Prospects for Long Lived Particle Searches with MATHUSLA

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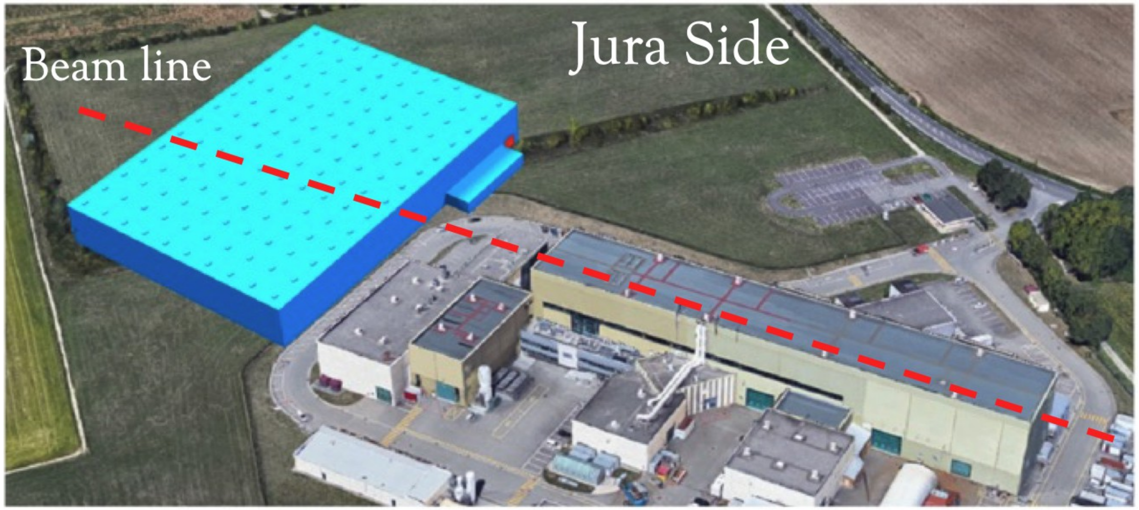
PHYSICS

Overview

- Long lived particles: Motivation
- MATHUSLA concept and collaboration
- Physics reach
- Detector design and R&D activities

MATHUSLA



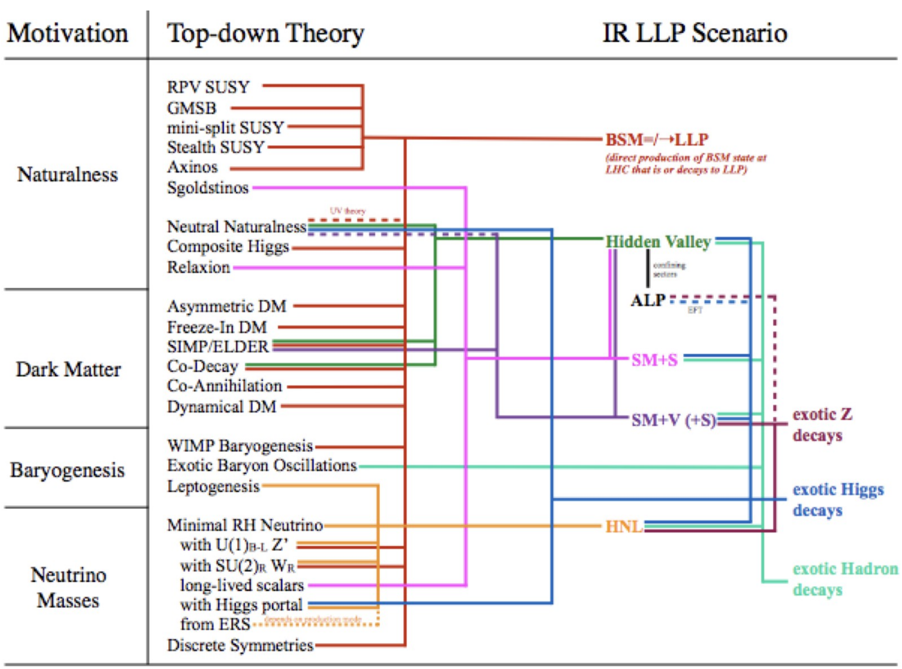
Long-lived particles?

Particles have long lifetimes due to inaccessibility of states into which they can readily decay (i.e. due to kinematics and/or couplings)

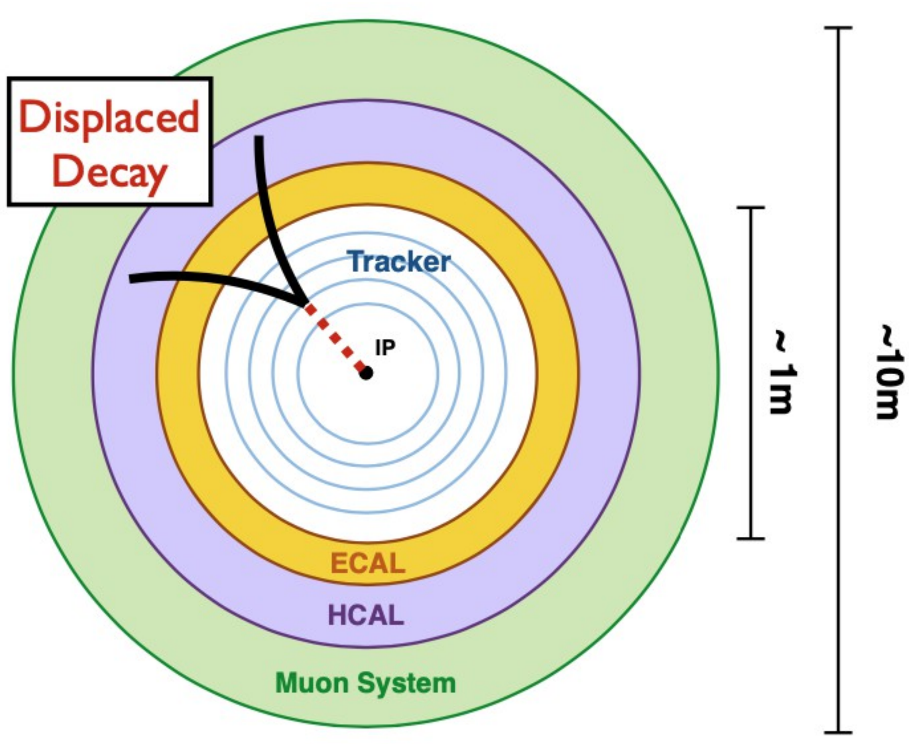
- Several examples exist within the SM, e.g. muons τ_{μ} ~ 2.2 μs
- Big Bang Nucleosynthesis limit on lifetimes of new particles is ~0.1s ($c\tau$ ~10^7 m)

→ **Reasonable to expect that beyond-SM particles may also have long lifetimes, particularly if they are light and/or have "feeble" couplings to the SM**

Various theories of beyond-SM physics (e.g. supersymmetry) "naturally" include particles that can be long lived:



How do we find them?



- Neutral long-lived particles (LLPs) cannot be directly detected in experiments
- Instead, the SM decay daughters must be detected and the LLP reconstructed based on the displaced decay vertex
- If the decay length $c\tau$ is too long, the decay can occur outside of the detector fiducial volume
- "Missing energy" searches are possible, but these signatures can be challenging due to resolution, background, and trigger issues

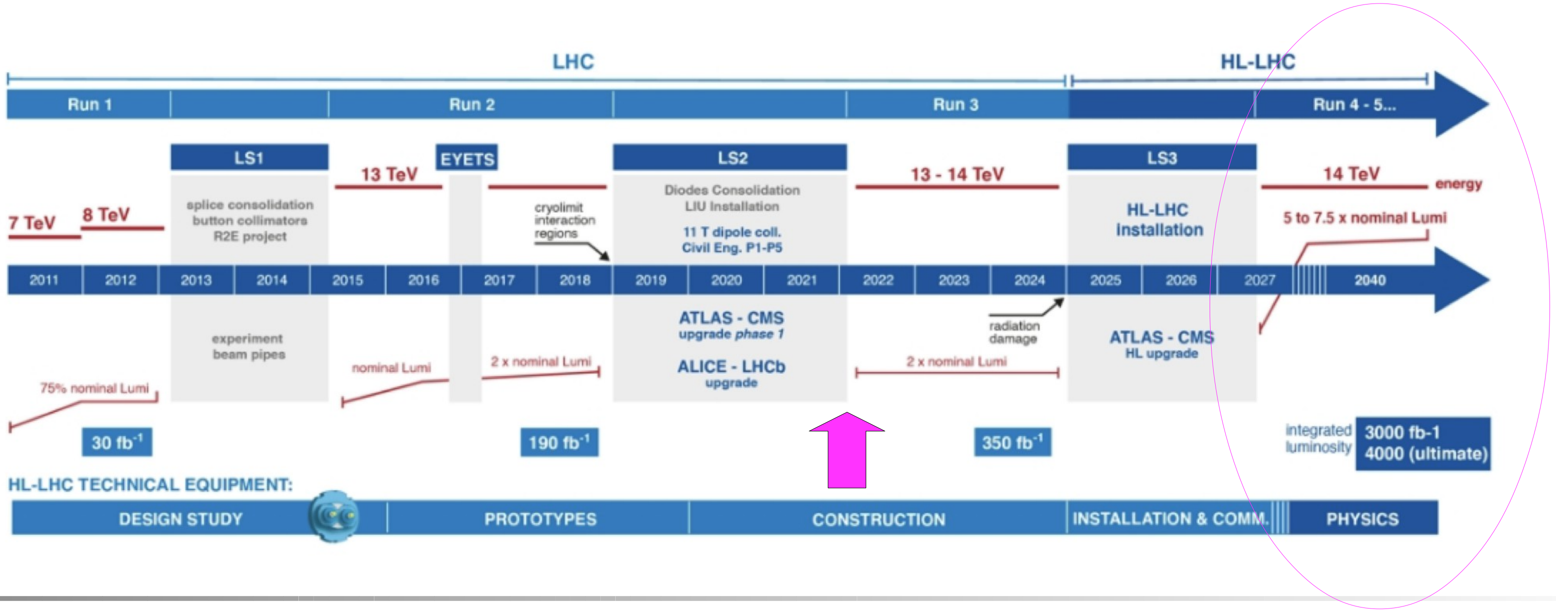
LLP searches have been identified by the [HL-]LHC community as a growing priority

- **However, the LHC could be making LLPs that are invisible to its main detectors**

Where to look?

Although experiments have been proposed at several facilities, the LHC has many advantages:

- High centre of mass energy gives access to heavy states that may be coupled to LLPs (e.g. Higgs)
- Very high luminosity (HL-LHC)
- **The LHC already exists...**

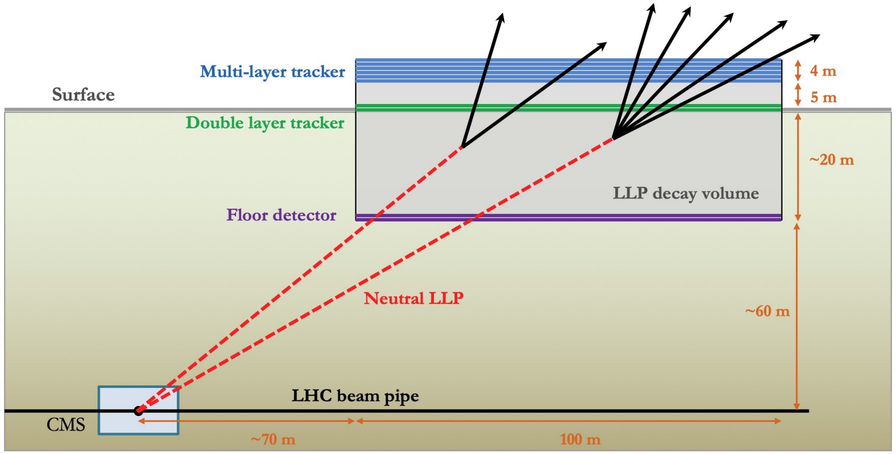


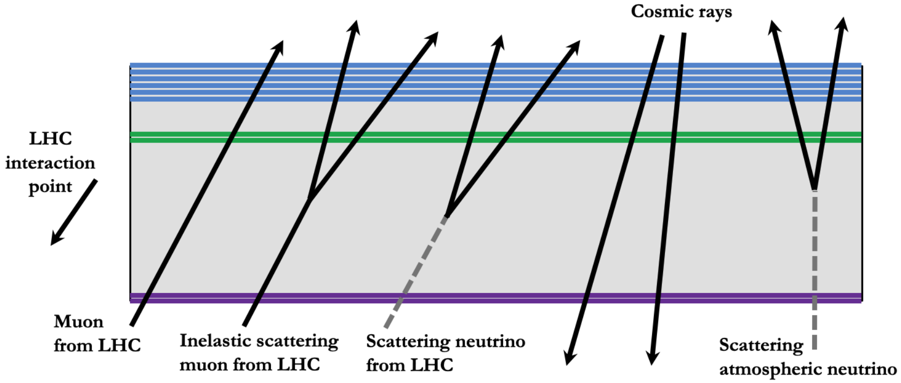
MATHUSLA

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

(MAssive Timing Hodoscope for Ultra Stable neutraL pArticles)

- Large-volume dedicated detector for LLPs with long decay lengths
- LLPs decay vertices are reconstructed by tracking their decay daughters
- Positioned on the surface near one of the LHC interaction regions, detector is shielded from LHC interactions by ~100m of rock





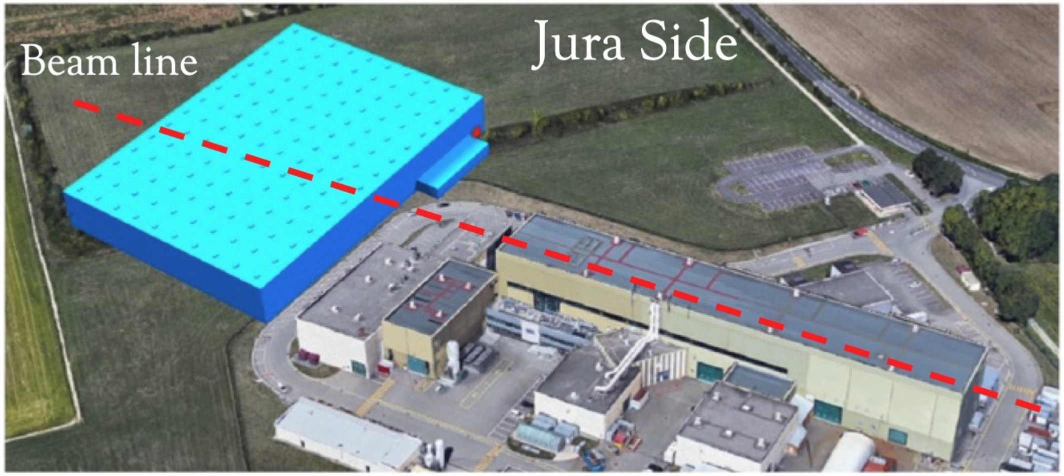
- LHC backgrounds vetoed by floor tracking layers and/or topology
- Up-down timing constraints to veto cosmic rays

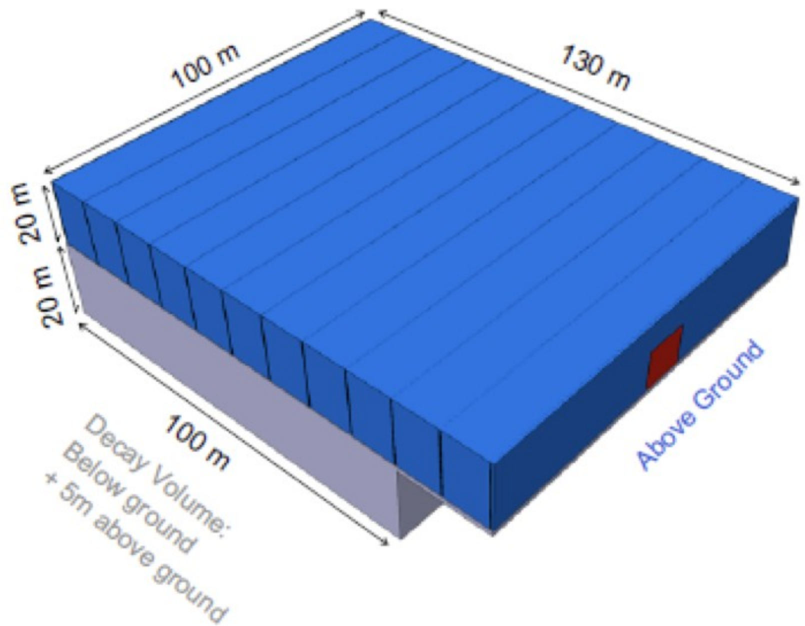
Capable of LLP searches with a near-zero background

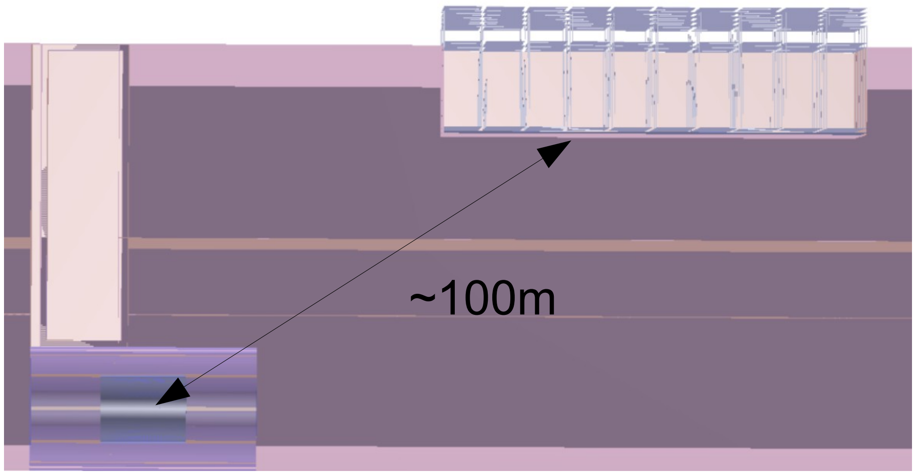
Where to put it?

No space near ATLAS, but there is appropriate space on CERN-owned land adjacent to the CMS experimental site.

- Sufficient space for a detector of dimensions ~ 100m x 100m, along with appropriate service/assembly space







MATHUSLA

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

(Massive Timing Hodoscope for Ultra Stable neutraL pArticles)

Fairly small experimental collaboration, with very strong theory contributions

- Three Canadian Universities represented in NSERC experimental project grant
- Several Canadian theorists are authors on MATHUSLA-related papers

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

MATHUSLA

2009.01693 LHCC-I-031-ADD-1

mathusla-experiment.web.cern.ch

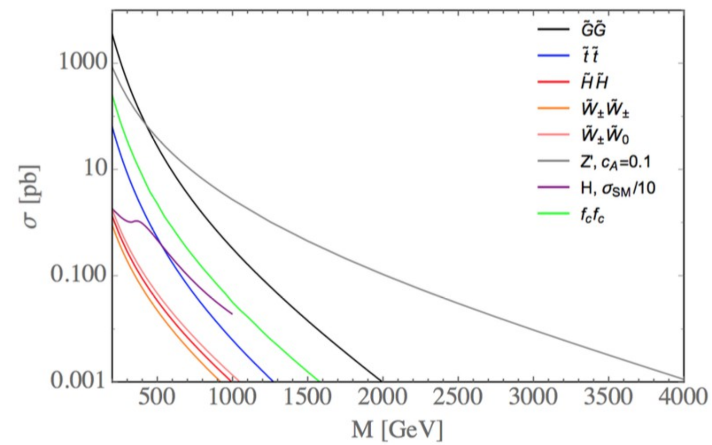
Cristiano Alpigiani,[1] Juan Carlos Arteaga-Velázquez,[2] Austin Ball,[3] Liron Barak,[4] Jared Barron,[5] Brian Batell,[6] James Beacham,[7] Yan Benhammo,[4] Karen Salomé Caballero-Mora,[8] Paolo Camarri,[9] Roberto Cardarelli,[9] John Paul Chou,[10] Wentao Cui,[5] David Curtin,[5] Miriam Diamond,[5] Keith R. Dienes,[11,12] Liam Andrew Dougherty,[3] Giuseppe Di Sciascio,[9] Marco Drewes,[13] Erez Etzion,[4] Rouven Essig,[14] Jared Evans,[15] Arturo Fernández Téllez,[16] Oliver Fischer,[17] Jim Freeman,[18] Jonathan Gall,[3] Ali Garabaglu,[10] Stefano Giagu,[19] Stephen Elliott Greenberg,[10] Bhawna Gomber,[20] Roberto Guida,[3] Andy Haas,[21] Yuekun Heng,[22] Shih-Chieh Hsu,[1] Giuseppe Iaselli,[23] Ken Johns,[11] Audrey Kvam,[1] Dragoslav Lazic,[24] Liang Li,[25] Barbara Liberti,[9] Zhen Liu,[12] Henry Lubatti,[1] Lillian Luo,[5] Giovanni Marsella,[26] Mario Iván Martínez Hernández,[16] Matthew McCullough,[3] David McKeen,[27] Patrick Meade,[14] Gilad Mizrachi,[4] O.G. Morales-Olivares,[8] David Morrissey,[27] Meny Raviv Moshe,[4] Antonio Policicchio,[19] Mason Proffitt,[1] Dennis Cazar Ramirez,[28] Matthew Reece,[29] Steven H. Robertson,[30] Mario Rozo Cahuantzi,[16] Albert de Roeck,[3] Amber Roepe,[31] Joe Rothberg,[1] James John Russell,[32] Heather Russell,[30] Rinaldo Santonico,[9] Marco Schioppa,[33] Jessie Shelton,[34] Brian Shuve,[35] Yiftah Silver,[4] Luigi Di Stante,[9] Daniel Stolarski,[36] Mike Strauss,[31] David Strom,[37] John Stupak,[31] Martin A. Subieta Vasquez,[38] Sanjay Kumar Swain,[39] Guillermo Tejeda Muñoz,[16] Steffie Ann Thayil,[10] Brooks Thomas,[40] Yuhsin Tsai,[41] Emma Torro,[42] Gordon Watts,[1] Charles Young,[43] Jose Zurita[44]

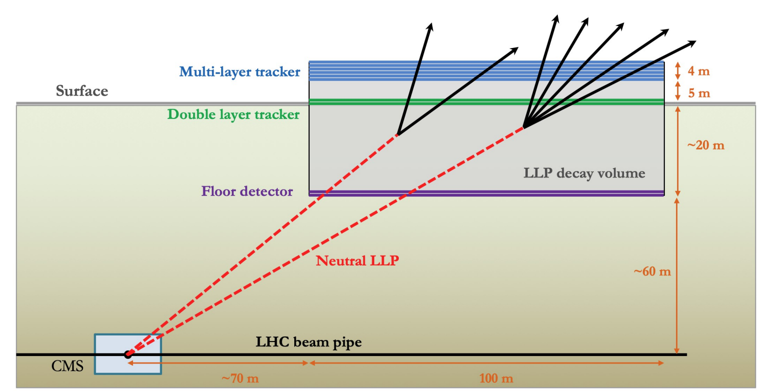
What to look for?

