The MATHUSLA Experiment

Steven Robertson
Institute of Particle Physics, Canada
&
University of Alberta

42nd International Symposium on Physics in Collision

Arica, Chile
Oct 12, 2023

INSTITUTE OF PARTICLE PHYSICS

MATHUSLA

UNIVERSITY OF ALBERTA

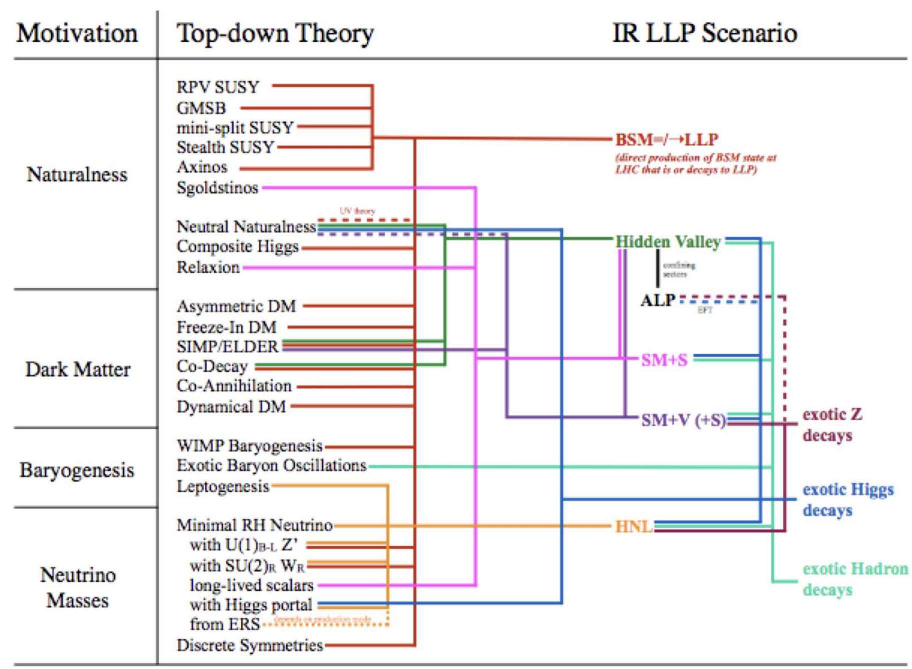
Long-lived particles

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

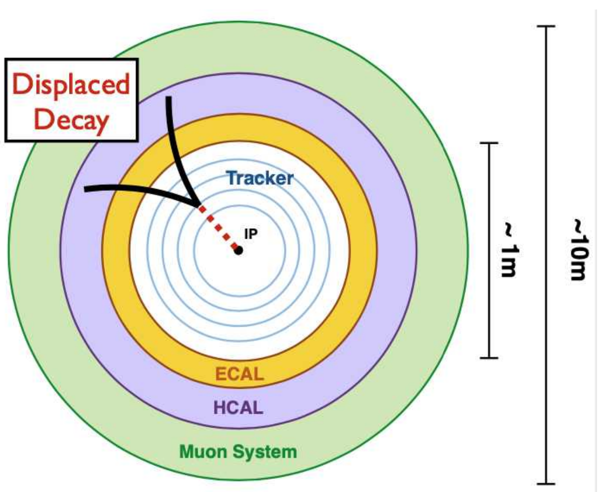
- Several examples exist already within the SM, e.g. muons $\tau_\mu \sim 2.2\ \mu s$
- Big Bang nucleosynthesis limit on long-lived new particles is ~0.1s ($c\tau \sim 10^7$ m)

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

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



Searching for LLPs



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

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

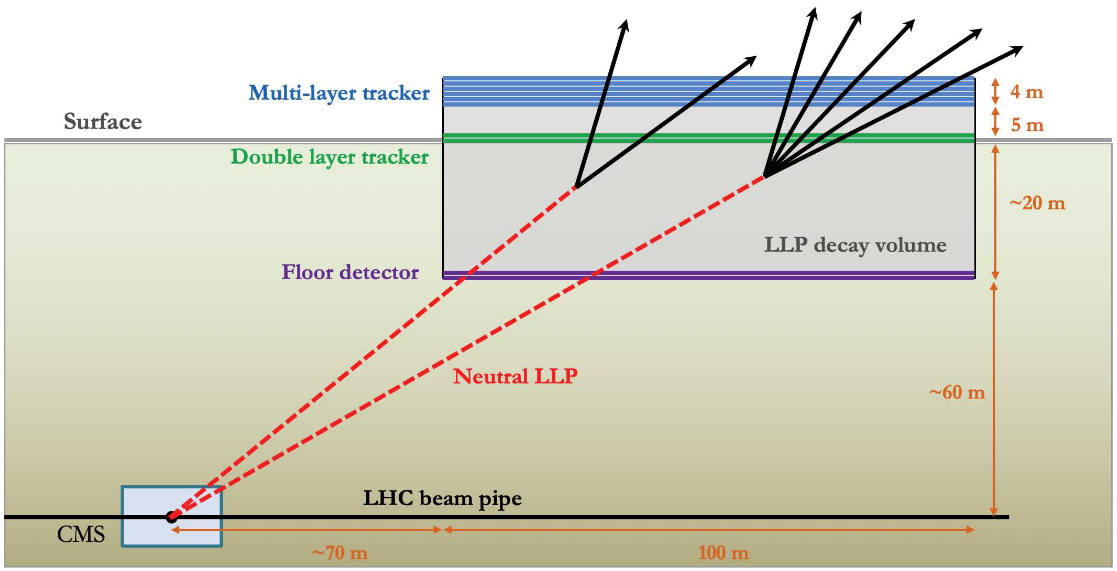
However, the LHC could be making LLPs that are effectively invisible to its main detectors

The MATHUSLA experiment is a proposed LLP detector for the HL-LHC

- Large-volume dedicated detector for LLPs with long decay lengths
  - Detector dimensions of ~100m x 100m x 30m
- Positioned on the surface near one of the LHC interaction regions
  - Shielded from LHC interactions by ~100m of rock
- LLPs decay vertices within the MATHUSLA decay volume are reconstructed by tracking their decay daughters through a series of active detector planes

- Up-down hit timing constraints used to veto cosmic rays
- LHC backgrounds rejected by floor tracking layers and decay vertex topology

Capable of LLP searches with a near-zero background



MATHUSLA

(Massive Timing Hodoscope for Ultra Stable neutraL pArticles)

mathusla-experiment.web.cern.ch/

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

MATHUSLA

mathusla-experiment.web.cern.ch

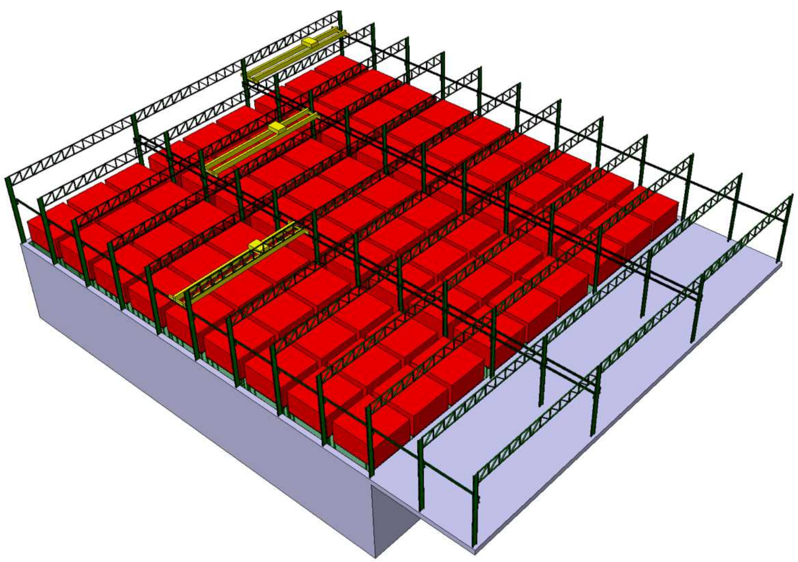
Cristiano Alpigiani,[1] Juan Carlos Arteaga-Velázquez,[2] Austin Ball,[3] Liron Barak,[4] Jared Barron,[5] Brian Batell,[6] James Beacham,[7] Yan Benhammo,[4] Karen Salomé Caballero-Mora,[8] Paolo Camarri,[9] Roberto Cardarelli,[9] John Paul Chou,[10] Wentao Cui,[5] David Curtin,[5] Miriam Diamond,[5] 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 Rodríguez-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]

arXiv:2009.01693 [physics.ins-det]
2009.01693 LHCC-I-031-ADD-1

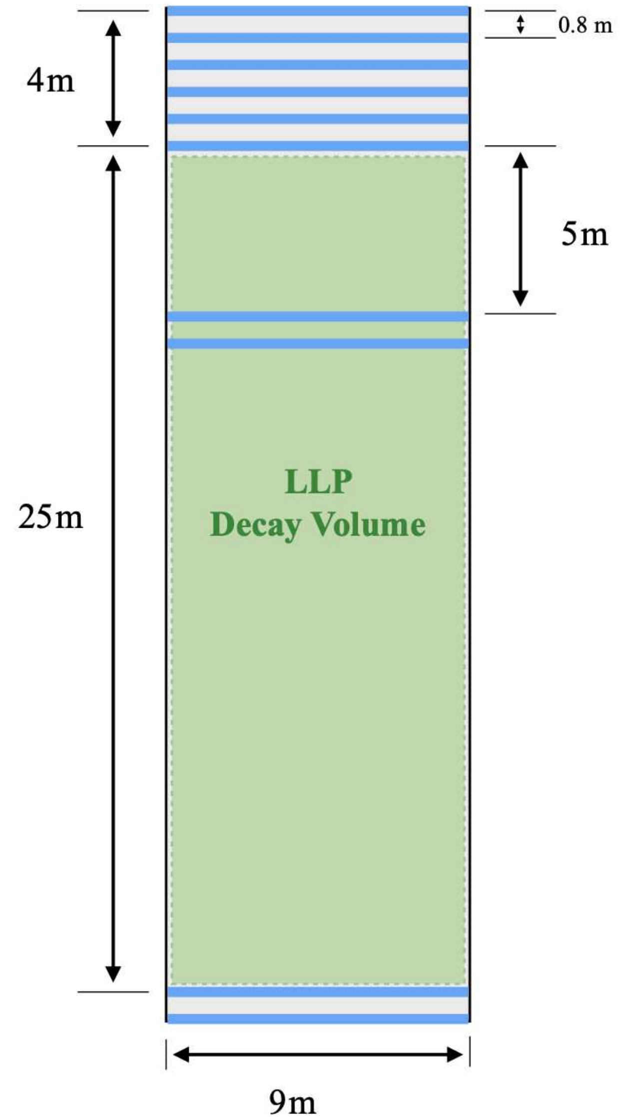
Concept

Detector concept is an array of ~100 "towers" of tracking layers instrumenting a ~30m high decay volume

- Module towers ~ 10m x 10m x ~30m
- Six tracking layers near the top, and "veto" layers at the bottom
- "Mid" layers to improve tracking lever-arm for decays near the bottom of the decay volume



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



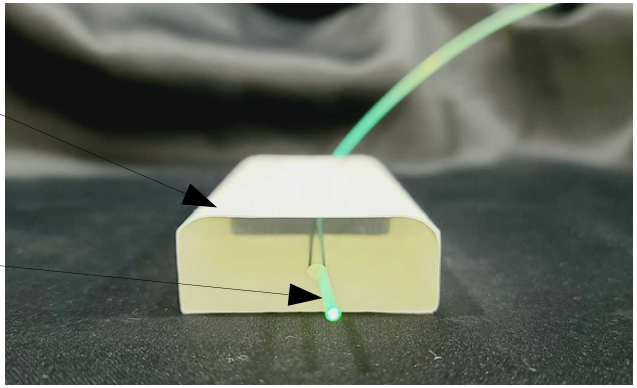
Detector

Very simple detector technology based on extruded plastic scintillator

- ~2.5m long scintillator bars, threaded with wavelength shifting optical fiber (WLSF)
- Silicon photomultiplier (SiPM) readout of fibers at bar ends

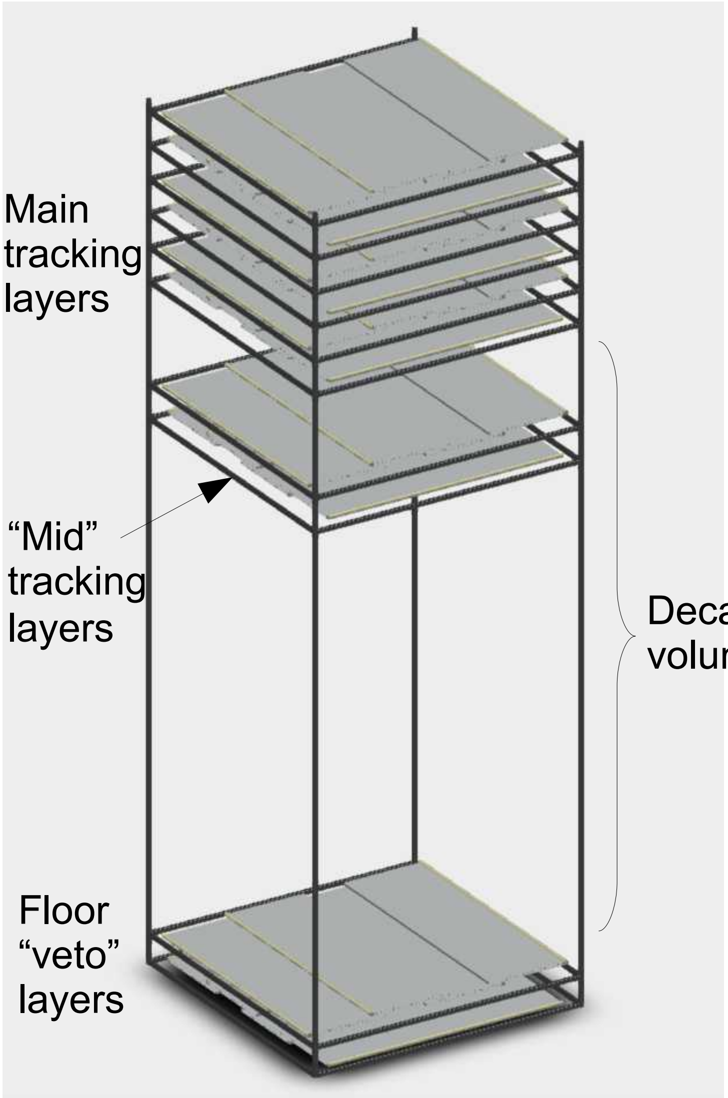
Extruded plastic scintillator is primary detector element

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



- O(10^6) electronic readout channels
- ~3 million metres of WLSF
- ~1000 tons of scintillator covering ~100000 m^2 of area

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

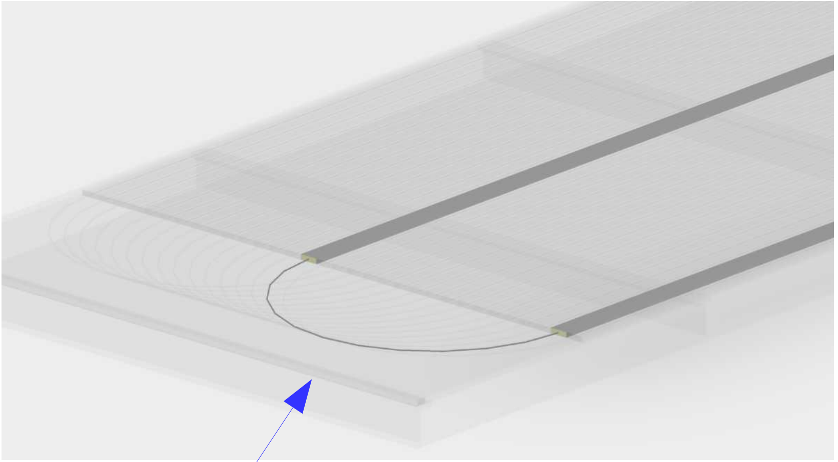


Drawings by Rodney Schnarr (Carleton)

