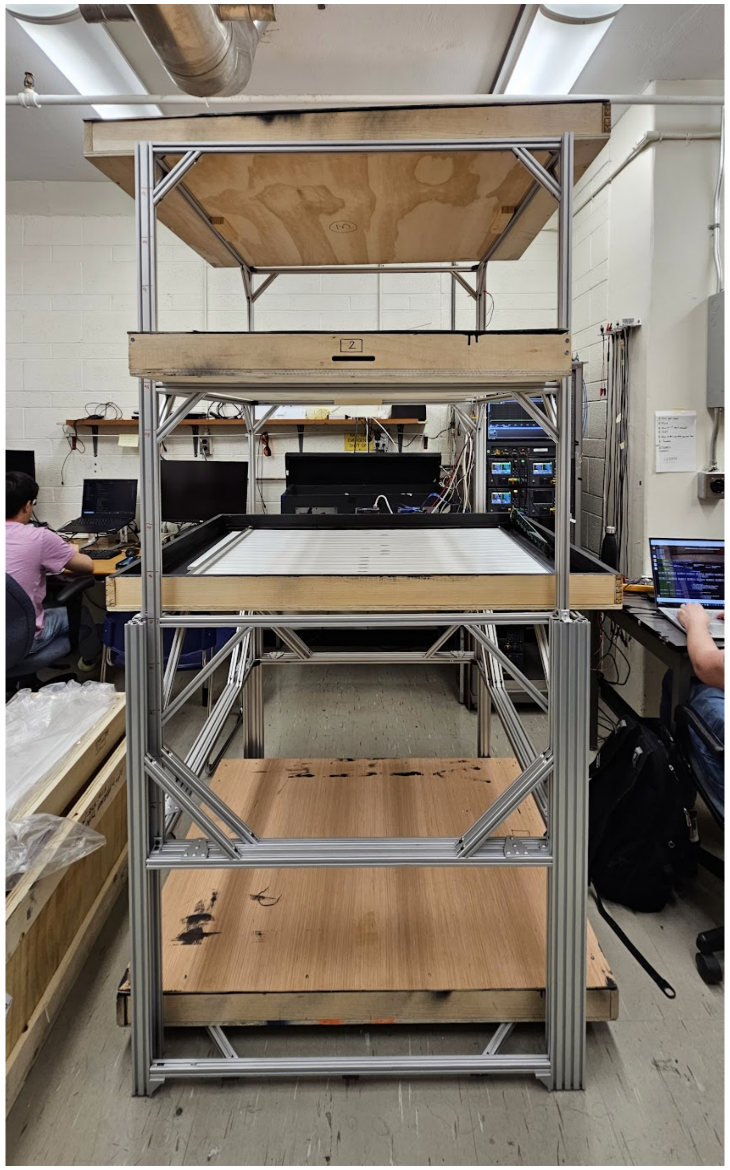


Data after “blue sky” substraction



Two new test stands

Two test stands in varying stages of operation at UVic and U.Toronto



- 4 layers
- ~1 m x 1 m layers of scintillator bars
- 0.8m spacing
- Adjacent layers rotated by 90deg
- Enclosed in dark box(es)

Two new test stands

UVic prototype

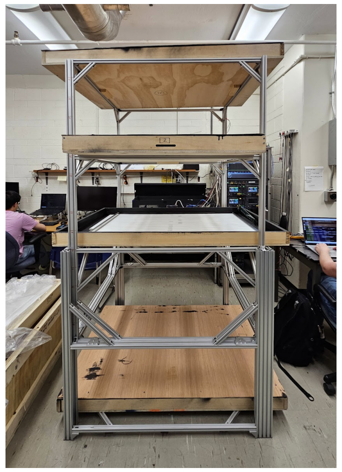
- 80 bars threaded with 32 WLSF
- 64 channel Hammamatsu SiPM array
- Can easily swap out fibres, SiPMs, bars to study components

