MATHUSLA

Cosmic ray physics at MATHUSLA

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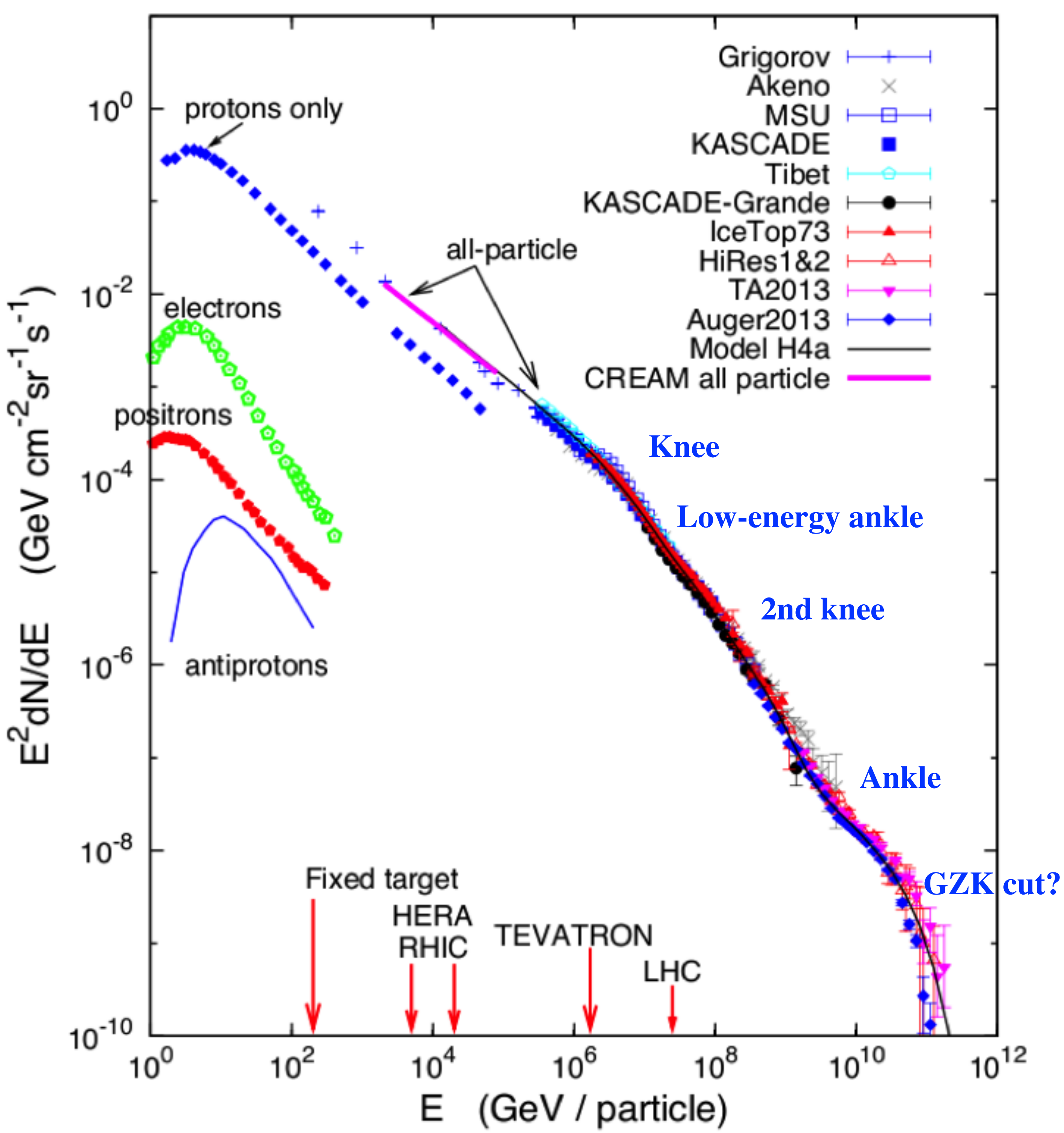
Searching for long-lived particles at the LHC and beyond: 9th workshop of the LLP community
May 25-28, 2021

Introduction

- 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** $F(E) = E^{-\gamma}$.
- **Origin:** Galactic (E < 10^{17} - 10^{18} eV)
  Extragalactic (E > 10^{18} eV).
- Open questions:
  - Origin or features in spectrum,
  - Distribution of sources,
  - Acceleration mechanism,
  - Propagation in space,
  - Energy, composition, etc.

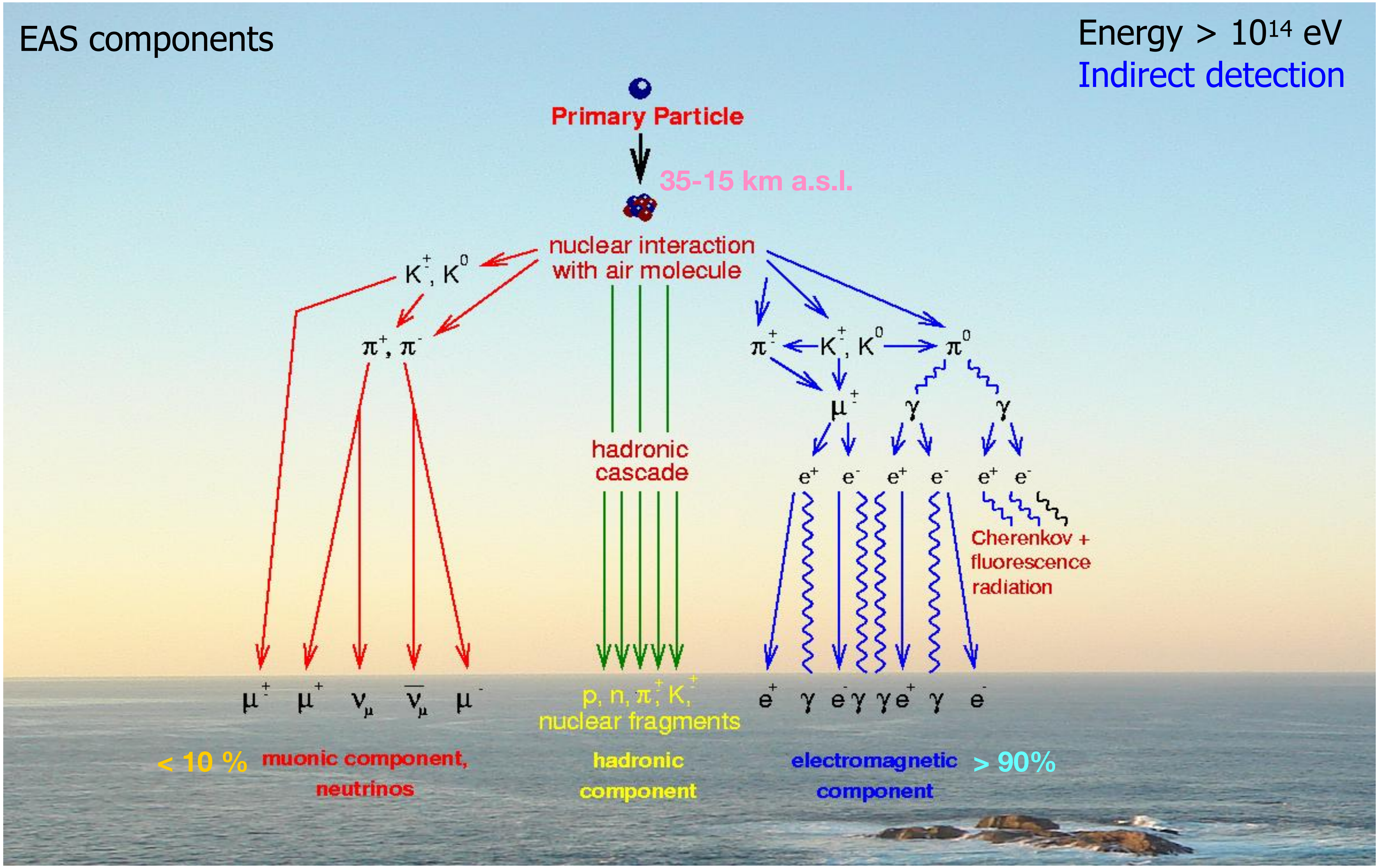
Energies and rates of the cosmic-ray particles



