μPPET:

studying the Cosmic Rays Muon Puzzle by probing muons with J-PETs

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

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Narodowe Centrum Nauki
SONATA BIS-13

Why are CRs interesting?

Cosmic Rays

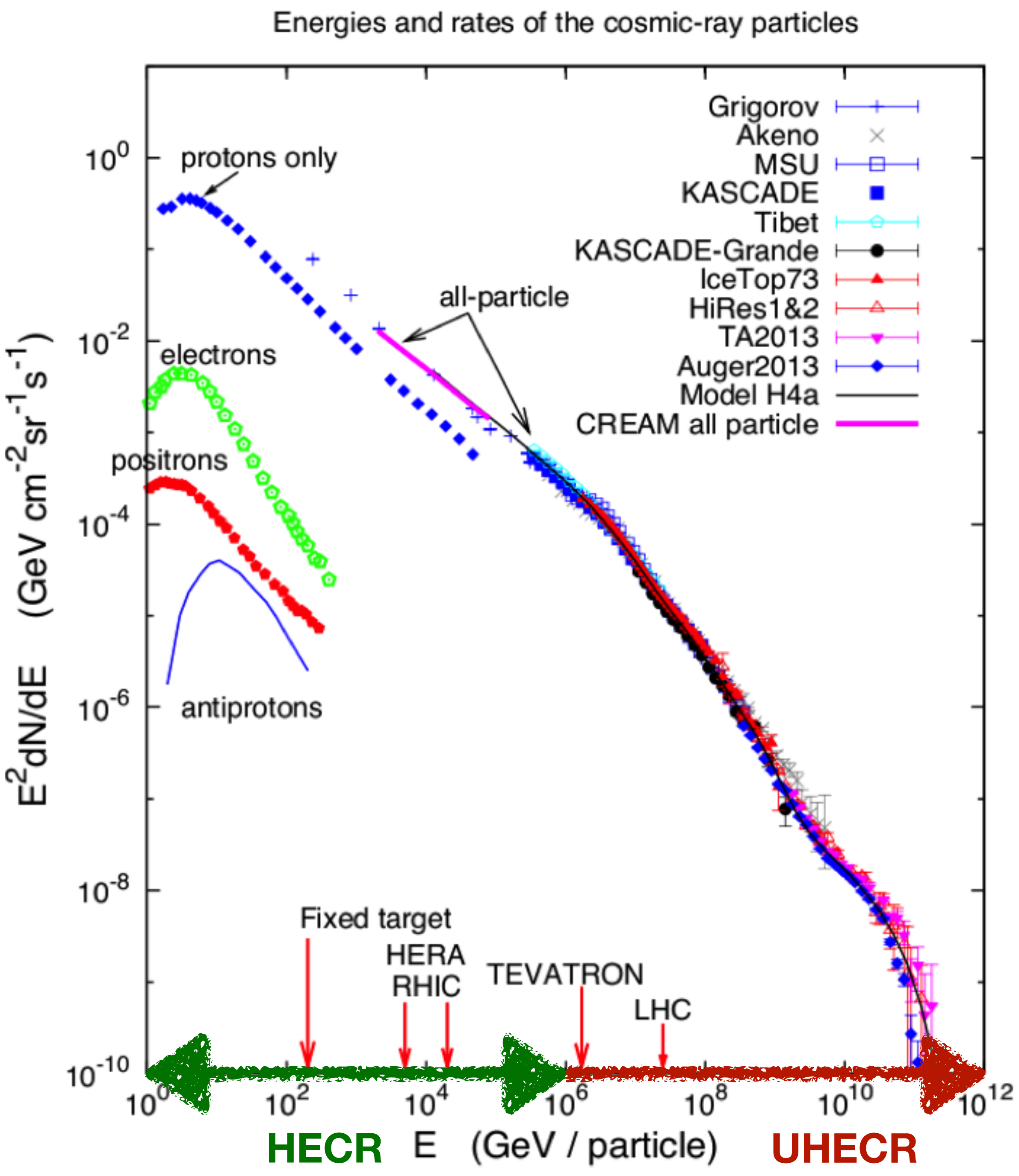
- Information on Astrophysical events and sources
- Testing ground of models and theories
- Cosmology

Questions: from where do they come?

- Energies and acceleration mechanisms?
- Masses?

Classification

Cosmic Rays



Classification

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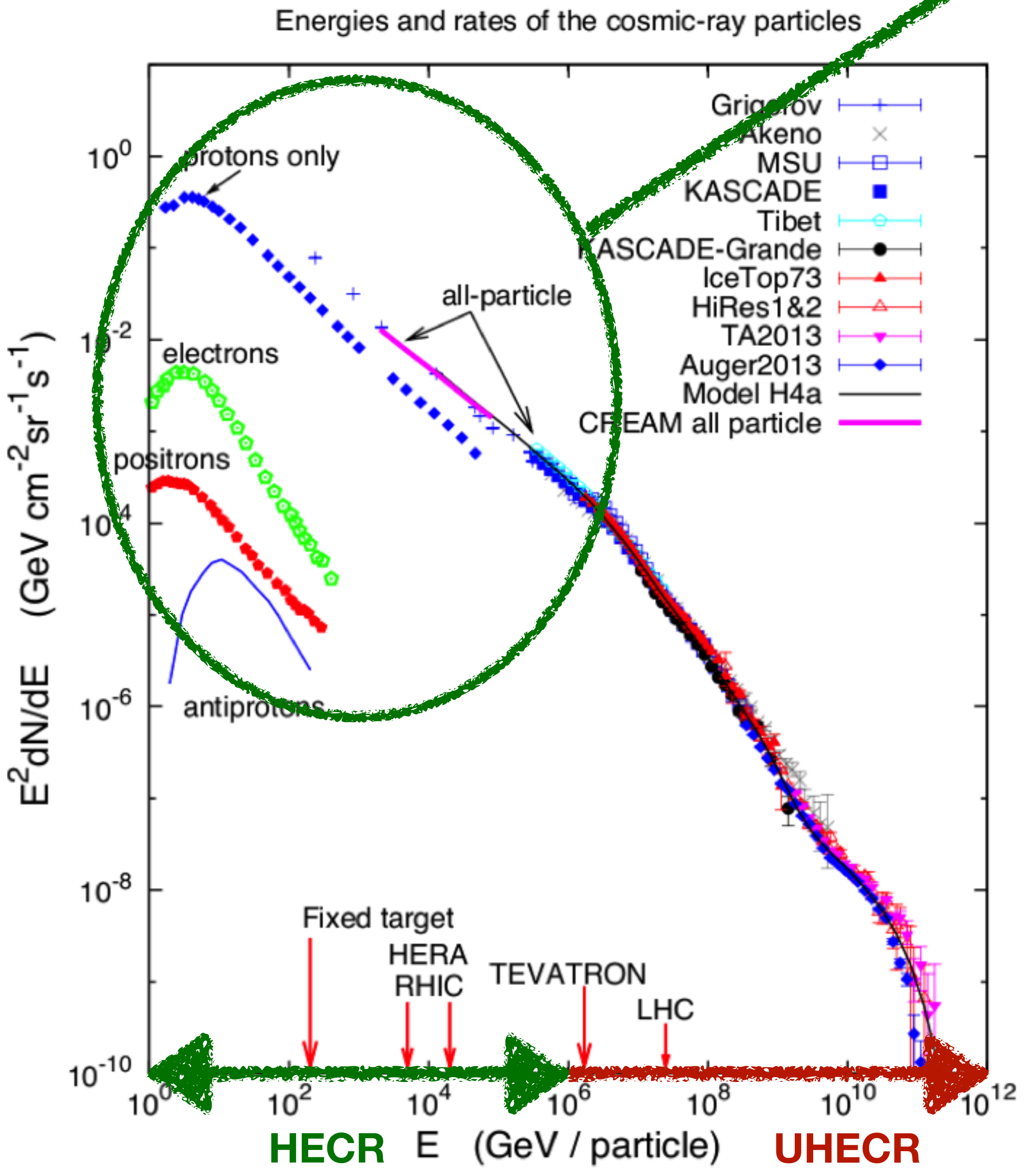


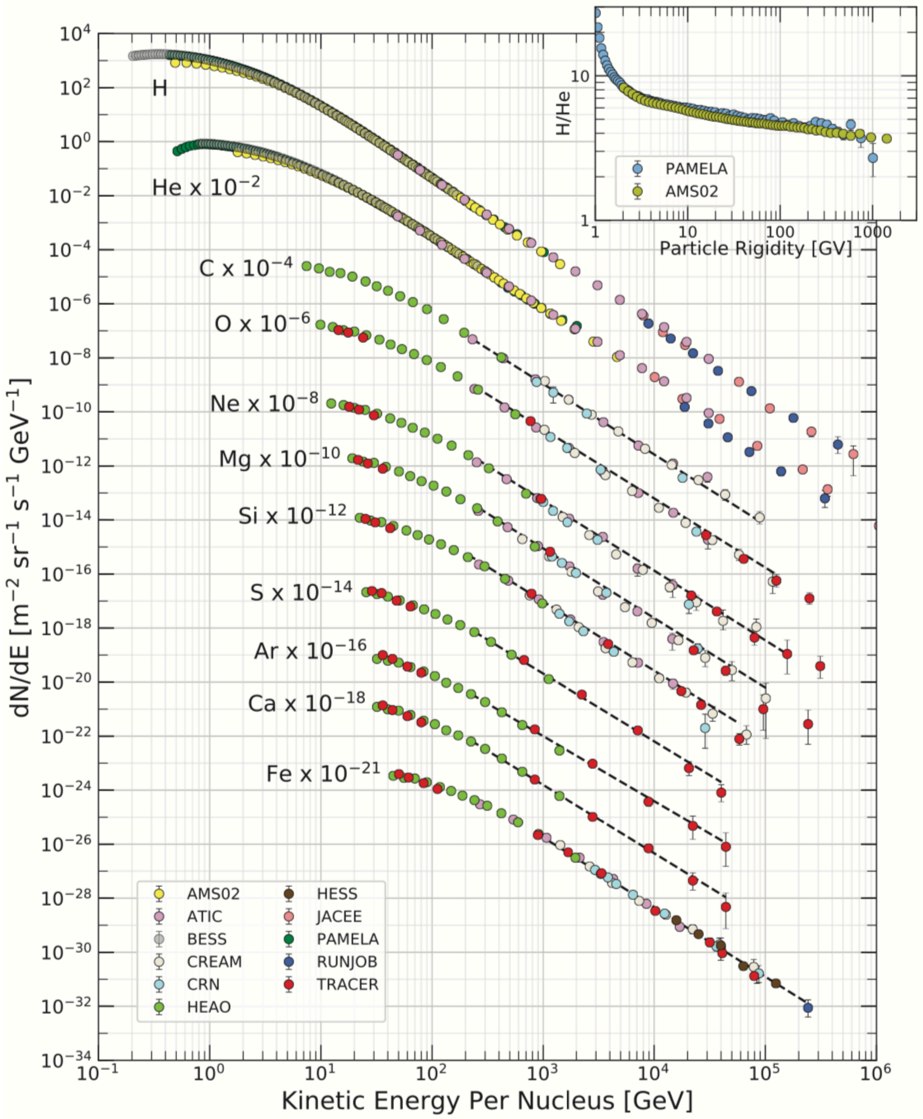
High **E**nergy **C**osmic **R**ays

(**HECR**)

Direct detection:

Balloon-borne detectors, Satellites,...

- Regular energy spectrum power law
- Well-know mass composition



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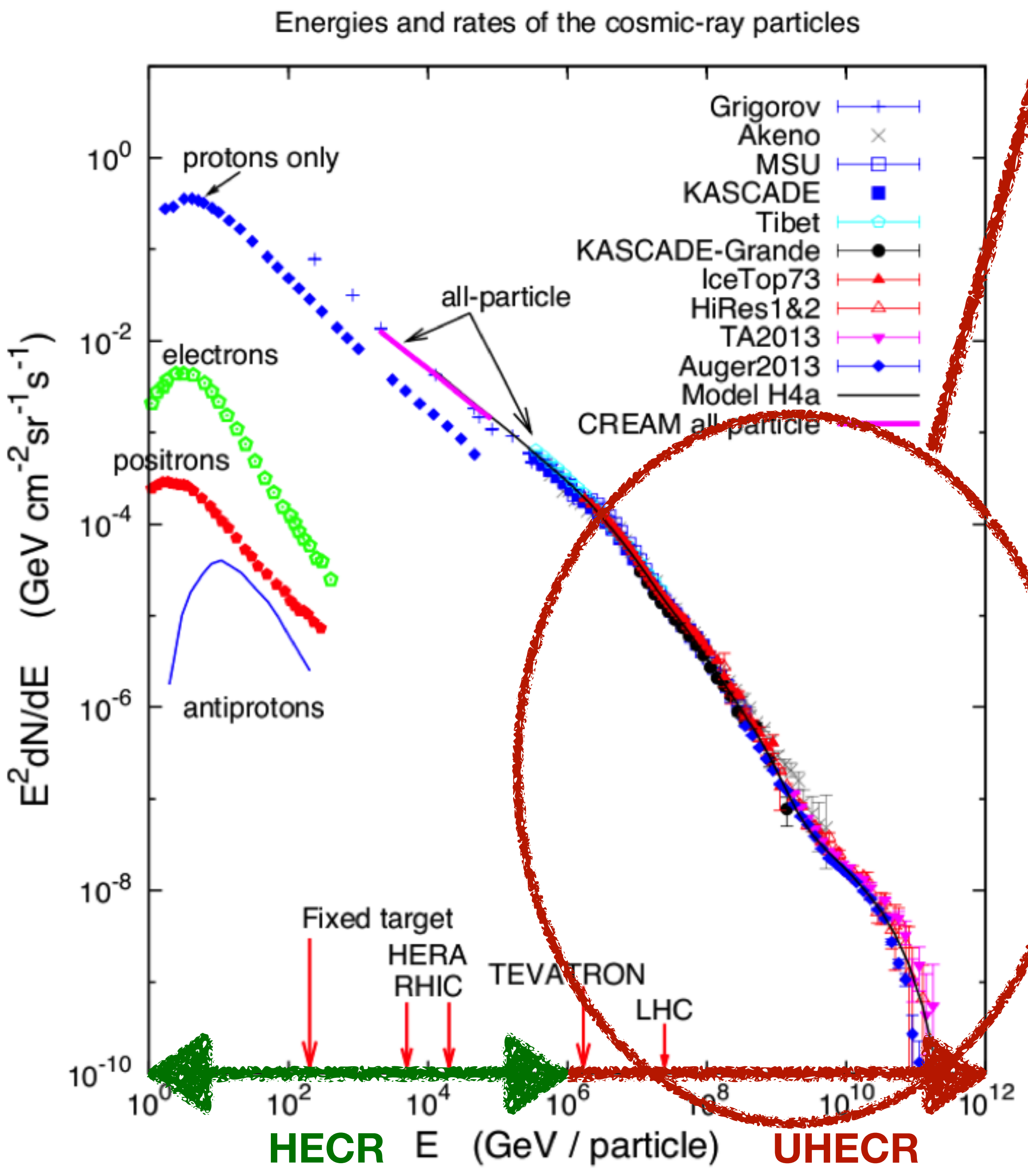
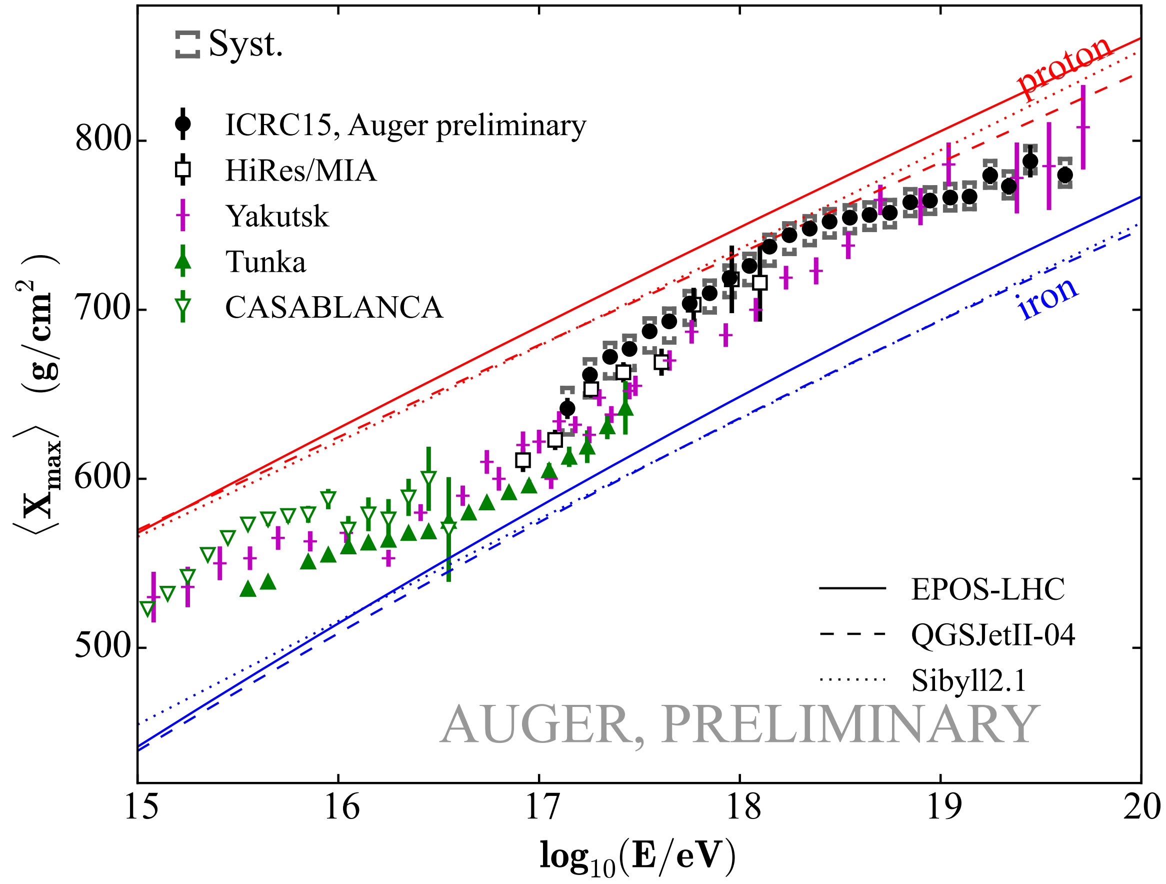


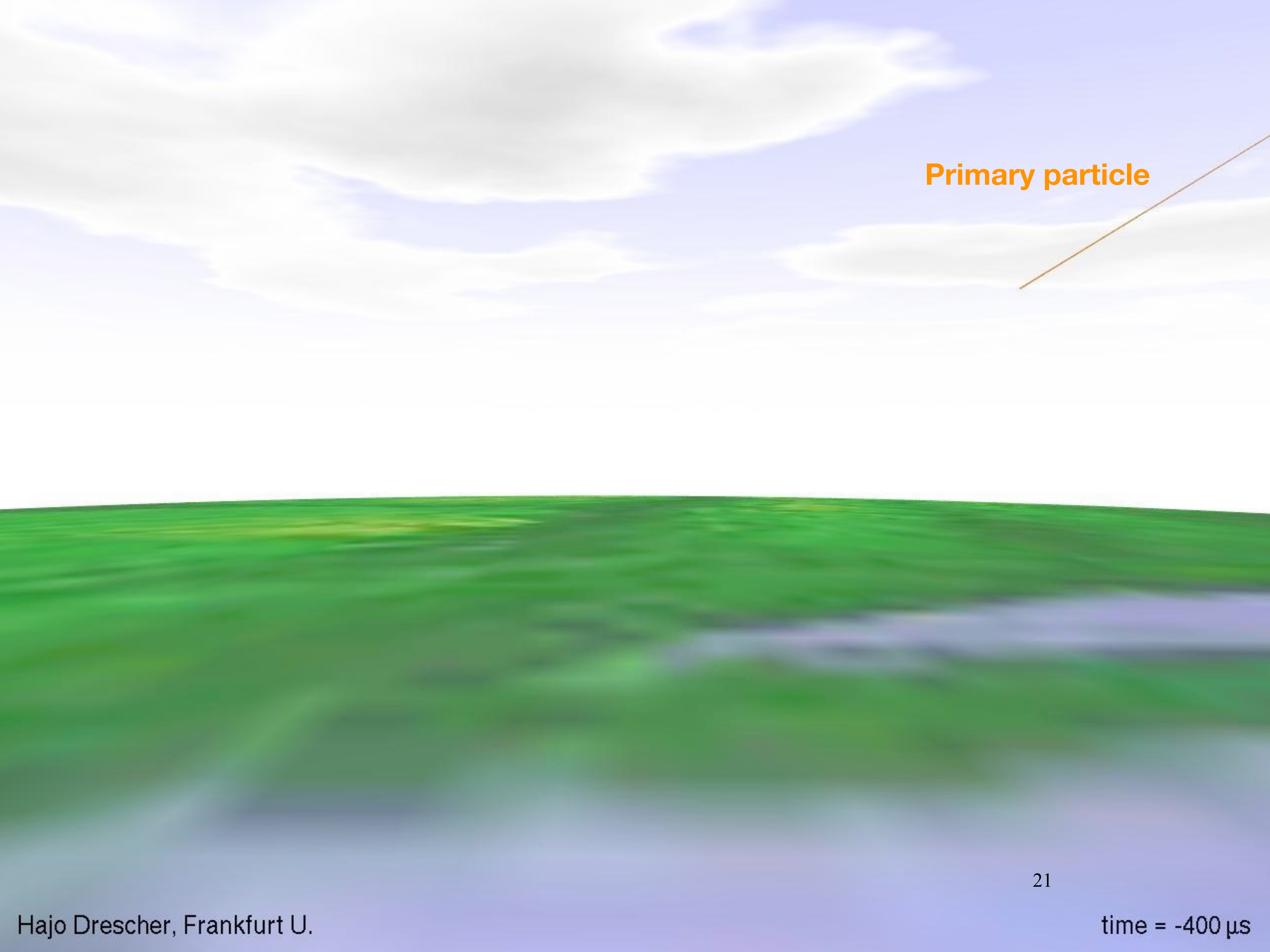
Ultra-High Energy Cosmic Rays (UHECR)

Indirect detection:
via Extensive Air Showers (**EAS**)

- Structures in the Energy Spectrum
- Structures in the Mass Composition

(changes of source types!)



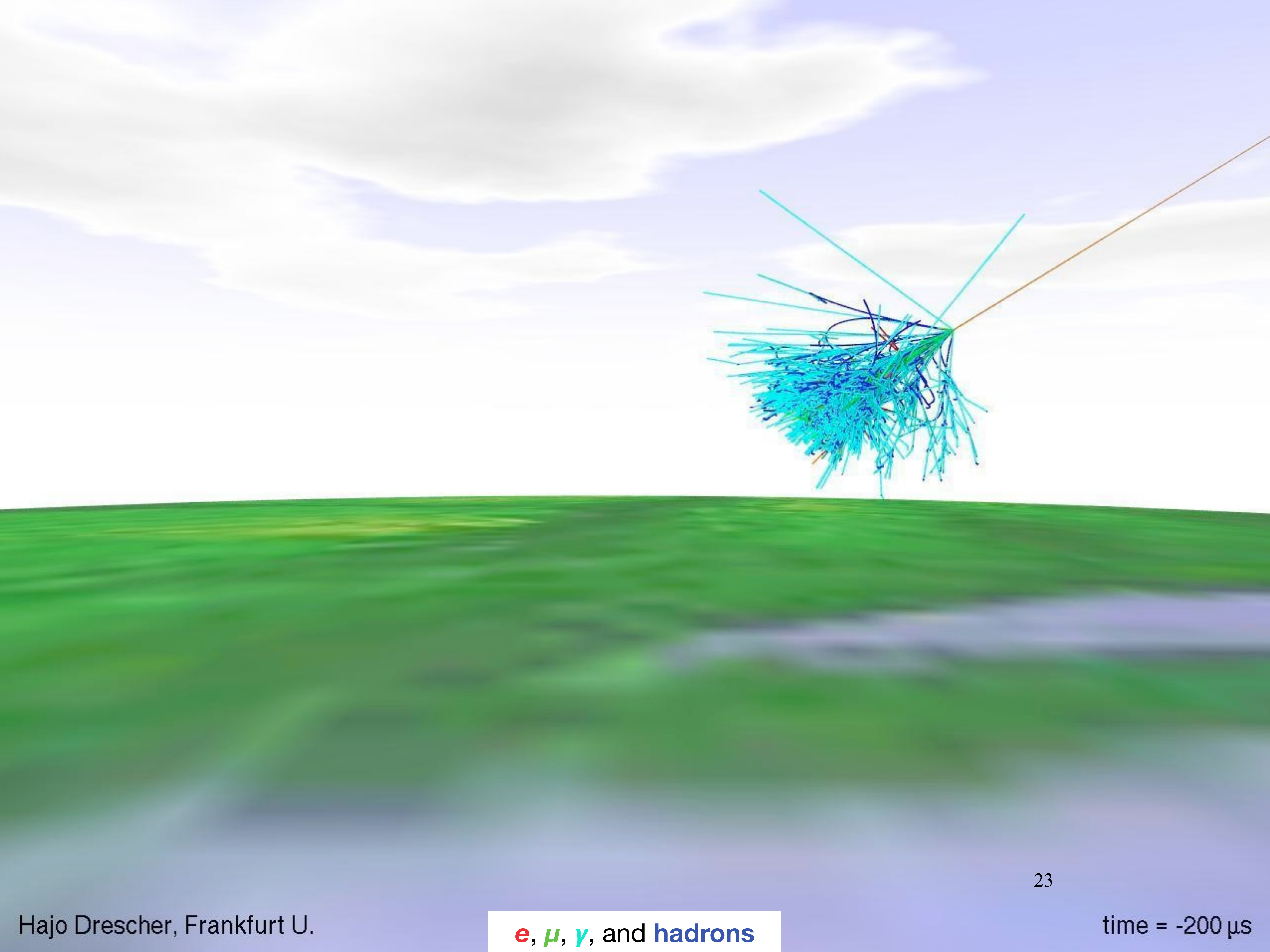


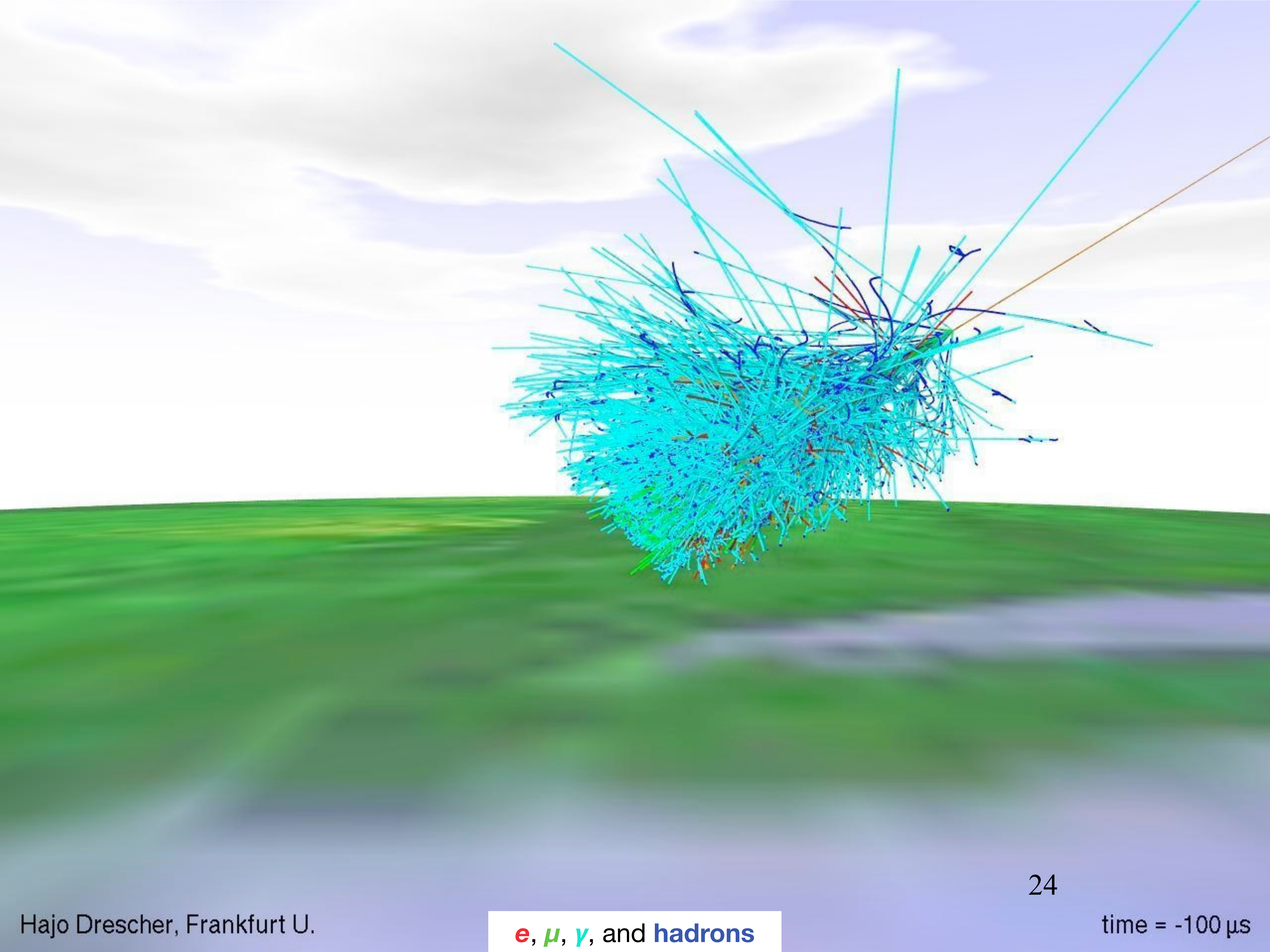
Hajo Drescher, Frankfurt U.

