MATHUSLA
A New Detector to Probe the Lifetime Frontier

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Lifetime Frontier in Dark Matter Searches

- How to discover DM candidate particles that are very long-lived on collider scales?
- Requires large volume for good acceptance, and requires suppression of SM backgrounds
- Detector on surface above CMS or ATLAS at LHC: O(90 m) of rock ranges out SM particles from LHC collisions ☺
- But, exposed to cosmic rays and atmospheric neutrinos ☹
- Good timing resolution, to veto downward-going cosmic rays
- Robust tracking for vertex reconstruction, to identify decays of long-lived neutral particles to charged objects

MAssive Timing Hodoscope for Ultra-Stable neutraL PArticles

J.P Chou, D. Curtin, H. Lubatti arXiv:1606.06298

MATHUSLA

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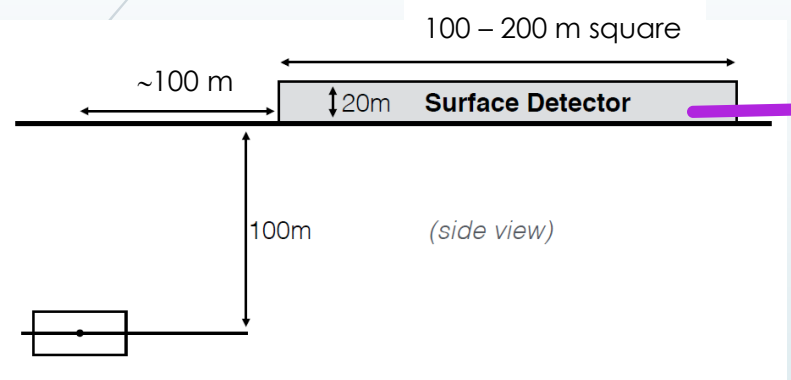
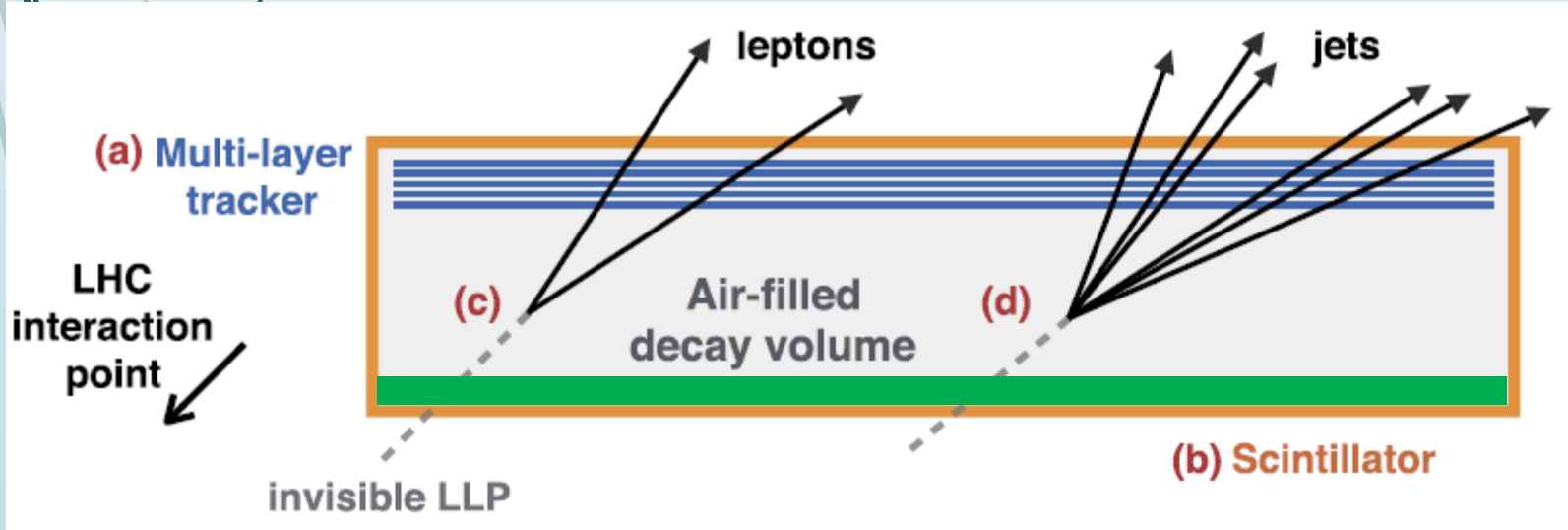


Proposed large area surface detector above an LHC IP, composed of air decay volume with tracking chambers



- For tracker, RPCs and extruded scintillators coupled to SiPMs are both being evaluated
- Need floor scintillators to reject interactions occurring near surface

MATHUSLA

Theory White Paper

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

1806.07396

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LoI submitted to LHCC

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

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CERN-LHCC-2018-025

Physics Case White Paper 1806.07396 (to be published in Physics Reports)

Based on 200 x 200 m^2 detector at 100m from IP on surface with IP 100 m below surface

Letter of Intent: CERN-LHCC-2018-025

Input to European Strategy for Particle Physics: 1901.04040v1

Outline

- Motivation & Sensitivity Estimates
- Signal Discrimination
- Background Estimates
- Layout
- Tracker Technologies
- Readout & Trigger
- Test Stand Results
- Going Forward

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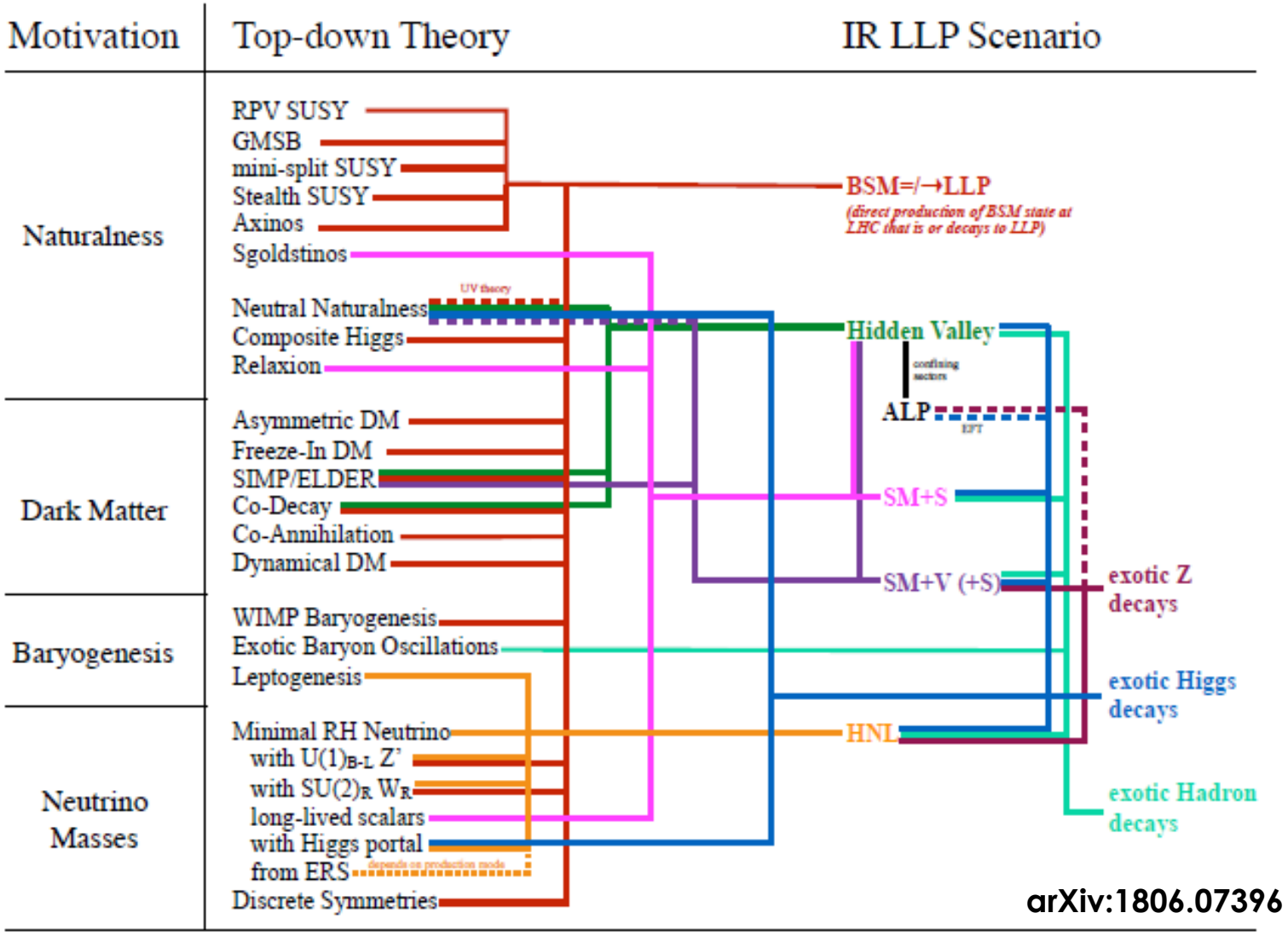
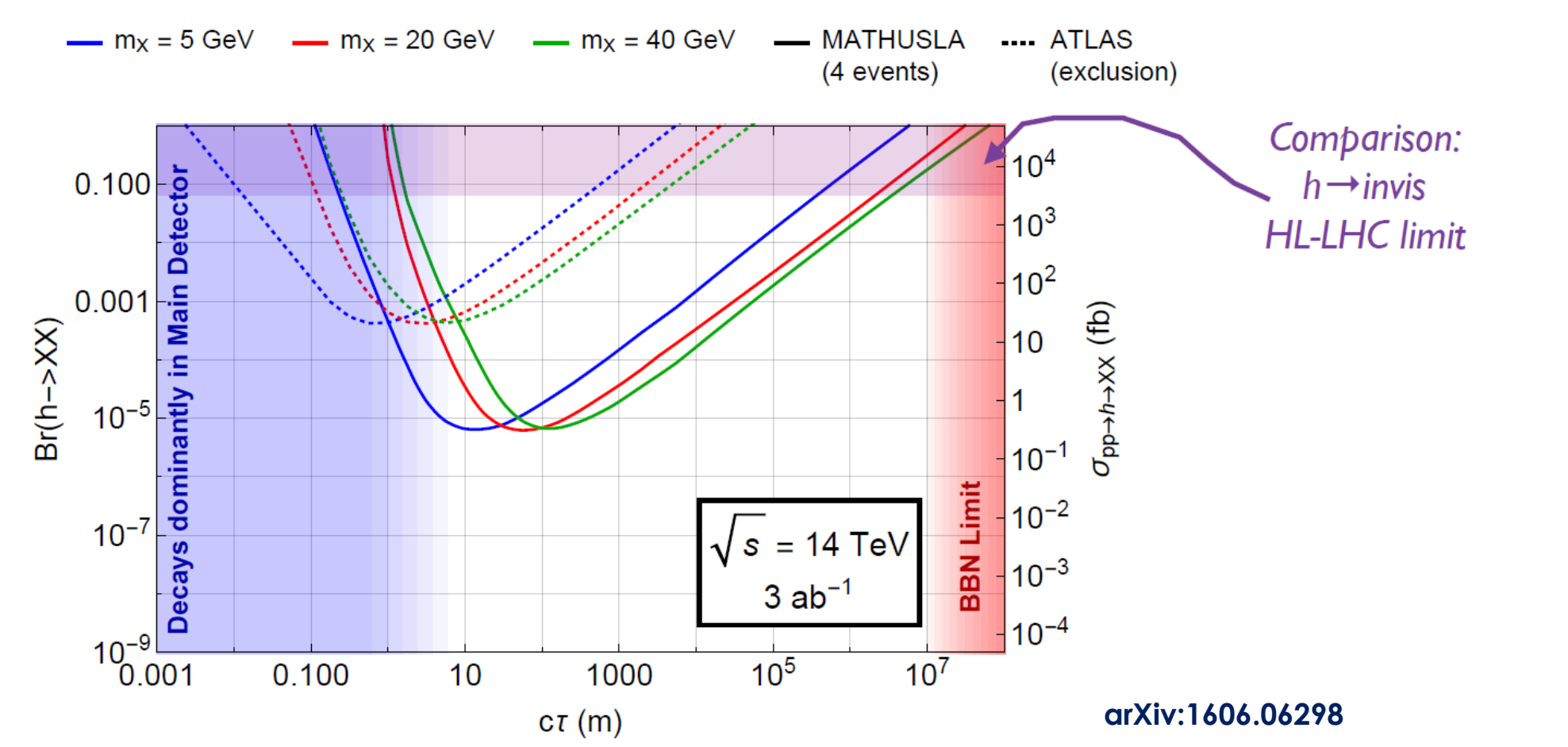
MATHUSLA Motivation

- **Long Lived Particles arise in wide variety of Beyond the Standard Model constructs:**



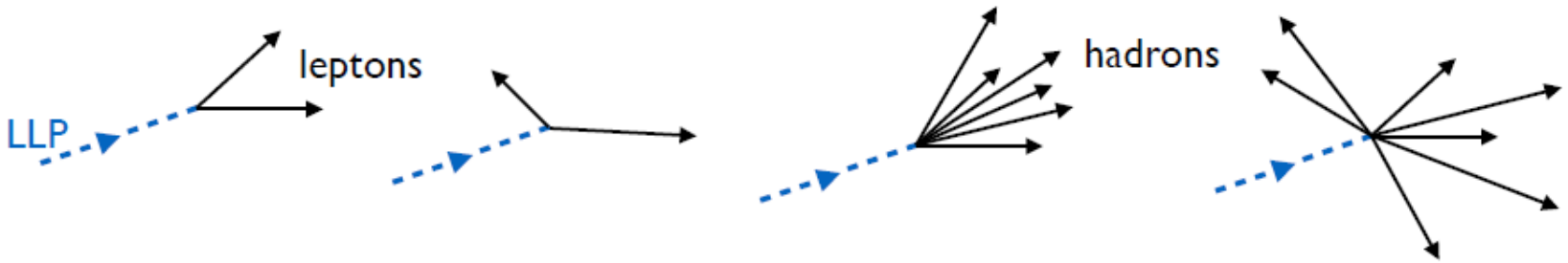
Sensitivity Estimates

- **Benchmark model: Higgs decay to pair of dark scalars, x, for several m_x**
- **Mathusla has no QCD backgrounds → sensitivity gain**
- **Can approach Big Bang Nucleosynthesis lifetime limit of ~0.1s**

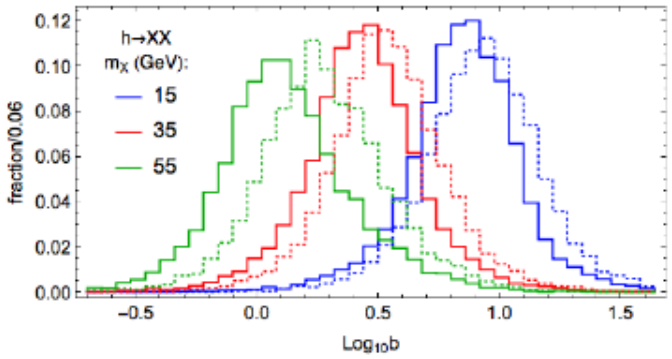


arXiv:1606.06298

Signal Discrimination



Geometry of LLP final state trajectories reveals LLP **boost** event-by-event



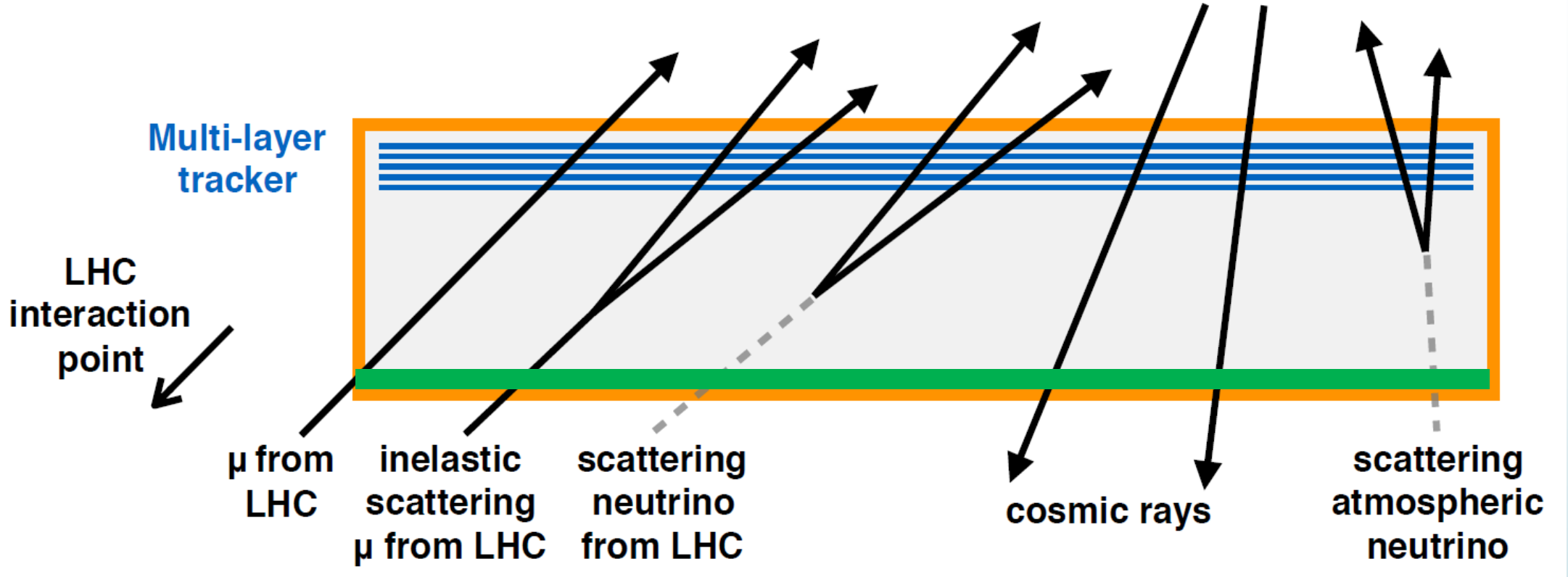
Final state multiplicity can diagnose **decay mode**.