Data acquisition

- CAEN DT-5202, 1 min data collection loop with software "trigger" skimming

Current studies

Development of data quality framework, geometry parsing, and tracking software



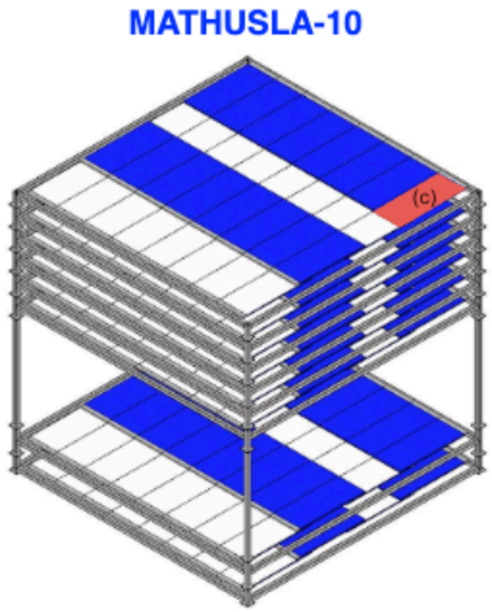
UofT prototype

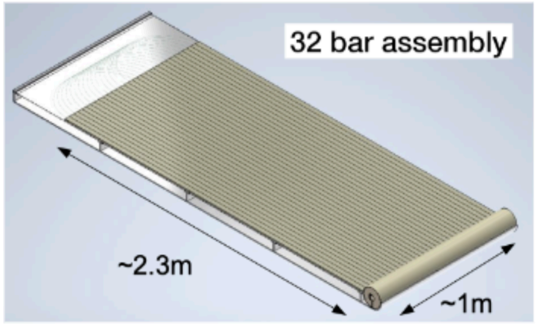
- 4x20 bars threaded with 40 WLSF
- End-mounted individual Hammamatsu SiPMs (s14160-3050)
- Testbed for ASIC/FEB development

Data acquisition

- PETsys TOFPET2 commercial ASIC developed for PET scans
  - Investigating use of this ASIC for MATHUSLA
- Custom frontend electronics

