Bounds on Lorentz Invariance Violation from muon fluctuations at the Pierre Auger Observatory

TEVPA 2026 | Based on Phys. Rev. Lett. (arXiv:2602.14720)

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INFN LNGS

Novel observable in UHECRs: First hadronic LIV bounds independent of primary mass composition

Why can muon fluctuations probe LIV?

→ LIV may modify particle interactions at extreme energies.

→ Modified interactions can alter the development of extensive air showers.

→ Muon fluctuations can therefore provide an indirect probe of LIV.

From Quantum Gravity to LIV

The search for a unified theory of gravity and quantum mechanics motivates **Quantum Gravity**

Some Quantum Gravity models predict or allow for **violations of Lorentz invariance**

These effects are expected to become relevant at **extremely high, potentially Planck-scale energies**

Modifications of the kinematics in particle interactions at extreme energies

A. Addazi et al., *Quantum gravity phenomenology at the dawn of the multi-messenger era — A review*, **Prog. Part. Nucl. Phys. 125 (2022) 103948**

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Neutrino

GW

Gamma rays

Cosmic Rays

High Energy Messengers

High Energy Messengers

Neutrino

GW

Gamma rays

Ultra High Energy Cosmic Rays

Modifications of the kinematics of interactions of cosmic messengers

The study of the appearance, disappearance, or shifting of the threshold energies of processes with respect to their values in SR is called the study of "anomalous thresholds"

Threshold anomalies can be seen as kinematic modifications of the SR description of interactions, and indeed, it is usually the only effect that is modelled to estimate the phenomenological consequences of LIV on the interactions of cosmic messengers.

Usually only introduced at the level of in-vacuo dispersion relations, modified by a high-energy scale E_{QG} (usually taken as the Planck scale)

Modified Dispersion Relation (MDR) : $m_i^2 = E_i^2 - \mathbf{p}_i^2 + f(E_i, \mathbf{p}_i, m_i, E_{QG})$

energy: $E_A + E_B = E_C + E_D$

momentum: $\mathrm{p}_A + \mathrm{p}_B = \mathrm{p}_C + \mathrm{p}_D$

LIV → modified kinematics → threshold anomalies

How can muon fluctuations probe LIV?

→ Extensive air showers

→ Pierre Auger Observatory

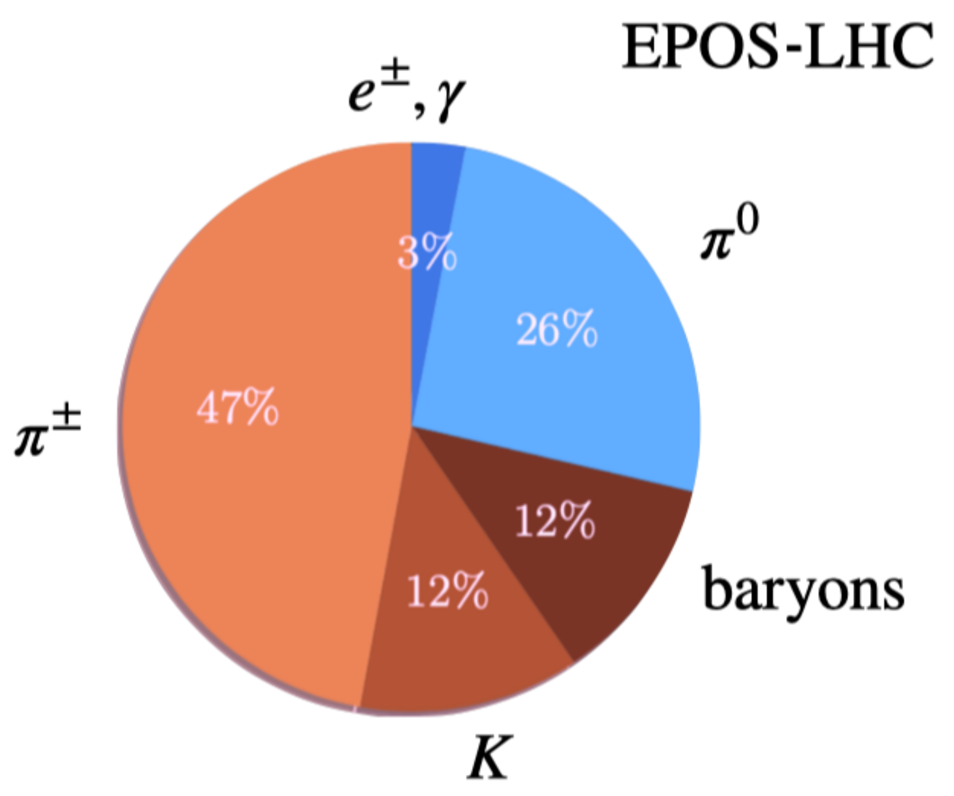
→ Muon Fluctuations measured by Pierre Auger

