Sensitivity of MATHUSLA to high-energy cosmic rays

J.C. Arteaga-Velázquez[1] for the MATHUSLA Collaboration

[1]**Universidad Michoacana de San Nicolás de Hidalgo**

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

RPC 2022

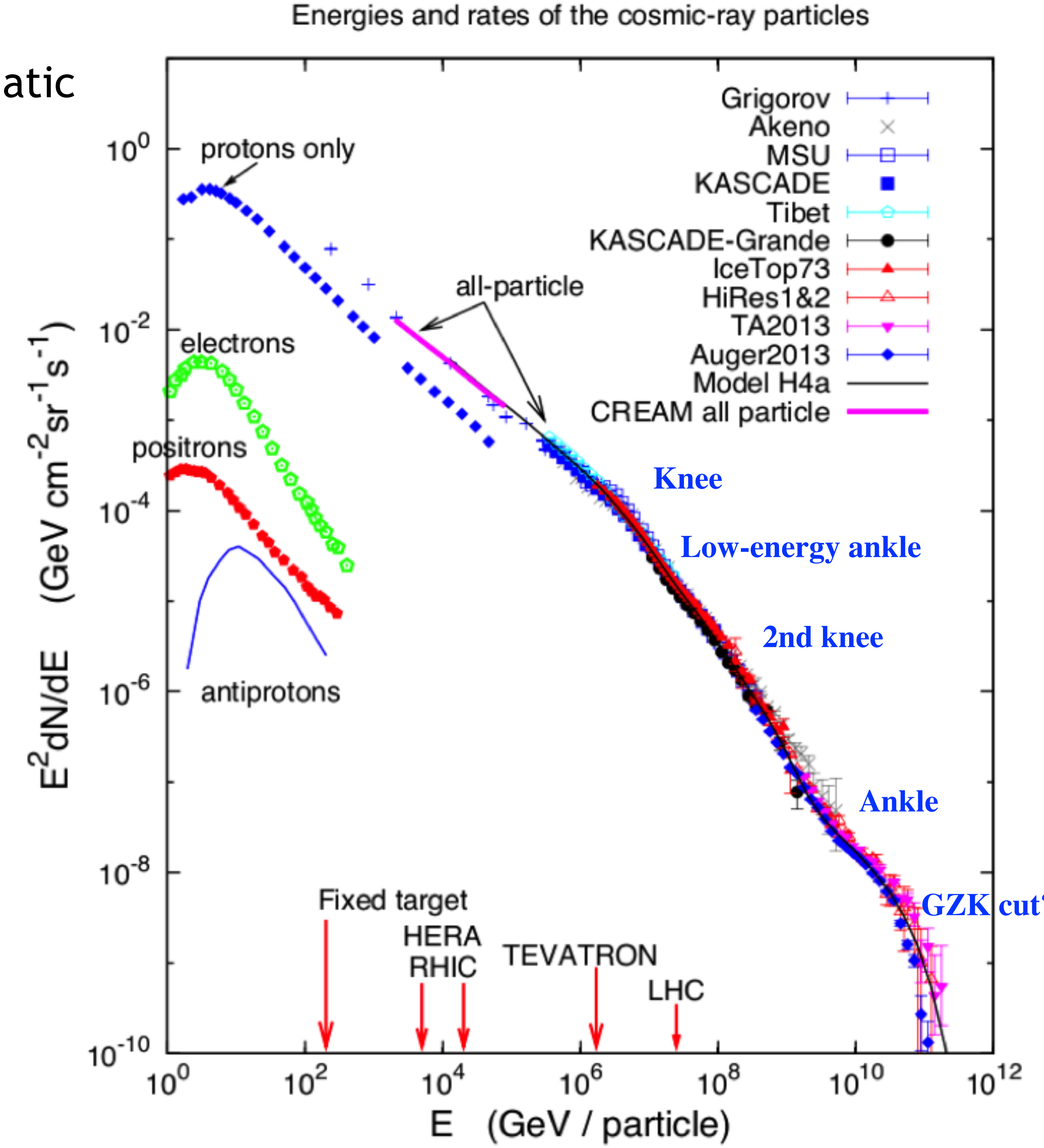
XVI Workshop on Resistive Plate Chambers and Related Detectors

September 26-30, 2022, CERN

Introduction

Cosmic rays

- One of the most energetic and enigmatic form of radiation from outer space
- **Composed** by atomic nuclei (99 %).
- **E =** [100 MeV, 10^{20} eV]
- **Spectrum** $F(E) = E^{-\gamma}$ (γ: spectral index)
- **Origin:** Galactic (E < 10^{17} - 10^{18} eV)
  Extragalactic (E > 10^{18} eV).
- Open question at high energies:
  - Origin or features in spectrum,
  - Type and distribution of sources,
  - Acceleration mechanism,
  - Propagation in space,
  - Energy, composition, etc.



P. Blasi, Astron.Astrophys.Rev. 21 (2013) 70

Introduction

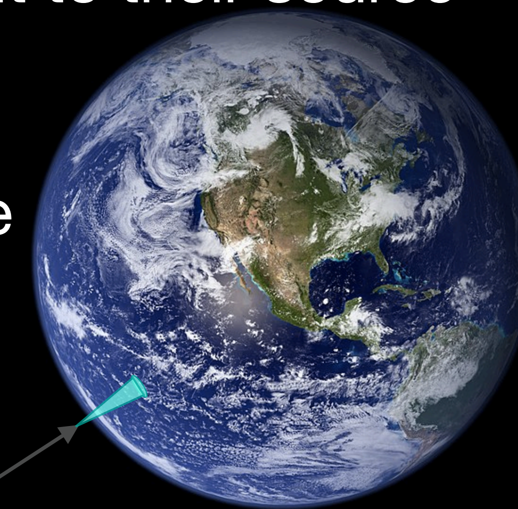
Galactic cosmic rays

Credit: Smithsonian institution

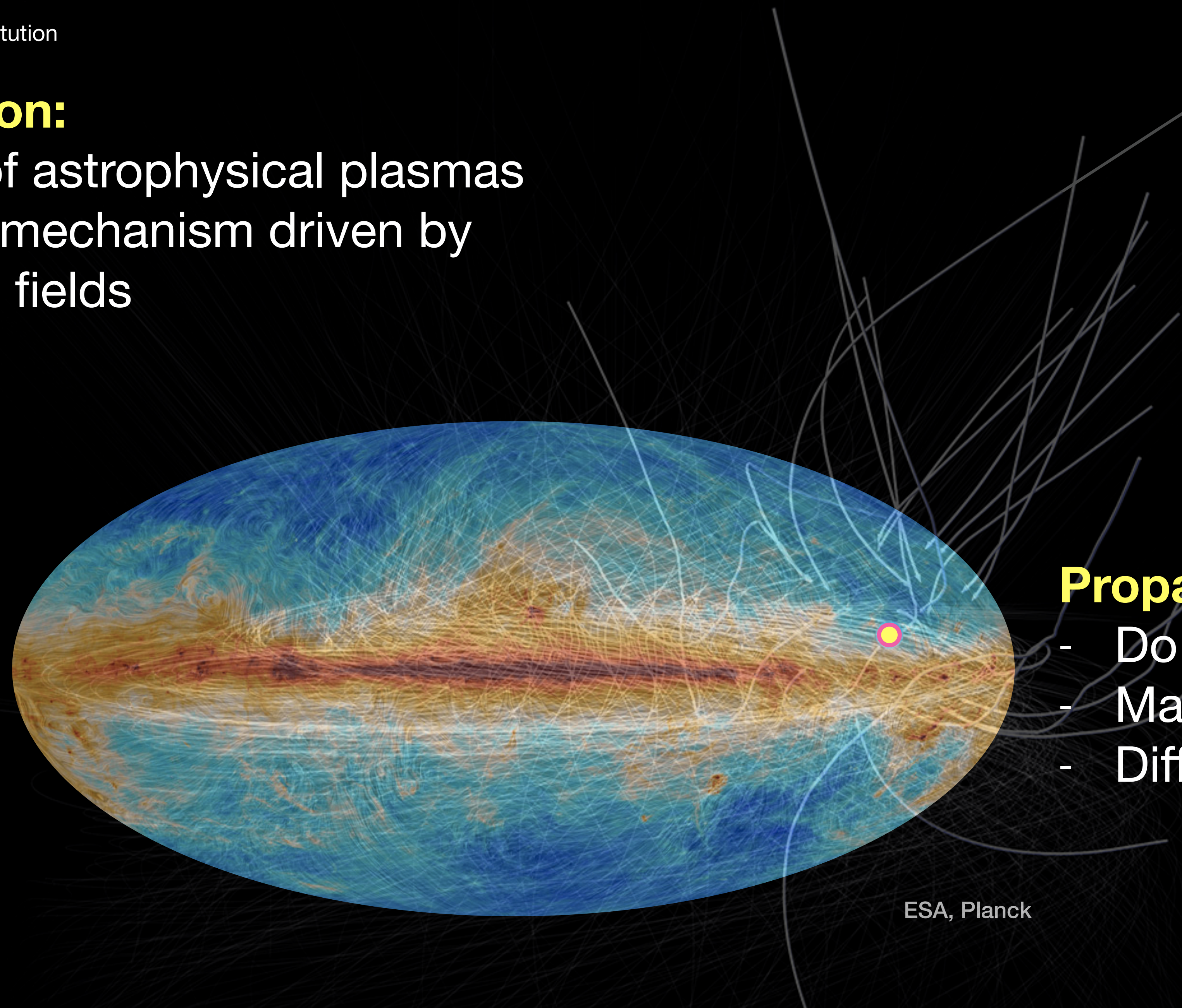
Origin:
-Supernova Remnants
-Pulsars
-Superbubbles

Acceleration:
- Shocks of astrophysical plasmas
- Diffusive mechanism driven by magnetic fields

Arrival to Earth:
- Do not point to their source
- Create air showers in atmosphere



NASA



ESA, Planck

NASA/AMES

Propagation:
- Do not travel in straight lines.
- Magnetic field interactions.
- Diffusive propagation.

Detection

Indirect detection of cosmic rays through **extensive air showers** (EAS)

