Study of the potencial of MATHUSLA as cosmic ray detector

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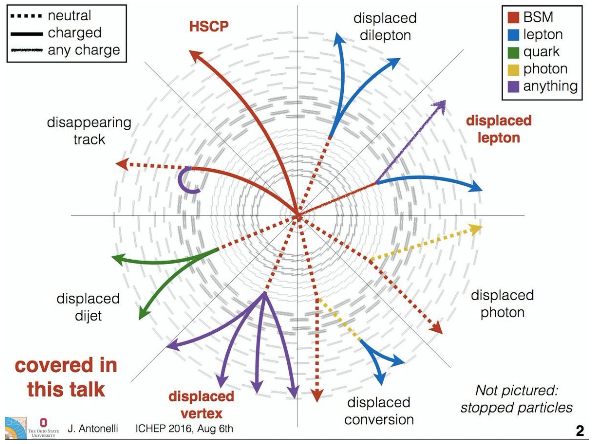
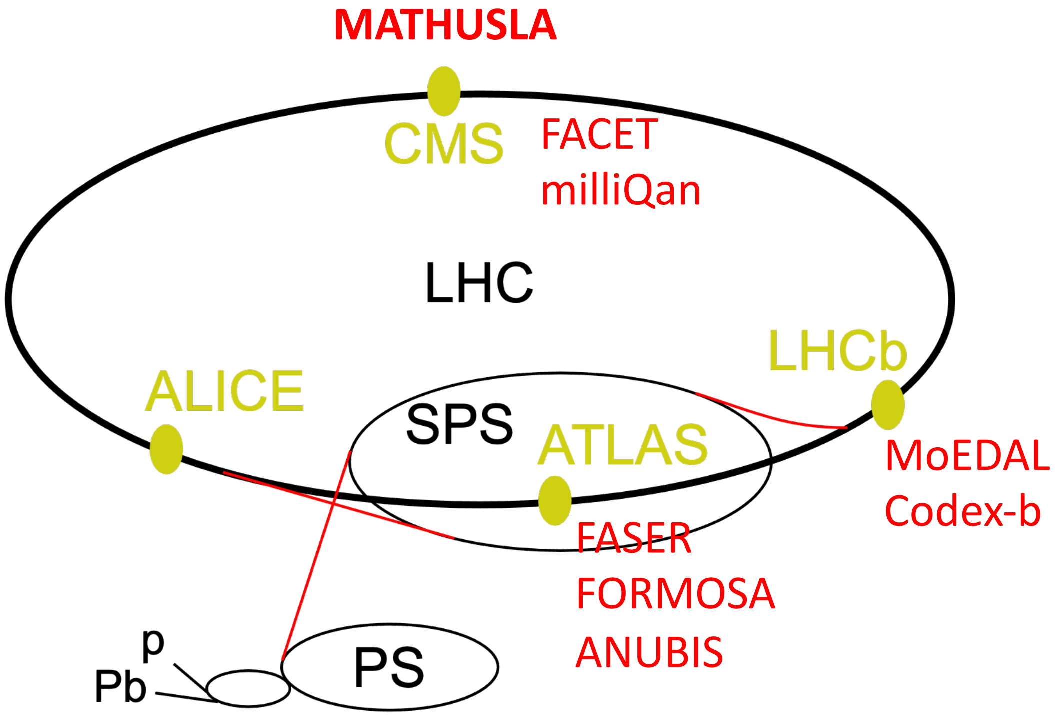
MATHUSLA

Massive Timinig Hodoscope for Ultra-Stable NeutraL Particles

mathusla-experiment.web.cern.ch

- Long-Lived particles (LLPs) predicted in most of the BSMs to explain Hierarchy Problem, Dark Matter, Baryogenesis, neutrino mass, etc.
- Neutral, LLPs could escape the standard detectors before decaying.
- Several search proposals for HL-LHC are under study.





Long-Lived Particles at the energy frontiere: the MATUSLA Case
Rep. Prog. Phys. 82,116201,2019

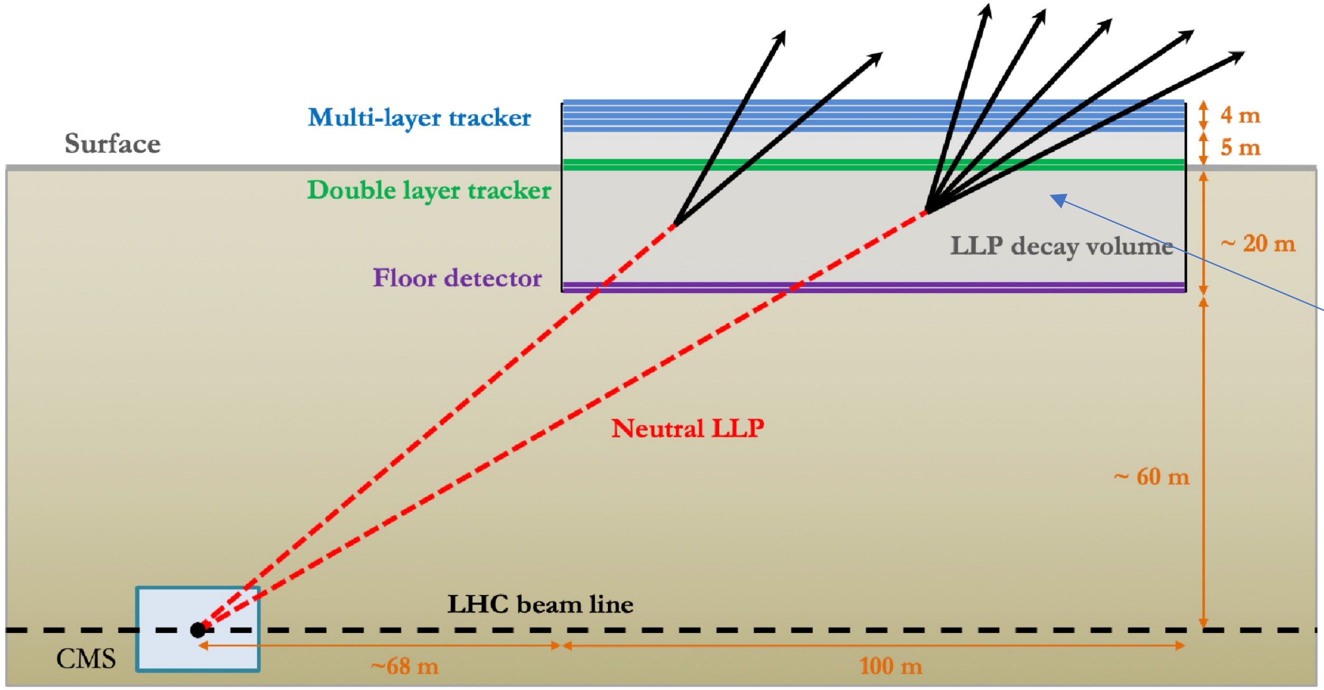
Letter of Intent:
Search for Long-Lived Particles at HL-LHC, submitted Sept. 2020, LHCC-1-031-ADD-1,
15 institutions -USA, Canada, México, Bolivia, Italy, Switzerland, ...

MATHUSLA

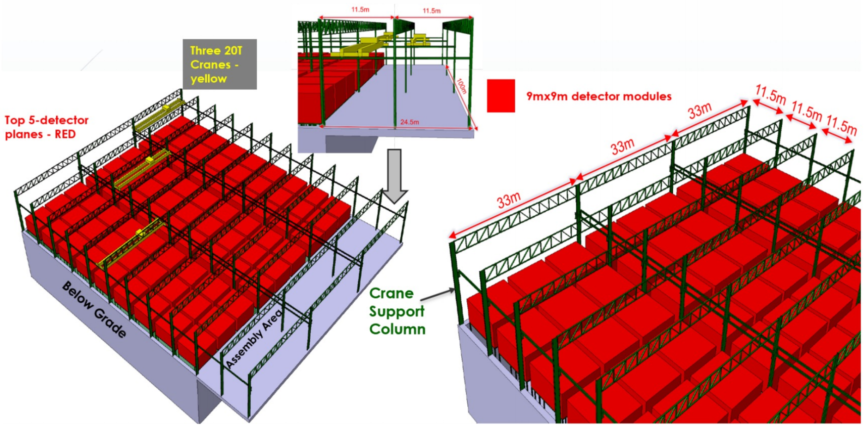
Massive Timinig Hodoscope for Ultra-Stable NeutraL Particles

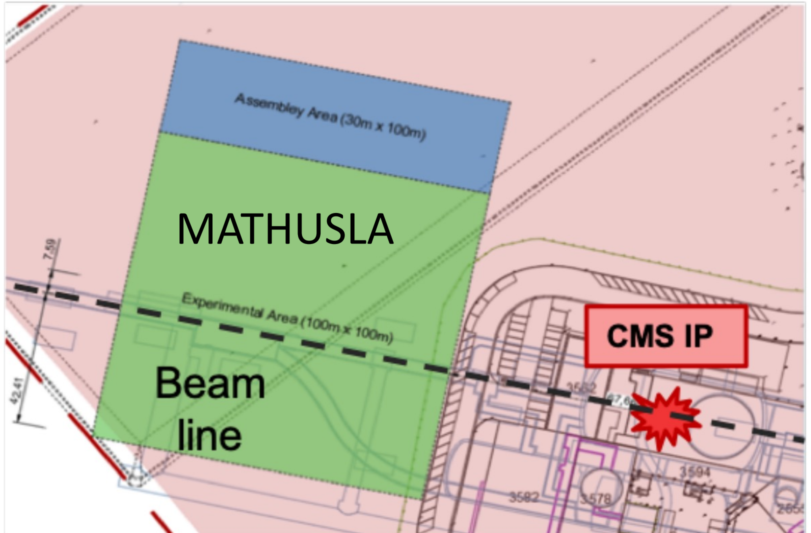
DETECTOR CONCEPT AND LAYOUT

- **A large-scale LLP detector for the HL-LHC**
- A big empty box on CERN-owned land near CMS. LLPs that decay inside will be reconstructed as displaced vertices.
- Stringent geometrical + timing LLP reconstruction criteria
- ~ 100 m of rock shielding: near-zero background environment.