Primary particle

Secondary particles

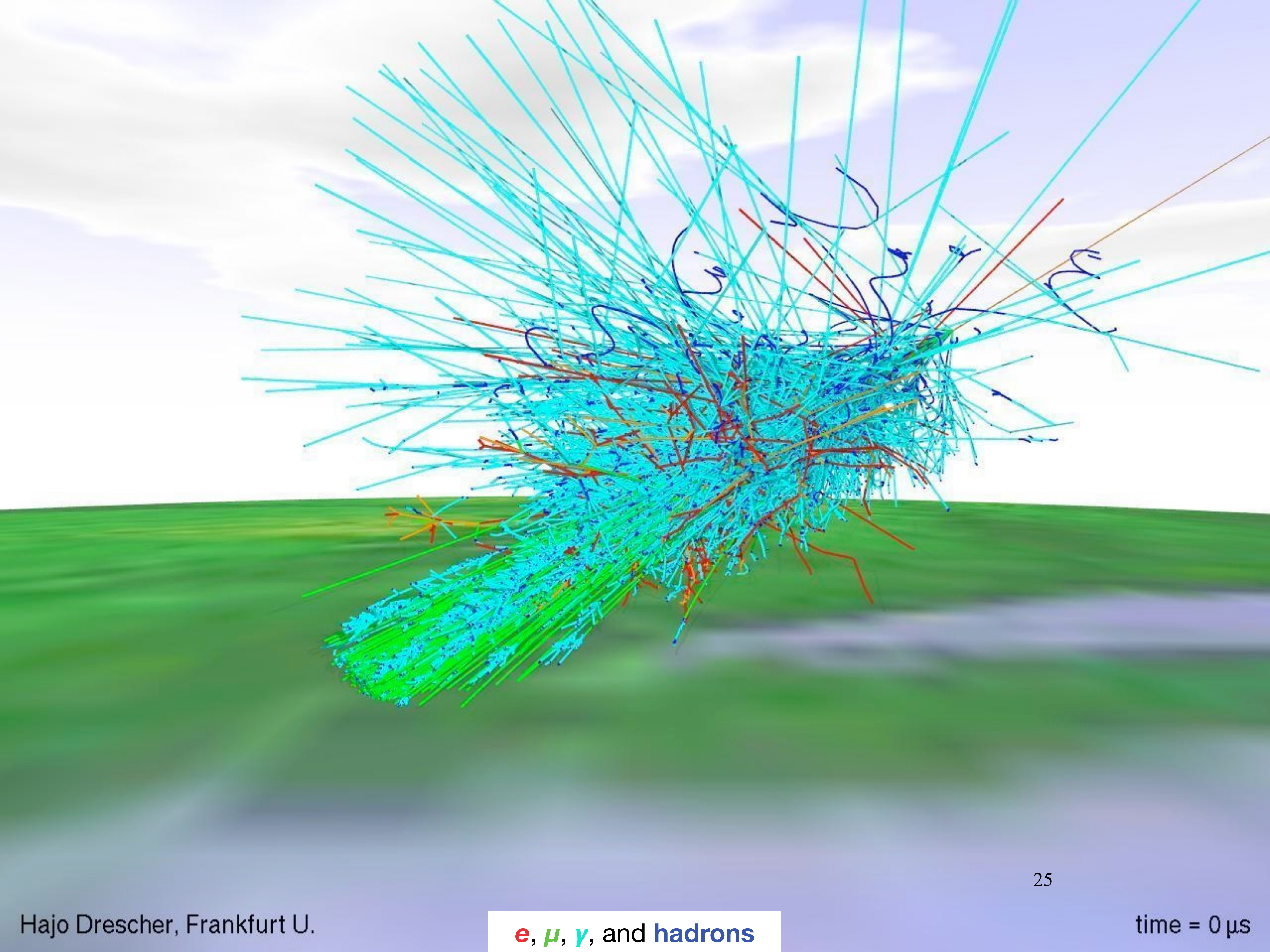
e, μ, γ, and **hadrons**


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



Hajo Drescher, Frankfurt U.

e, *μ*, *γ*, and **hadrons**



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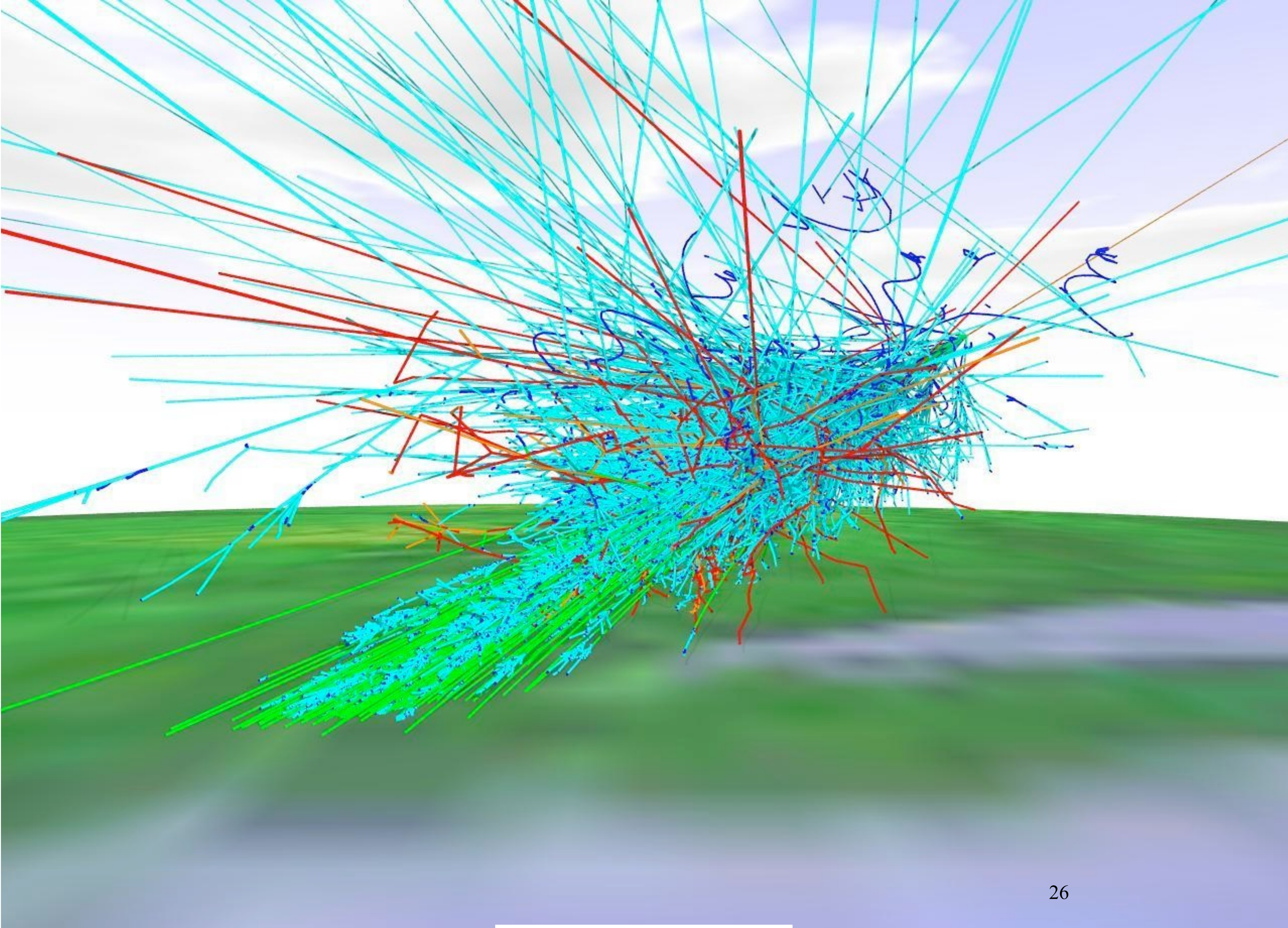

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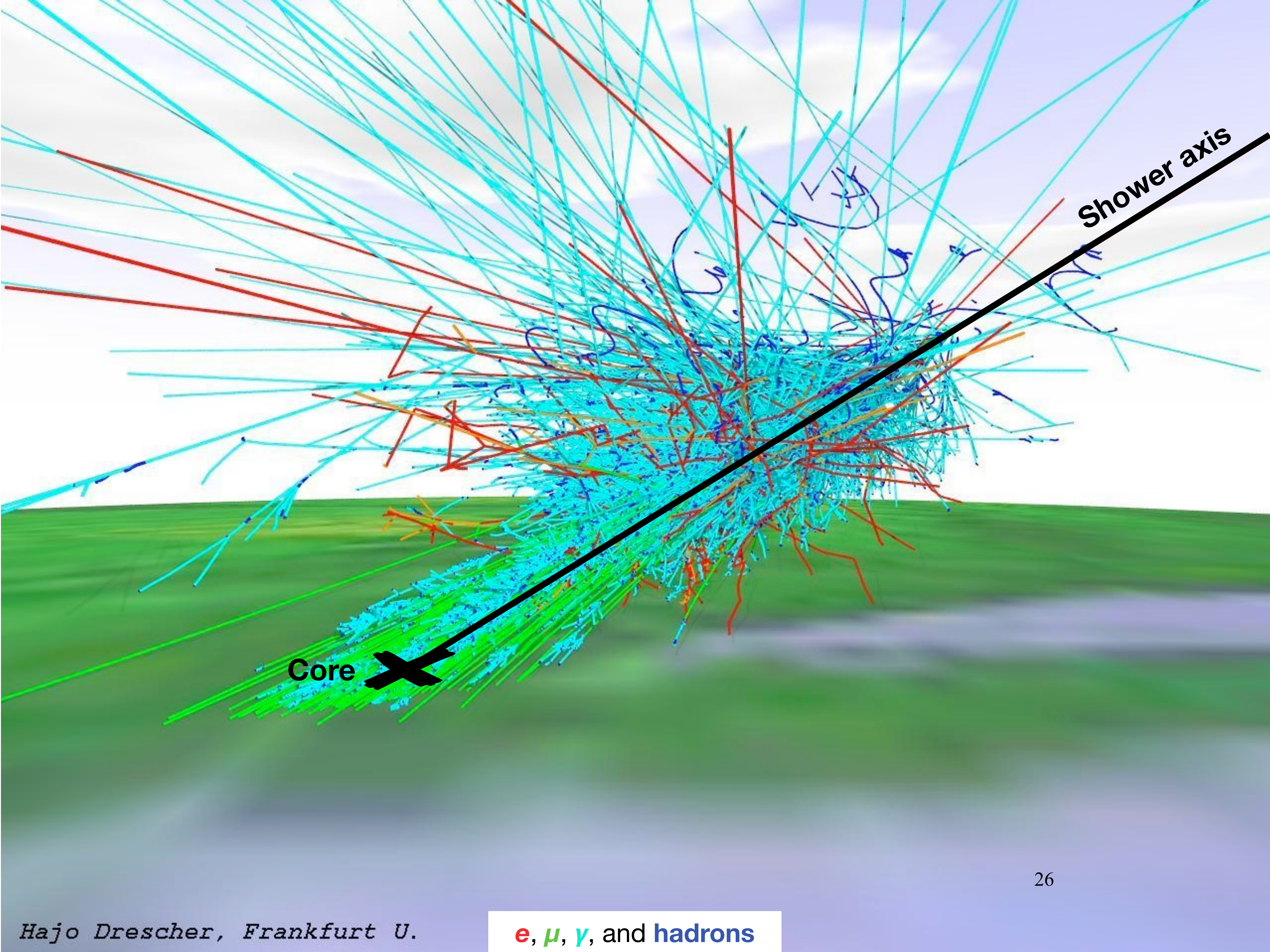
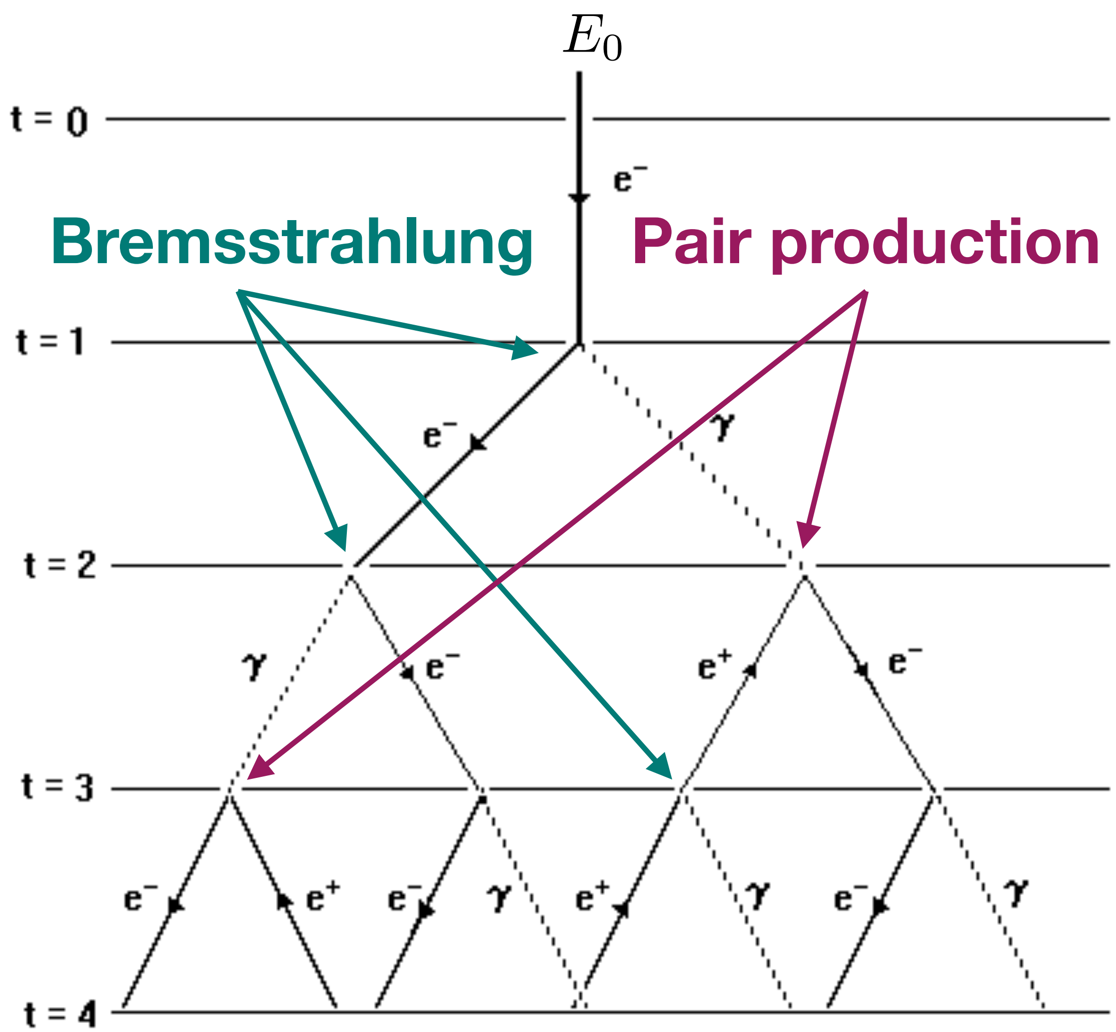


Hajo Drescher, Frankfurt U.

e, ***μ***, ***γ***, and **hadrons**

EM cascade

Air as a calorimeter: Heitler Model



The Model

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

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

EM cascade

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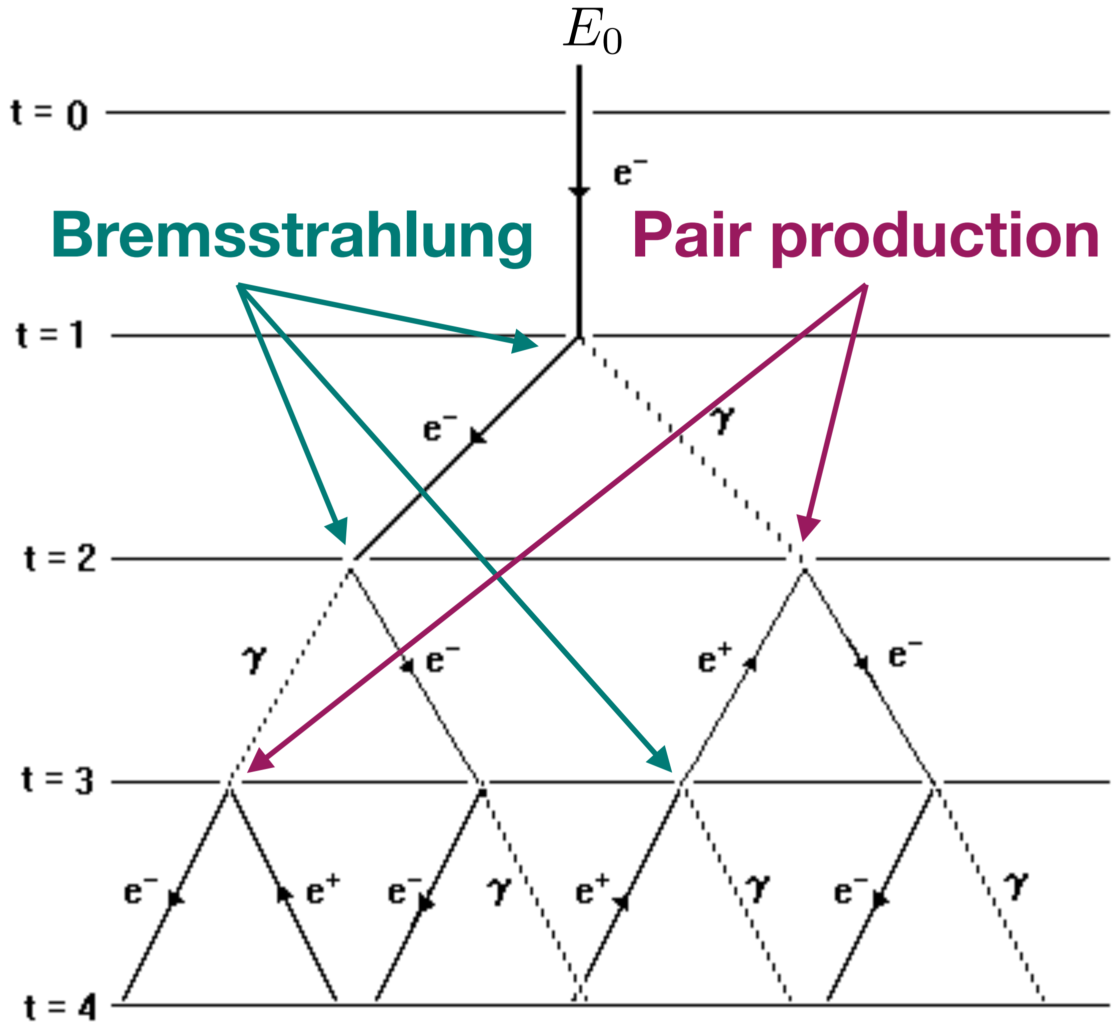

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The process stops after $t_{\max}$ steps

@ 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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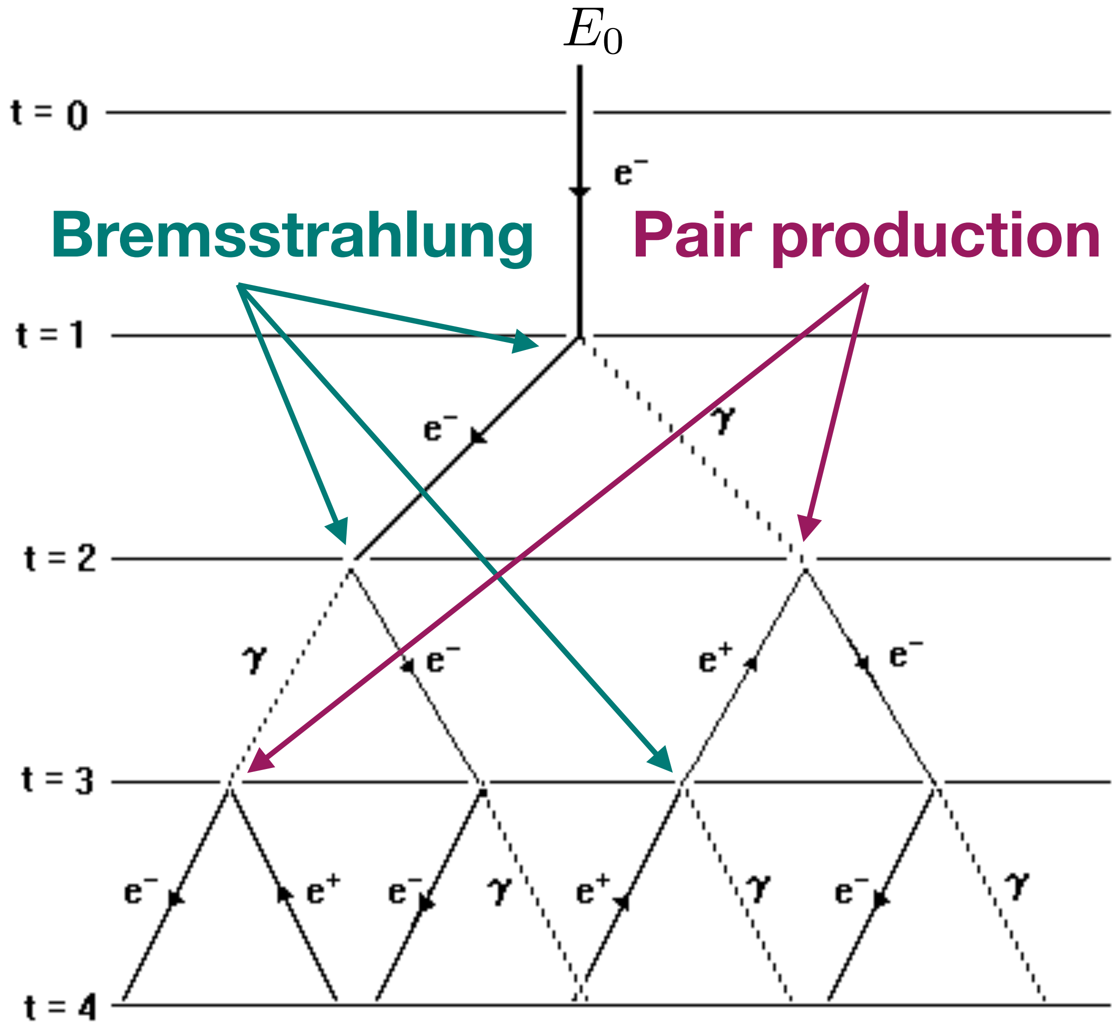

Bremsstrahlung

Pair production

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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

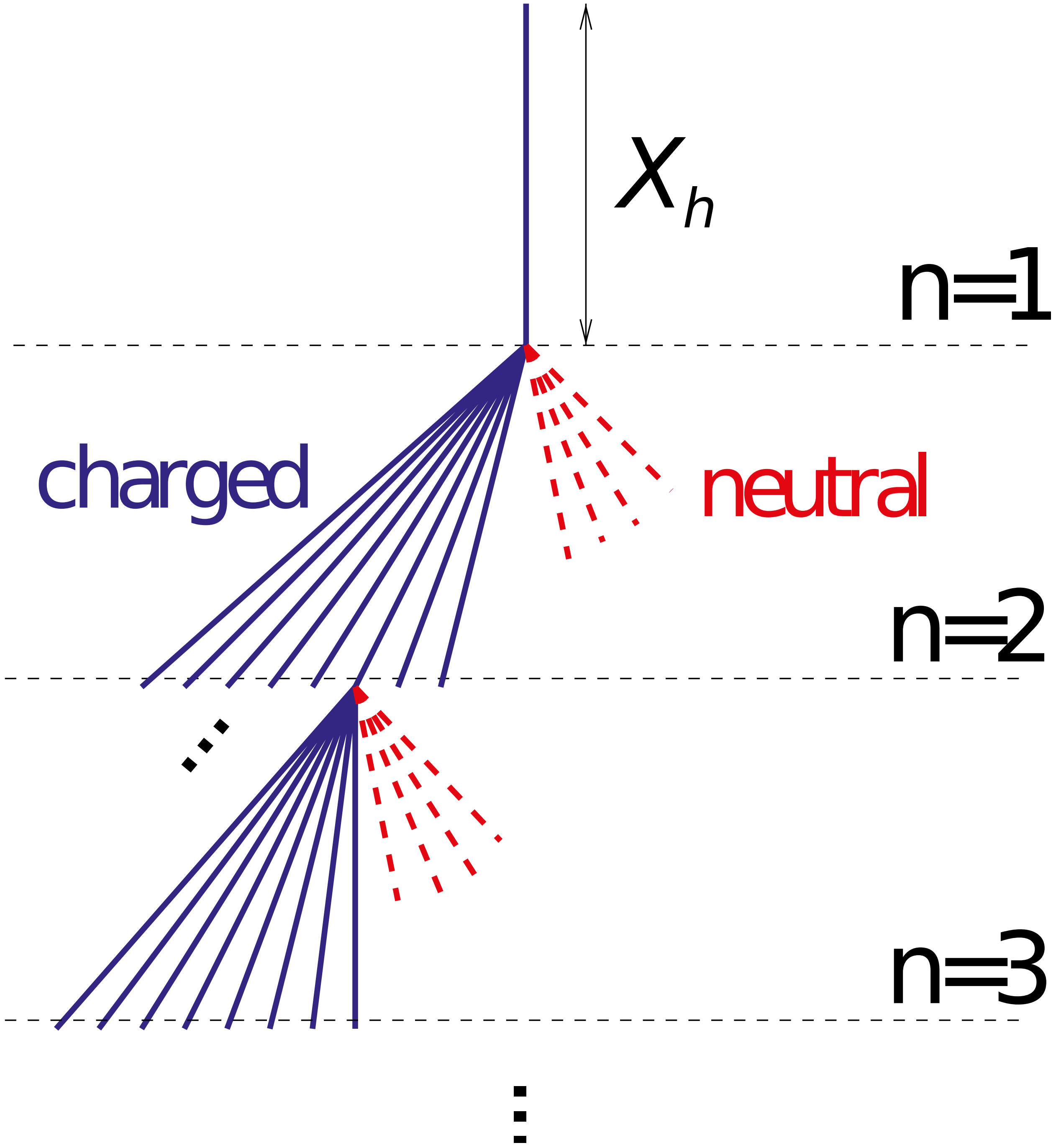
$$N_{\max} = \frac{E_0}{E_{\text{crit}}}$$

- 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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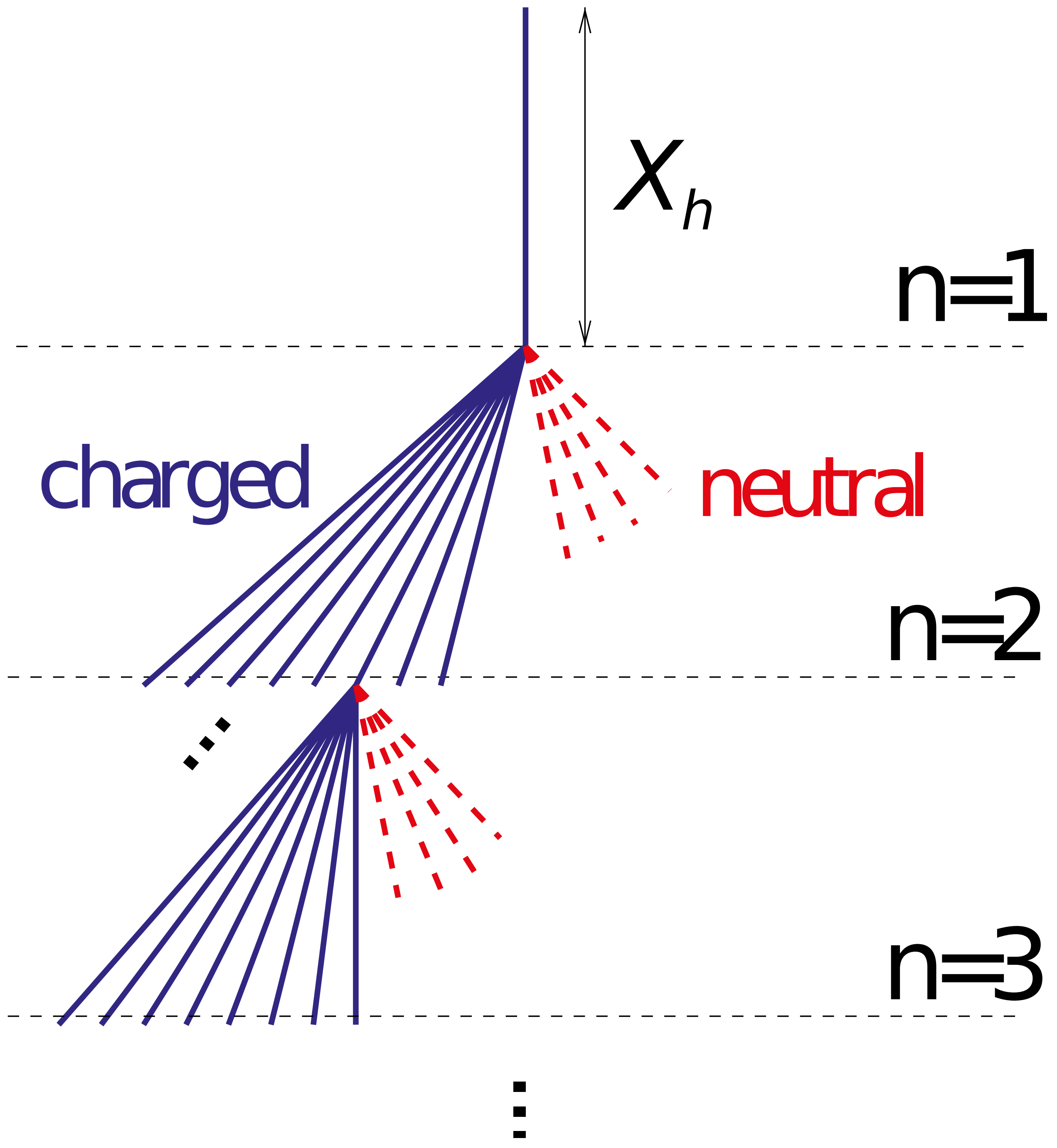