Module 0

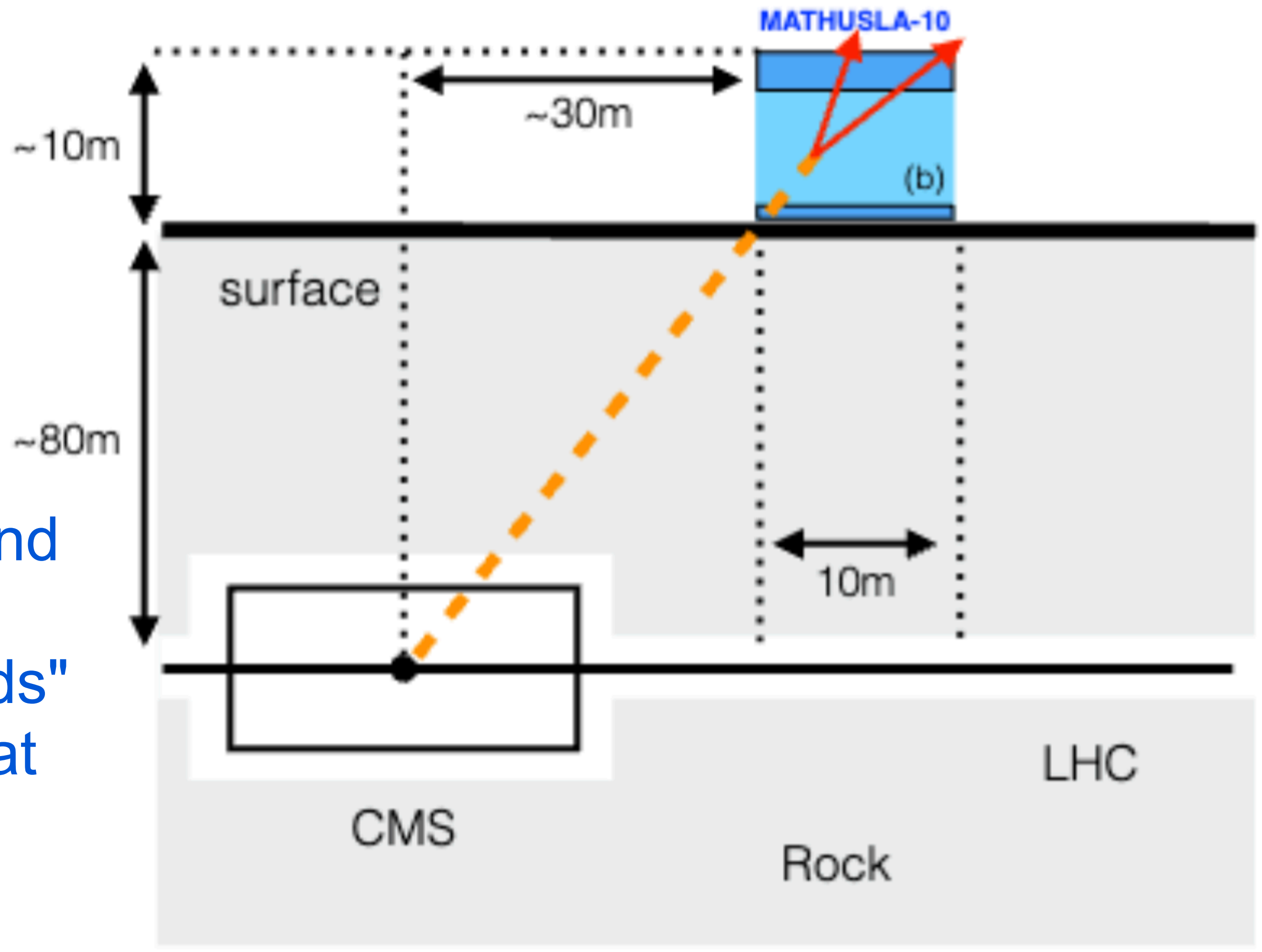




Proposal for **MATHUSLA-10** (Canada)

- Dimensions **~10 x 10 m², H~flexible**
- Prototype for the detector technology
- To be placed above CMS, and even as a stand-alone module can extend the LHC reach for LLP

- Manufacturing and operating the building blocks of the large scale detector.
- Exercise on real data: tracking, efficiency and timing resolution using CR, at UofT.
- Characterize "beam-associated backgrounds" (rare SM particles in HL-LHC by operating at CERN P5 during LHC runs.



