2nd Symposium on new trends in Nuclear and Medical Physics
24-26 September 2025
Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University in Krakow, Poland

μPPET
a J-PET application for cosmic rays investigation

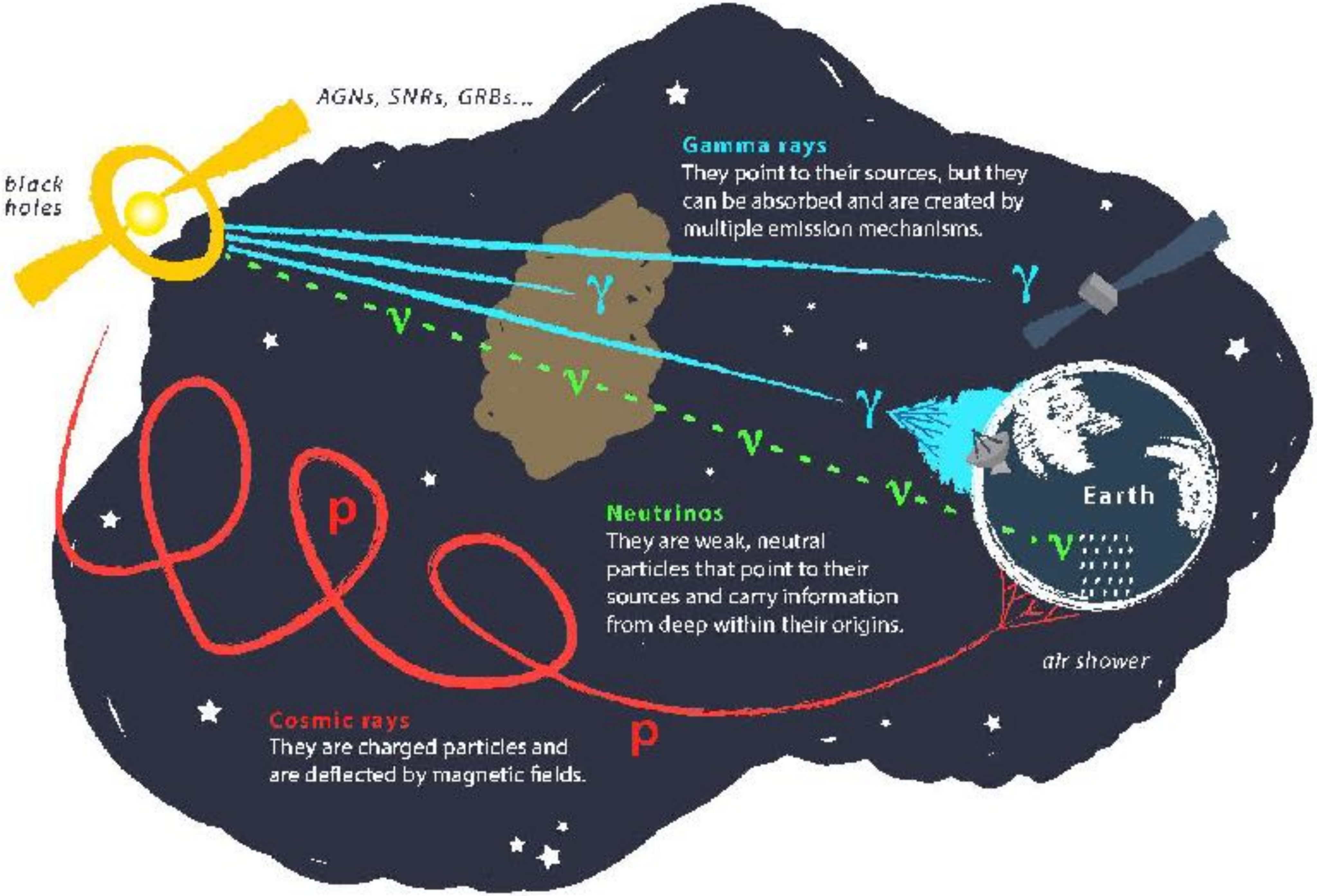
Universidad de Antofagasta
Centro de Investigación, Tecnología, Educación y Vinculación Astronómica

Jagiellonian University in Cracow
Faculty of Physics, Astronomy, and Applied Computer Science

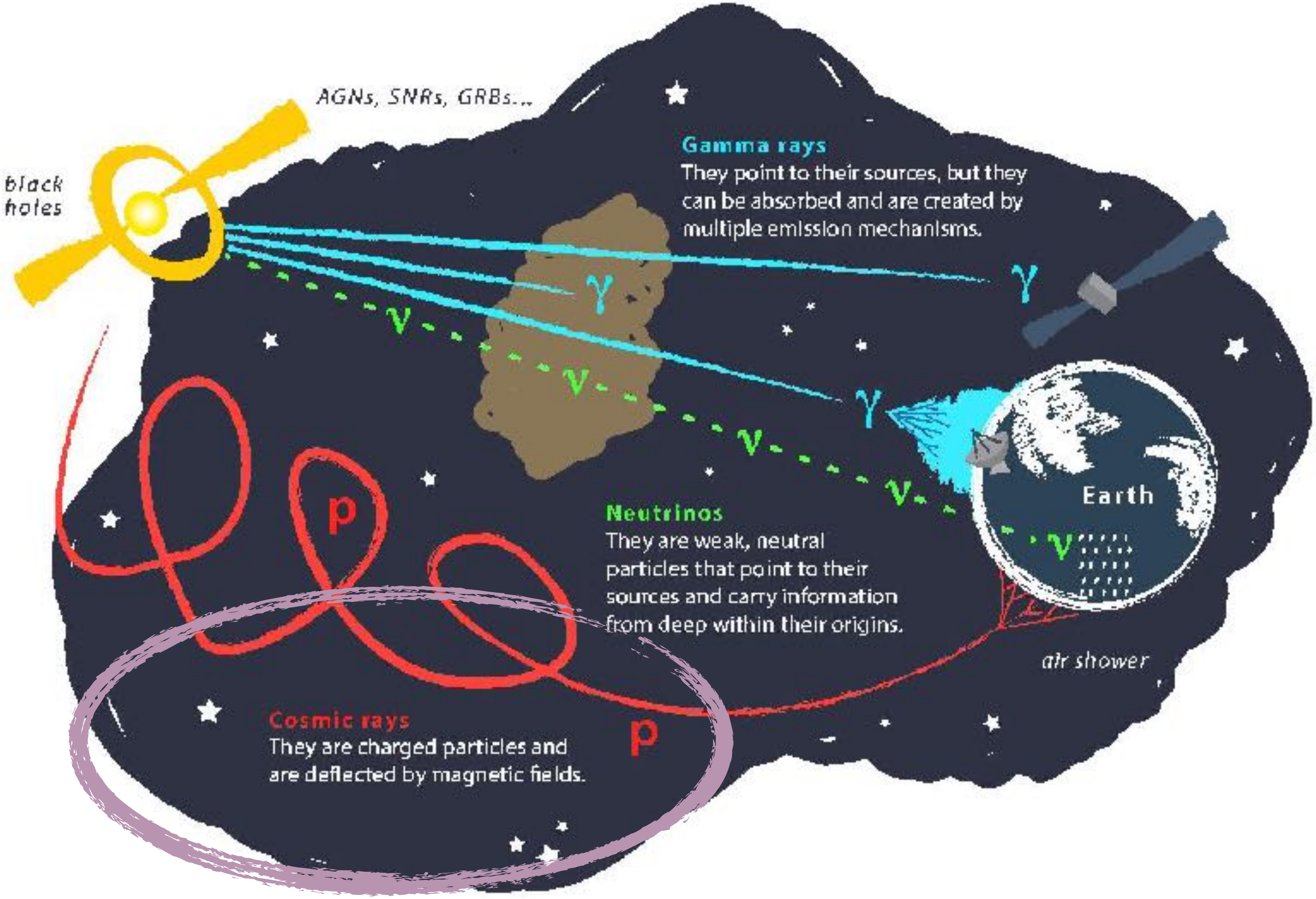
Dr. Alessio Porcelli — 24th September 2025

Narodowe Centrum Nauki
SONATA BIS-13

The Messengers

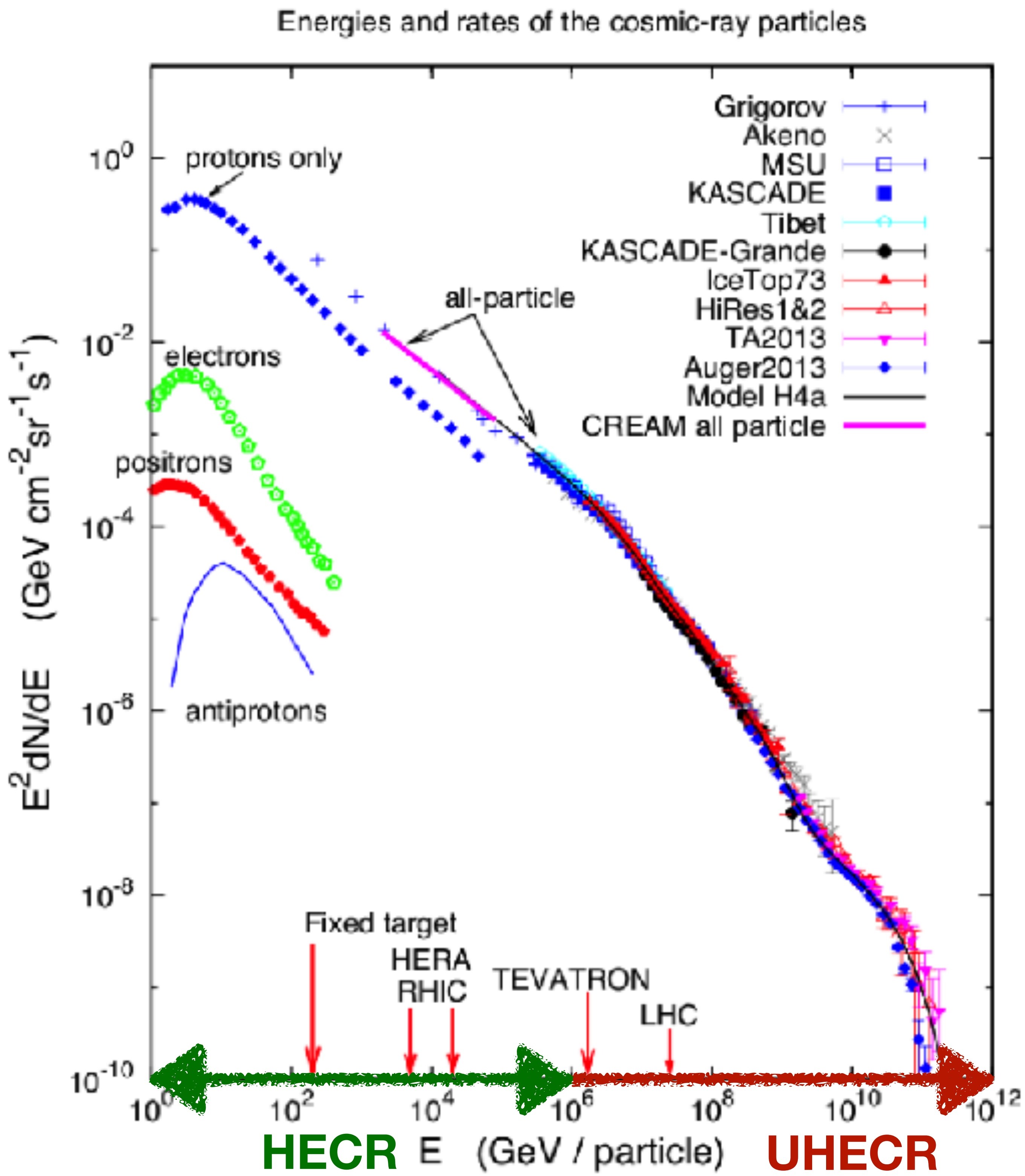


The Messengers



Classification

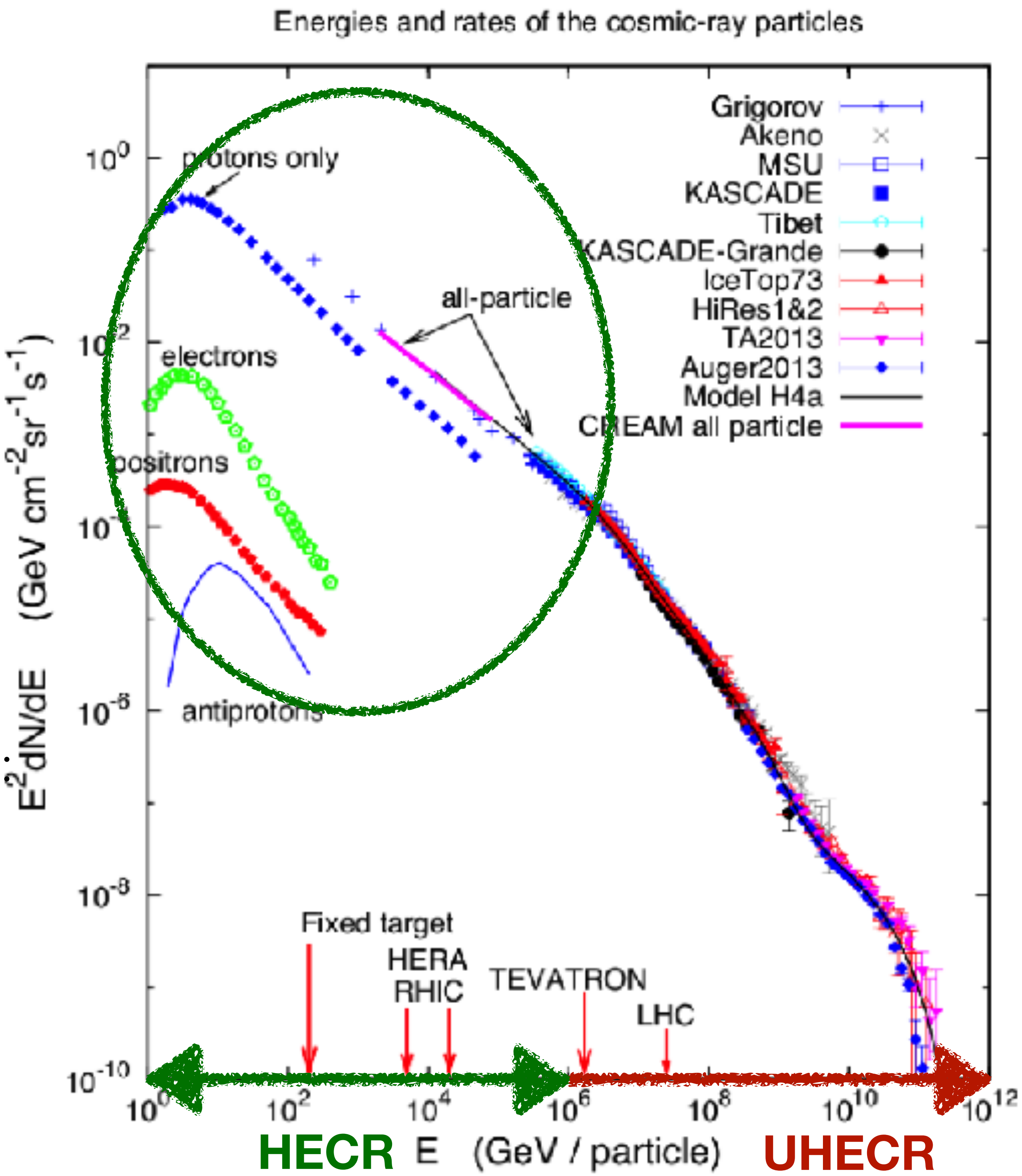
Cosmic Rays



Classification

Cosmic Rays

High Energy
Cosmic Rays
(HECR)
Direct detection:
Balloon-borne
detectors,
Satellites,...
Indirect detection:
ground-based
detectors



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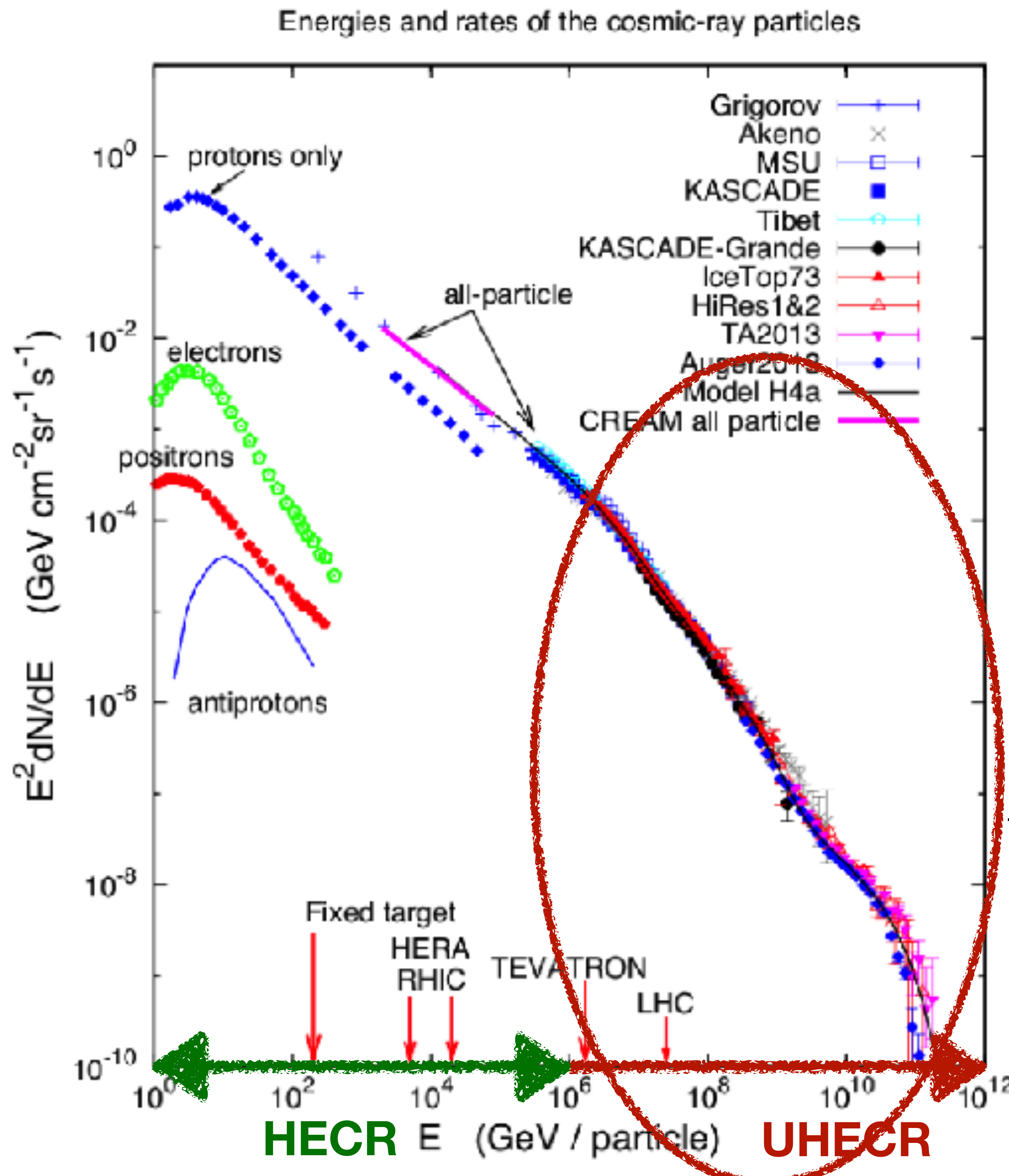
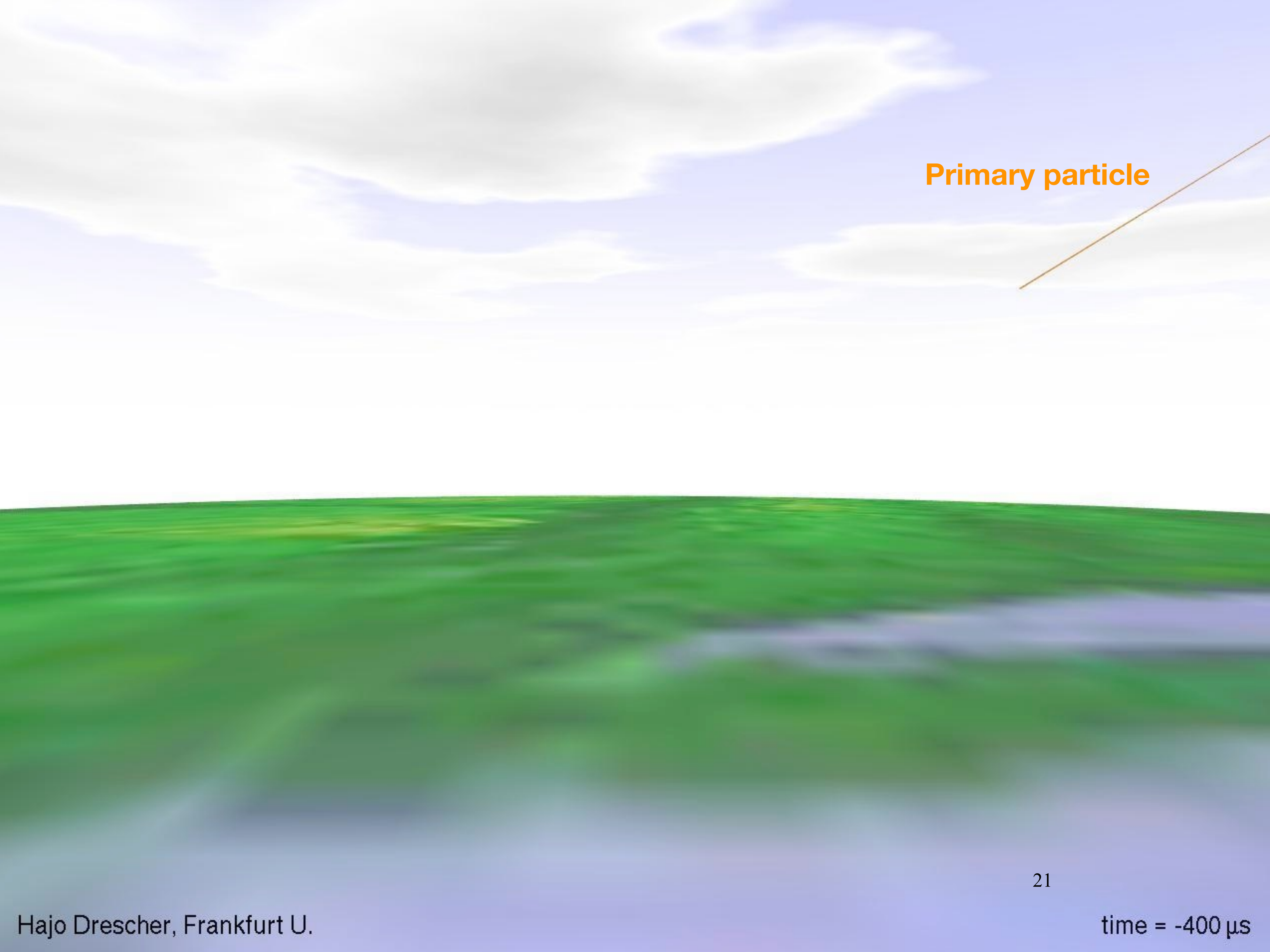
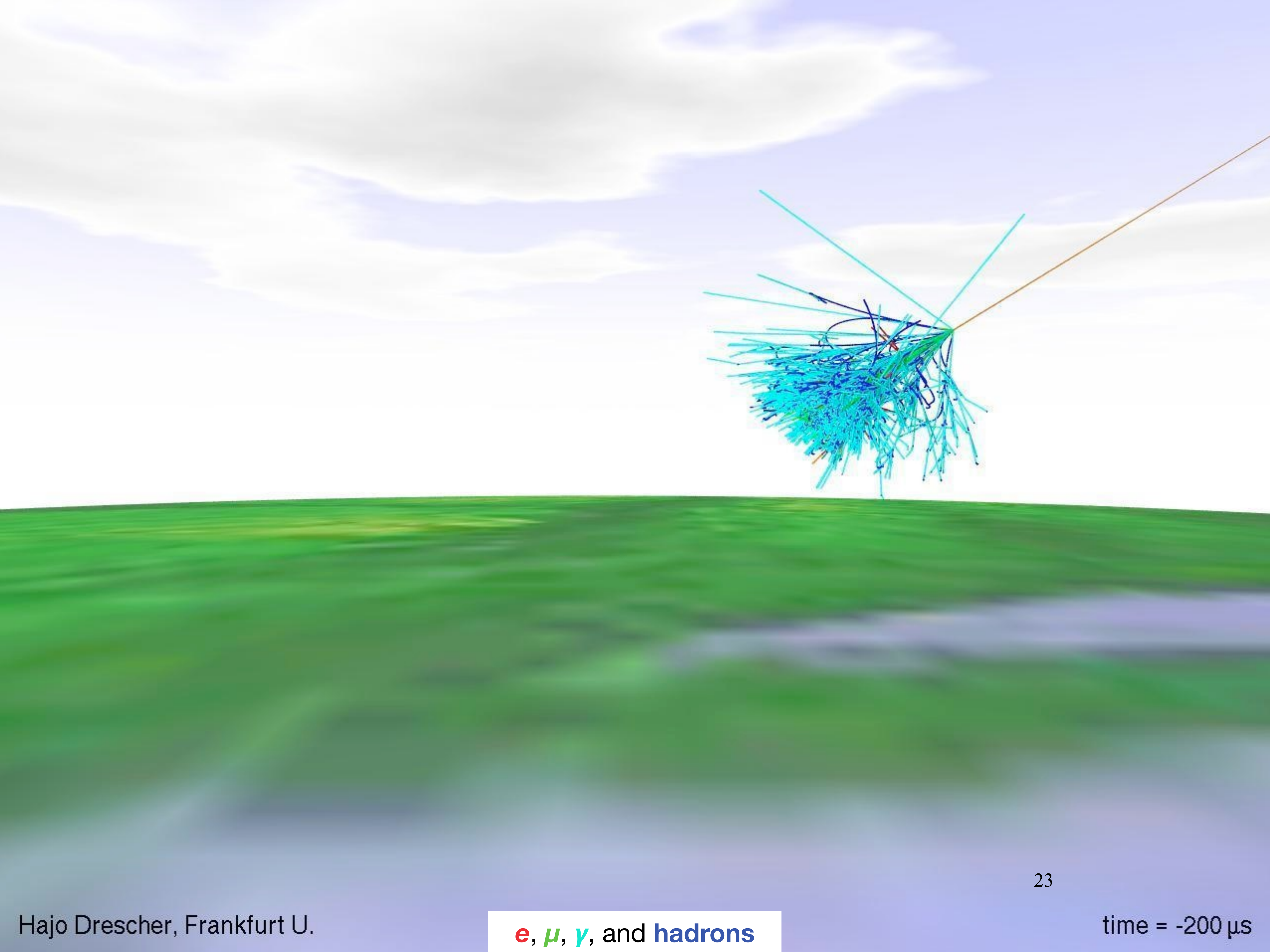


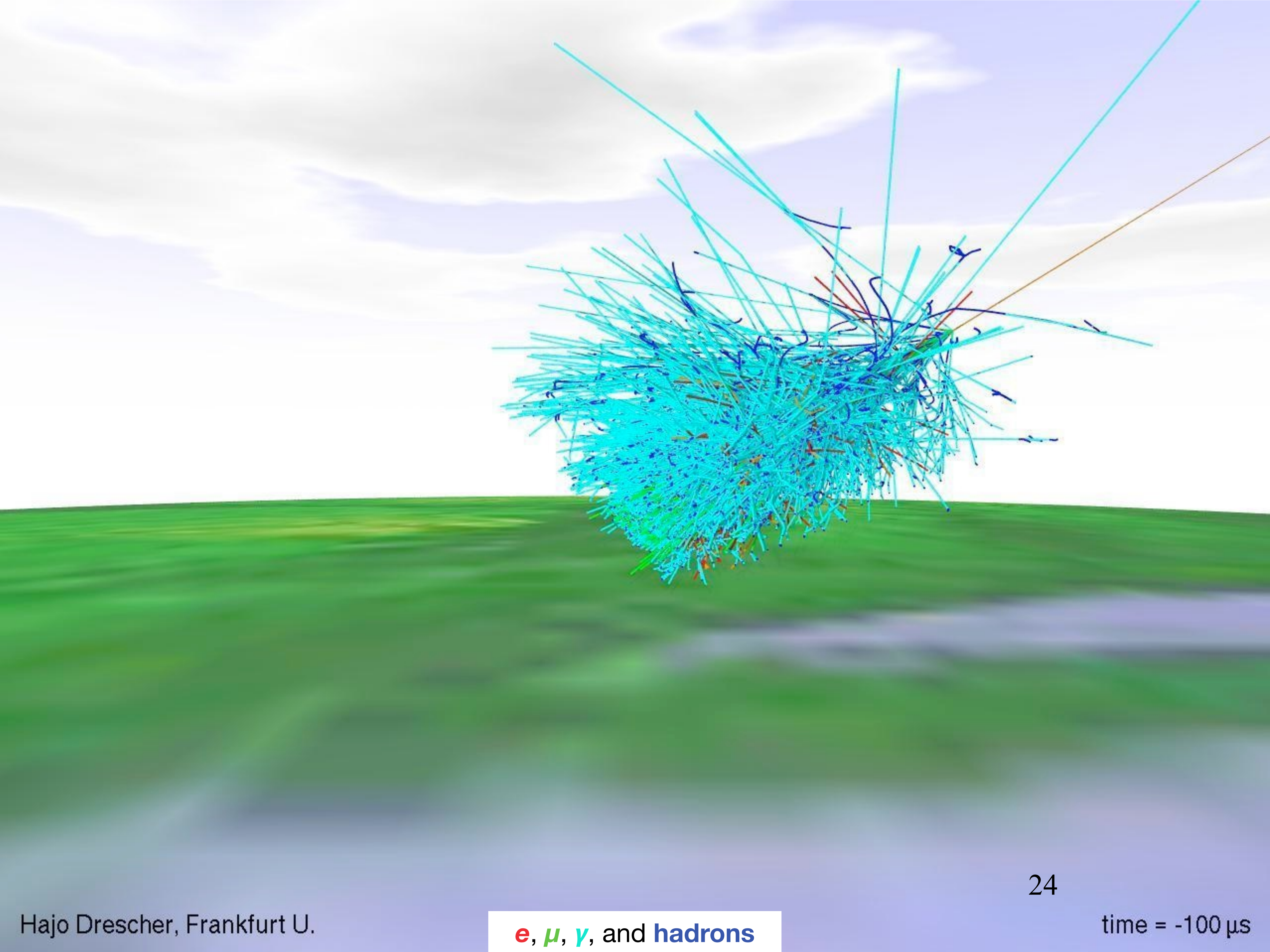
Ultra-High Energy Cosmic Rays (UHECR)

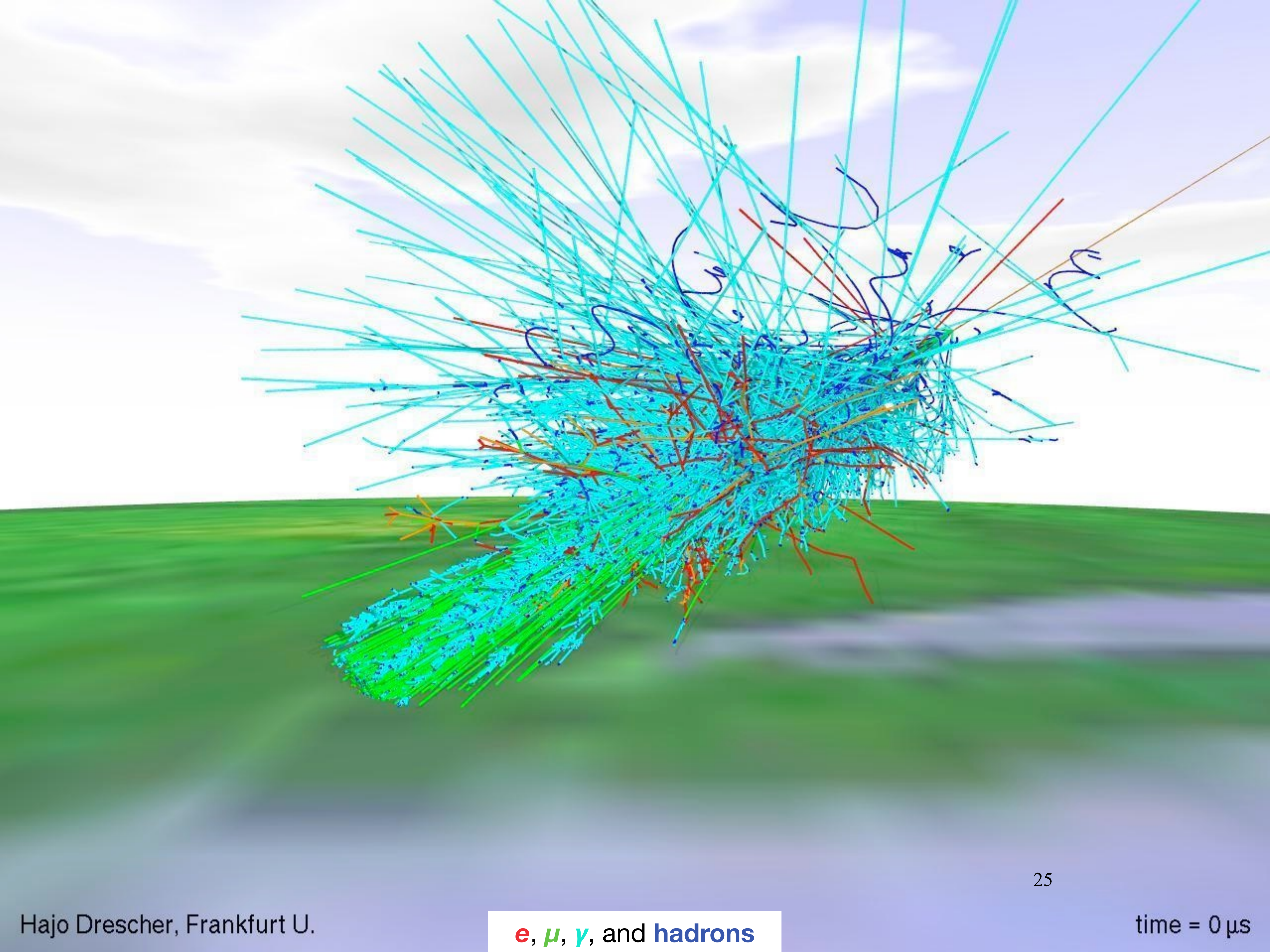
Only Indirect detection: ground-based detectors through Extensive Air Showers (**EAS**)

