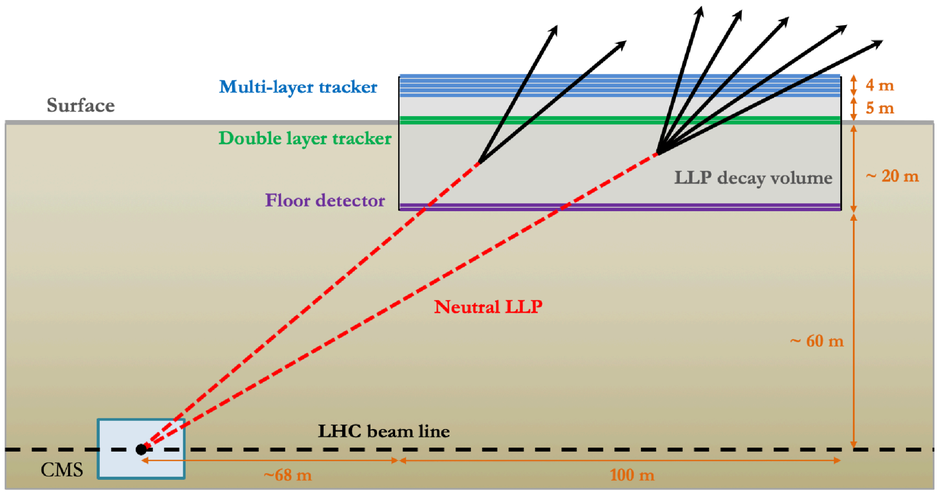
MATHUSLA LLP Detector Proposal: Current Status and Prospects

Quarks "2020" Virtual Workshop
New Physics at the Intensity Frontier

8 June 2021

David Curtin

UNIVERSITY OF TORONTO



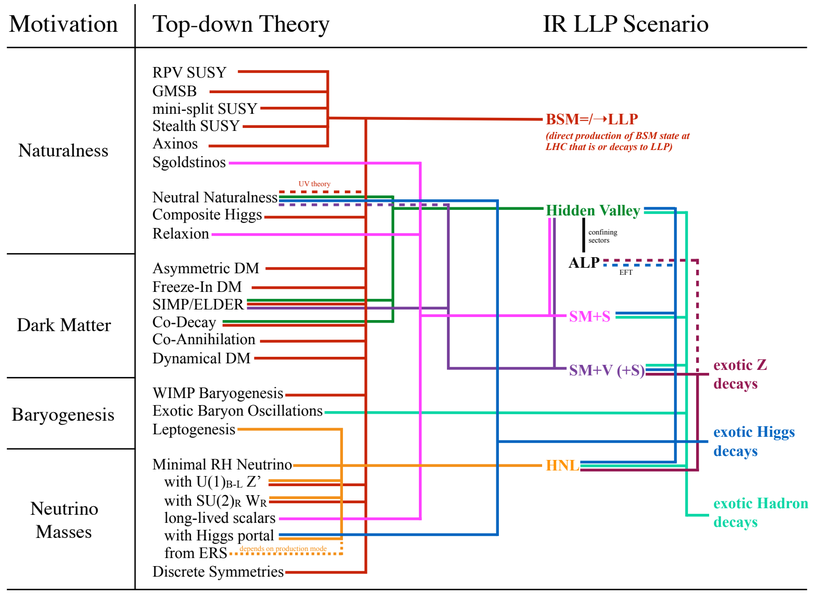
mathusla-experiment.web.cern.ch

Introduction

At this workshop, motivation for LLPs and FIPs needs no introduction:

- motivated by analogy to SM long-lived states
- motivated by the big problems of particle physics: Hierarchy Problem, DM, Baryogenesis, m_ν…

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case 1806.07396



LHC is crucial machine to access LLPs: offers both **intensity as well as mass reach**.

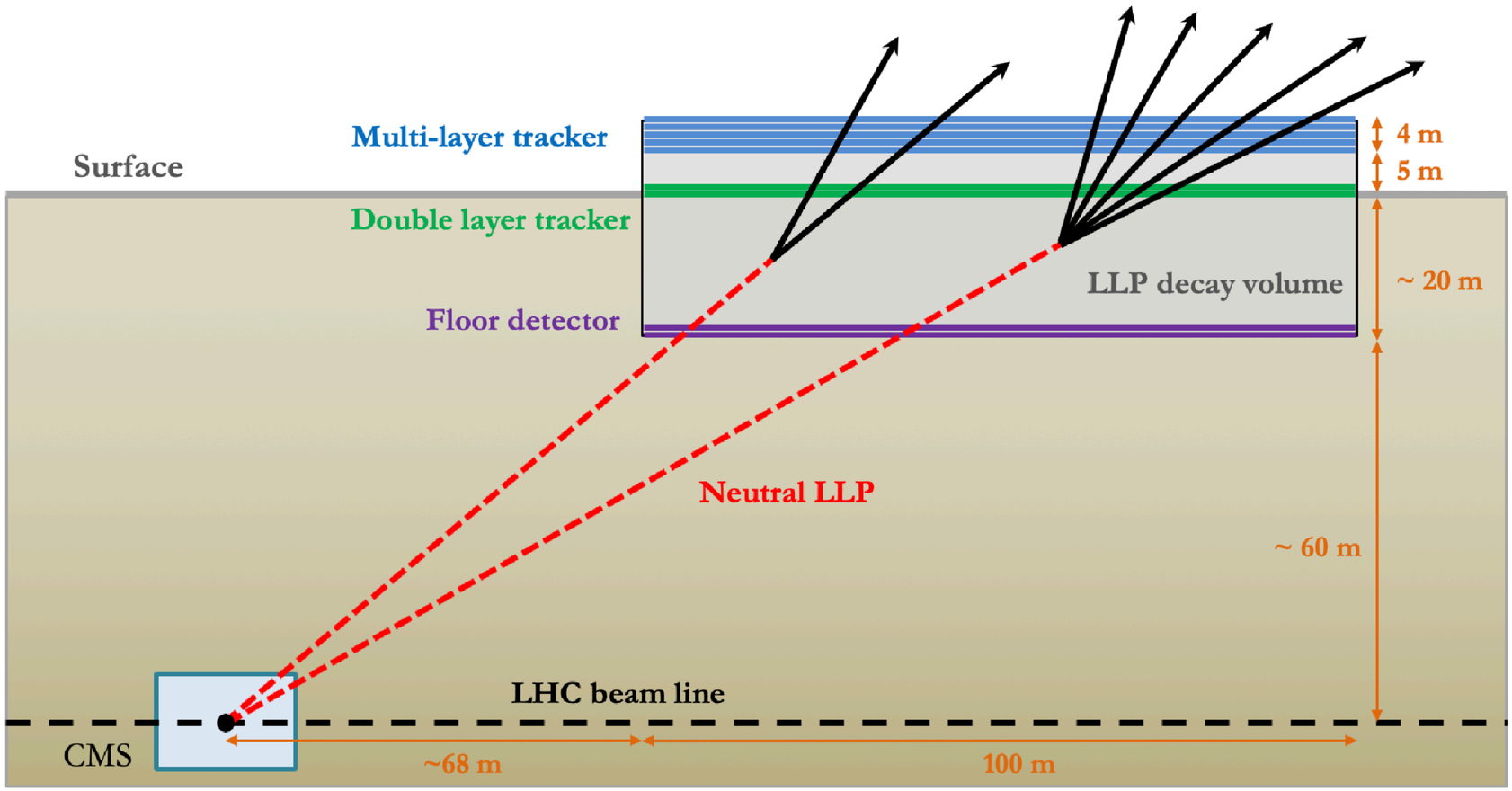
LLP searches @ LHC are booming, but have to battle complicated backgrounds and trigger limitations, especially for **long lifetimes up to the BBN limit (1s).**

This motivates a dedicated LLP detector for the LHC with high acceptance and low background!

Chou, DC, Lulbatti 1606.06298

MATHUSLA: a large-scale LLP detector for the HL-LHC

Build a big empty box with trackers on CERN-owned land near CMS.
LLPs that decay inside will be reconstructed as displaced vertices.



Stringent geometrical + timing LLP recon criteria and ~100m of rock shielding allow for LLP searches in "near-zero background environment"

MATHUSLA Collaboration

International collaboration including members & institutions from US, Canada, Chile, Bolivia, Mexico, Italy, Switzerland, …

TDR in progress, aim publish early 2022.

Begin MATHUSLA operation with HL-LHC!

