



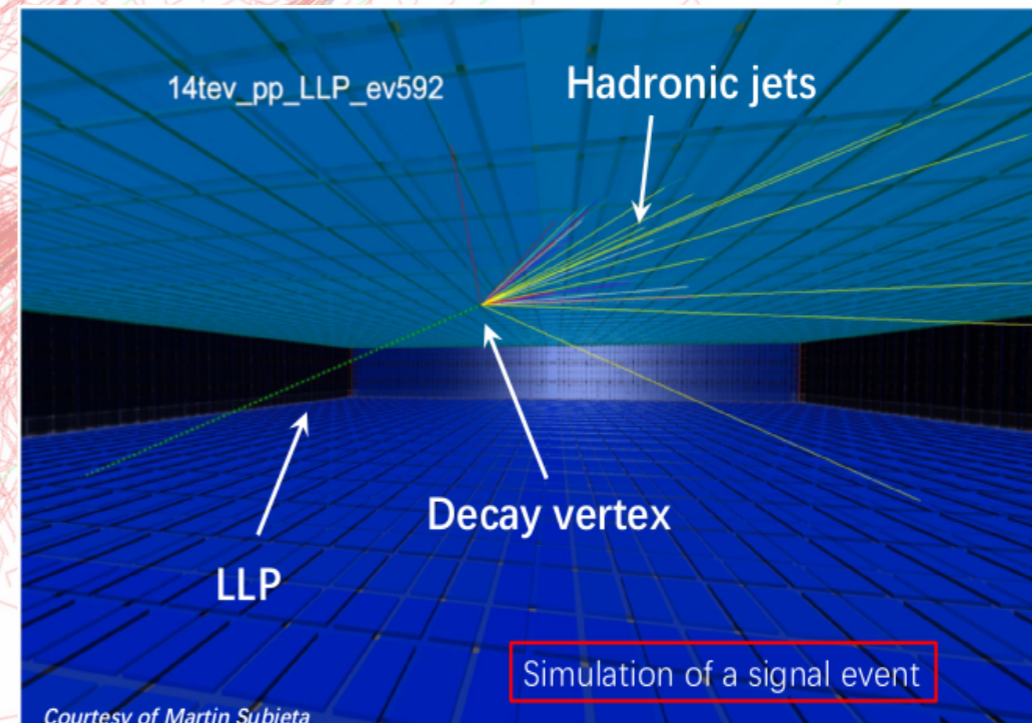
Potential of MATHUSLA for cosmic ray research

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July 9-10, 2020



Introduction

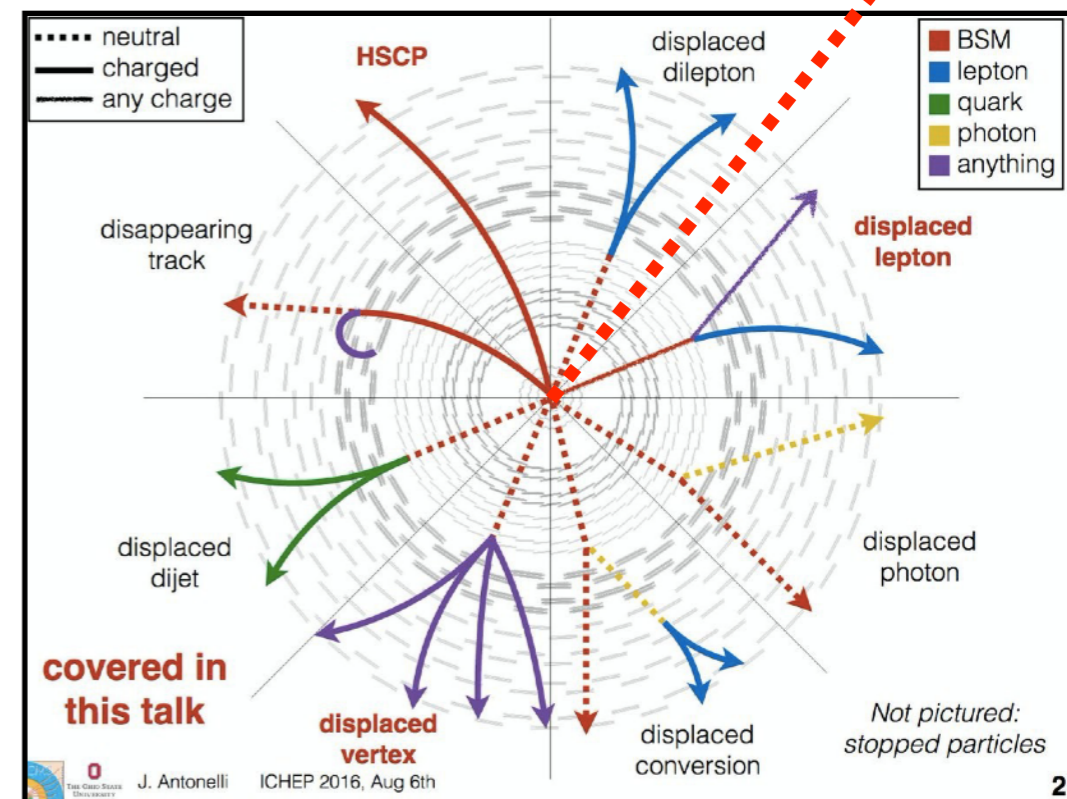
Motivation

- There are not signals of physics beyond standard model (**BSM**) at LHC yet.
- Limitations of the LHC detectors? Looking in wrong place?
 - New neutral particles with long lives (**LLPs**) may escape the detector without being observed.
- LLPs appear in the context of different **BSM** scenarios:
 - Dark matter.
 - Asymmetry of matter-antimatter in the universe.
 - Smallness of neutrino mass.
 - Inflation.
 - Hierarchy problem, etc.

Examples: Gluinos, neutralinos, hidden hadrons, axions, Dark photons, etc.

LLPs may decay outside detector

Prompt decays are observed



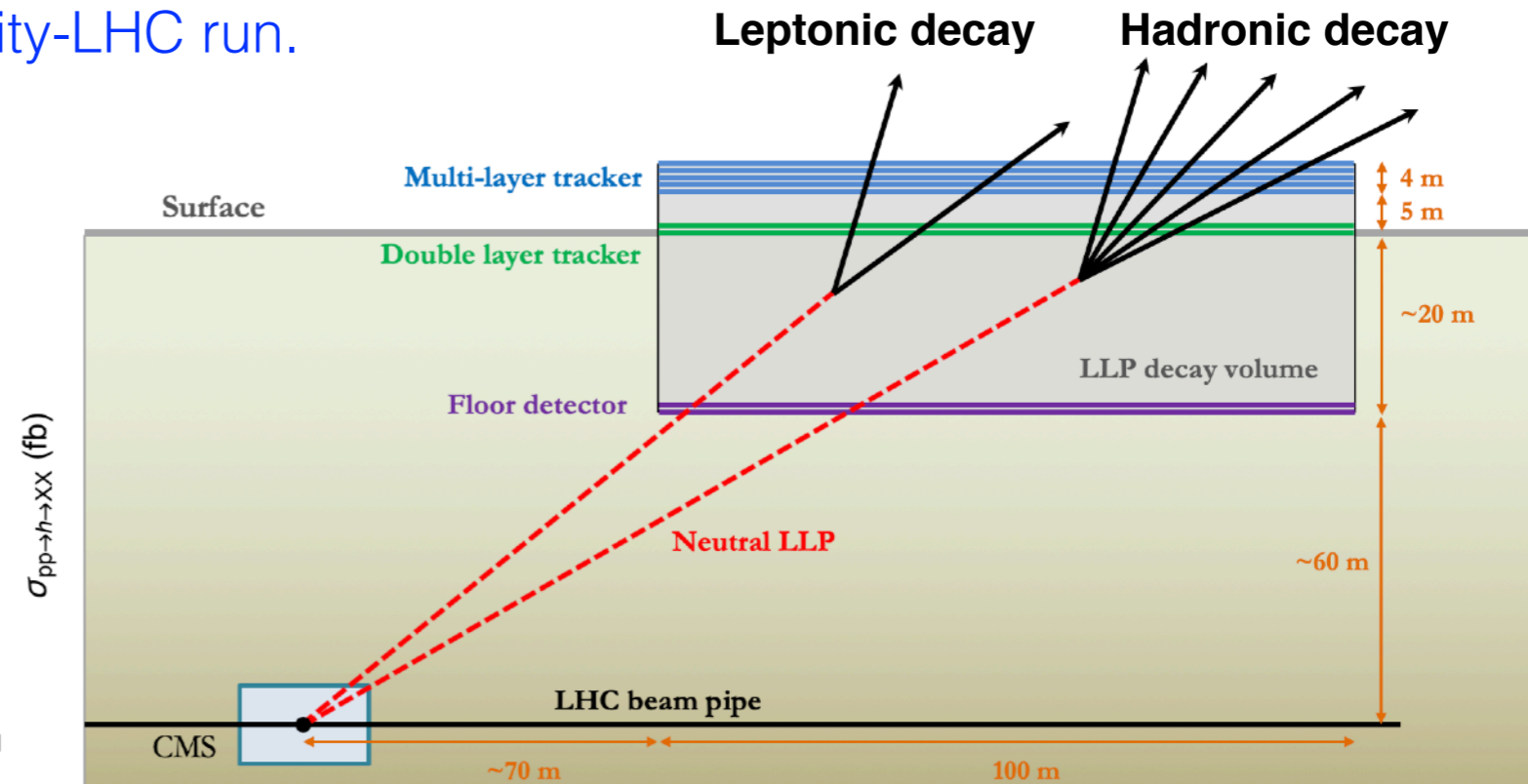
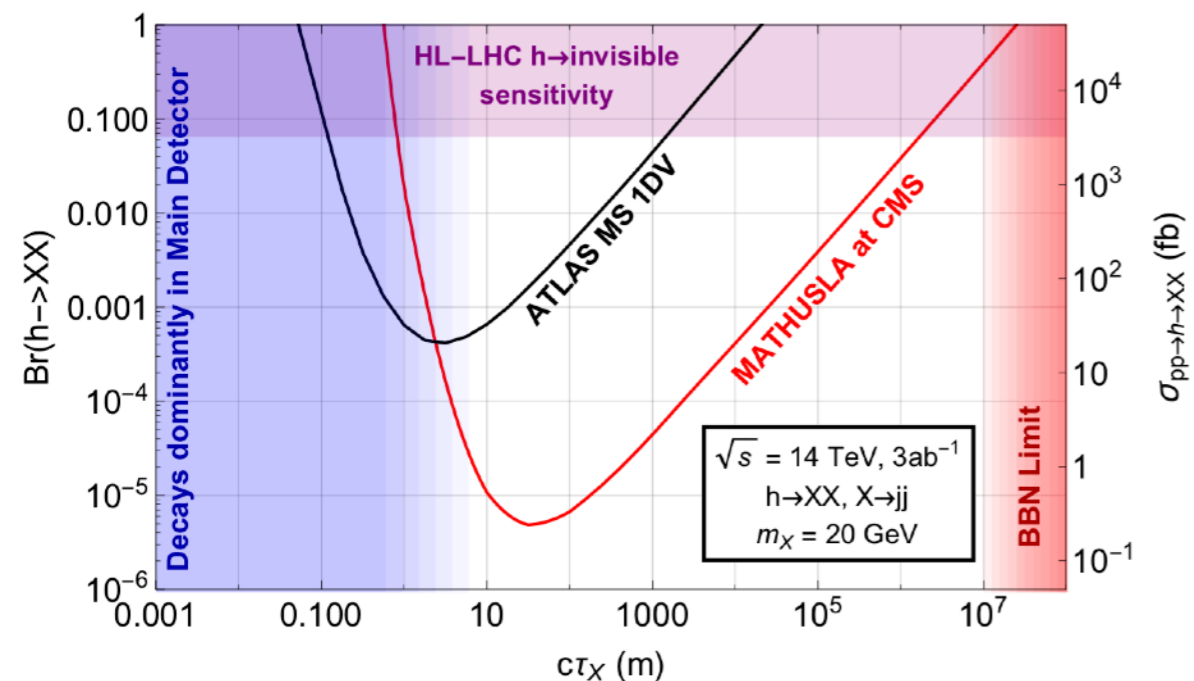
CMS Collab., PRD 94 (2016)112004

- Need to complement searches for **BSM** physics at the LHC

Mathusla proposal

- To build a large area hodoscope detector to look for decay of LLPs in a volume of 100 m x 100m x 25 m of air.
- On the surface above CMS, at 70 m from interaction point.
- Environment with low background.
- Planned for the next High Luminosity-LHC run.

