Searches for ultra long-lived particles with

MATHUSLA

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ON BEHALF OF THE MATHUSLA COLLABORATION

XVIII Vulcano Workshop on Frontier Objects in Astrophysics and Particle Physics

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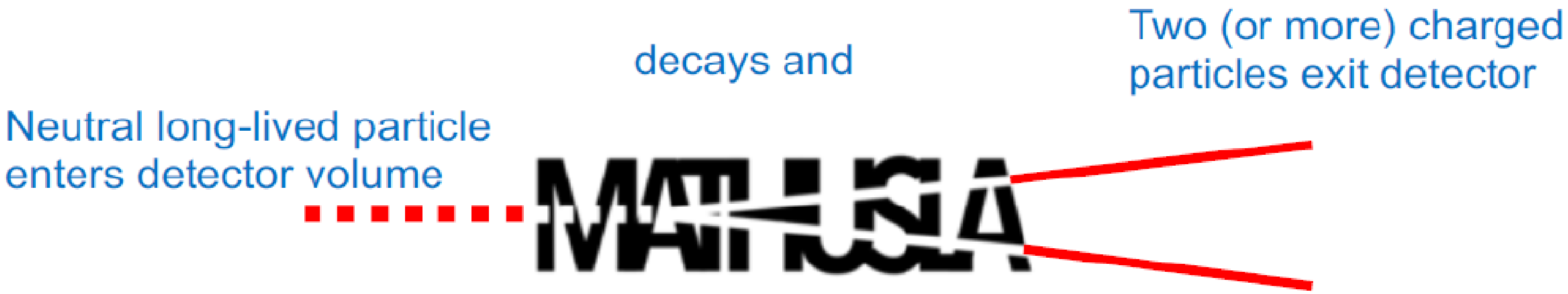
Outline

- Basic description of the Mathusla experiment
  - Experimental site
  - LLP identification
  - Backgrounds
- Detector design
- LLP sensitivity
- The reasons for a layer of RPCs in the Mathusla detector
- The MATHUSLA Test Stand
- Cosmic-ray physics with MATHUSLA

Basic Concept



MAssive **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** P**A**rticles

LLPs at the [HL-]LHC

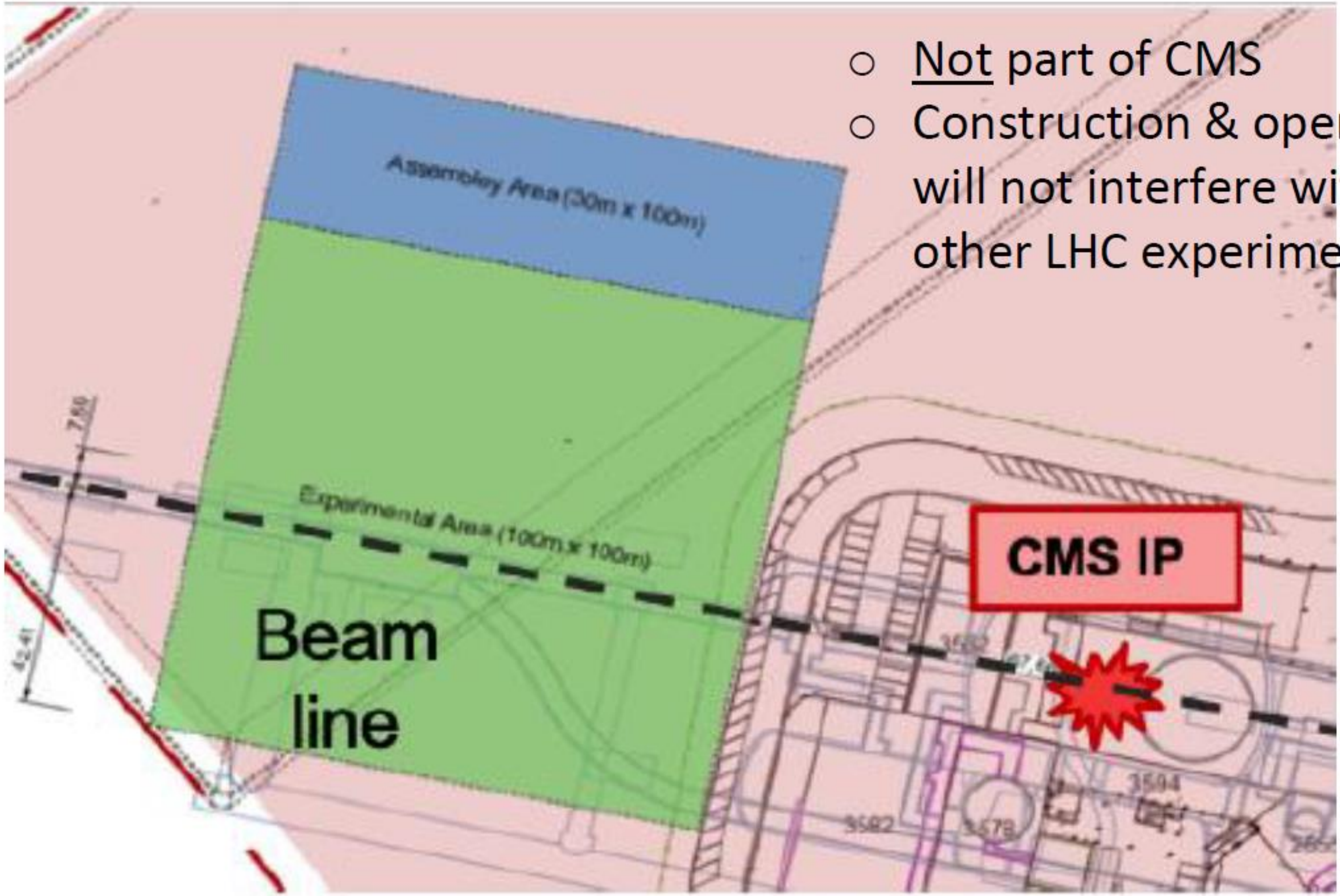
Seeking to go Beyond the Standard Model (BSM) motivates the possibility of so-far-undiscovered LLPs

- "**Top-down**": Various BSM theories (e.g. supersymmetry) constructed to explain the "fundamental mysteries" naturally include new LLPs
- "**Bottom-up**": LLPs occur in the SM (e.g. muons), and can occur via similar mechanisms when adding new particles to the model

The problem of long lifetimes: LHC could be making LLPs that are invisible to its main detectors!

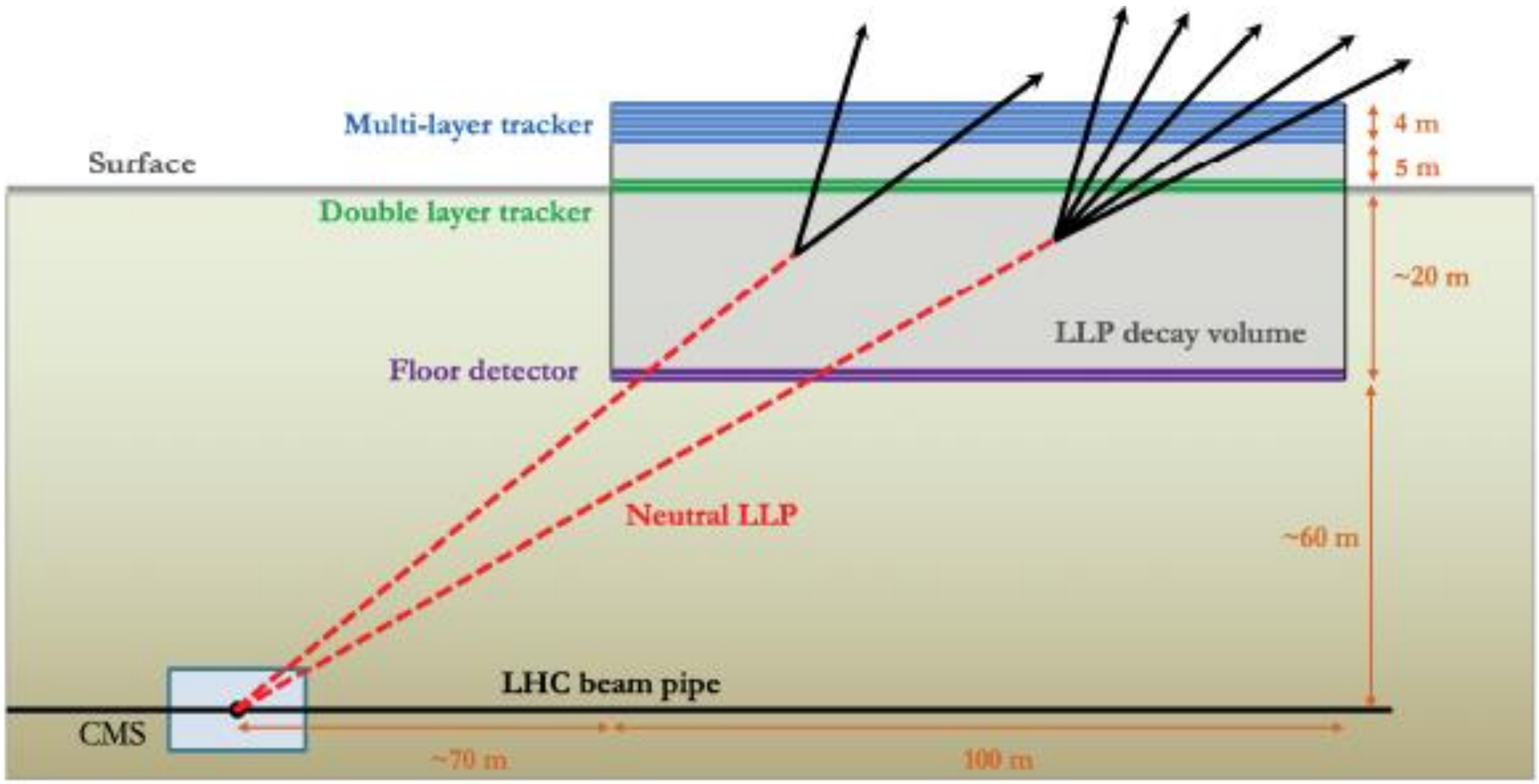
- **If the LLP has c · lifetime >> detector size, most escape the detector**
- **Even LLPs that decay in the detector, but a significant distance away from the Interaction Point, are difficult to spot**
- **If the LLPs decay in the detector with only a tiny rate, they get swamped by backgrounds**

An External LLP Detector for HL-LHC



- Not part of CMS
- Construction & operation will not interfere with any other LHC experiments