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After X_h, every step produces n_{mult} pions

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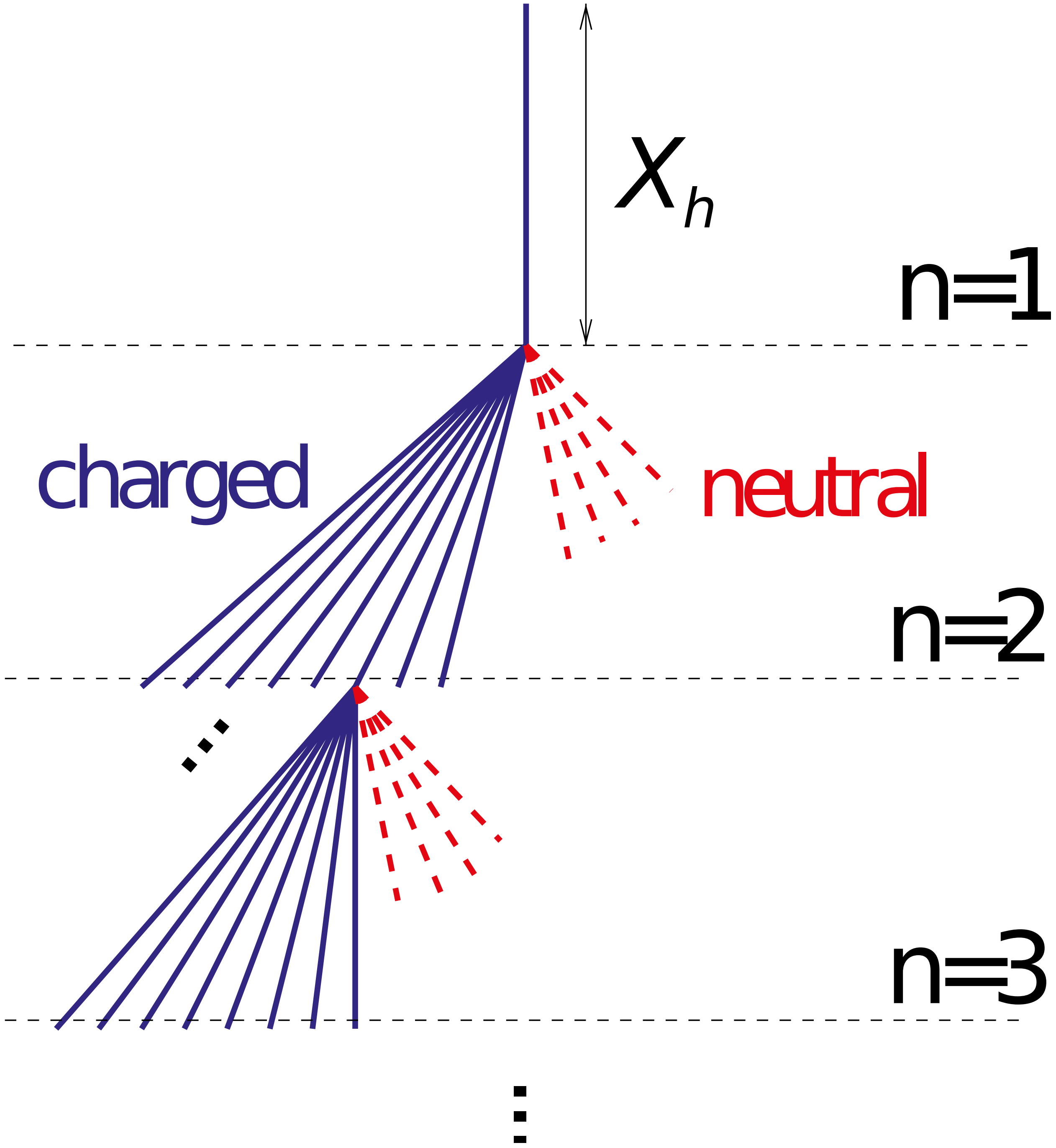

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- Every π^0 initiates 2 E.M. cascades with starting energy $E_0/(2n_{\text{mult}})$
- 2/3 are charged pions that produce the next generation $n_{\text{ch}} = 2/3n_{\text{mult}}$
- $E_{\text{crit}}^{\text{decay}} \approx 20$ GeV in air

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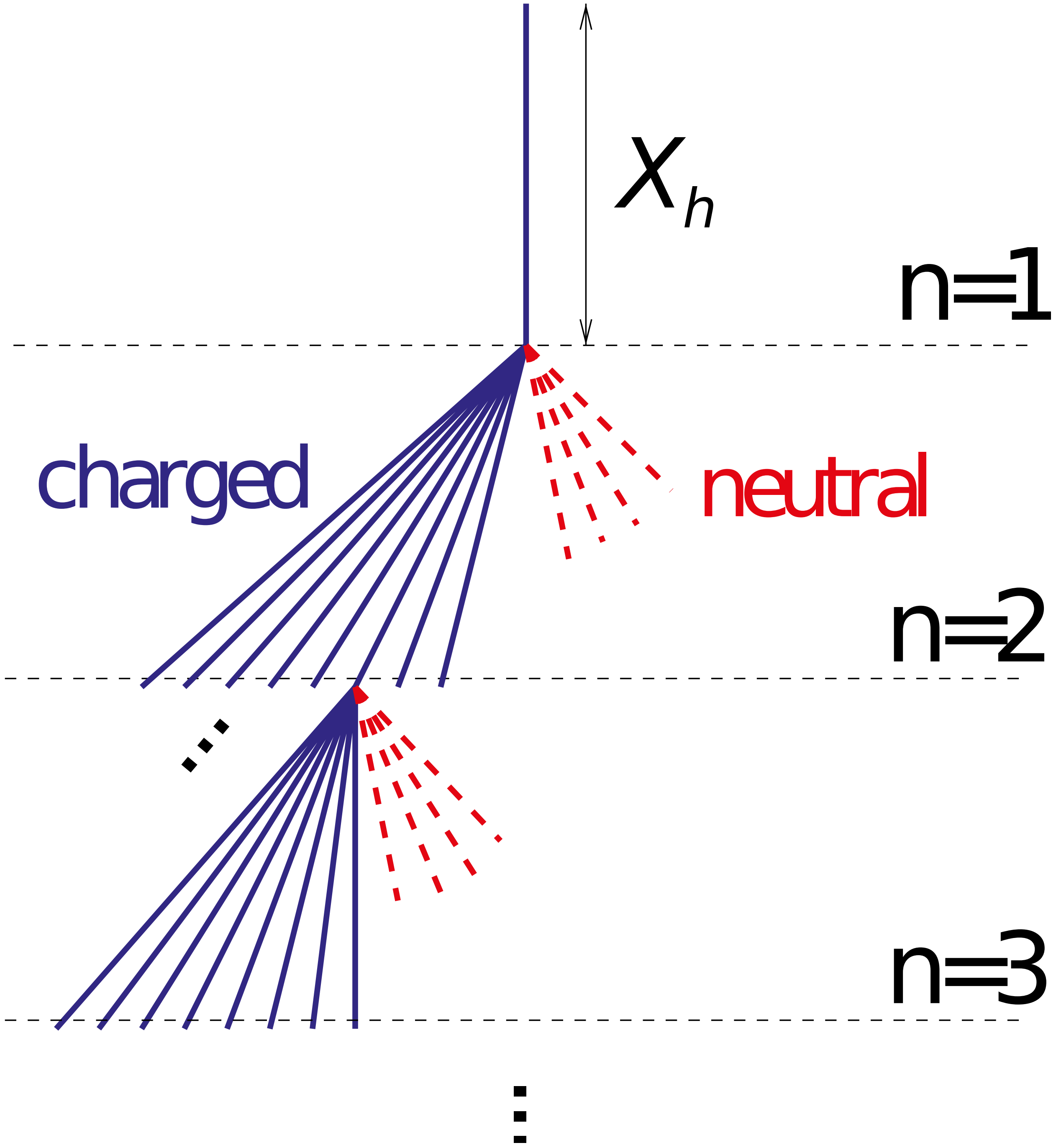

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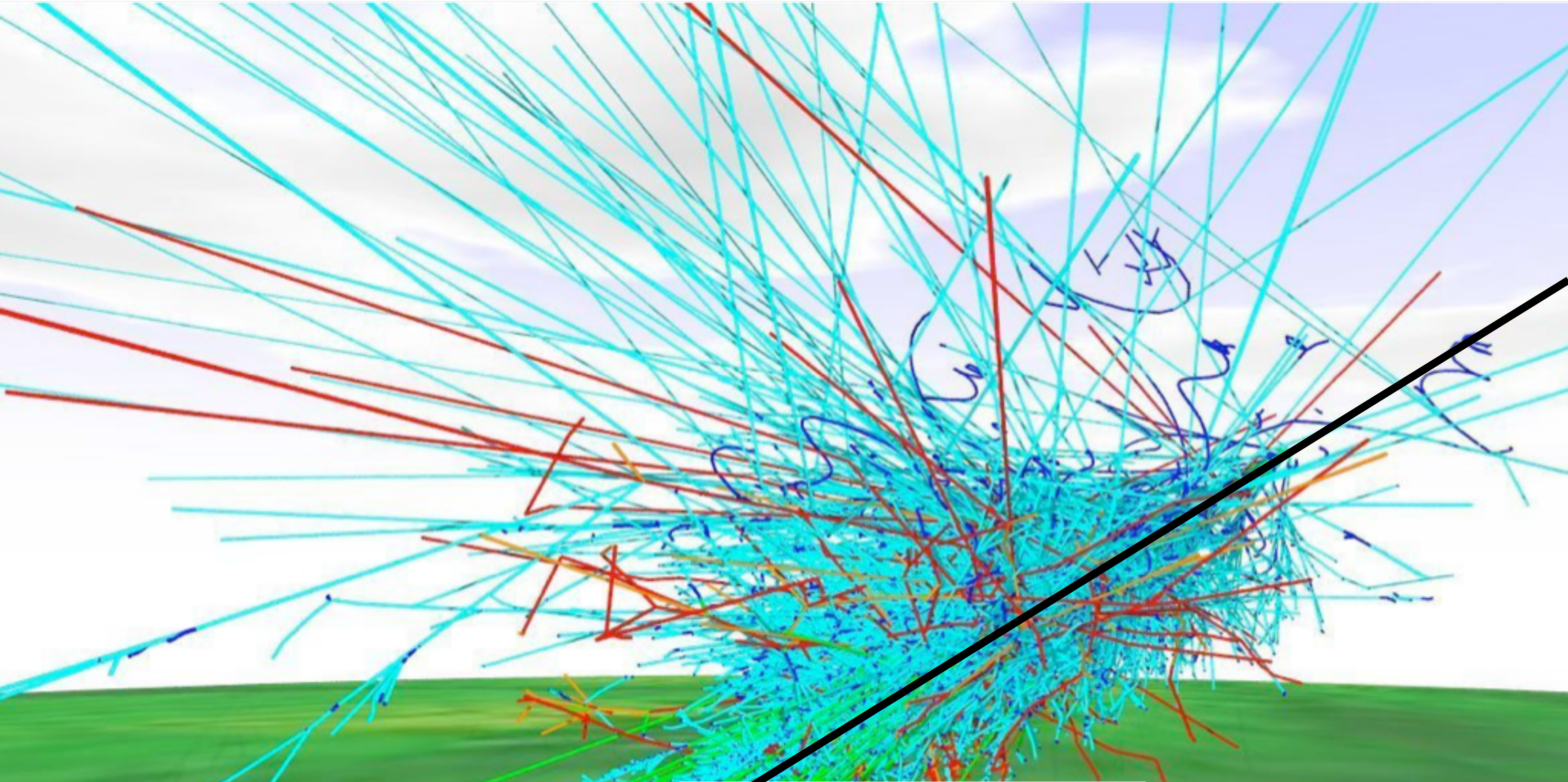
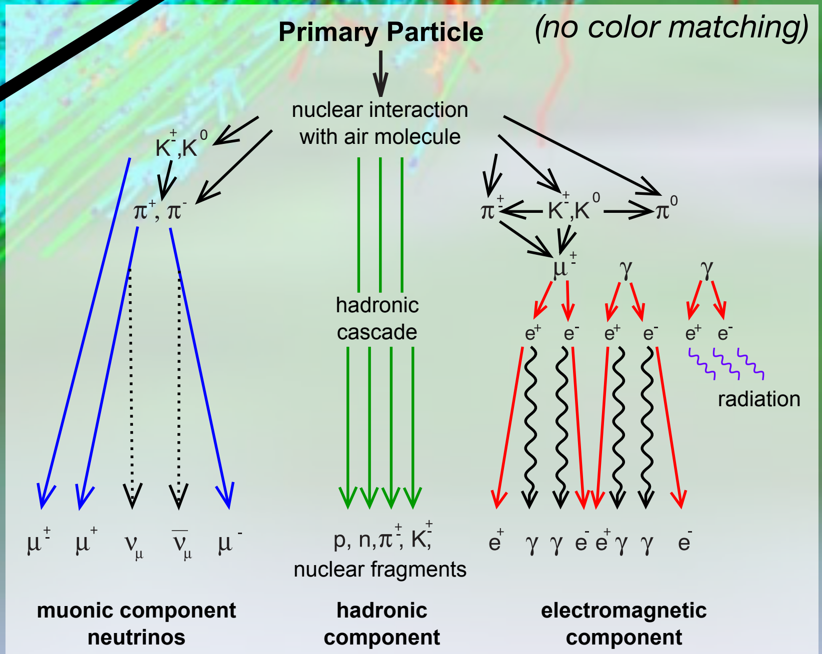
$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0 \qquad E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

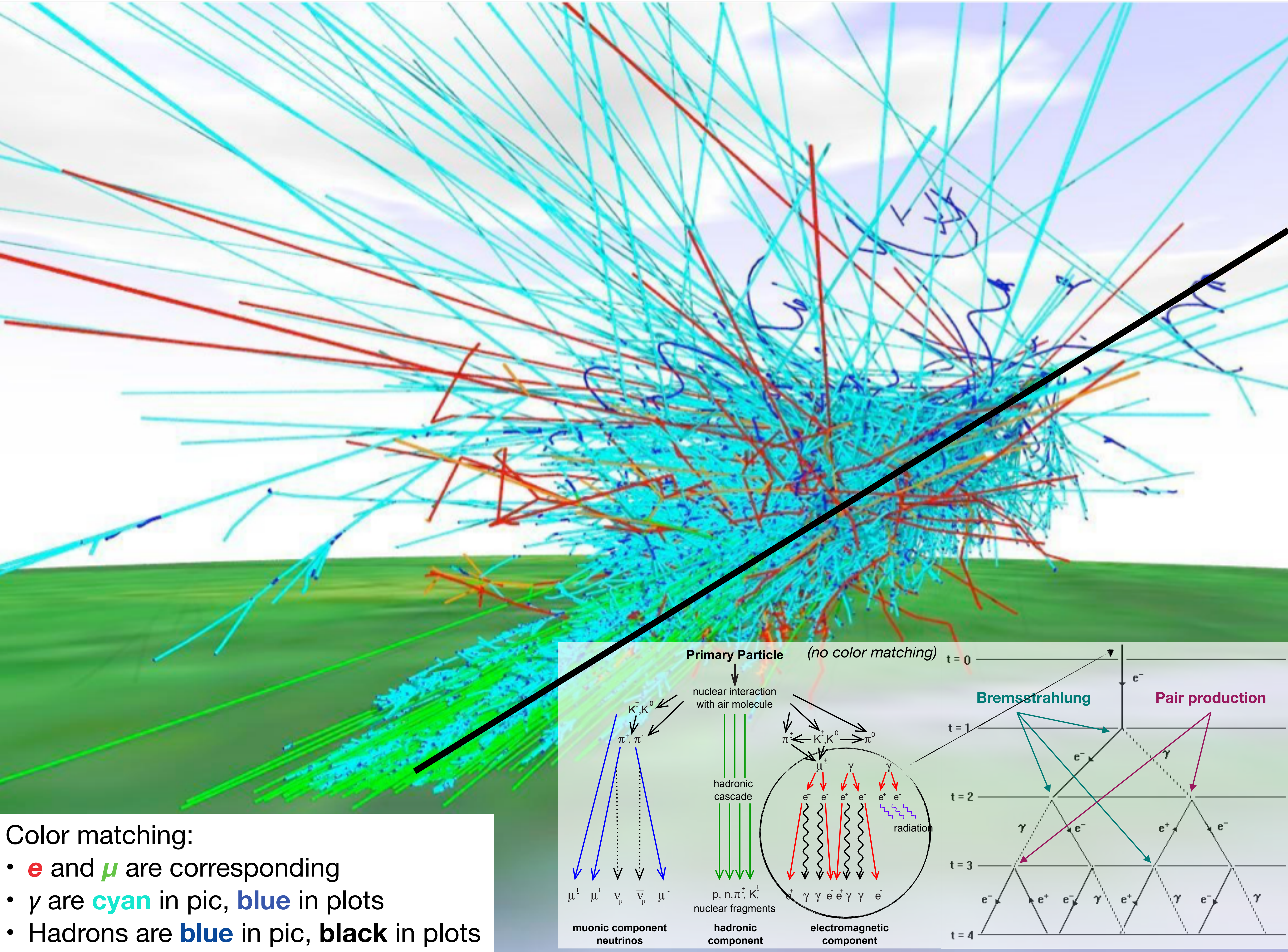




(no color matching)

Color matching:

- *e* and *μ* are corresponding
- *γ* are cyan in pic, **blue** in plots
- Hadrons are **blue** in pic, **black** in plots



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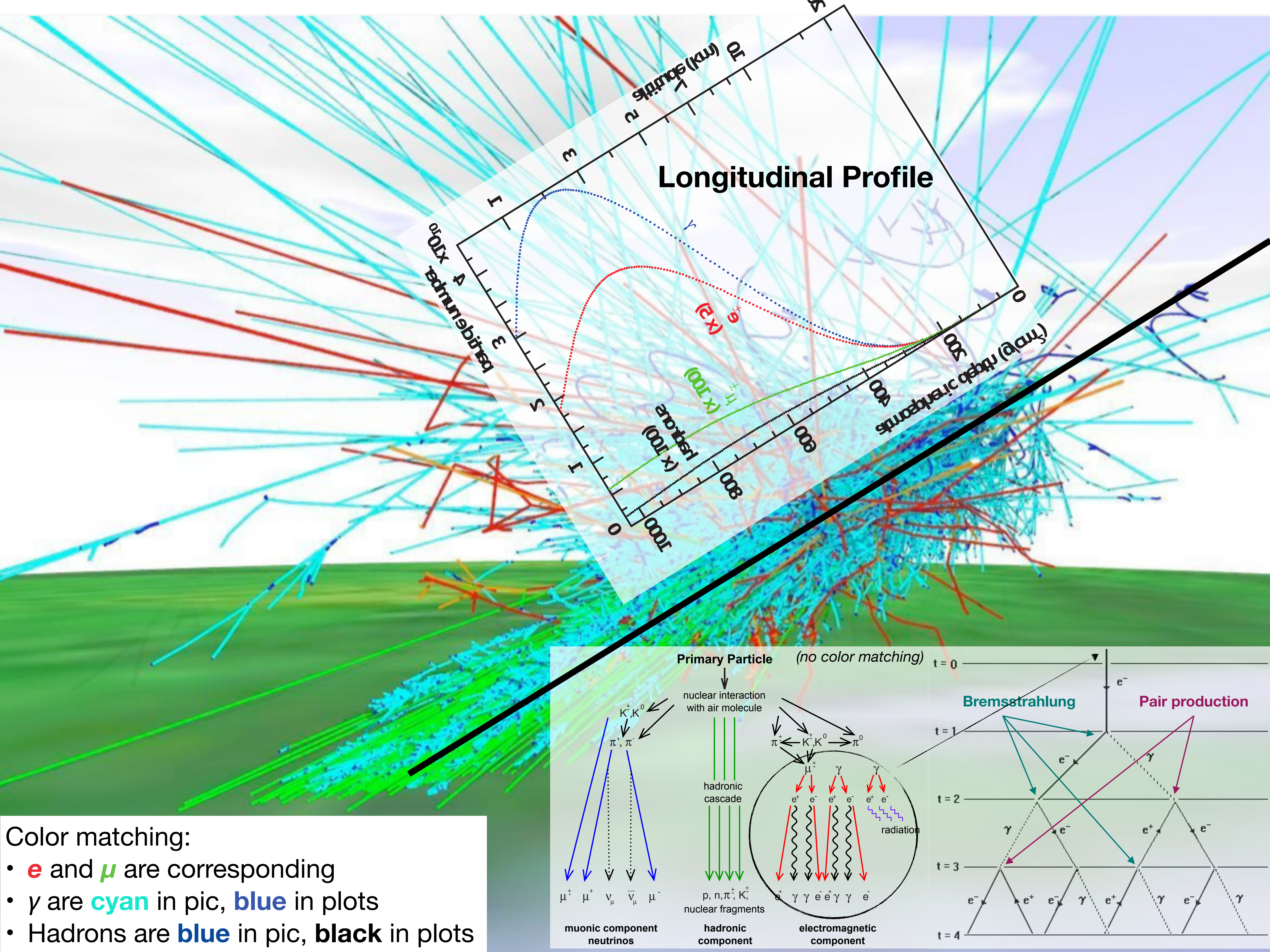

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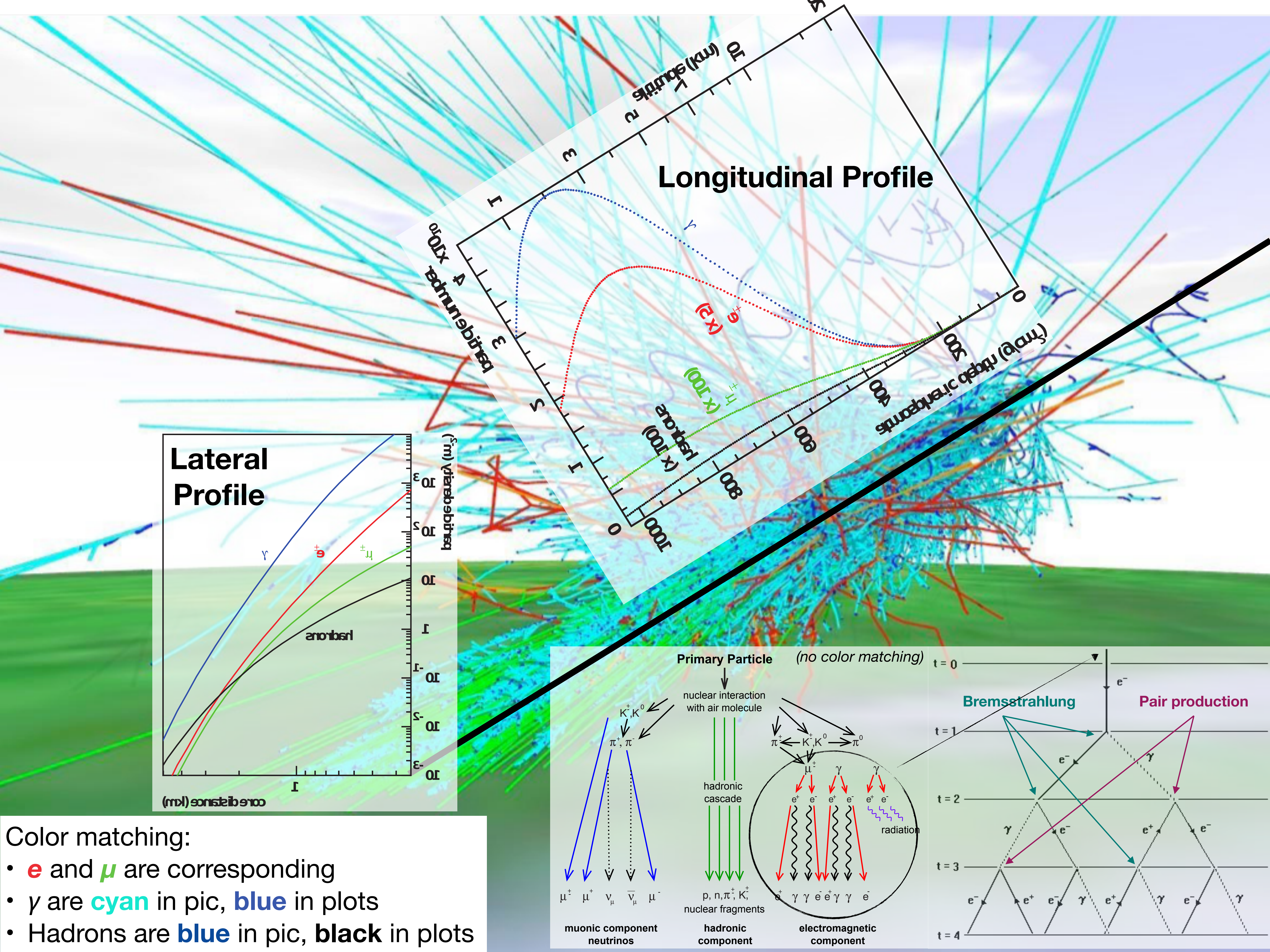

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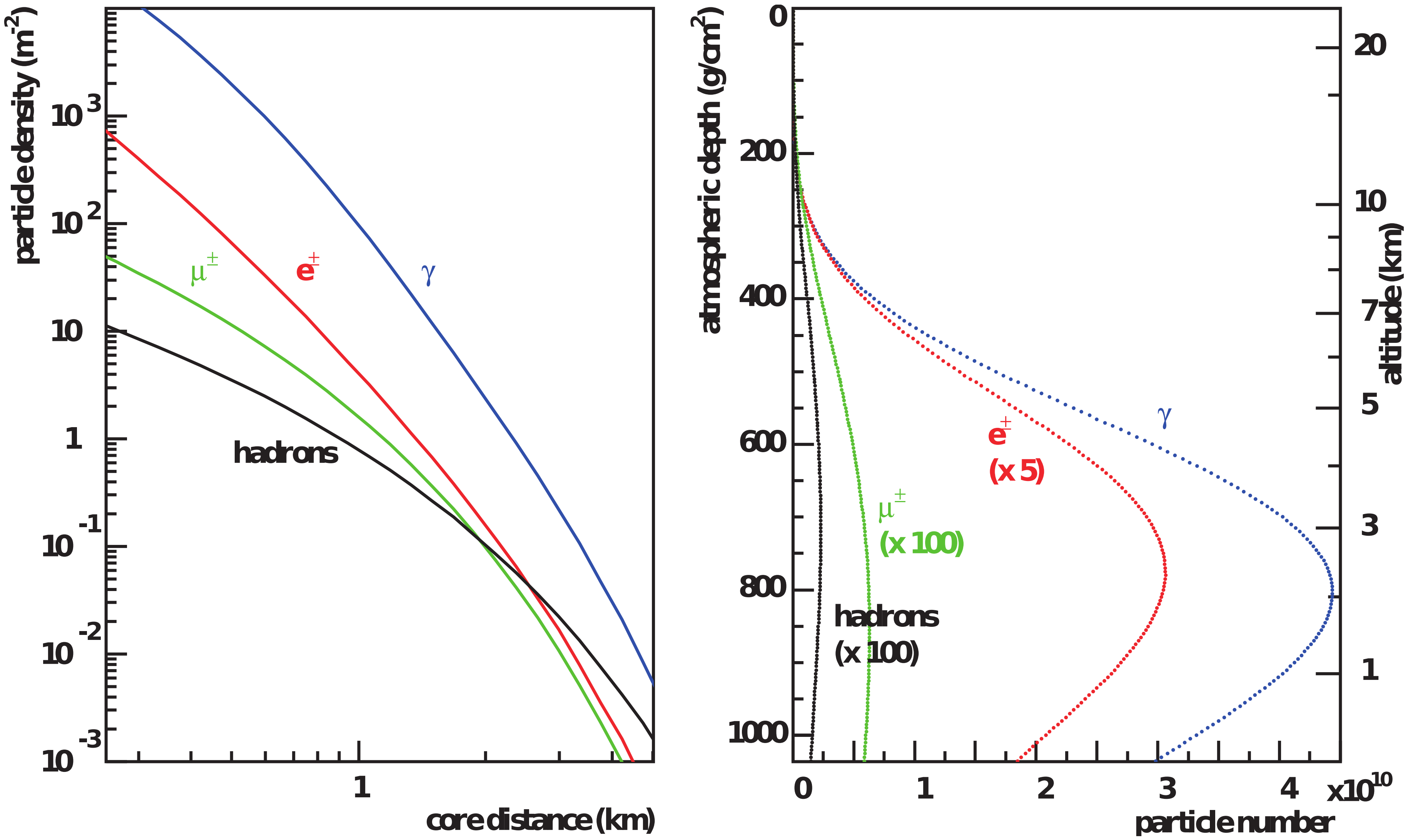
Air Shower development