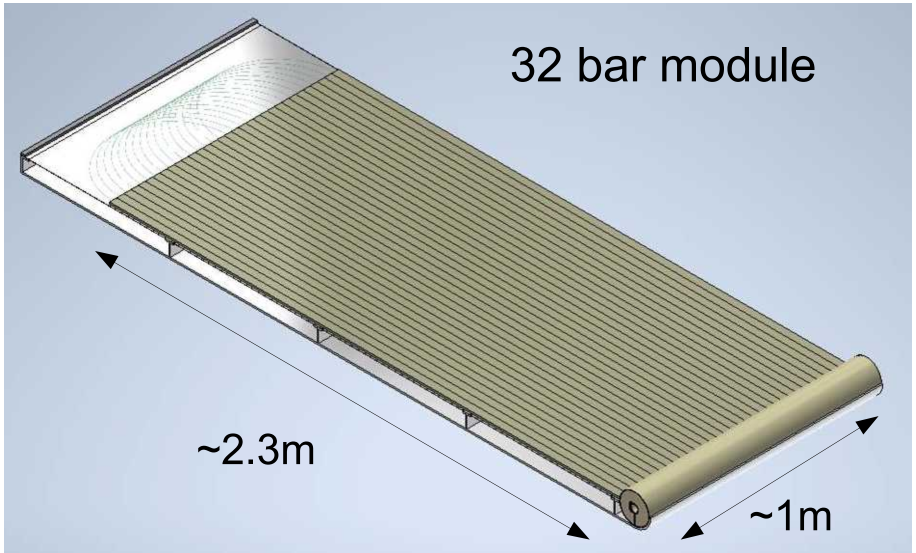
Detector

Scintillator bars provide 2-D geometrical space-points with ~1 cm resolution

- Layers alternate in x-y orientation to provide 3-D tracking
- Absolute hit timing used for event timing (relative to LHC bunch crossing time) and to distinguish upward and downward going tracks
  - 80 cm layer spacing → ~1 ns timing resolution needed



WLSF looped through two adjacent bars so all signals are readout at “front” face



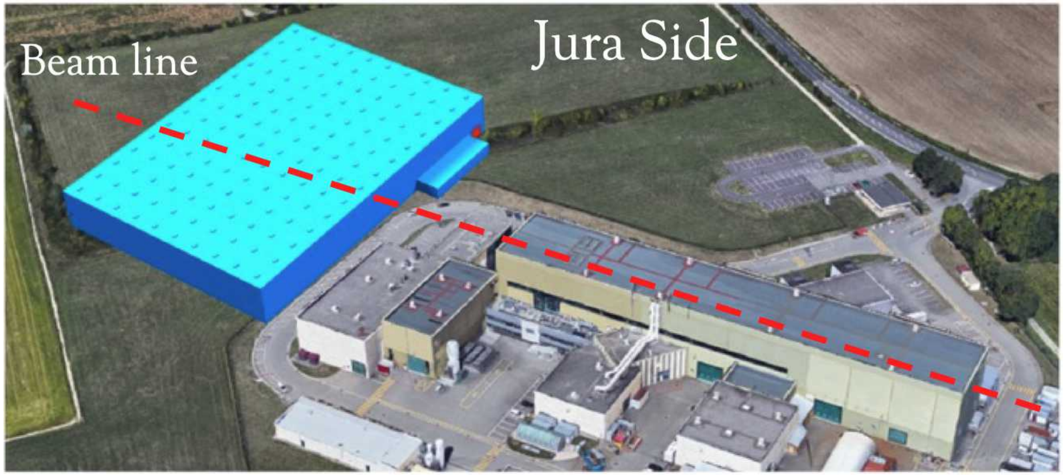
Differential timing of signals in opposite ends of the fiber provide additional spatial coordinate

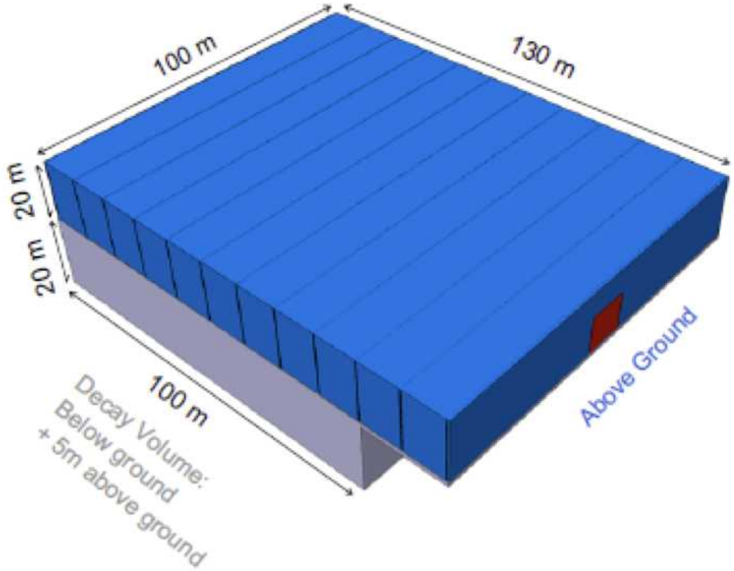
- ~15 cm difference in hit position results in ~1 ns difference in differential timing

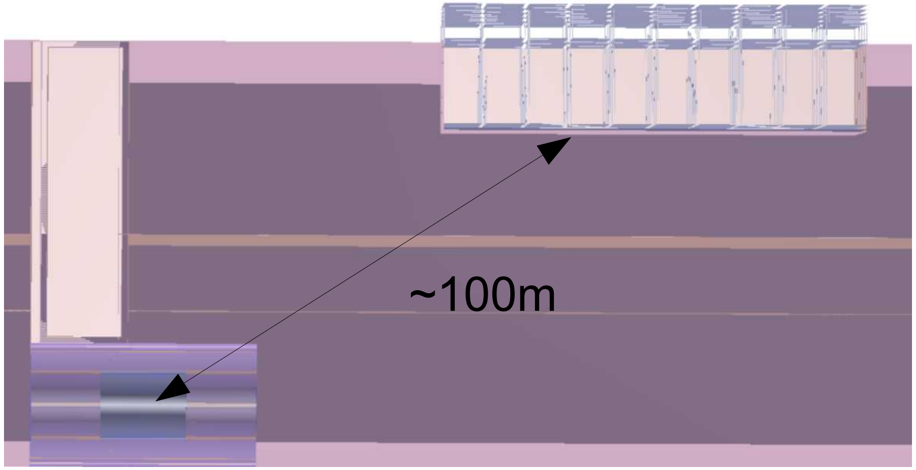
Location

Appropriate space is available on CERN-owned land on the surface adjacent to the CMS interaction region

- Height restrictions dictate that most of decay volume will be within an excavated pit
- Feasibility has been assessed by CERN civil engineering





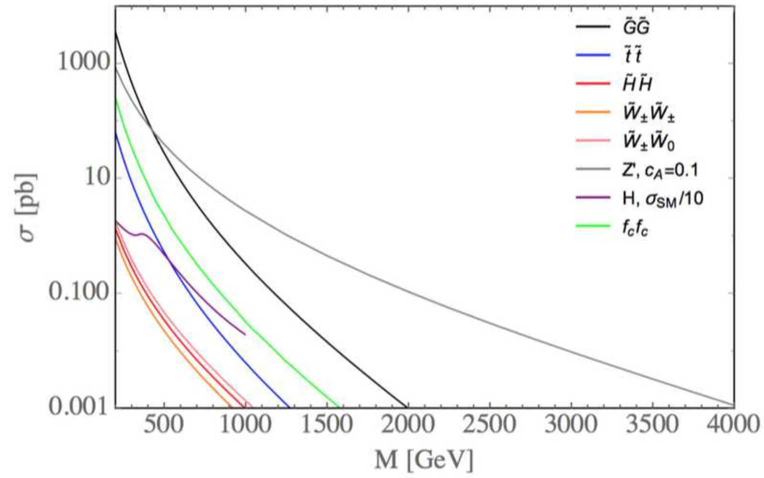


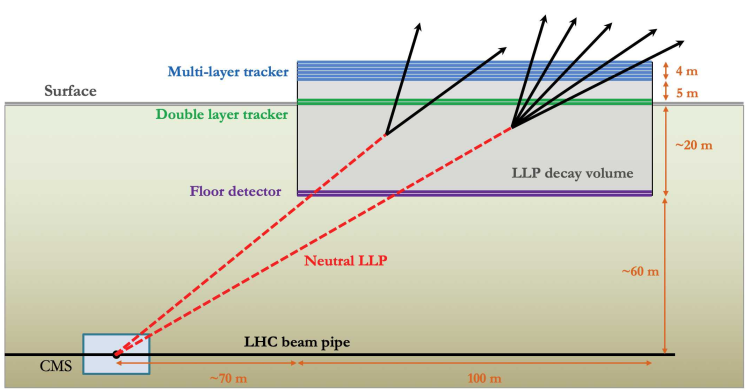
Physics objectives

MATHUSLA can search for two general categories of physics signatures:

- Hadronically decaying LLPs ranging from a few GeV to TeV scale
  - High multiplicity final states are 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:



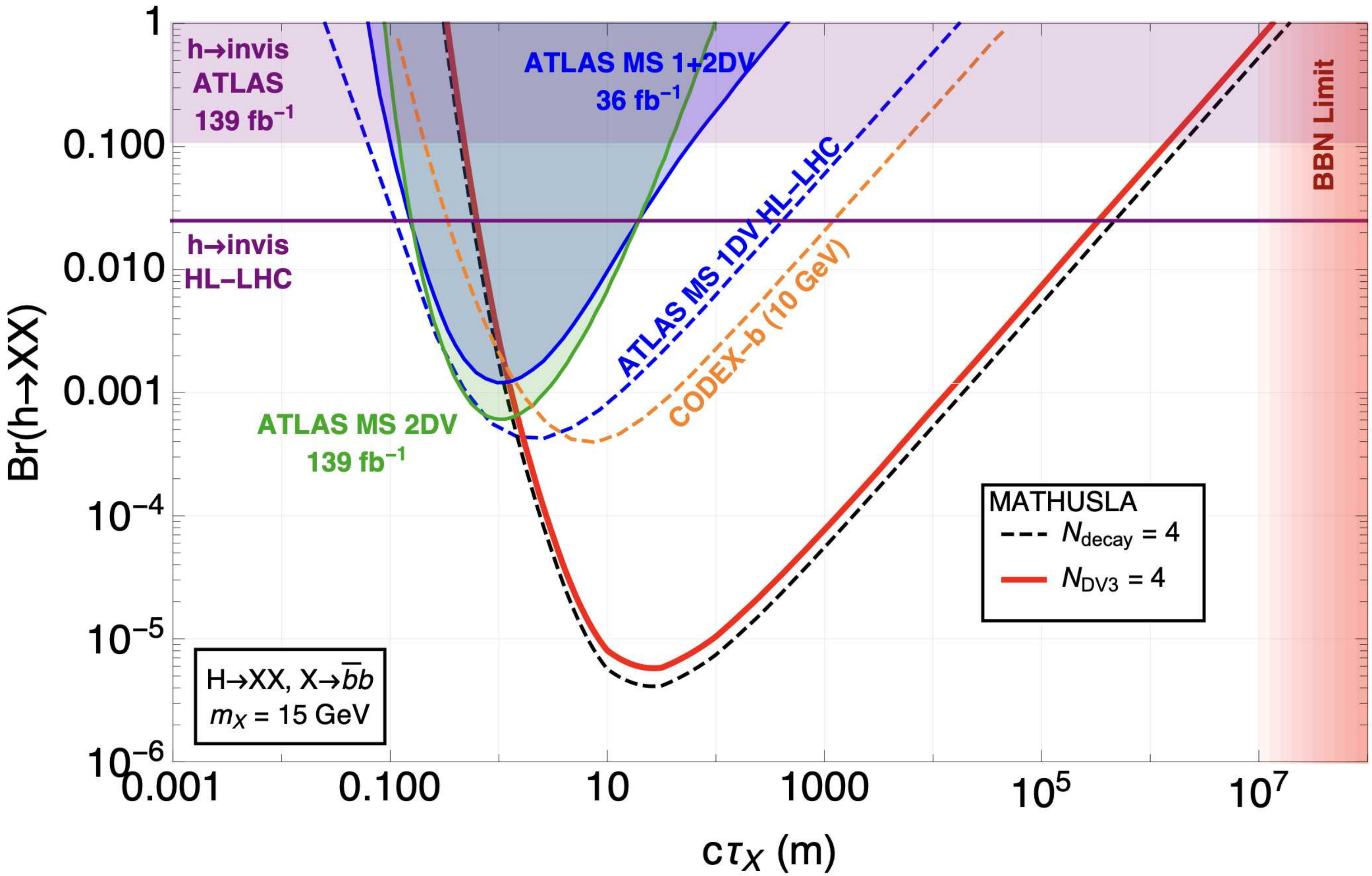


Second category provides the main benchmarks for detector design

Exotic Higgs Decays

Higgs decay into hadronically decaying LLPs:

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

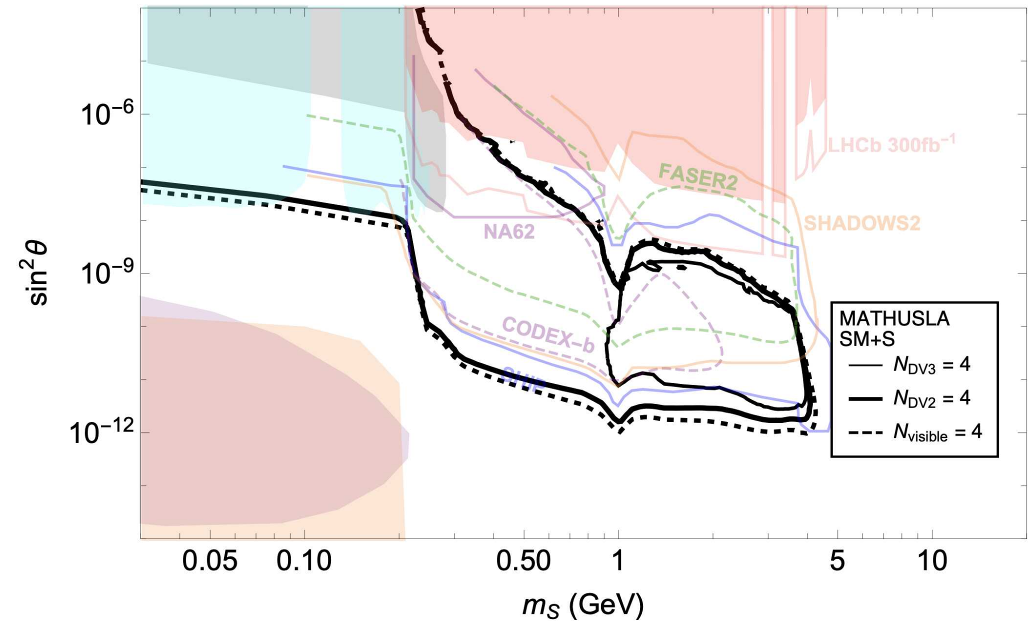


GeV-scale LLPs

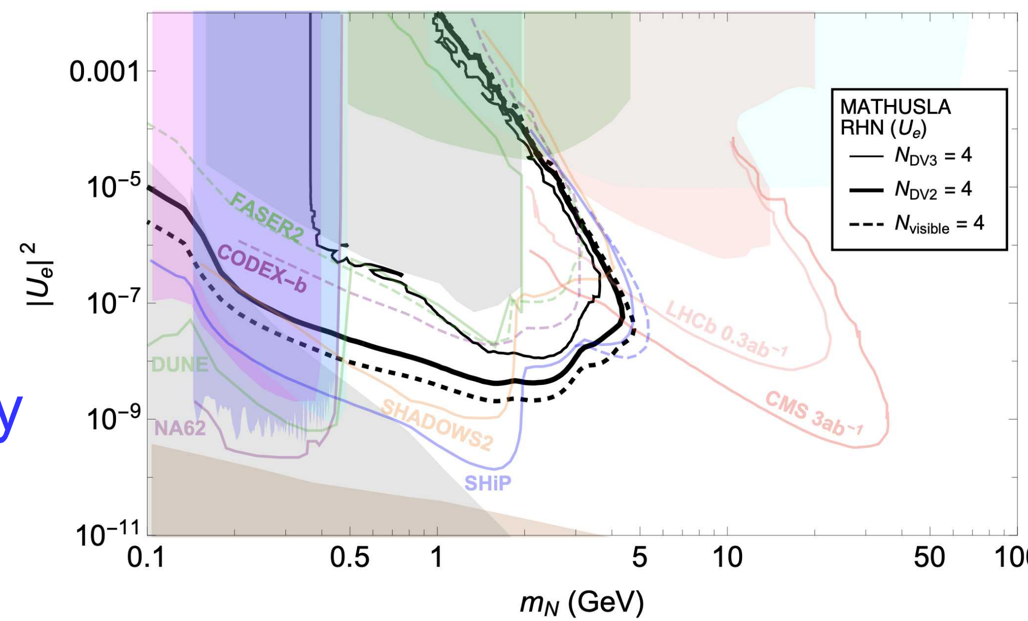
arXiv:2308.05860

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

- Production in B, D, K meson decays:



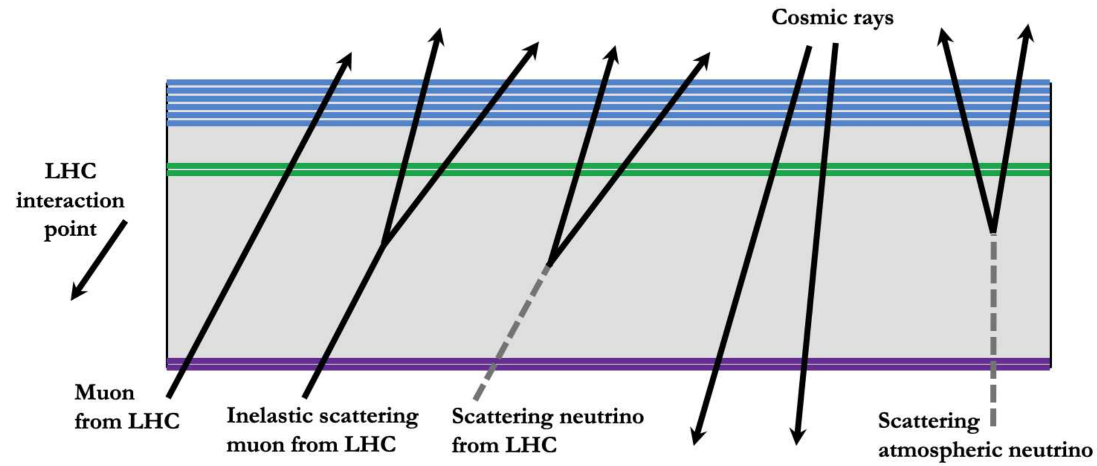
LLP right-handed neutrino mixing with ν_e



Competitive and complementary sensitivity relative to other proposed LLP experiments

Backgrounds

- Primary physics target (high multiplicity DV) is essentially background-free
- Secondary physics target of low-mass, low multiplicity LLP decays have backgrounds that need to be carefully studied



GeV-scale atmospheric neutrinos:

- Scattering within the decay volume result in about 30 events per year
- Can be vetoed to rate of <<1 per year using time-of-flight track measurements

LHC muons:

- Muons with E > 40GeV can penetrate rock shielding, but do not generally form vertices
- Delta rays and rare decays can be rejected based on vertex topology

Cosmic rays:

- ~2 MHz flux to entire detector rejected by directionality (timing)
- Cosmic ray nucleons can undergo inelastic backscatter in detector floor
- Results in O(1000) non-relativistic K_S^0 (over life of experiment) traveling into MATHUSLA volume and decaying into charged particles that could reach the ceiling trackers.
- Can be characterized with beam off, and distinctive low momentum signature

CMS combined analysis

MATHUSLA can discover/exclude new physics based purely on information from the MATHUSLA detector

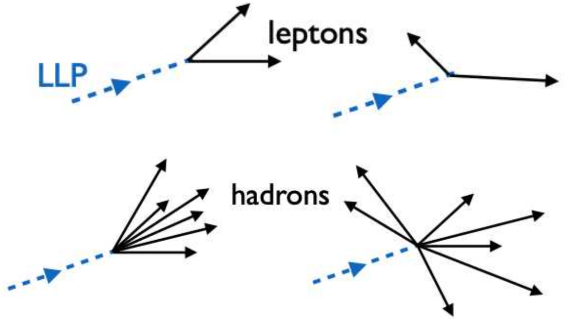
- MATHUSLA provides information about LLP boost and decay mode
- CMS detector reveals production mode and parameters of underlying model (parent mass, LLP mass)

→ Combined analysis ca provide a complete characterization of LLP with as few as O(100) events

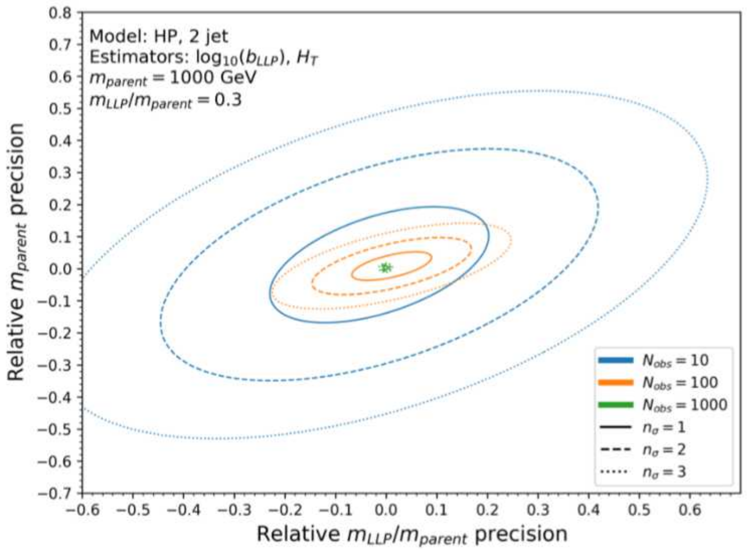
MATHUSLA can trigger independently, then use timestamps to correlate these with CMS events offline, however, preferable to directly use MATHUSLA as a L1 trigger for CMS

- MATHUSLA will need to provide CMS with a trigger signal within the CMS trigger pipeline buffer
- 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.

LLP boost can be determined event-by-event from the track geometry:

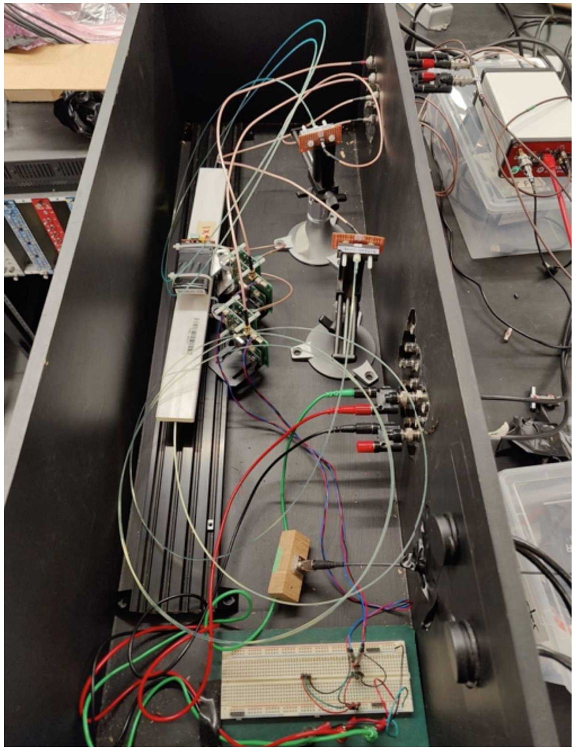


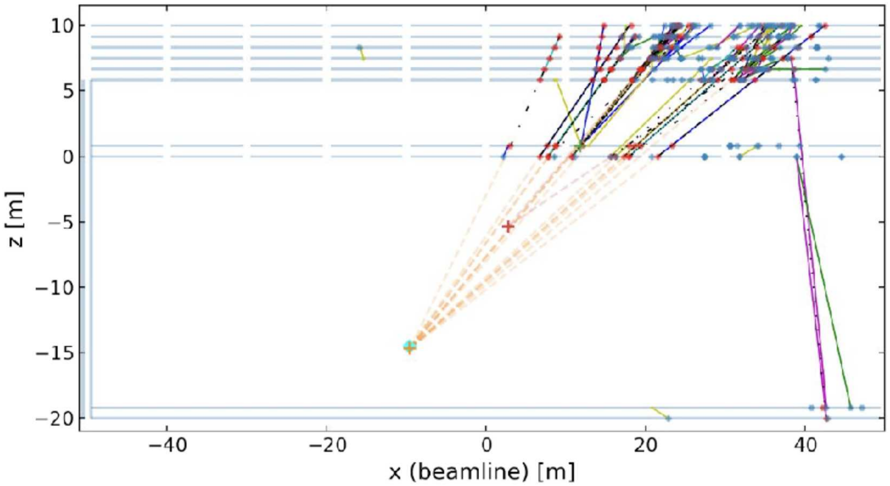
arXiv:2007.05538 [hep-ph]
Jared Barron and David Curtin



Ongoing R&D activities

- Studies of improved reflective cladding for extrusion
  - Small improvements in reflectivity can have big impacts on light yield
- Studies of new WLSF formulations with higher yield, shorter decay times and longer attenuation lengths
  - Light yield impacts timing resolution (not efficiency), and reduces material costs
- Cost/performance optimization for SiPMs
  - SiPM performance not a limiting factor
  - Define QA/QC criteria





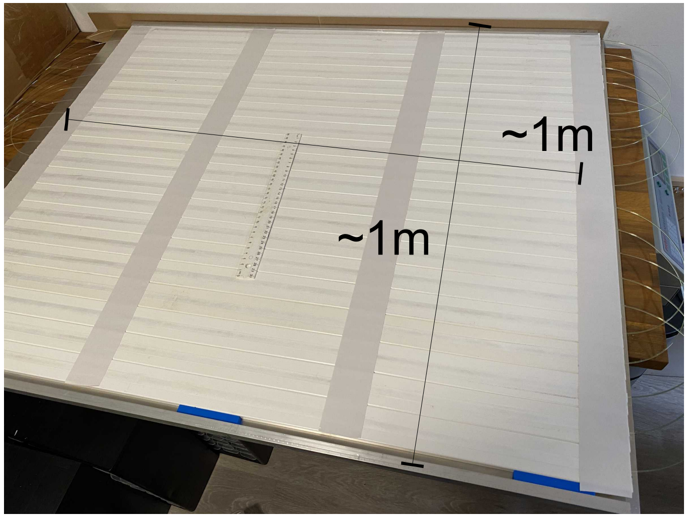
- Detailed GEANT4 simulation studies with robust pattern recognition/ track finding (Kalman filter) and vertexing

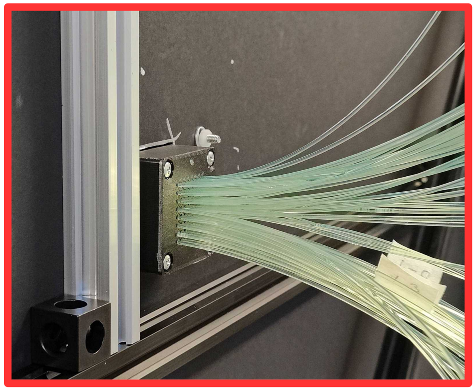
"Global" performance optimization of extrusion, WLSF and SiPMs still to be performed (detailed technical design)

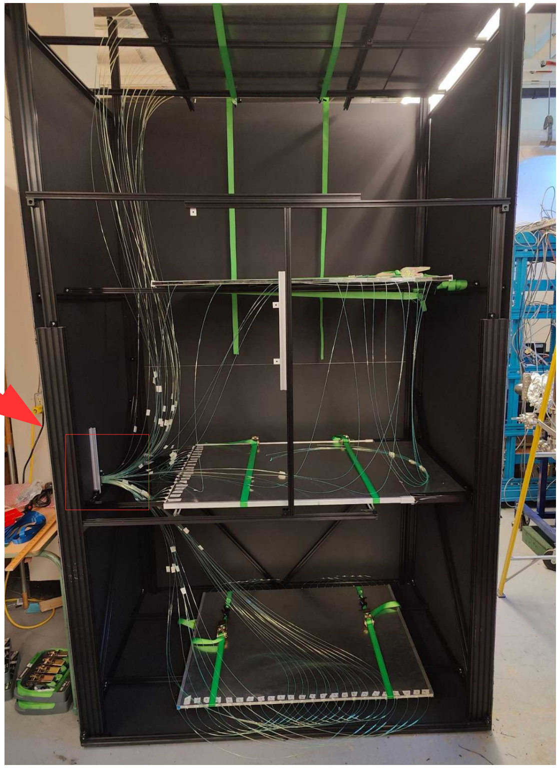
Ongoing R&D activities

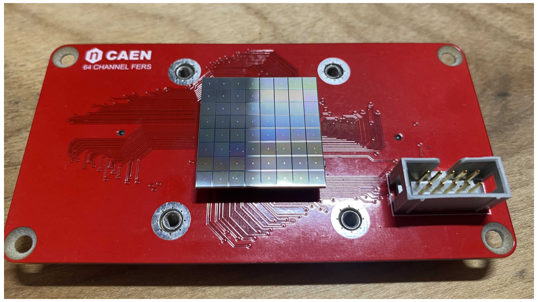
Testing of prototype scintillator bar modules in large cosmic ray hodoscope (UVic)

- Tracking with four-layer x-y arrays with looped WLSF and 80cm layer spacing
- Scintillator bars, fiber and SiPMs with close to MATHUSLA nominal specifications









- Scintillator bars are not full length, but WLSF is the same as in a full-sized bar module
- Instead of individual SiPMs mounted on bar ends, WLSFs are routed back to a single 64 channel SiPM array

Future tests planned with full MATHUSLA-specification bars, and custom front end electronics (UofT)

Prospects

Robust MATHUSLA physics case based on realistic simulation studies

- Recent improvements in simulation, tracking and vertexing

Ongoing R&D effort toward detector design

- Technical feasibility of the detector concept has been demonstrated in benchtop studies, but work is ongoing towards design optimization

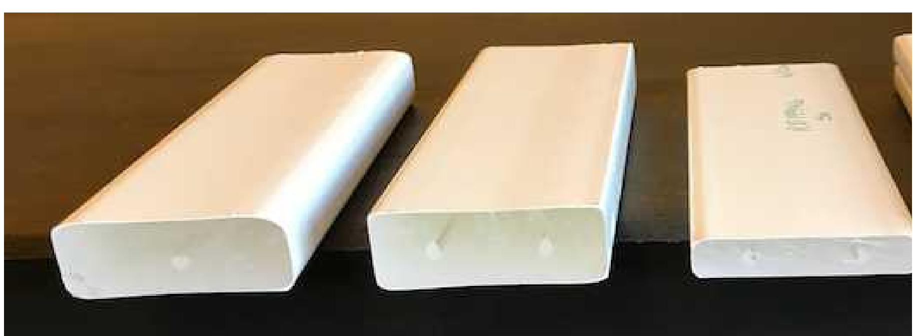
Conceptual design report is currently undergoing internal review and is expected to be made publicly available in the near future

Backup Slides

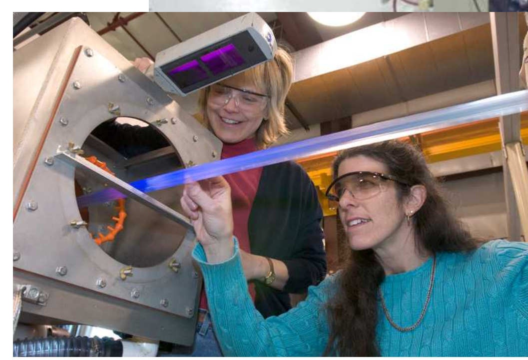
Extruded plastic scintillator

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



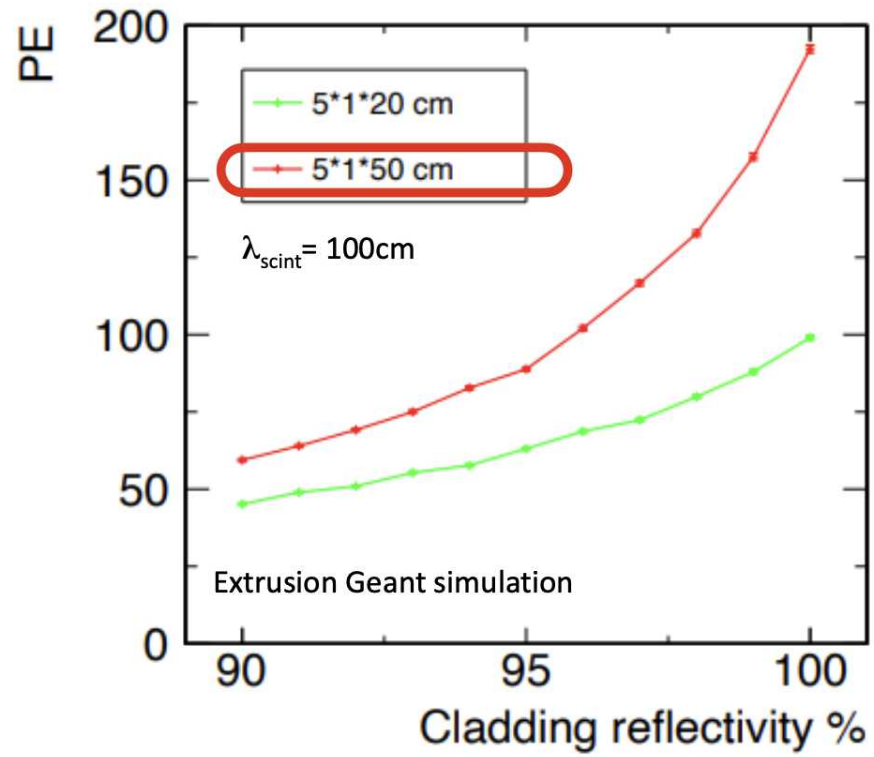
- TiO_2 reflective coating co-extruded
- Various profiles can be extruded, with hole(s) for inserting WLSF

Extrusion Improvement

J. Freeman, FNAL

Possibility of improving reflectivity of cladding around scintillator extrusion to improve light yield

- 2% improvement can result in 30% more light.
- Could reduce MATHUSLA scintillator requirement by 30%.