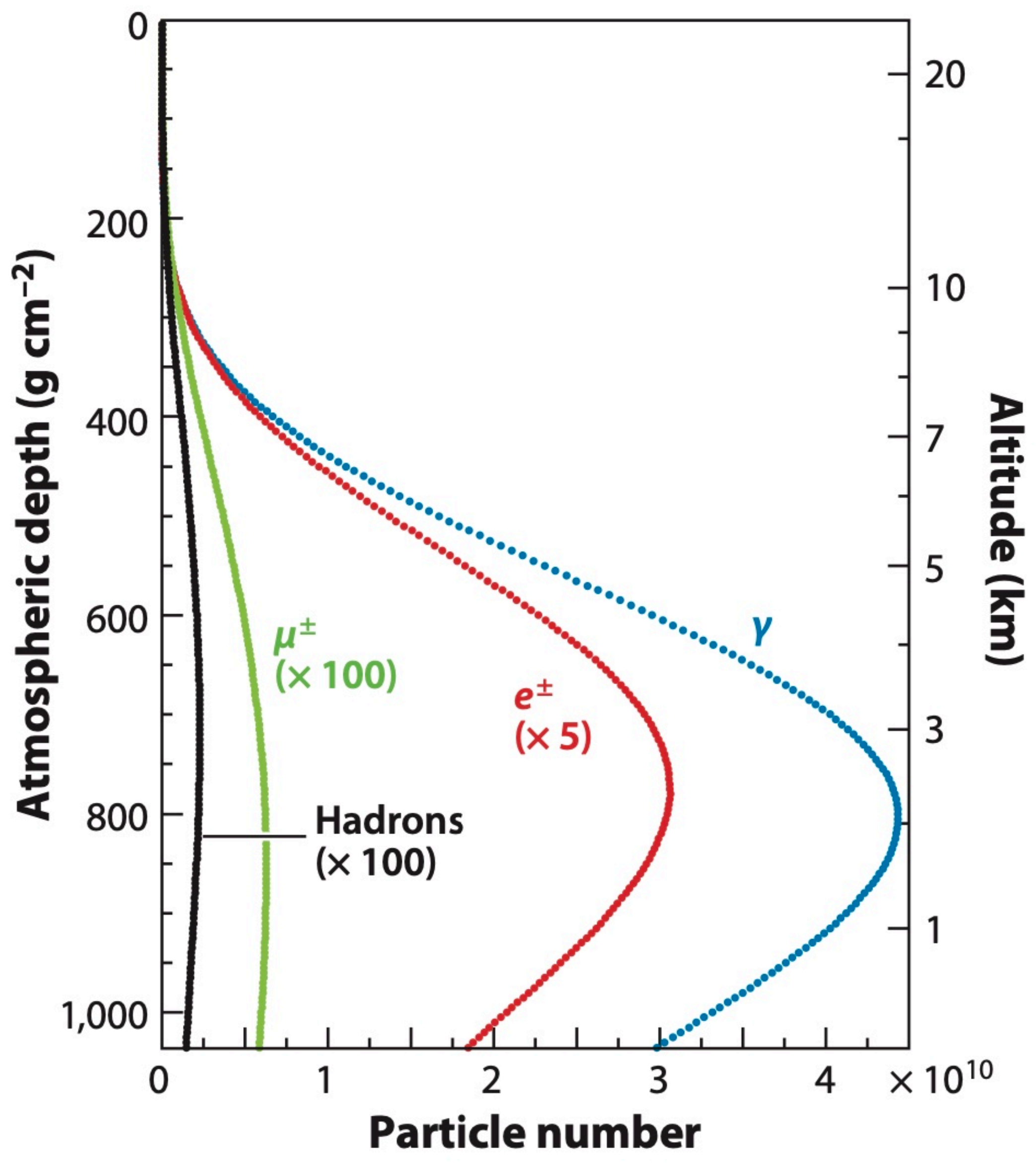
→ LIV framework

→ Conex Simulations and LIV effects on the shower development

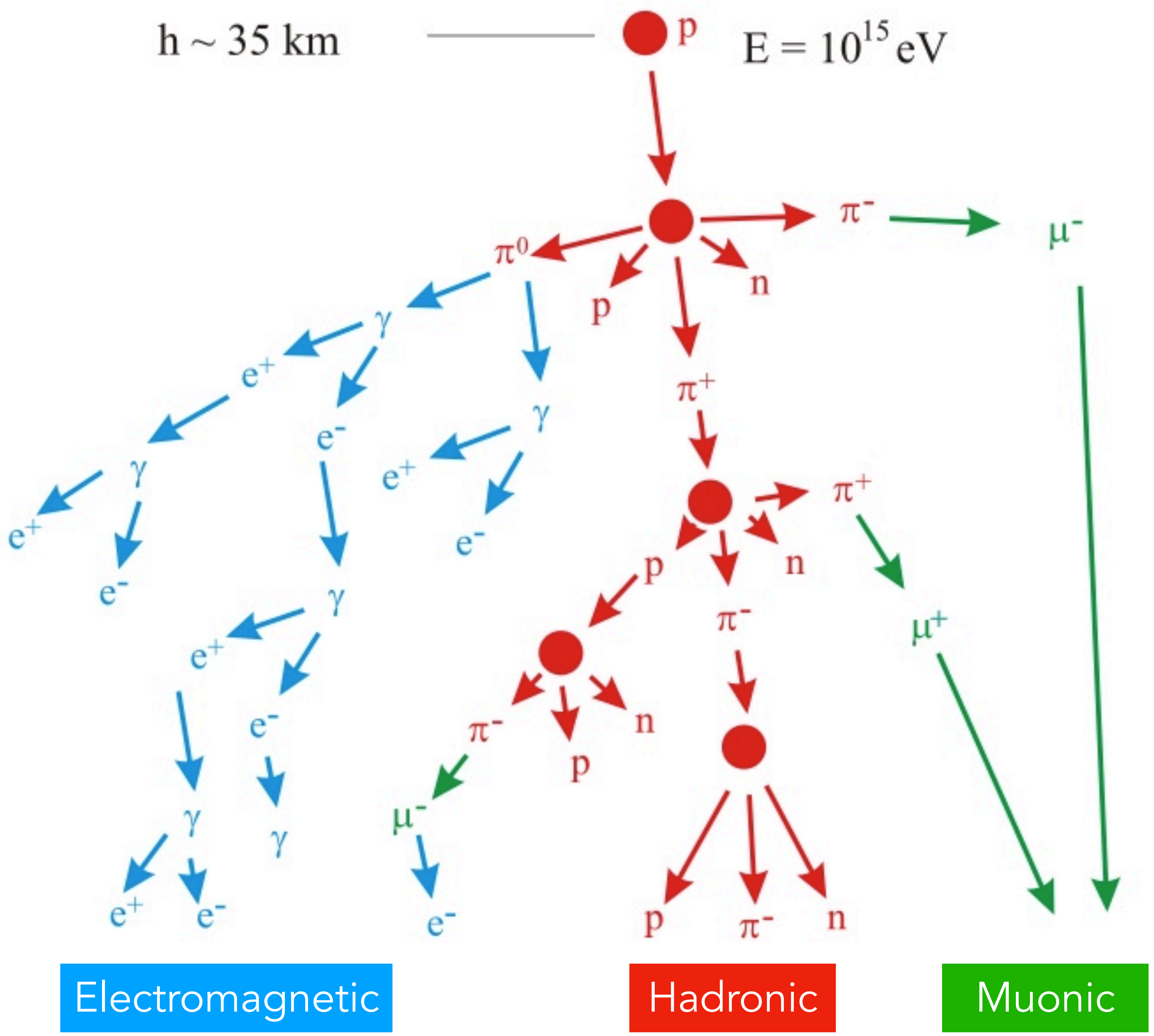
→ The LIV model and constrains on the hadronic interaction model

Extensive Air Showers

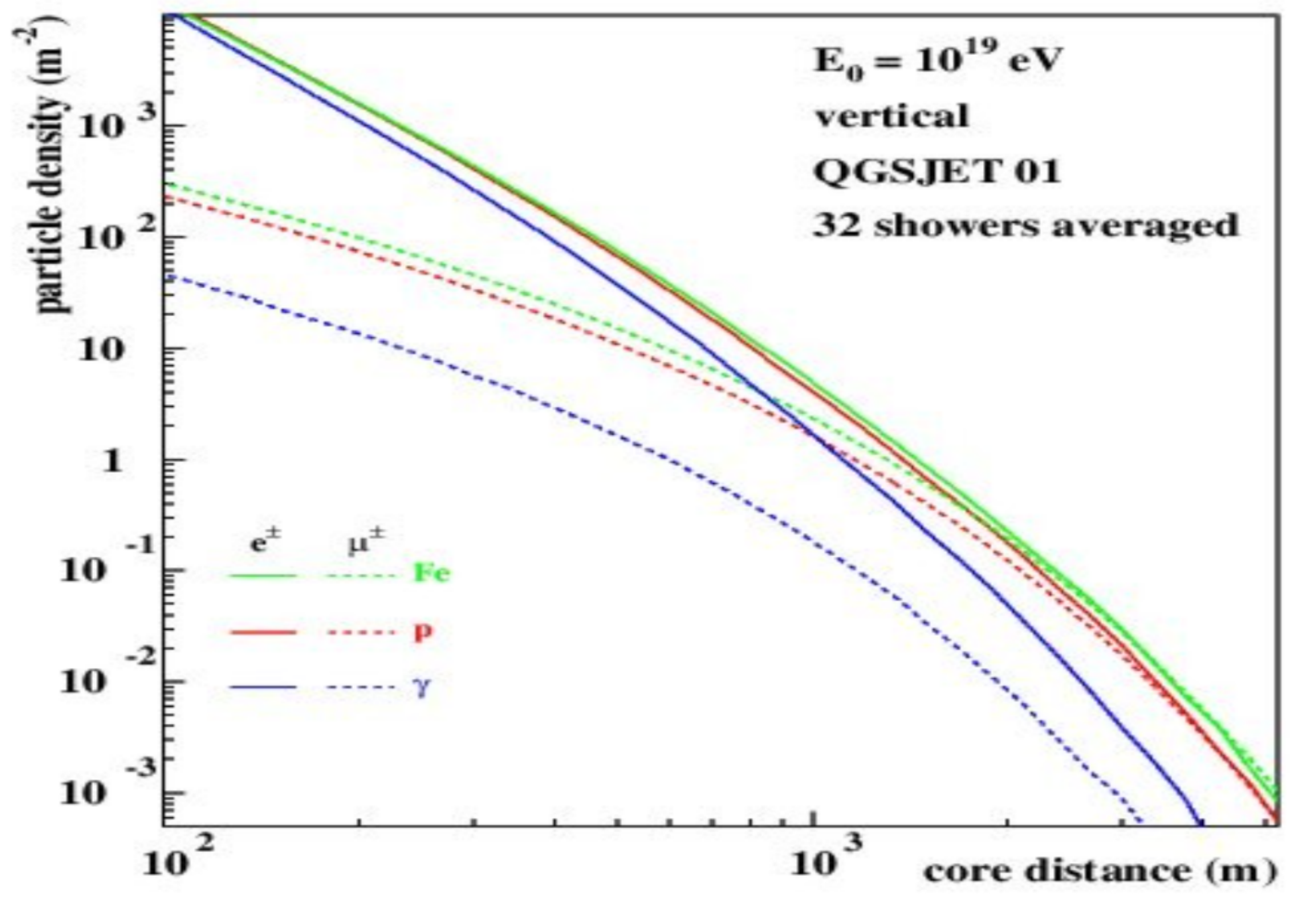




- Longitudinal development
  > Number of particles as a function of the depth X
  > Larger number of particles at X_{max}