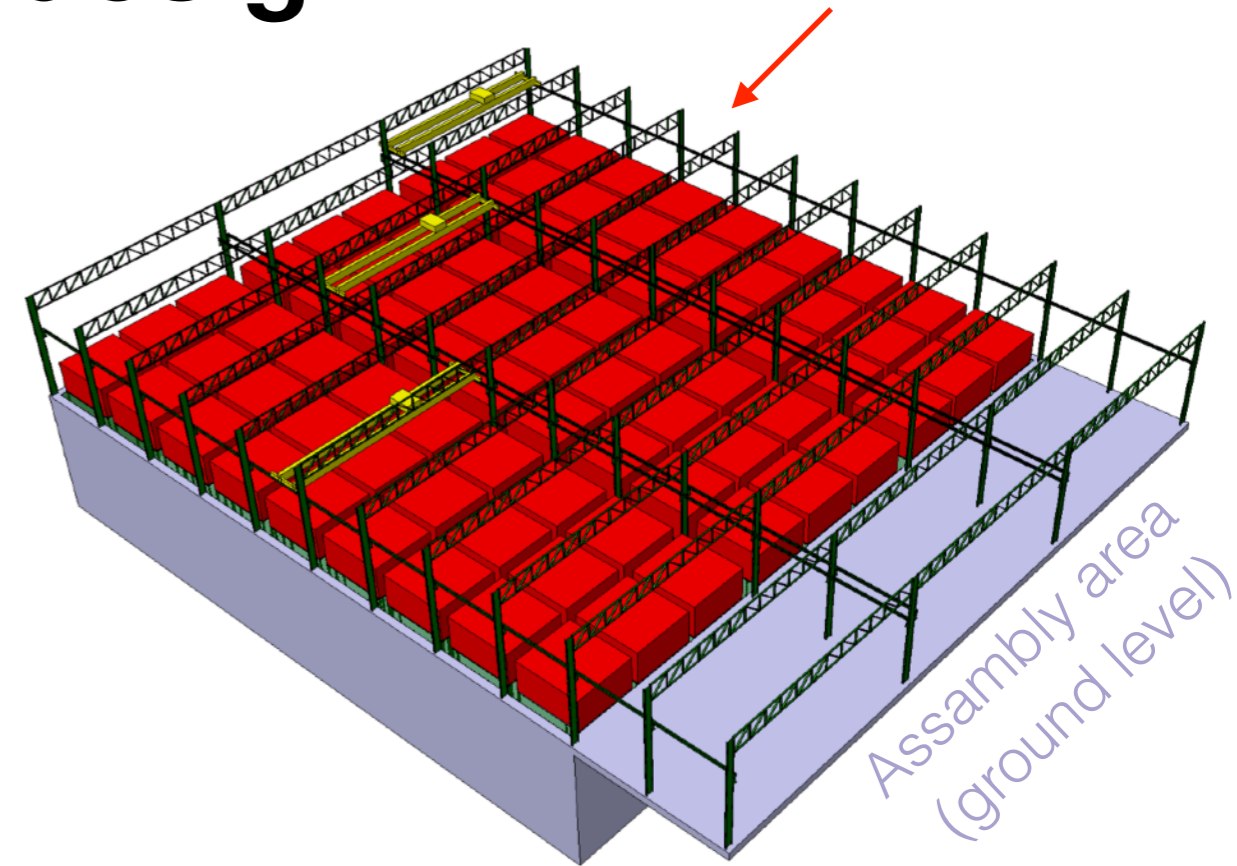
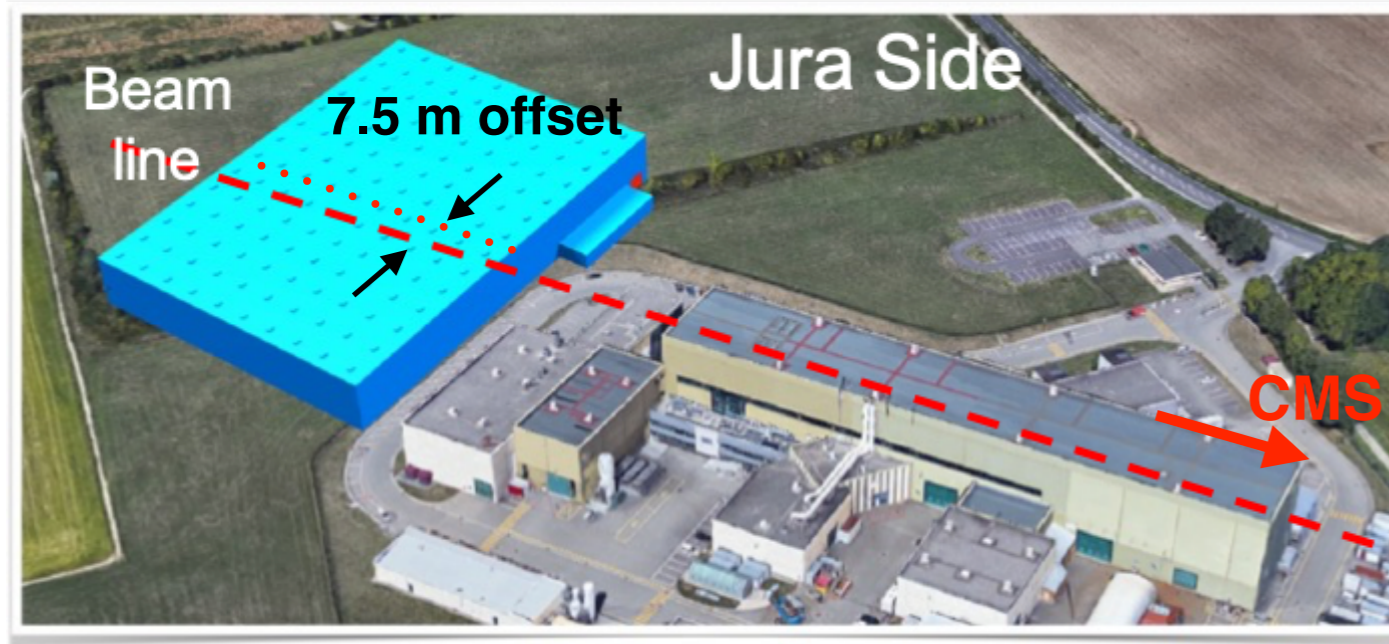
Mathusla coll., Rep.Phys.Prog. 82 (2019)



- Limits to LLPs in the MeV - TeV mass range and $c\tau = [0.1, 10^7]$ m interval.

Experimental design

9 m x 9 m modules/layer

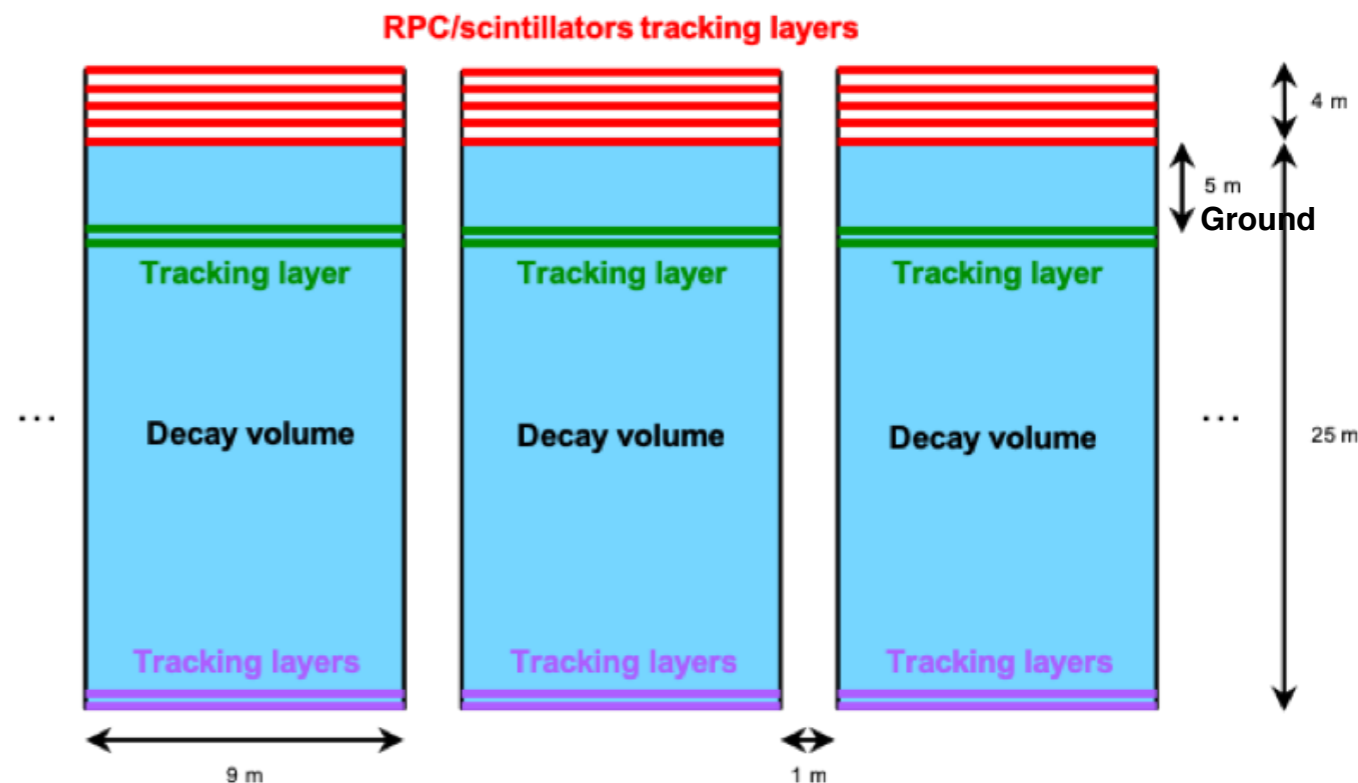
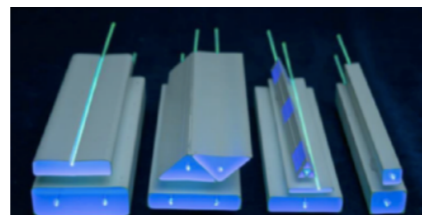


- Tracker:

- 9 scintillator layers
 - **5 on the top. : Trigger**
 - **2 intermediate: Increase performance**
 - **2 at bottom. : Veto for charged particles**

- Scintillator bars:

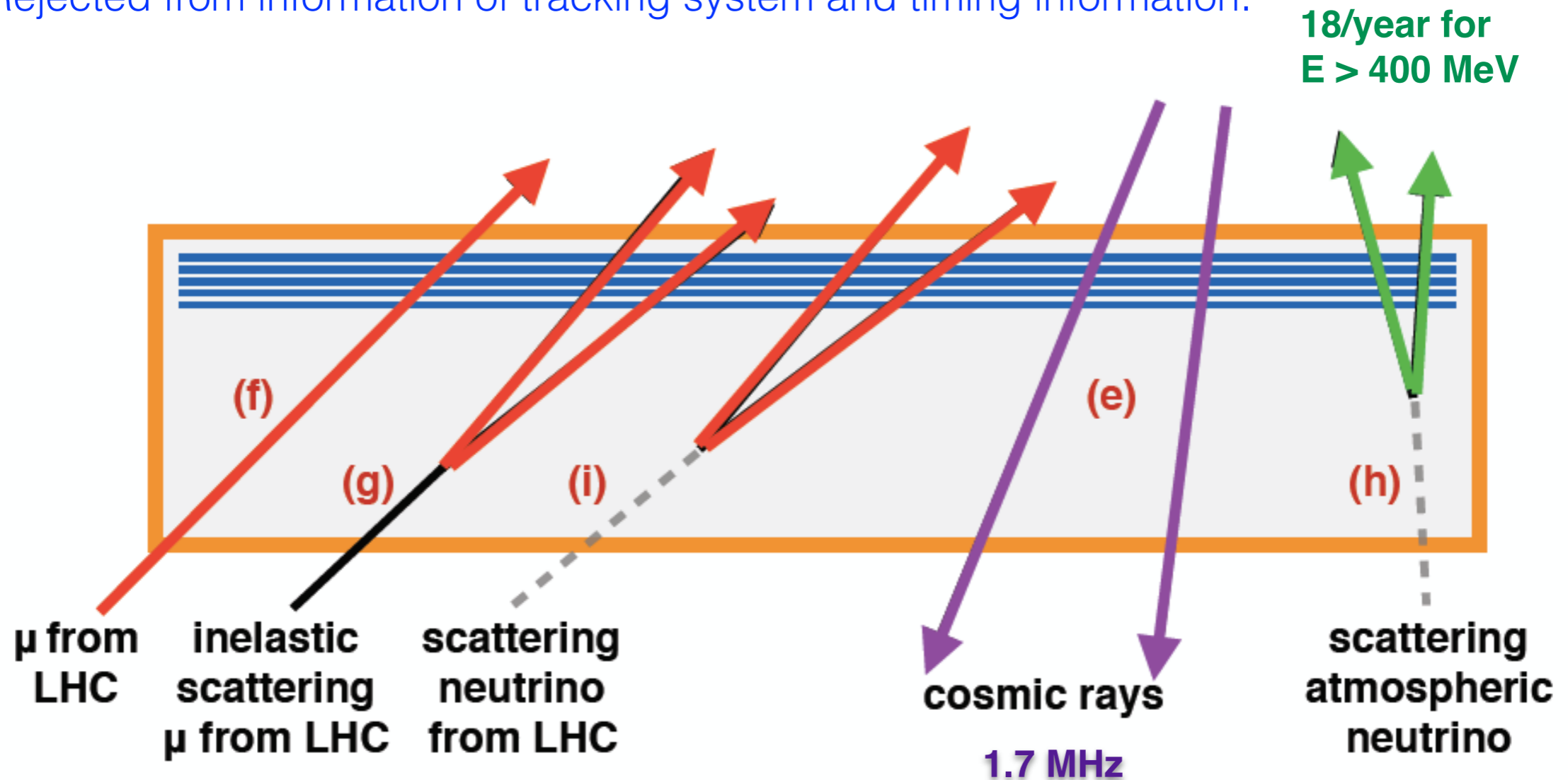
- Coupled to SiPMs with wavelength shifters
- 5m x 4cm x 2cm
- From one layer to the other, long dimension of the bar rotated 90°.
- Spatial resolution: 1 cm
- Time resolution. : 1 ns



Experimental design

Mathusla proposal

- Background from neutrinos and muons from LHC, atmospheric neutrinos, cosmic rays.
- Rejected from information of tracking system and timing information.



Letter of Intent for MATHUSLA, CERN-LHCC-2018-025, LHCC-I-031

Test stand

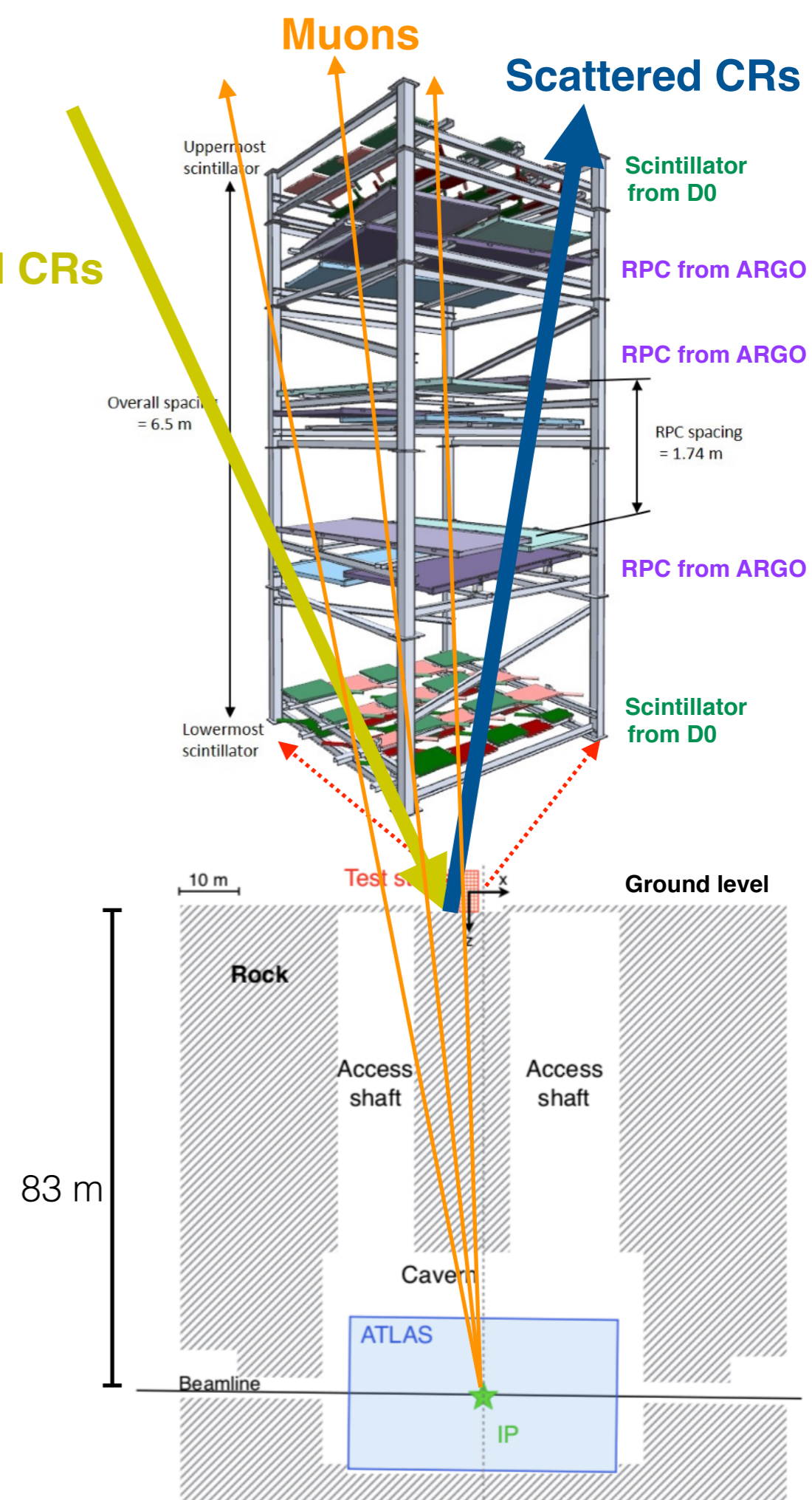
- Characteristics:

- Data collected during **2018**
- Above ATLAS interaction point ($\Delta x, \Delta y$) = (2.4 m, 0 m)
- 2.5 m x 2.5 x 6.5 m volume
- 6 RPC/2 Scintillator layers
- Reconstruction of tracks using a χ^2 fit
- Time resolution : 2.5 ns

- Goal:

- Design studies.
- Measure dominant sources of background at MATHUSLA:
 - ❖ **Downward cosmic rays.**
 - ❖ **Upward SM charged particles.**
 - **Muons from pp collisions at LHC.**
 - **Inelastic backscattering from CRs.**

Downward CRs

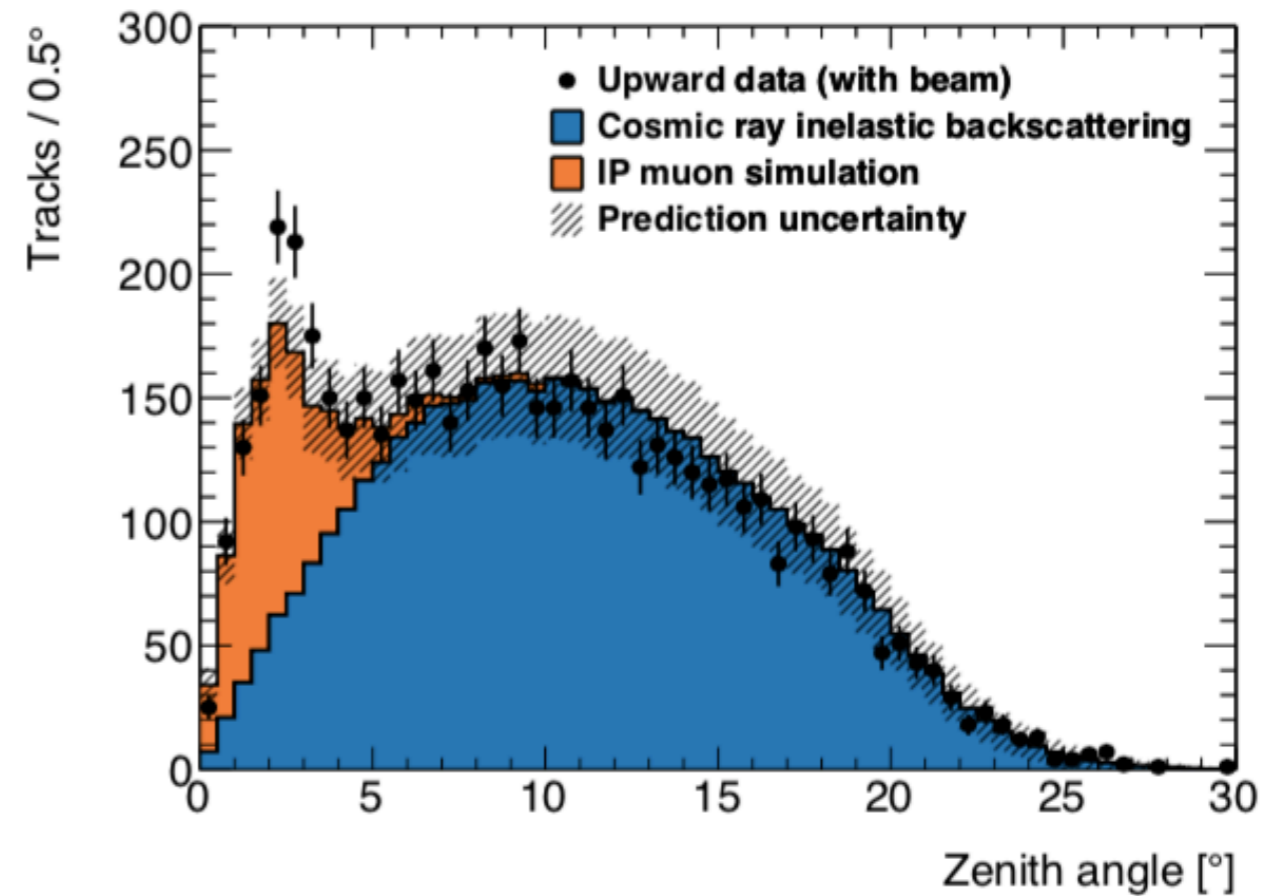
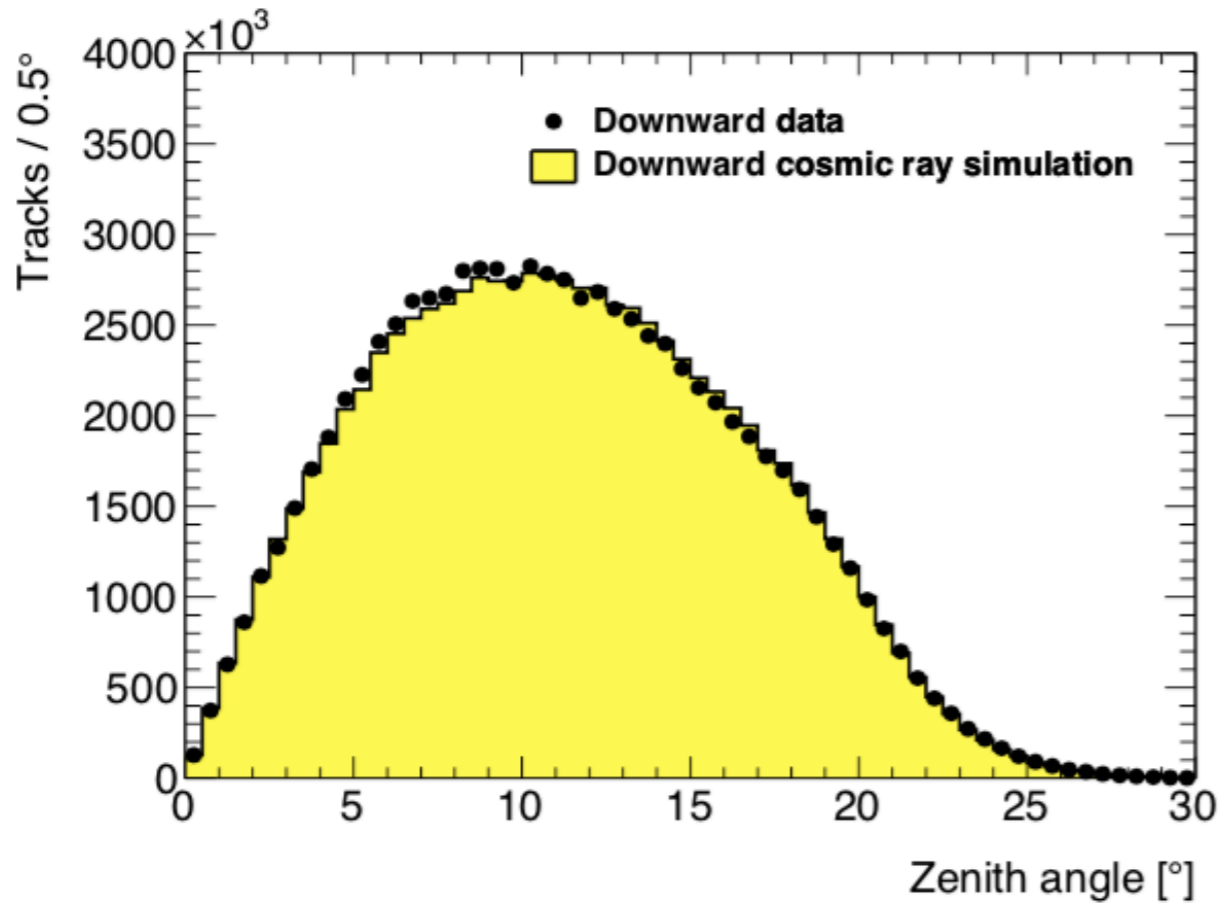




Test stand

Downward signals from CRs

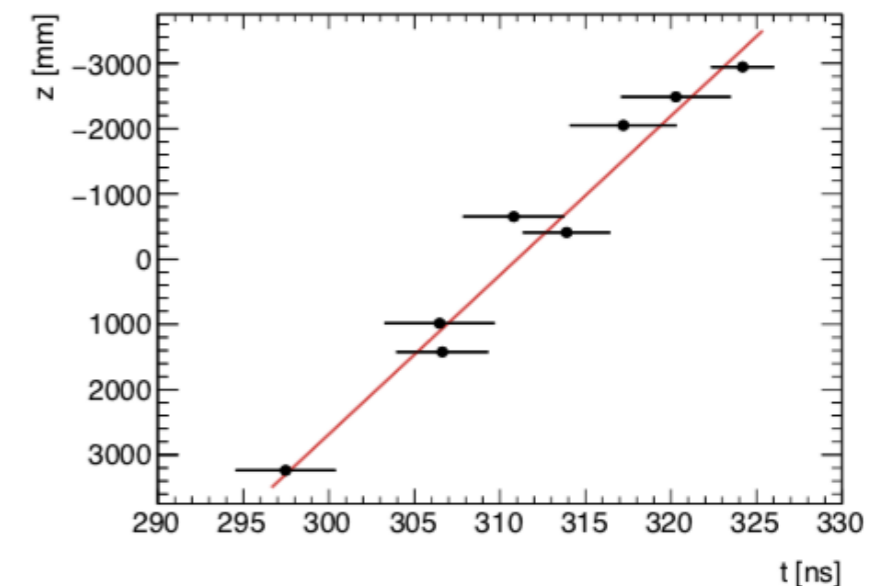
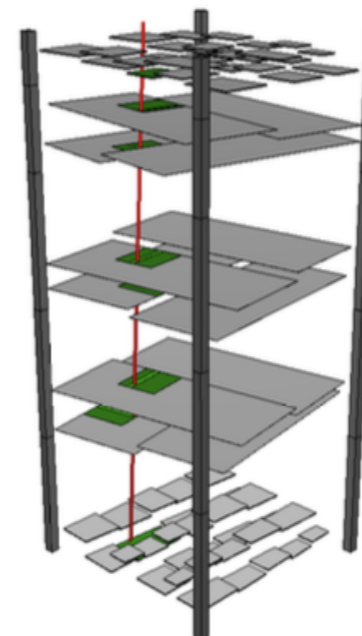
Upward muons from LHC + backscattered CRs



Example of upward-going track in data

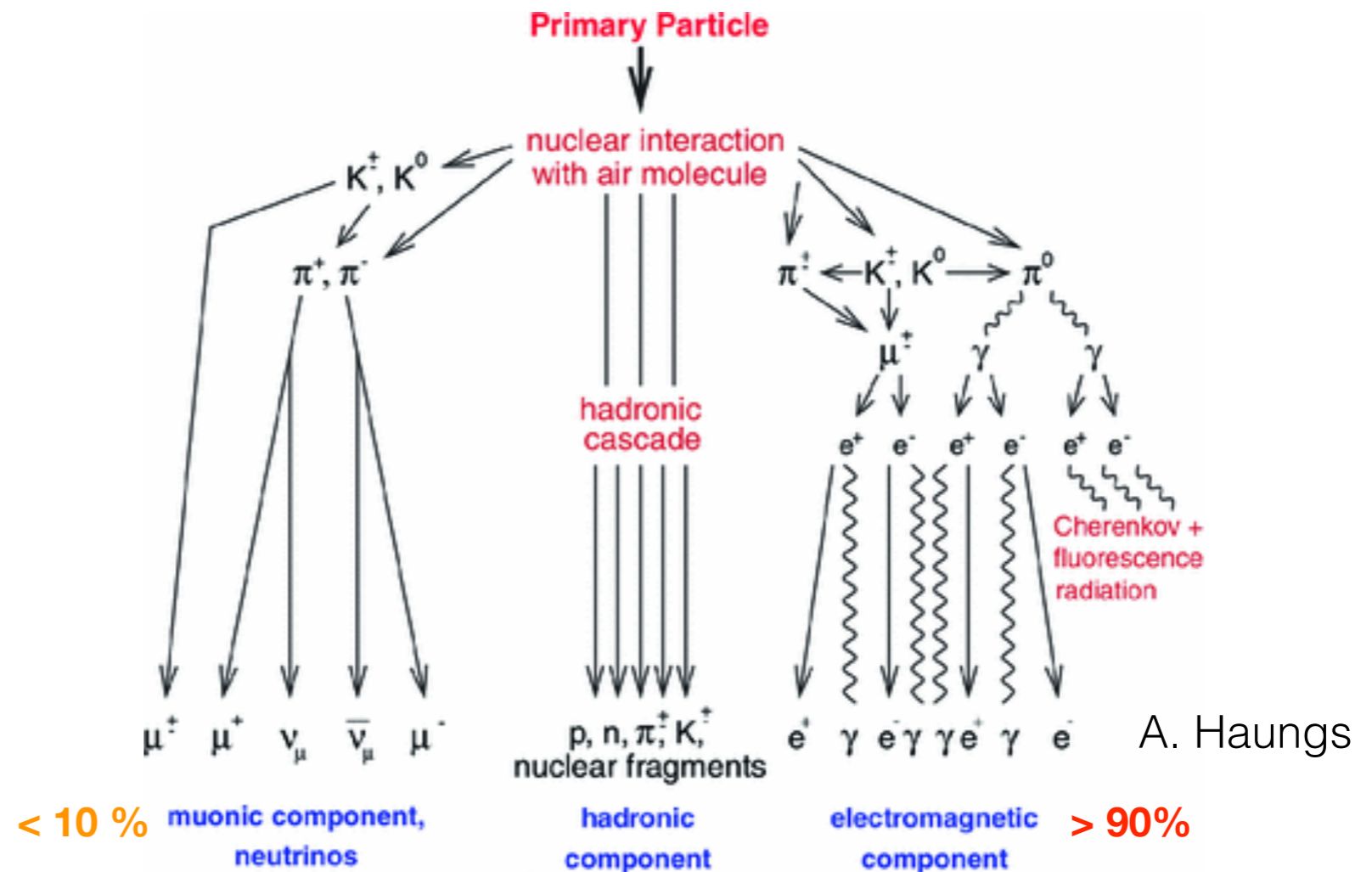
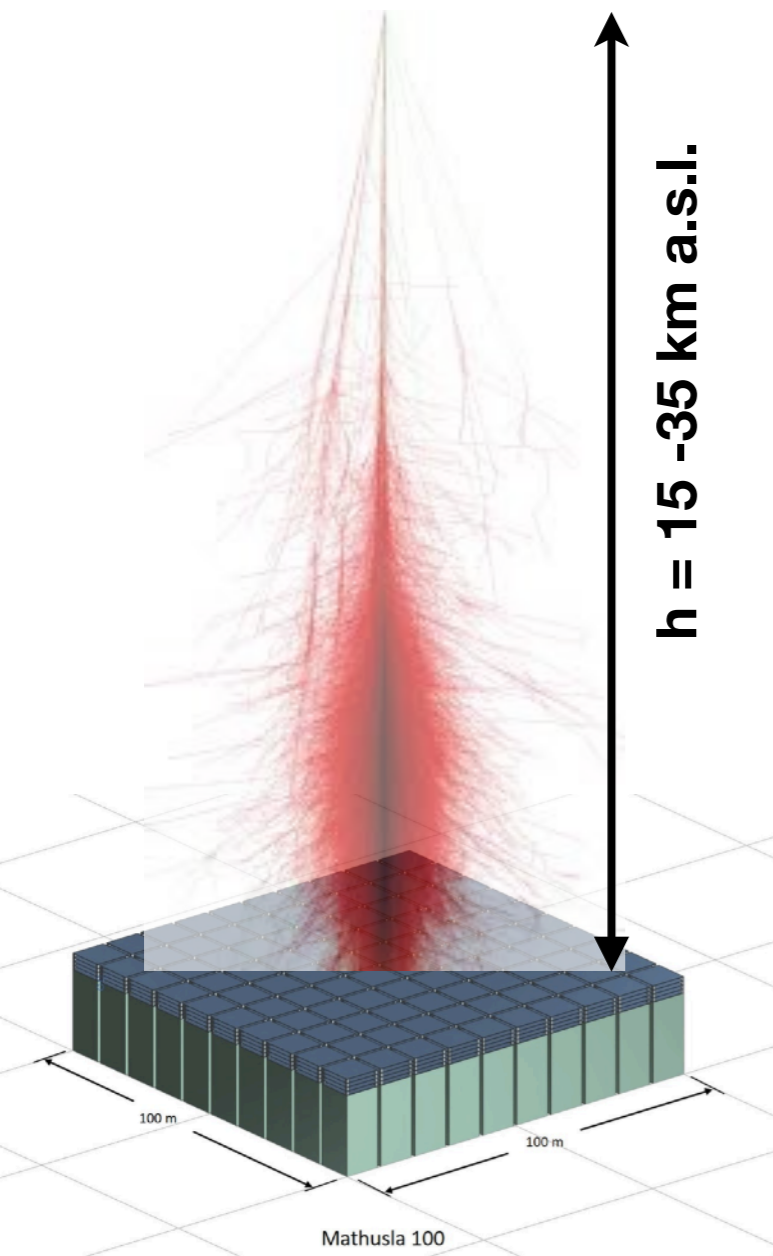
Results:

- Data is in agreement with MC simulations.
- Background under control.



Mathusla as a cosmic ray detector

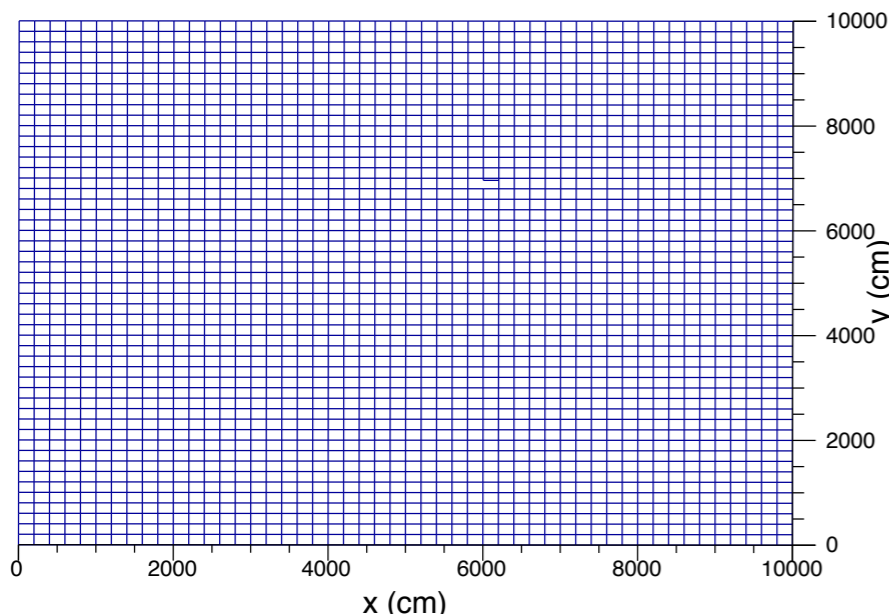
- Mathusla could also detect the extensive air showers (**EAS**) that **cosmic rays** produce in the atmosphere
 - Opportunity for cosmic ray research
 - But problem of signal saturation at the scintillator bars for more than 1 hitting particle.



- Important to measure as many components of the EAS

Mathusla as a cosmic ray detector

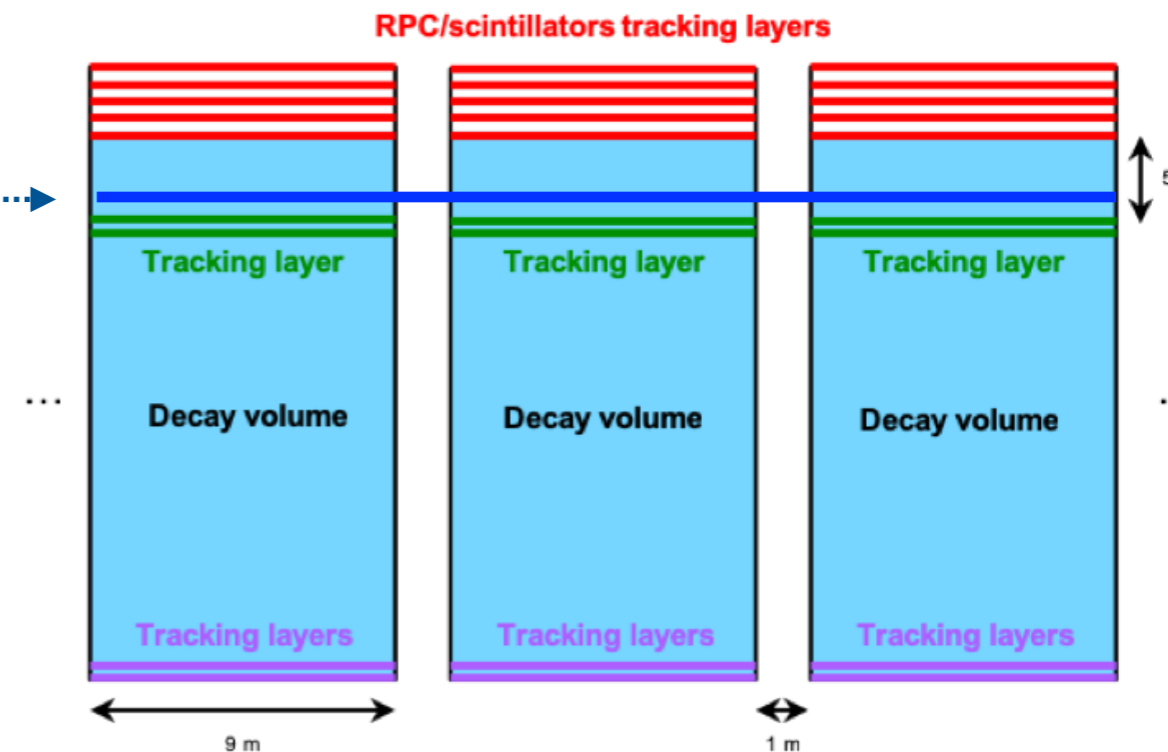
- Plan to add an **extra RPC layer** to enhance EAS detection for cosmic ray research.
 - Measurements of charged particles at EAS ($e + \mu$):
 - ❖ **Densities** (up to several 10^4 charged particles/m²)
 - ❖ **Arrival times** of 1st particle per strip (time res.= 1 ns)
 - 2500 big pad sizes: 2 m x 2 m
 - **Big pads would provide fine space-time structure of EAS.**



1m above **middle double layer**

ARGO-like design: Glass gas mixture of Argon (15%), Isobutane (10%) and Tetraflouroethane (75%).

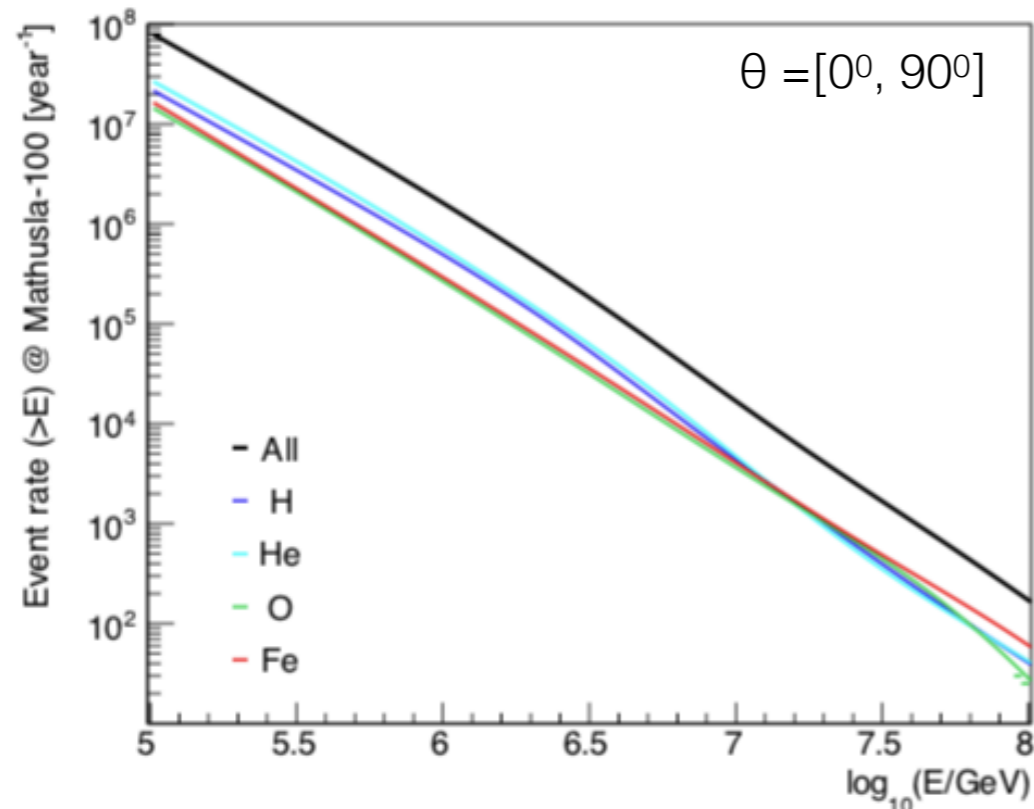
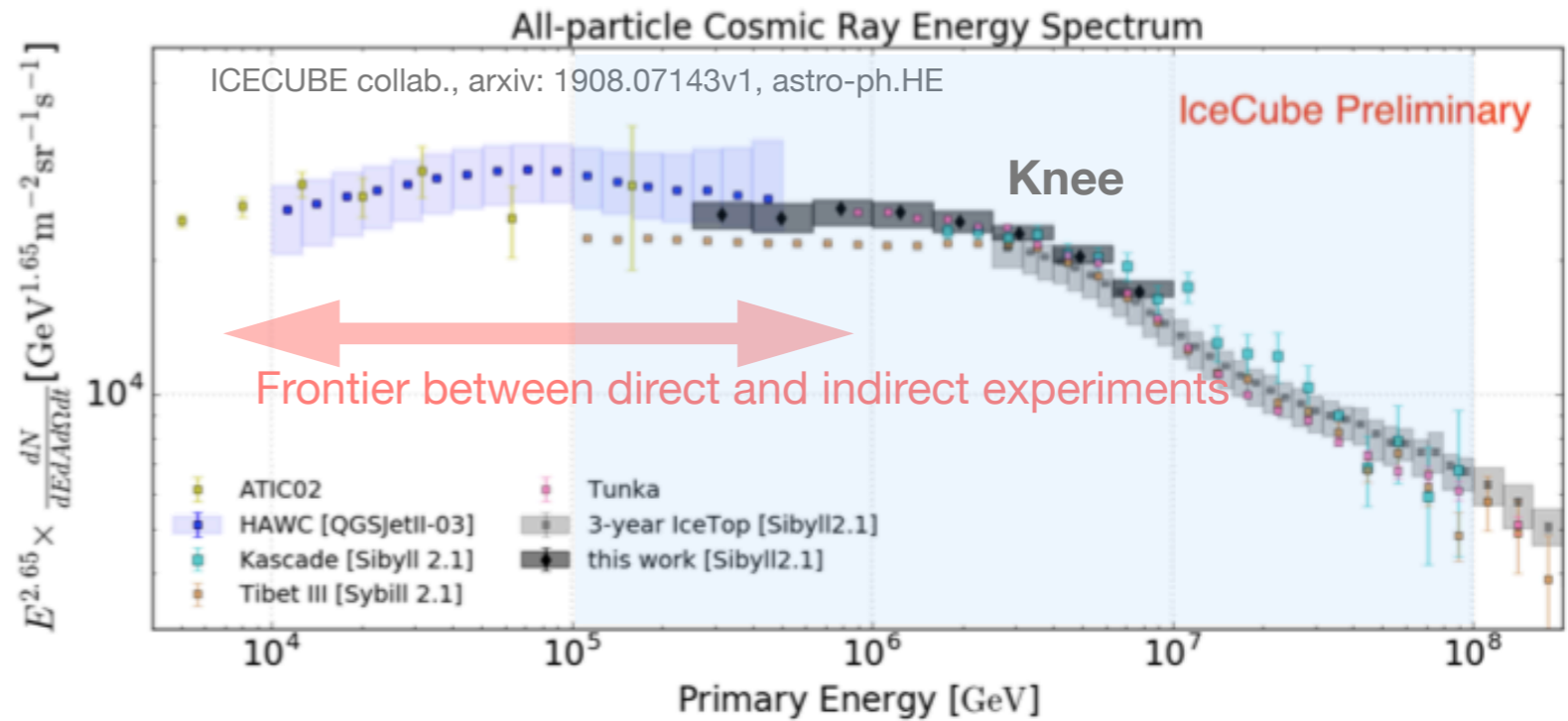
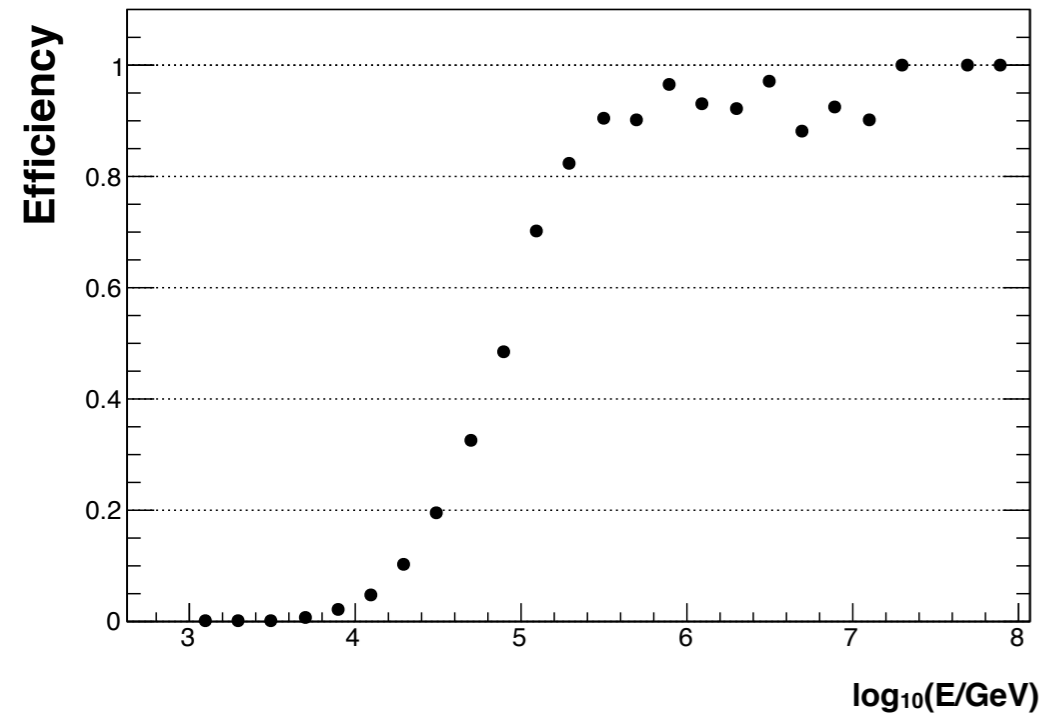
B. Bartoli et al., Astroparticle Physics 67 (2015) 47–61