Wrapper	Relative Light Yield
TiO_2 coextruded cladding	1.0
Tyvek	1.08
ESR	1.46
Black wrapper	0.24

Yucun Xie (UMD) performing GEANT4 simulations to study the effect of different reflectivity cladding on extrusion.

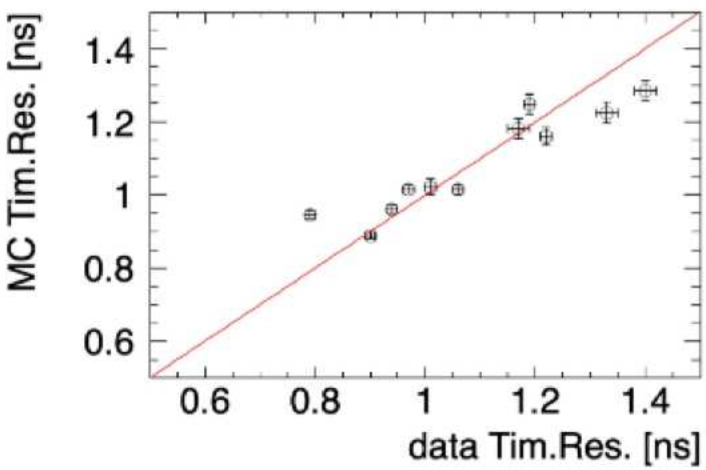
- Replace TiO_2 coating with possible new materials

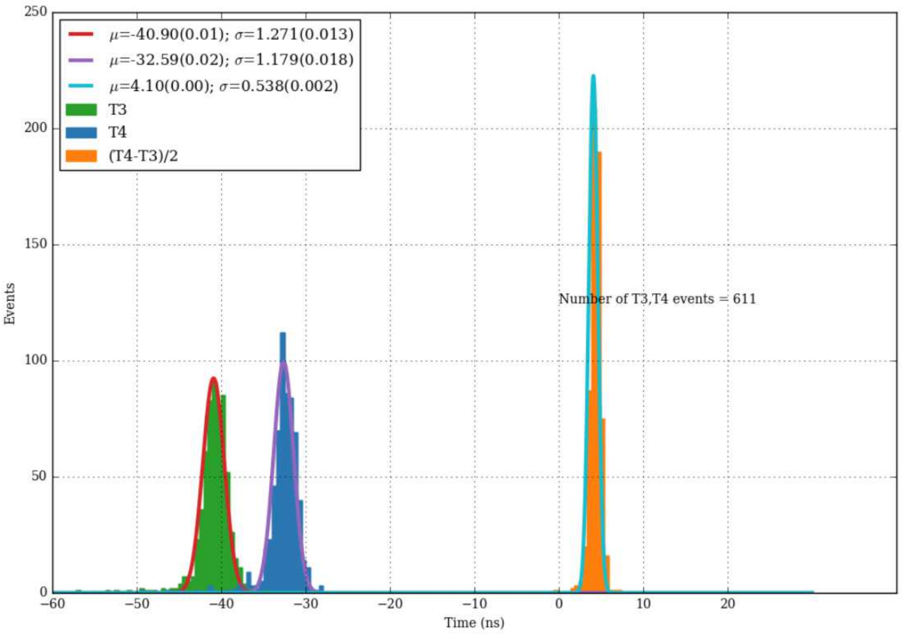
Timing resolution

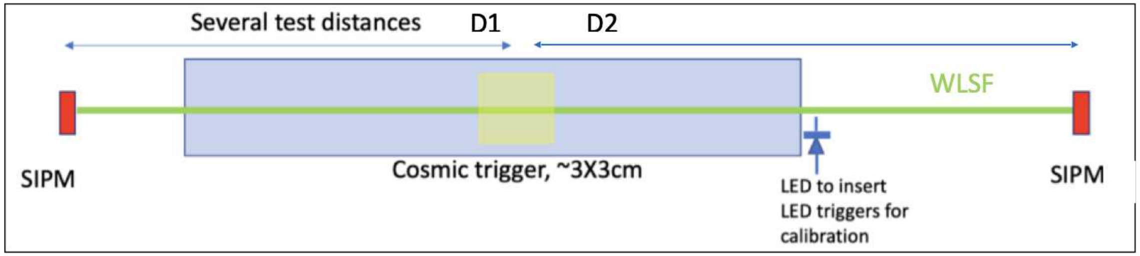
Chin Lung Tan (University of Rochester (US)),
Jim Freeman (Fermi National Accelerator Lab. (US)

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



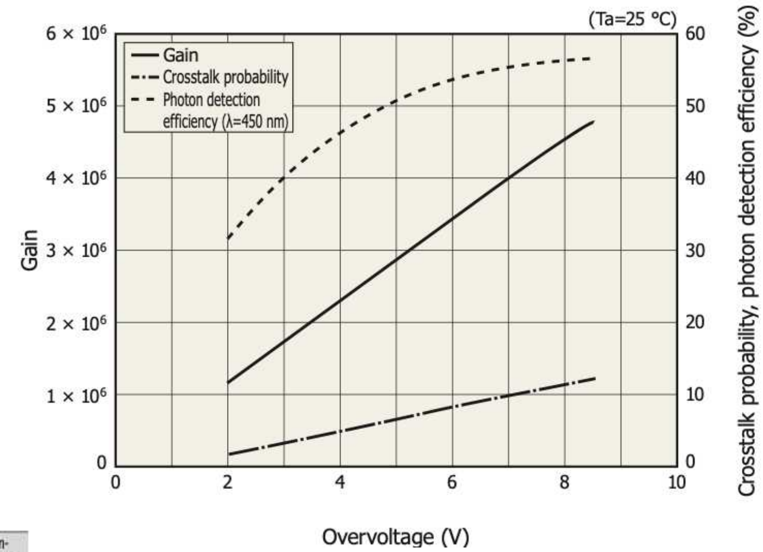




Timing measurement for a 5m long f ber through a 1X4cm extrusion. This location is at 250cm along the f ber, equidistant from the 2 SIPMs. Time distributions (relative to the cosmic trigger start time) are shown for the 2 SIPM channels (Chan 3, Chan 4). Also shown is the difference, (T4-T3)/2. We note 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.

Silicon Photomultipliers

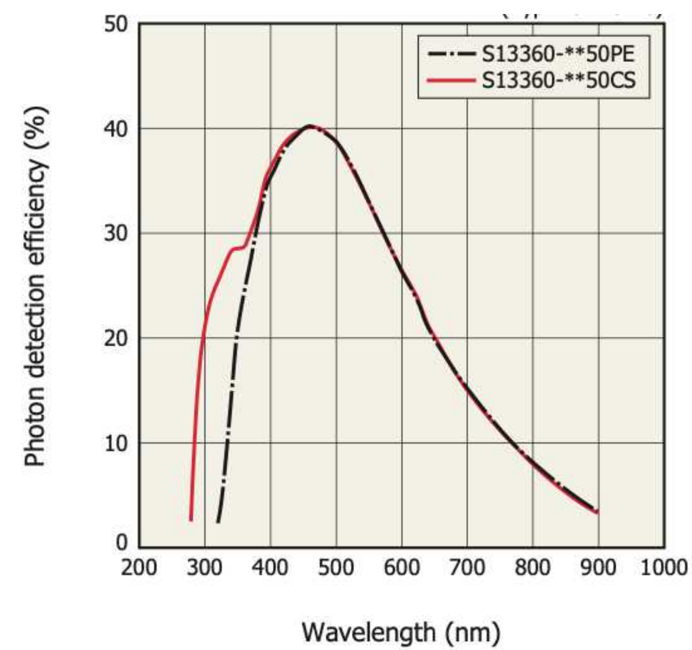
- Very large gain, adjustable via bias voltage, but also very sensitive to device temperature
- Spontaneous pixel breakdown results in dark noise (or dark current)
- Photon detection efficiency (PDE) depends on both quantum efficiency and geometric properties of device



increasing pixel size

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 VBR (V)	Crosstalk probability (%)	Recommended operating voltage Vop (V)	Temperature coefficient at recommended operating voltage ΔTVop (mV/°C)
S13360-1325CS		270 to 900			70	210	60					
S13360-1325PE		320 to 900										
S13360-3025CS	Vover =5 V	270 to 900		25	400	1200	320	7.0 × 10^5		1	VBR + 5	
S13360-3025PE		320 to 900										
S13360-6025CS		270 to 900			1600	5000	1280					
S13360-6025PE		320 to 900										
S13360-1350CS		270 to 900			90	270	60					
S13360-1350PE		320 to 900										
S13360-3050CS	Vover =3 V	270 to 900	450	40	500	1500	320	1.7 × 10^6	53 ± 5	3	VBR + 3	54
S13360-3050PE		320 to 900										
S13360-6050CS		270 to 900			2000	6000	1280					
S13360-6050PE		320 to 900										
S13360-1375CS		270 to 900			90	270	60					
S13360-1375PE		320 to 900										
S13360-3075CS	Vover =3 V	270 to 900		50	500	1500	320	4.0 × 10^6		7	VBR + 3	
S13360-3075PE		320 to 900										
S13360-6075CS		270 to 900			2000	6000	1280					
S13360-6075PE		320 to 900										

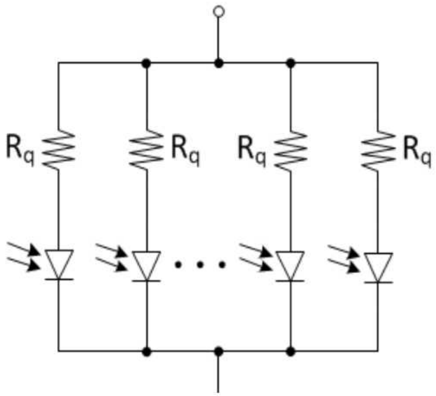
*4: Photon detection efficiency does not include crosstalk or afterpulses.
*5: Threshold=0.5 p.e.
Note: The above characteristics were measured at the operating voltage that yields the listed gain. (See the data attached to each product.)

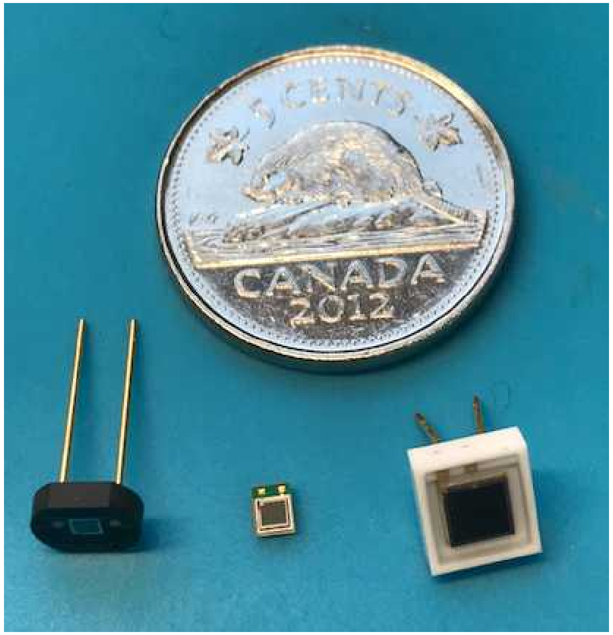


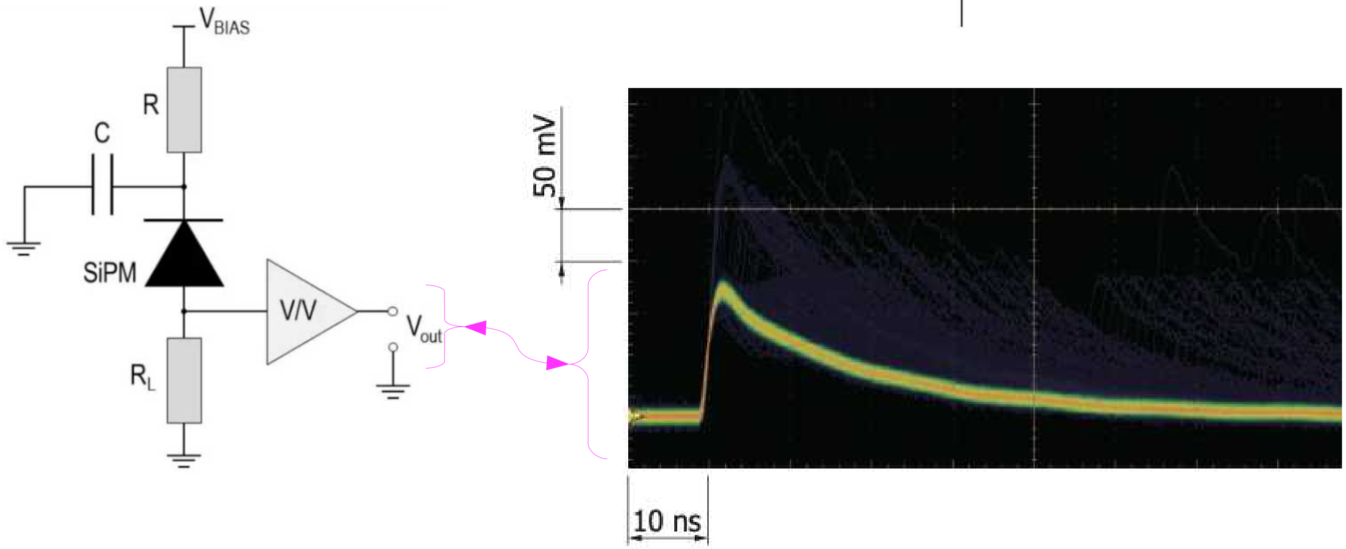
Silicon Photomultipliers

WLSF light measured by SiPMs mounted at the fibre 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**