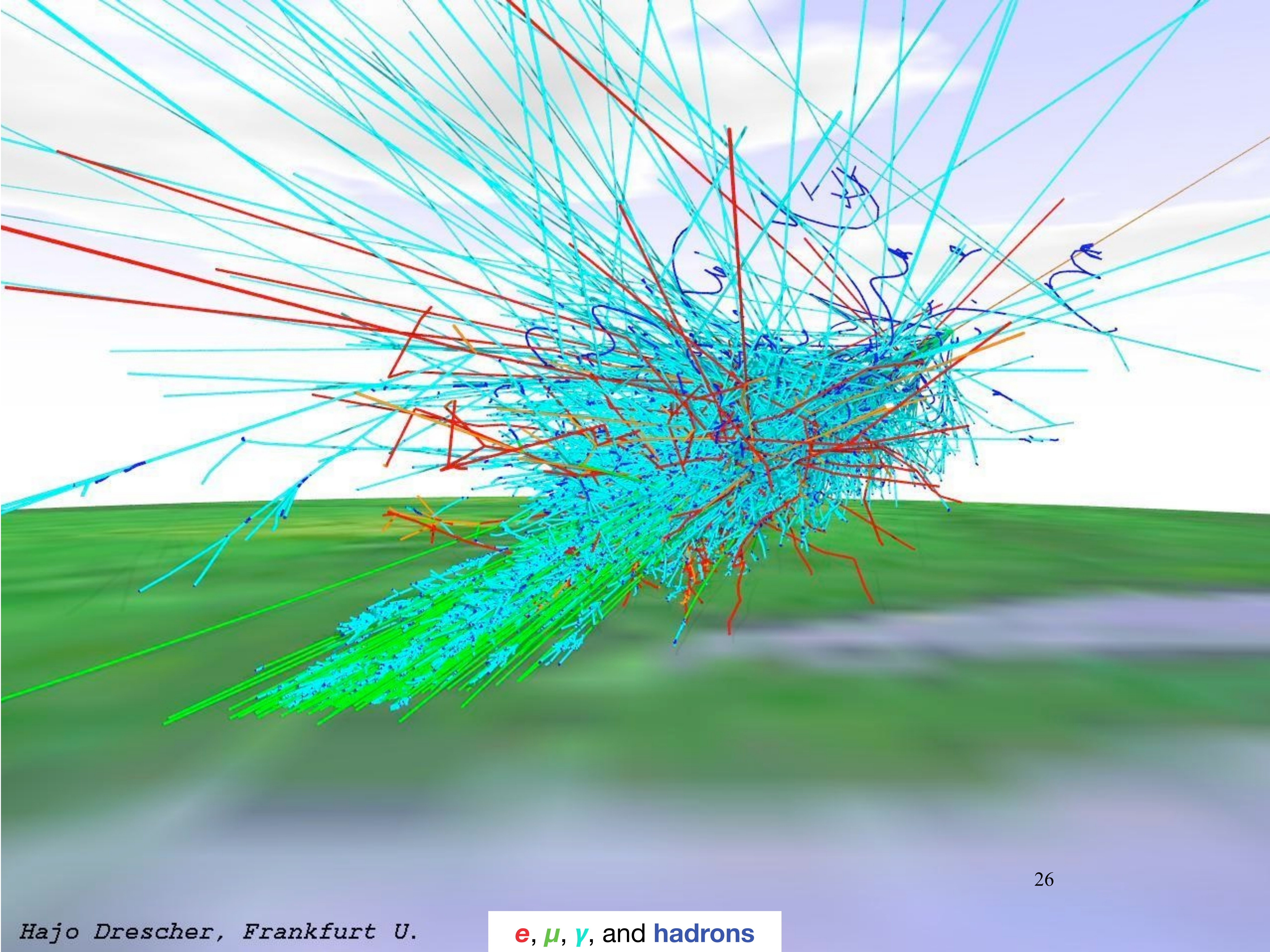

Primary particle
Hajo Drescher, Frankfurt U.
time = -400 μs


Primary particle
Secondary particles
Hajo Drescher, Frankfurt U.
e, μ, γ, and hadrons
time = -300 μs

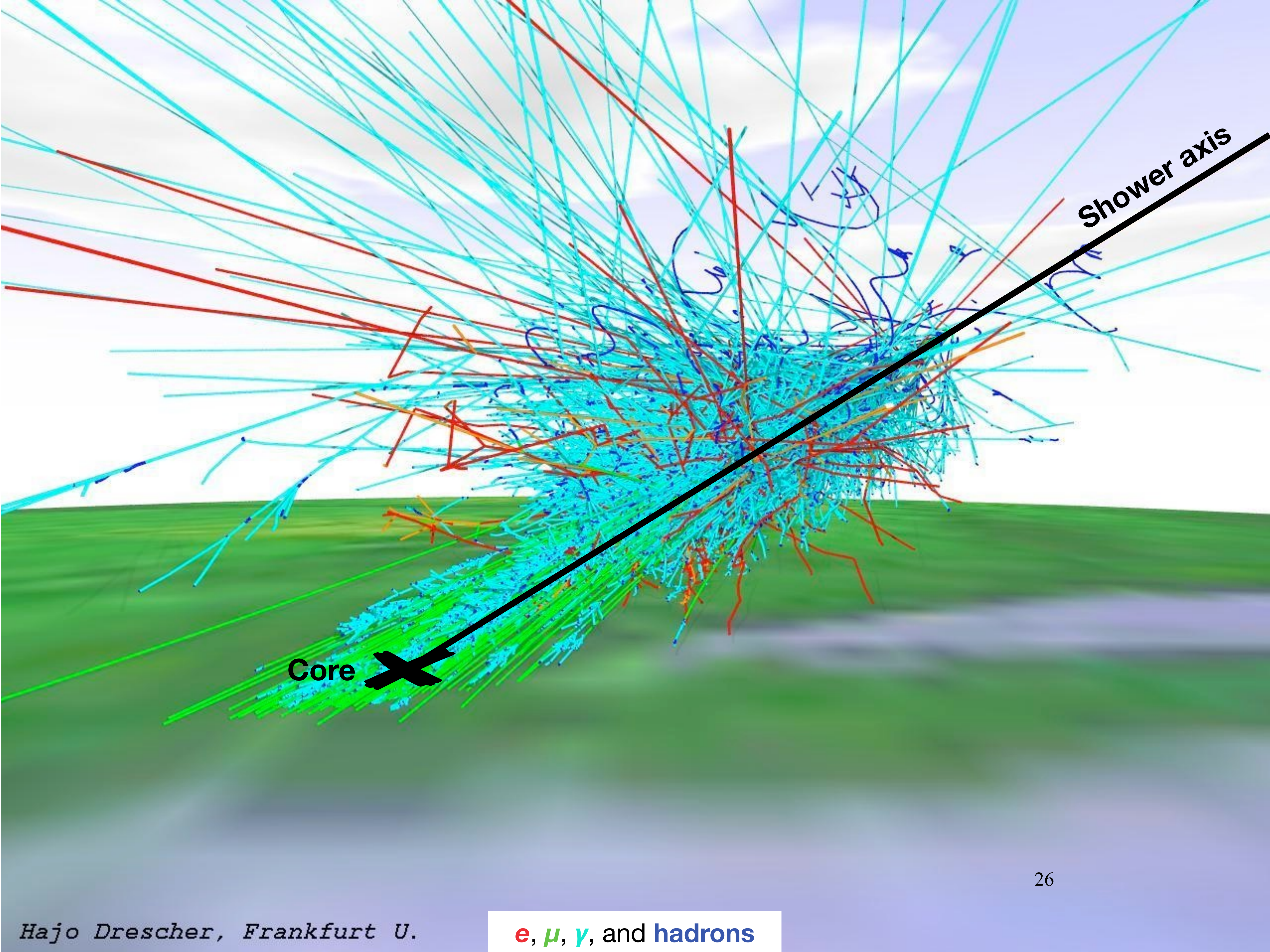

Hajo Drescher, Frankfurt U.
e, μ, γ, and hadrons
time = -200 μs

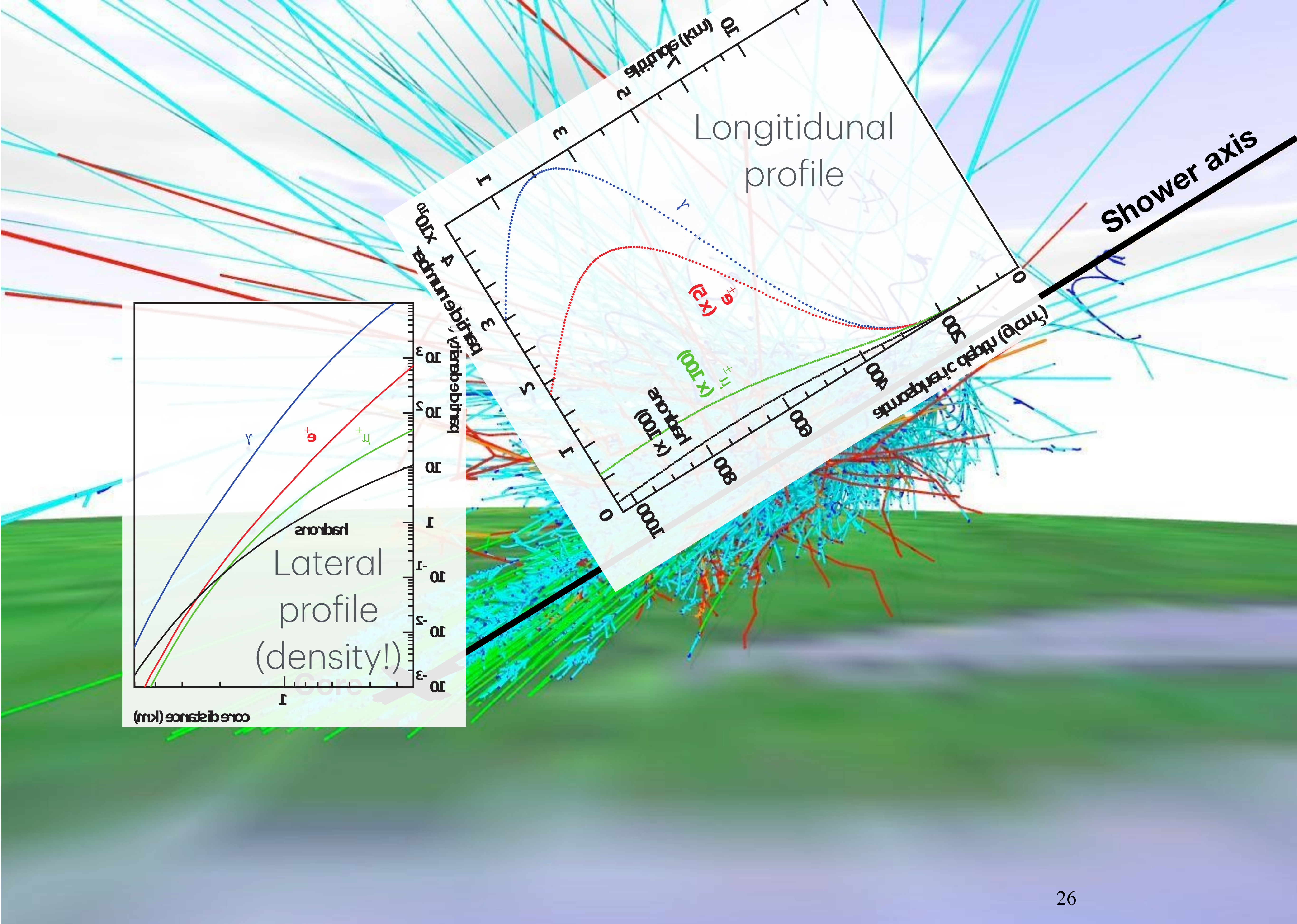

Hajo Drescher, Frankfurt U.
e, *μ*, *γ*, and **hadrons**
time = -100 µs


Hajo Drescher, Frankfurt U.
e, μ, γ, and hadrons
time = 0 µs



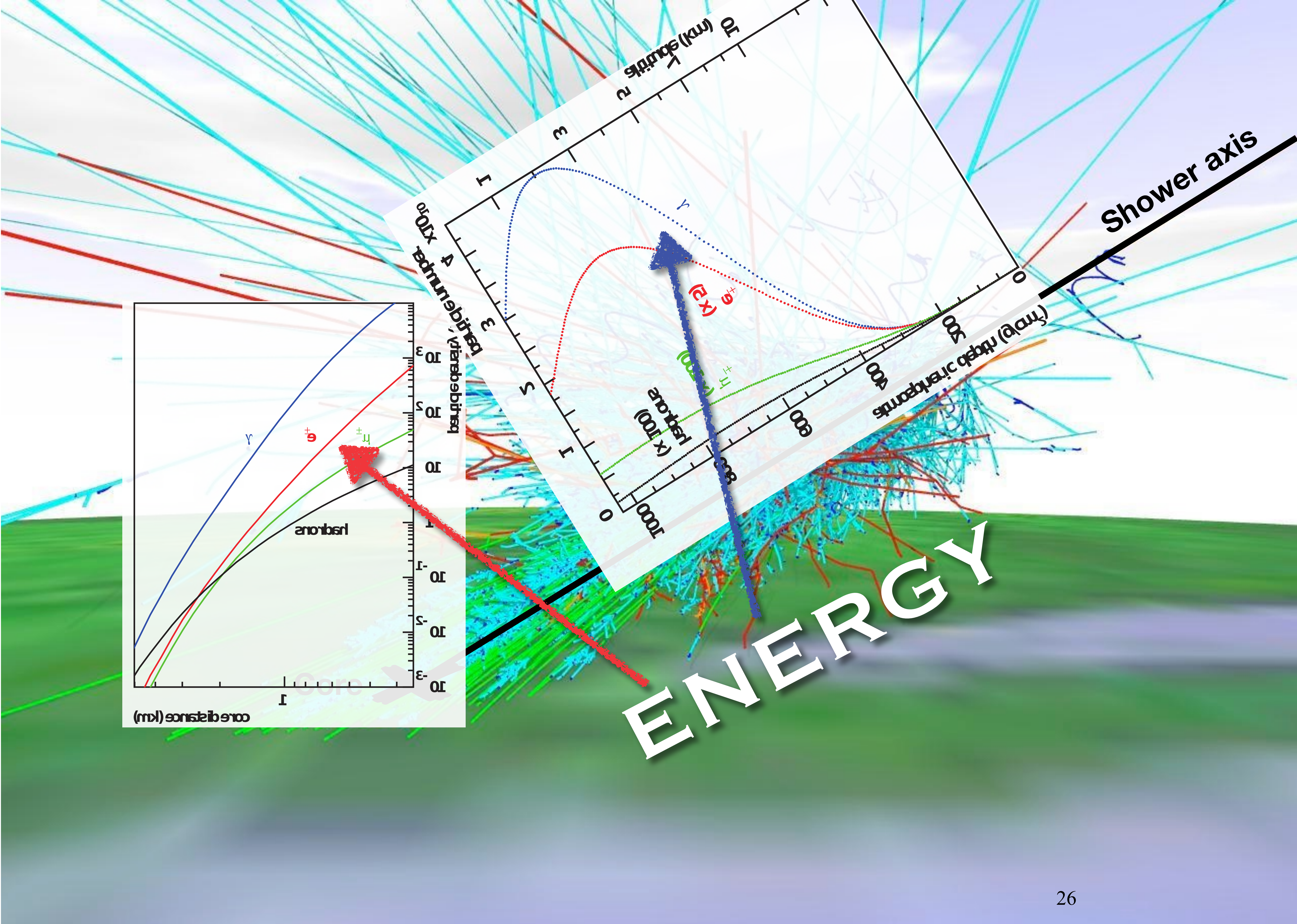
e, μ, γ, and hadrons


Shower axis
Core
Hajo Drescher, Frankfurt U.
e, μ, γ, and hadrons



Hajo Drescher, Frankfurt U.

e, ***μ***, ***γ***, and **hadrons**



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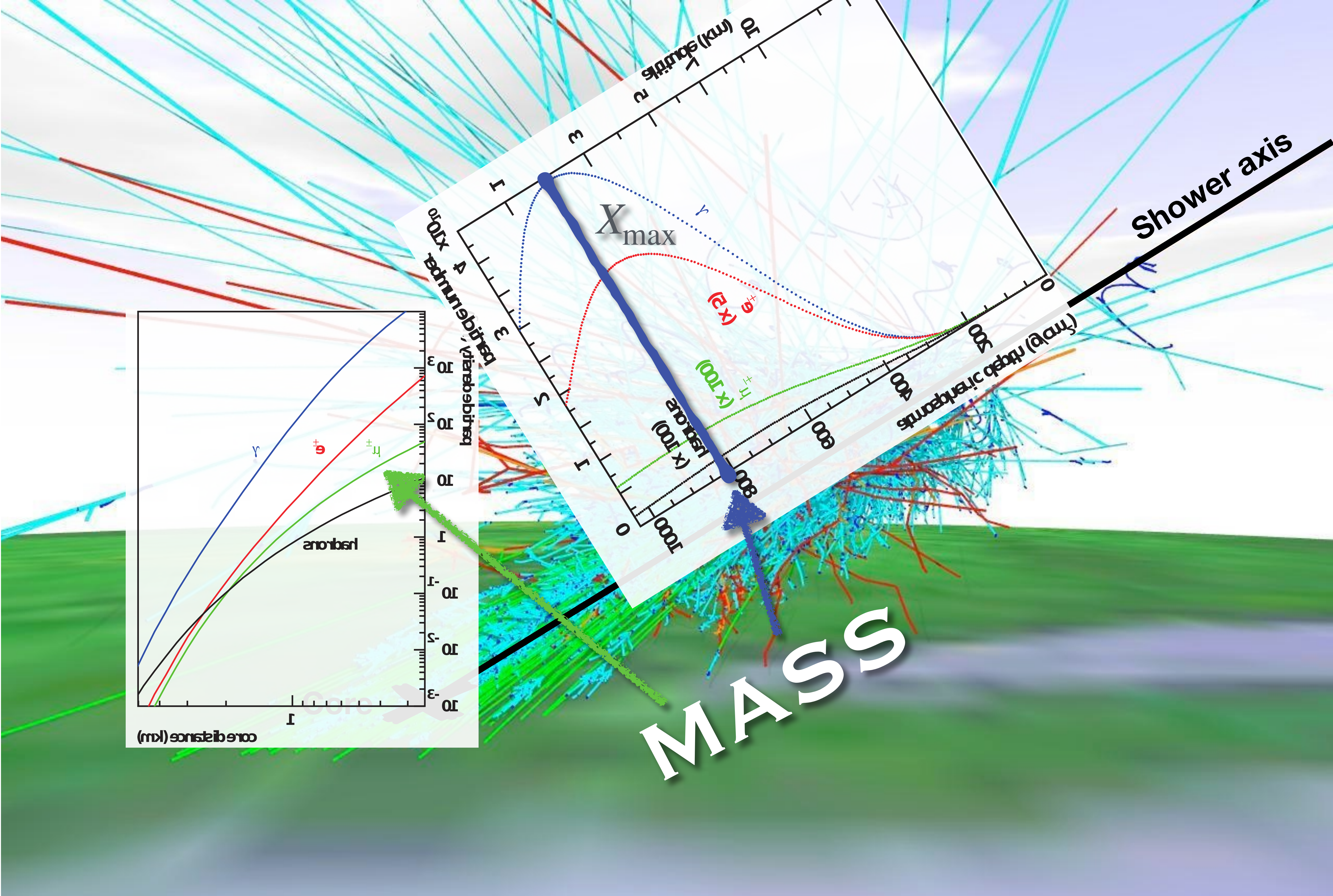
e, μ, γ, and **hadrons**



Hajo Drescher, Frankfurt U.

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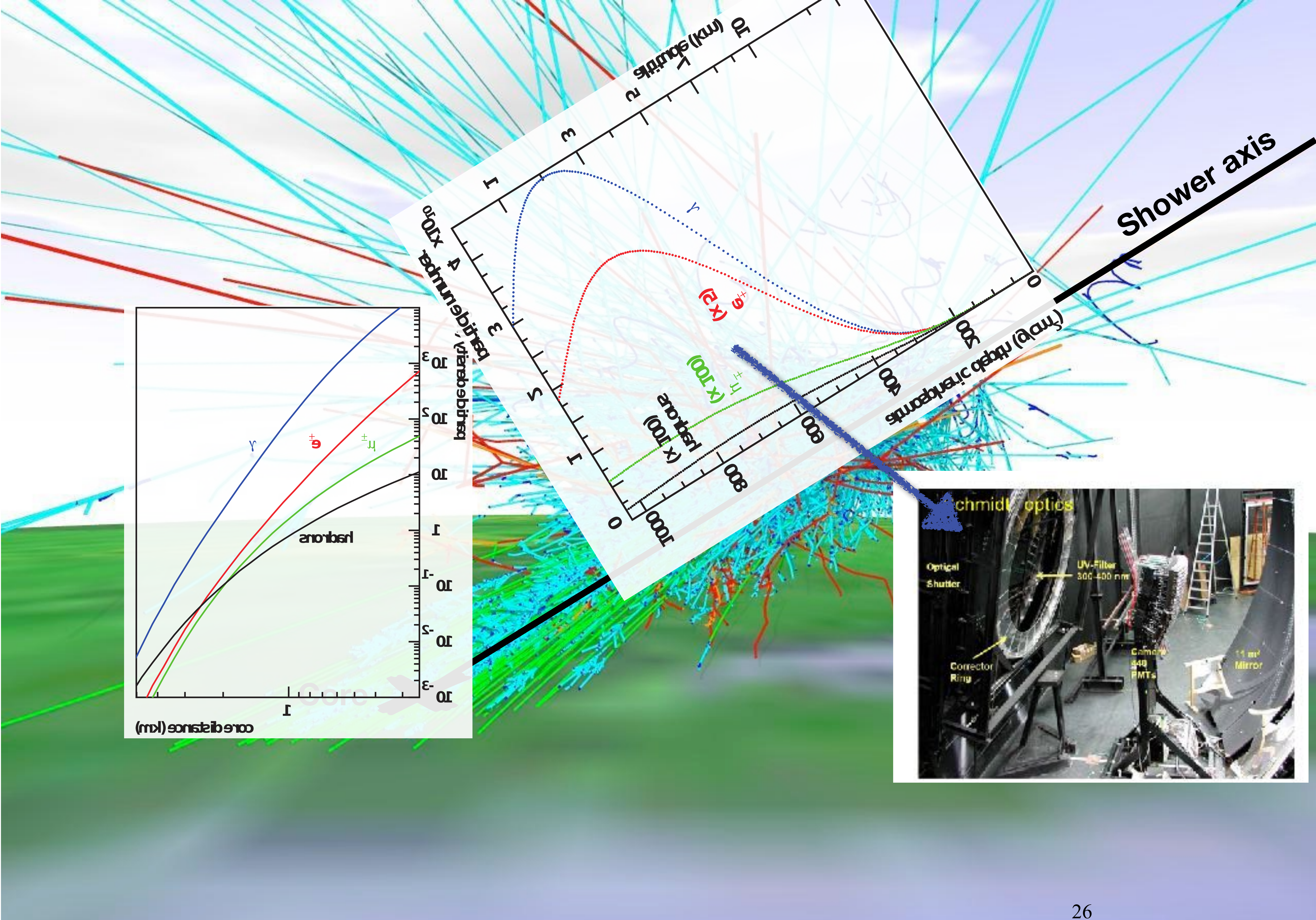

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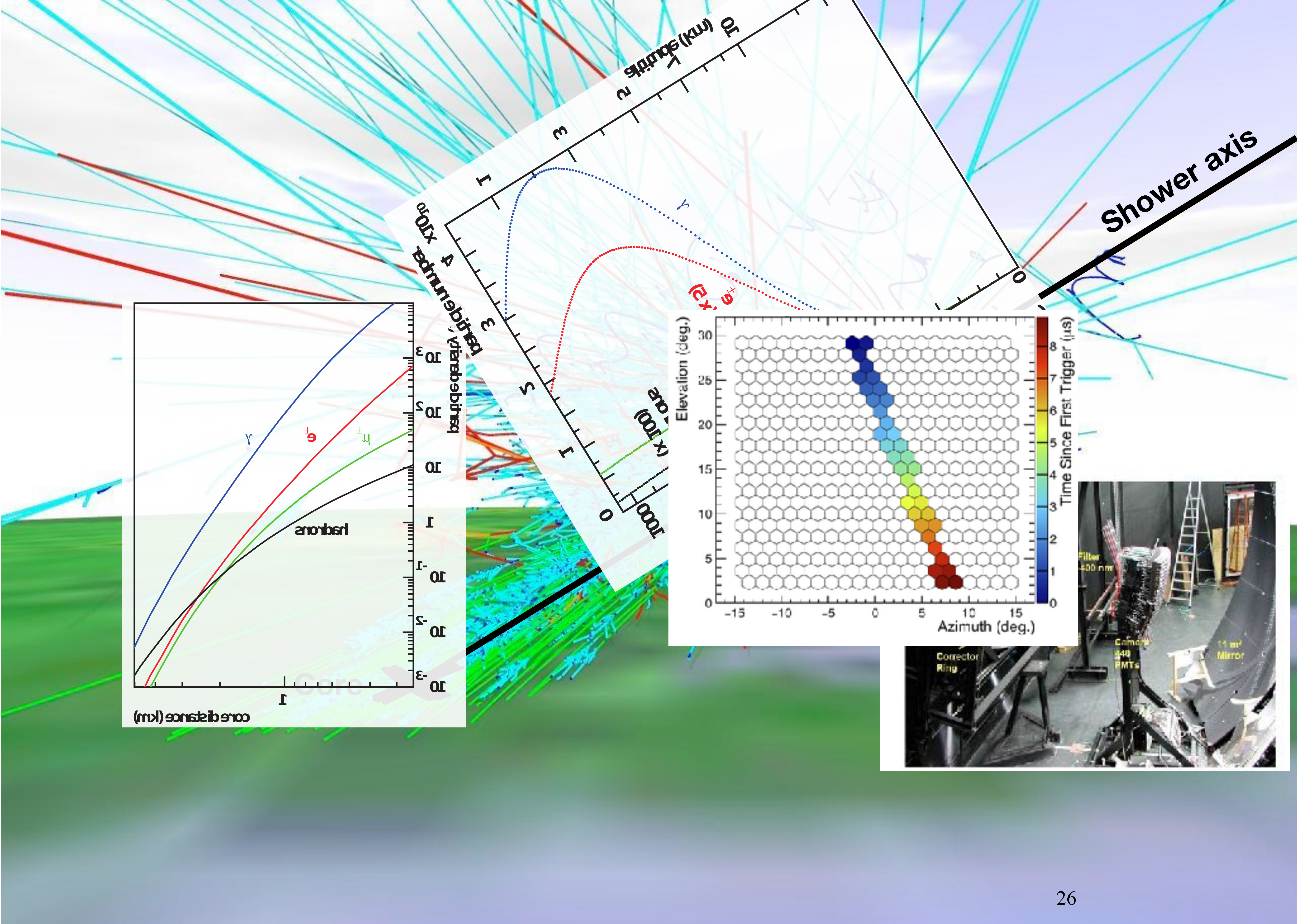

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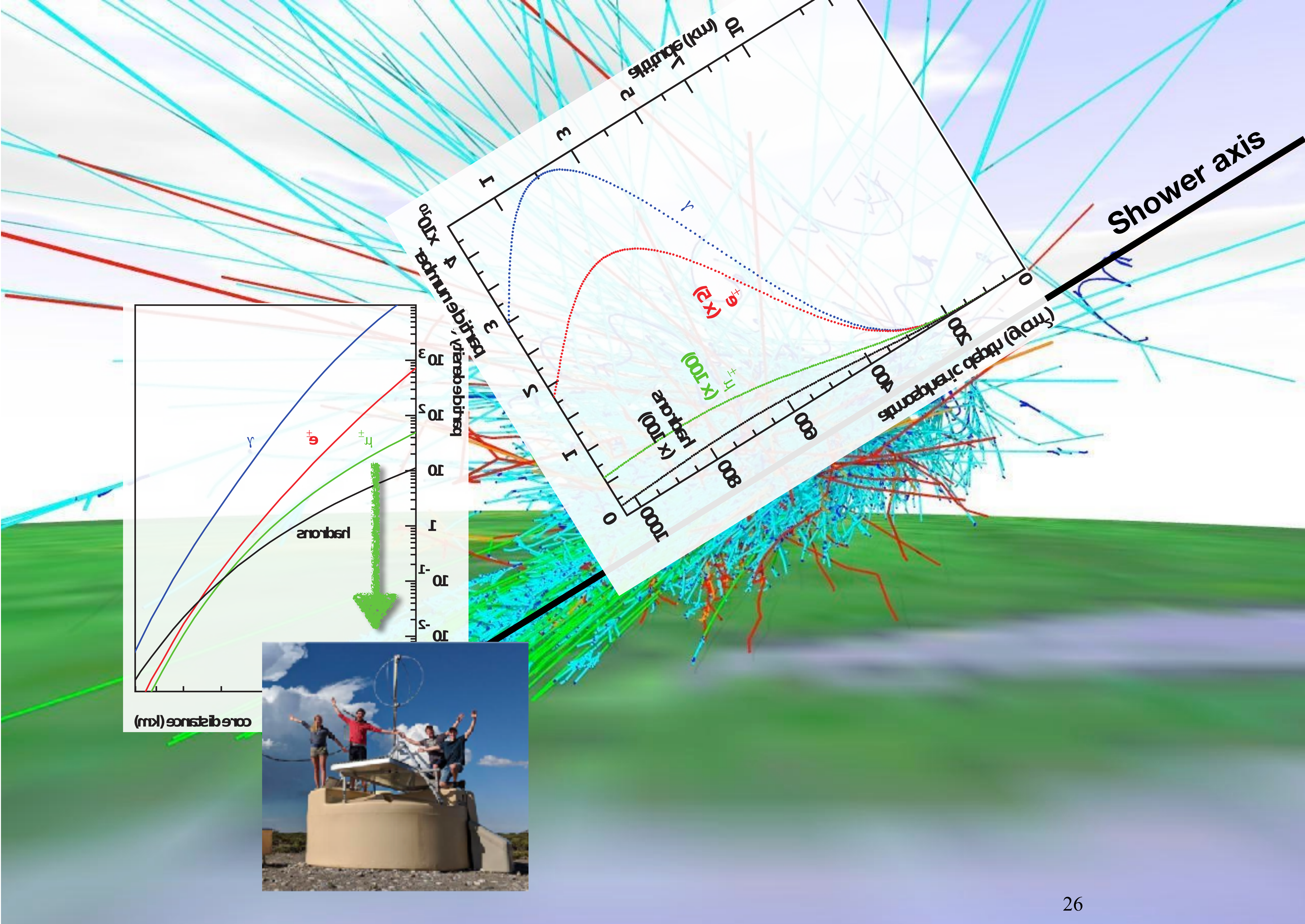

Hajo Drescher, Frankfurt U.

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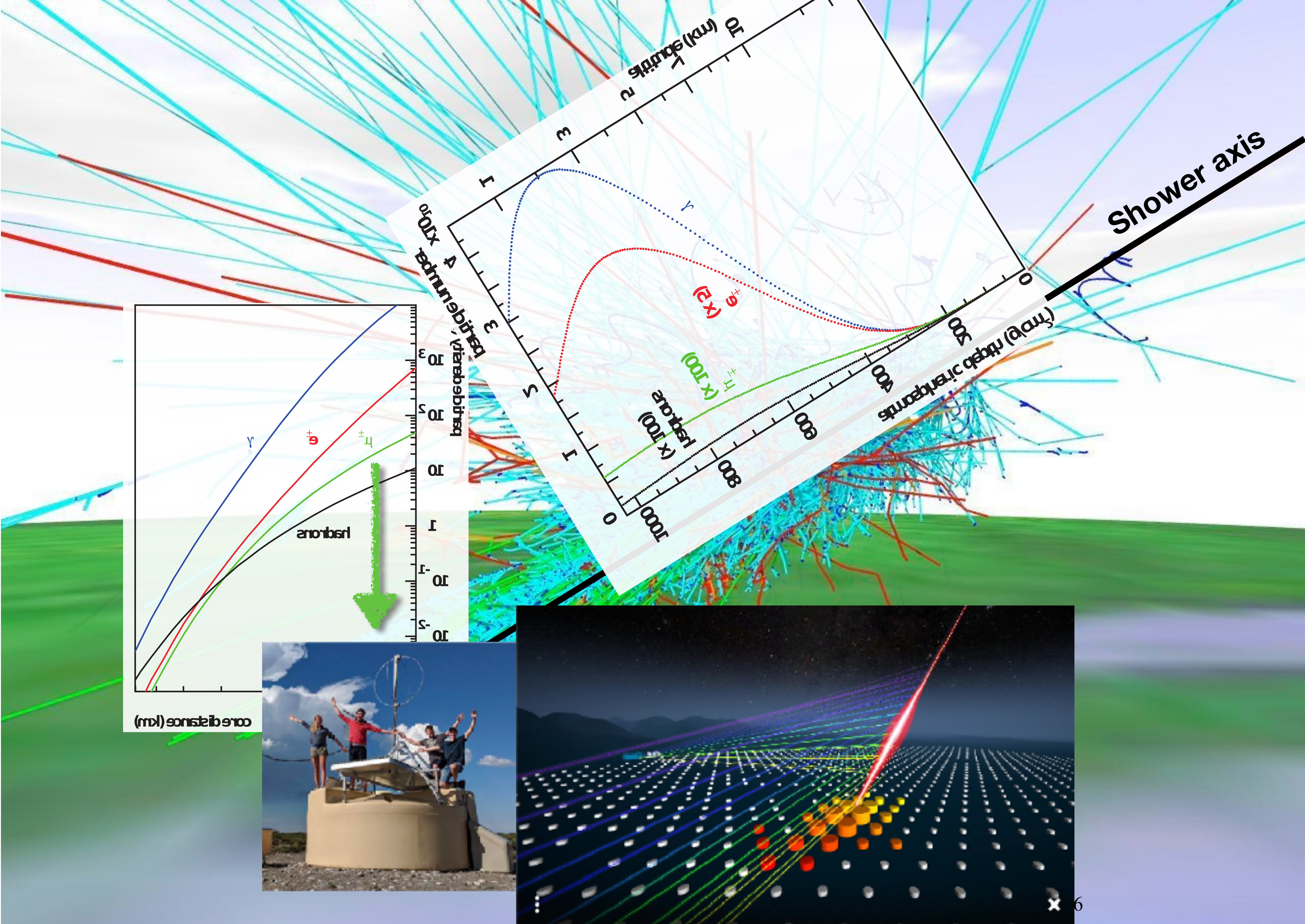


6

e, μ, γ, and hadrons

Hajo Drescher, Frankfurt U.