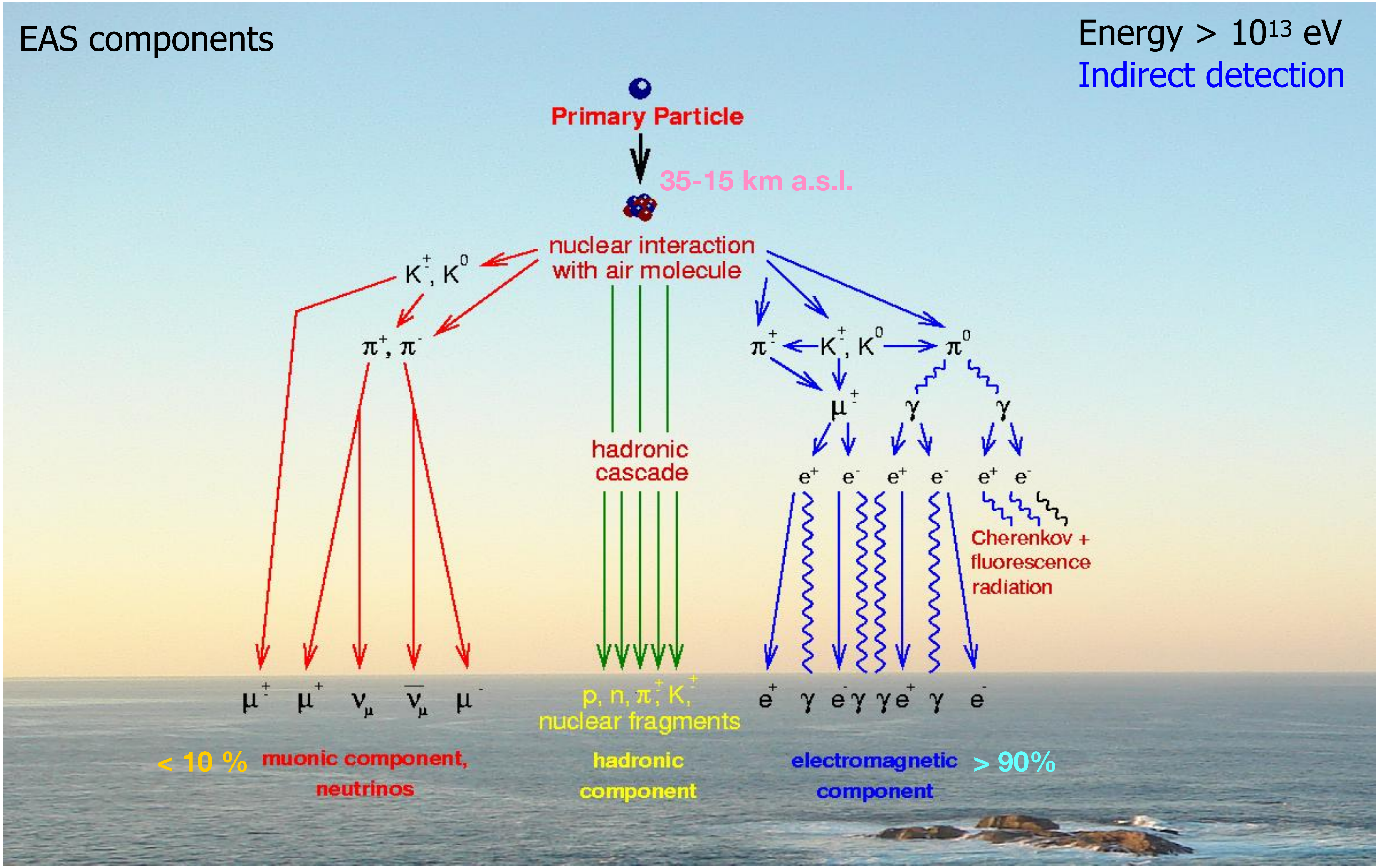
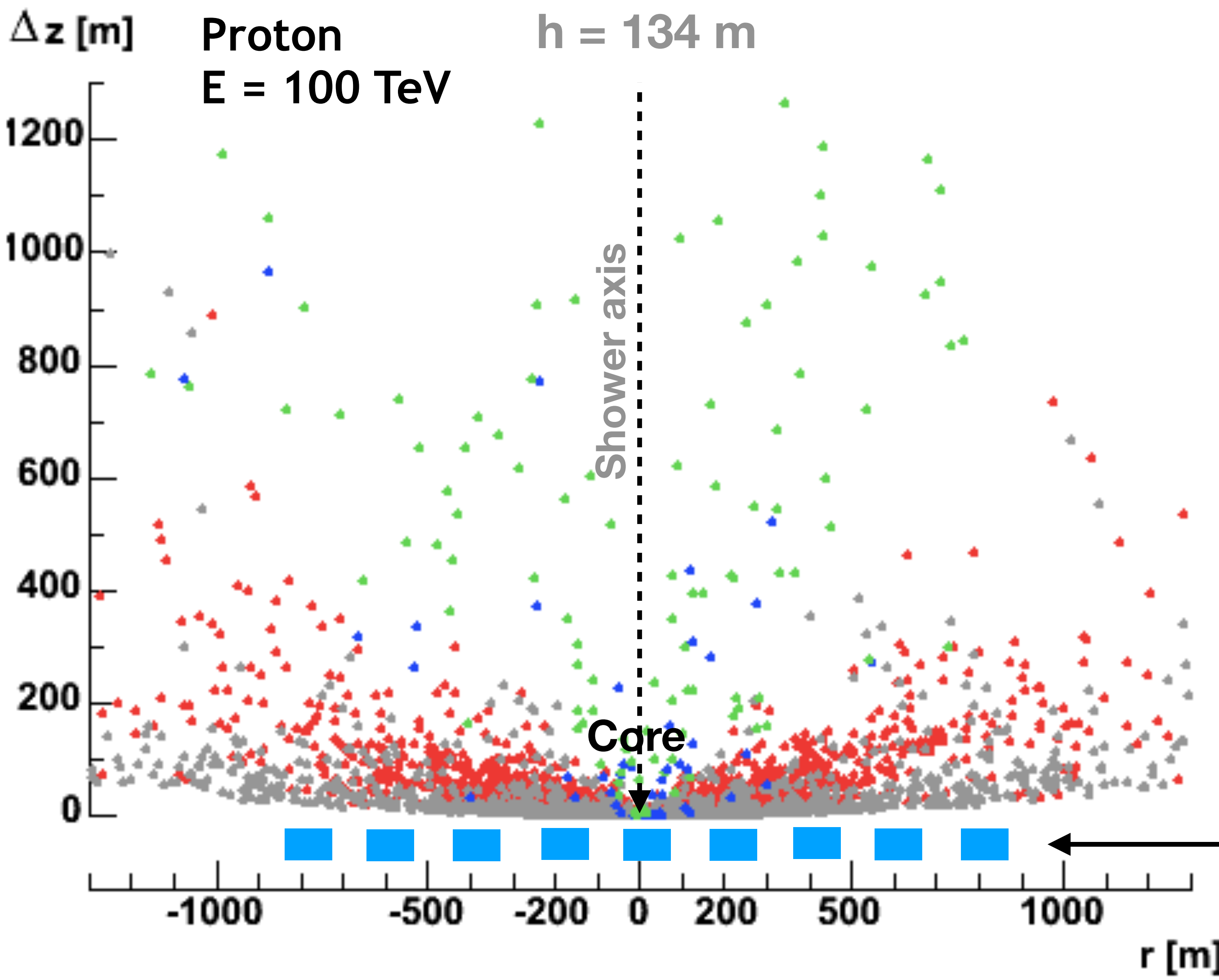
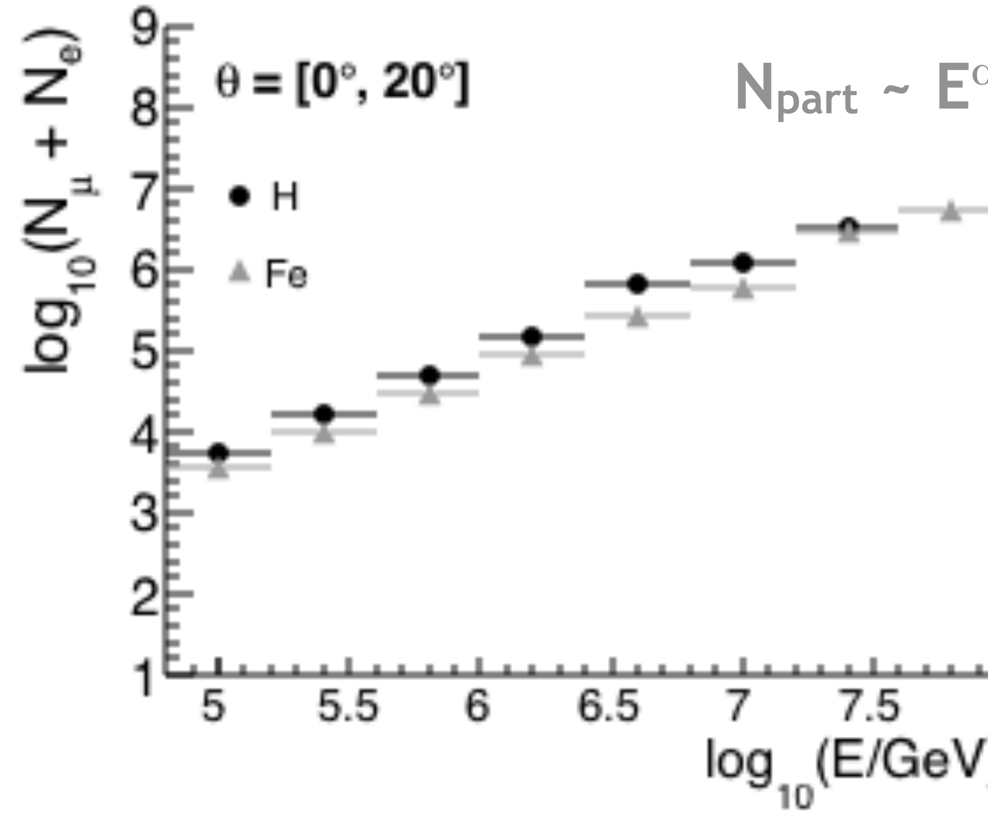


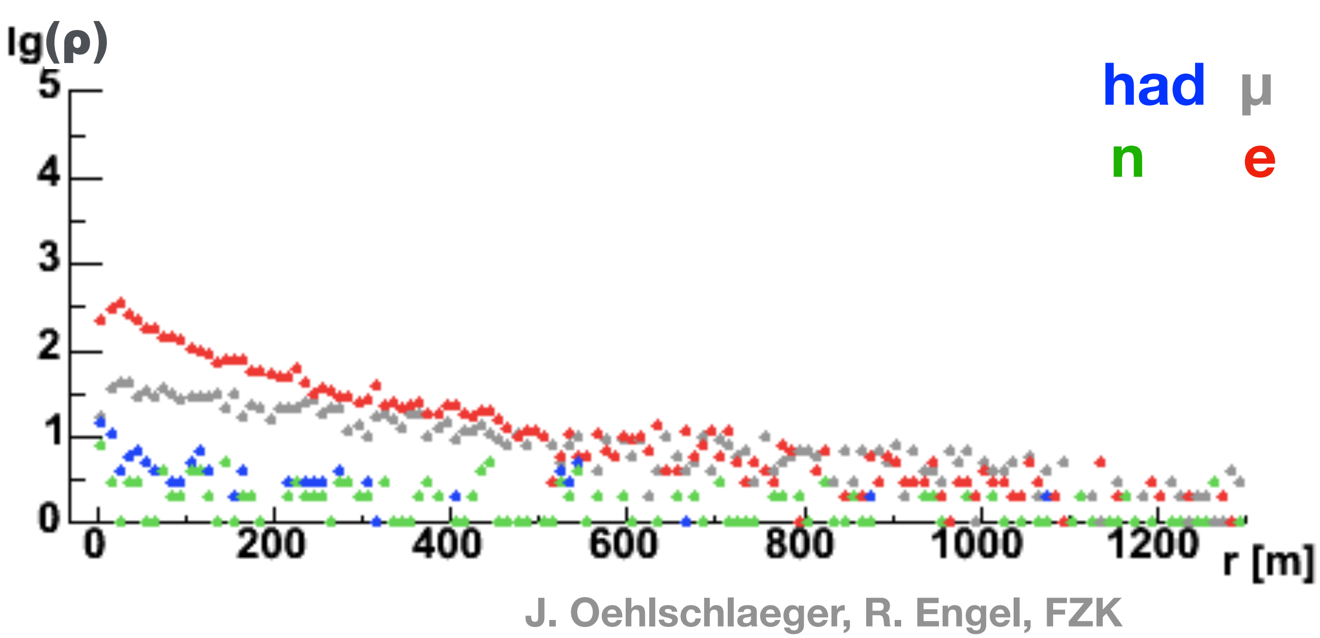
Photo: J.C.A.V

EAS diagram: A. Haungs

Detection







- Particle detector arrays
  - Local particle density measurements
  - Arrival times of shower particles.