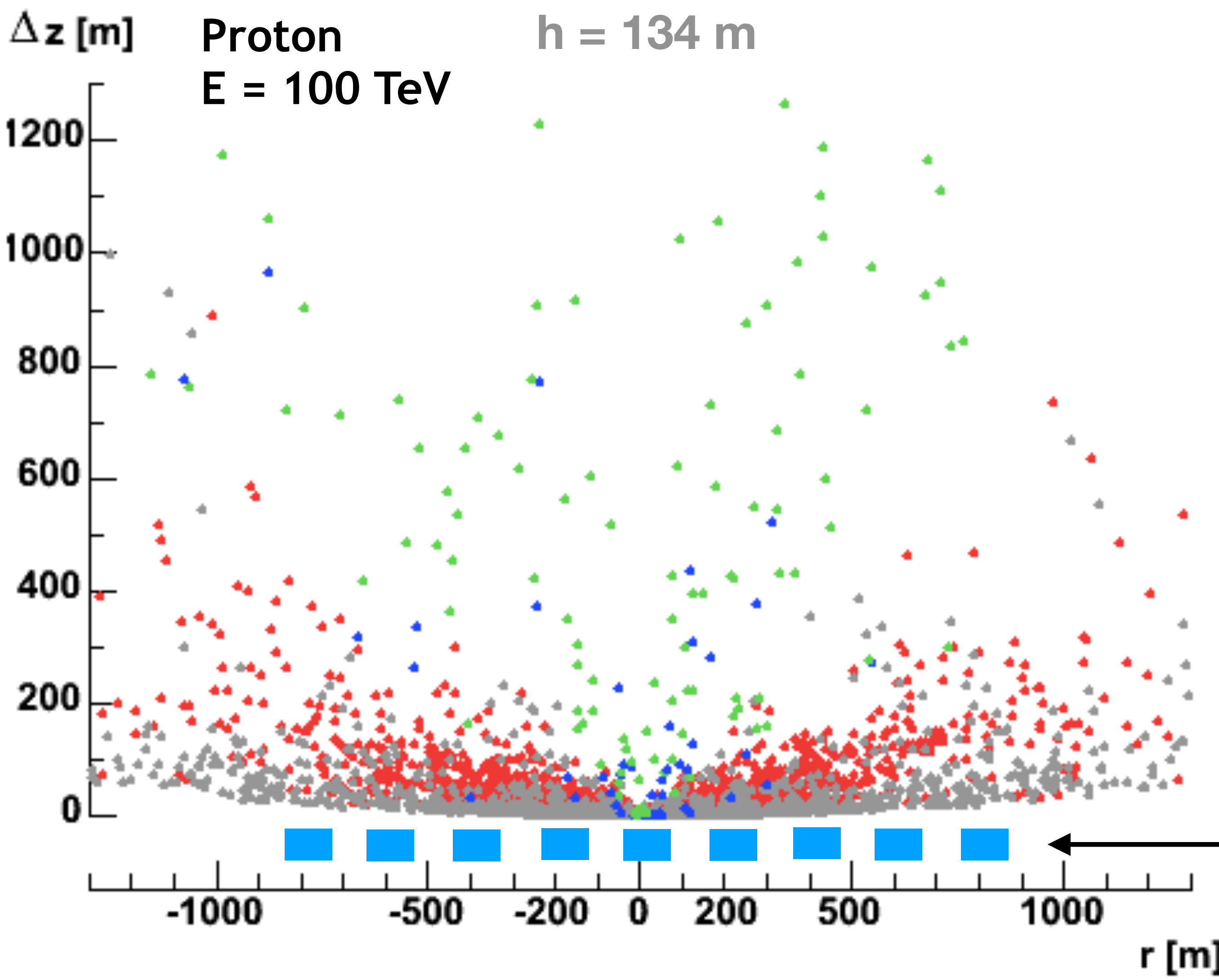
P. Blasi, Astron.Astrophys.Rev. 21 (2013) 70

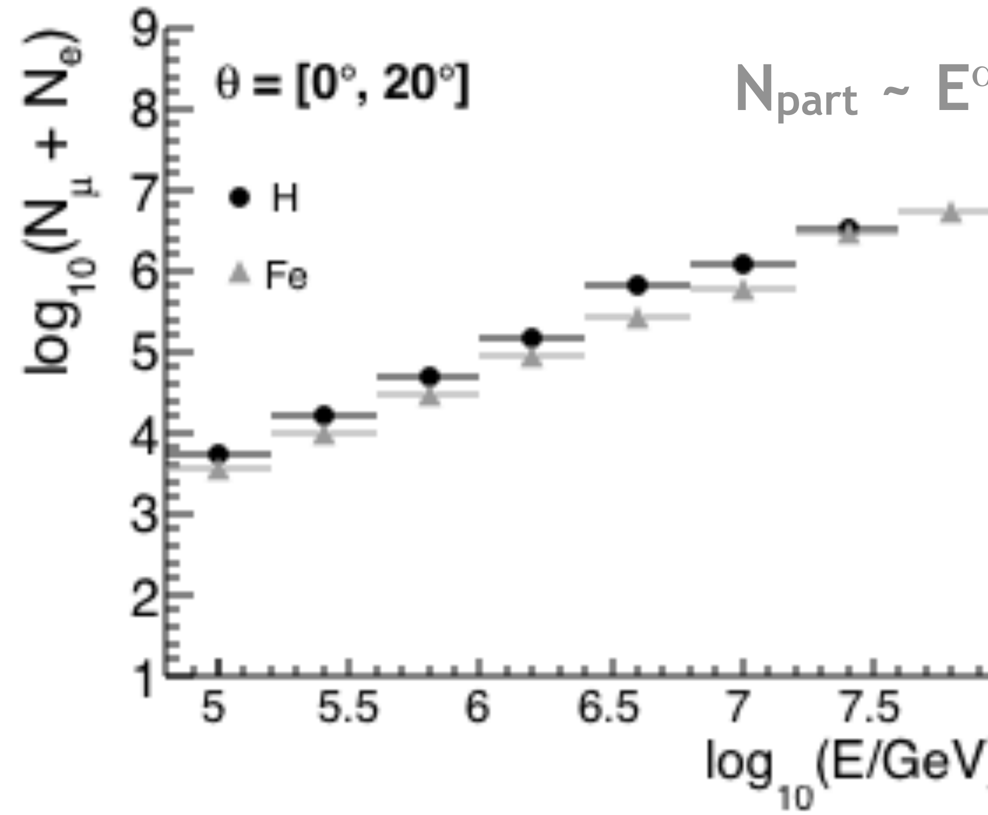
Detection

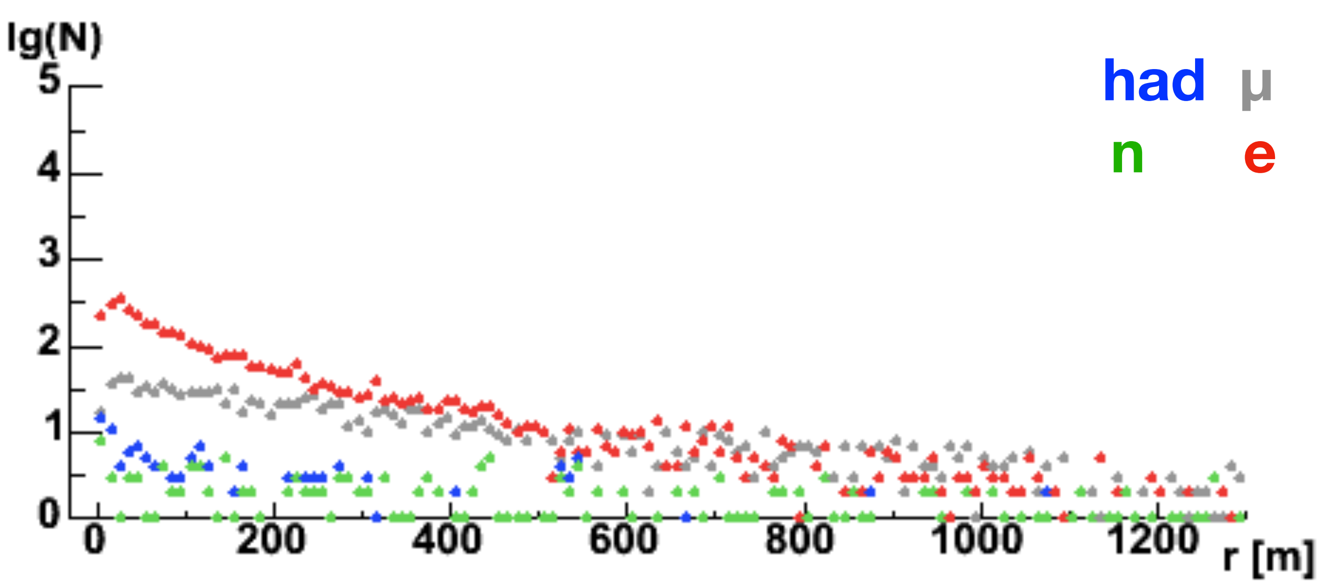
Indirect detection of cosmic rays through **extensive air showers** (EAS)