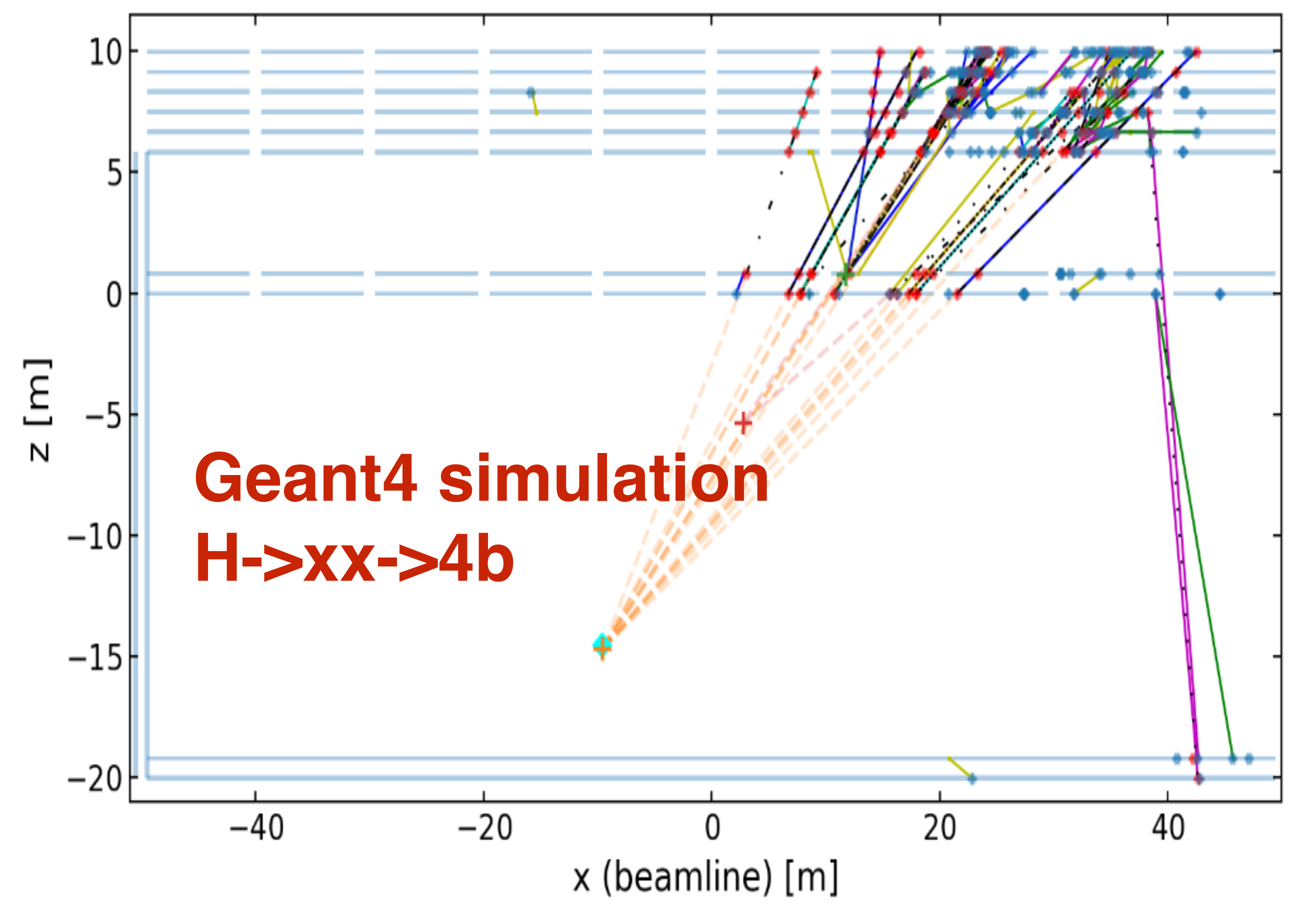
Software, Simulation

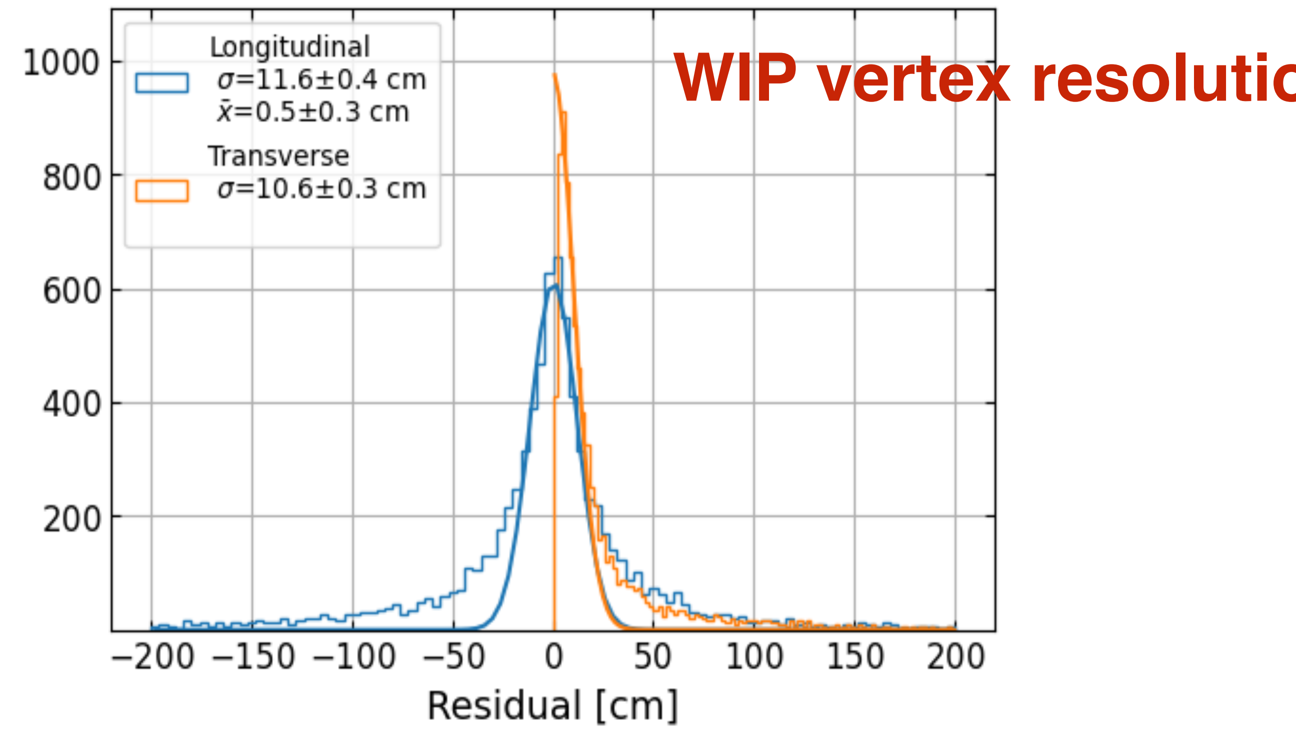
Simulation

- **MATHUSLA_FastSim**, geometry-only detector simulation, used in our sensitivity studies and projections arXiv:2308.05860
- **Full Geant4 simulation**
  - Detector implemented, sensitivity studies are in progress