100 m x 100 m x 25 m



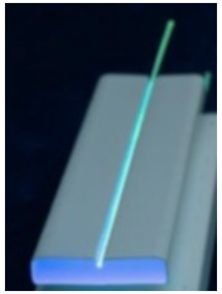


Displacement from IP:
70m horizontally,
60m vertically

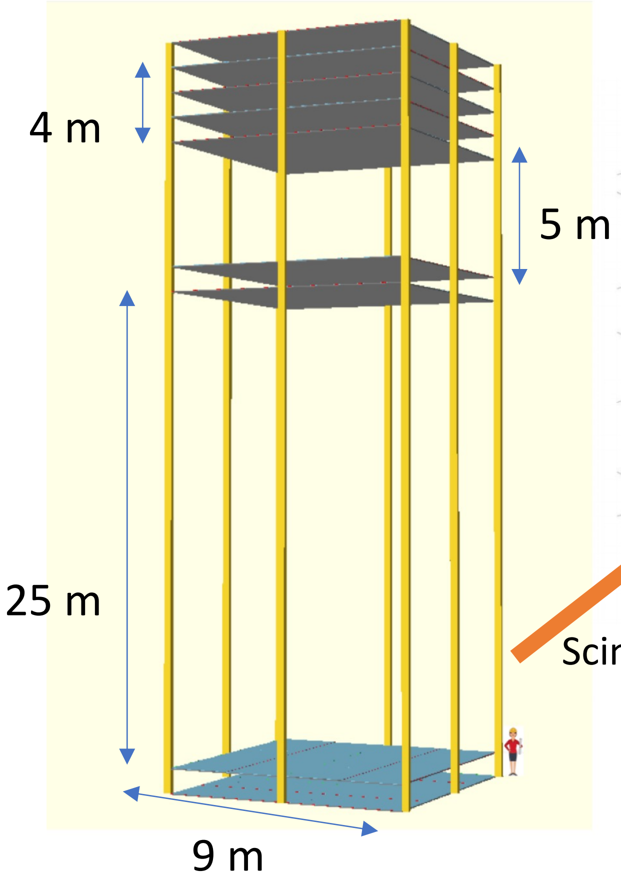
Modular Detector Design

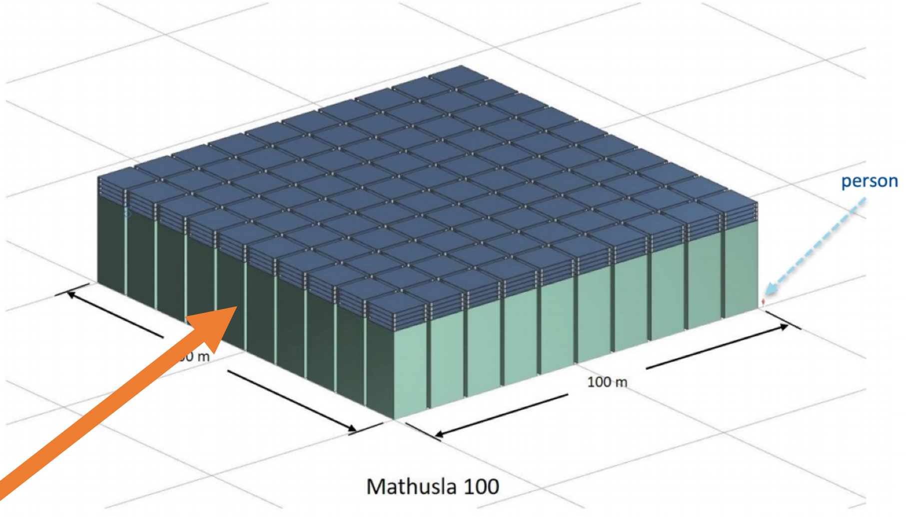
- 100 modules, 9 m x 9 m area base, 1 m gap

- Tracker technology is based on extruded scintillators:



4.5 m long x 4.5 cm width x 2 cm thick
Central wavelength shifting fiber,
readout by SiPM.





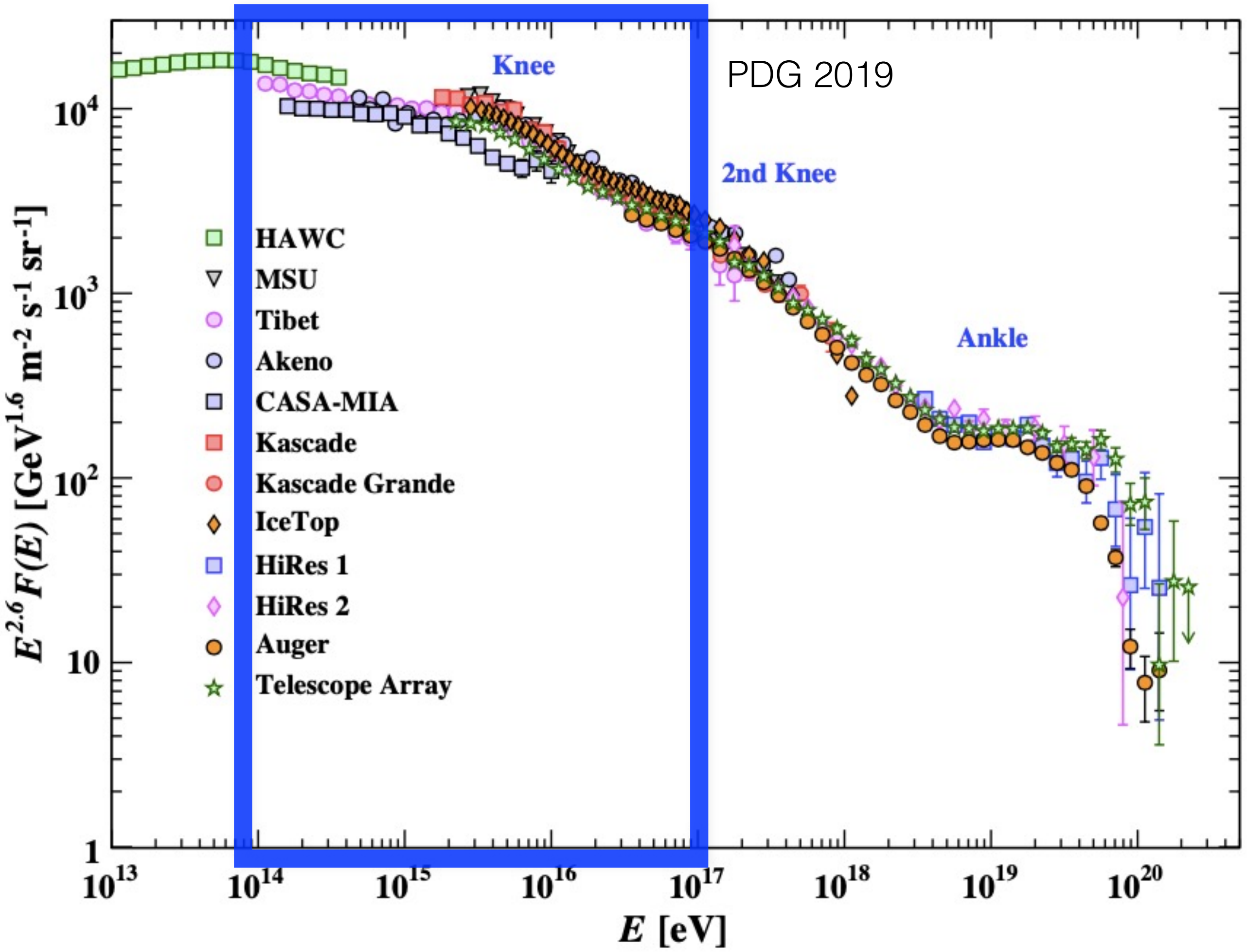
Scintillator tower module

- From one layer to the other, long dimension of the bar is rotated 90^0

MATHUSLA aparatus as a Cosmic Ray detector

Full efficiency: E=10^{14} - 10^{17} eV

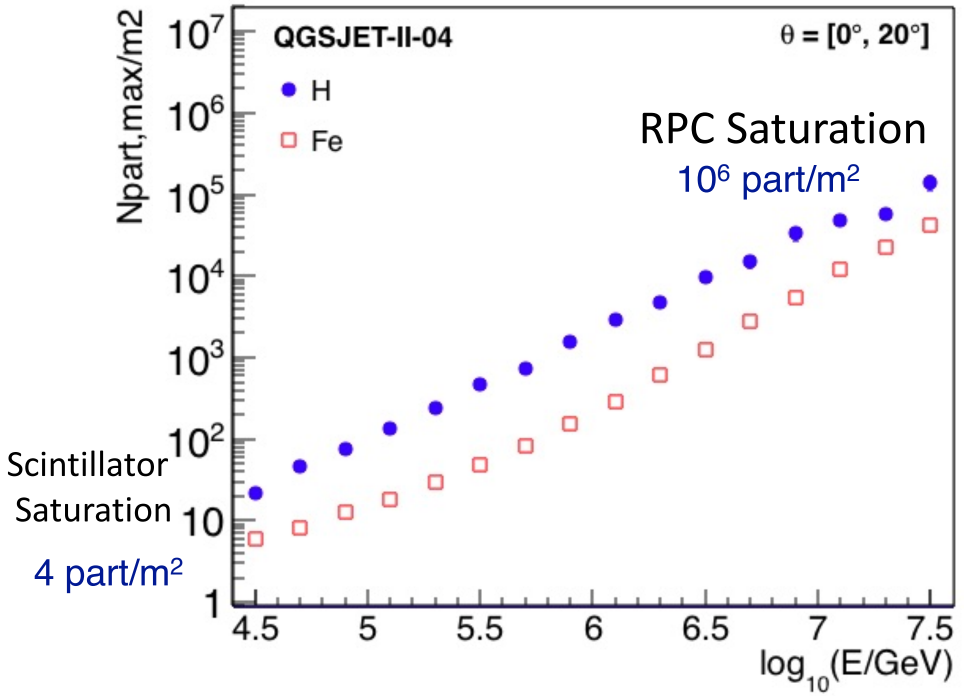
MATHUSLA with 9 tracking scintillator planes is an excellent option for studying EAS in the knee region via detection of charged particles.