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

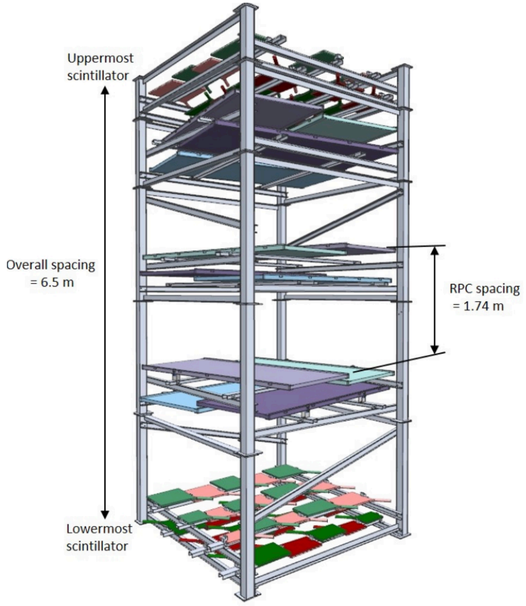
1811.00927
LHCC-I-031

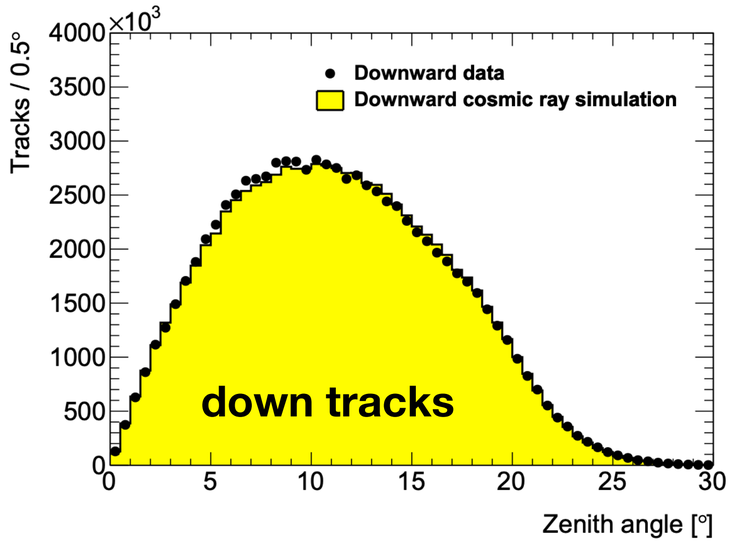
Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

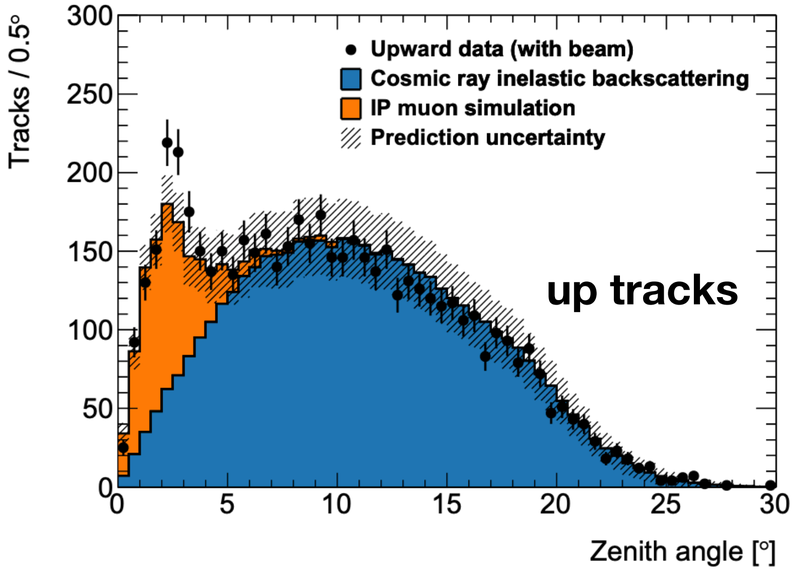
Test Stand

MATHUSLA Test Stand

Operated above ATLAS in 2018, results in 2005.02018







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

$$R_{\text{up-to-down}} = \frac{(\text{Number of upward tracks})_{\text{data, no beam}}}{(\text{Number of downward tracks})_{\text{data, no beam}}} = (7.0 \pm 0.2) \times 10^{-5}$$

LOI Update

Sep 2020: Letter-of-Intent Update

Summarizes progress since the LOI:

- Realistic detector geometry: 1/4 the size of MATHUSLA200, same sensitivity
- Updated detector design: scintillators instead of RPCs
- Some more tracking layers to be on the safe side
- Background studies calibrated by test stand data
- Next steps

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

MATHUSLA

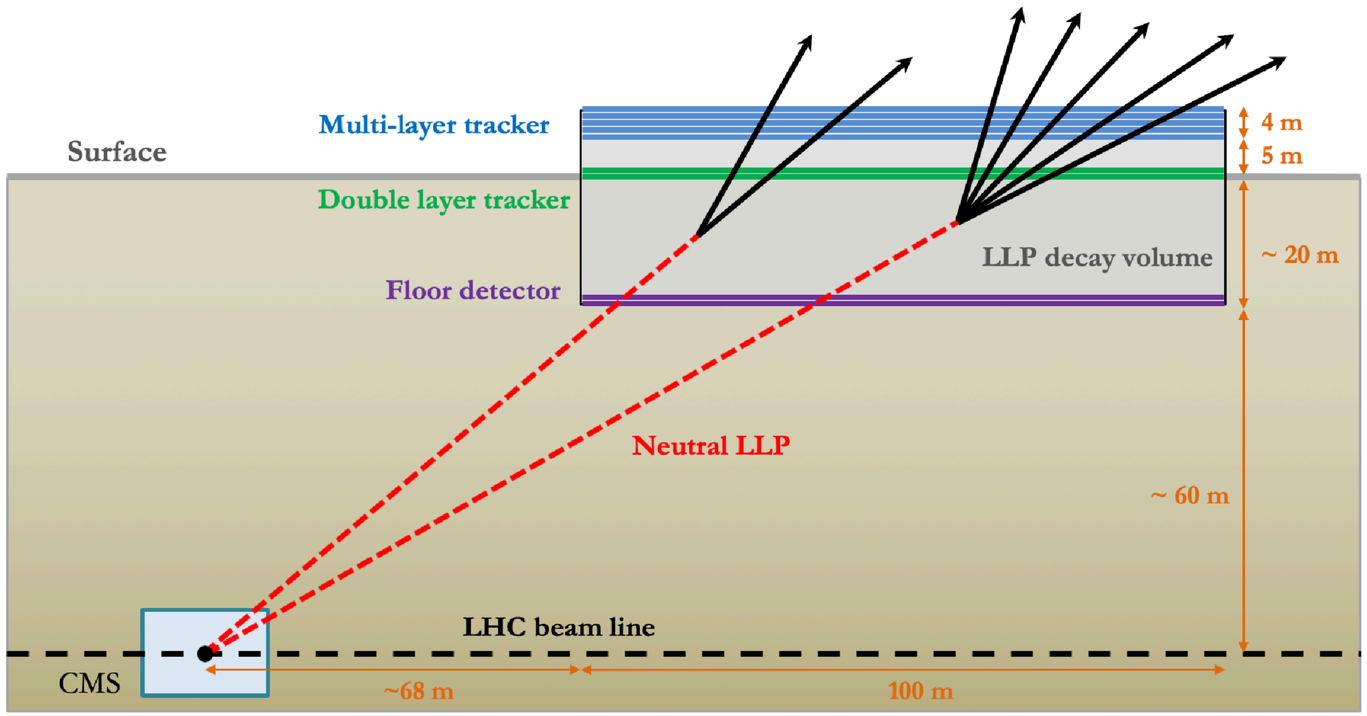
mathusla-experiment.web.cern.ch

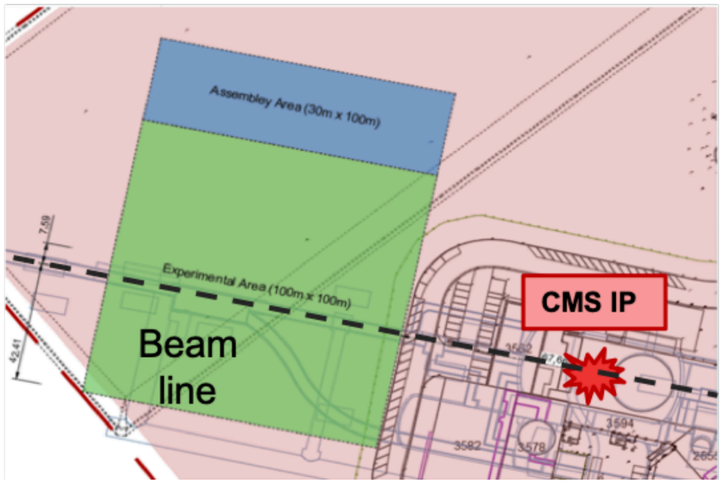
Cristiano Alpigiani,[1] Juan Carlos Arteaga-Velázquez,[2] Austin Ball,[3] Liron Barak,[4] Jared Barron,[5] Brian Batell,[6] James Beacham,[7] Yan Benhammo,[4] Karen Salomé Caballero-Mora,[8] Paolo Camarri,[9] Roberto Cardarelli,[9] John Paul Chou,[10] Wentao Cui,[5] David Curtin,[5] Miriam Diamond,[5]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

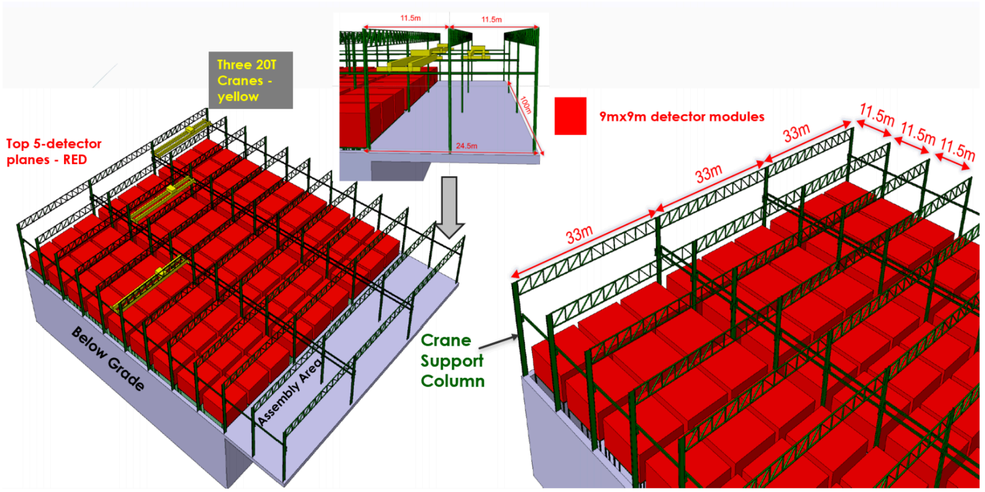
2009.01693
LHCC-I-031-ADD-1

MATHUSLA @ CMS

CERN Engineers conducted site-specific engineering study to identify location for partially **excavated** decay volume on CERN-owned land, and exploratory design of building structure..







