

METHUSelah

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 **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** **P**Articles
Extending the LHC LLP horizon with large but simple apparatus



July 2024

Erez Etzion, on behalf of the MATHUSLA team

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.

SUSY - Natural fine tuning solution?

- MSSM (Weak scale SUSY) every bosonic and fermionic d.o.f gets SUSY d.o.f
- spin 1/2 gaugino for each SM gauge boson
- scalar partner for each SM gauge boson
- Two complex Higgs doublets cancel triangle anomalies; selectrons ..
- $R_{parity} = (-1)^{3(B-L) + 2s}$ conservation? (sparticle -1) -> lightest SUSY (LSP) stable (DM candidate)

Strong SUSY

Weak SUSY

Strong SUSY

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0, H_d^0, H_u^+, H_d^-$	h^0, H^0
squarks	0	-1	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R, \tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R, \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$	
sleptons	0	-1	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e, \tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu, \tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$	
neutralinos	1/2	-1	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$	
charginos	1/2	-1	$\tilde{W}^\pm, \tilde{H}_u^\pm, \tilde{H}_d^\pm$	
gluino	1/2	-1	\tilde{g}	
goldstino (gravitino)	3/2	-1	\tilde{G}	

(partial) List of Exotic Models

Extra dimensions:

- RS Kaluza Klein (KK) Graviton (dibosons, dileptons, diphotons)
- RS KK gluons (top antitop)
- ADD (monojets, monophotons, dileptons, diphotons)
- KK Z/gamma bosons (dileptons)

Grand Unification (GUT) symmetries

- (dielectons, dimuons, ditaus)
- Leptophobic topcolor Z' boson (top antitop to dileptons, l+j, all had)

SS- color octet scalars (dijets)

- String resonance (dijets,)
- Benchmark Sequential SM (SSM) Z', W'
- W' (lepton+MET, dijets, tb)
- W* (lepton+MET, dijets)
- Quantum Black Holes (dijet, l+j)
- Black Holes (l+jets, same sign leptons)

Technihadrons (dileptons, dibosons)

Dark Matter

- WIMPs (monojet, monophotons, monoX..)

Excited fermions

- q*, Excited quarks (dijets, photon+jet)
- l*, excited leptons (dileptons+photon)

Leptoquarks (1st, 2nd, 3rd generations)

- higgs -> hidden sector (displaced vertices, lepton jets)

Contact Interaction

- llqq CI
- 4q CI (dijets)

Doubly charged Higgs (multi leptons, same sign lepton)

4th generation

- t' -> Wb, t' -> ht, b' -> Zb, b' -> Wt
- (dileptons, same sign leptons, l+J)

VLQ-Vector Like quarks

Magnetic Monopoles (and HIP)

Heavy Majorana neutrino and RH W

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.

CMS (preliminary)

Overview of SUSY results: squark pair $pp \rightarrow \tilde{t}\tilde{t}$
137 fb⁻¹ (13 TeV)

$pp \rightarrow \tilde{t}\tilde{t}$

Combination: SUS-20-002

$\tilde{t} \rightarrow t\tilde{\chi}_1^0$

Marion 2021

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
dimen.	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1-4 j	Yes	139	M_D 11.2 TeV $n=2$
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO
	ADD OBH	-	2 j	-	139	M_{BH} 9.4 TeV $n=6$
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{BH} 9.55 TeV $n=6, M_D=3 \text{ TeV, rot BH}$
Gau	HVT $W' \rightarrow WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass 340 GeV 4.3 TeV $g_V=3$
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV 4.3 TeV $g_V=3, g_{VH}=1, g_F=0$
	HVT $Z' \rightarrow WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV 5.0 TeV $g_V=3$
	LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	-	80	W_R mass 3.9 TeV 5.0 TeV $m(N_R)=0.5 \text{ TeV, } g_L=g_R$
Cl	Cl $qqqq$	-	2 j	-	37.0	Λ 21.8 TeV η_{LL}
	Cl $\ell\ell qq$	2 e, μ	-	-	139	Λ 35.8 TeV η_{LL}
	Cl $eebs$	2 e	1 b	-	139	Λ 1.8 TeV $g_s=1$
	Cl $\mu\mu bs$	2 μ	1 b	-	139	Λ 2.0 TeV $g_s=1$
DM	Axial-vector med. (Dirac DM)	-	2 j	-	139	m_{med} 376 GeV 3.8 TeV $g_a=0.25, g_s=1, m(\chi)=10 \text{ TeV}$
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	m_{med} 376 GeV 3.8 TeV $g_a=1, g_s=1, m(\chi)=1 \text{ GeV}$
	Vector med. Z' -2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$ 800 GeV 3.0 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_a 800 GeV 3.0 TeV $\tan\beta=1, g_s=1, m(\chi)=10 \text{ GeV}$
LQ	Scalar LQ 1 st gen	2 e	$\geq 2j$	Yes	139	LQ mass 1.8 TeV $\beta=1$
	Scalar LQ 2 nd gen	2 μ	$\geq 2j$	Yes	139	LQ mass 1.7 TeV $\beta=1$
	Scalar LQ 3 rd gen	1 τ	2 b	Yes	139	$\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1$
	Scalar LQ 3 rd gen	0 e, μ	$\geq 2j, \geq 2b$	Yes	139	$\mathcal{B}(LQ_3^+ \rightarrow t\nu) = 1$
	Scalar LQ 3 rd gen	$\geq 2e, \mu, \geq 1\tau, \geq 1j, \geq 1b$	-	-	139	$\mathcal{B}(LQ_3^+ \rightarrow t\tau) = 1$
	Scalar LQ 3 rd gen	0 e, $\mu, \geq 1\tau, 0-2j, 2b$	Yes	139	$\mathcal{B}(LQ_3^+ \rightarrow b\nu) = 1$	
	Vector LQ mix gen	multi-channel $\geq 1j, \geq 1b$	Yes	139	$\mathcal{B}(U_1 \rightarrow t\mu) = 1, Y\text{-M coupl.}$	
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	2e/2 $\mu \geq 3e, \mu \geq 1b, \geq 1j$	-	-	139	T mass 1.46 TeV SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet
	VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	2(SS) $\geq 3e, \mu \geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	
	VLQ $T \rightarrow Ht/Zt$	1 e, $\mu \geq 1b, \geq 3j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$	
Excit. ferm.	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV only u^* and $d^*, \Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	1 b, 1 j	-	139	b^* mass 3.2 TeV $\Lambda = 4.6 \text{ TeV}$
	Excited lepton τ^*	2 τ	$\geq 2j$	-	139	τ^* mass 4.6 TeV $\Lambda = 4.6 \text{ TeV}$
Other	Type III Seesaw	2,3,4 e, μ	$\geq 2j$	Yes	139	N^0 mass 910 GeV $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$
	LRSM Majorana ν	2 μ	2 j	-	36.1	N_R mass 350 GeV 3.2 TeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 1.08 TeV DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.85 TeV DY production, $ q = 5e$
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV DY production, $ g = 1g_D, \text{ spin } 1/2$
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	

So far, no hints for new physics

$\tilde{t} \rightarrow (t\tilde{\chi}_1^0/b\tilde{\chi}_1^{\pm} \rightarrow bW\tilde{\chi}_1^0)$

1 ℓ : arXiv:1912.08887
2 ℓ opposite-sign: arXiv:2008.05936 $x = 0.5$
Combination: SUS-20-002 $\Delta M_{\tilde{\chi}_1^{\pm}} = 5$
0 ℓ : arXiv:1909.03460;2103.01290 $\Delta M_{\tilde{\chi}_1^{\pm}} = 5 \text{ GeV}$

$\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{f}\tilde{\chi}_1^0$

0 ℓ : arXiv:1909.03460;2103.01290 $\Delta M < 80 \text{ GeV (max. exclusion)}$

$\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{f}\tilde{\chi}_1^0$

0 ℓ : arXiv:1909.03460;2103.01290 $\Delta M < 80 \text{ GeV (max. exclusion)}$

$\tilde{t} \rightarrow c\tilde{\chi}_1^0$

0 ℓ : arXiv:2103.01290 $\Delta M < 80 \text{ GeV (max. exclusion)}$

$\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\nu\tilde{\ell} \rightarrow b\nu\ell\tilde{\chi}_1^0$

2 ℓ : arXiv:2008.05936

$\tilde{b} \rightarrow b\tilde{\chi}_1^0$

pp $\rightarrow \tilde{b}\tilde{b}$
0 ℓ : arXiv:1909.03460;1908.04722

$\tilde{b} \rightarrow t\tilde{\chi}_1^{\pm} \rightarrow tW\tilde{\chi}_1^0$

2 ℓ same-sign and $\geq 3\ell$: arXiv:2001.10086 $M_{\tilde{\chi}_1^{\pm}} =$

$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

pp $\rightarrow \tilde{q}\tilde{q}$
0 ℓ : arXiv:1909.03460;1908.04722
0 ℓ : arXiv:1909.03460;1908.04722 one ℓ

mass scale [GeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless indicated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM , respectively, unless indicated otherwise.

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

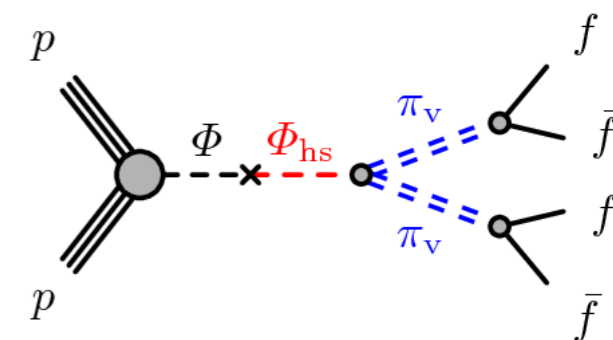
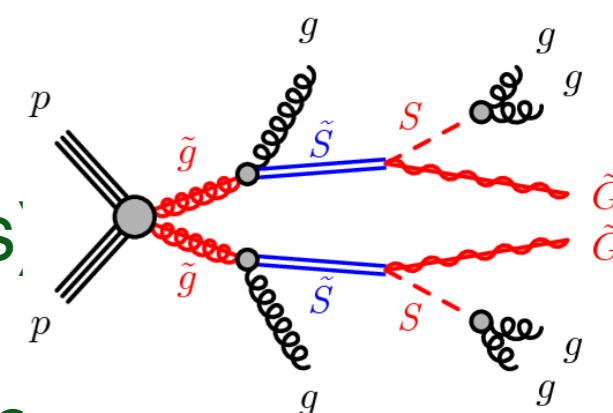


**Long Lifetimes
are typical!**

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**

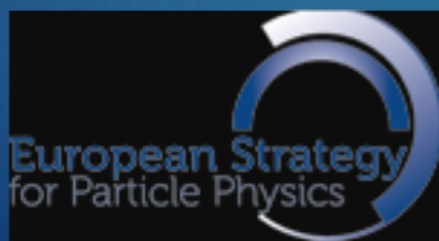
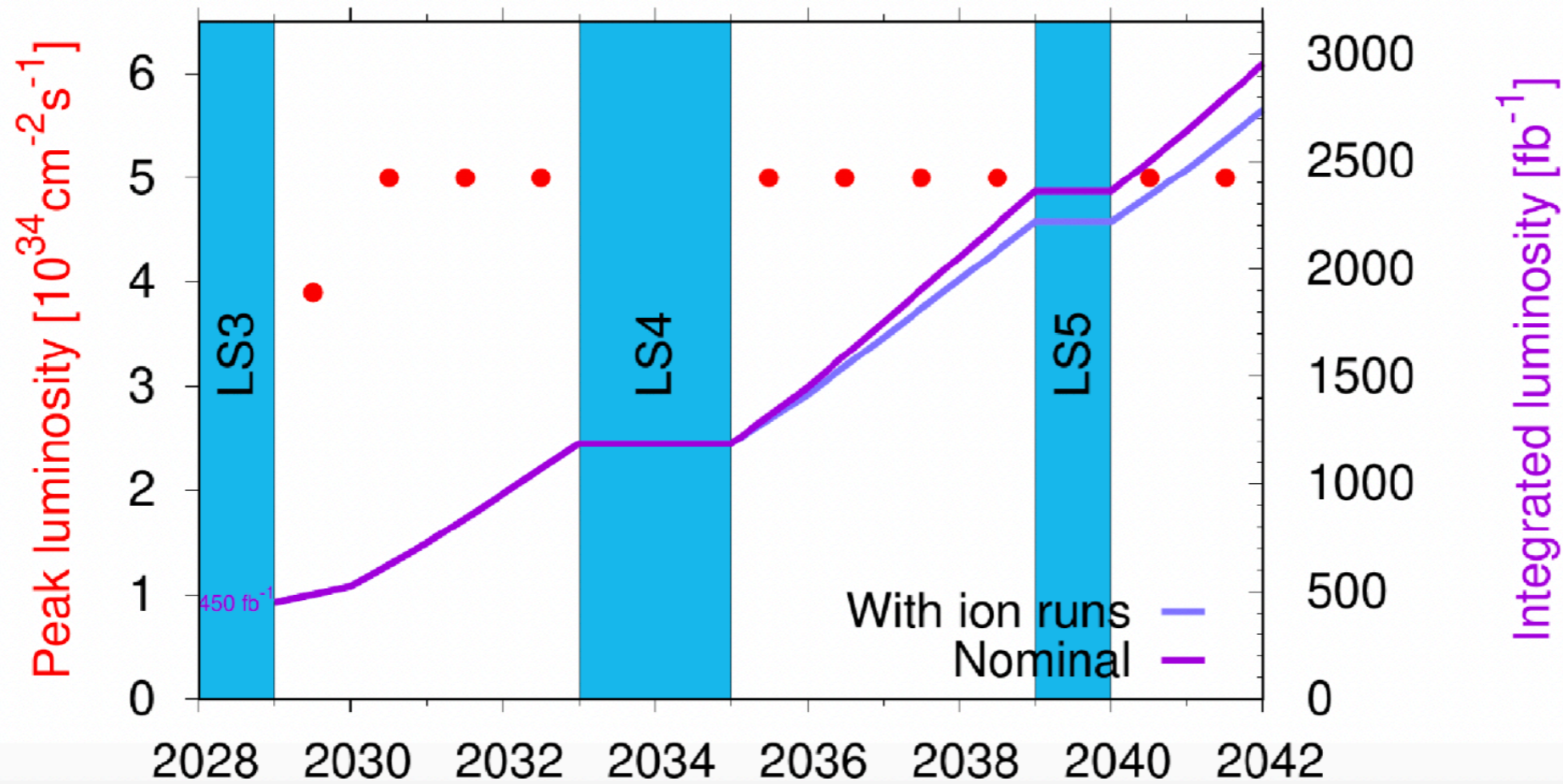