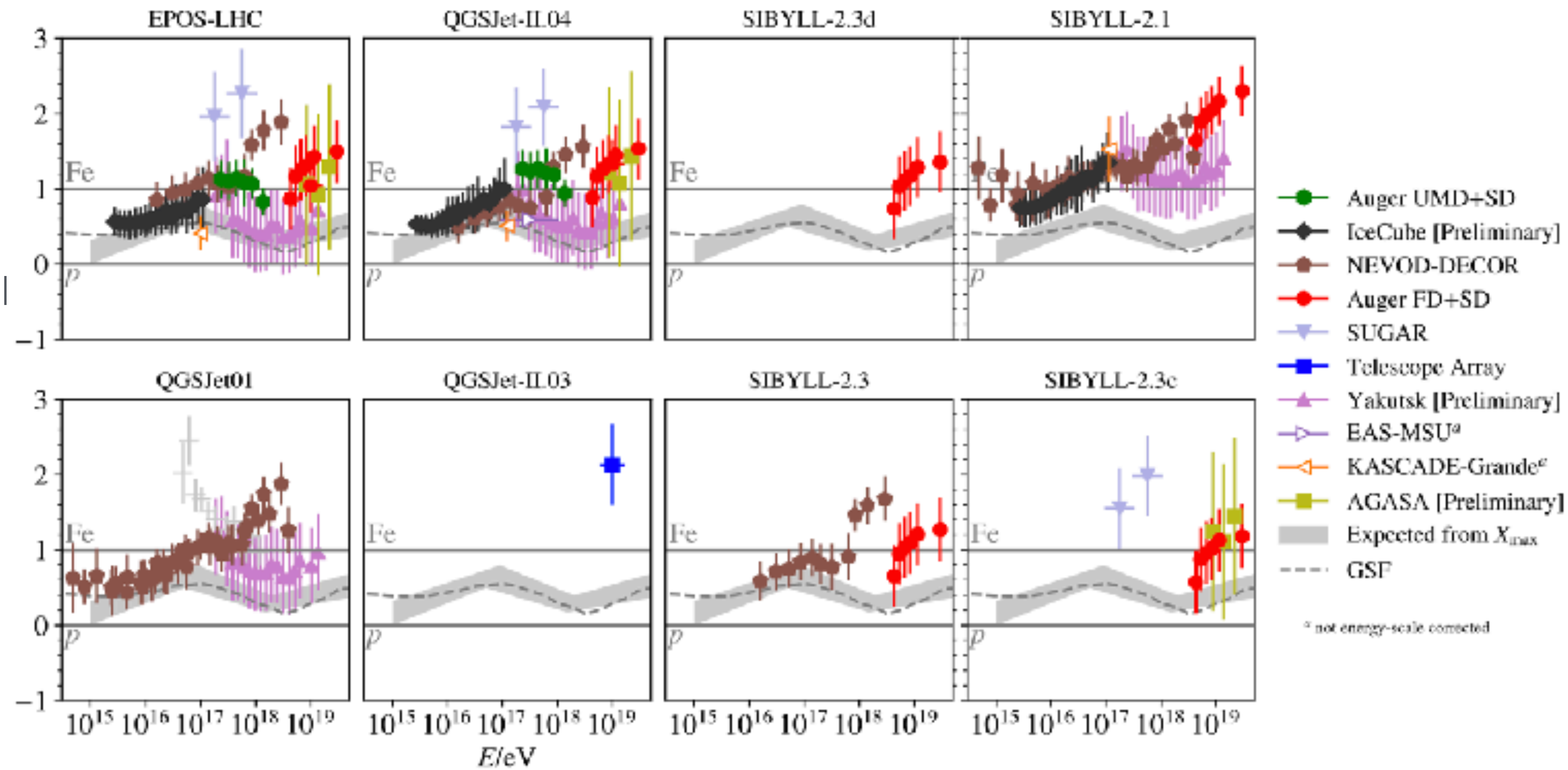
Houston, we have a problem!

3 Hadronic interaction Models used (+ variants)

Data

$$z = \frac{\log \rho_\mu - \log \rho_\mu^p}{\log \rho_\mu^{\mathrm{Fe}} - \log \rho_\mu^p}$$

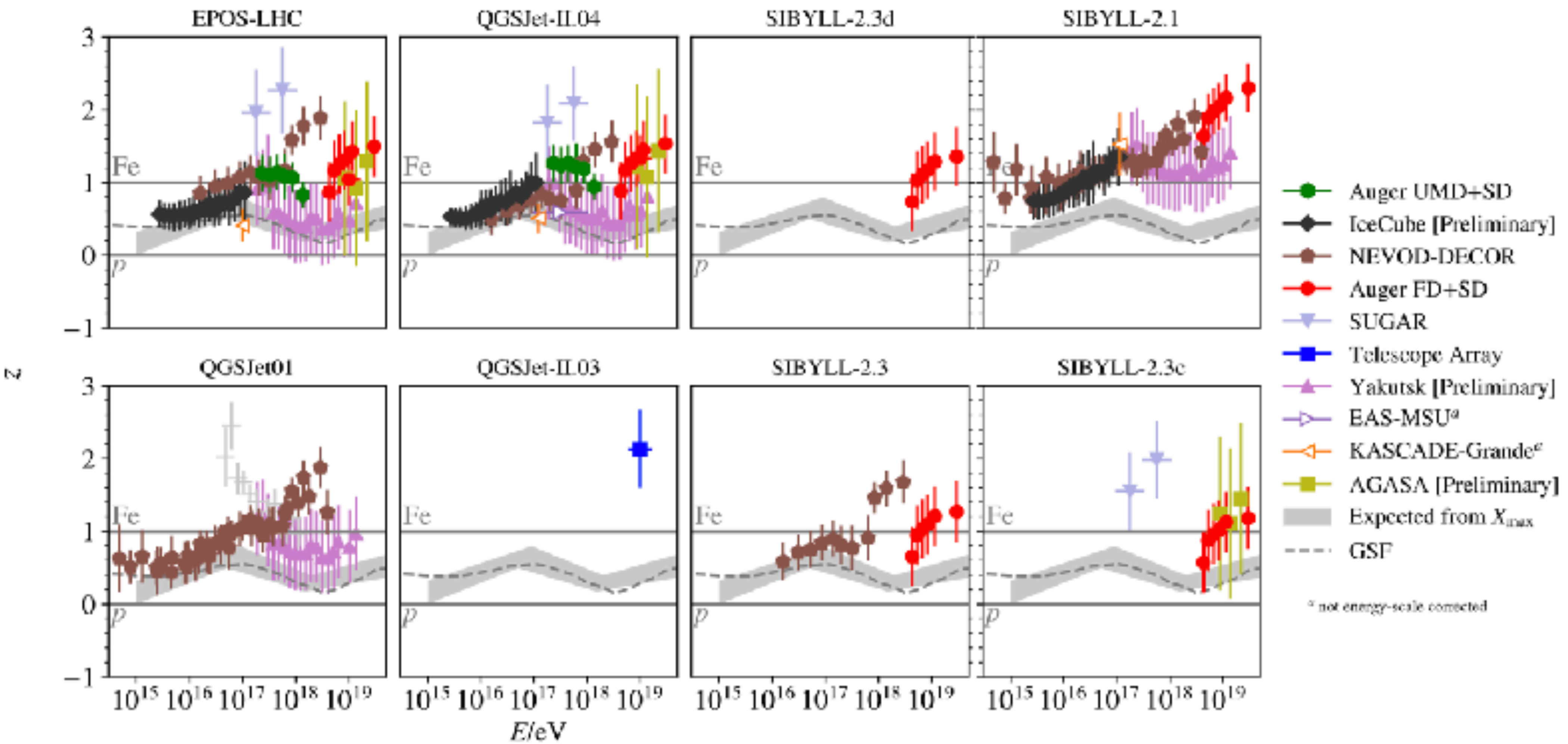
Model



...a discrepancy occurs!

3 HEHI Models (+ variants)

$$z = \frac{\log \rho_\mu - \log \rho_\mu^p}{\log \rho_\mu^{\mathrm{Fe}} - \log \rho_\mu^p}$$



- $X_{\max}$ correct

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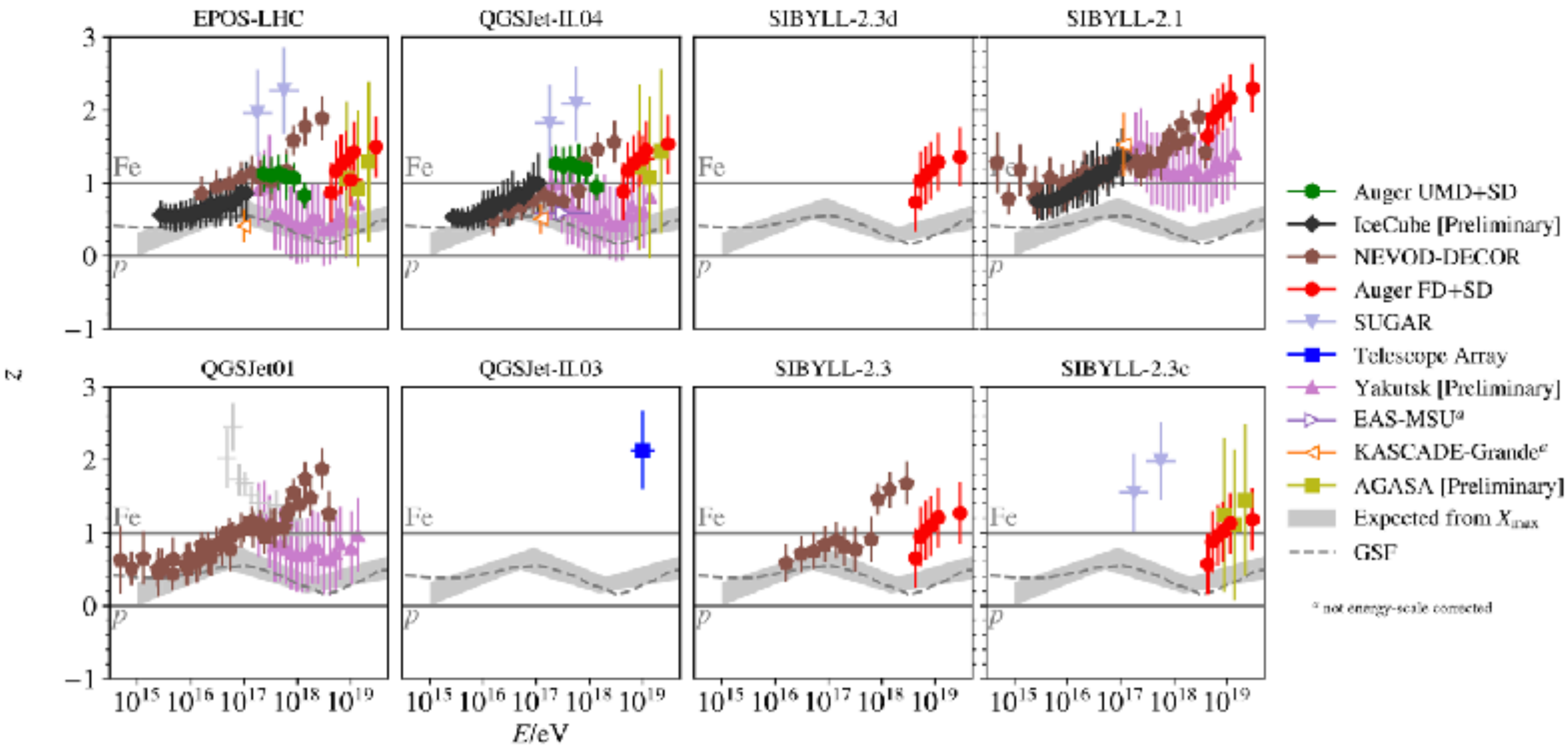

- $X_{\max}$ correct
- Lateral density incorrect

…a discrepancy occurs!

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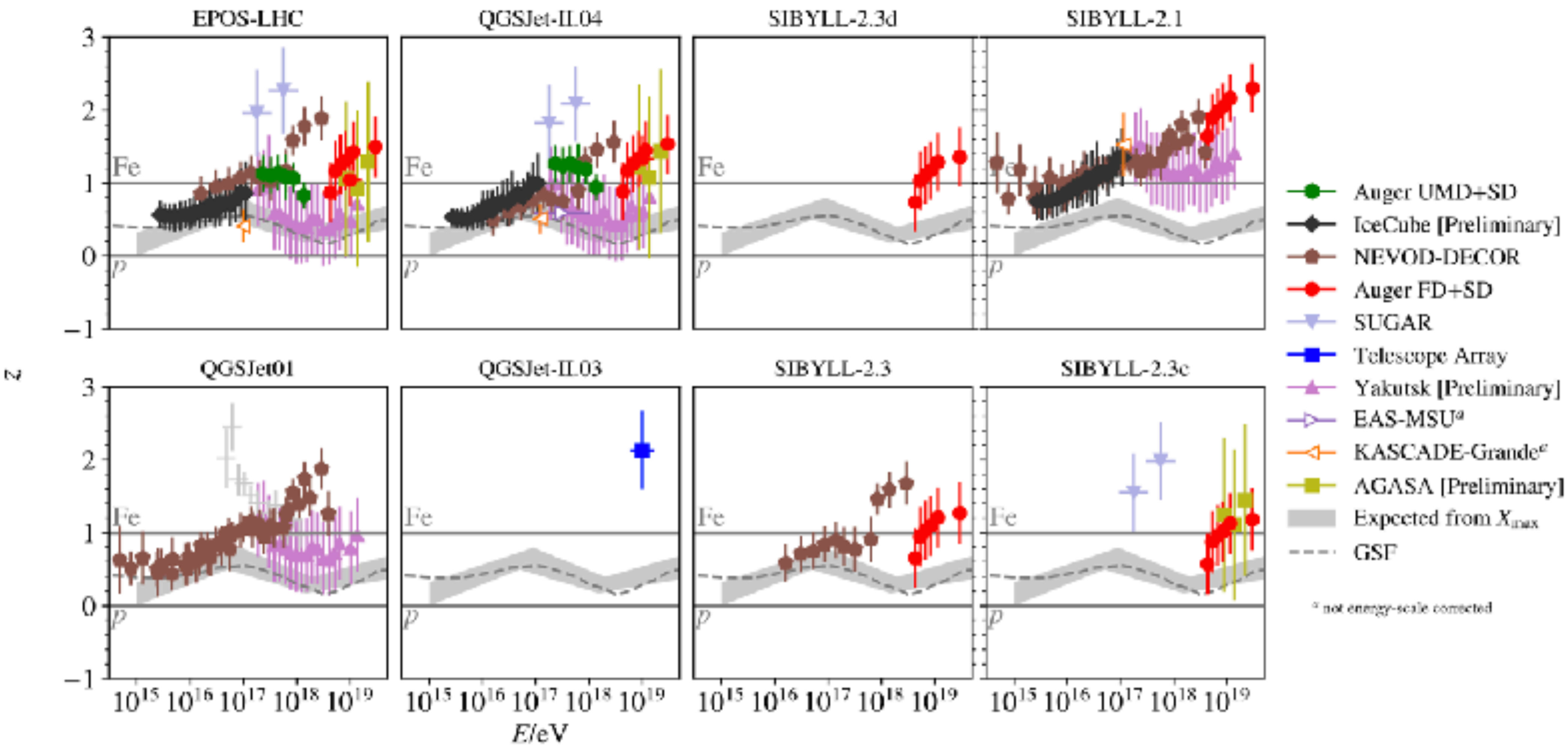

- $X_{\max}$ correct
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- At <100 PeV, the discrepancy is not evident

…a discrepancy occurs!

3 HEHI Models (+ variants): **SOME "EFFECT" IS MISSING!**

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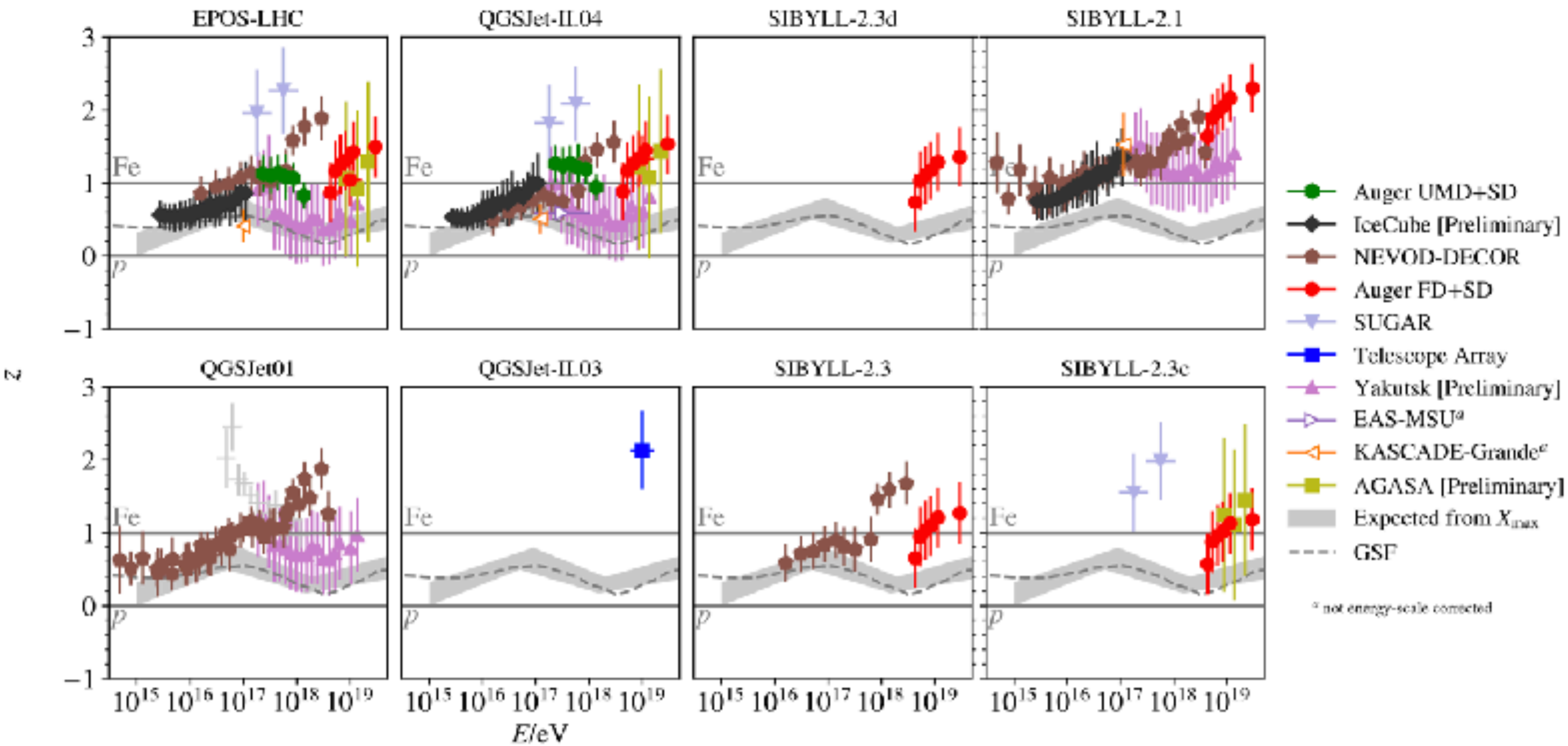

Early stages of the EAS: Isn't it there, or is it negligible?

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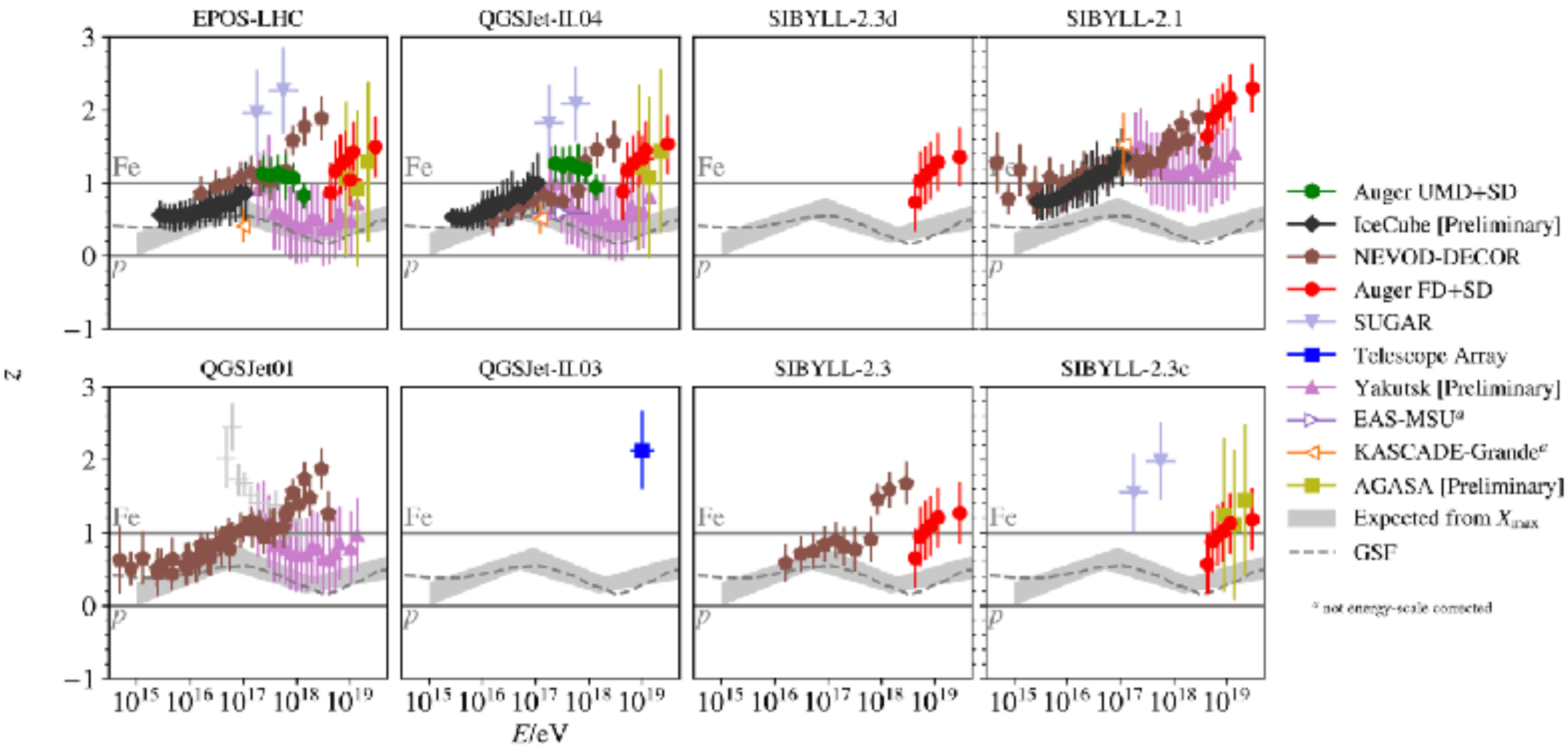

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Later stages of the EAS: Does the effect occur here, or is it magnified?

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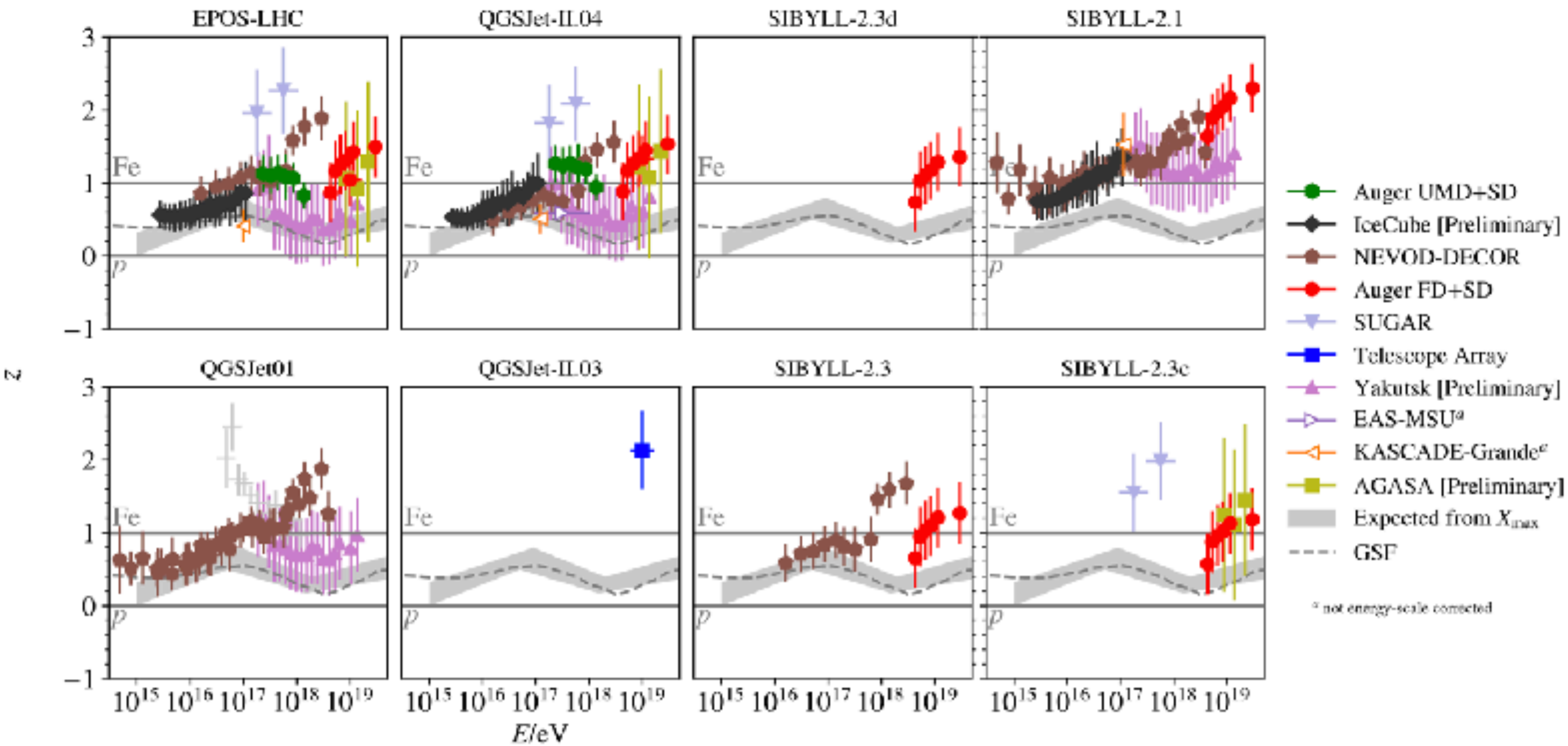


Early stages of the EAS: Isn't it there, or is it negligible?

- X_{max} correct

Later stages of the EAS: Does the effect occur here, or is it magnified?

- Lateral density incorrect

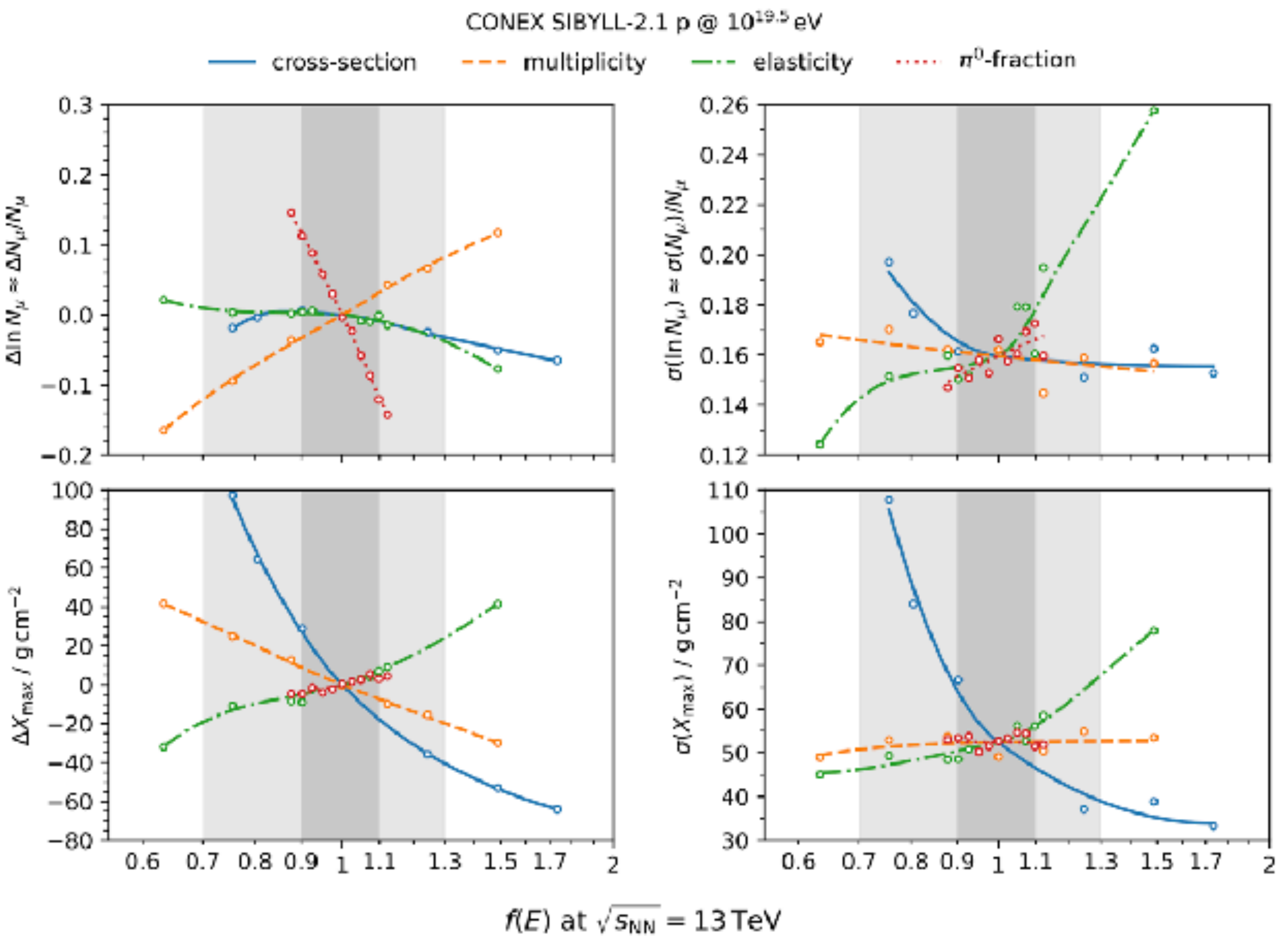
Does it not happen often at low energies? Does shower physics balance it out at high n?

- At <100 PeV, the discrepancy is not evident

The Muon Puzzle

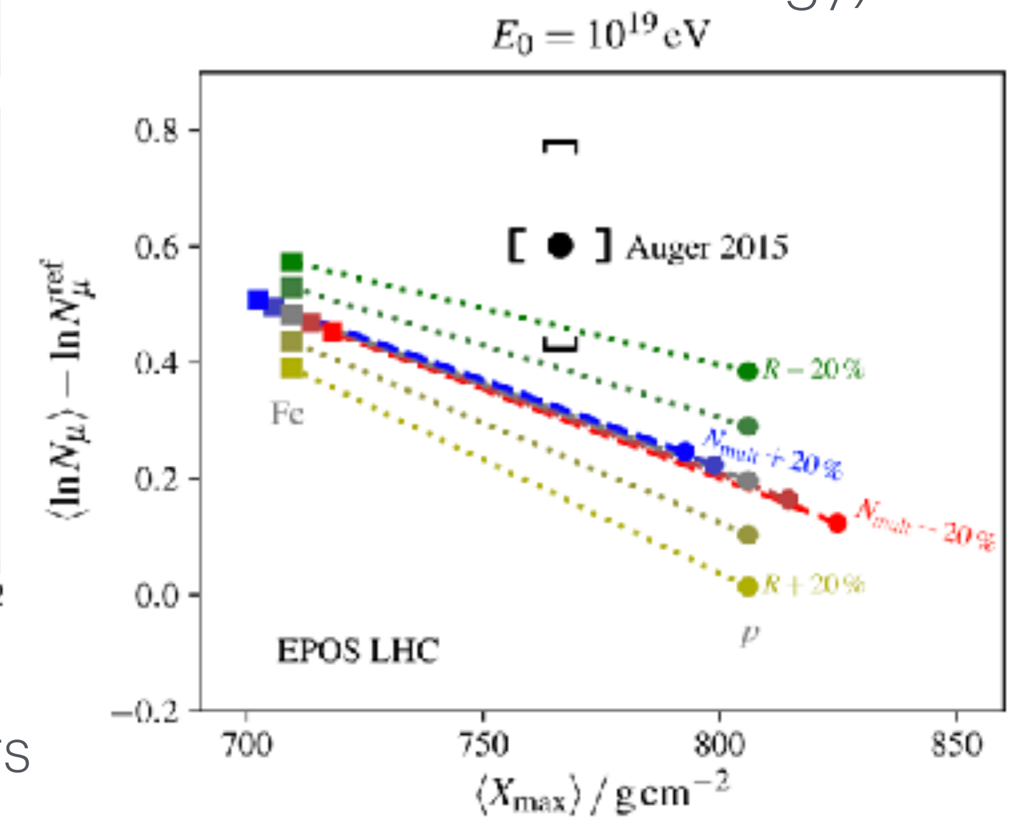
State-of-the-art [Astrophys. Space Sci. 367 3, 27 (2022)]

Simulations predict fewer muons than Reality!