Two general categories of physics signatures:

- Hadronically decaying LLPs ranging from a few GeV to TeV scale
  - High multiplicity final states, so relatively easy to vertex and distinguish from backgrounds
  - Factor of 1000 improvement over LHC for LLPs with mass < ~100GeV (LHC searches background limited and are difficult to trigger)
- LLPs with mass less than a few GeV (any decay mode)
  - Typically low multiplicity (i.e. 2 tracks) final states
  - Sensitivity **very dependent on detector geometry and performance** due to both signal efficiency and background rejection requirements

Any production process with σ>1fb can give a signal. Sensitivity to multi-TeV scales:

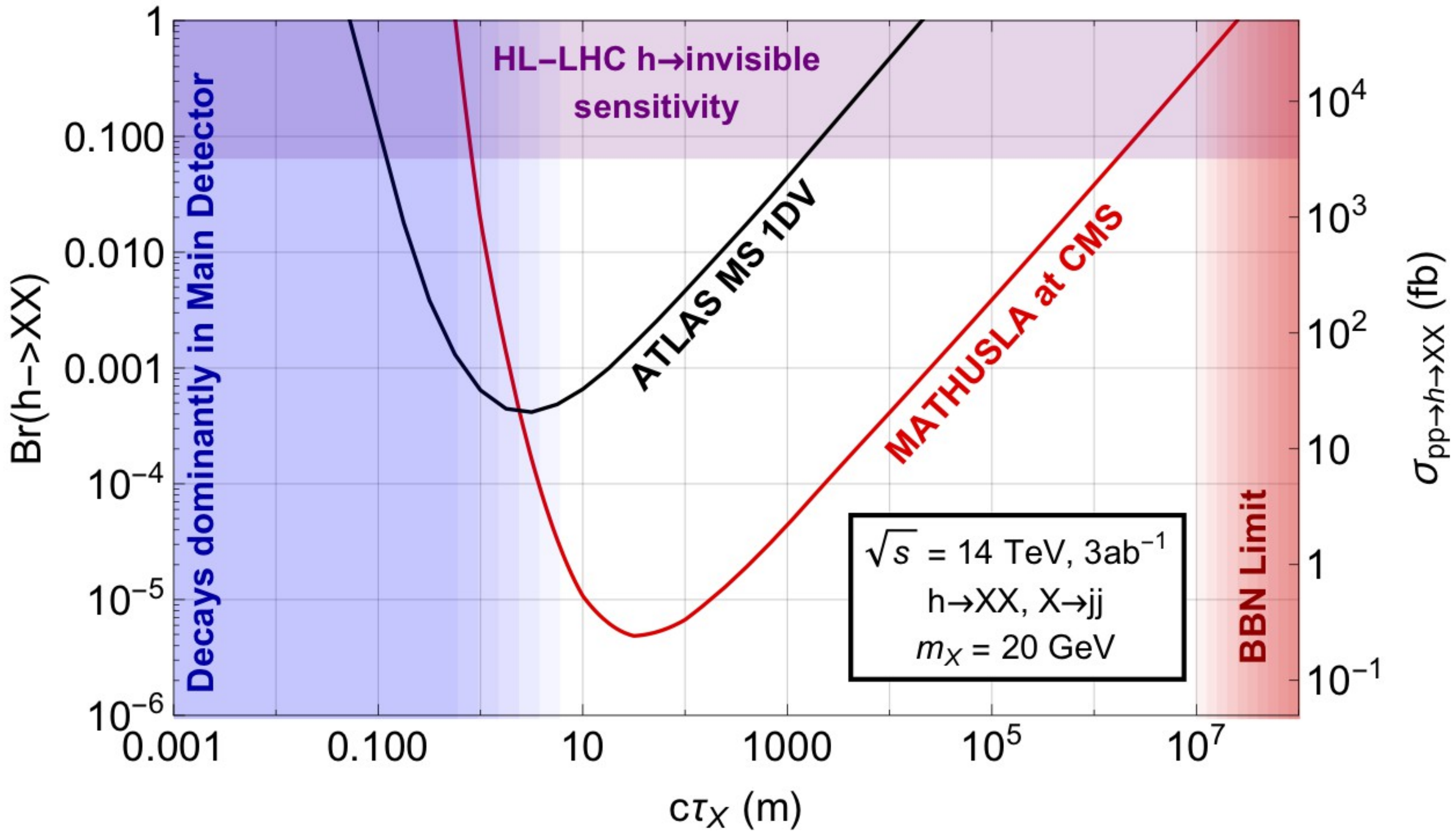




Higgs Decays to LLPs

Standard Model Higgs decay into pairs of (hadronically decaying) LLPs:

- up to 1000 times better sensitivity than LHC main detector experiments



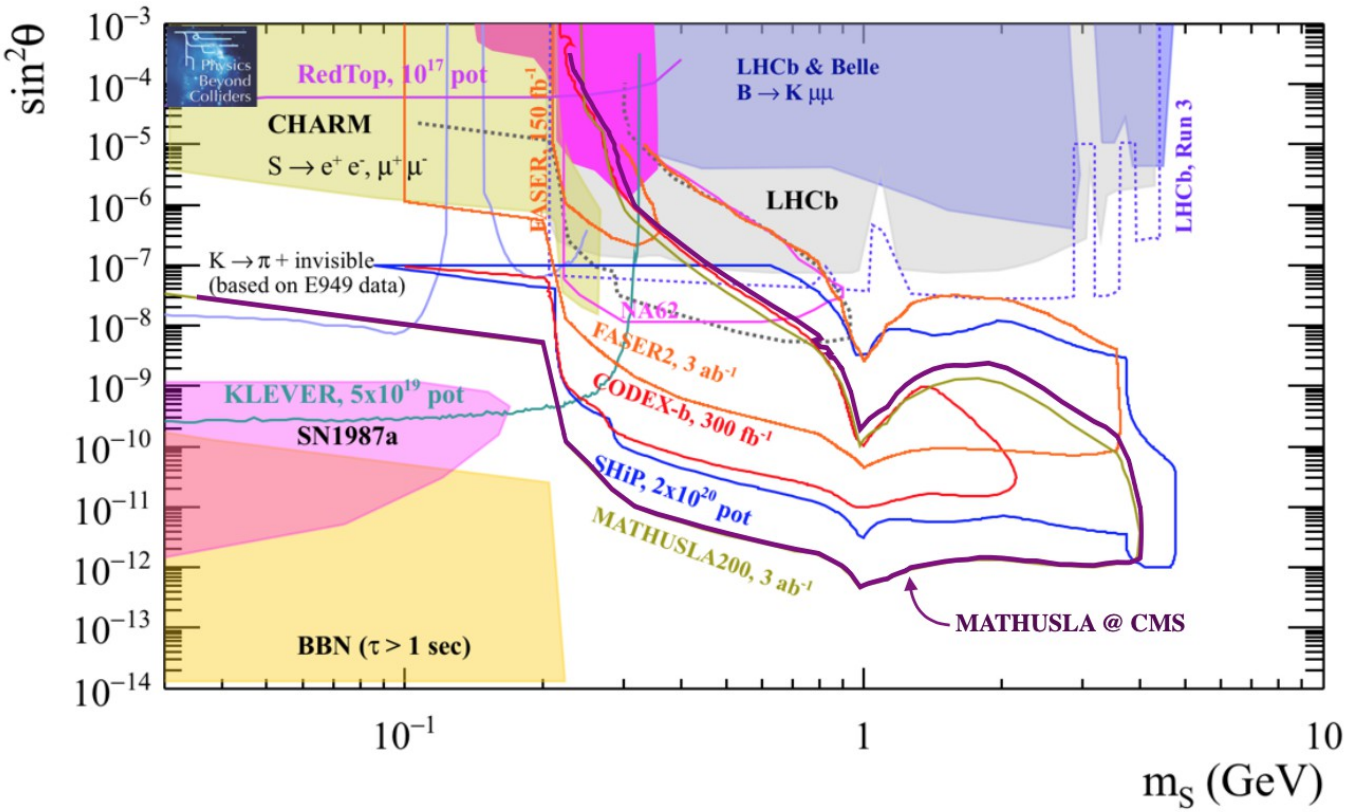
Red curve: MATHUSLA@CMS sensitivity (4 observed events) for LLPs of mass m_X = 20 GeV produced in exotic Higgs decays.
Black curve: reach of ATLAS search for a single hadronic LLP decay in the Muon System at the HL-LHC [

Dark scalar

MATHUSLA update 2009.01693
PBC 1901.09966

Singlet dark scalar S mixing with Standard Model Higgs with mixing angle θ

- Assuming production in exotic B, D, K meson decays only:



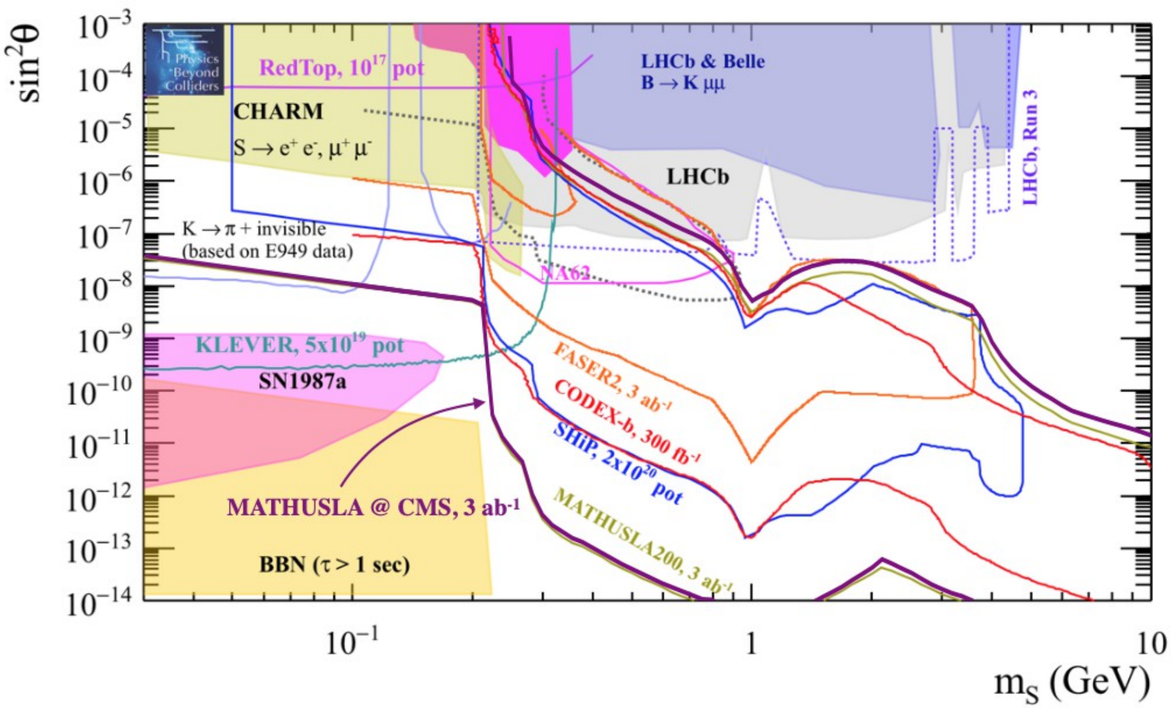
- Mass reach (obviously) limited by parent meson mass, but MATHUSLA probes smaller mixing angles / longer lifetimes

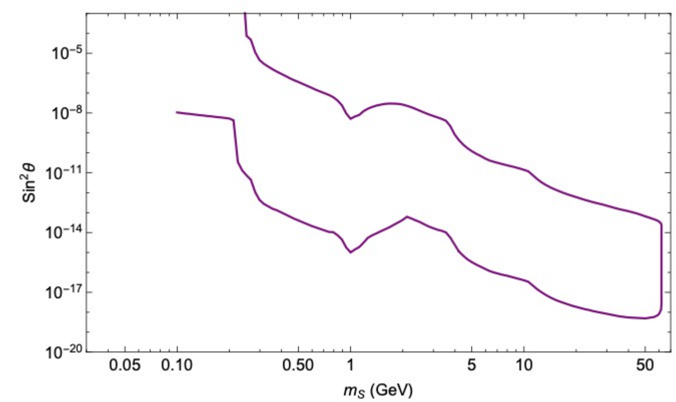
Dark scalar

MATHUSLA update 2009.01693
PBC 1901.09966

Singlet dark scalar S mixing with Standard Model Higgs with mixing angle θ

- Assuming additional production in exotic Higgs decays with Br(h → SS) = 1%

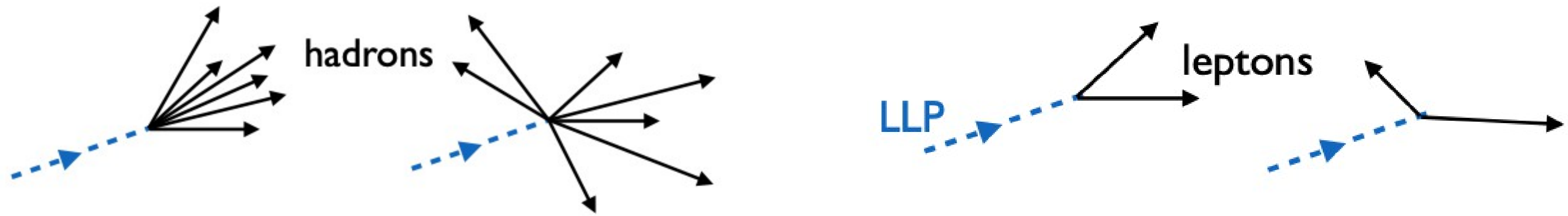




- Big boost in sensitivity from this production mechanism, which is only possible at high energy experiments (i.e. LHC)

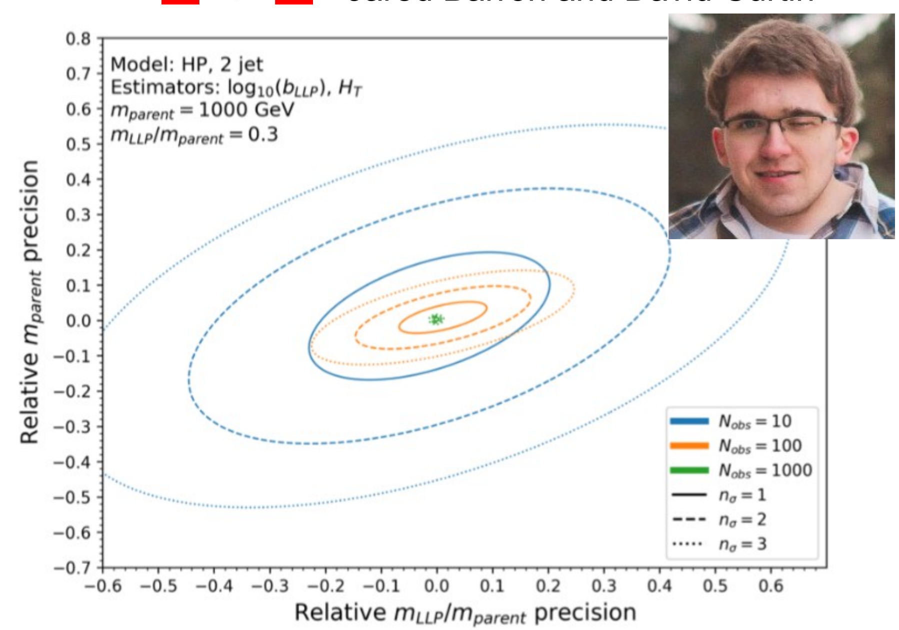
CMS combined analysis

MATHUSLA can't measure track momenta (no magnetic field...), but the LLP boost can be determined event-by-event from the track geometry:



- Geometrical information from MATHUSLA detector provides information about LLP boost and decay mode
- Information from CMS detector reveals production mode and parameters of underlying model (parent mass, LLP mass)
- **Combined analysis ca provide a complete characterization of LLP with as few as O(100) events**

arXiv:2007.05538 [hep-ph]
Jared Barron and David Curtin



CMS and triggering

MATHUSLA can trigger independently on decay vertices produced by upward-going tracks

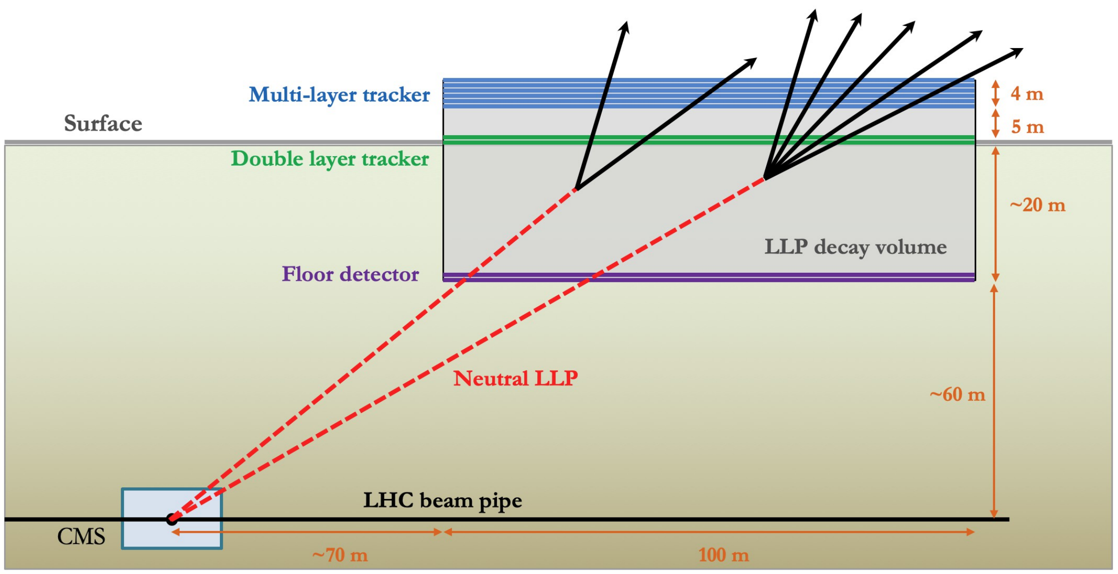
- However, additional information about the production mechanism and event kinematics can be obtained by correlating the MATHUSLA event with the corresponding CMS event

→ Desirable to use MATHUSLA as a L1 trigger for CMS

- Due to time of flight of the (massive) LLP, cannot uniquely specify the bunch crossing, but can provide a "window" of crossings that CMS can potentially record.

Limiting factor is how quickly MATHUSLA can provide such a trigger signal, which needs to occur within the CMS trigger pipeline buffer

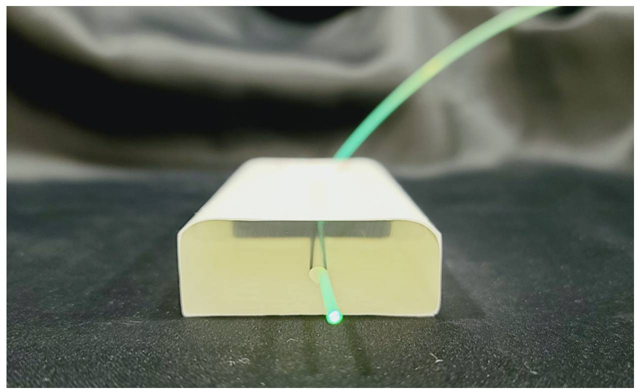
→ so far seems feasible!



MATHUSLA detector concept foresees large modular detector with “towers” composed of 10 layers of tracking detectors

- O(100) towers instrumenting 100m x 100m x 30m

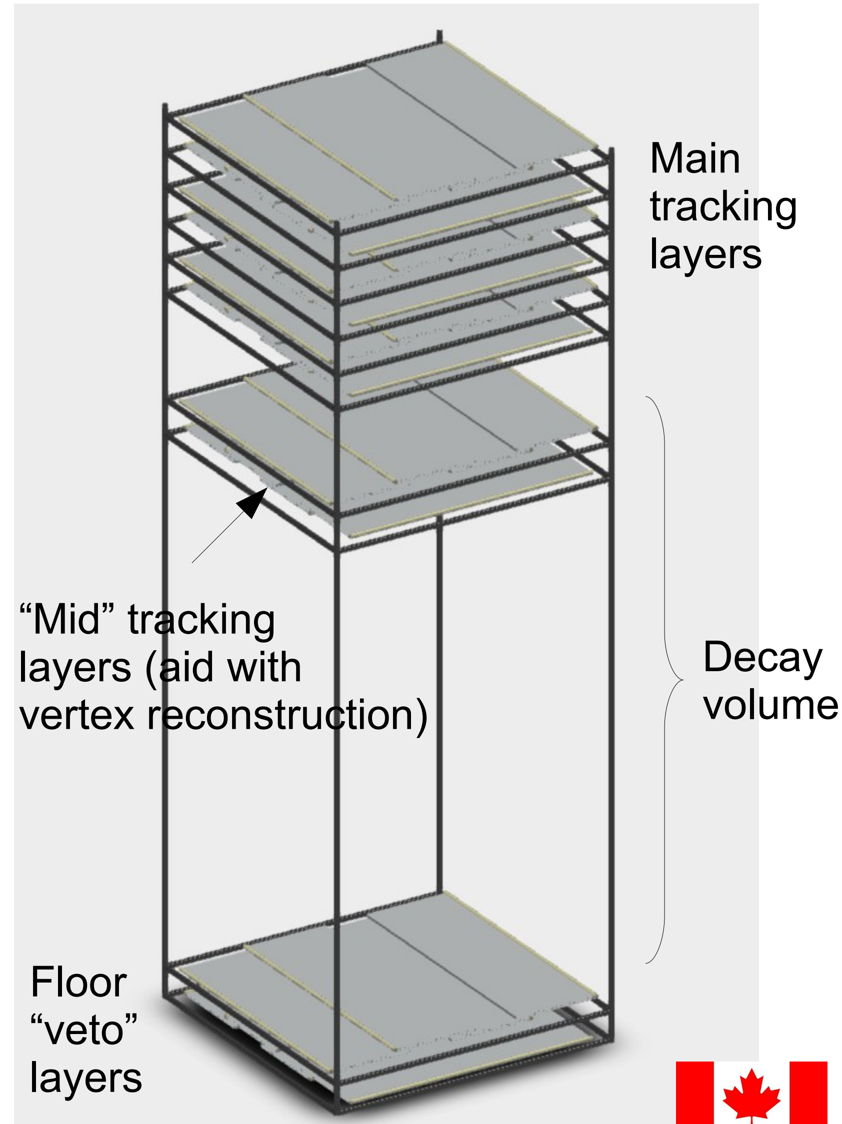
Light brought to the bar ends via blue-green wavelength shifting optical fiber (WLSF)



Extruded plastic scintillator is primary detector element

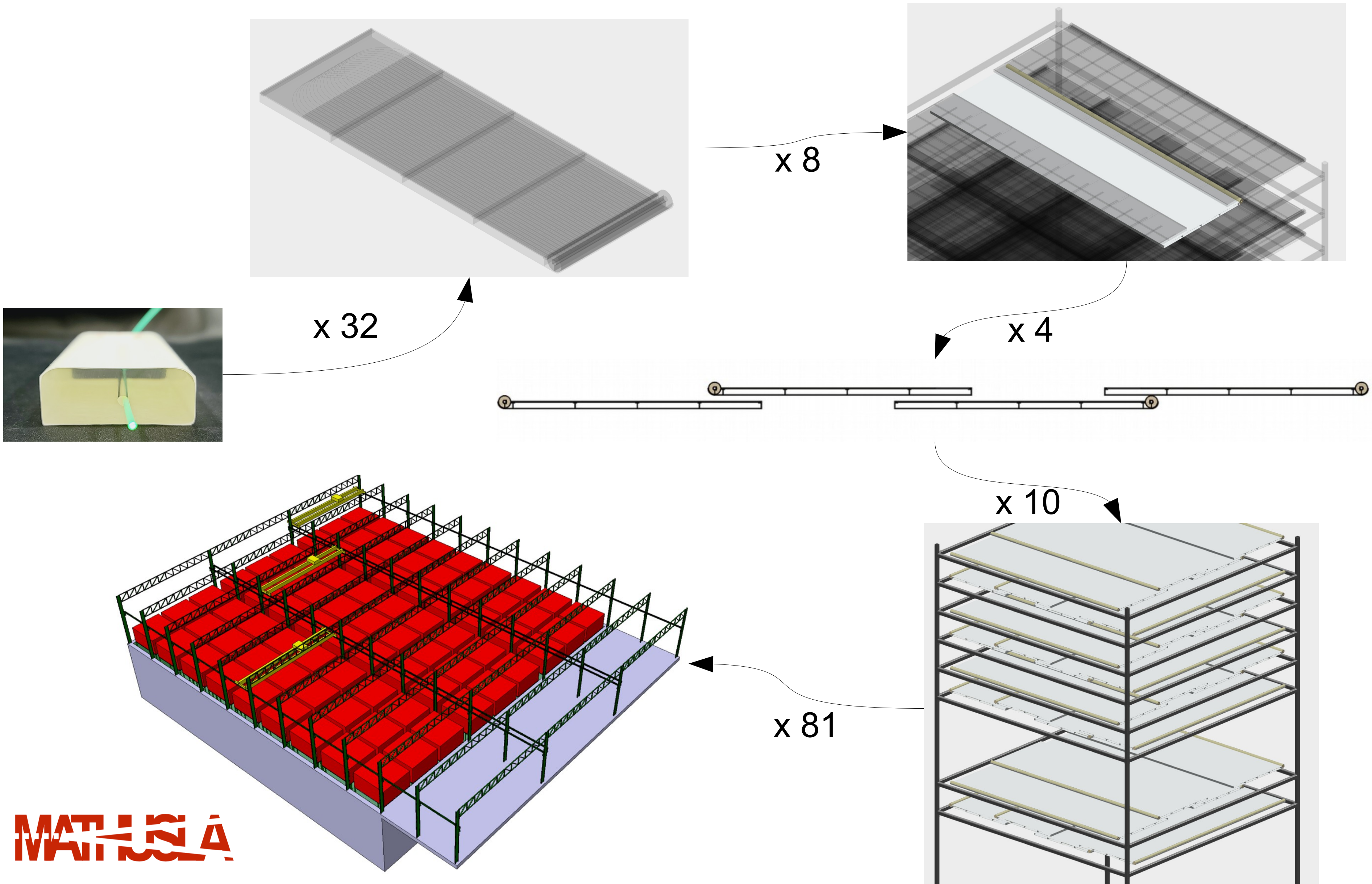
- ~1 million electronic readout channels
- ~3 million metres of WLSF
- ~1000 tons of extruded scintillator, 100000 m^2 of scintillator area

Cost is (obviously) a major design consideration...