Correlate with main detector to diagnose **production mode!**

Optional: layer of material between tracking layers for e/μ discrimination and γ detection

For known production mode, **boost ~ LLP mass**!

Background Estimates



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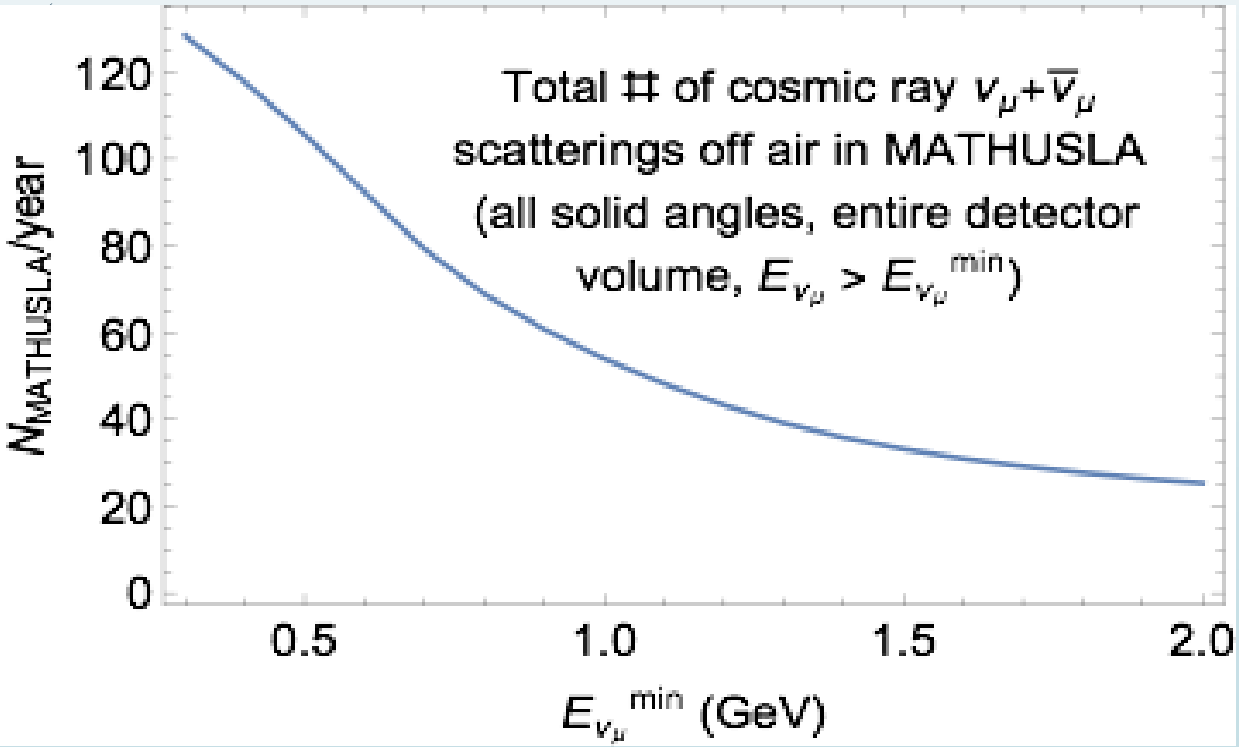
Very small LHC backgrounds
Cosmic ray background: 1.7 MHz for $(100m)^2$ detector

Background Estimates

- Cosmic muon rate ~1.7 MHz for 100m x 100m detector
  - **Reject with timing and entrance hit position**
- Upward atmospheric/cosmic neutrinos interacting in air decay volume
  - Most have low-momentum proton (~300 MeV) rejected with time of flight
  - ~ 10-100 per year above 300 MeV



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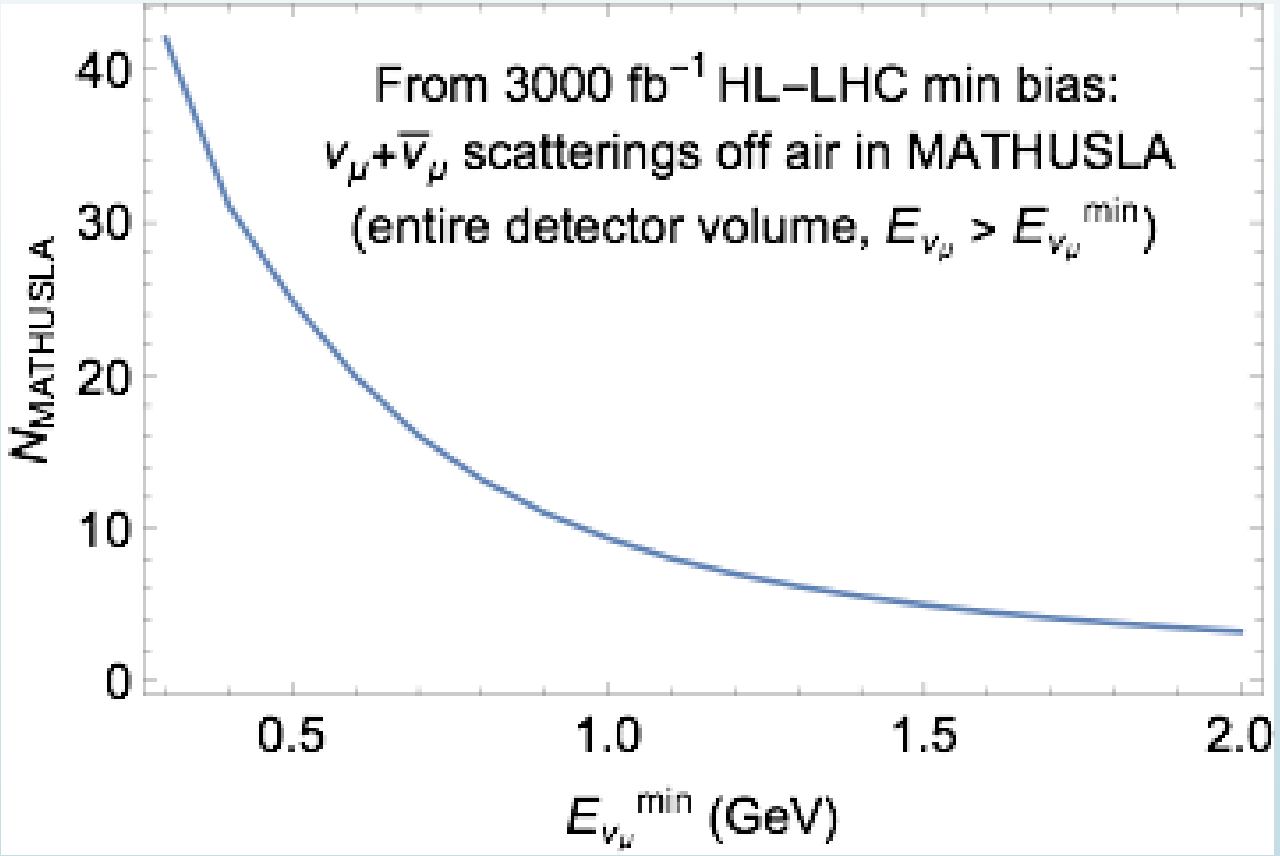
Background Estimates

- LHC collision backgrounds
  - LHC muons ~10 Hz: reject with tracking, timing, and entrance hit position
  - LHC neutrinos: subdominant



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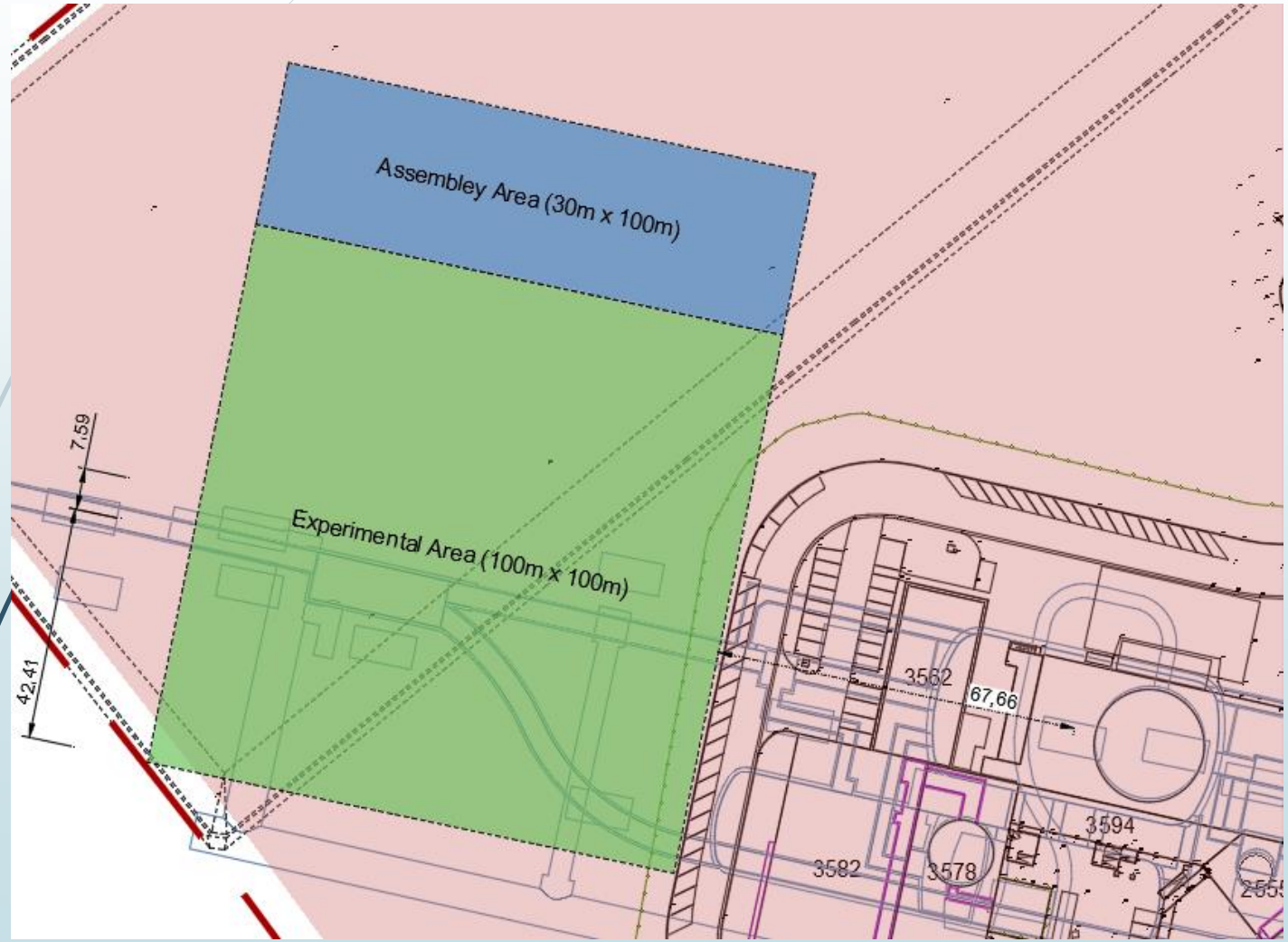
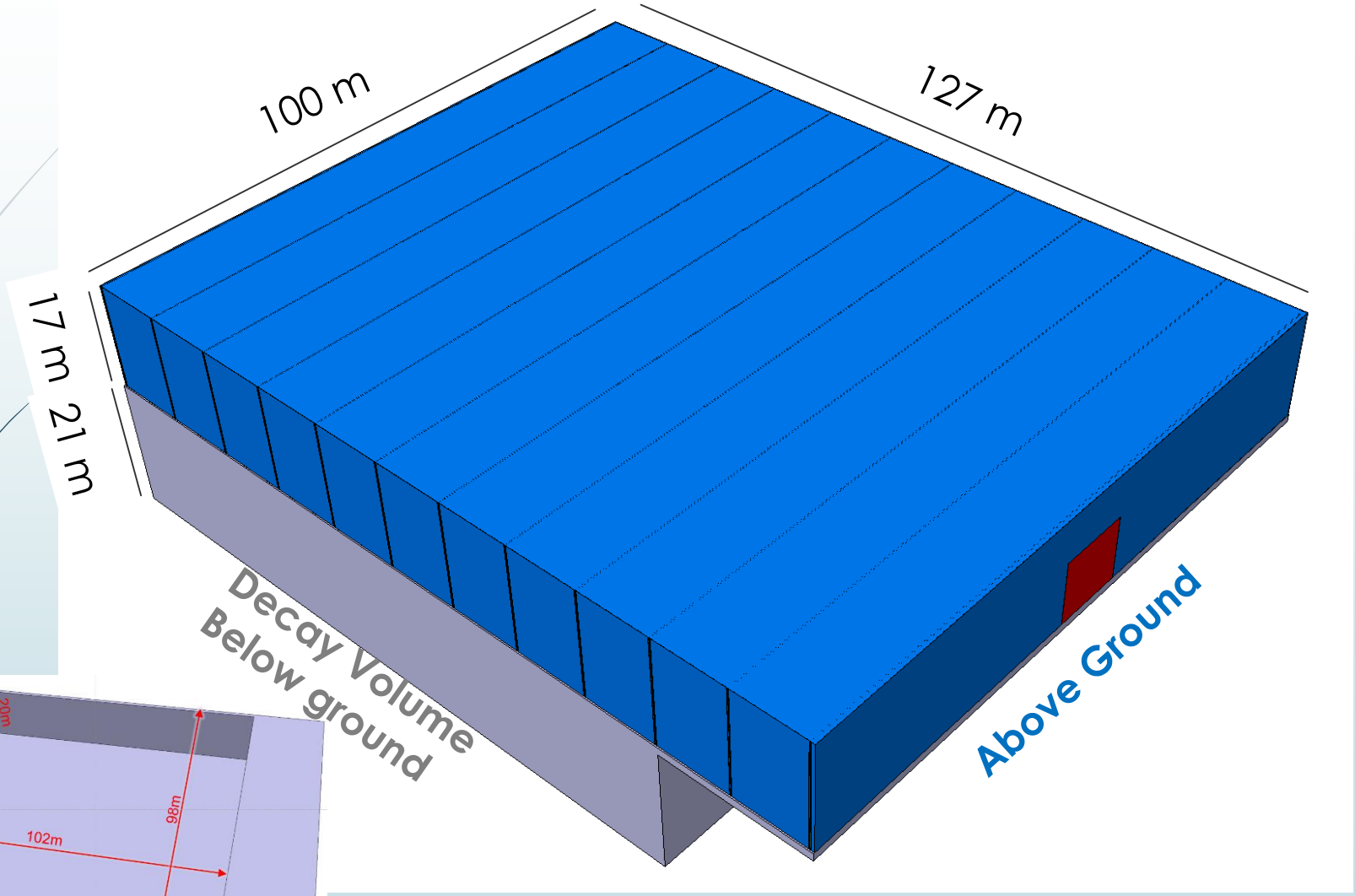
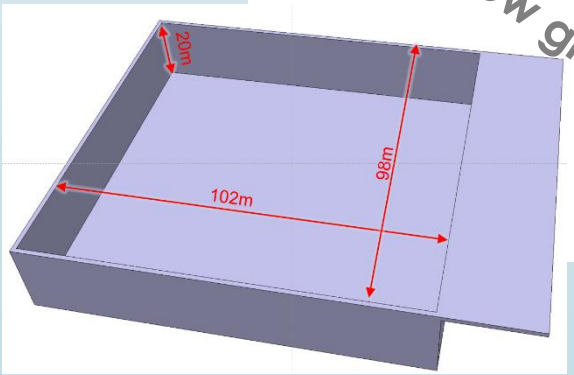
Preliminary Layout