(Observable changes in varying the simulation parameters
Grey areas: ±10% and 30% of variation)

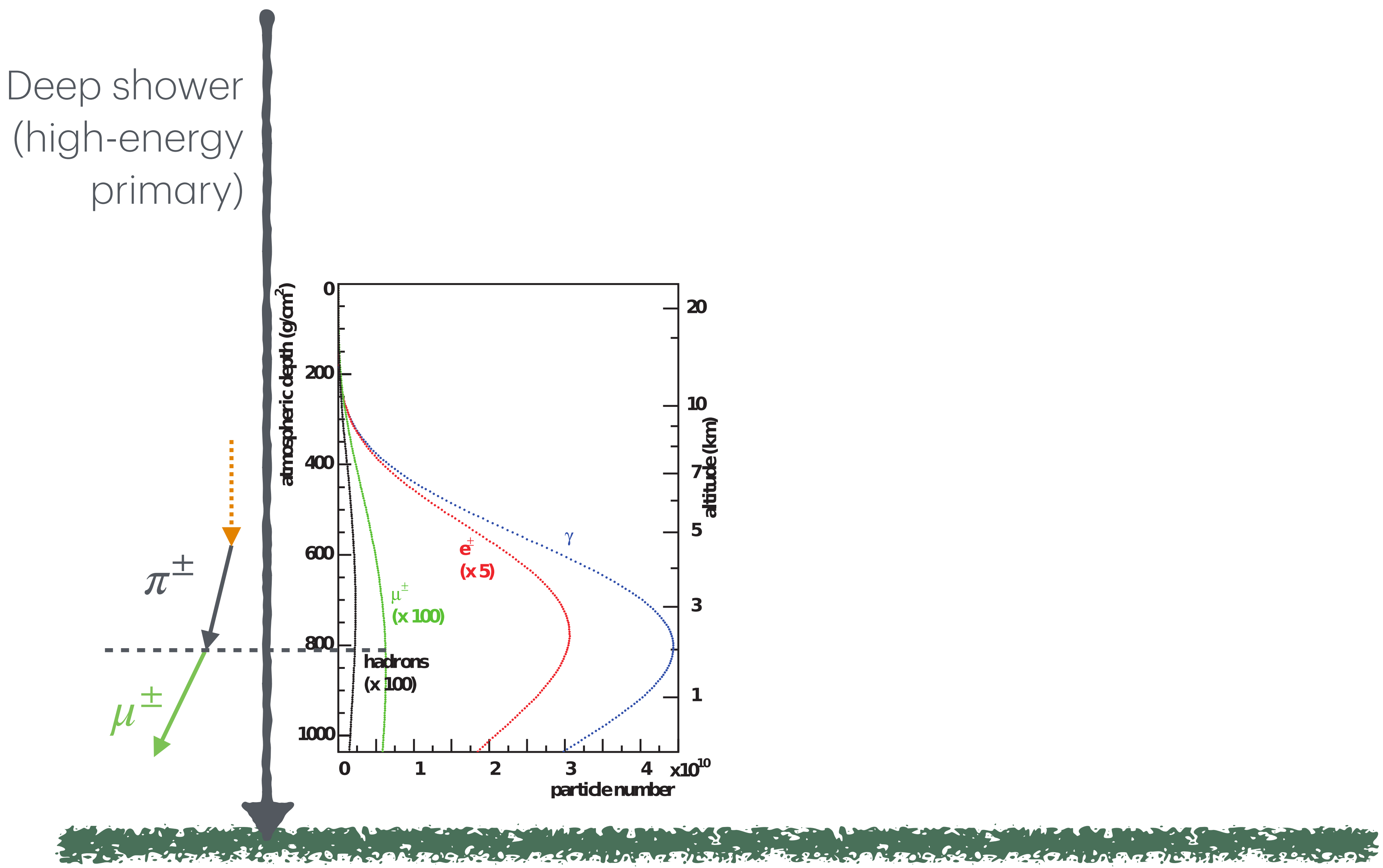
Modifying n_{mult} and R
(ratio of electromagnetic
to hadronic energy)



A Hypothesis…

What if Polarization is the cause of the Muon Puzzle?

Different outgoing angles after interaction $\Rightarrow$ more interaction lengths



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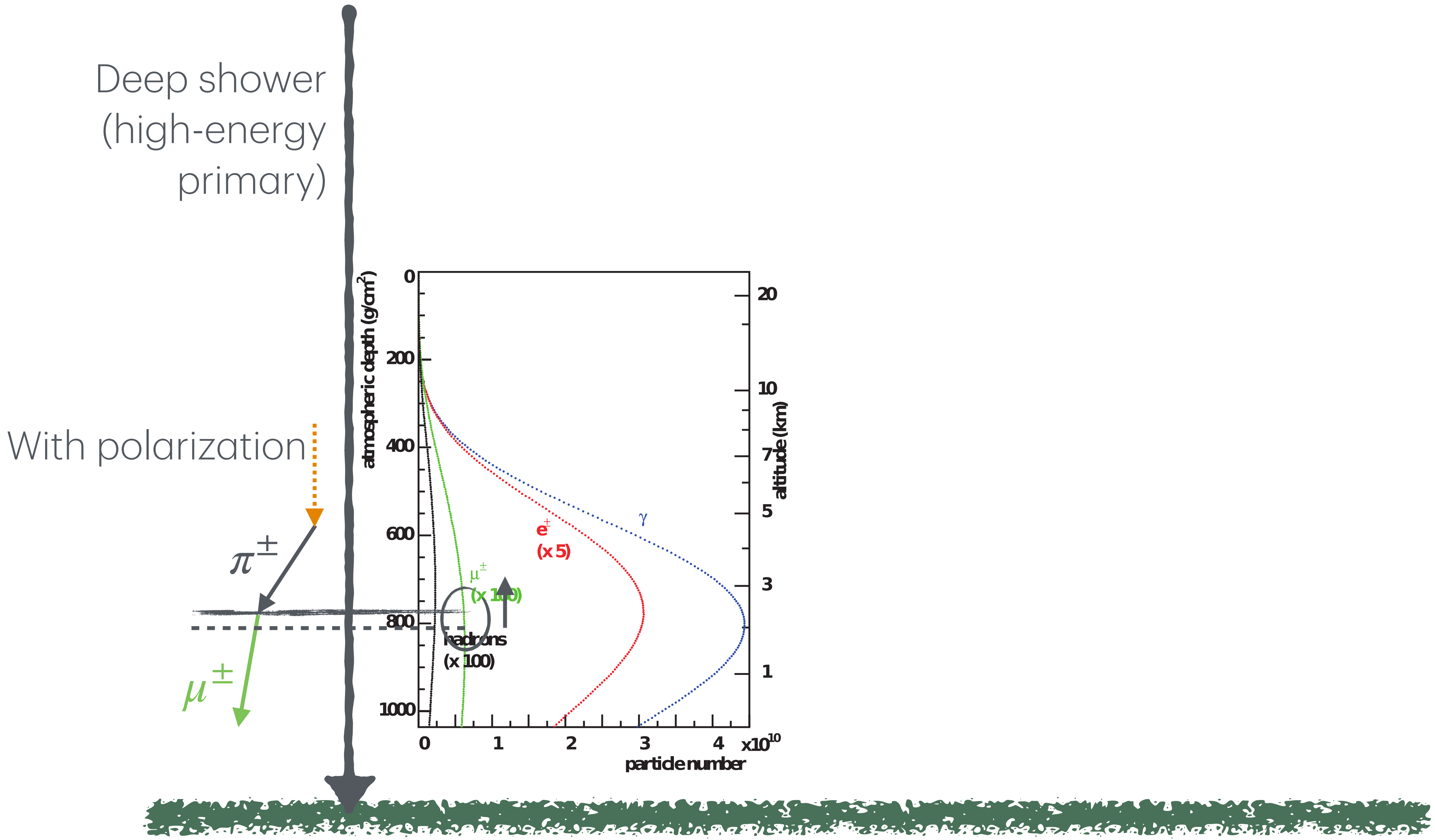

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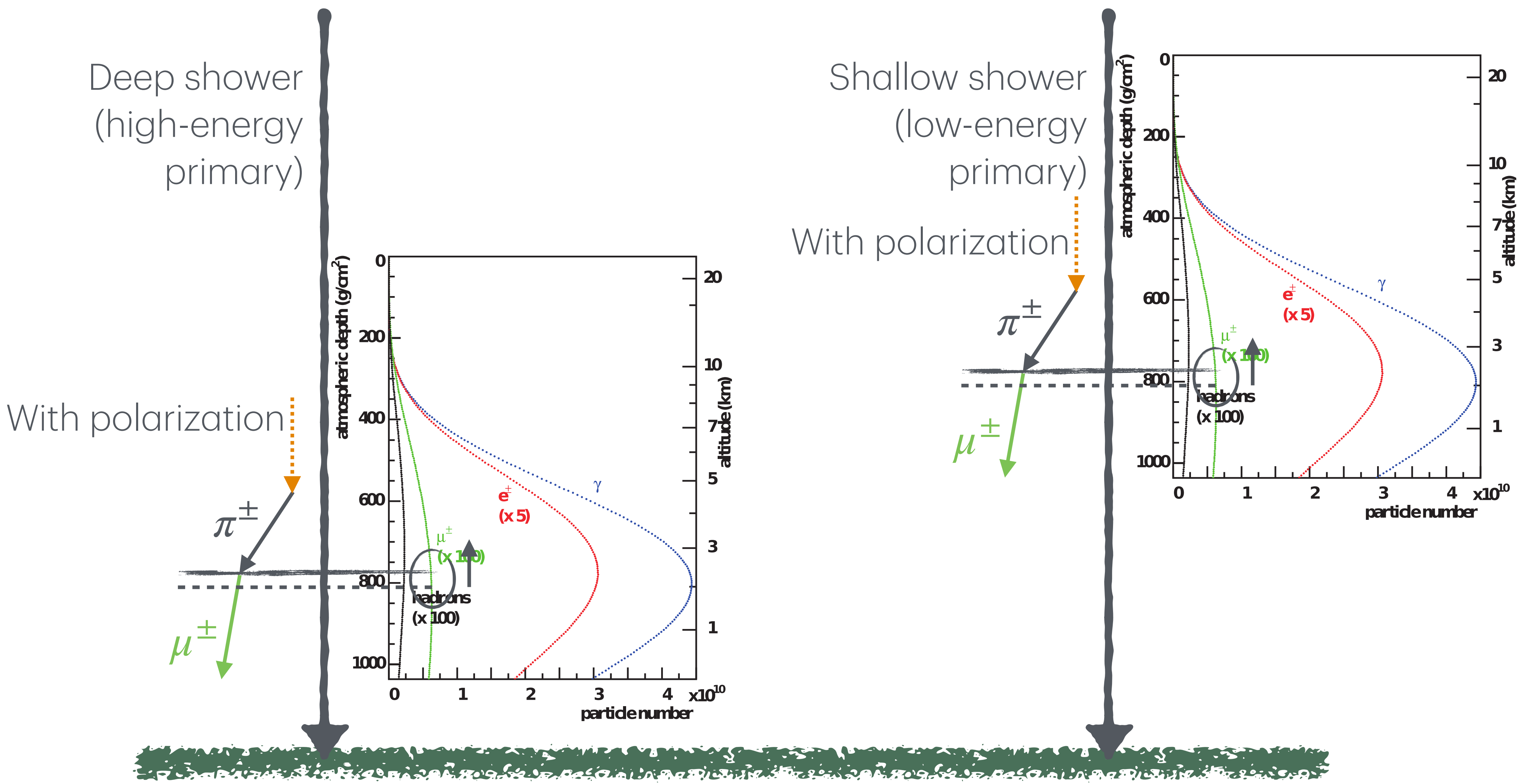

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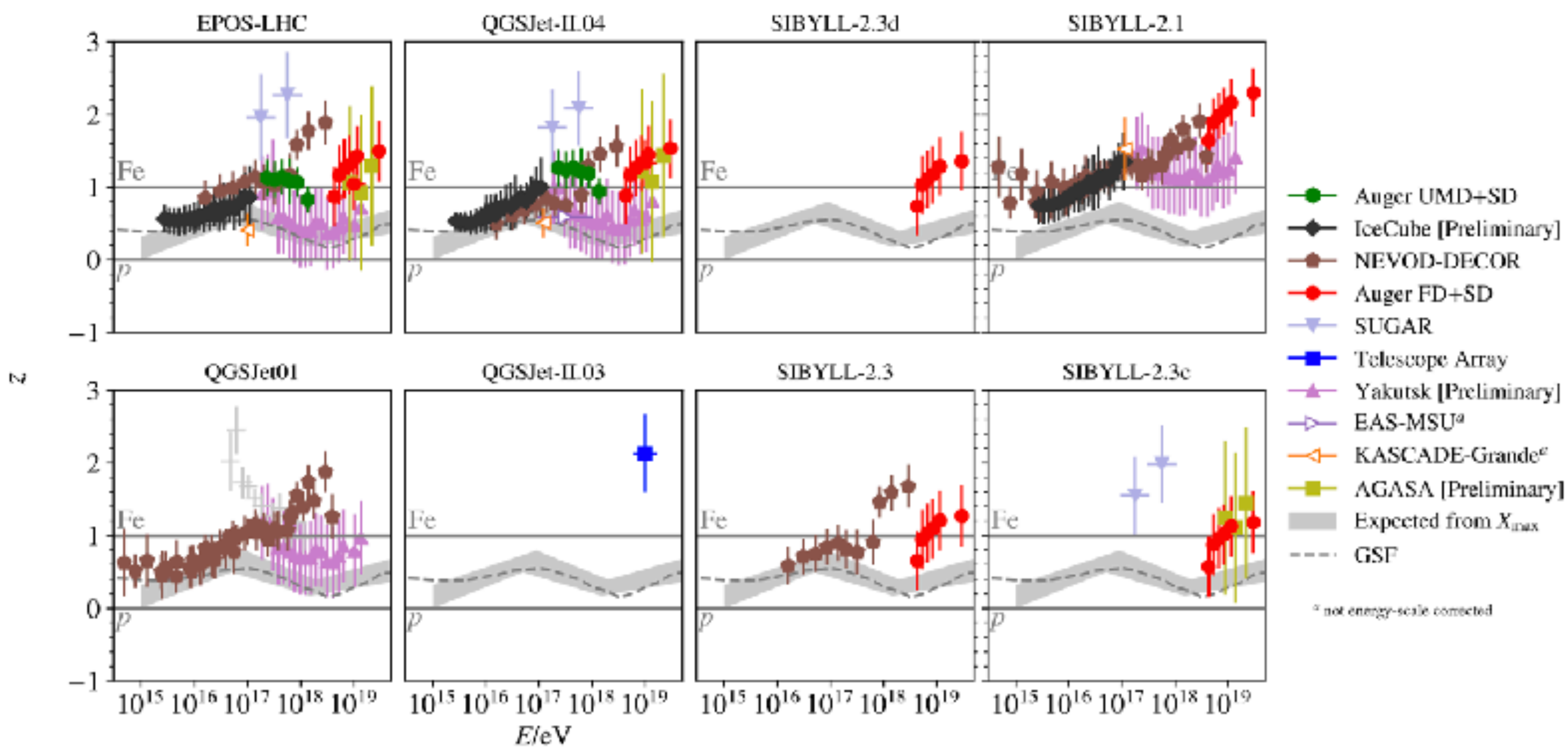

Experimental conditions

A Krakow case!

Krakow altitude
~200 m a.s.l.

To test it, we need:

- Testing discrepancies in the muon trajectory predictions
  - The shallower, the more discrepancies on trajectories accumulate
- Reducing the variables (unknown Energy and Mass descriptions)
- A good charge separation due to the Geomagnetic field
  - related to how many particles are polarized

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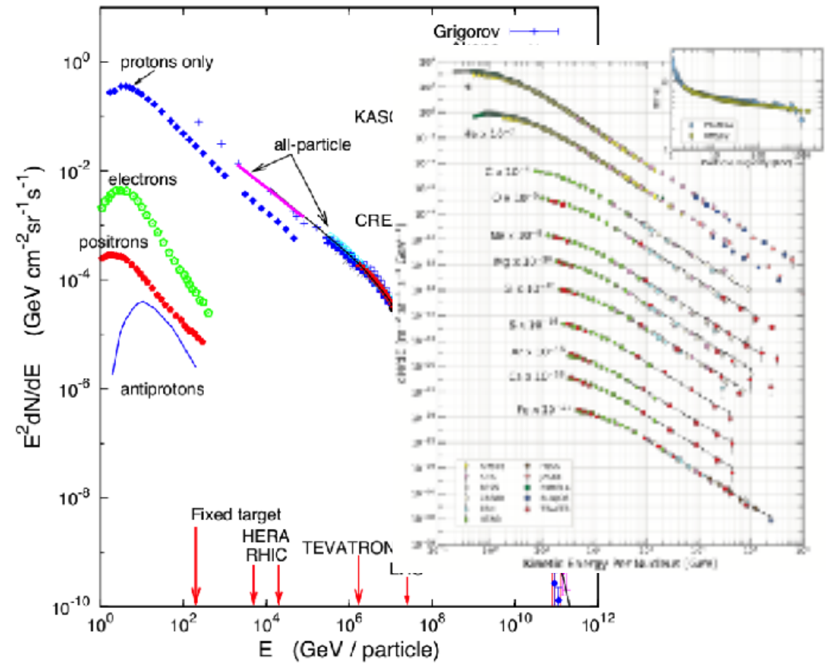
Let’s use HECR!
know E and mass



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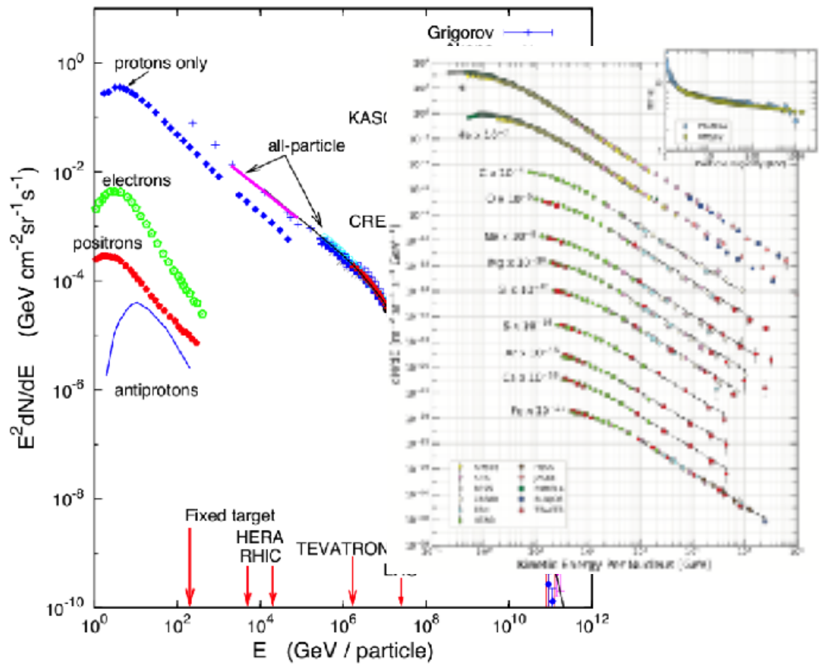
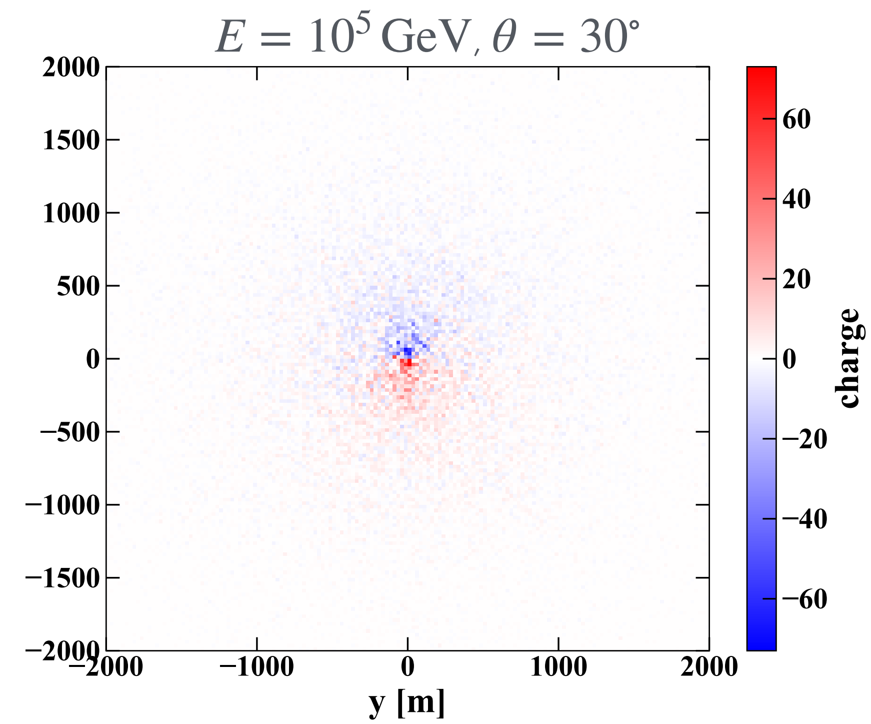


From simulations,
a clear charge separation!



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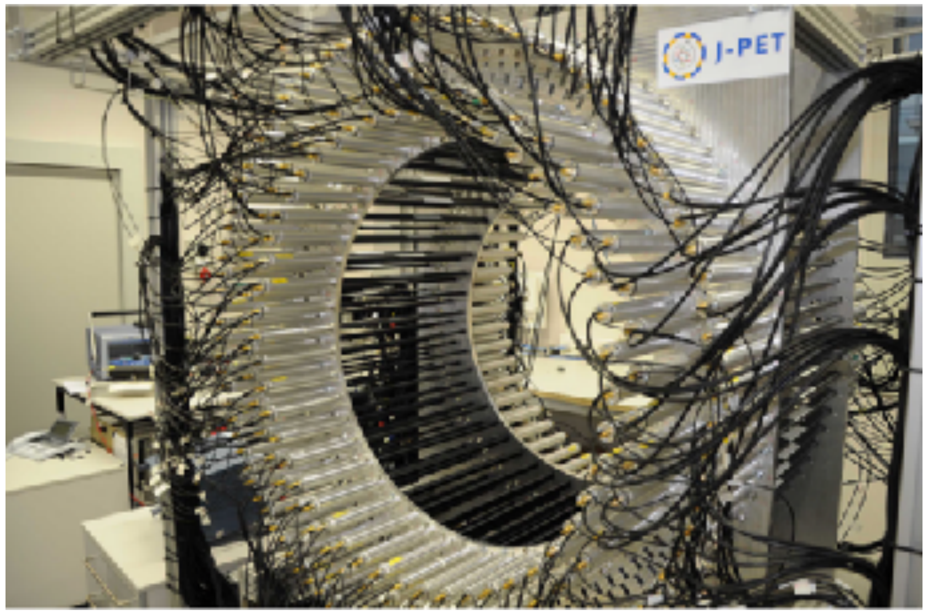
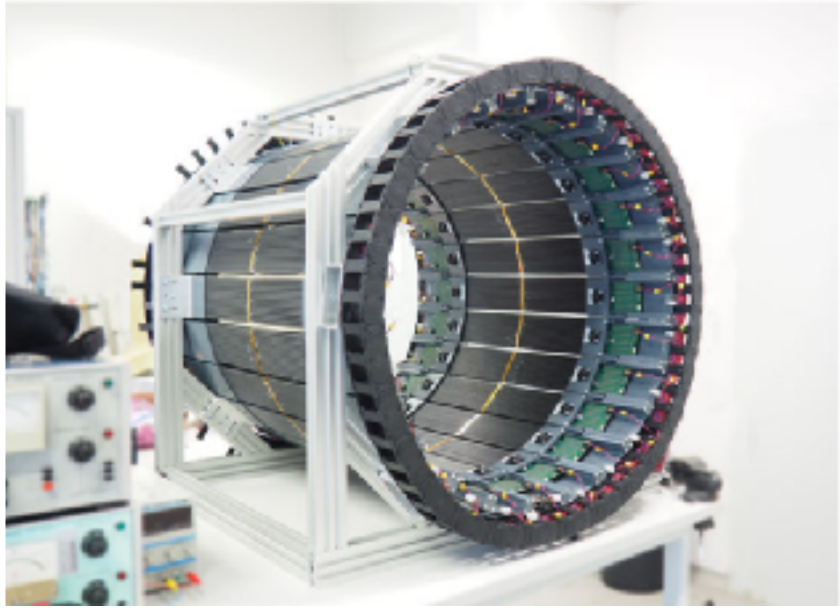
μPPET

μ-Puzzle with J-**PET**

Big Barrel J-PET



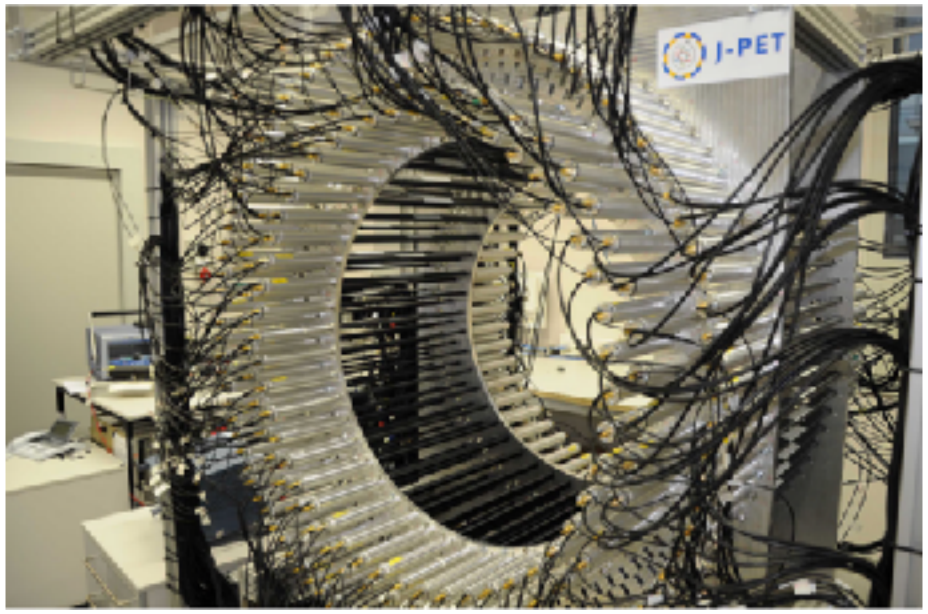
Modular J-PET



μPPET

The muon tracker

Big Barrel J-PET



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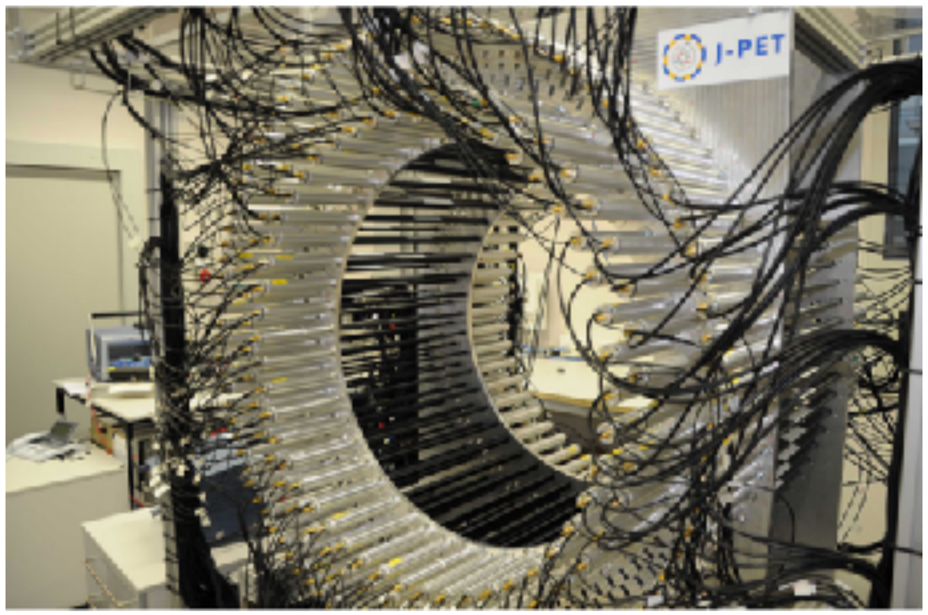
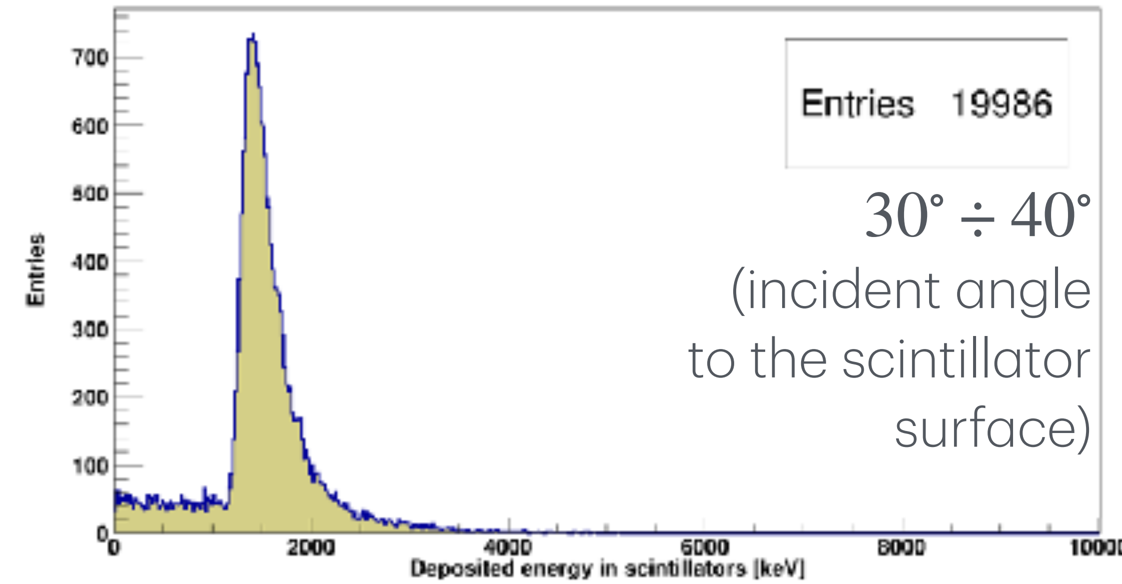
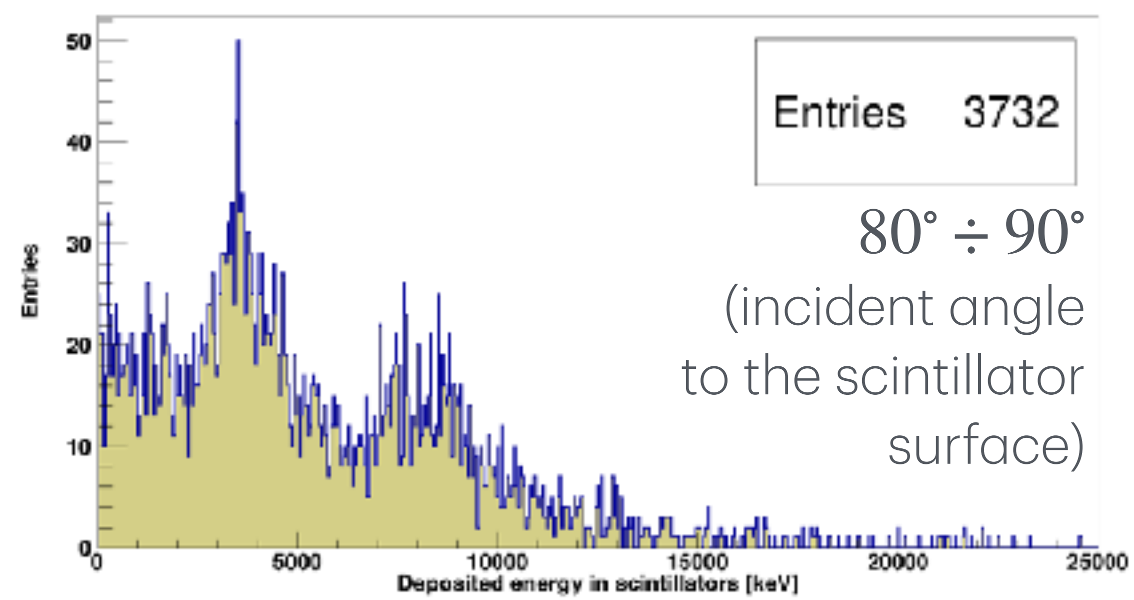


Calibration: $\mathrm{d}E \leftrightarrow \mathrm{ToT}$





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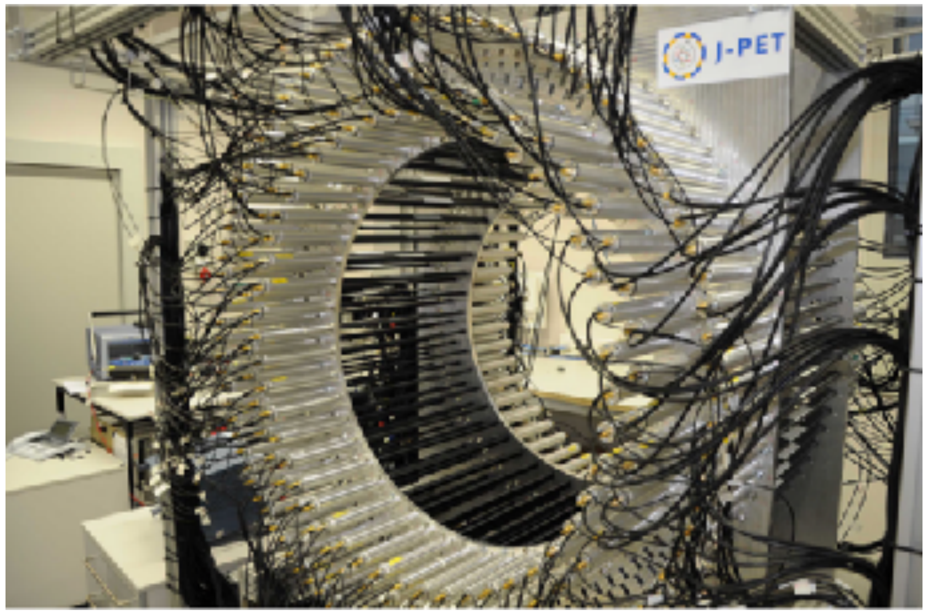