Mathusla as a cosmic ray detector

- Primary cosmic ray energy range: $E = [10^5, 10^8]$ eV



- Measurements around the **knee of the total energy spectrum** —> **Galactic cosmic rays**

DAQ period = 3 yr (HL-LHC Run 4: 2026-2029)

Field of view = π sr

—> Acceptance $\sim 3 \times 10^{12} \text{ m}^2 \cdot \text{s} \cdot \text{sr}$.

Mathusla as a cosmic ray detector

Energy spectrum extends from $\approx(100)$ MeV up to ZeV

> CR questions:

1) More fine structures in individual spectra of nuclei?

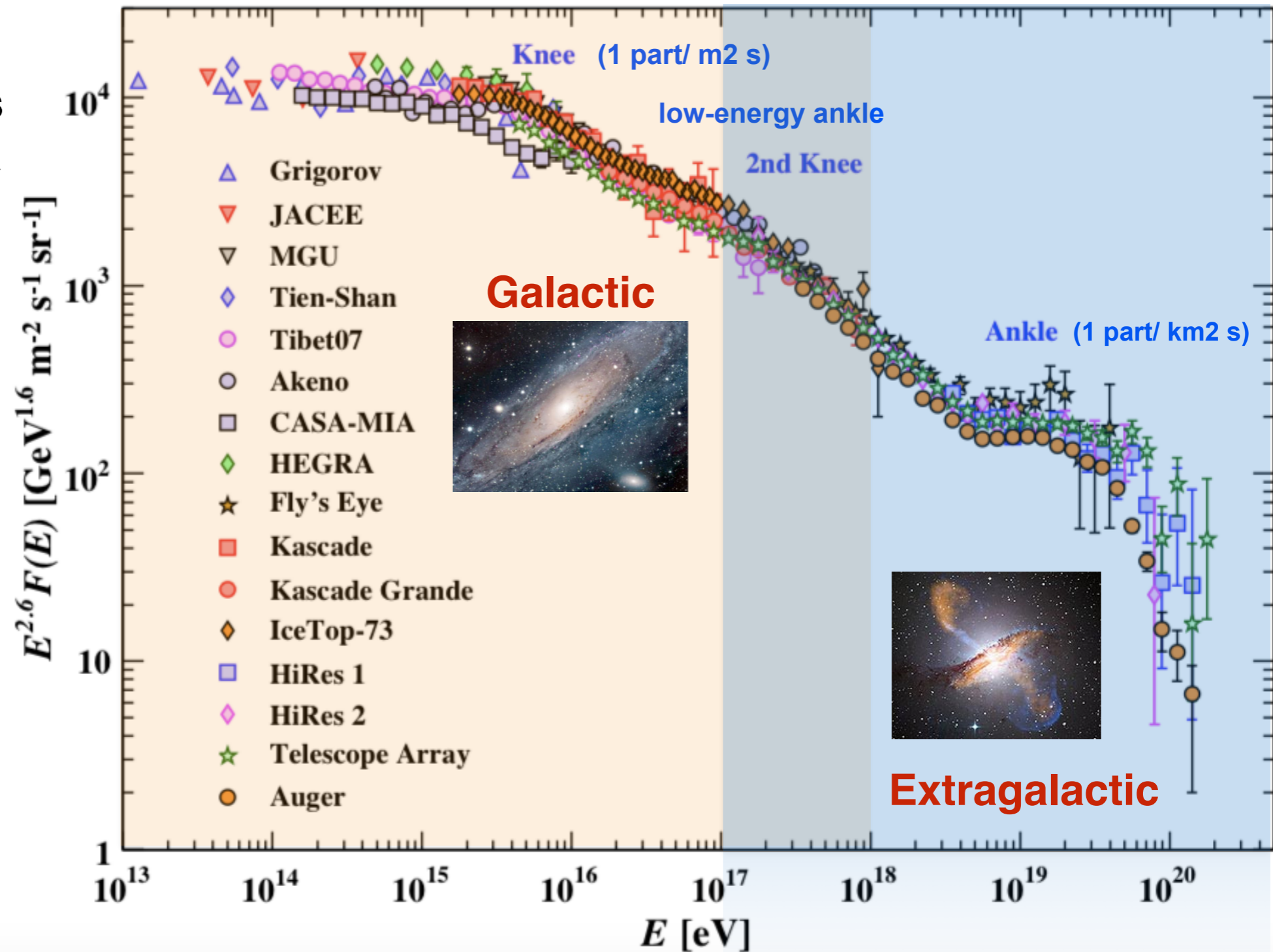
2) Composition.

—> Acceleration Mechanisms.

3) Anisotropies

—> Sources

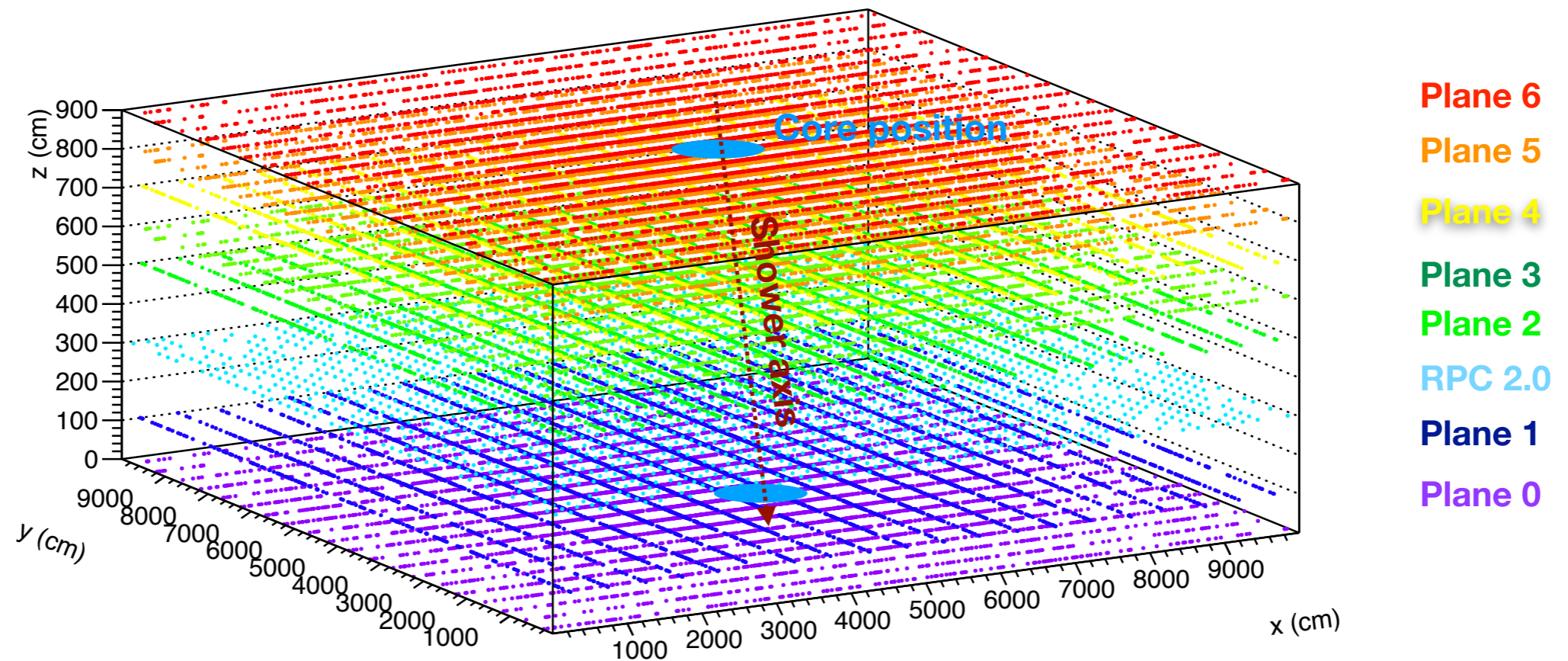
—> Propagation.



Mathusla as a cosmic ray detector

Example for a MC vertical shower

Proton, $\log_{10}(E/\text{GeV}) = 6.71$, $\theta = 6.97^\circ$



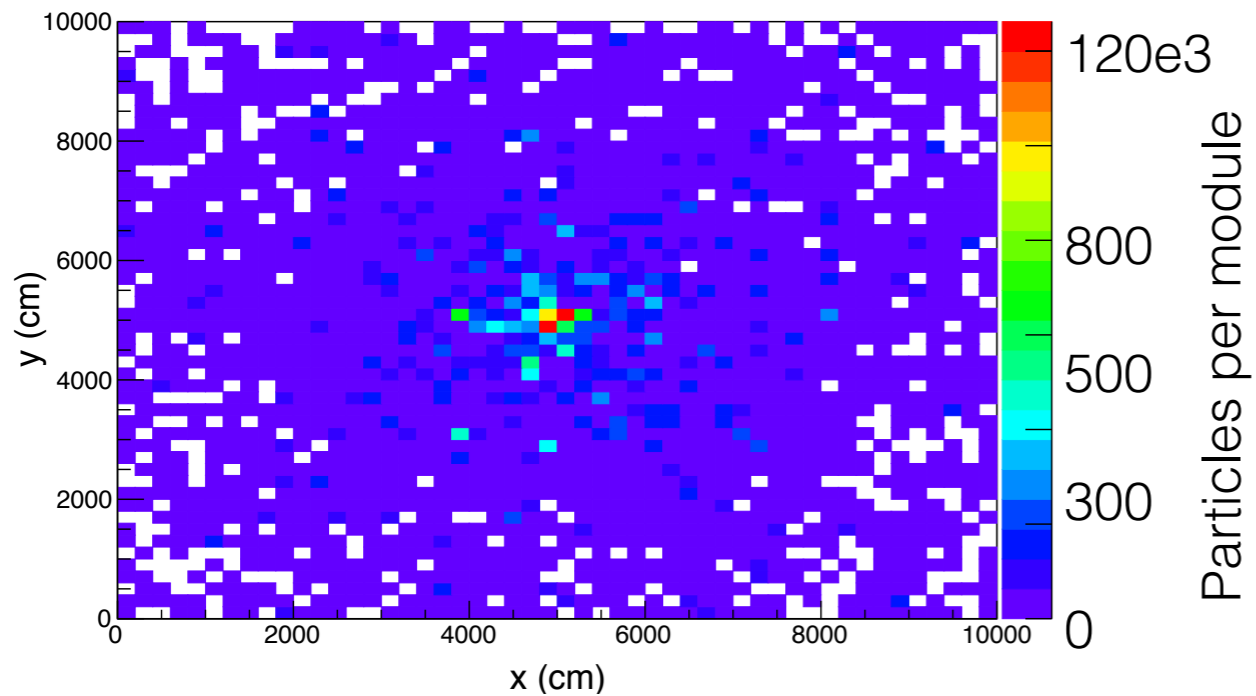
Coordinates of the center of each bar/Big Pad with signal due to the shower event in each plane of MATHUSLA