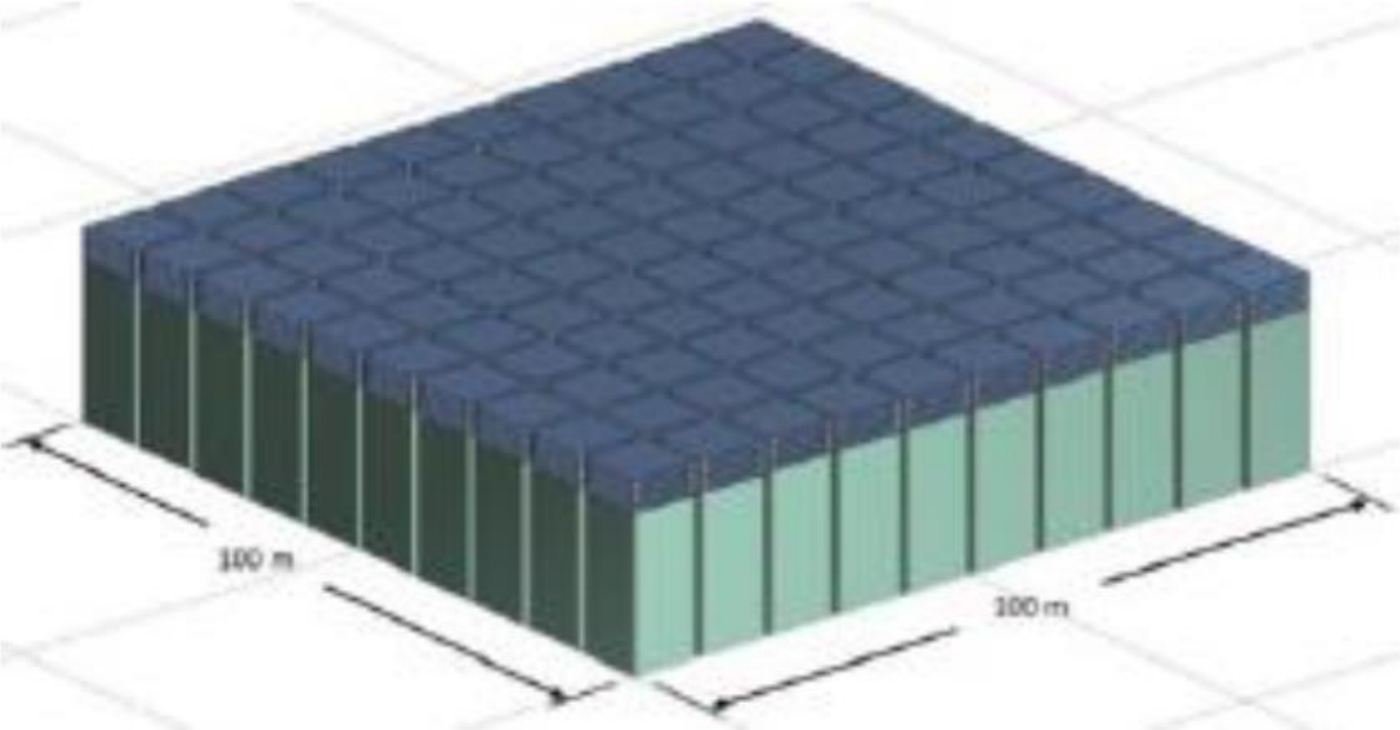
An external LLP detector for HL-LHC

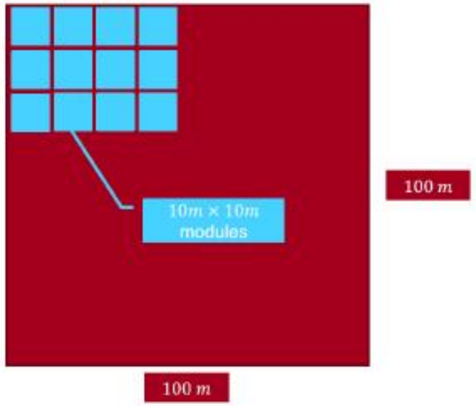


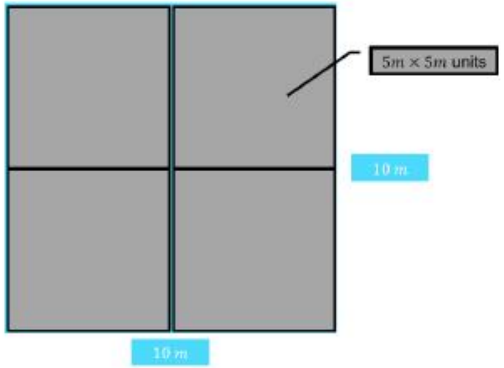
100m x 100m x 25m decay volume
Displacement from IP: 70m horizontally, 60m vertically

Detector Design

Modular design facilitates staged construction and commissioning



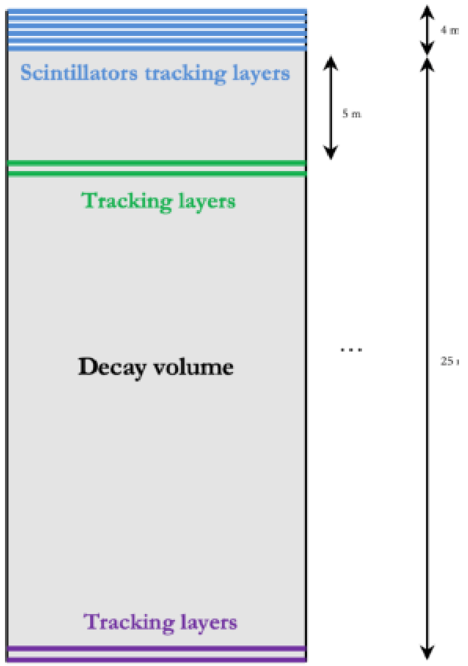




100 Modules in
$100m \times 100m$
Footprint

4 Detector Units per Module Plane

Detector Design



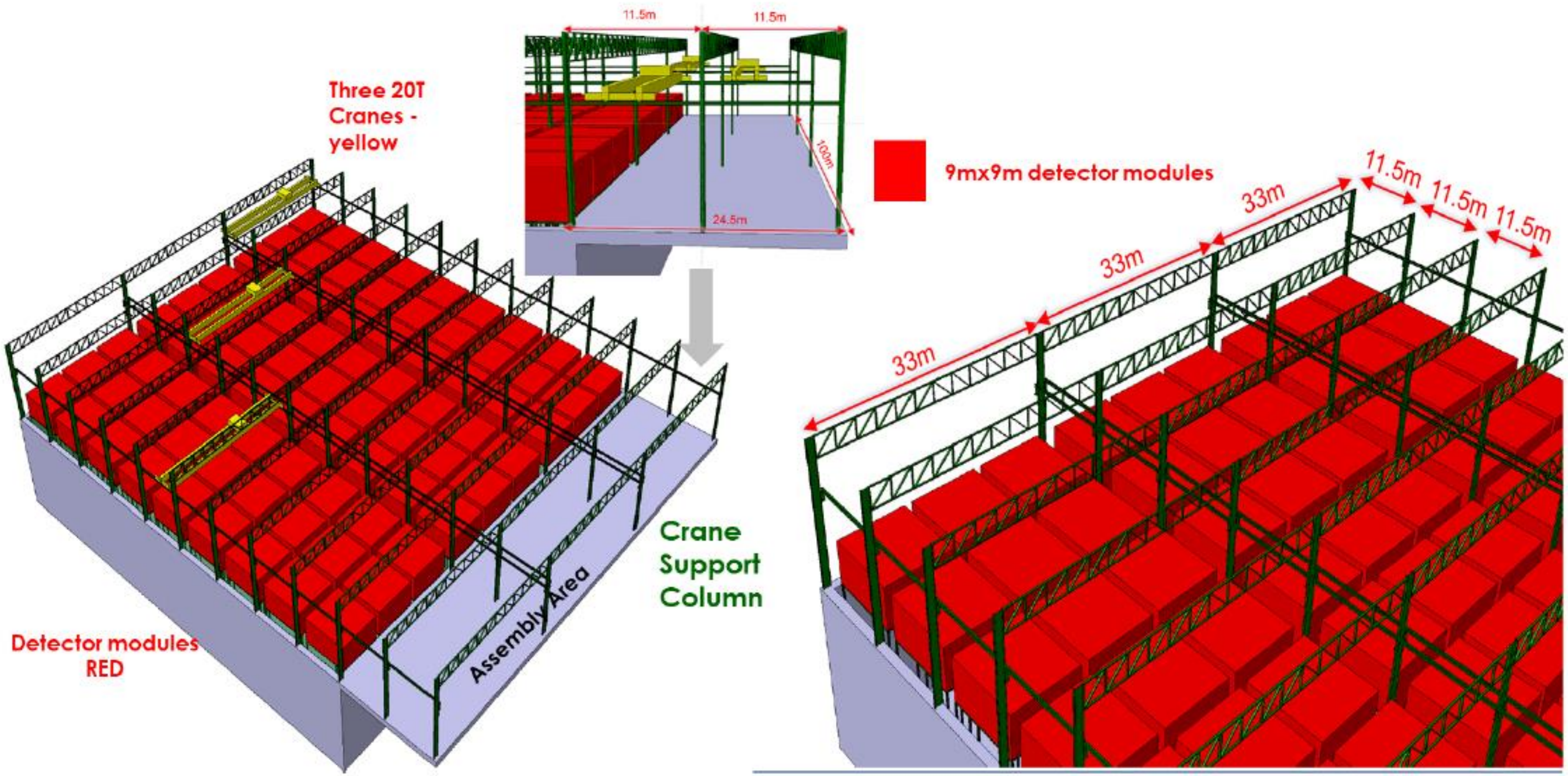
Each module is composed of:

6 tracking layers on top

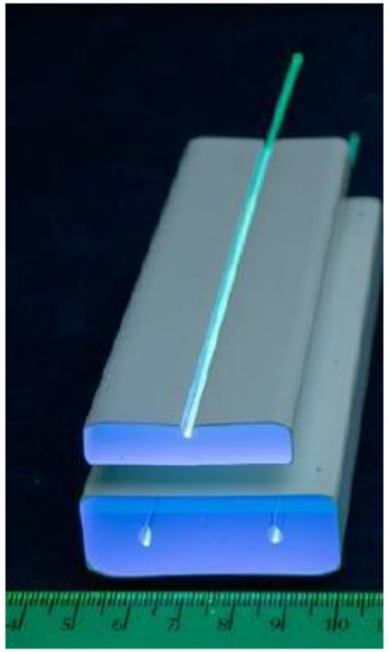
+ 2 floor layers

+ 2 mid-level layers

Detector Design



Trackers



Tracker layers: Composed of extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers

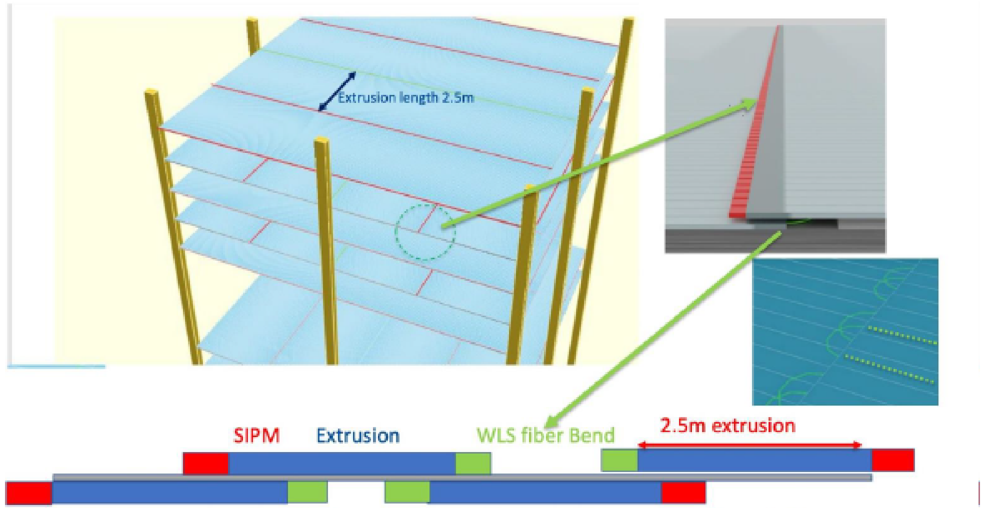
- Extrusion facilities in FNAL used for several experiments (e.g. Belle muon trigger upgrade, Mu2e)
- Possibility of adding Resistive Plate Chamber layers