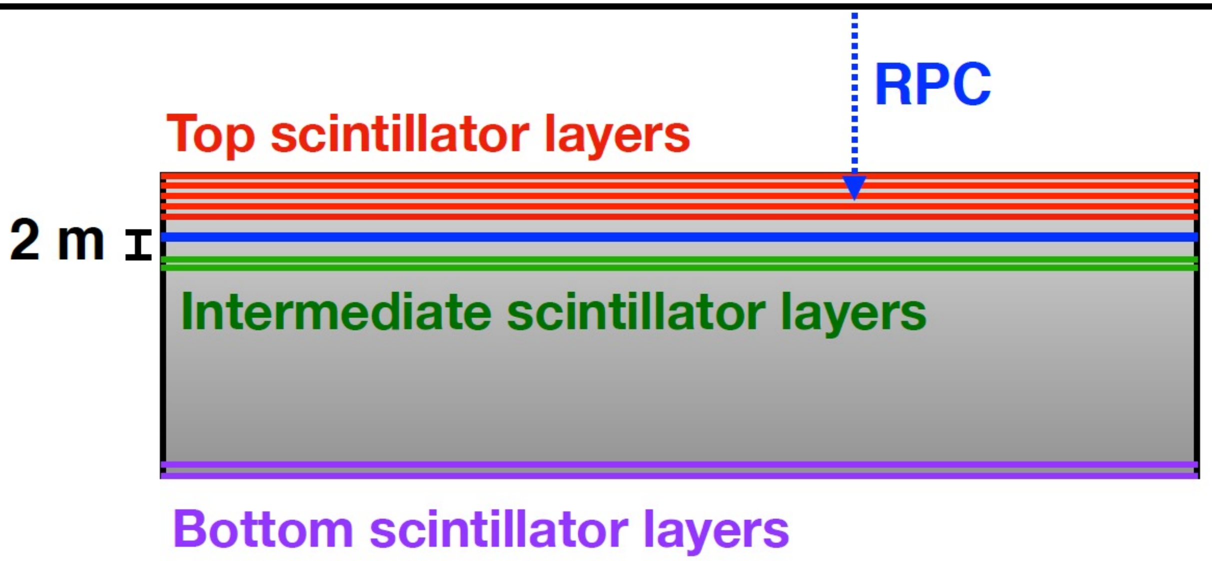
MATHUSLA aparatus as a Cosmic Ray detector

Adding an RPC* plane to current MATHUSLA detector layout would provide data on spatial-time distribution of charged particles.

MATHUSLA detector would significantly enhance EAS detection and reconstruction.



- RPC characteristics
  - Big Pads: 1.1 m x 0.9 m
  - 242 cm² strips
  - RPC in Avalanche mode.
  - 1 mm gas gaps (like in ATLAS BI RPCs)
  - Big Pad signal ∝ local charge density.



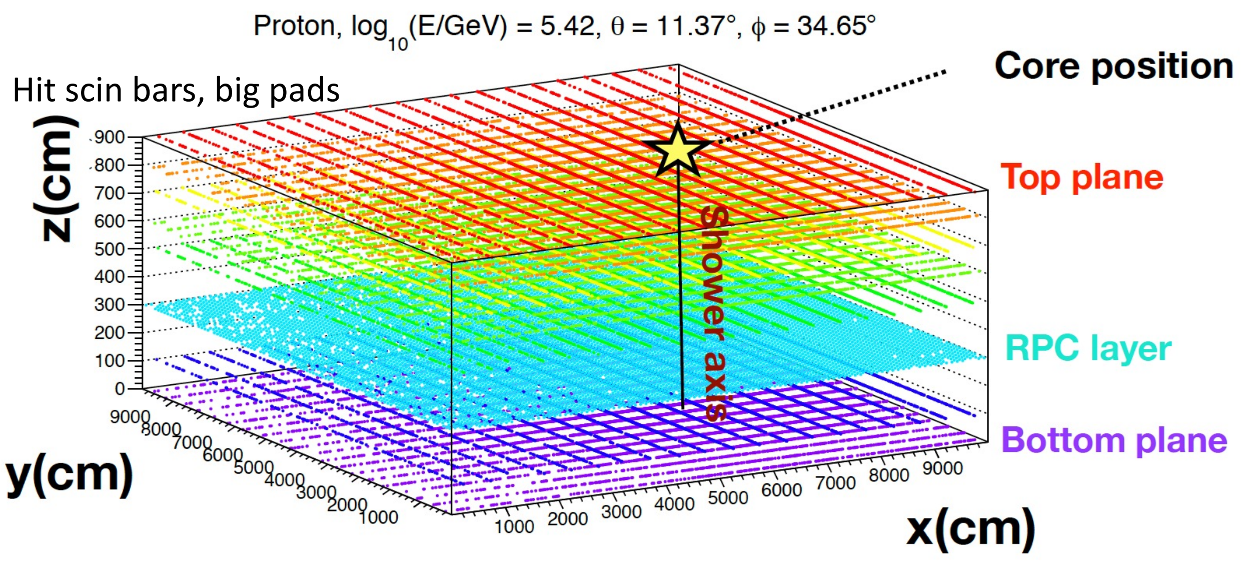
*Proof of Principle: ARGO-YBJ

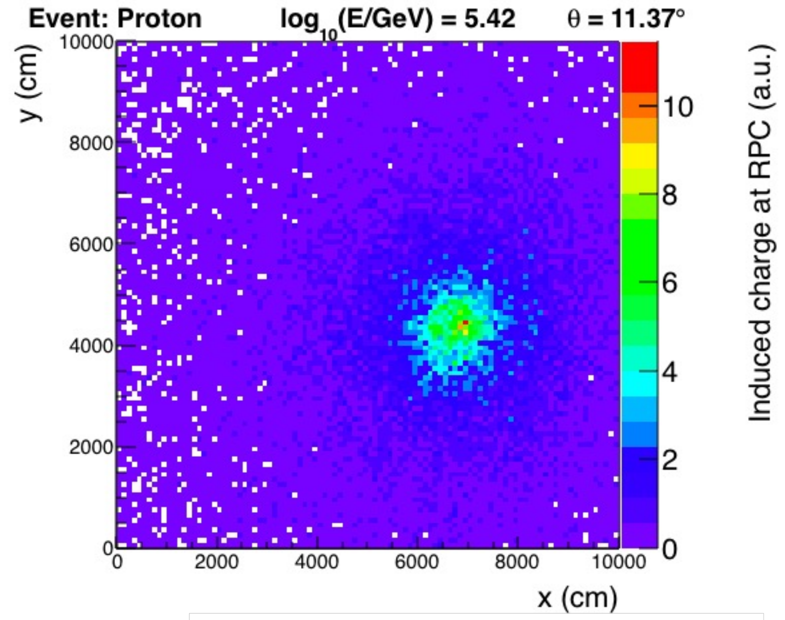
Simulations

- **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: CORE LOCATION, ARRIVAL DIRECTION
MC VERTICAL SHOWER





EAS Core reconstruction

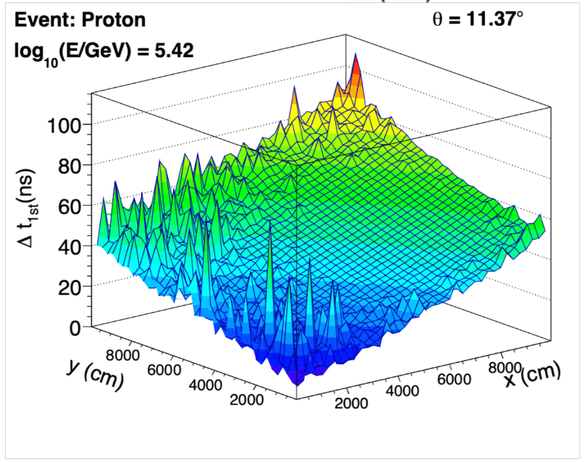
Exponential fit to X (Y)
projected hit bars/induced charge

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

EAS Direction reconstruction

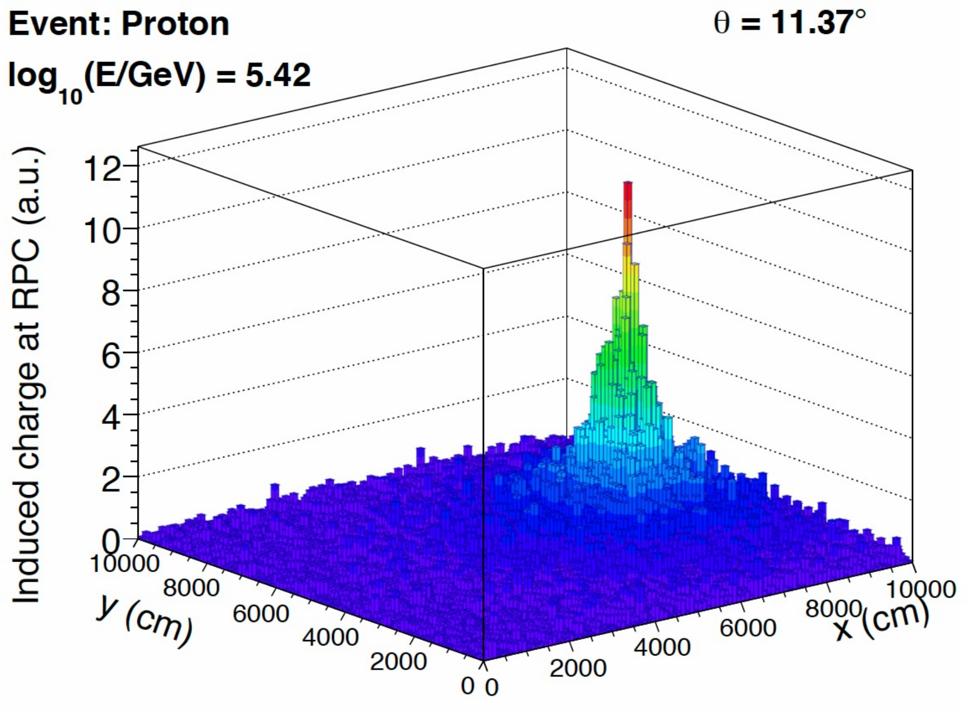
fits with a plane to arrival times of EAS front after time curvature corrections.