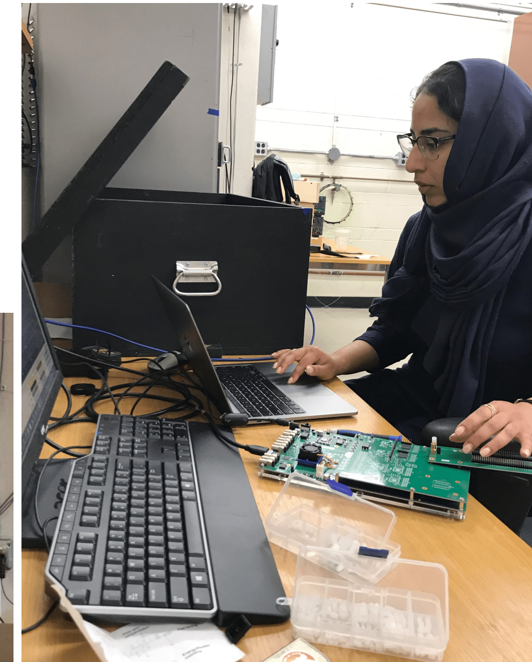


CAD by Rodney Schnarr (Carleton)

MATHUSLA



Canadian activities



Canadian effort is ramping up with the funding of the SAPES project grant request in 2022

- Ongoing physics performance studies, detector development and prototype testing

Exciting opportunity for detector development and testing for undergrads and graduate students

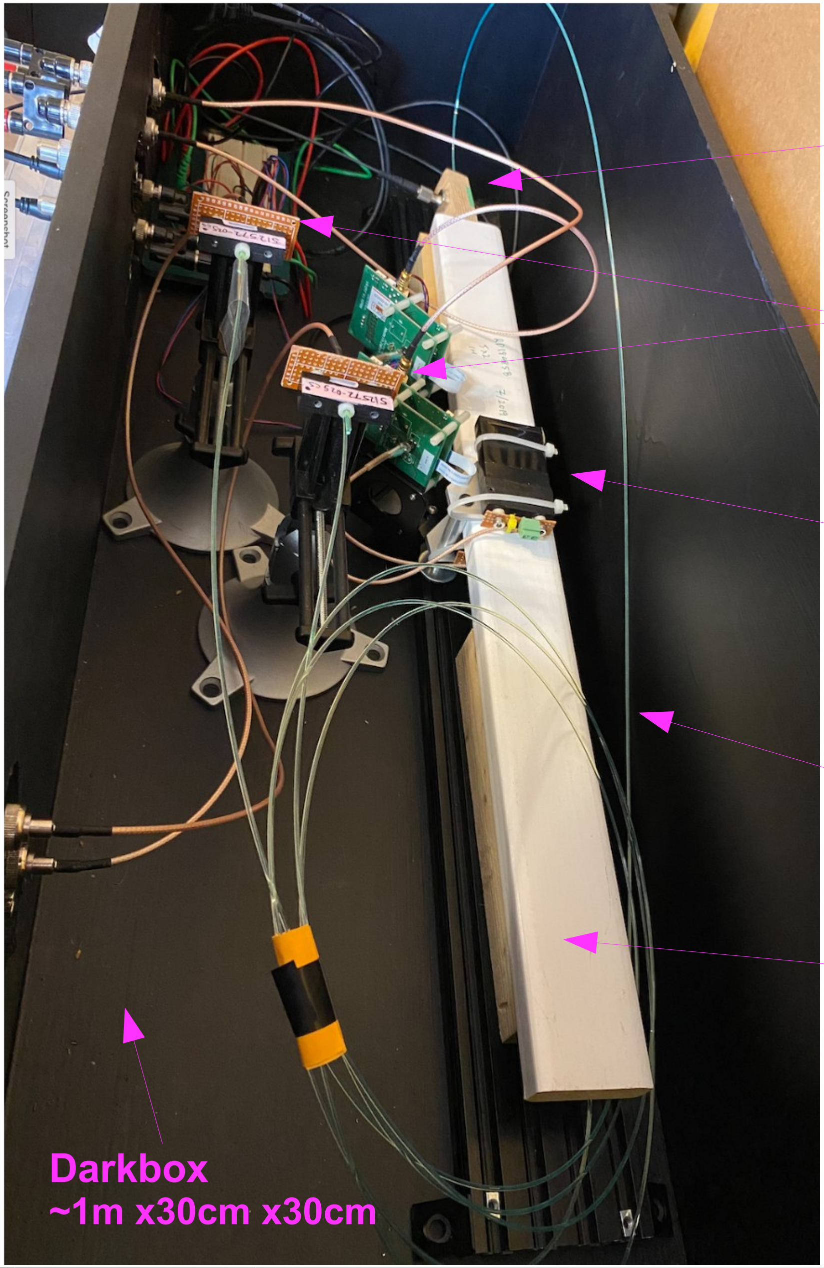
- Postdocs to join the group in coming months

Characterization studies

In spite of the large MATHUSLA detector size, performance measurements can easily be made using "desktop"-scale prototypes

- MIP signals from cosmic rays
- Due to high light attenuation in extruded scintillator, signals are "local" hence no need for bars longer than ~50cm
- WLSF can be directly excited using visible (~405nm) light

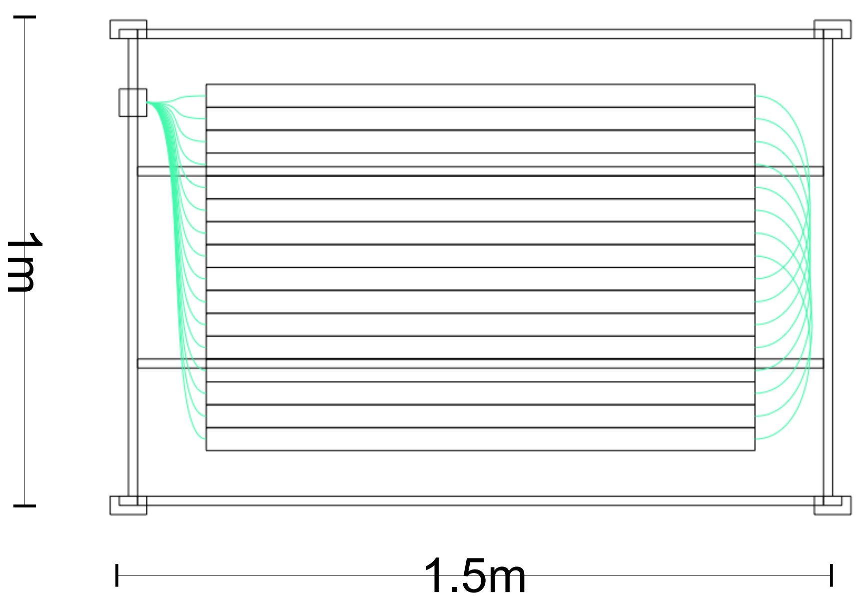
Light yield, attenuation, timing, SiPM performance etc

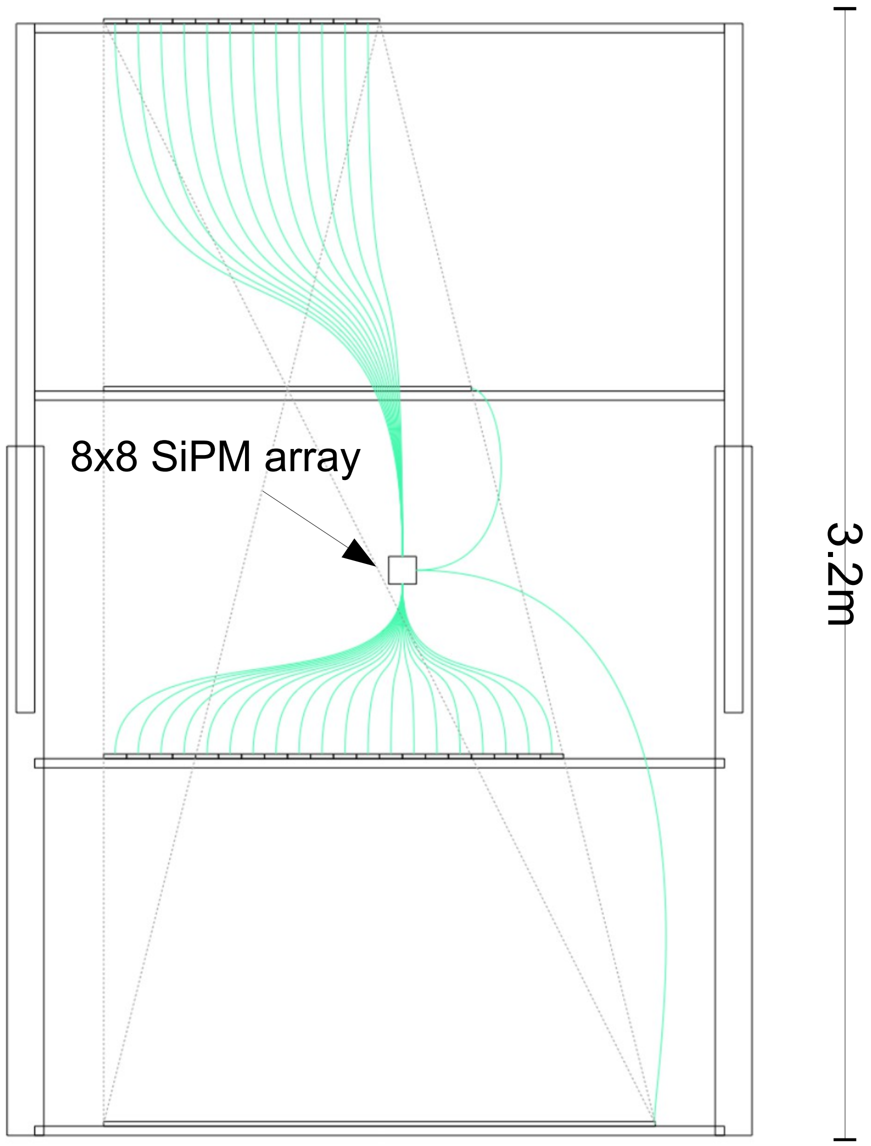


Tracking prototype

64 channel 4 layer prototype to be constructed at UVic this summer

- modules of“short” scintillator bars read out via nominal ~5.5m WLSF
- will replicate MATHUSLA tracking environment for resolution and efficiency studies
- contributions from all Canadian groups





Prospects

- Technical demonstration of scintillator/WLSF/SiPM performance is in progress, with results to date looking very promising
  - Conceptual design of detector well advanced, but engineering design has barely started (not needed for TDR)
  - In parallel, very active effort from theory and simulation groups towards benchmarking of physics sensitivity (important for detector design)
- Work is ongoing towards a MATHUSLA technical proposal
  - To be submitted to the LHCC for consideration by late 2022
- HL-LHC provides a unique opportunity to search for exotic new physics processes. It is important that we use this opportunity to maximum potential

Additional material

Documentation

The physics case for a MATHUSLA-like detector is well documented:

- "New Detectors to Explore the Lifetime Frontier", John Paul Chou, David Curtin, H. J. Lubatti, arXiv:1606.06298.
- "Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case", arXiv:1806.07396 [hep-ph].
- "A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS", arXiv:1811.00927.
- "An Update to the Letter of Intent for MATHUSLA: Search for Long-Lived Particles at the HL-LHC" arXiv:2009.01693.
- Physics Beyond Colliders at CERN: "Beyond the Standard Model Working Group Report" arXiv:1901.09966 [hep-ph].
- US Cosmic Visions: "New Ideas in Dark Matter 2017: Community Report", arXiv:1707.04591 [hep-ph].
- 2018 Update to European Strategy for Particle Physics: "MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LHC", arXiv:1901.04040 [hep-ex].
- Snowmass MATHUSLA whitepaper (no public link yet)

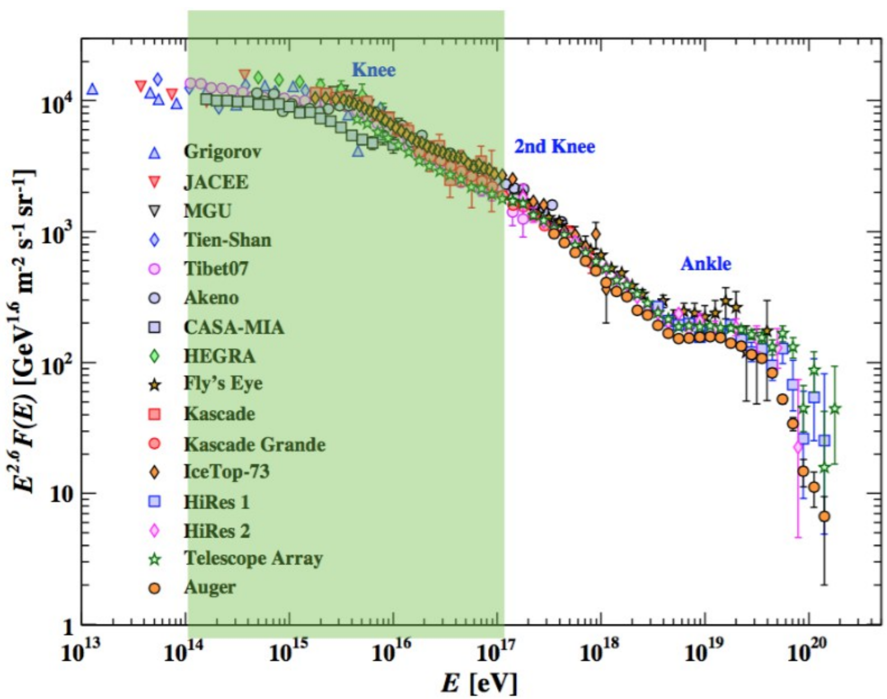
Community planning exercises

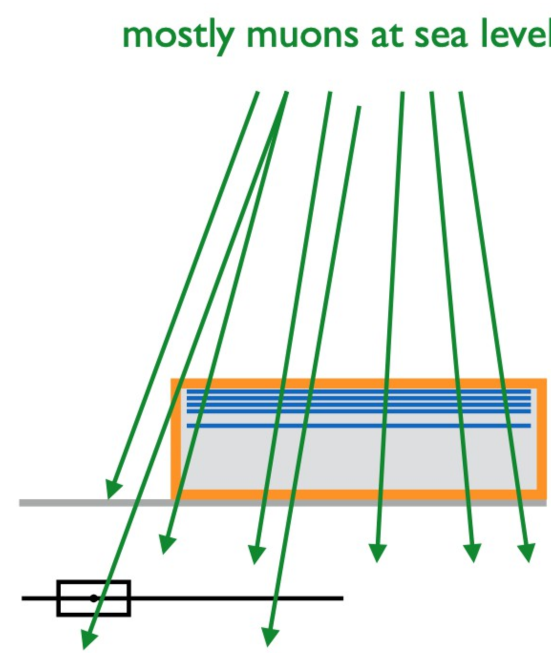
...and of course a whitepaper submitted as part of the recent Canadian Subatomic Physics Long Range Plan

Potential bonus...

The physical size of MATHUSLA makes it potentially interesting as a **cosmic ray detector**

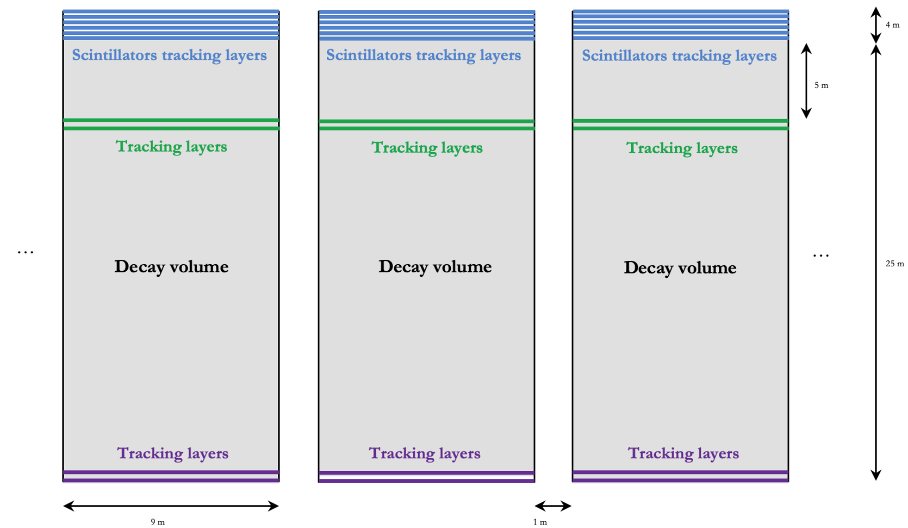
- Main background for MATHUSLA, so necessarily can reconstruct these well
- Potential to study primary cosmic ray energy and composition
- Capability to reconstruct extensive air showers extremely dependent on detector design decisions. Studies ongoing...

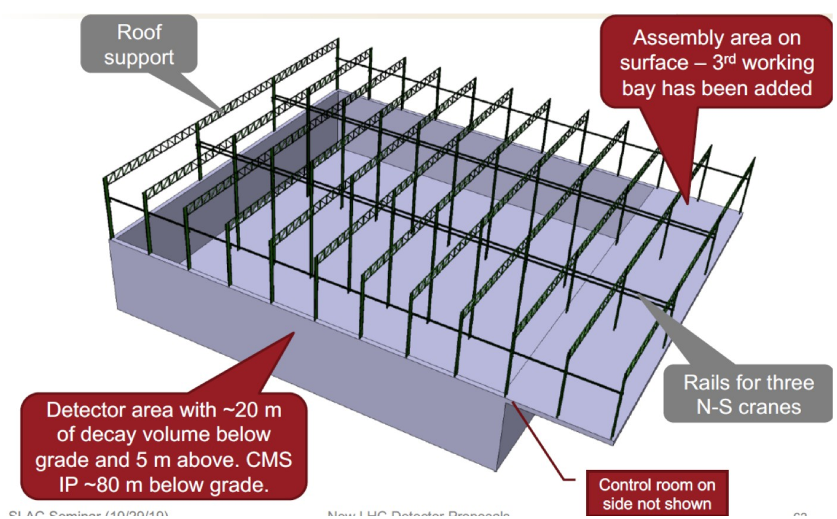


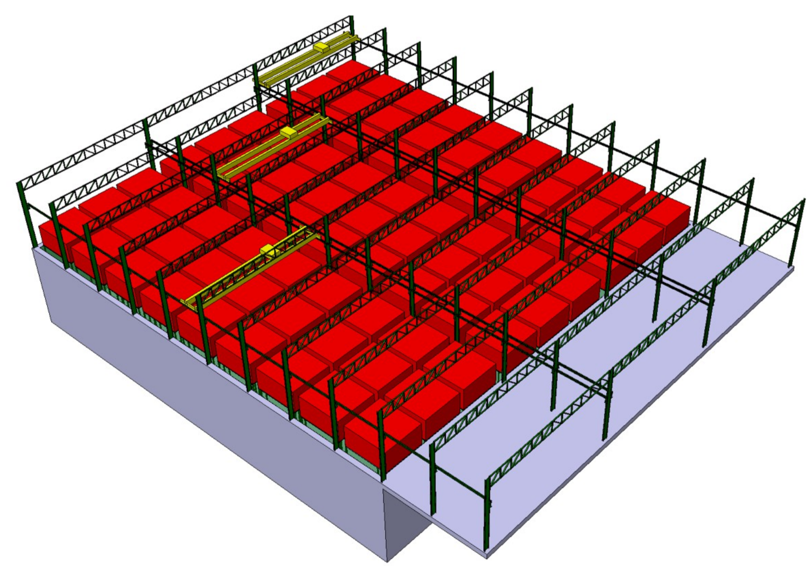


Physics sensitivity determined by combination of solid angle coverage and size of the decay volume

- Modular detector with tracking layers near the top, and "veto" layers at the bottom
- Module "towers" ~ 10m x 10m