- **Above CMS IP**
- **Experimental and assembly area in an enclosed building with crane coverage**
- **Fits on CERN-owned land and avoids <u>known</u> Roman artifacts (!)**
- **68 m to IP on surface, IP ≈ 80m below surface, ~7.5m offset from beam**

Preliminary Layout

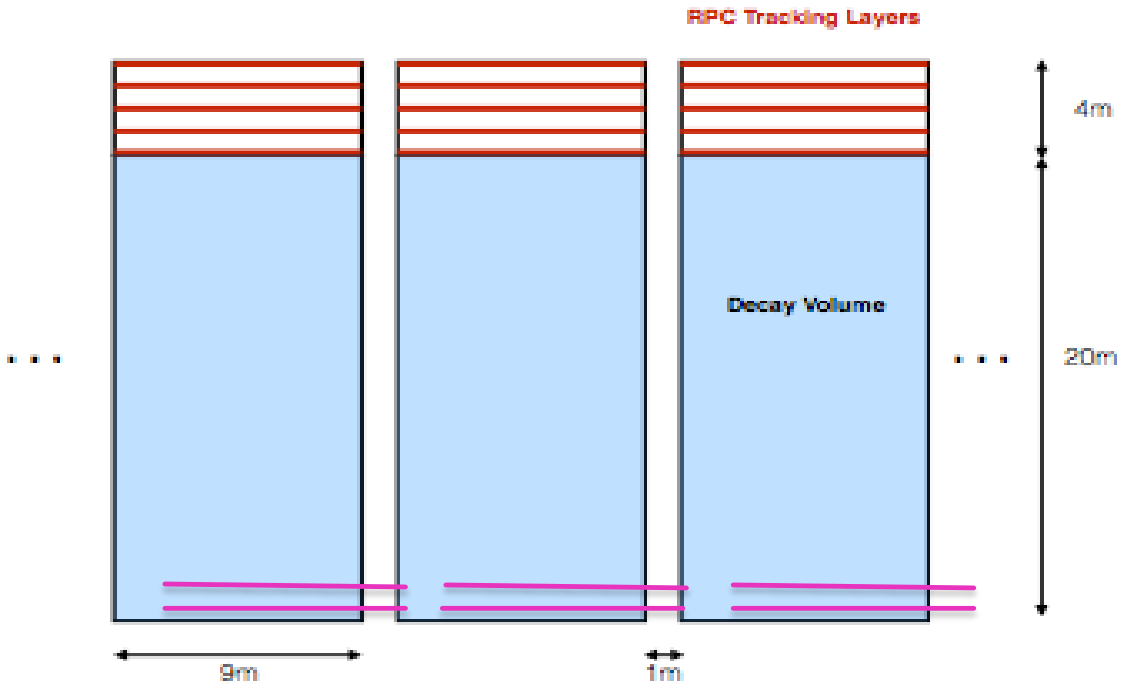




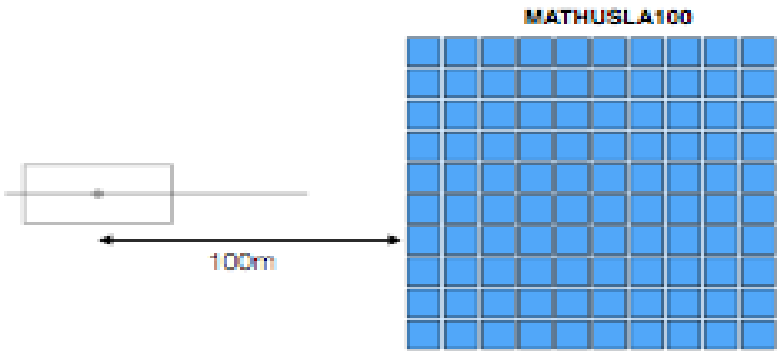
- **Modular design: easy to adapt to site specific conditions**
- **Modular construction, staged installation of modules, incremental ramp-up**

Preliminary Layout

- Individual 9 m X 9 m modules: 5 tracking/timing planes (red) at top of 20 m decay volume and bottom veto layers (violet)
- Allows for possibility of adding material for electron identification (e/μ in cosmic rays)

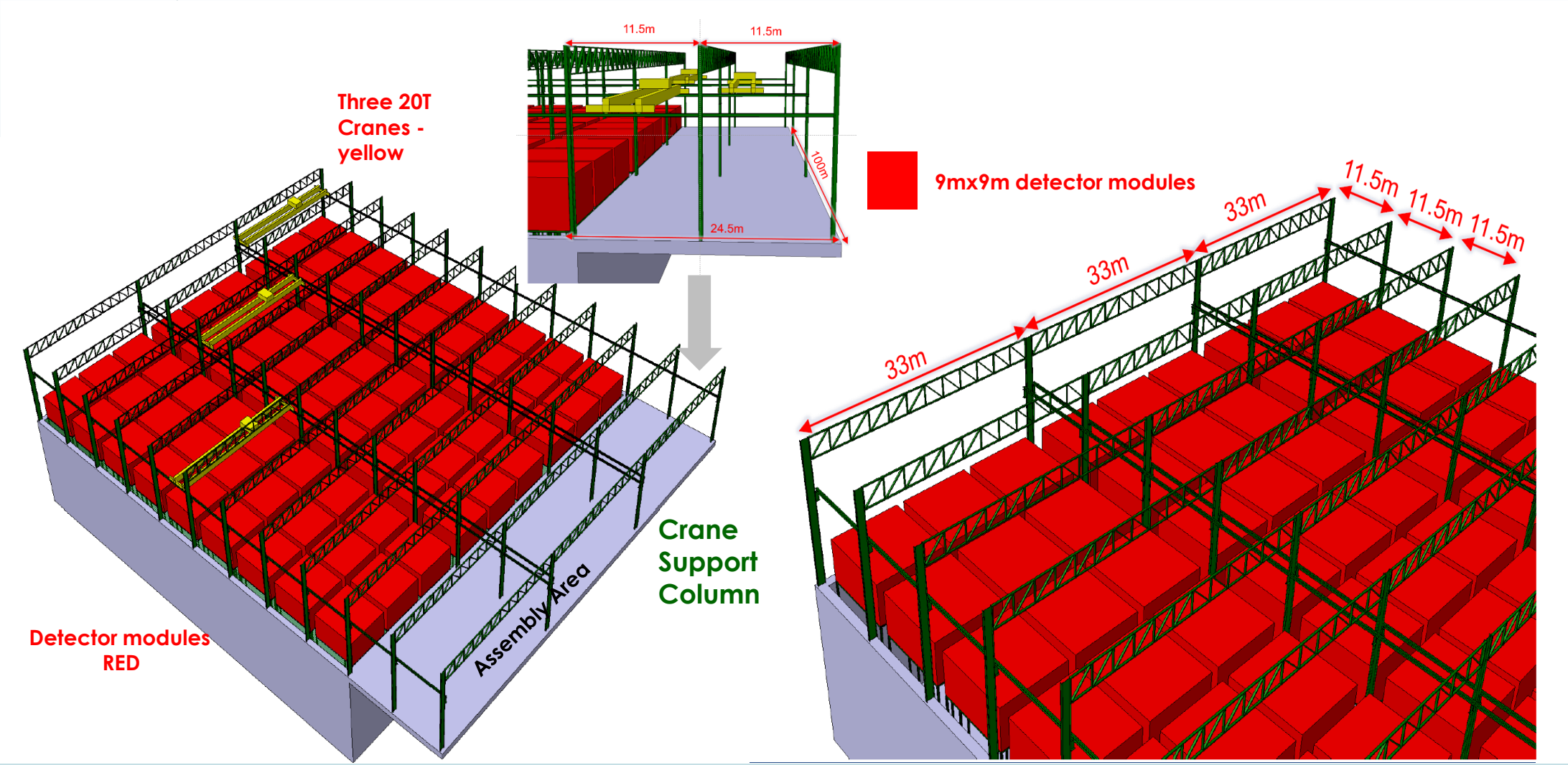


side view



aerial view

Preliminary Layout



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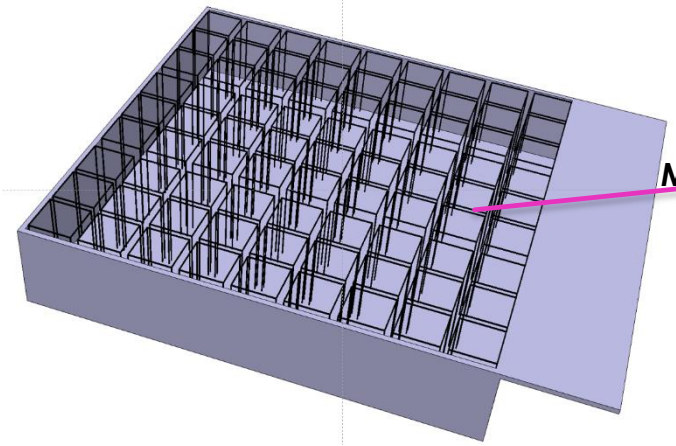
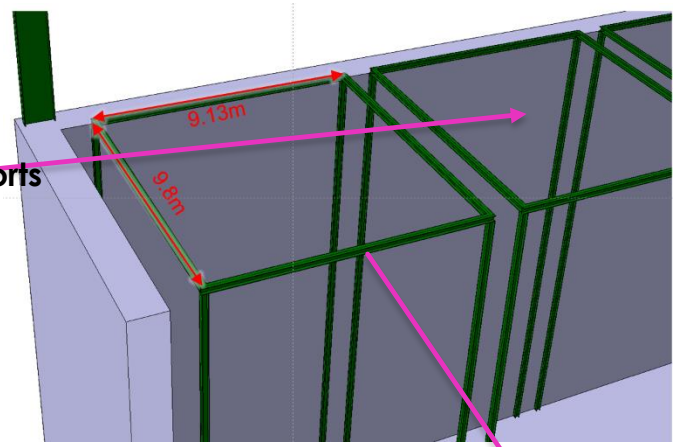
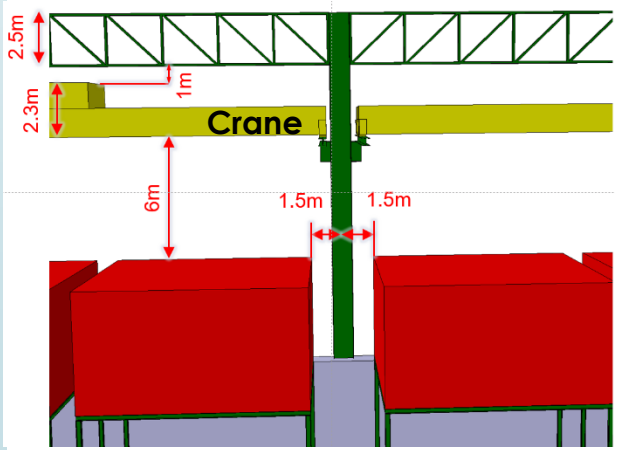
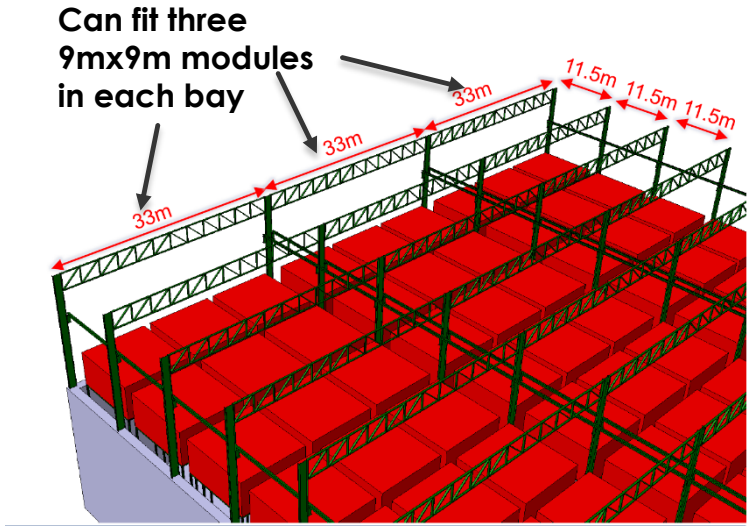
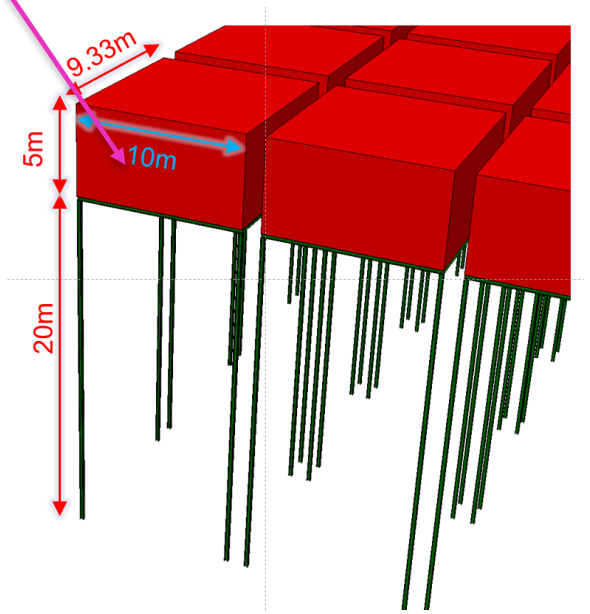








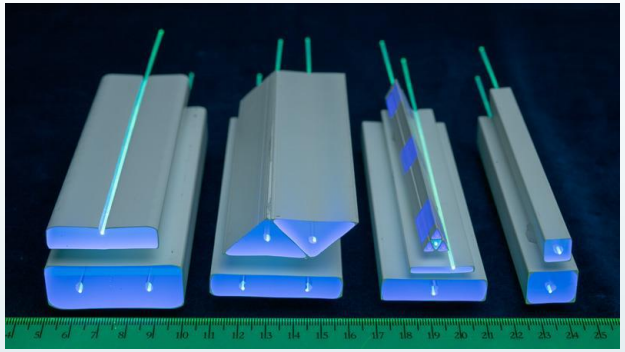


Tracker Technologies: RPCs

- Resistive Plate Chambers used in many LHC detectors
- **THE GOOD ☺**
  - Proven technology with good timing and spatial resolution
  - Low costs per area covered
- **The Not-So-Good ☹**
  - Require high voltage (~10 KV)
  - Gas mixture currently used in ATLAS & CMS has high Global Warming Potential and will not be allowed for HL-LHC