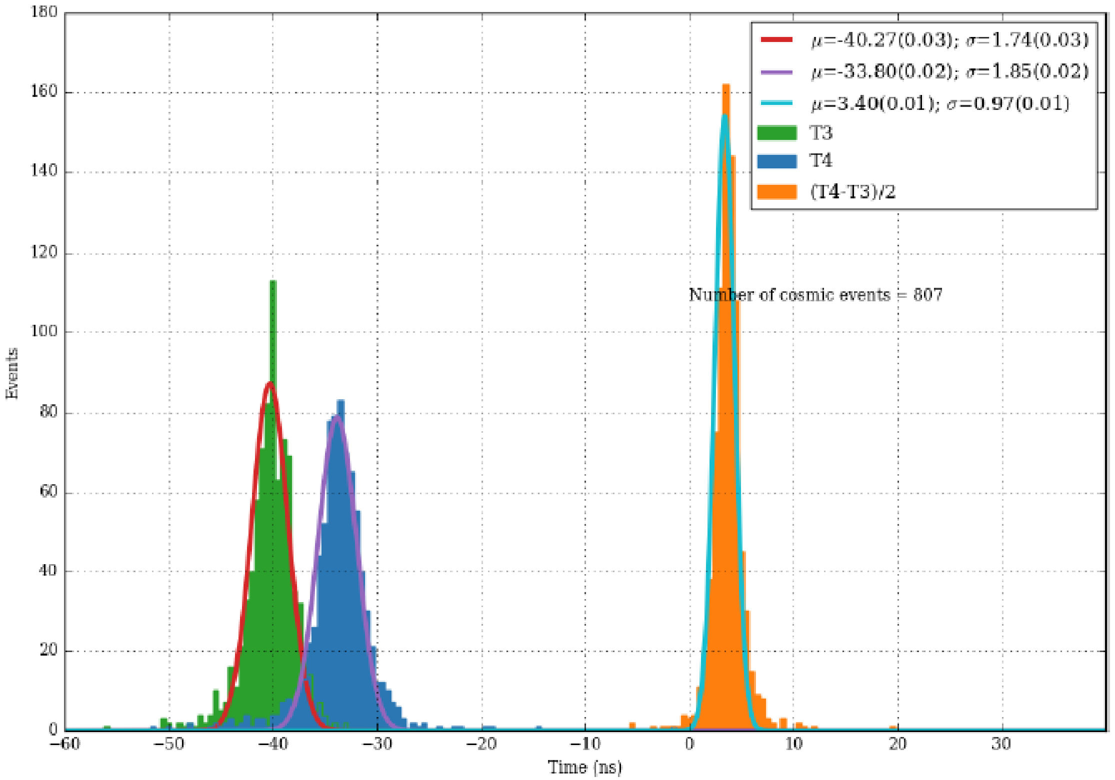
Each scintillator bar 2.4m x 3.5cm x 1.5cm with readout at both ends

- Or 2.5m with looped fiber for readout at one end
- Transverse resolution $\sigma \approx 1$ cm
- Δt between two ends gives longitudinal resolution: ~ 15 cm

Trackers

~1ns timing resolution of cosmic ray hits recently achieved in ~5m bar test setup





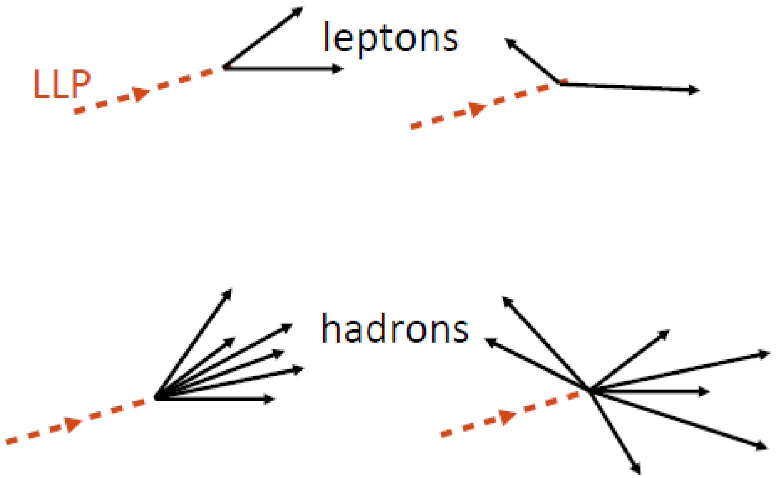
Ongoing R&D:

- Various WLSFs
  - Attenuation
  - Light collection
- Various SiPMs
  - Dark counts
- Scintillator bar geometry

Identifying LLPs

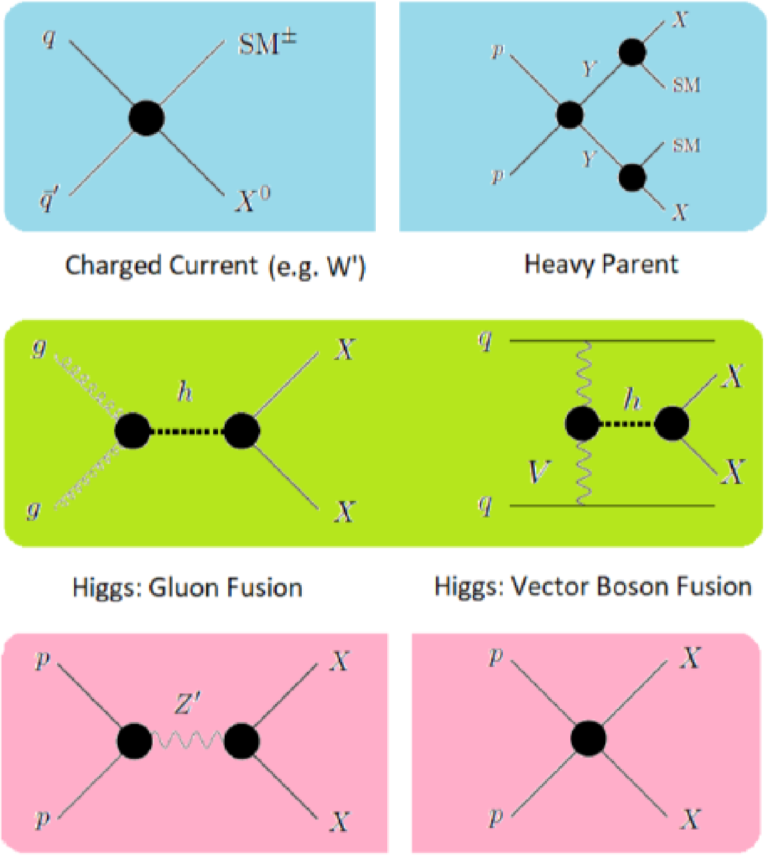
MATHUSLA can't measure particle momentum or energy, but:

track geometry →
measure of LLP boost



Incorporate MATHUSLA into CMS L1 Trigger

Correlate event info off-line →
LLP production mode

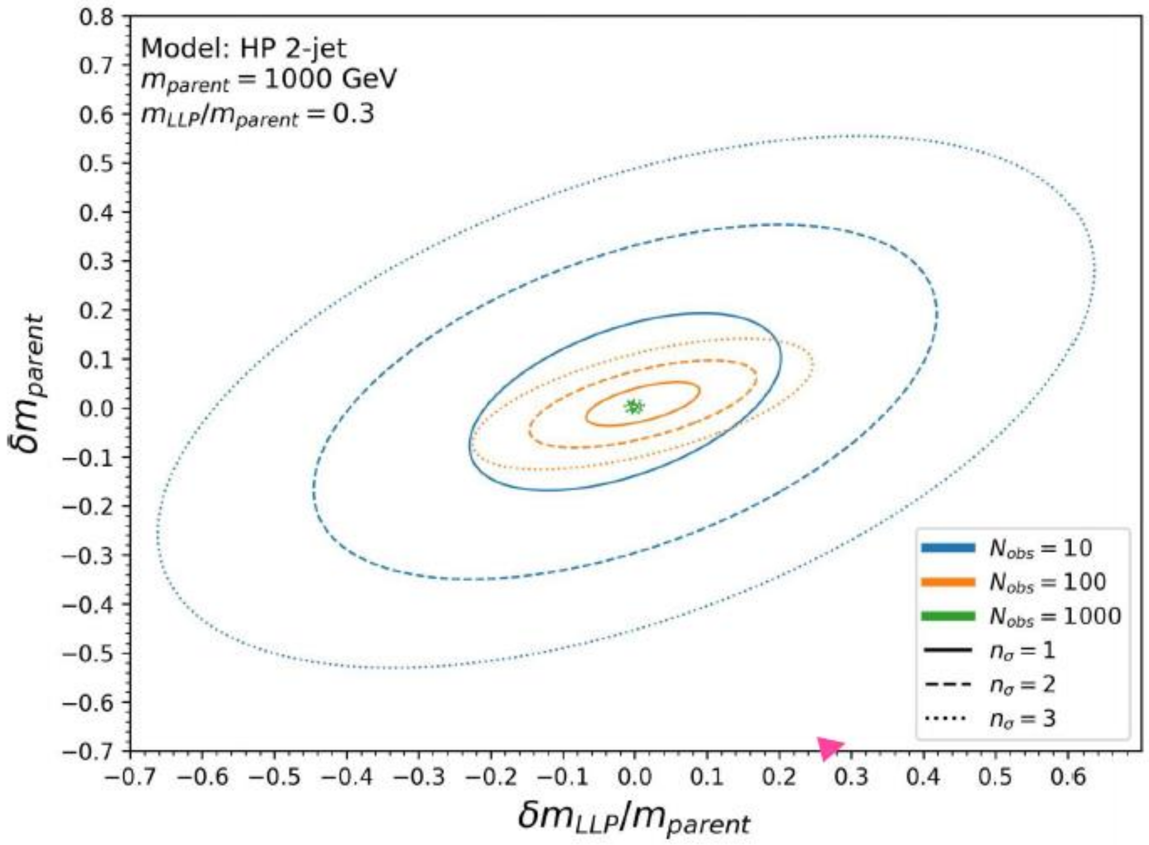


Charged Current (e.g. W') | Heavy Parent
Higgs: Gluon Fusion | Higgs: Vector Boson Fusion
Heavy Resonance | Direct Pair Production

Identifying LLPs

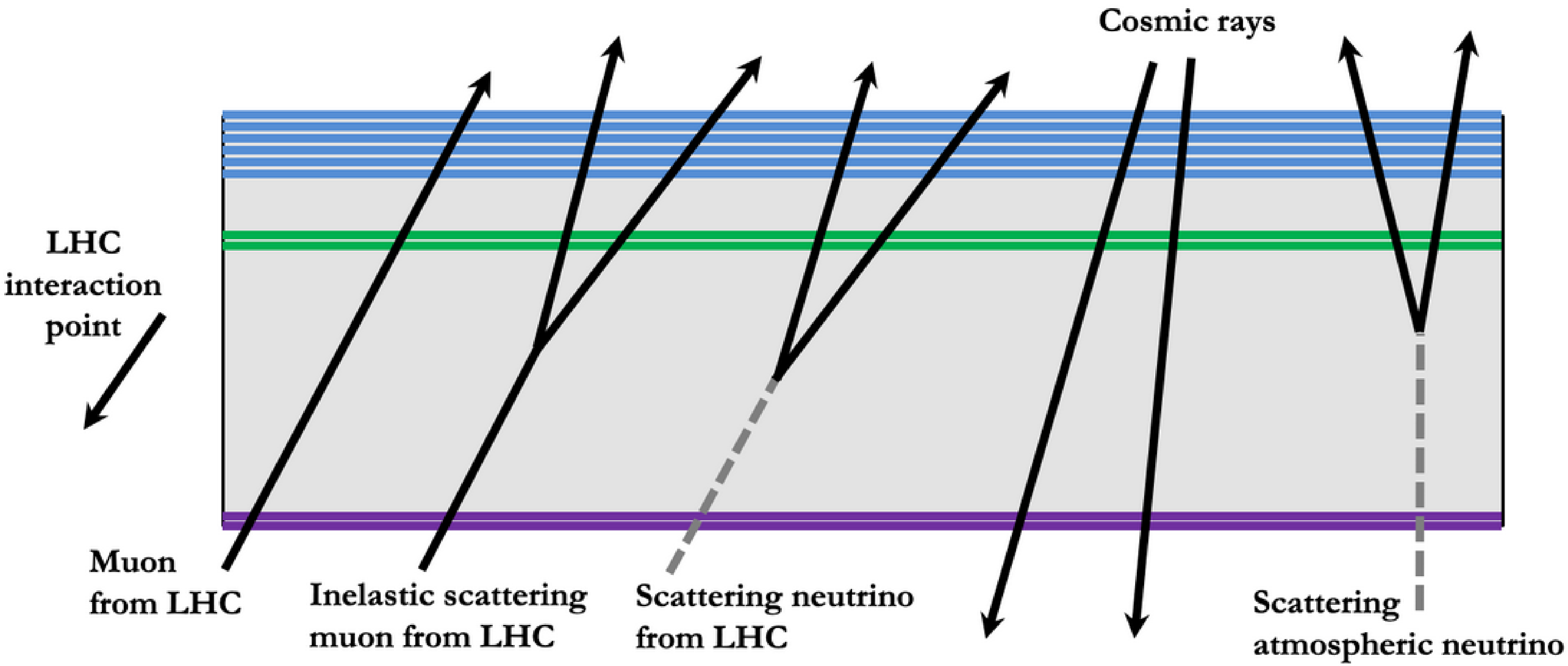
If production mode is known: Boost distribution → LLP mass
If LLP mass is known: Track multiplicity → LLP decay mode

MATHUSLA + CMS analysis can reveal model parameters (parent mass, LLP mass) with just ~100 observed LLP events!



arXiv:2007.05538 , 1809.01683

Backgrounds



LLP displaced vertex (DV) signal has to satisfy many stringent geometrical and timing requirements (“4D vertexing” with cm/ns precision)

These requirements, plus a few extra geometry & timing cuts, provide “near-zero background” (< 1 event per year) for neutral LLP decays!