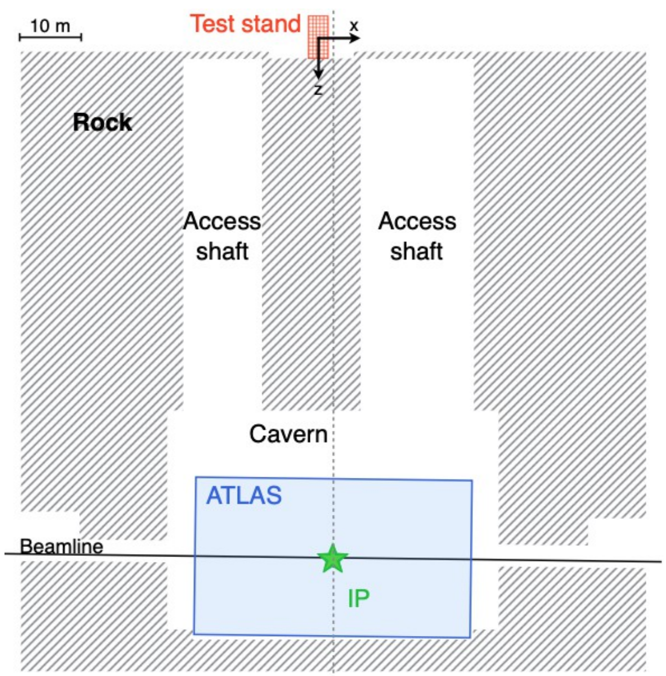
Work is in progress towards the detailed layout of the detector

MATHUSLA Test Stand

Nucl.Instrum.Meth.A 985 (2021) 164661
2005.02018 [physics.ins-det]

A MATHUSLA test stand was operating on the surface above the ATLAS pit in 2018

- Primary goal was to evaluate background sources from cosmic rays and the LHC
- Results published in 2021

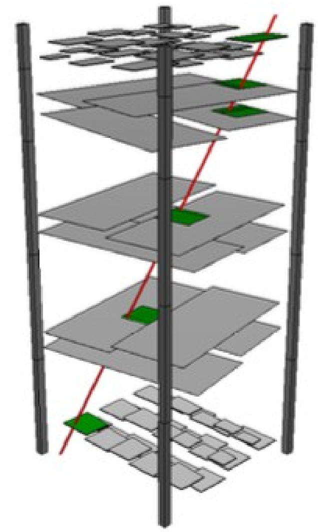


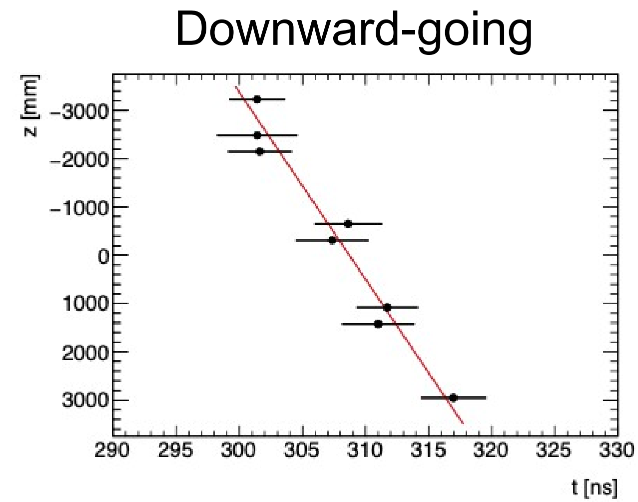
- Two layers of trigger scintillators
- Three layers of RPCs for tracking

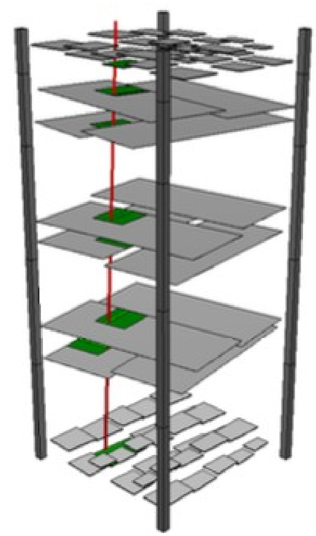
Nucl.Instrum.Meth.A 985 (2021) 164661
2005.02018 [physics.ins-det]

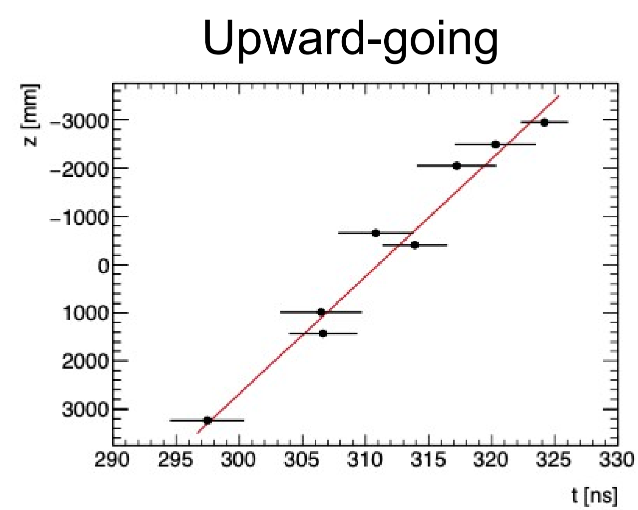
Example events:

- Can easily differentiate upward and downward going tracks based on hit timing
- Directionality (θ,Φ) determined by track reconstruction









MATHUSLA Test Stand

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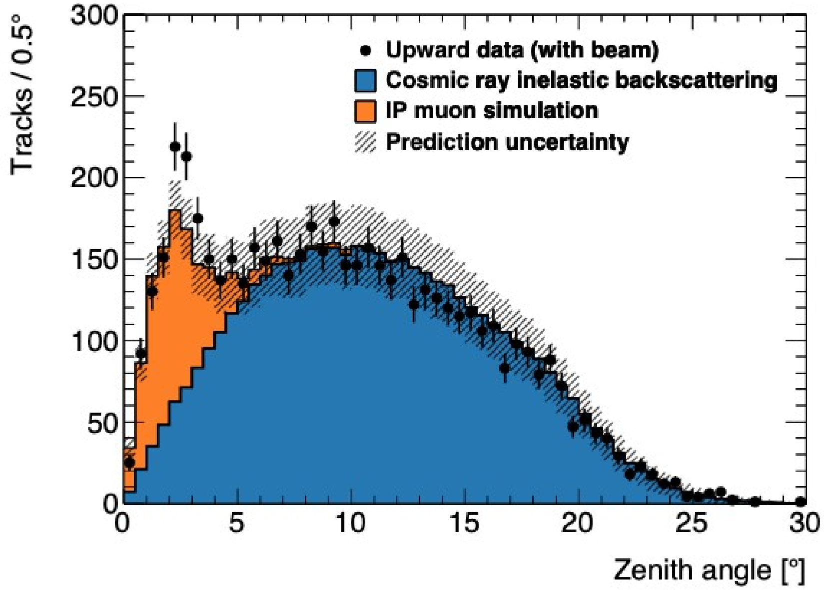
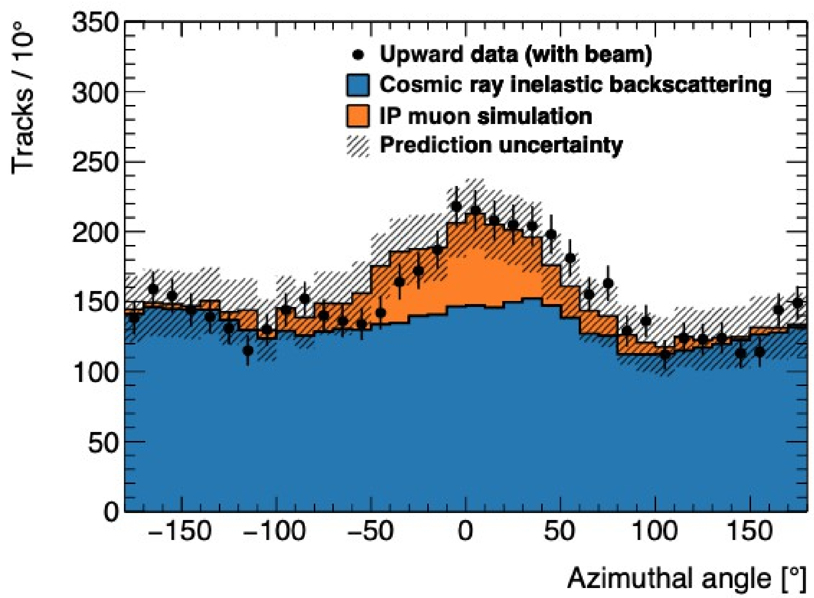
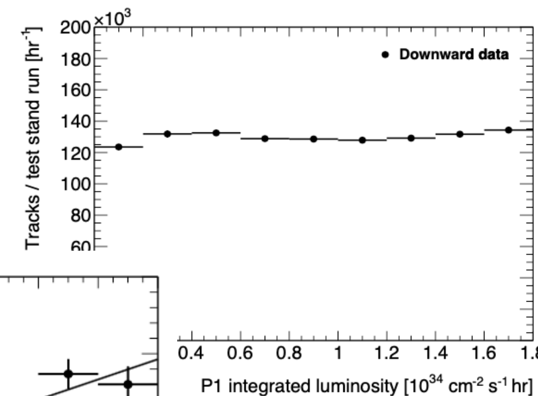
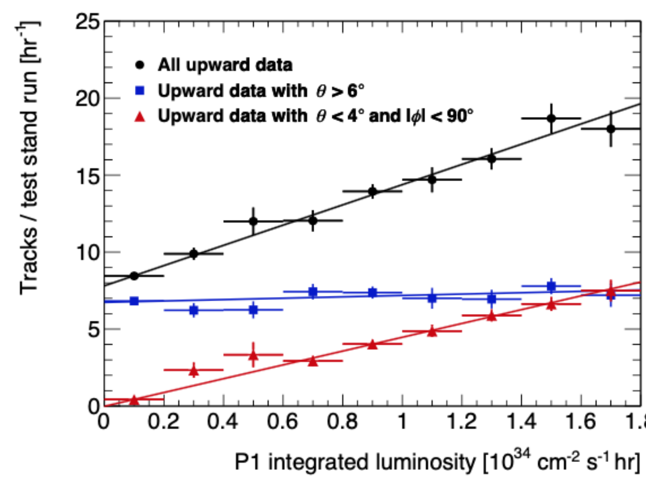




Test stand could see the LHC very clearly!

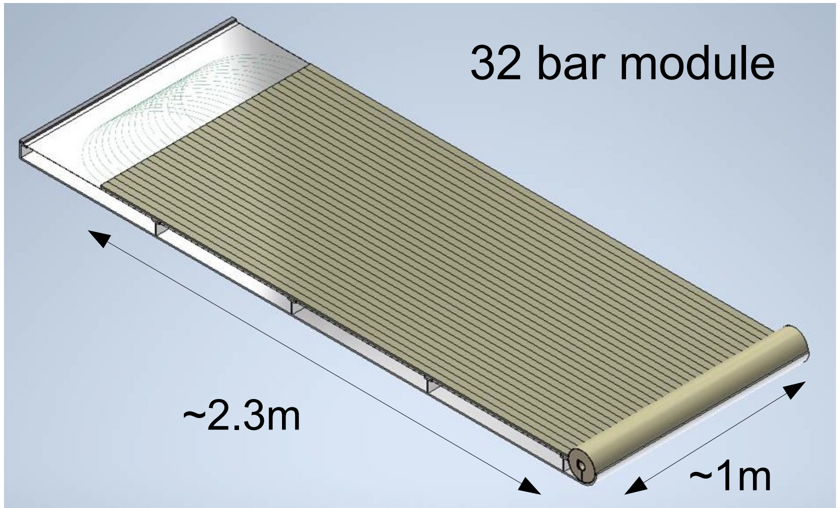
- Good agreement with the cosmic ray and IP simulation

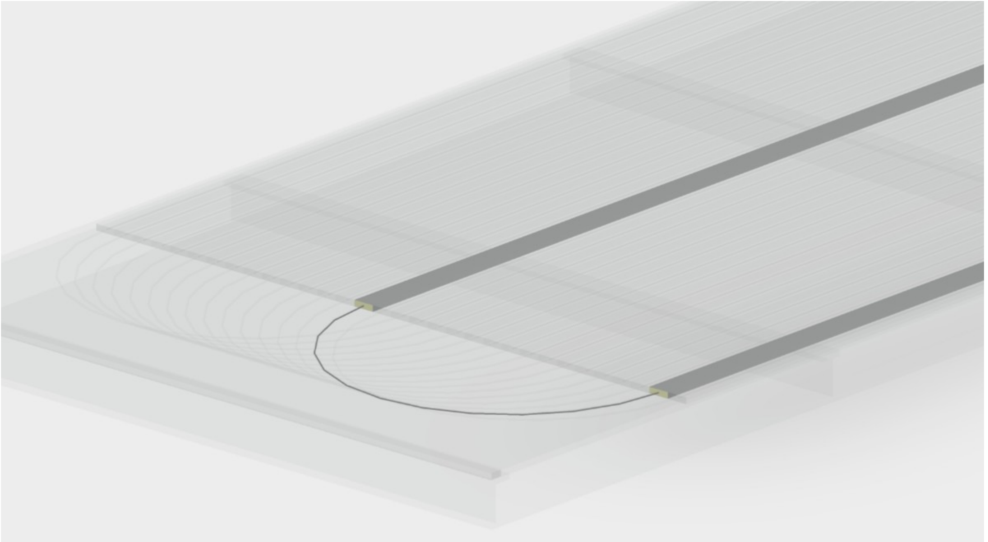




Rate of upward going tracks correlates with LHC instantaneous luminosity

- Bar locations provide 2-D geometrical spacepoints
- Differential timing of signals in opposite ends of the fiber provide additional spatial coordinate (resolution?)
  - 10cm difference in hit position results in ~1ns difference in differential timing
- Absolute hit timing provides final coordinate for “4-D” tracking



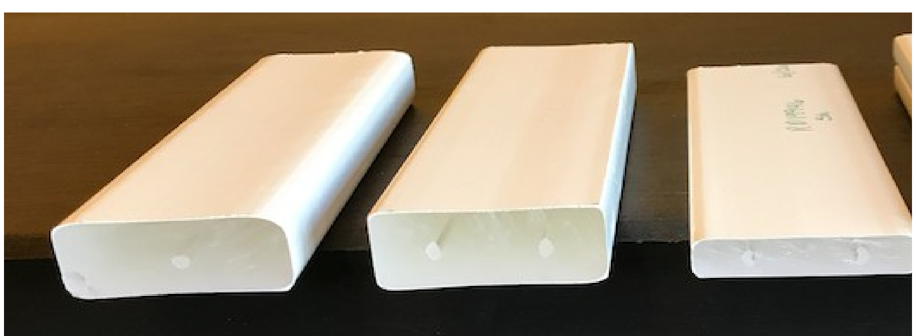


~5.5m long WLSF, looped at far end to so all signals are readout on “front” end

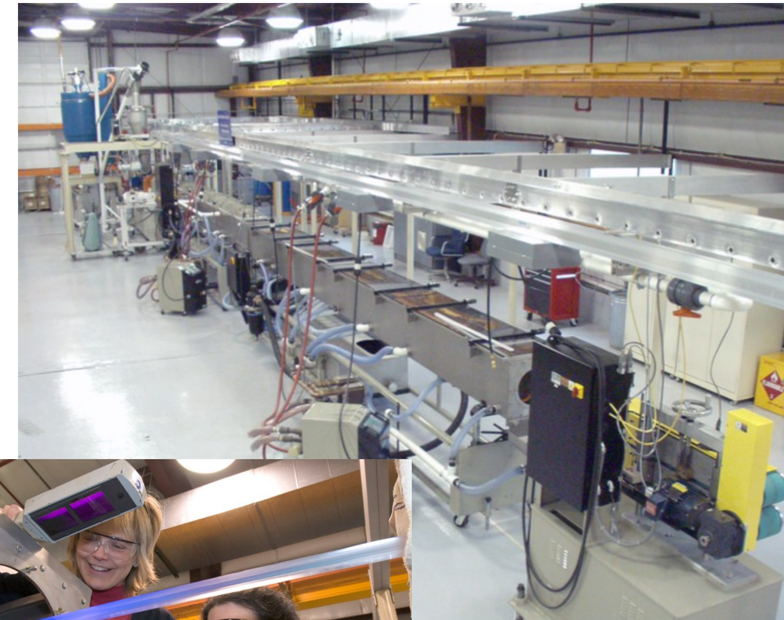
Extruded plastic scintillator

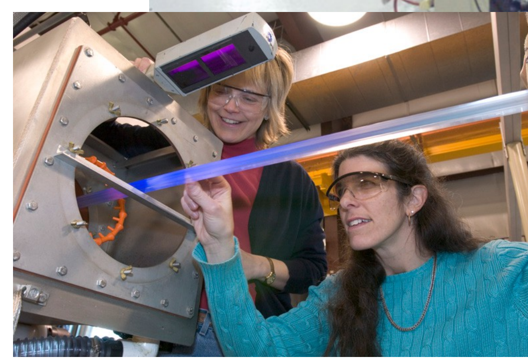
Extruded scintillator based on commercial polystyrene pellets with added dopants

- Primary dopant: ~1% PPO
  2,5-diphenyloxazole
- Secondary dopant ~0.02% POPOP
  (wavelength shifter)
  1,4-bis(5-phenylxazole-2-yl)benzene
- Intrinsic light yield comparable to cast scintillator, but poorer optical quality (i.e. attenuation length O(10cm))
- MUCH cheaper than "cast" scintillator



Fermilab extrusion facility



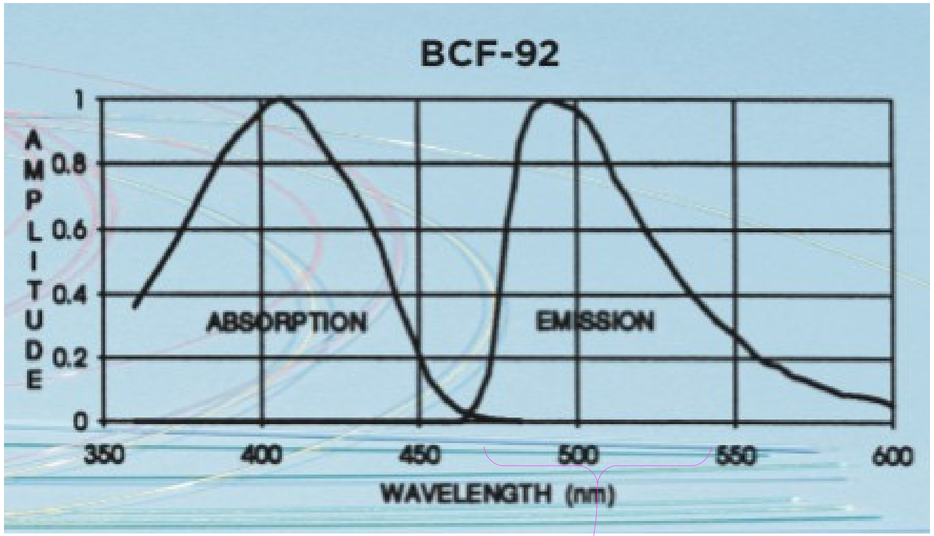


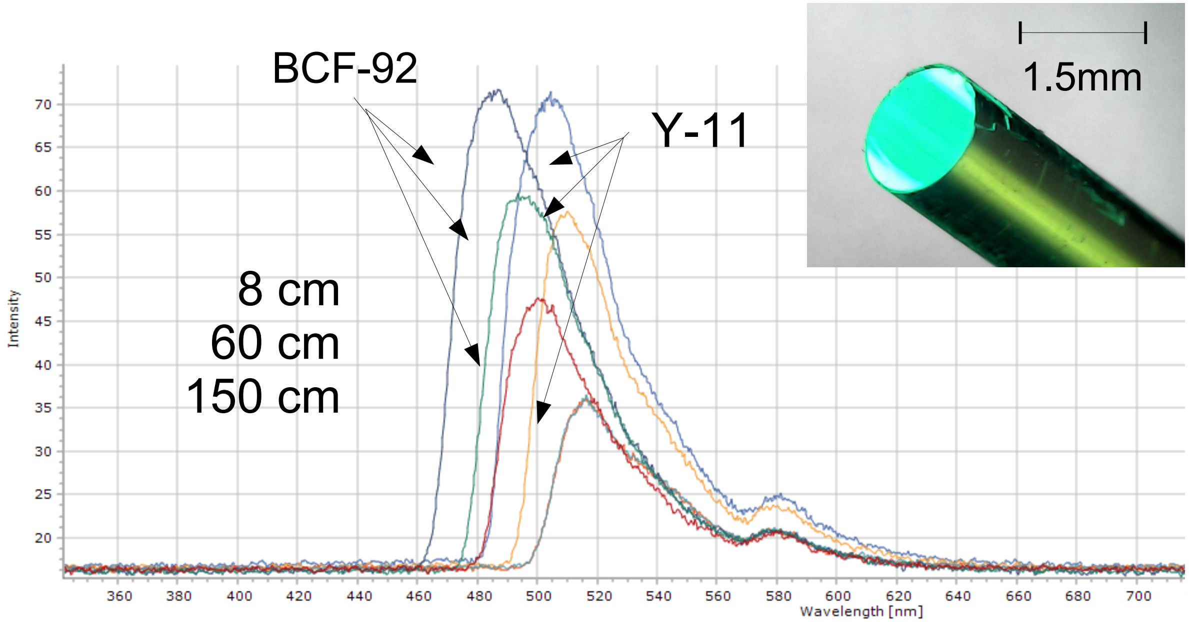
- TiO_2 reflective coating co-extruded
- Various profiles can be extruded, with hole(s) for inserting WLSF

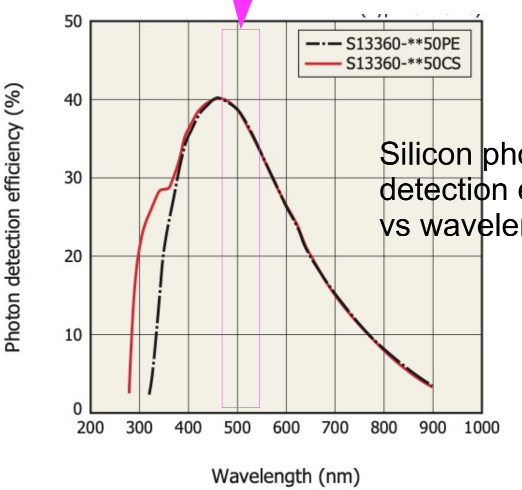
Wavelength Shifting Fiber

Plastic optical fiber with core doped with fluor(s)

- Blue – green WLSF to match spectrum of extruded scintillator light
- Challenge for MATHUSLA is to ensure sufficient light reaches the photo-detectors to achieve target timing resolution