Tracker Technologies: Extruded Scintillators

- Extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers: cost-competitive with RPCs
- **THE GOOD**
  - SiPMs operate at low-voltage (25 - 30 V)
  - No gas
  - Timing resolution can be competitive with RPCs
  - Tested extrusion facilities in FNAL
  - Used in several experiments, e.g. Belle muon trigger upgrade, Mu2e
- Each scintillator bar ~ 5m x 4cm x 2cm, with readout at both ends
  - Transverse resolution $\sigma \approx 1$ cm
  - Time difference between two ends gives longitudinal resolution: need $\approx$ 90 ps per SiPM



Readout & Trigger

- Readout: 700,000 channels
  - Does not require sophisticated ASIC
  - Goal for front-end: $1/channel

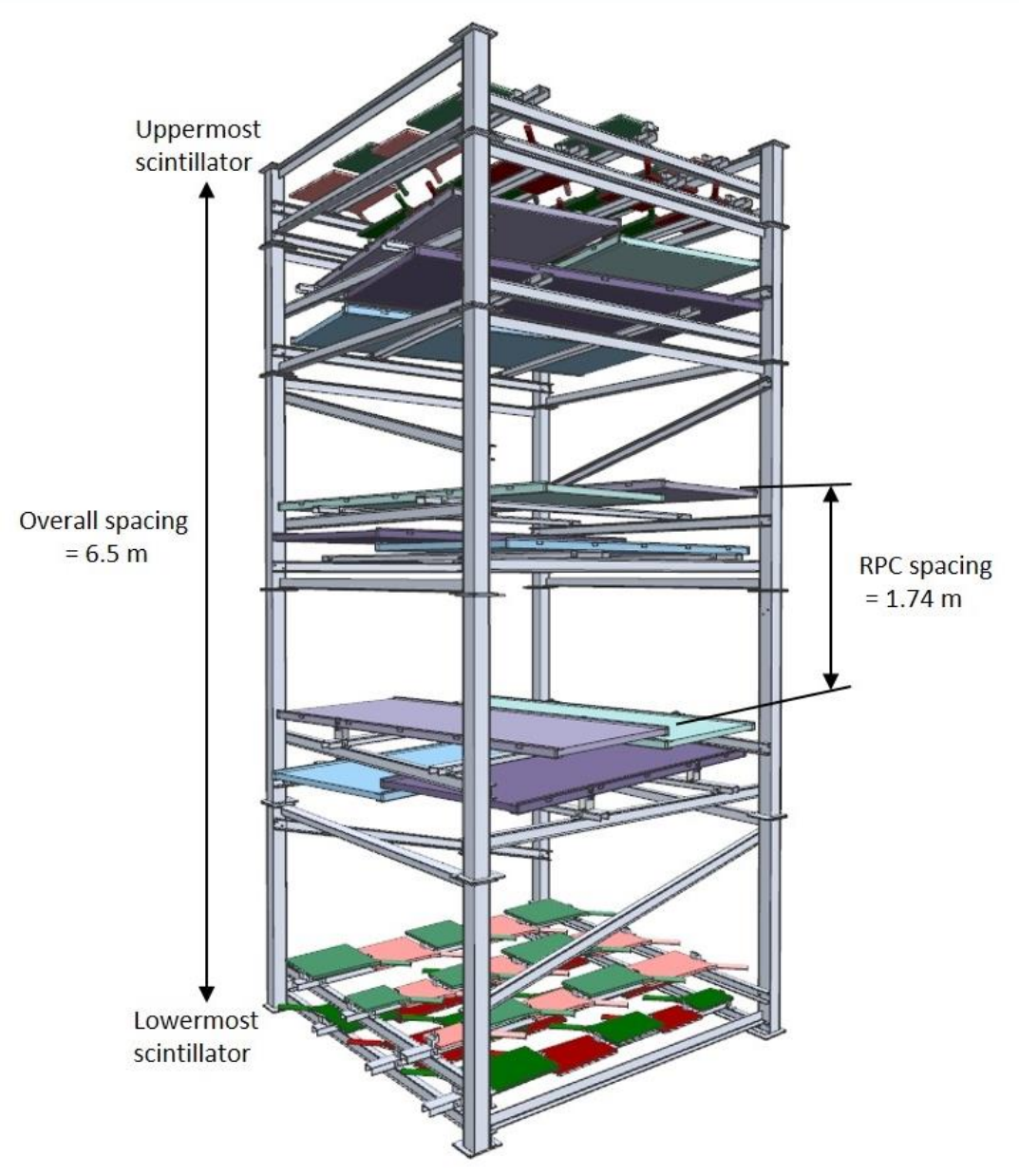
- Collect all detector hits with no trigger selection
  - Separately record trigger data and move it to central trigger processor
- Want to associate trigger with CMS bunch crossings
  - MATHUSLA will have ~9 μs to form trigger and get the data to CMS Level-1 trigger
- Trigger rate ~ 2 MHz
- Trigger unit: 3 x 3 modules
  - ~1 MB/s (~30 TB/year) per module

Test Stand

- To understand LHC collision backgrounds (upward-going muons), we built a test stand
- ~2.5 x 2.5 x 6 m^3 , 3 layers of RPCs plus top and bottom scintillator layers
  - RPCs from Rinaldo Santonico Rome -- spares from ARGO experiment
  - Scintillators recycled from D0 forward muon trigger wall

Took data above the ATLAS IP in 2018!

Test Stand

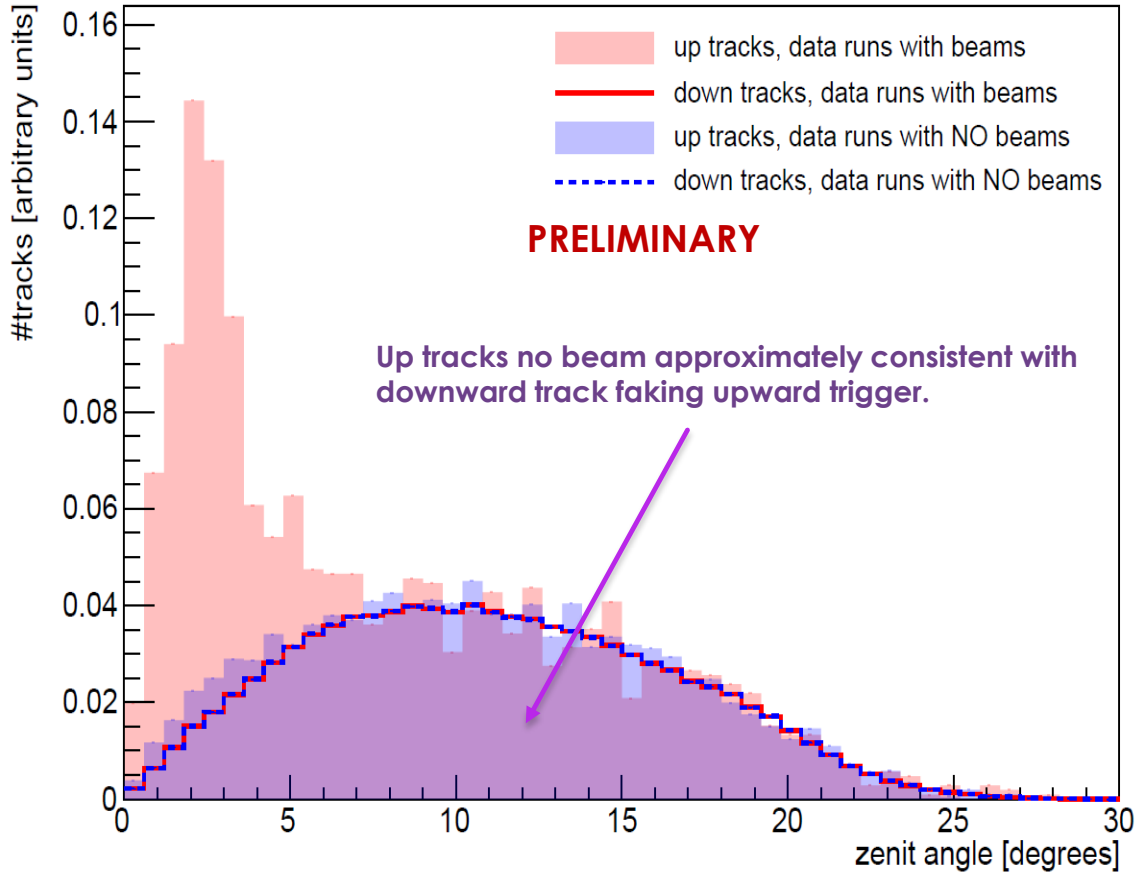


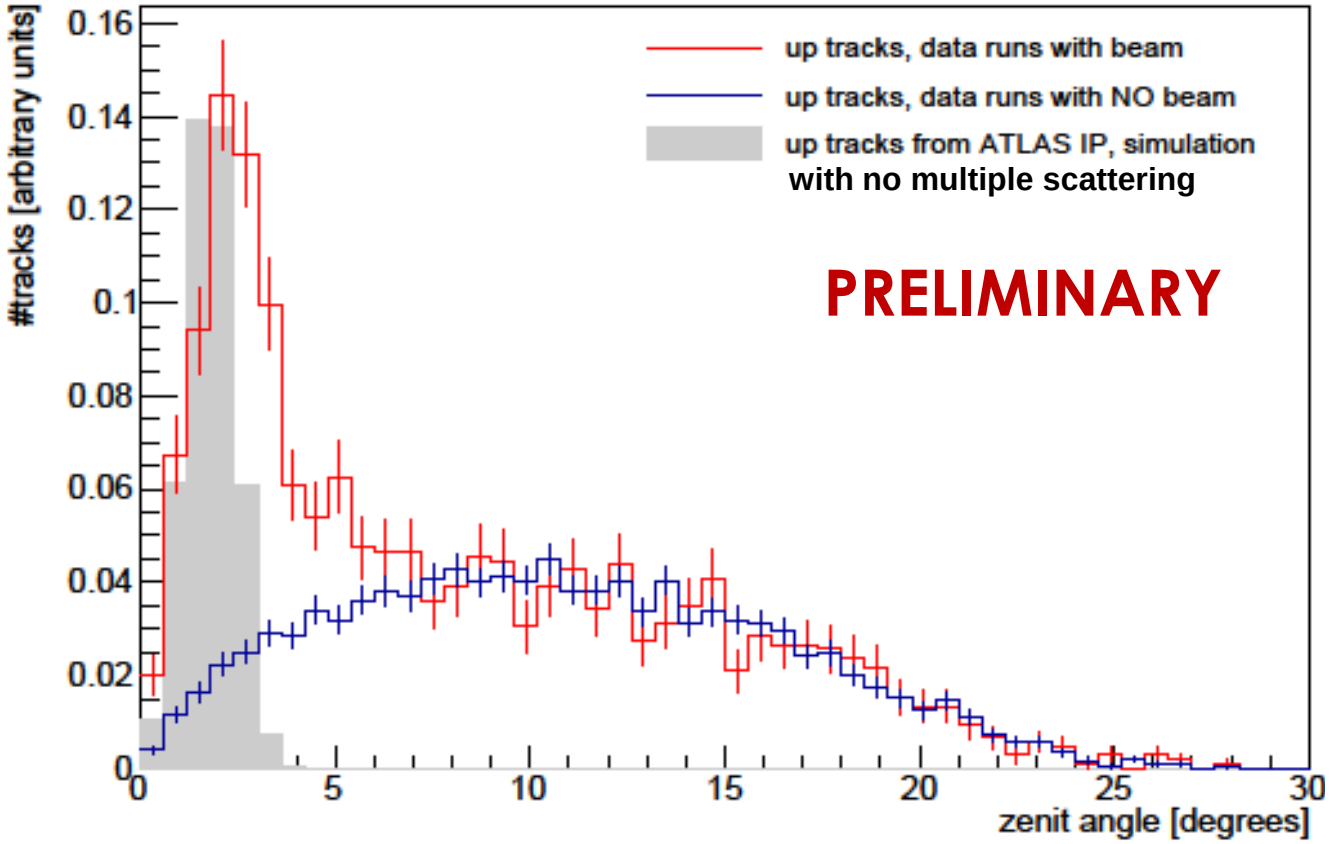
- RPCs and scintillators had timing resolution $\sigma \sim 2.5$ ns
- Top-to-bottom $\Delta t \sim 20$ ns or 8σ
- Two triggers running simultaneously:
  - Downward trigger for cosmic rays
  - Upward trigger for tracks from IP

Test Stand Results

- **Accumulation for zenith angle < ~ 4° consistent with upward-going tracks from IP when collisions occur**

Not corrected for efficiency

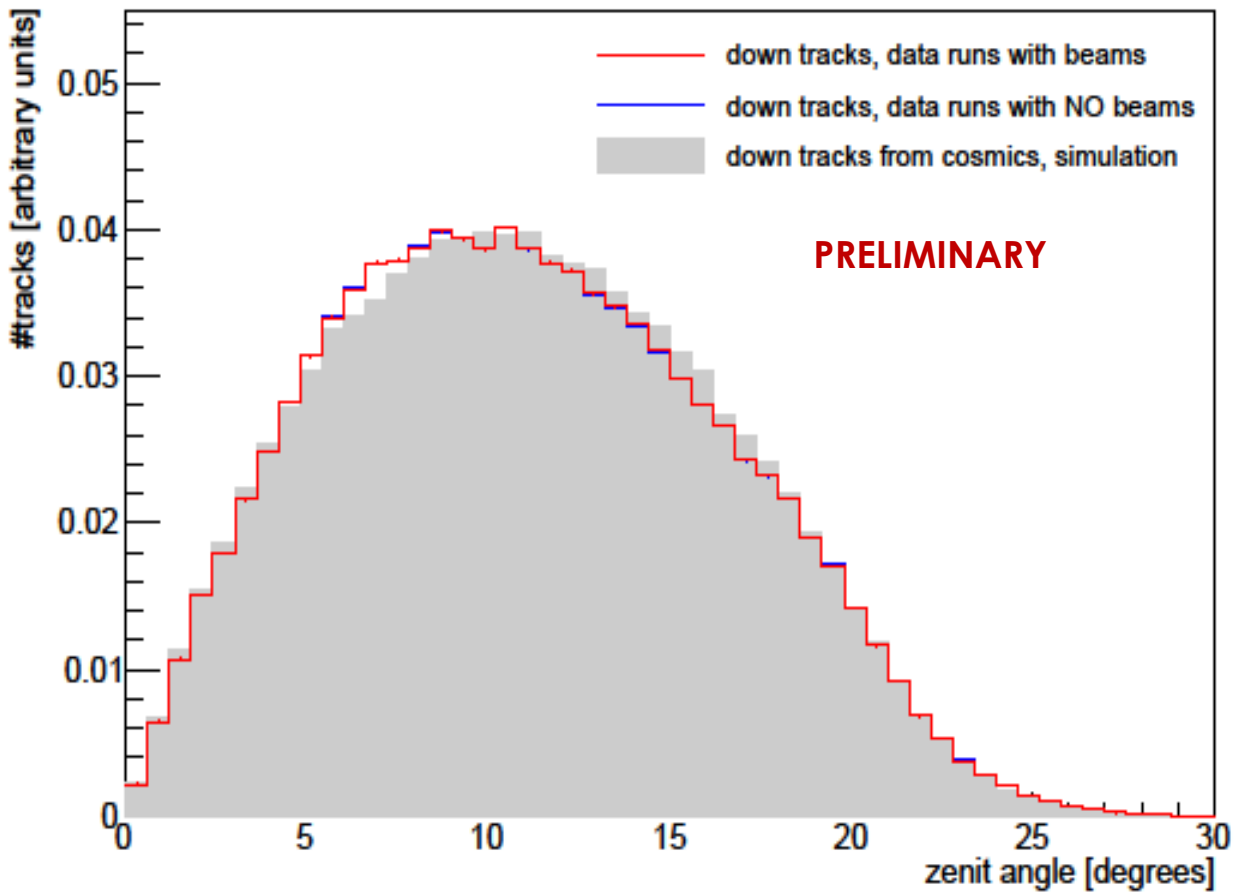




Test Stand Results

- **Downward-going tracks consistent with cosmic-ray simulations**

Not corrected for efficiency



Going Forward

- Detector footprint at CMS to be finalized
- Building details coming together
- Goal: preliminary cost estimate this year, choose tracker technology early next year
- Open items include:
  - Front-end electronics
  - Trigger details
  - Cabling
  - Tracking chamber support structure
  - Installation procedures
- Complete Technical Design Report by end of 2020