Updated geometry compared to earlier benchmarks:

100m x 100m x 25m decay volume,

displacement from IP is 70m horizontally, 60m vertically

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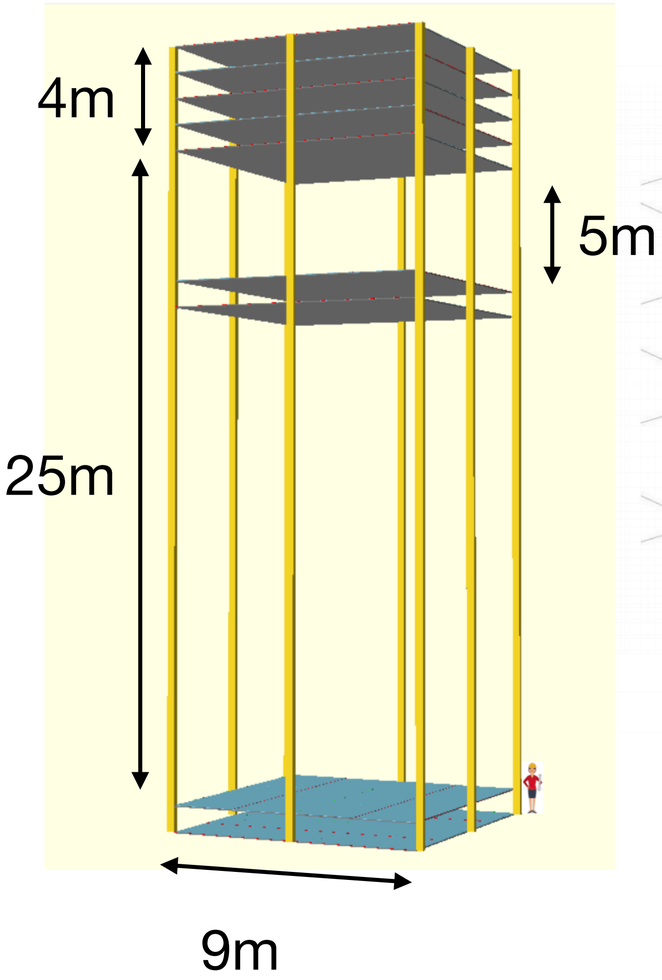
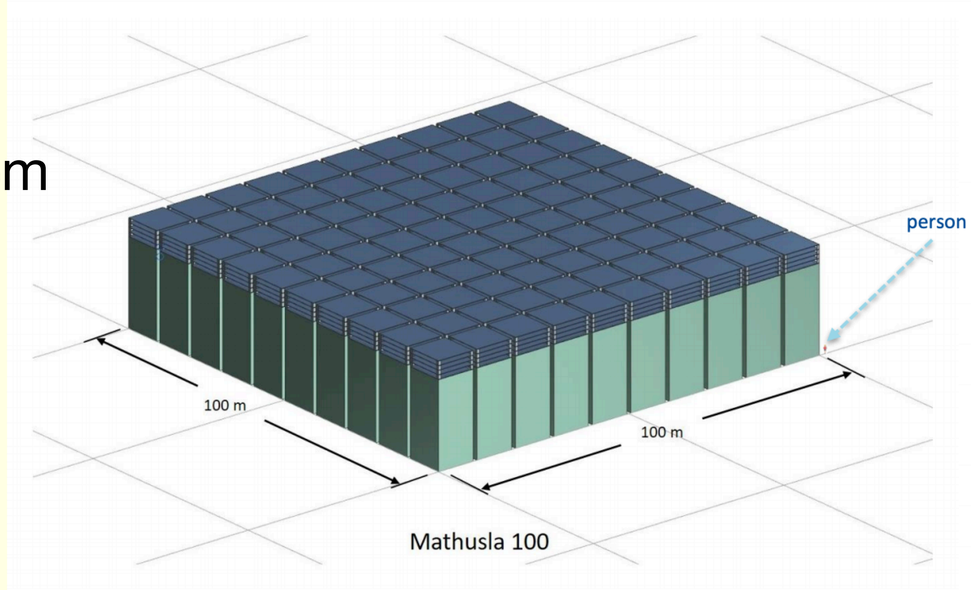
Modular Detector Design





- Preliminary design!
- added floor & middle tracking layers. (?)
- 100 modules, 9m x 9m, 1m gap
- Tracker technology is extruded scintillators: bars of length ~ 2.5m, width ~5cm, thick ~2cm + central wavelength shifting fiber, readout by SiPM.

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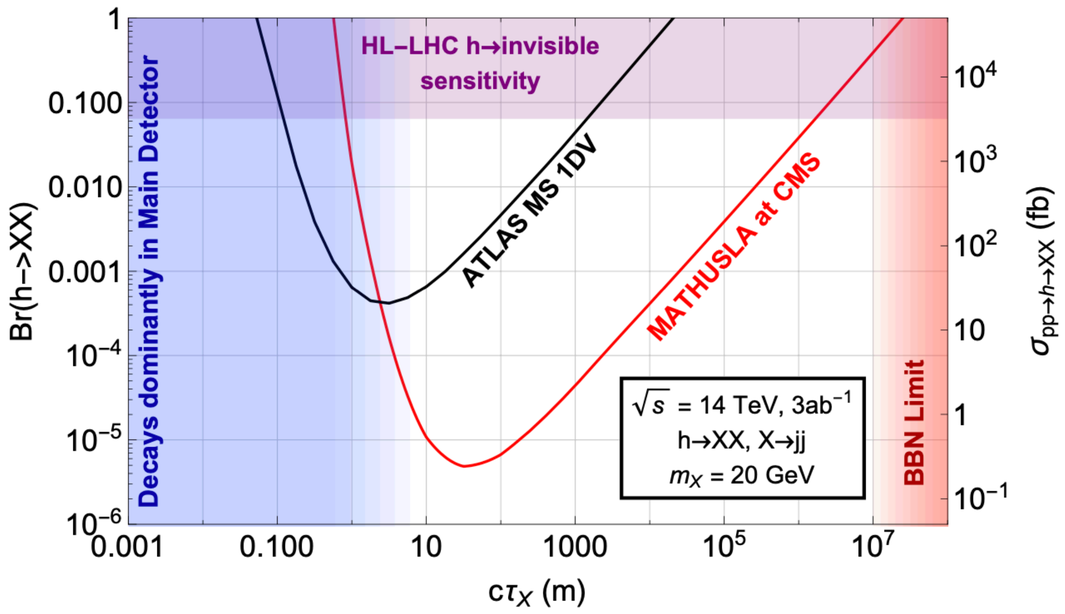
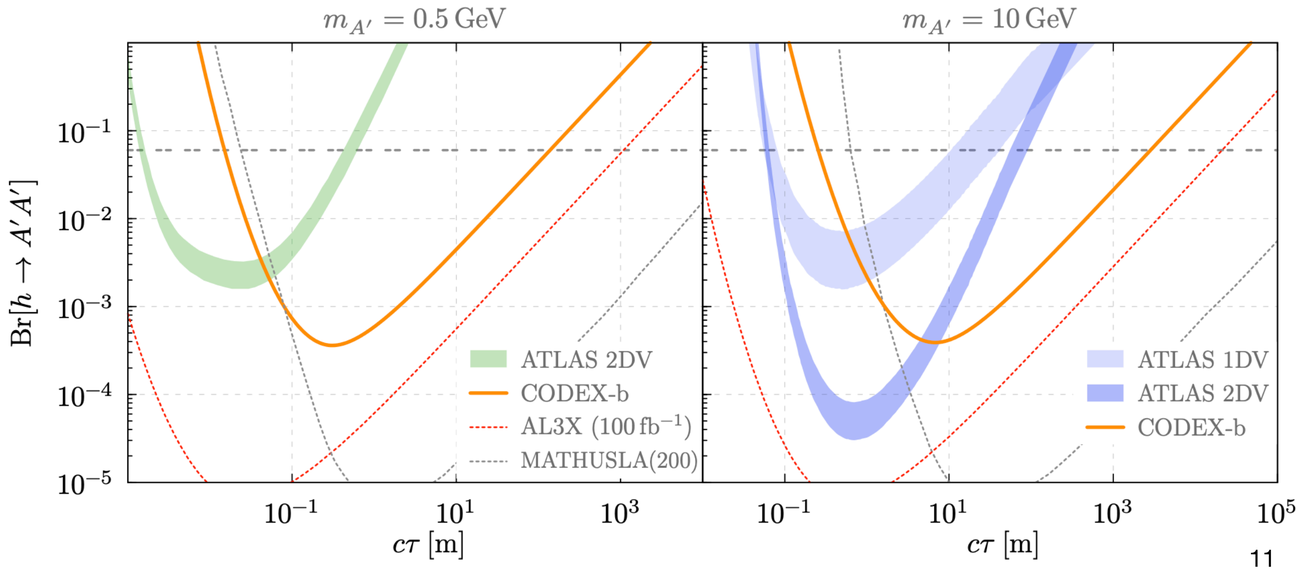
LLP Sensitivity: $h \to \mathrm{LLP}$





MATHUSLA@CMS = MATHUSLA200!