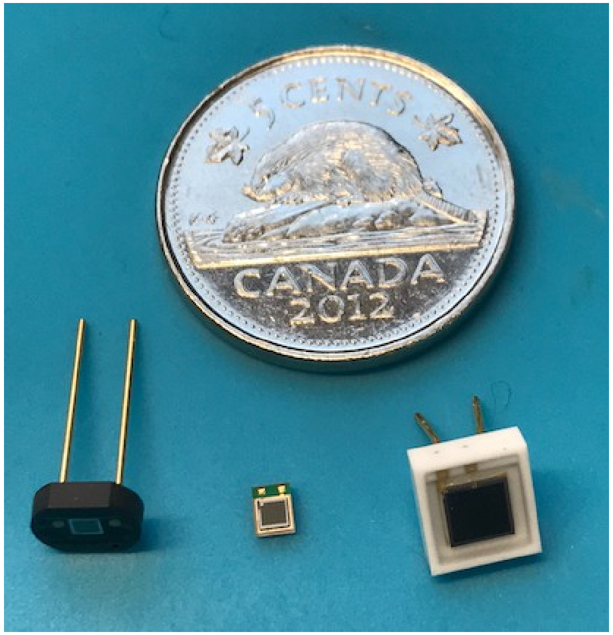


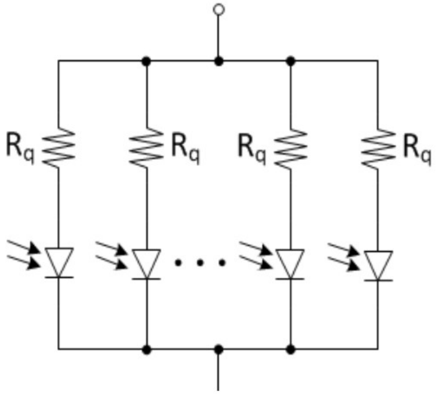
Silicon photomultiplier detection efficiency vs wavelength

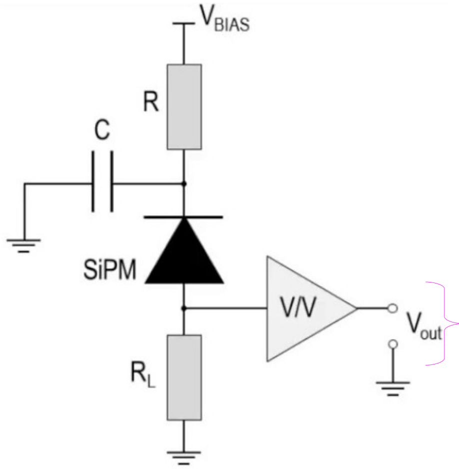
Silicon Photomultipliers

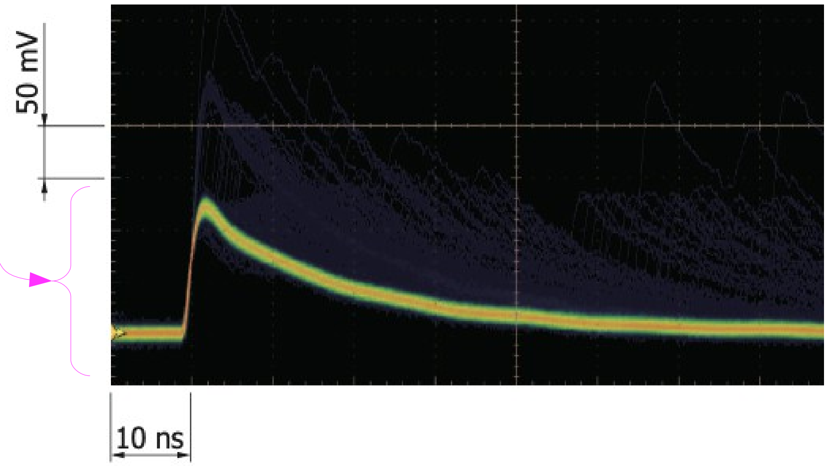
WLSF light measured by SiPMs mounted at thh fiber ends

- basically, a large array of photodiodes connected in parallel and operated just above the breakdown voltage
- each photodiode (or "pixel") produces a current pulse in response to an incident photon
- **resulting signal is proportional to number of incident photons**





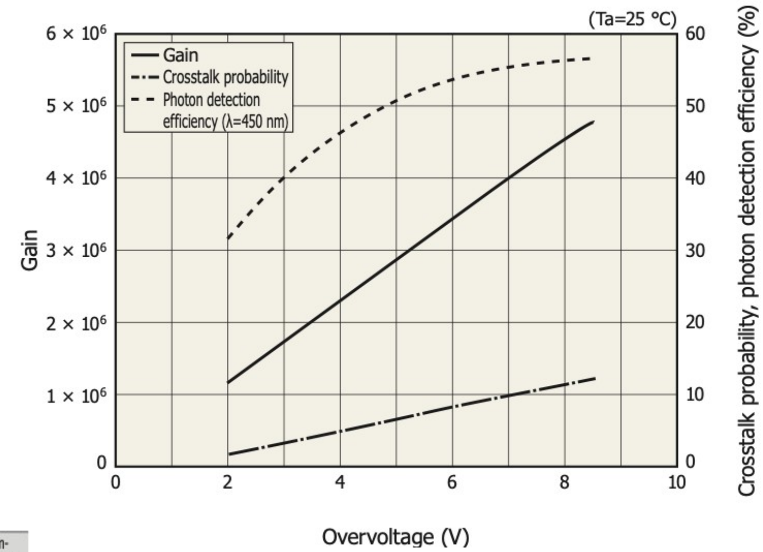




However, output signals are typically shaped and amplified to optimize for specific application, e.g. for fast timing

Silicon Photomultipliers

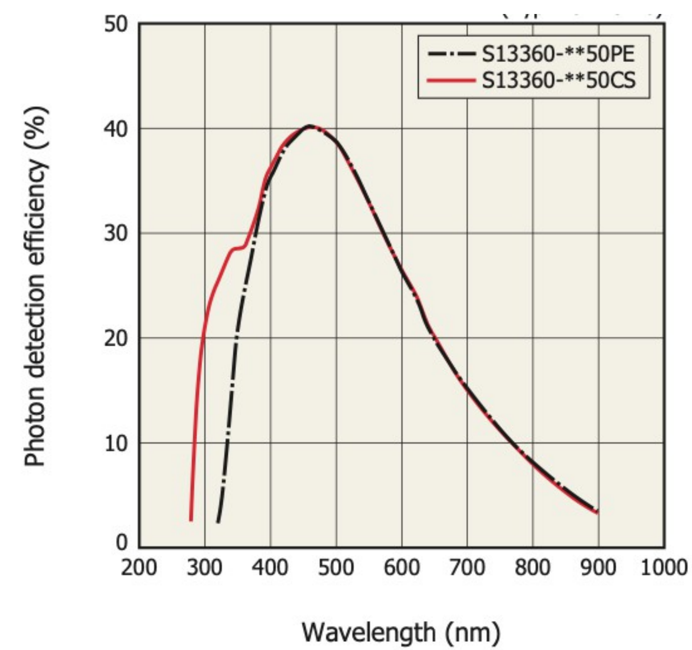
- Very large gain, adjustable via bias voltage, but also very sensitive to device temperature
- Spontaneous pixel breakdown results in dark noise (or dark current)
- Photon detection efficiency (PDE) depends on both quantum efficiency and geometric properties of device



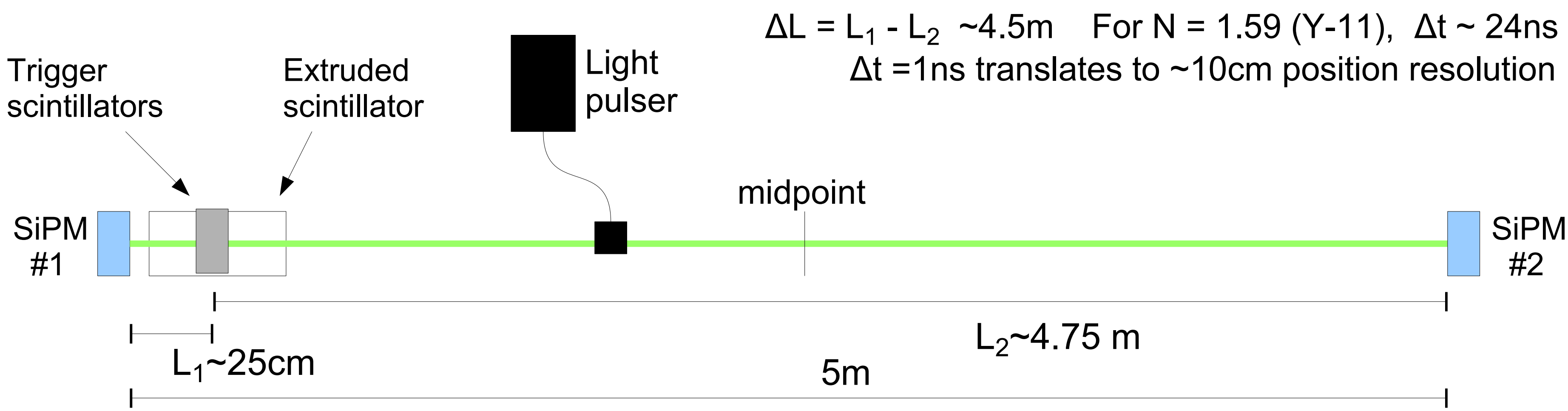
Type no.	Measurement conditions	Spectral response range λ (nm)	Peak sensitivity wavelength λp (nm)	Photon detection efficiency PDE*4 λ=λp (%)	Dark count*5 Typ. (kcps)	Dark count*5 Max. (kcps)	Terminal capacitance Ct (pF)	Gain M	Breakdown voltage V_{BR} (V)	Crosstalk probability (%)	Recommended operating voltage Vop (V)	Temperature coefficient at recommended operating voltage ΔTVop (mV/°C)
S13360-1325CS	Vover =5 V	270 to 900	450	25	70	210	60	7.0×10^5	53 ± 5	1	V_{BR} + 5	54
S13360-1325PE		320 to 900										
S13360-3025CS		270 to 900			400	1200	320					
S13360-3025PE		320 to 900										
S13360-6025CS		270 to 900			1600	5000	1280					
S13360-6025PE		320 to 900										
S13360-1350CS	Vover =3 V	270 to 900		40	90	270	60	1.7×10^6		3	V_{BR} + 3	
S13360-1350PE		320 to 900										
S13360-3050CS		270 to 900			500	1500	320					
S13360-3050PE		320 to 900										
S13360-6050CS		270 to 900			2000	6000	1280					
S13360-6050PE		320 to 900										
S13360-1375CS	Vover =3 V	270 to 900		50	90	270	60	4.0×10^6		7	V_{BR} + 3	
S13360-1375PE		320 to 900										
S13360-3075CS		270 to 900			500	1500	320					
S13360-3075PE		320 to 900										
S13360-6075CS		270 to 900			2000	6000	1280					
S13360-6075PE		320 to 900										

*4: Photon detection efficiency does not include crosstalk or afterpulses.
*5: Threshold=0.5 p.e.
Note: The above characteristics were measured at the operating voltage that yields the listed gain. (See the data attached to each product.)

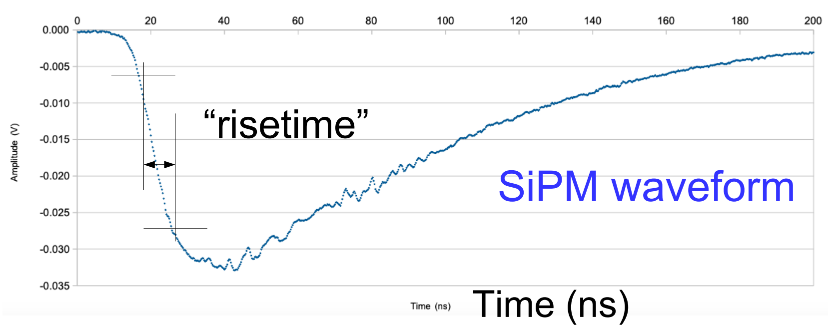
increasing pixel size

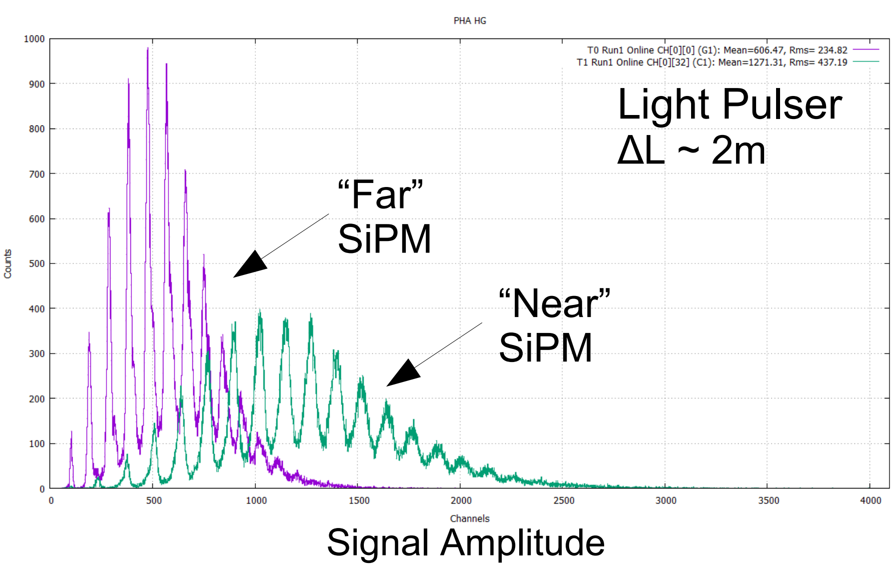


Characterization measurements



- SiPM waveforms, signal amplitudes and timing characteristics can be measured based on either cosmic rays or light pulser signals
- For MIP signals (cosmics ray muons), SiPM **signals in the range of ~10 – 50 PE**



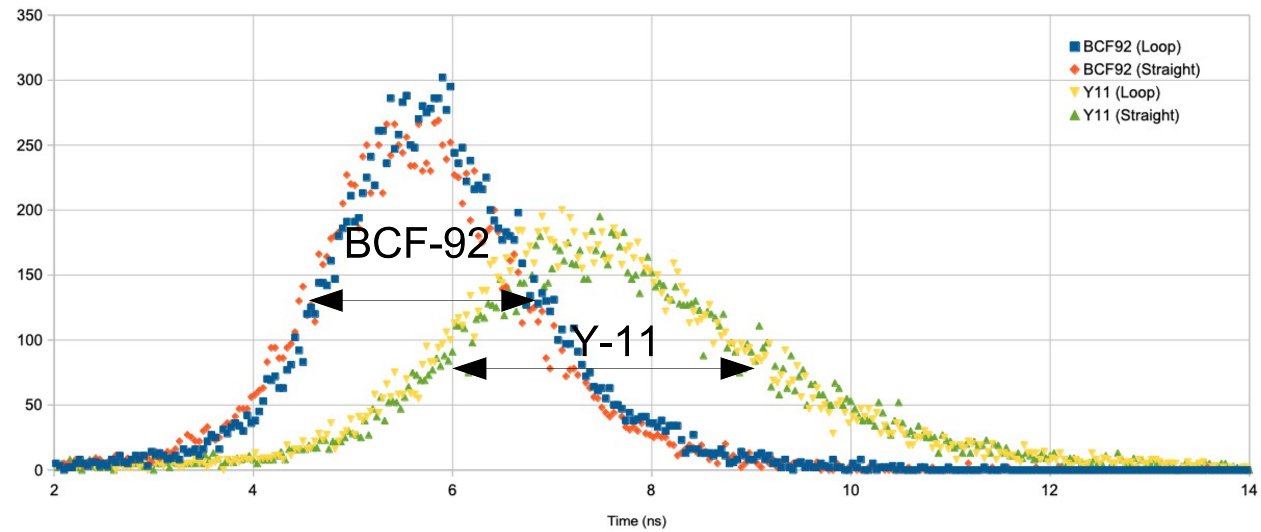


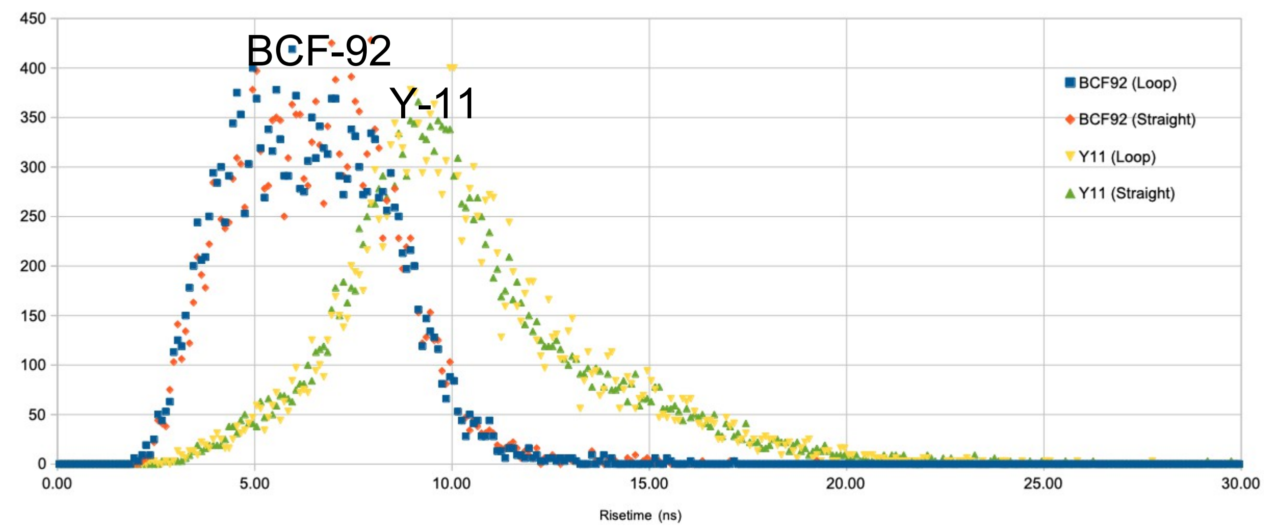
Timing resolution

Fiber bending test:

- Straight fiber
- Loop (~12cm diameter)
- total bending is worse than MATHUSLA detector

→ bending does not cause a measurable impact on timing

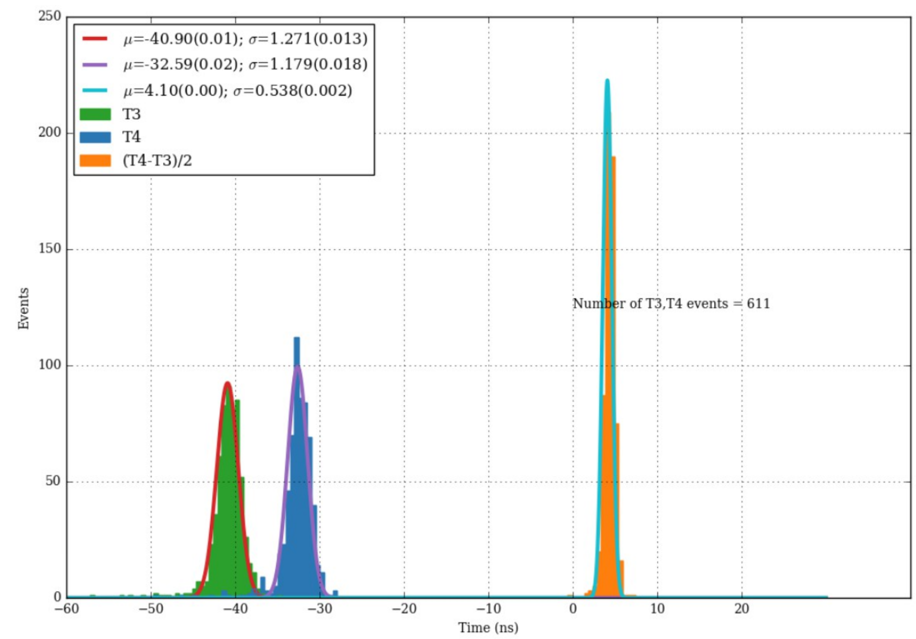


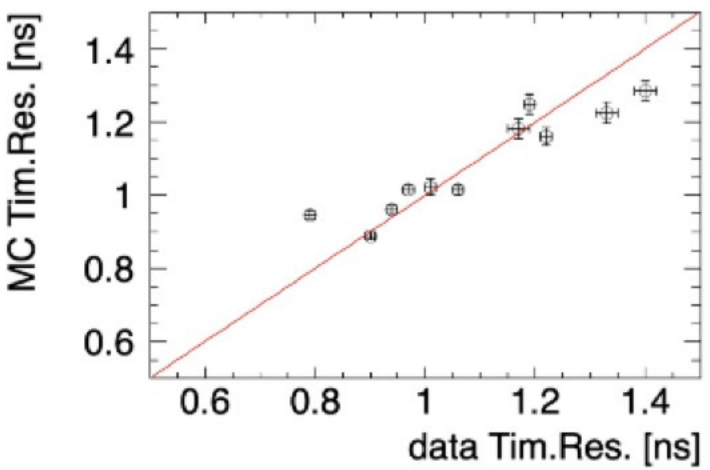


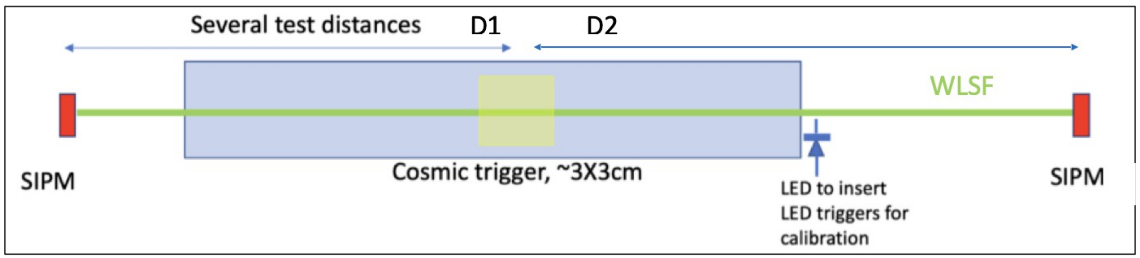
Timing resolution

- FNAL group has recently tested other proprietary formulations from Saint Gobain and Kuraray which appear to yield adequate light yield and sub-ns timing
- this work is still in progress

Chin Lung Tan (University of Rochester (US)),
Jim Freeman (Fermi National Accelerator Lab. (US)

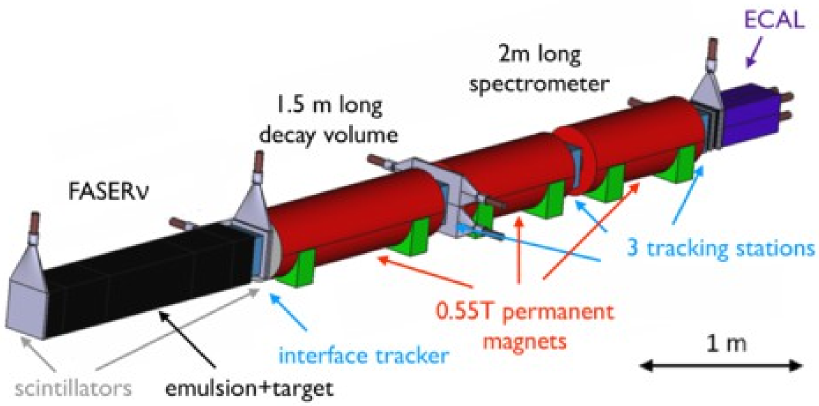




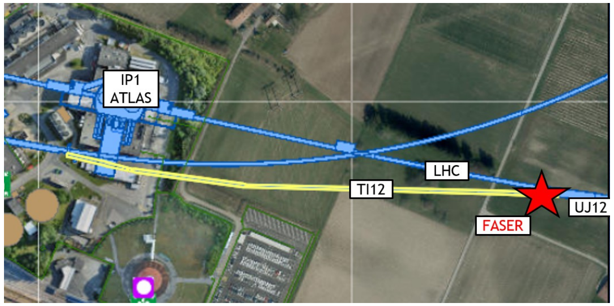


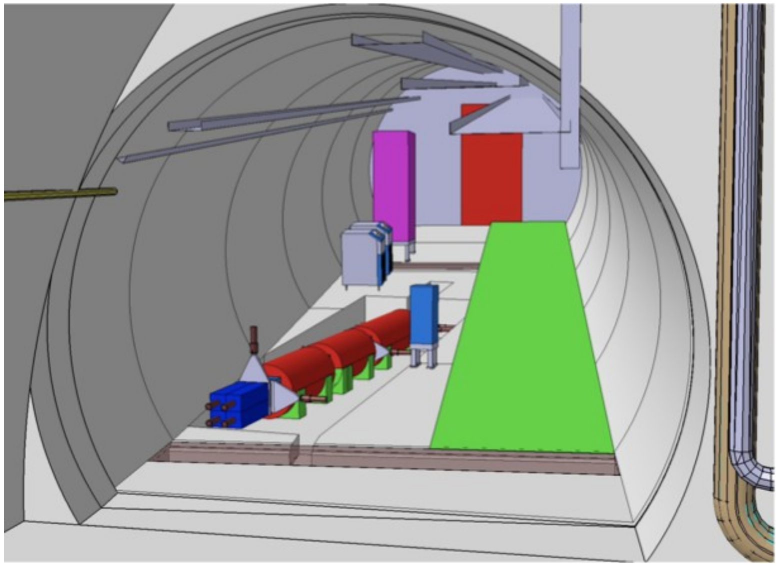
Timing measurement for a 5m long f ber through a 1X4cm extrusion. This location is at 250cm along the f ber, equidistant from the 2 SIPMs.
Time distributions (relative to the cosmic trigger start time) are shown for the 2 SIPM channels (Chan 3, Chan 4). Also shown is the difference, (T4-T3)/2.
We note this difference divided by 2 is our f gure of merit for timing. The factor of 2 comes from the observation that different points along the f ber separated by delta have a +delta increase in distance from one SIPM, and a -delta decrease in distance from the other. The timing resolution of 0.538ns corresponds to about 9cm rms position resolution, well within MATHUSLA requirement.