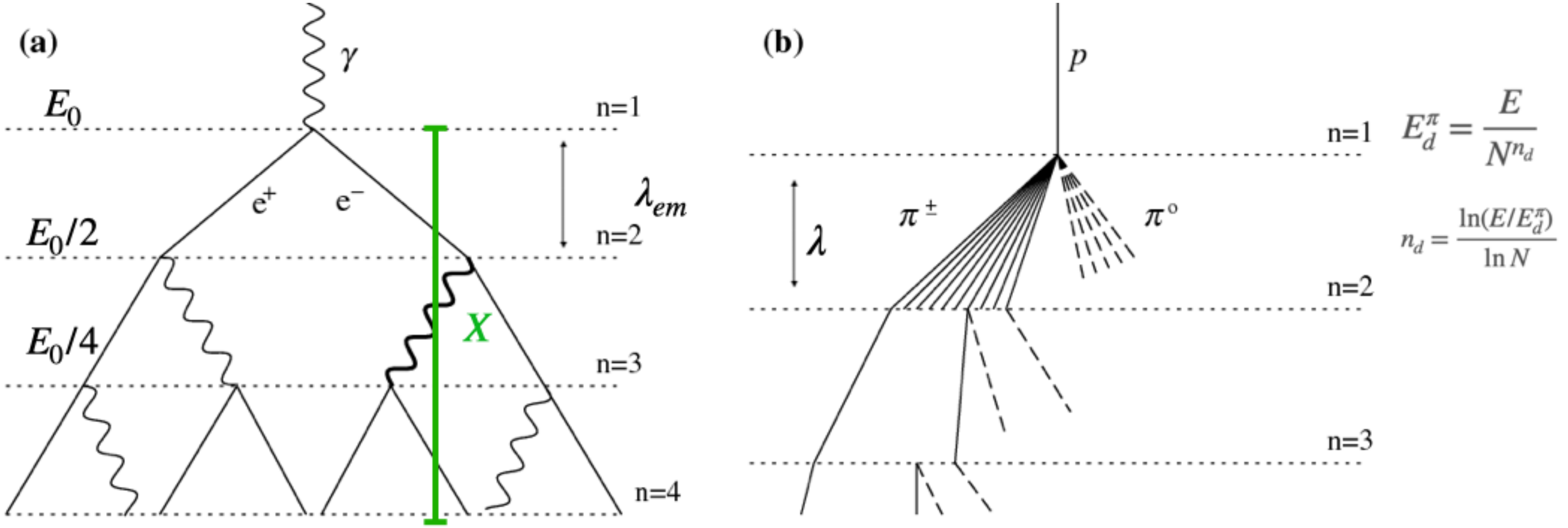


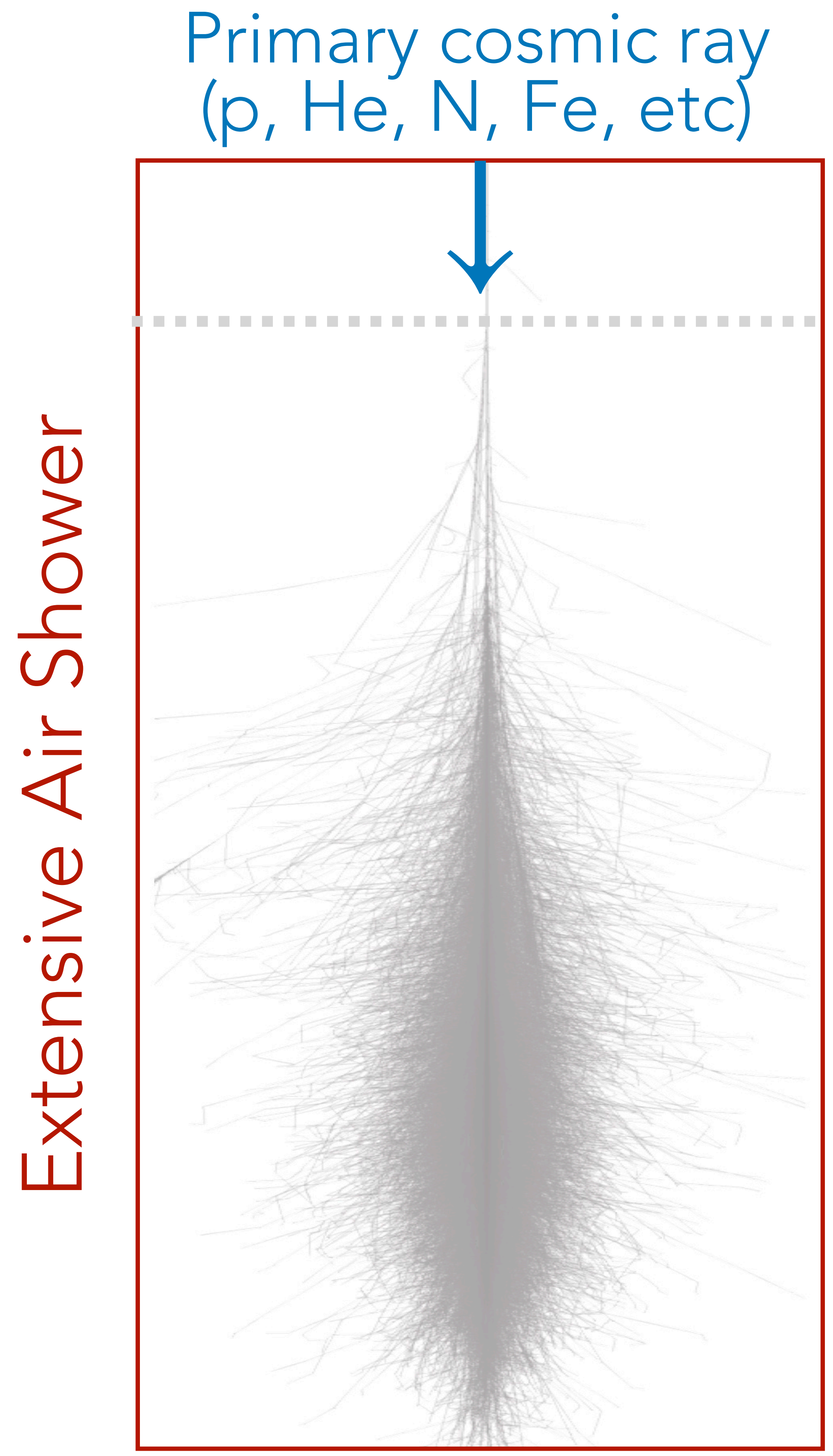
- Lateral Distribution
  > Particle density at ground wrt distance to shower axis
  > Muons, electrons or mixture



$$E_{\mathrm{had}} = \left(\frac{2}{3}\right)^n E_0$$

$$E_{\mathrm{EM}} = \left(1 - \left(\frac{2}{3}\right)^n\right) E_0$$





At a depth X the number of particles in the shower is $N(X) = 2^n = 2^{\frac{X}{\lambda}}$.

Key definitions: $N_{max} = E_0/E_c$ and $X_{max} = X_0 + \lambda_{em} log_2(E_0/E_c)$

$$N_\mu = \frac{E_0}{\xi_c} \prod_{i=1}^{c} \alpha_{\text{had},i}$$

A nucleus with mass A and energy E_0 is considered as A independent nucleons with energy E_0/A each.

The superposition of the individual nucleon showers yields:

1) $X_{max} \propto \lambda \dfrac{E_0}{AE_c}$

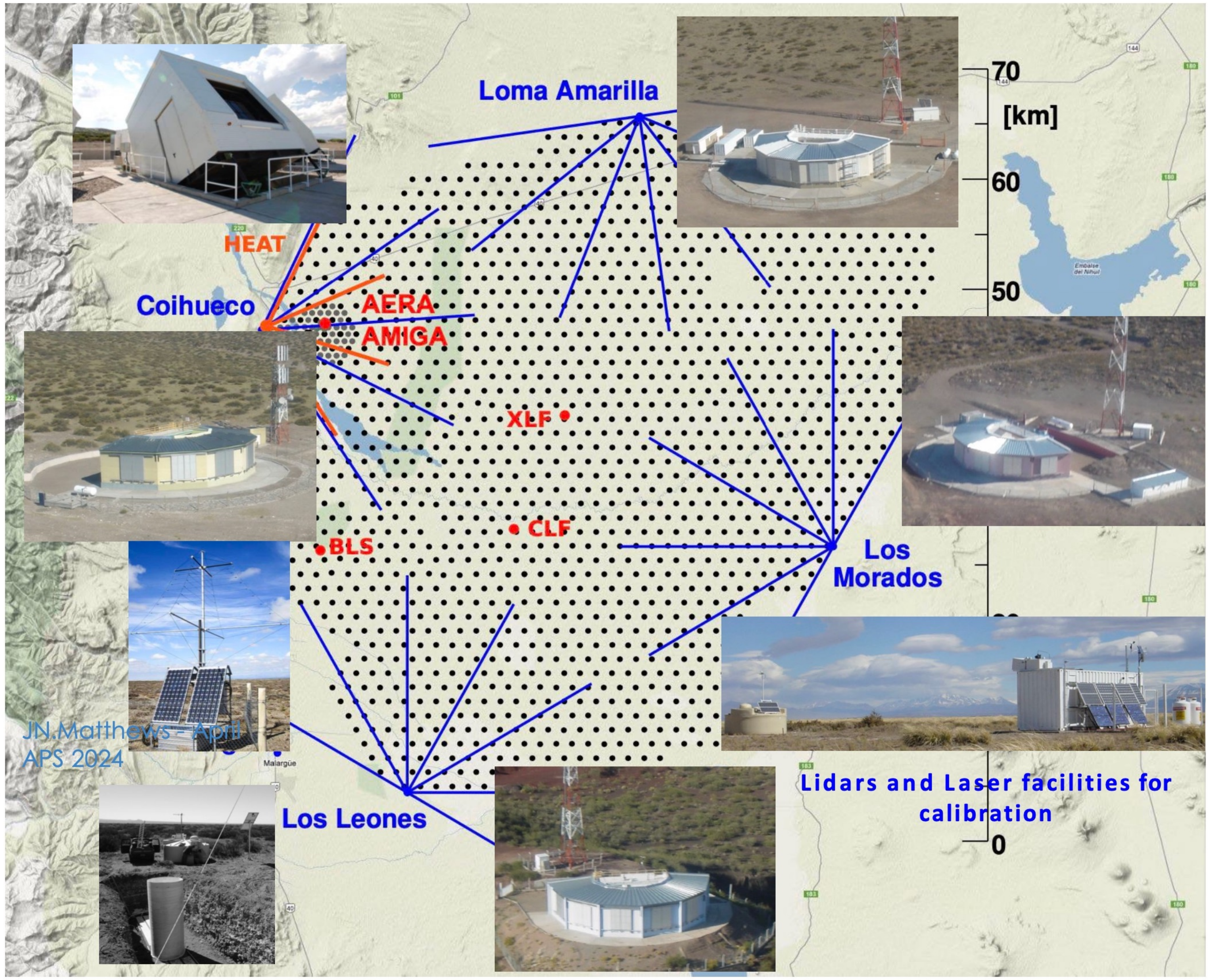
2) $N_\mu^A(X_{\max}) = A\left(\dfrac{E_0/A}{E_{dec}}\right)^{\alpha} = A^{1-\alpha} N_\mu^p(X_{\max})$

Showers with the same primary energy develop differently

The muon fluctuation: $\dfrac{N_\mu}{\langle N_\mu \rangle} = \alpha_1 .. \longrightarrow \dfrac{N_\mu}{\langle N_\mu \rangle} = \dfrac{\alpha_1}{A} ..$

The Heitler-Matthews model

A description of the average development of a cosmic-ray air shower



Observatory in the Southern Hemisphere:
- Malargüe, Mendoza Argentina

WCD Surface Detectors (SD) ➜ $12 m^3$ water
- 1600 stations @ 1.5 km ➜ 3000 km^2 — $E > 10^{18.5}$ eV
- 61 stations @ 750 m ➜ 23.5 km^2 — $E > 10^{17.5}$ eV

Fluorescence Detector (FD) ➜ 440pmts, $13 m^2$ mirror
- 24 telescopes in 4 Sites FoV 0°- 30° — $E > 10^{17.7}$ eV
- HEAT ➜ 3 telescopes , FoV 30°- 60° — $E > 10^{17}$ eV

Auger Engineering Radio Array (AERA)
- 153 antennae ➜ 17 km^2 array — $E > 10^{17.5}$ eV

Underground Muon Detector (UMD)
- 61(19) in 750(433)m array — $10^{16.5} < E < 10^{19}$ eV

Auger Phase I
- Data taken between 2004 and 2021

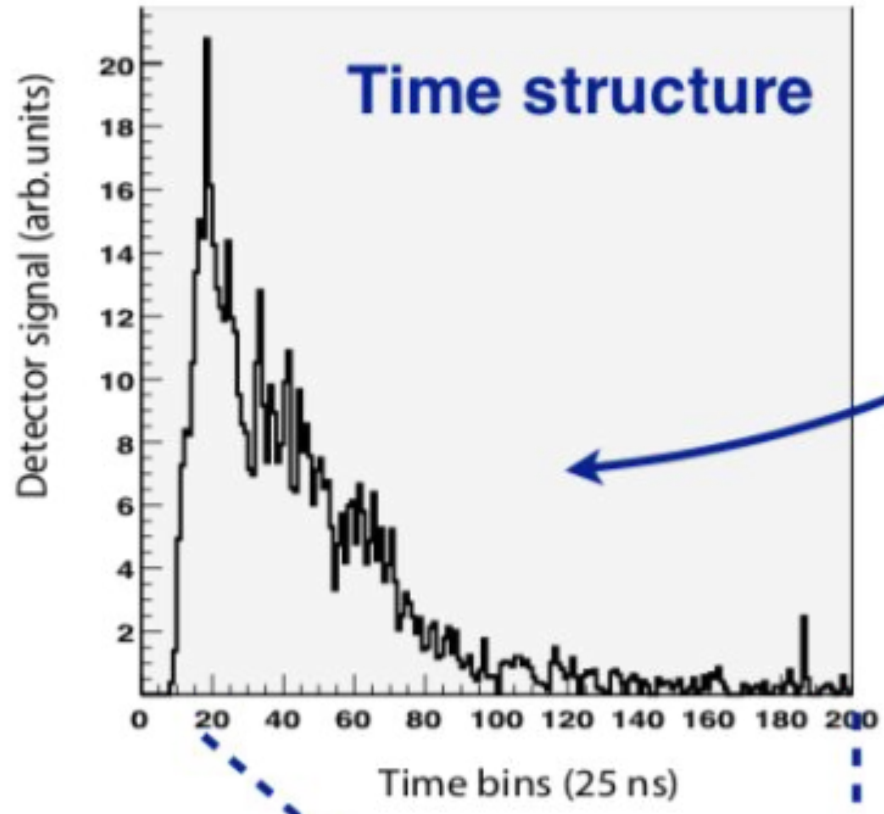
Auger Phase II (with AugerPrime)
- Data taken between 2022 and 2035