Detection







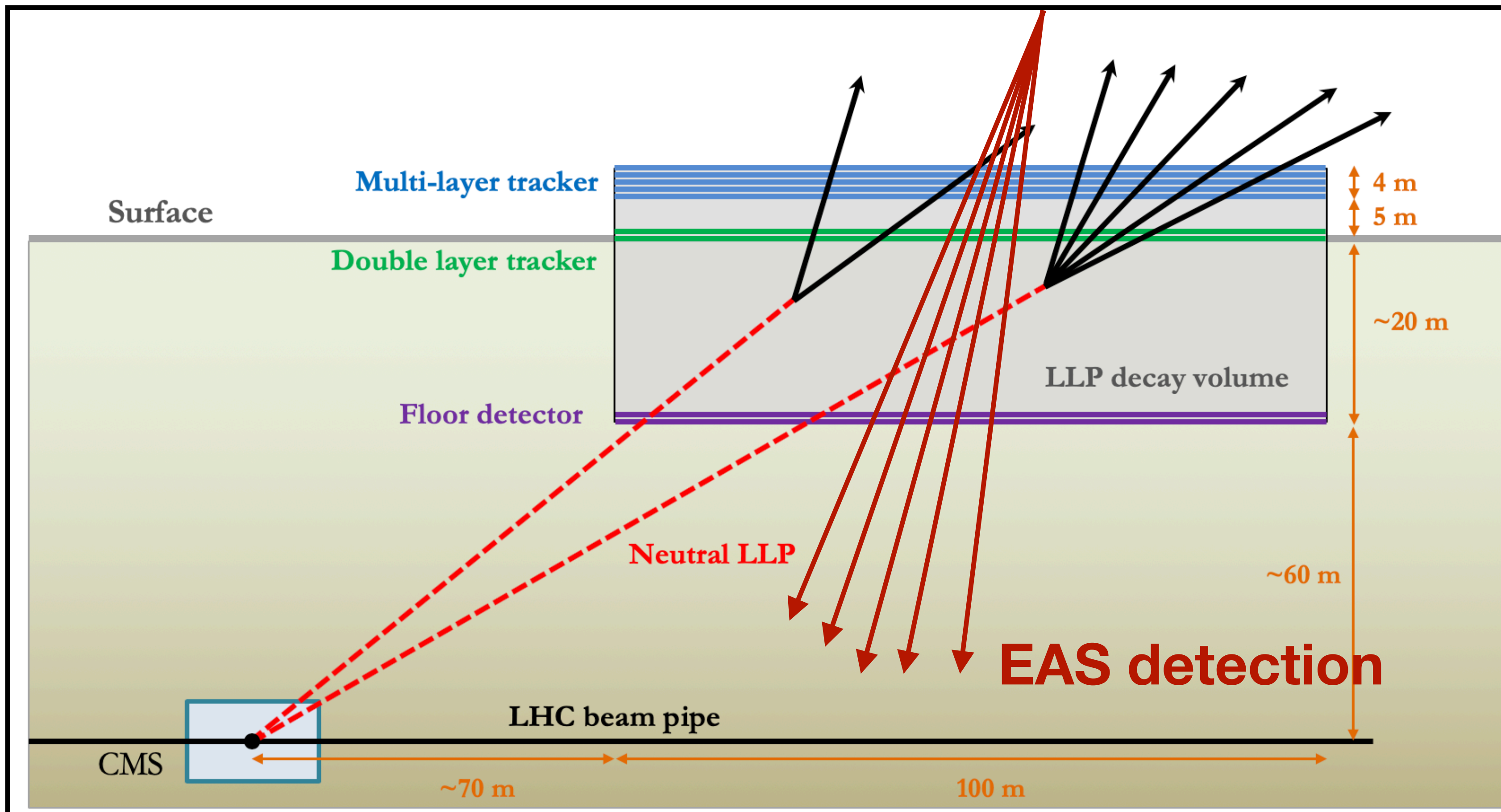
J. Oehlschlaeger, R. Engel, FZK

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

Mathusla proposal

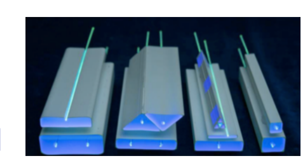
- To build a large area hodoscope detector to look for decay of LLPs in a volume of **100 m x 100 m x 25 m** of air.

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



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

- Scintillator bars:



  - 4.6 m x 4.5 cm x 2 cm
  - From one layer to the other, long dimension of the bar is rotated 90^0.