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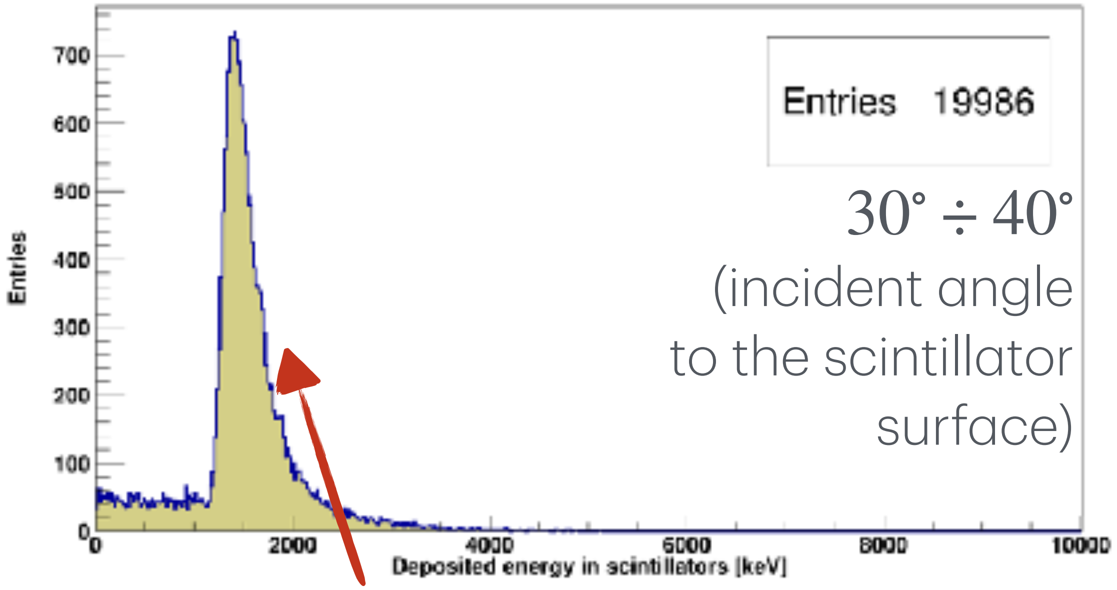
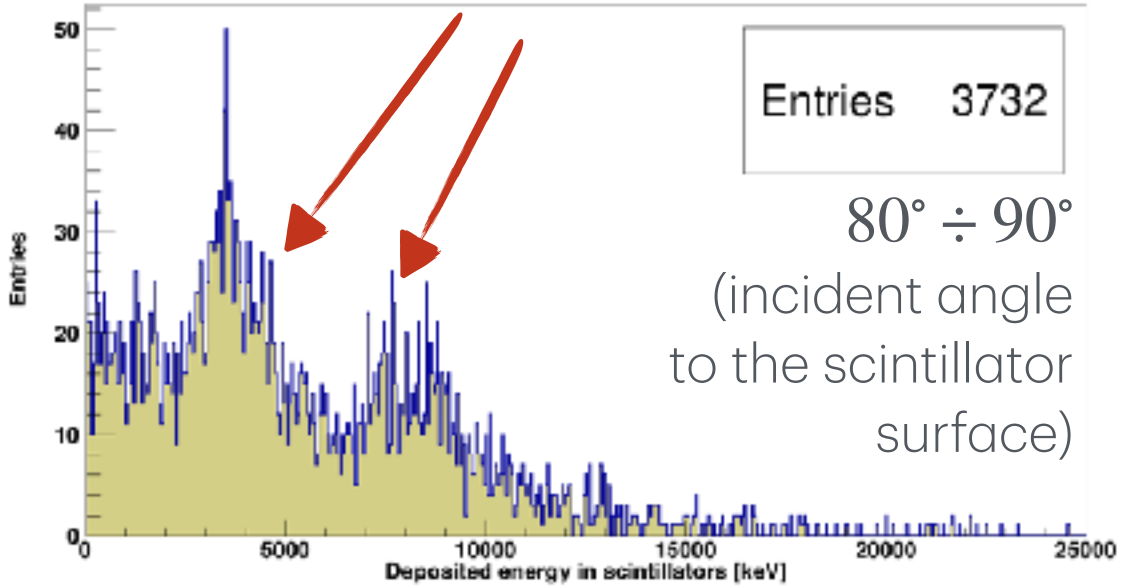


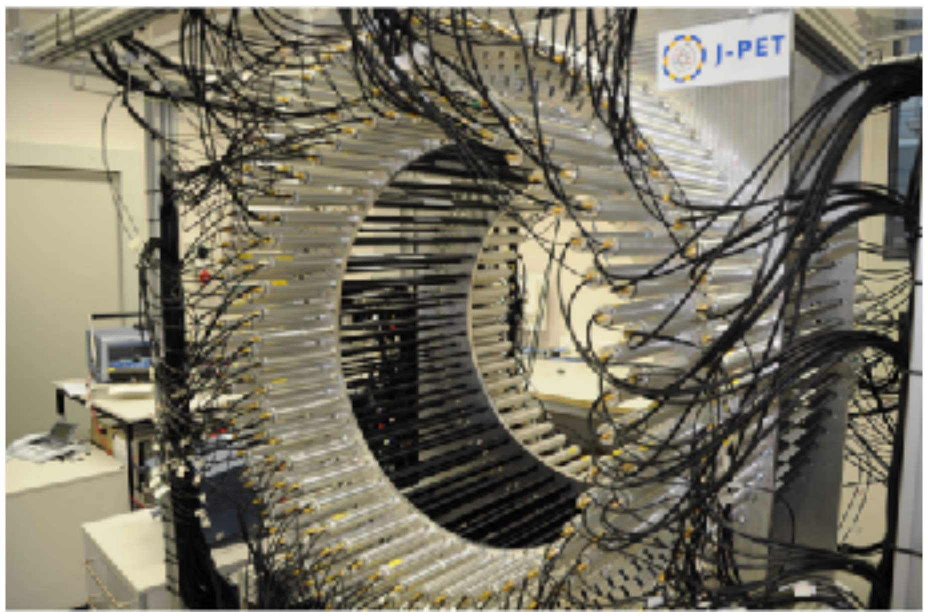
MIP: $\mathrm{d}E \propto \mathrm{d}X$



µPPET

The muon tracker

Big Barrel J-PET



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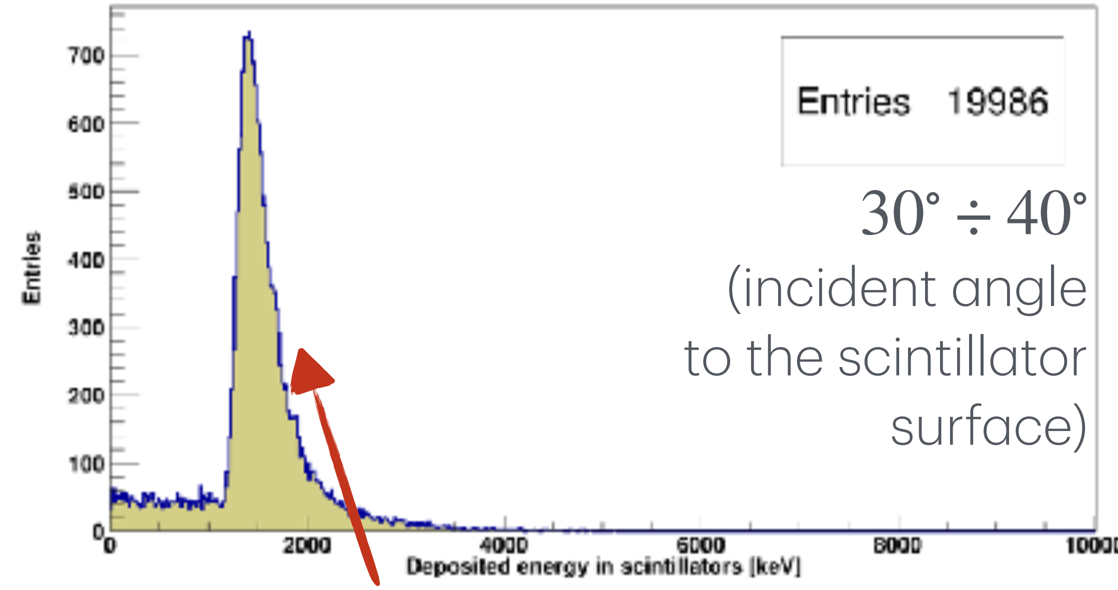

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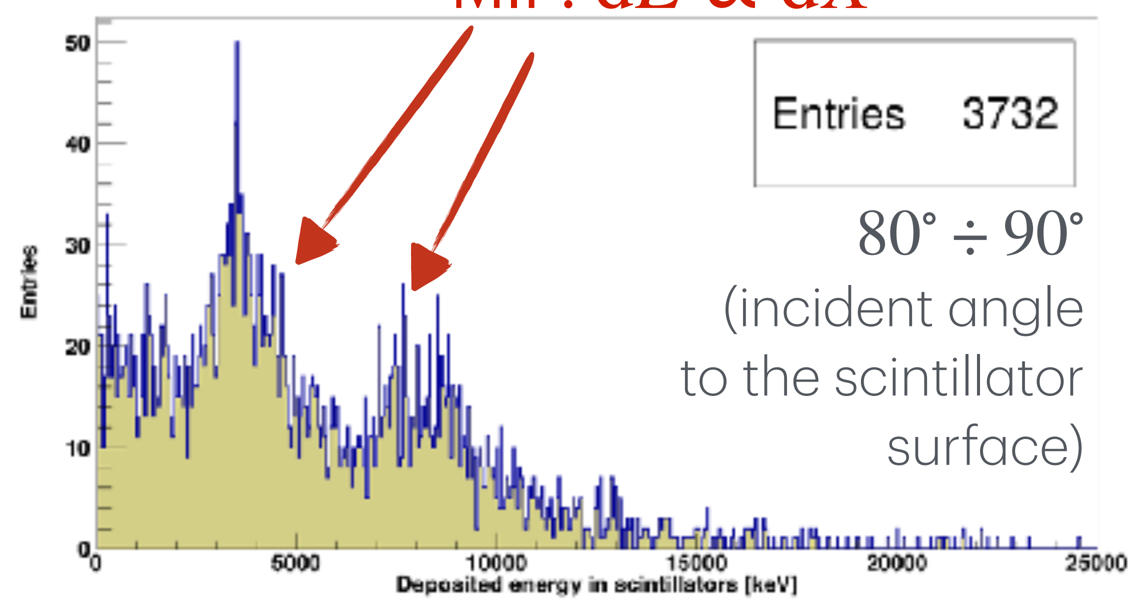
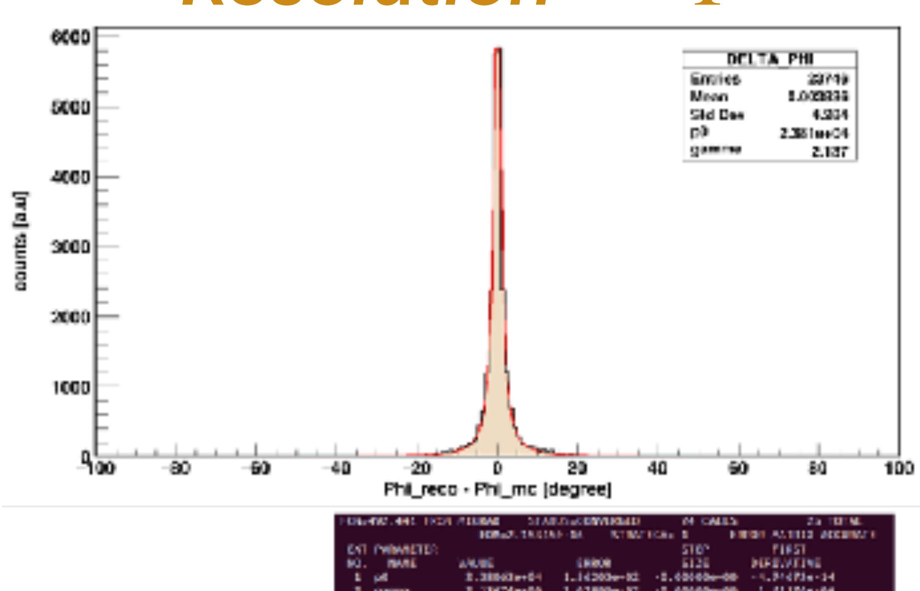


Resolution $\simeq 1^\circ$



μPPET

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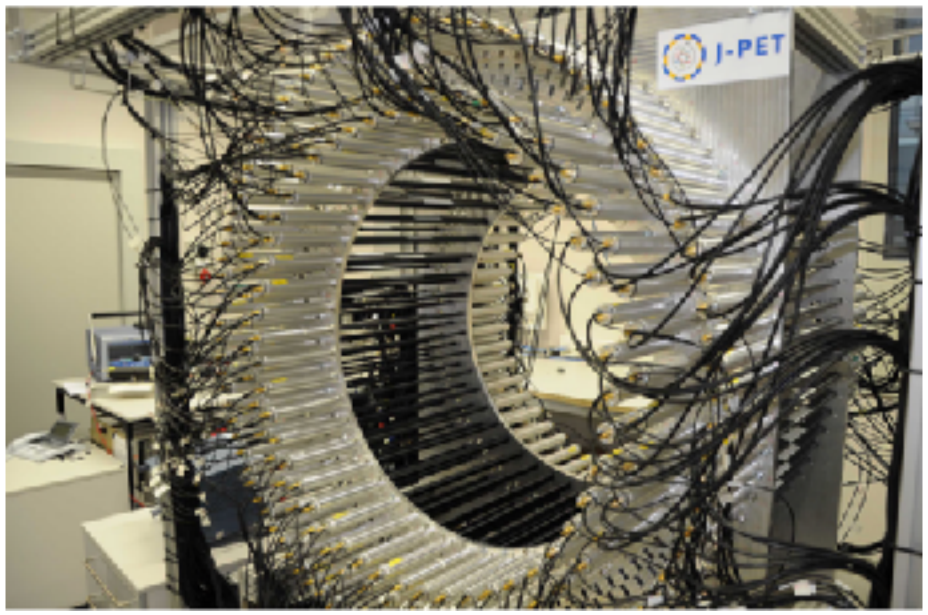

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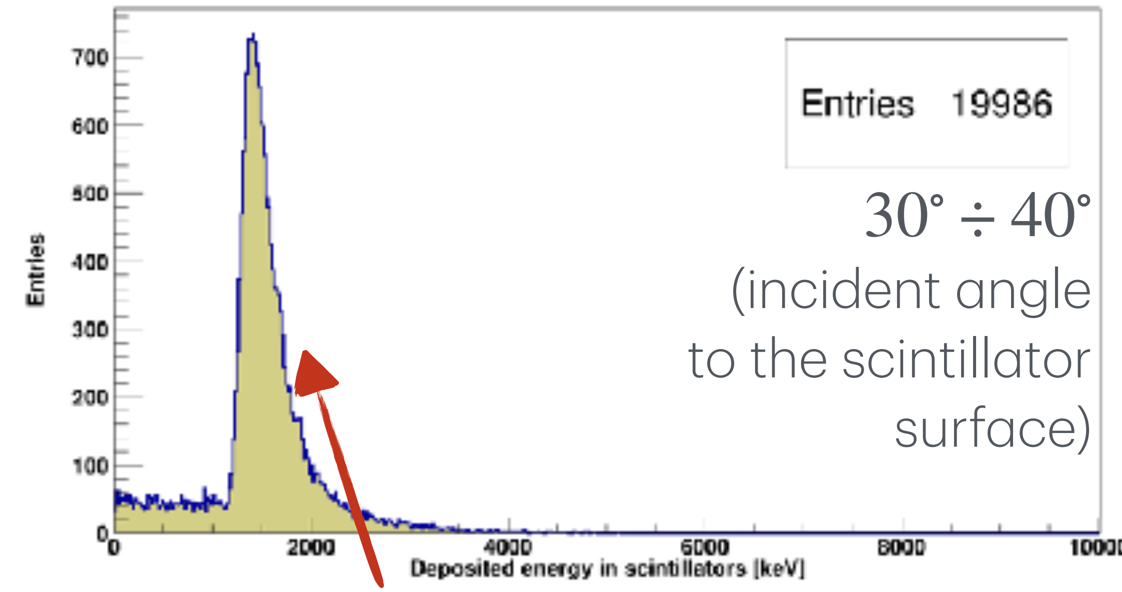
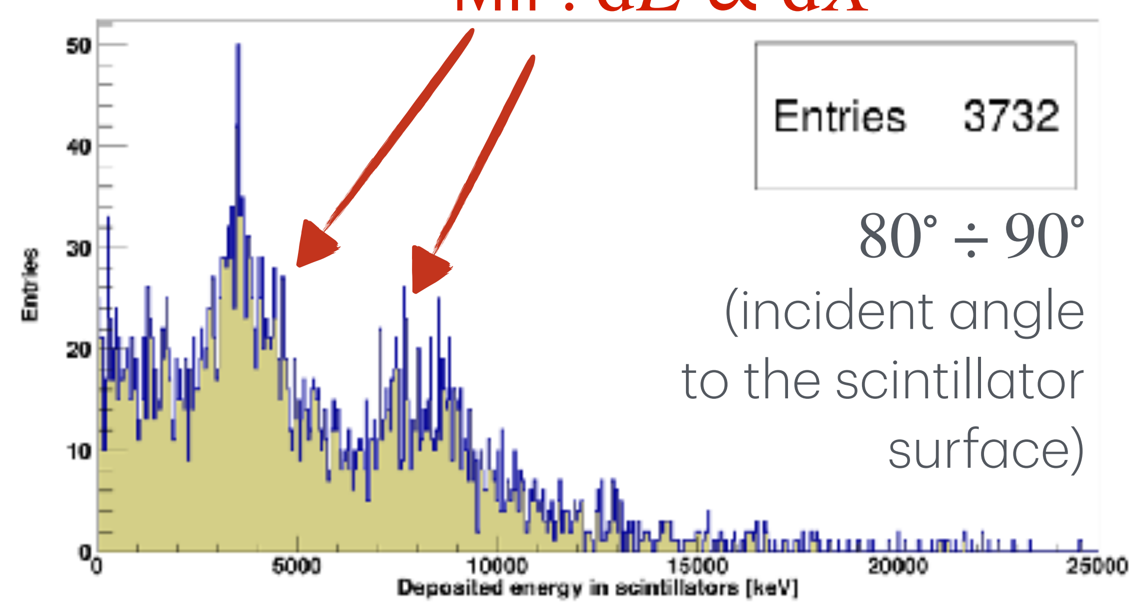


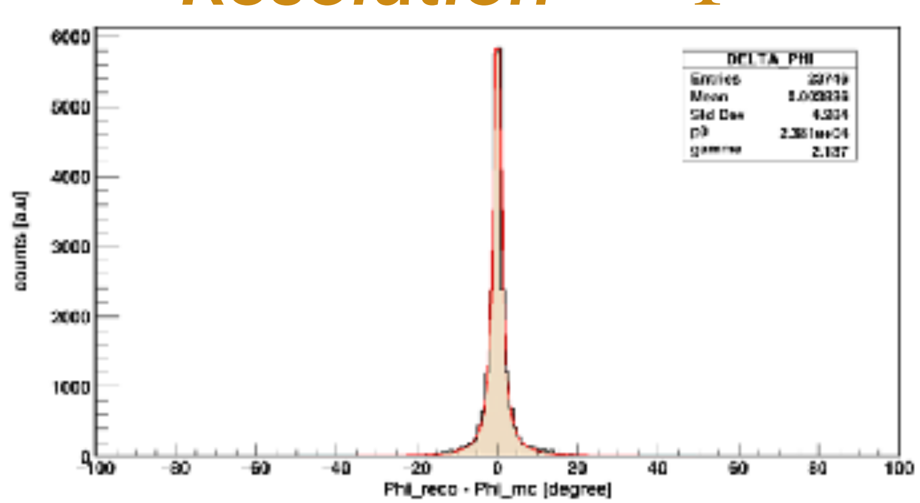
$30^\circ \div 40^\circ$
(incident angle
to the scintillator
surface)

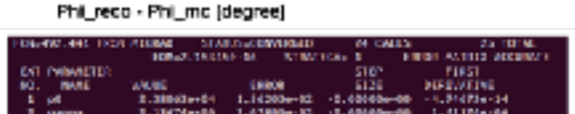
MIP: $\mathrm{d}E \propto \mathrm{d}X$



$80^\circ \div 90^\circ$
(incident angle
to the scintillator
surface)

Resolution $\simeq 1^\circ$





Improvement: Physics-Informed NN (PINN)

μPPET

The muon tracker

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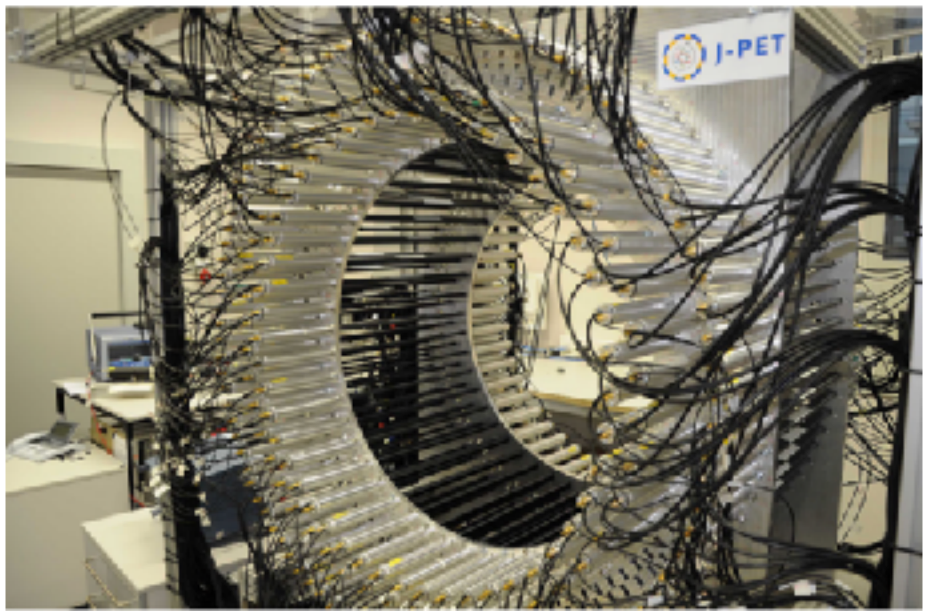

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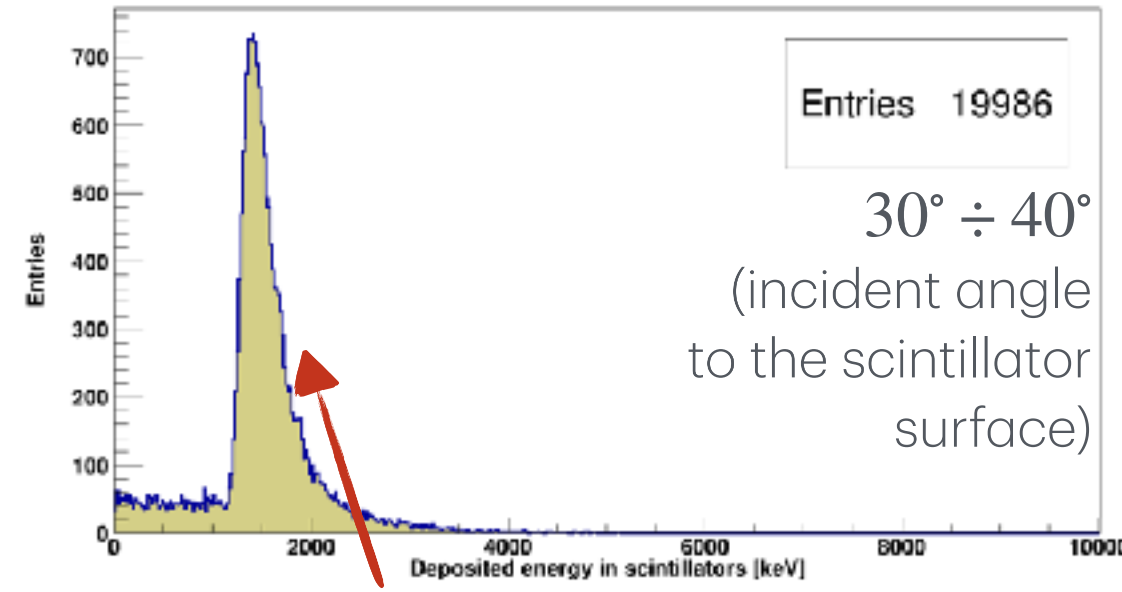
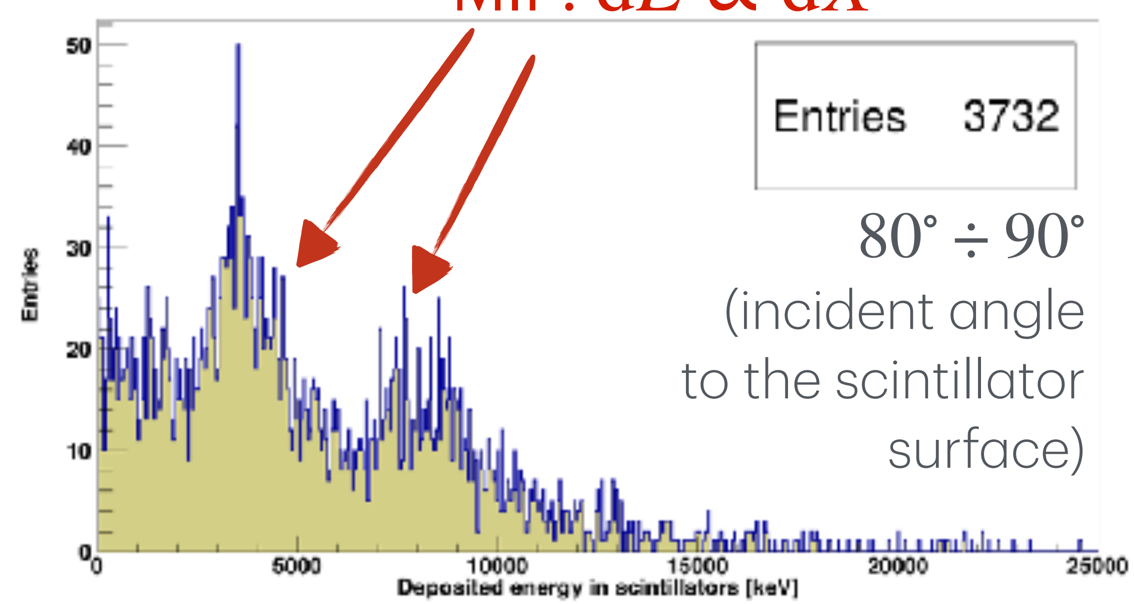
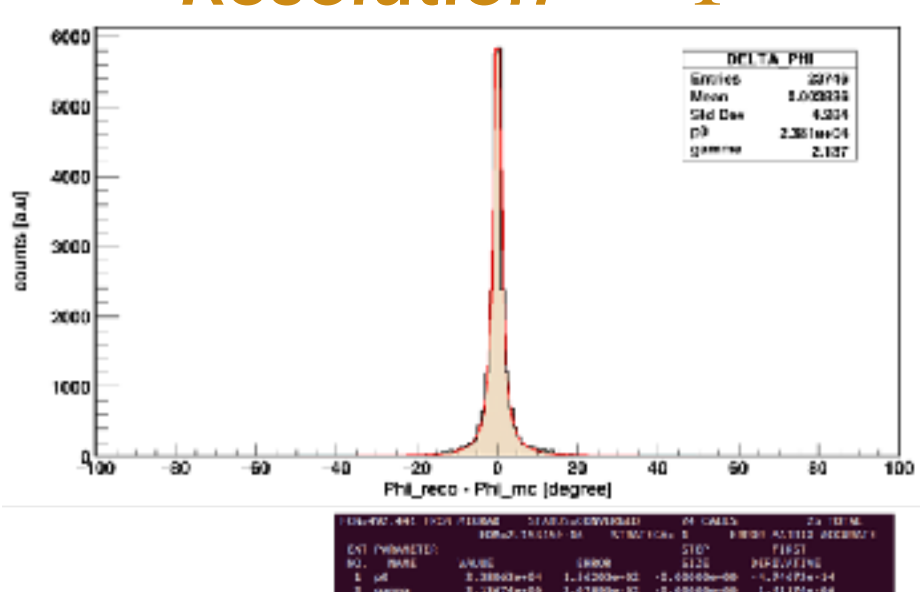


MIP: $\mathrm{d}E \propto \mathrm{d}X$



Resolution $\simeq 1^\circ$

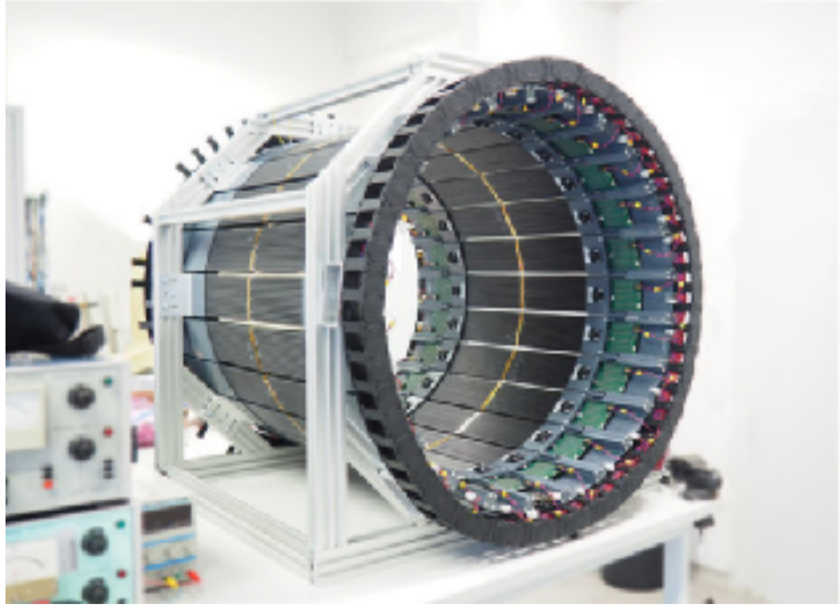


Improvement: Physics-Informed NN (PINN)
[expected an enhancement in the position
Resolution for J-PET]

μPPET

Shower reconstructor

Modular J-PET



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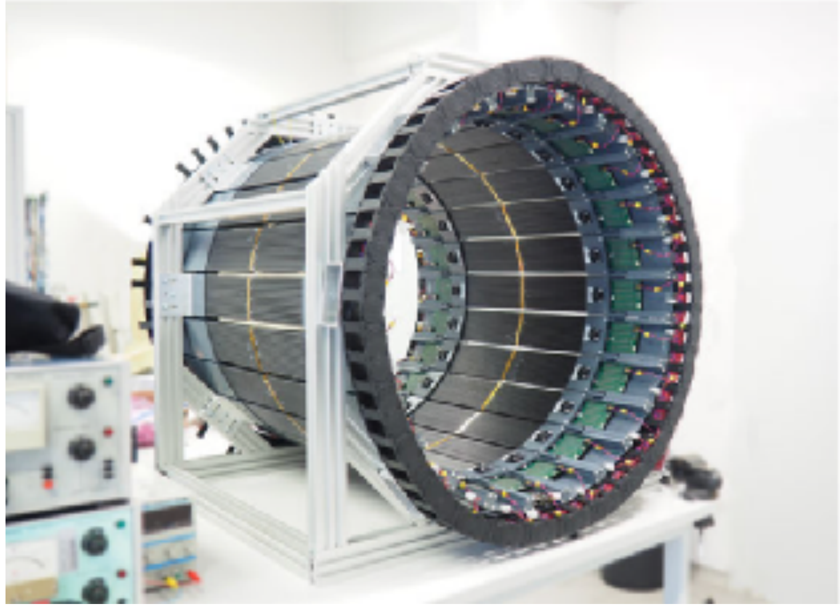
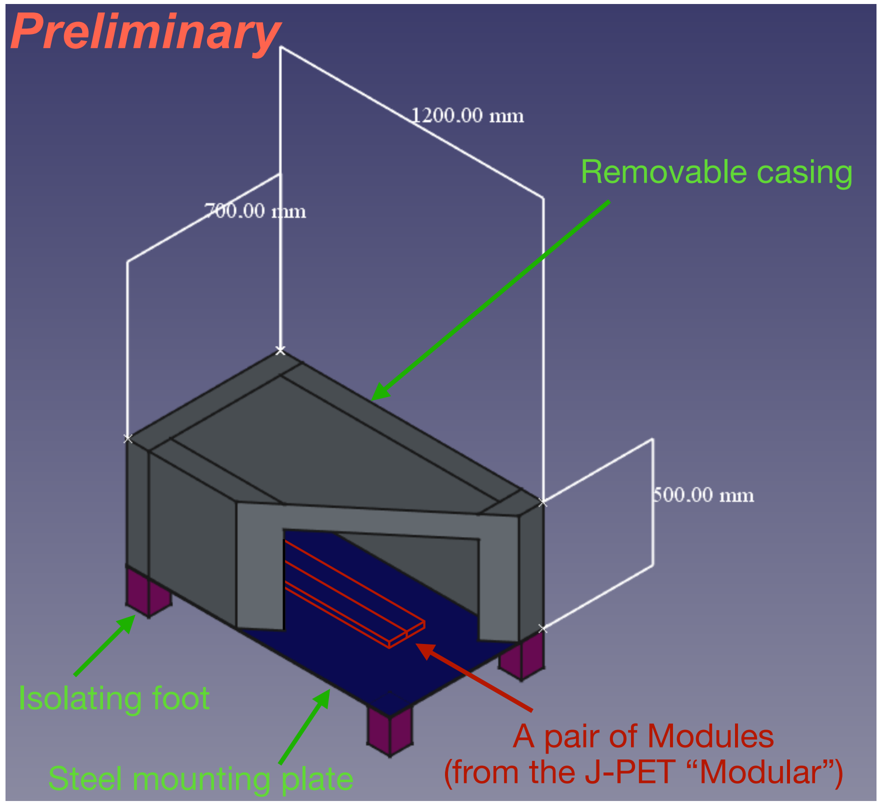