Pierre Auger Observatory
Province Mendoza, Argentina

The Pierre Auger Observatory

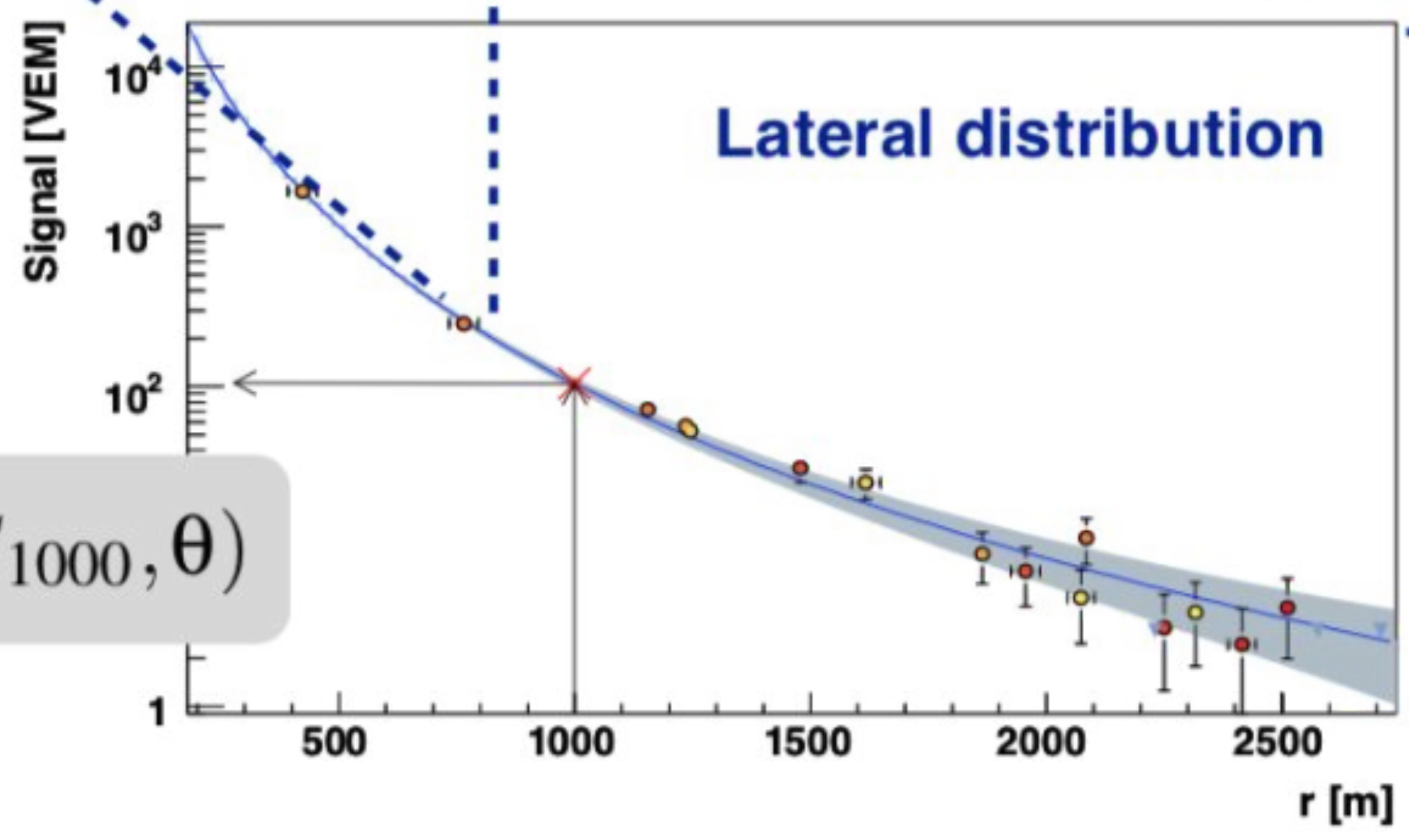
The Hybrid detection method

Sensitivity to mass and type of primary

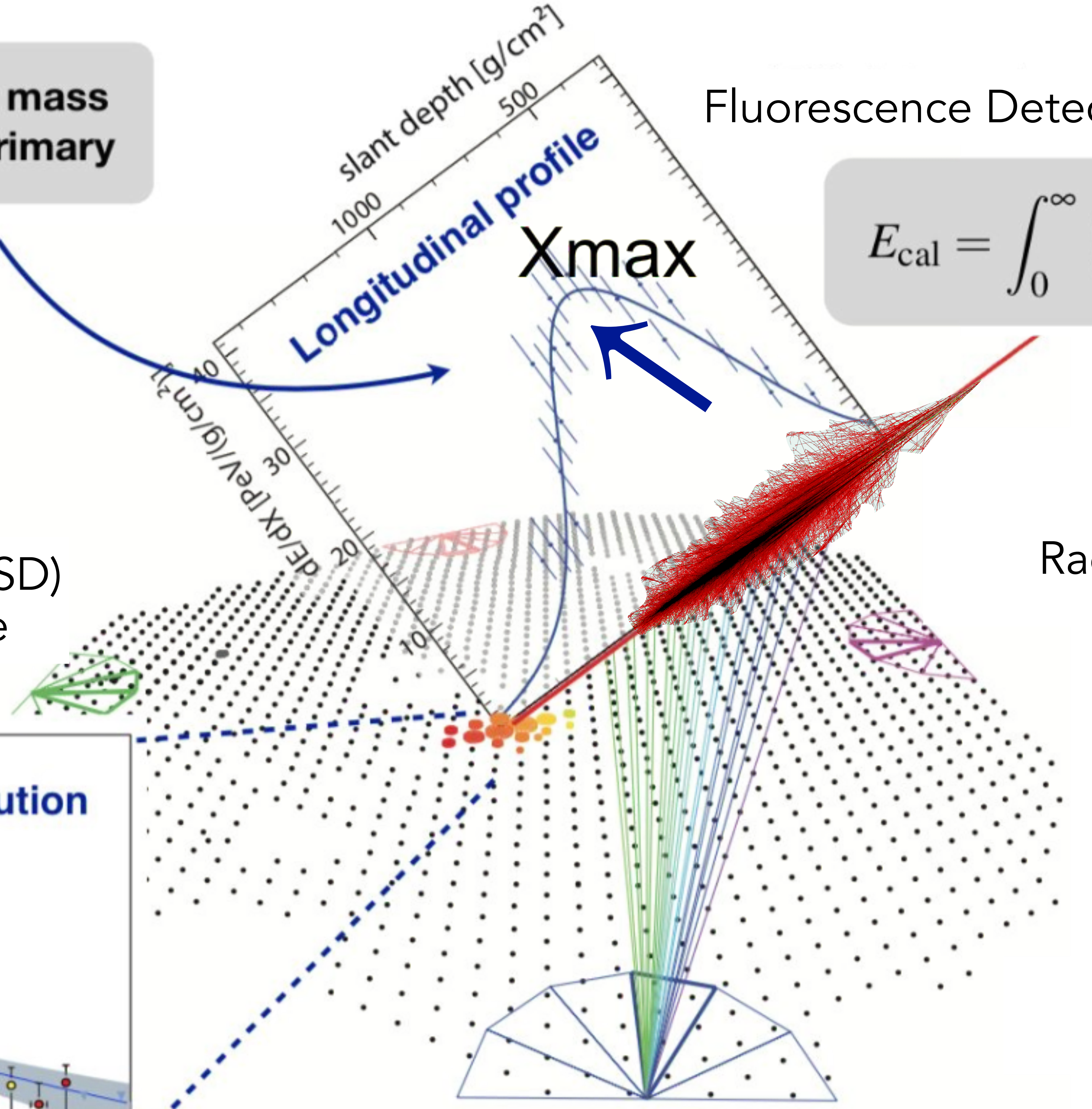


Surface Detector (SD) 100% duty cycle

The SDs measure photons and charged particles at ground level



$$E_{\rm rec} = f(S_{1000}, \theta)$$



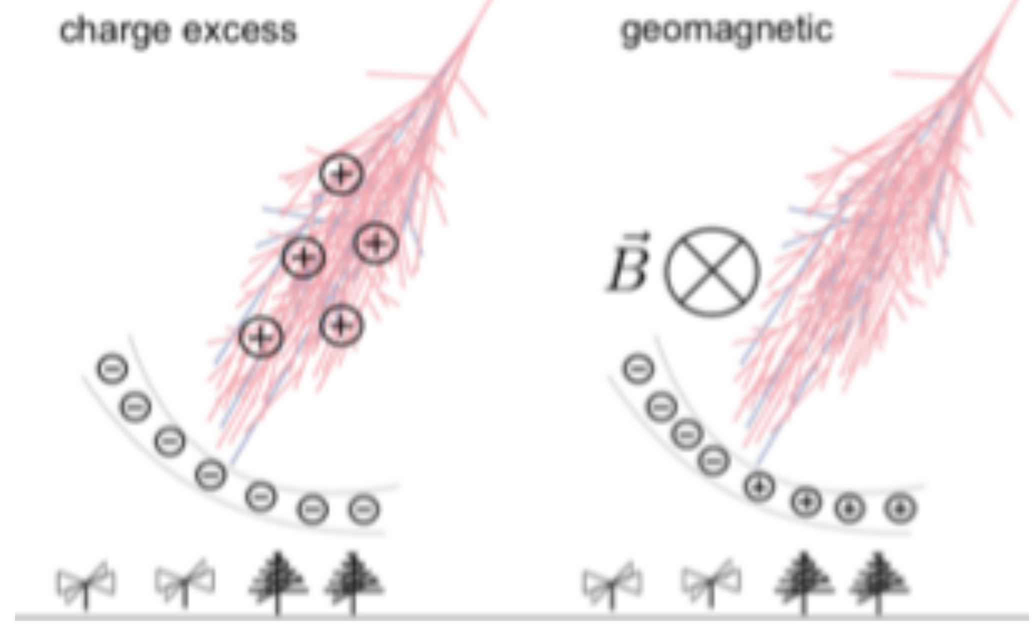
Example: event observed with Auger Observatory