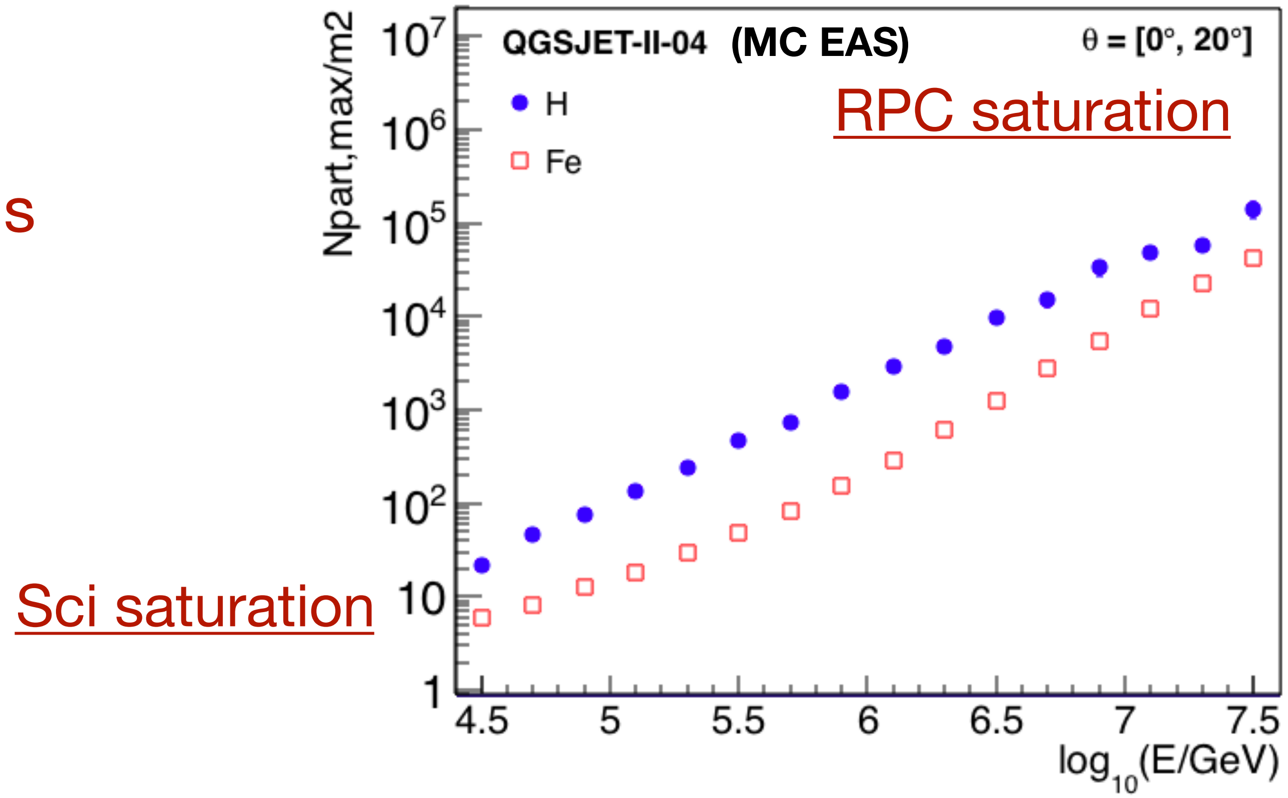
Mathusla proposal

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

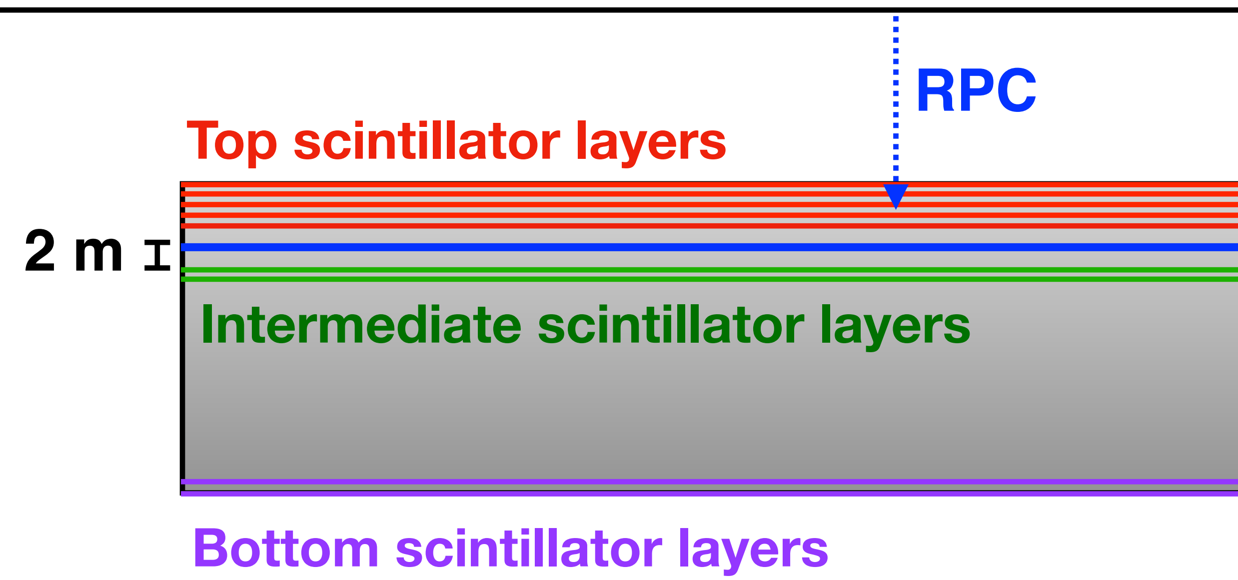
- Saturation of detector elements

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

- RPC data:
  - Detail spatial-time distributions of charged particles



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



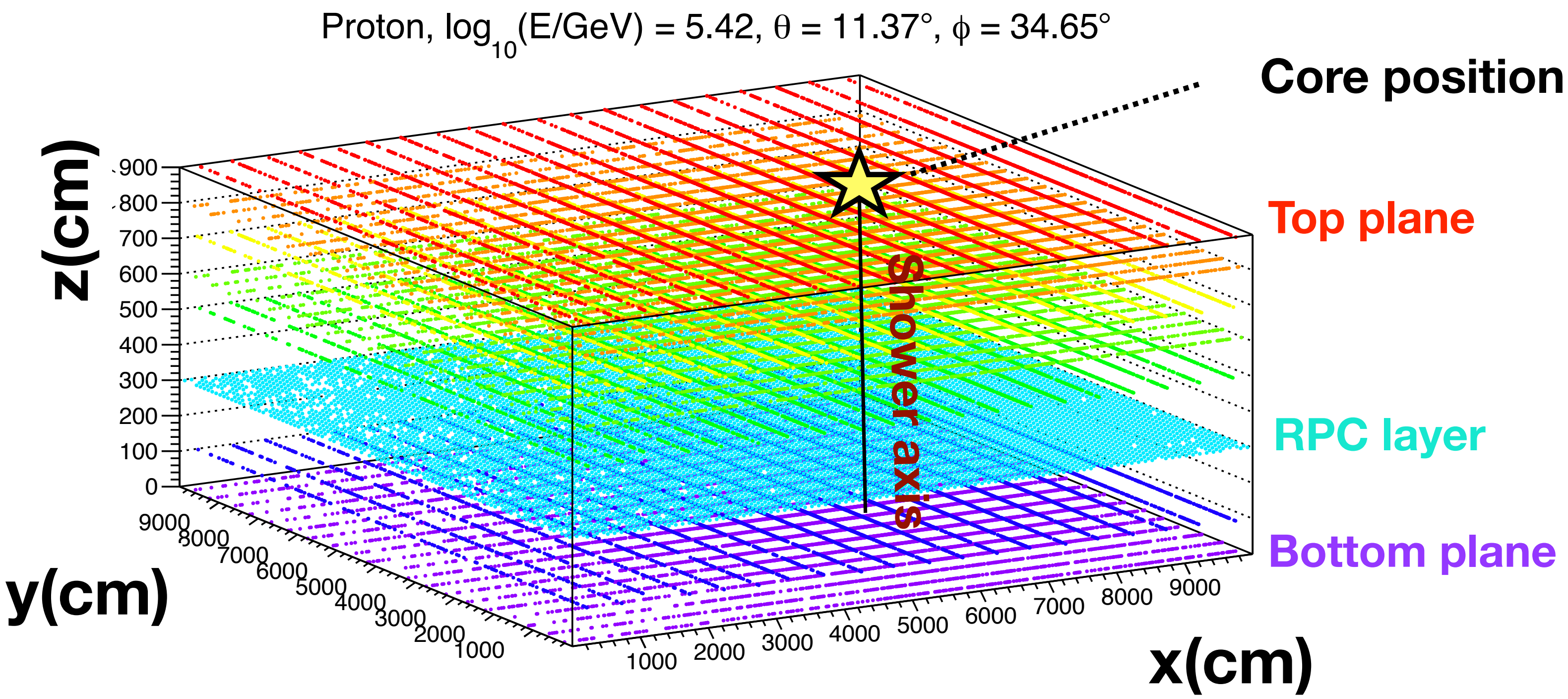
Simulations

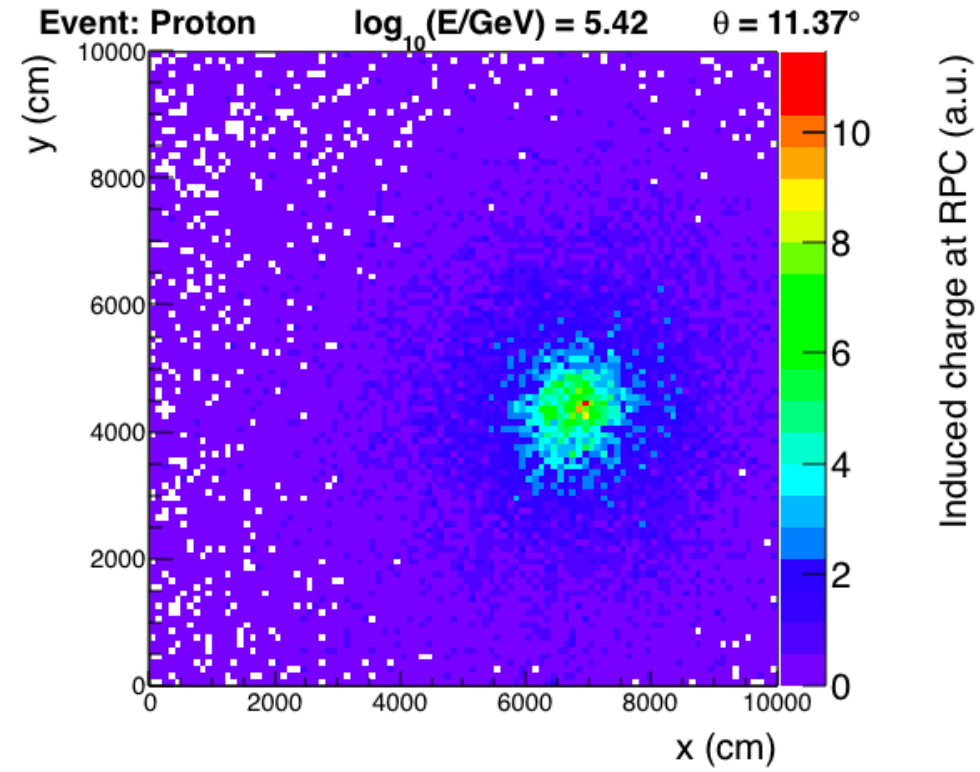
- **CORSIKA 7.64** is used to simulate creation and development of **EAS** in atmosphere.
  - 2.2 x 10^5 simulations
  - Hadronic interaction models: FLUKA (E_h < 200 GeV)/ QGSJET-II-04
  - H, Fe primaries
  - Spectrum: E^{-2}
  - Zenith angles: 0°- 20°, 70° - 80°
  - Curved atmosphere
  - Magnetic field 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
    * 4 cm x 5 m scintillator bars
  - Big Pads: 1 m x 1 m

EAS reconstruction

Example of a MC vertical shower



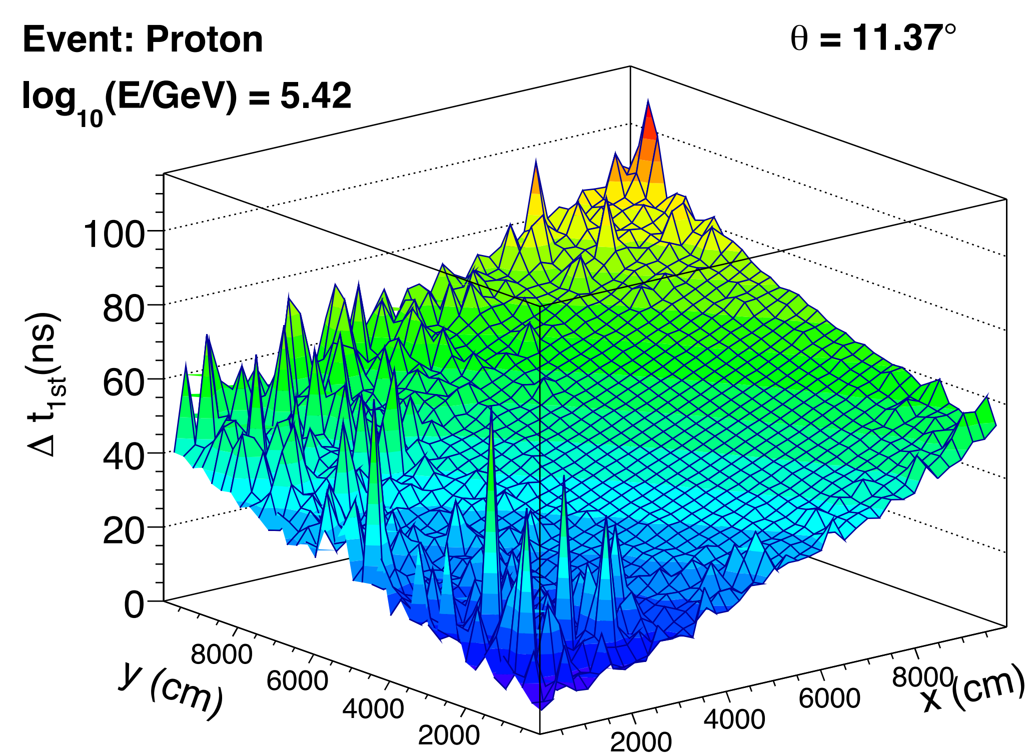


- EAS reconstruction:
  - **Core** from **exponential fit** to X (Y) projected hit bars/induced charge