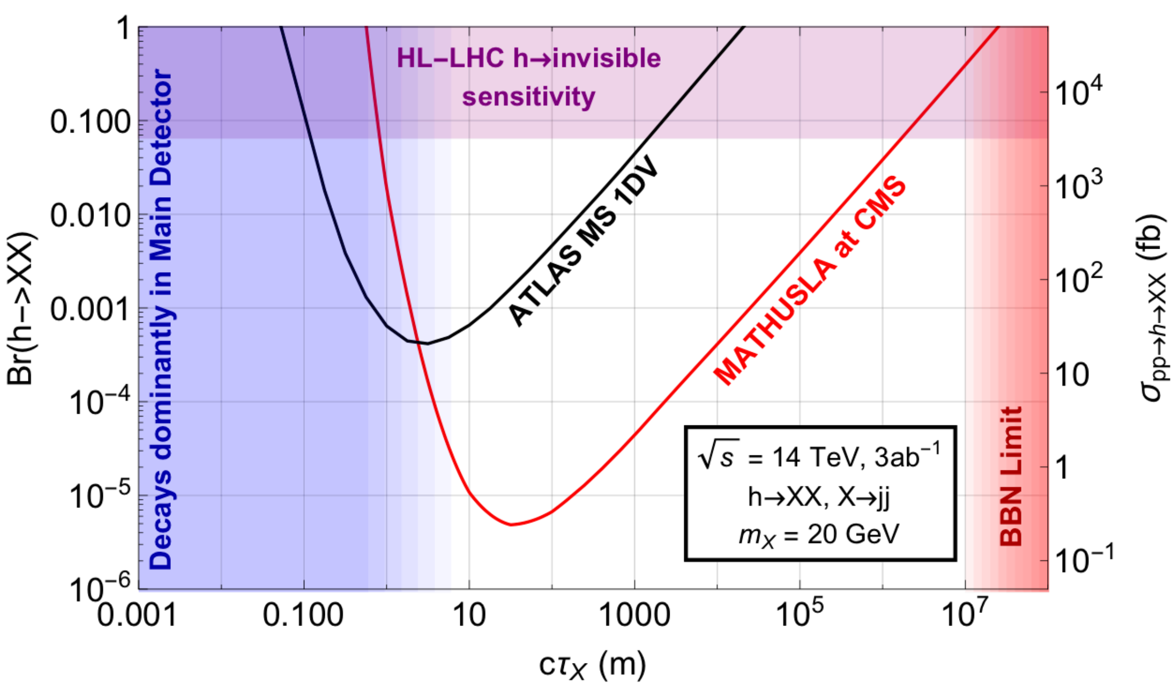
- Cosmic ray properties
  - Energy
  - Composition
  - Arrival direction

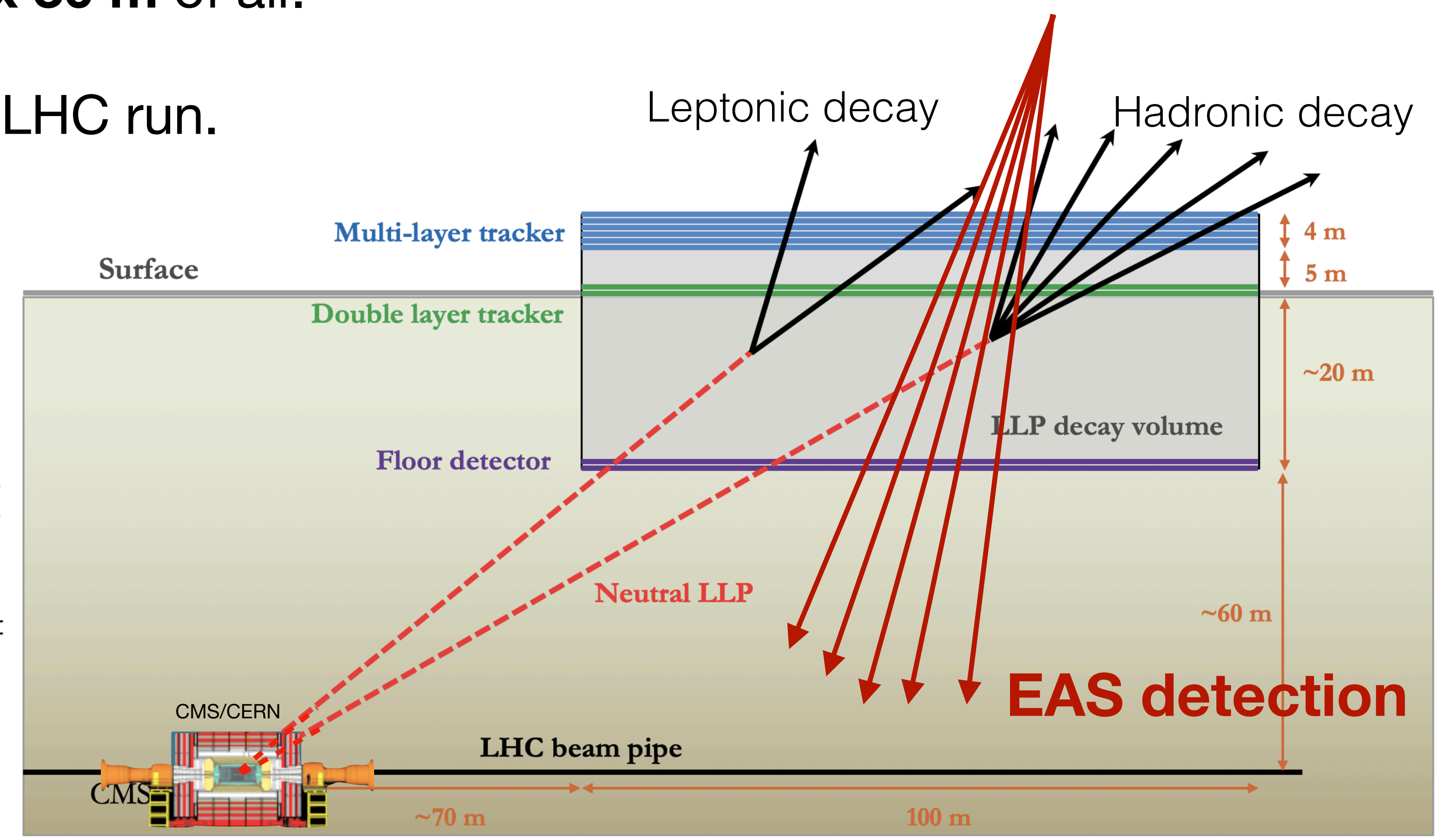
Mathusla proposal

- To build a large area hodoscope detector to look for decay of neutral **L**ong **L**ive **P**articles (LLPs) in a volume of **100 m x 100 m x 30 m** of air.

- Planned for the next High-Luminosity LHC run.

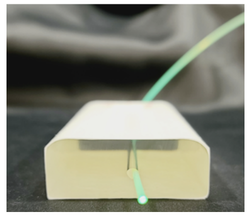
A. Coccaro et al., PRD94, 113003 (2016)





- Complement LLP searches at LHC in the MeV - TeV mass range and for cτ= [0.1, 10^7] m.

- Tracker: 9 scintillating layers
  - 6 on the top : Trigger
  - 2 intemediate: Increase performance
  - 2 at bottom : Veto for charged particles
- 2.5 m x 5 cm x 1 cm extruded sci. bars.



Mathusla proposal

MATHUSLA

- Sensitivity to cosmic ray detection: Detection of charged EAS particles ($e^{\pm} + \mu^{\pm} + h^{\pm}$)

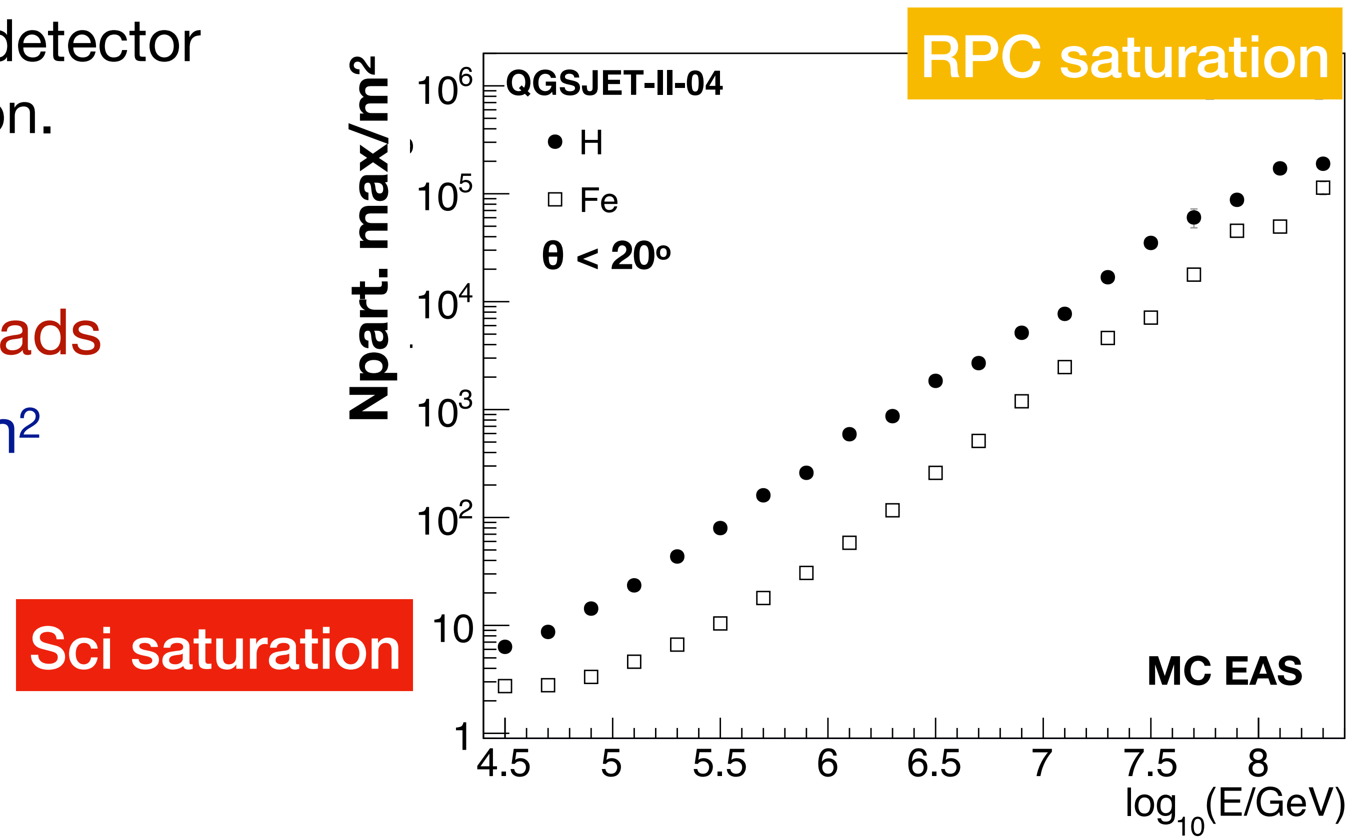
- Adding an RPC layer to the MATHUSLA detector would significantly enhance EAS detection.