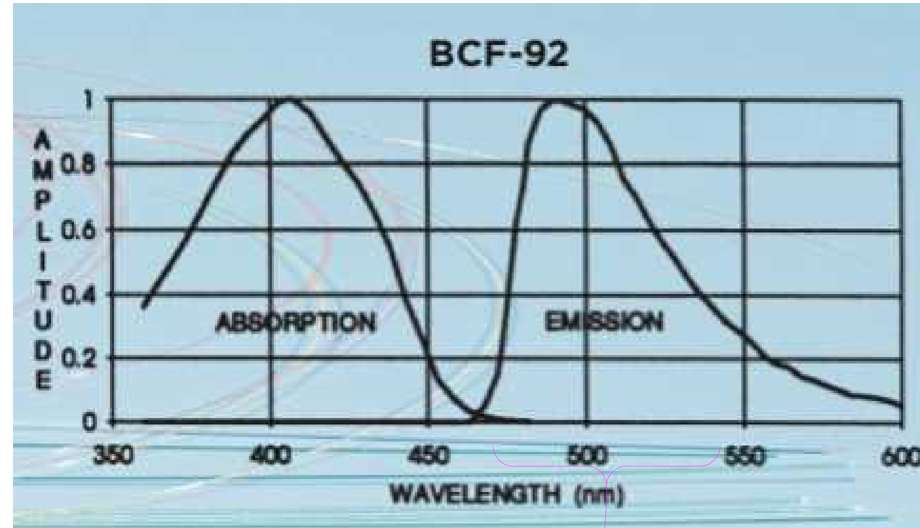


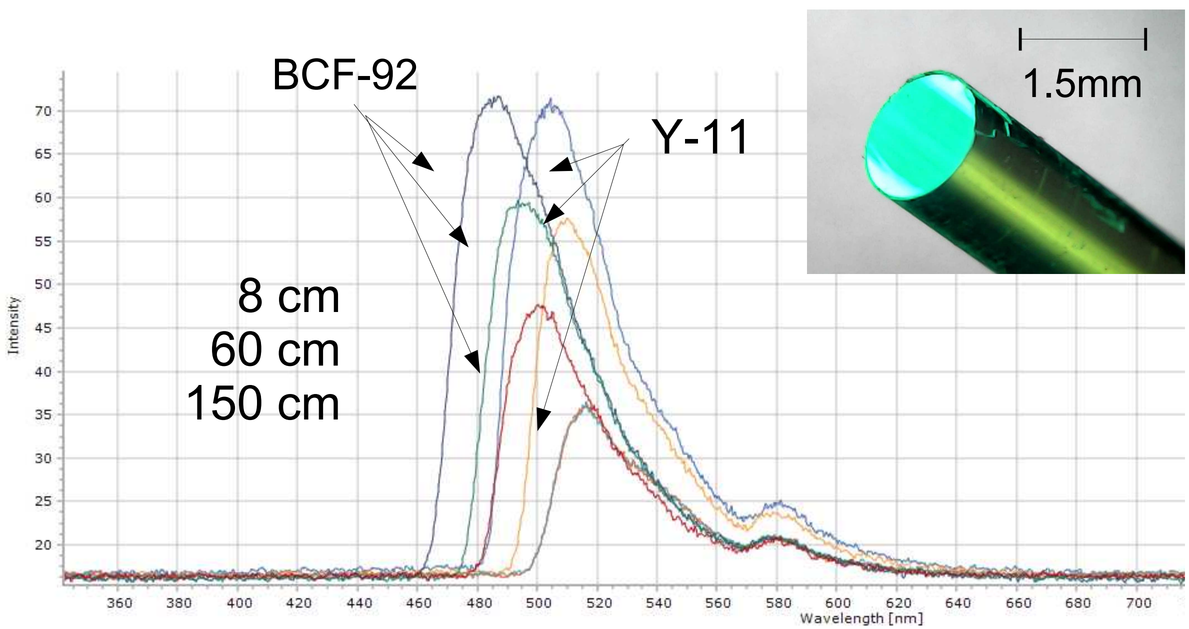
However, output signals are typically shaped and amplified to optimize for specific application, e.g. for fast timing

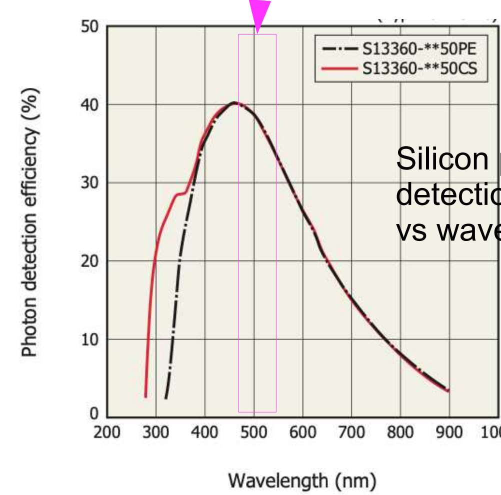
Wavelength Shifting Fibre

Plastic optical fibre 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 the target timing resolution

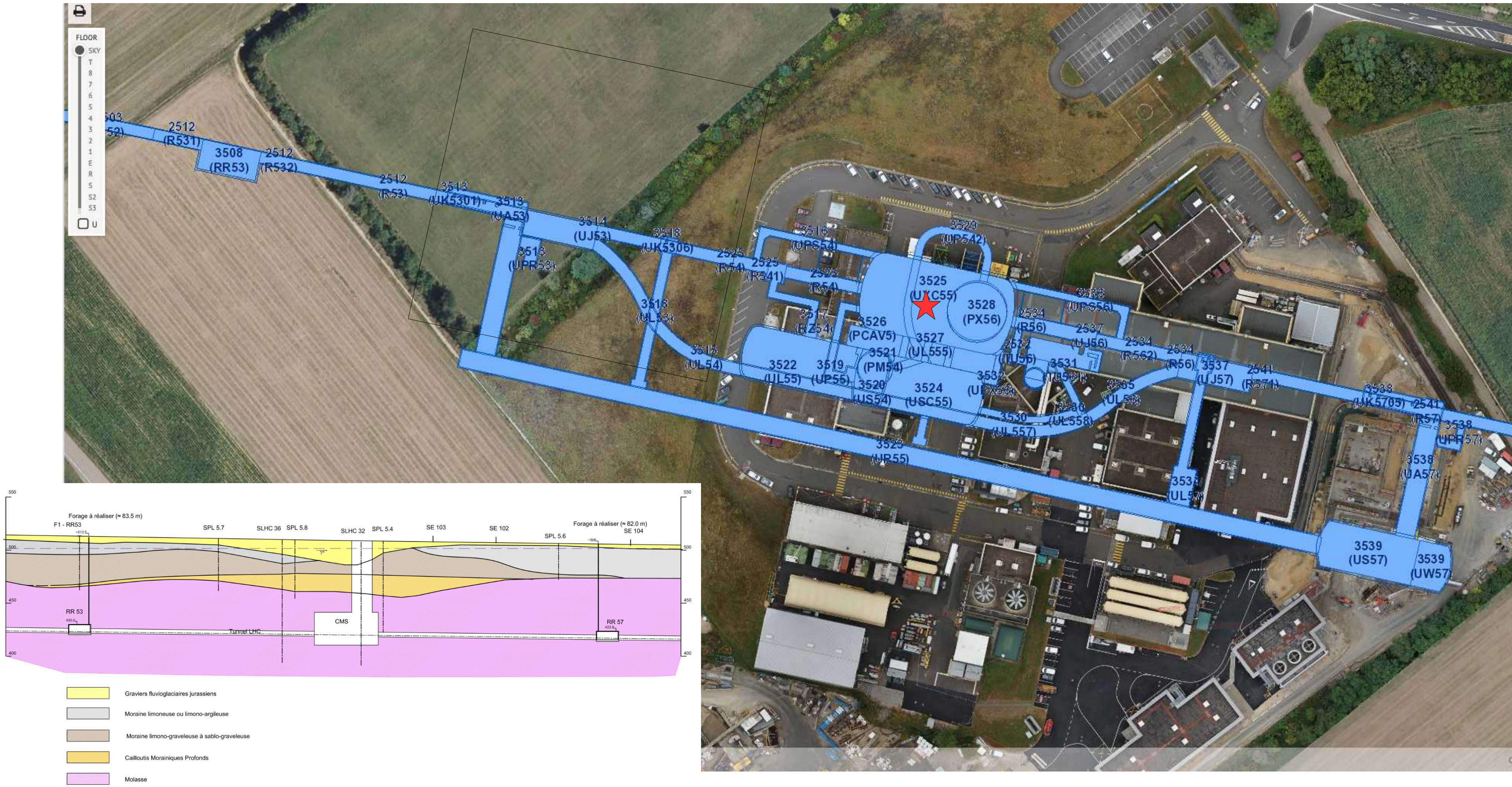






Silicon photomultiplier detection efficiency vs wavelength

Location

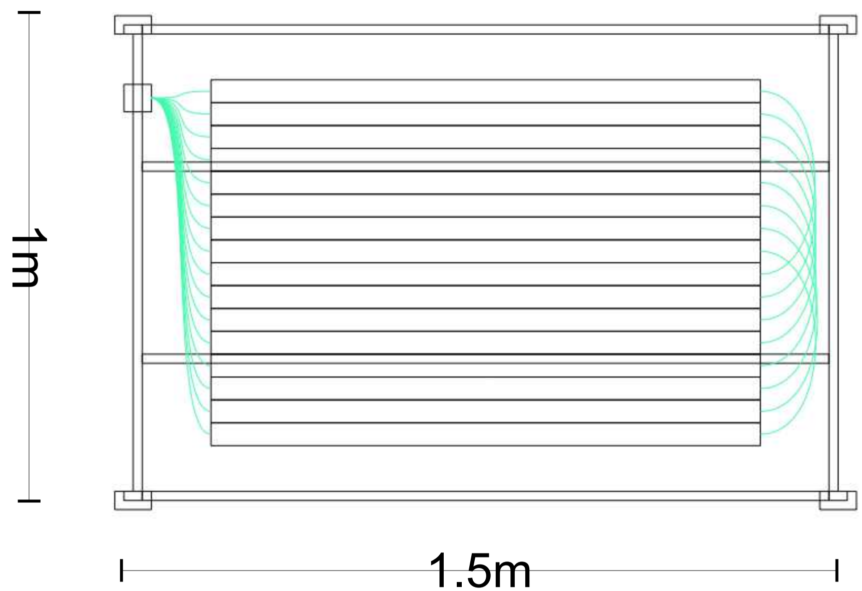


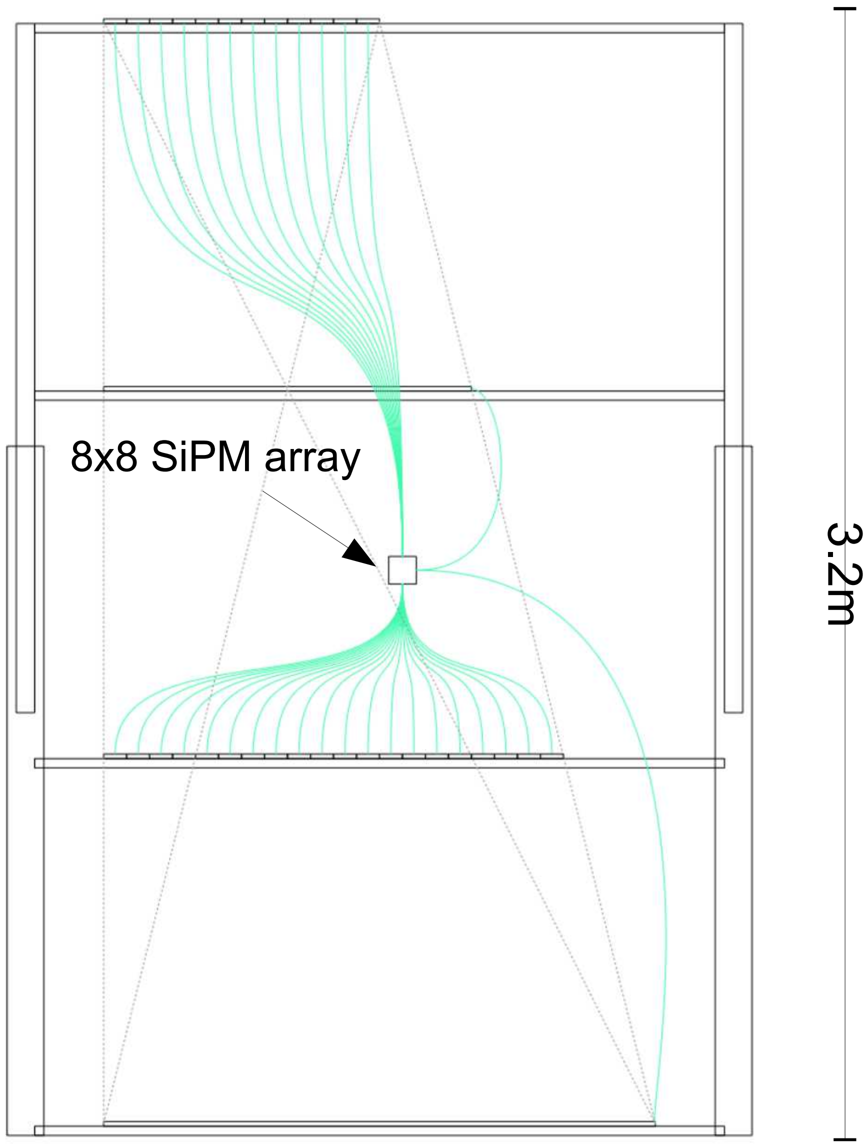
3508 (RR53)
2512 (R531)
2512 (R532)
2512 (R53)
3514 (UJ53)
3525 (UXC55)
3528 (PX56)
3526 (PCAV5)
3527 (UL555)
3522 (UL55)
3519 (UP55)
3521 (PM54)
3520 (US54)
3524 (USC55)
3523 (UR55)
3539 (US57)
3539 (UW57)
3538 (UA57)
2541 (R571)
3537 (UJ57)
Forage à réaliser (≈ 83.5 m)
F1 - RR53
SPL 5.7
SLHC 36
SPL 5.8
SLHC 32
SPL 5.4
SE 103
SE 102
SPL 5.6
Forage à réaliser (≈ 82.0 m)
SE 104
RR 53
CMS
Tunnel LHC
RR 57
Graviers fluvioglaciaires jurassiens
Moraine limoneuse ou limono-argileuse
Moraine limono-graveleuse à sablo-graveleuse
Cailloutis Morainiques Profonds
Molasse

Tracking prototype

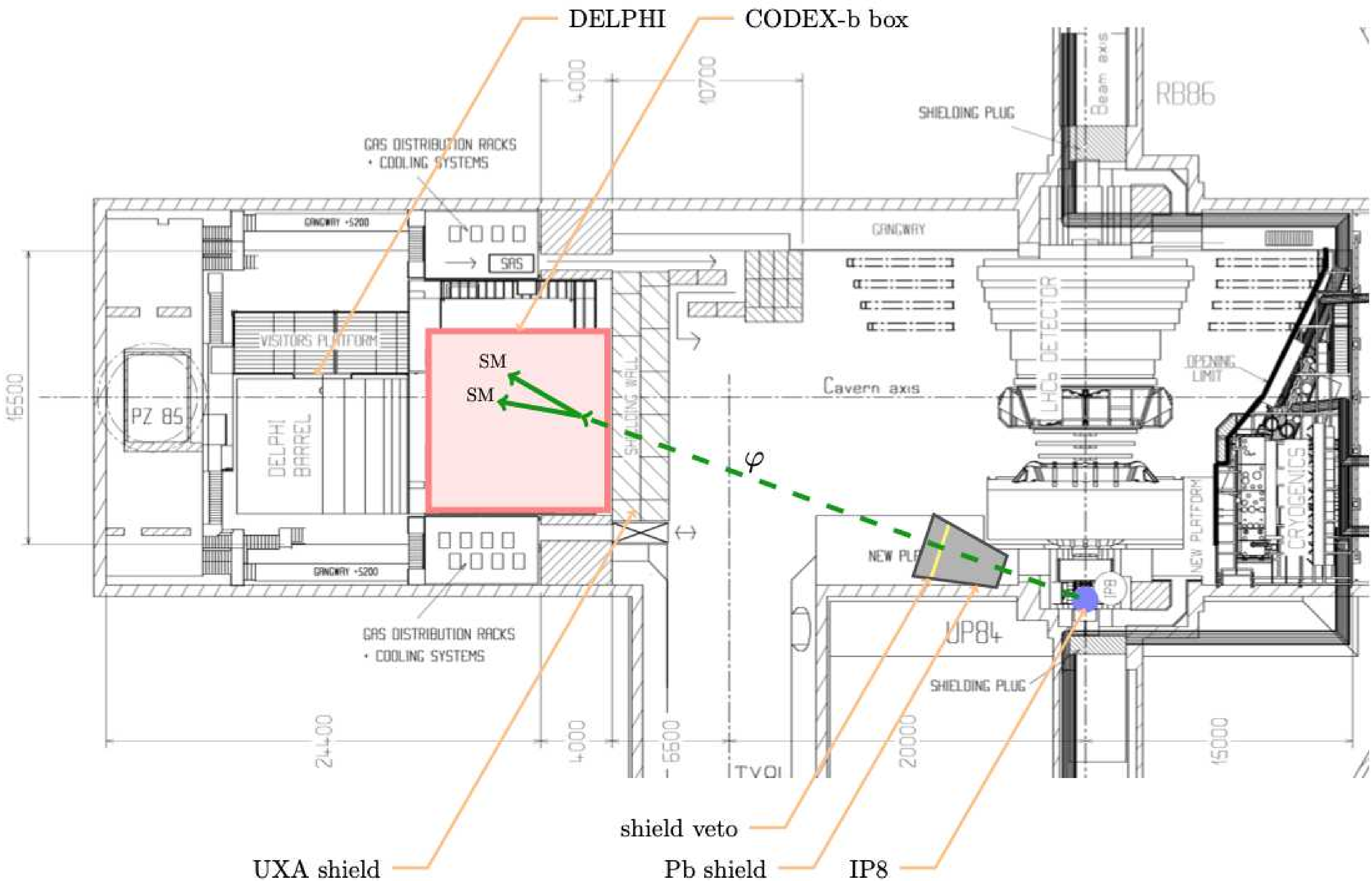
64 channel 4 layer prototype being constructed at UVic this summer