Observables in atmosphere



With $n \approx 6$, ~90% of E_0 is carried by the E.M. particles

⇓

after the first X_h, **the shower development is ~ an E.M. cascade!**

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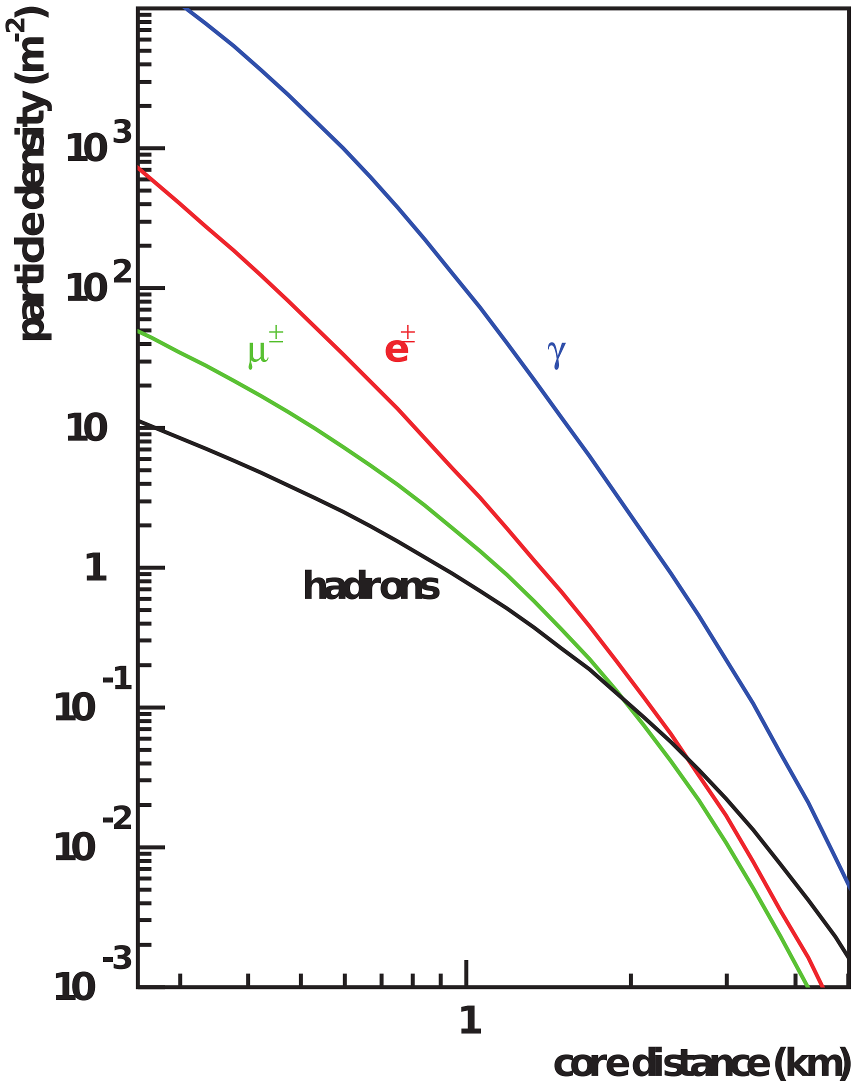

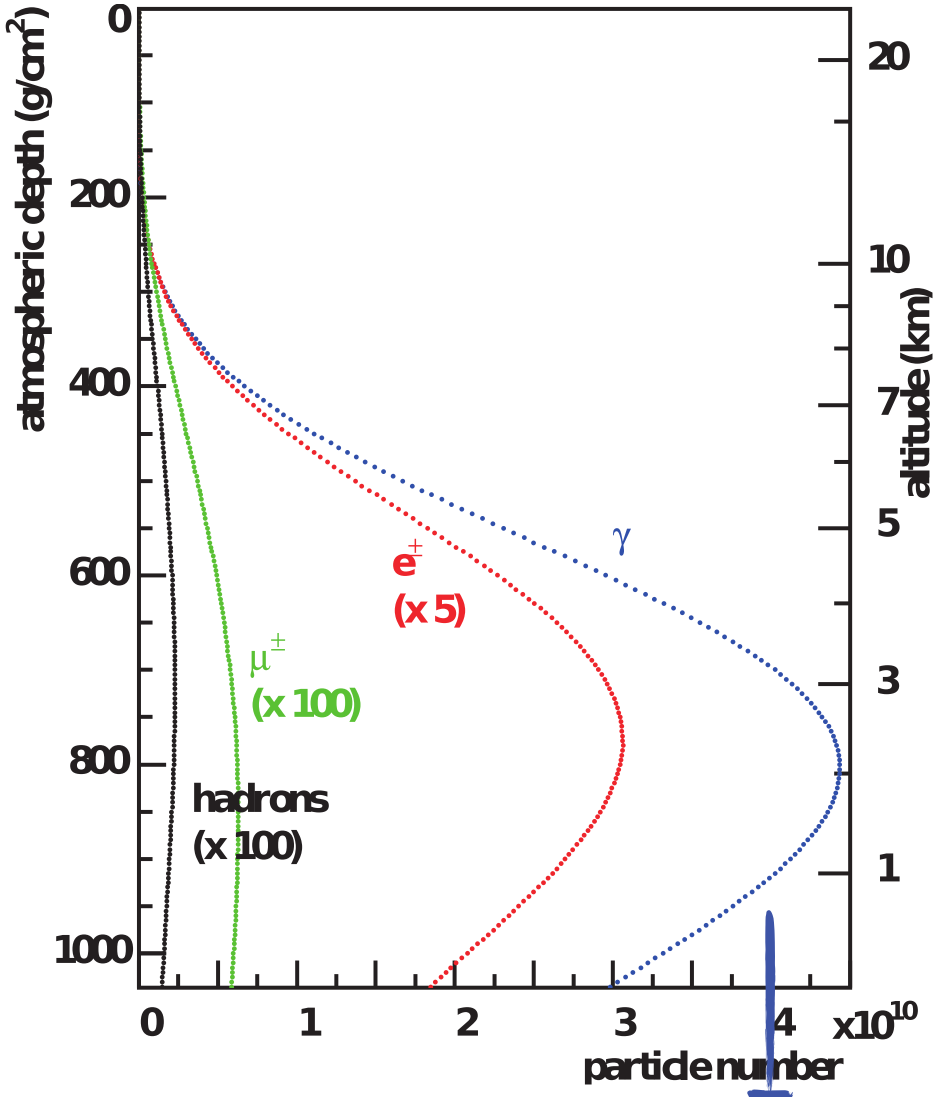

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Integral: Energy

$X_{\max}$: mass

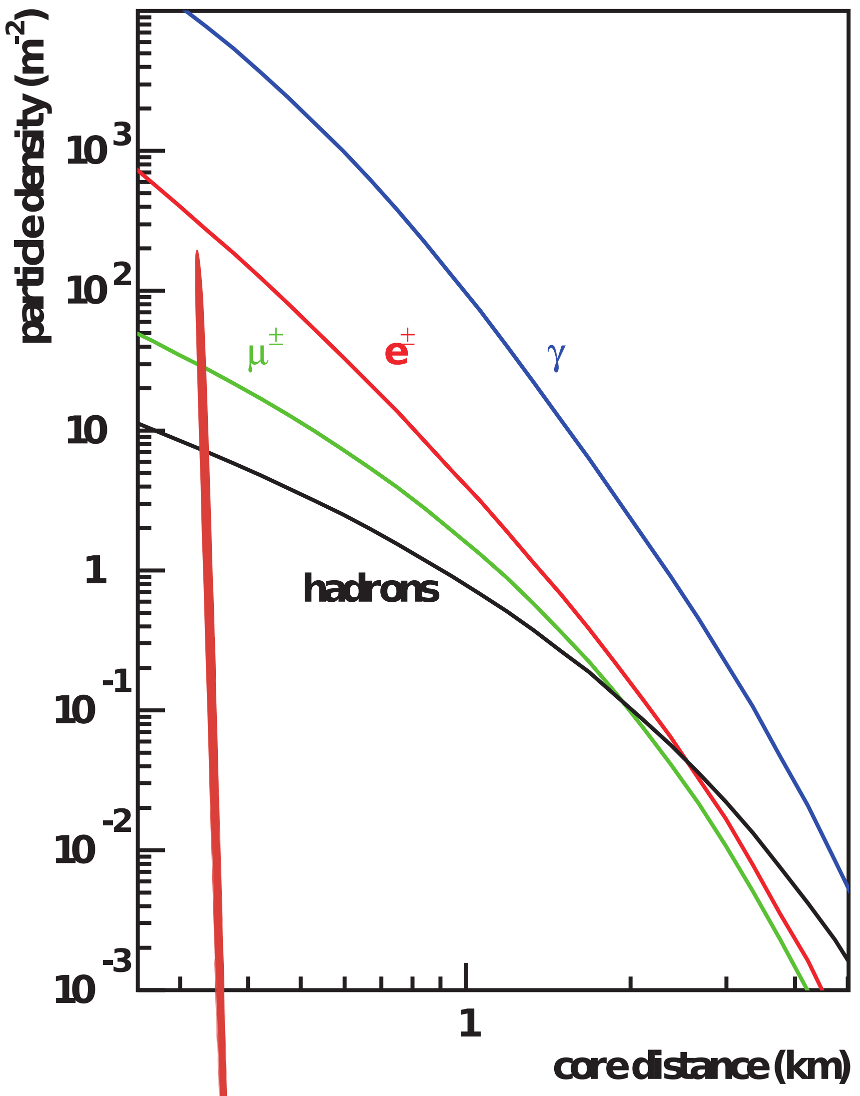
$$X_{\max} \approx X_h + X_{\max}^{\mathrm{em}}\left(\frac{E_0}{2n_{\mathrm{mult}}}\right) = X_h + \frac{X^{\mathrm{em}}}{\ln 2}\ln\left(\frac{E_0}{2n_{\mathrm{mult}}E_{\mathrm{crit}}^{\mathrm{decay}}}\right)$$

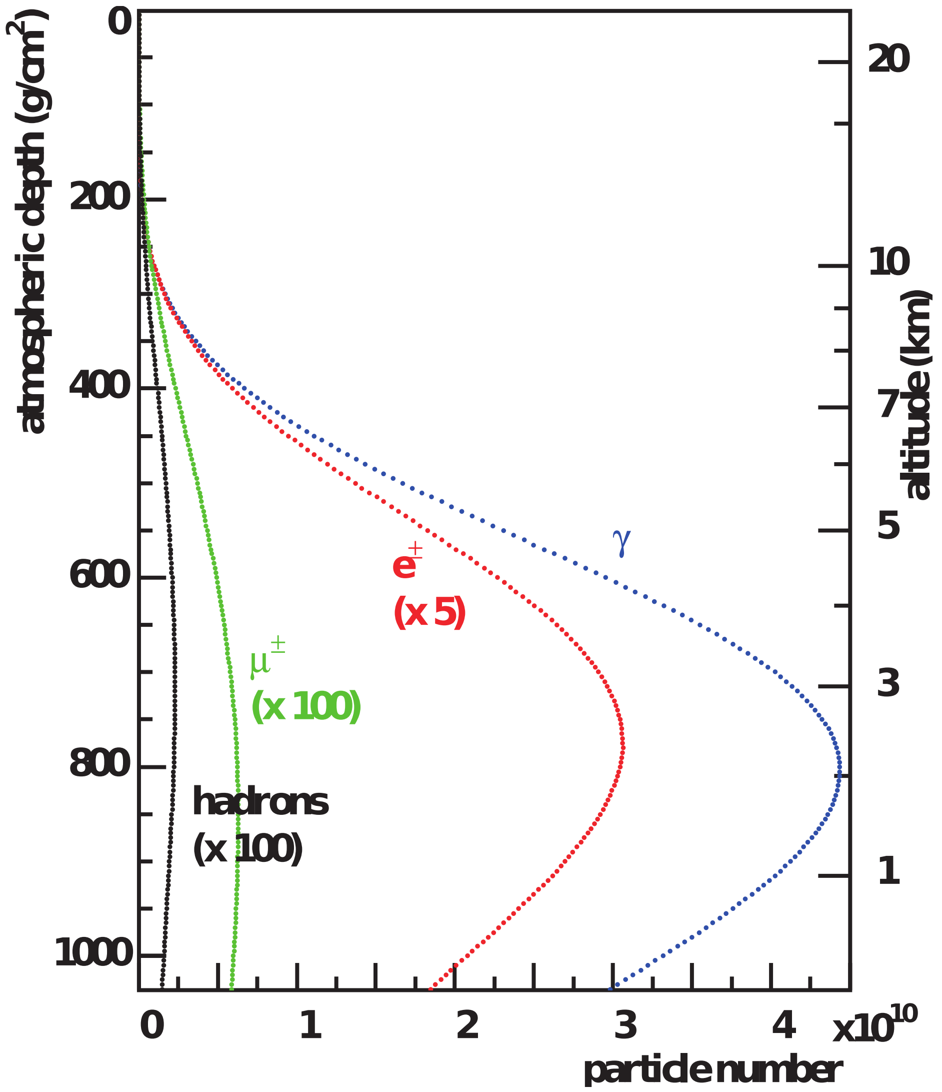
The more Energetic, the deeper;

the less, the shallow (particle absorption starts earlier in X!)

Air Shower development

Observables in atmosphere





With $\boldsymbol{n \approx 6}$, ~90% of $\boldsymbol{E_0}$ is carried by the E.M. particles

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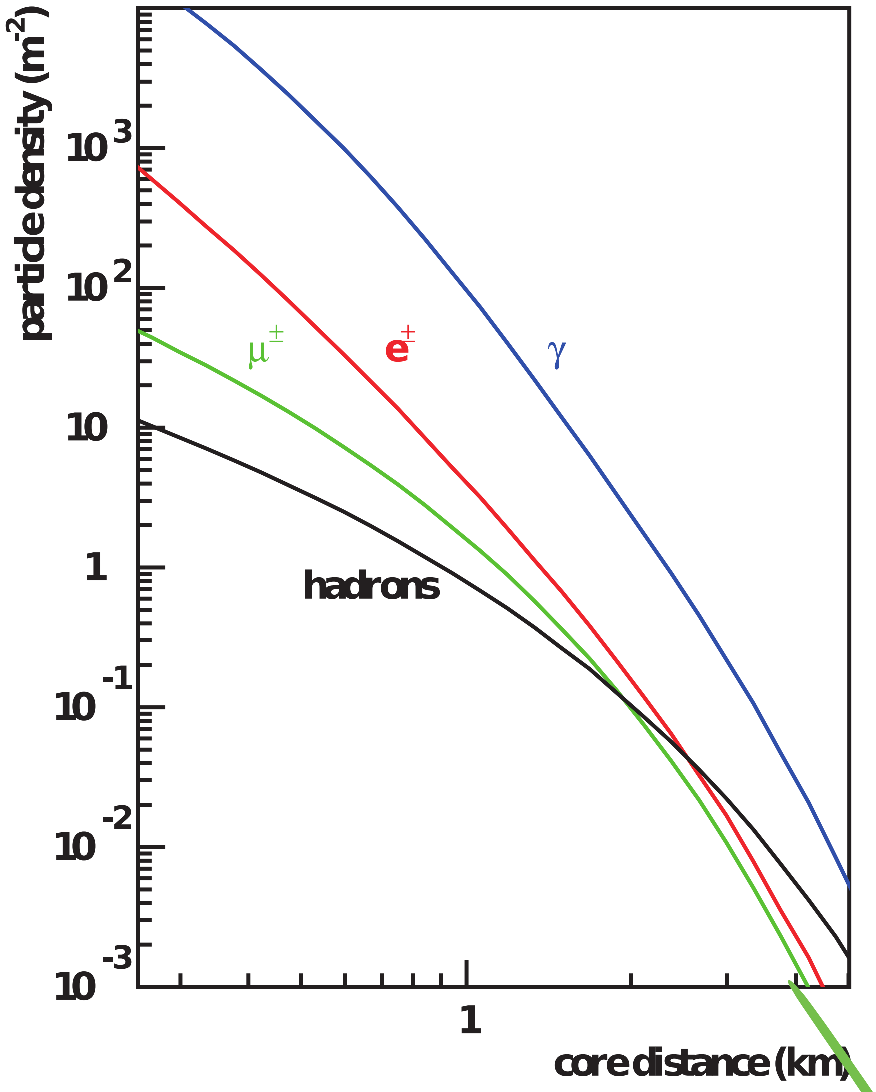
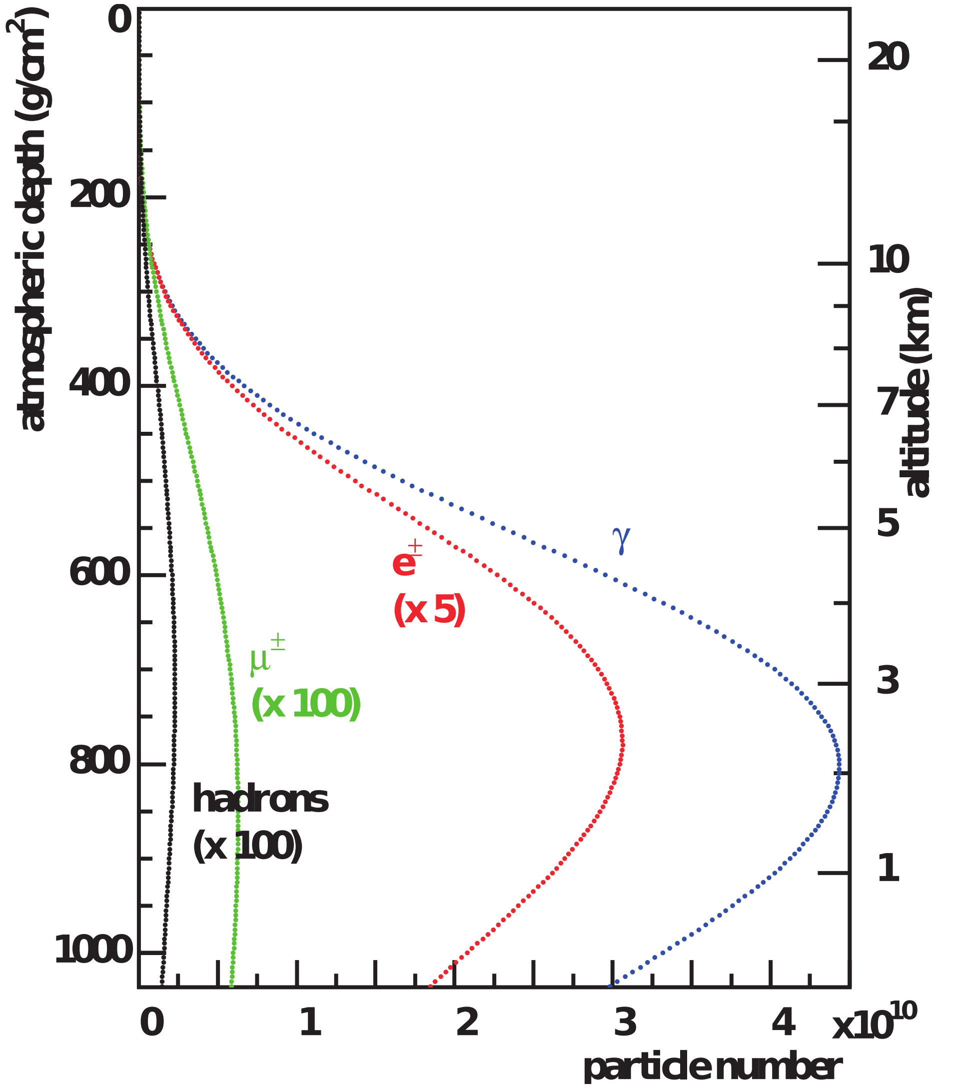
$$N_e = \frac{E_0}{E_{\mathrm{crit}}}\left[1-\left(\frac{2}{3}\right)^n\right] \propto E$$

Air Shower development

Observables in atmosphere





With $n \approx 6$, ~90% of E_0 is carried by the E.M. particles

$\Downarrow$

after the first X_h, the shower development is ~ an E.M. cascade!

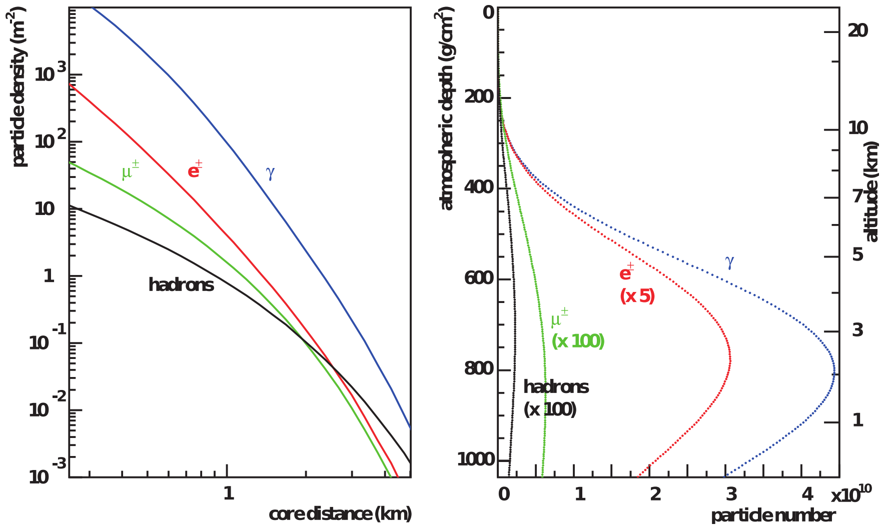
$$X_{\max} \approx X_h + X^{\rm em}_{\max}\left(\frac{E_0}{2n_{\rm mult}}\right) = X_h + \frac{X^{\rm em}}{\ln 2}\ln\left(\frac{E_0}{2n_{\rm mult}E^{\rm decay}_{\rm crit}}\right)$$

$$N_e = \frac{E_0}{E_{\rm crit}}\left[1-\left(\frac{2}{3}\right)^n\right]$$

$$N_\mu = \left(\frac{E_0}{E^{\rm decay}_{\rm crit}}\right)^\alpha \quad \text{with } \alpha = \frac{\ln n_{\rm ch}}{\ln n_{\rm mult}} \sim f(Z,A)$$

From observables to the primary

The mass composition



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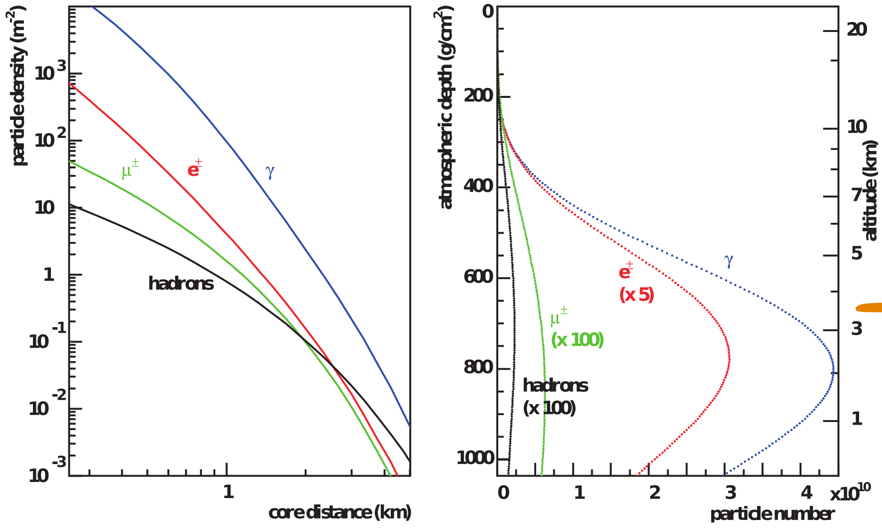

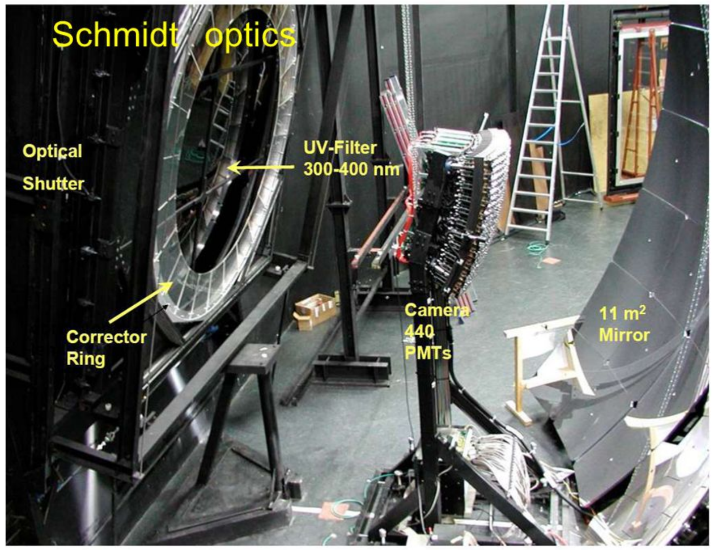

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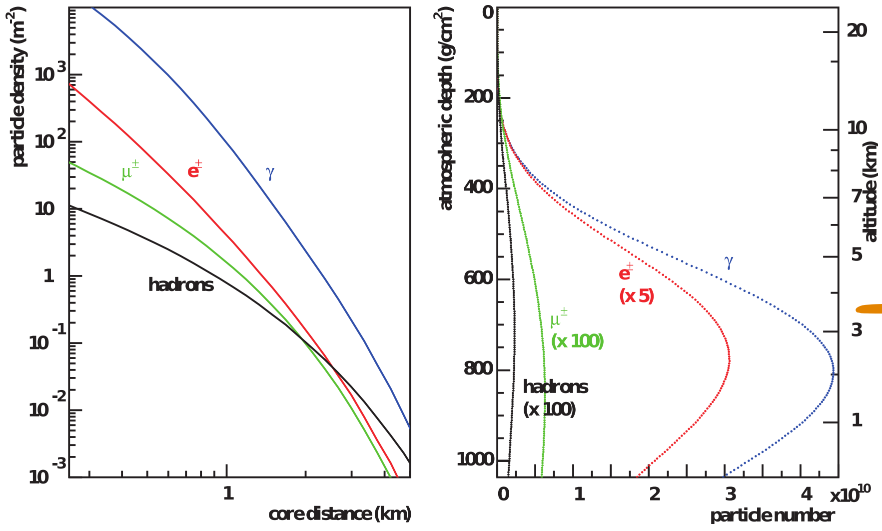