- Saturation of detector elements

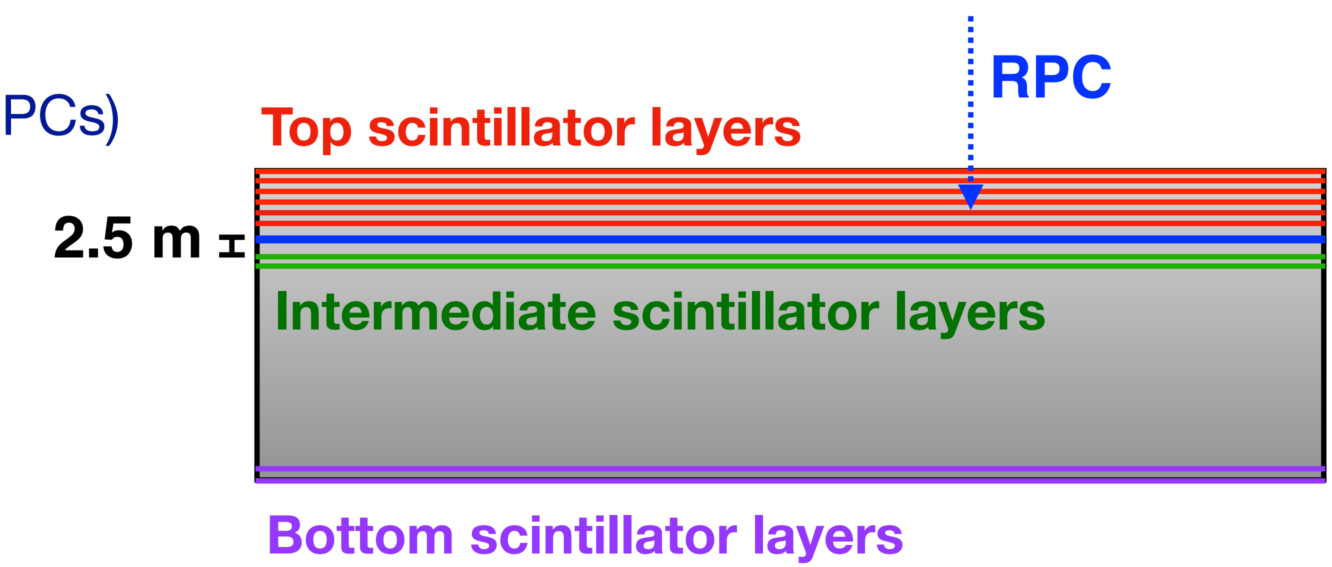
Scintillator bars		RPC Bid Pads
8 part/m^2	vs	10^6 part/m^2

- RPC data:

  - Detail spatial-time distributions of charged particles



- RPC characteristics
  - 1 mm gas gaps (like in ATLAS Phase-II BI RPCs)
  - 242 cm^2 strips (2.2 m long)
  - Big Pads: 1.1 m x 0.9 m
  - RPC in avalanche mode.
  - Big Pad signal ∝ local charge density.
  - Cosmic ray trigger



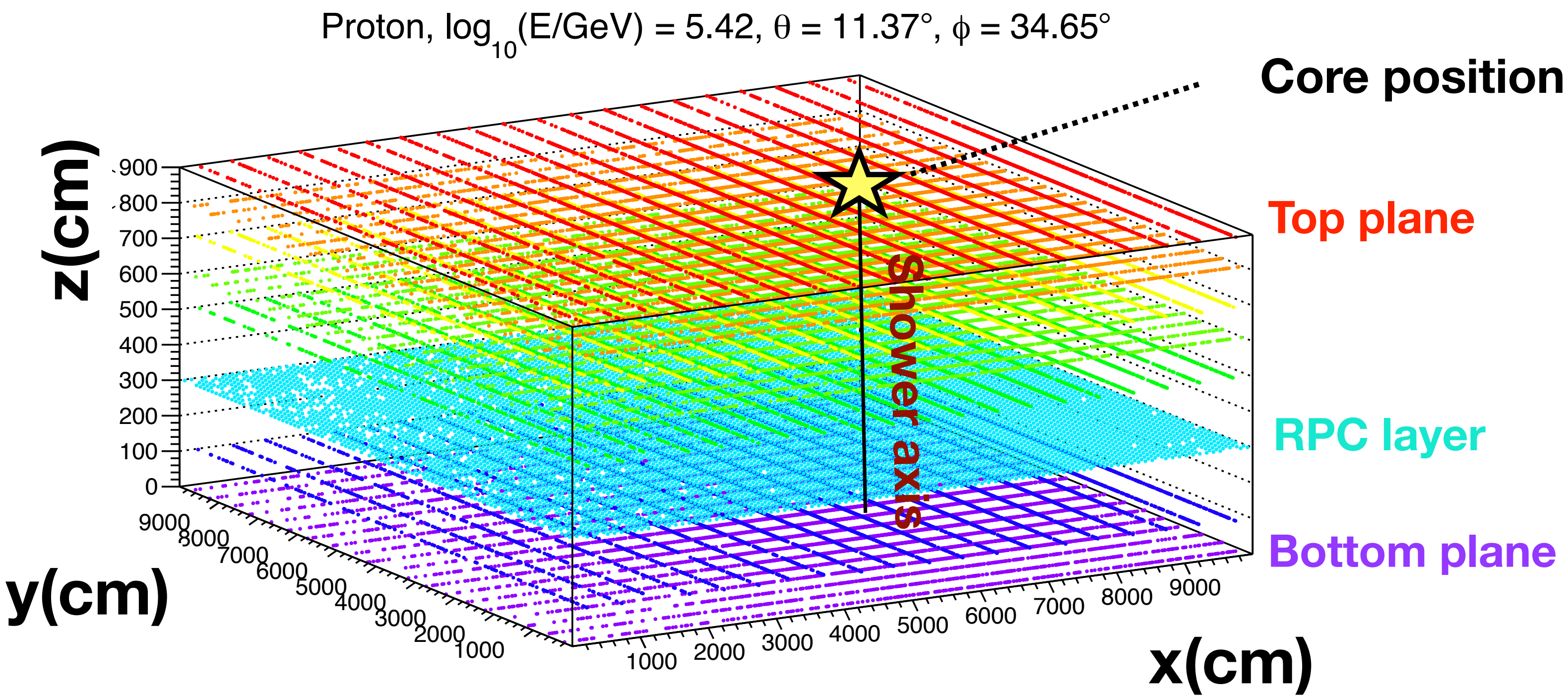
Simulations

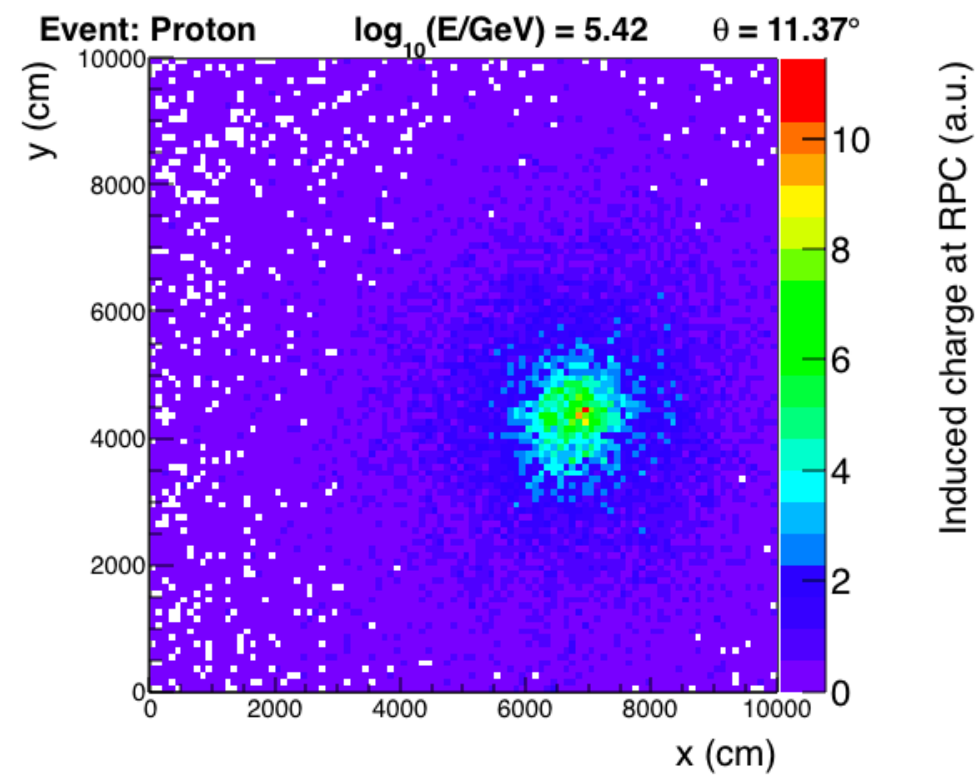
- **CORSIKA 7.64** is used to simulate creation and development of **EAS** in atmosphere.
  - 2×10^5 simulations
  - Hadronic interaction models: FLUKA (E_h < 200 GeV)/ QGSJET-II-04
  - H, Fe primaries
  - Spectrum: E^{-2}
  - Zenith angles: 0^o- 20^o, 70^o - 80^o
  - Curved atmosphere
  - Magnetic field at site NOAA https://www.ngdc.noaa.gov/geomag-web/#igrfwmm

- Toy model of MATHUSLA (based on **ROOT**) to study the potential gain of using an RPC layer:
  - Size: 100 m x 100 m
  - Scintillator layers:
    - * Seven on the top
    - * Ignore the two layers 25 m at the bottom
    - * 5 m x 4 cm scintillator bars
  - Big Pads: 1 m x 1 m

EAS reconstruction

Example of a MC vertical shower



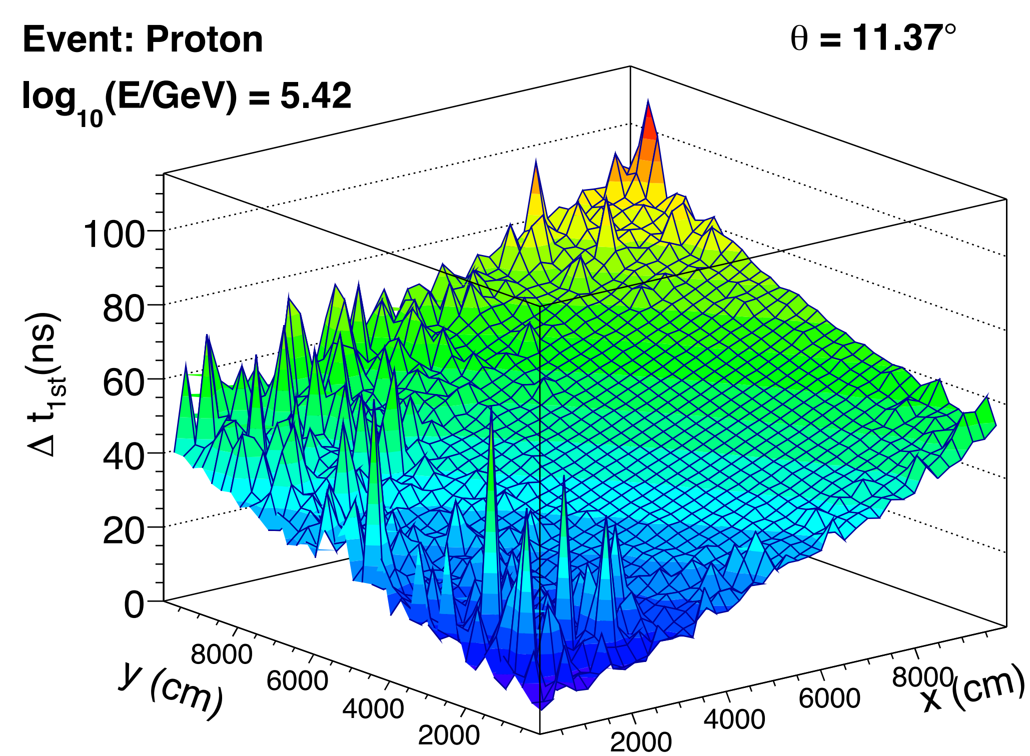


- EAS reconstruction:
  - **Core** from **exponential fit** to X (Y) projected hit bars/induced charge

$$N_{\mathrm{hits},i} = a_i e^{-b_i \cdot |x_i - x_{c,i}|}$$

  - **Direction** from **fits with a plane** to arrival times of EAS front after time curvature corrections.