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

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

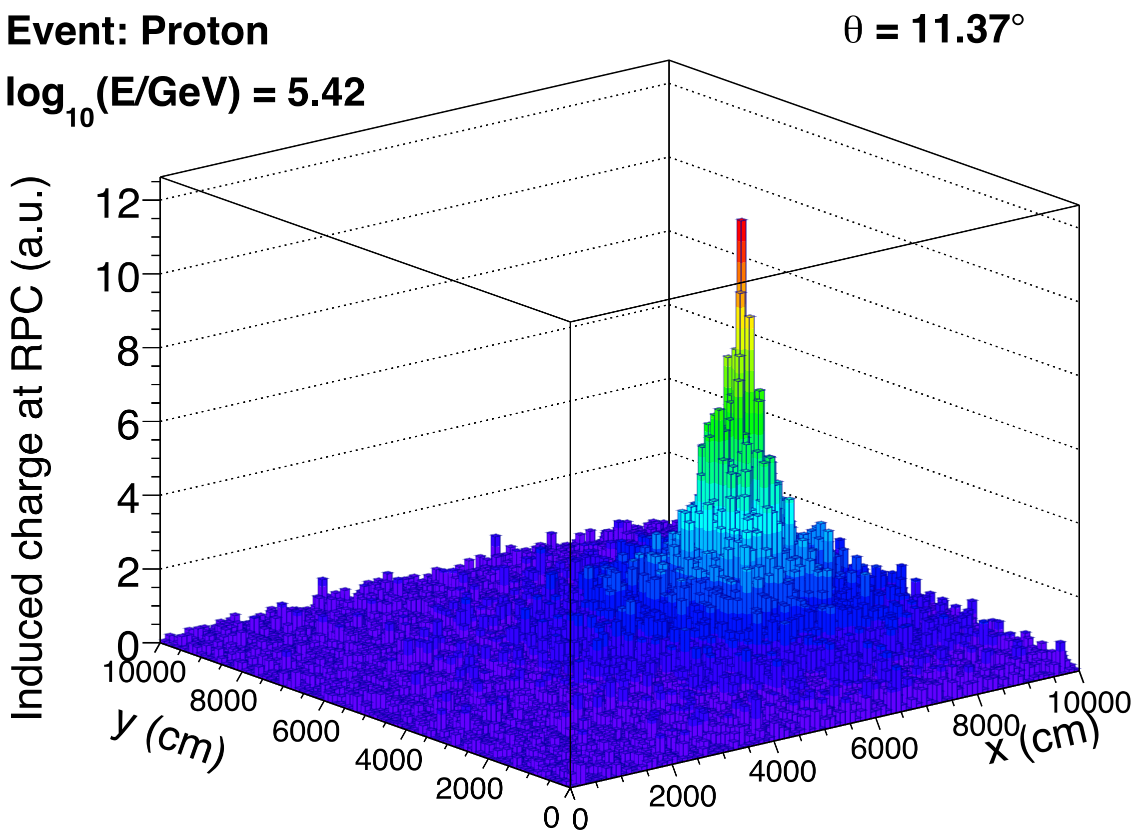
$$a_1 \cdot x_i + a_2 \cdot y_i + a_3 = ct_{1st,i}$$



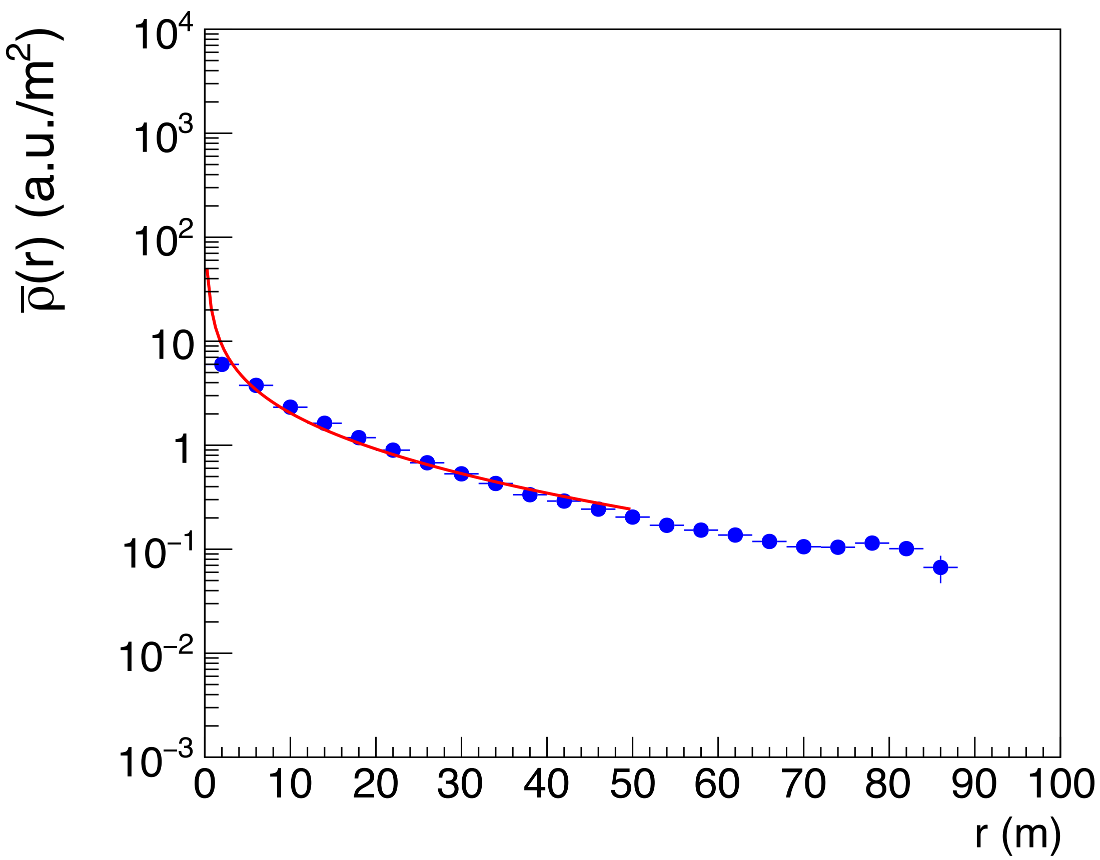
EAS reconstruction

Example of a MC vertical shower

Charge density at the RPC



Lateral charge density at RPC



Fit to the lateral charge density with a Nishimura-Kamara-Greisen function:

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

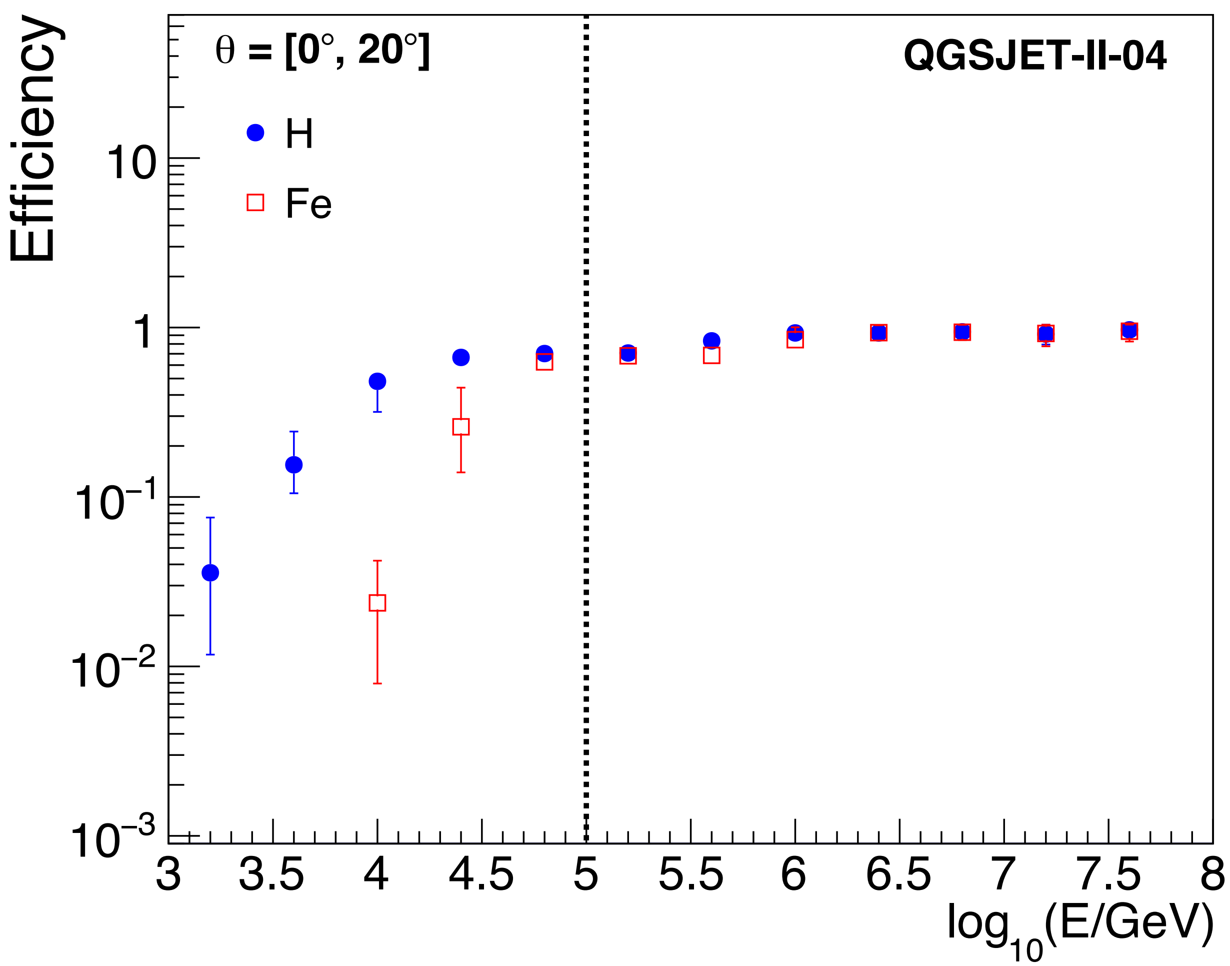
Shower age parameter (slope of distribution)
—> **Provides composition dependent parameter**