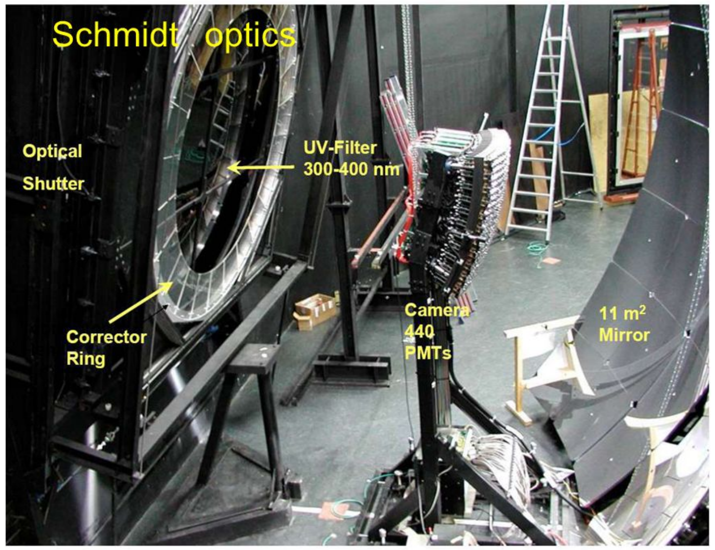

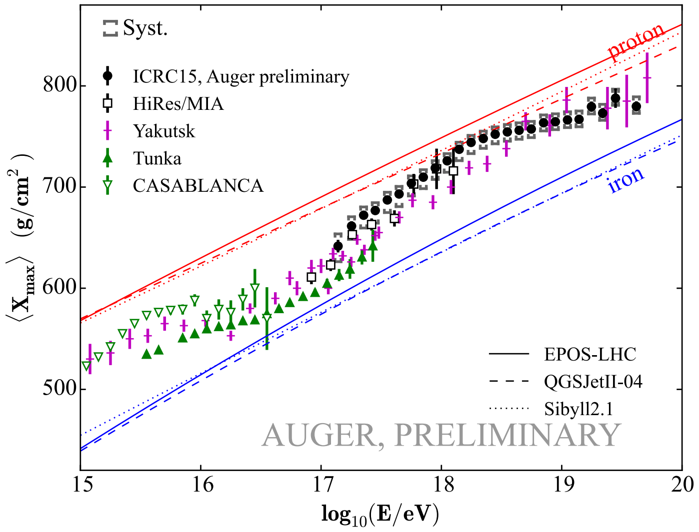

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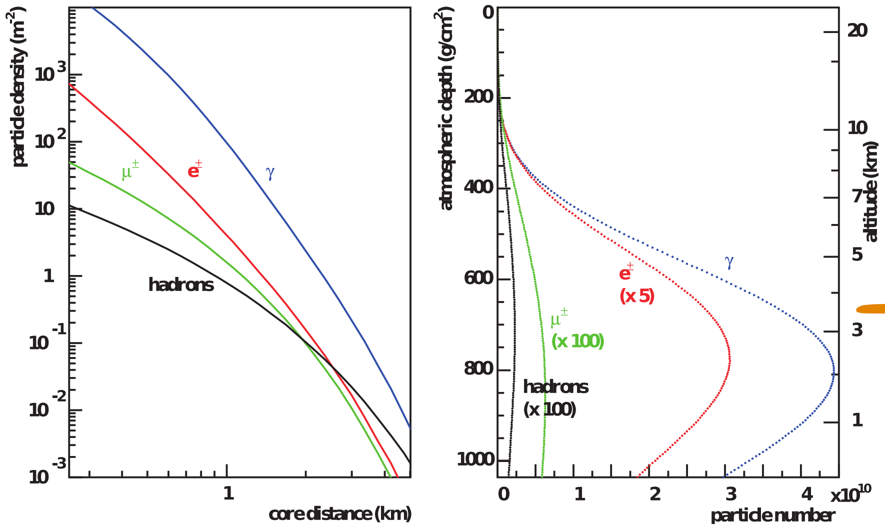
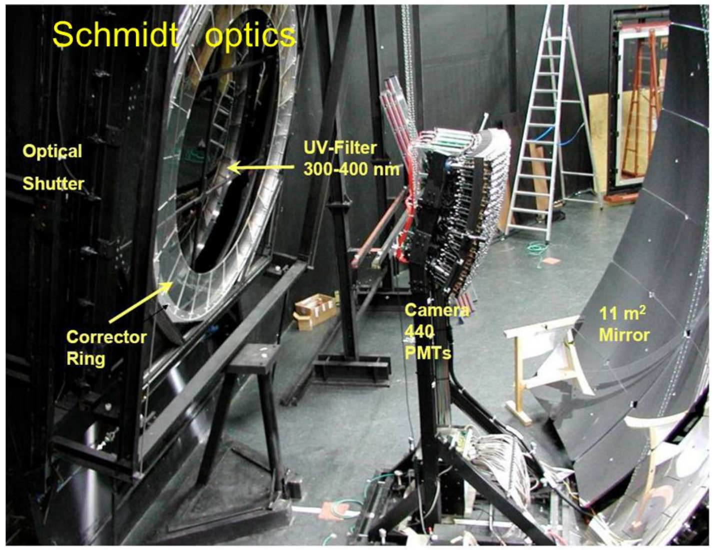
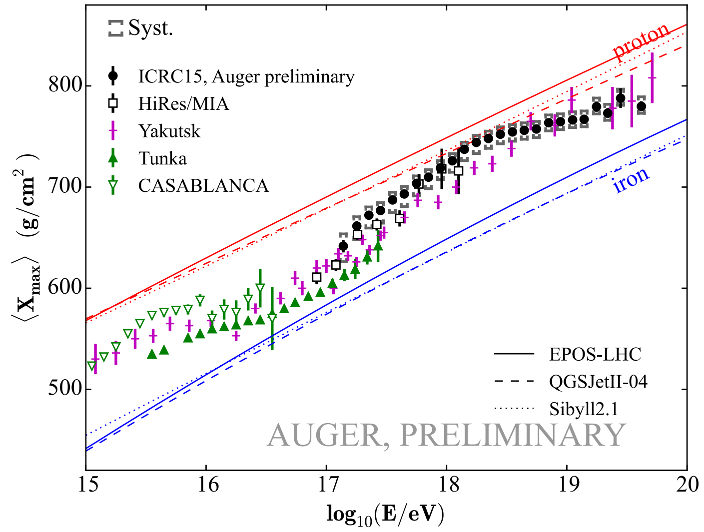
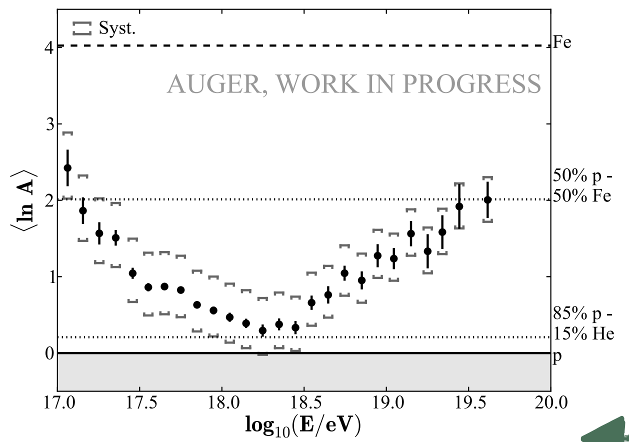
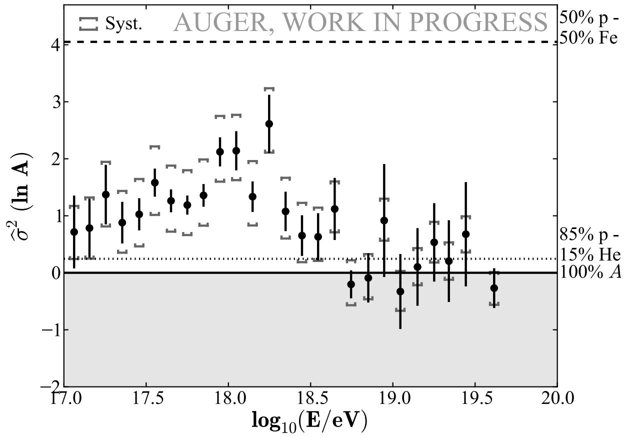








Sibyll2.1 (Mean of ln A)



Sibyll2.1 (Std. Deviation of ln A)

Via High-Energy Hadronic Interaction (HEHI) Models

From observables to the primary

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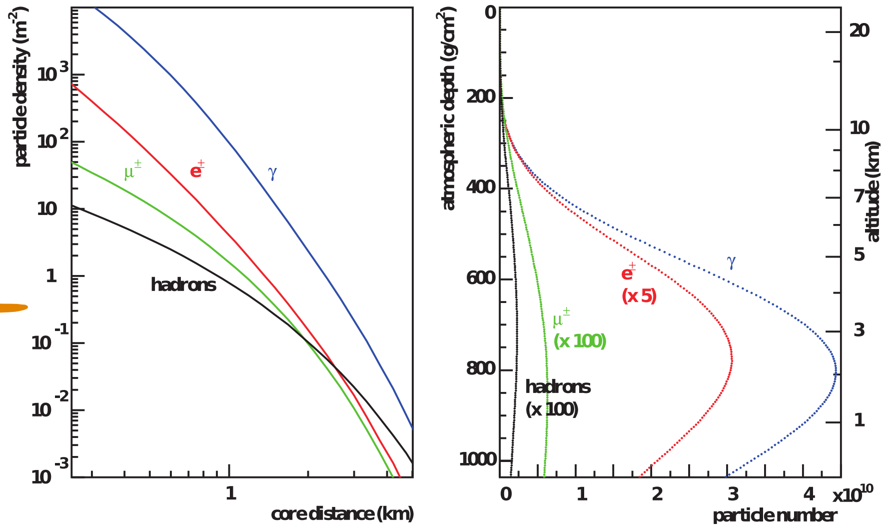

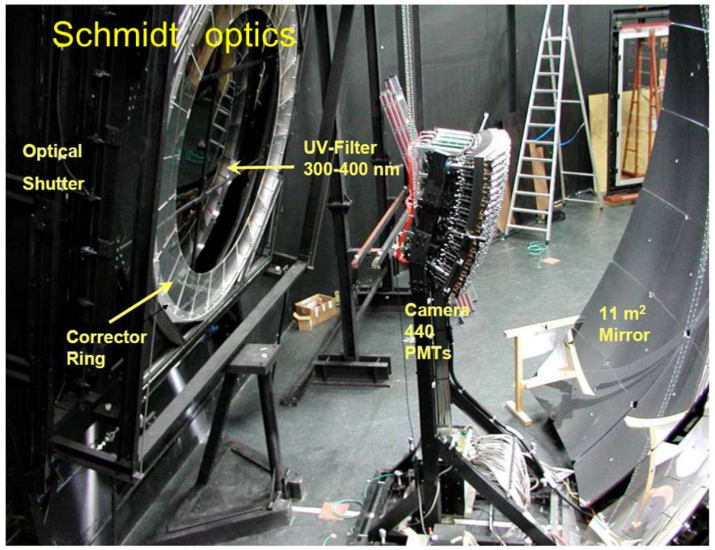

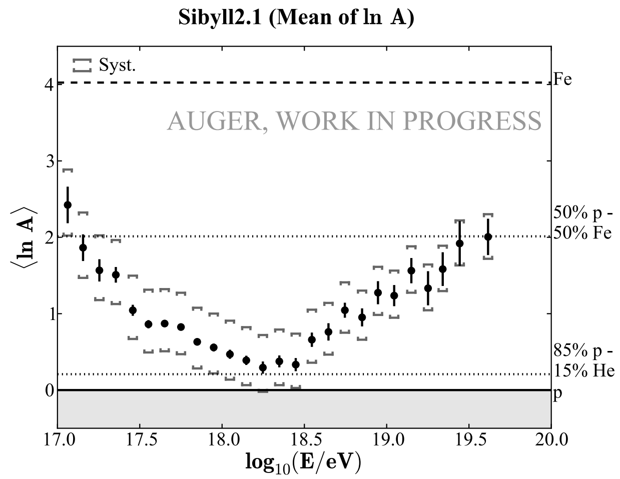

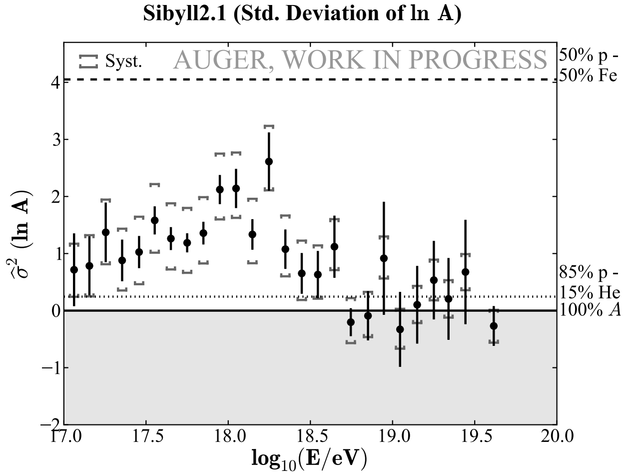

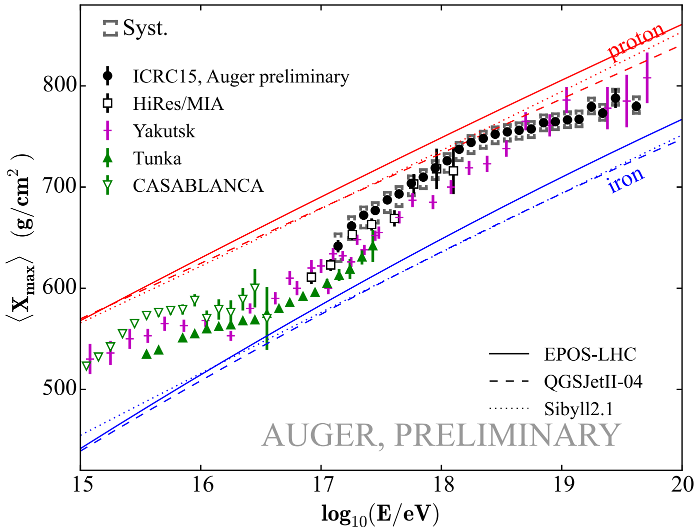

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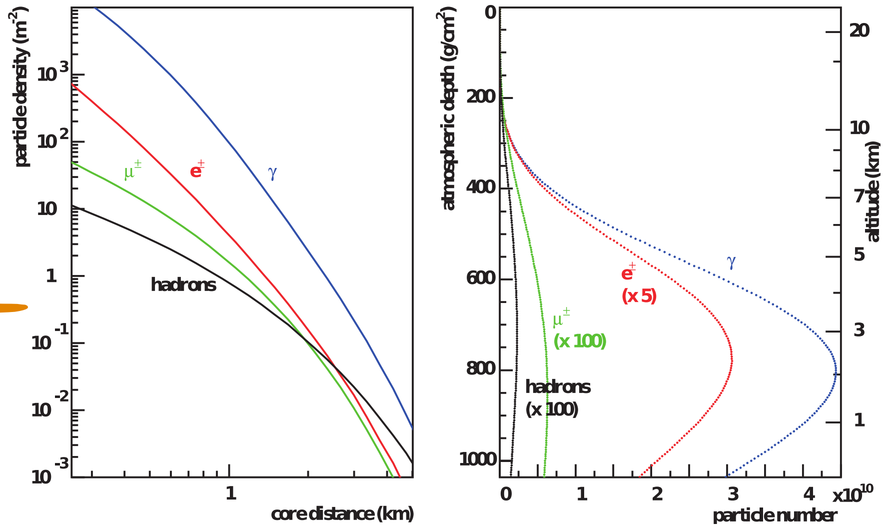
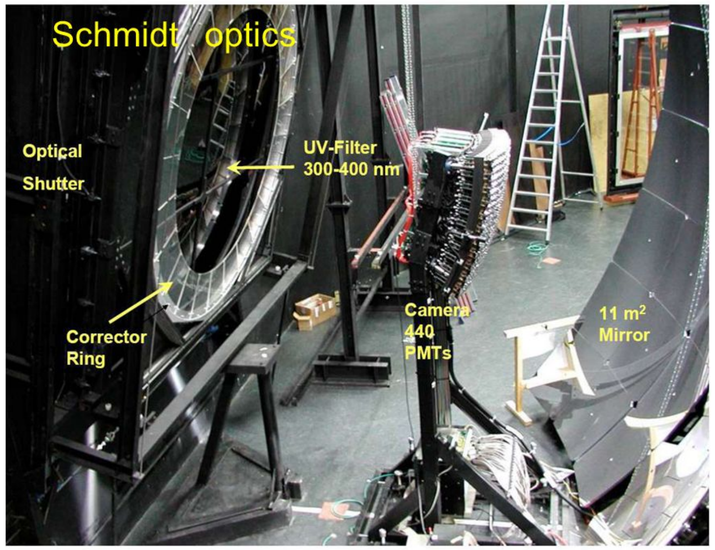
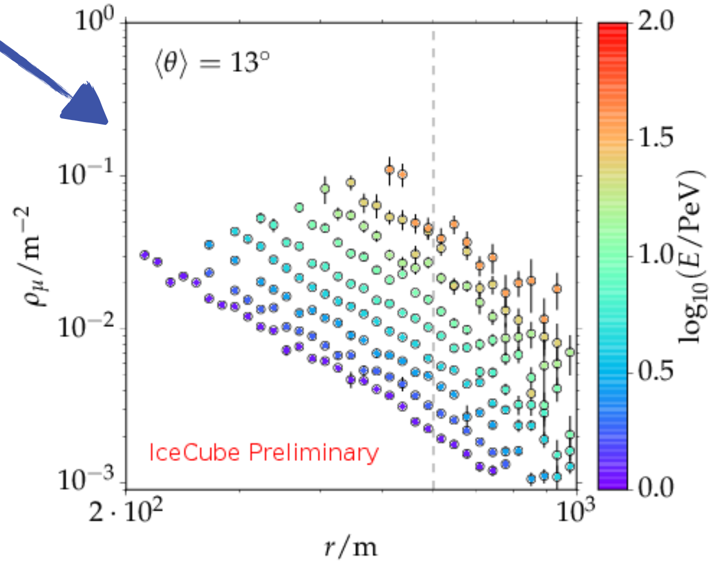
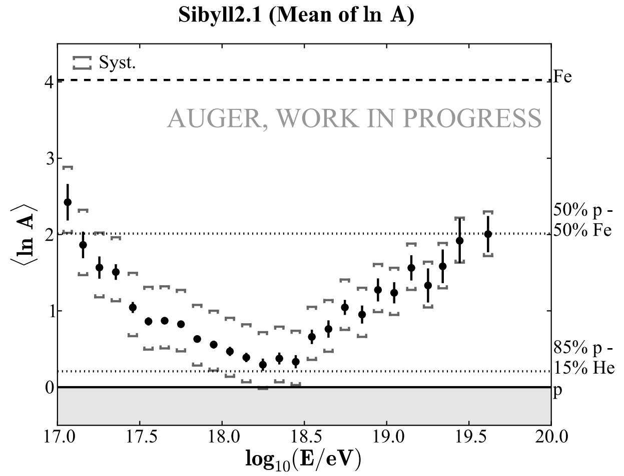
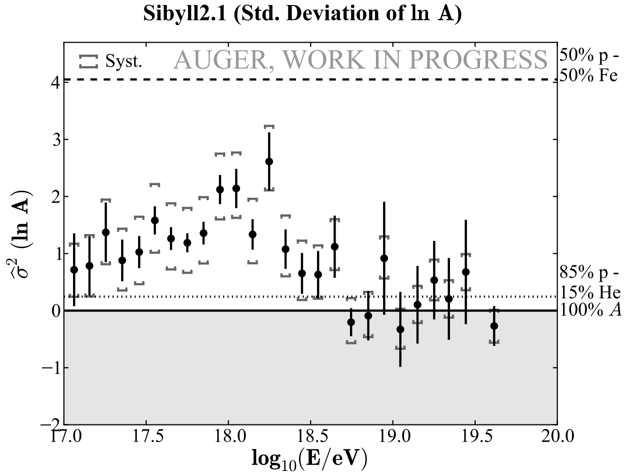
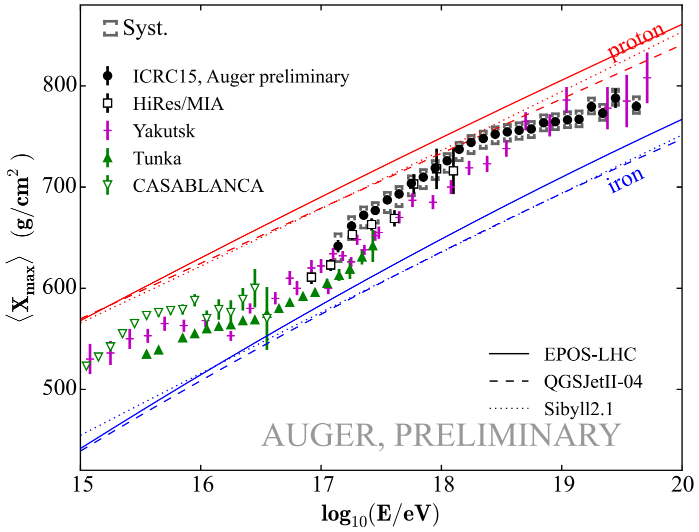






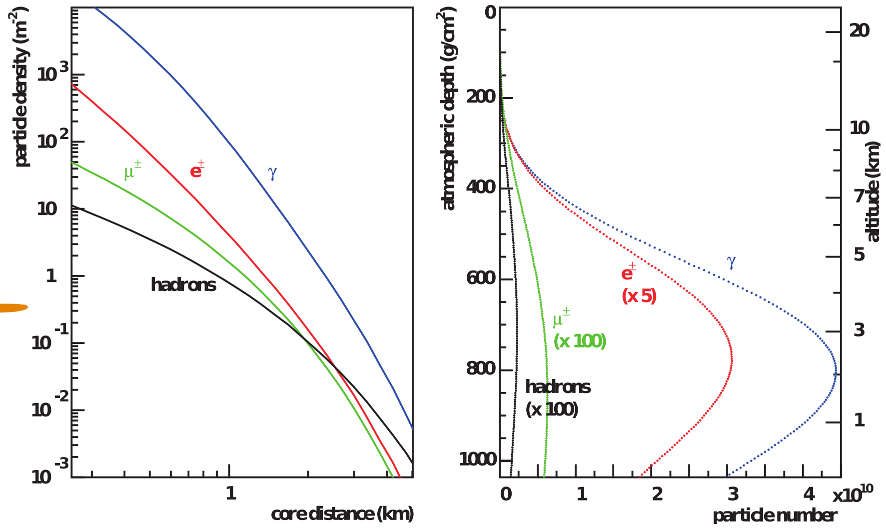


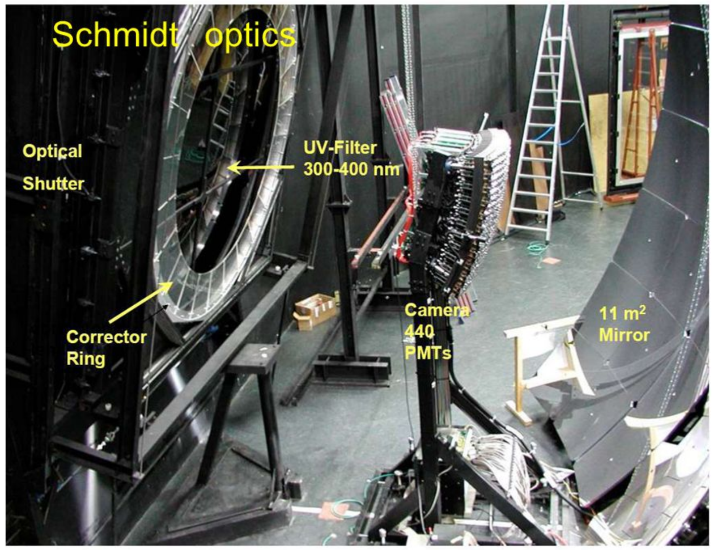


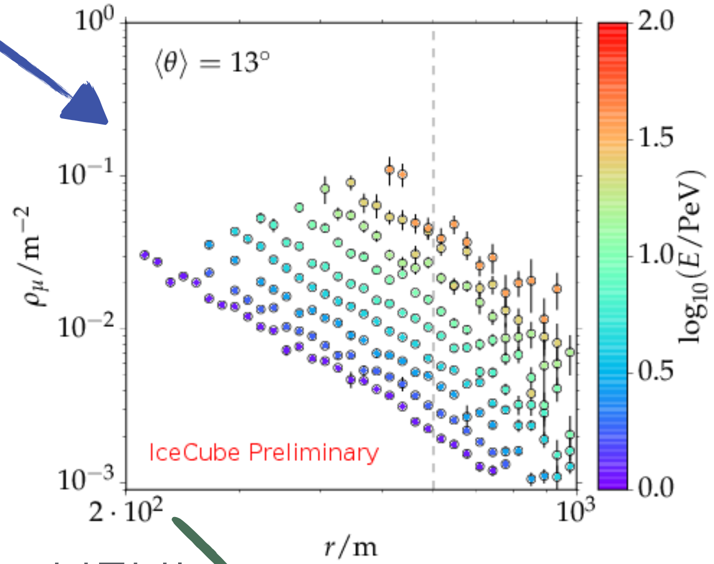


From observables to the primary

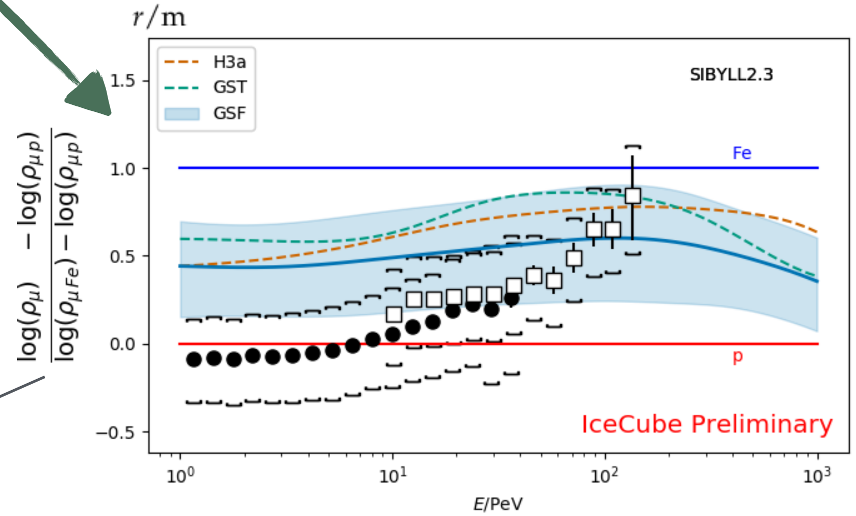
The mass composition





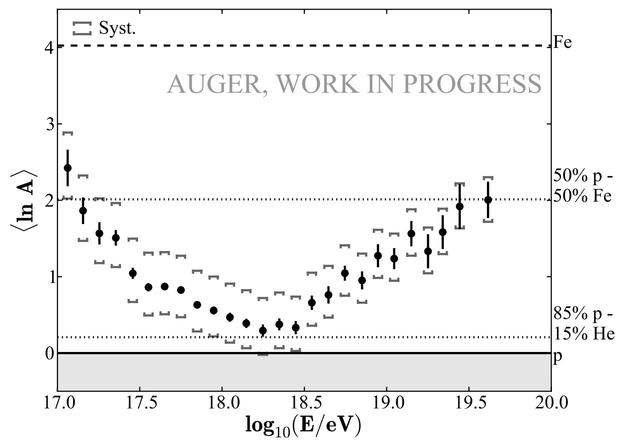


Via HEHI Models

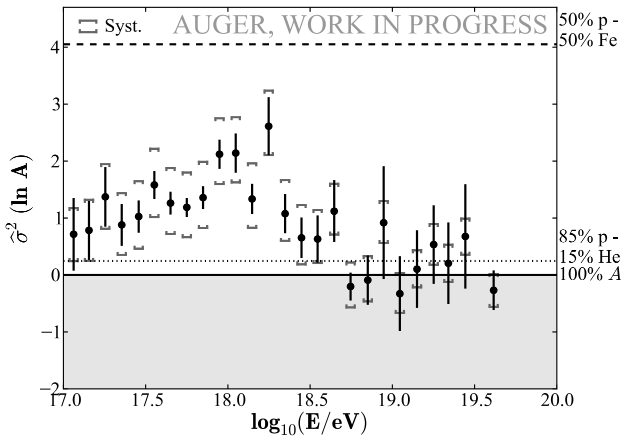


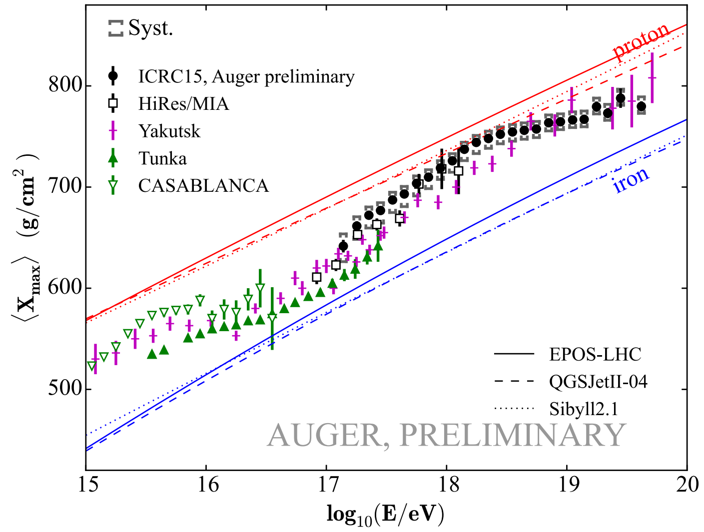
z:
from 0 (p)
to 1 (Fe)

Sibyll2.1 (Mean of ln A)



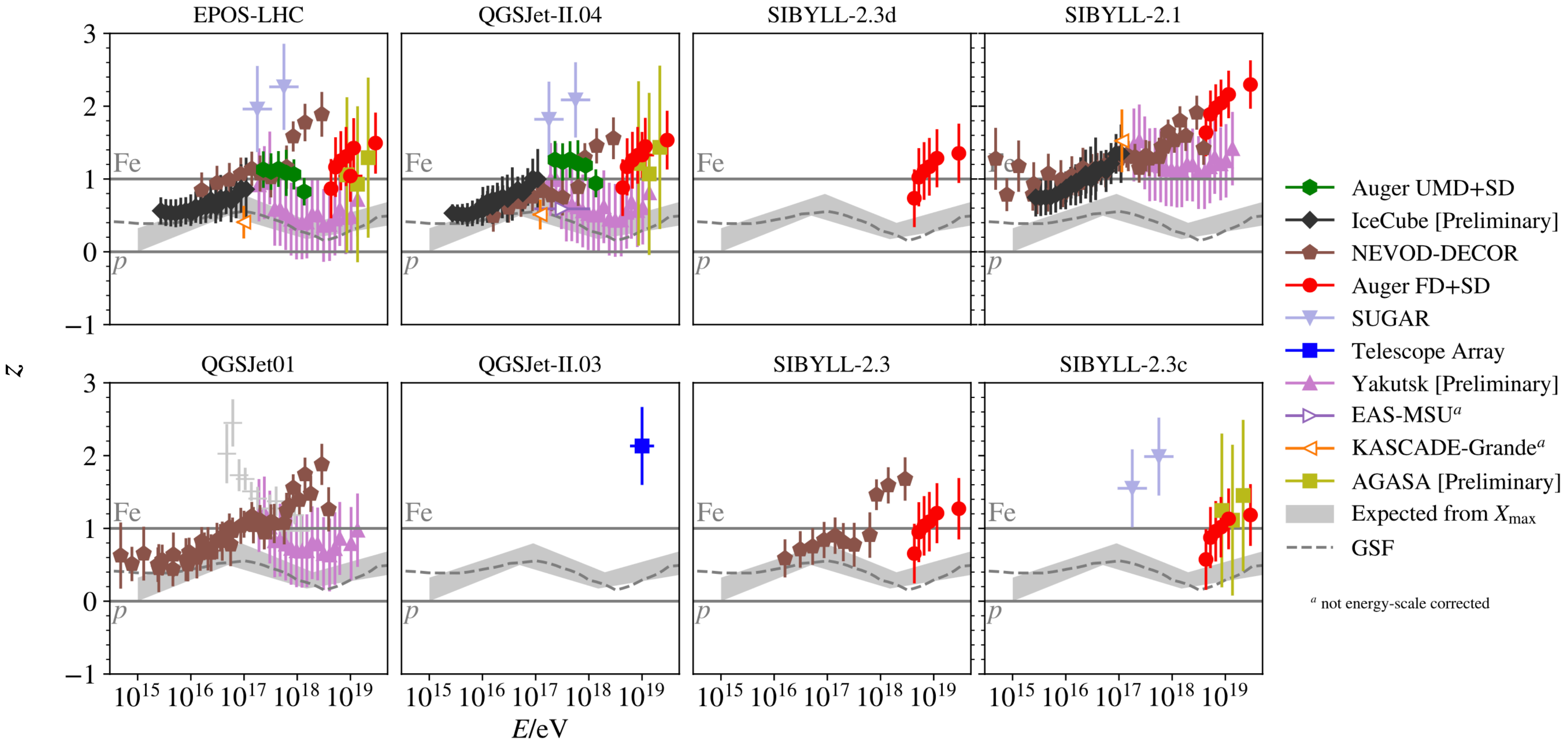
Sibyll2.1 (Std. Deviation of ln A)





…a discrepancy occurs!