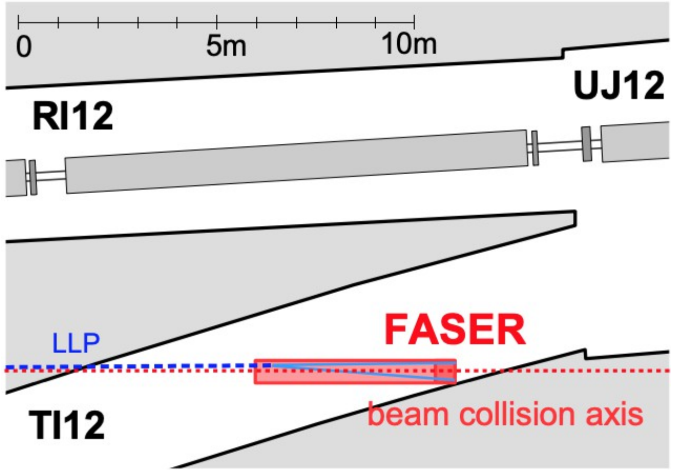
FASER

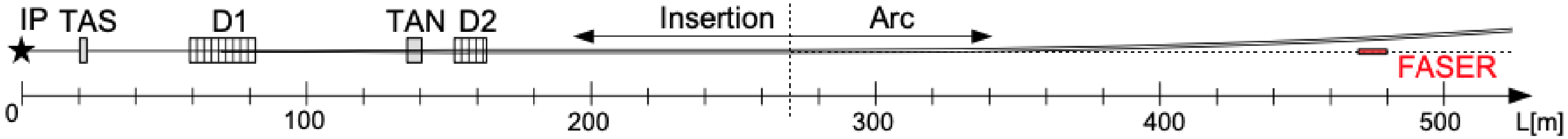


https://home.cern/science/experiments/faser

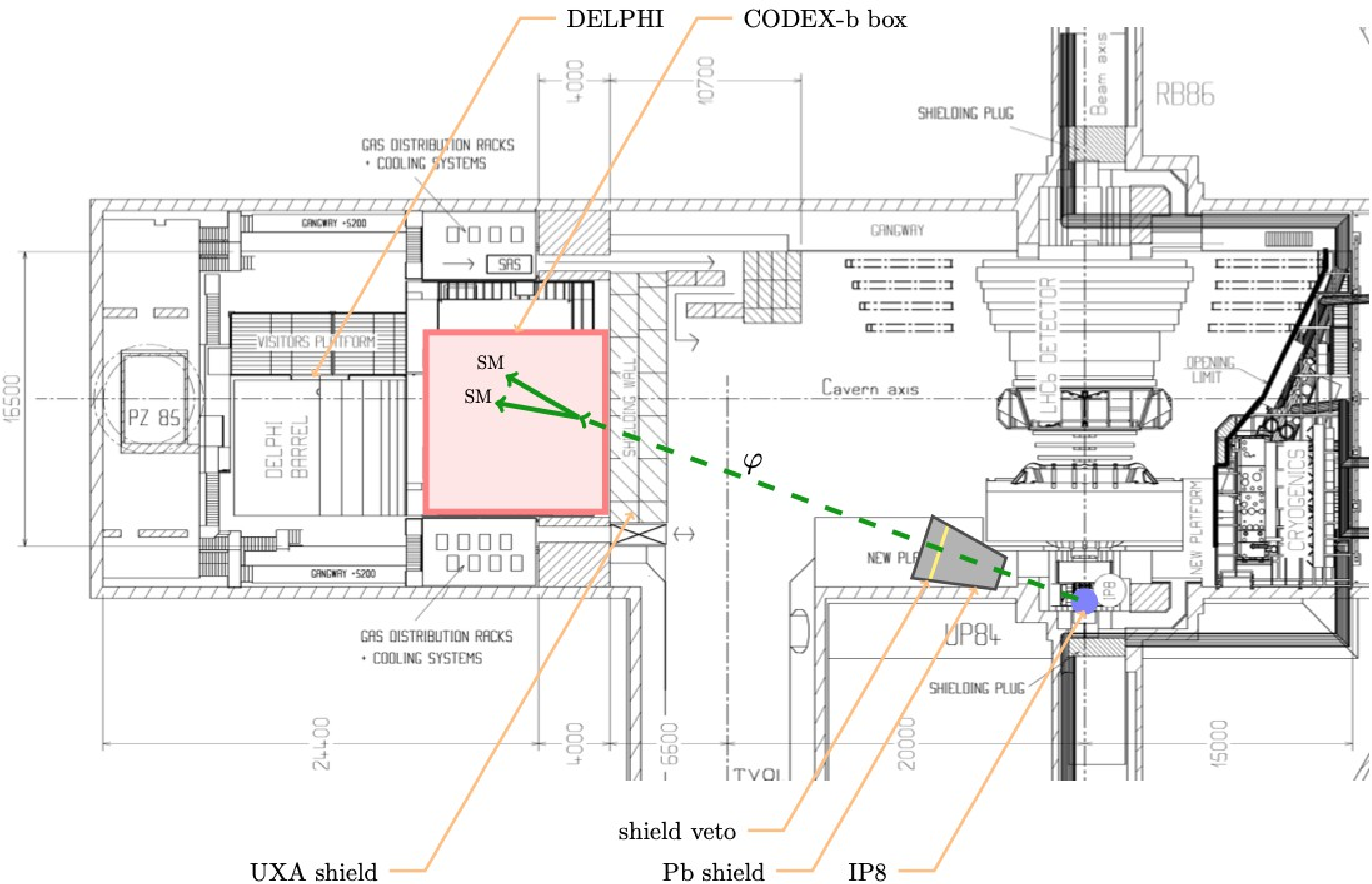






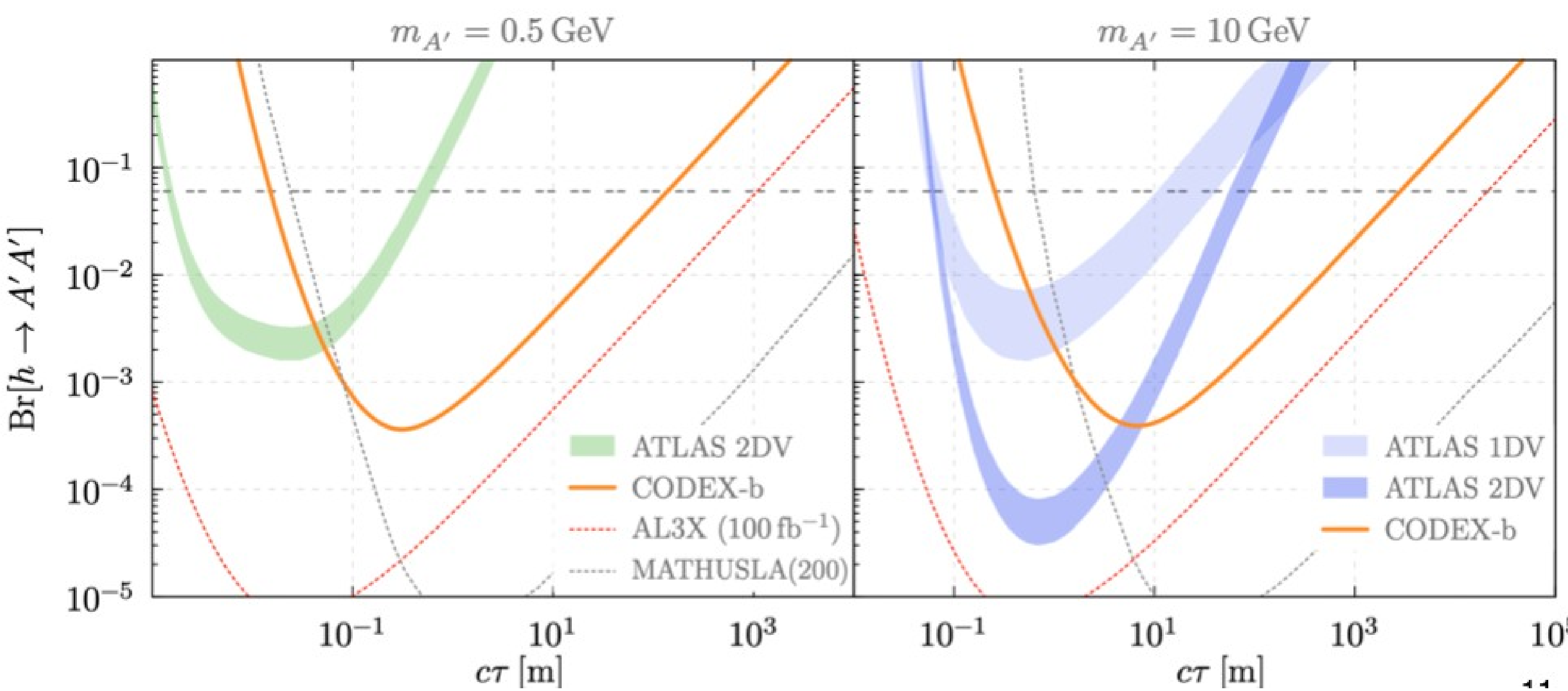


CODEX-b


DELPHI
CODEX-b box
SM
SM
UXA shield
shield veto
Pb shield
IP8
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
VISITORS PLATFORM
DELPHI BARREL
PZ 85
SHIELDING WALL
Cavern axis
LHCb DETECTOR
SHIELDING PLUG
RB86
Beam axis
GANGWAY
OPENING LIMIT
CRYOGENICS
NEW PLATFORM
UP84
4000
10700
16500
2400
6600
20000
15000

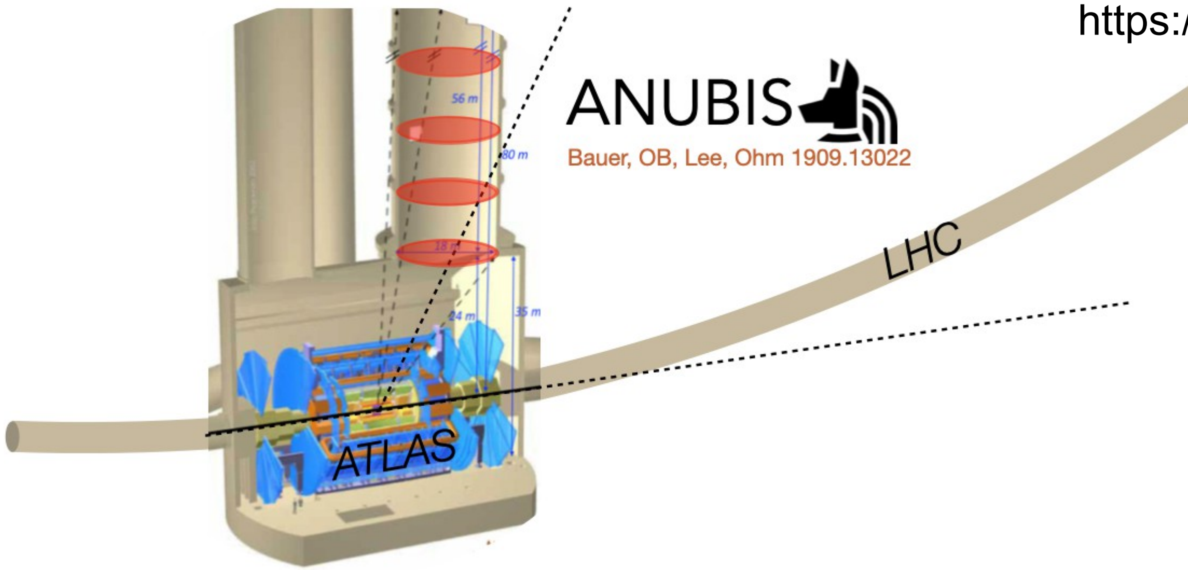
CODEX-b

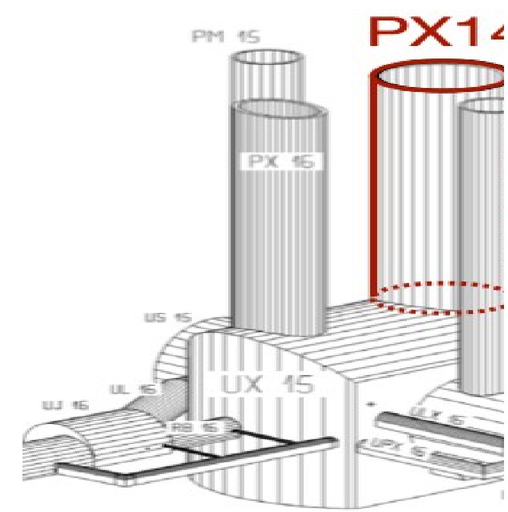
MATHUSLA update 2009.01693
CODEX-b EOI 1911.00481
Hirsch, Wang 2001.04750

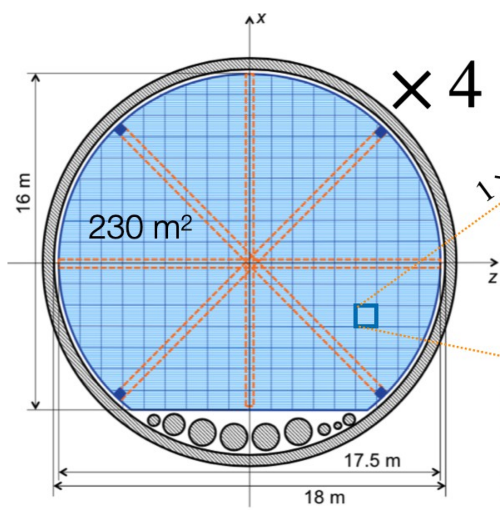


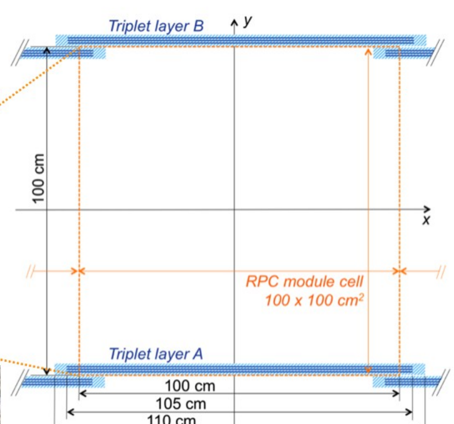
ANUBIS

https://twiki.cern.ch/twiki/bin/view/ANUBIS/









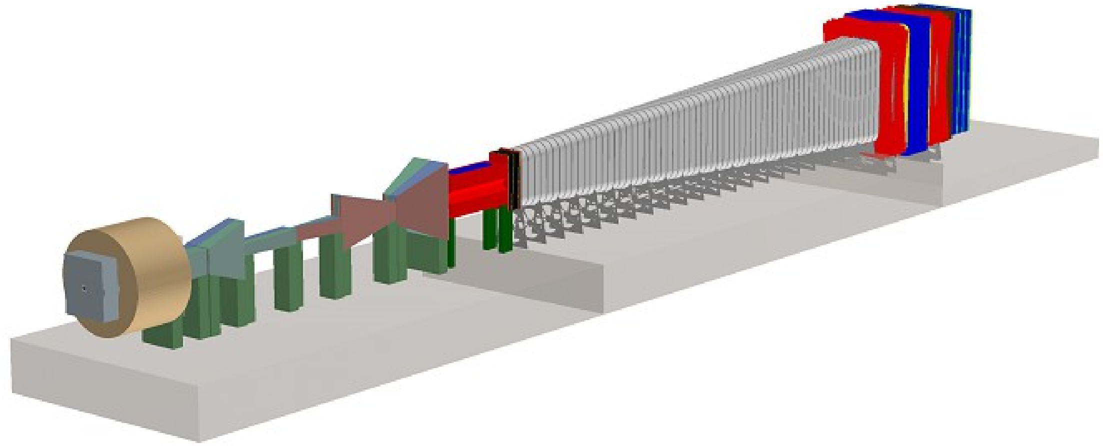
Tracking stations affixed with cams: extract tracking stations to surface quickly & easily in an emergency

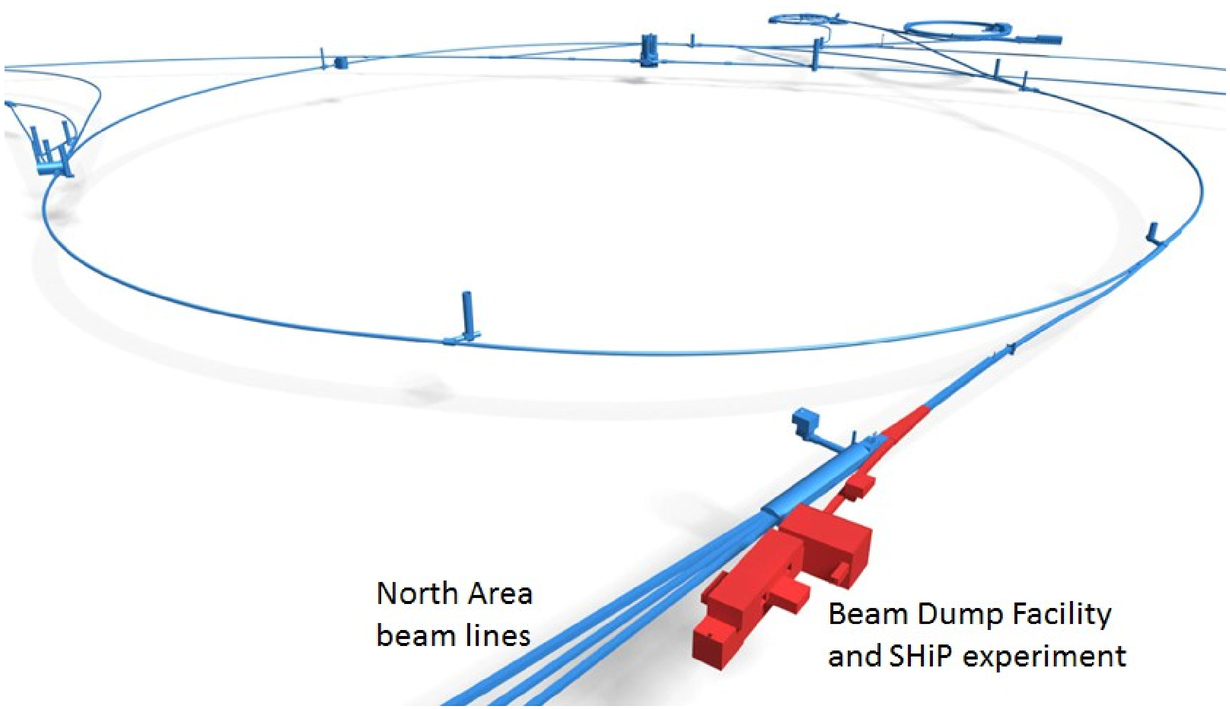
Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$

Removable array of detector planes proposed to be inserted into PX14 vertical shaft in the ATLAS experimental area

SHiP

SHiP is a proposed general-purpose experiment to be installed in a beam dump facility at the SPS



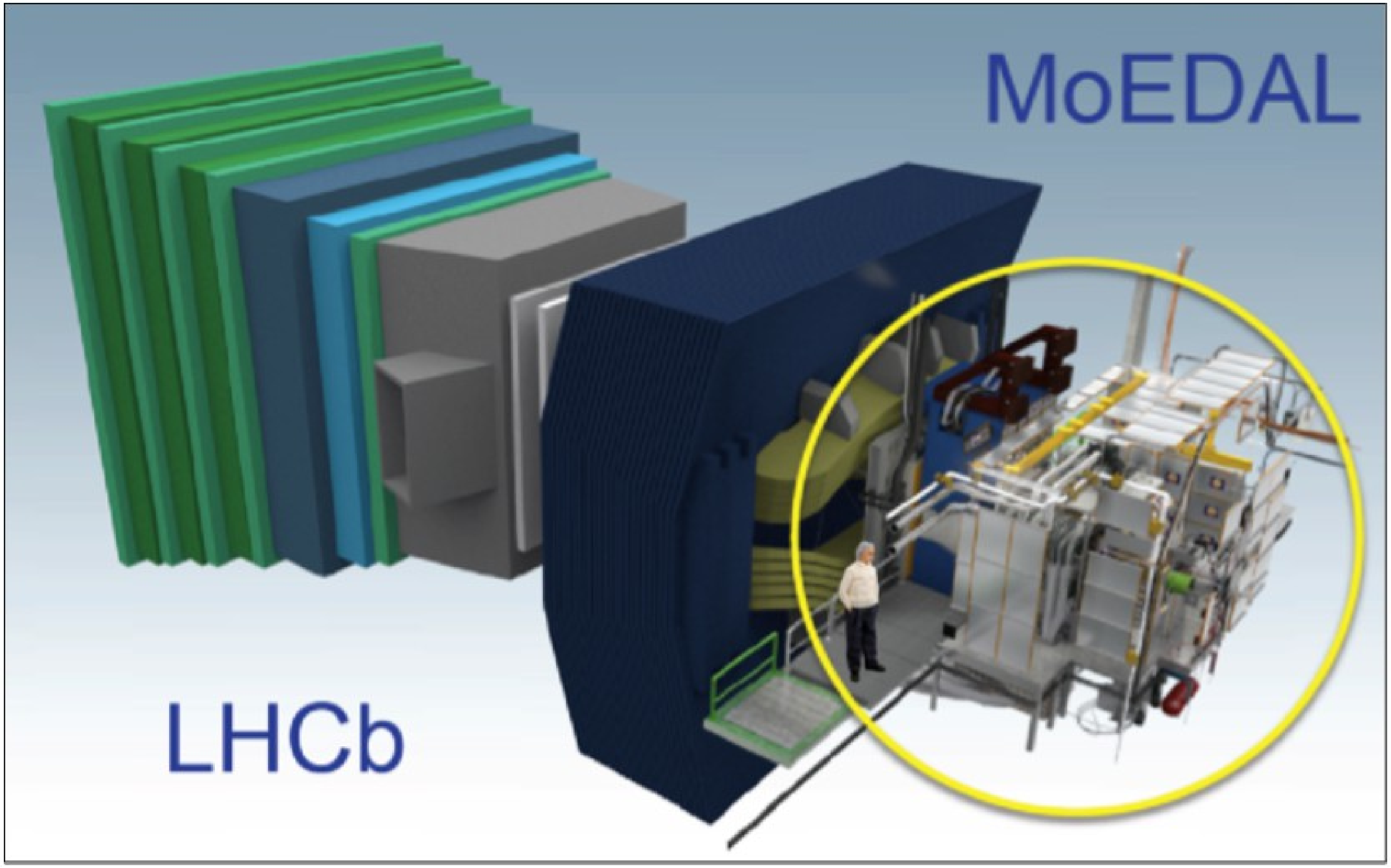


SHiP
Search for Hidden Particles

https://ship.web.cern.ch/

MoEDAL

Monopole and Exotics Detector at the LHC



MoEDAL shares the cavern at Point 8 with LHCb, and its prime goal is to directly search for the magnetic monopole (MM) or dyon and other highly ionizing stable massive particles (SMPs) and pseudo-stable massive particles via the Schwinger effect. To detect these particles, the project uses nuclear track detectors (NTDs), which suffer characteristic damage due to highly ionizing particles. As MMs and SMPs are highly ionizing, NTDs are perfectly suited for the purpose of detection.