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

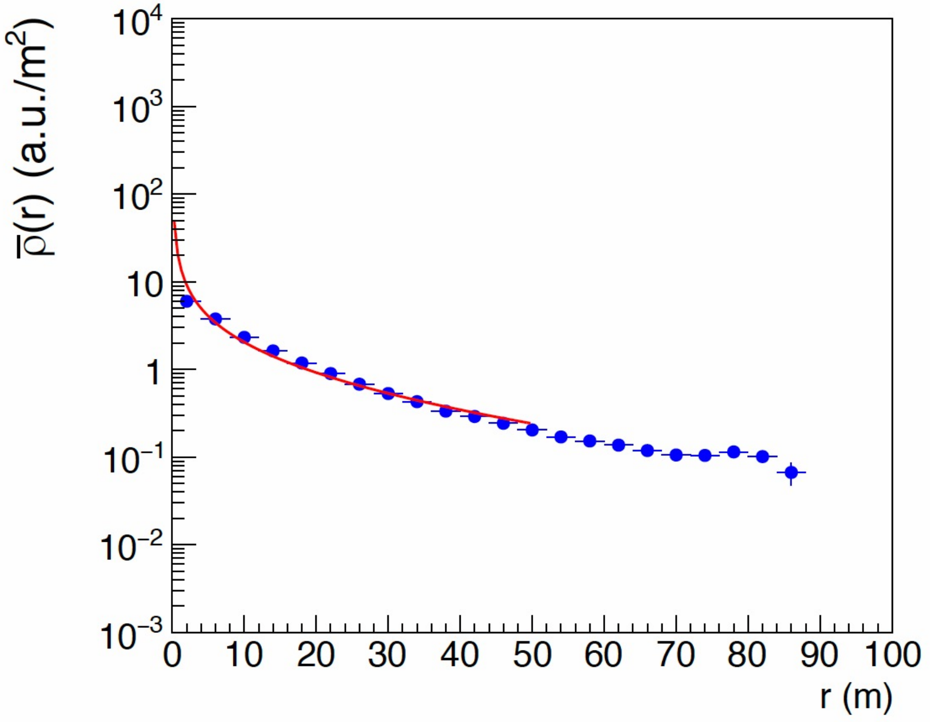


EAS RECONSTRUCTION: Charge density, Lateral charge density
RPC MC data (Vertical Shower)

Charge density at the RPC



Lateral charge density at RPC



Nishimura-Kamara-Greisen (NKG) function:

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

A: Amplitud distribution → Energy Scale

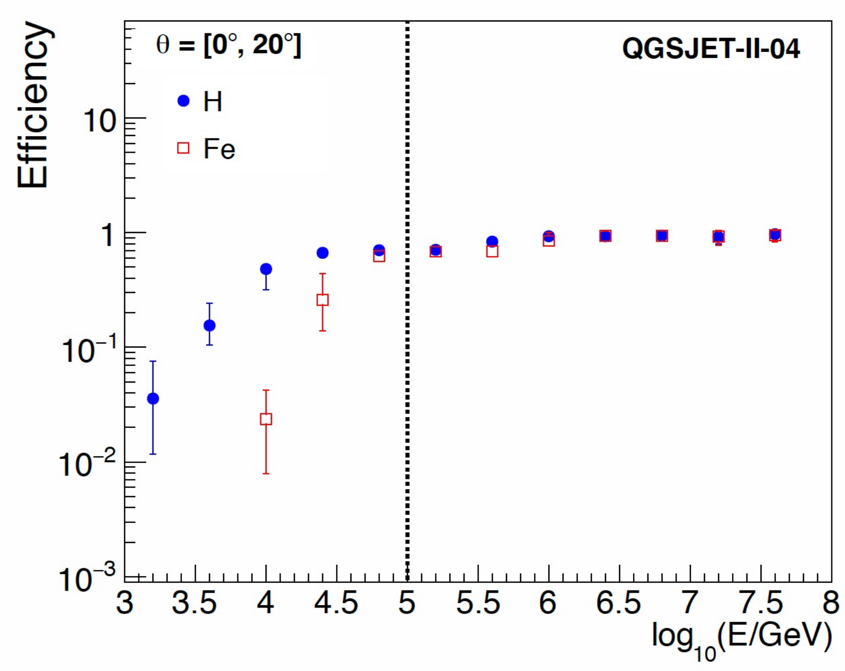
s: Shower age parameter → Composition dependent parameter

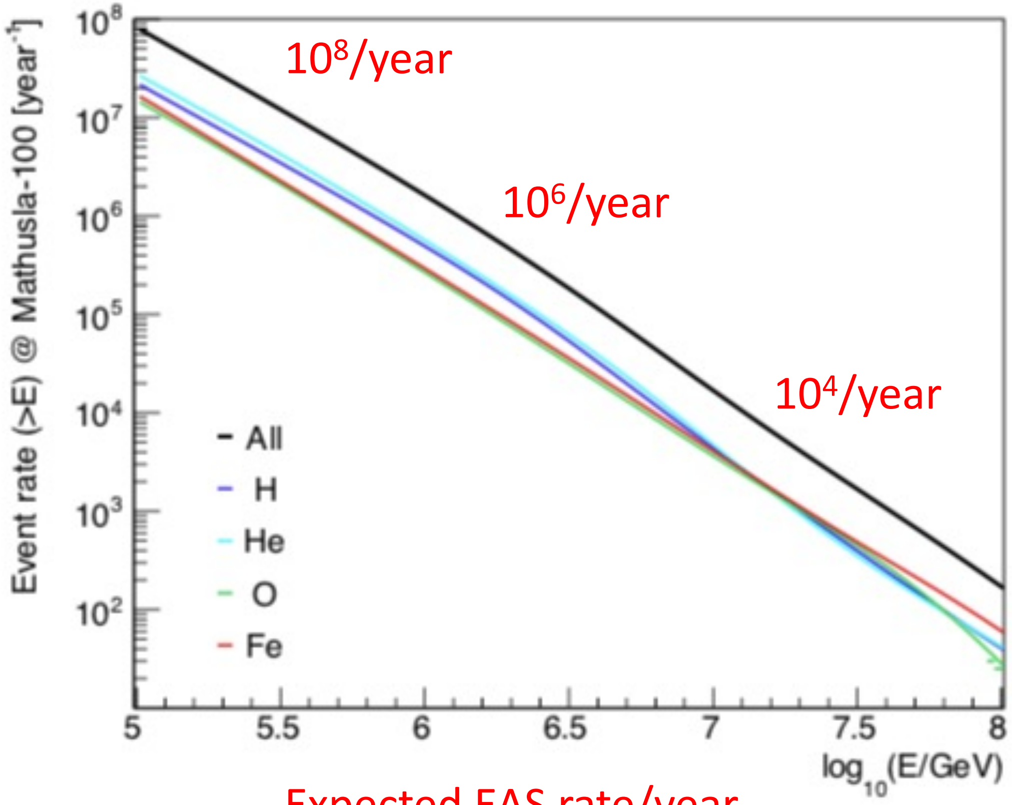
r_0 : Molière radius, at sea level

MC EAS Analysis

Vertical showers, nhit > 100

Trigger reconstruction efficiency





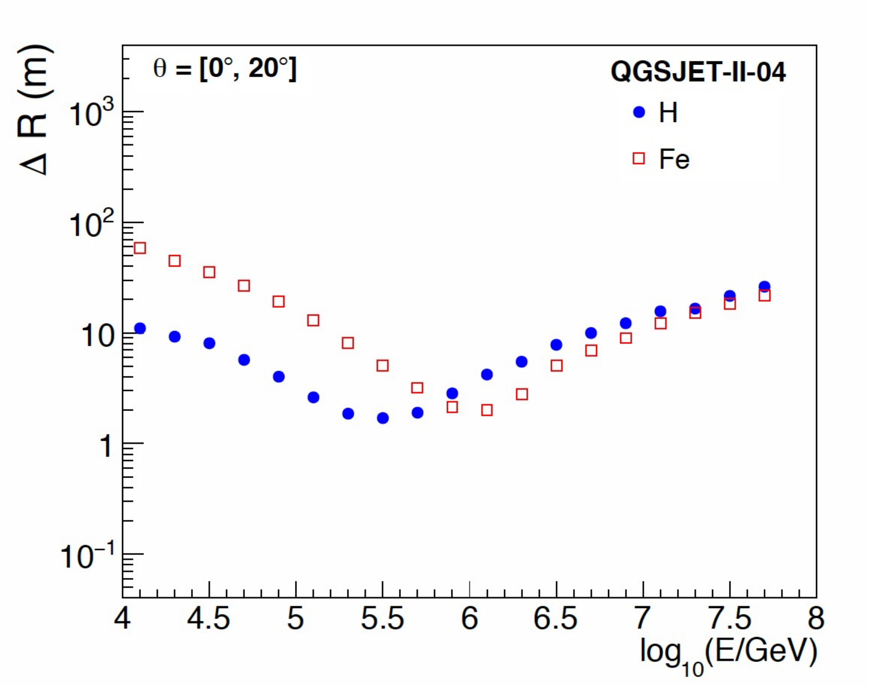
θ =[0⁰, 90⁰]