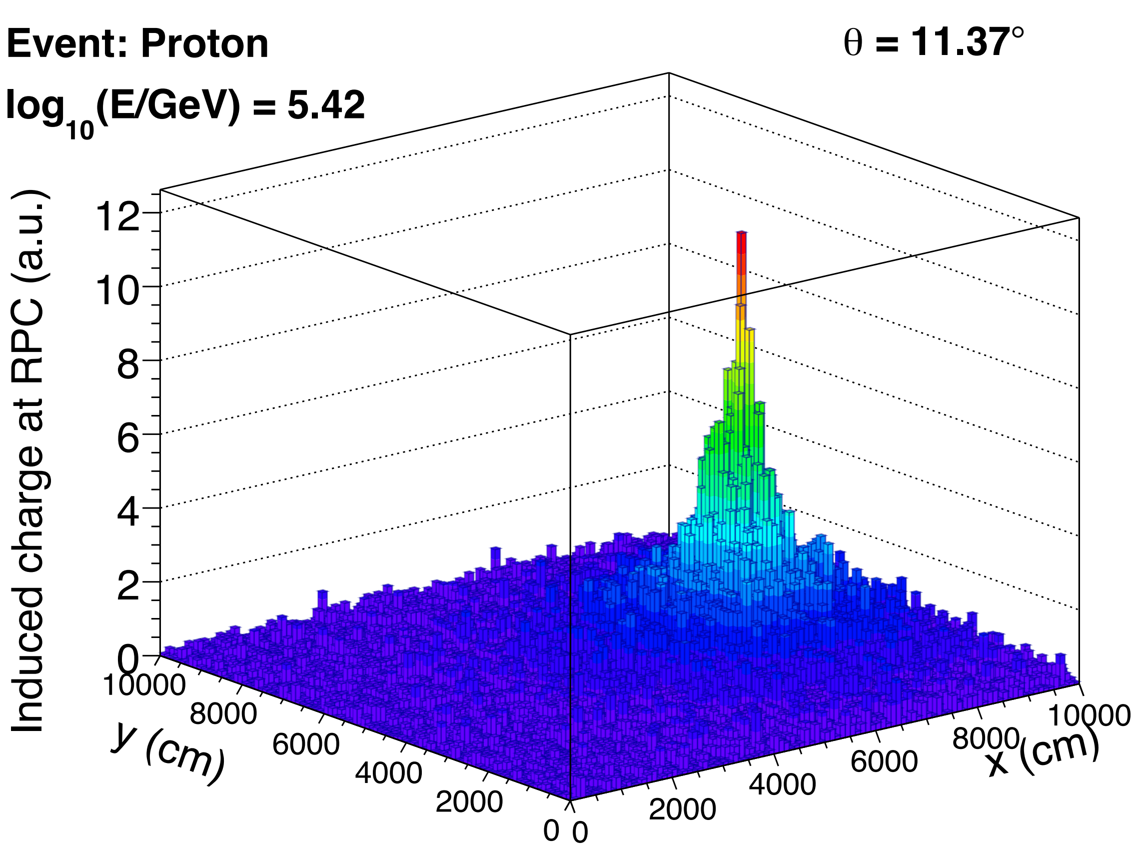
$$a_1 \cdot x_i + a_2 \cdot y_i + a_3 = ct_{1st,i}$$



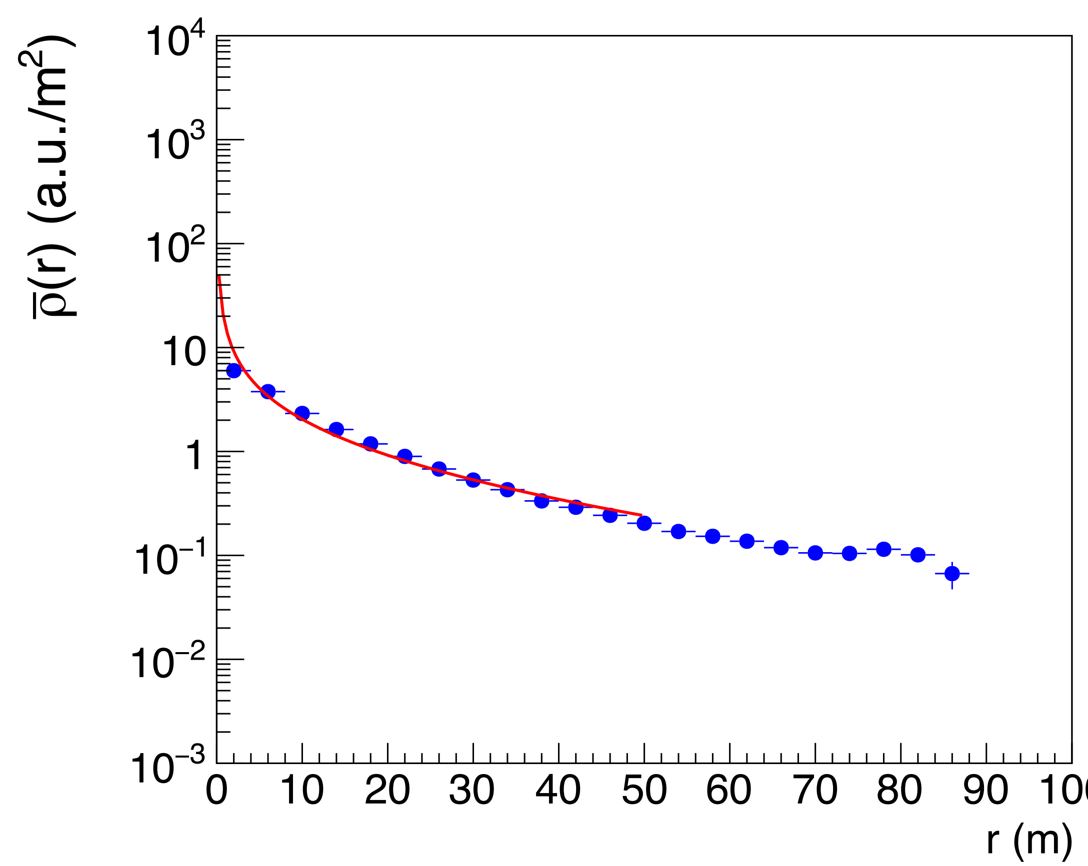
EAS reconstruction

Example of a MC vertical shower

Charge density at the RPC



Lateral charge density at RPC



Fit to the lateral charge density (**LD**) with a Nishimura-Kamara-Greisen function:

$$\rho(r) = A \cdot \left(\frac{r}{r_0}\right)^{s-2} \left(1 + \frac{r}{r_0}\right)^{s-3.5}$$

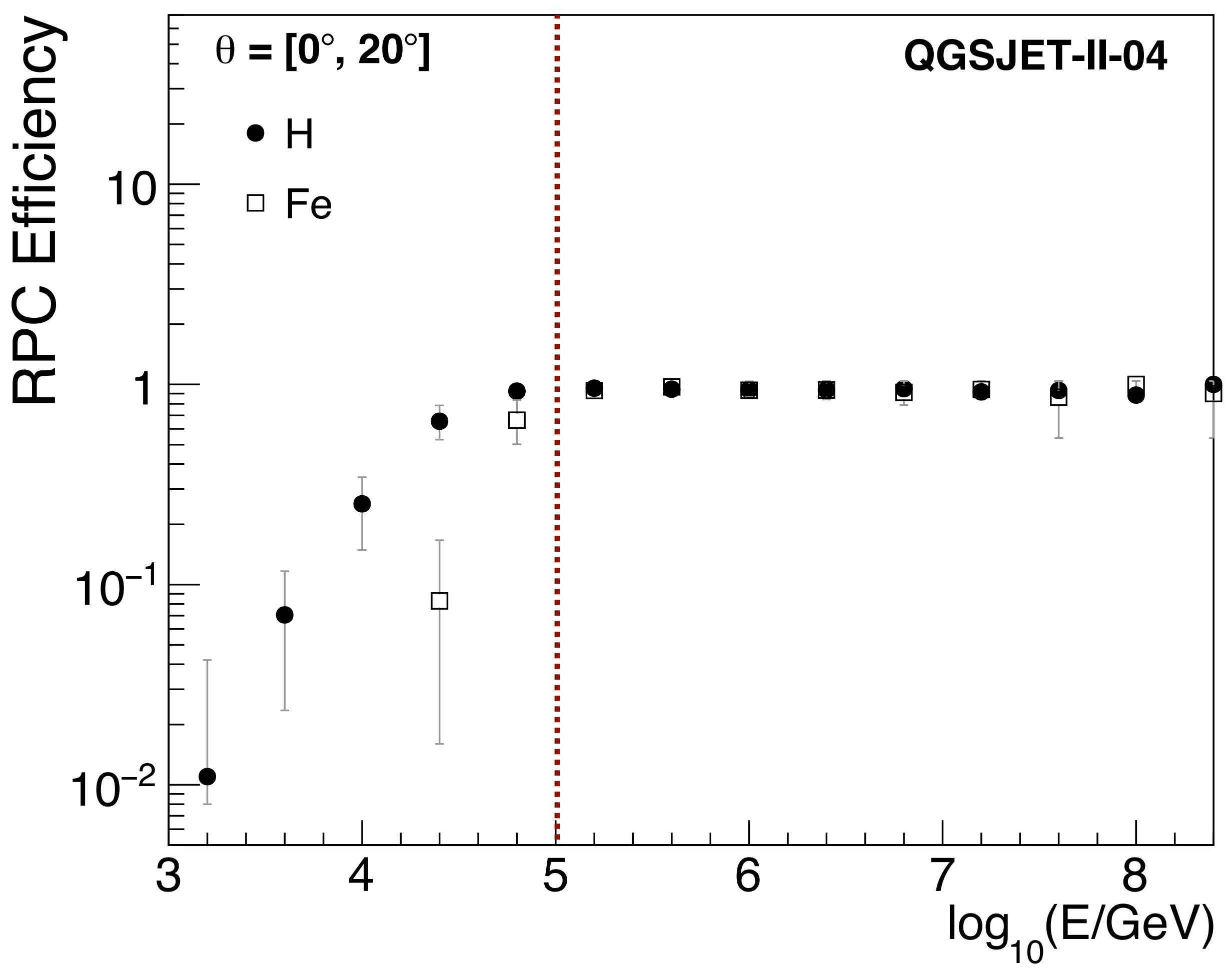
Shower age parameter (slope of distribution)
—> **Provides composition dependent parameter**