Accessing the hidden sectors

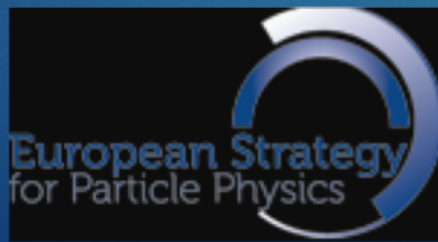
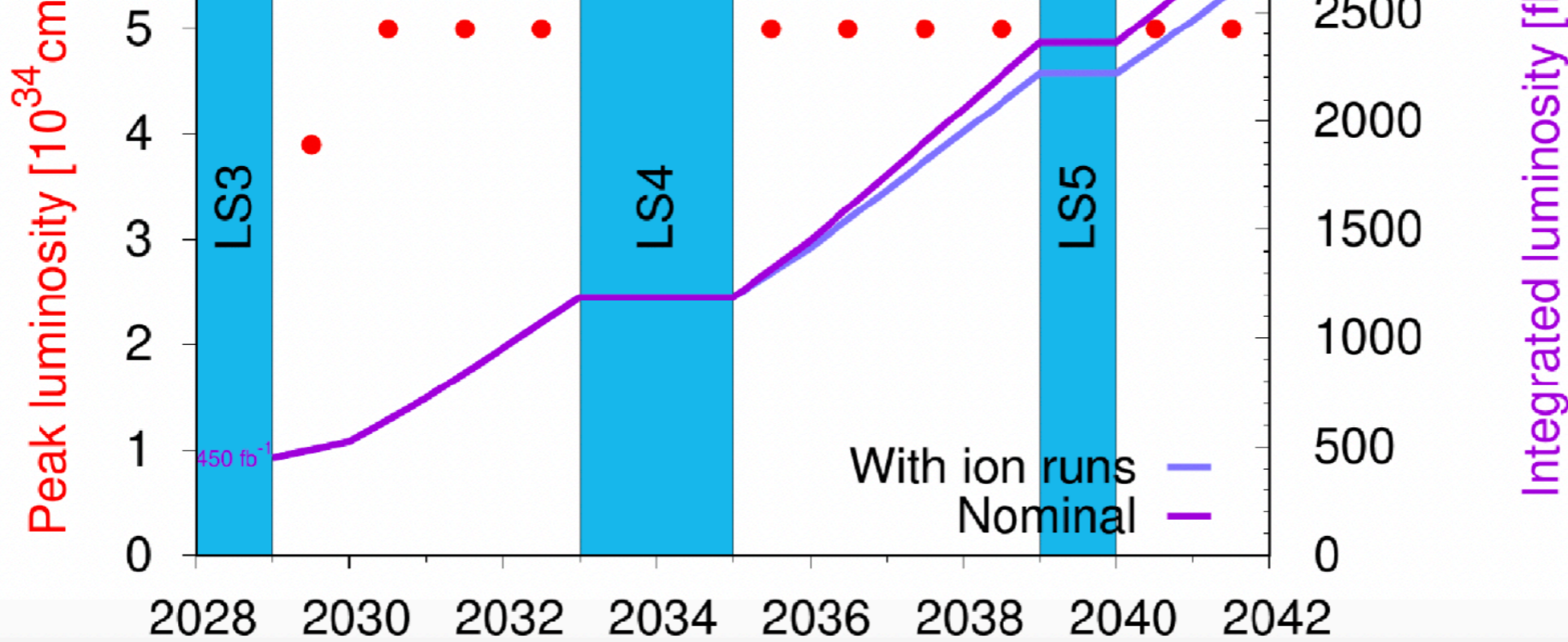
- ▶ The nontrivial signature could be why we haven't seen any hint yet..
 - ▶ **Can be turned to an advantage ...**
- ▶ With dedicated searches, these signatures could allow a small number of events for discovery!
- ▶ New mindset:
 - ▶ **Dedicated analyses, new triggers /tracking..**
 - ▶ **New experiments?**
 - ▶ 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 $\sim 3000 \text{ fb}^{-1}$ should be delivered 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”

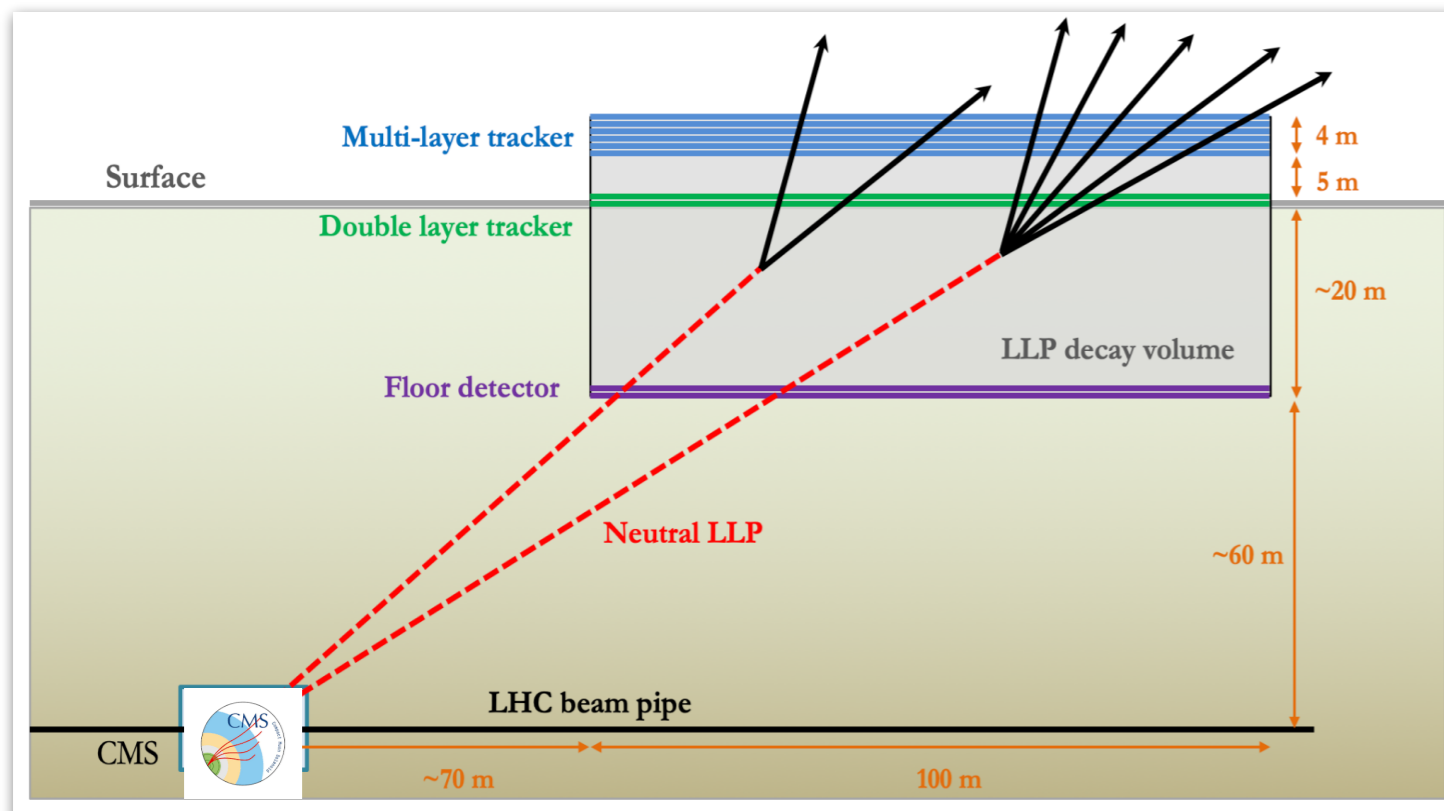


“Europe’s **top priority** should be the **exploitation** of the **full potential of the LHC**, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030”

- ▶ By ~ 2040 plan to collect $\sim 3 \text{ ab}^{-1}$ 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**

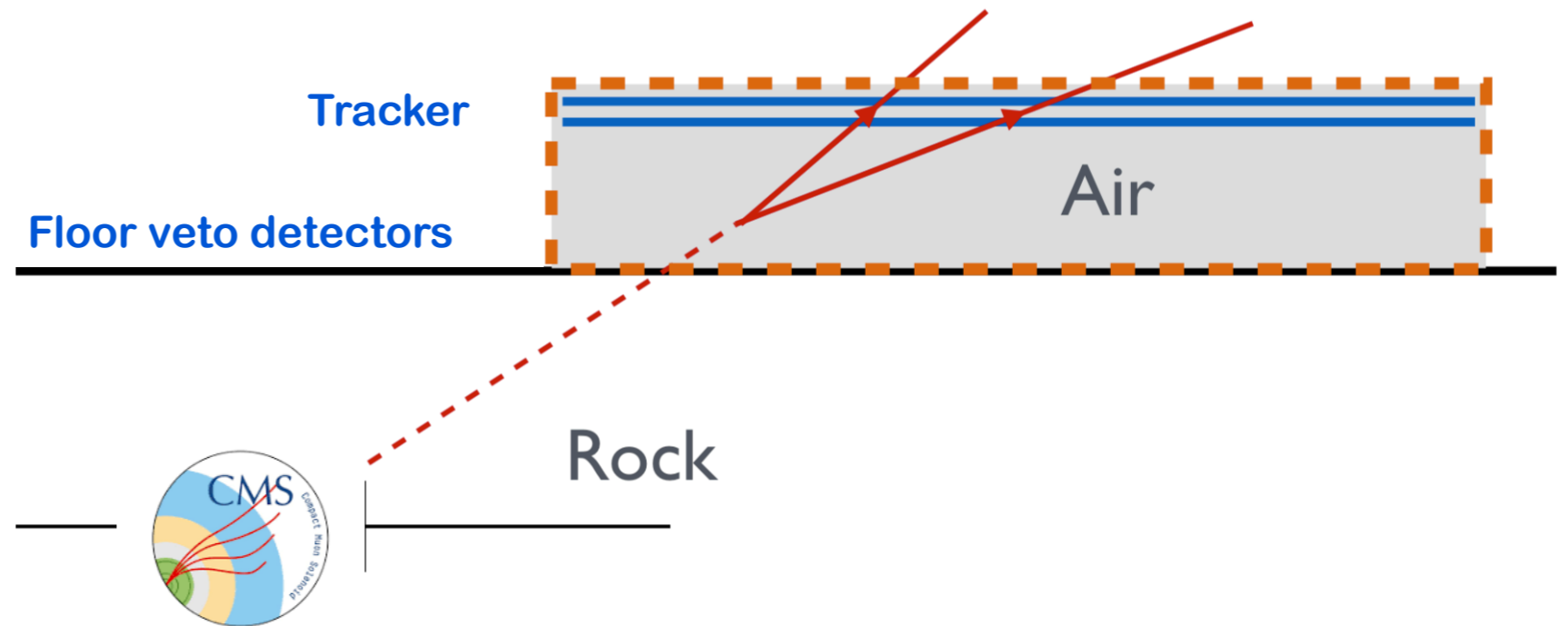
- ▶ Assume ULLPs are produced in exotic Higgs decays with $\text{Br} > 10\%$
- ▶ Assume a lifetime near the Big Bang nucleosynthesis (BBN) limit: $c\tau \sim 10^7\text{m}$
- ▶ The LHC makes a lot of Higgs bosons...
- ▶ A few of these LLPs will decay in ATLAS or CMS!
- ▶ Detection requires:
 - ▶ High 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 $H \sim 20$ 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

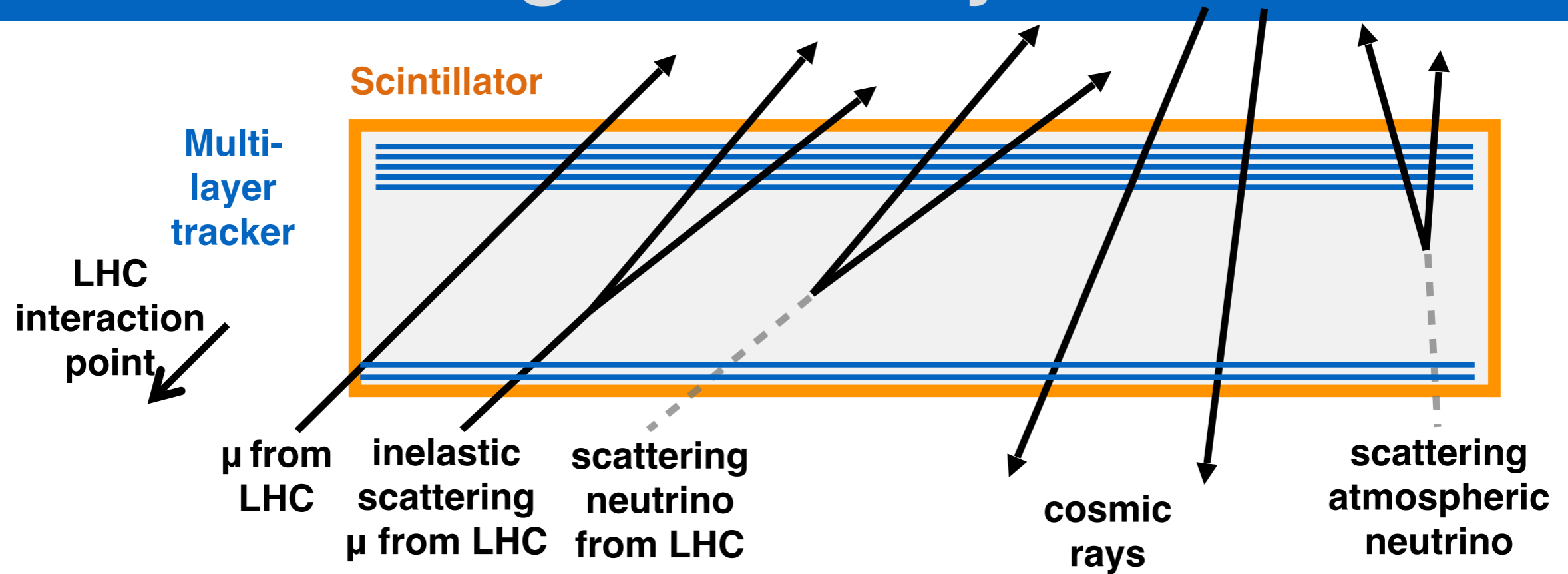


- ▶ Searching for upward going vertex in the detector volume
 - ▶ LLP may decay to jets or lepton pair, signal requires \geq two
 - ▶ Particles reaching the ground should be relativistically boosted
 - ▶ The tracks come from common vertex
 - ▶ The vertex within a cone from the CMS IP
 - ▶ Material could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