Showing sensitivity for $\mathrm{Br}(h \to \mathrm{LLP})$.

Familiar result: orders of magnitude improvement over main detector possible, especially for hadronically decaying or light LLPs.

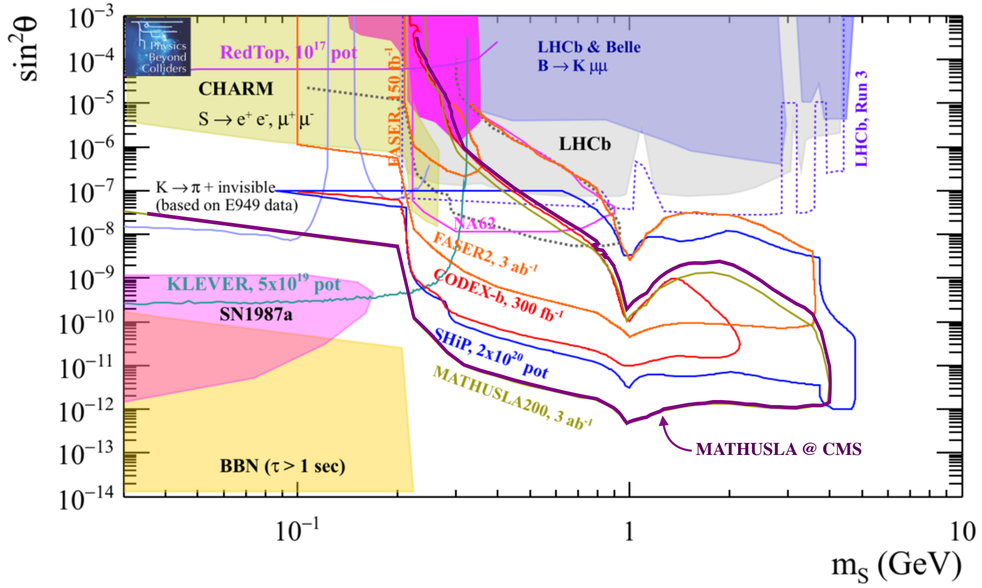
← Comparing MATHUSLA and CODEX-b.

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

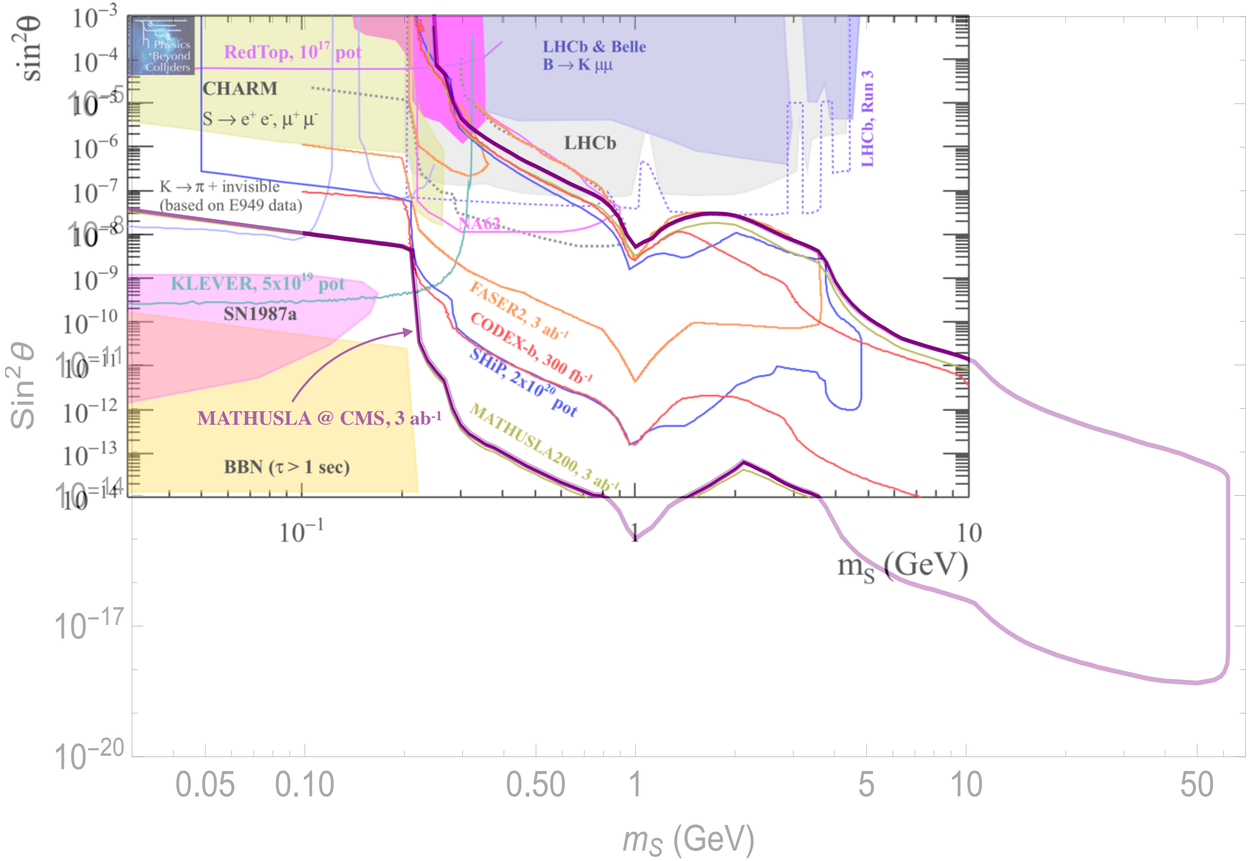
LLP Sensitivity: SM+S

MATHUSLA update 2009.01693
PBC 1901.09966

LLP production in meson decays



LLP production in meson and higgs decays



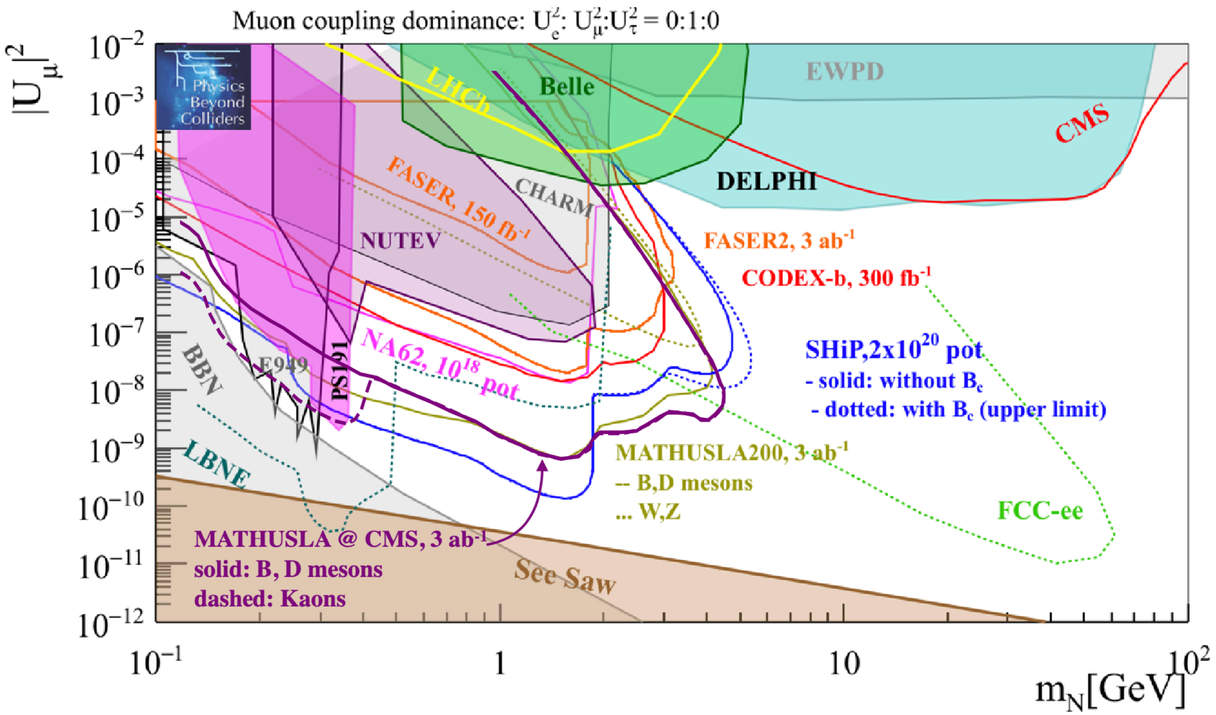
LLP production in exotic meson decays.
Results from PBC report 1901.09966 ~ unchanged.