Fluorescence Detector (FD) 15% duty cycle

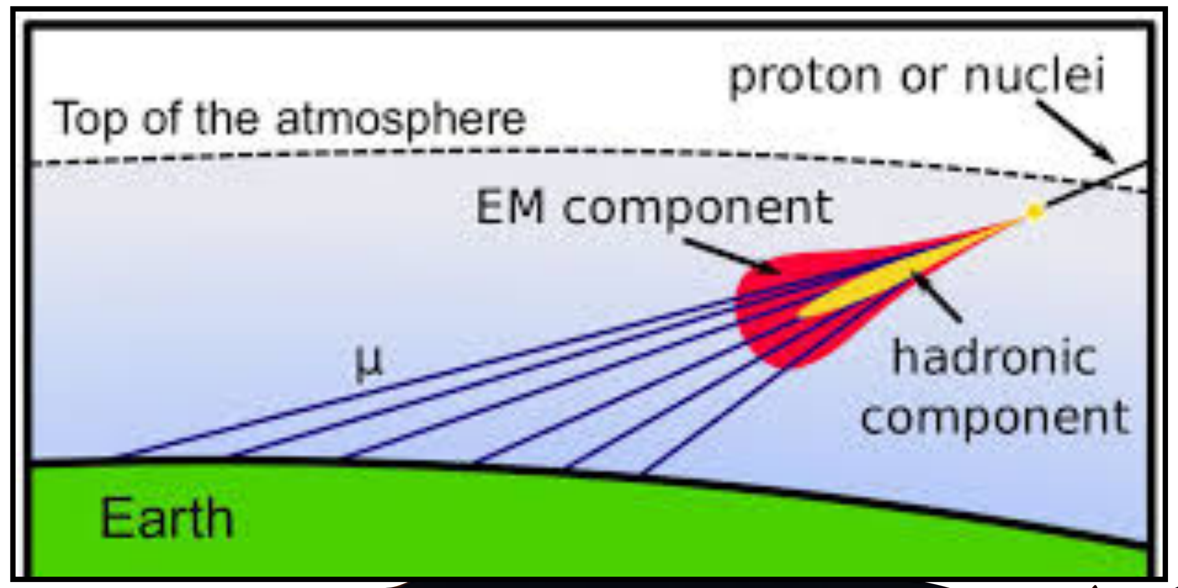
$$E_{\rm cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\rm obs} dX$$

It observes the longitudinal development of air showers in the atmosphere

Radio detector (RD) 100% duty cycle



It complements this setup studying radio emission from air showers



1. From Heitler–Matthews

Predicts the average muon number for a primary energy E_0

$$\langle N_\mu \rangle = f(E_0, \text{primary mass})$$

2. Showers fluctuate

For the same E_0, different events give different N_μ

$$N_\mu = \langle N_\mu \rangle + \delta N_\mu$$

3. What we measure

Distribution of N_μ for many events

Characterized by:

- mean $\langle N_\mu \rangle$
- standard deviation $\sigma(N_\mu)$
- relative fluctuation (width)

$$\frac{\sigma(N_\mu)}{\langle N_\mu \rangle}$$

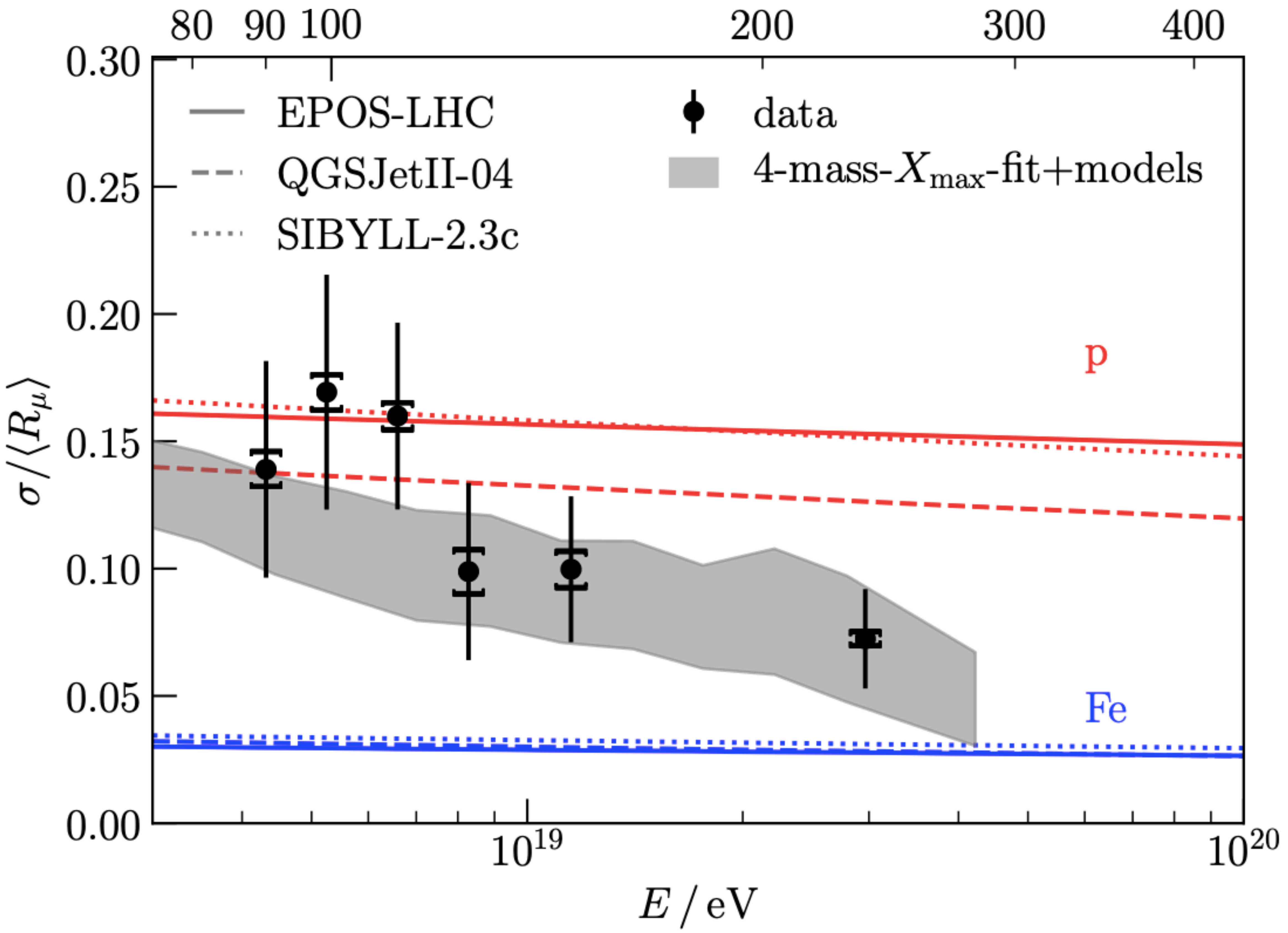
$$\left(\frac{\sigma_{N_\mu}}{\langle N_\mu \rangle}\right)^2 = \sum_{i=1}^{c} \left(\frac{\sigma(\alpha_{\text{had},i})}{\langle \alpha_{\text{had},i} \rangle}\right)^2$$

4. Why fluctuations are special

They are driven **MAINLY** by the **FIRST INTERACTION**

- After the first interaction, the details of the cascade play a smaller role
- Therefore, fluctuations are more stable and robust
- Less sensitive to hadronic interaction models and their uncertainties

$$\langle N_\mu(E) \rangle = m^g = CE^\beta \rightarrow \sigma(m_i) = \frac{\sigma(m)}{\sqrt{N_{i-1}}}$$



In the standard case: $\frac{N_\mu}{\langle N_\mu \rangle} = \alpha_1 \ldots$

$\rightarrow$ for primary particle with mass A: $\frac{N_\mu}{\langle N_\mu \rangle} = \frac{\alpha_1}{A} \ldots$

Proton (A=1): larger fluctuations

Heavy nucleus (large A): smaller fluctuations

Muon number fluctuations carry information on the **mass composition** of cosmic rays

Muon Relative Fluctuations

Ratio of the fluctuations to the average number of muons

Lorentz Invariance Violation effects and signatures can be observed changing the kinematics and energy thresholds of interactions

Modified dispersion relation

$$E_i^2 - p_i^2 = m_i^2 + f(\overrightarrow{p_i}, M_{\mathrm{Pl}}; \eta_i) \longrightarrow E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \eta_i^{(n)} \frac{p_i^{n+2}}{M_{\mathrm{Pl}}^n}$$

Where $\eta^{(n)}$ is a **dimensionless** constant and is called LIV parameter.
It depends on the secondary and the primary particle.

Pierre Auger Collaboration, *JCAP* **01 (2022) 023**, arXiv:2112.06773.

Pierre Auger Collaboration, **Phys. Rev. Lett. (2026), in press**; arXiv:2602.14720.