Expected EAS rate/year

MC EAS Analysis

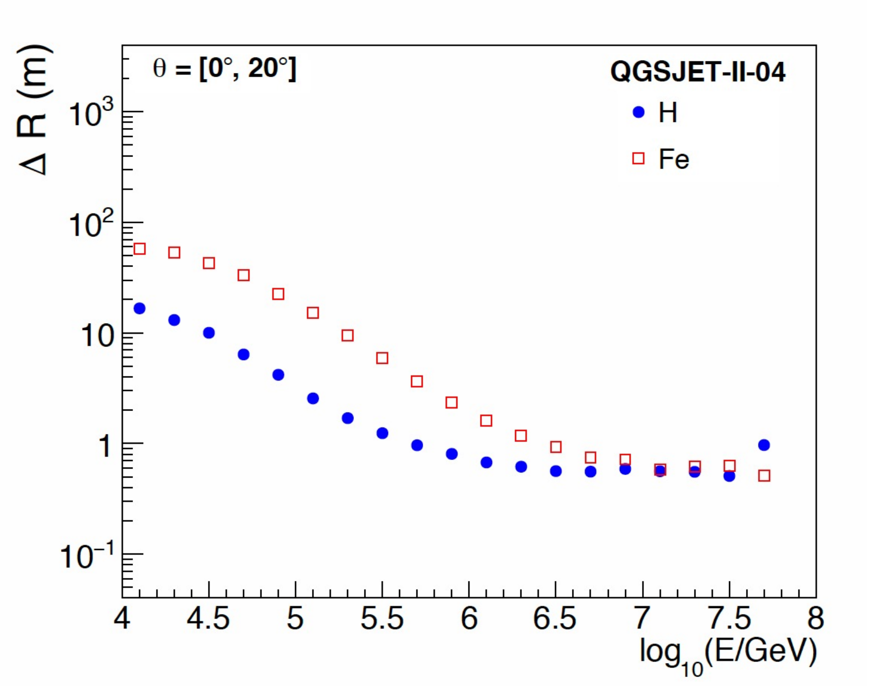
Vertical showers: Core resolution

Core resolution (68% confinement) at scintillator layer



Scintillator layers: For E> 10^{15} eV, quality of EAS reconstruction decreases

Core resolution (68% confinement) at RPC

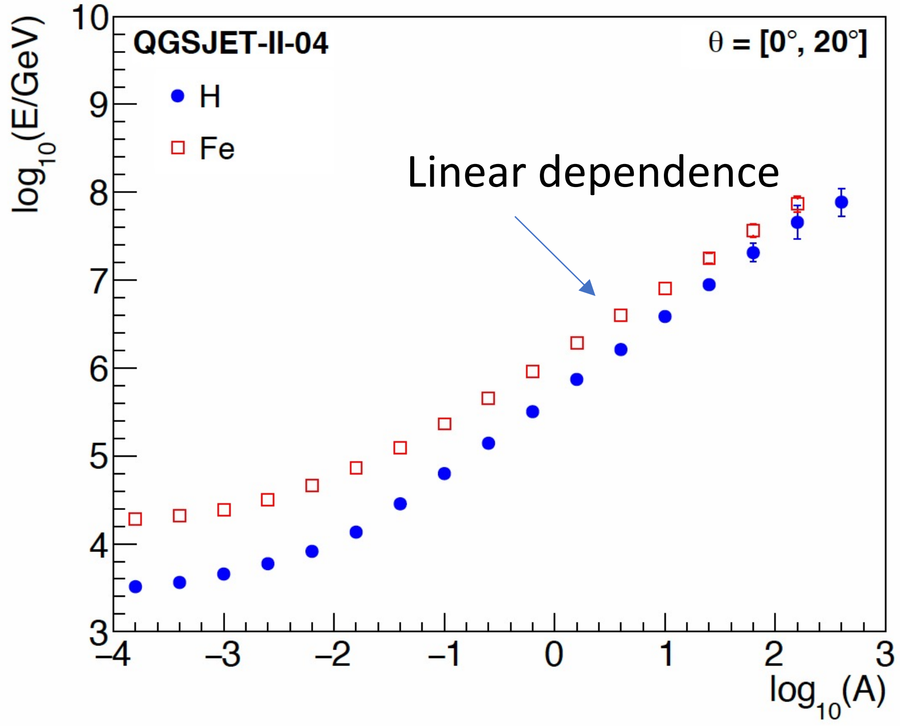


With RPC, core resolution improves for E> 10^{15} eV

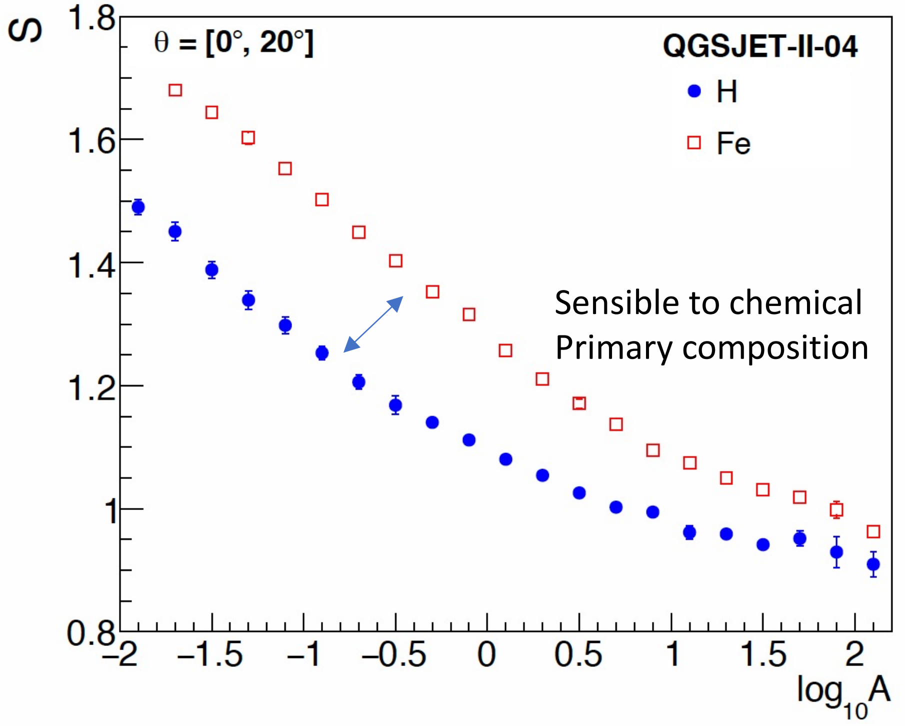
MC EAS Analysis

Charge density Lateral distribution (LD)
Amplitud of lateral distribution (A) , Shower age (s)

Amplitude of lateral distribution (LD)



Shower age (slope of LD) vs amplitude

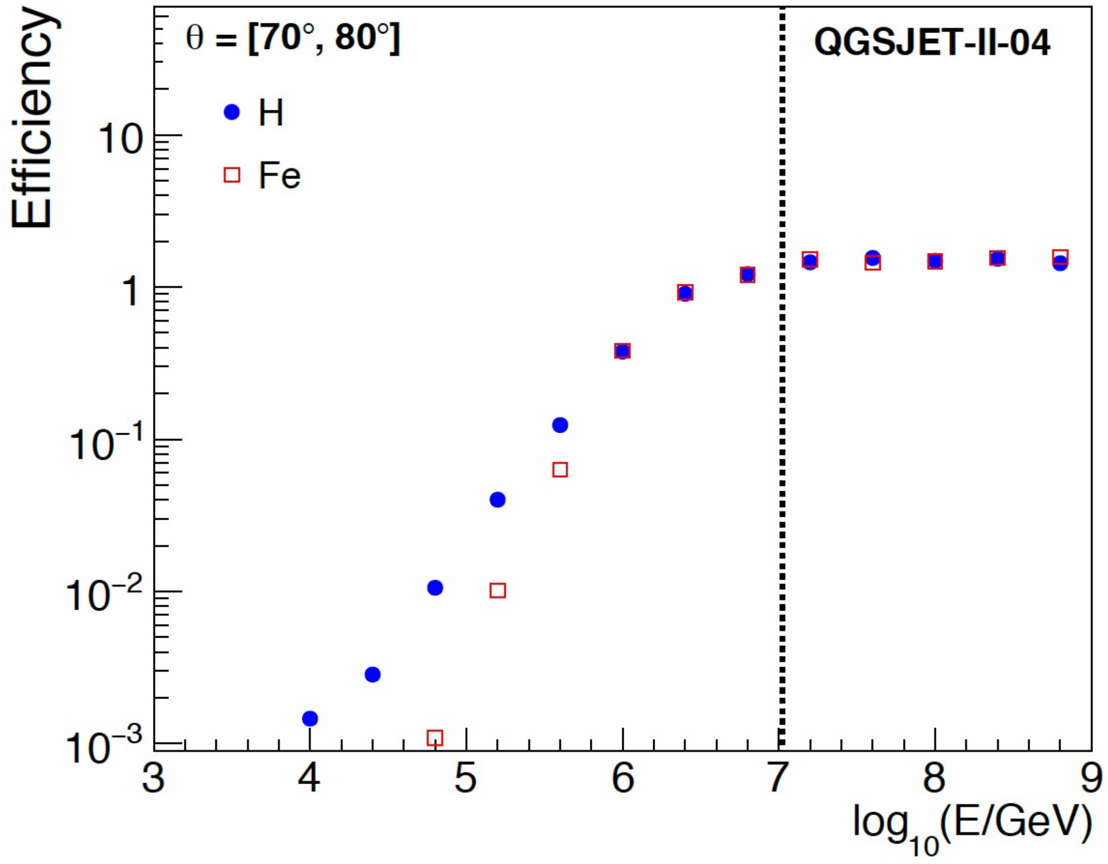


RPC layer allows to extend **CR energy** and **composition studies above E = 10^{15} eV.**