- 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





CODEX-b

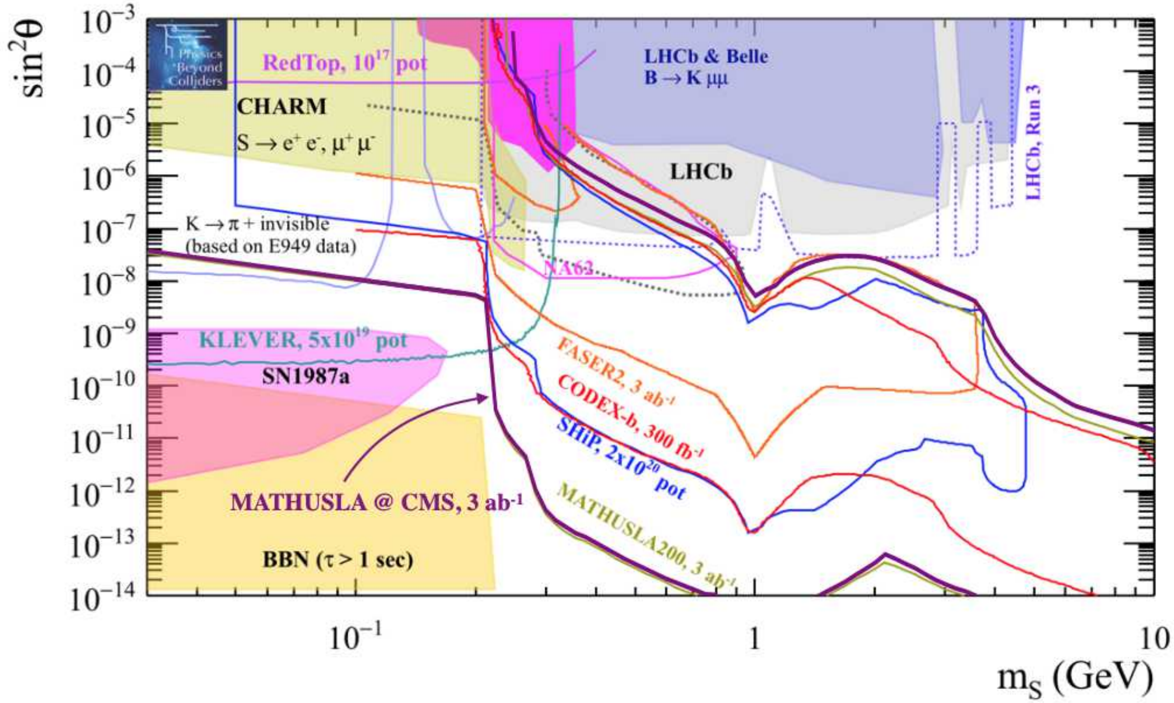

DELPHI
CODEX-b box
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
SHIELDING PLUG
RB86
GANGWAY
VISITORS PLATFORM
PZ 85
DELPHI BARREL
SM
SM
SHIELDING WALL
Cavern axis
LHCb DETECTOR
OPENING LIMIT
CRYOGENICS
NEW PLATFORM
UP84
IP8
SHIELDING PLUG
GAS DISTRIBUTION RACKS
+ COOLING SYSTEMS
16500
24400
4000
6600
20000
15000
4000
10700
shield veto
UXA shield
Pb shield
IP8

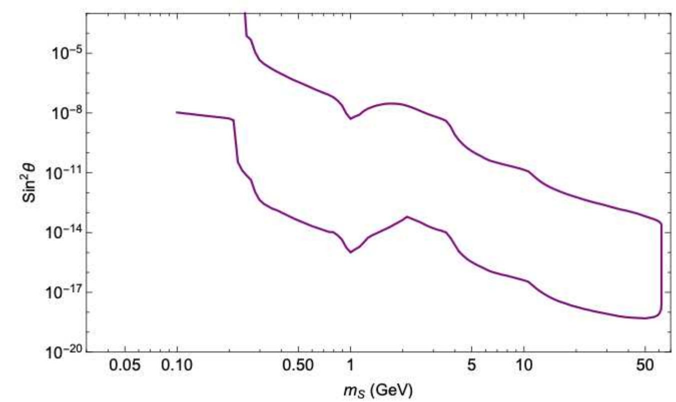
Dark scalar

MATHUSLA update 2009.01693
PBC 1901.09966

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

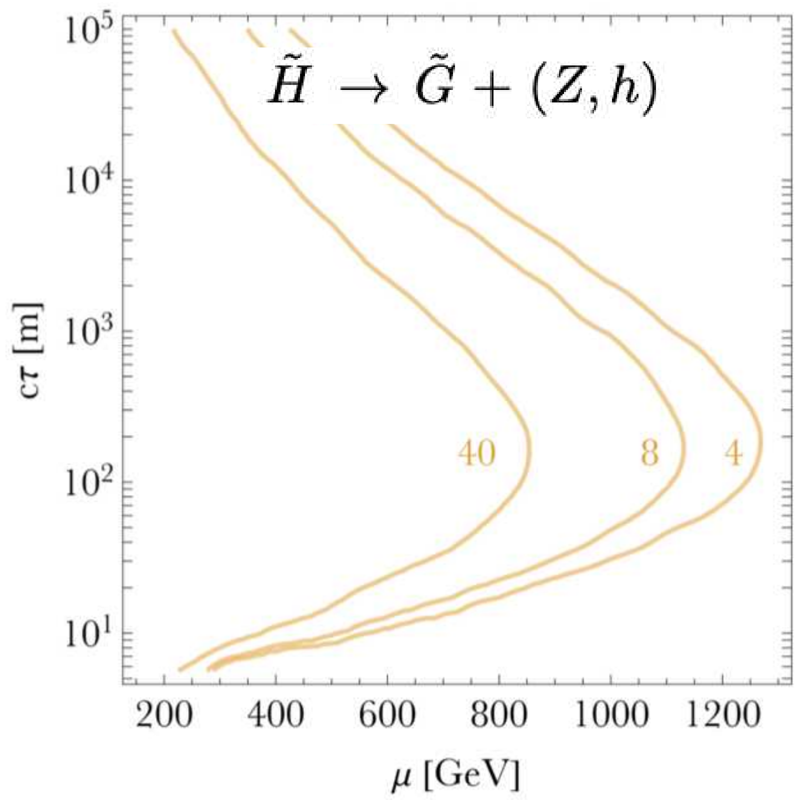
- Assuming additional production in exotic Higgs decays with Br(h → SS) = 1%

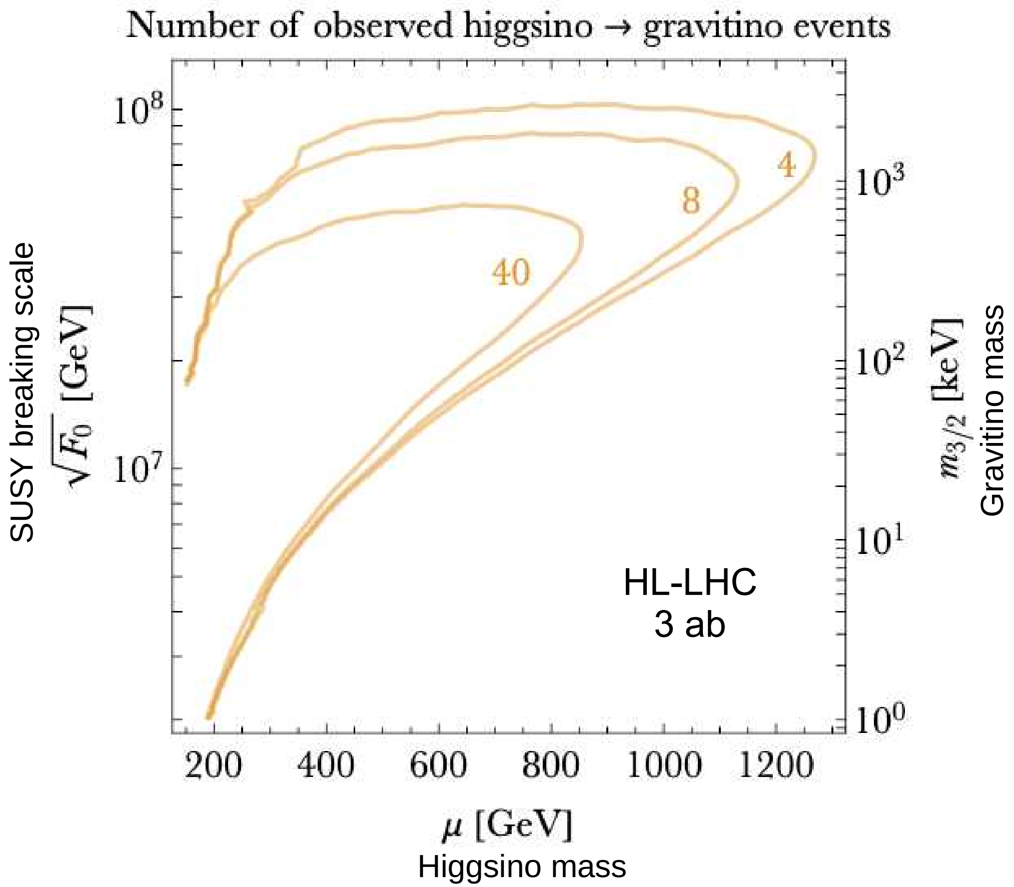




- Big boost in sensitivity from this production mechanism, which is only possible at high energy experiments (i.e. LHC)

Higgsino to gravitino

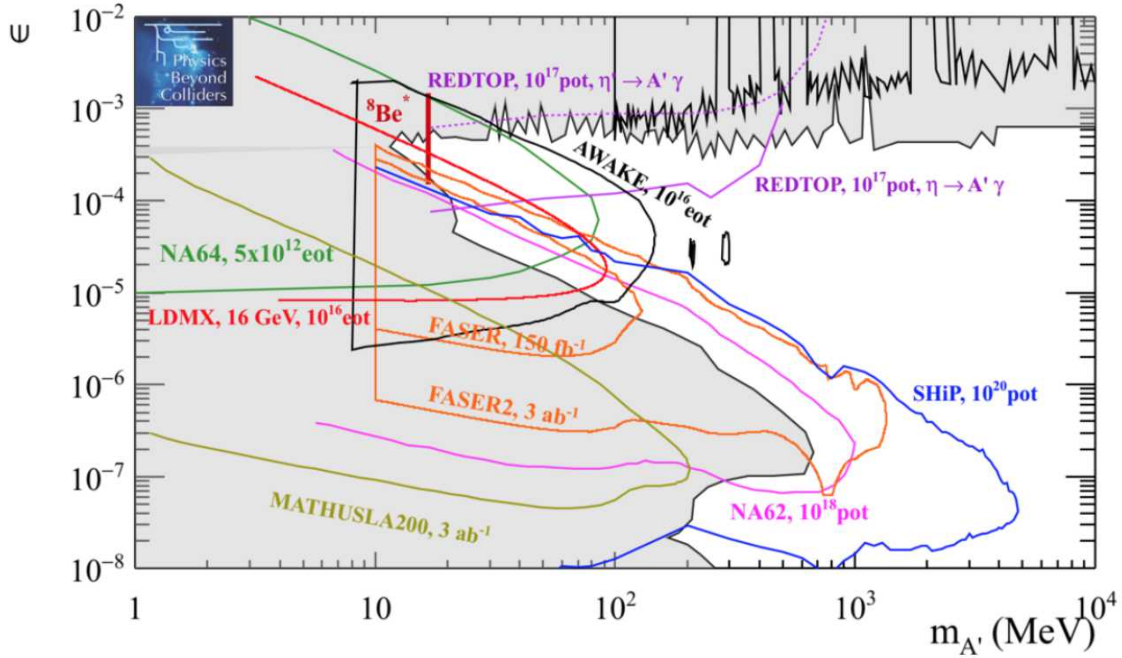




For higgsino lifetimes ranging from smaller than 10m to larger than 10^5 m, MATHUSLA could provide a discovery of new physics with electroweak cross-sections for which the HL-LHC would fail to discover new physics.

Dark photon only

PBC BSM working group report 1901.09966



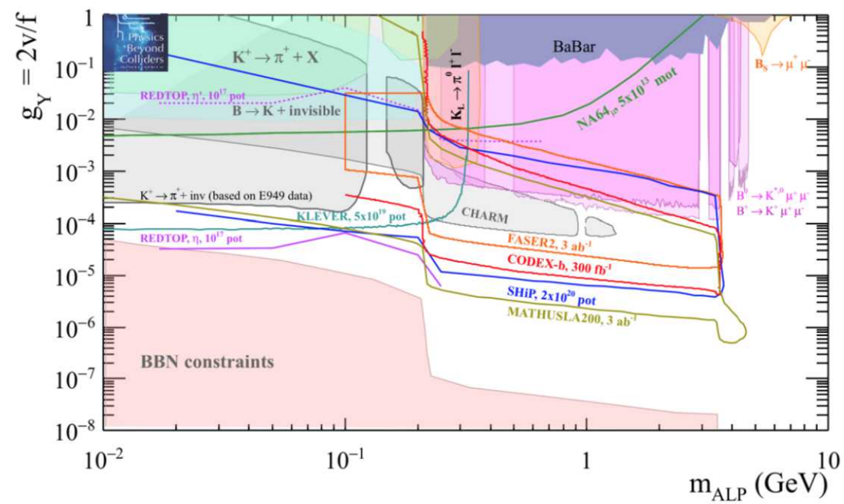
MATHUSLA sensitivity for dark photon signatures is not great, however this estimate neglects high rate of secondary production of dark photons in the main detector calorimeters etc.