Backgrounds

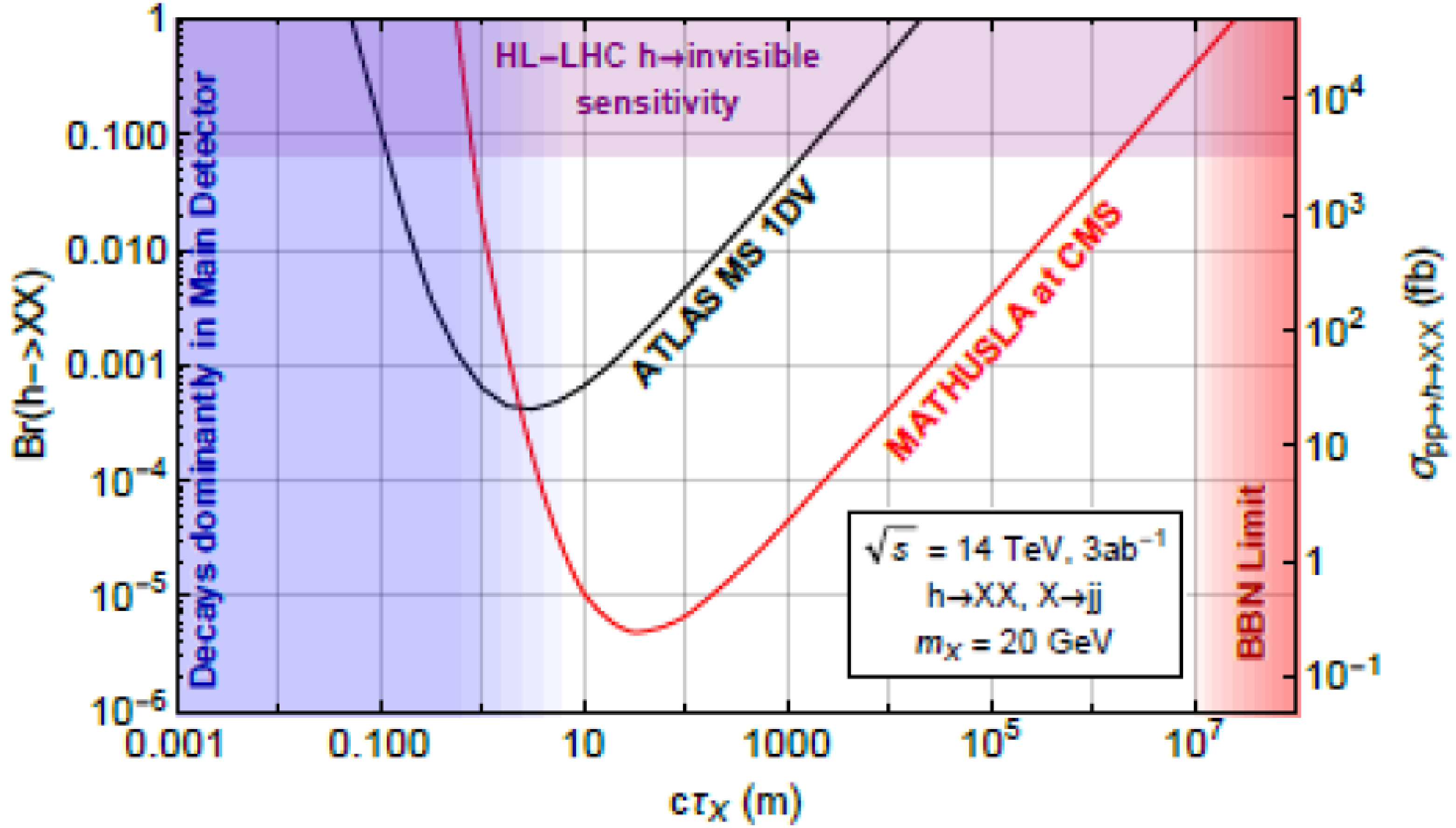
- *Cosmic rays*
  - Calibrations performed using Test Stand measurements (taken above ATLAS IP in 2018); arXiv: 2005.02018
  - Downward-going events ~3 x 10^{14} over entire HL-LHC run, distinguished from LLPs using timing cuts
  - Upward-going events ~2 x 10^{10} : inelastic backscatter from CRs hitting the floor, or decay of stopped muons in floor. Only tiny fraction (estimates underway) produce fake DV, via decay to charged tracks
  - Full simulation studies of rare K_L^0 production in floor currently being completed, can be vetoed with variety of strategies; the concern here is with incident protons (and neutrons)

- *Upward-going muons from HL-LHC collisions*
  - Roughly 10^{11} muons from 3 ab^{-1} of HL-LHC collisions reach MATHUSLA, mostly from W and $b\bar{b}$ production
  - Most can be vetoed with floor detectors; small fraction gives rise to displaced vertices due to scattering or rare decays
  - Full-simulation studies currently being completed, variety of veto strategies allows this background to be handled

- *Charged particles from neutrino scattering in decay volume*
  - Neutrinos from HL-LHC collisions << 1 “fake” DV/year
  - Atmospheric neutrinos ~30 “fake” DV/year, reduced to < 1 with cuts

LLP Sensitivity: Weak- to TeV- Scale

Up to 1000x better sensitivity than LHC main detectors
e.g. hadronically-decaying LLPs in exotic Higgs decay



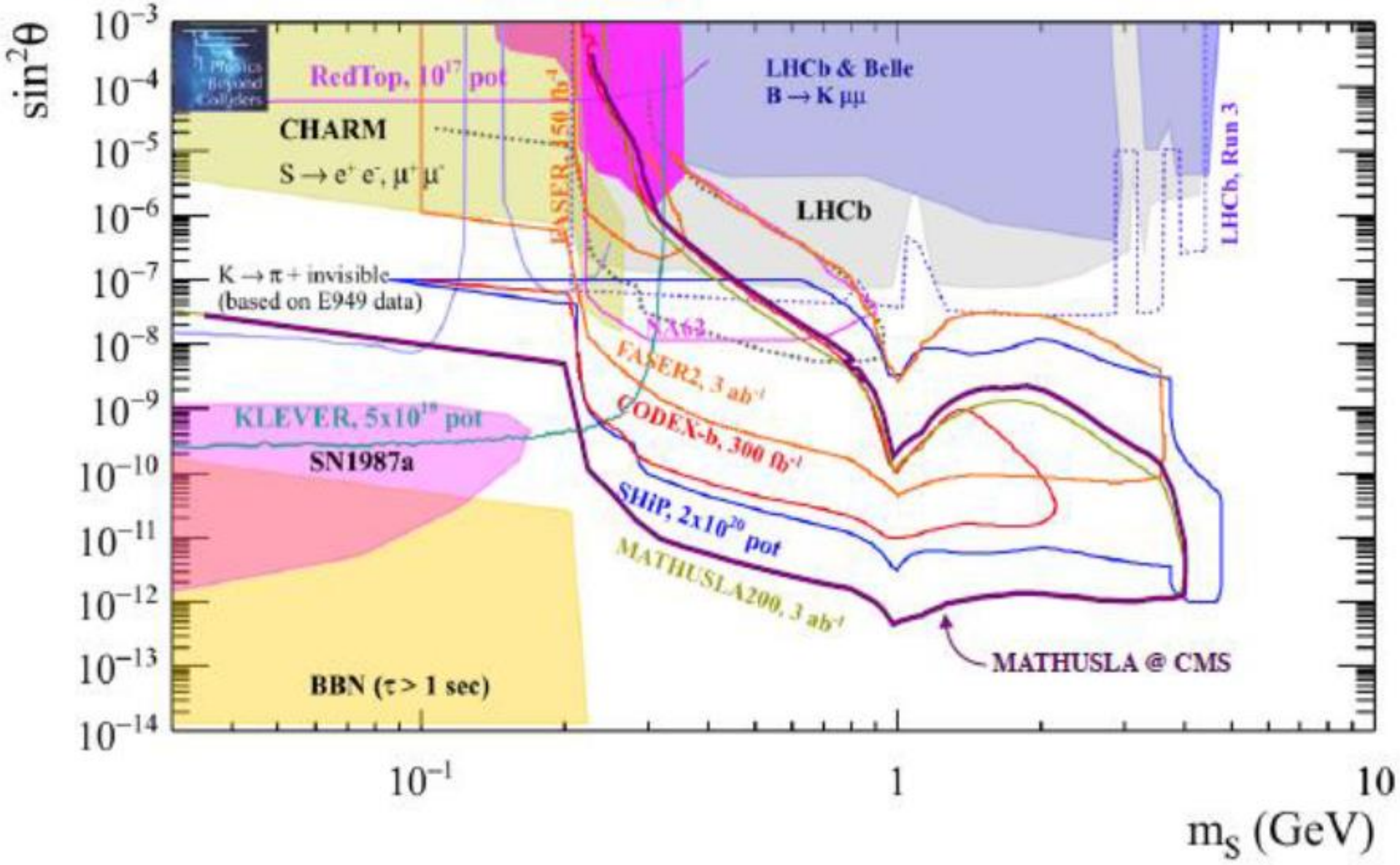
Any LLP production process with σ > fb can give signal in MATHUSLA

arXiv:2001.04750

LLP Sensitivity: GeV-Scale

For scenarios where the long-lifetime limit (>100m) is accessible, MATHUSLA is complementary to other planned experiments