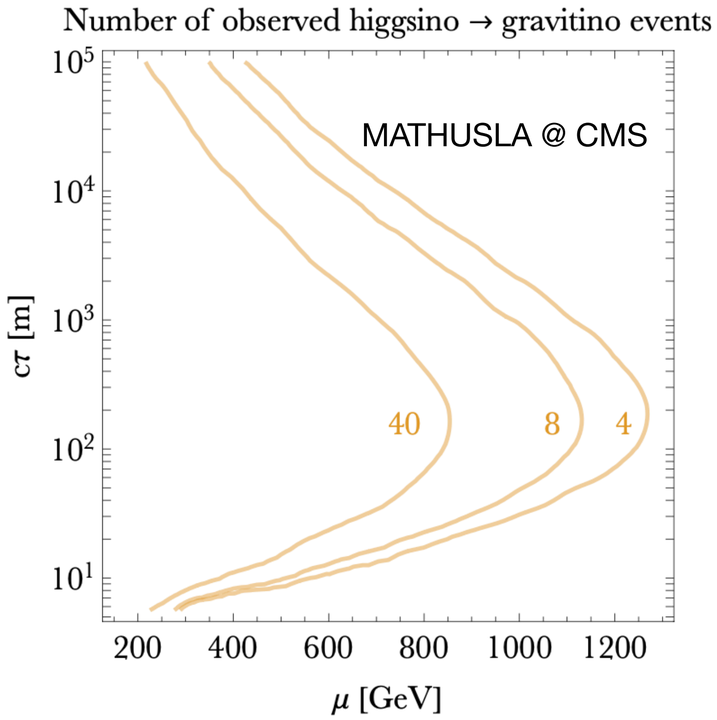
FASER + CODEX-b + MATHUSLA allows LHC to cover parameter space very nicely.

Huge sensitivity boost if LLPs are produced in exotic higgs decays (1% on right) as well: **the LHC advantage!**

Note these sensitivity estimates do not take reconstruction efficiency in the detector into account. Topic of ongoing study!

LLP Sensitivity: RHN and Higgsinos





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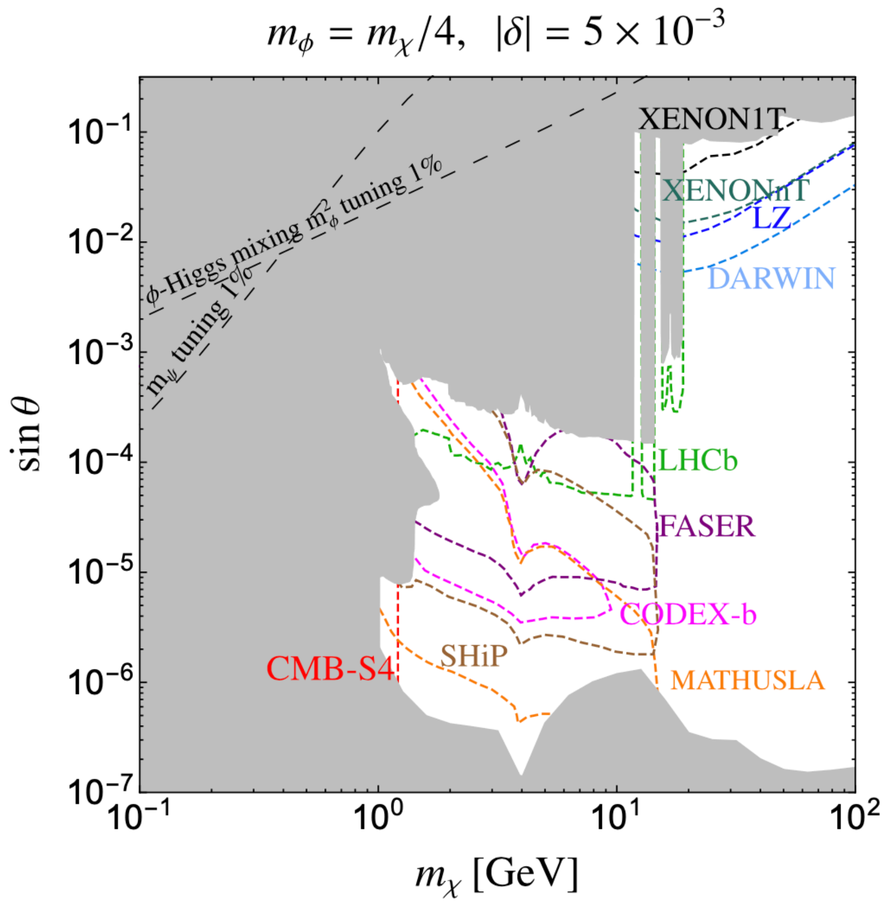
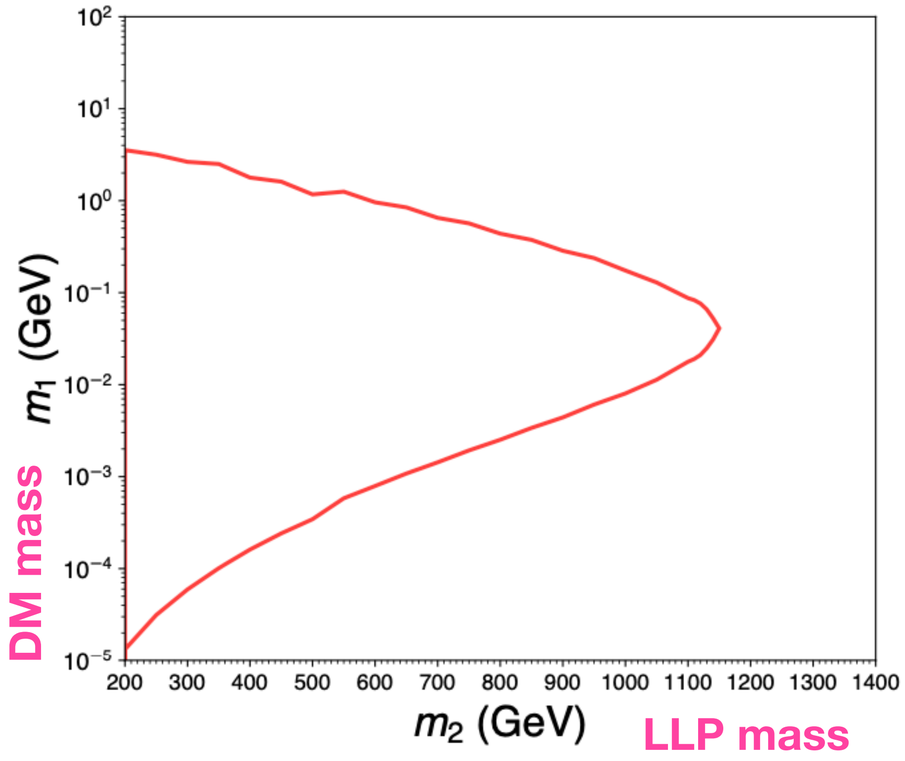
LLP searches = DM searches!

In many DM scenarios, properties of LLP in primordial plasma control 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 experiment!

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

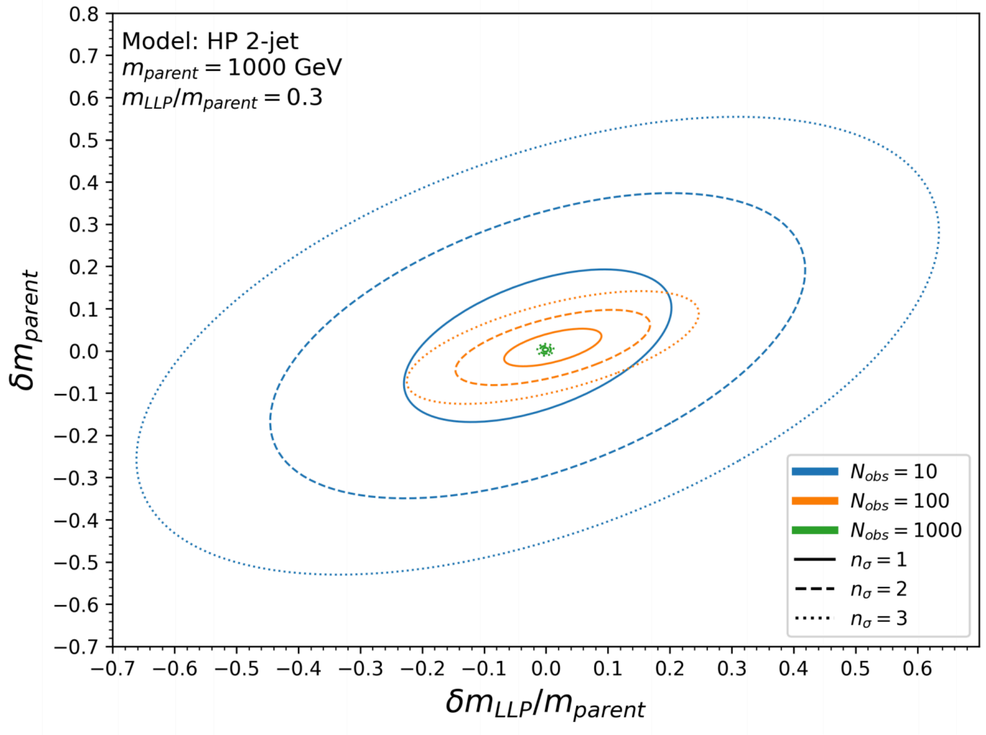
Theory Updates

CMS Integration: Characterizing the new Physics

MATHUSLA can supply L1 trigger signal to CMS → record main detector information on LLP production event!