EAS Analysis

Inclined EAS showers θ = [70º, 80º] nhit > 50

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



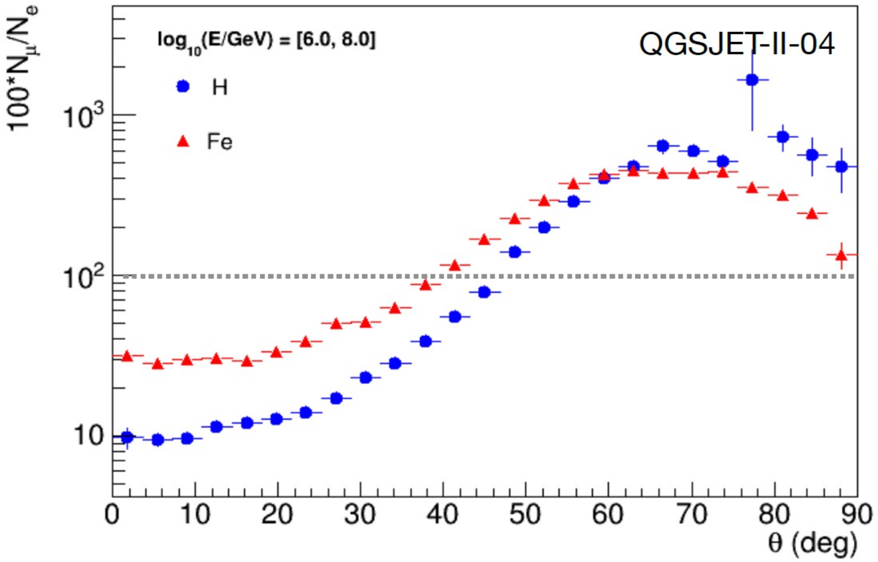
Resolution for inclined EAS @ E = 10^{16} eV

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

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

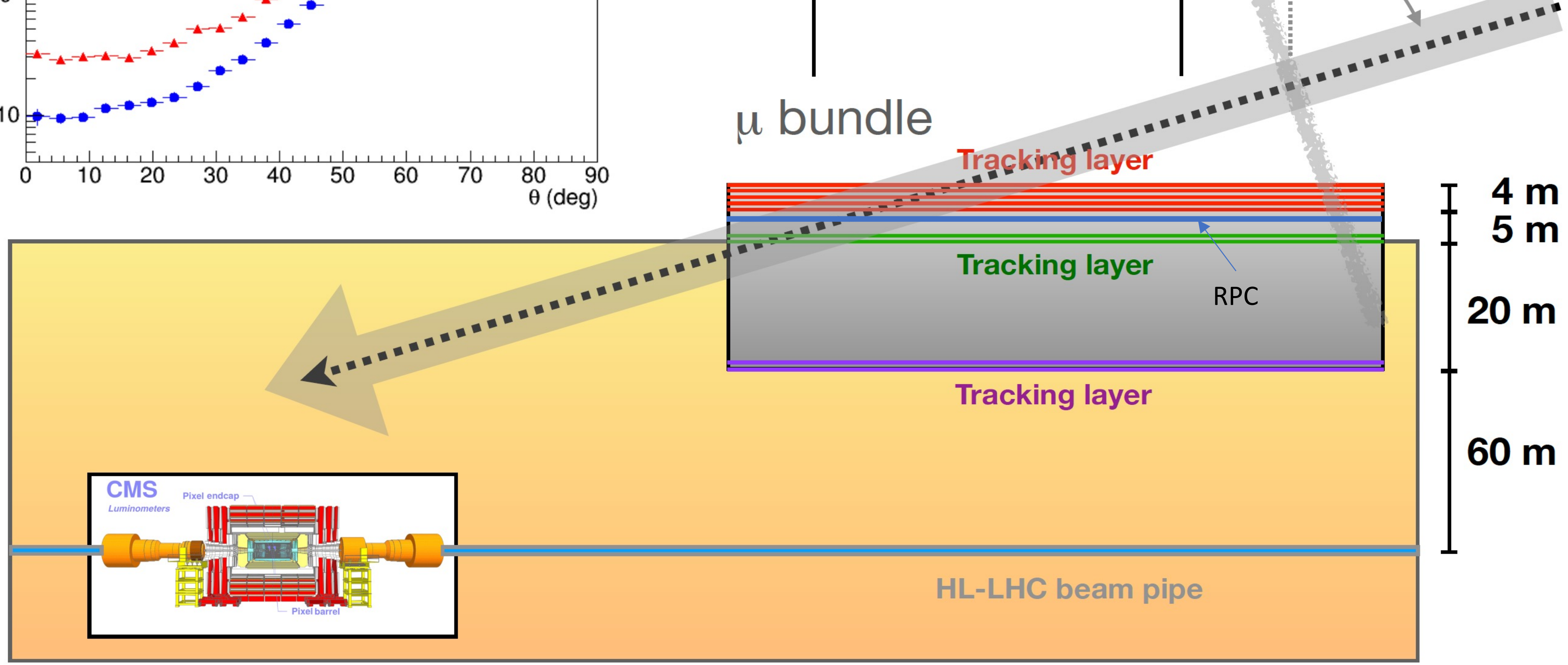
RPC: measure particle density in detector elements with multiplicity hits > 1

Inclined EAS in MATHUSLA



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

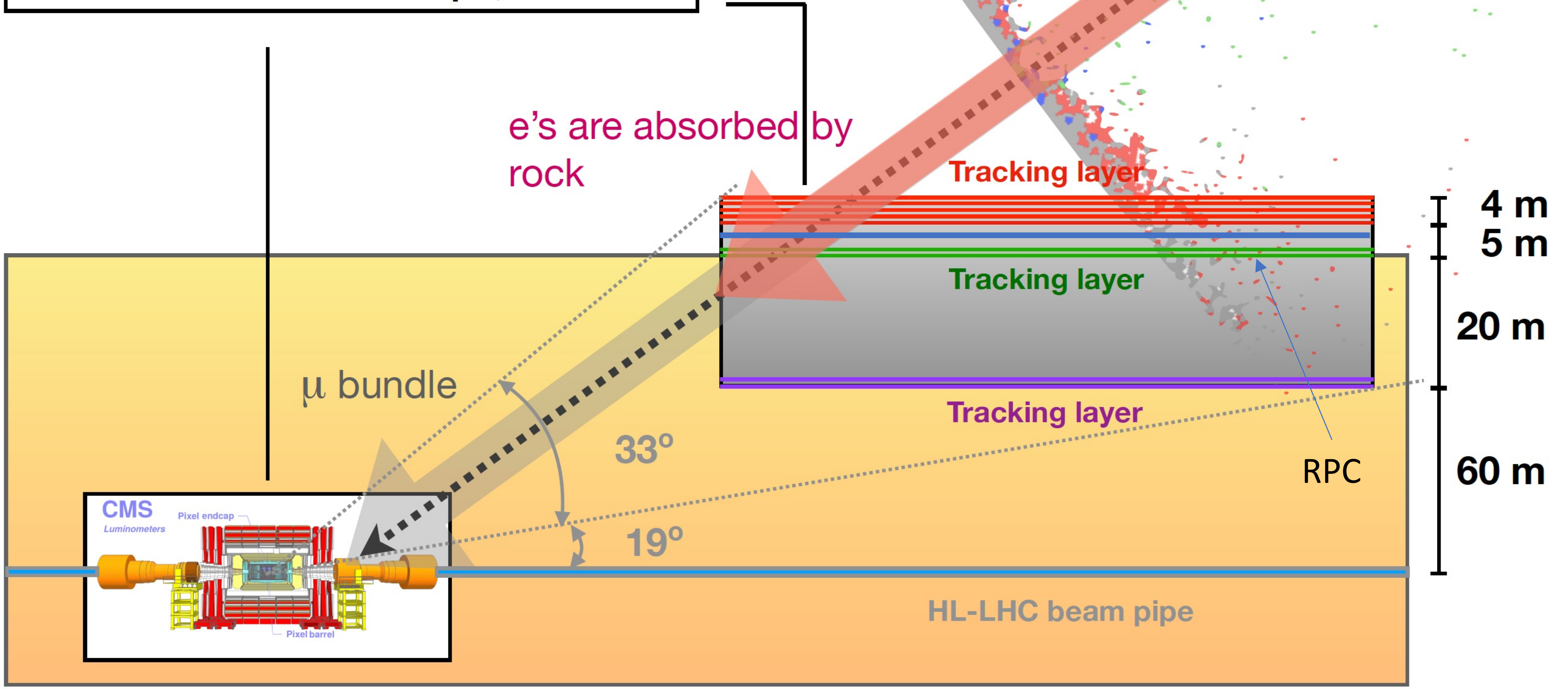
Inclined EAS (θ > 50°): μ's are dominant, γ/e's are strongly absorbed in atmosphere



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 aparatus as a Cosmic Ray detector

MATHUSLA (Scintilator+RPC) detector 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.

MATHUSLA Physics potential contributions:

- E = [10^{14} eV, 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 (CMS+MATHUSLA)

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

Comparison with other experiments

Summary

- MATHUSLA: An excellent tool for searching LLPs at the HL-LHC.

- Its volume and tracking capabilities permits using this detector as a cosmic ray observatory.

- With an extra RPC 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.

- Immediate plans: Technical Design Report by early 2022, followed by prototype module and full detector for HL-LHC.

We welcome more participation from the cosmic ray physics community.
Please contact me if you would like to join the MATHUSLA cosmic ray physics team.