milliQan

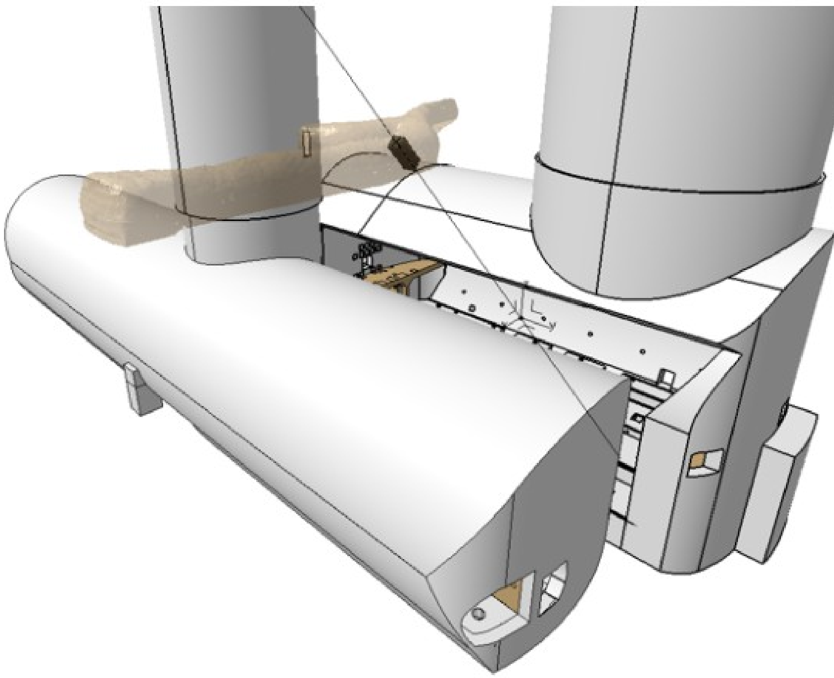


Figure 5.44: A 3D model showing the optimal position of milliQan within the PX56 Drainage and Observation gallery located above CMS UXC.

1/100th scale milliQan demonstrator installed in 2000

Dark sectors?

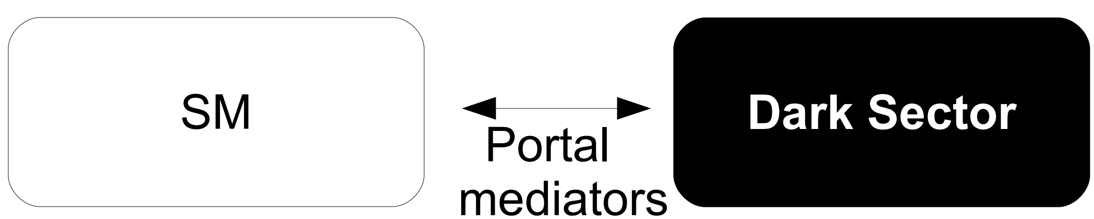
Maybe dark matter is not specifically related to solution to problems of the SM and is, in effect, a distinct "sector"

- Dark sector fermions which carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.
- Effective Field Theory provides a number of "portals" to access this dark sector:

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal Higgs portal Neutrino portal

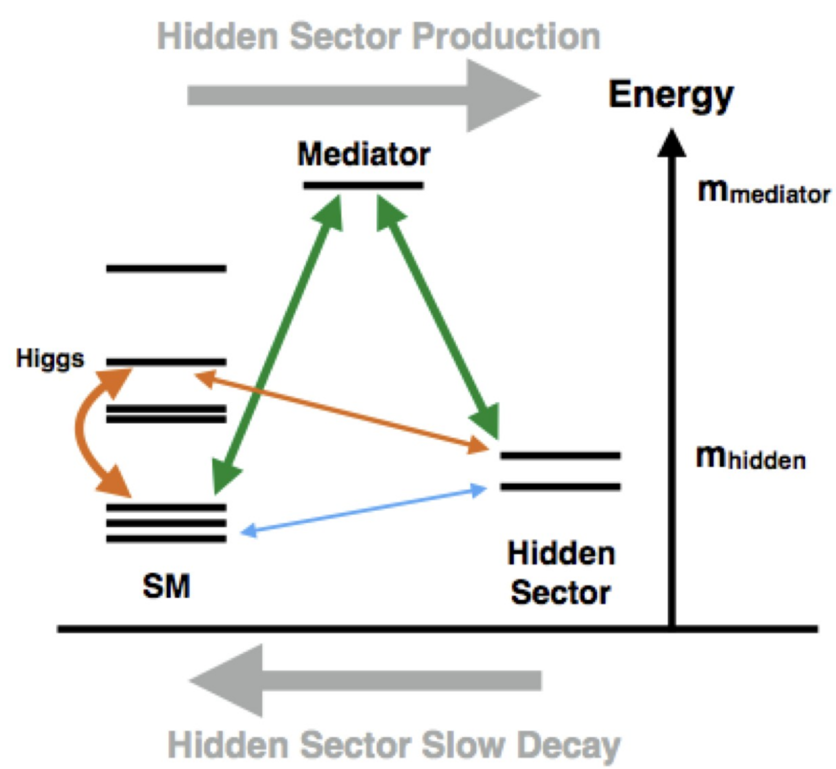


Dark sector can be probed via mixing of the portal mediators with SM bosons

Dark sectors?

Metastable dark (hidden) sector states can only decay to Standard Model particles via mediators with small couplings

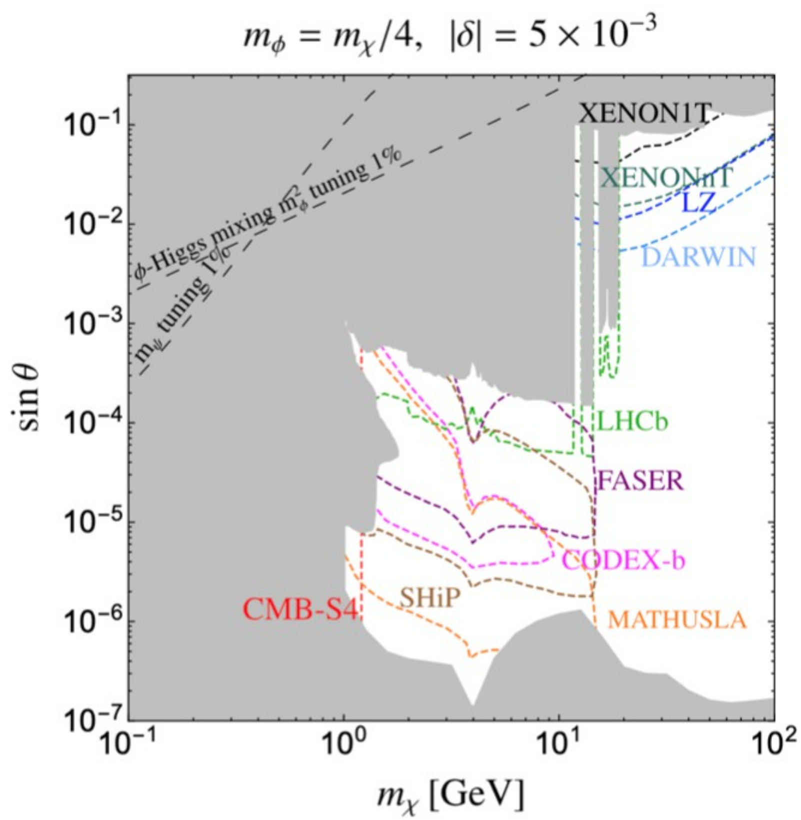
Consequently, they are long-lived...



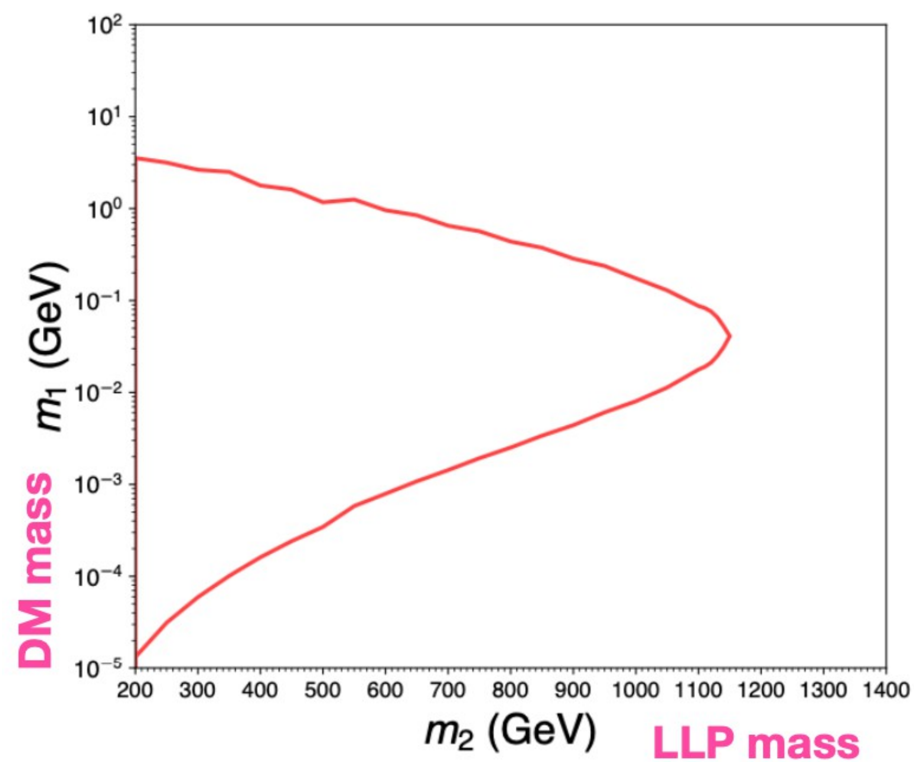
Dark Matter

In many Dark Matter scenarios, properties of LLP in primordial plasma control the DM abundance

- LLP searches can be best or ONLY way to discover DM

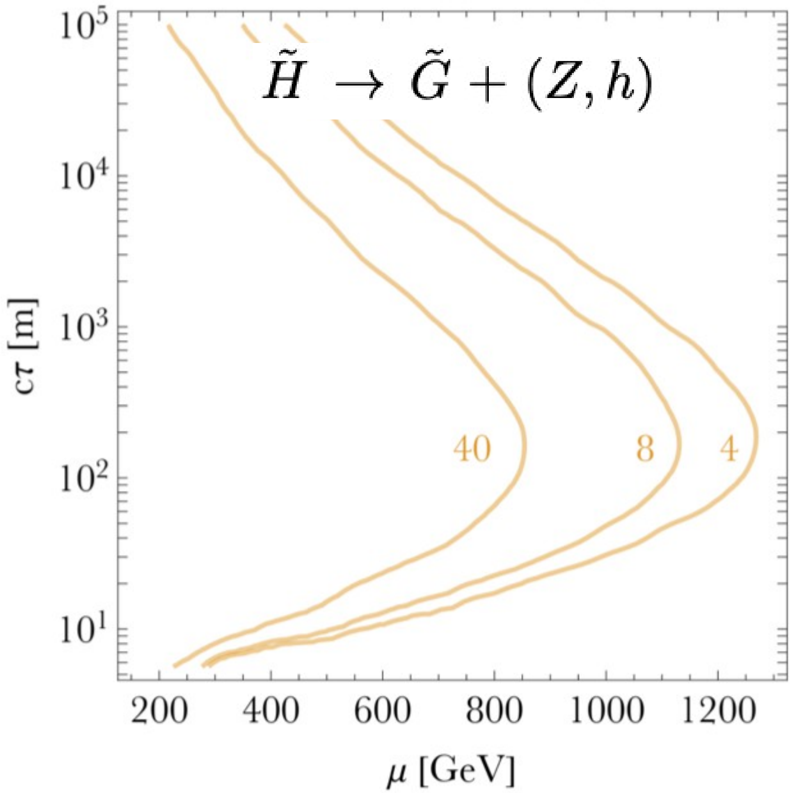


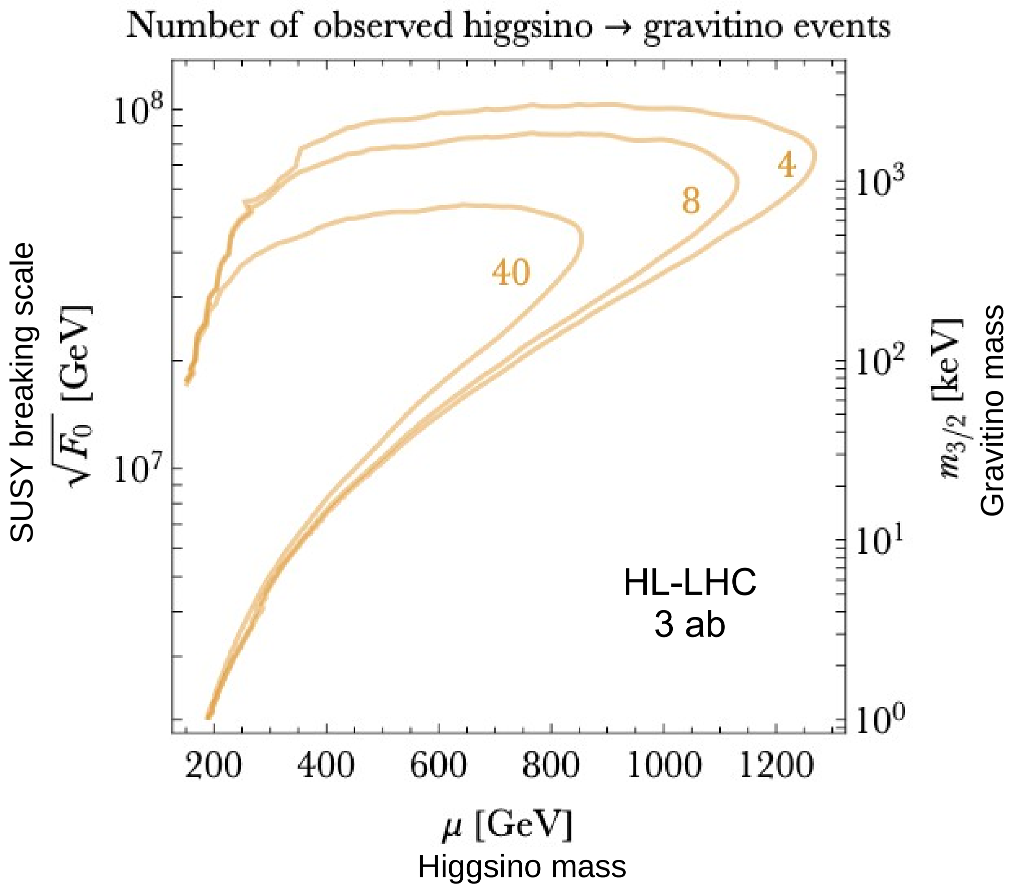
Inelastic DM model (1810.01879, Berlin, Kling) can be discovered via **SM+S LLP searches** at much lower mixing angles than direct detection experiments



MATHUSLA @ CMS reach for Freeze-In DM (1908.11387, No, Tunney, Zaldivar).

Higgsino to gravitino

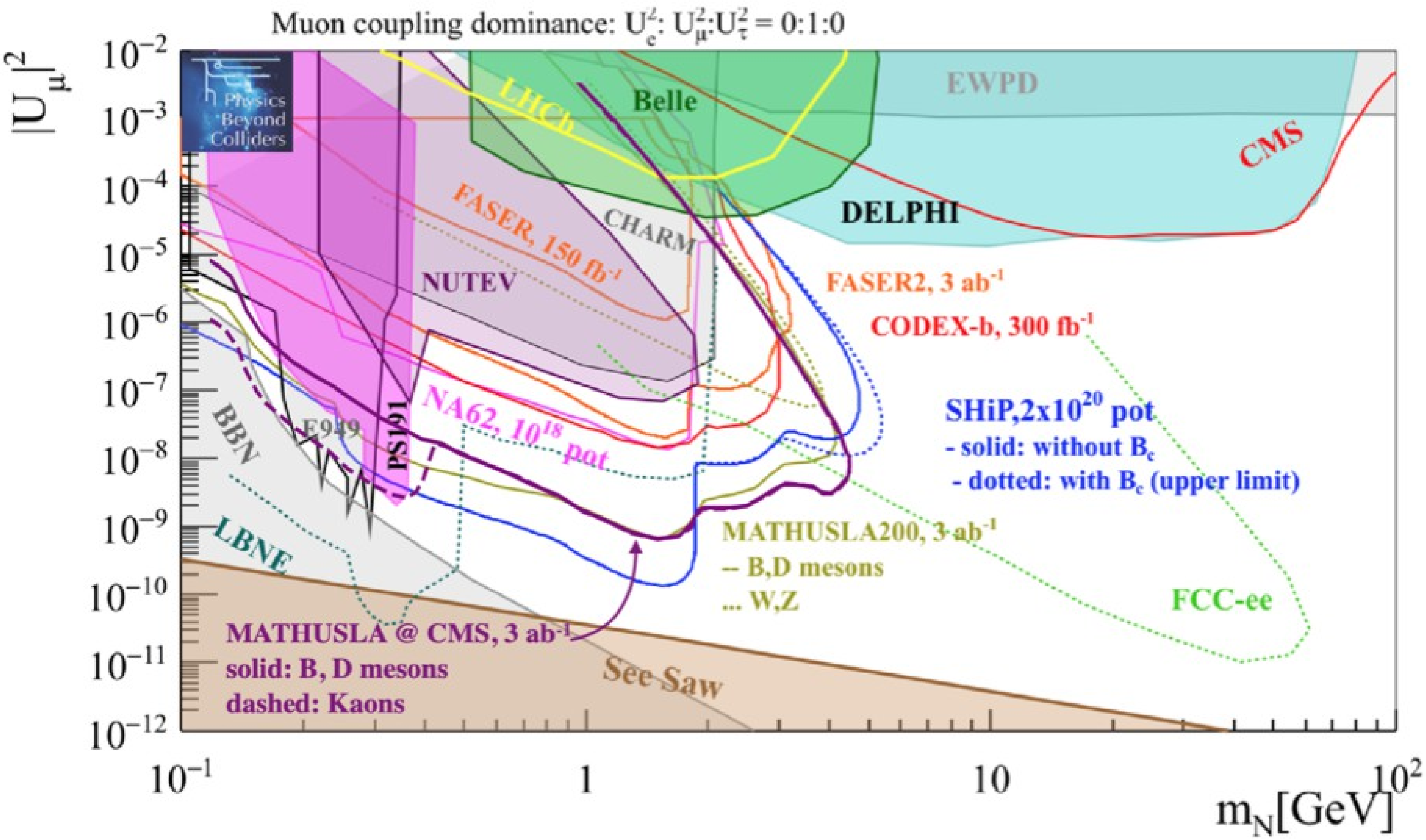




For higgsino lifetimes ranging from smaller than 10m to larger than 10^5 m, MATHUSLA could provide a discovery of new physics with electroweak cross-sections for which the HL-LHC would fail to discover new physics.

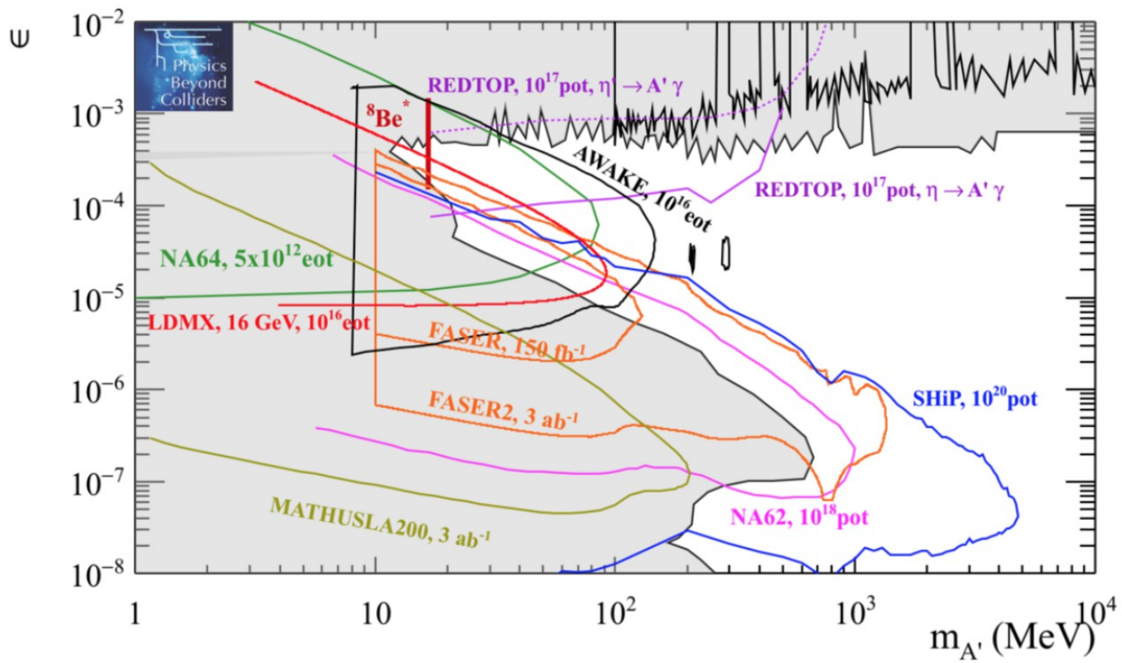
Sterile RH neutrinos

LoI update
2009.01693



Dark photon only

PBC BSM working group report 1901.09966



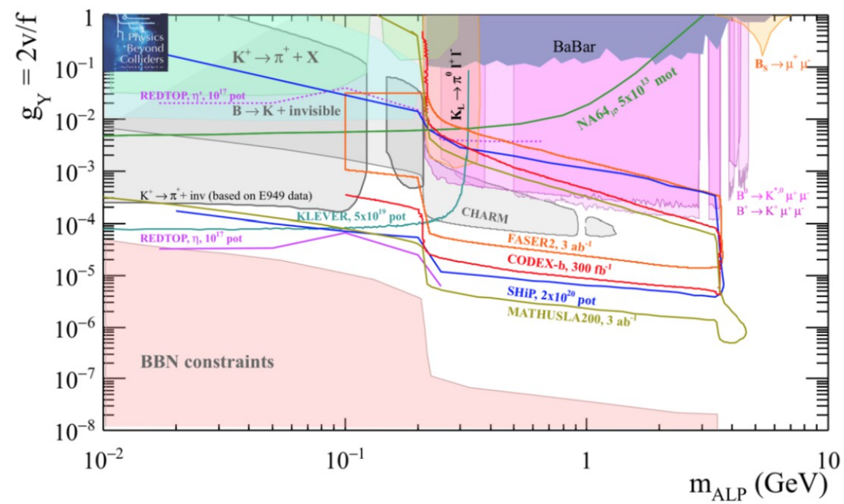
MATHUSLA sensitivity for dark photon signatures is not great, however this estimate neglects high rate of secondary production of dark photons in the main detector calorimeters etc.