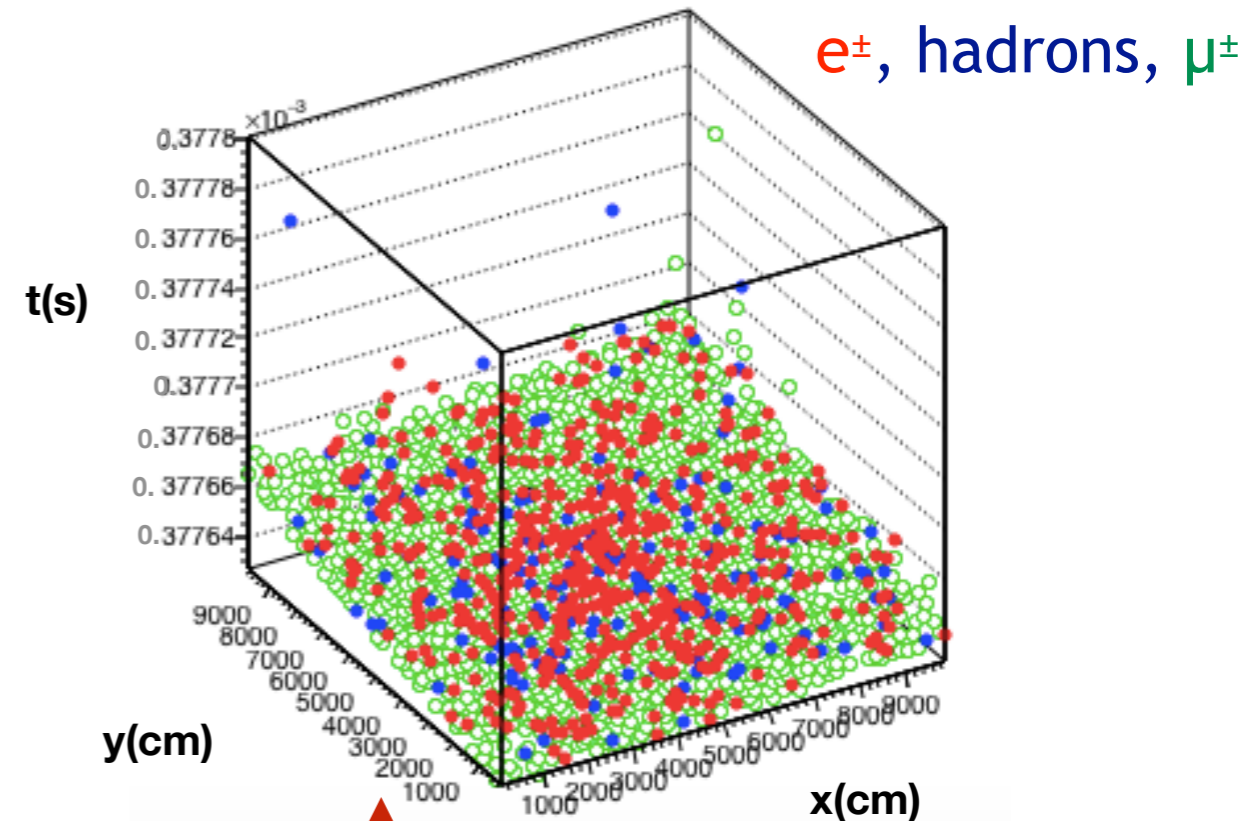
Mathusla as a cosmic ray detector

Vertical event from MC

Shower core position and density at RPC

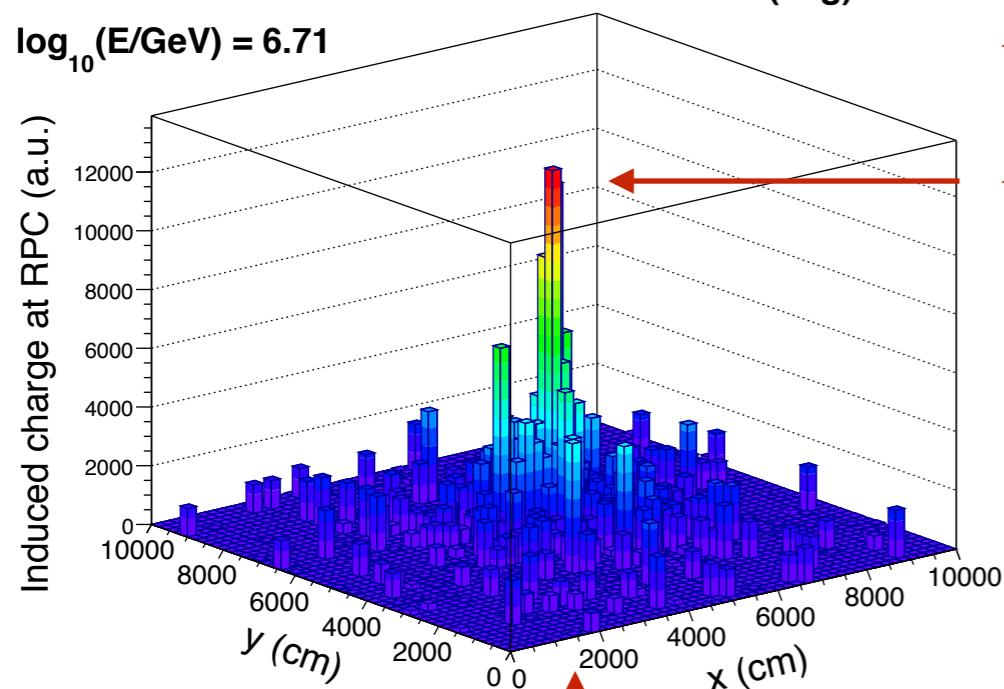


Arrival times of shower front

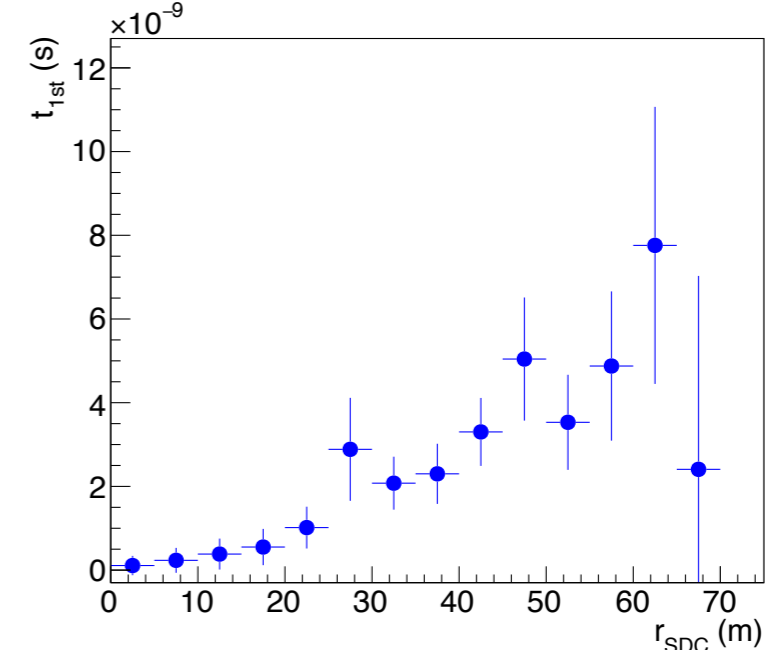


Event: Proton
 $\log_{10}(E/\text{GeV}) = 6.71$

$\theta(\text{deg}) = 6.97$



- Times
- > Arrival direction
- Amplitude of distribution
- > Energy scale
- Signal distribution
- > Shower core

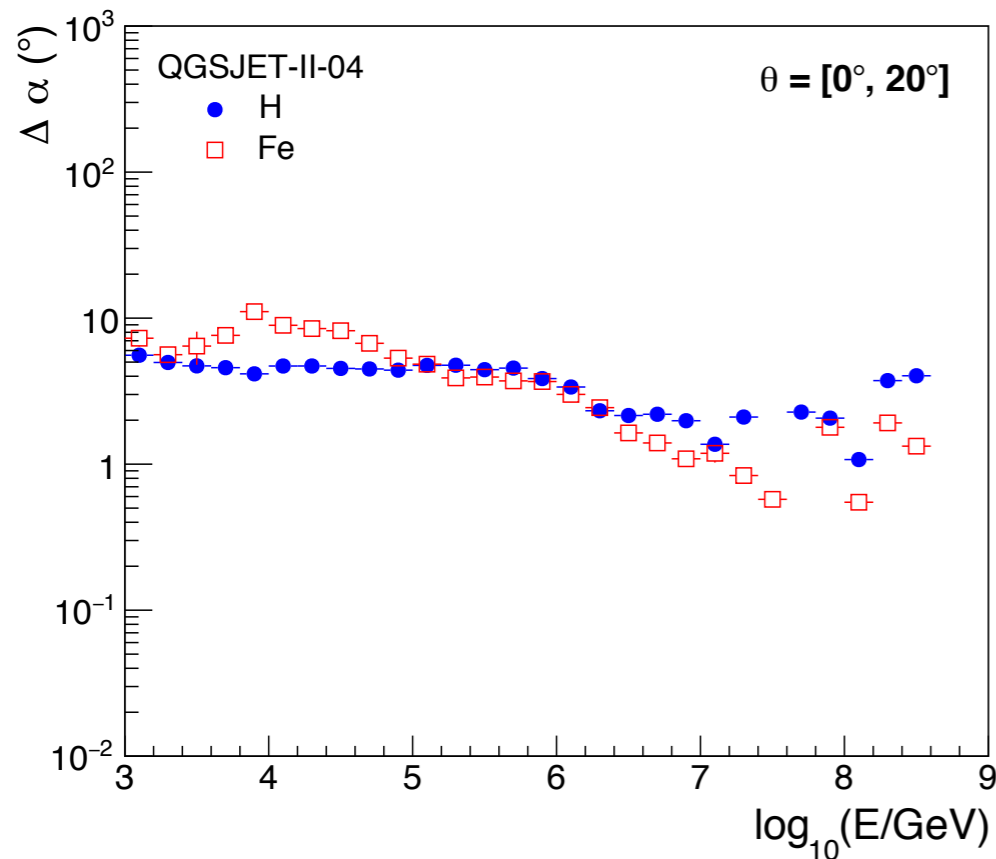


Mathusla as a cosmic ray detector

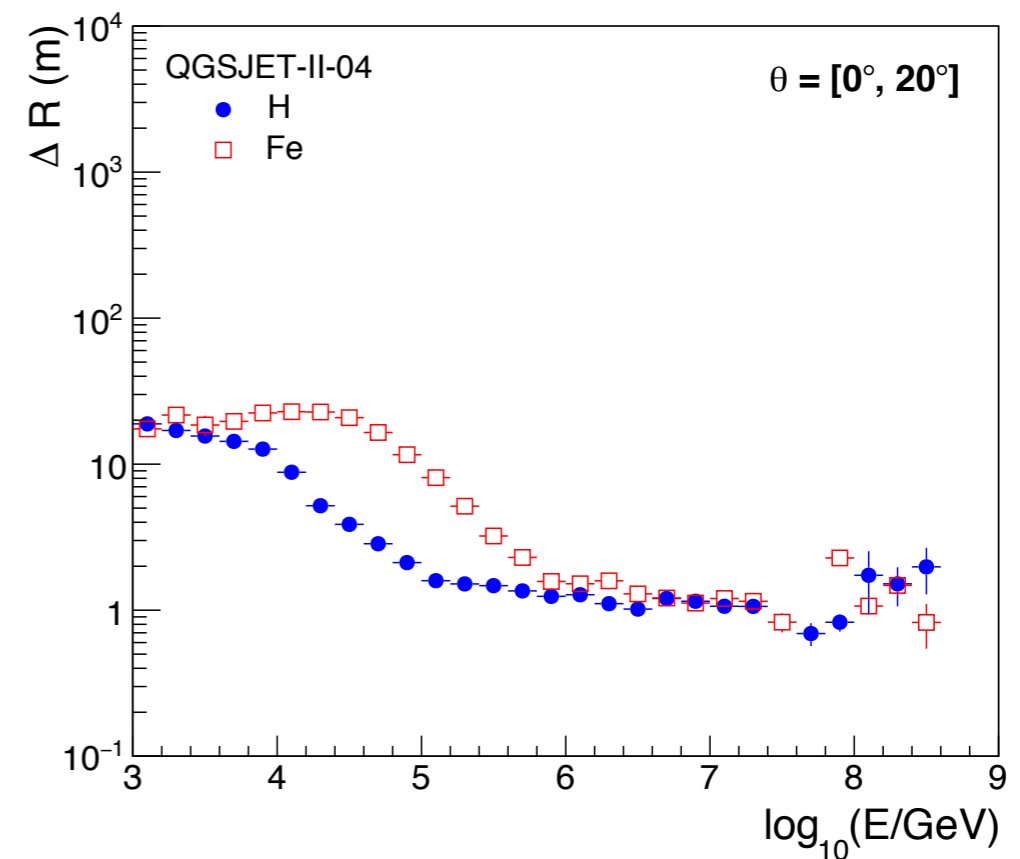
EAS reconstruction

Hits > 50
 $\theta < 20^\circ$

Arrival direction with RPC
 (fitting a plane to arrival times)



Core position with RPC
 (fitting a cone to density distributions)



The above are only upper limits, they can be improved with better reconstruction methods!