Sensitivity for LLP detection

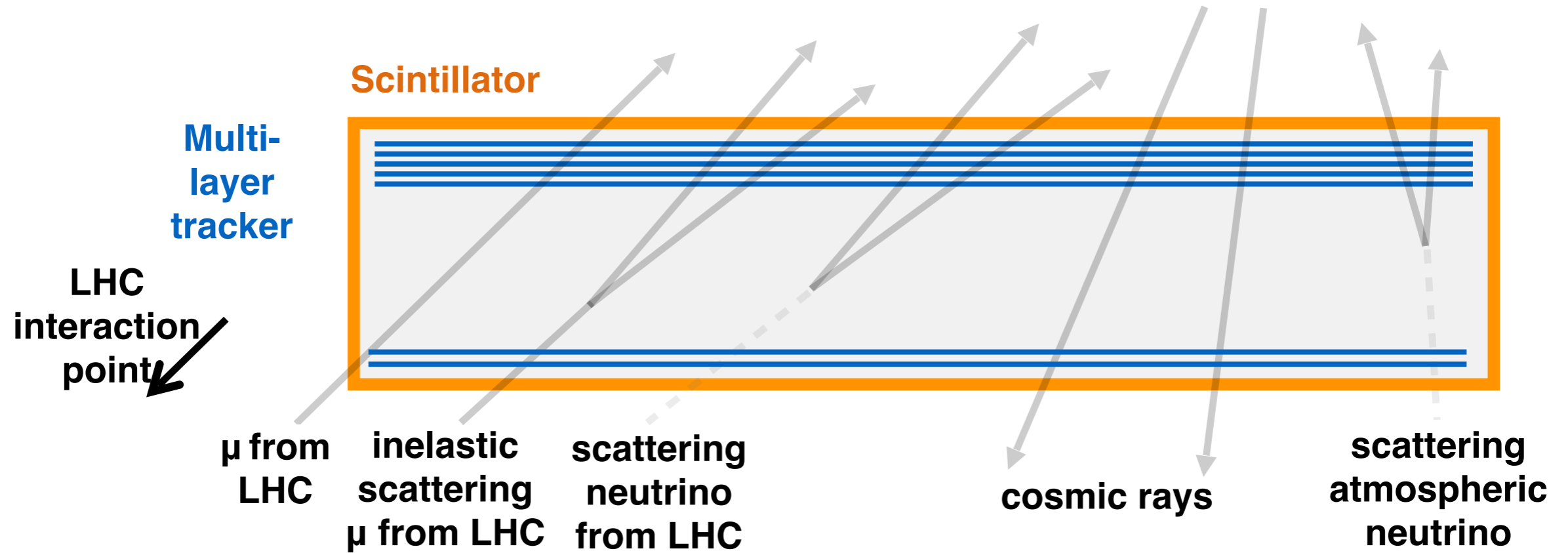
- ▶ Characterization of the signals:
 - ▶ Clean vertex of lepton pair
 - ▶ Vertex with two energetic jets, large angular separation
 - ▶ LLP decay length upto 10^8 m..
- ▶ Signal sensitivity
 - ▶ Geometrical acceptance
 - ▶ Detector efficiency
 - ▶ Decay volume .vs. the LLP decay length
 - ▶ Background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

CERN-TH-2018-142
CP3-Origins-2018-023 DNR90
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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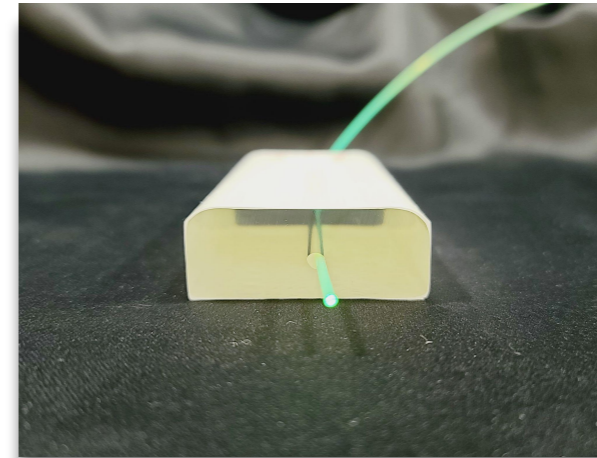
arXiv:1806.07396v2 [hep-ph] 5 Mar 2019

Technology

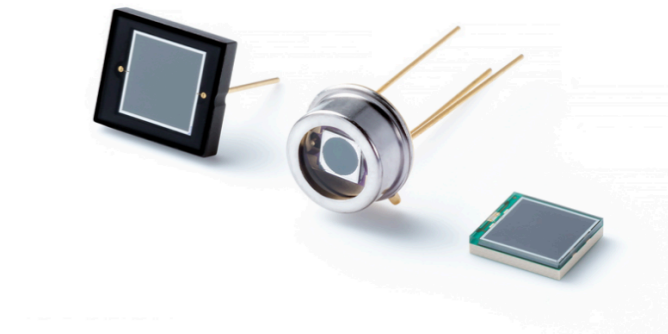
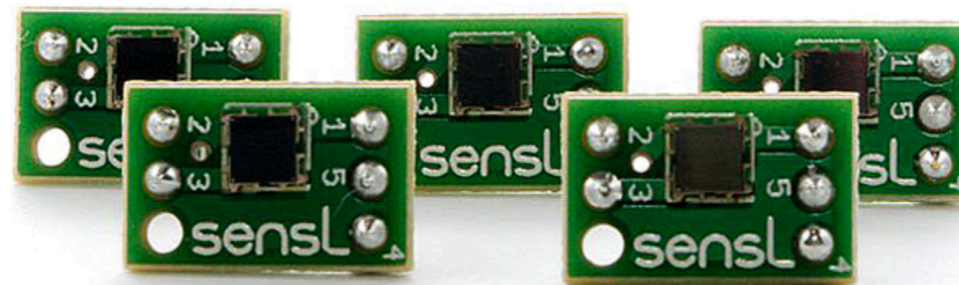
Extruded Scintillators

[arXiv:2005.02018](https://arxiv.org/abs/2005.02018) (Test stand)
[arXiv:2009.01693](https://arxiv.org/abs/2009.01693) (update Lol)
[arXiv:2203.08126](https://arxiv.org/abs/2203.08126) (Snowmass22)

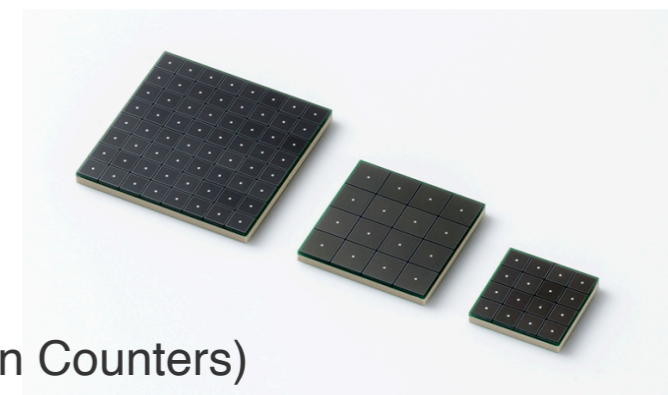
- ▶ A cheaper method to produce plastic scintillators is extrusion. Studies at Fermilab (FERMILAB-PUB-05-344) show they reach ~75% of the light yield of BC408, or similar to Kuraray SCSN-81.
- ▶ Insert WLS fibers into holes prepared during extrusion to increase the light yield.
- ▶ Used before by MINOS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



Light readout



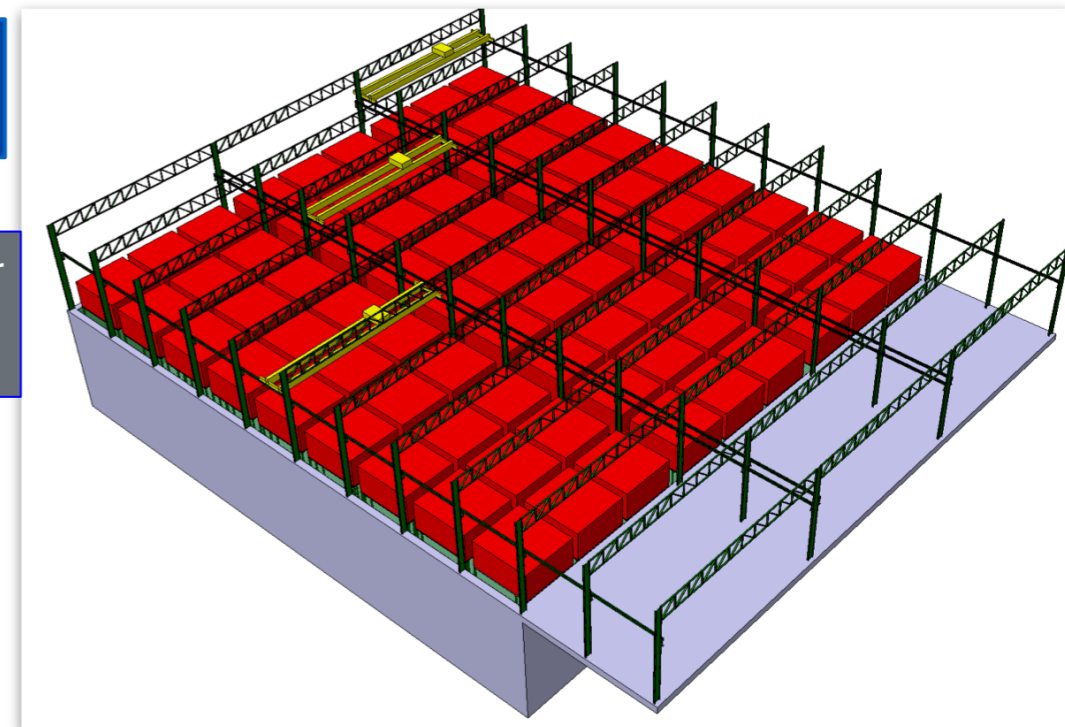
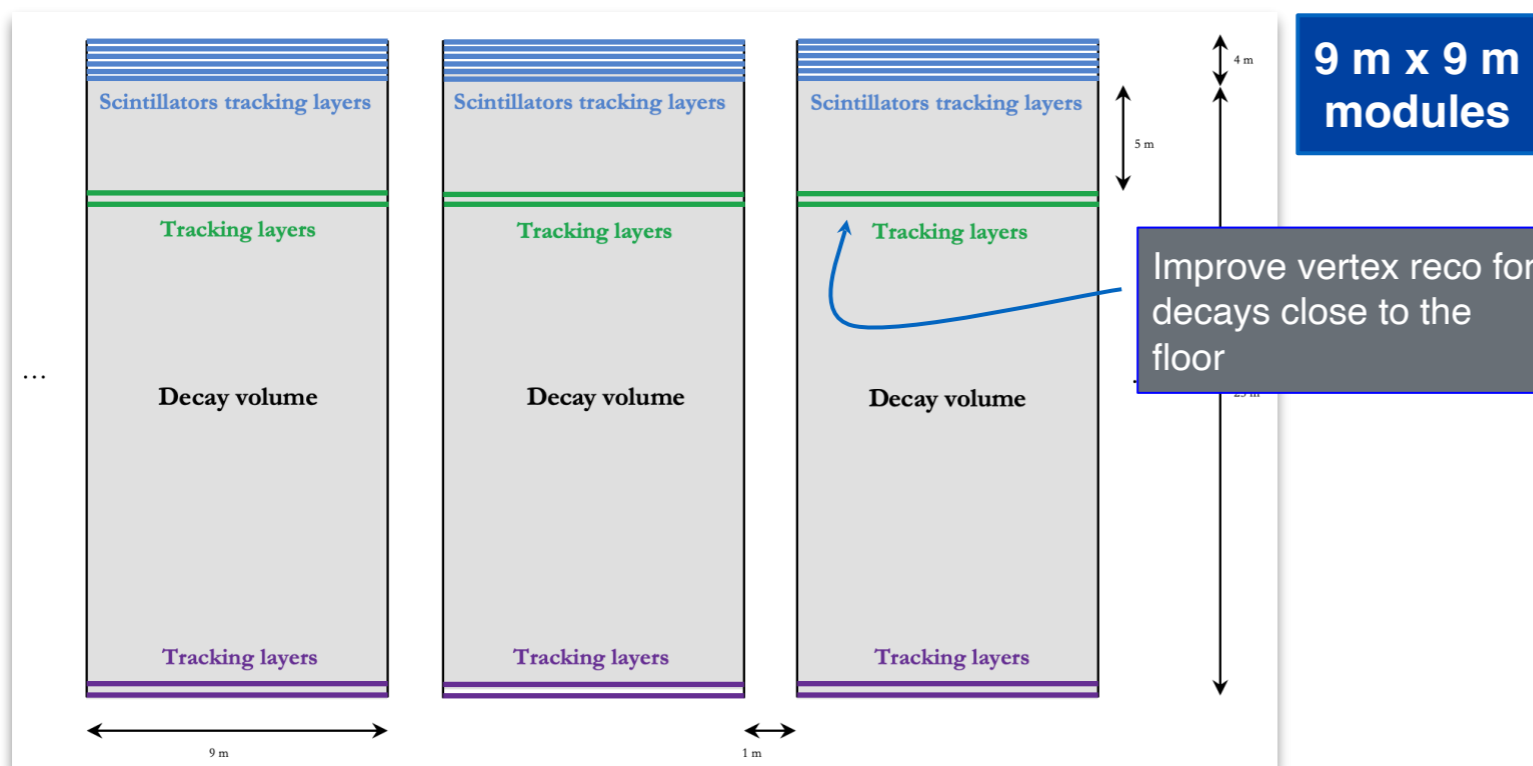
- ▶ SiPM – low cost, high-performance alternative.
- ▶ Bias voltage ~30-35V
- ▶ Sensors are available in several sizes (1-6mm)
- ▶ Single units and arrays