Geometrical information in MATHUSLA gives info on **LLP boost, decay mode, invisible decay component.**

Analysis with main detector information reveals **production mode** and parameters of underlying model (**parent mass, LLP mass**) with ~ **100 observed events!**



1705.06327 DC, Peskin
1809.01683, Ibarra, Molinaro, Vogl

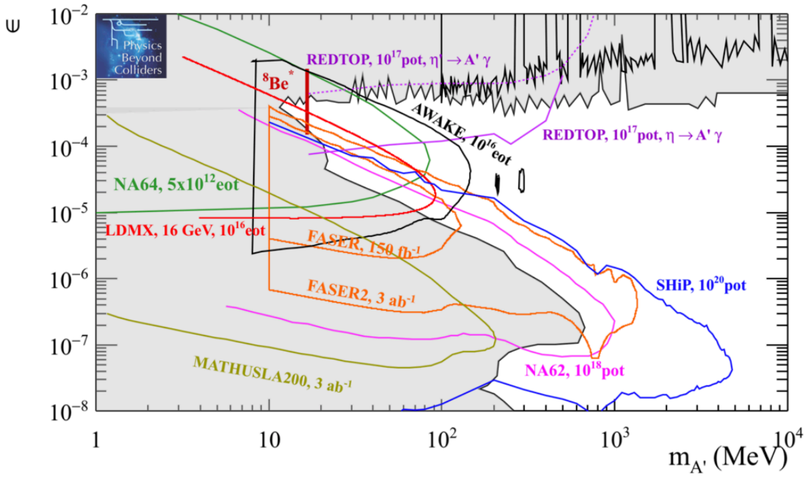
2007.05538, **Jared Barron**, DC

Secondary Production of Dark Photons

1901.09966

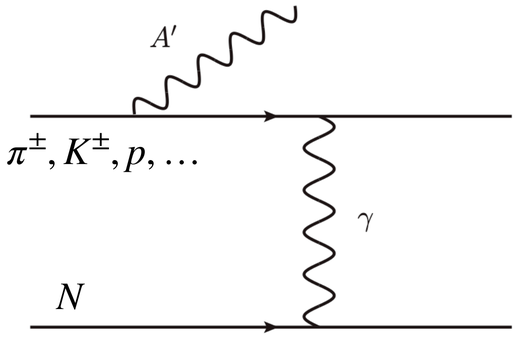
For dark-photon simplified model with only kinetic mixing

$$\mathscr{L} \supset \epsilon F_D^{\mu\nu} F_{\mu\nu} + m_A^2 A_\mu A^\mu$$



MATHUSLA seems to have **very poor sensitivity**, direct production rate too low for $c\tau \gtrsim 100\text{m}$.

However, this estimate neglected high rate of secondary production of dark photons in *main detector calorimeter*!



Exploits huge QCD rate at the LHC: approaches fixed-target-exp levels!

Unique source of LLPs at the LHC only available to external detectors!

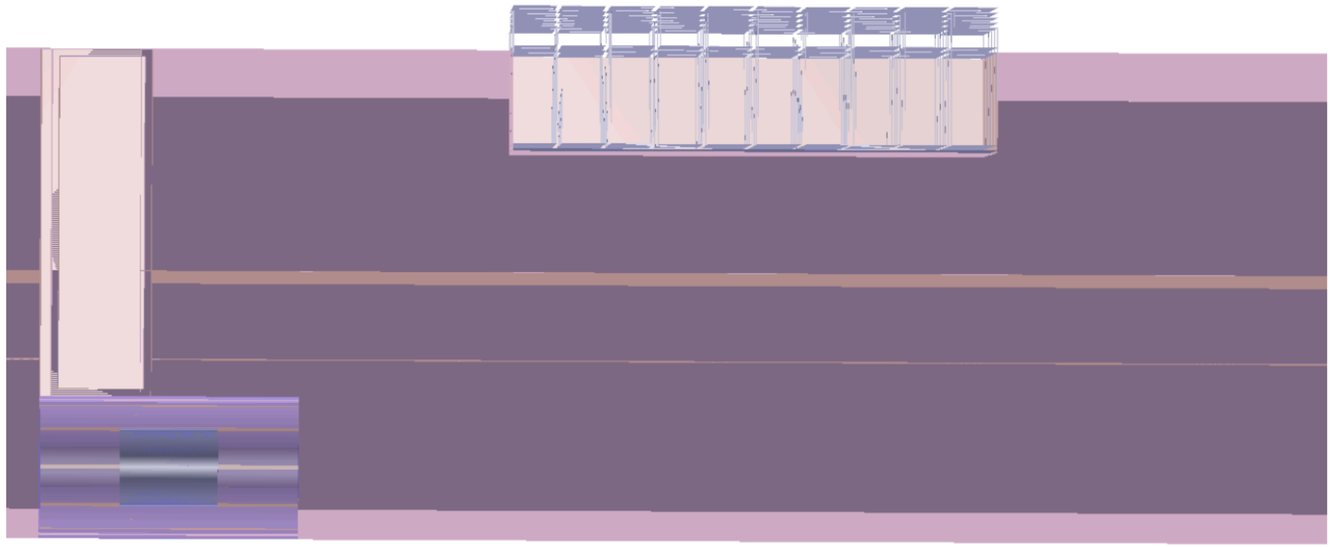
Investigation in progress with **Rachel Nguyen (UIUC grad), Josh Foster (MIT PD),** Yoni Kahn (UIUC)

Updates on

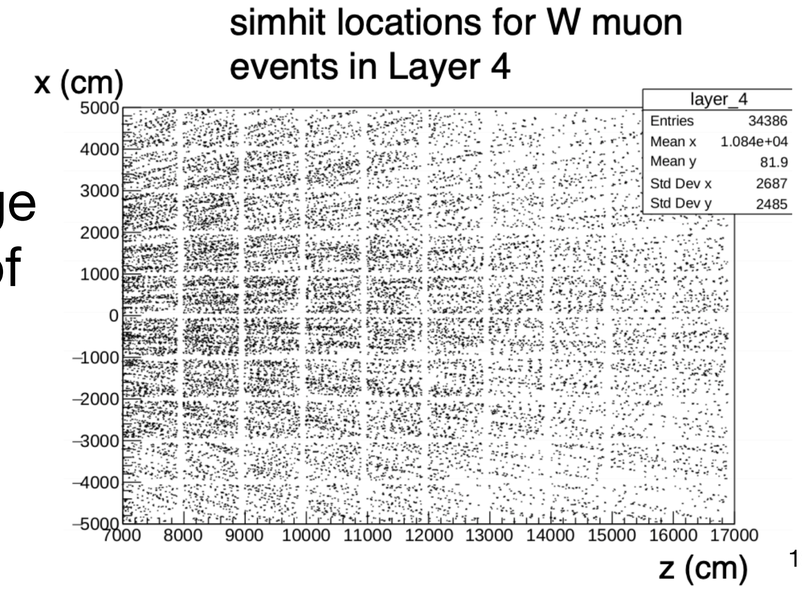
Simulation & Backgrounds

Full GEANT simulation for MATHUSLA@CMS

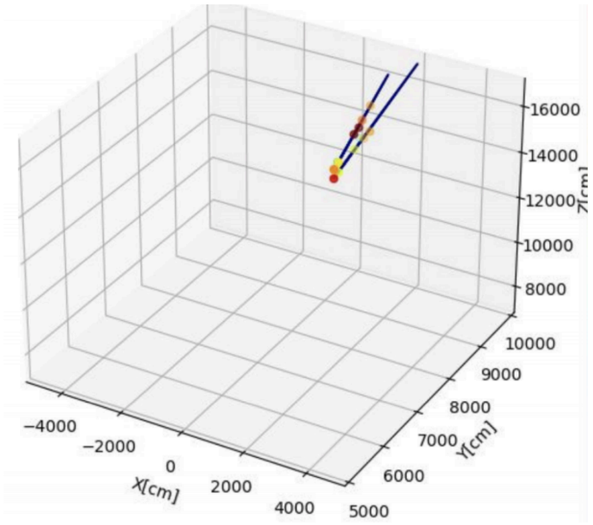
- Cavern, access shaft, CMS, rock, and detector are all modeled.
- Rock is from a geological survey (same as for test stand)
- CMS is a hollow cylinder ~10 interaction lengths of iron



Simulating passage & reconstruction of upwards muons



First pass at tracking algorithms reconstructs displaced vertices. *More sophisticated methods under develoment!*



LHC Muons

Refined earlier estimates of muon flux with more precise GEANT4 modelling of rock layers between CMS and MATHUSLA, CMS detector, and CMS cavern.