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

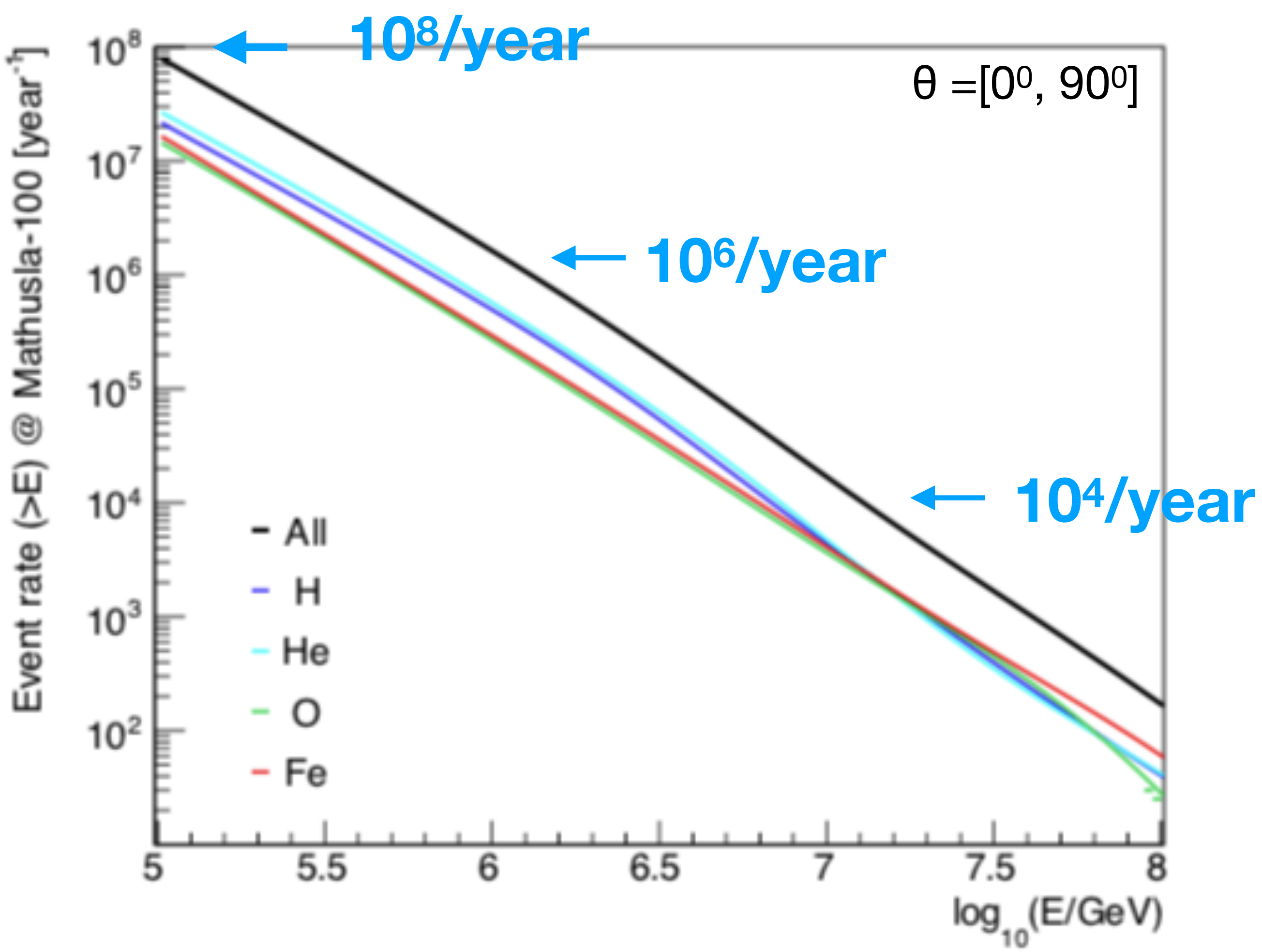
Results

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

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

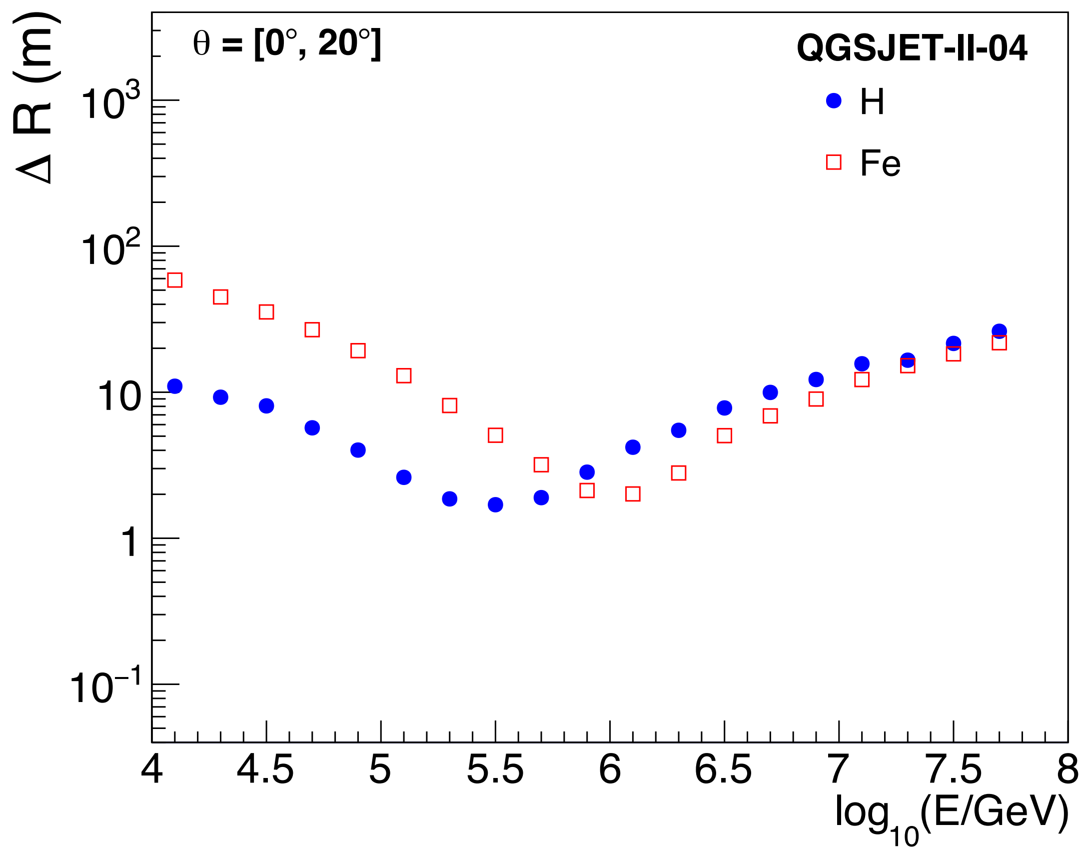


Expected EAS rate/year

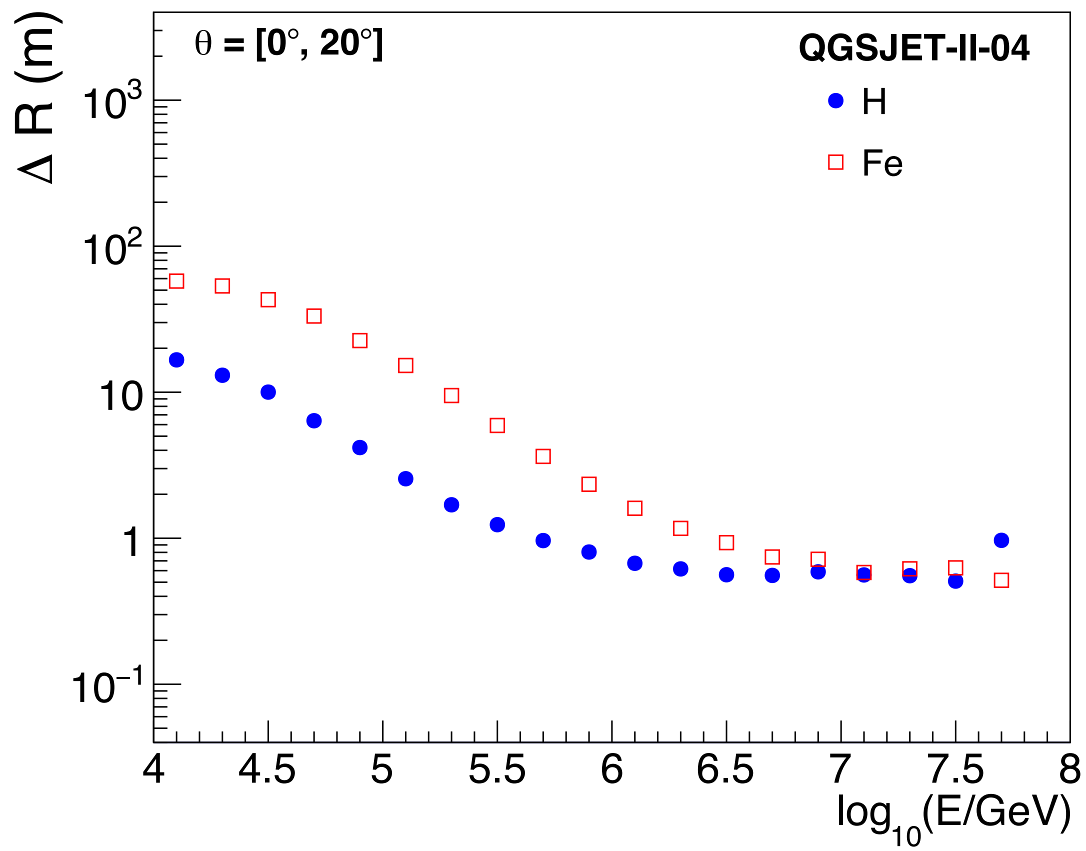


Results

Core resolution (68% confinement) at scintillator layer



Core resolution (68% confinement) at RPC

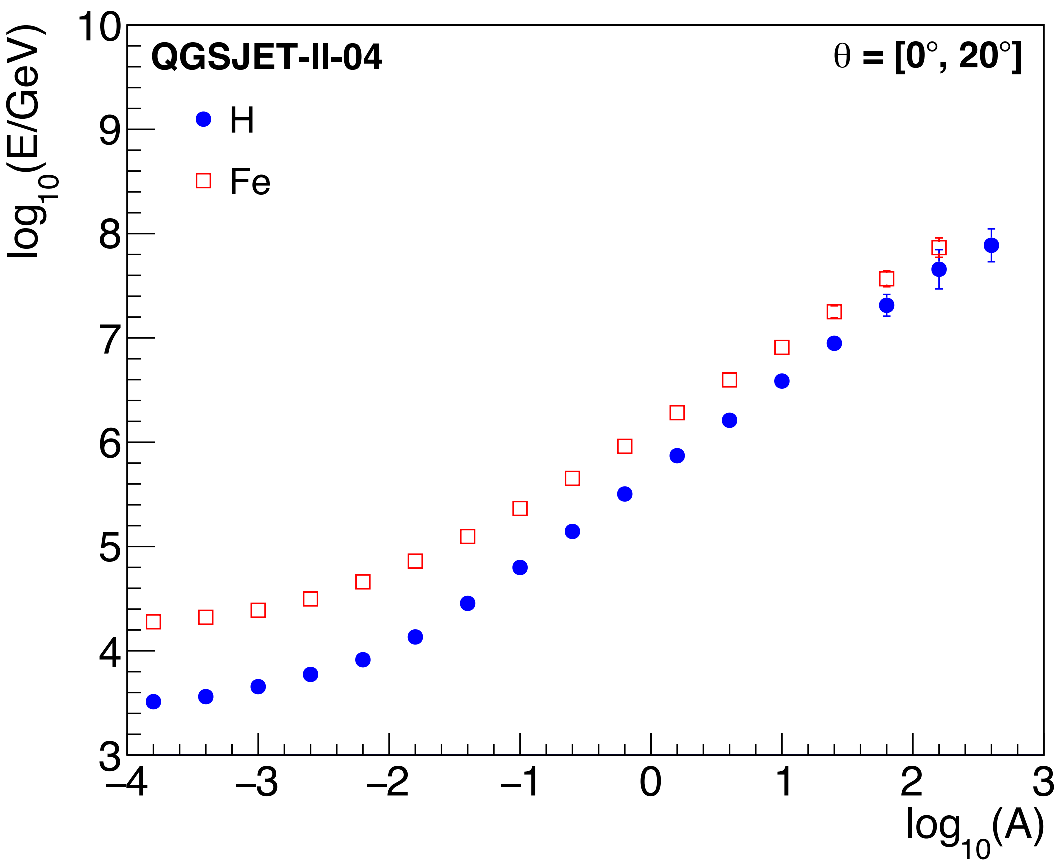