C. Trimarelli for the Pierre Auger Collaboration, EPJ Web Conf.283 (2023) 05003

first order n=1:

$$E_i^2 - p_i^2 = m_i^2 + \eta_i^{(1)} \frac{p_i^3}{M_{Pl}}$$

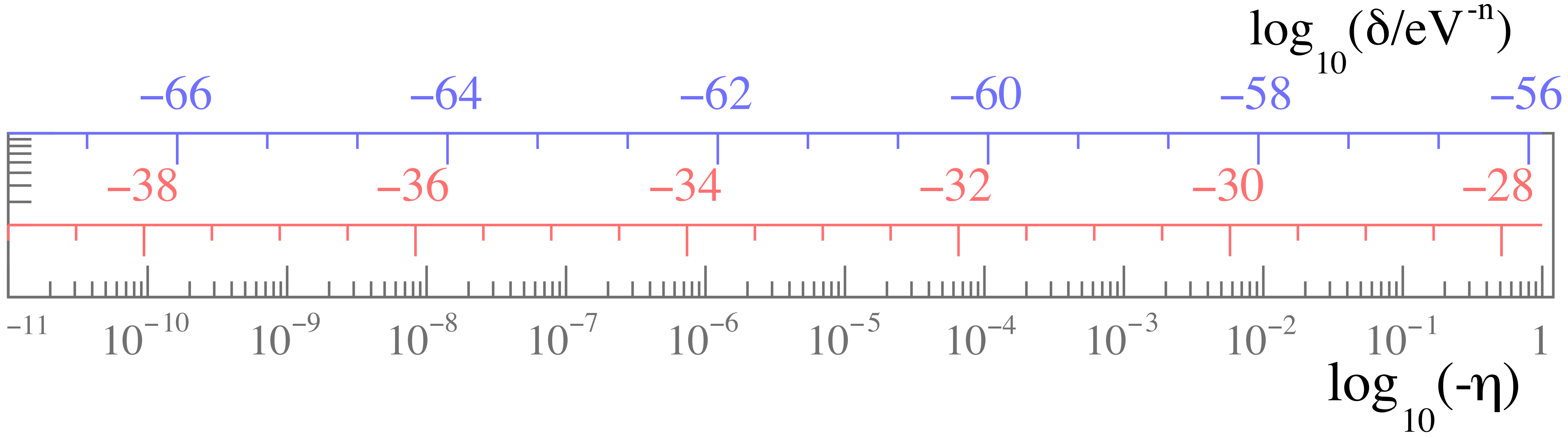
Nuclei:

$$E_{A,Z}^2 - p_{A,Z}^2 = m_{A,Z}^2 + \eta_{A,Z}^{(1)} \frac{p_{A,Z}^3}{M_{Pl}}$$

$$\eta_A = \eta_p / A^2$$

Dimensional

$$\boxed{\delta^{(n)} = \frac{\eta^{(n)}}{M_{\mathrm{Pl}}^n}}$$



$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} p_i^{n+2}$$

$$\delta_A^{(n)} = \delta_p^{(n)} / A^n$$

LIV framework

Lorentz Invariance Violation effects and signatures can be observed changing the kinematics and energy thresholds of interactions

Modified dispersion relation

$$E_i^2 - p_i^2 = m_i^2 + f(\overrightarrow{p_i}, M_{\mathrm{Pl}}; \eta_i) \longrightarrow E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \eta_i^{(n)} \frac{p_i^{n+2}}{M_{\mathrm{Pl}}^n}$$

We consider the right-hand side of the modified dispersion relation as a new mass:

$$m_{\mathrm{LIV}}^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\mathrm{Pl}}^n}$$

We can define the Lorentz factor as: $\gamma_{\mathrm{LIV}} = \dfrac{E}{m_{\mathrm{LIV}}}$ → Inserted in CONEX to build LIV shower libraries

The lifetime τ of particles becomes: $\tau = \gamma_{\mathrm{LIV}} \tau_0$

Superluminal and subliminal LIV can be tested!
$\eta^{(n)}$ assumes both positive and negative values!

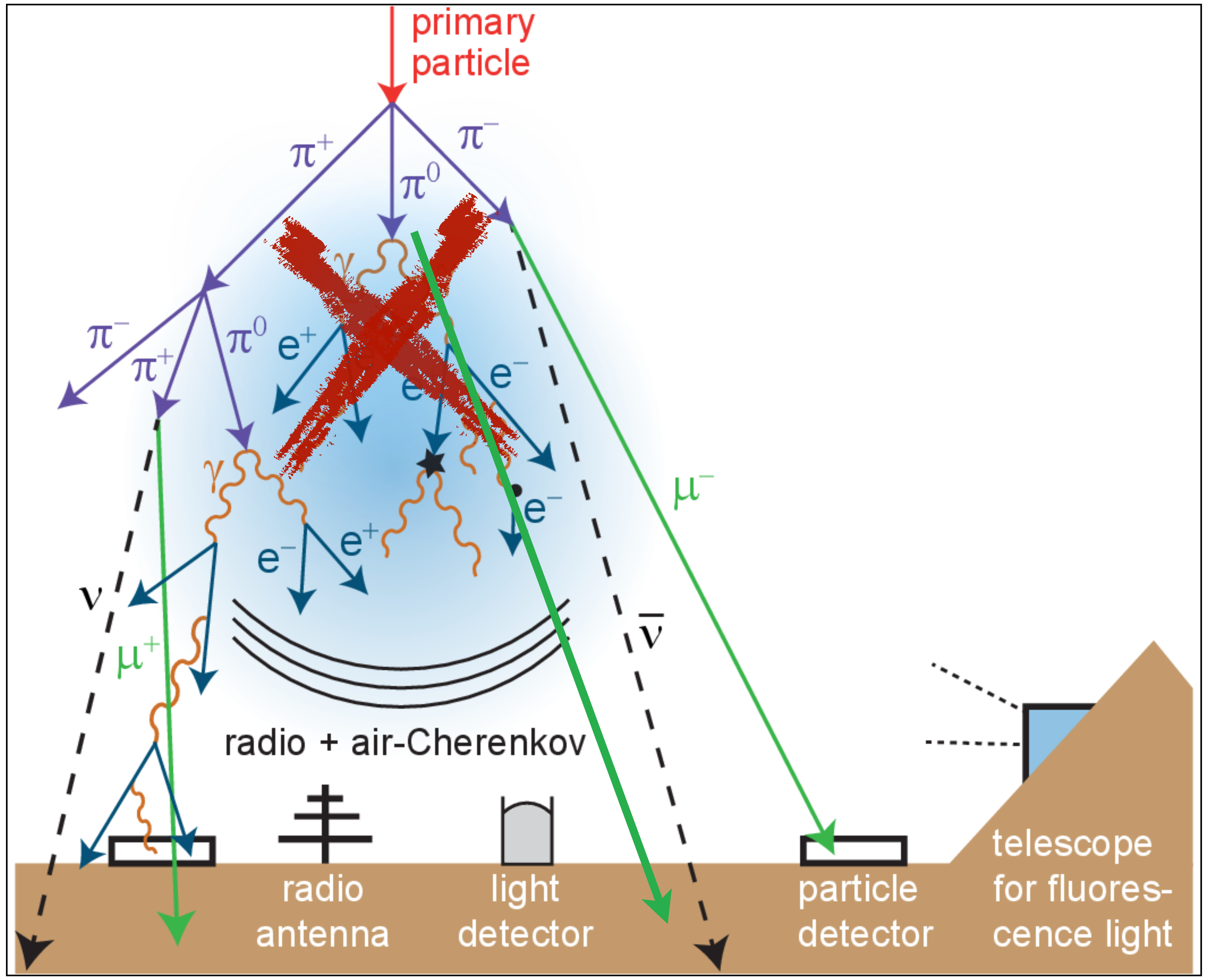
LIV framework

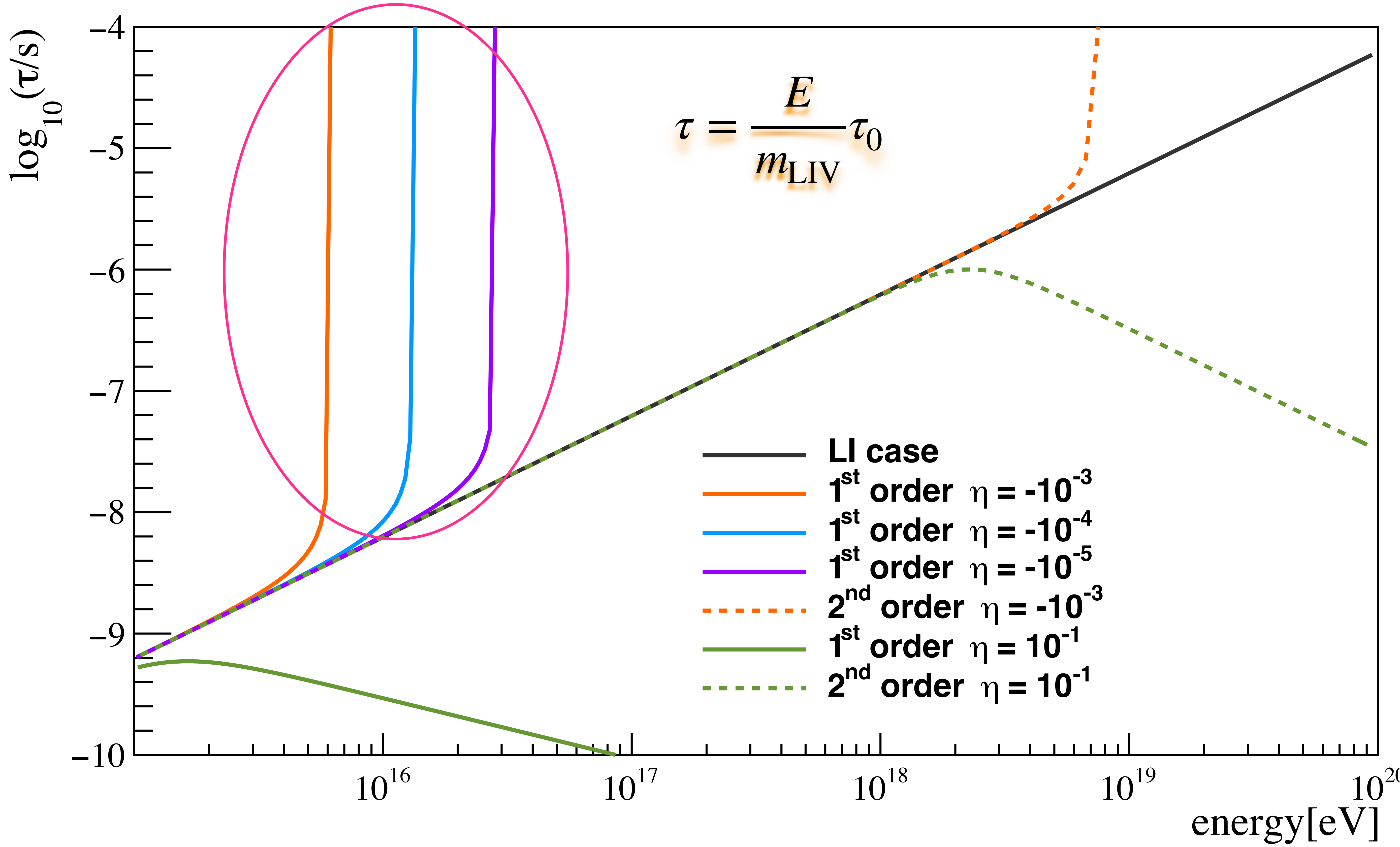
π^0 **Decay:** $\pi^0 \to \gamma\gamma$ $\boxed{\tau_0 = 8.4 \cdot 10^{-17}\text{s}}$

Subluminal affects more!