- Exploits huge QCD rate at the LHC: approaches fixed-target-exp levels. Unique source of LLPs at the LHC only available to external detector

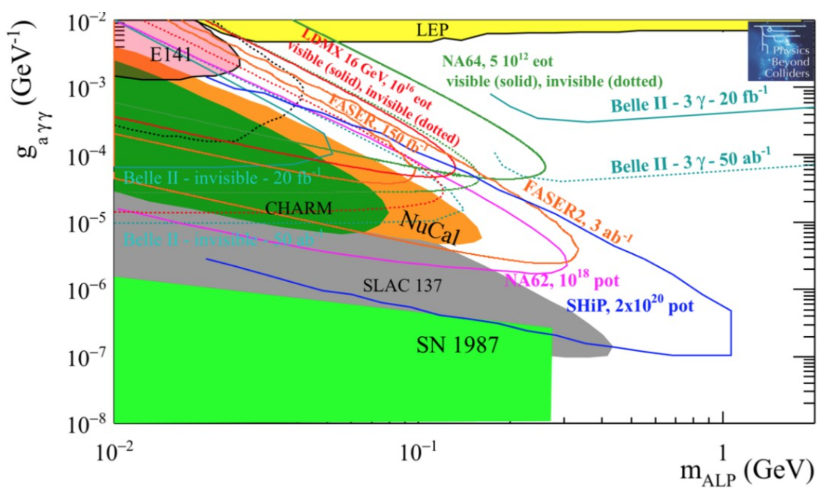
Axion-Like Particles

PBC BSM working group report 1901.09966

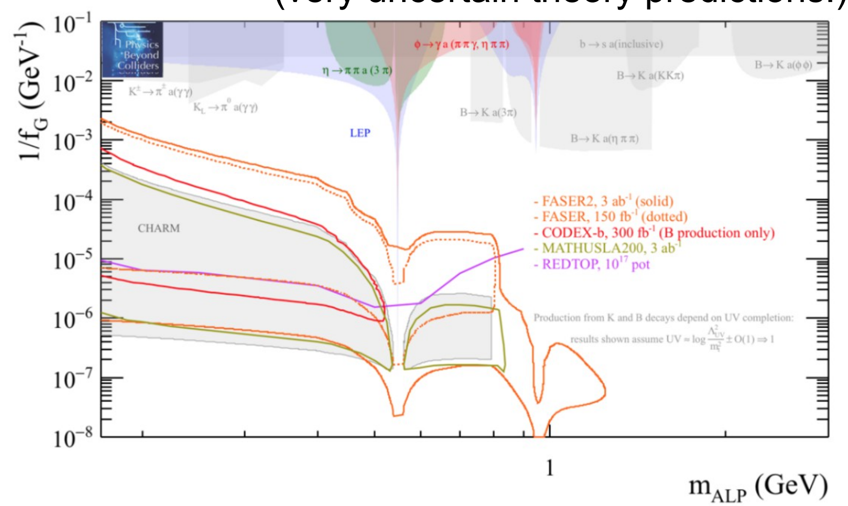
Pure fermion coupling



Pure photon coupling



Pure gluon coupling
(very uncertain theory predictions!)



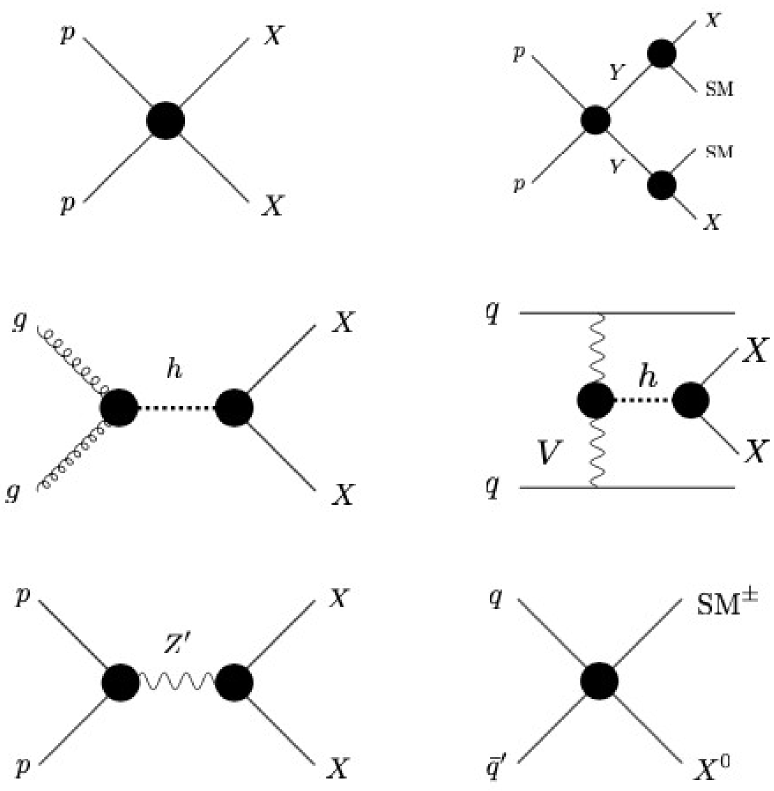


Figure 2.1: Schematic illustrations of LLP production modes in our simplified model framework. From top to bottom and left to right: direct pair production (DPP); heavy parent (HP); Higgs modes (HIG), including gluon fusion and VBF production (not shown here is VH production); heavy resonance (RES); charged current (CC).

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha\ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q}\to jX$ or gluino pair $\tilde{g}\to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell}\to \ell X$ or chargino pair, $\tilde{\chi}\to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h\to XX$ or $\to XX+\text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h\to X+\text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z')\to XX$ or $\to XX+\text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z')\to X+\text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W')\to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

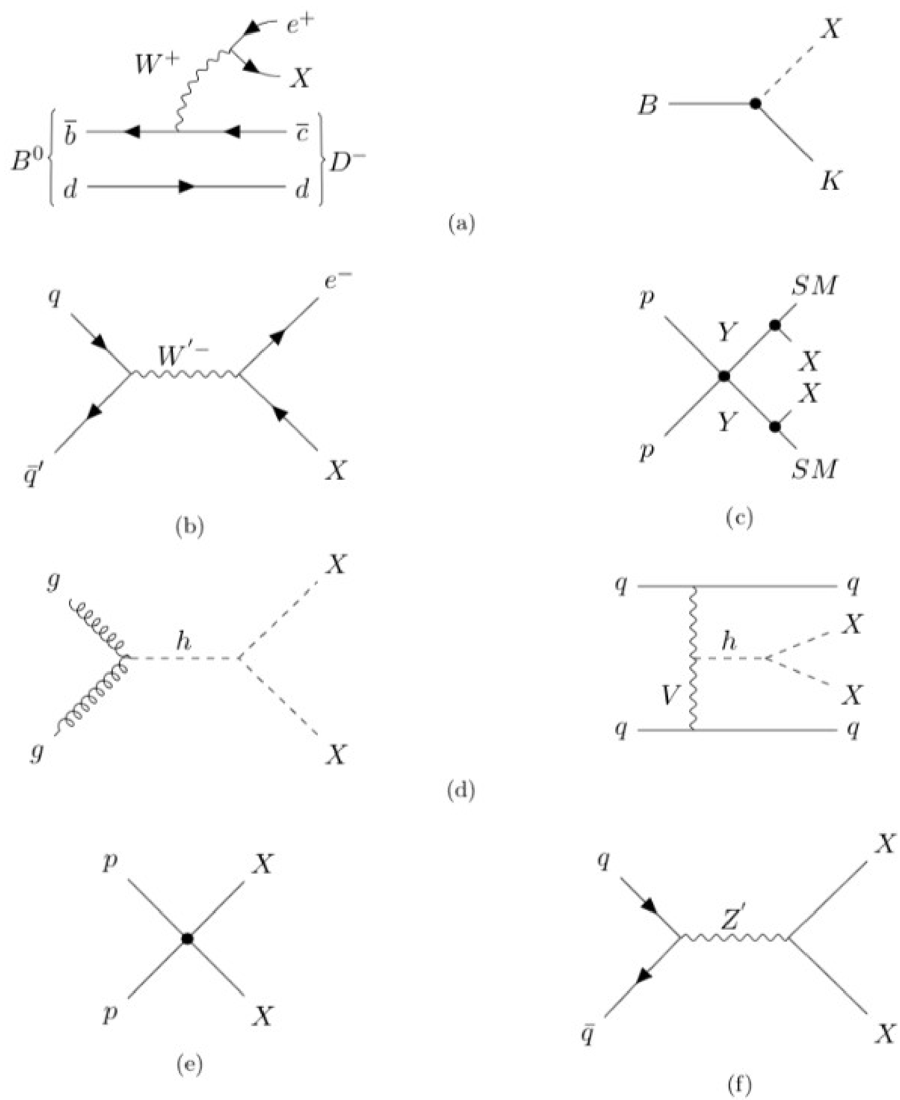
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

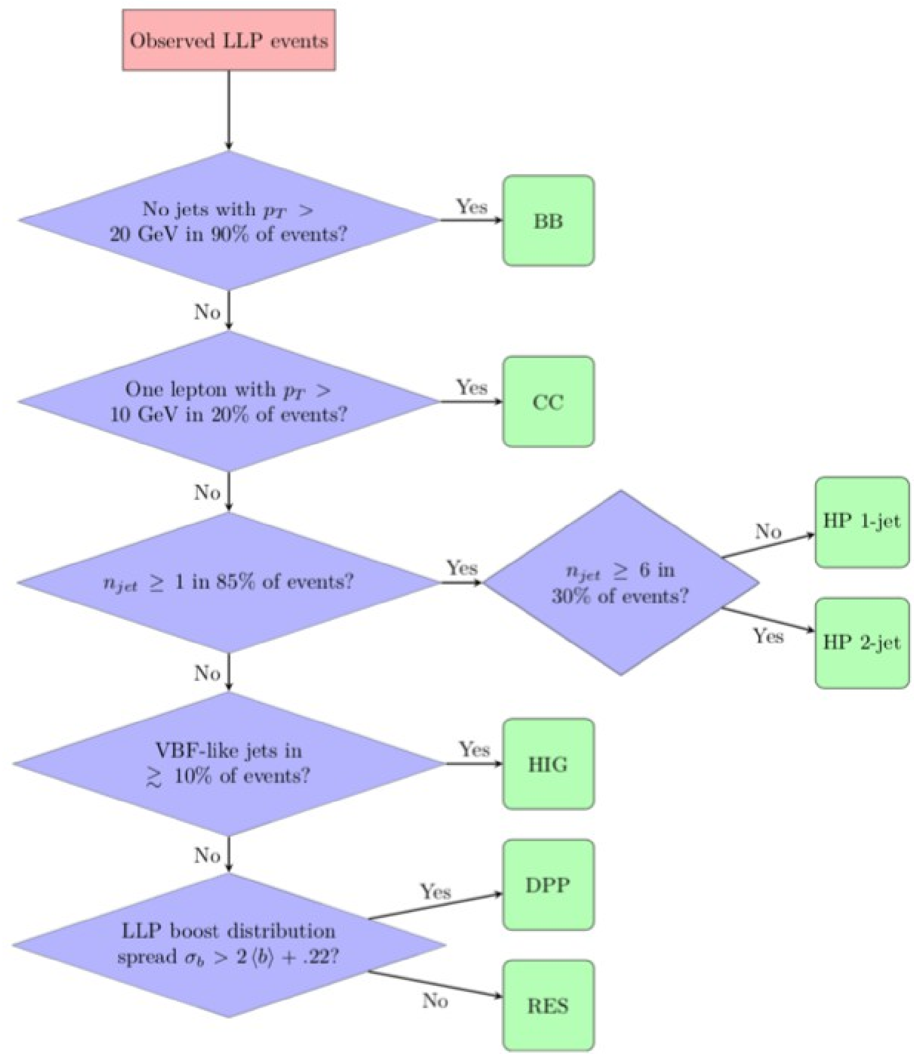
March 6, 2019

1903.04497

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly

2007.05538
Jared Barron and David Curtin

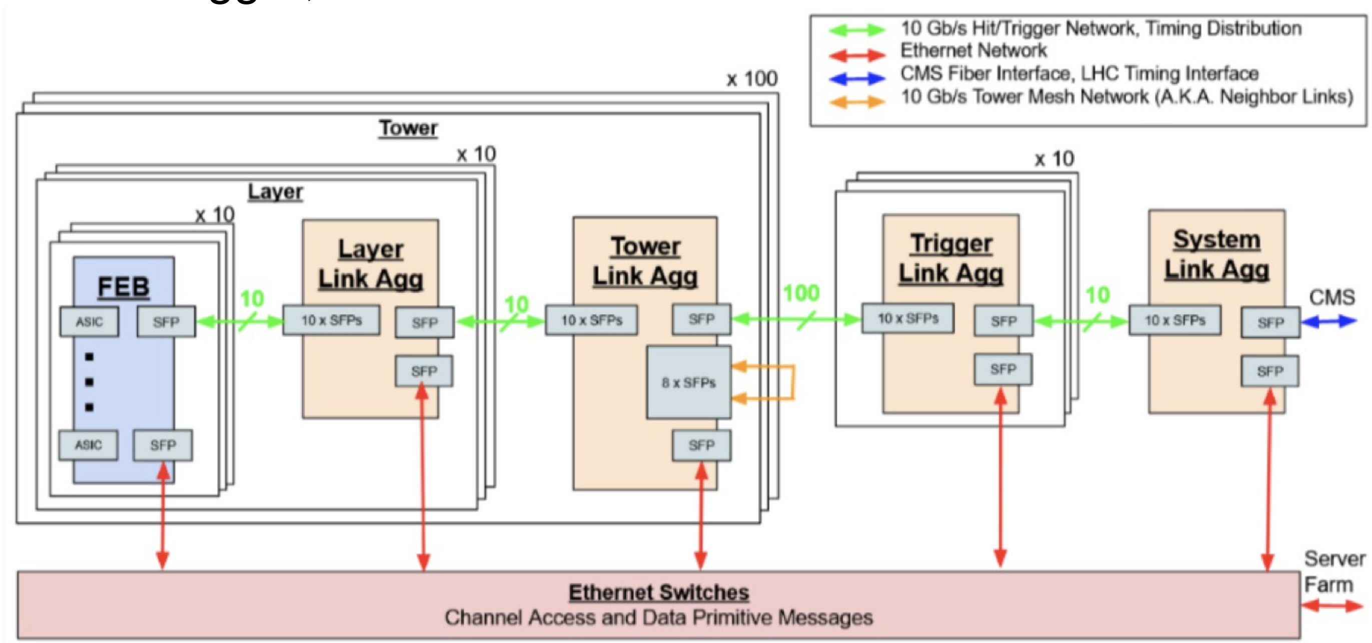




Trigger and DAQ

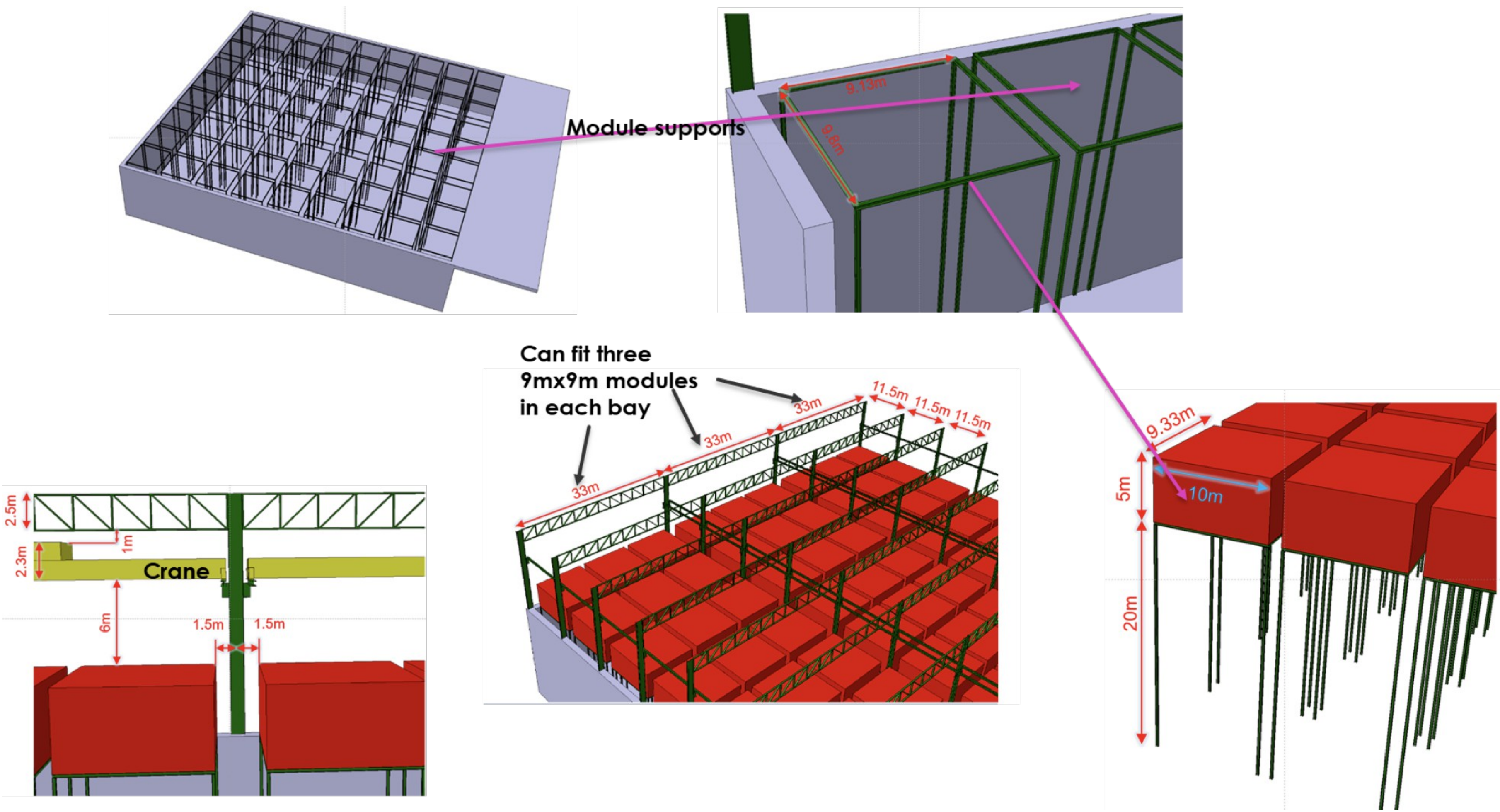
MATHUSLA trigger based on upward-going tracks within 3x3 tower volume

- vertex formed by upward-going tracks within fiducial volume is signal signature
- modular FEB design as well as link aggregation boards
- hits buffered for trigger; data rate is well within COTS servers



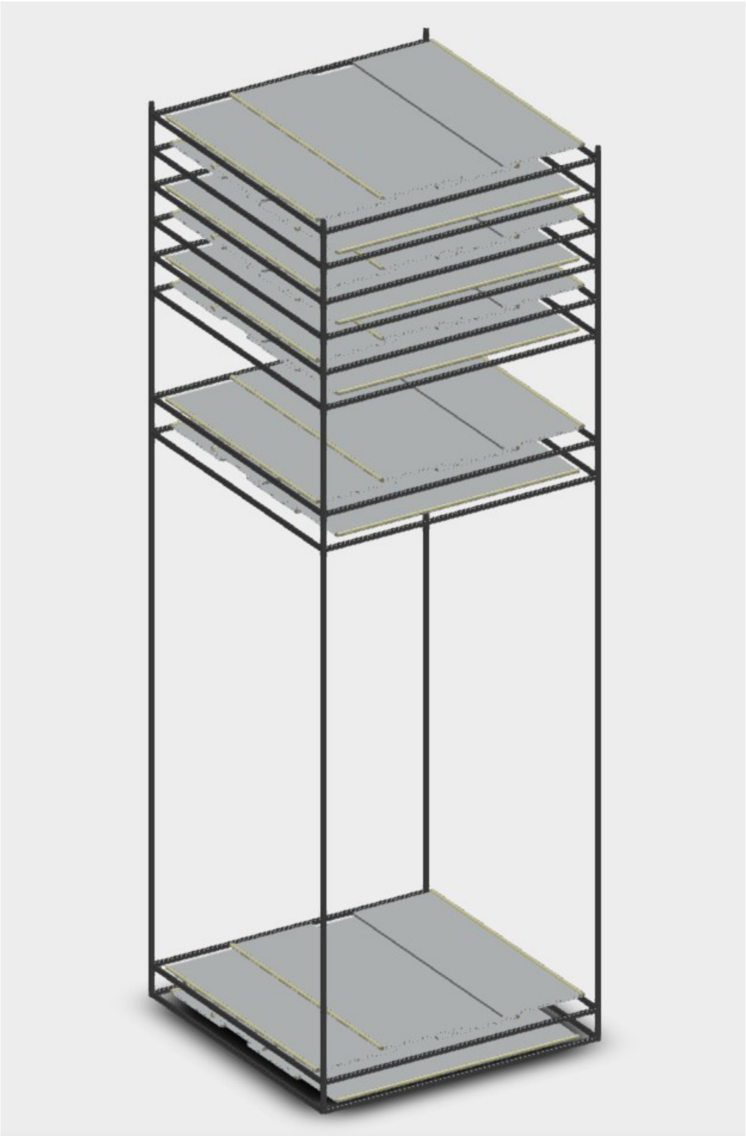
- triggered events written from buffer to permanent storage
- L1 trigger signal sent to CMS; latency estimates appear compatible with CMS L1 buffer

Larry Ruckman, JJ Russell, Charlie Young



Module supports
Can fit three
9mx9m modules
in each bay
33m
33m
33m
11.5m
11.5m
11.5m
2.5m
2.3m
1m
Crane
6m
1.5m
1.5m
9.33m
10m
5m
20m

Work is in progress towards the detailed layout of the detector



CAD by Rodney Schnarr (Carleton)