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

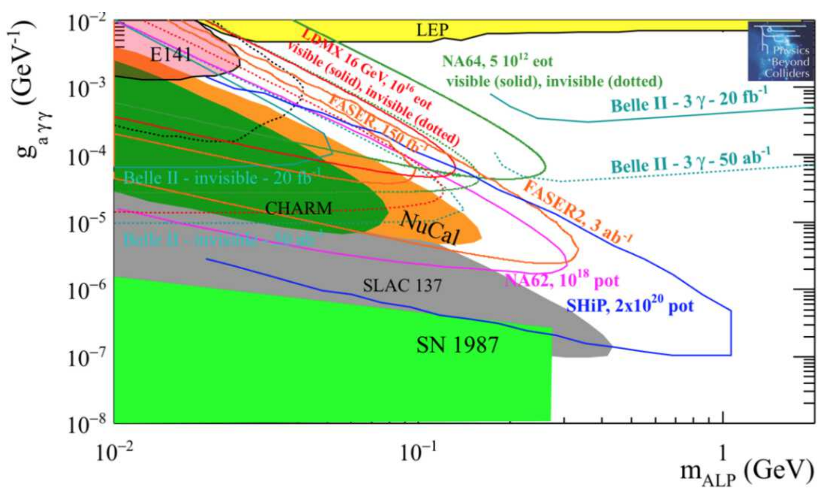
Axion-Like Particles

PBC BSM working group report 1901.09966

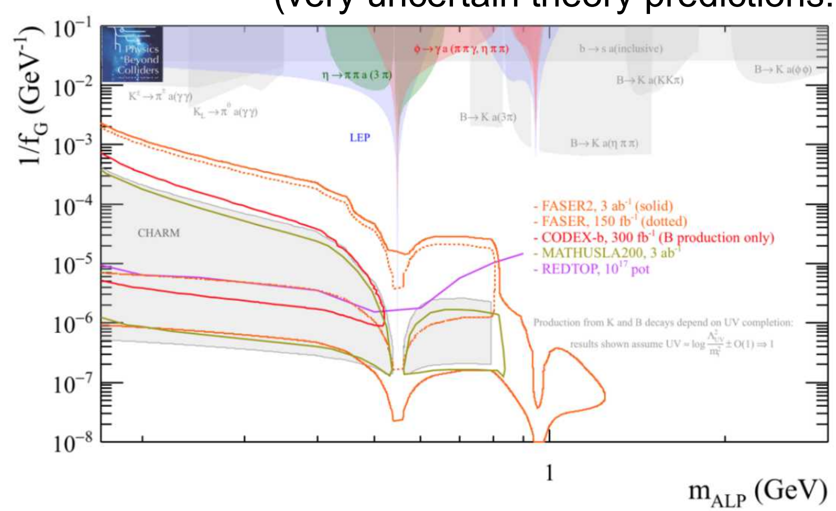
Pure fermion coupling



Pure photon coupling



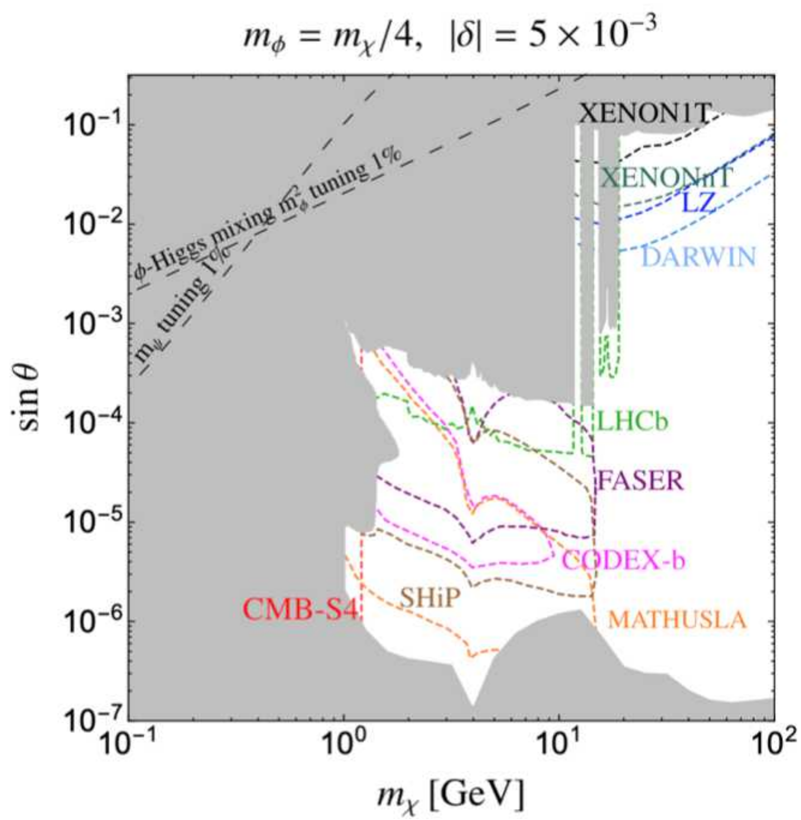
Pure gluon coupling
(very uncertain theory predictions!)



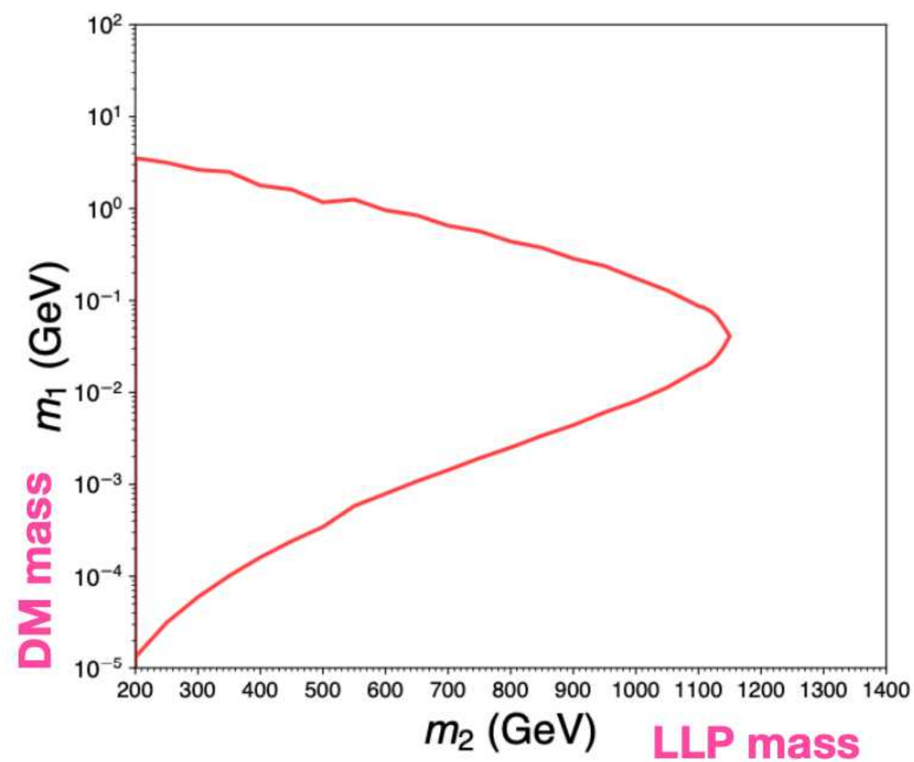
Dark Matter

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



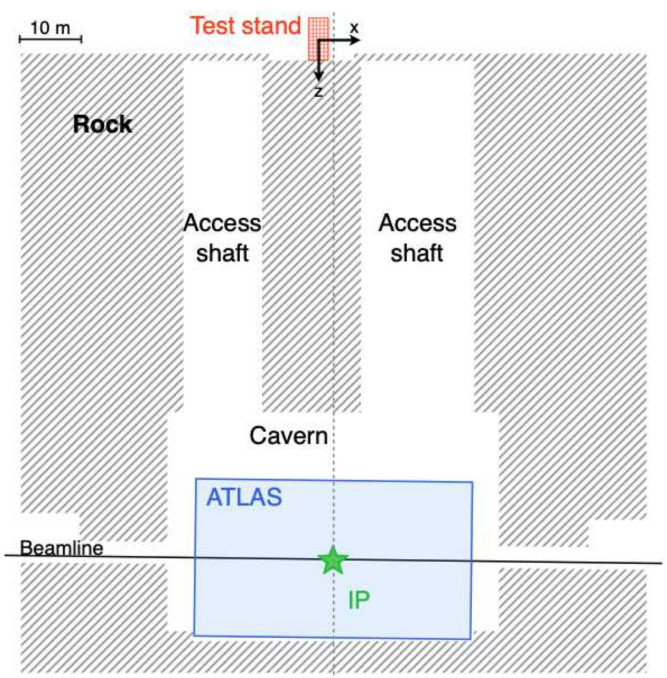
MATHUSLA @ CMS reach for Freeze-In DM (1908.11387, No, Tunney, Zaldivar).

MATHUSLA Test Stand

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

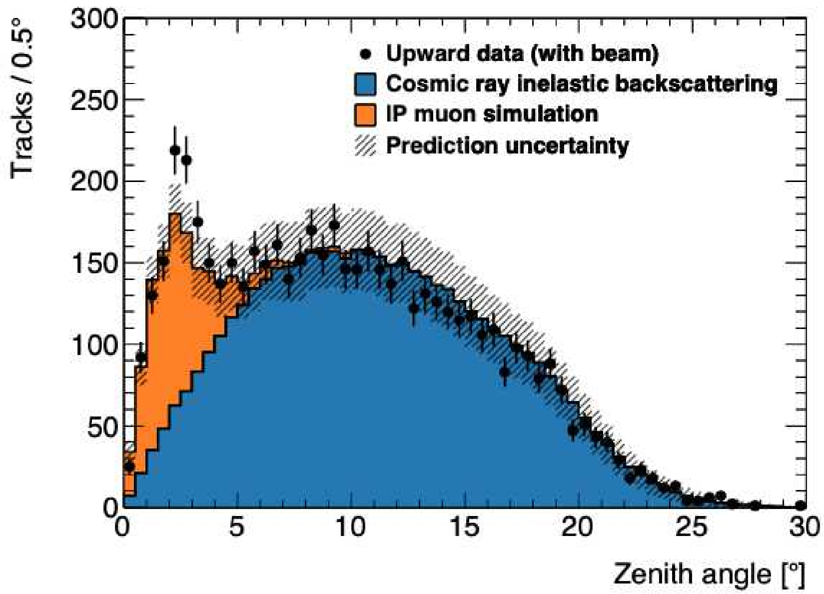
A MATHUSLA test stand was operating on the surface above the ATLAS pit in 2018

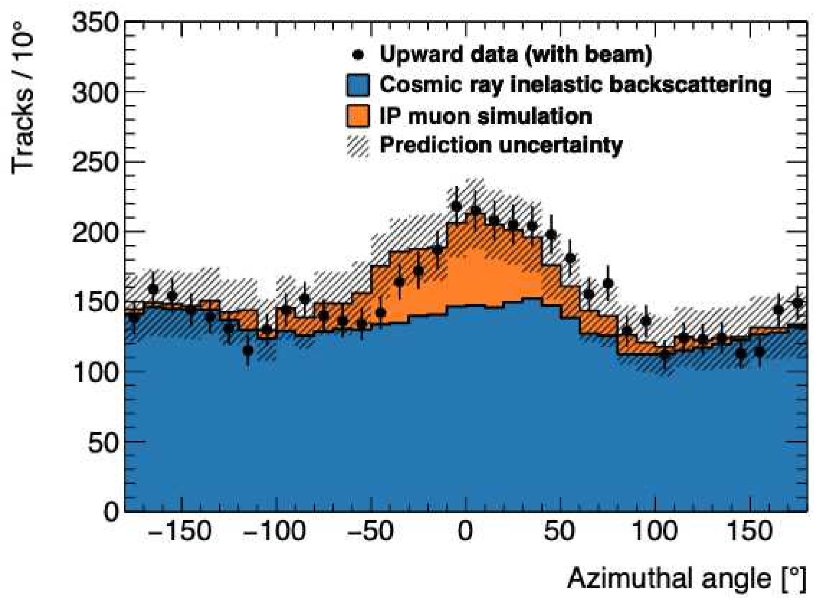
- Primary goal was to evaluate background sources from cosmic rays and the LHC
- Results published in 2021



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

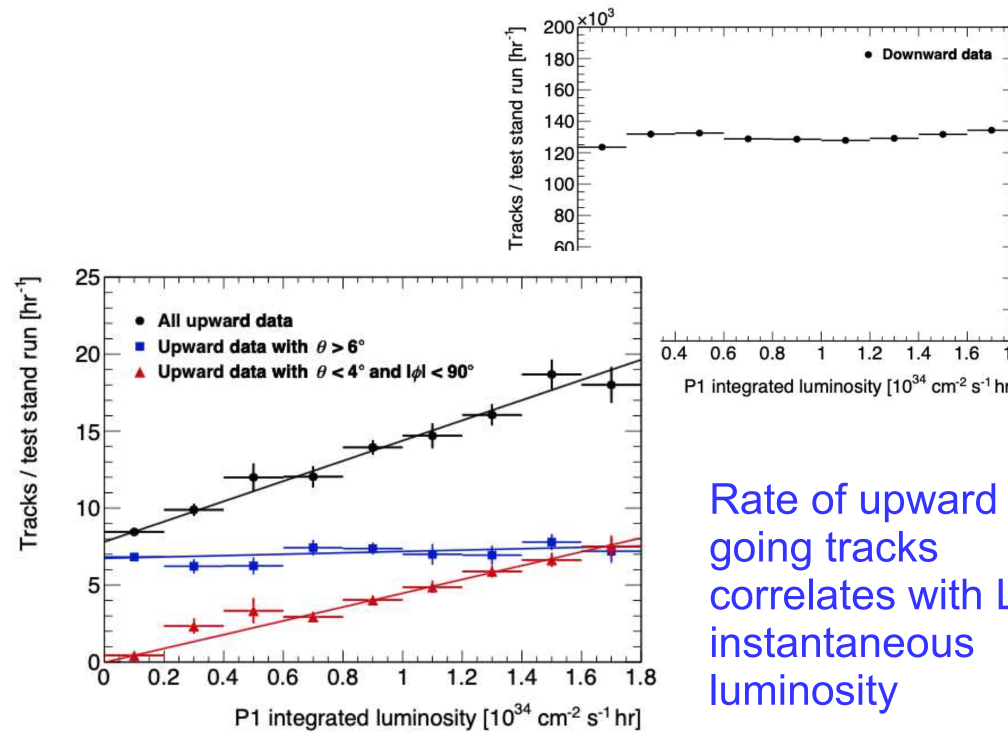
Nucl.Instrum.Meth.A 985 (2021) 164661
2005.02018 [physics.ins-det]





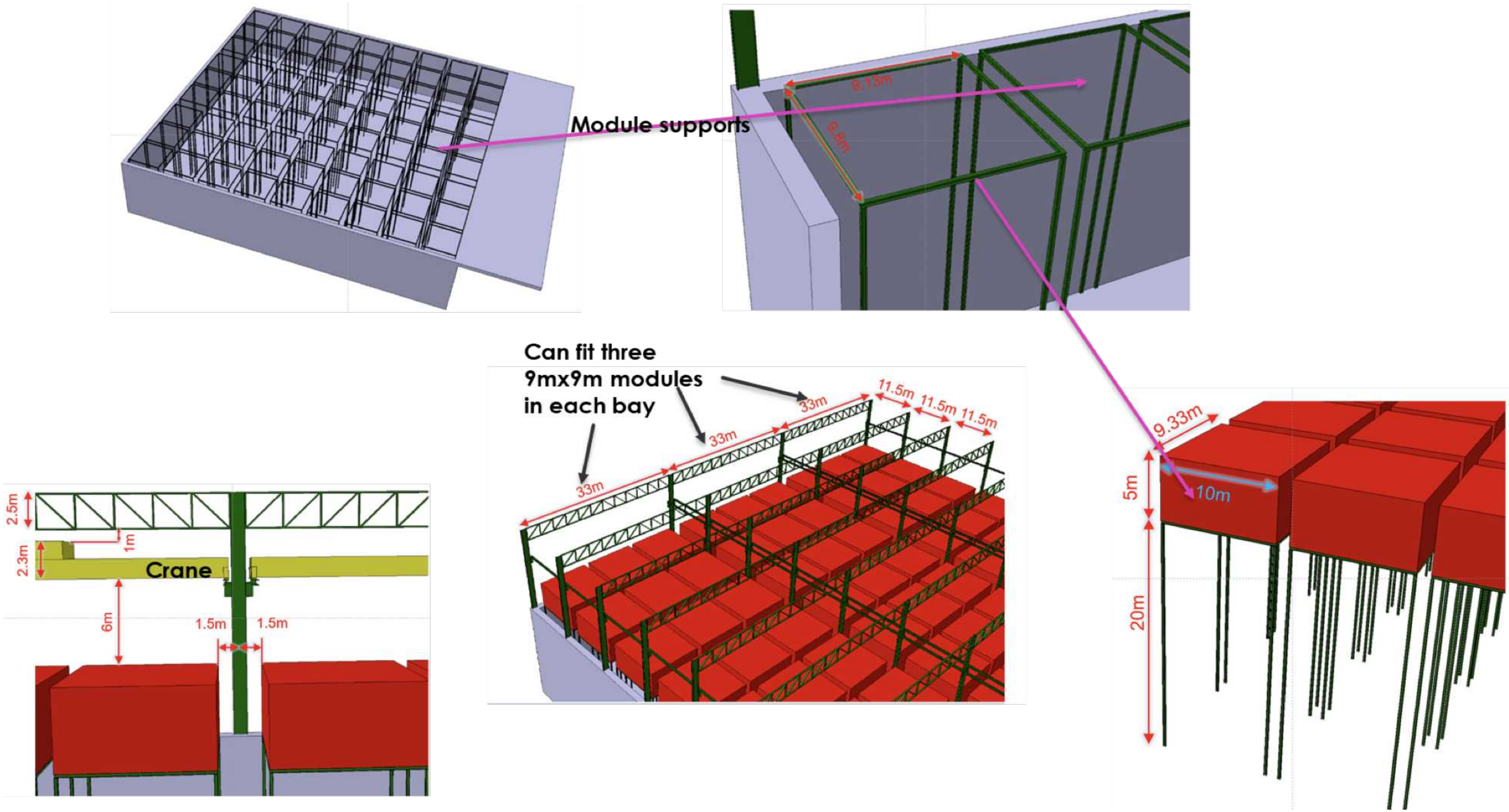
Test stand could see the LHC very clearly!