Reconstruction

- Kalman filter based track and vertex reconstruction are under development

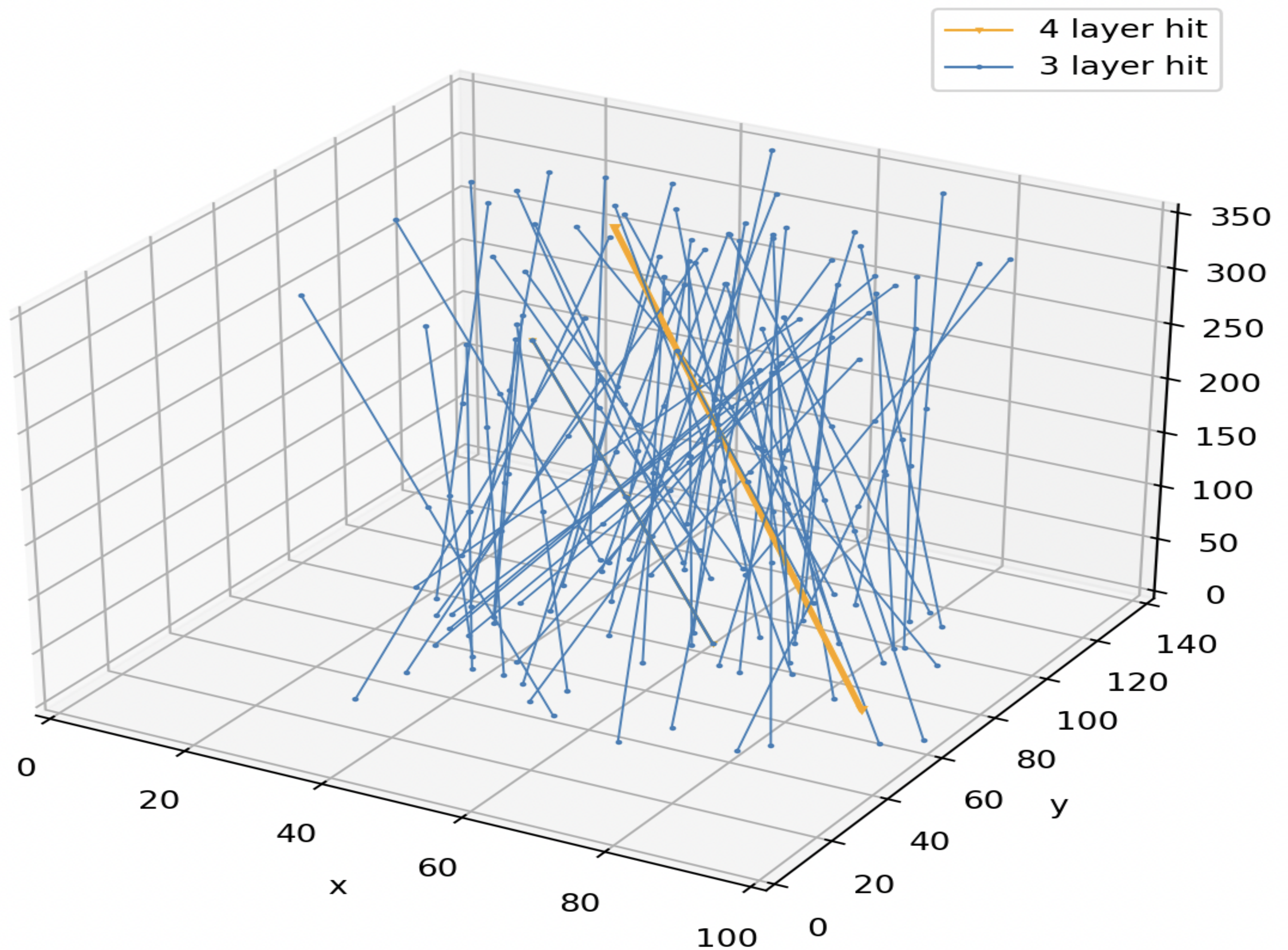




Uvic test stand results

Performance test: e.g. timing tests, temperature to timing correlation etc

Work ongoing on selection and track reconstruction

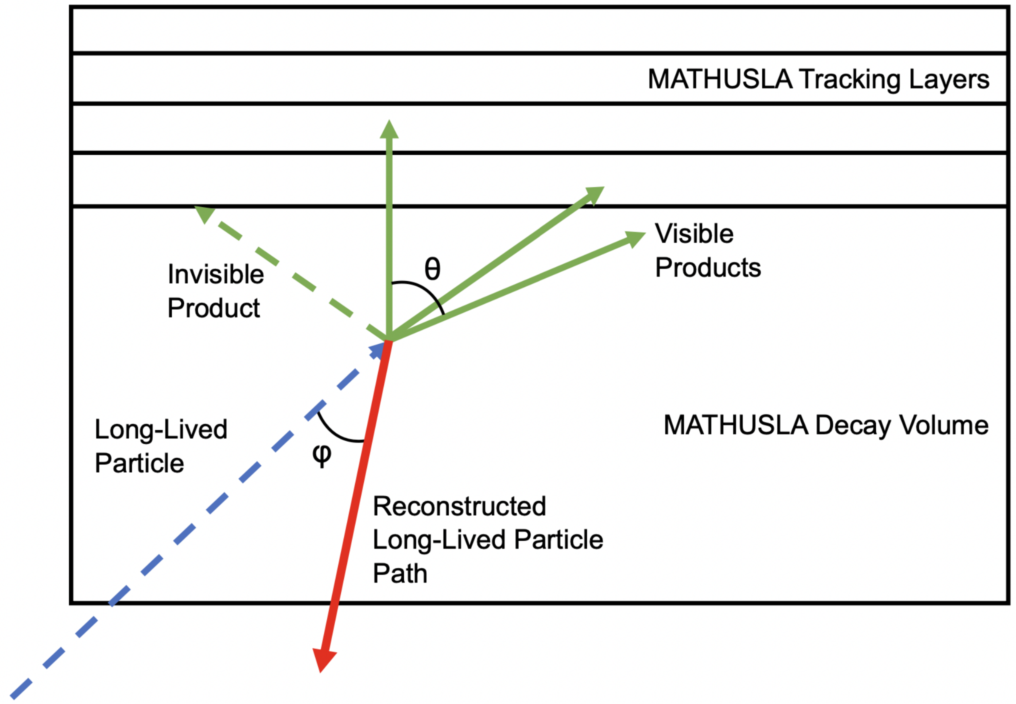


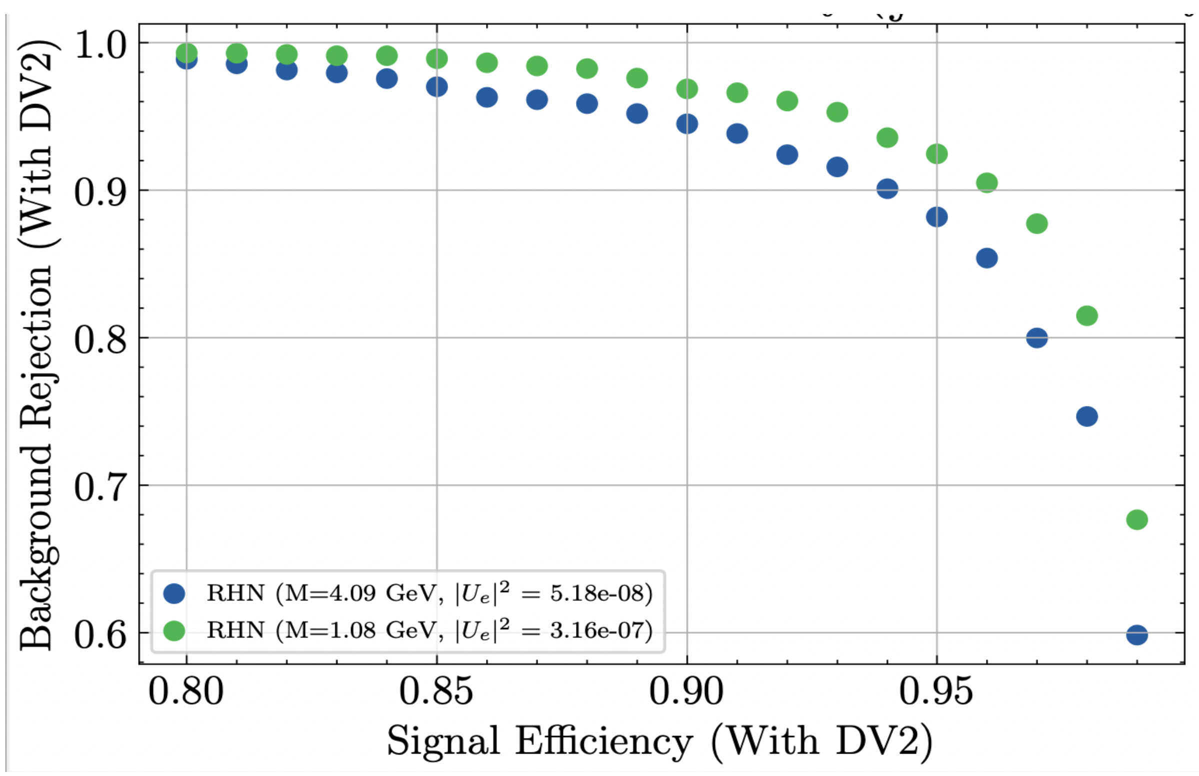
Best 70 tracks (χ^2) with at least 3 above-threshold hits from 33 hours of cosmics data taking

Neutrino BG rejection

>LLP decays with significant invisible track fraction do not point back to the interaction point.

>Background from **atmospheric neutrino - air scatter** also form non-pointing vertices. Mostly reject the nonrelativistic p. (30 evt/year -> 1 evt/year in M100)





Work on developing simple **rectangular cuts** to reject significant background even when only requiring **two track vertices (DV2)**

Concluding remarks

- Existence of LLP is a key question in understanding the extensions to SM (Naturalness.. DM..).
- HL-LHC will be factory of Higgses enabling e.g. search for hidden sector via Higgs portal.
- Extending LHC program (FASER, Codex-B, ANUBIS, SHiP…)
- **MATHUSLA** even with a descoped detection and air volume with well - established detection techniques will extend the LHC reach for LLP by orders of magnitude.
- Background rejection requires an excellent understanding of LHC and CR to reach very high rejection rates required for discovery
- Current efforts focus on HW - testbenches, SW – tracking, simulation, TH – analyses techniques, and Engineering.
- Modul zero prototype will inform the final design.

Long Lived the ????