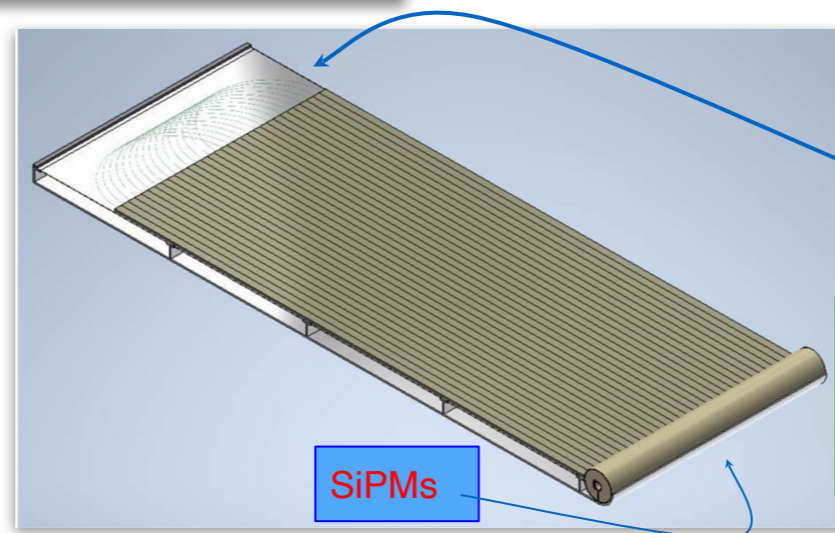
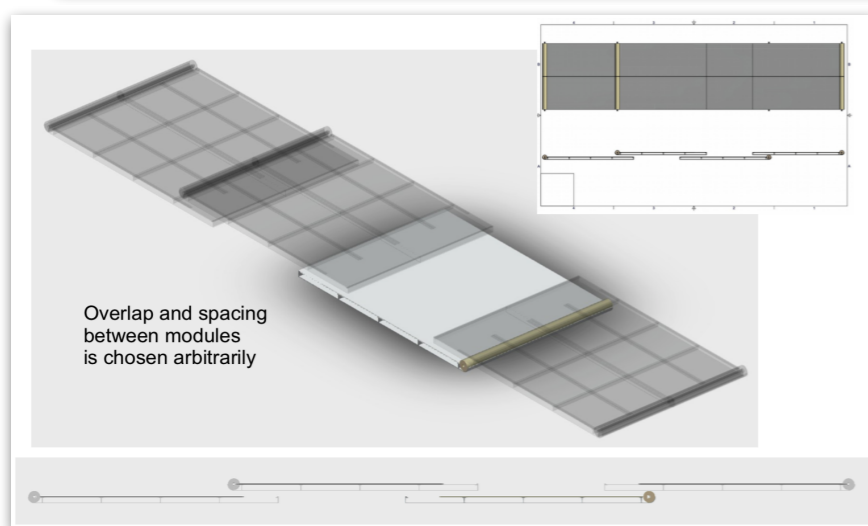
MPPCs (Multi-Pixel Photon Counters)

Detector structure

[arXiv:2005.02018](https://arxiv.org/abs/2005.02018) (Test stand)
[arXiv:2009.01693](https://arxiv.org/abs/2009.01693) (update Lol)
[arXiv:2203.08126](https://arxiv.org/abs/2203.08126) (Snowmass22)



Detector + assembling

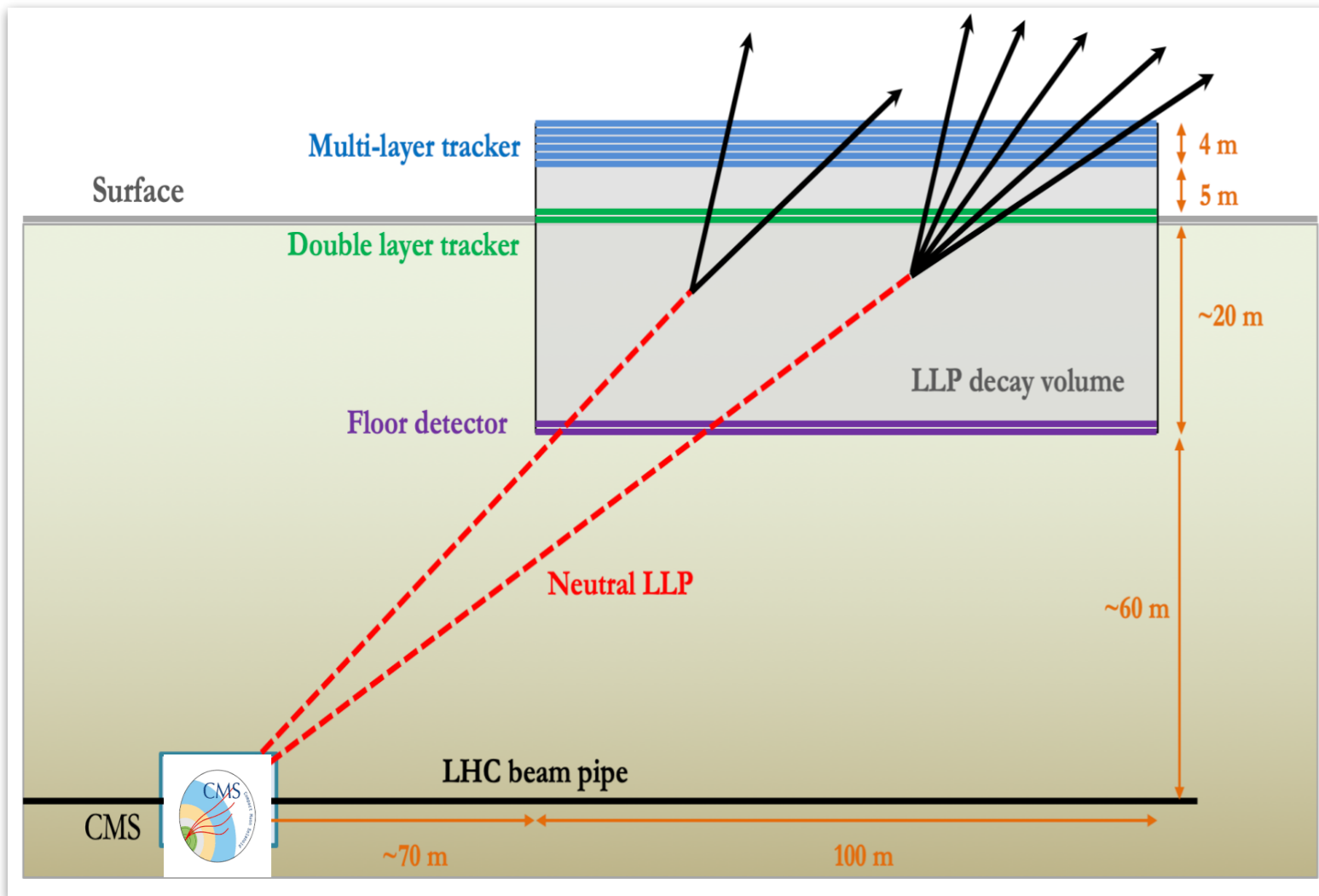


U-readout:
 two bars connected at one end (every N-bars). Info read by SiPM only on one side of the bar

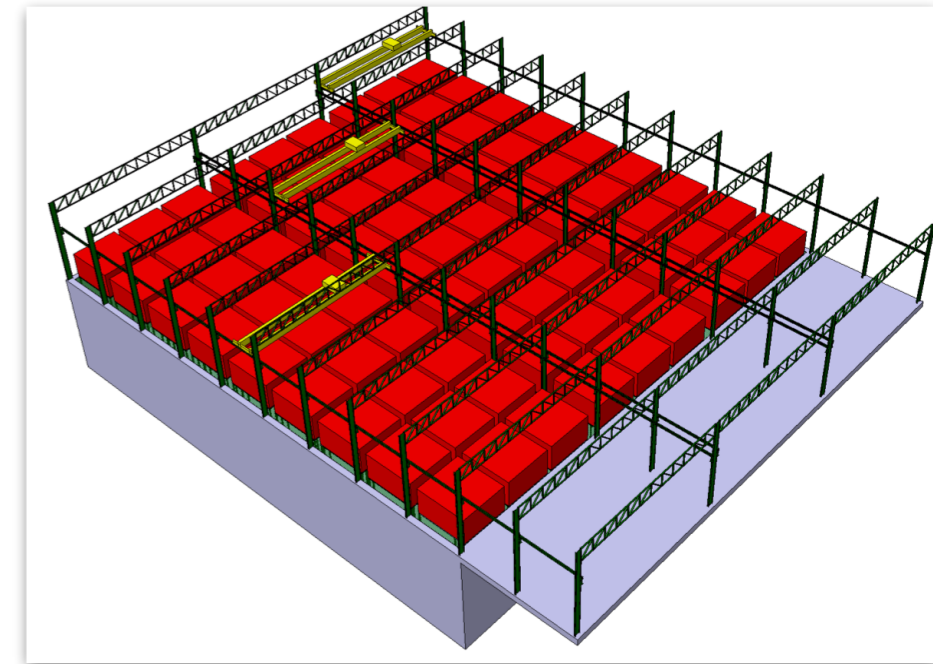
Reached timing resolution of ~ 0.54 ns (i.e. 9 cm RMS position resolution) Worst case light-yield: 29 PE

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

CDR Design



[arXiv:2005.02018](https://arxiv.org/abs/2005.02018) (Test stand)
[arXiv:2009.01693](https://arxiv.org/abs/2009.01693) (update LoI)
[arXiv:2203.08126](https://arxiv.org/abs/2203.08126) (Snowmass22)

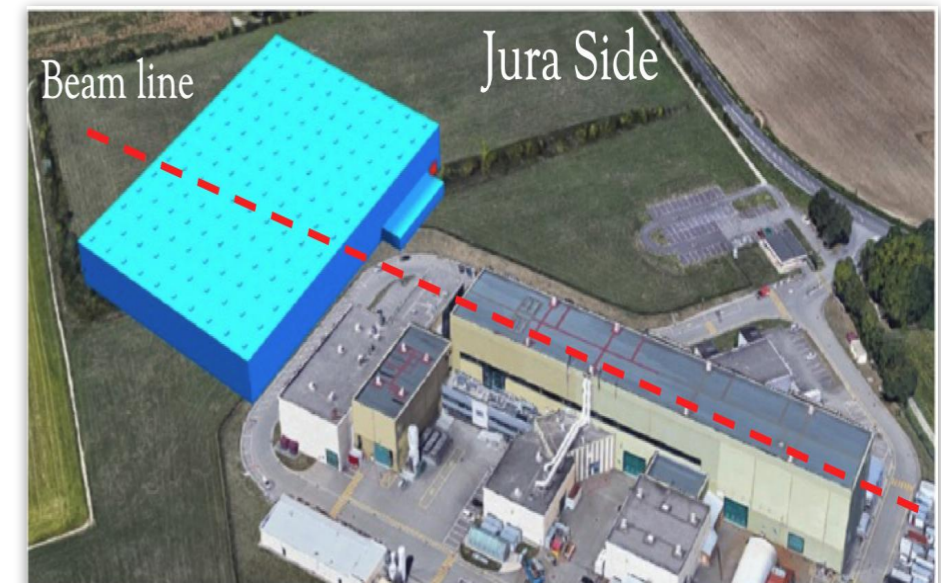


Modular structure

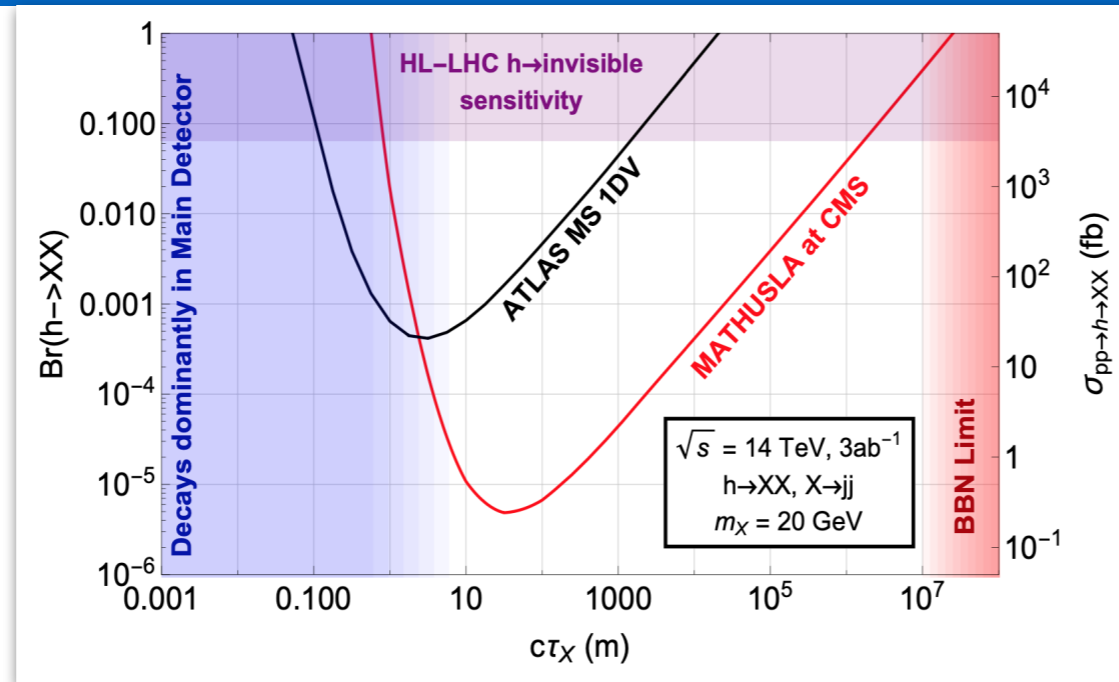
100 modules x (9 x 9 m²)

-> ~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 $\sigma(pp \rightarrow h \rightarrow XX)$ 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