Amplitude of distribution
—> **Provides energy scale**

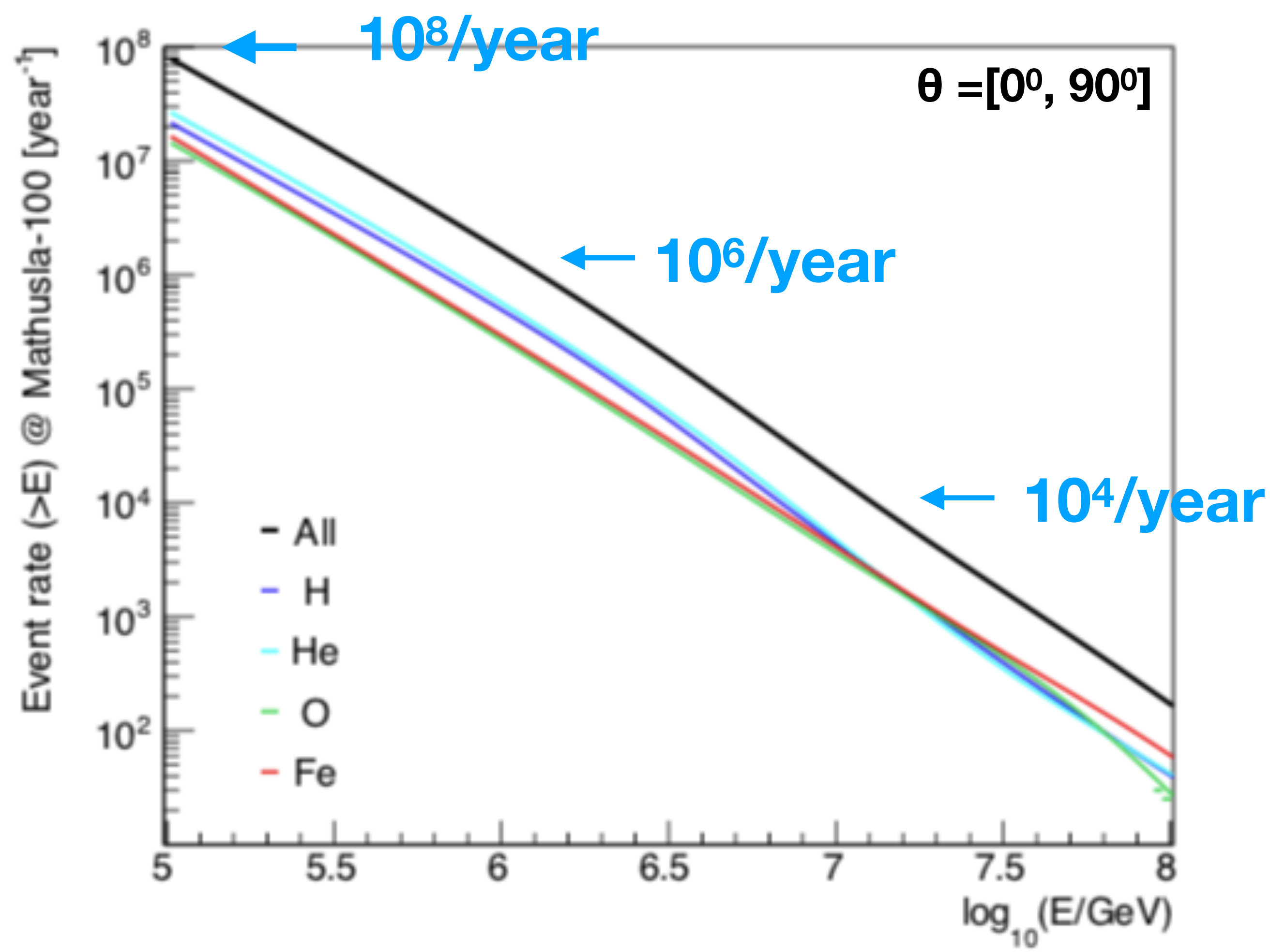
Results

Vertical data $\theta < 20^o$
$n_{hit} > 100$

Maximum trigger/reconstruction efficiency ($E > 10^{14}$ eV)

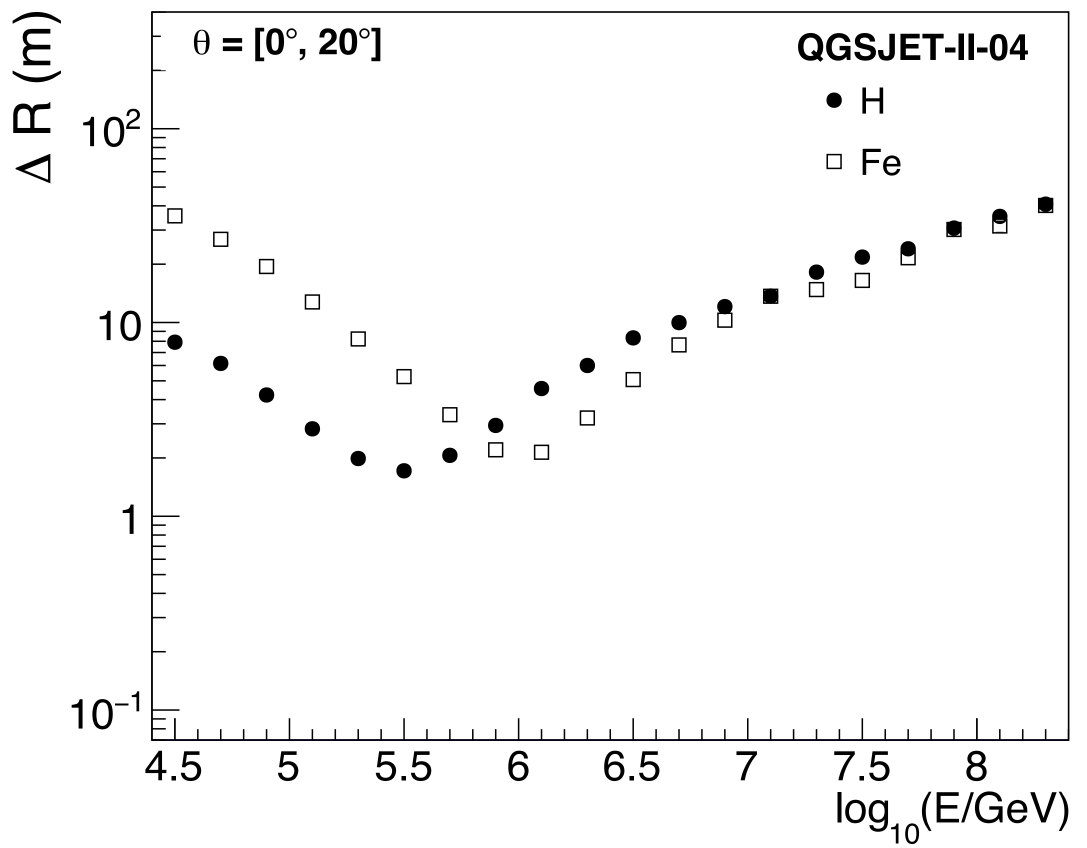


Expected EAS rate/year

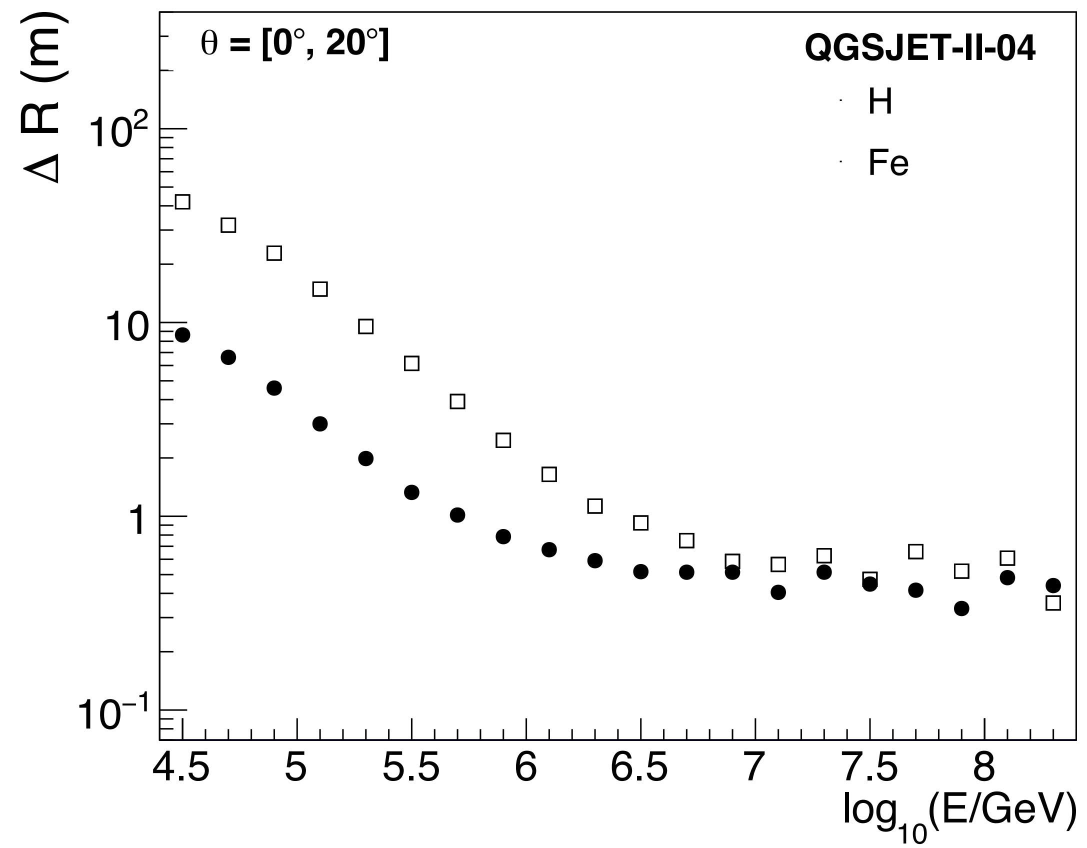


Results

Core resolution (68% confinement) at scintillator layer



Core resolution (68% confinement) at RPC

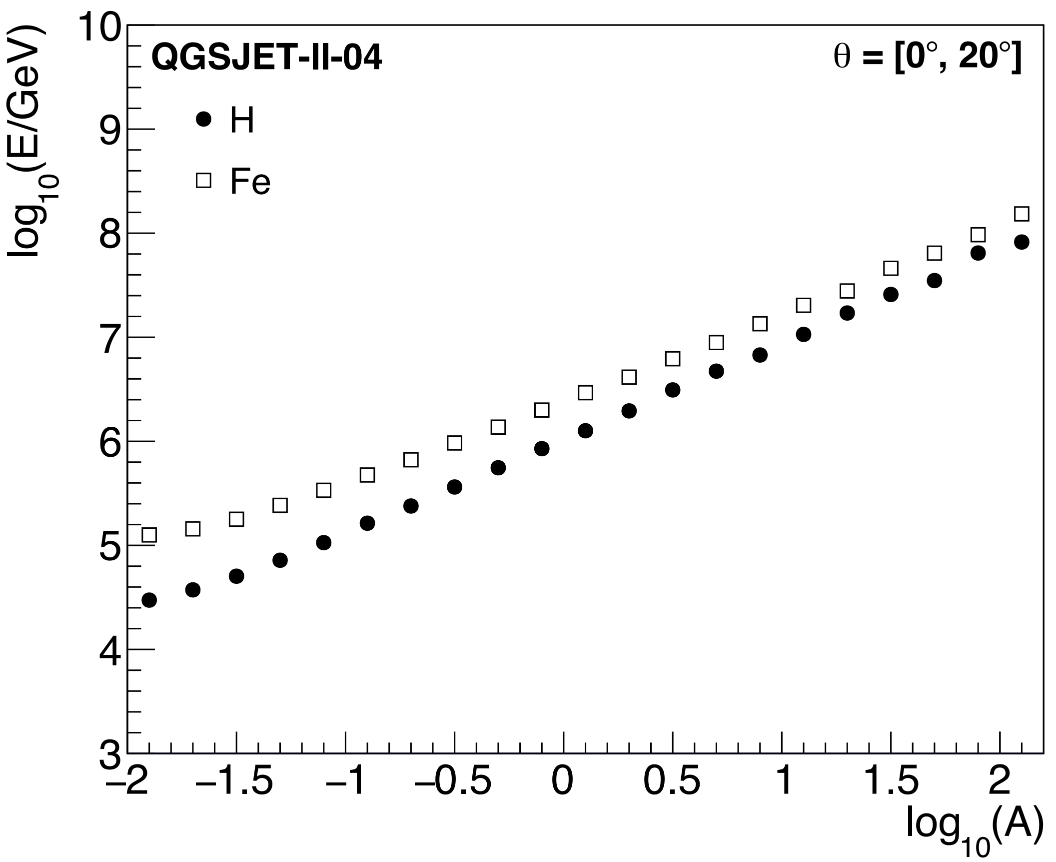


- Quality of **EAS reconstruction at the scintillator layers get worst for E > 10^{15} eV** due to loss of EAS confinement and saturation of the number of hit detector elements