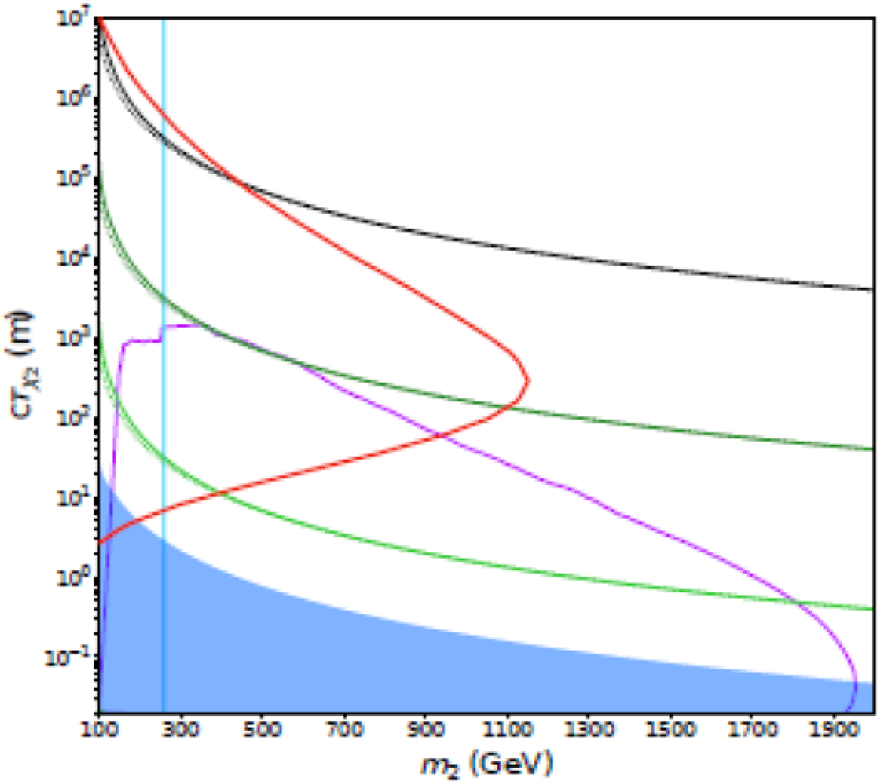
e.g. singlet dark scalar S, mixing angle θ with SM Higgs

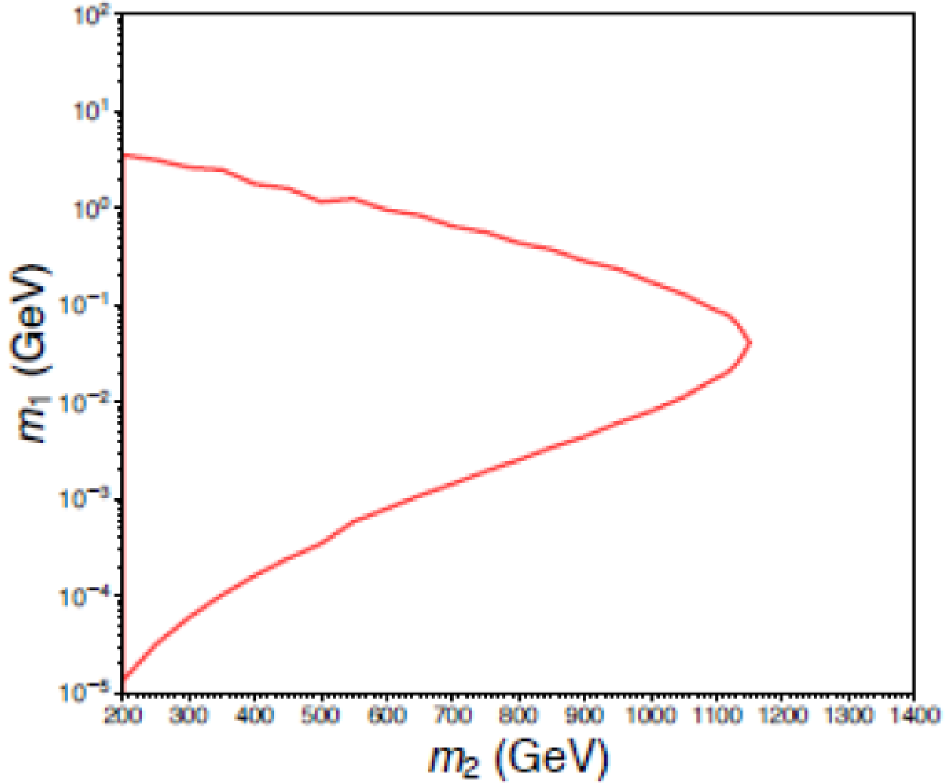


LLP Sensitivity: DM

Scenarios where LLP → DM + SM decay is the only way to see the DM

e.g. Freeze-In Dark Matter: BSM mass eigenstates χ_1 (DM) and χ_2 (LLP), where χ_2 was in thermal equilibrium with primordial plasma





Lyman-α exclusion
DV + MET 95% CL (3000 fb-1)
Disappearing Tracks 95% CL (3000 fb-1)
MATHUSLA200 (4 observed events, 3000 fb-1)

$\Omega h^2 = 0.12$ (m_1 = 1 GeV, T_{EW} = 50 GeV)
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$\Omega h^2 = 0.12$ (m_1 = 100 KeV, T_{EW} = 50 GeV)
$\Omega h^2 = 0.12$ (m_1 = 100 KeV, T_{EW} = 160 GeV)

More benchmark models for LLP search

- Physics Beyond Colliders CERN report;

  J. Phys. G: Nucl. Part. Phys. **47** 010501

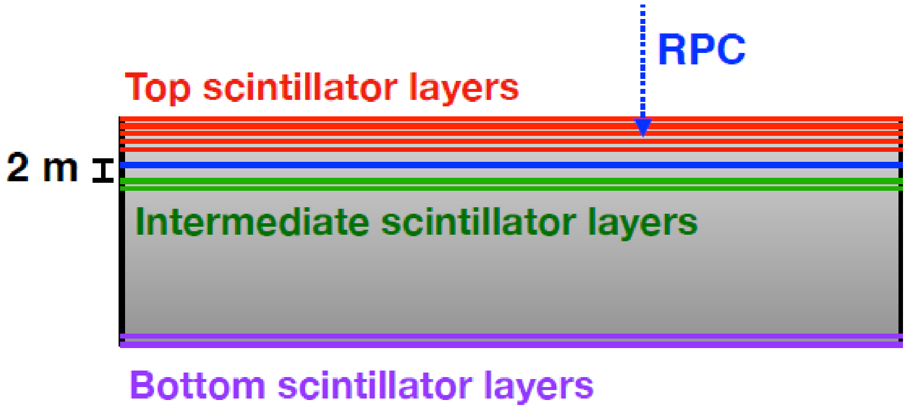
- For more sensitivity projections, see the MATHUSLA physics case; arXiv 1806.07396

The reasons for a layer of RPCs in MATHUSLA (1)

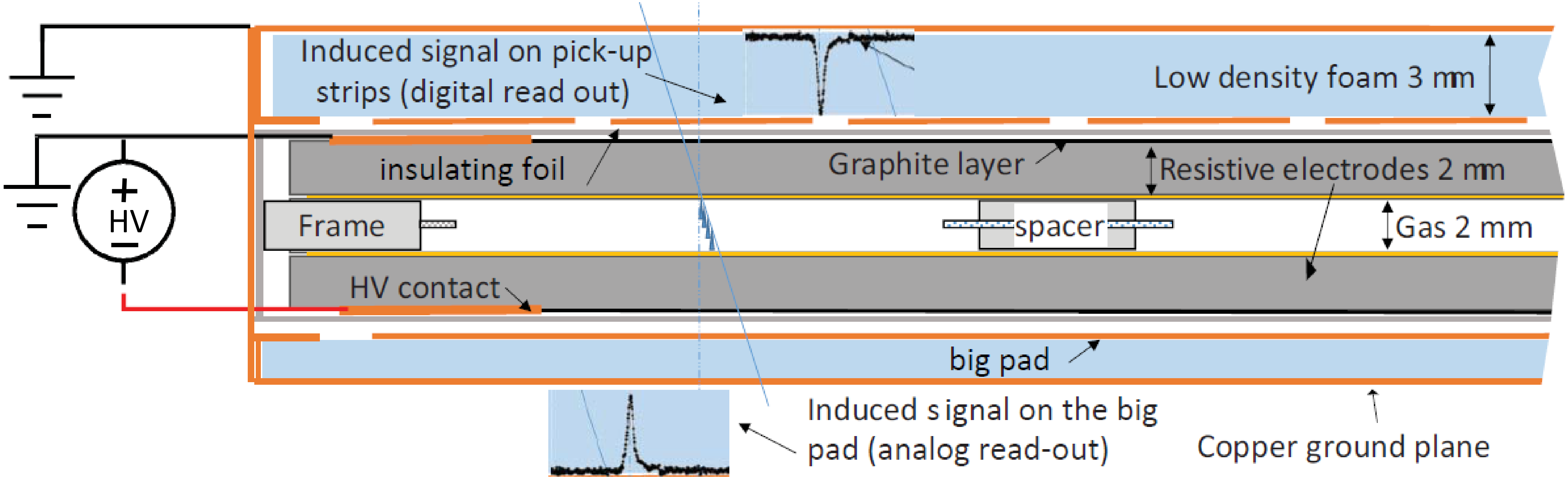
- RPCs give the following supplemental information:
  - Lower multi-hit probability in one strip due to the finer segmentation of the RPC read-out strips
  - Estimation of the pulse charge from the «time-over-threshold» measurement; this gives an approximate evaluation of the hit multiplicity in one strip provided the number of simultaneous hits is significantly > 1
  - However, the information from the RPC layer is crucial for cosmic-ray studies with MATHUSLA: linear response for hit density up to 10^4 hits/m^2 in the detection of air-shower cores, thanks to the «big-pad» analog read-out, to be compared to the scintillator digital response.

The reasons for a layer of RPCs in MATHUSLA (2)

- RPC characteristics
  - Big Pads: 1.1 m x 0.9 m
  - 242 cm^2 strips (11-mm pitch)
  - RPC in Avalanche mode.
  - 1 mm gas gaps (like in ATLAS BI RPCs)
  - Big Pad signal ∝ local charge density.



Scheme of a Resistive Plate Chamber

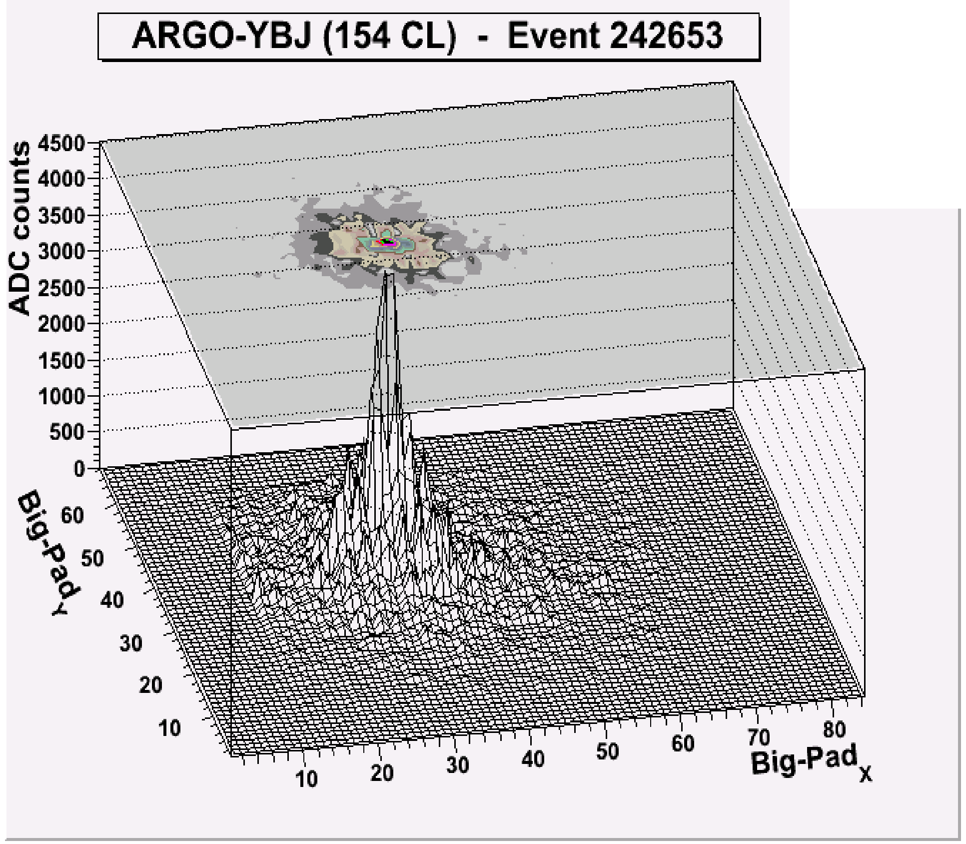


- A RPC is just a gas filled plane capacitor with high resistivity electrodes
- External signal pick-up electrodes can be easily tailored with any shape (11 mm in this case)
- Chamber size: 0.9x2.2 m^2; Time resolution < 1 ns
- Eco-friendly gas mixture for operation in avalanche mode
- Two “big pads” of 0.9x1.1 m^2 allow the analog readout