- Good agreement with the cosmic ray and IP simulation



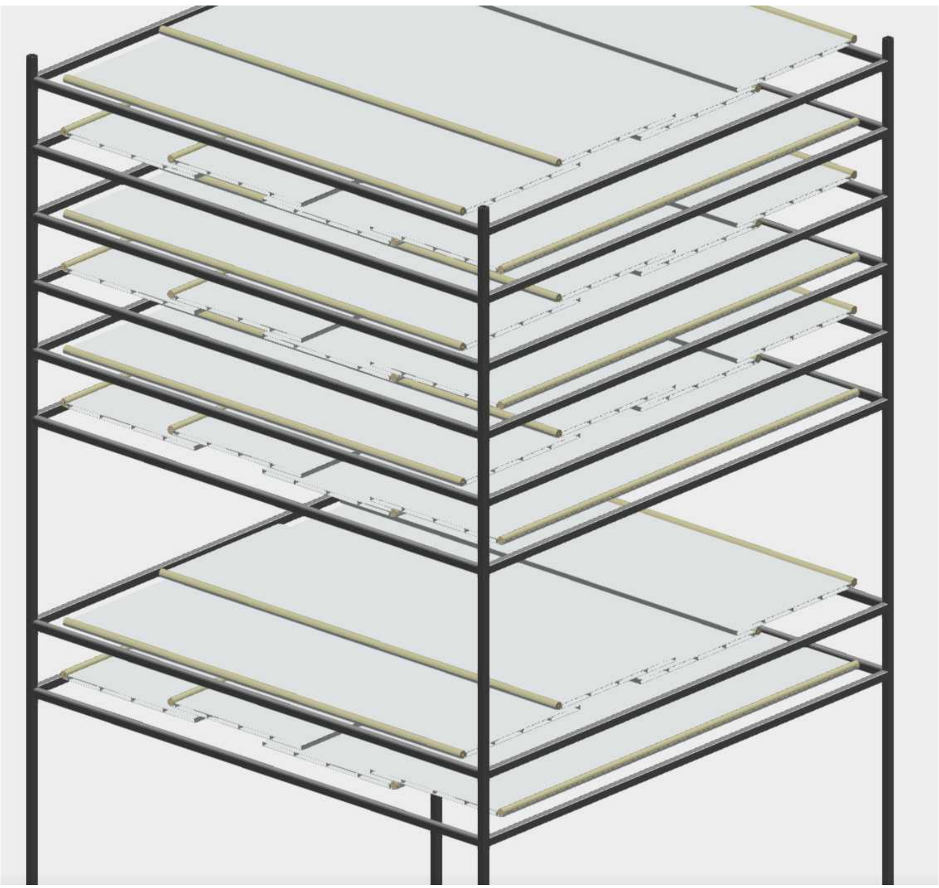
Rate of upward going tracks correlates with LHC instantaneous luminosity

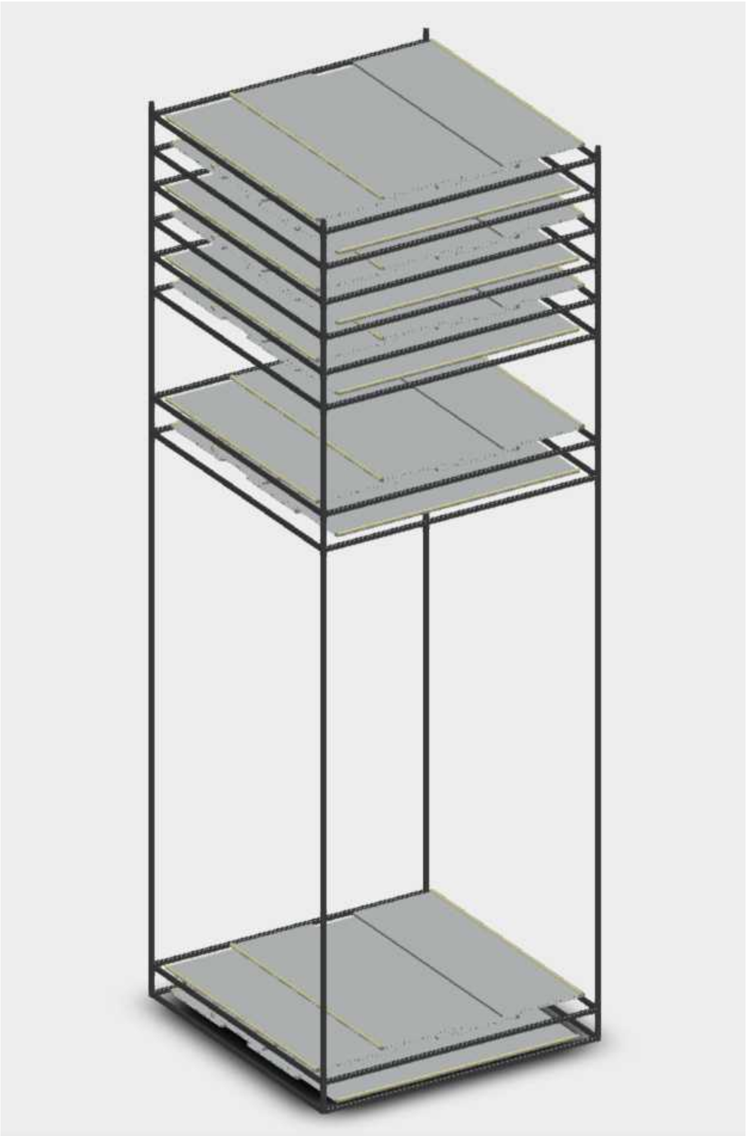
MATHUSLA



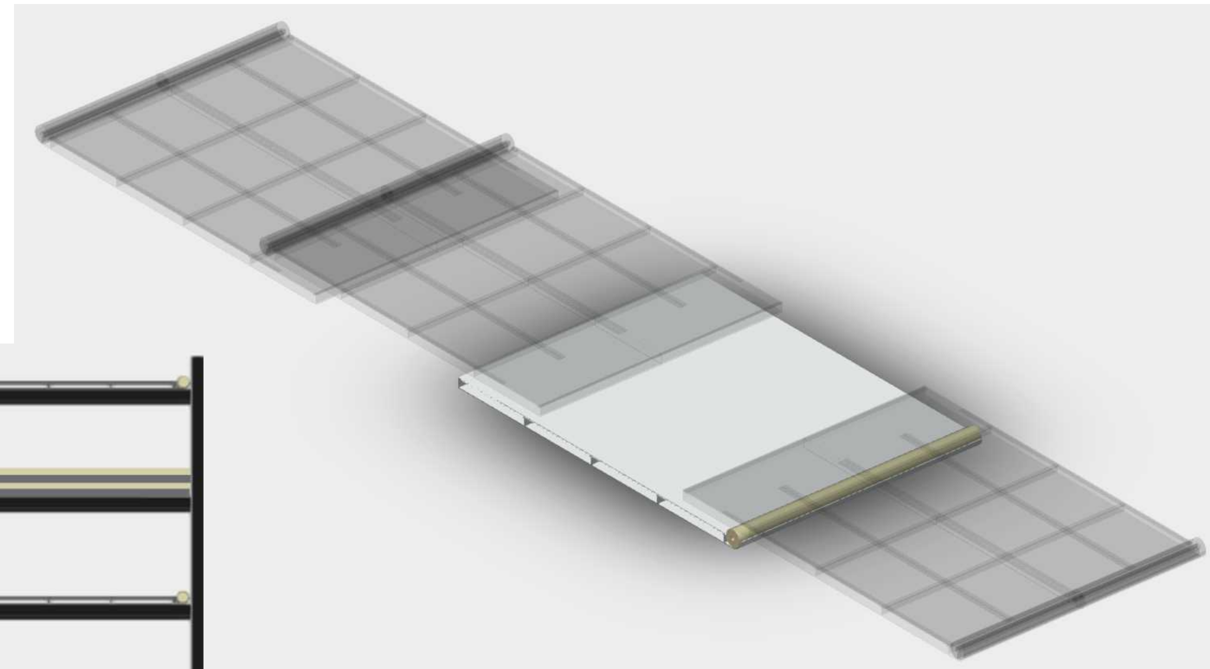
Module supports
9.13m
9.8m
Can fit three 9mx9m modules in each bay
33m
33m
33m
11.5m
11.5m
11.5m
9.33m
10m
5m
20m
2.5m
1m
2.3m
Crane
6m
1.5m
1.5m

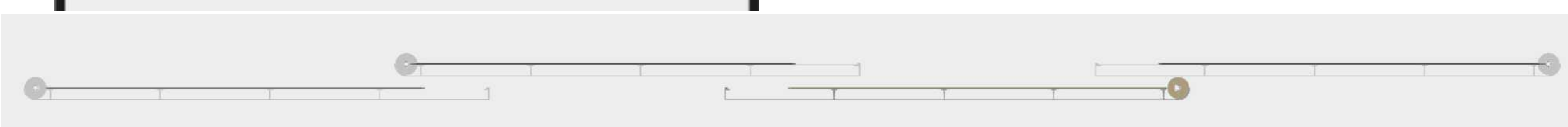
Work is in progress towards the detailed layout of the detector

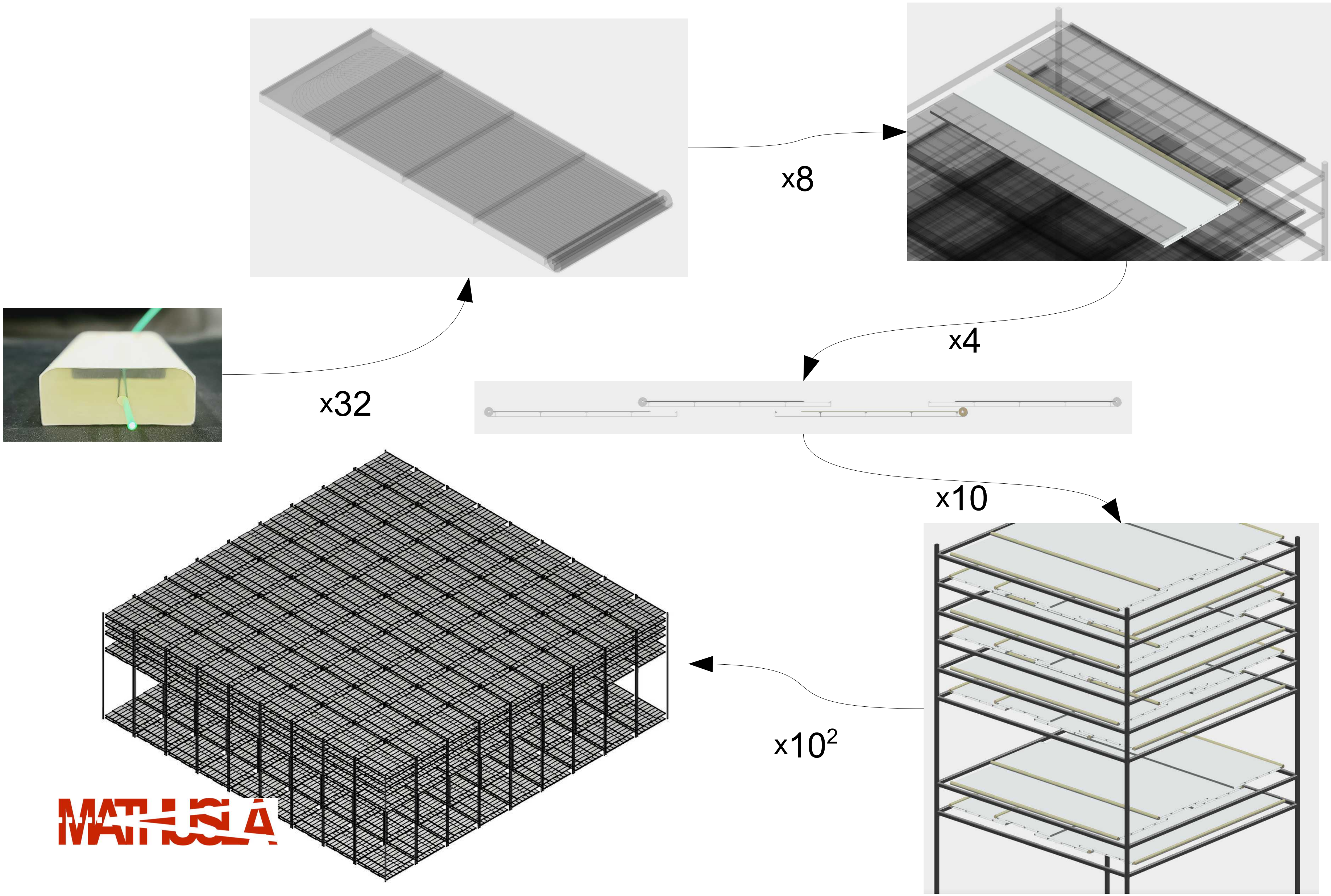




CAD by Rodney Schnarr (Carleton)



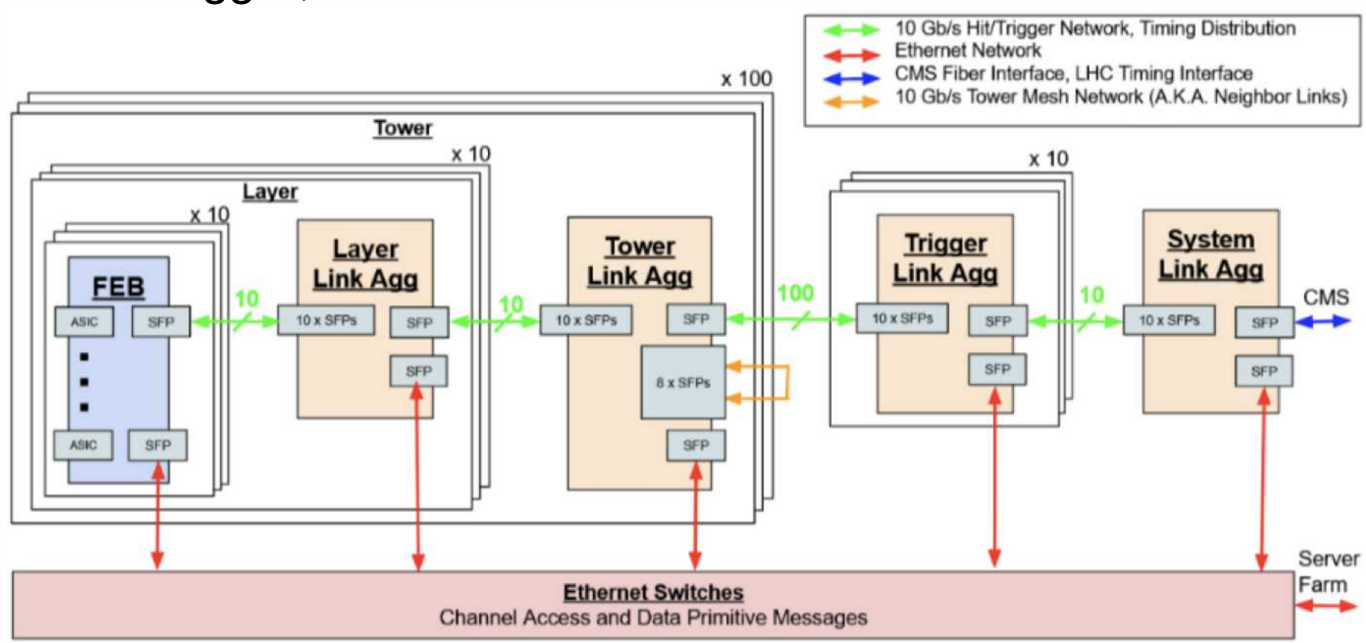



x8
x4
x32
x10
x10^2

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

References

John Paul Chou, David Curtin, and H.J. Lubatti. New detectors to explore the lifetime frontier. Physics Letters B, 767:29–36, Apr 2017.

Cristiano Alpigiani et al. A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS, 2018, arXiv:1811.00927.

David Curtin and Michael E. Peskin. Analysis of long-lived particle decays with the MATHUSLA detector. Physical Review D, 97(1), Jan 2018.

David Curtin et al. Long-lived particles at the energy frontier: the MATHUSLA physics case. Reports on Progress in Physics, 82(11):116201, Oct 2019.

Imran Alkhatib. Geometric Optimization of the MATHUSLA Detector, 2019, arXiv:1909.05896.

Cristiano Alpigiani. Exploring the lifetime and cosmic frontier with the MATHUSLA detector, 2020, arXiv: 2006.00788.

M. Alidra et al. The MATHUSLA Test Stand, 2020, arXiv:2005.02018.

Jared Barron and David Curtin, On the Origin of Long-Lived Particles, 2020, arXiv:2007.05538.

Cristiano Alpigiani et al. An Update to the Letter of Intent for MATHUSLA: Search for Long-Lived Particles at the HL-LHC, 2020, arXiv:2009.01693.