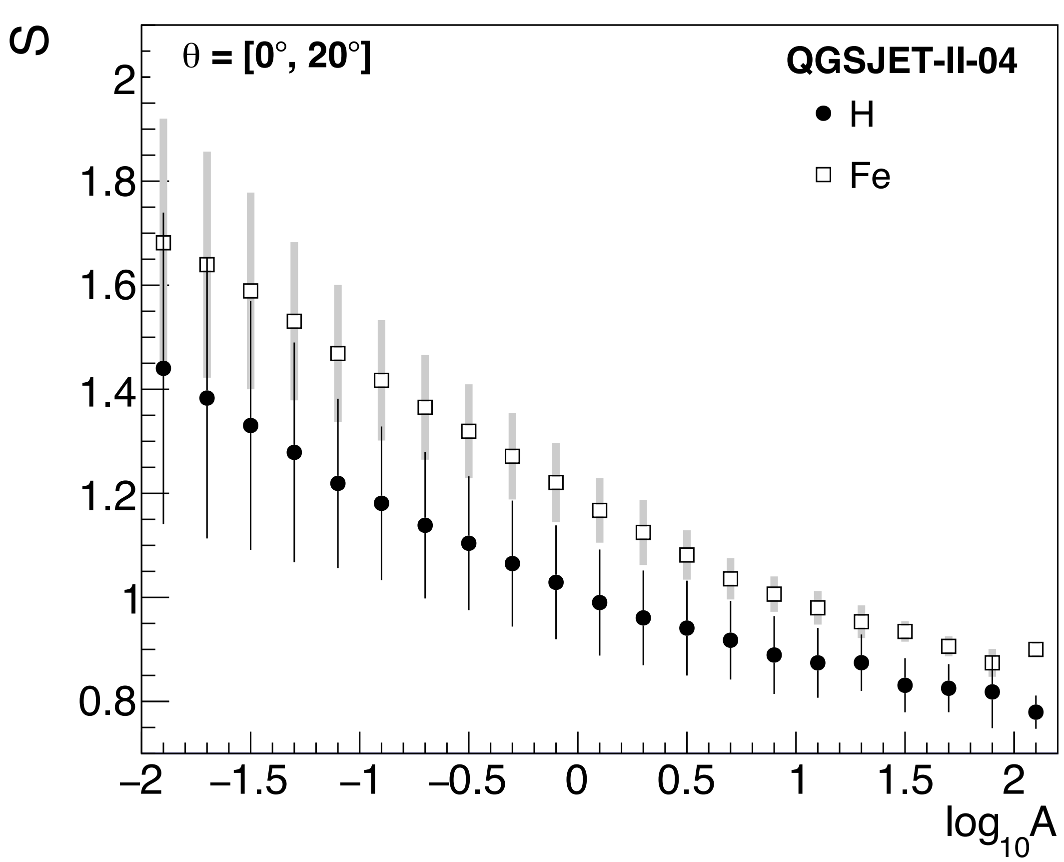
- For E > 10^{15} eV, improvement in core resolution with the RPC.

Results

Amplitude of lateral distribution (LD)



Shower age (slope of LD) vs amplitude



- In region of maximum efficiency linear dependence of logE with logA.

—> **It could provide energy scale**

- Shower age shows sensitivity to primary composition.

—> **Useful for composition studies**

- RPC allows to **extend CR** energy and composition **studies above E = 10^{15} eV.**

Results

Detailed view of the EAS morphology

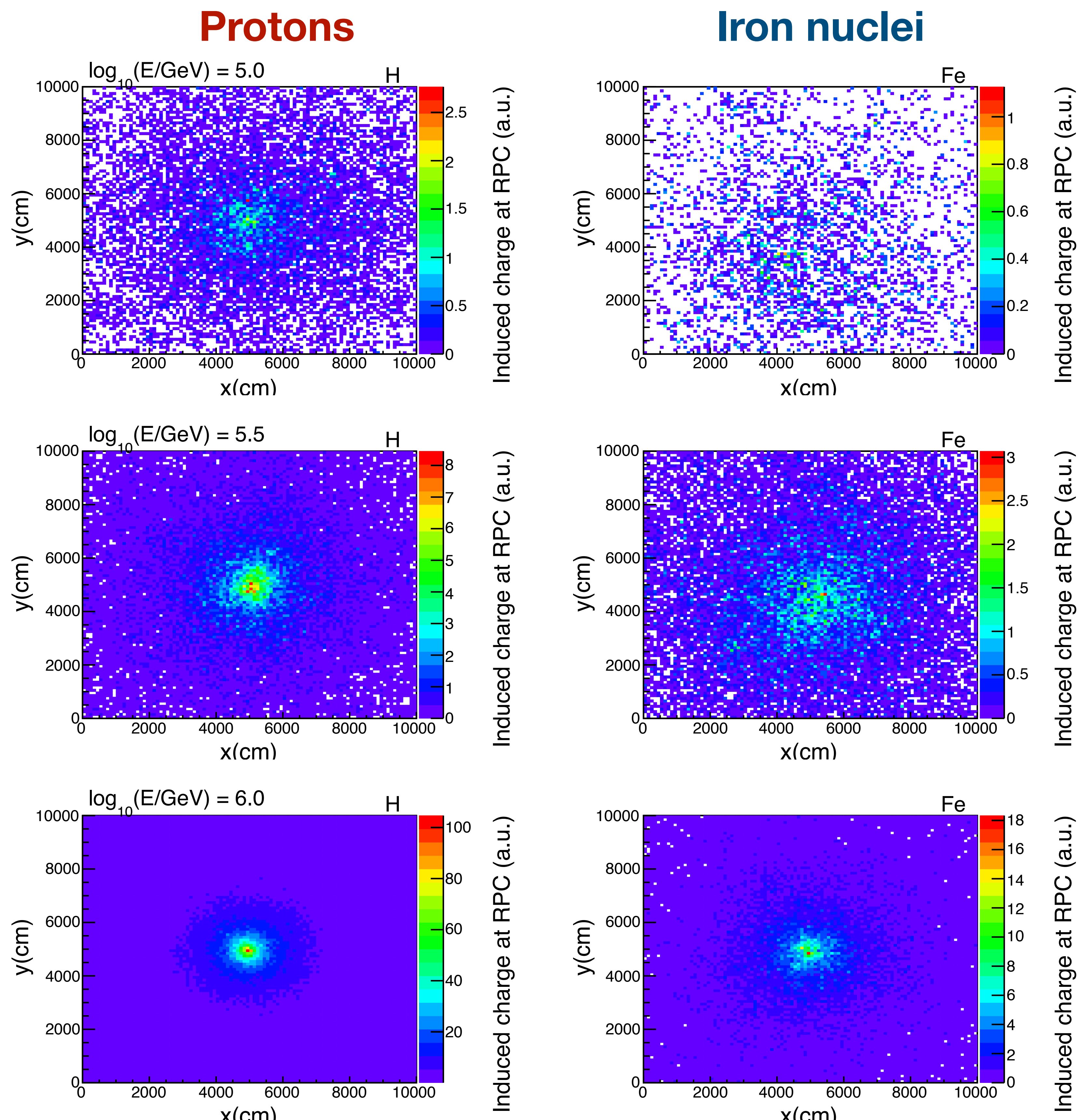
- Noticeable differences depending of the energy and mass:

  ❖ **HE's: Less fluctuations, larger amplitudes, sharper edges.**

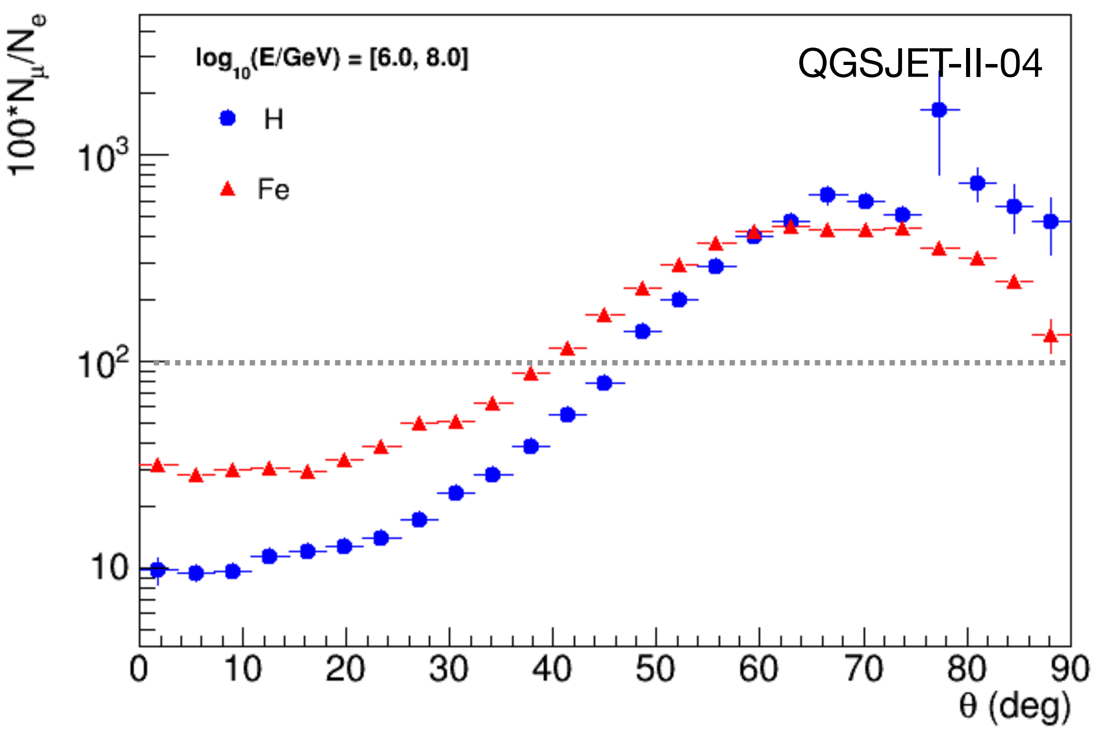
  ❖ **Light mass: More compact, less clumpy.**

-> Useful for energy and composition studies

- Position of EAS core is clearly seen at high energies.

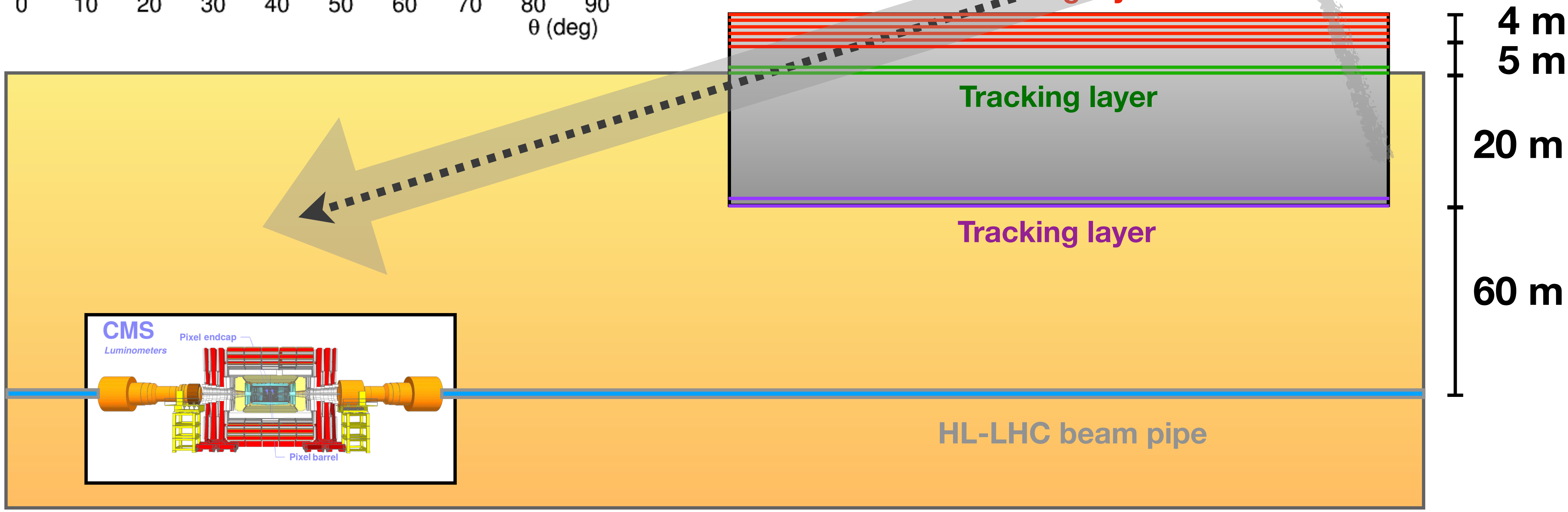


Inclined EAS in MATHUSLA



Study muon anomalies in EAS [WHISP Collab., arxiv: 2001.07508v1 [astro-ph.HE]]