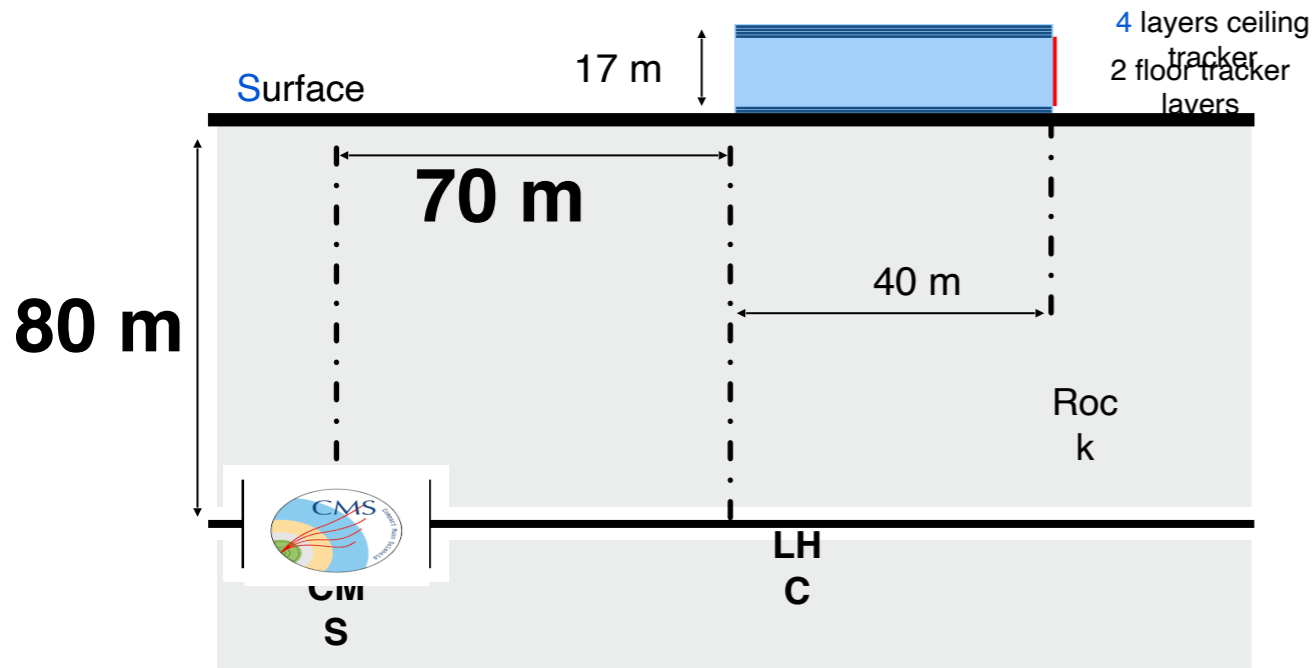


Sensitivity \propto Volume while Cost \propto Area

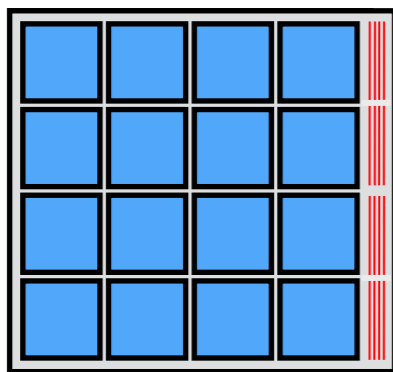
- MATHUSLA can still significantly contribute to the LLP searches (hadronic decays in the 10-100 GeV range) with a reduced size
 - Need to rescope the detector to make it affordable
- Investigating the possibility of housing a smaller-scale MATHUSLA-like detector in existing buildings near ATLAS and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

Updated design

40 m x 40 m x 17 m

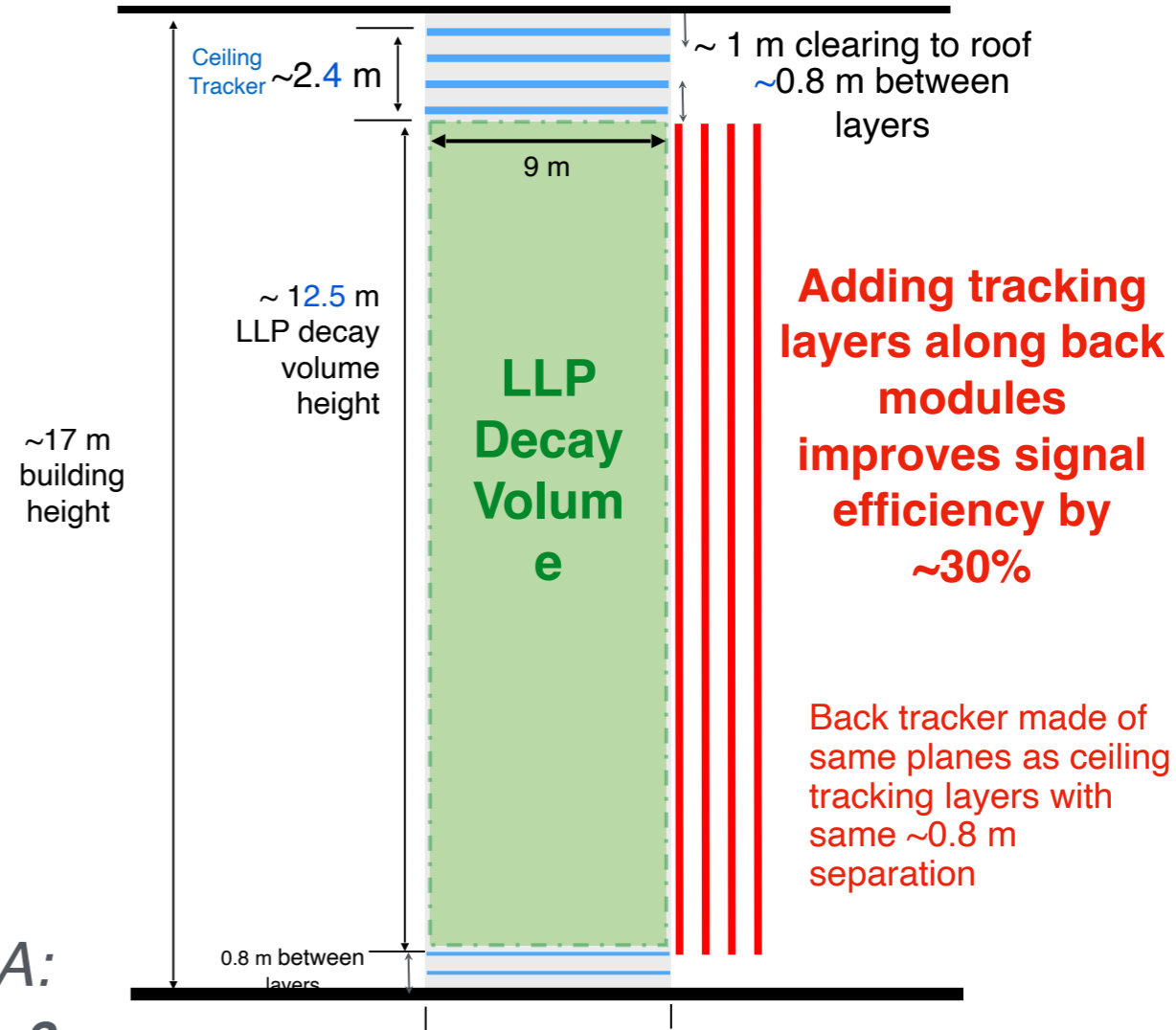


Side view



Back

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.)

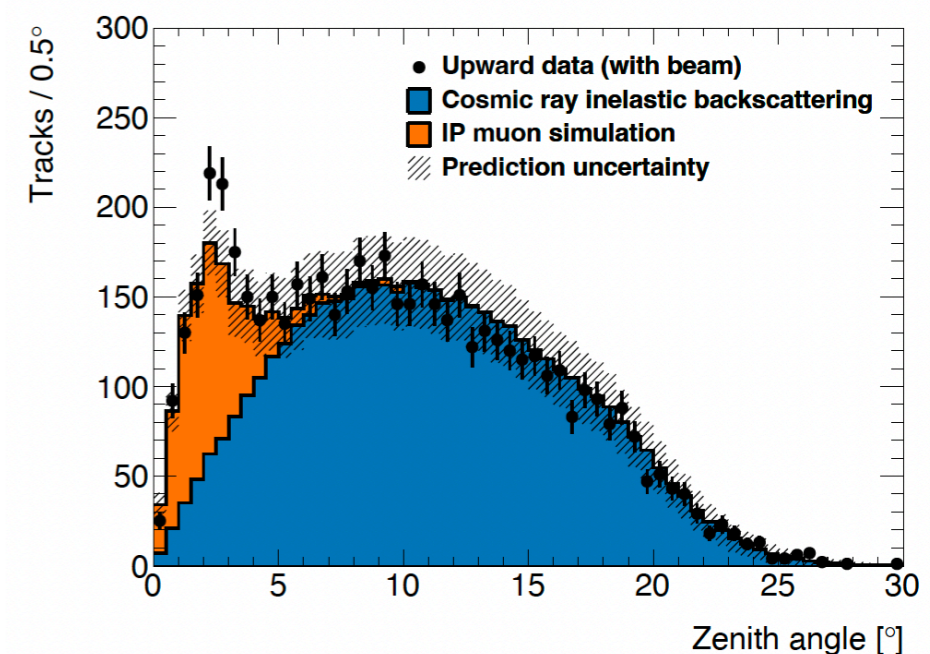
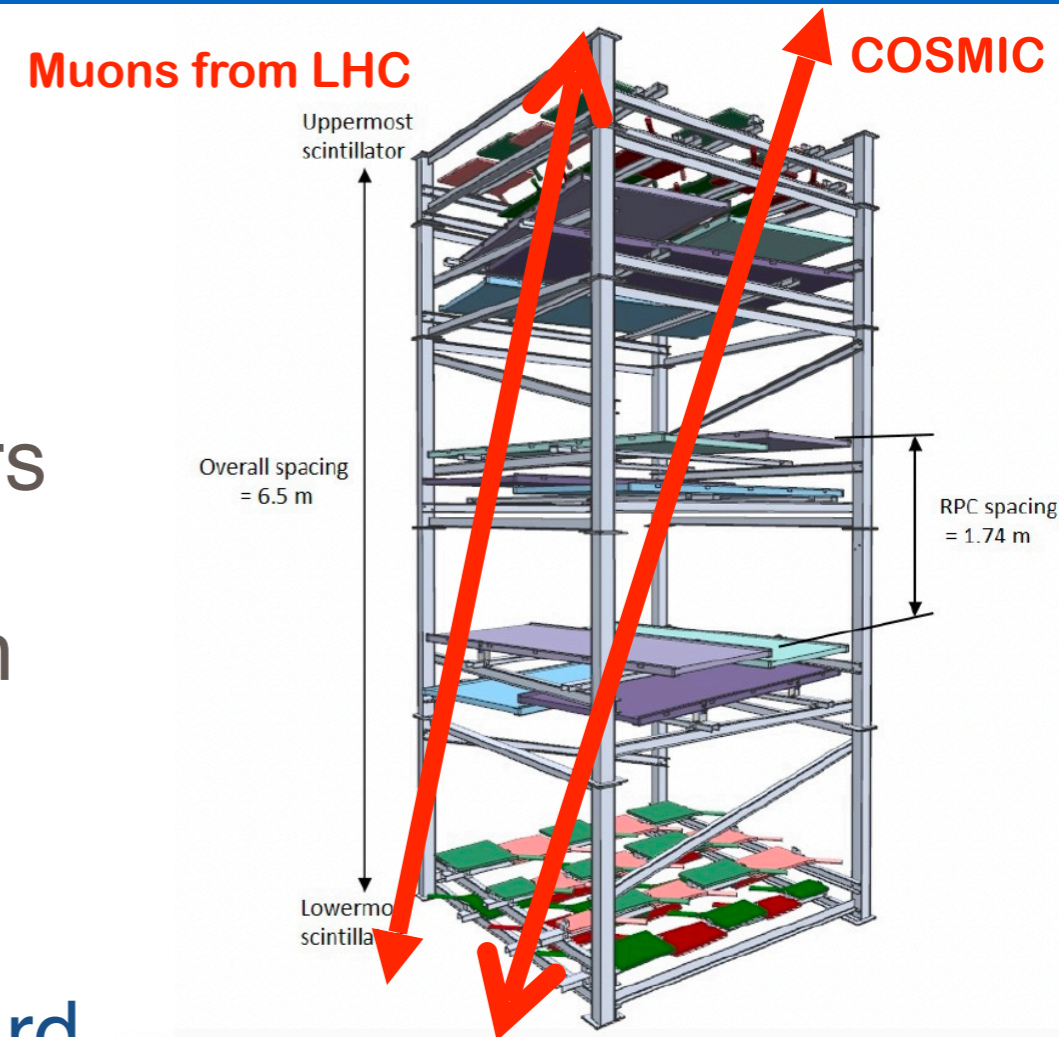
Goal to reduce both infrastructure and detector costs to roughly 1/10 of original design

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

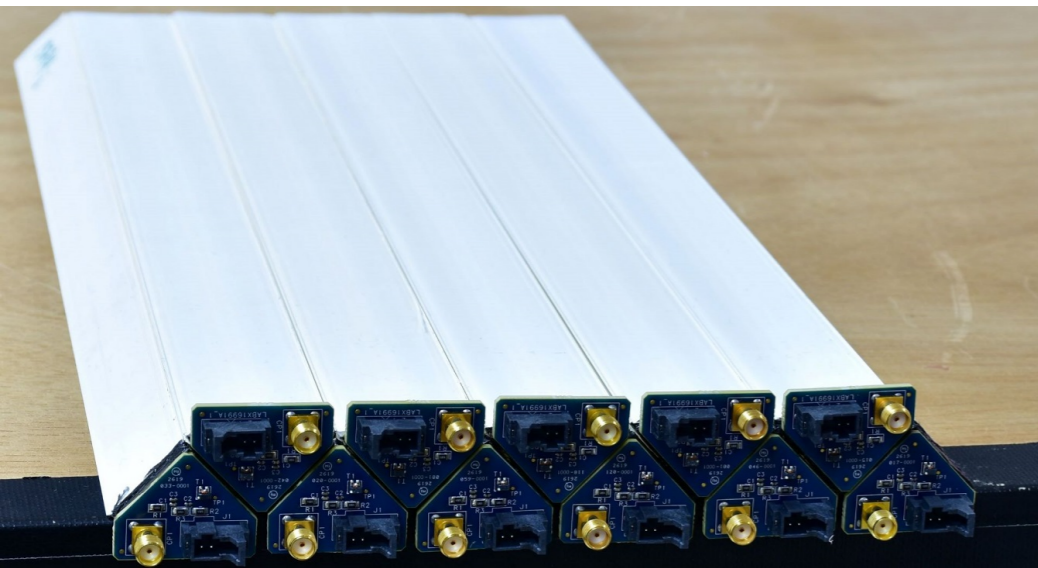
[arXiv:2005.02018](https://arxiv.org/abs/2005.02018) (Test stand)

- ▶ Two layers of **scintillators** used for trigger
- ▶ **RPC** arranged in six $2.50 \times 2.80 \text{ m}^2$ 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.