- Quality of **EAS reconstruction at the scintillator layers get worst for E > 10^{15} eV** due to loss of EAS confinement and saturation of the number of hit detector elements

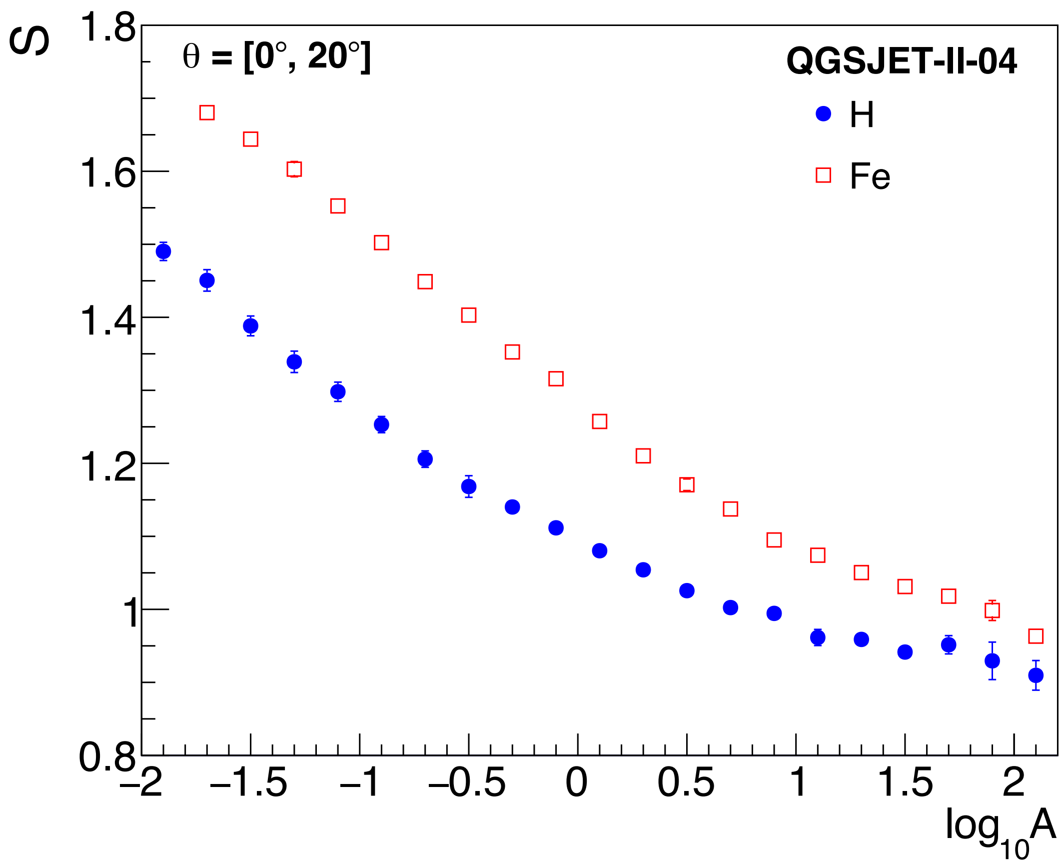
- For E > 10^{15} eV, improvement in core resolution with the RPC.

Results

Amplitude of lateral distribution (LD)



Shower age (slope of LD) vs amplitude



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

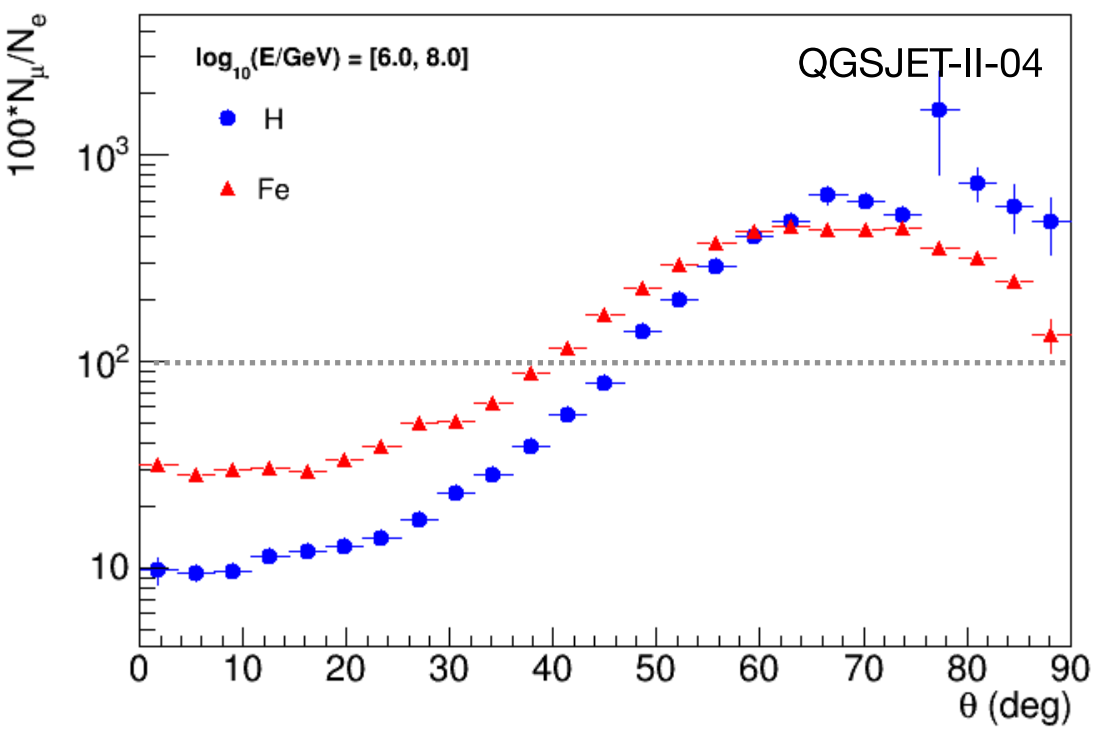
—> **It could provide energy scale**

- Shower age shows sensitivity to primary composition.