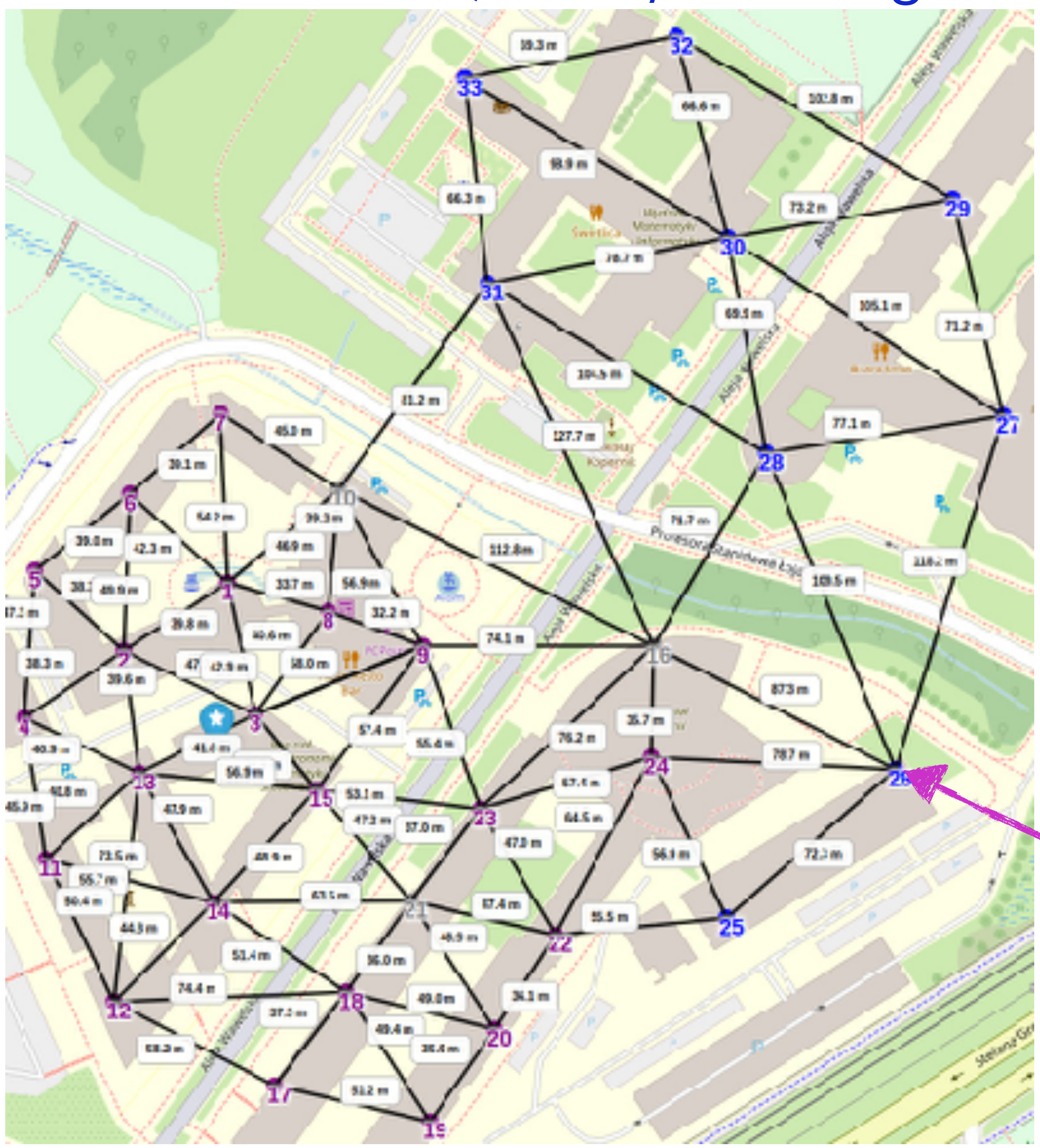


µPPET

Shower reconstructor

Flexible Array on rooftops

12/24 active station, close/far to Big Barrel



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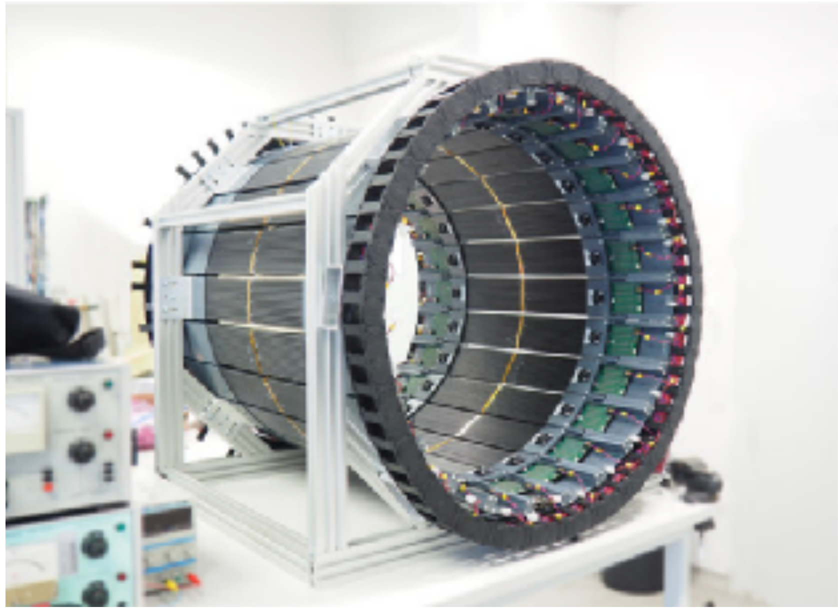

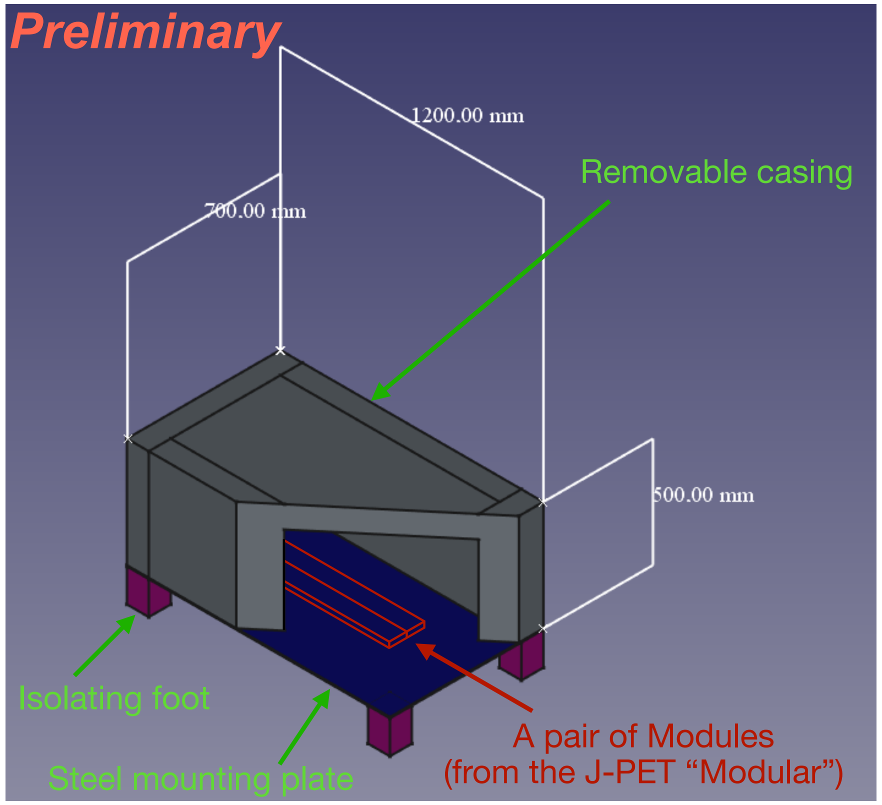

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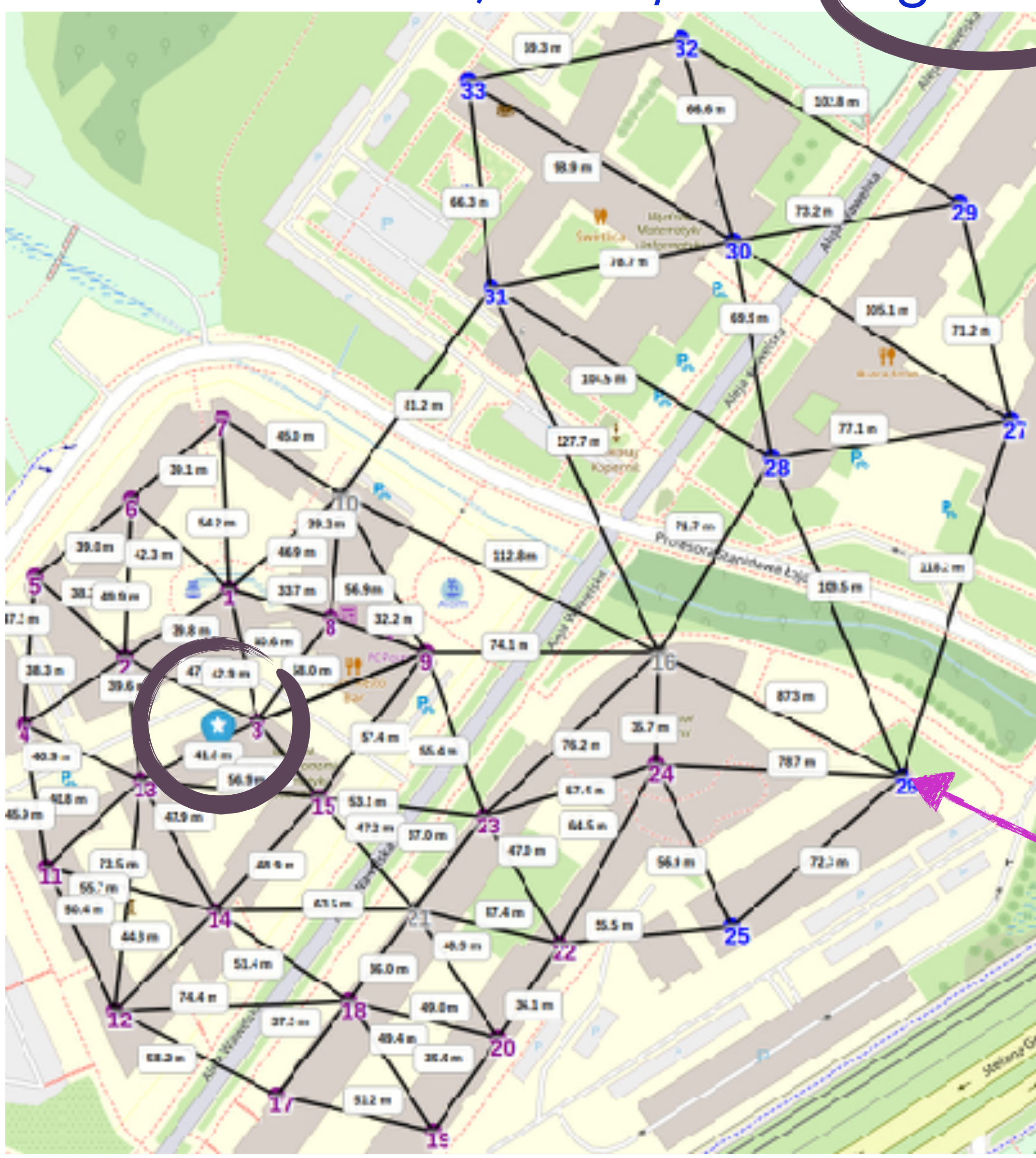

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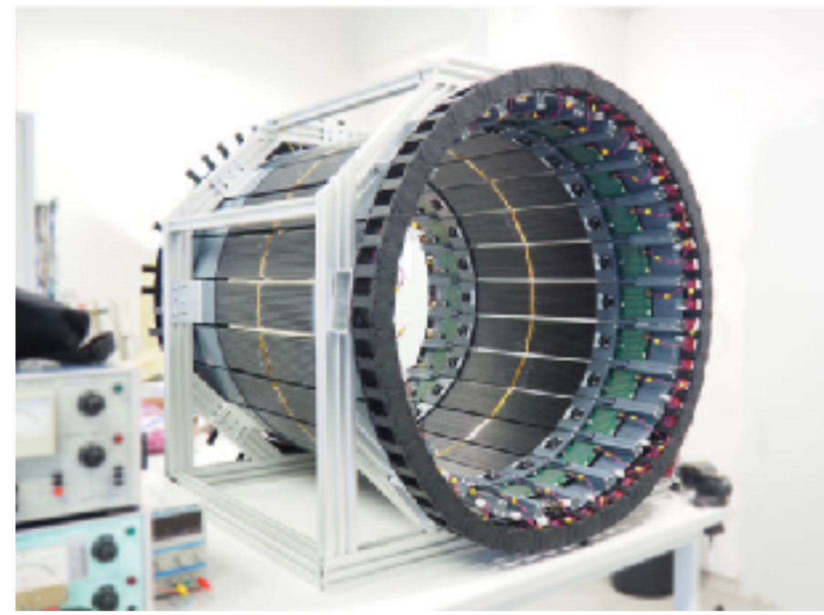

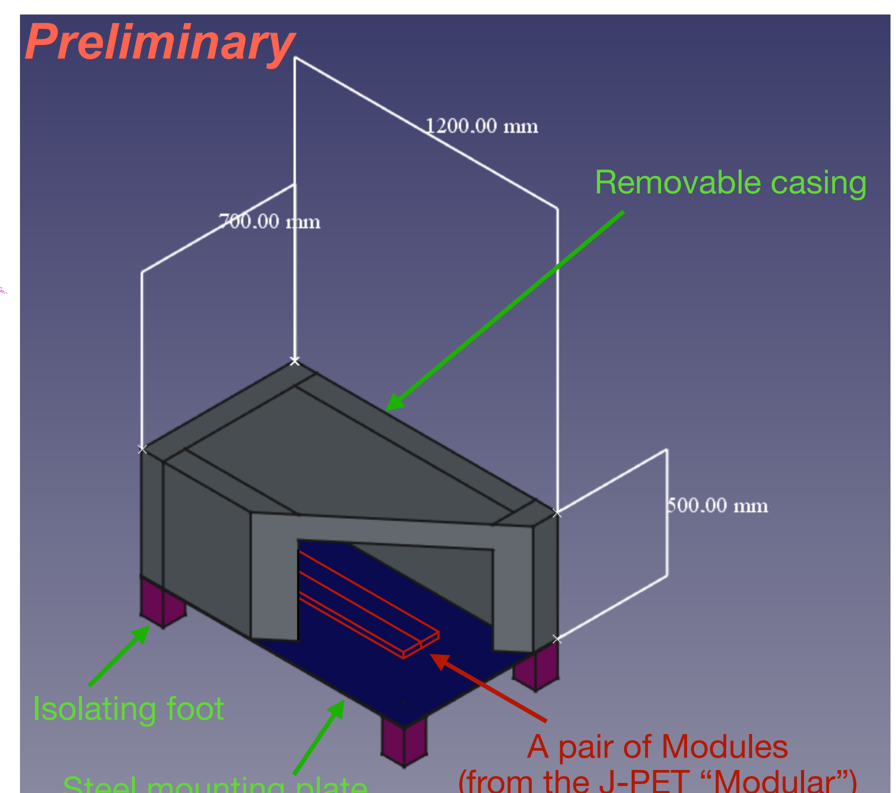

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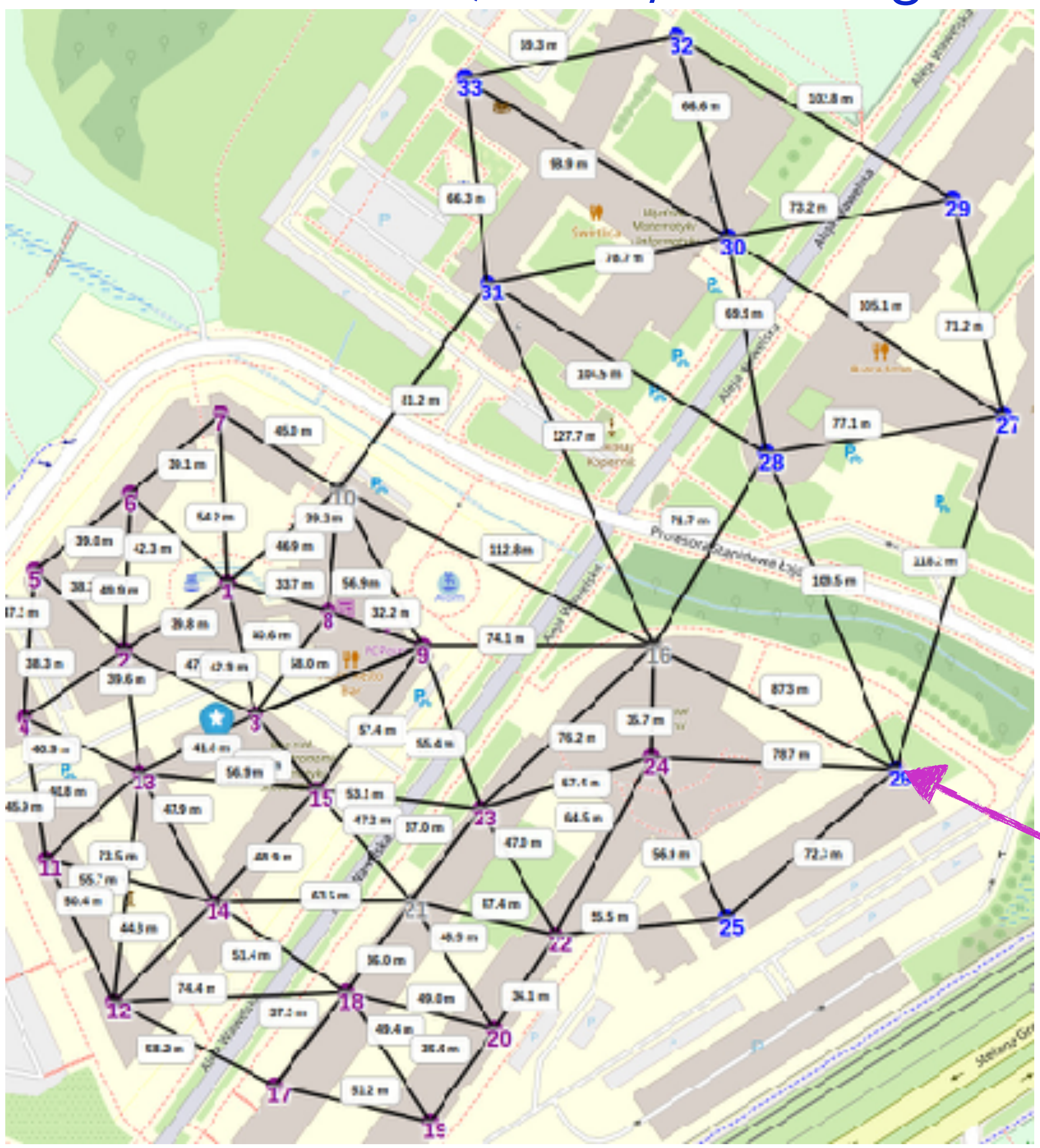
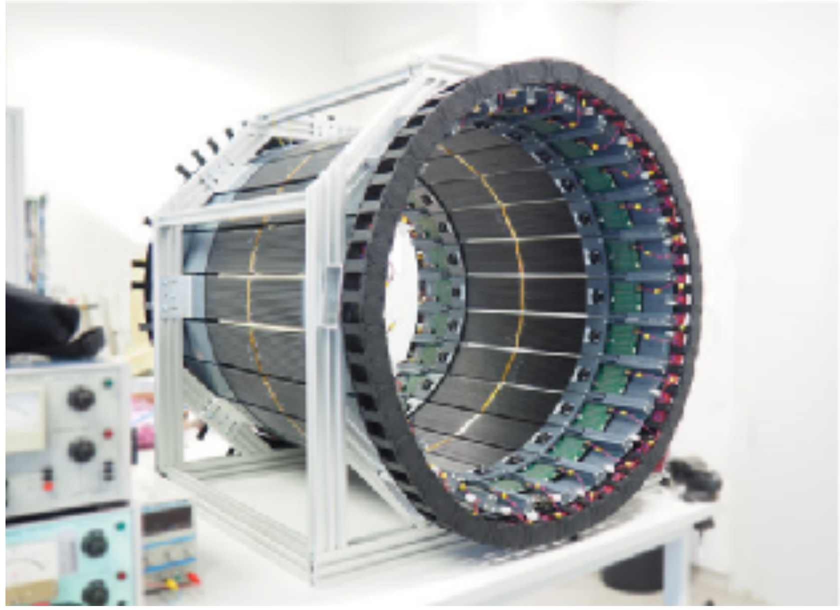
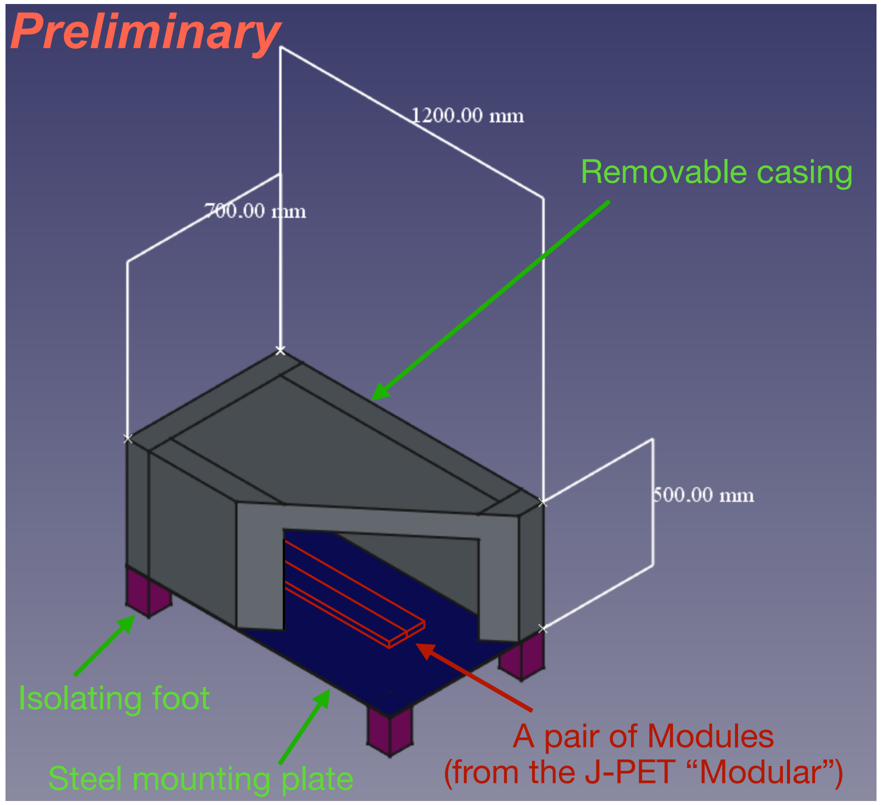


Improved Reconstruction with Graph NN

Modular J-PET





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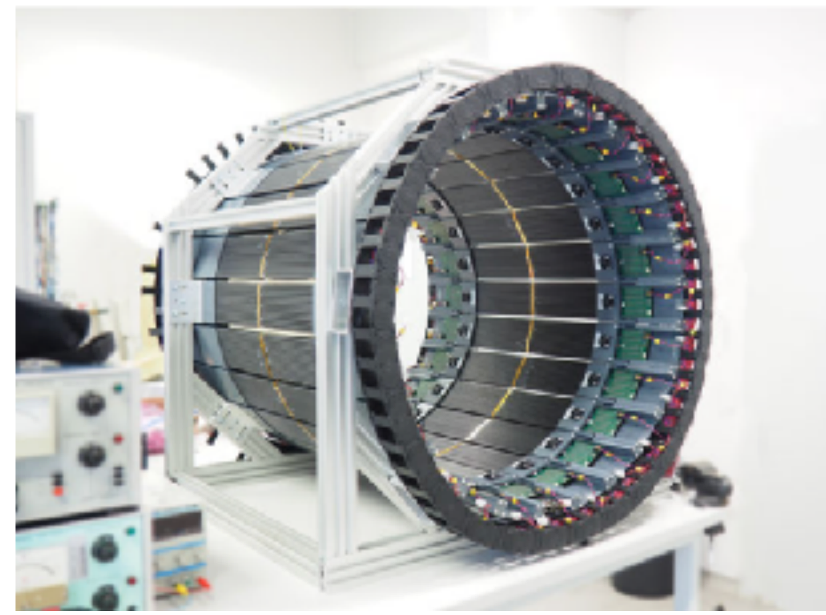

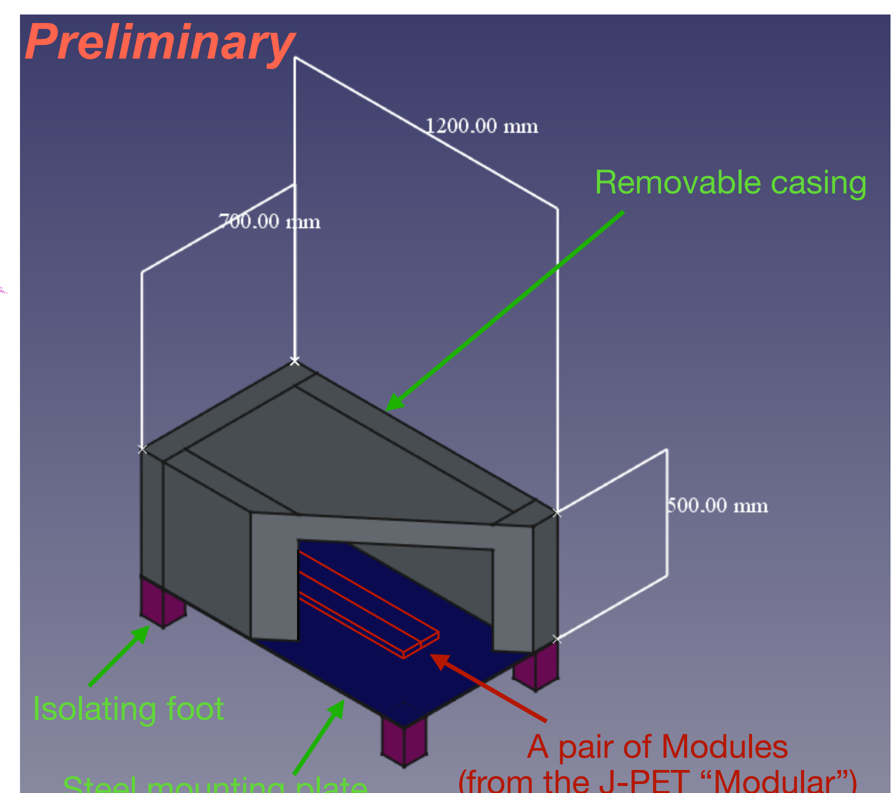

PONNS [Physical Observables NN System]
A hybrid architecture 2xCNN+PINN to reconstruct events observable in a station: position, direction, energy, and **charge**

Outlook

A new hypothesis for a 15-years long issue—the Muon Puzzle

J-PET repurposed: suitable detectors and experimental conditions

Experimental setup

- Search for anomalies in muon trajectories
- Big Barrel as a muon tracker
- Modular as a shower reconstructor

Analysis technology

- Detailed calibration [J-PET interest]
- Better tracker resolution, developing a Physics-Informed Neural Network (**PINN**) [J-PET interest]
- Accurate shower reconstruction and event rejection rate reduction via Graph Neural Network (**GNN**)
- Access to new observables—charge—(**PONNS**) [J-PET interest]

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THANK YOU!

Acknwoledgments

Narodowe Centrum Nauki (NCN) for SONATA BIS 13 grant no. DEC-2023/50/E/ST9/00576

Polish high-performance computing infrastructure PLGrid (HPC Center: ACK Cyfronet AGH) for providing computer facilities and support within the computational grant no. PLG/2024/017688

Faculty of Physics, Astronomy and Computer Science of the Jagiellonian University

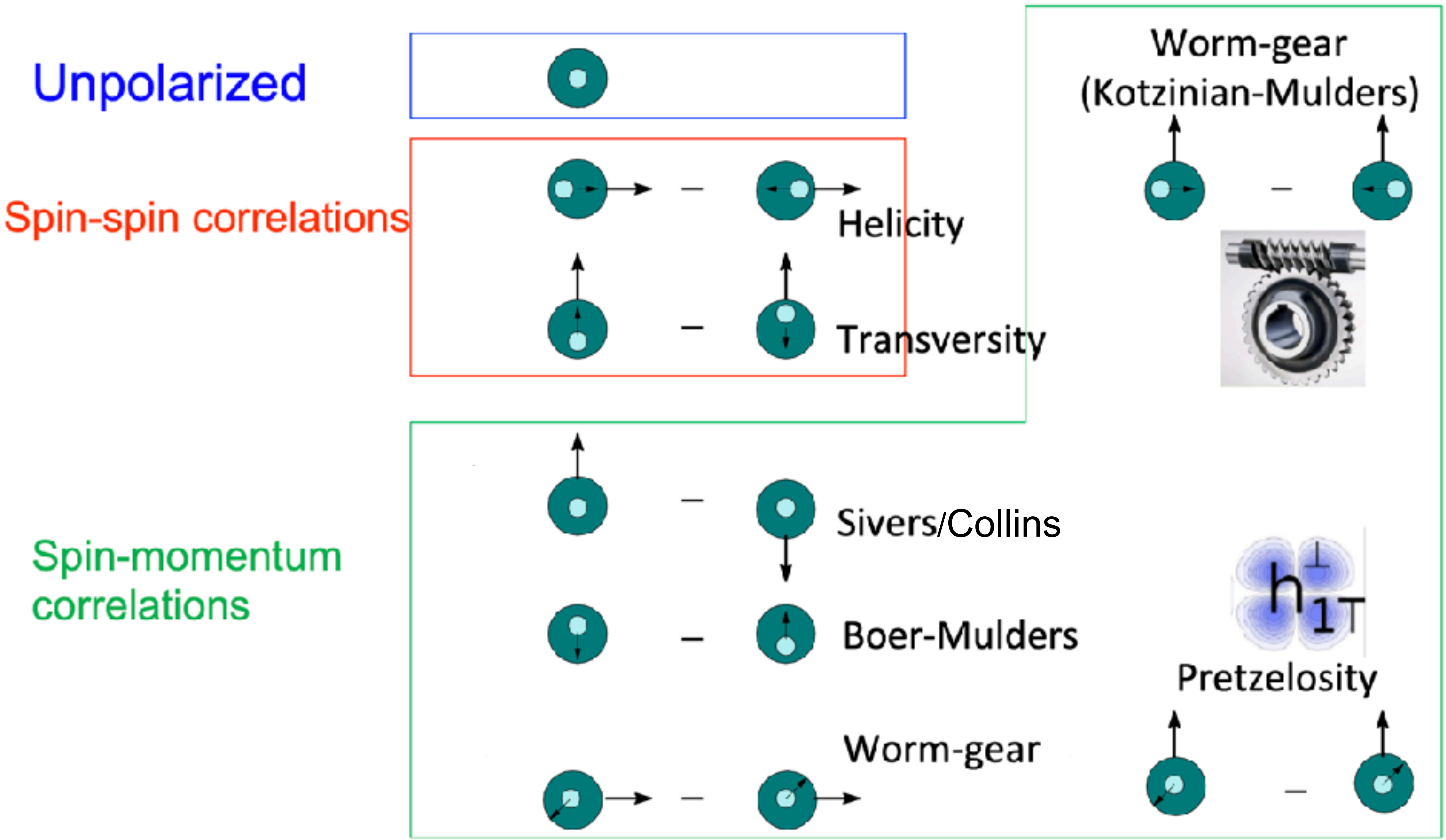
THANK YOU!

Backups

We have a geomagnetic field!