3 HEHI Models (+ variants)



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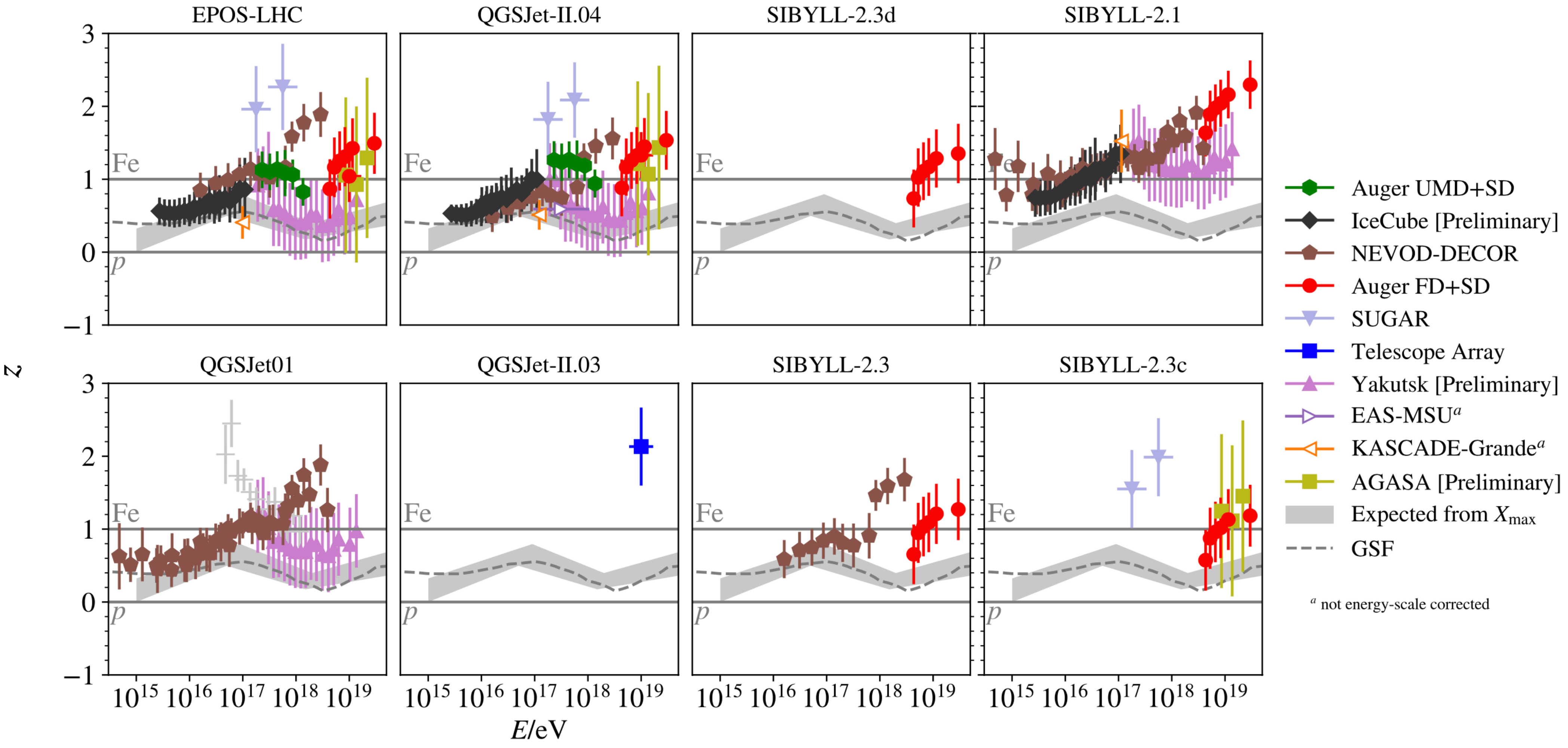
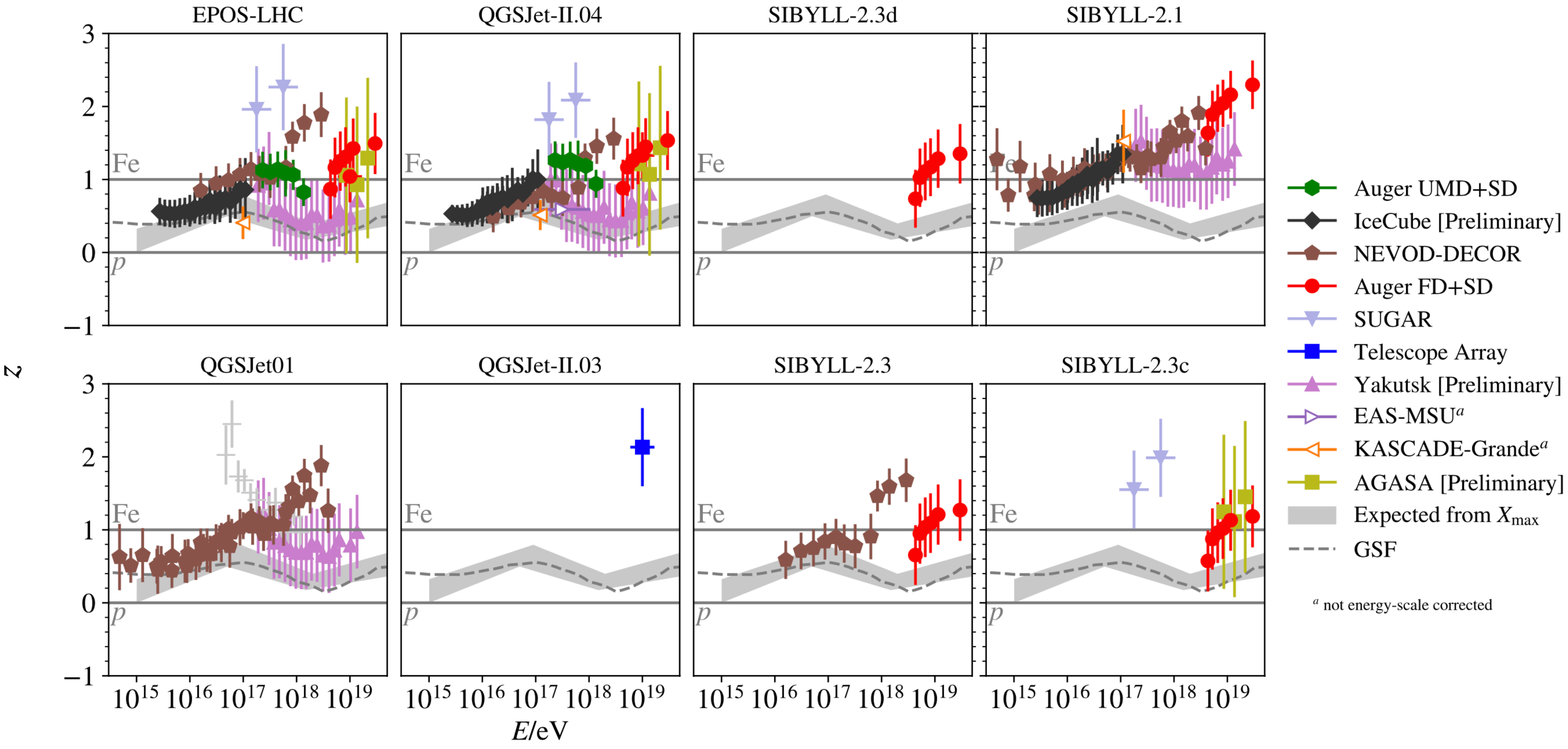


- ○ $X_{\max}$ correct

…a discrepancy occurs!

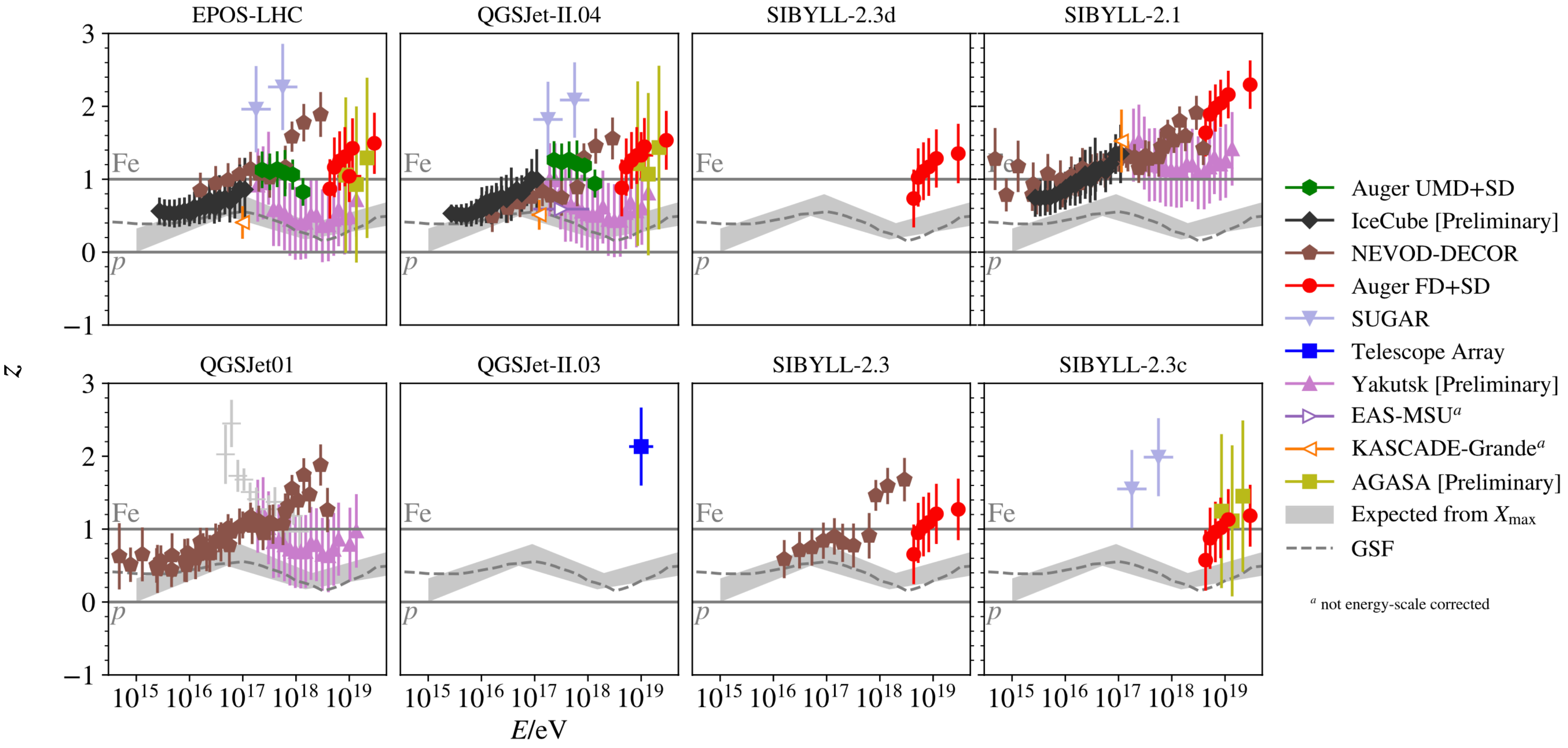
3 HEHI Models (+ variants)



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

…a discrepancy occurs!

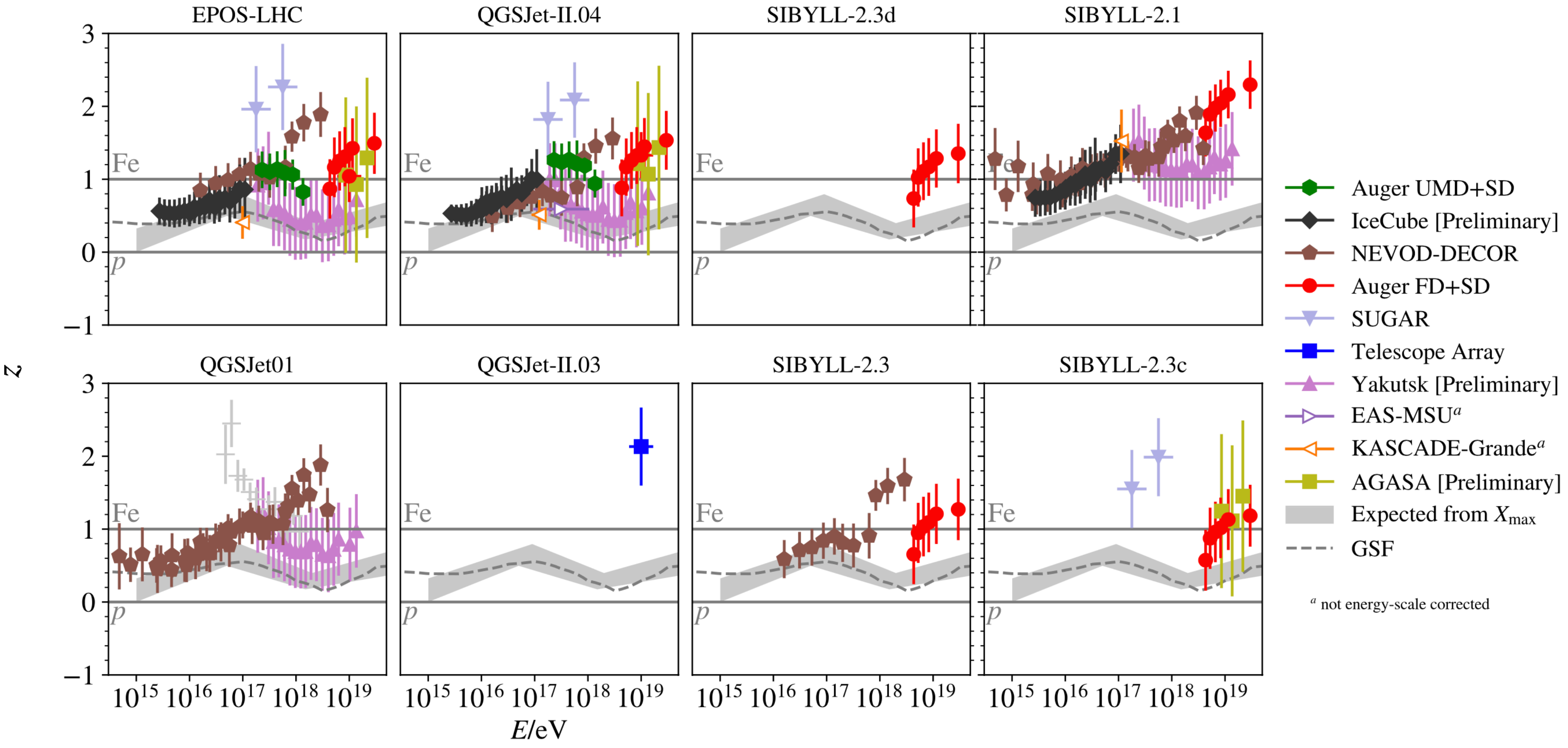
3 HEHI Models (+ variants)



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

…a discrepancy occurs!

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



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

- $X_{\max}$ correct

- Lateral density incorrect

- At <100 PeV, the discrepancy is not evident

…a discrepancy occurs!

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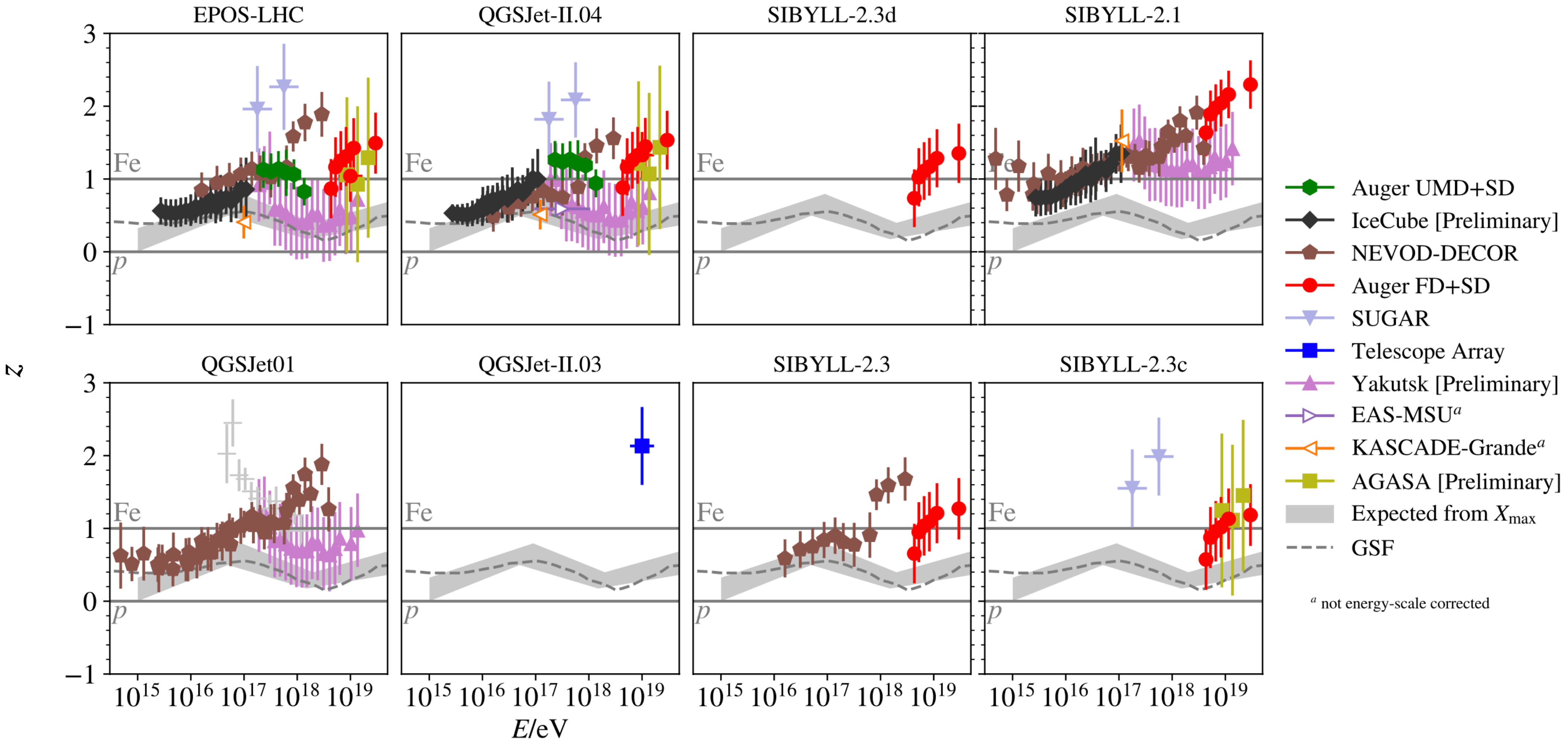

Early stages of the EAS: Isn’t it there, or is it negligible?

- $X_{\max}$ correct

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

- Lateral density incorrect
- At <100 PeV, the discrepancy is not evident

…a discrepancy occurs!

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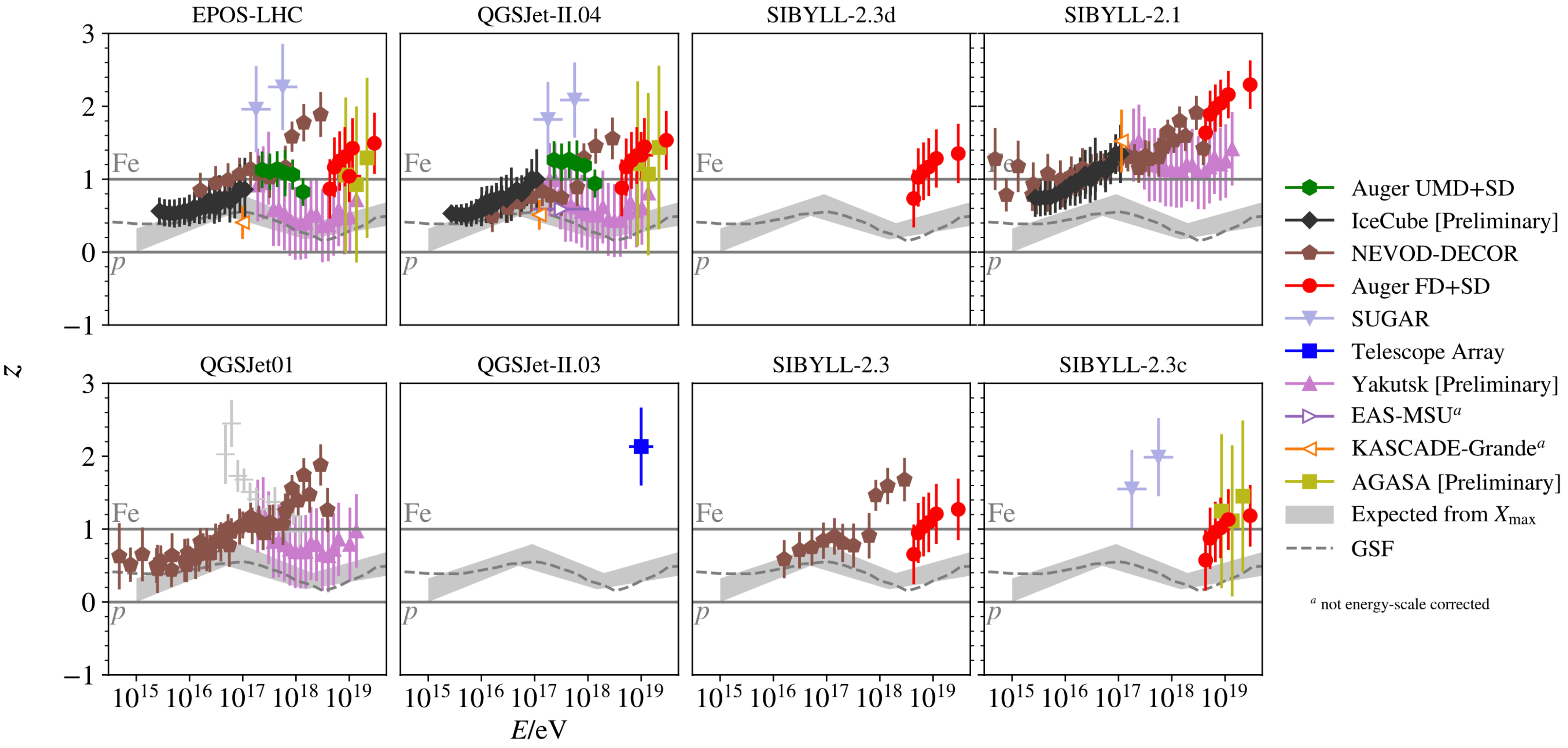


Early stages of the EAS: Isn’t it there, or is it negligible?

- $X_{\max}$ correct

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

- Lateral density incorrect

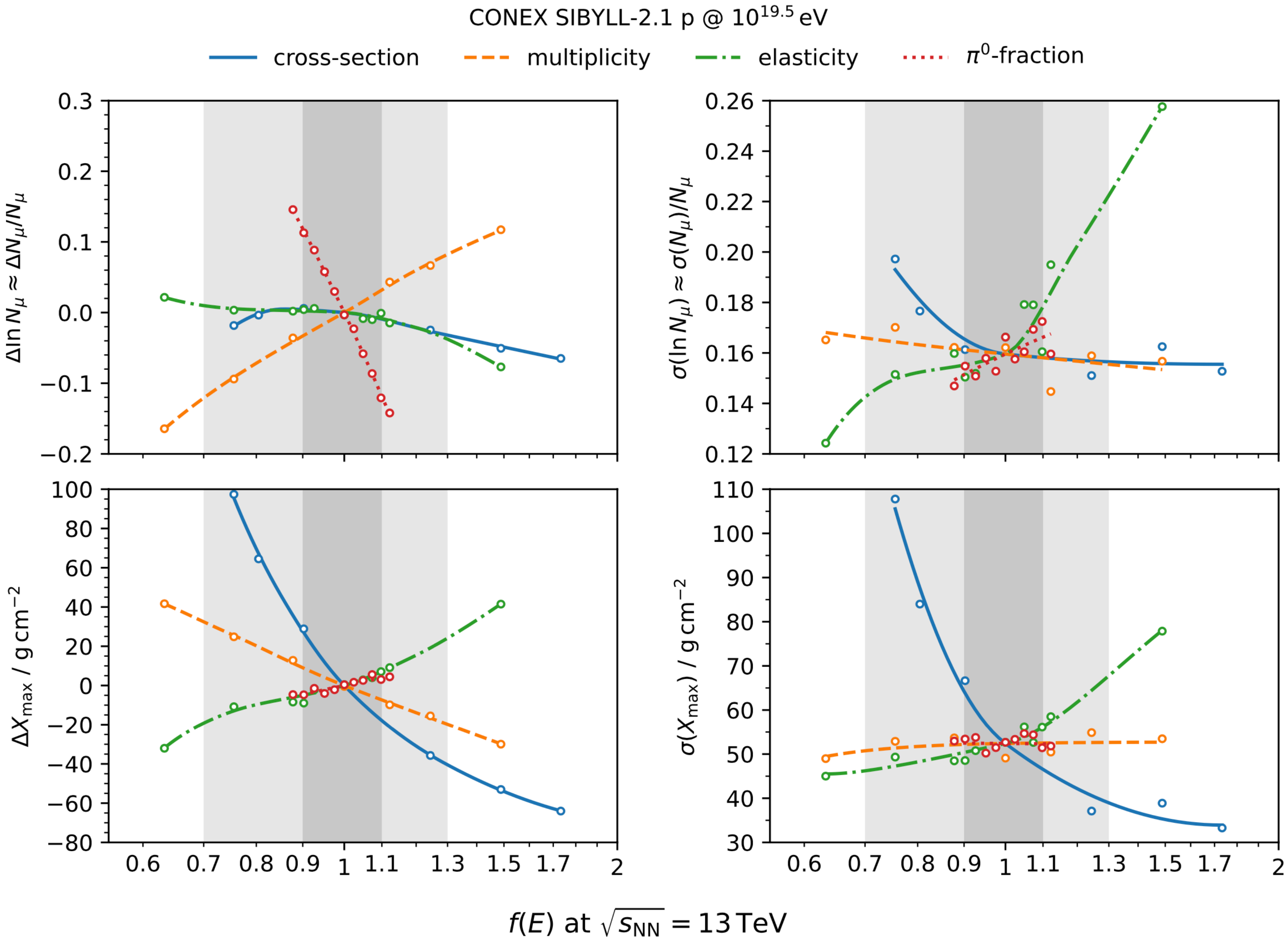
Does it not happen often at low energies? Does shower physics balance it out at high n?

- At <100 PeV, the discrepancy is not evident

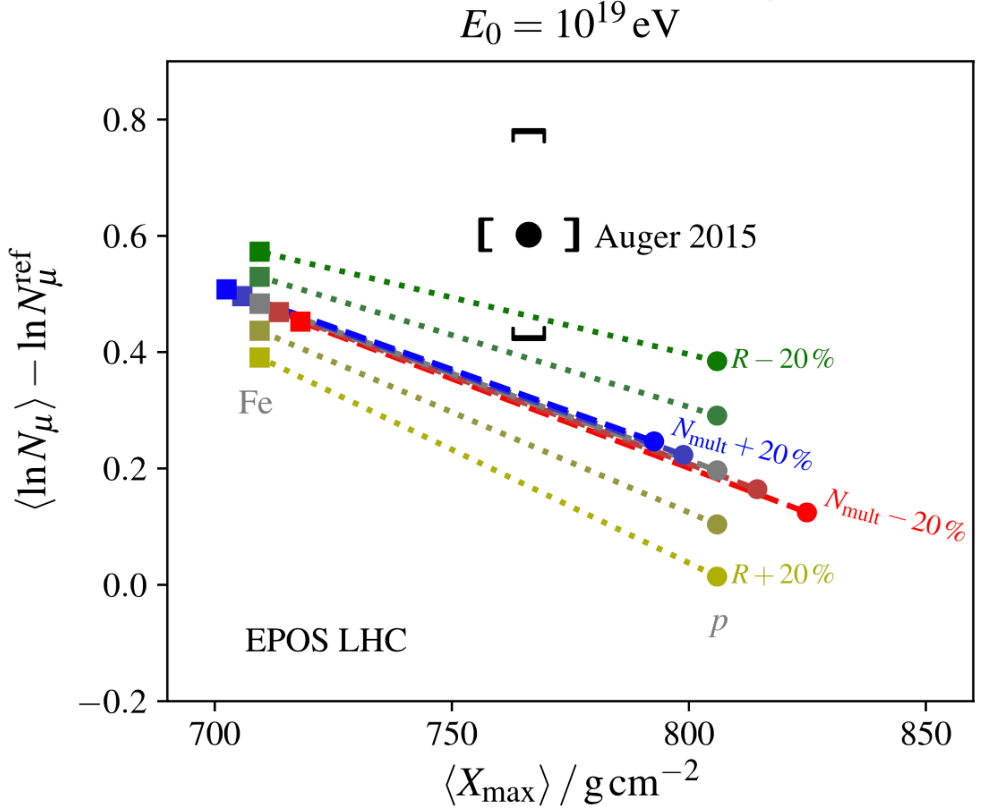
The Muon Puzzle

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

Simulations predict fewer muons than Reality!