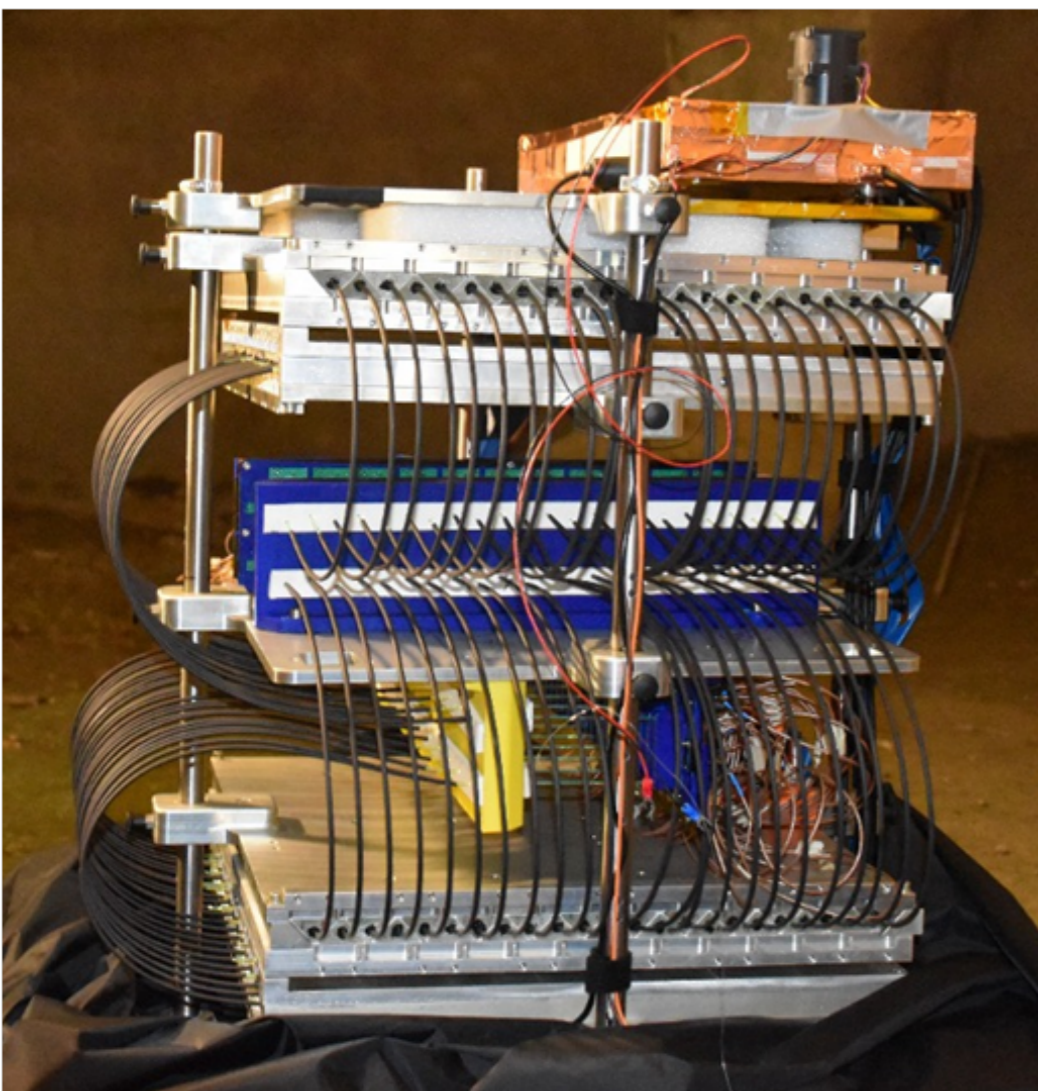
Muon tomography

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

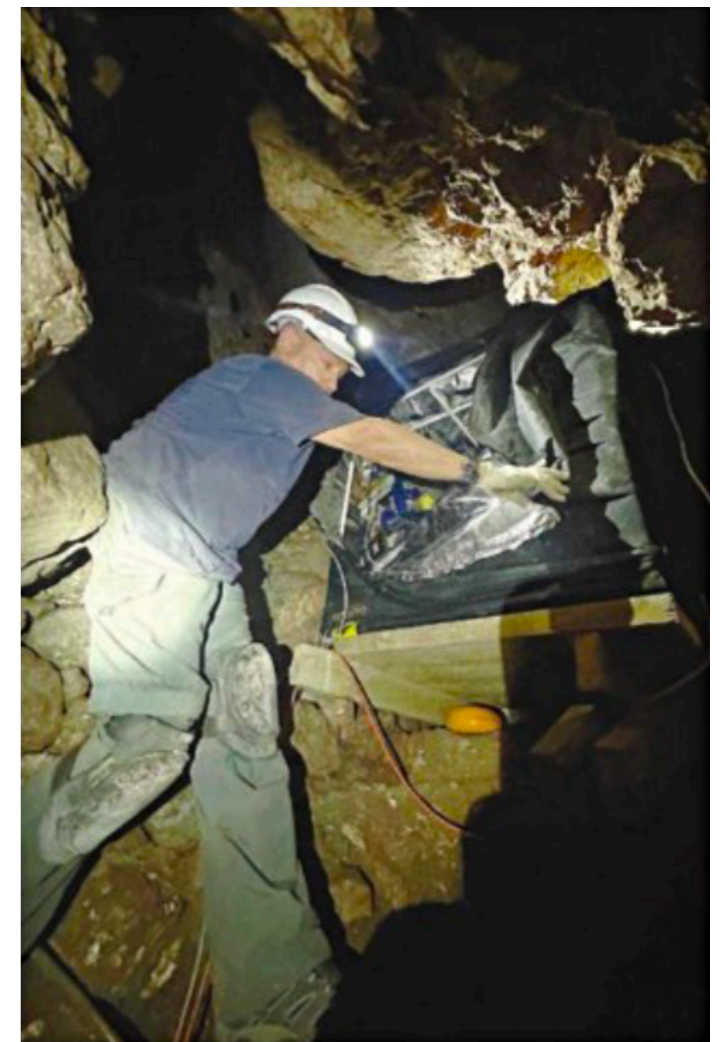
Scintillating bars



Four tracking layers demonstrator

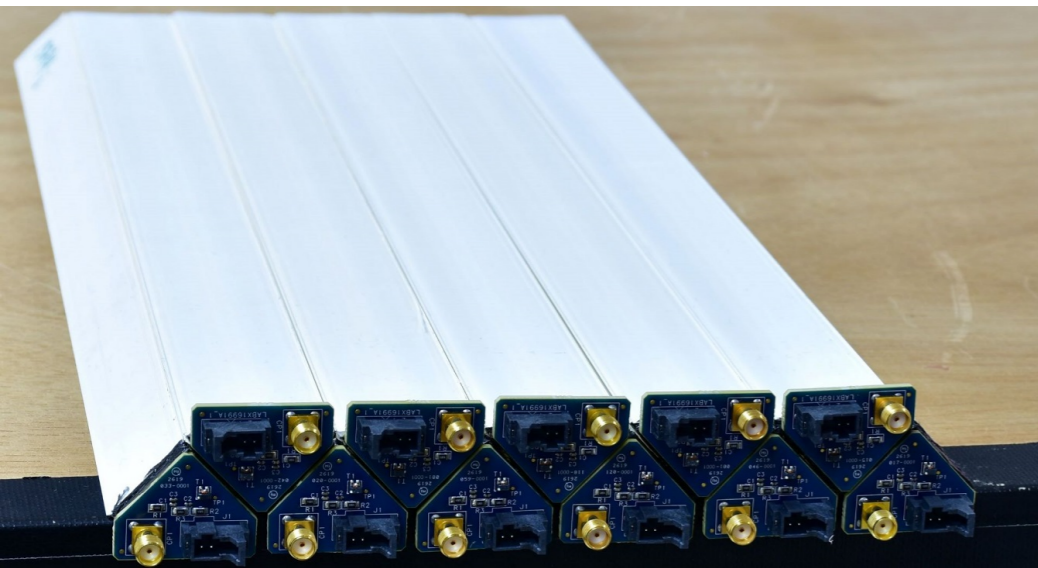
Extruded scint. FNAL
WLS BCF91A
SiPM Sensel 30035
DAQ CAEN DT5550W

The detector underground



Muon tomography

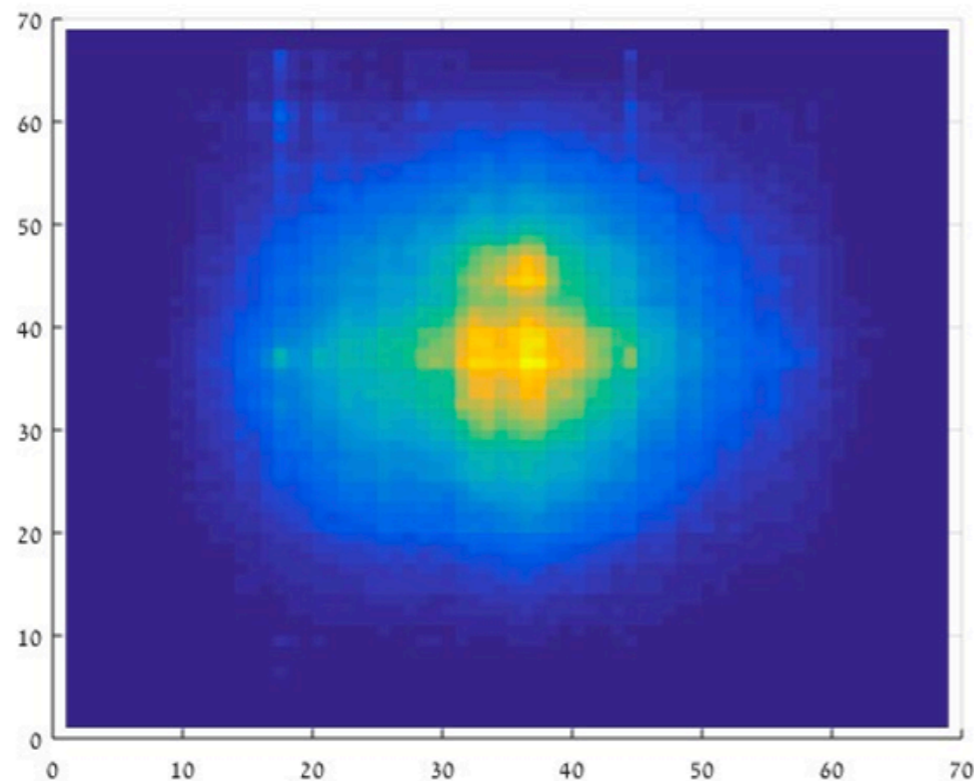
NIM-A 1042 (2022) 167412



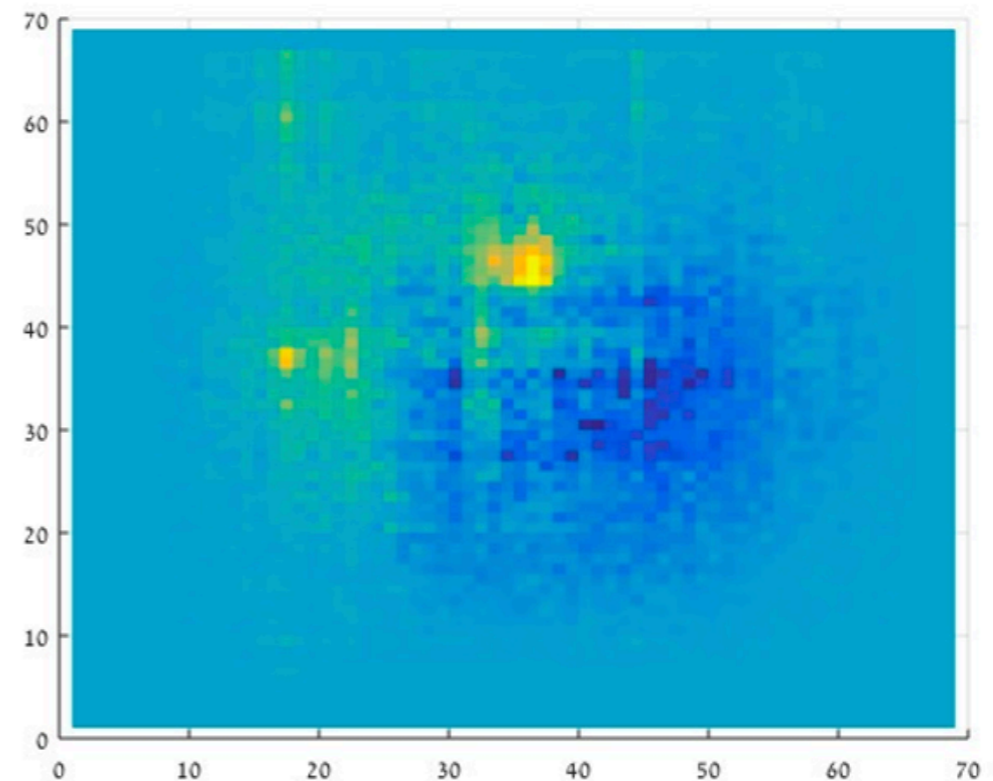
An early demonstrator of MATHUSLA is used as an underground detector. It uses cosmic ray muons, penetrating through the ground, for 3D imaging in the City of David Archeological site