Polarization modifies the cross-section

(whether target, projectile, or both)

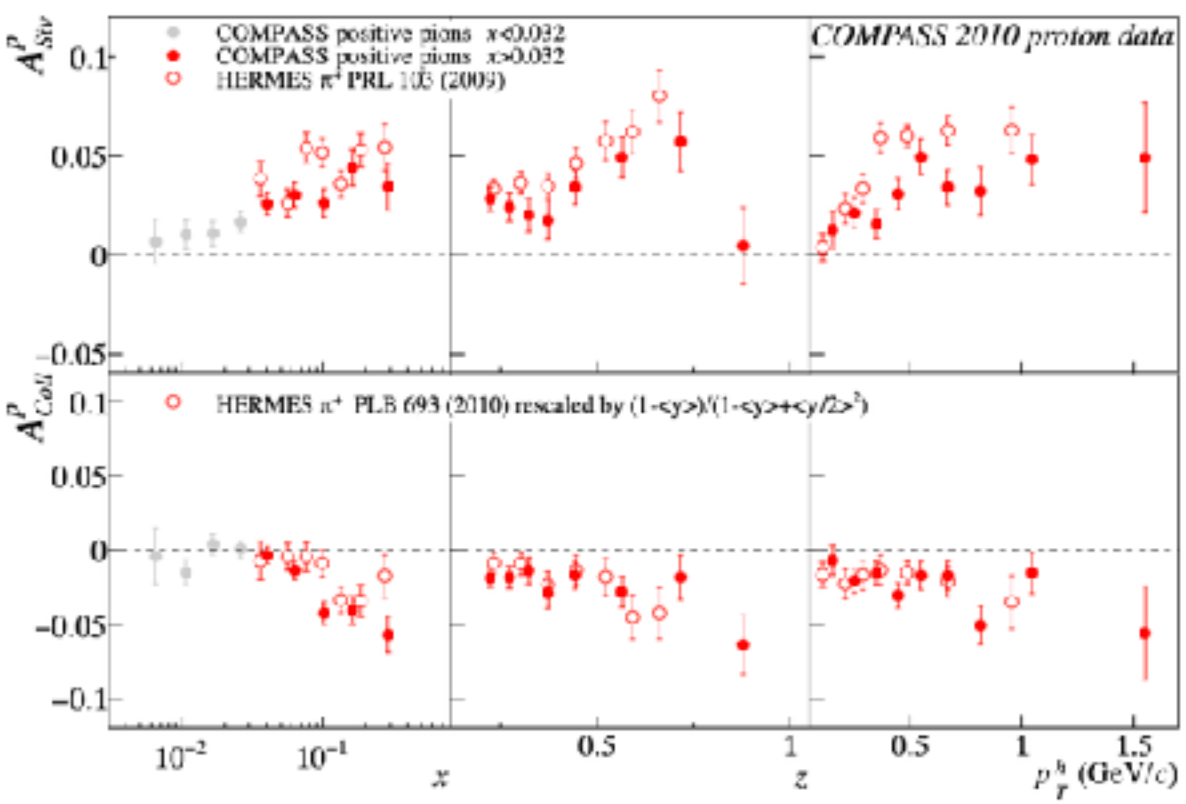


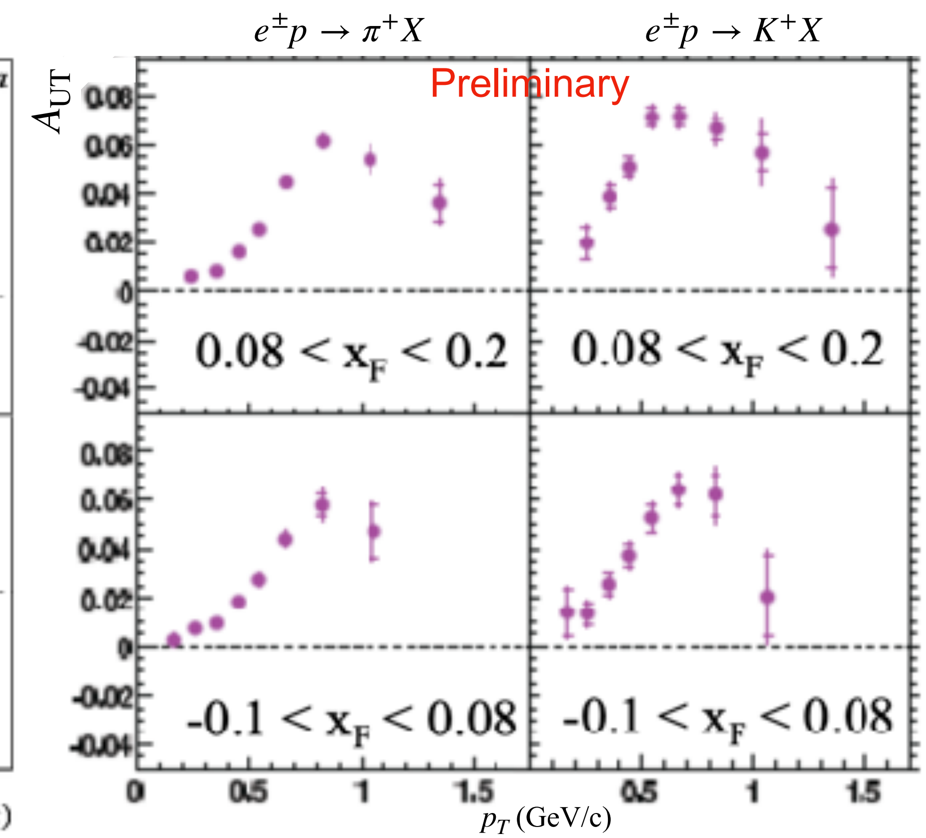
We have a geomagnetic field!

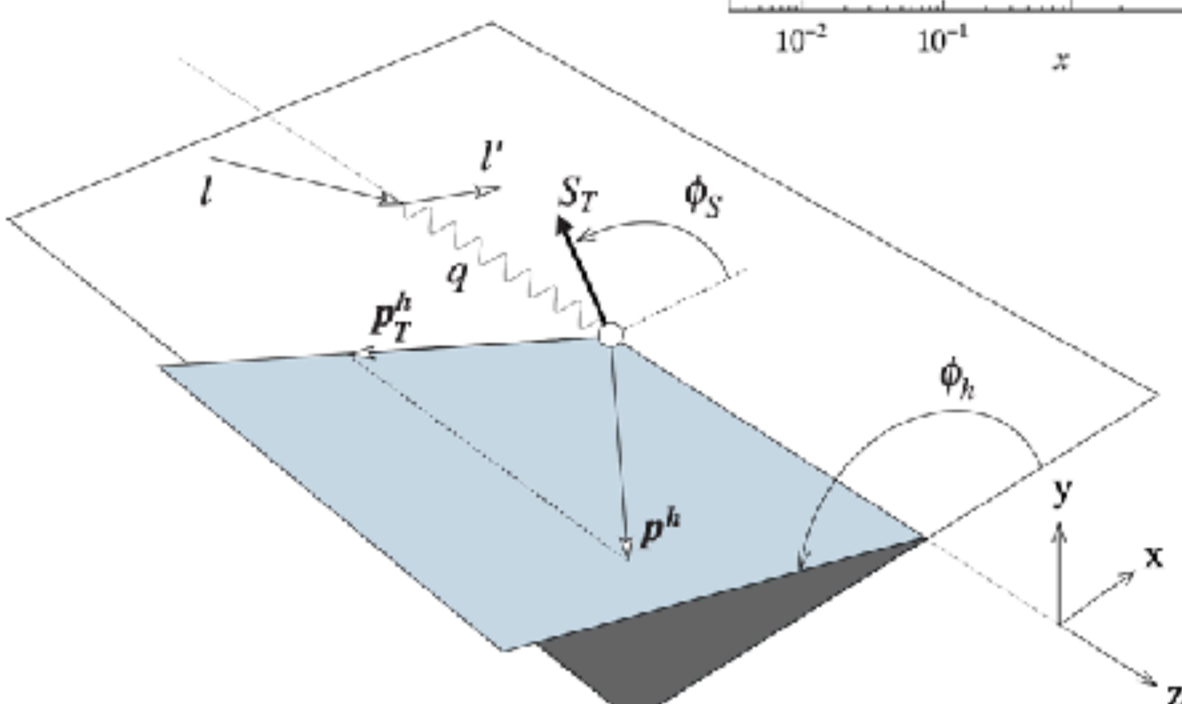
Polarization modifies the cross-section, BUT NOT ONLY!

(whether target, projectile, or both)

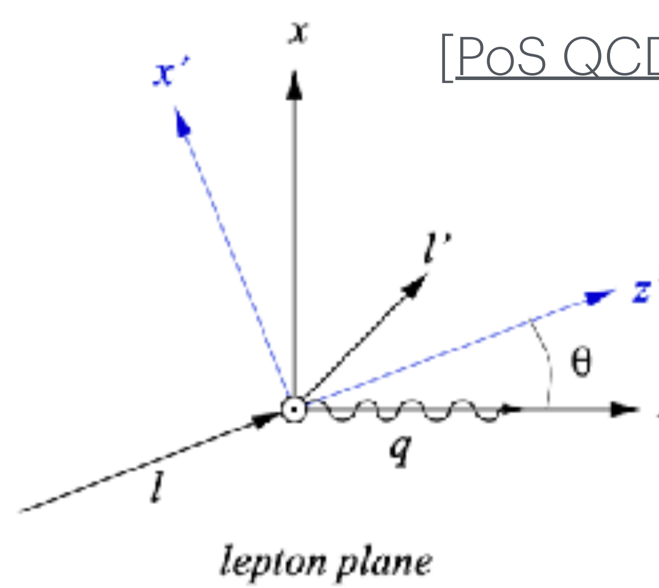
From HERMES and COMPASS: an extra transverse momentum appears!







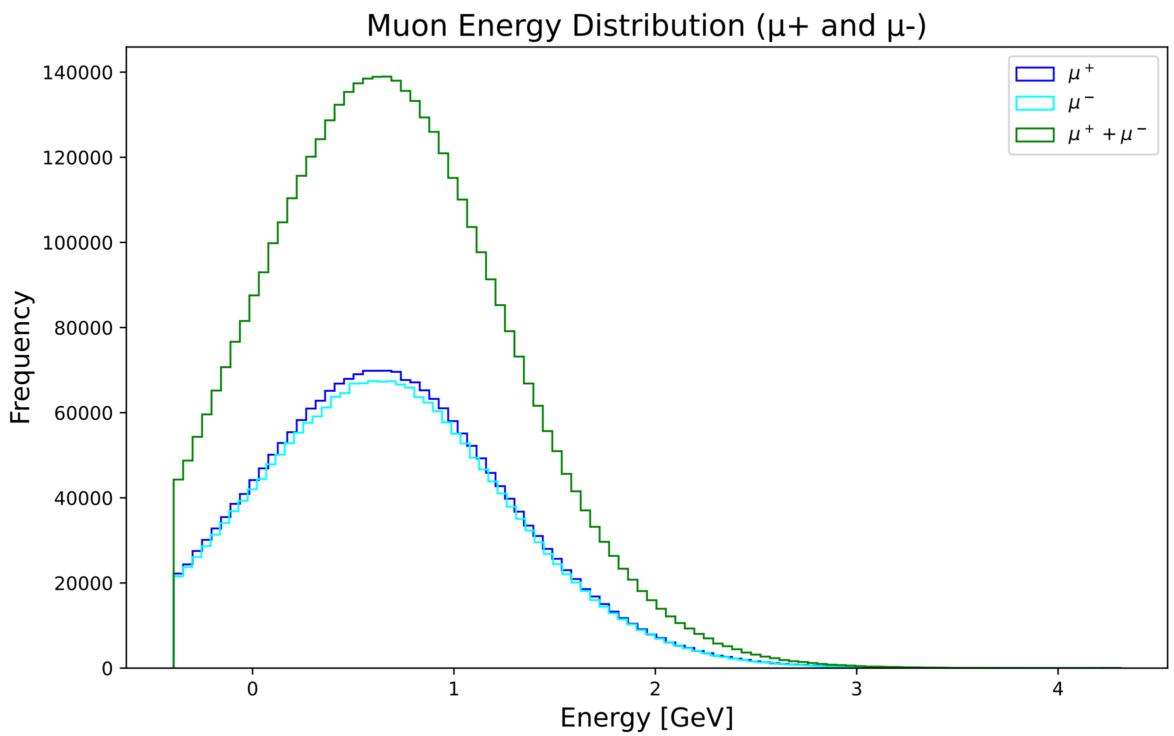
[PoS QCDEV2015 007 (2016)]

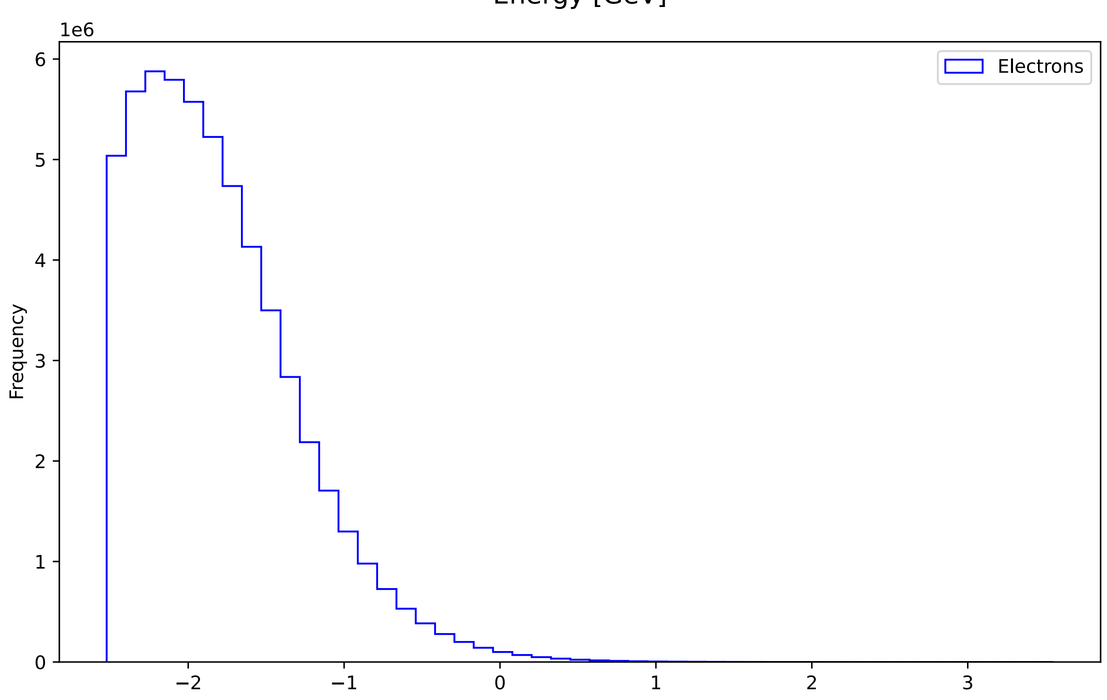


A Hypothesis…

What if Polarization is the cause of the Muon Puzzle?

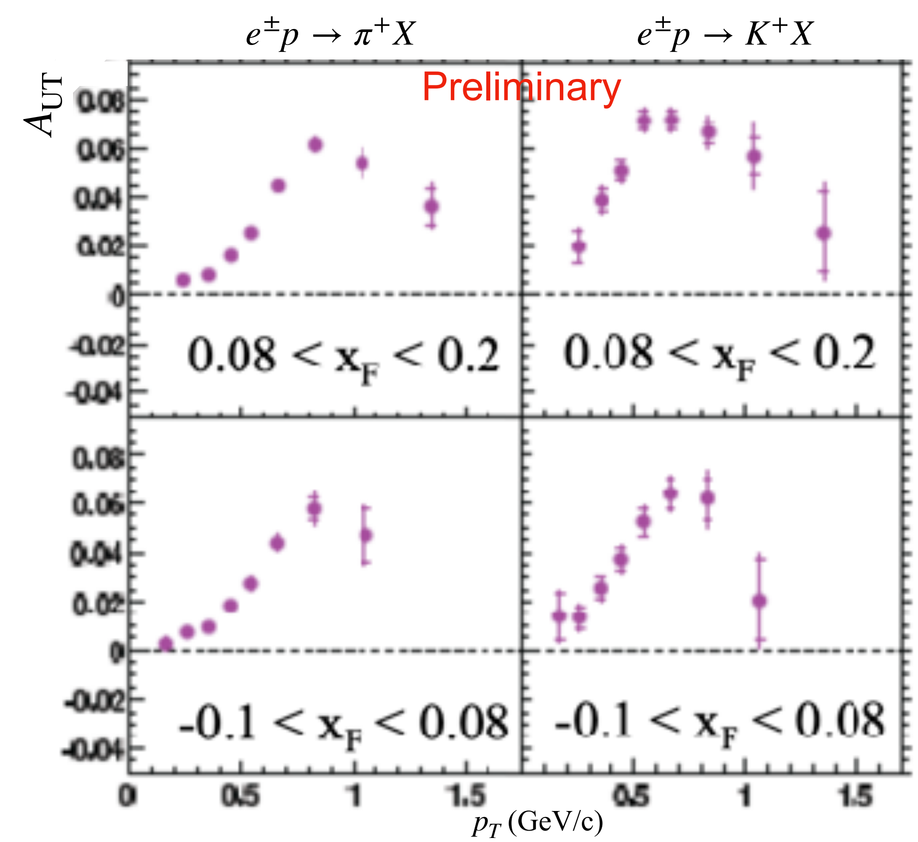
☑ The right scale of energy





Secondaries in Krakow from 1000 showers at

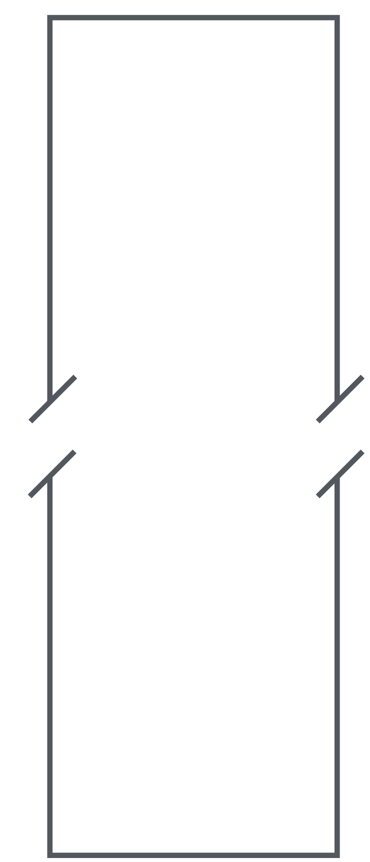
$10^4 < E[\mathrm{GeV}] < 10^5$



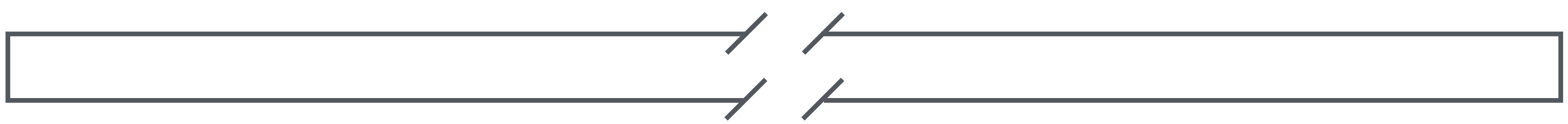
The geometry of calibration

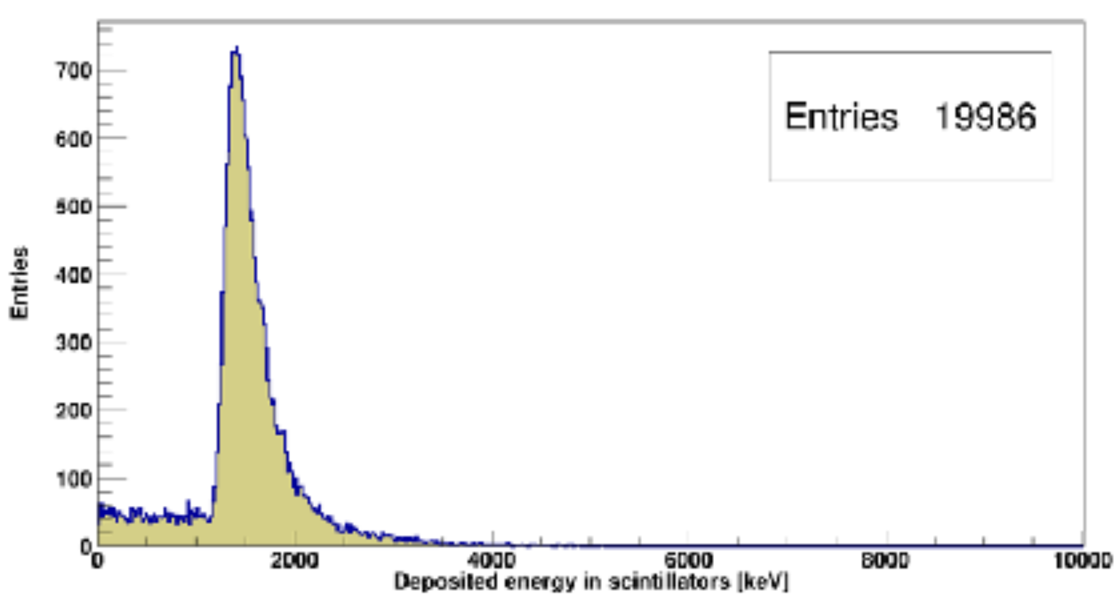
Short side

Top side



Long side





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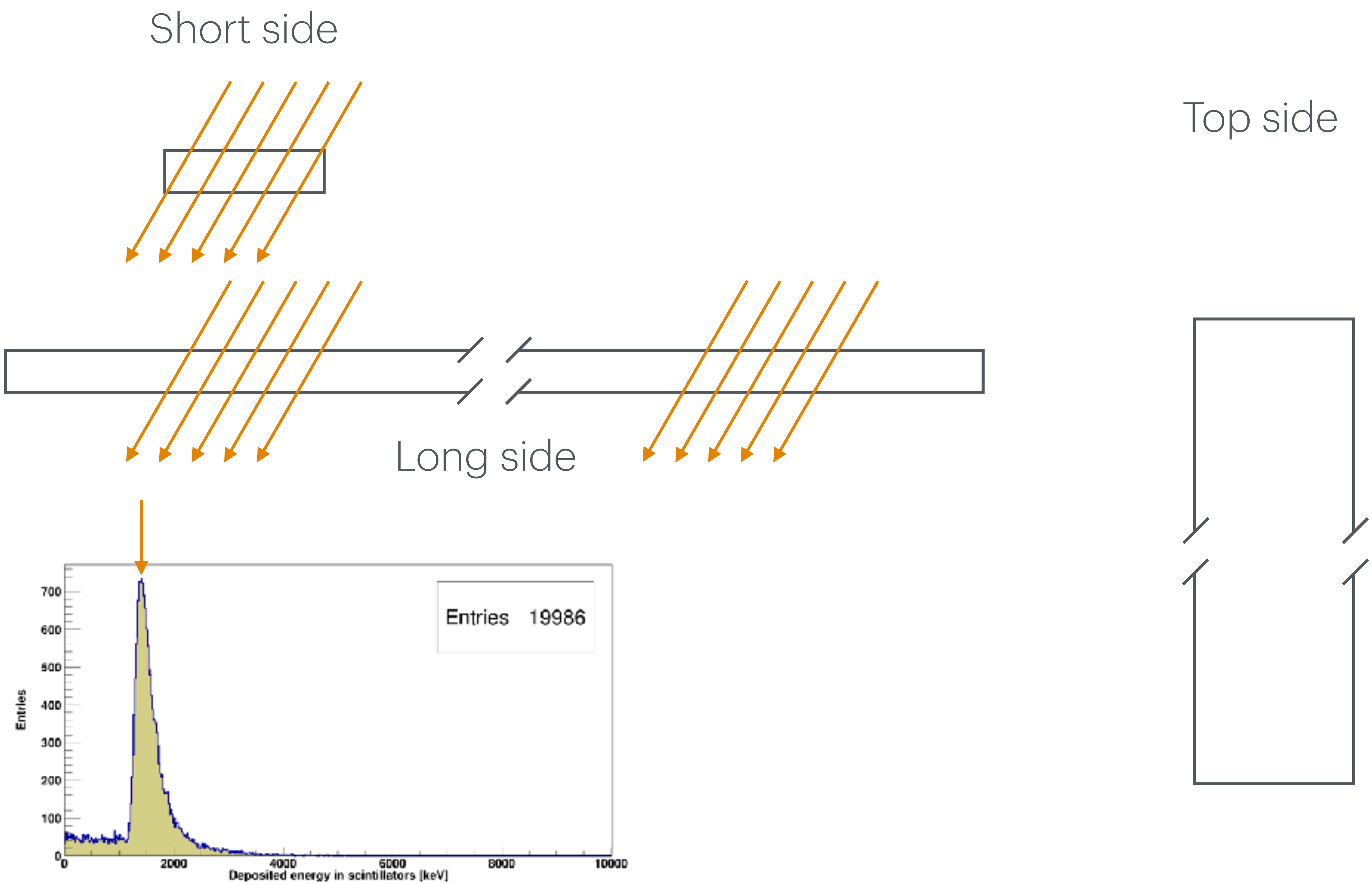

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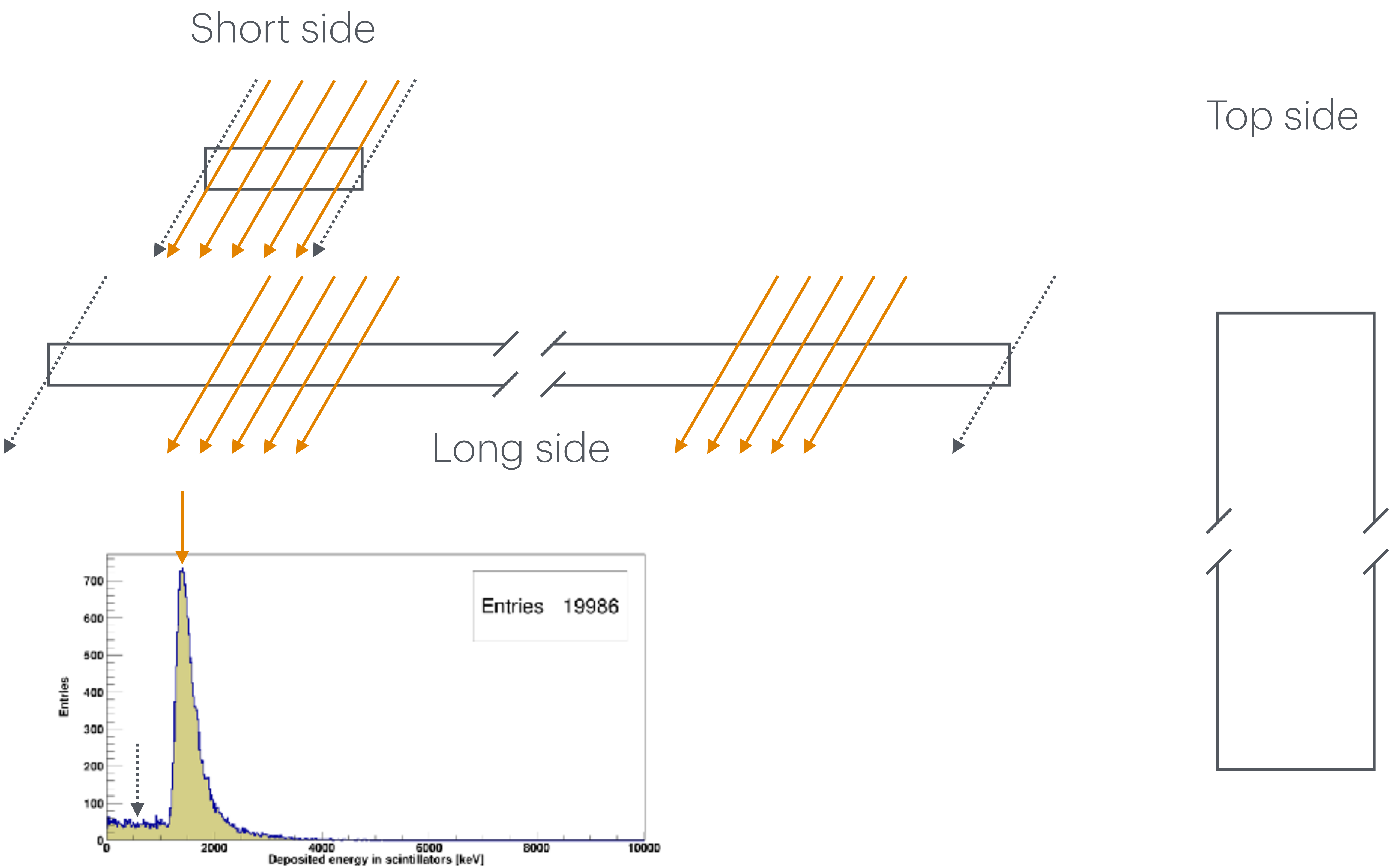

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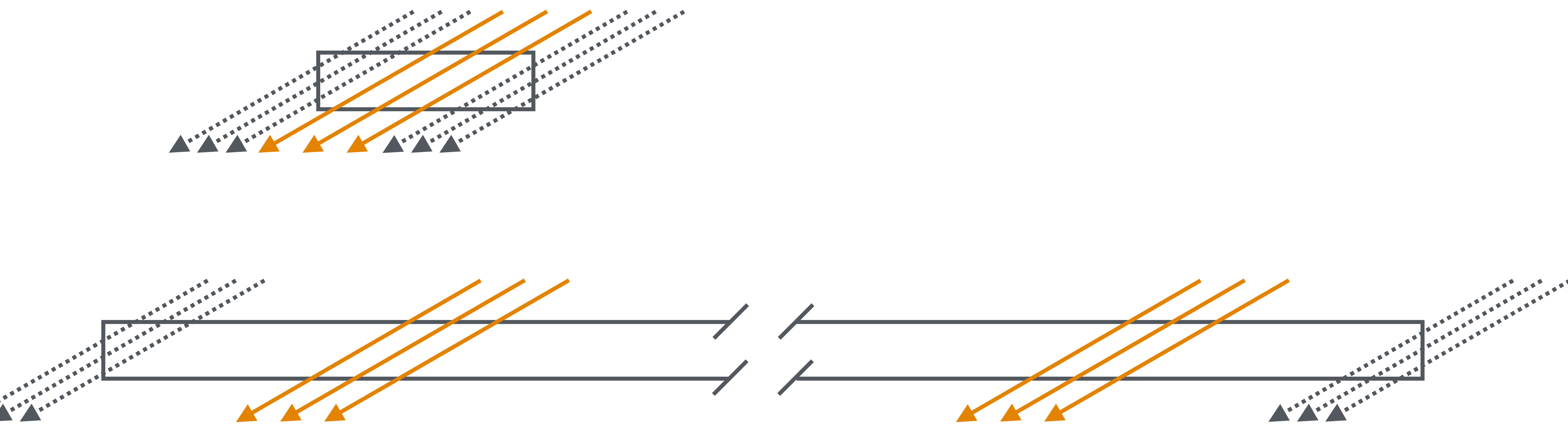

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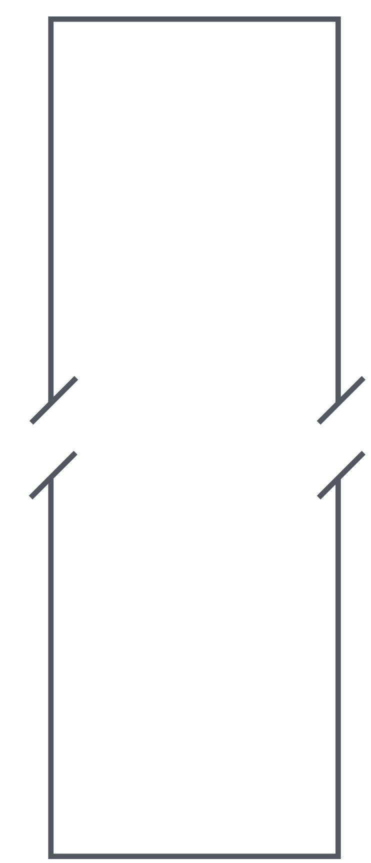
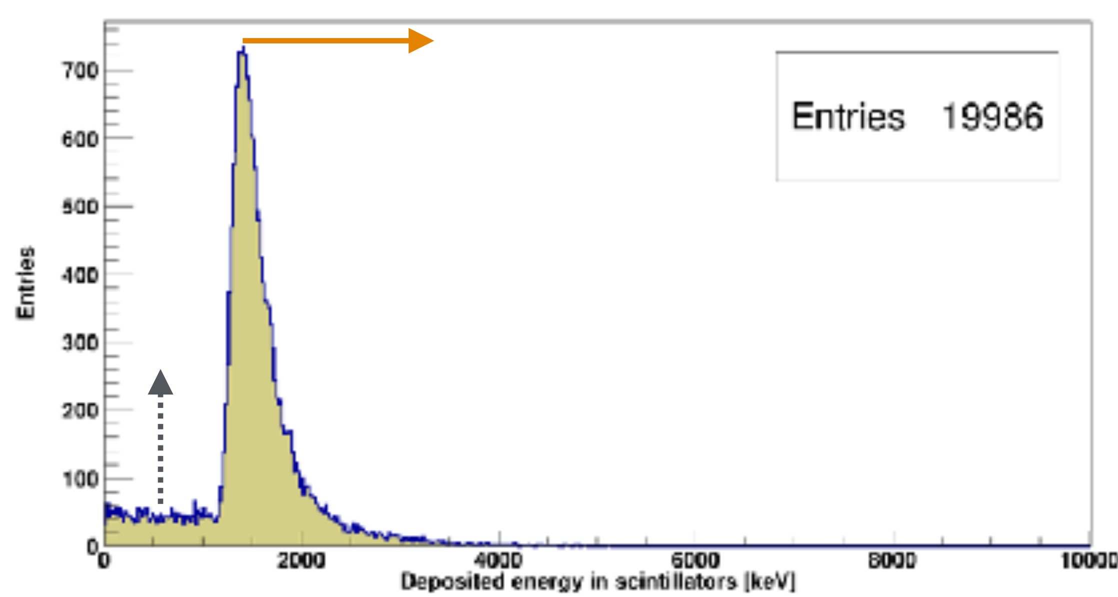
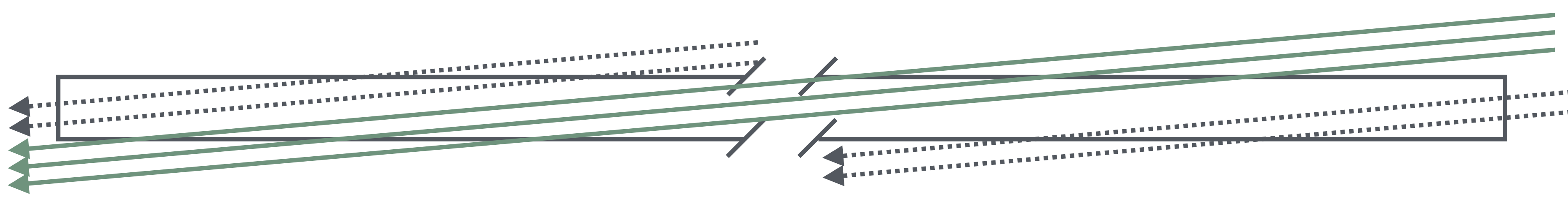




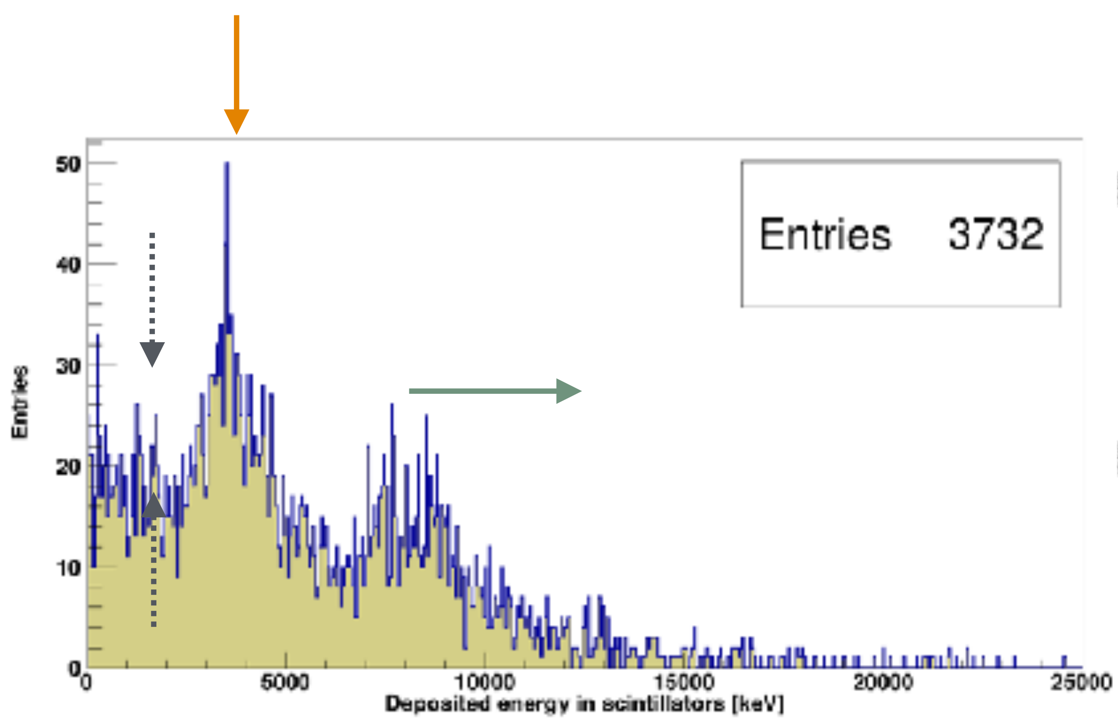
- Peak moves: $\propto X$
- “Low energy” region increases