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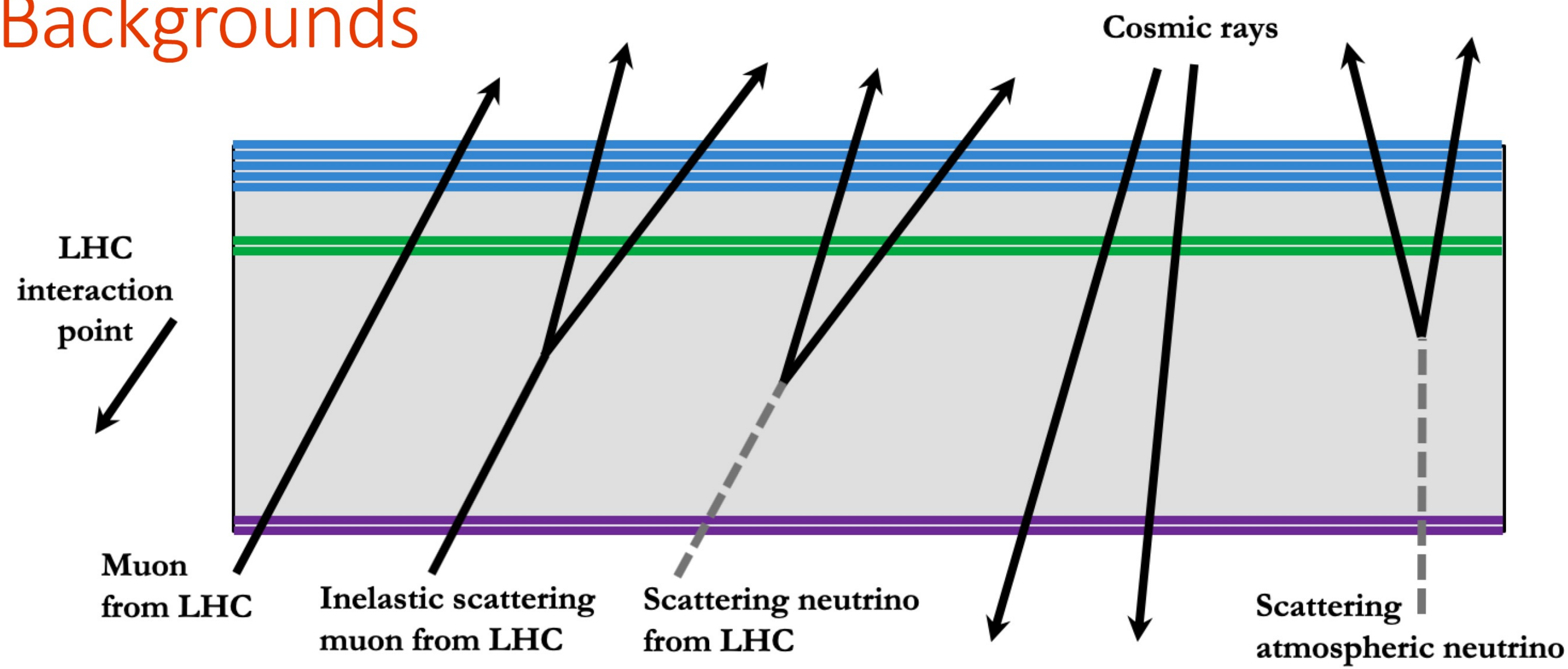
BACKUP Slides

Backgrounds



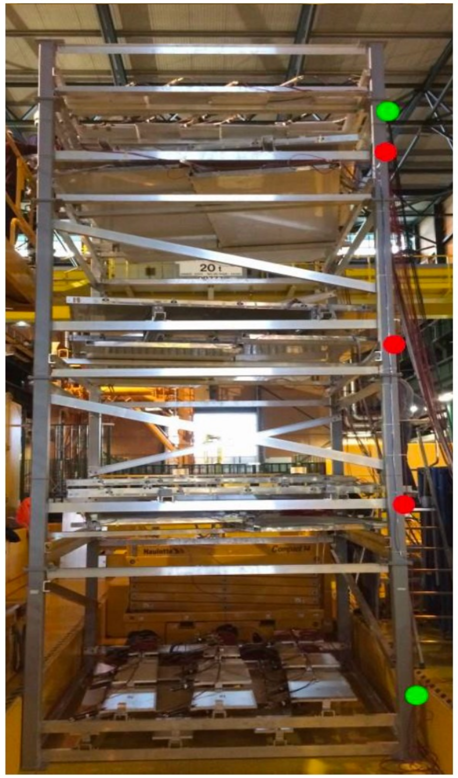
LLP displaced vertex (DV) signal has to satisfy many stringent geometrical and timing requirements (“4D vertexing” with cm/ns precision)

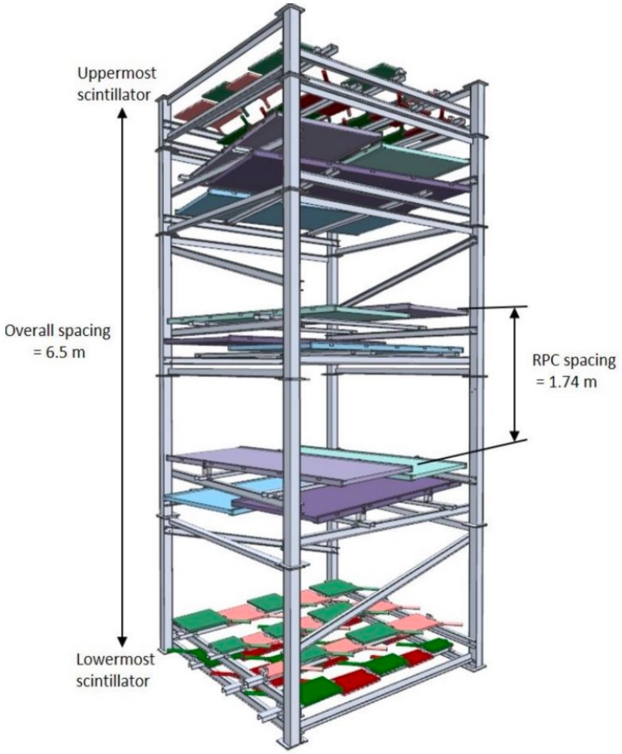
These requirements, plus a few extra geometry & timing cuts, provide “near-zero background” (< 1 event per year) for neutral LLP decays!

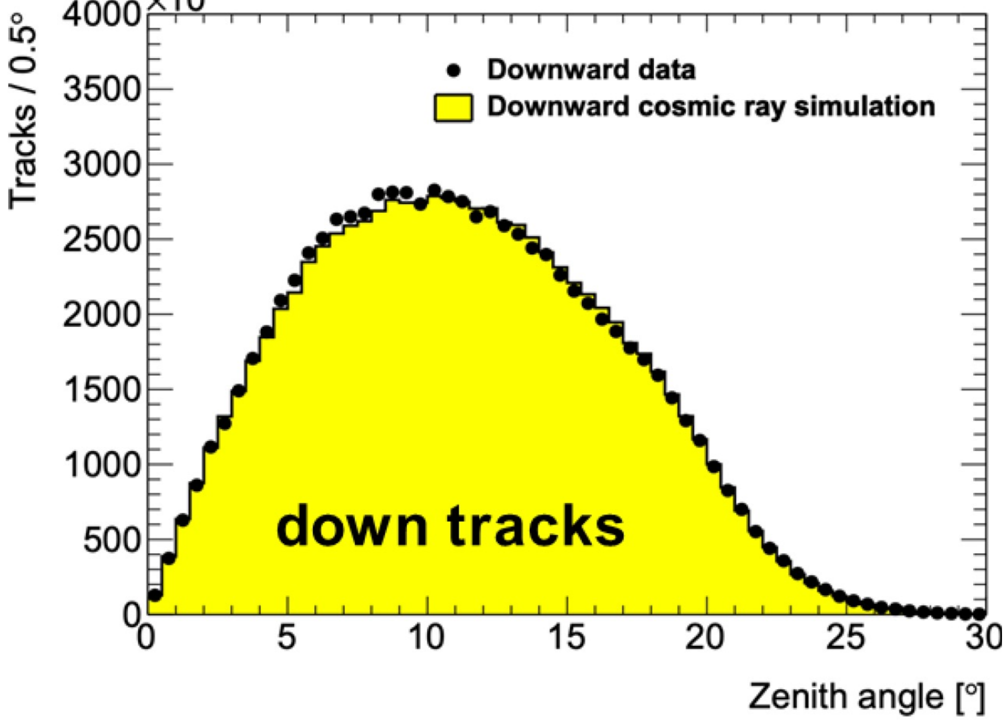
MATHUSLA Test Stand

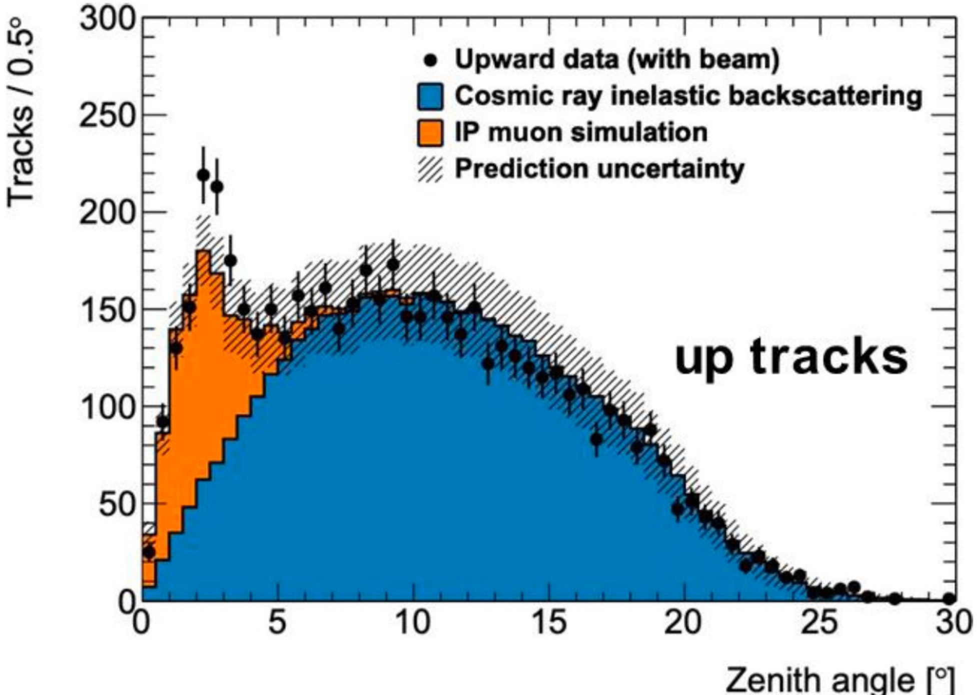
Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164661