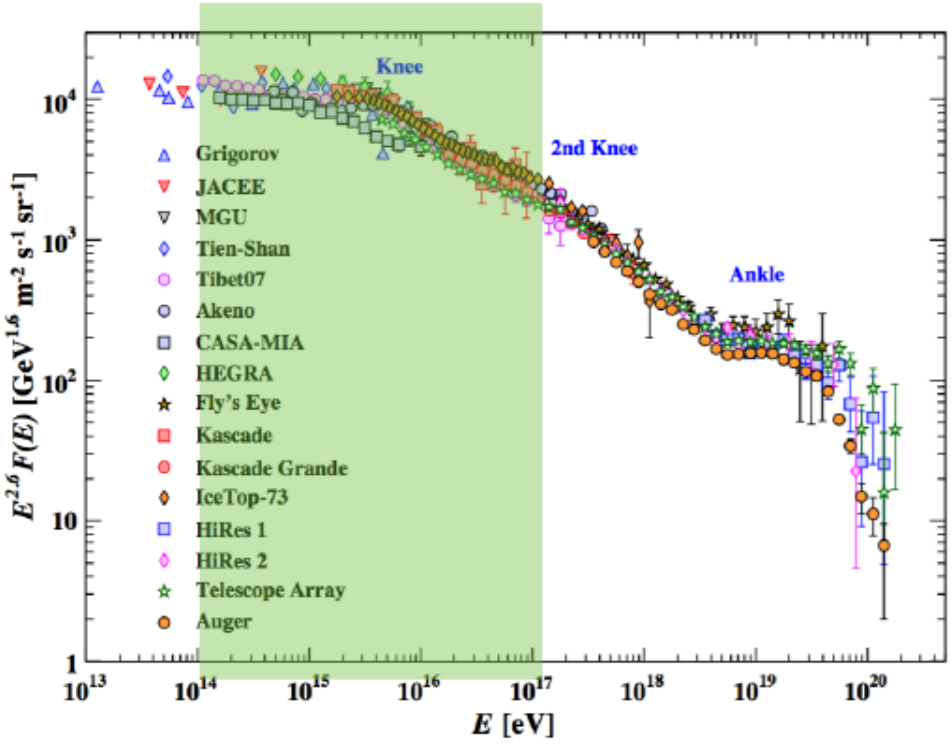
contact: mathusla.experiment@cern.ch

SUPPLEMENTAL MATERIAL

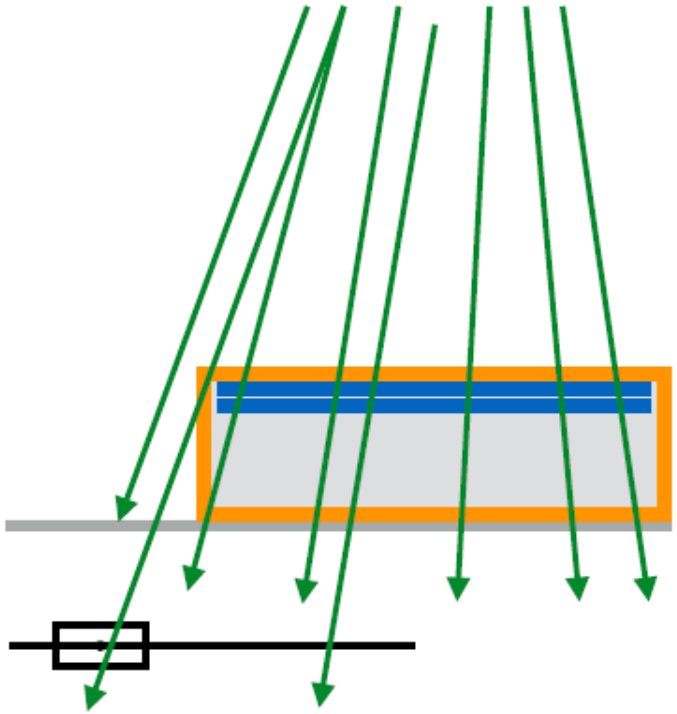
BONUS: Cosmic Ray Physics

MATHUSLA is an excellent Cosmic Ray Telescope!

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



~90% e, ~10% μ, less hadrons



BONUS: Cosmic Ray Physics

Primary Cosmic Ray spectra and composition

Cosmic Ray Anisotropies at PeV energies

Highly inclined Showers:
electron/photon-depleted, mostly muons.
Probe various shower parameters (attenuation length etc).
Probe neutrino production in atmosphere or Jura mountains (!)

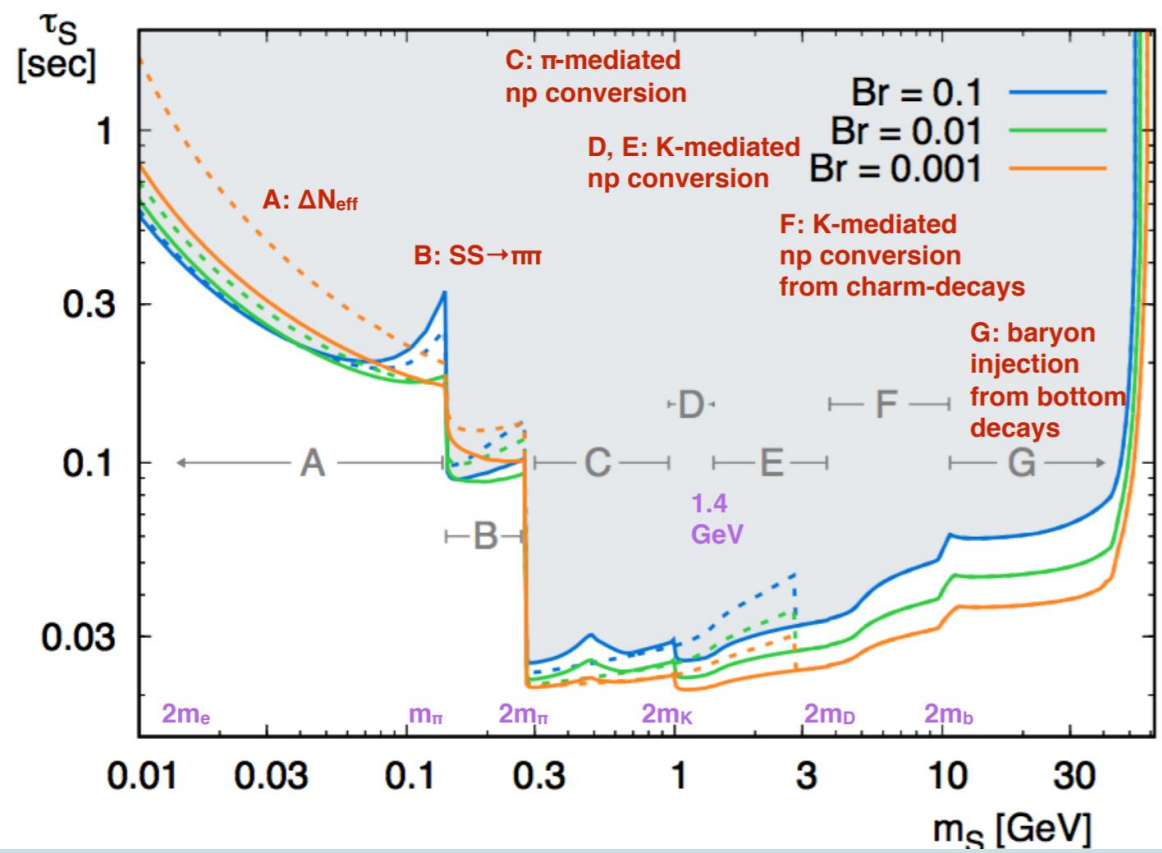
Study of extended air showers, including precise spatial-temporal structure, to help develop **hadron interaction models**, important for all CR experiments

High-Multiplicity Muon Bundles, observed at LEP & ALICE, point to either Iron-rich CRs around knee (or BSM ???)

Guaranteed Physics Return!

Big Bang Nucleosyntheses (BBN) lifetime limit

- Unstable decays at time of nucleosyntheses would upset equilibrium.
- A. Fradette and M. Pospelov, arXiv:1706.01920v1 examined the BBN lifetime bound on lifetimes of long-lived particles in the context of constraints on a scalar model coupled through the Higgs portal, where the production occurs via $h \rightarrow SS$, where the decay is induced by the small mixing angle of the Higgs field h and scalar S.
- For $m_S > m_\pi$ the lifetime $\tau < 0.1$ s
- Conclusion does not depend strongly on $Br(h \rightarrow SS)$.



BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA
Hidden Valleys (HV)	Small portal to visible sector and possibly hidden sector confinement $\rightarrow$ meta-stable states.	Any.	MCFODO, especially if LLPs are significantly below the weak scale or decay hadronically.
SM+S	Small mixing $\rightarrow$ scalar LLP for $m_S < 2m_H$. Large mixing $\rightarrow$ S could decay to HV LLPs.	Any.	MCFODO. Complementarity with SHiP.
SM+V	Dark photon/dark Higgs LLP could be produced in exotic Higgs/Z decays. Dark photon with non-tiny kinetic mixing could be copiously produced at LHC and decay to HV LLPs.	Any.	MCFODO. Significantly extends main detector long-lifetime reach for dark photons and dark Higgs produced in exotic H and Z decays. For LLPs produced in dark photon decays, see HV.
Exotic Higgs decays	Higgs coupling to new states, like HV or other LLPs, is highly generic and leads to large production rates at LHC.	Any.	MCFODO for Br $\lesssim 0.1 - 0.01$. Higgs portal motivates hadronic LLP decays, for which MATHUSLA has 10^3 better Br reach than main detectors. MATHUSLA also has significantly better sensitivity for LLP masses $\lesssim 10$ GeV even if they decay leptonically, or for LLPs with subdominant leptonic decays.
Asymmetric DM	Relating DM to baryon abundance requires operator connecting DM number and Baryon/Lepton number $\rightarrow$ higher dimensional operator $\rightarrow$ LLPs	Any, depending on kind and scale of physics generating the operator.	MCFODO (highly dependent on production and decay mode).
Dynamical DM	DM sector includes spectrum of states with varying life-time up to highly stable DM.	Any, long lifetimes generic in DM sector spectrum.	MCFODO (highly dependent on production and decay mode).

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA
Neutral Naturalness	Discrete symmetry stabilizing Higgs mass → Hidden Valley with Higgs portal. Cosmology → HV particles are LLPs.	Any, but $\mathbb{Z}_2$ arguments favor lower $\hat{\Lambda}_{QCD}$ and hence long lifetimes.	Mirror glueballs with long lifetimes can only be discovered at MATHUSLA.
WIMP Baryogenesis	Out-of-equilibrium decay of WIMP-like LLP produces baryon asymmetry.	For weak-scale LLP masses, $\gtrsim$ 1-100 m.	Decays to baryons → MATHUSLA likely much greater sensitivity than main detectors. MCFODO
FIMP DM	Freeze-in via decay requires LLPs with SM couplings.	Fixed by masses & cosmology. Long lifetimes generic.	Model-dependent, but in long-lifetime regime MCFODO.
Co-decaying DM	Out-of-equilibrium decay of hidden sector LLP determines DM abundance. Also, small portal → visible sector LLPs.	For weak scale LLP masses, most of parameter space is long lifetimes.	Depending on model details (production & decay mode), MCFODO.
Co-annihilating DM	DM relic abundance relies on small mass splitting with another state → other state is LLP.	Any, long lifetimes generic.	Depends on model details, but e.g. for Higgs Portal implementations, MCFODO.
SUSY: Axinos	High PQ-breaking scale V_{PQ} suppresses axion/axino couplings, making LOSP an LLP	Any, long lifetimes generic.	For high V_{PQ}, MCFODO.
SUSY: GMSB	Low SUSY breaking scale F (motivated by flavor problem) leads to light gravitino and small couplings to LOSP, which can hence be LLP.	Any, long lifetimes generic.	MCFODO, depending on spectrum and lifetime.
SUSY: RPV	small RPV couplings (motivated by avoiding flavor violation, proton decay, baryon washout) → LOSP can be LLP	Any, long lifetimes generic.	MCFODO, especially for EW-charged LSPs or squeezed spectra.

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA
SUSY: Sgoldstinos	SUSY breaking scale F suppresses sgoldstino coupling to supercurrents $\rightarrow$ can be LLP.	Any. Long lifetimes $\rightarrow$ smallest production, hardest to probe.	Similar to SM+S. For masses $\lesssim$ 5 GeV, MATHUSLA and/or SHiP may be only/first discovery opportunity.
minimal RH neutrino model	Type-1 see-saw $\rightarrow$ tiny mixing between ν_L and ν_R $\rightarrow$ ν_R LLPs	Any, long lifetimes favor lower m_{ν_R}	In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.
$\hookrightarrow$ with $U(1)_{B-L}$ Z'	Weakly gauged $B-L$ breaking generates M_N, additional ν_R production mode from Z'.	$m_{\nu_R} \sim$ 1-10 GeV suggests long lifetime regime.	For sub-weak-scale m_{ν_R}, MCFODO.
$\hookrightarrow$ with $SU(2)_L$ W_R	ν_R part of gauged $SU(2)_R$, breaking generates M_N. Additional ν_R prod. from $W_R^{\pm}$.	Any, long lifetimes favor lower m_{ν_R}.	For $m_{W_R} \sim$ 10 TeV: main detector probes weak-scale m_{ν_R}; MATHUSLA/SHiP only discovery opportunity for $m_{\nu_R} \lesssim 5$ GeV.
$\hookrightarrow$ with Higgs Portal	GUT motivates extra broken $U(1)$ gauge groups, extended scalar sectors mix with Higgs $\rightarrow$ produce ν_R in H decays.	Any, long lifetimes favor lower m_{ν_R}.	MCFODO, improves Br reach of main detectors by at least order of magnitude.
m_ν via discrete symmetries	Discrete sym. generates m_ν and stabilizes FIMP DM.	See FIMP DM.	LLPs with EW charge $\rightarrow$ MCFODO, especially for $m \lesssim 10$ GeV

BSM Scenario	Role of LLPs	Typical $c\tau$	Role of MATHUSLA
SIMP/ELDER DM	Strong dynamics of HV generate DM abundance. HV $\rightarrow$ LLPs.	Any.	See HV.
Relaxion	Relaxion or other new scalars in theory generically mix with Higgs $\rightarrow$ SM+S.	Any.	See SM+S.
Axion-like particles	ALP couplings to h and Z are generic in EFT framework. $1/f$ suppression makes ALP an LLP.	Any.	MCFODO for low-scale f.
Leptogenesis	Motivates minimal RH neutrino model and other neutrino extensions, which generically feature LLPs.	Any, long lifetimes favor lower m_{ν_R}.	Generally very difficult to probe, especially at high leptogenesis scale. In long-lifetime/low-mass regime, MATHUSLA and/or SHiP may be only/first discovery opportunity.
Scalars in neutrino extensions	Gauge extensions in neutrino models give rise to new scalars that can mix with Higgs $\rightarrow$ SM+S. Also provides additional S production modes via heavy gauge boson decay.	Any.	See SM+S, with some additional production modes (new heavy gauge bosons).