If η_π assumes negative values!

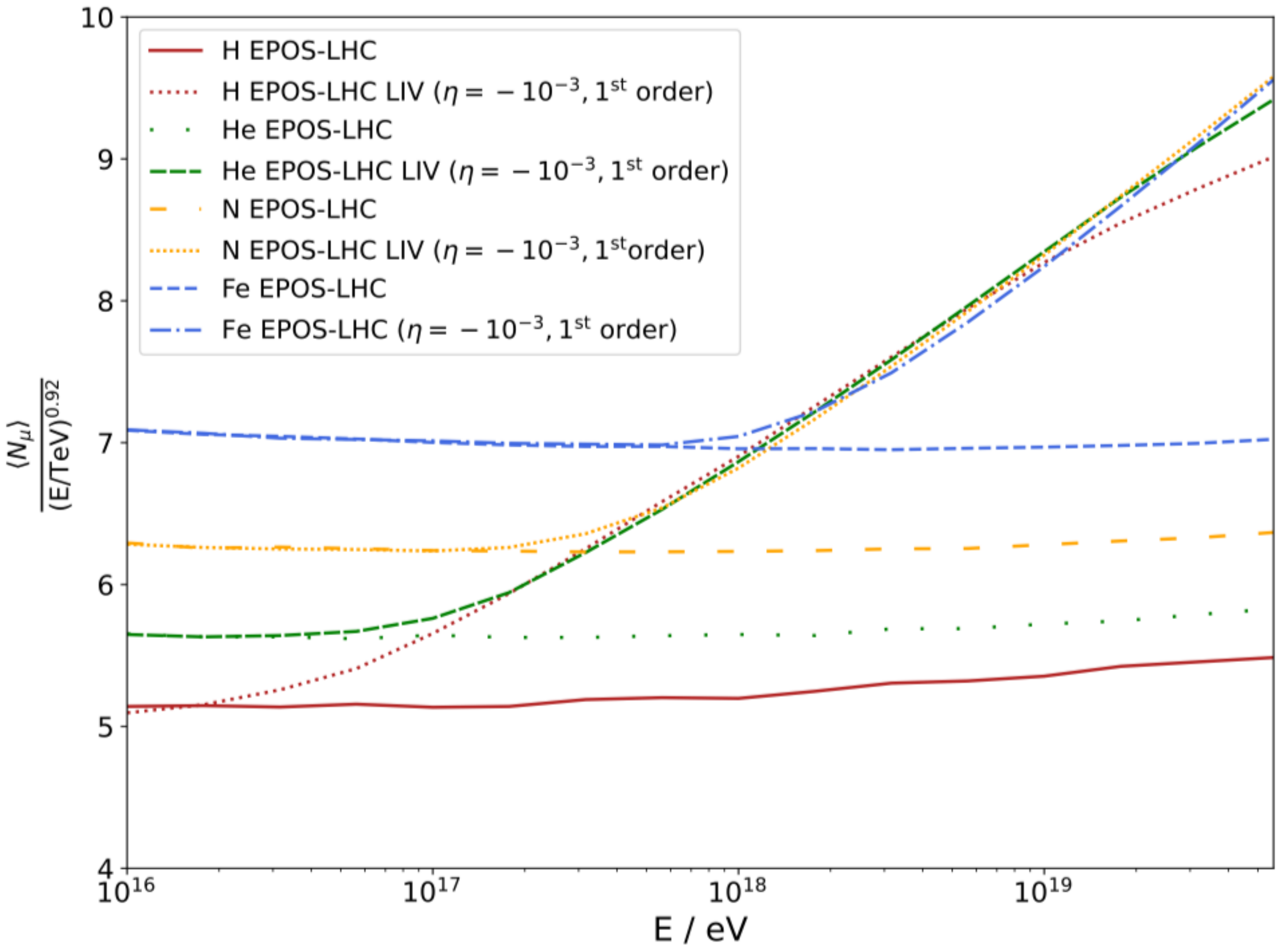
The decay is forbidden if: $m_\pi^2 + \eta_\pi^{(n)} \frac{p_\pi^{n+2}}{M_{Pl}^n} < 0.$





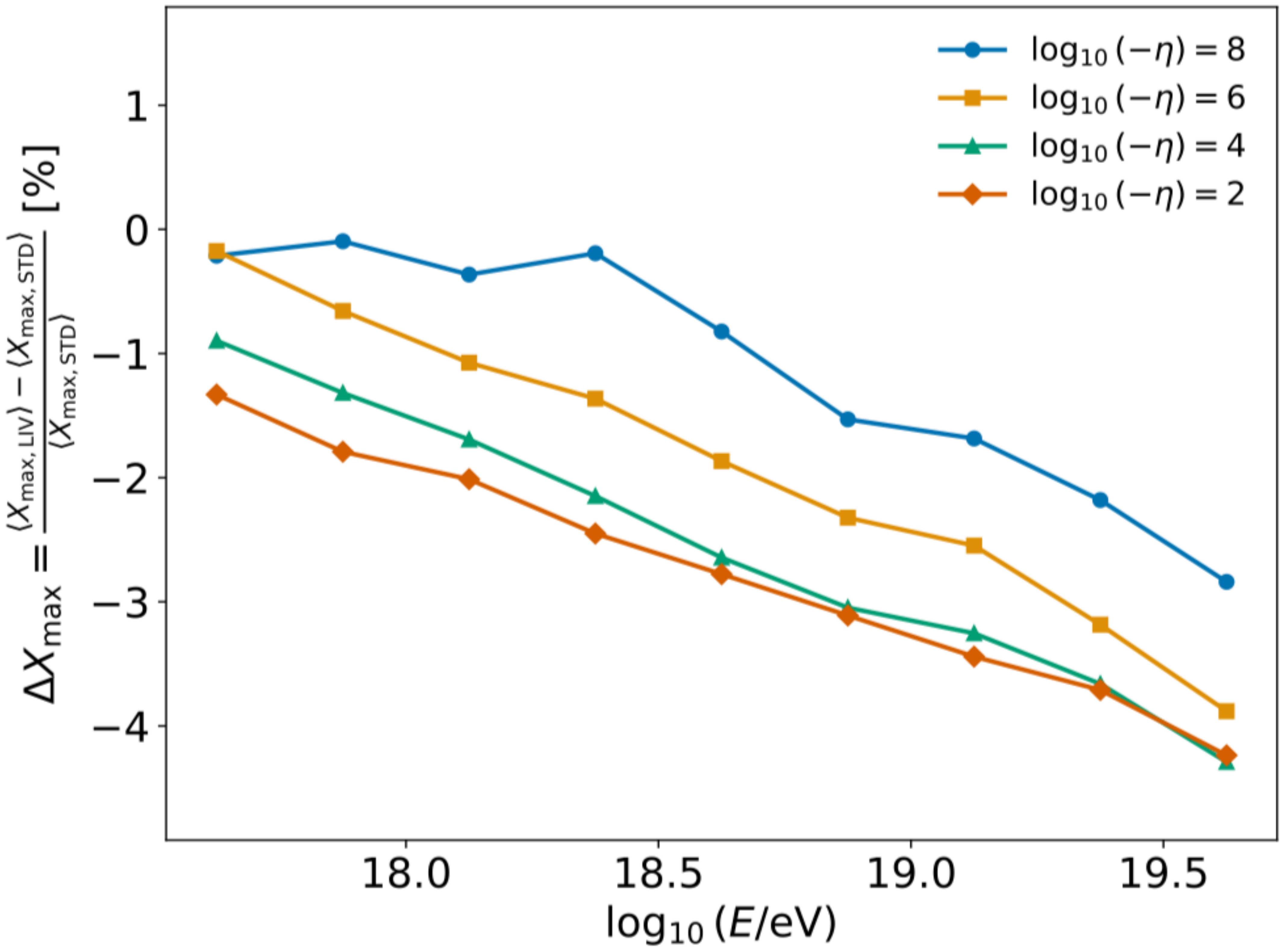
Neutral pion decay

Average number of muons at ground increases!



Under LIV, the neutral pion behaves like a charged pion, feeding the hadronic cascade.