Operated above ATLAS in 2018





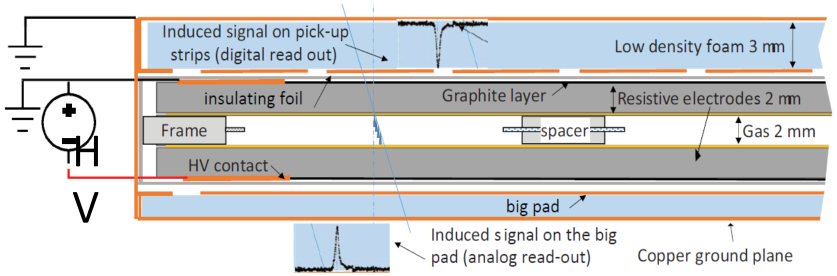


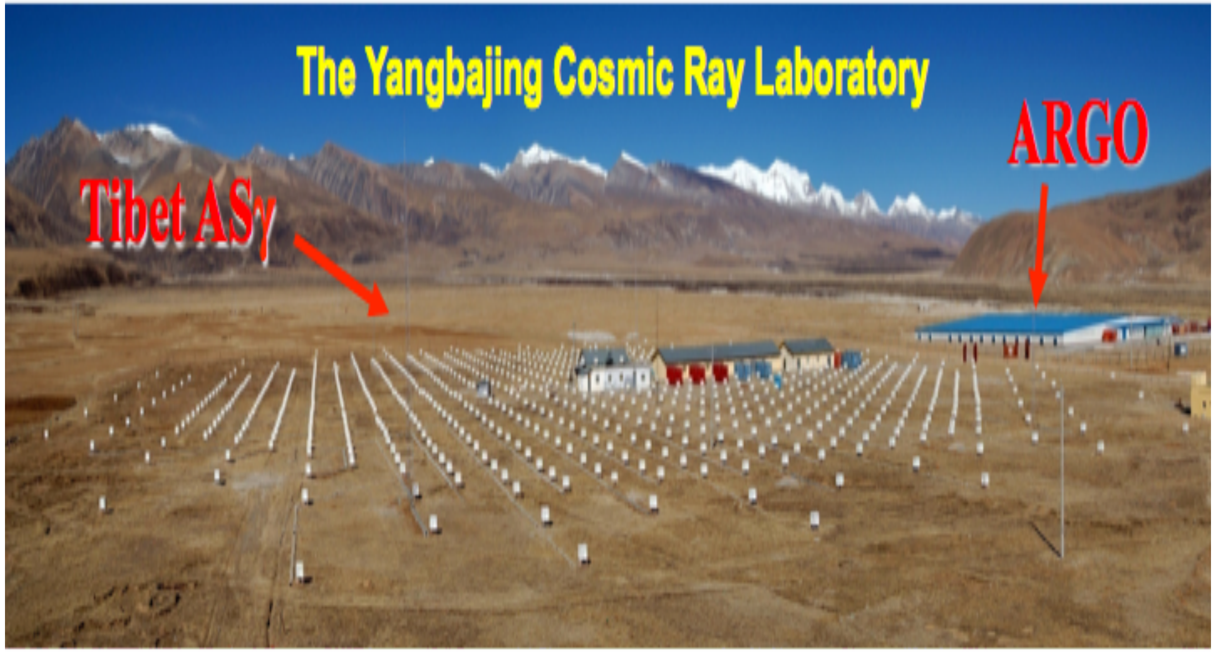


Downward cosmic rays, upward LHC muons and upward CR backscatter well described by simulations

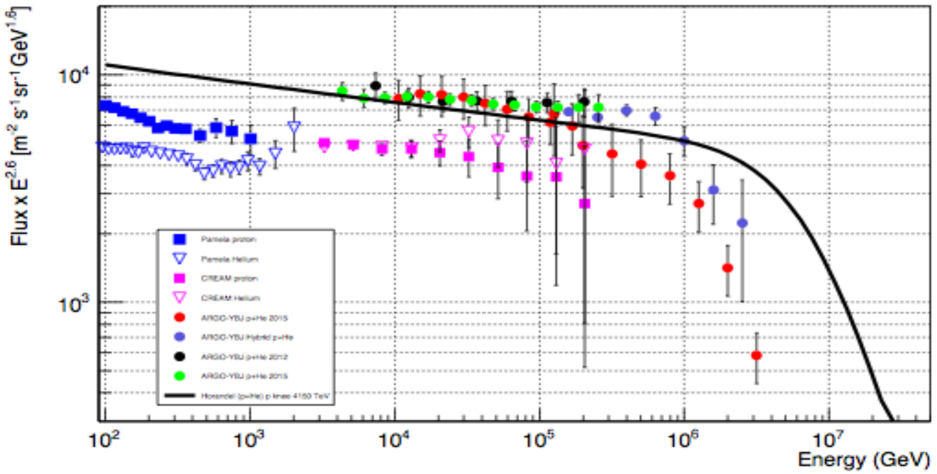
The ARGO-YBJ experiment (2007-2015)

Longitude: 90° 31’ 50” East
Latitude: 30° 06’ 38” North
4300 m above sea level $\sim 600\ \mathrm{g/cm^2}$
90 km North from Lhasa (Tibet)





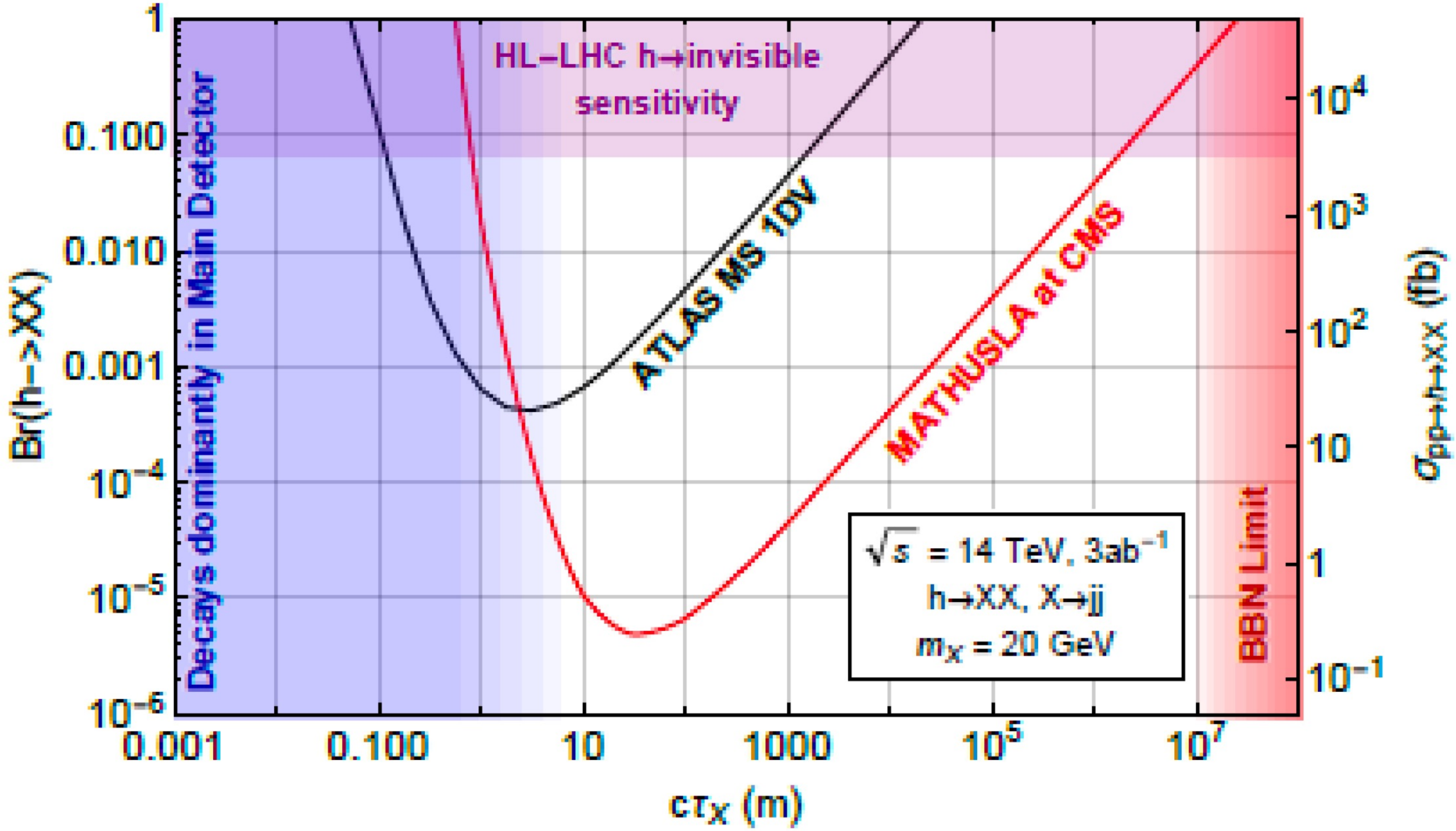
Light component spectrum
(3 TeV- 5 PeV) →



LLP Sensitivity: Weak- to TeV- Scale

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

arXiV:2001.04750



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