MCFODO **M**athusla **C**ould be **F**irst or **O**nly **D**iscovery **O**pportunity

Sensitivity

MATHUSLA ≈ ATLAS/CMS - short-lifetime sensitivity + zero BG, no trigger issues

similar geometric acceptance for LLP decays in long-lifetime limit…

… you sacrifice sensitivity for short lifetimes…

… but you gain clean environment for LLP searches

Very easy to estimate sensitivity at MATHUSLA:

$$N_{\mathrm{MATHUSLA}} \approx (\#\ \mathrm{LLPs\ produced\ at\ LHC}) \times P_{\mathrm{decay}}^{\mathrm{MATHUSLA}}$$

$$P_{\mathrm{decay}}^{\mathrm{MATHUSLA}}(c\tau) \approx \epsilon_{\mathrm{geometric}} \quad P_{\mathrm{decay}}(\bar{b}c\tau, L_1, L_2)$$

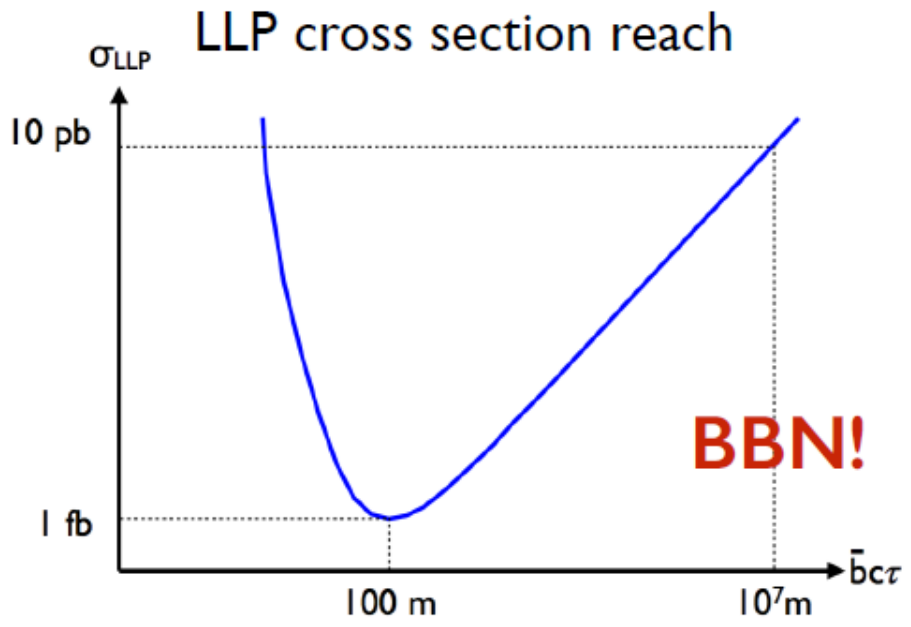
only modest O(1) dependence on LLP production process.

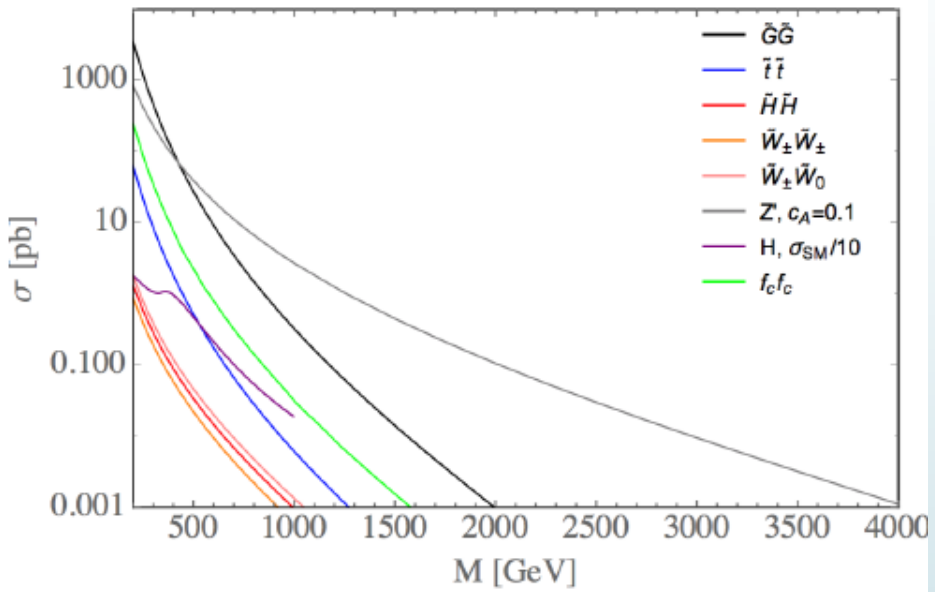
~ 0.05

$\sim \frac{(30\mathrm{m})}{\bar{b}c\tau}$

in long lifetime regime

Sensitivity





$$\bar{b} = \frac{m_{\rm eff}}{2m_{\rm LLP}}$$

$$\bar{b}c\tau_{\rm max} \sim (10^3\ {\rm m}) \left(\frac{\sigma_{\rm sig}^{\rm LHC}}{\rm fb}\right)$$

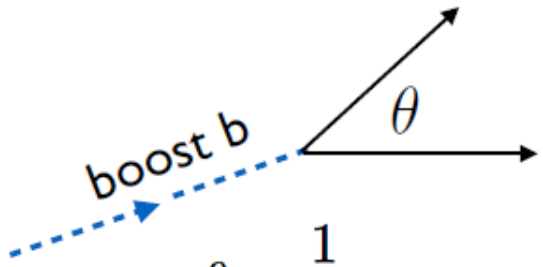
Any LLP production process with σ > fb can give signal.

TeV+ mass reach!

Sensitivity: Low-Mass Regime

Spatial resolution Δx of trackers is most important bottleneck:

Corresponds to maximum LLP boost for which multi-pronged DV can be reconstructed, which is crucial for BG rejection!



$$\theta \sim \frac{1}{\bar{b}}$$

$$b_{LLP}^{max} \sim 1000 \left(\frac{1cm}{\Delta x}\right)$$

→ Minimum LLP mass that can be probed "without BG"

$$m_{LLP}^{min} \sim \frac{m_{parent}}{2b_{LLP}^{max}} \sim \left(\frac{m_{parent}}{2000}\right)\left(\frac{\Delta x}{1cm}\right)$$

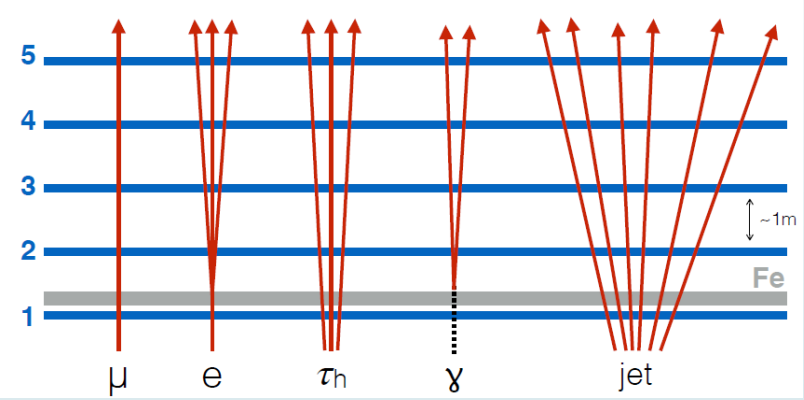
~ 10 MeV for LLPs from B decays

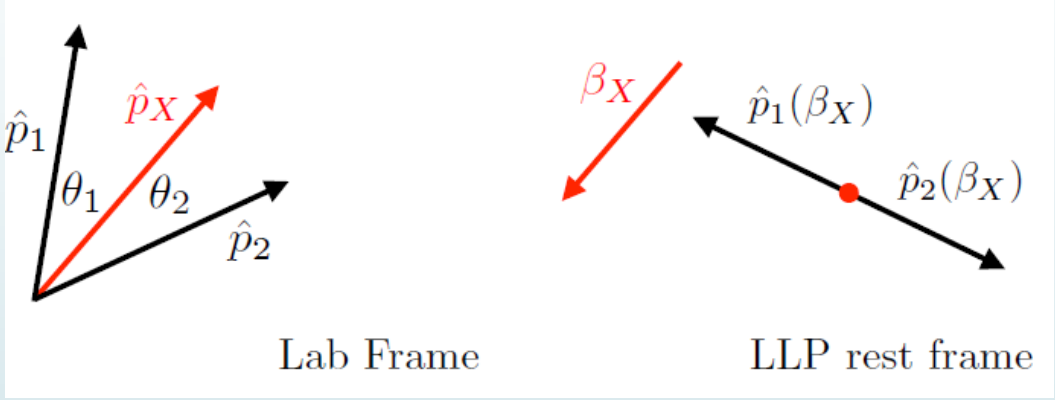
~ 0.1-1 GeV for weak-TeV scale production

Interesting complementarity with SHiP?

Signal Discrimination

- **Determine boost from opening angle**





various decay signatures

Boost 2-body decay to its rest frame

$$\beta_X = \frac{\beta_1 \beta_2 \sin(\theta_1 + \theta_2)}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_1}$$

Angles θ_1 and θ_2 well measured

arXiv:1705.06327

Design Constraints

- Working with Civil Engineers from CERN EN-ACE group (J. Gall and L. Dougherty) to define building and the layout of MATHUSLA at P5.

- Basic concept of modular detector units ~ 9mX9m – allows for phased construction and simplifies installation.
- Cover approximately 10^4 m^2 – Physics requirement.
- Minimum decay volume ~ 20 m – Physics requirement.
- Geometry driven by CERN owned space at P5, existing structures, HSE, HE and CE requirements.
- Maximum width 100 m – CE requirement.
- Maximum height above ground level 17 m – CE requirement.
- Space for access between modules 1 m – HSE requirement.
- Space between columns supporting crane and detector units 1.5 m - HE requirement.

Background Rejection (gory details)

Most important part of background rejection is the *extremely* conspicuous, multi-faceted and tightly defined nature of LLP decay signal:

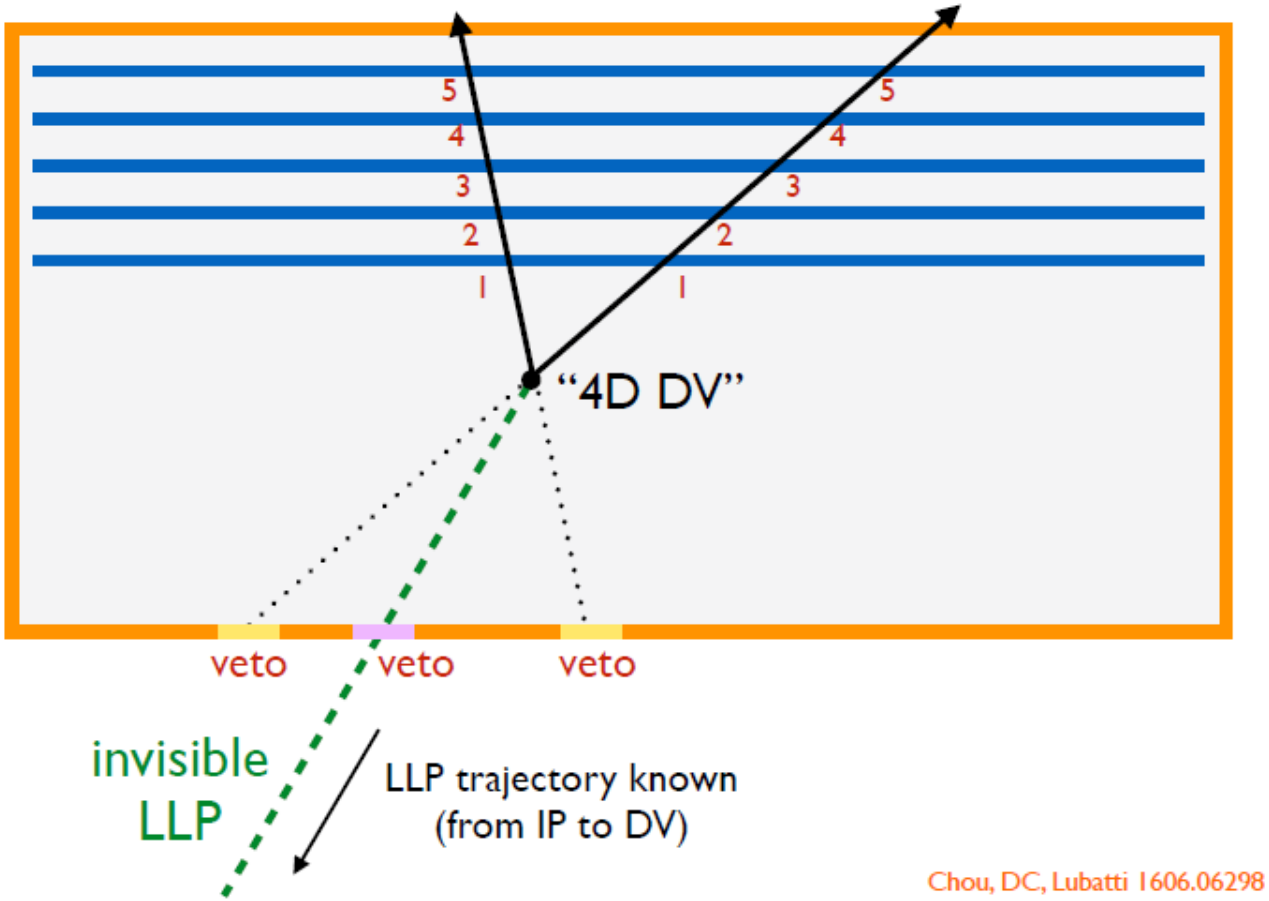
$\Delta t \gtrsim 3.5$ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns

~1m

tracks are reconstructed in 3D *and* with detailed timing information at each layer, so DV is really a "4D DV"

Shown is "leptonic" 2-body LLP decay. These requirements become exponentially more difficult to fake when decay is hadronic with ~10 charged final states!

most basic CR rejection: LLP decay products are upwards going tracks!



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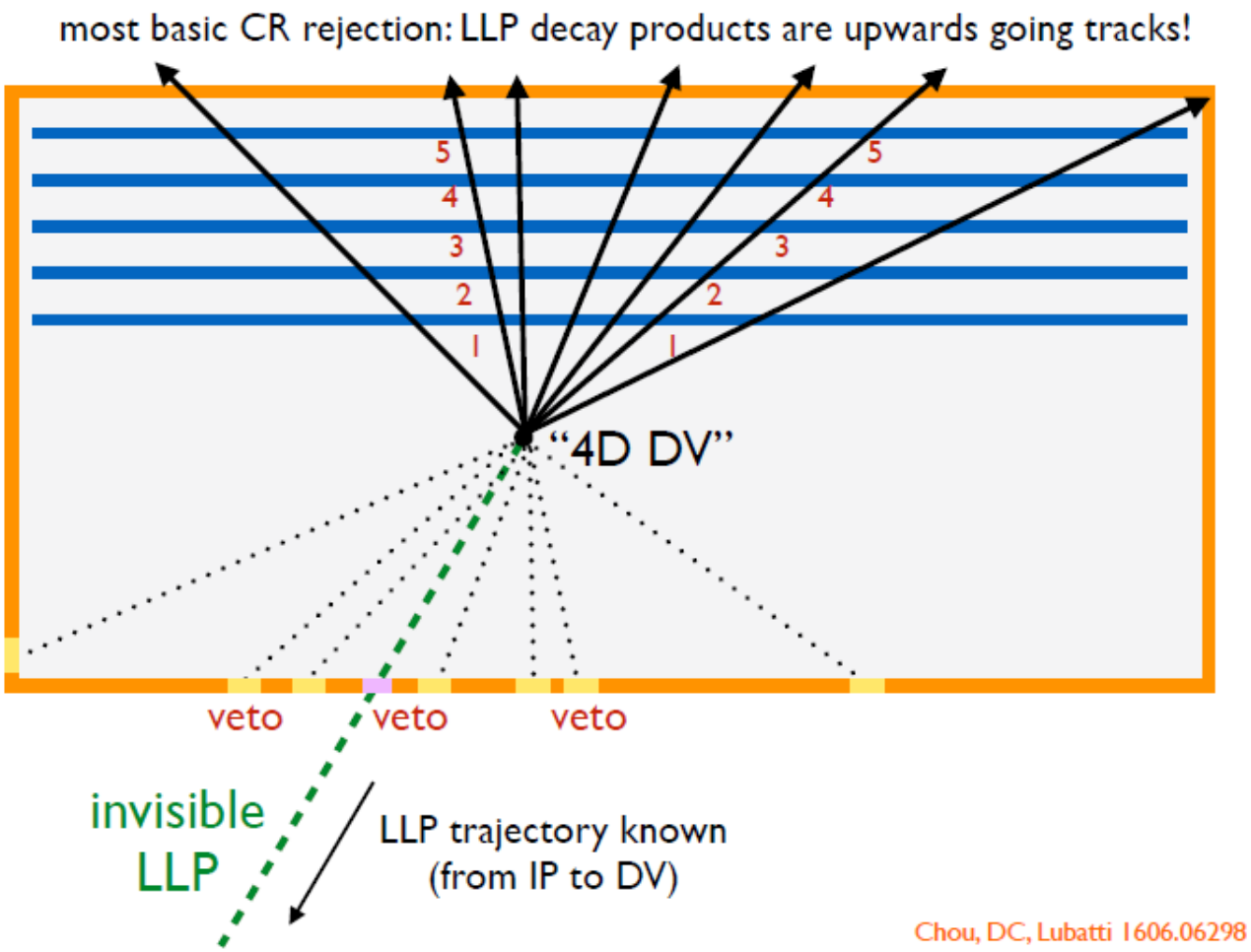
Like so.