The RPC analog readout in ARGO-YBJ

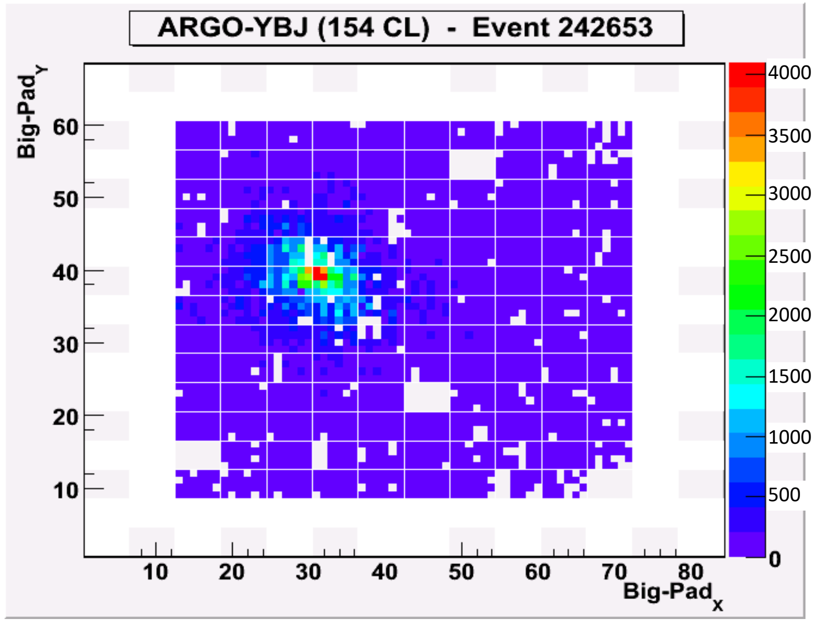
Extending the dynamical range up to PeV

- Crucial to extend the covered energy range above 100 TeV, where the strip read-out saturates
- Max digital density ~20/m^2 Max analog dens ~10^4/m^2

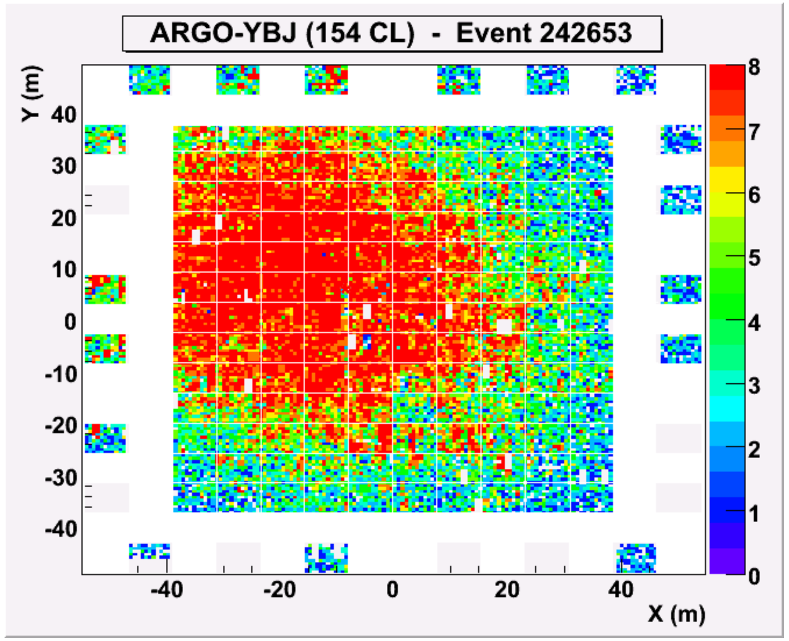


Fs: 4000 -> 1300/m^2

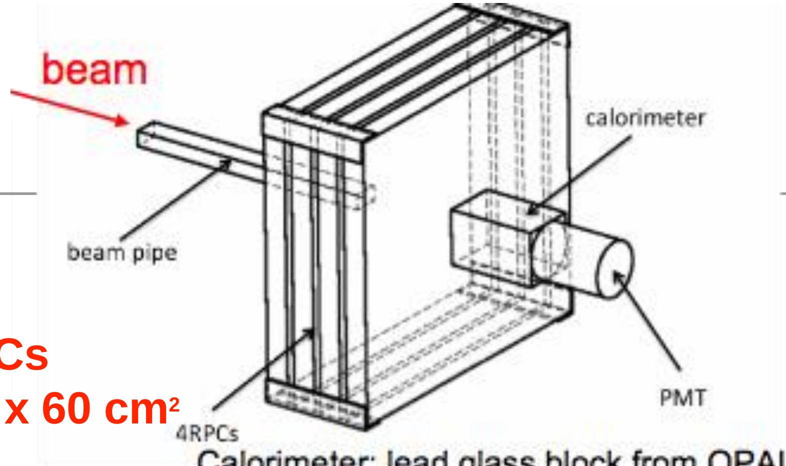
Analog



Digital



RPC intrinsic linearity: test at the BTF facility



4 RPCs
60 x 60 cm^2

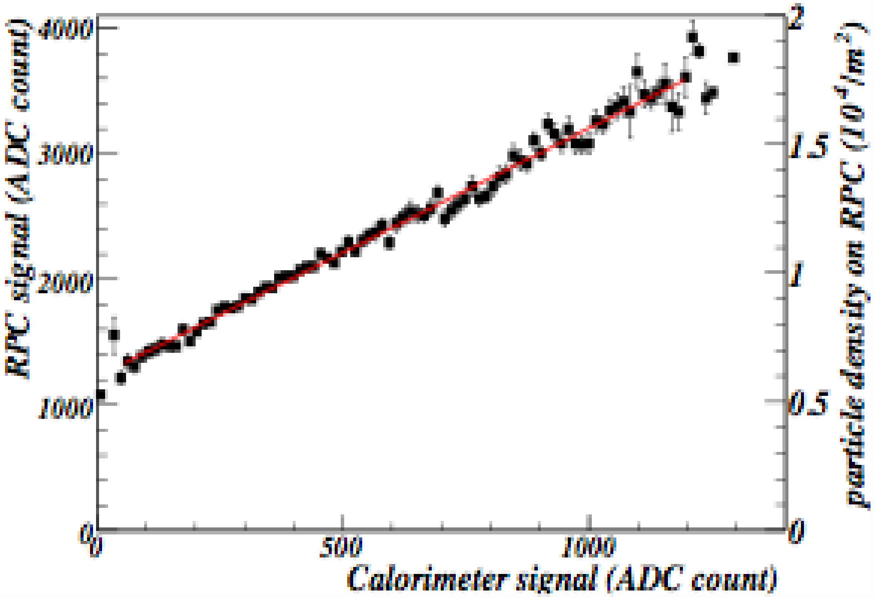
Calorimeter: lead glass block from OPAL,
PMT a Hamamatsu R2238.

Linearity of the RPC @ BTF

at INFN Frascati Lab:

- *electrons (or positrons)*
- *E = 25-750 MeV (0.5% resolution)*
- *<N>=1÷10^{8}particles/pulse*
- *10 ns pulses, 1-49 Hz*
- *beam spot uniform on 3×5 cm^2*

The RPC signal vs the calorimeter signal



➔ **Linearity up to ≈ 2 · 10^4 particle/m^2**

The MATHUSLA Test Stand (1)

(a) (b)

Fig. 1. (a) 3D model of the MATHUSLA test stand. (b) Photo of the final assembled structure installed above the ATLAS IP. The green dots identify the two scintillator layers used for triggering, while the red dots mark the three RPC double-layers used for tracking. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

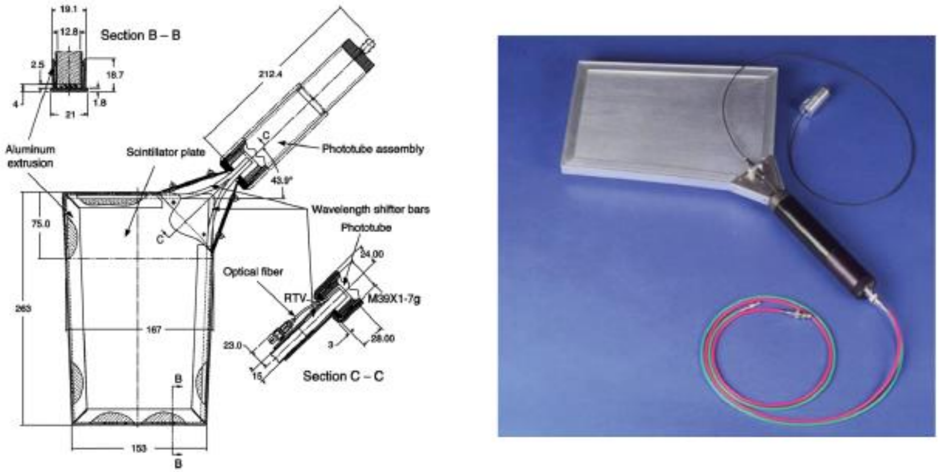
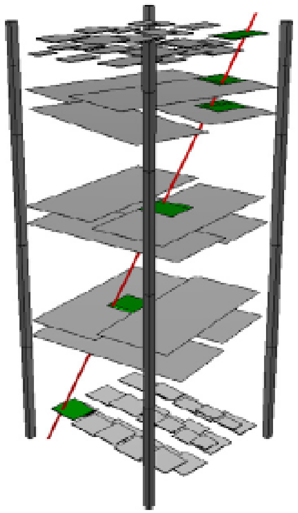
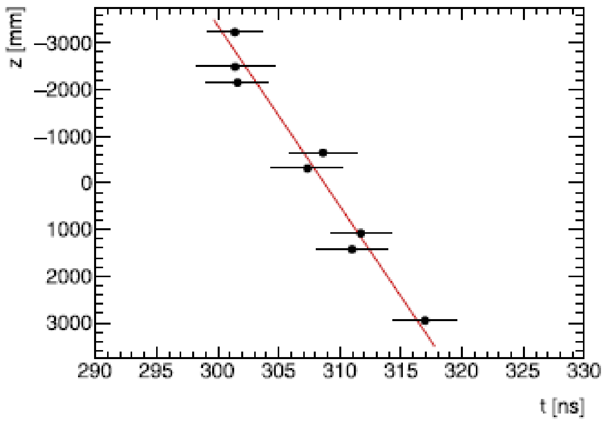


Fig. 2. Schematic [3] and photo of a DØ forward muon scintillation trigger counter.

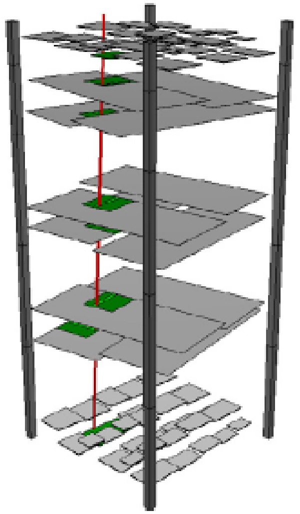
- A small-scale experiment, the MATHUSLA test stand, was constructed and installed on the surface above the interaction point of the ATLAS detector (LHC Point 1) and collected data during 2018.
- The test stand was operational both during LHC pp collisions and when the LHC was not operating.
- The goal was to measure the rate of muons from LHC pp collisions reaching the surface, as well as the rate of inelastic backscattering from cosmic rays that could create upward-going tracks, and to determine how well simulation models could reproduce the data.
- This information is a very useful input for future studies on the background expectations for the proposed MATHUSLA experiment.
- The test stand used scintillation counters recovered from the Tevatron Run II D∅ forward muon trigger system; they were arranged to form two planes of 2.5×2.5 m^2 area each
- Spare RPCs of the ARGO-YBJ experiment were arranged in six layers between the scintillator planes, and used to track charged particles crossing the test stand.