Thanks

Backup

arXiv:2308.05860 [hep-ph]

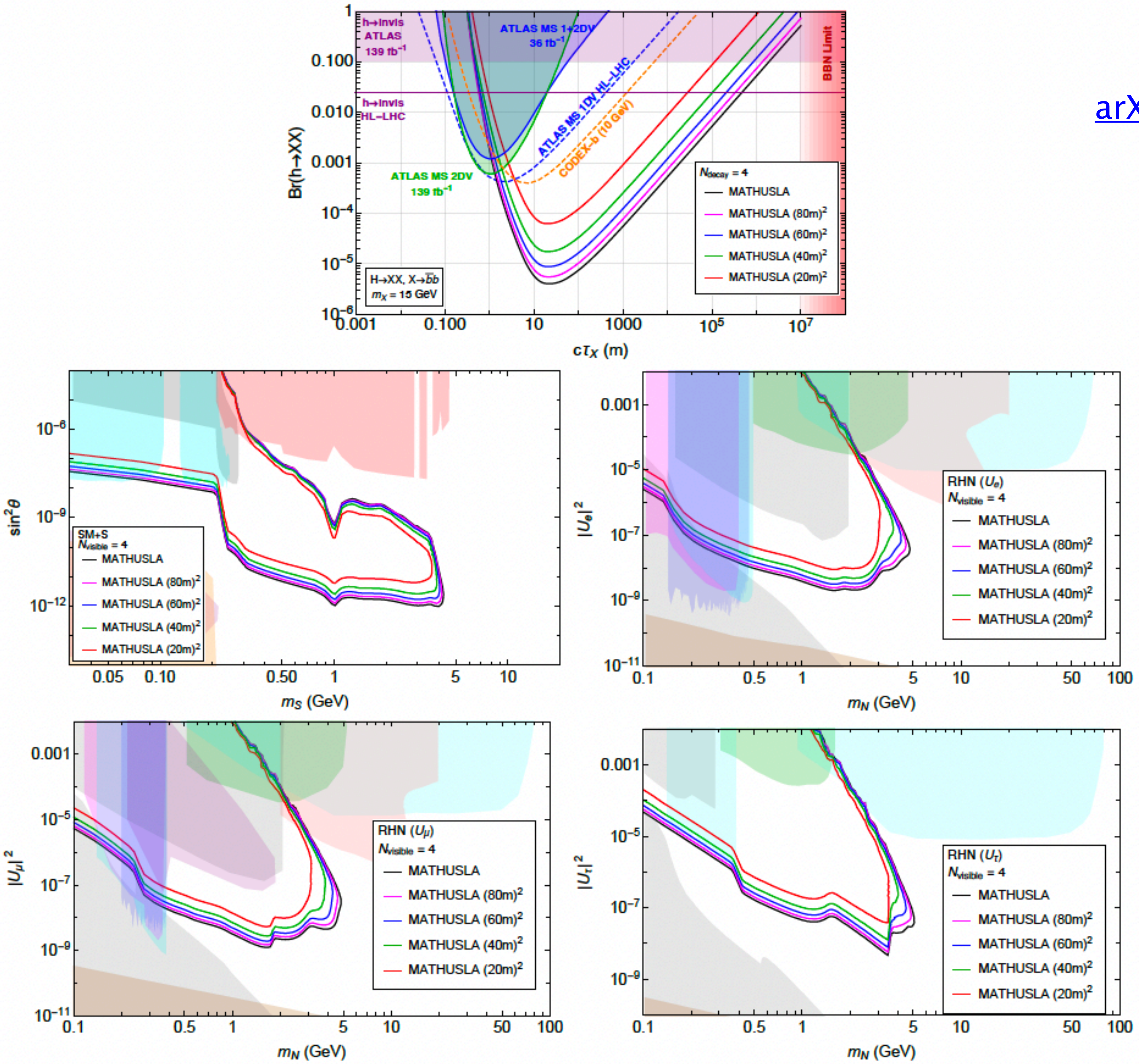


FIG. 11. Comparing the idealized reach of the MATHUSLA baseline geometry in Figure 1 to similarly situated versions of MATHUSLA with smaller area.