KASCADE: $\Delta\alpha < 0.3$ deg

NIMA Volume 513, Issue 3, 11 November 2003, Pages 490–510

ARGO: $\Delta\alpha < [0.4, 1]$ deg

Astroparticle Physics 93 (2017) 46–55

ICETOP: $\Delta\alpha = [0.2, 1]$ deg

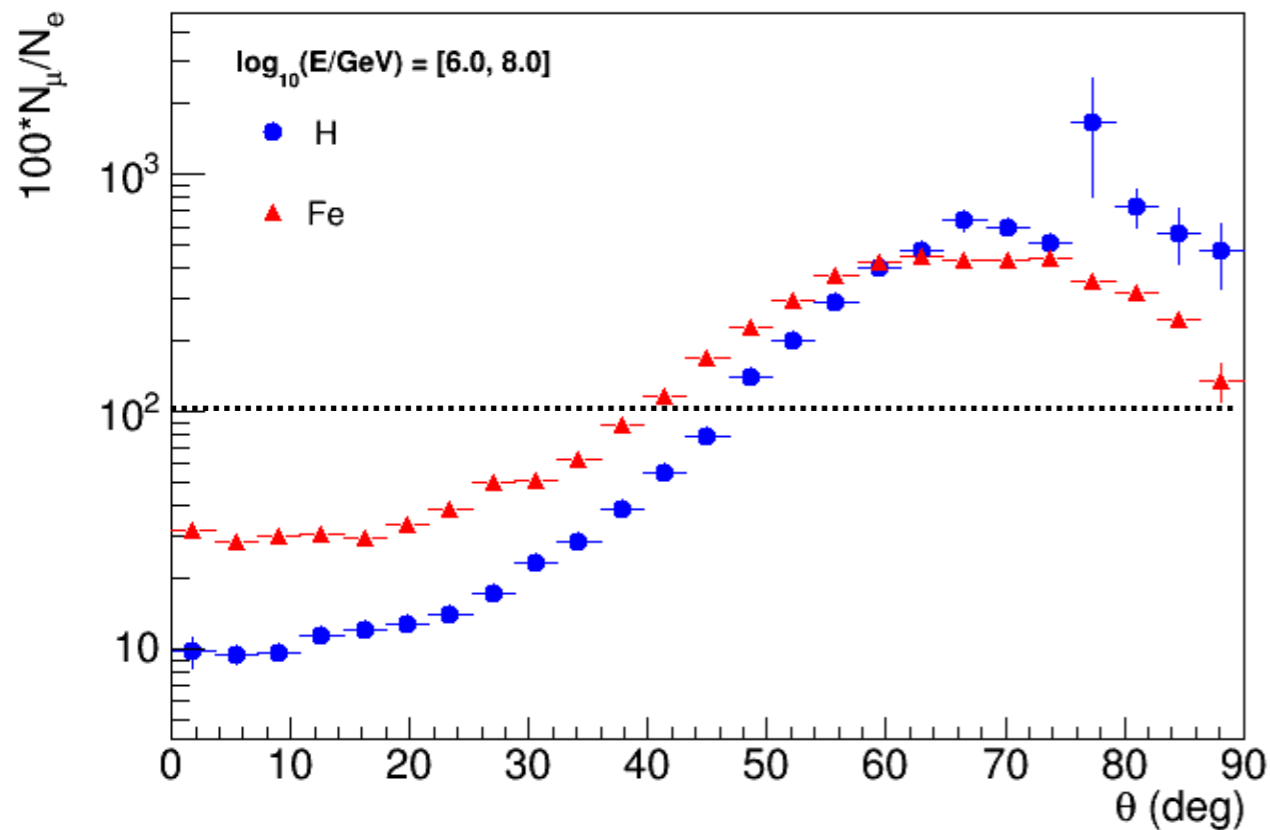
J. Phys.: Conf. Ser. 718 052033

KASCADE: $\Delta R < 1$ m

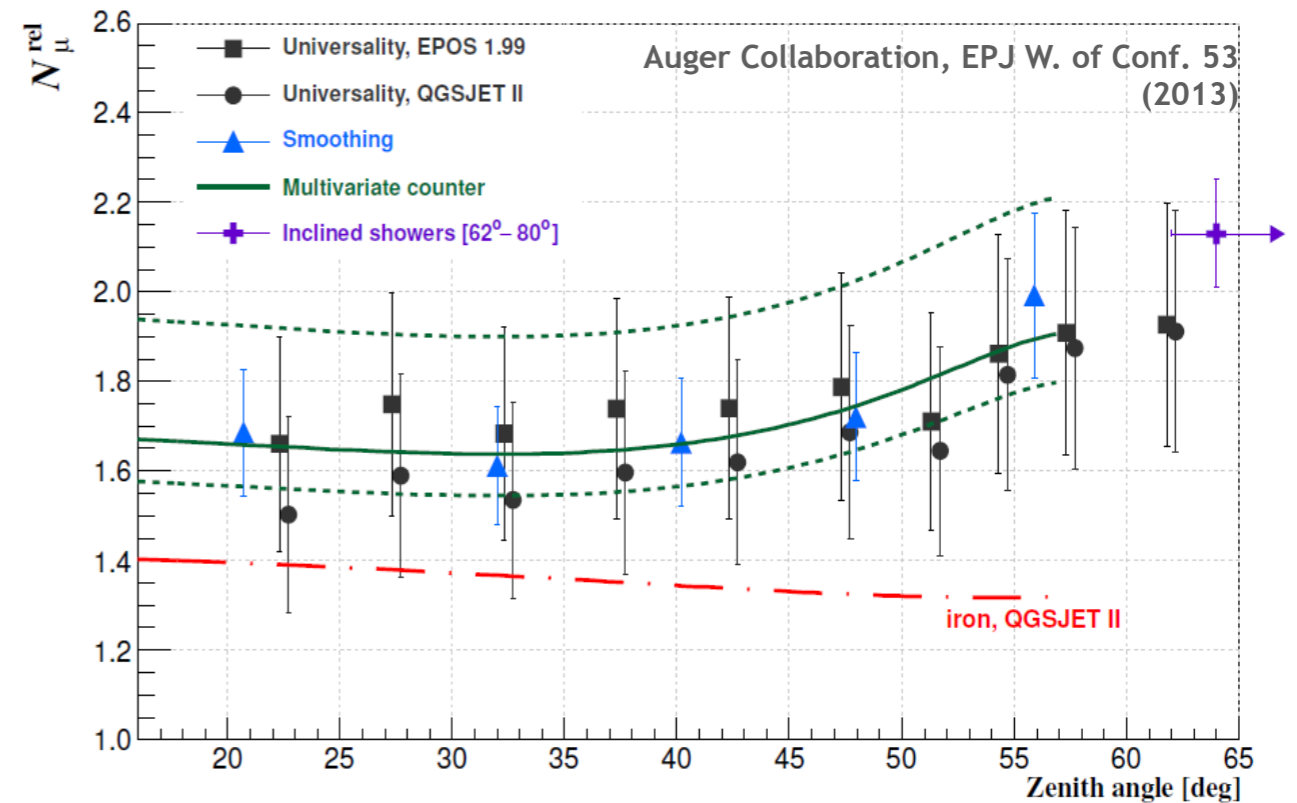
ARGO: $\Delta R < 1$ m

ICETOP: $\Delta R < [4, 18]$ m

Inclined air showers



At ultra-high energies muon discrepancies have been observed by Auger: Deficit of muons in MC predictions (zenith angle effect)



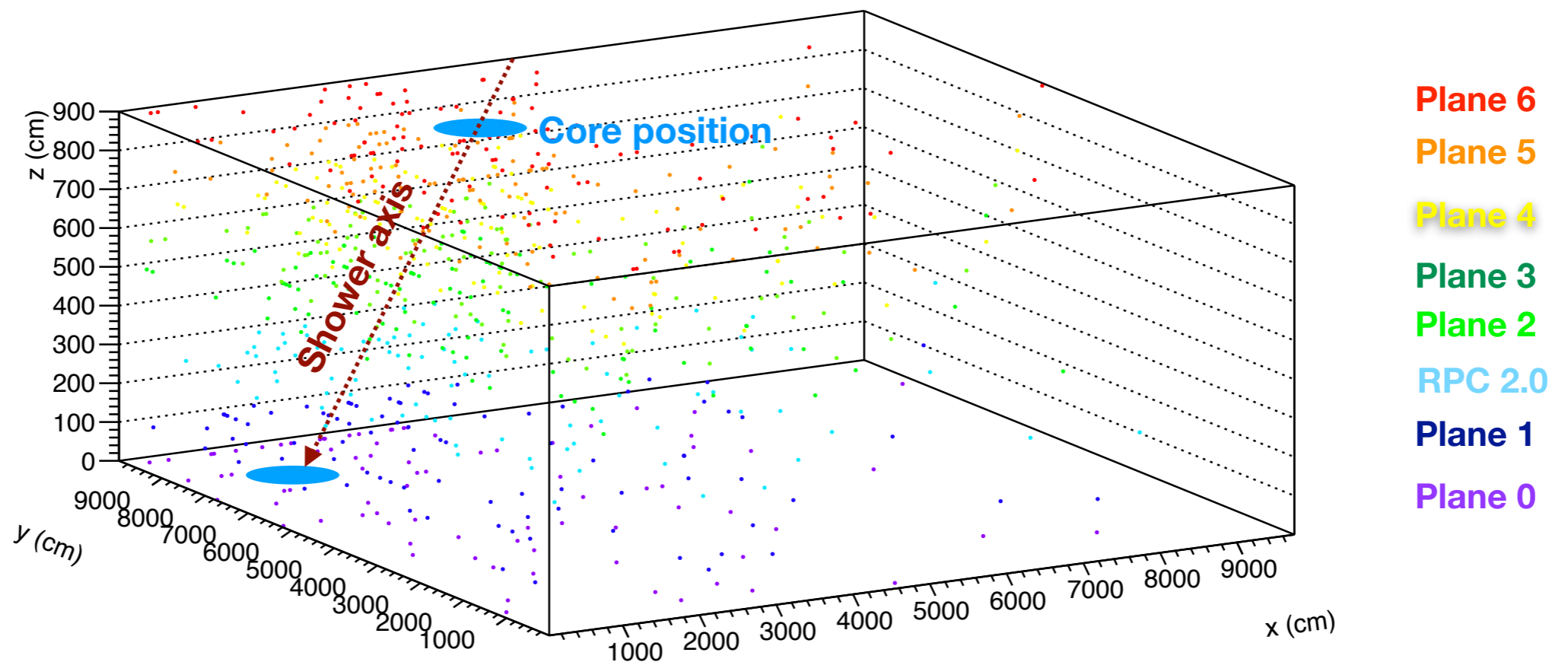
Relative number of muons (measured data over protons QGSJET-II predictions at 10^{19} eV) at 1000 m from the EAS core.

- For **inclined EAS** the attenuation of the $e + \gamma$ component is more important.
- **Muons** are the dominant component for high energy EAS at MATHUSLA altitude and $\theta > 50^\circ$.
- **Important deviations** between muon data and predictions have been found for inclined EAS.

Mathusla as a cosmic ray detector

Example for a MC inclined shower

Proton, $(x_c, y_c) = (2500, 8000)$ cm, $\log_{10}(E/\text{GeV}) = 7.62$, $\theta = 74.60^\circ$

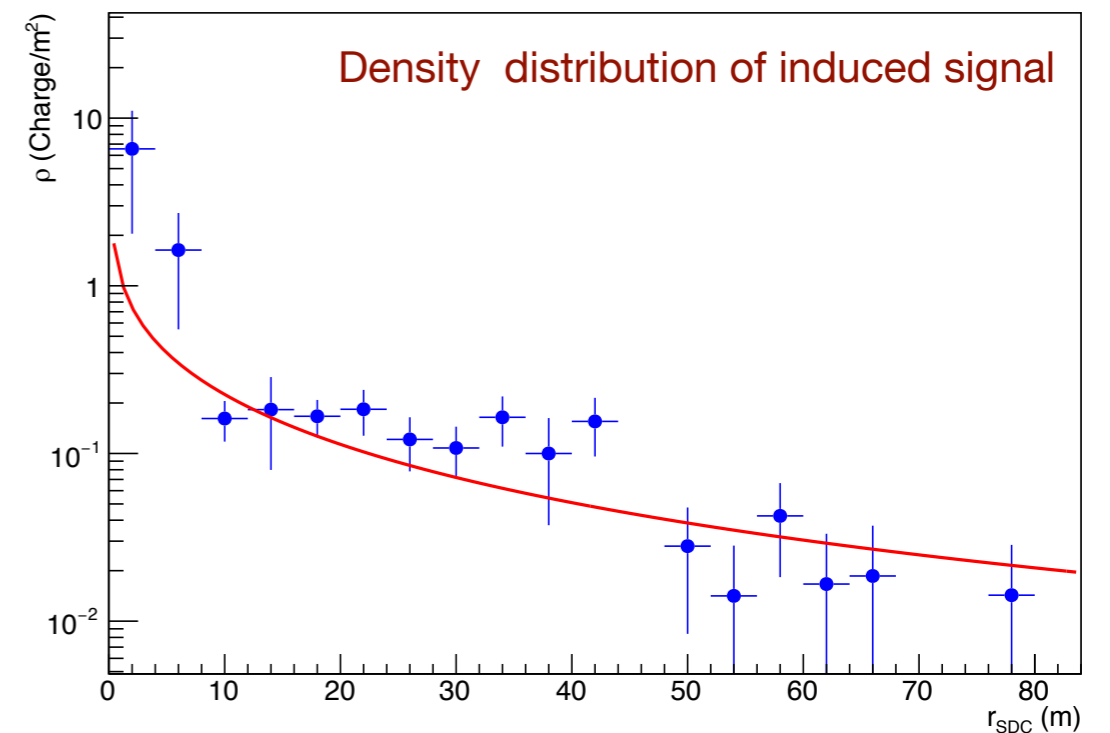
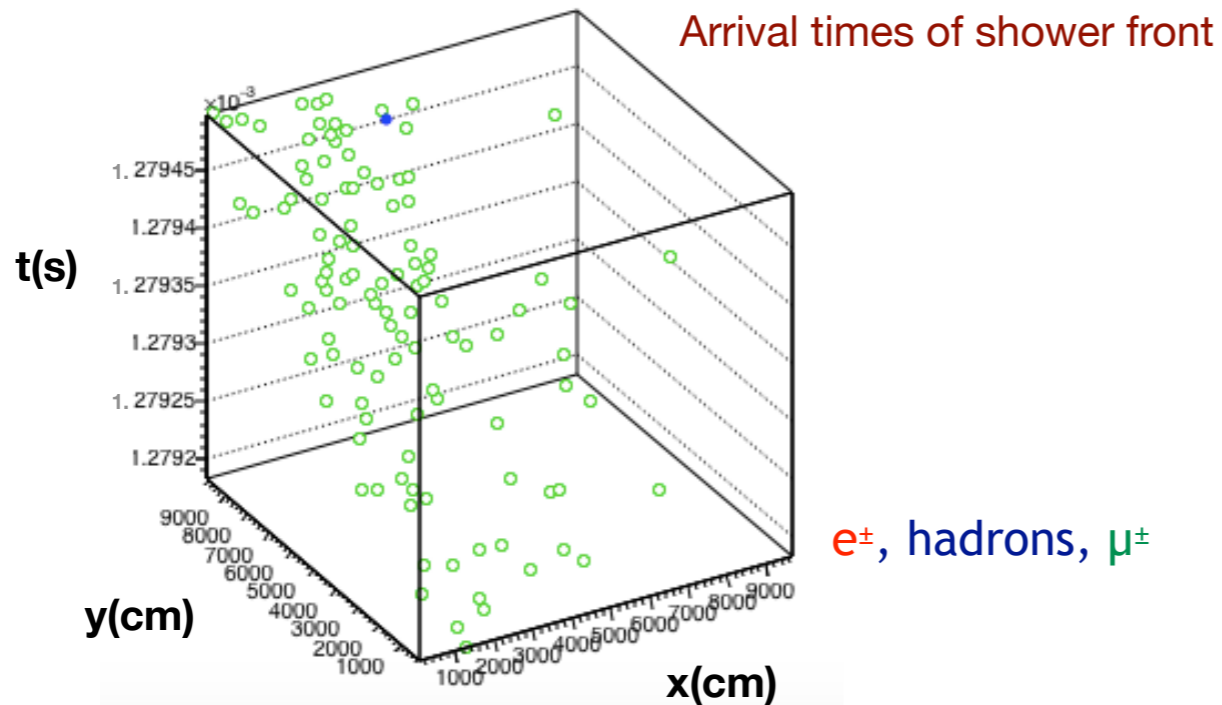
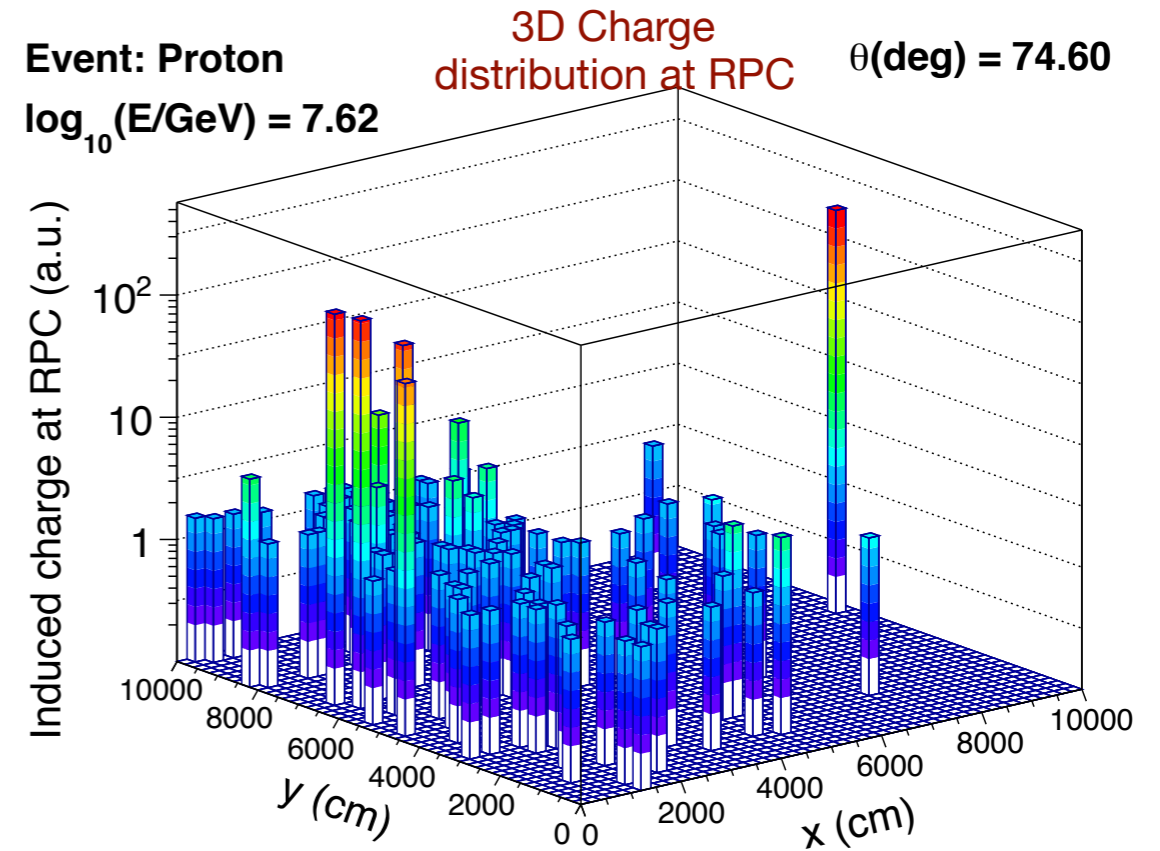
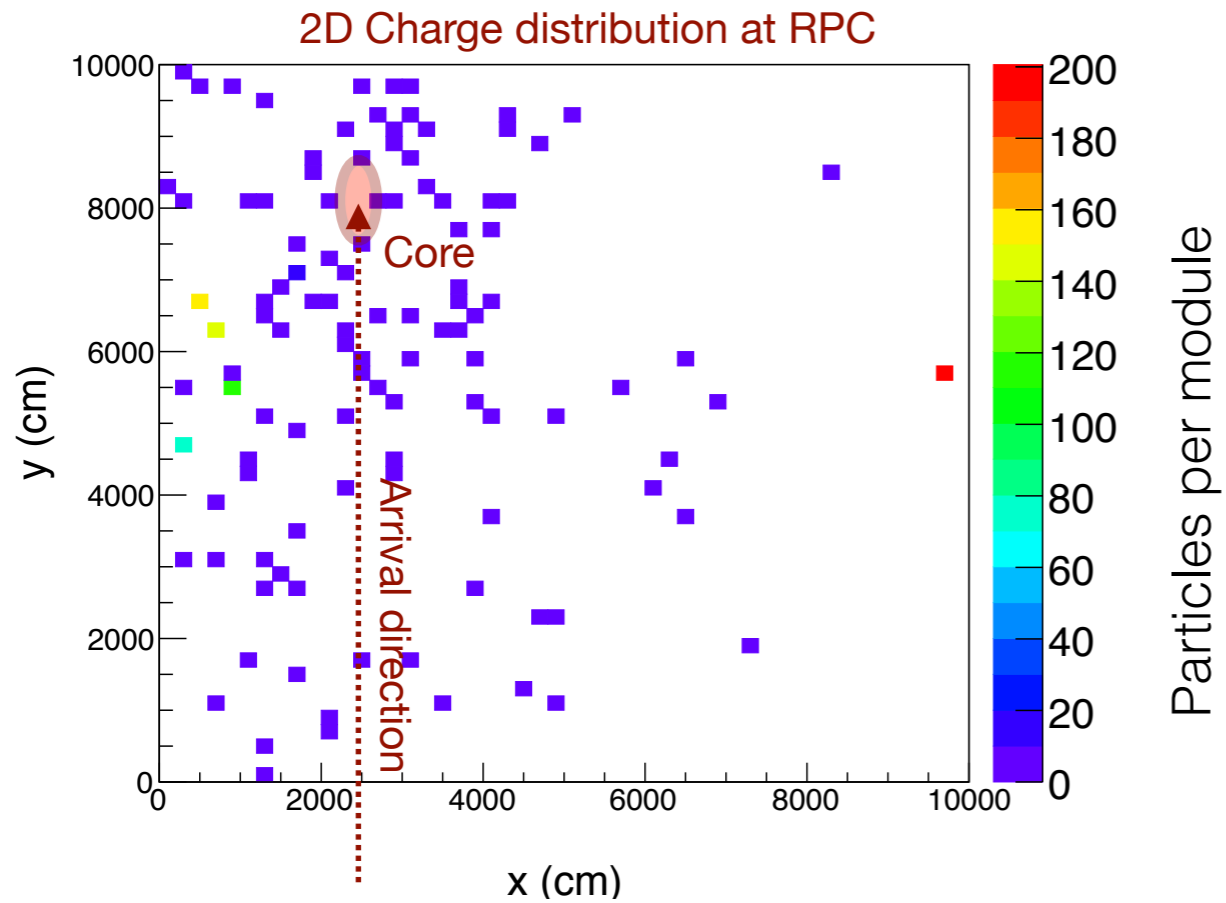