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

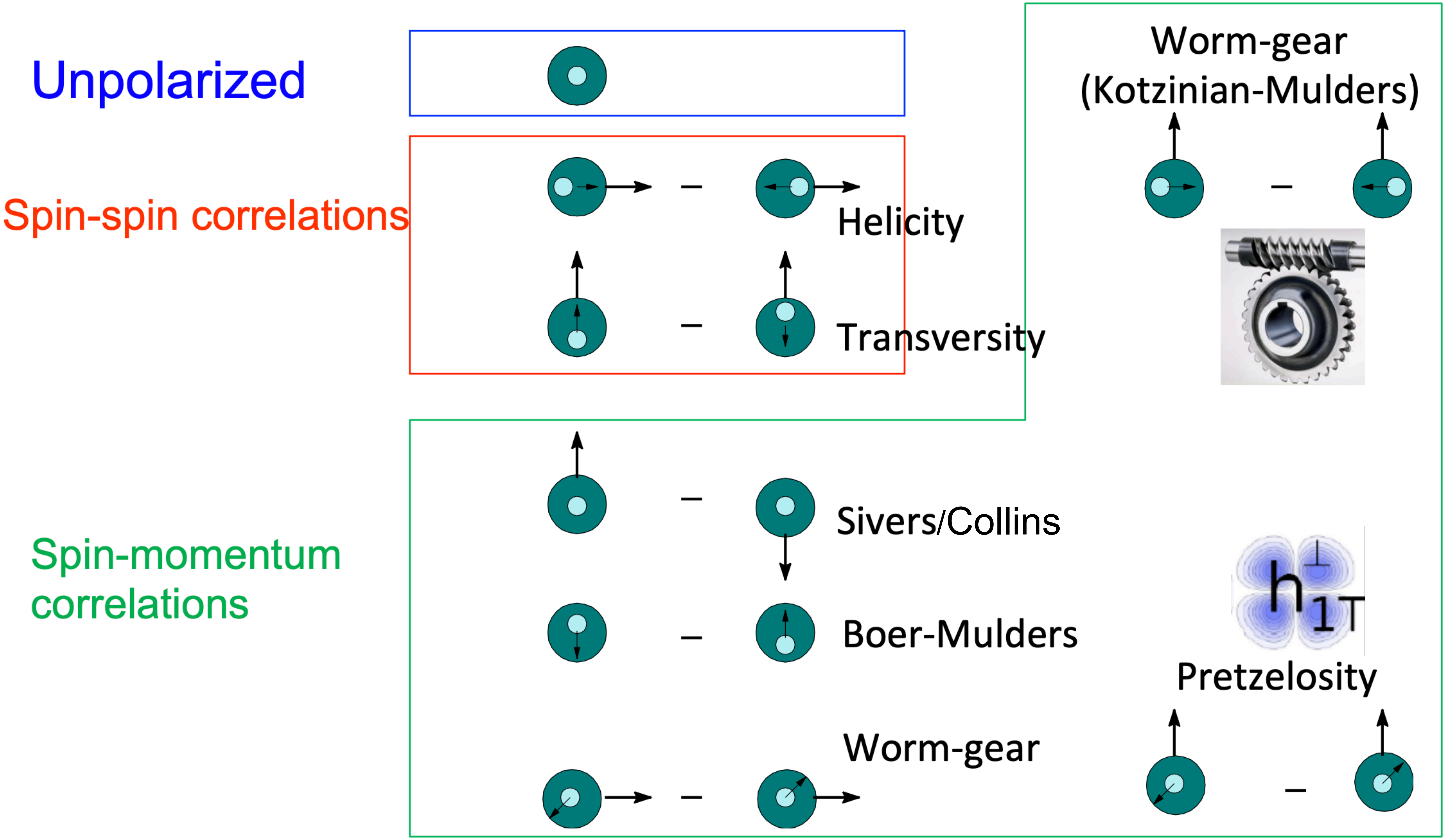


(Observable changes in varying the simulation parameters
Grey areas: ±10% and 30% of variation)

The Spin Puzzle

Polarization modifies the cross-section

(whether target, projectile, or both)



Unpolarized

Spin-spin correlations

– Helicity

– Transversity

Spin-momentum correlations

– Sivers/Collins

– Boer-Mulders

– Worm-gear

Worm-gear (Kotzinian-Mulders)

–

Pretzelosity

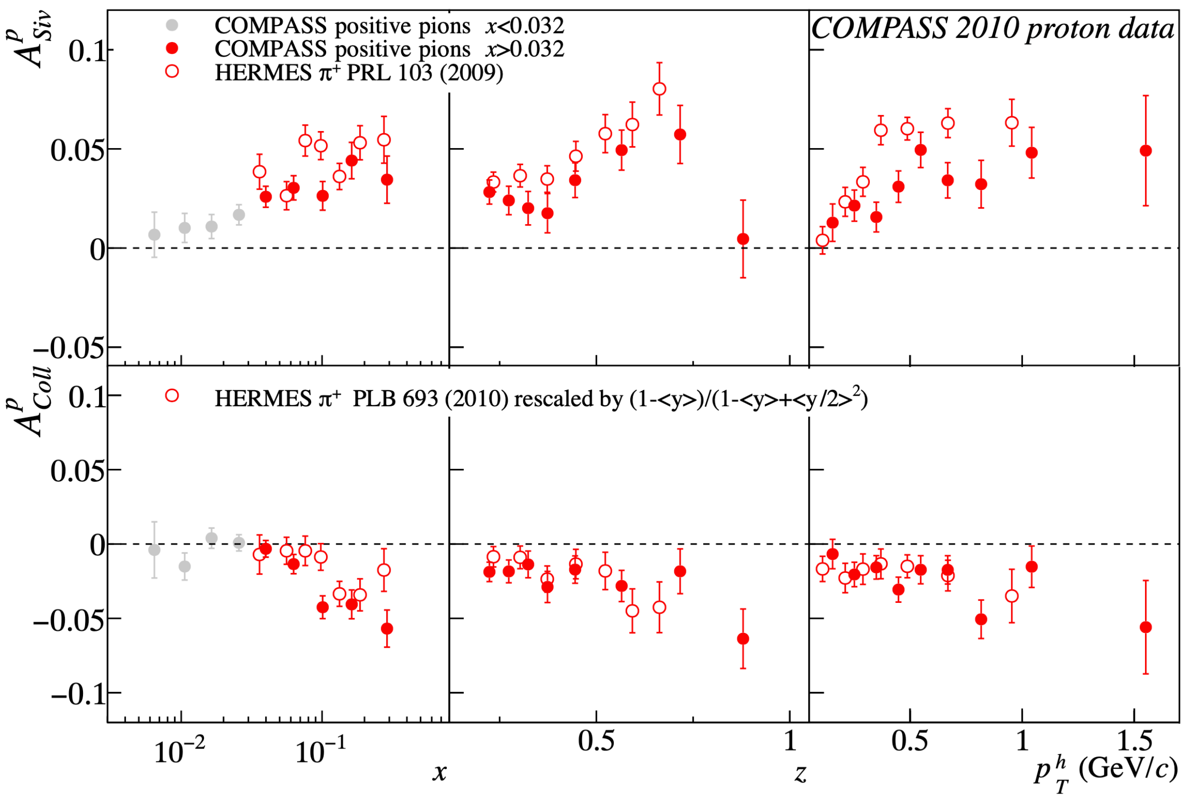
–

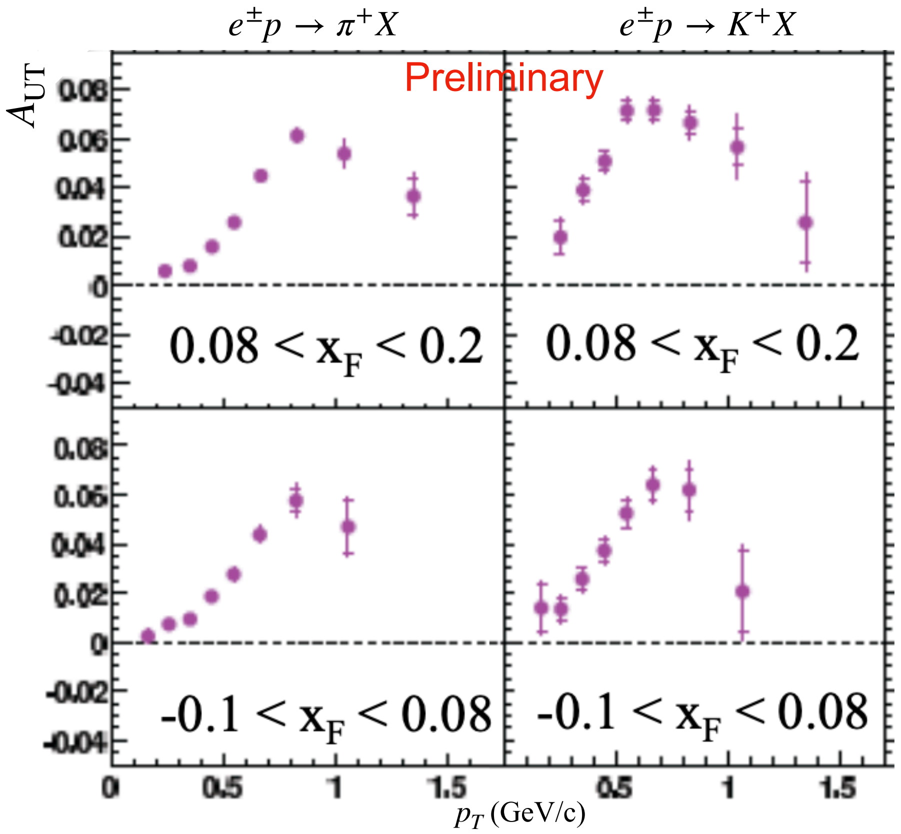
The Spin Puzzle

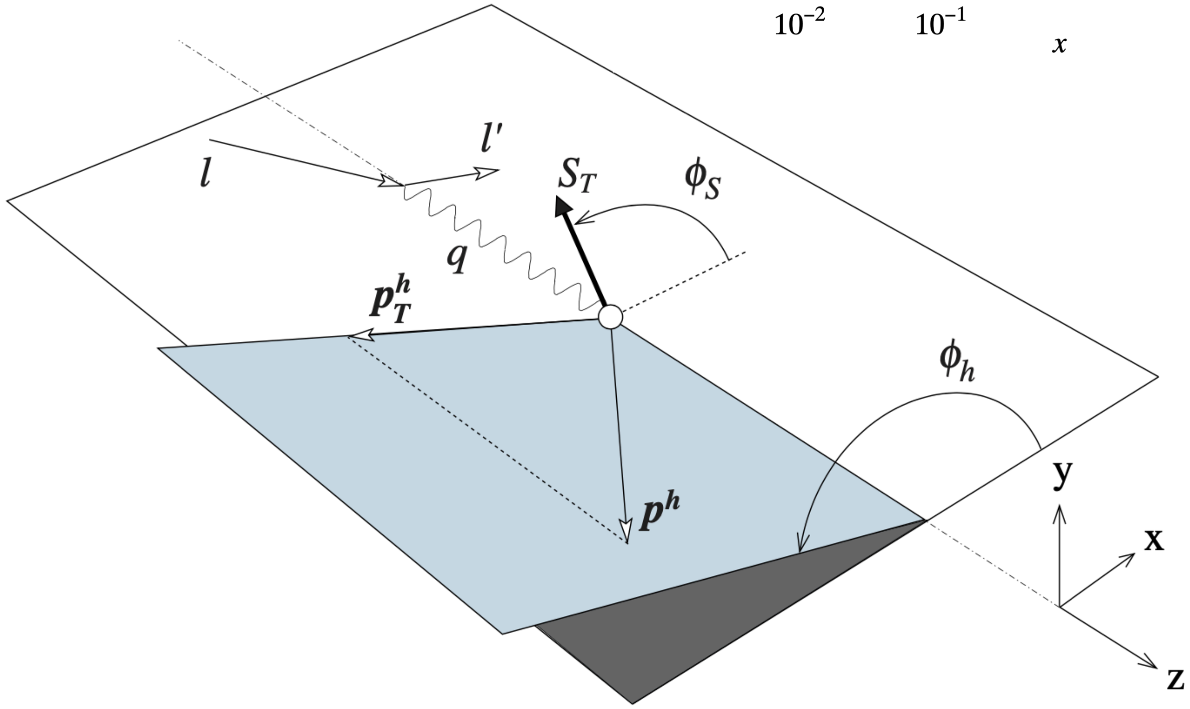
Polarization modifies the cross-section, BUT NOT ONLY!

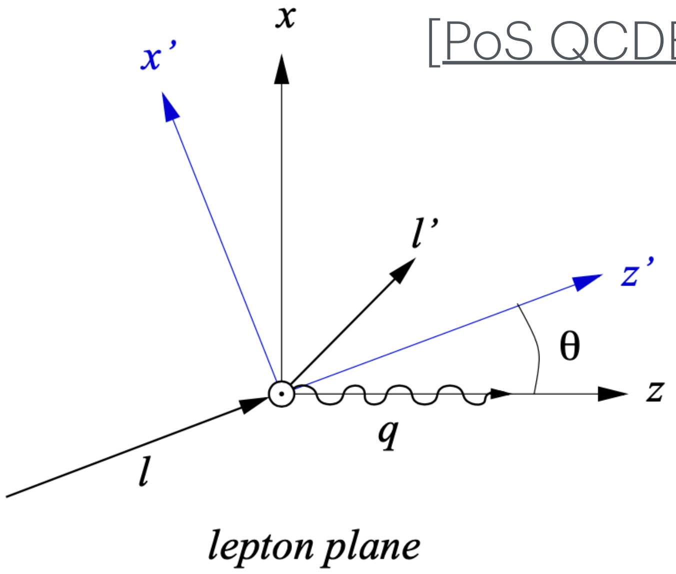
(whether target, projectile, or both)

From HERMES and COMPASS: an extra transverse momentum appears!







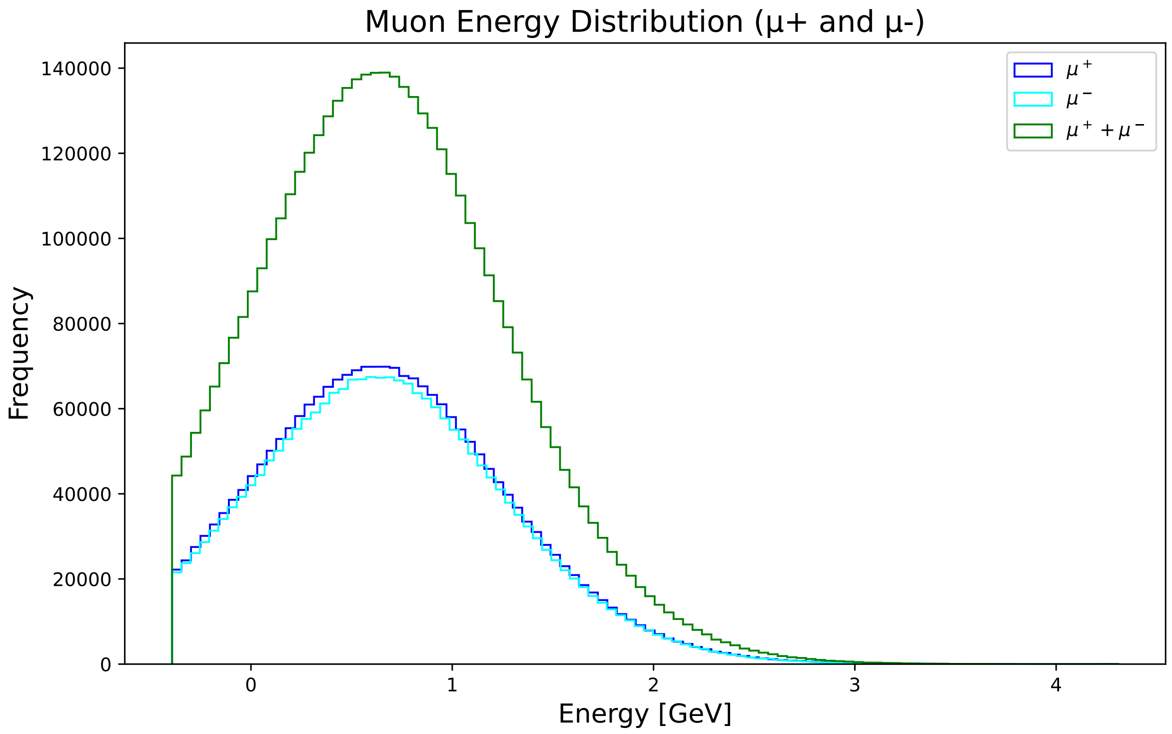


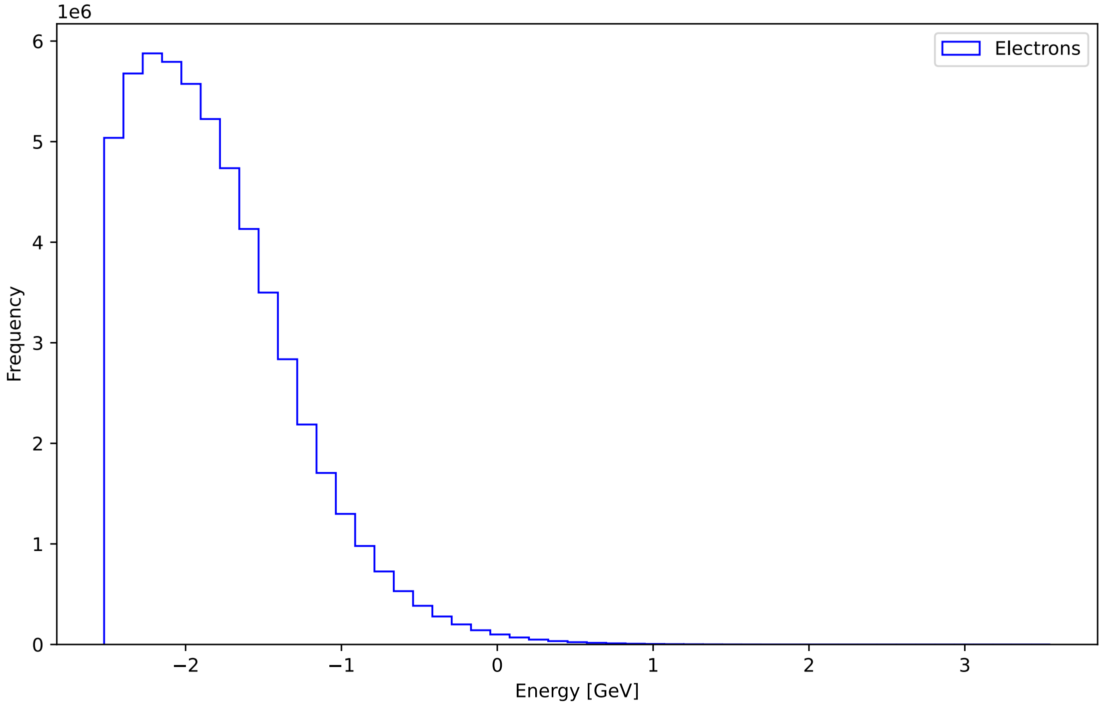
[PoS QCDEV2015 007 (2016)]

A Hypothesis…

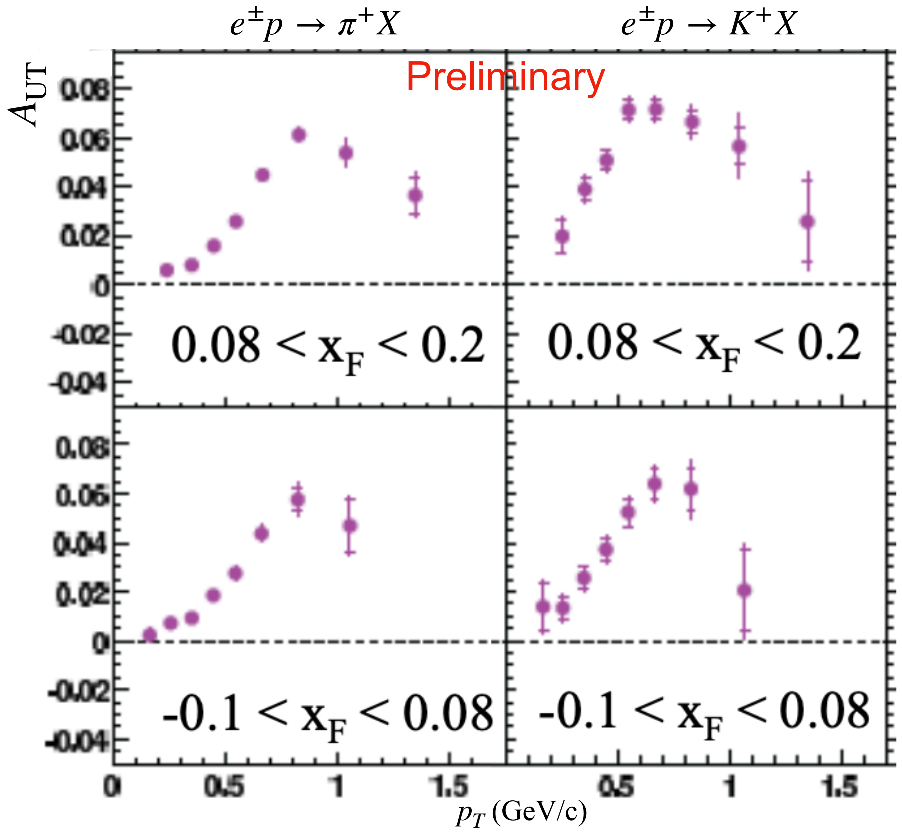
What if the Spin Puzzle is the cause of the Muon Puzzle?

☐ Right energy Range





Secondaries in Krakow from 1000 showers at $10^4 < E[\text{GeV}] < 10^5$



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- ☑ Right energy Range: Yes, for muons at the ground!
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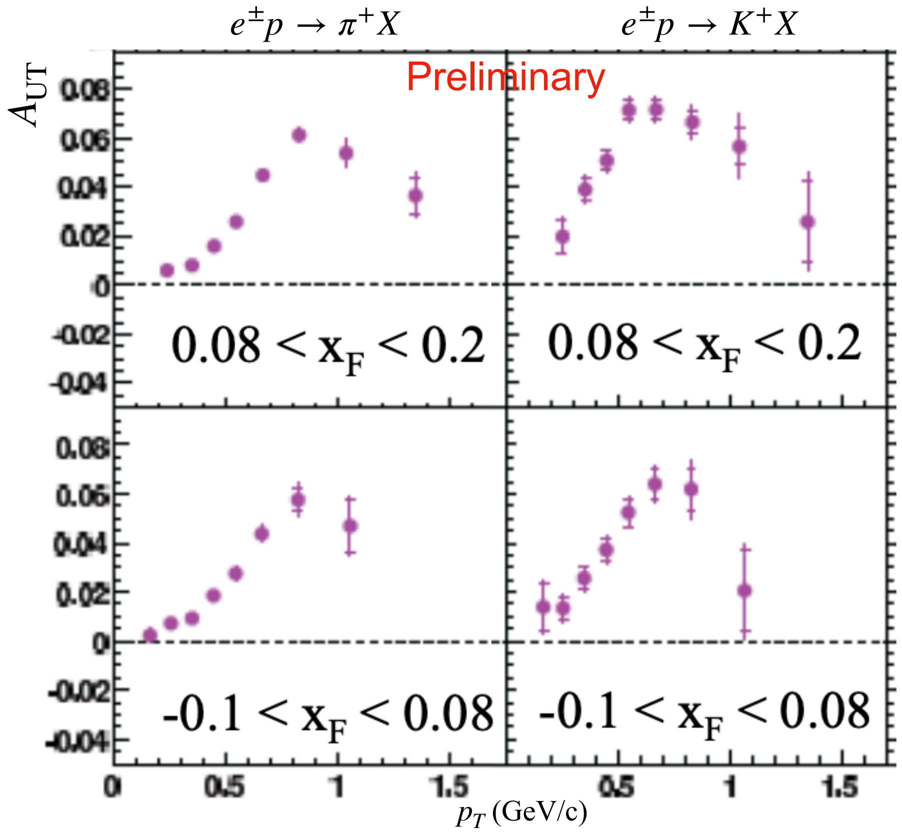
  - ☐ No change on X_{max} at the Early stages



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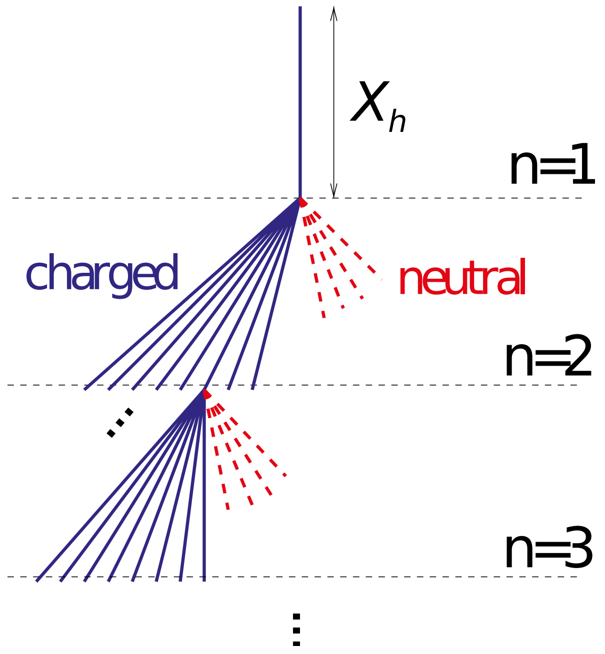
  - ☐ More n, more absorption lengths when $(E < E_{\mathrm{crit}}^{\mathrm{decay}})$: It can balance out/reduce the extra muons produced for <100 PeV showers



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

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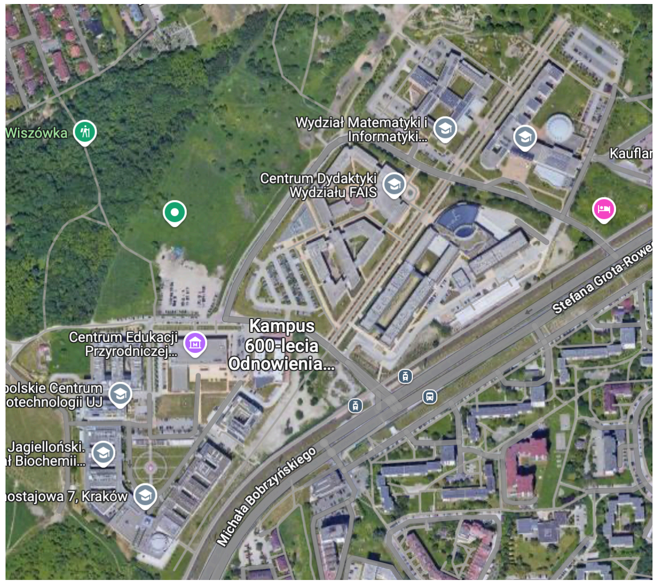
- Reducing the variables (unknown Energy and Mass descriptions)
- A good charge separation due to the Geomagnetic field
  - related to how much particles are polarized

Experimental conditions

A Krakow case!

Krakow altitude
~200 m a.s.l.