Inclined EAS ($\theta > 50^o$): μ's are dominant, γ/e's are strongly absorbed in atmosphere

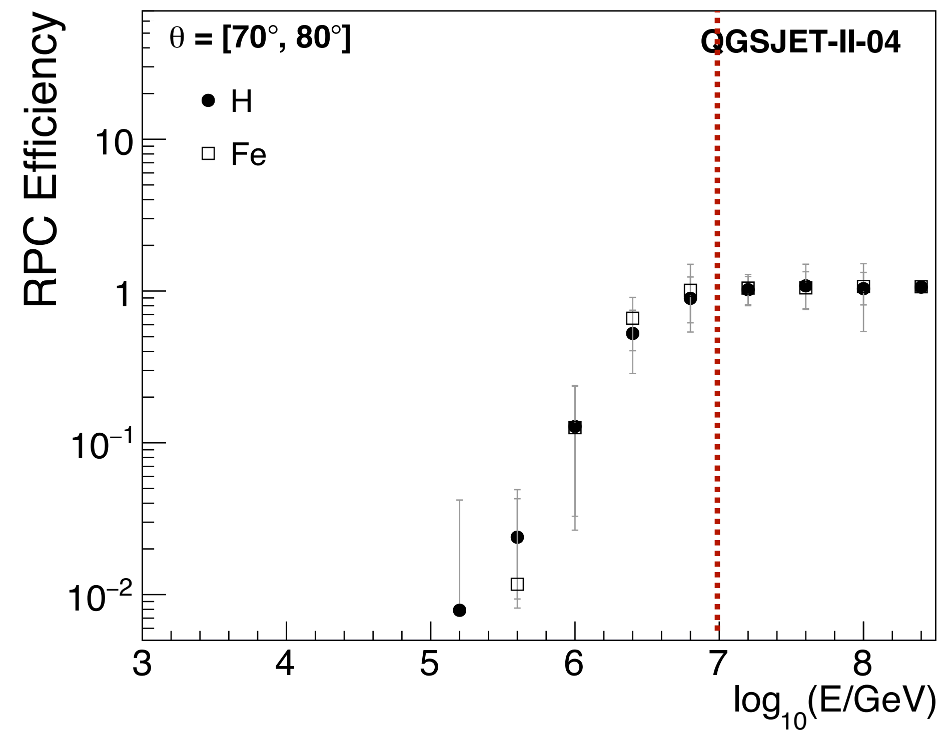


Inclined EAS in MATHUSLA

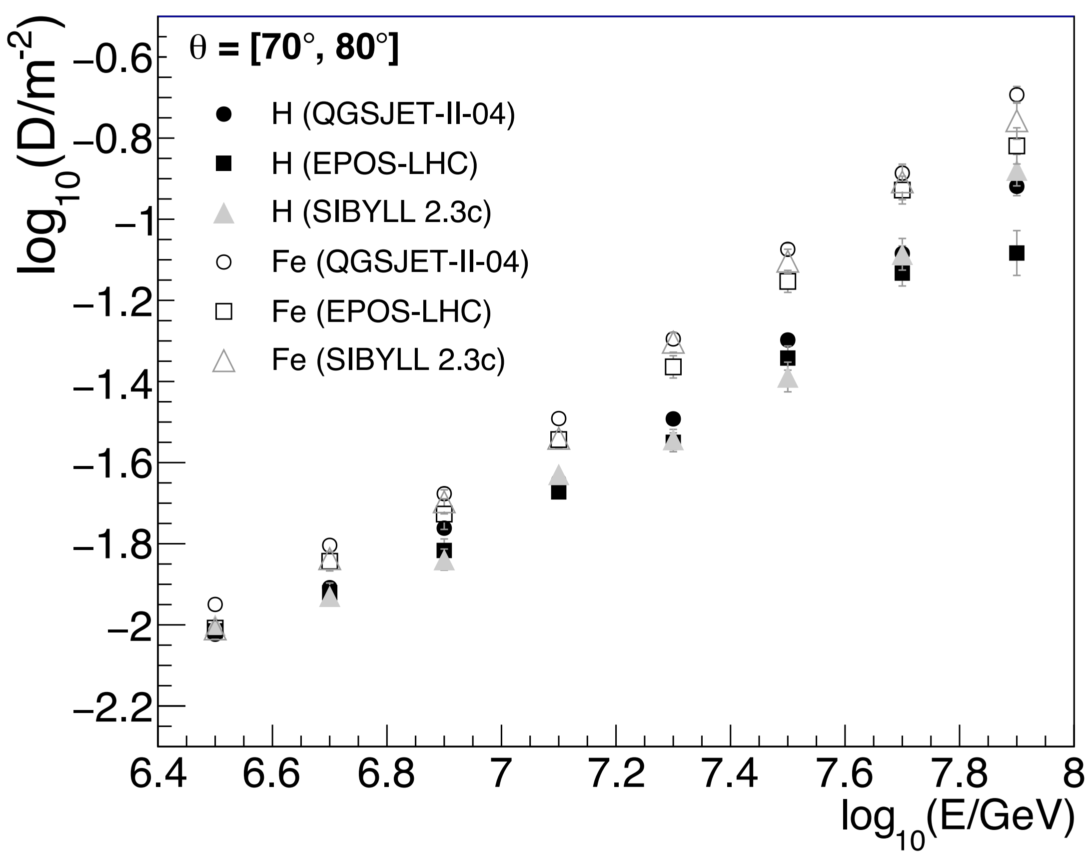
MATHUSLA

Inclined data θ = [70°, 80°]
n_{hit} > 50

Max trigger and reconstruction efficiency: E >10^{16} eV



Observed muons/detector area vs primary energy



Resolution for inclined EAS @ E = 10^{16} eV

Experiment	Core position	Pointing direction
MATHUSLA-100		
RPC	$\lesssim$ 36 m	$\lesssim 2^{o}$
Scintillator	$\lesssim$ 30 m	$\lesssim 2^{o}$

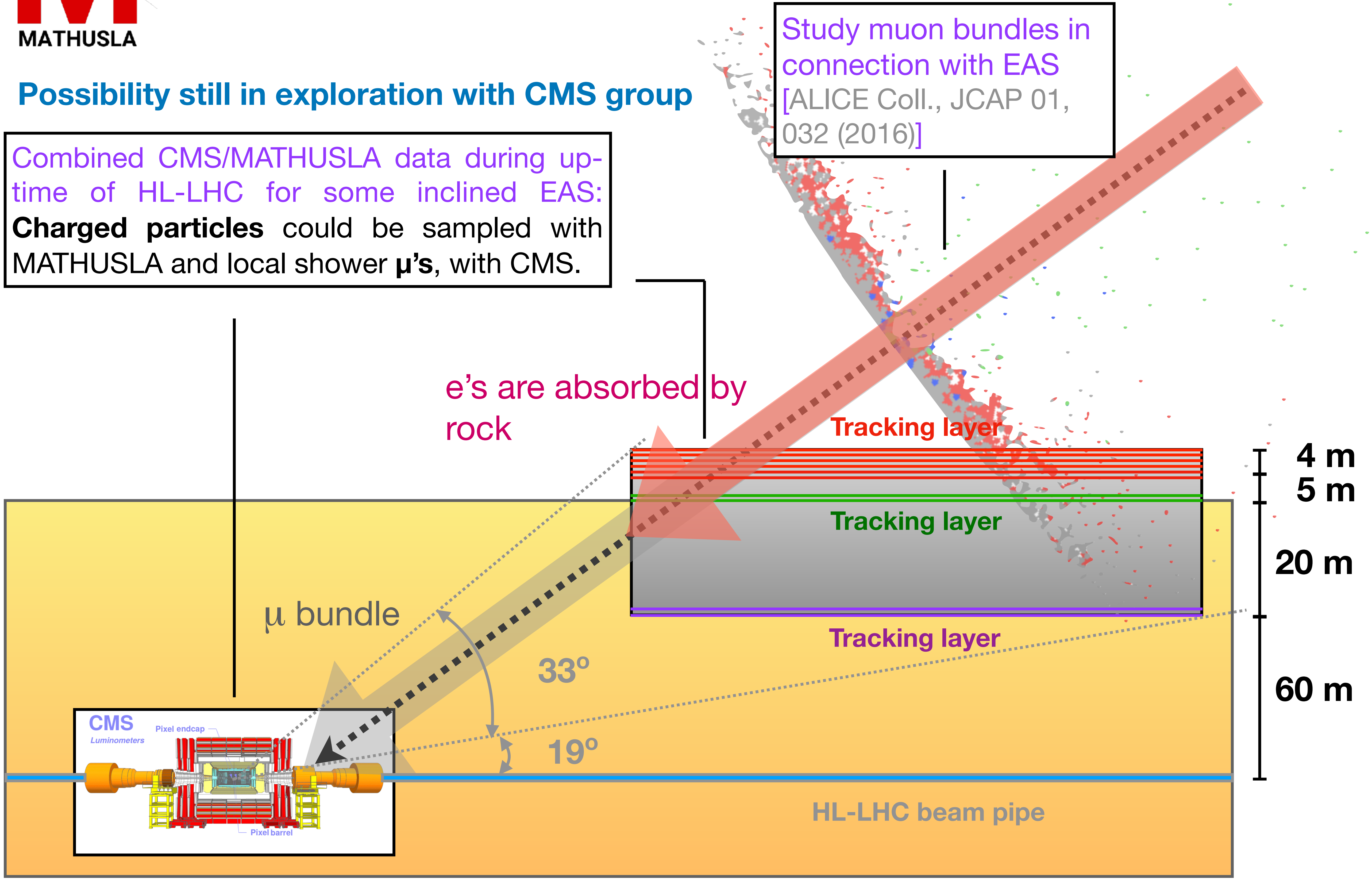
RPC: It is still important to measure particle density in detector elements with multiplicity hits > 1.

Scintillators: It can be used for arrival direction, core position, tracking.

Combined CMS/MATHUSLA events

Possibility still in exploration with CMS group

Combined CMS/MATHUSLA data during up-time of HL-LHC for some inclined EAS: **Charged particles** could be sampled with MATHUSLA and local shower **μ's**, with CMS.



Mathusla as a cosmic ray detector

- **MATHUSLA + RPC would have several advantages:**
  - Full coverage (81%). No other running CR detector has such capabilities.
  - Detail measurements of the temporal and spatial structure of the EAS.
  - Muon data from very inclined EAS at PeV energies.

Experiment	**Energy range (PeV)**	**Coverage (%)**	**Size (10^4 m^2)**
LHAASO			
e.m. array	$10^{-1} - 10^3$	0.52	100
ARGO-YBJ			
Central carpet	$0.003 - 3$	93	0.58
HAWC	$10^{-3} - 1$	57.1	2.2
ICETOP/ICECUBE			
Ice Cherenkov array	$0.25 - 10^3$	0.42	100
Telescope array			
e.m. array	$2 - 2 \times 10^3$	2.2×10^{-4}	7×10^4
MATHUSLA	$10^{-1} - 100$	81	1
KASCADE			
Central calorimeter	$1 - 100$	97.66	0.032

- **MATHUSLA Physics potential: E = [10^{14}, 10^{17} eV]**
  - 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.

Summary

1. MATHUSLA could complement the search for LLPs at the LHC during the next High Luminosity runs at CERN.

2. The detector could also work as a cosmic ray air shower observatory.

3. Enhancement of EAS detection capabilities at $E > 1$ PeV can be achieved by using an extra RPC detector layer.

4. 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**.

5. Paper in preparation with results on the performance of MATHUSLA for EAS detection.

Thank you!

Documents

1. John Paul Chou, David Curtin, H. J. Lubatti, New Detectors to Explore the Lifetime Frontier, Phys. Lets 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, NIMA 985, 164661 (2021).

6. Mathusla Collaboration, et al., Récent progress and next steps for the MATHUSLA LLP detector, arXiv:2203.08126 **[hep-ex]**.

7. TDR in progress.

- **Link to webpage:**

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