Upward muon rate is **higher** than earlier MATHUSLA200 estimates due to less shielding from LHC collision. Over HL-LHC run:

$$N_\mu \approx 2 \times 10^8$$

Not an irreducible LLP background.

In progress: full GEANT study to demonstrate rejection of this background while maintaining high LLP signal DV efficiency.

Test-bed for custom tracking algorithms in unique MATHUSLA environment!

Cosmic Backgrounds

Test stand measurements confirmed expected downward cosmic ray flux.

$$N_{\text{down}} \sim 3 \times 10^{14}$$

Does not constitute LLP background. However, cosmic rays hitting the floor can produce upwards traveling particles, mostly $e^{\pm}, p, n$:

$$N_{\text{up}} \sim 2 \times 10^{10}$$

Random crossings unlikely to produce fake LLP DVs (<< 0.01), but tiny fraction of upwards traveling particles can produce fake DV via decay to three charged tracks.

Might get O(10) from pions and muons. Rare production of K_L^0 harder to estimate. Veto strategies are available. **Working on precise estimates & studying rejection.**

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Atmospheric ν Backgrounds

LOI Update presented first full simulation study (GENIE 2.12.10) of background from inelastic scattering of atmospheric neutrinos off nuclei in the air-filled decay volume.

Using measured atmospheric neutrino flux by Frejus, get ~ 30 “fake” DVs per year of running, reduced to < 1 by imposing “slow proton veto” thanks to good timing resolution of tracker.

Neutrino flux from HL-LHC is dominated by secondary production from decaying mesons in CMS HCAL. << 1 events per year.

These results are lower than previous estimates. Neutrino background unlikely to be a problem for MATHUSLA LLP searches!

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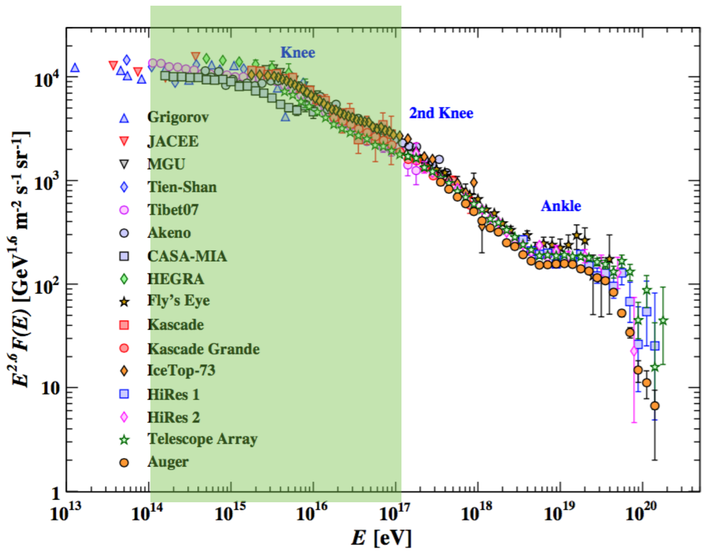
Cosmic Ray Physics Updates

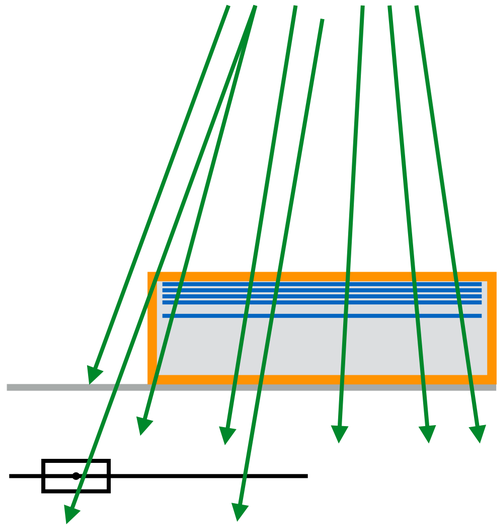
Cosmic Ray Physics

MATHUSLA can be an excellent Cosmic Ray Telescope!

Has unique abilities in CR experimental ecosystem
(precise resolution, directionality, full coverage of its area)



mostly muons at sea level



Cosmic Ray Physics white paper with CORSIKA simulation studies in final stages of write-up.

Cosmic ray searches with the MATHUSLA detector

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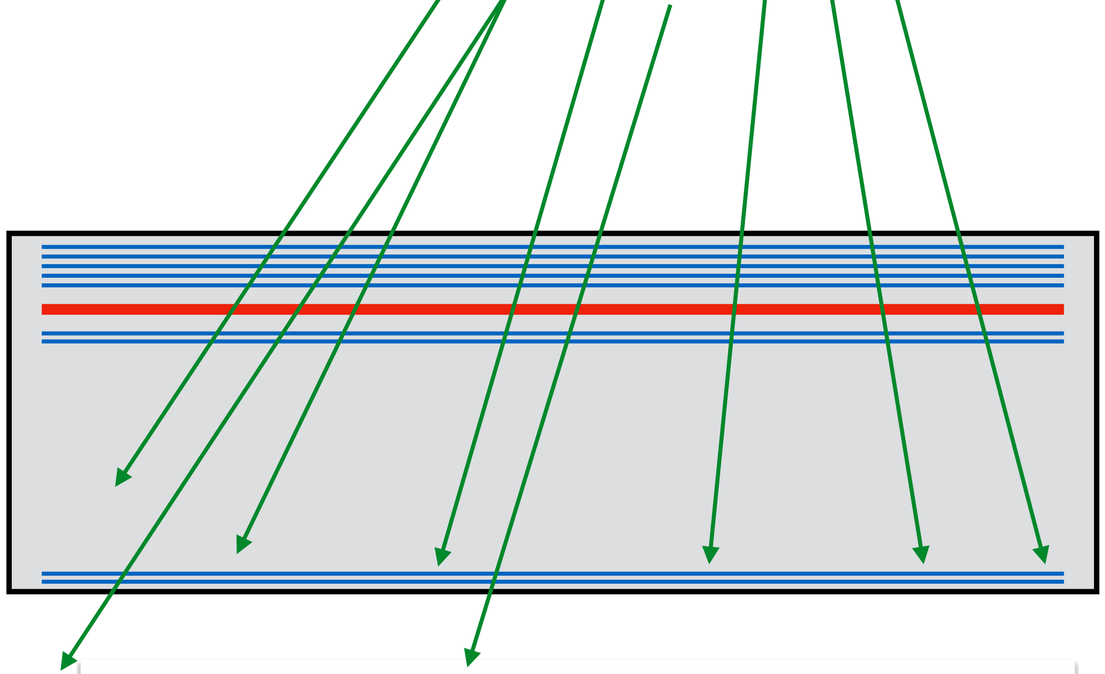
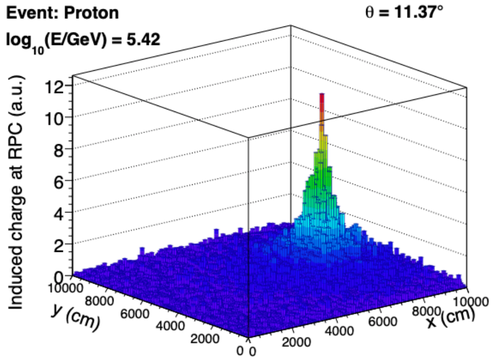
Cosmic Ray Physics

CR physics reach would be greatly enhanced by **adding an analog RPC layer** due to scintillator saturation.

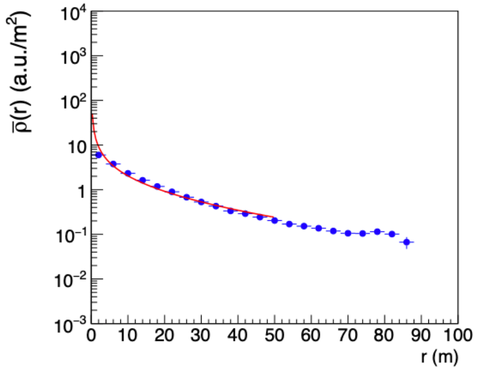
Allows for primary CR energy and composition measurements, studies of shower structure, test hadronic interaction models, muon bundles, …