All ~10 tracks have to meet in both space and time at DV and pass vetos on floor/walls.

(also, hadronic decay mode is perhaps a bit more of a MATHUSLA target due to main detector gap in coverage.)



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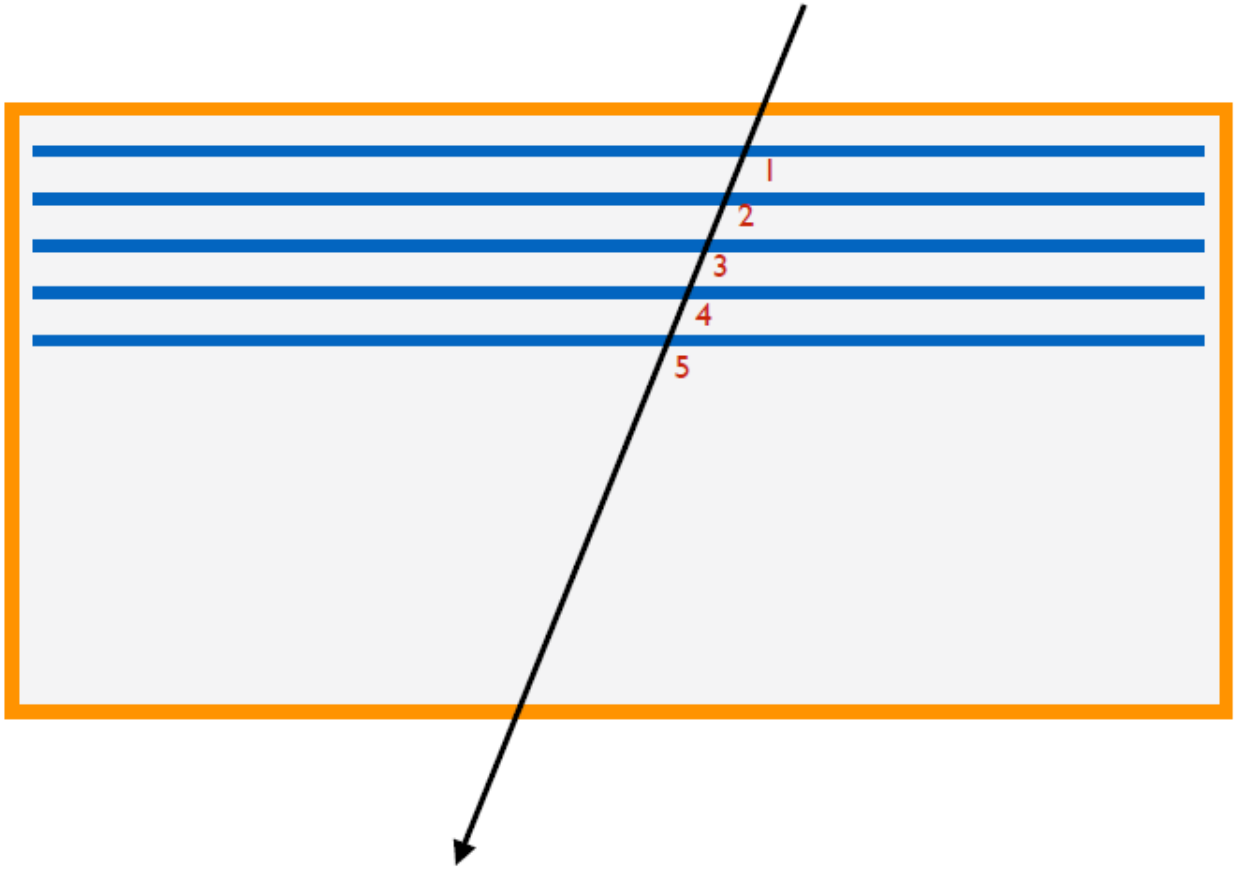
Background Rejection (gory details)

Compare to Cosmic Rays: about 10^{15} charged particles over HL-LHC run

$\Delta t \gtrsim 3.5$ns per tracker layer,
17 ns for all 5 layers
tracker time resolution: 1ns

~1m



For *single* downward-traveling charged particle from CR, assuming only *three* layers with 1ns timing resolution within 5m, **chance of downward *consistently* reconstructing as upward going is $\epsilon_{down \to up} \lesssim 10^{-15}$**

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Background Rejection (gory details)

Cosmic Rays: about 10^{15} charged particles over HL-LHC run

In this naive estimate, simple up-vs-down rejection *easily* gets rid of *all* cosmic ray backgrounds by itself.

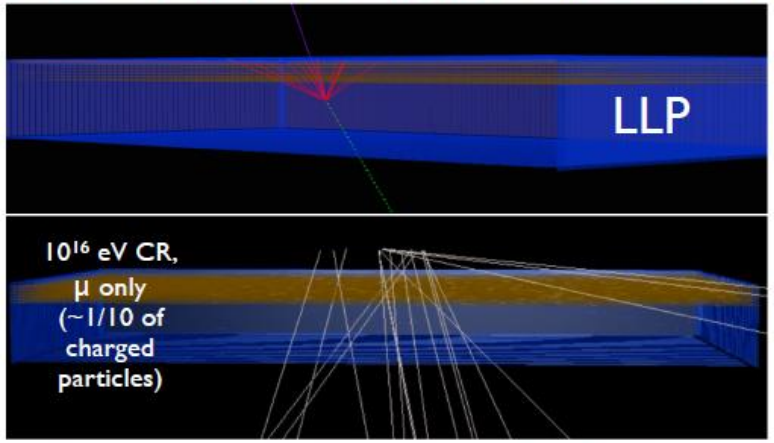
Of course, our estimate of $\epsilon_{down\to up}$ by itself is much too naive, based on purely gaussian time resolution, in reality tails are non-gaussian etc.

But this estimate only used 3 layers. We specified MATHUSLA to have 5.

Furthermore: single down→up fake does NOT fake the LLP signal. You need:

- ***two* down→up fakes** occurring `at same time' (so $\epsilon_{down\to up}^2$)
- they need to **cross in space to form a DV**: requires either spatial mismeasurements (most CRs don't do this) OR very rare CR trajectory crossings
- the huge timing errors made by 5 tracking layers for each track have to be such that the **tracks reconstruct to be coincident *in time* at the fake DV as well**
- the **scintillators have to fail** to register the two CRs on their way out of the decay volume.

Most CR tracks are highly correlated, forming Extensive Air Showers:



Indeed, these showers are the best chance for all these unlikely things to occur and fake an LLP 4D-DV.

BUT YOU CAN JUST "BLIND" THE DETECTOR WHILE IT HAS HIGH OCCUPANCY THAT IS OBVIOUSLY FROM A CR SHOWER.

Blind time has negligible effect on uptime & LLP sensitivity.

There might be very weird things that give rise to DVs in CR events: neutron decays, air scatterings of CR particles etc…

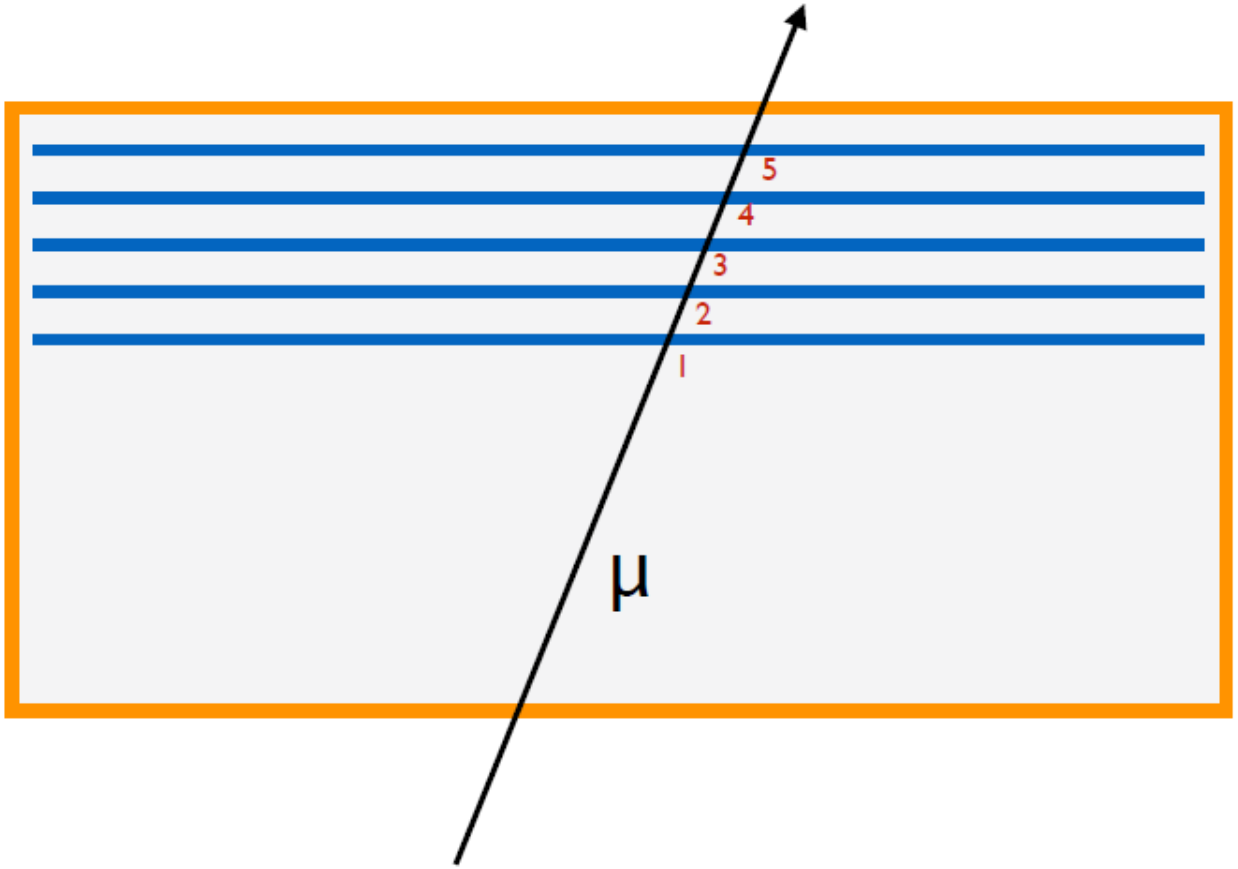
These much rarer occurrences will be studied in detail, but again, most of them would occur in highly correlated CR showers that are vetoed just based on occupancy.

Finally, this CR background is inherently *studyable*: during ~50% of time when HL-LHC beam is off, you can verify CR rejection strategies on data that is guaranteed to be only background.

Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

They do travel upwards, but they do not reconstruct a displaced vertex.



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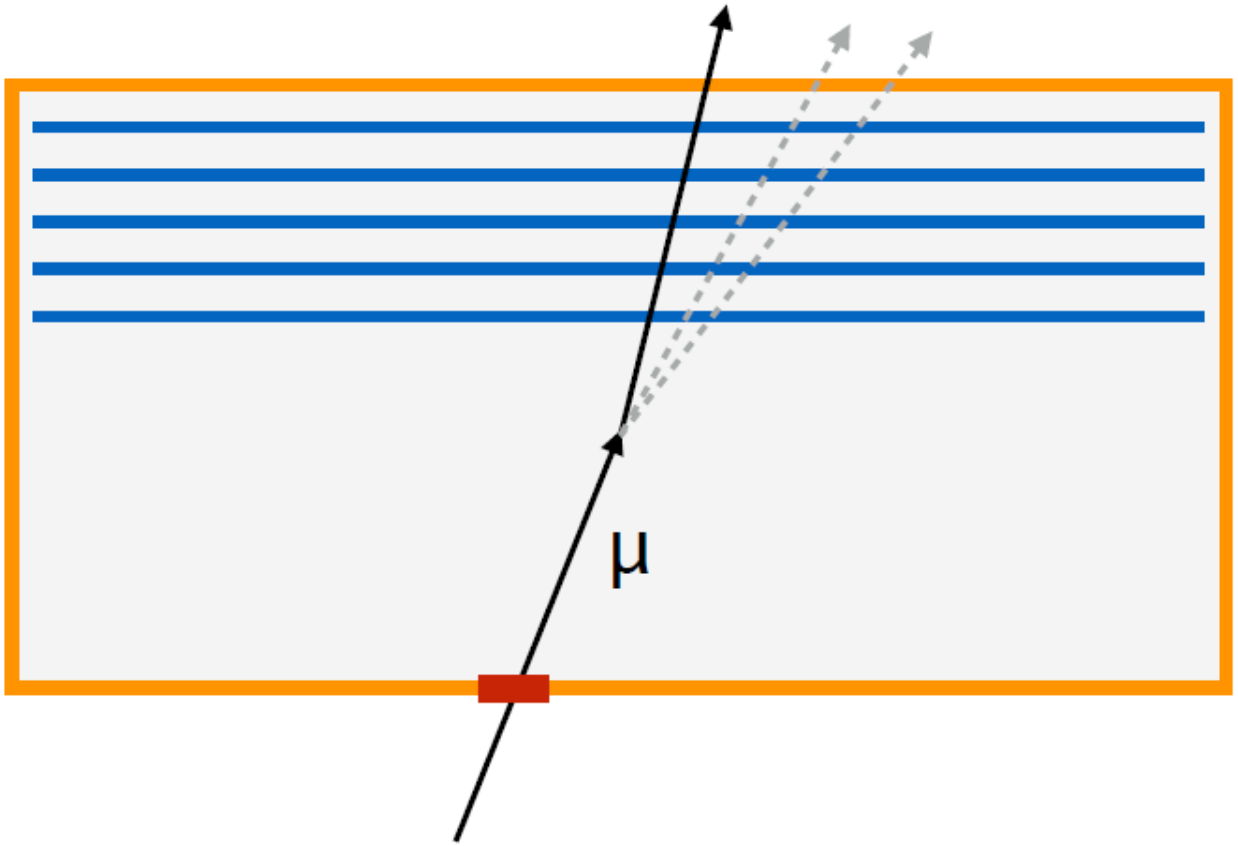
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

Ignoring orders-of-magnitude suppression from boost (!!)
<< 10^7 decay in volume, but again,
no DV
(and detectable by intersection of final and initial state trajectory)