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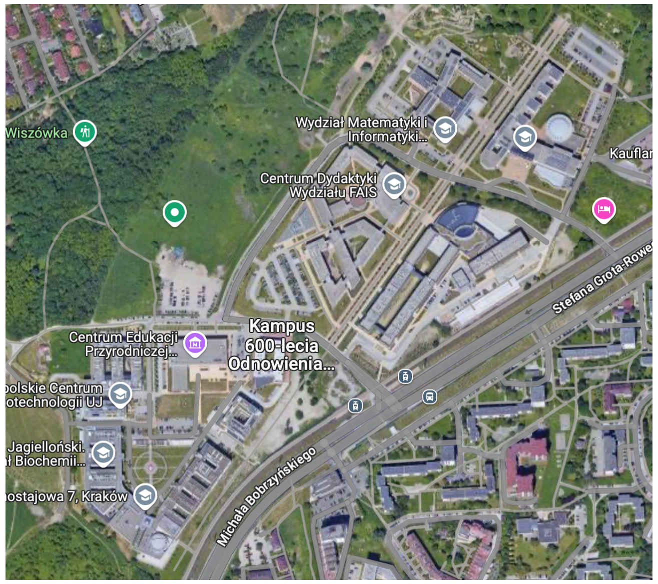
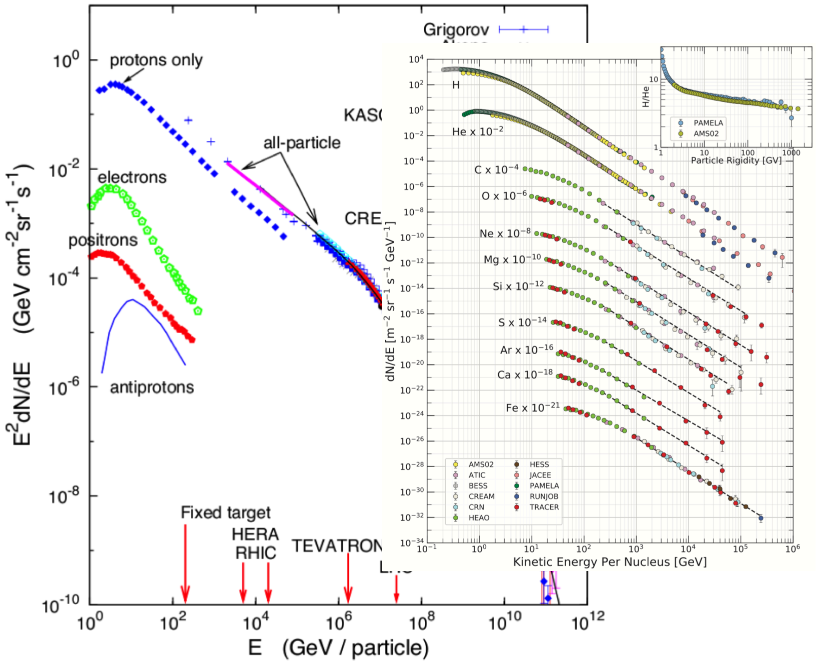
Let's use HECR!
know E and mass





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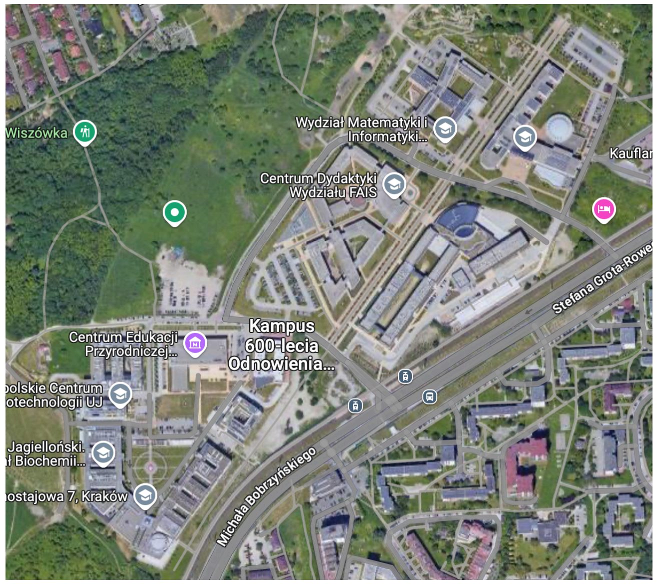
Experimental conditions

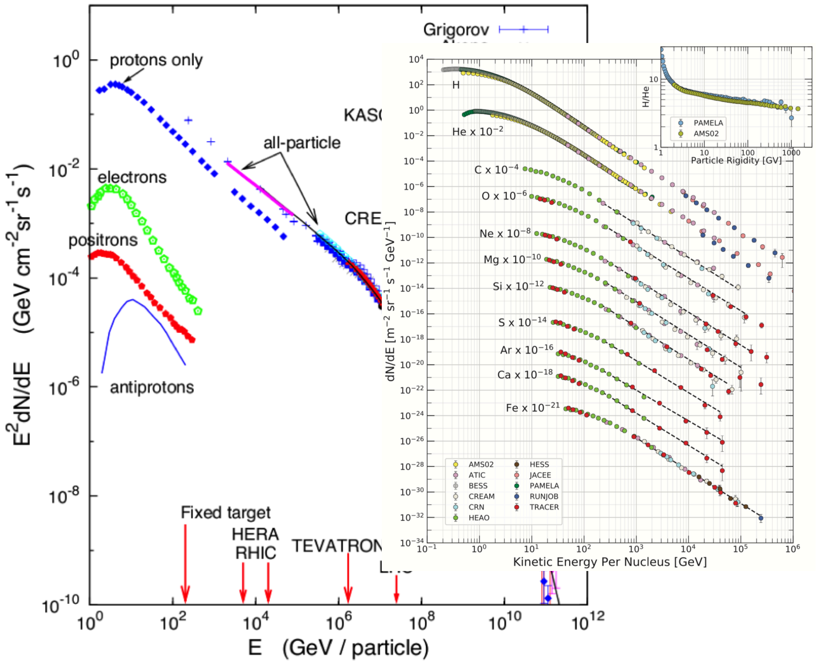
A Krakow case!

Krakow altitude
~200 m a.s.l.

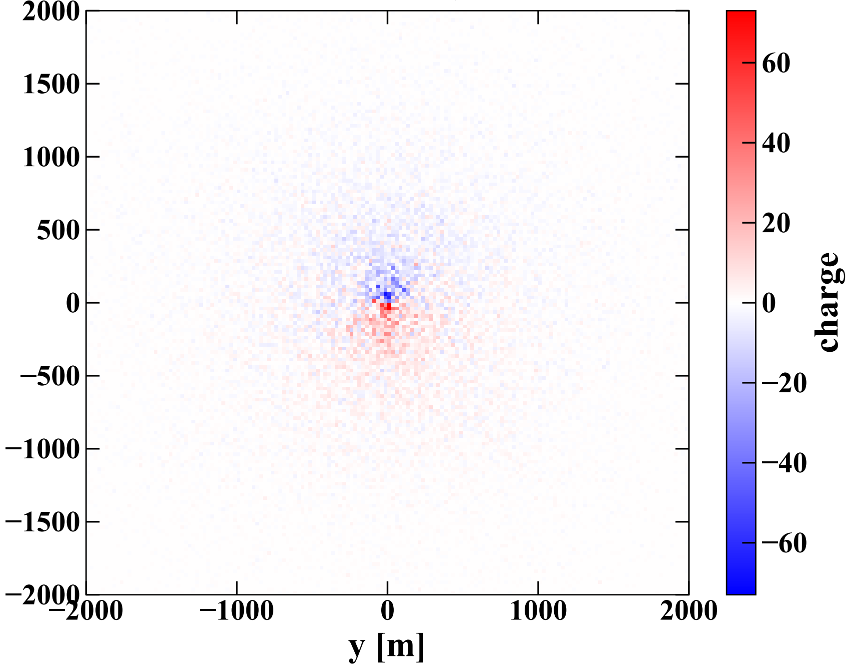
Let's use HECR!
know E and mass

From simulations,
a clear charge separation!





$E = 10^5\,\mathrm{GeV}, \theta = 30°$



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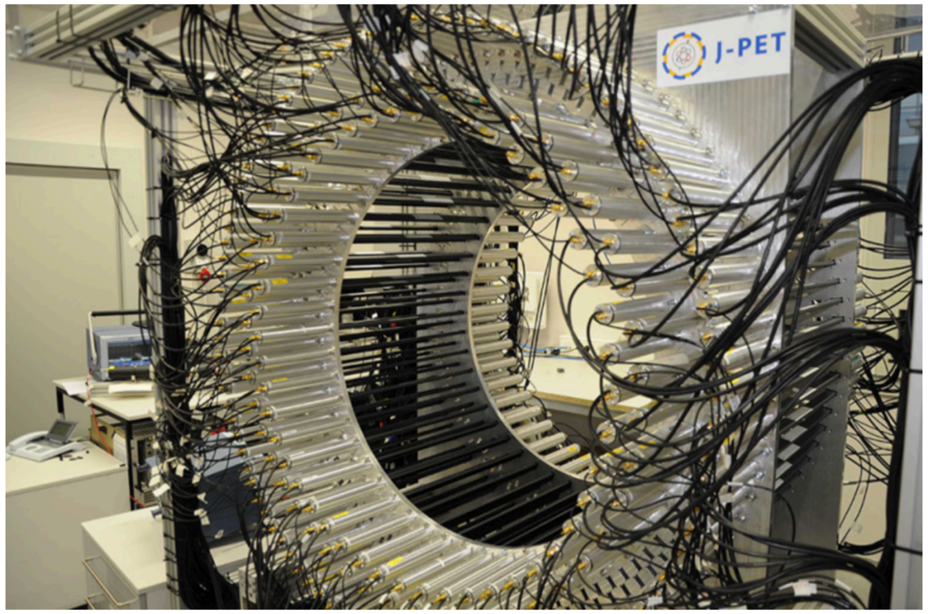
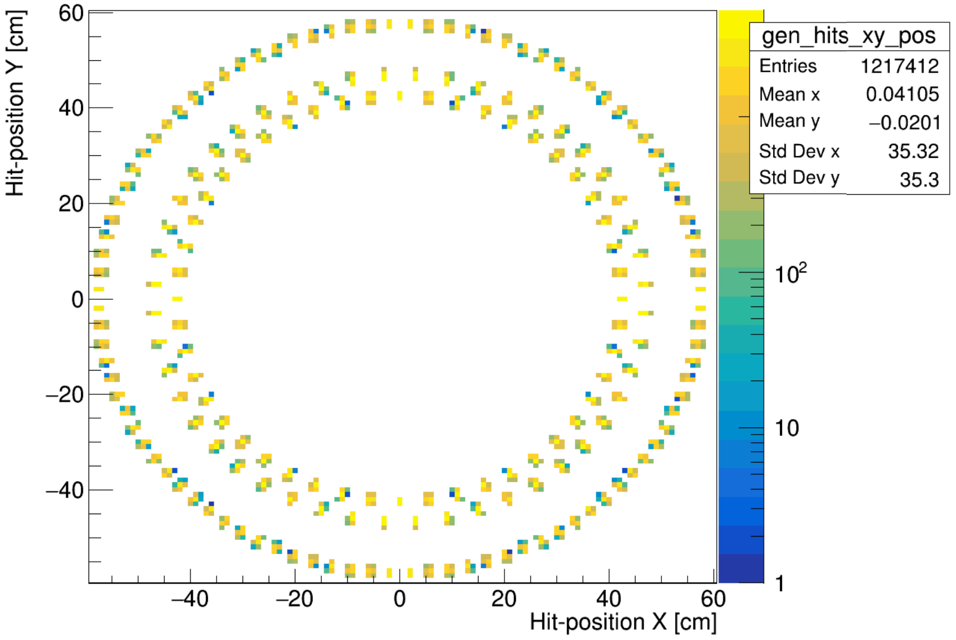
μPPET

μ-**P**uzzle with J-**PET**

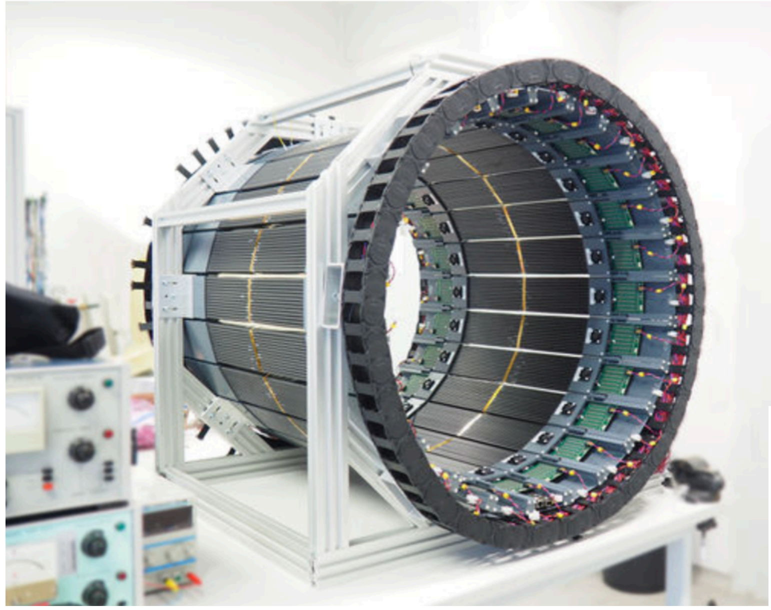
Big Barrel J-PET

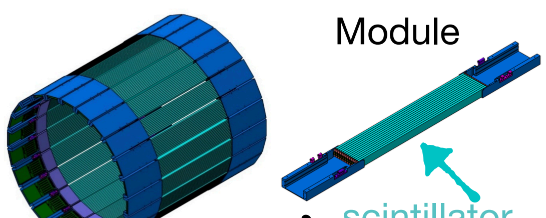


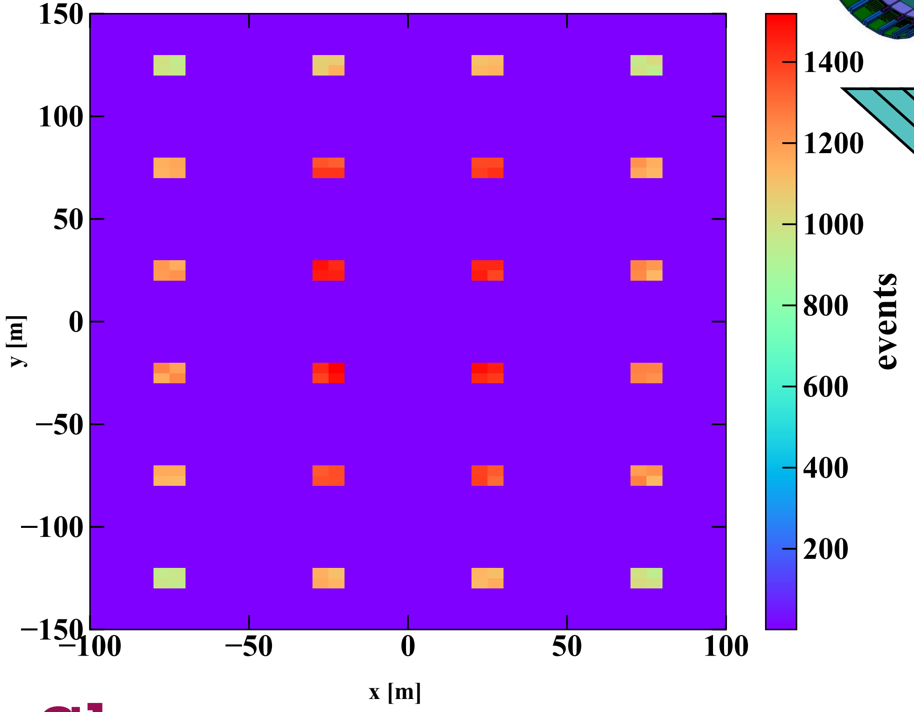


Probe:
Muon Tracker

Modular J-PET



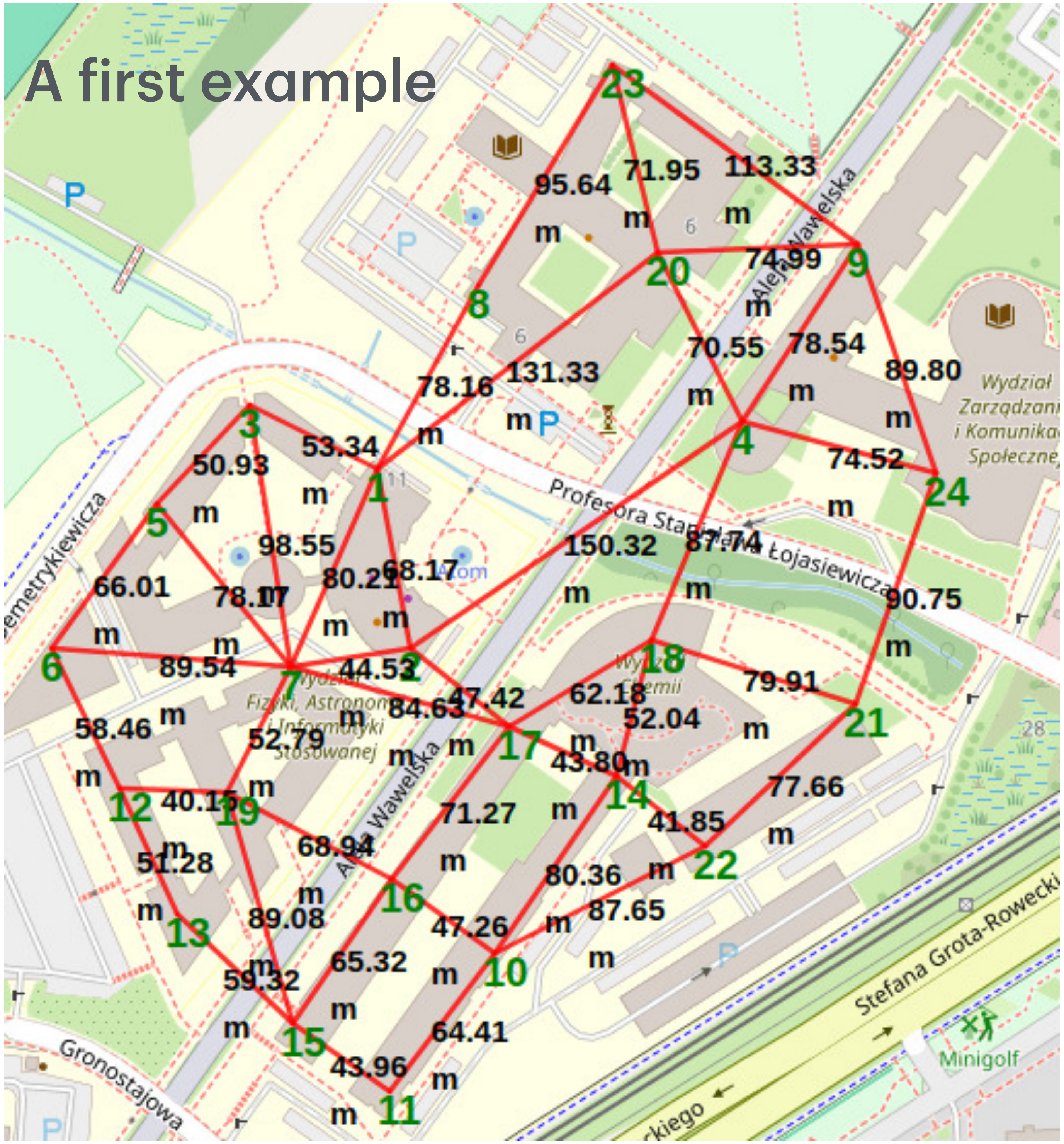




Shower reconstructor:
Primary Core and diretion

Shower Reconstructor

Repurposing Modular J-PET as a scintillator array

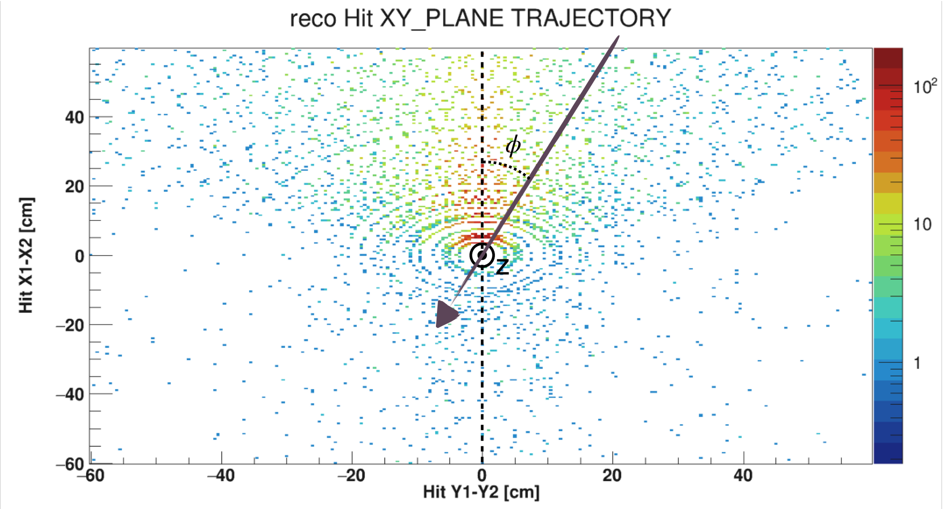

A first example

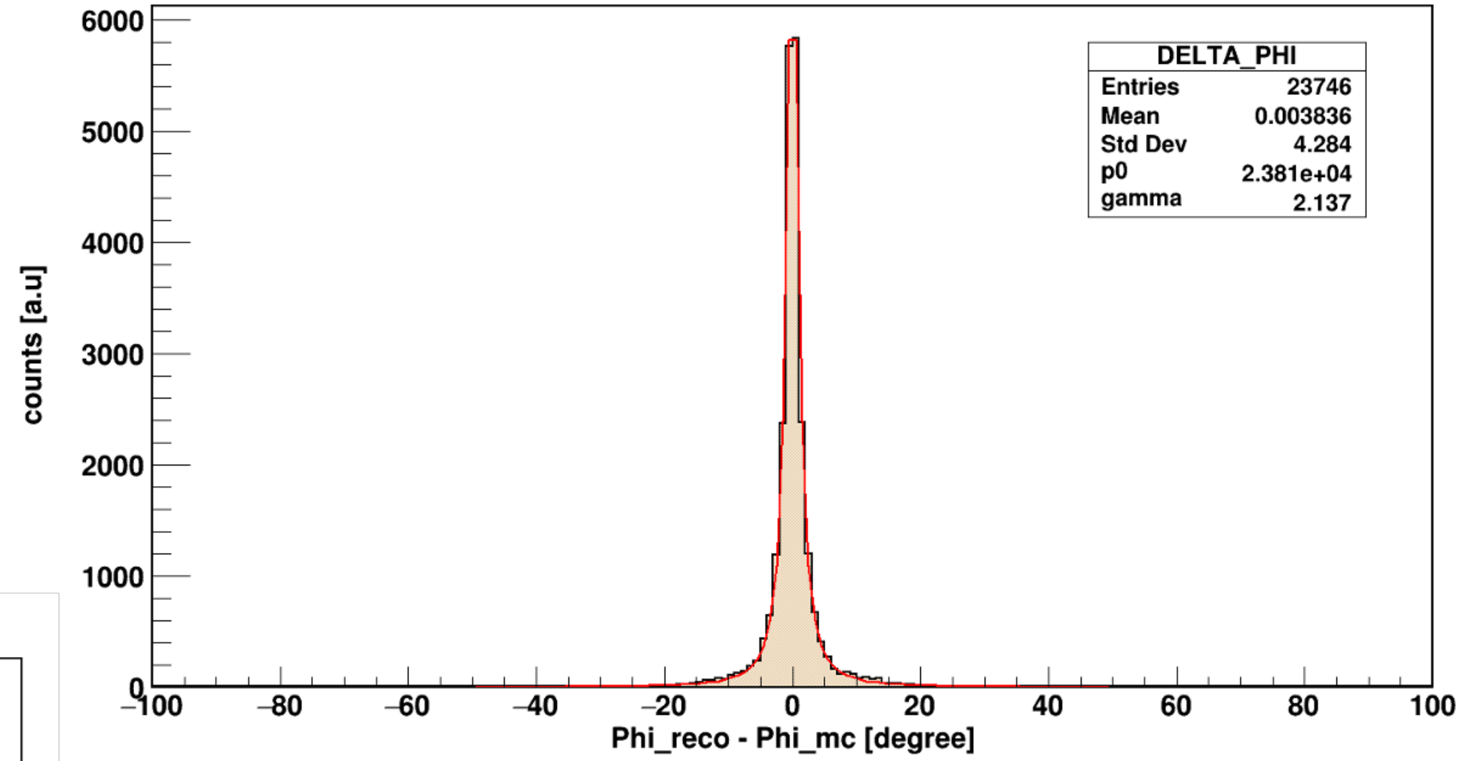
- Optimized for electrons (more abundant)
- Reconstruction of the geometry of the shower (Core and Direction)
  - **Brass Events**: a single triggered detector for calibration and testing (no geometry reconstructions!)
  - **Silver Events**: 3 or more triggered for geometry reconstruction and Charge separation constraints

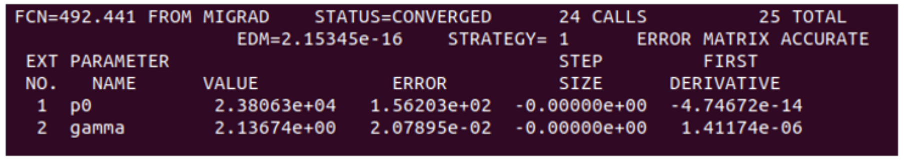
Probe

Big-Barrel J-PET as a muon tracker

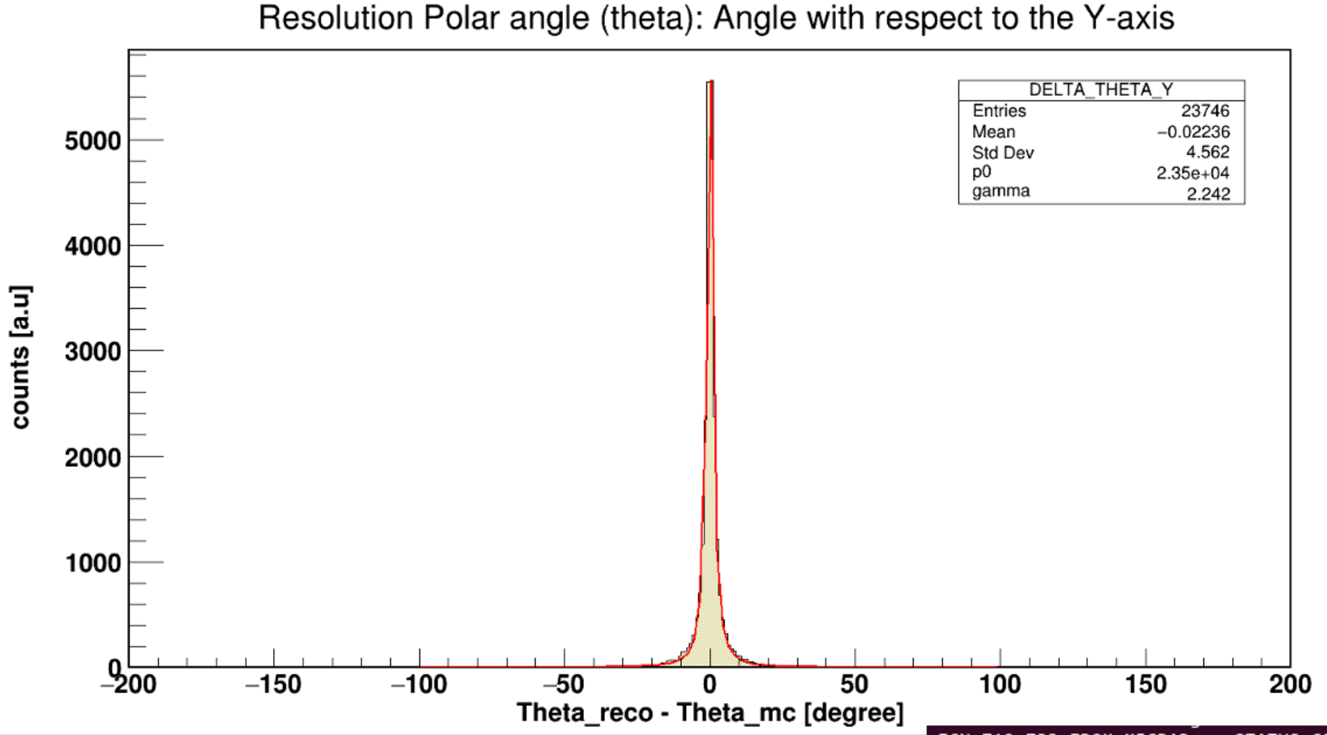
Trajectories from vertical muons (not cut, not reconstructions!)

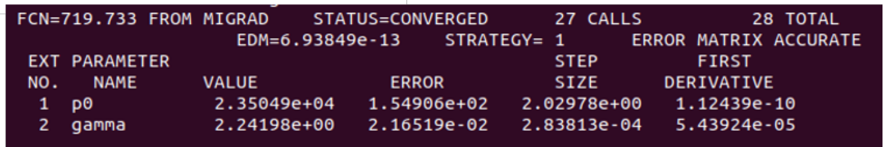






```
FCN=492.441 FROM MIGRAD    STATUS=CONVERGED      24 CALLS          25 TOTAL
                     EDM=2.15345e-16    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                   STEP         FIRST
 NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
  1  p0           2.38063e+04   1.56203e+02  -0.00000e+00  -4.74672e-14
  2  gamma        2.13674e+00   2.07895e-02  -0.00000e+00   1.41174e-06
```





```
FCN=719.733 FROM MIGRAD    STATUS=CONVERGED      27 CALLS          28 TOTAL
                     EDM=6.93849e-13    STRATEGY= 1      ERROR MATRIX ACCURATE
 EXT PARAMETER                                   STEP         FIRST
 NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
  1  p0           2.35049e+04   1.54906e+02   2.02978e+00   1.12439e-10
  2  gamma        2.24198e+00   2.16519e-02   2.83813e-04   5.43924e-05
```

$$f(x) = p_0 \frac{1}{\pi} \frac{\frac{1}{2}\Gamma}{x^2 + \frac{\Gamma^2}{4}},$$

with Γ the FWHM

⇒ Resolutions $\sigma < 1$ for both

Strategy

Experimental and Phenomenological side simultaneously

Experimental and Analysis

- **Brass Events**: for calibration and testing (no geometry reconstructions!)
- **Silver Events**: for Charge separation constraints to Polarization
- **Golden Events**: Probe + 2 (or more) triggered scintillators to measure the muon trajectory discrepancy
  - **Golden** + **Silver**: combined analysis (Bayesian and NN)

Phenomenology

- Including the Spin Puzzle in the HEHI models
- Including the Polarization parameters
- Updates back-and-forth along with experimental results

Outcome

👍 ***Breakthrough + Pathfinder!***

👎 ***Hypothesis rejected + Survey***