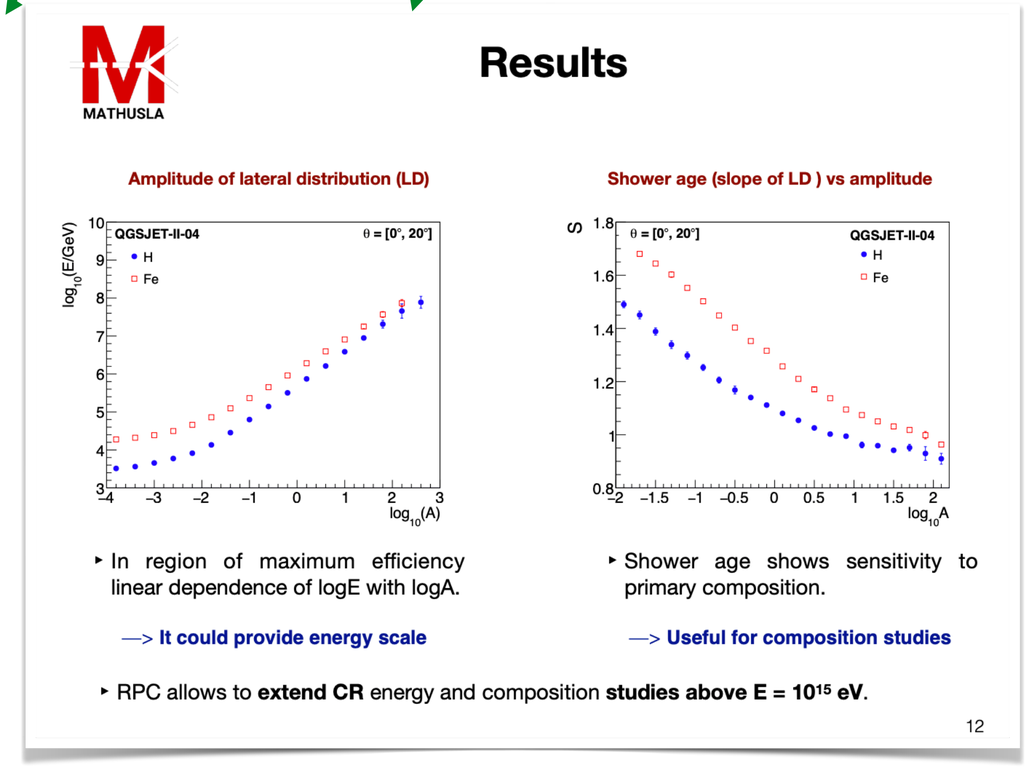


Charge density at the RPC



Lateral charge density at RPC





See LLP9 slides by Juan Carlos Arteaga-Velázquez

Hardware Development

Ongoing R&D Program

Efforts in collaboration currently focusing on:

- Evaluating different fibers, SiPMs

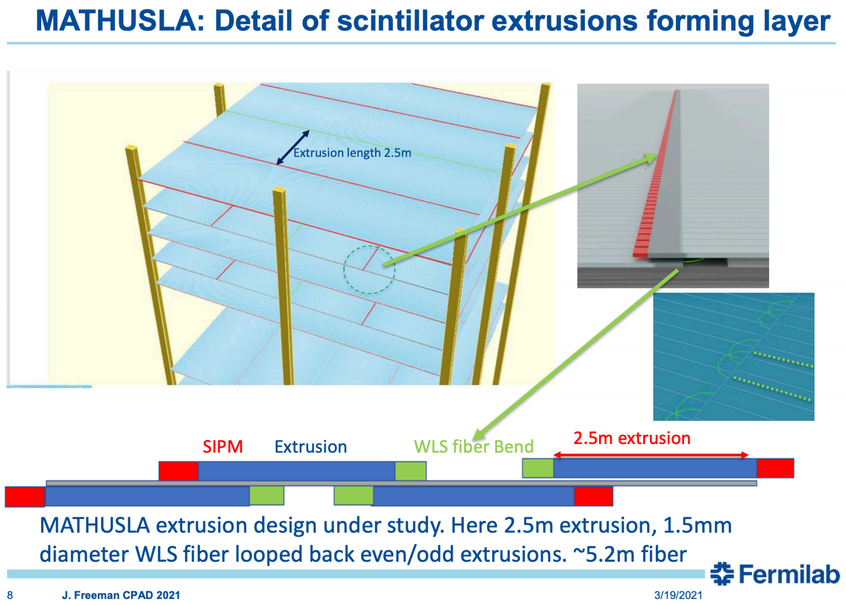
- Scintillator bars: geometry, timing, dark counts

- DAQ/trigger

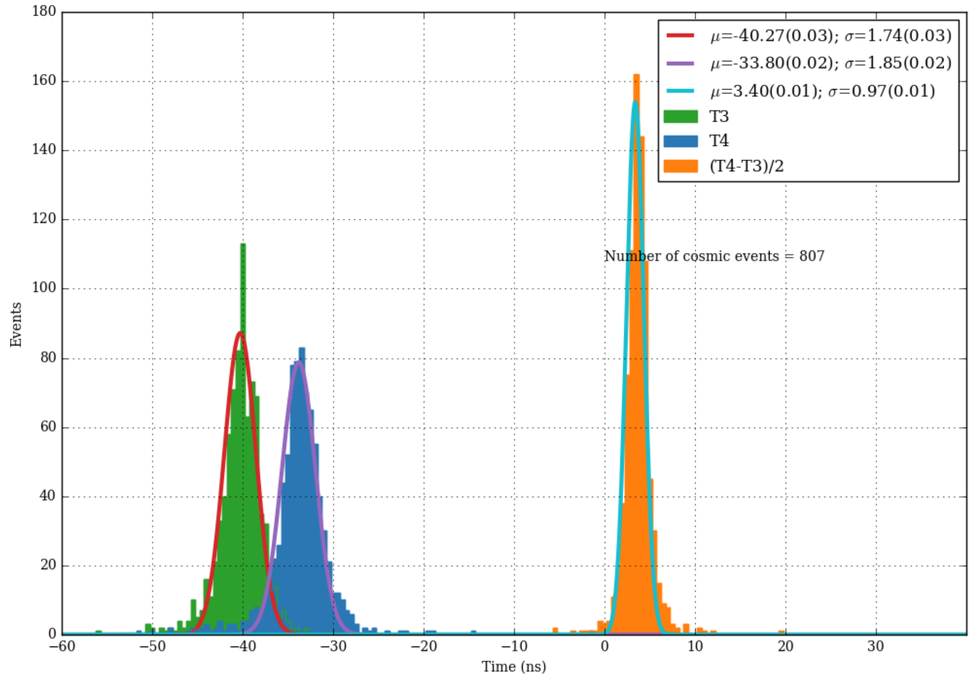
- Overall system integration

Scintillator

Critical design goal for LLP reconstruction and background rejection:
1ns timing resolution of hits (!)



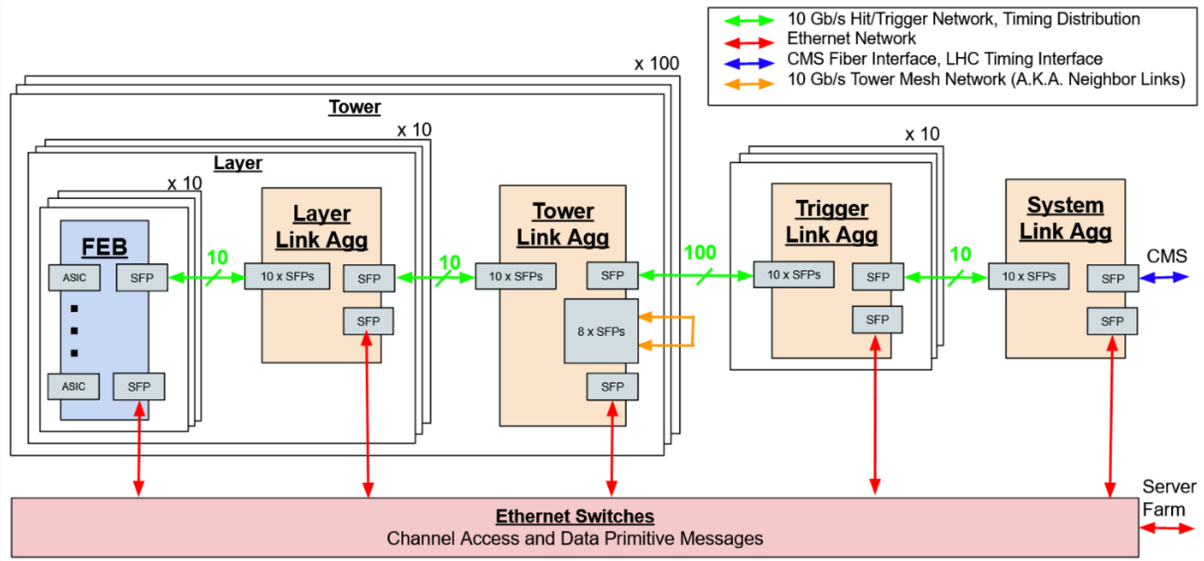
Recently achieved in measurement by Keane Tan (U Rochester grad student) with 5.2m fiber bar using cosmic data



see also CPAD 2021 slides by Jim Freeman

DAQ Preliminary Design Overview

- MATHUSLA trigger latency estimates appear compatible with CMS L1 latency budget
- Modular design of the Front End Boards (FEBs) and link aggregation boards
- Data rates is well within COTS server
- Tower aggregation module triggers on upward going tracks that form a vertex within a 3 x 3 tower volume
- Tower-by-tower philosophy makes it scalable
  - … and stage-able
- LHC timing is distributed across all modules to synchronize Mathusla to CMS



Larry Ruckman, JJ Russell, Charlie Young

Conclusion

Conclusions

All external LLP detectors for the LHC can probe deep into LLP parameter space.

MATHUSLA offers greatest and most versatile reach.

DM search program is not complete without LLP searches!

Significant recent progress and ongoing efforts within MATHUSLA collaboration:

- Hardware: extruded scintillators, fibers, SiPMs, trigger, DAQ
- simulation studies of rare backgrounds, especially K_L^0 production from CRs hitting the floor
- custom tracking algorithms for MATHUSLA's unique environment, achieve high LLP reconstruction efficiency for light, low-multiplicity LLPs.
- Cosmic ray physics case

Hope to produce TDR by early 2022, followed by prototype module and full detector for HL-LHC.

New member contributions always welcome!