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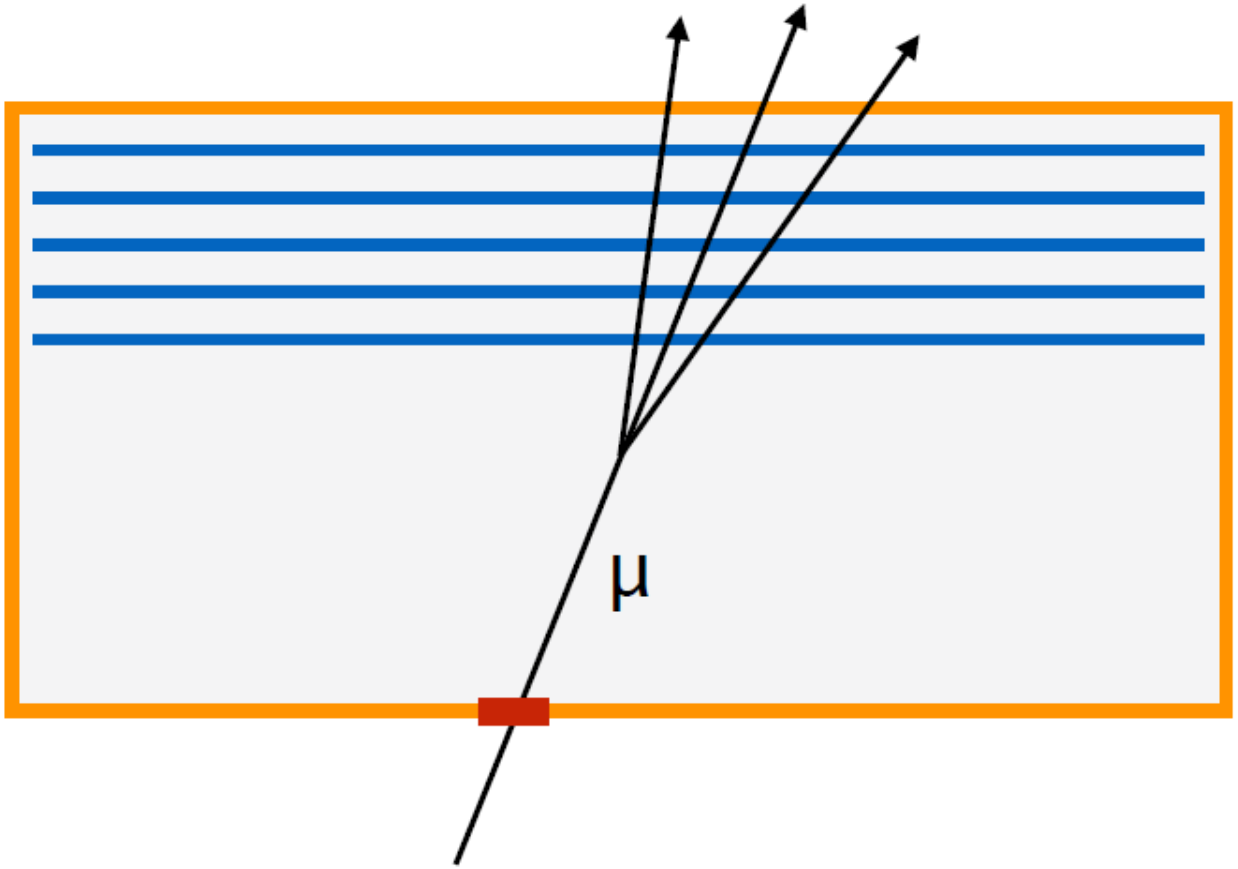
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

~ 1000 undergo rare decay into eeeνν (Br ~ 3×10^{-5}) → genuine DV!

Two possible rejection strategies:

1) reject *narrow* decay cones (where all particles are caught by tracker) with *odd* numbers of tracks, indicating charged parent particle
2) reject with scintillator and main detector vetoes (assuming efficiencies 99% and 90% respectively)



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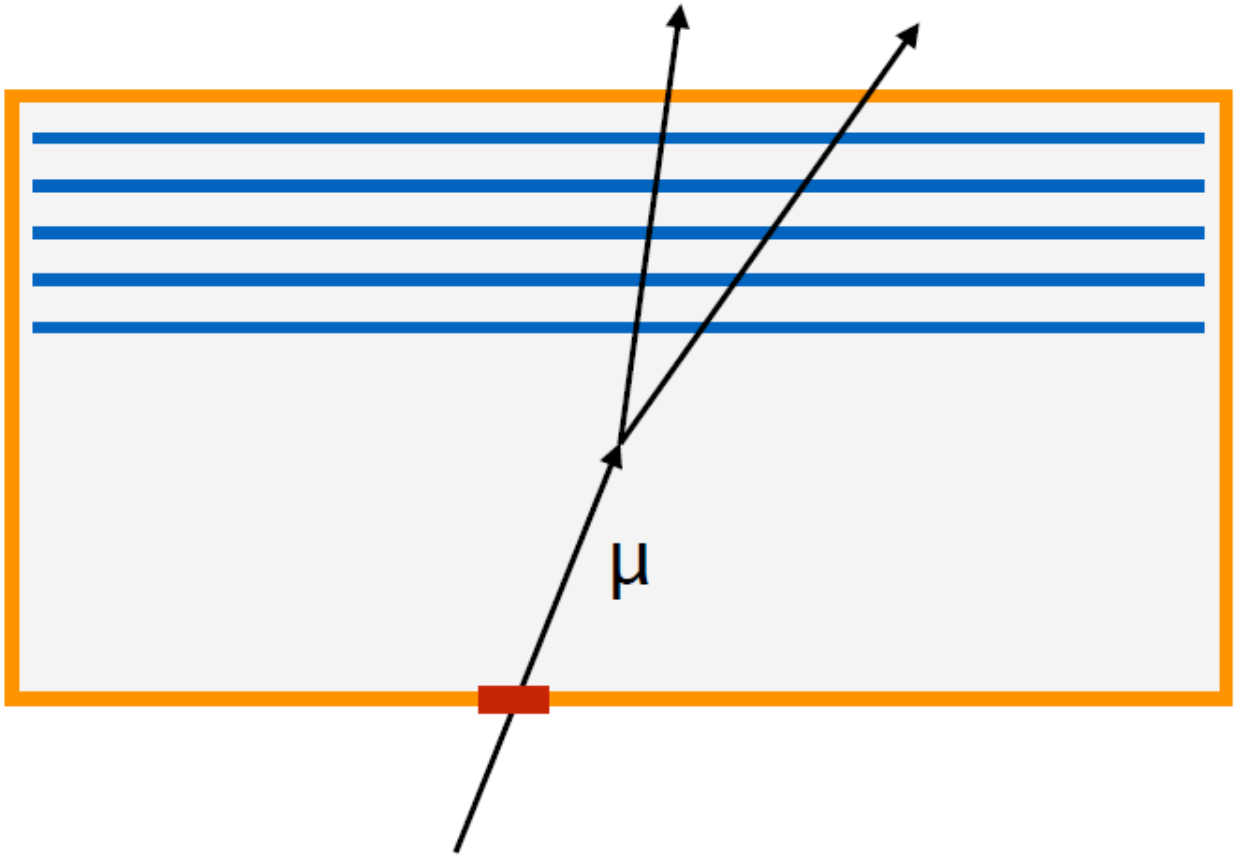
Background Rejection (gory details)

Muons from LHC: Have to have energy ≳ 50 GeV to reach detector, incident with rate ~10Hz → ~10^9 over HL-LHC run

~ 10 scatter off air and form genuine DV

easily veto with scintillator alone.



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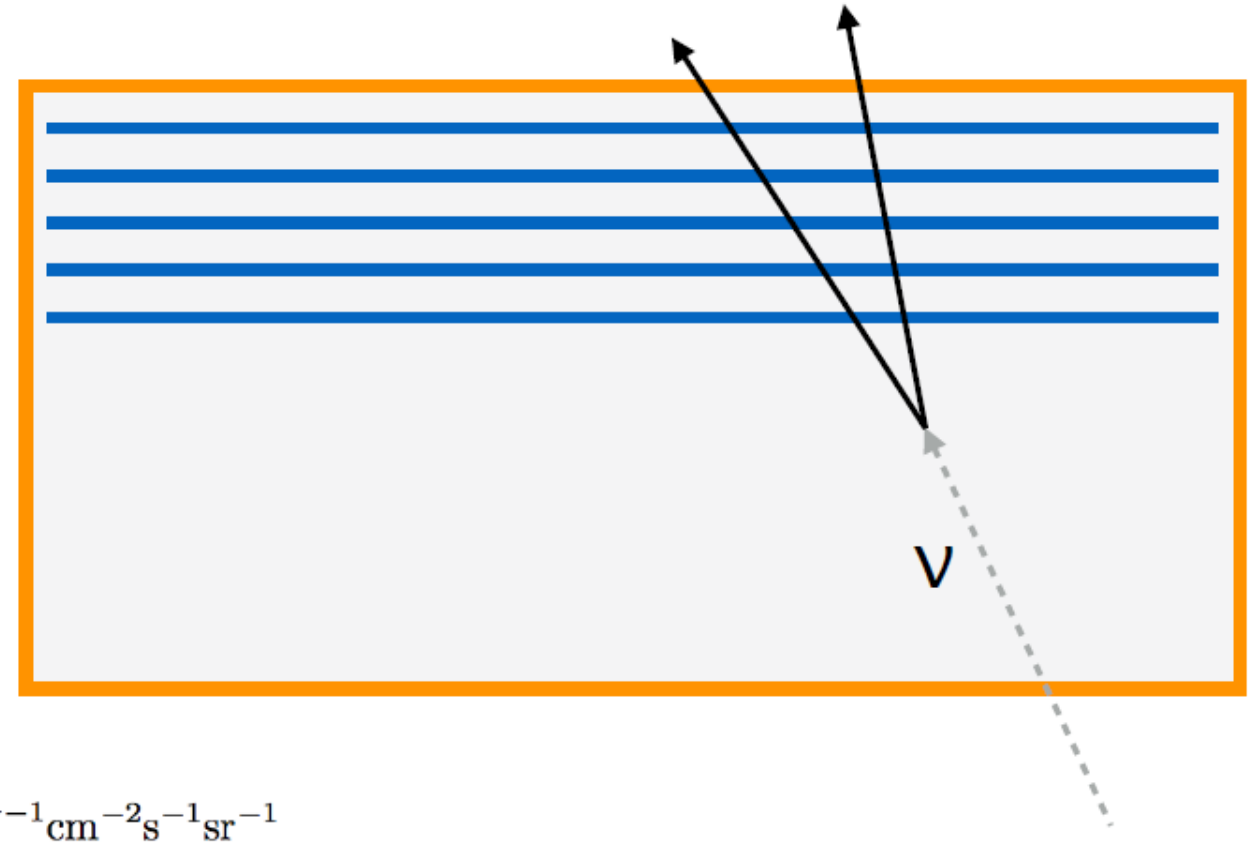
Background Rejection (gory details)

Isotropic neutrino haze from CR interactions with atmosphere:

Most dangerous BG, naively it looks exactly like LLP signal

Can compute rate using Frejus measurements of atmospheric ν_μ flux. (ν_e much lower, can be dealt with similarly)



$$\frac{d\Phi}{dE_\nu} \sim 0.06 \left(\frac{\mathrm{GeV}}{E_\nu}\right)^3 \ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

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Background Rejection (gory details)

Isotropic neutrino haze from CR interactions with atmosphere:

Only have to worry about neutrino scatters that give 2+ charged particles to give DV.

Exclusive scattering cross sections known at ~30% level Formaggio, Zeller, 1305.7513

Get about 60 events per year with proton in final state.

- Most of these protons are highly non-relativistic, can be tagged using MATHUSLA's ~0.05c **speed resolution** on charged particle tracks.
- Vetoing low-multiplicity DVs with single highly-NR track eliminates most of these BG events.
- Can also use geometric cuts: LLPs decaying to visible particles are either narrow cones pointing back to IP or broad cones. Neutrino final states (especially relatively high-energy ones with relativistic protons) are very narrow cones, mostly not pointing at IP.
- **applying both NR-proton-veto (v < 0.6c) and geometric cut, get < 1 event/year (using very low cut on v and pessimistic estimates of final state kinematics)**

Get about 10 events per year without protons in final state

- This small number can be vetoed using above geometry cut alone

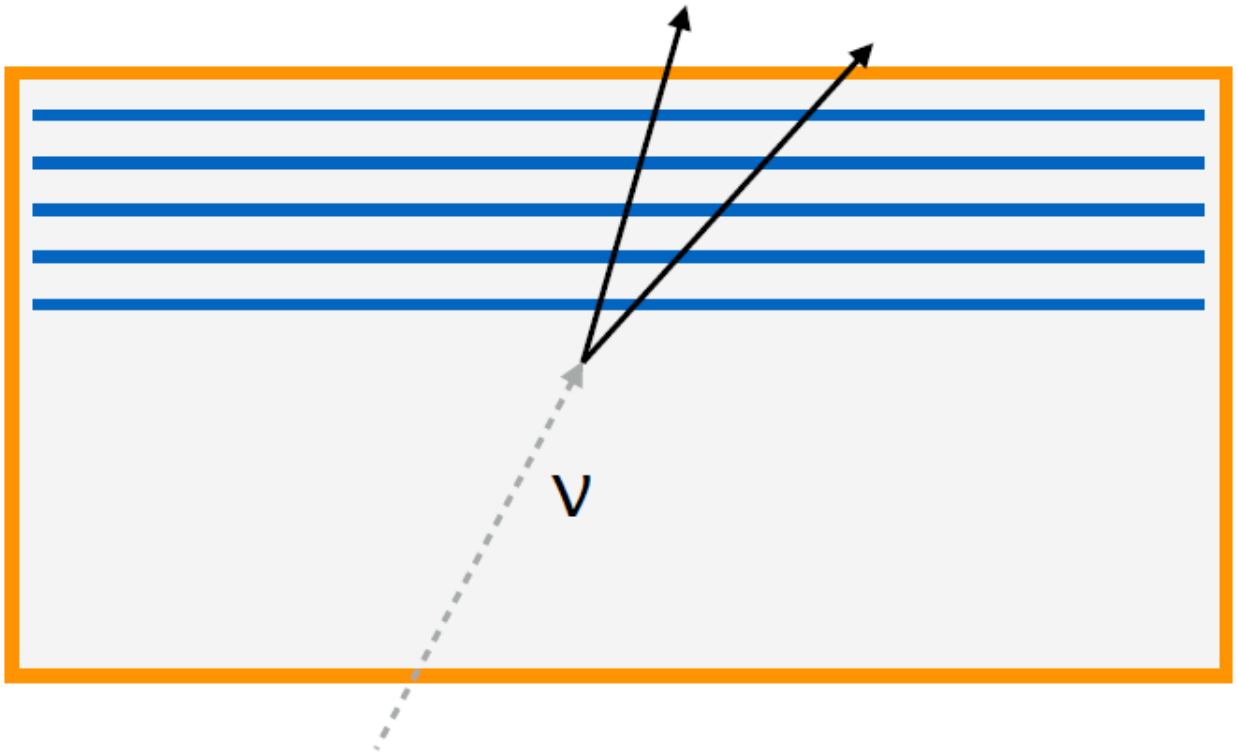
Background Rejection (gory details)

Also get neutrinos from LHC collisions, mostly low-energy , from hadron decays

Can estimate rate using generic GEANT simulation of main detector.

Cannot use naive geometric cut used on CR neutrinos, but after NR-proton-veto, only left with O(1) events per year.

There are other handles on their decay (detailed geometry, multiplicity, speed, …)
→ with further study should easily be able to reject.



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Background Rejection (gory details)

None of these BG rejection strategies seriously affect signal efficiency.

*Rarer BG processes: production of *isolated* Kaons in rocks from CR scattering that migrate to detector and decay, etc… estimates of rates << previous BGs*

ALL OF THIS HAS TO BE STUDIED IN MORE DETAIL WITH MORE SIMULATIONS. Most importantly:

- CR simulations & MATHUSLA test stand data to sanity-test rejection strategies to the extent possible using MC statistics (+ some cleverness to go beyond simple statistical?)

- Full simulation of neutrino background and rejection strategies. Refine geometric veto, especially for neutrinos from LHC.
  Get more realistic estimate of NR-proton-veto efficiency (will be better than our estimates, due to pessimistic assumptions we made about final state kinematics, and by ignoring remnants of shattered nucleus)