The geometry of calibration

Short side



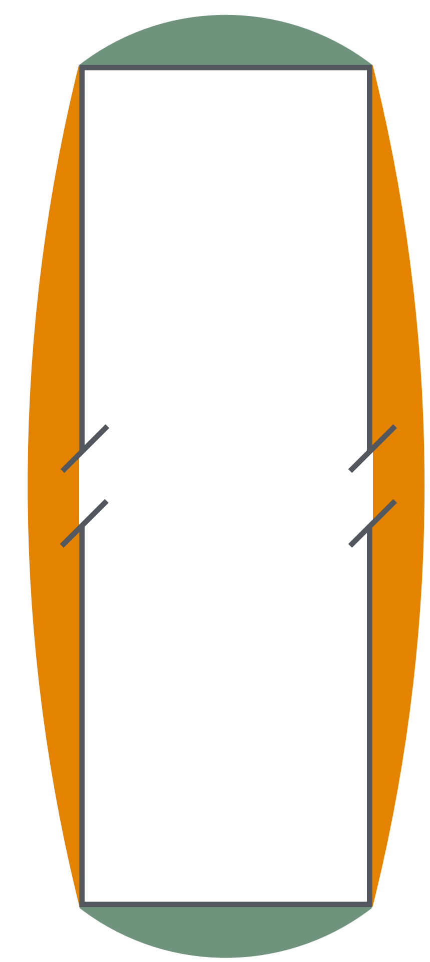
Long side



- Peak reaches a plateau (more events because Azimuth)
- A second peak appears (long side keeps with $\propto X$)
- "Low energy" reduces its importance after a maximum and behaves more as a landau tail

Top side

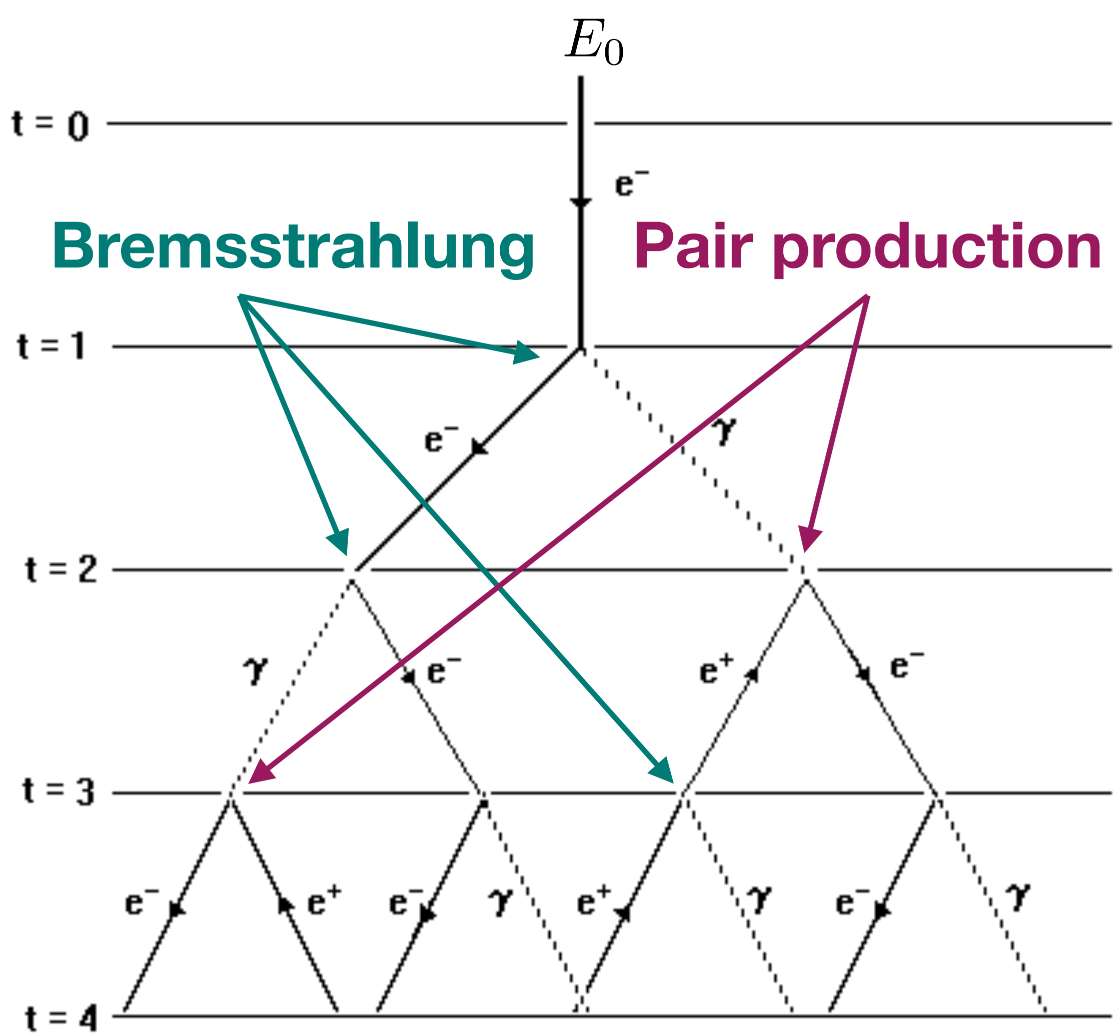
More Azimuthal angles involve the short side



Less azimuthal angles involve the long side

EM cascade

Air as a calorimeter: Heitler Model



The Model

Every radiation length $l/\rho = X_{em}$ (≈ 37 g cm^{-2} in air):

- e^+ and e^- do Bremsstrahlung, emitting a photon γ
- γs do $e^+ + e^-$ pair productions
- Energy is ~halved: $E_t = E_0/2^t$

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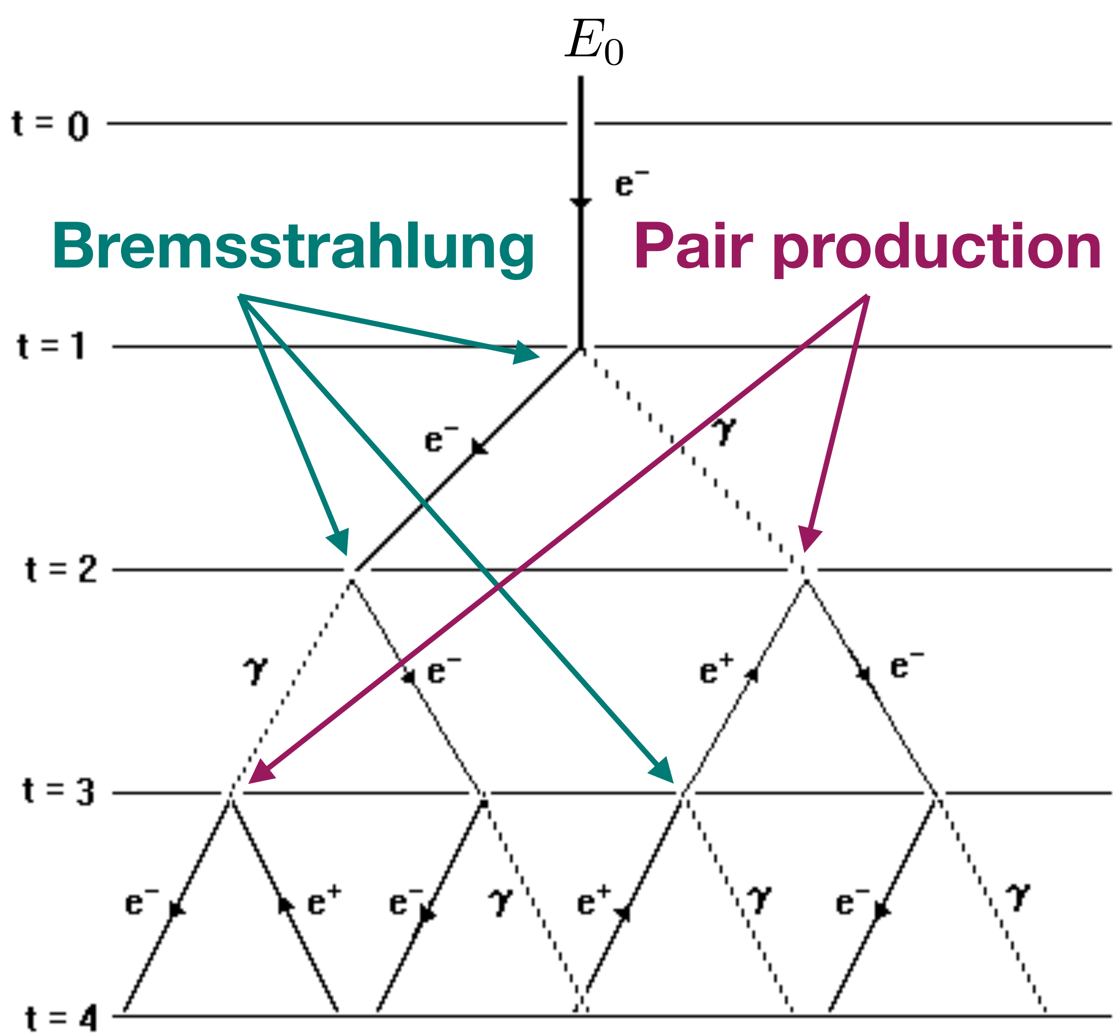

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The process stops after $t_{\max}$ steps

@ E_{crit} ≈ 86 MeV in air, i.e.

$$\left.\frac{\mathrm{d}E}{\mathrm{d}X}\right|_{E=E_{\mathrm{crit}}}^{\mathrm{ioniz}} \approx \left.\frac{\mathrm{d}E}{\mathrm{d}X}\right|_{E=E_{\mathrm{crit}}}^{\mathrm{brems}}$$

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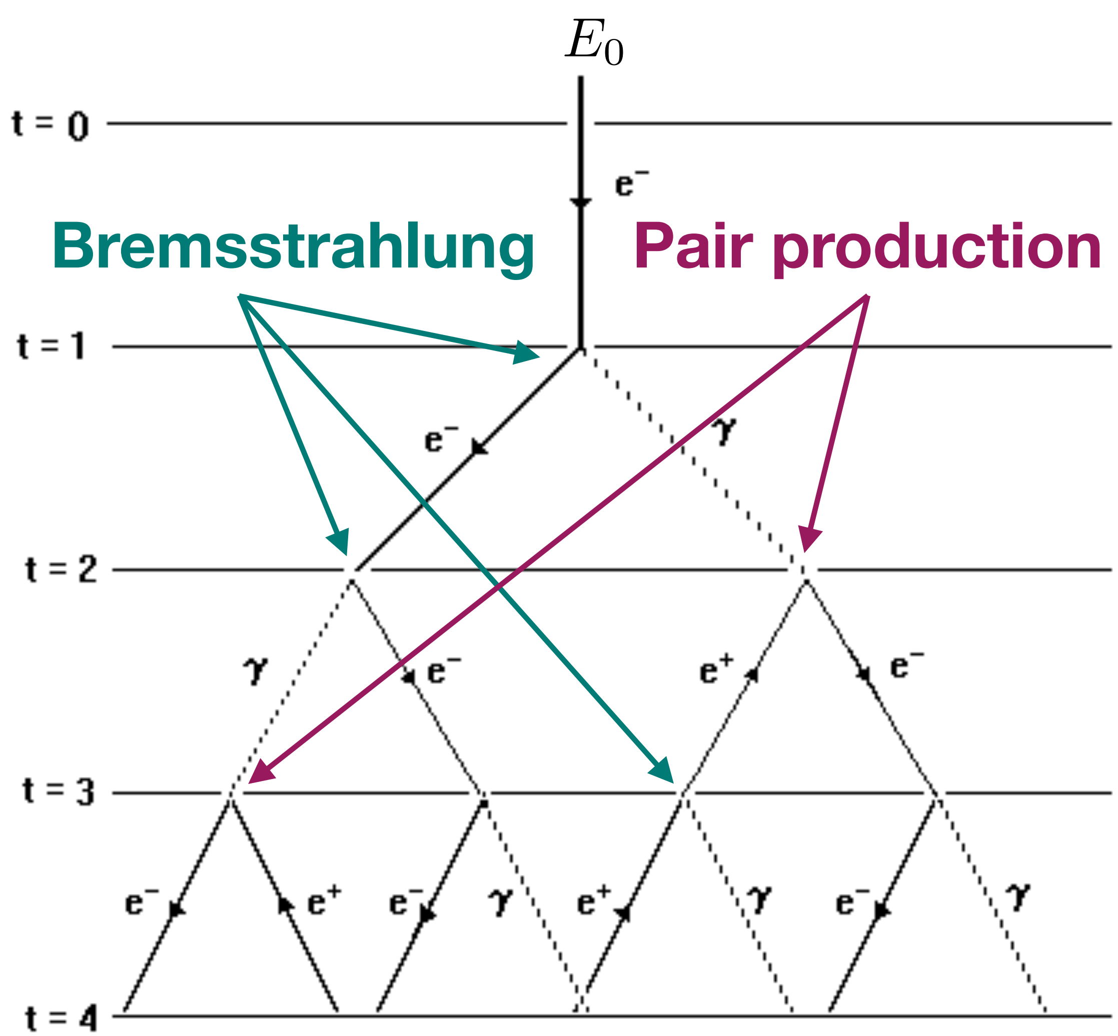

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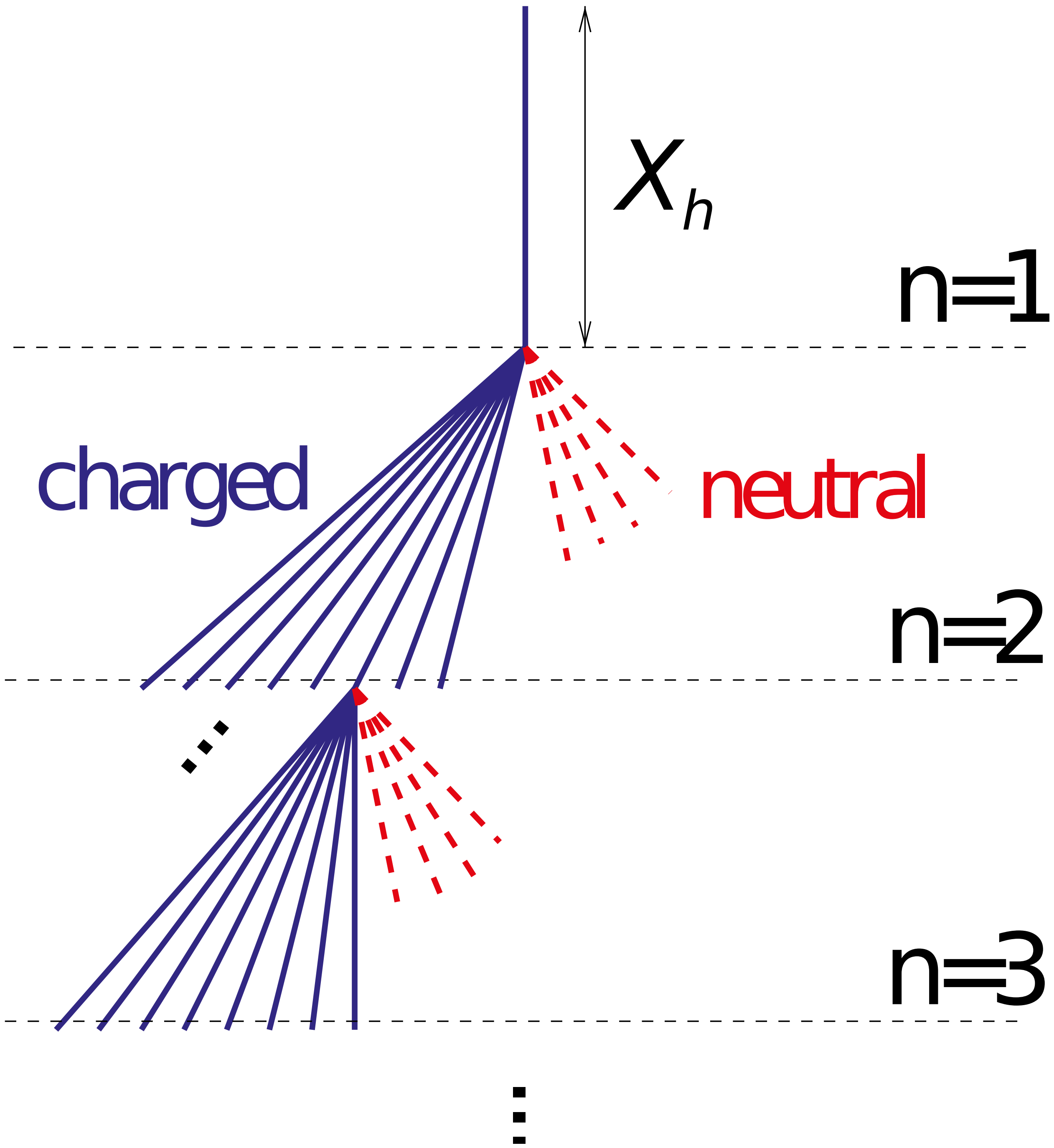
- step t with the radiative maximum production $$t_{\max} = \frac{1}{\ln 2} \ln\left(\frac{E_0}{E_{\text{crit}}}\right)$$
- Number of particles at the radiative maximum $$N_{\max} = \frac{E_0}{E_{\text{crit}}}$$
- Depth of the radiative maximum $$X_{\max} = X_{\text{em}} \cdot t_{\max} = \frac{X_{\text{em}}}{\ln 2} \ln\left(\frac{E_0}{E_{\text{crit}}}\right)$$

Hadronic cascade

Air as a calorimeter: Heitler-Matthews Model



Mesons are mostly Pions and Kaons,
Ks decay in πs faster than π^+/π^-,
Pion shower!

Hadronic cascade

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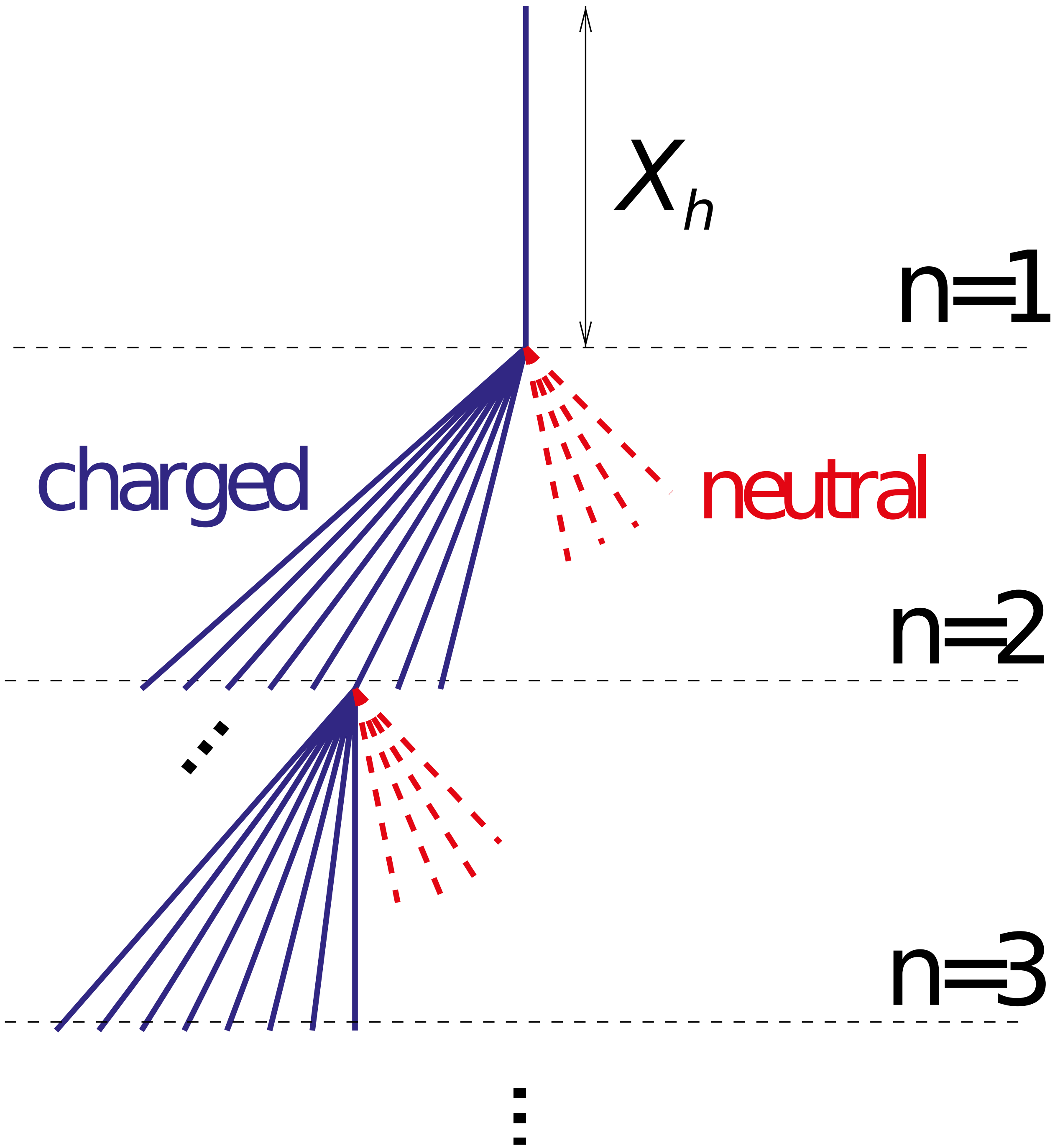

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After X_h, every step produces n_{mult} pions

- 1/3 are π^0s
- π^0s decay faster than π^+/π^-

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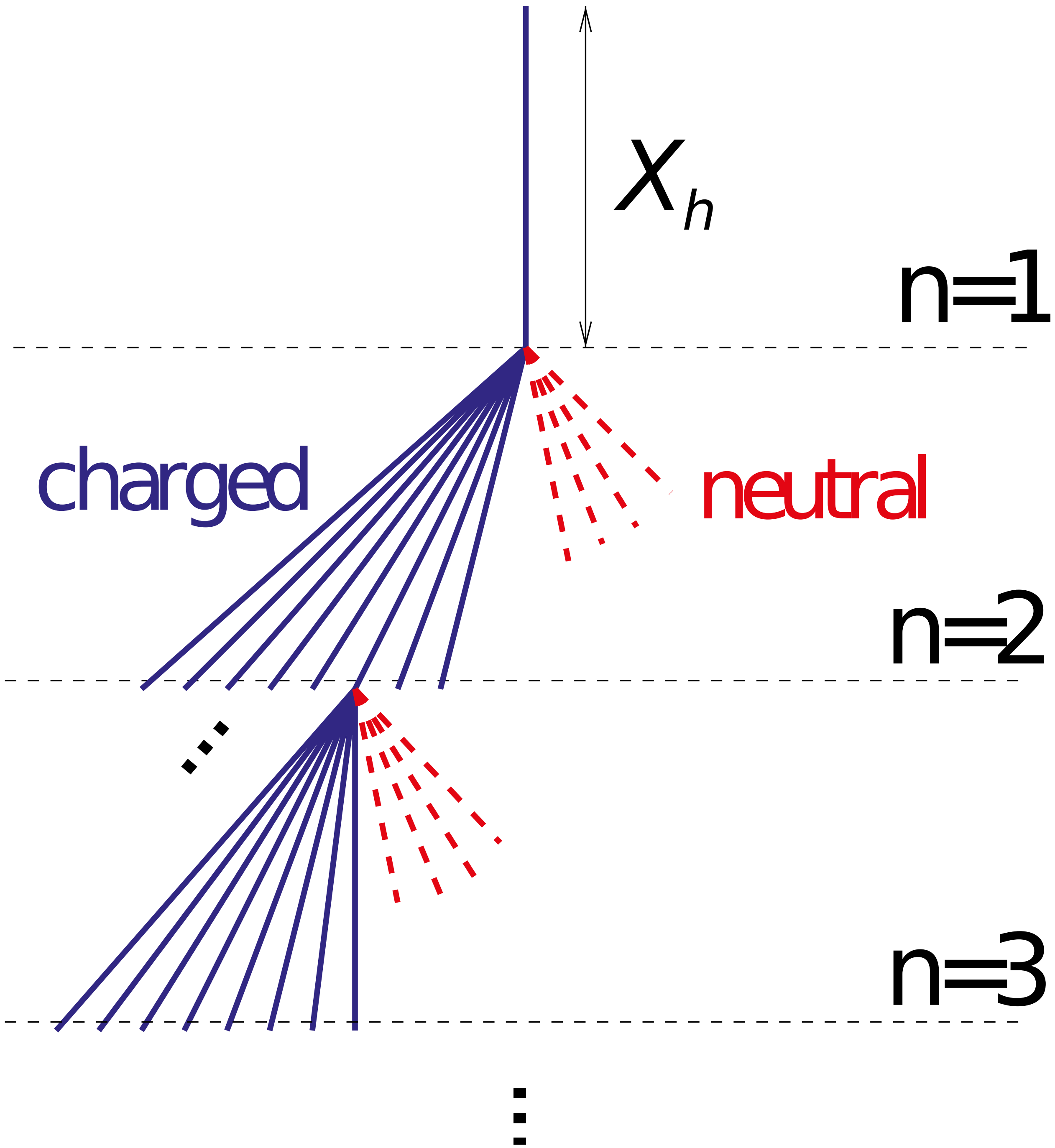

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- 2/3 are charged pions that produce the next generation $n_{\text{ch}} = 2/3 n_{\text{mult}}$
- $E_{\text{crit}}^{\text{decay}} \approx 20$ GeV in air

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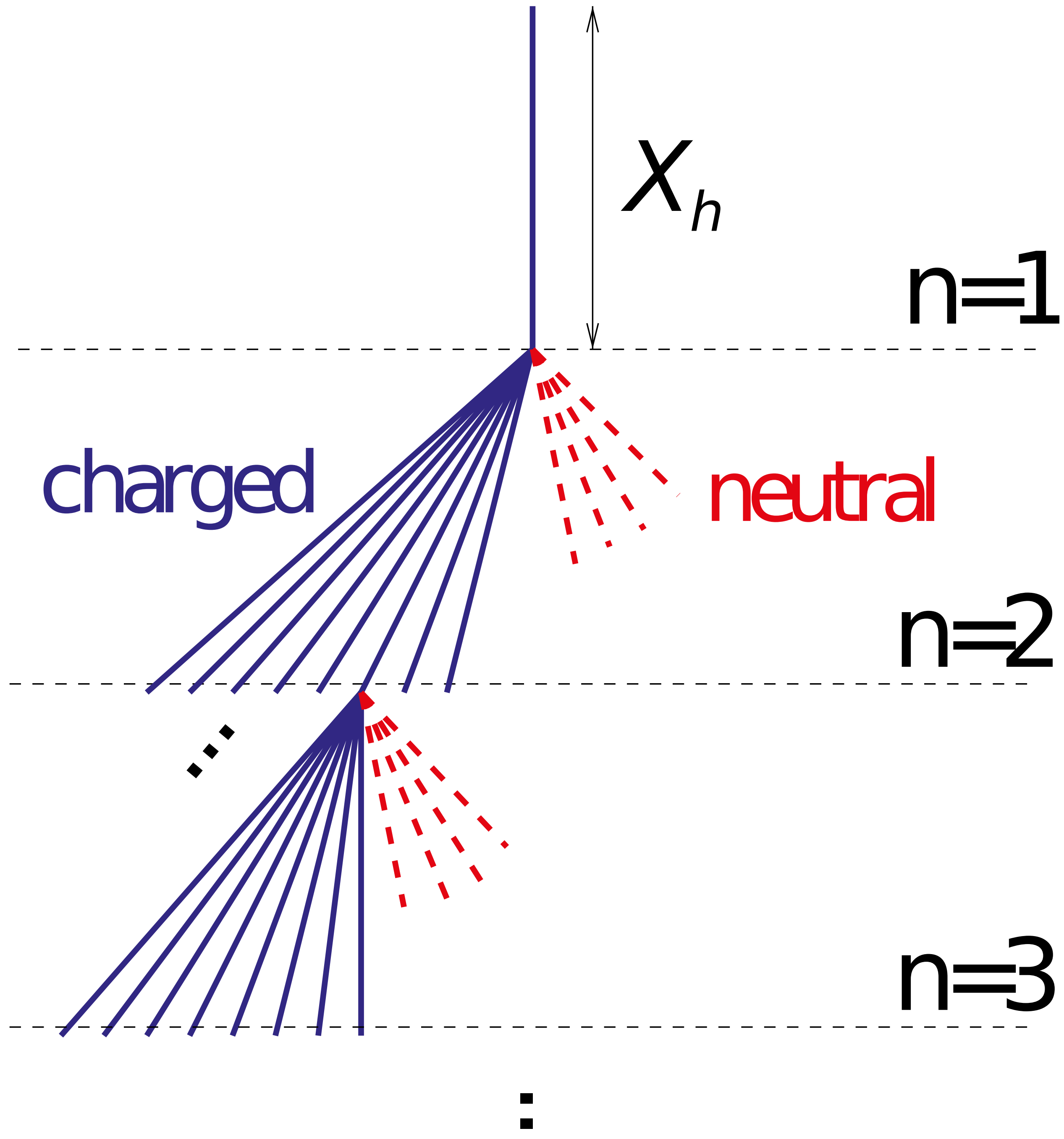

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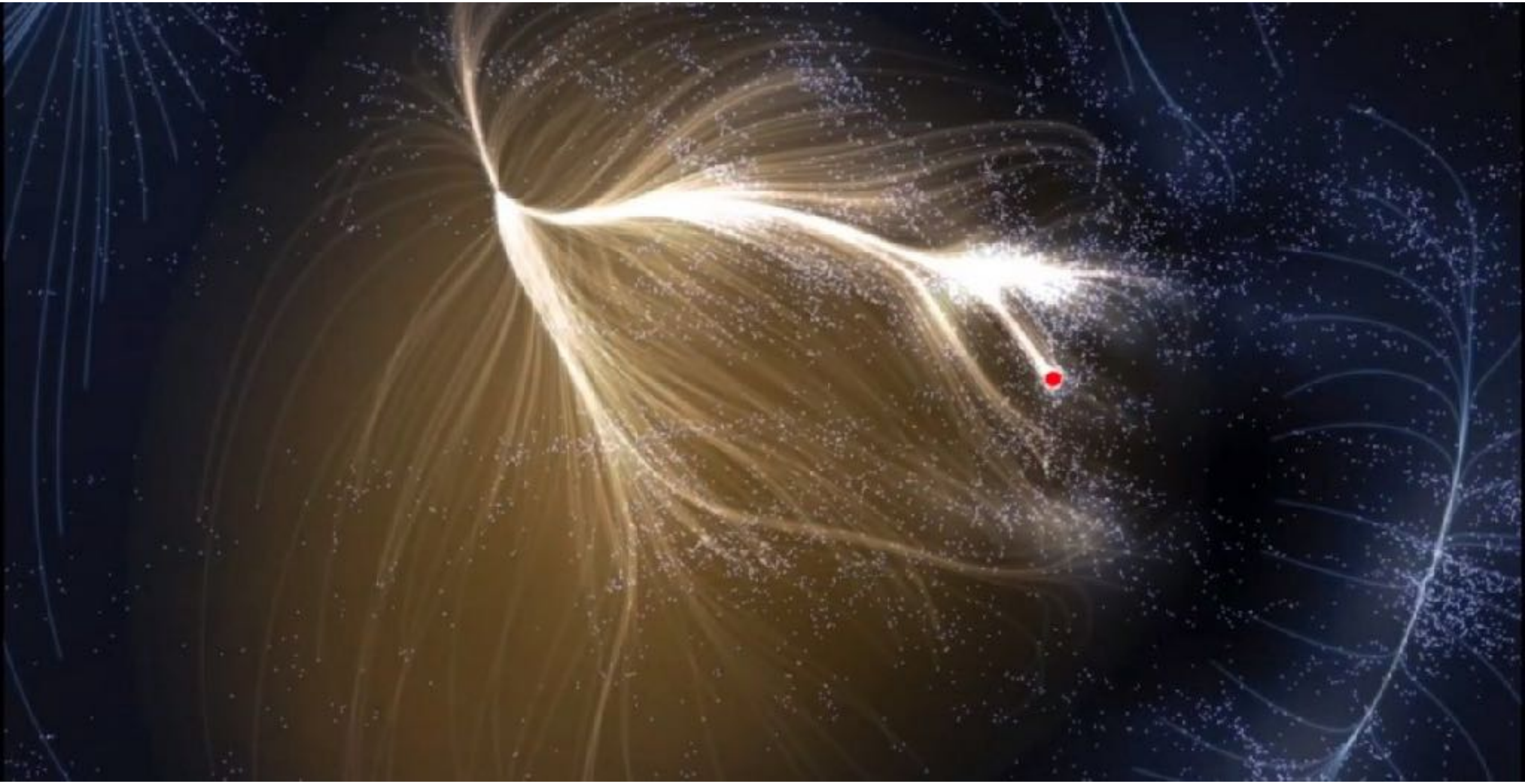
- $E_{\mathrm{crit}}^{\mathrm{decay}} \approx 20$ GeV in air

$$E_{\mathrm{had}} = \left(\frac{2}{3}\right)^n E_0 \qquad E_{\mathrm{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

Laniakea



Galaxy movements shows all supeclusters attracted gravitationally by something…

The Great Attractor