—> **Useful for composition studies**

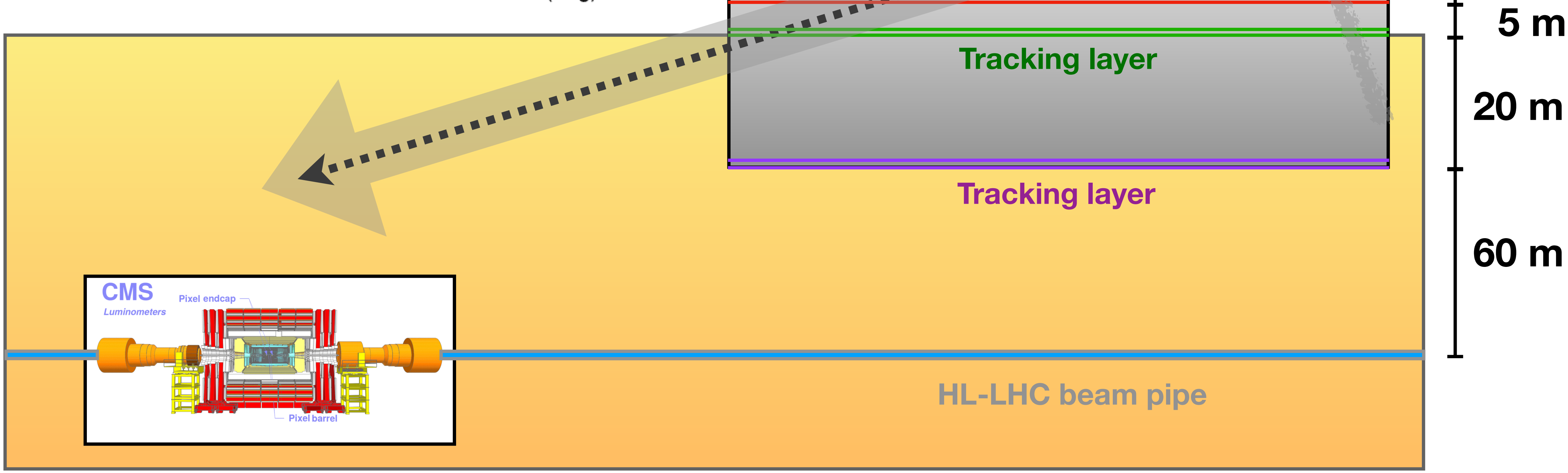
- RPC allows to **extend CR** energy and composition **studies above E = 10^{15} eV.**

Inclined EAS in MATHUSLA



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

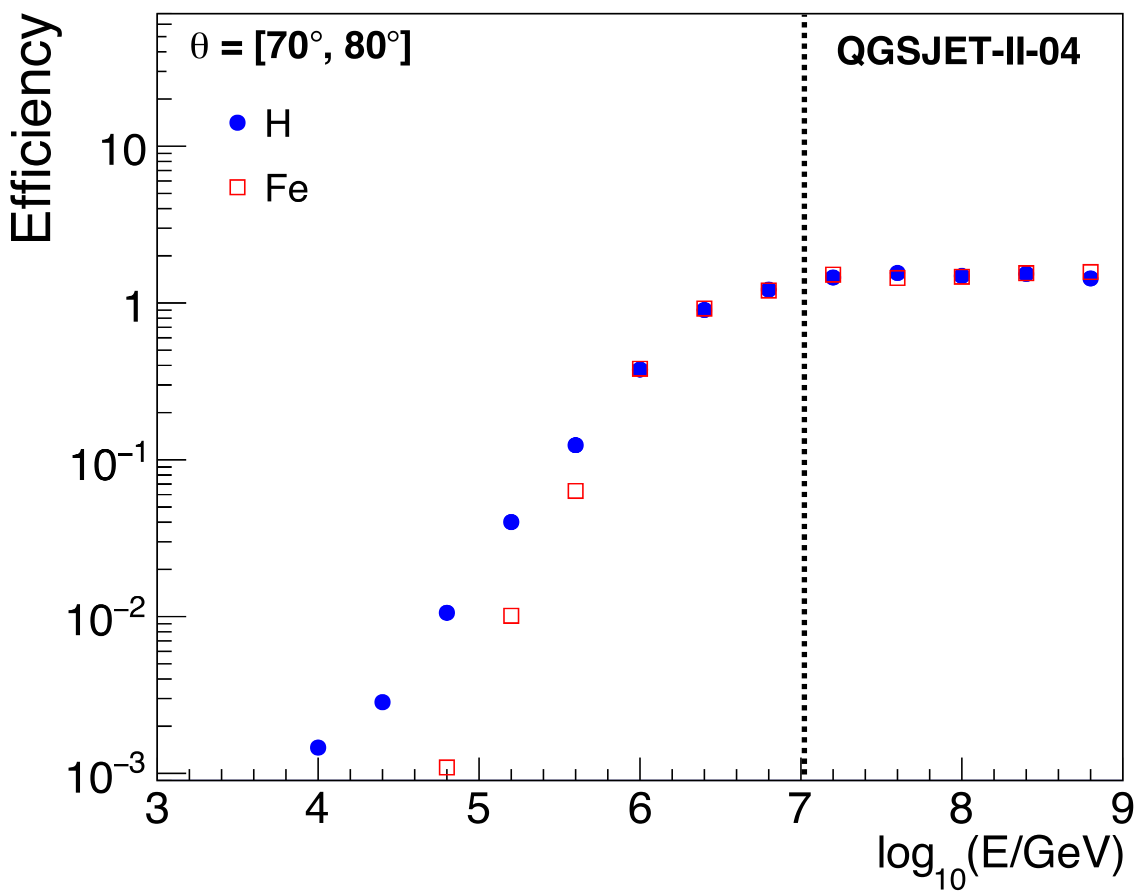
Inclined EAS (θ > 50°): μ's are dominant, γ/e's are strongly absorbed in atmosphere



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

Inclined EAS in MATHUSLA

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



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

Experiment	Core position	Pointing direction
MATHUSLA-100		
RPC	$\lesssim 50\,\mathrm{m}$	$\lesssim 4^\circ$
Scintillator	$\lesssim 25\,\mathrm{m}$	$\lesssim 2^\circ$

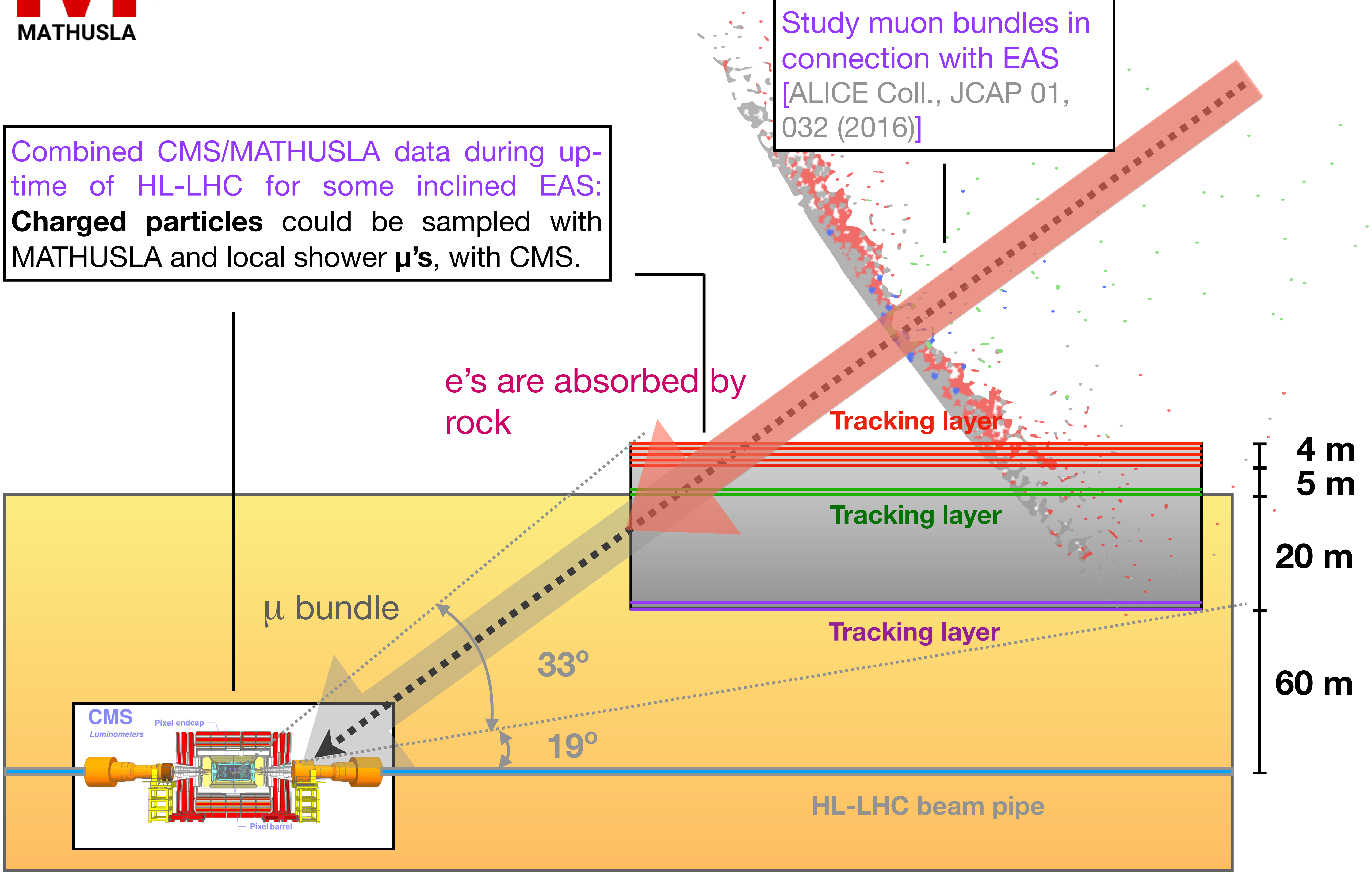
RPC: It is still important to measure particle density in detector elements with multiplicity hits > 1.

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

Combined CMS/MATHUSLA events

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.

Study muon bundles in connection with EAS [ALICE Coll., JCAP 01, 032 (2016)]



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	$10^{-3} - 10^3$	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. Target Journal: Journal of Cosmology and Astrophysics.

Thank you!