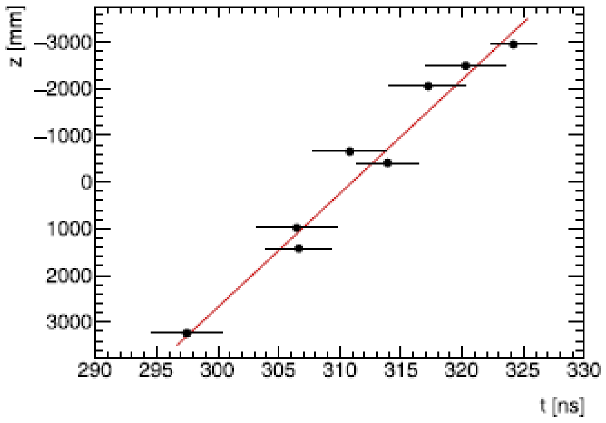
The MATHUSLA Test Stand (2)





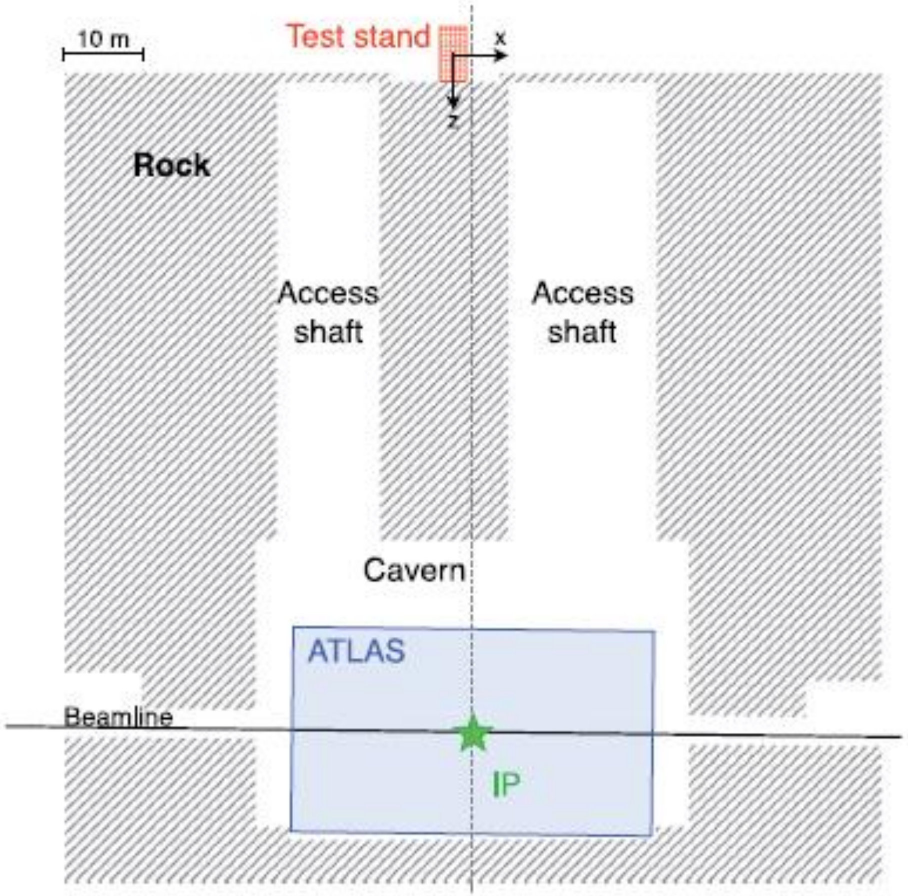
Example of a downward-going track





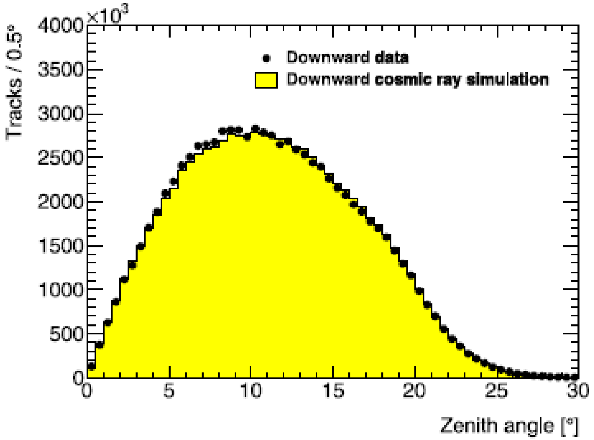
Example of an upward-going track

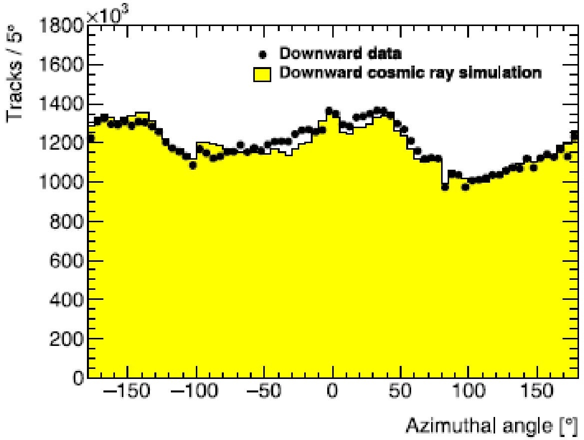
The MATHUSLA Test Stand (3)



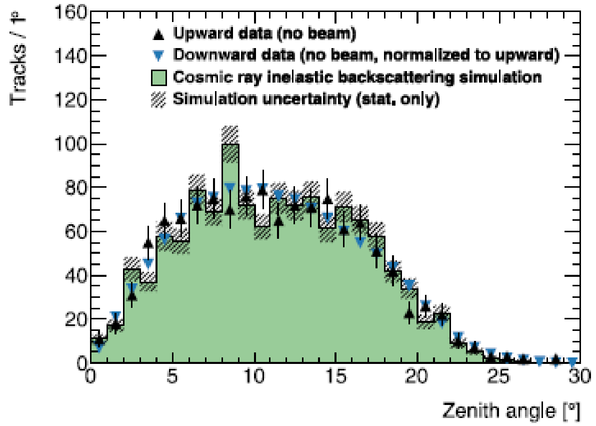
Schematic view, in the vertical plane, of the position of the MATHUSLA Test Stand with respect to the ATLAS detector

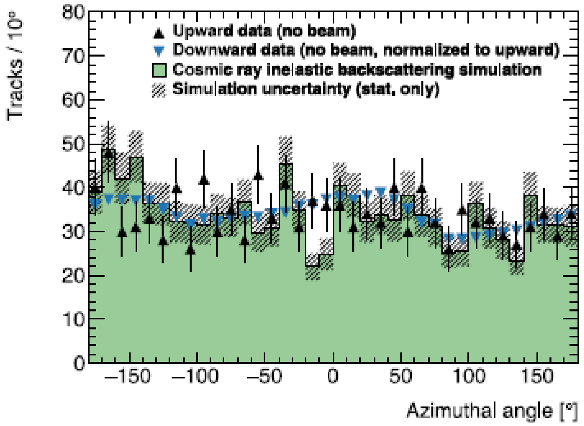
The MATHUSLA Test Stand (4)





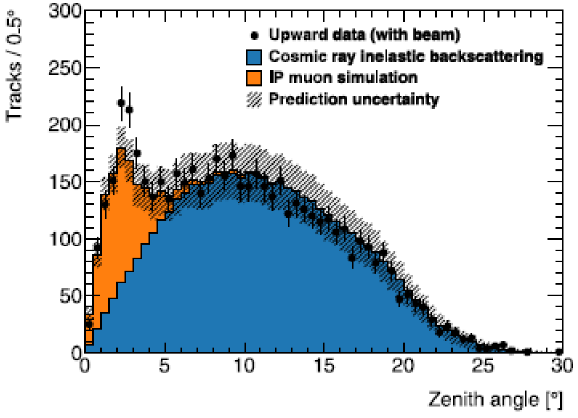
Experimental and simulated angular distributions for downward-going tracks

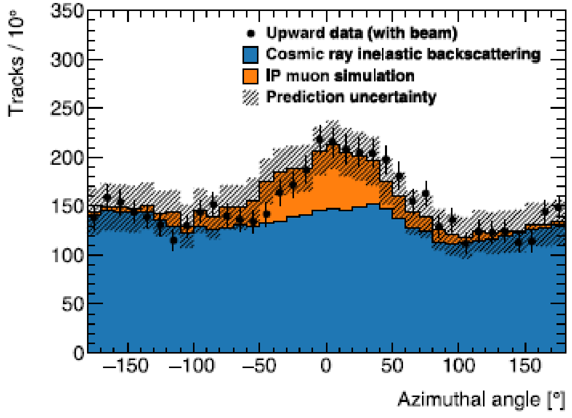




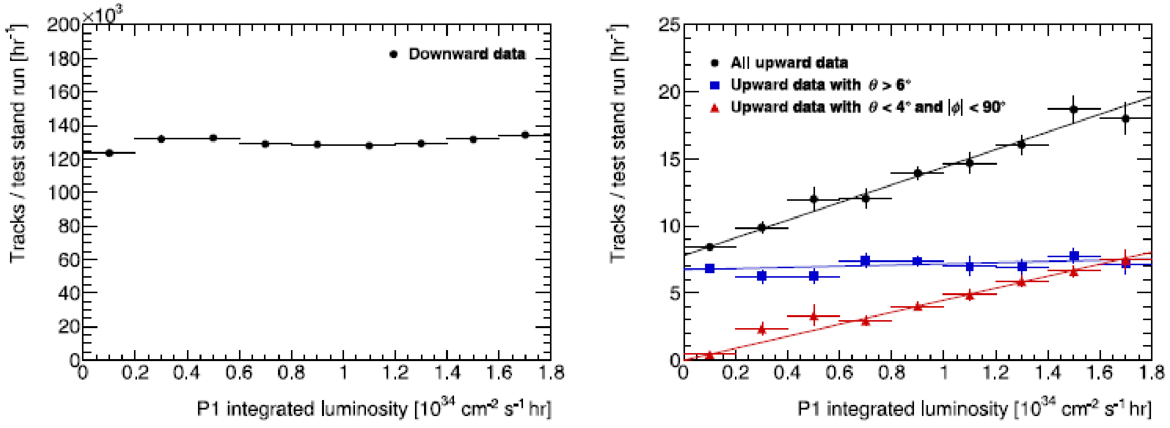
Experimental and simulated angular distributions for single upward-going tracks (no LHC beam) from cosmic-ray albedo

The MATHUSLA Test Stand (5)





Experimental and simulated angular distributions for upward-going tracks (with LHC beam)



(a) (b)

Fig. 11. Distribution of the number of reconstructed tracks as a function of the ATLAS integrated luminosity during each one-hour test stand run. Left: Downward tracks. Right: Upward tracks (black circles), including tracks with a zenith angle (θ) > 6° (blue squares) and tracks with a zenith angle < 4° and absolute value of azimuthal angle (ϕ) < 90° (red triangles).

The test-stand results confirm the background assumptions in the MATHUSLA proposal and demonstrate that there are no unexpected sources of background.

These results give confidence in the MATHUSLA projected physics reach.