Scintillating bars

Raw data

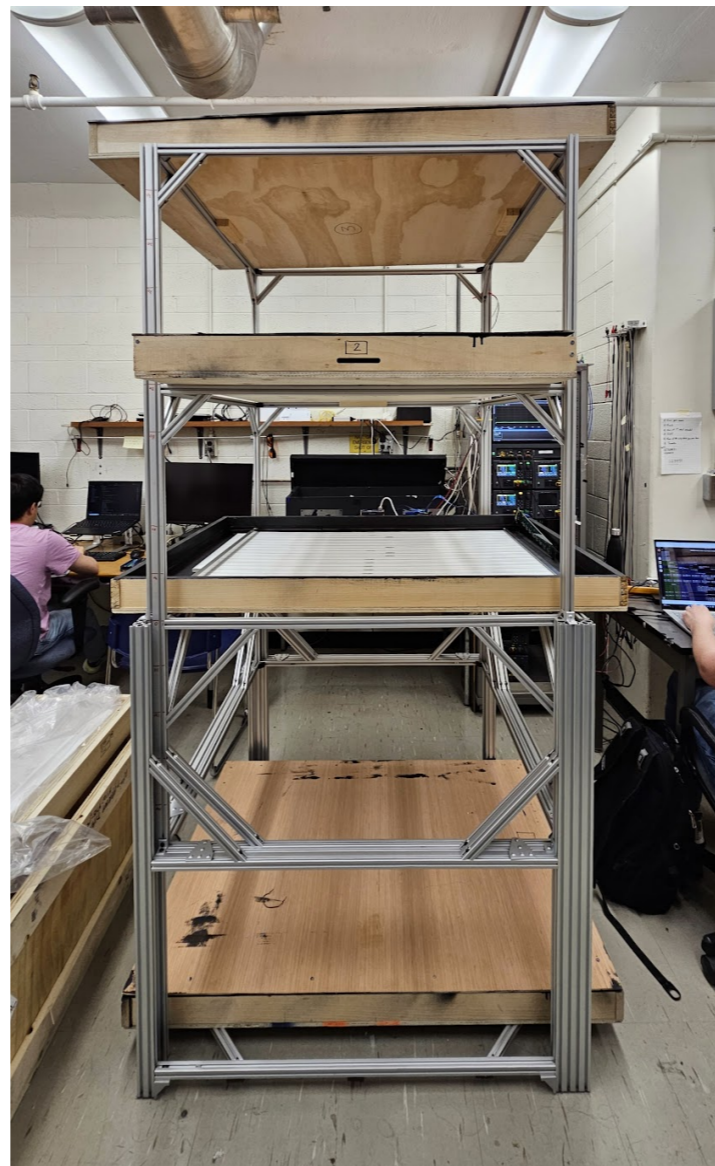


Data after "blue sky" subtraction



Two new test stands

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



- 4 layers
- $\sim 1 \text{ m} \times 1 \text{ m}$ layers of scintillator bars
- 0.8m spacing
- Adjacent layers rotated by 90deg
- Enclosed in dark box(es)

Two new test stands



UVic prototype

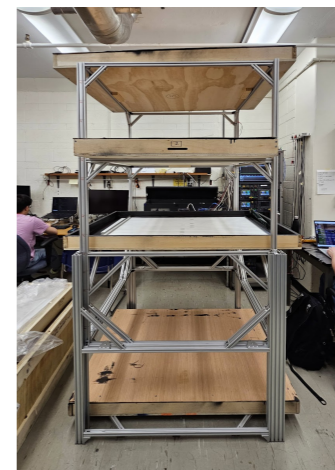
- 80 bars threaded with 32 WLSF
- 64 channel Hamamatsu SiPM array
- Can easily swap out fibres, SiPMs, bars to study components

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

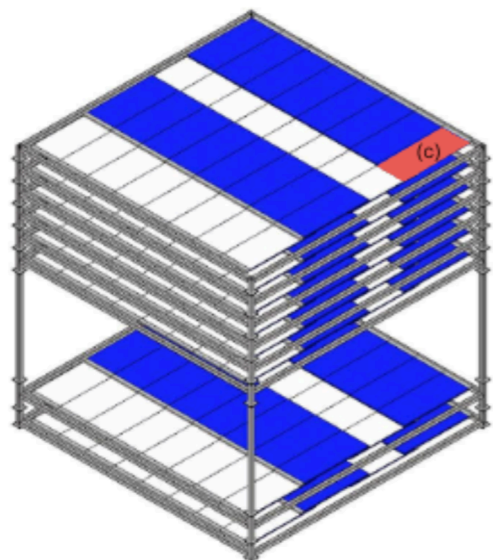
- 4x20 bars threaded with 40 WLSF
- End-mounted individual Hamamatsu SiPMs (s14160-3050)
- Testbed for ASIC/FEB development

Data acquisition

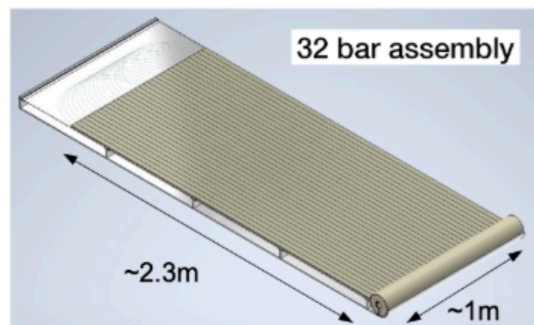
- PETsys TOFPET2 commercial ASIC developed for PET scans
 - Investigating use of this ASIC for MATHUSLA
- Custom frontend electronics

Module 0

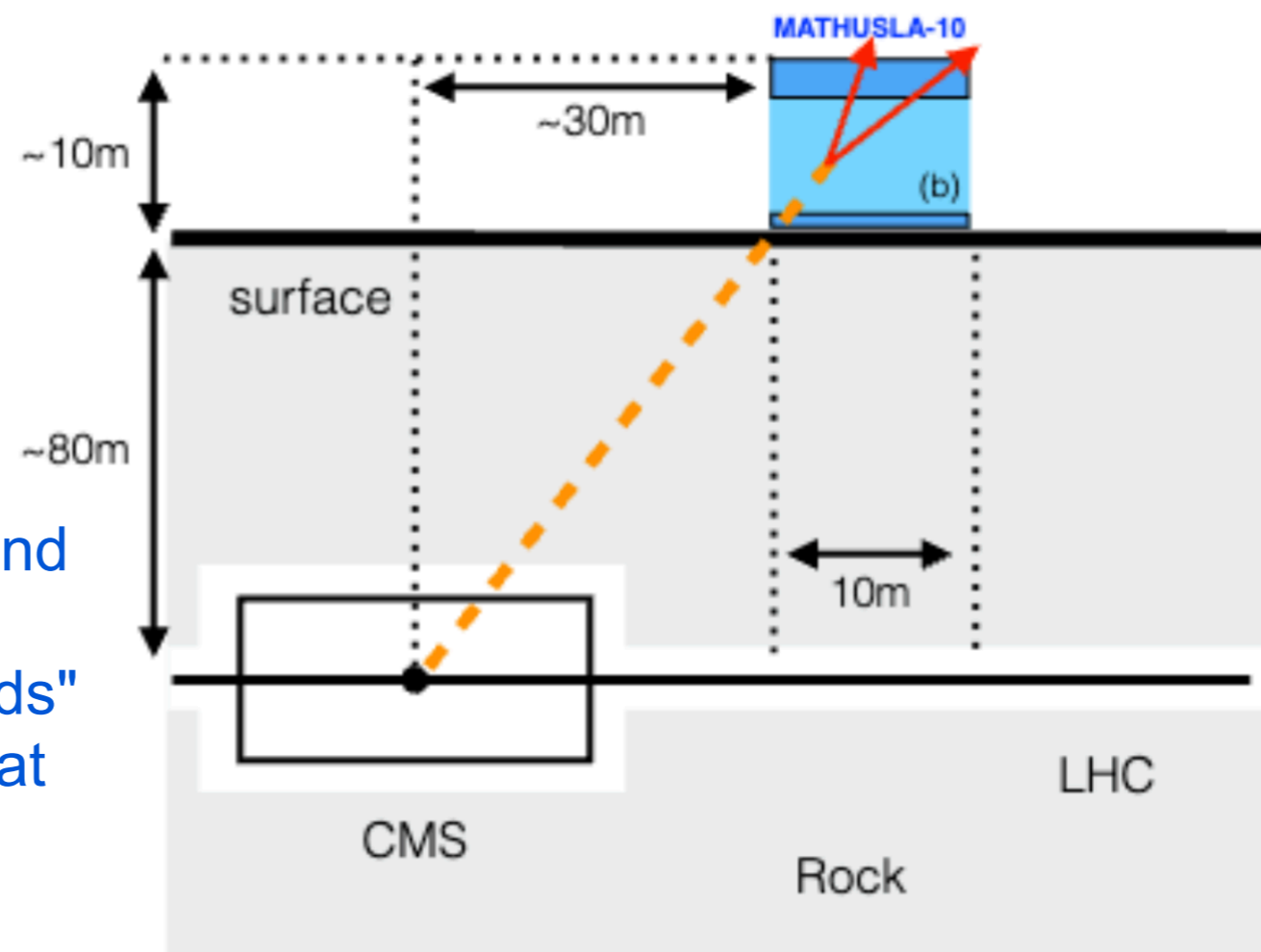
MATHUSLA-10



- ▶ Proposal for **MATHUSLA-10** (Canada)
- ▶ Dimensions $\sim 10 \times 10 \text{ m}^2$, $H \sim \text{flexible}$
- ▶ Prototype for the detector technology
- ▶ To be placed above CMS, and even as a stand-alone module can extend the LHC reach for LLP



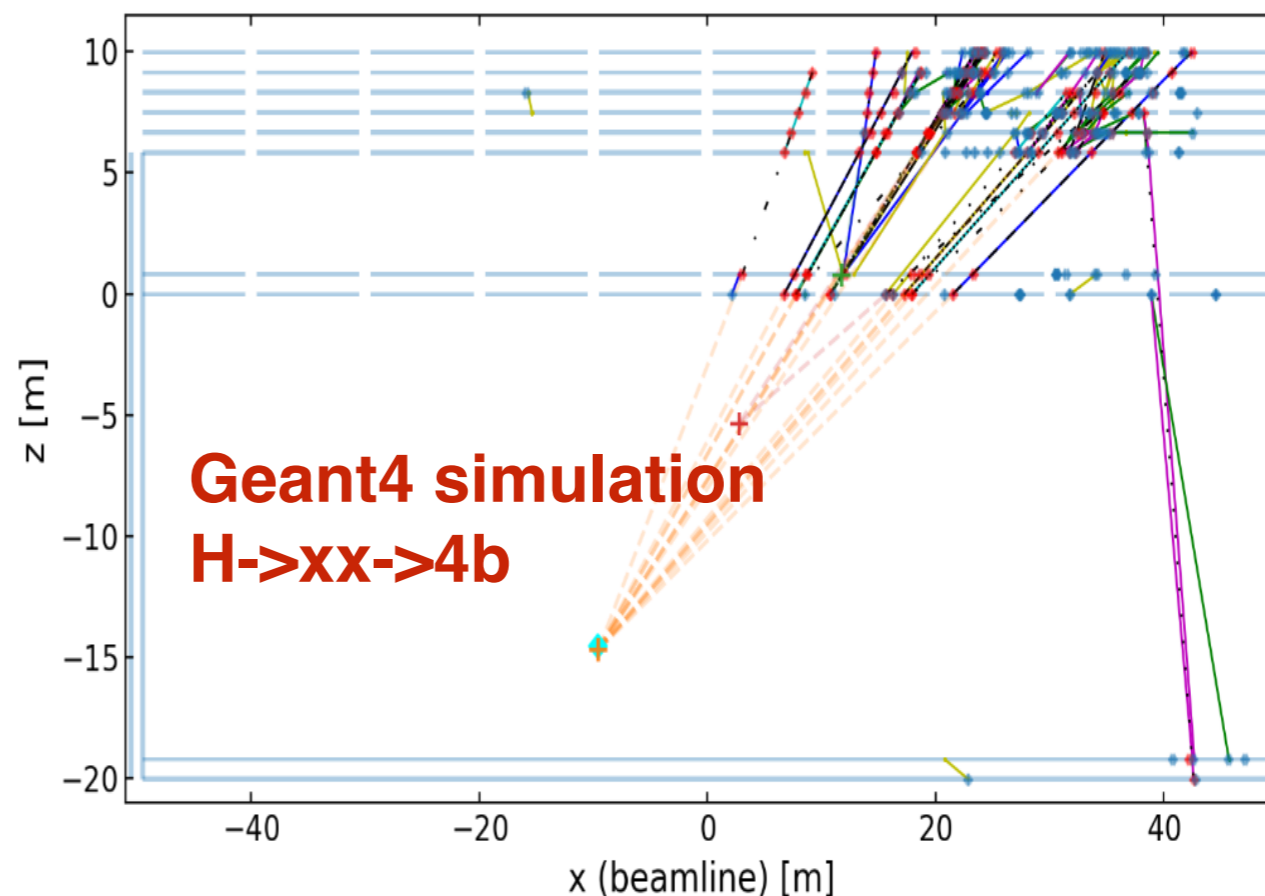
- Manufacturing and operating the building blocks of the large scale detector.
- Exercise on real data: tracking, efficiency and timing resolution using CR, at UofT.
- Characterize “beam-associated backgrounds” (rare SM particles in HL-LHC by operating at CERN P5 during LHC runs.