Coordinates of the center of each bar/Big Pad with signal due to the shower event in each plane of MATHUSLA



Mathusla as a cosmic ray detector

Inclined MC event: Core position, density, times



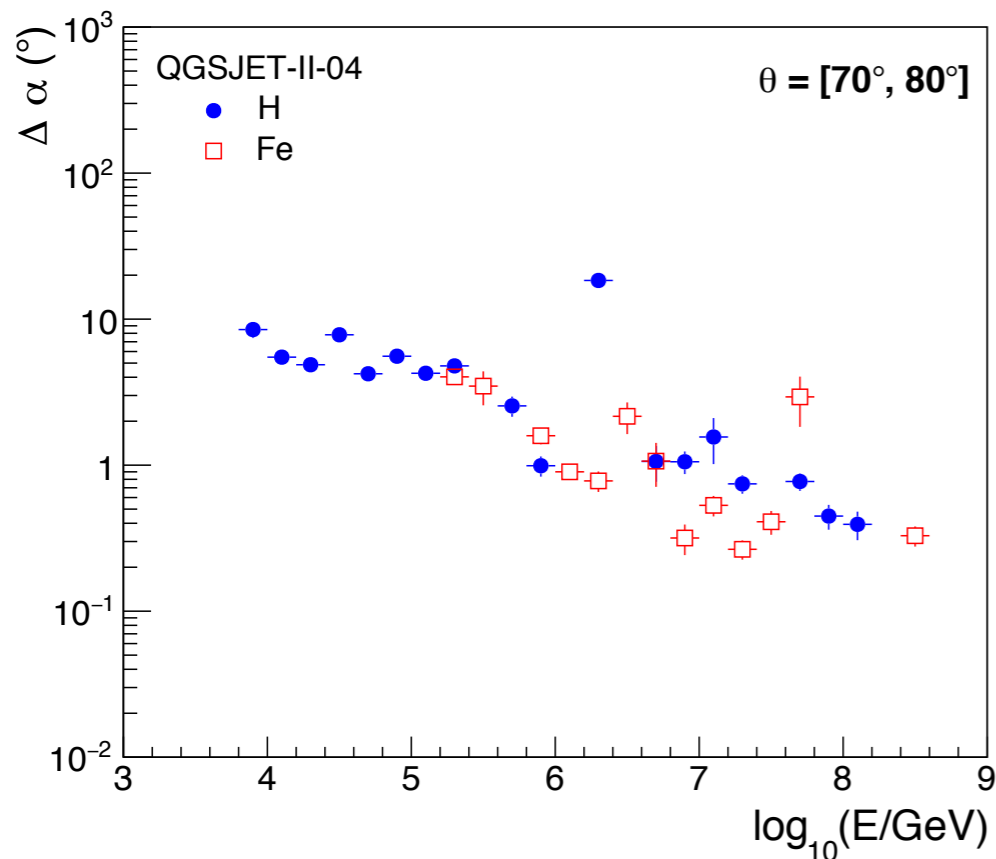
Mathusla as a cosmic ray detector

EAS reconstruction

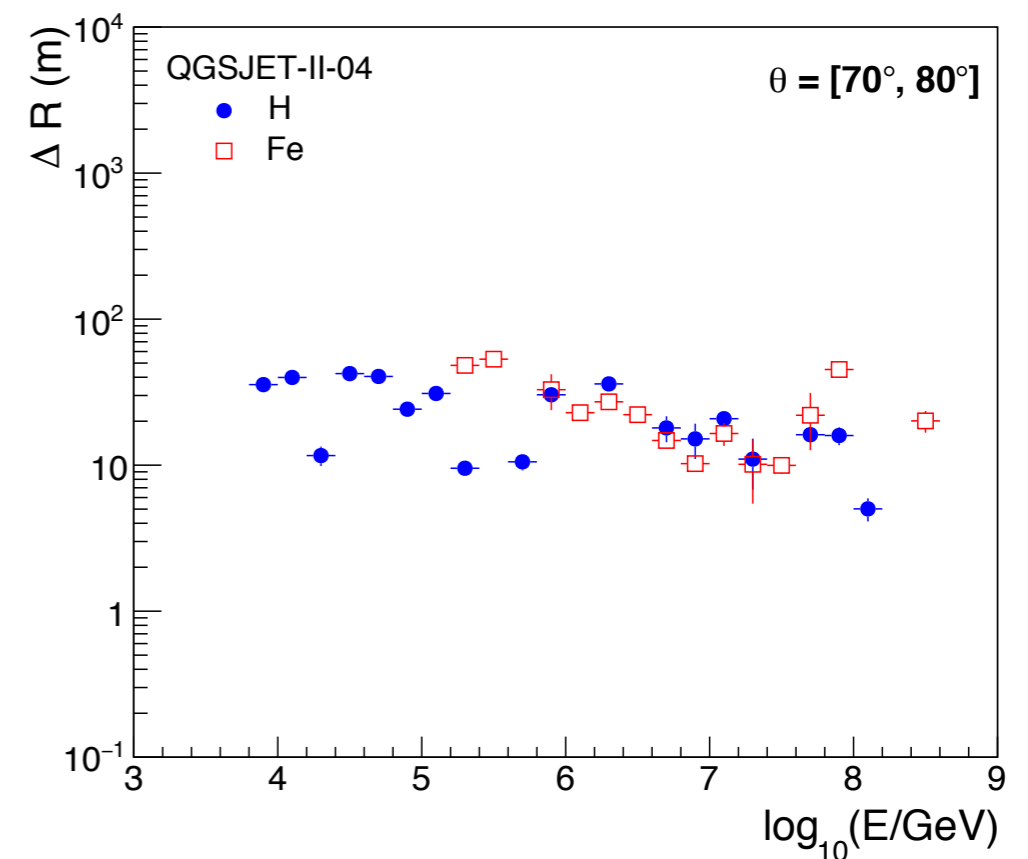
Hits > 50

$70^\circ < \theta < 80^\circ$

**Arrival direction with RPC
(fitting a plane to arrival times)**



**Core position with RPC
(fitting a cone to density distributions)**



The above are only upper limits, they can be improved with better reconstruction methods!

KASCADE: $\Delta\alpha < 0.6$ deg

ICRC 2007, ID 491, Vol. 4 (HE part 1), pages 203–206

KASCADE: $\Delta R < 40$ m

Auger: $\Delta\alpha < 0.5$ deg

JCAP, Volume 2014, August 2014

Auger: $\Delta R < 108$ m



Mathusla as a cosmic ray detector

Experiment	Energy range (PeV)	Altitude (m a. s. l)	Size (10^4 m^2)	Technique
MATHUSLA-100	(0.1, 10^2)	380-436	1	RPC, TD
HAWC-Outrigger	(10^{-4} , $O(1)$)	4100	12	WCD
Taiga	> 0.1	675	25	IACTs
IceTop [9]	(1, 10^3)	2835	100	ICD
LHAASO	(10^{-4} , 10^2)	4410	100	WCD,AC,Sci.
TALE (TA)	(30, 10^5)	1550	10^3	FD, Sci.

RPC: Resistive plate chamber
 TD: Tracking detector
 WCD: Water Cherenkov detector
 IACT: Imaging air Cherenkov telescope
 ICD: Ice Cherenkov detector
 Sci: Scintillator detector
 AC: Air Cherenkov
 FD: Atmospheric fluorescence detector

MATHUSLA + RPC would have several advantages:

- Full coverage (80 %). No other running CR detector has such capabilities.
- Detail measurements of the temporal and spatial structure of the EAS.
- New muon data from very inclined EAS at PeV energies.

Physics potential:

- Cosmic ray spectrum and composition.
- Anisotropies in the arrival direction of cosmic rays.
- Study the structure of the EAS front.
- Tests of hadronic interaction models.
- Muon bundles.



Cosmic Ray physics group

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5. Benemérita Universidad Autónoma de Puebla, Mexico
6. Universidad Mayor de San Andrés, Bolivia



Invitation is open to participate



Mathusla as a cosmic ray detector

- Documents:

1. John Paul Chou, David Curtin, H. J. Lubatti, [New Detectors to Explore the Lifetime Frontier](#), Phys. Lett B 767 (2017) 29.
2. D. Curtin, M. E. Peskin, [Analysis of long-lived particle decays with the MATHUSLA detector](#), PRD 97 (2018) 015006.
3. Mathusla Collaboration, [Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case](#), Rep.Phys.Prog. 82 (2019), Number 11.
4. Mathusla Collaboration, [MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LHC](#), input for the European Strategy for Particle Physics, arXiv:1901.04040 [**hep-ex**].
5. M. Alidra et al, [The MATHUSLA Test Stand](#), arXiv:2005.02018 [**physics**].
6. TDR in progress.

- Link to webpage:

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



The MATHUSLA experiment

MATHUSLA (Massive Timing Hodoscope for Ultra Stable neutral pArticles) is a proposed detector at CERN with the aim of going online with the HL-LHC upgrade to the Large Hadron Collider in ~2025.

Many extensions of the Standard Model (SM) include particles that are neutral, weakly coupled, and long-lived that can decay to final states containing several SM particles. Missing energy (MET) searches at ATLAS and CMS are undoubtedly crucial in probing new physics giving rise to more than several hundred GeV of MET, but the sensitivity drastically drops for softer signals. Searches for long-lived particles (LLP) in the LHC detectors have set significant ct exclusion limits from a few centimetres to tens of meters, but the detection reach of the LHC detectors is limited by trigger and background difficulties. Therefore, even if an LLP was already produced at the LHC, it might have been inevitably missed.

No existing or proposed search strategy will be able to observe the decay of neutral LLPs with masses above ~GeV and lifetimes up to



Summary

1. MATHUSLA could complement the search for LLPs at the LHC during the next High Luminosity runs at CERN.
2. The detector is planned to be installed at the surface, close to the CMS interaction point.
3. MATHUSLA would be composed of a tracking array of 9 planes of scintillator detectors, each of them with a modular design.
4. The detector could also work as a cosmic ray air shower observatory.
5. Enhancement of the air shower detection capabilities can be achieved by using an extra RPC detector layer.
6. With this extra layer, MATHUSLA could become a new kind of instrument to
 - **Study the spatial and temporal structure of extensive air showers,**
 - **Test the predictions of hadronic interaction models, muon bundles,**
 - **Perform research on some open issues of the physics of PeV cosmic rays.**

Thank you!