NIM A 985 (2021) 164661

Cosmic-ray physics with MATHUSLA (1)

- MATHUSLA is mainly conceived for searching LLPs produced by LHC collisions
- Cosmic-ray tracks are a background to LLP detection, as seen before
- The layers of long scintillating bars have limited capability of detecting Extensive Air Showers produced by primary cosmic rays since they cannot provide the coordinates of several charged tracks hitting the same bar within a narrow time interval. This results in saturation and information loss. A much better calorimetric capability is required for shower-core detection, where densities of the order of 10^4 charged particles/m^2 can be reached for a primary particle of ~ 1 PeV and greater
- The MATHUSLA geometry offers a unique chance of extending the detector with the addition of a full-coverage layer of Resistive Plate Chambers (RPCs), which would be dedicated to EAS detection and would provide redundancy for LLP detection
- Main constraints to cosmic-ray physics with MATHUSLA:
  - Very modest altitude of the experimental site (about 374 m a.s.l.)
  - Sensitive area not exceeding 10^4 m^2

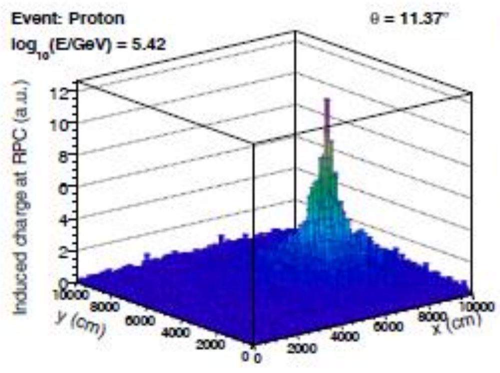
Cosmic-ray physics with MATHUSLA (2)

Taking into account all this, cosmic-ray studies with MATHUSLA may be focused on the following items:

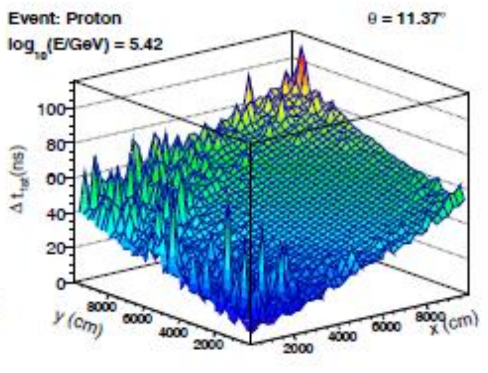
- Cosmic-ray composition (measurement of the atomic number Z of the primary particle)
- Bundles of parallel muons. They can be observed when the electro-photonic component of the shower is absorbed before the shower hits the detector («pure muonic shower»). For vertical showers they can be seen only at low energy, while for inclined or almost horizontal showers they can be observed also at high or very high energy due to the larger thickness of the atmosphere. This study is crucial both again for cosmic-ray composition studies and for discriminating among different high-energy hadronic interaction models.

EAS detection in MATHUSLA

The space-time-charge information provided by the RPC big pads allow the EAS front reconstruction, its inclination with respect to the horizontal plane and the local hit density



Induced charge on the RPC big pads in the event

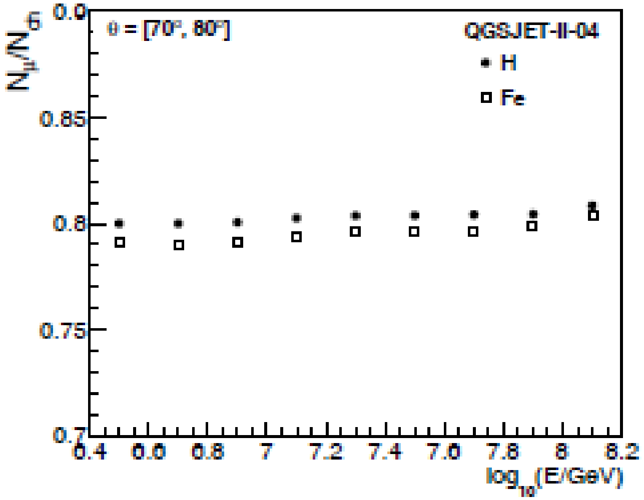


Time delay of the RPC big pads with respect to the first hit in the event

Simulated event for a vertical primary proton of 263 GeV

Muon bundles in MATHUSLA (1)

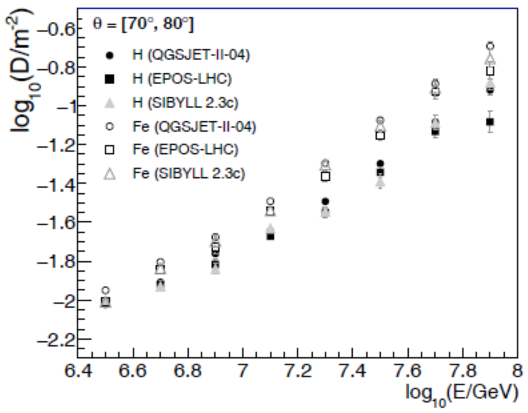
- If the EAS arrival direction is greater than about $65°$, muons are the main component of the EAS.
- At the MATHUSLA site, inclined EAS from H and Fe primary nuclei of $\sim 1 - \sim 100\ \mathrm{PeV}$ have an average muon content of about $(80 \pm 1)\%$, as predicted by QGSJET-II-04 MC simulations

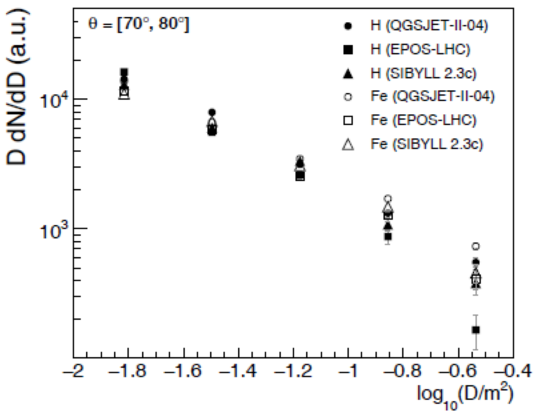


QGSJET-II-04 MC simulation for the EAS muon content in the zenith-angle range between $70°$ and $80°$ for H and Fe primary nuclei in the $1 - 100\ \mathrm{PeV}$ energy range at the MATHUSLA site

Muon bundles in MATHUSLA (2)

- The average value and the spectrum of the local muon density D in MATHUSLA for inclined EAS events generated by H and Fe primaries in the $1 - 100$ PeV energy range have been simulated and studied using several high-energy hadronic interaction models, assuming that the primary energy spectra have a behaviour $\sim E^{-2}$
- Above 10 PeV the local magnitude of D increases linearly with the primary energy in log scale and it is greater for heavy primaries than for light ones.
- The D spectra for EAS with a high content of muons are harder than the D spectra for EAS with a low muon multiplicity, and a slight spread is observed depending on the high-energy hadronic interaction model: so, such curves can be used to test the prediction of different models and discriminate among them.





Left: local muon density *D* vs primary energy (log-log scale)

Right: *D* times (*D* spectrum) (log-log scale)

The MATHUSLA collaboration and progress status

- The Letter of Intent (2019 + addendum in 2020) was signed by 83 researchers from USA (Spokesperson: Prof. Henry Lubatti, University of Washington, Seattle), Canada, Europe (11 from Italy), Israel, Central and South America
- The Technical Design Report is being written, and is expected to be presented to CERN soon

Conclusions

- MATHUSLA is a planned external LLP detector for the HL-LHC that can probe deep into the LLP parameter space in a variety of Beyond-the-Standard-Model scenarios, including many DM models
- Significant recent progress and ongoing effort:
  - Extruded scintillators, fibers, SiPMs, trigger, DAQ
  - MC studies of rare backgrounds
  - Tracking algorithms for MATHUSLA's specific environment
  - Cosmic-ray physics case
- TDR will be produced by end of 2022, followed by prototype module and full detector for HL-LHC
- New collaborators are very welcome!

Further references

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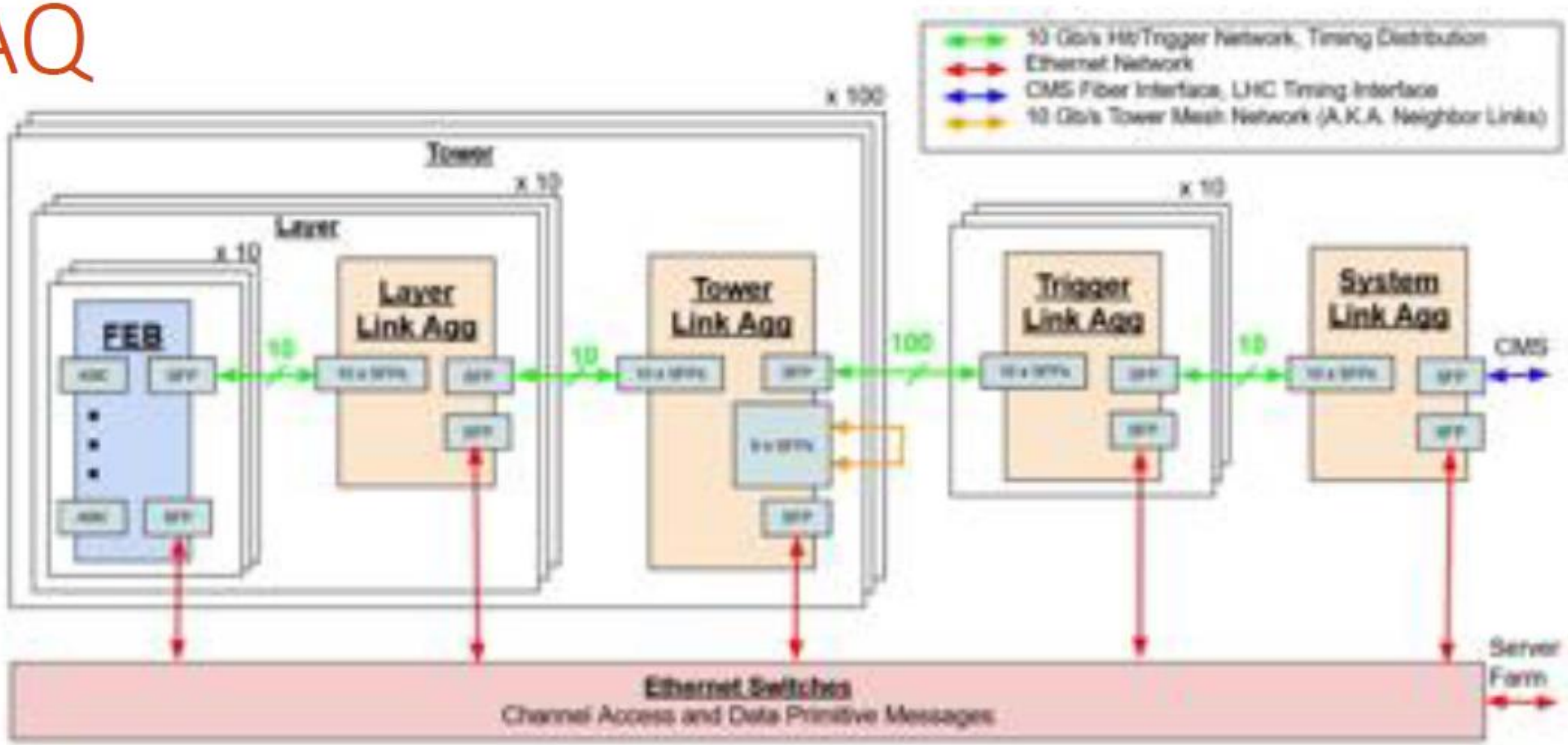
Backup slides

DAQ



Preliminary design: tower-by-tower approach, with modular design of FEBs and link aggregation boards, is scalable and stage-able

Tower aggregation module triggers on upward-going tracks that form a vertex within a 3x3 tower module

LHC timing distributed across all modules to synchronize with CMS