Software, Simulation

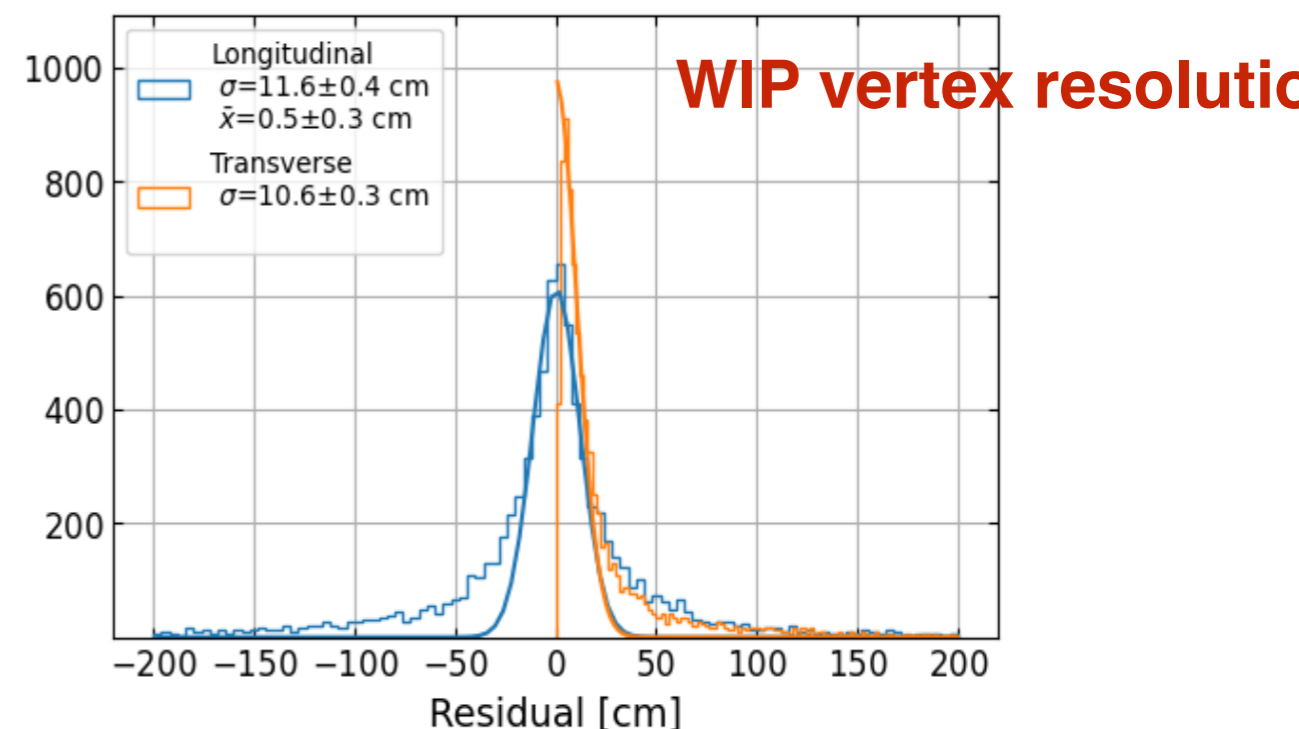
Simulation

- [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

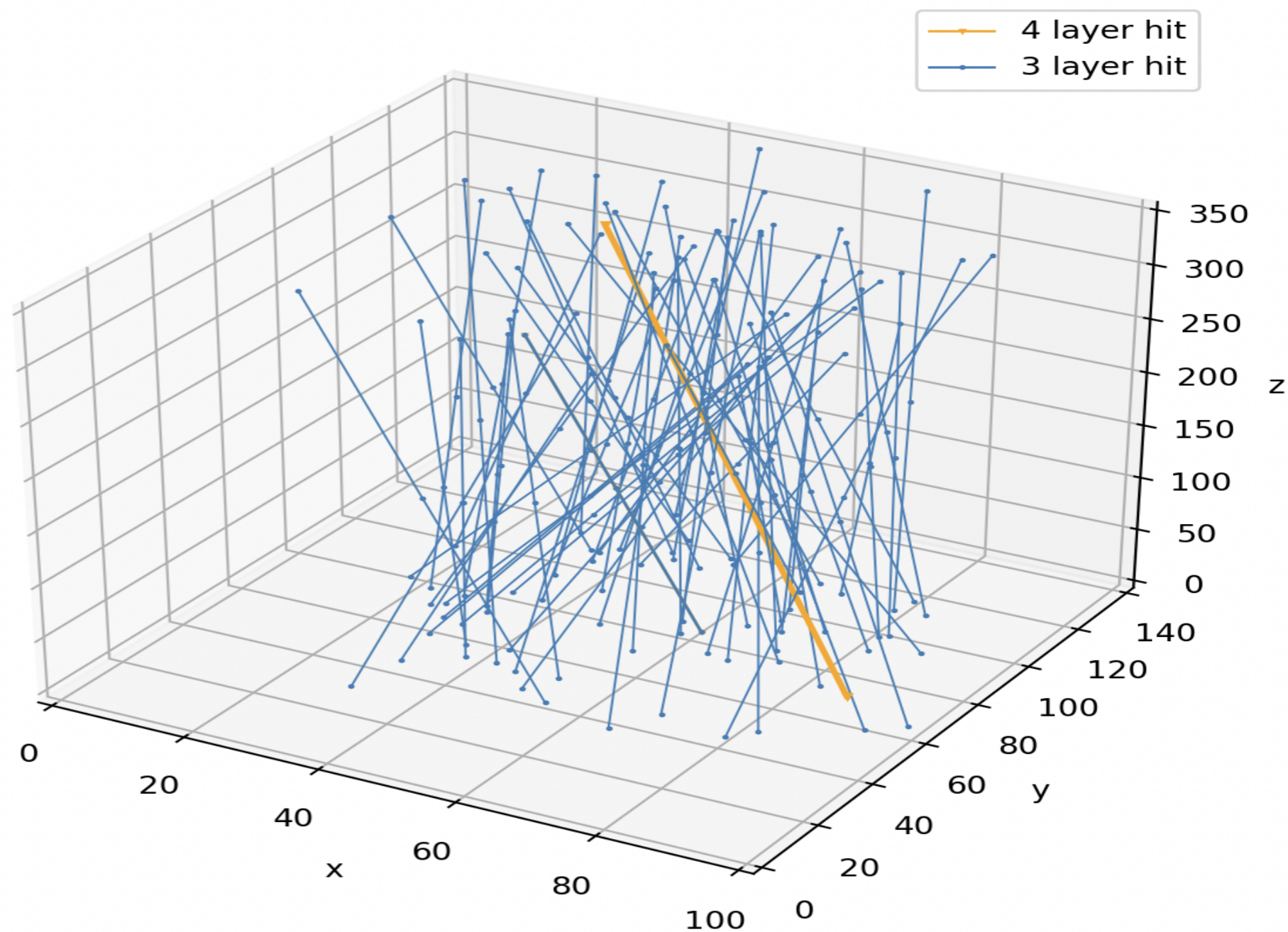
- Kalman filter based track and vertex reconstruction are under development



Uvic test stand results

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

Work ongoing on selection and track reconstruction

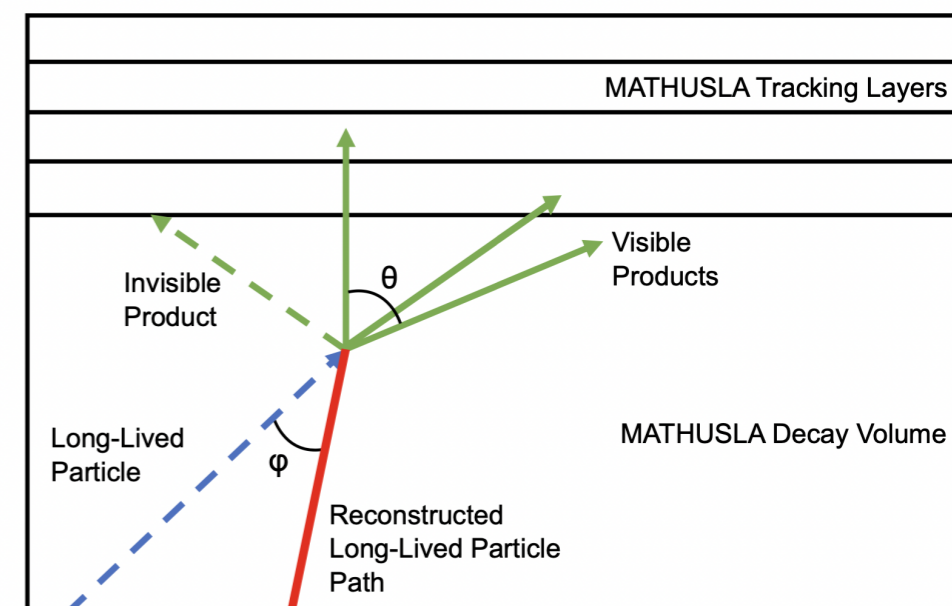
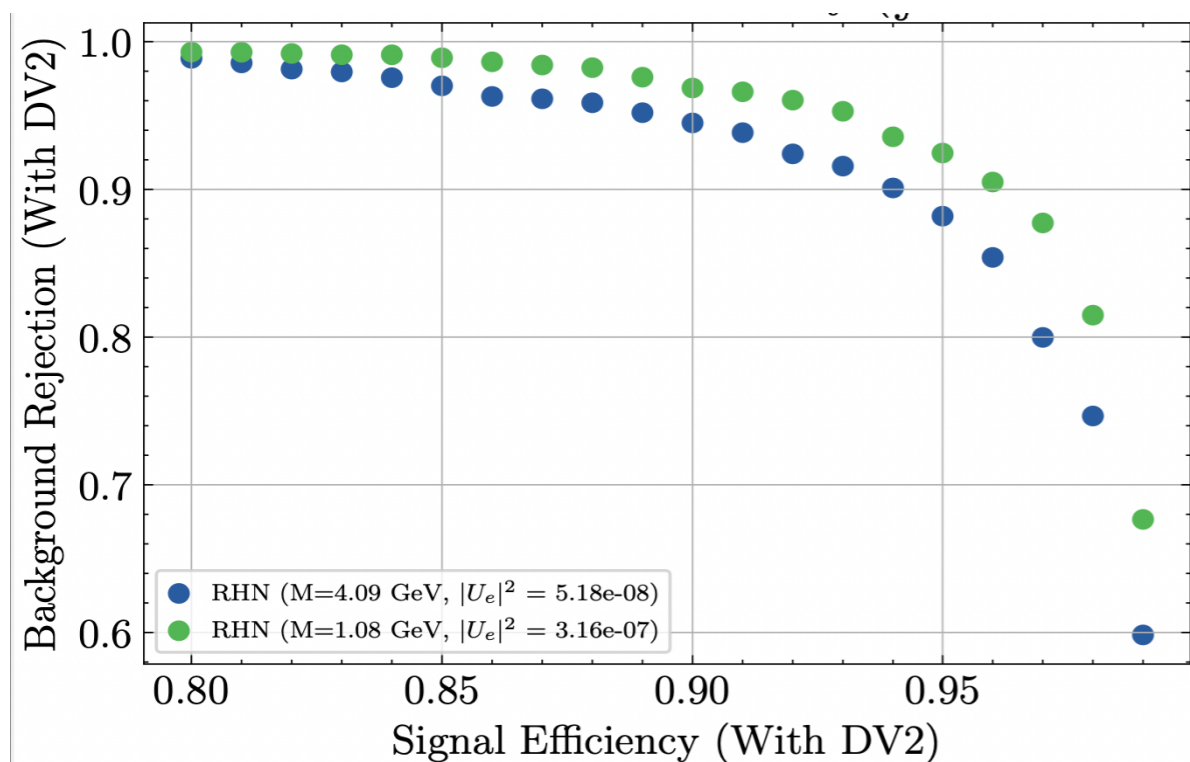


Best 70 tracks (χ^2) with at least 3 above-threshold hits from 33 hours of cosmics data taking

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 \rightarrow 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]

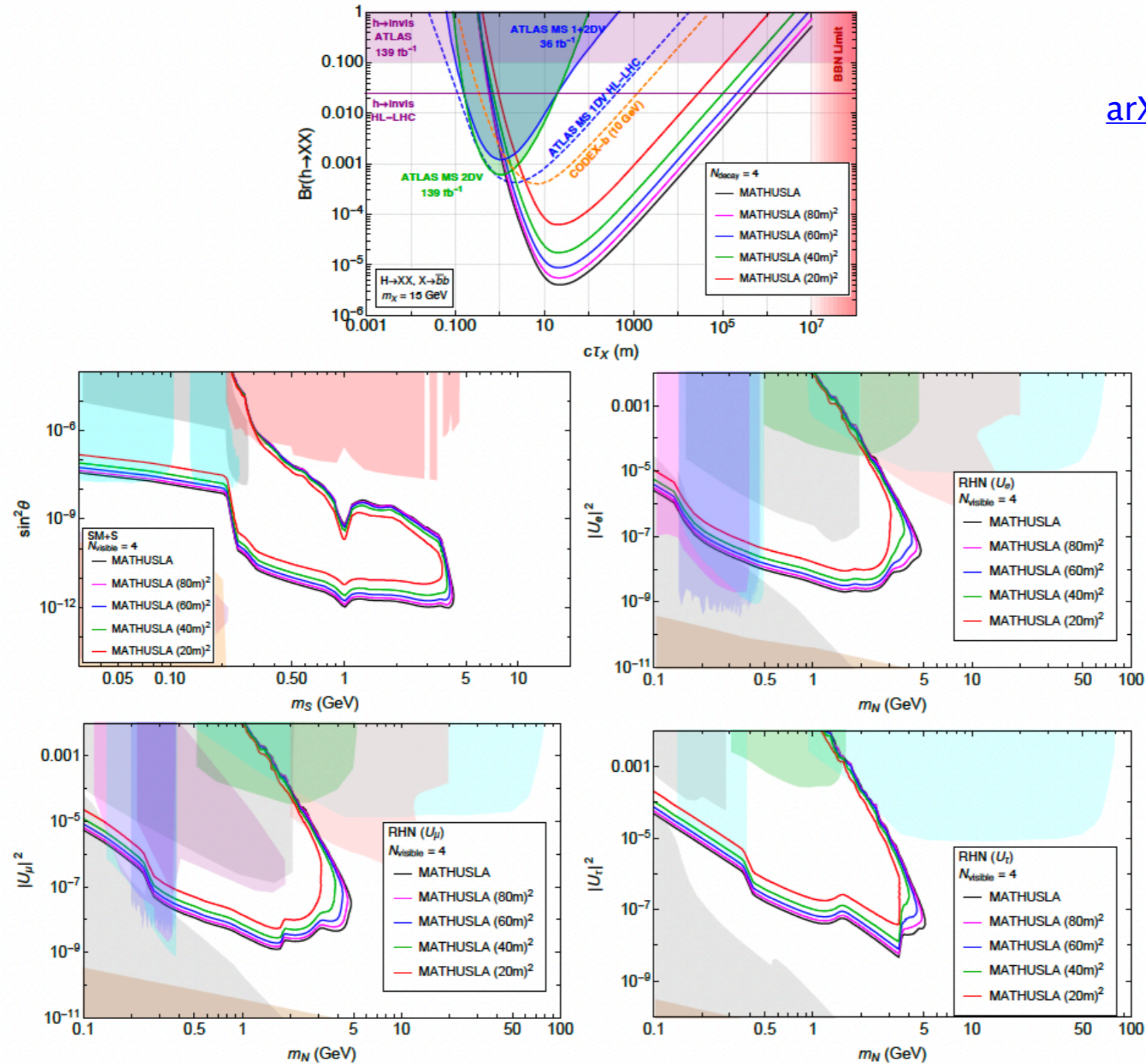


FIG. 11. Comparing the idealized reach of the MATHUSLA baseline geometry in Figure 1 to similarly situated versions of MATHUSLA with smaller area.