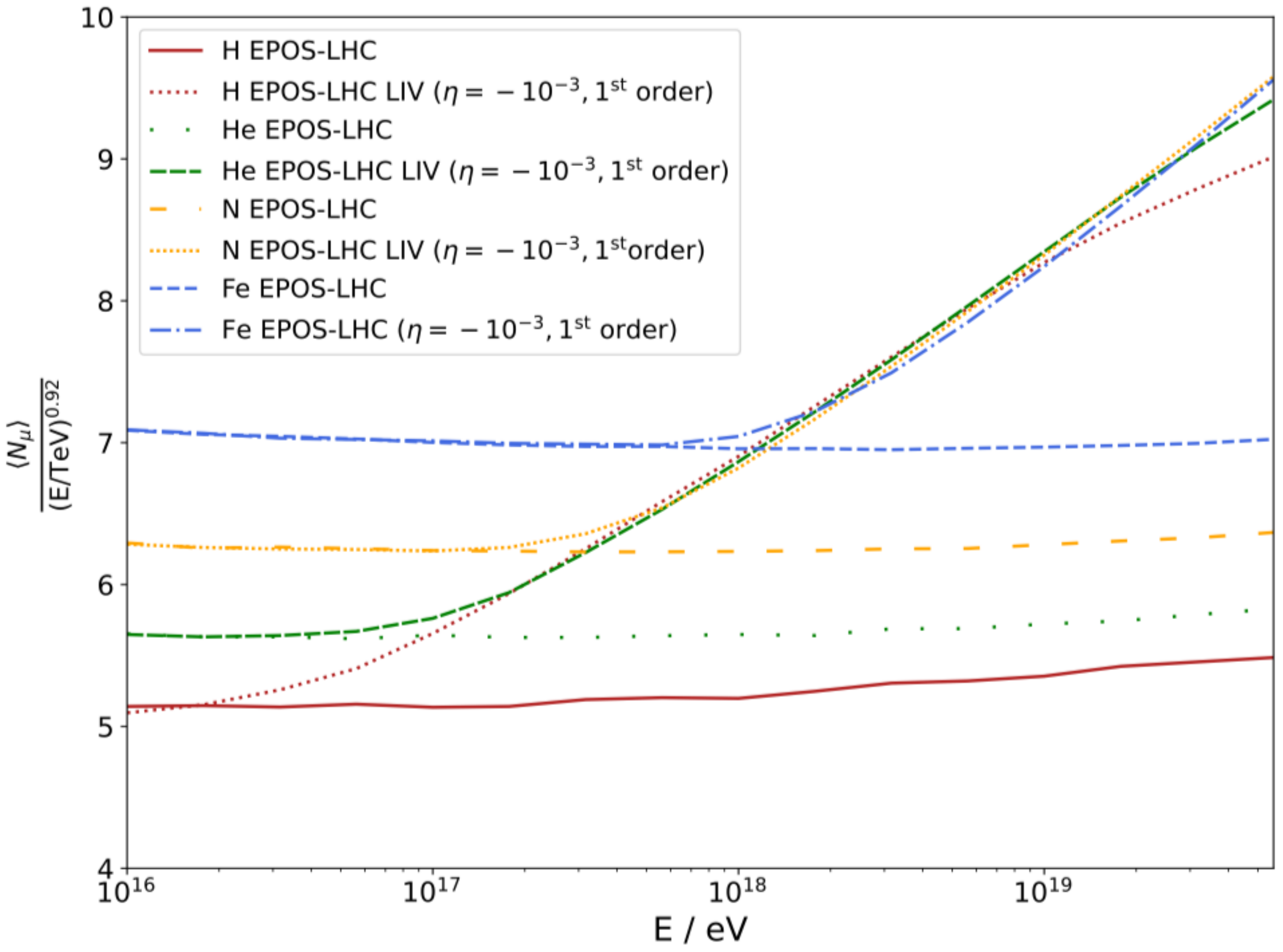
Decrease in the electromagnetic component



Modified CONEX shower library

The LIV effects on some shower observables

Average number of muons at ground increases!



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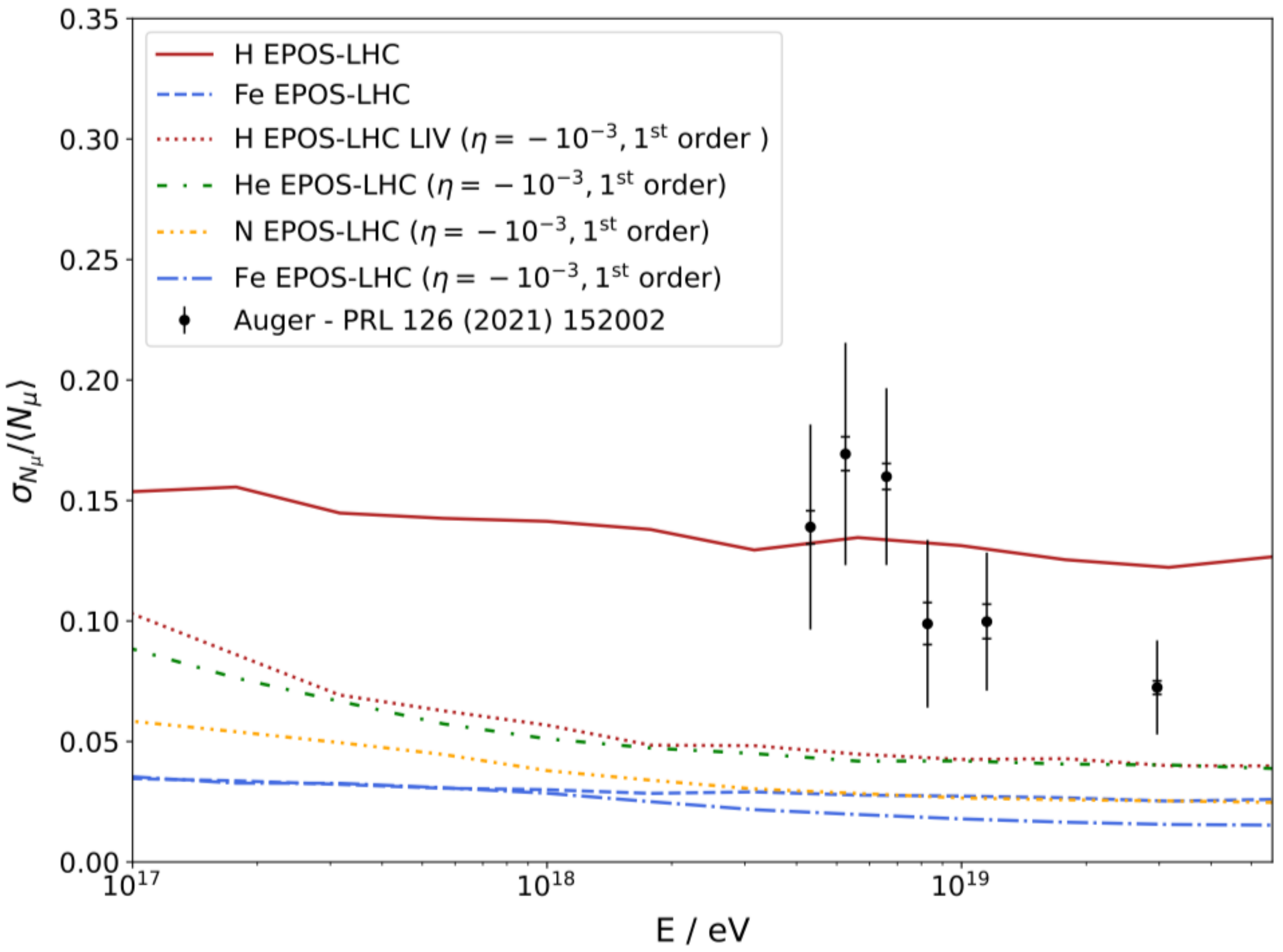
Reduction of Muon Fluctuations



Modified CONEX shower library

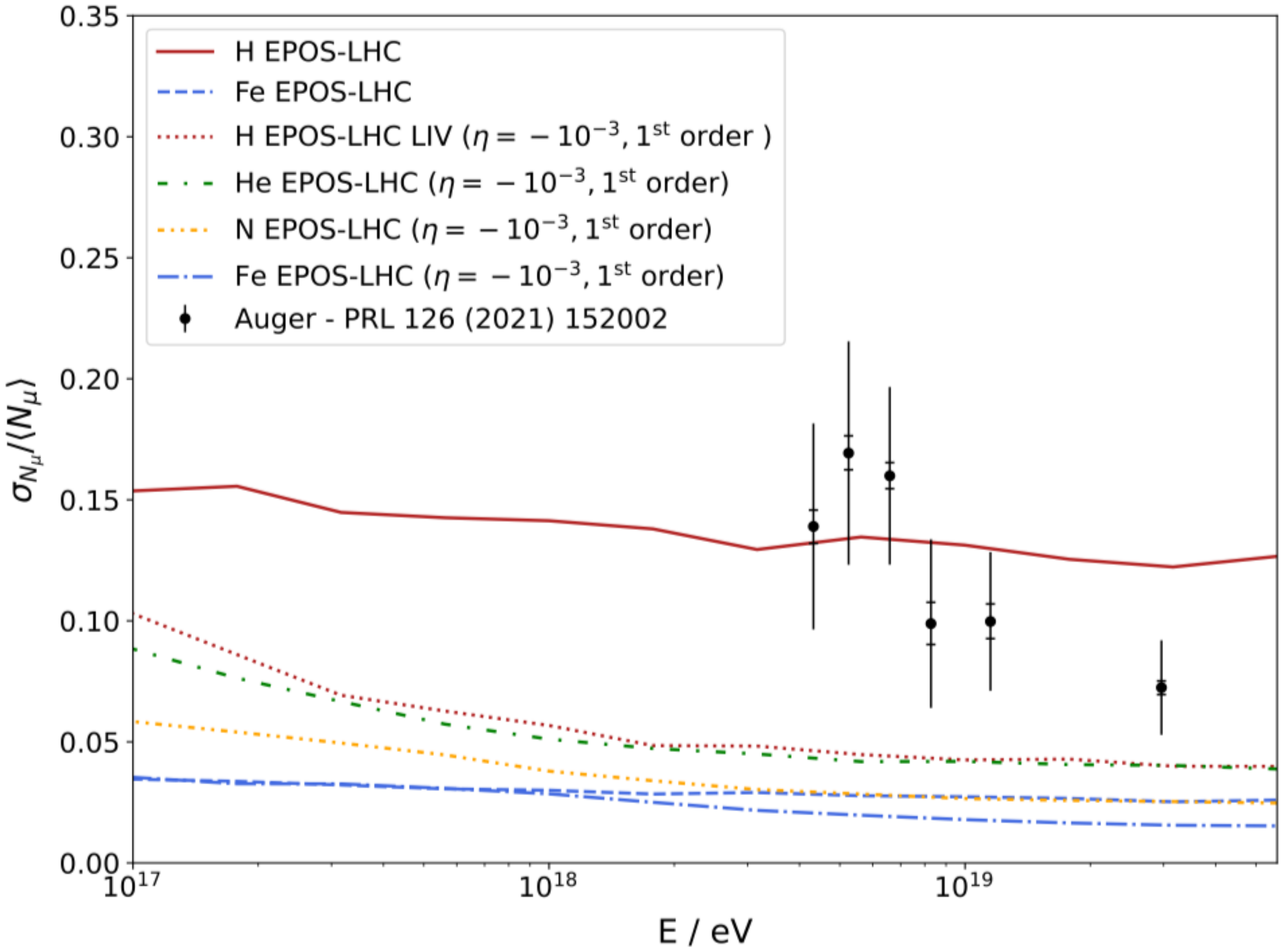
The LIV effects on some shower observables

Reduction of Muon Fluctuations

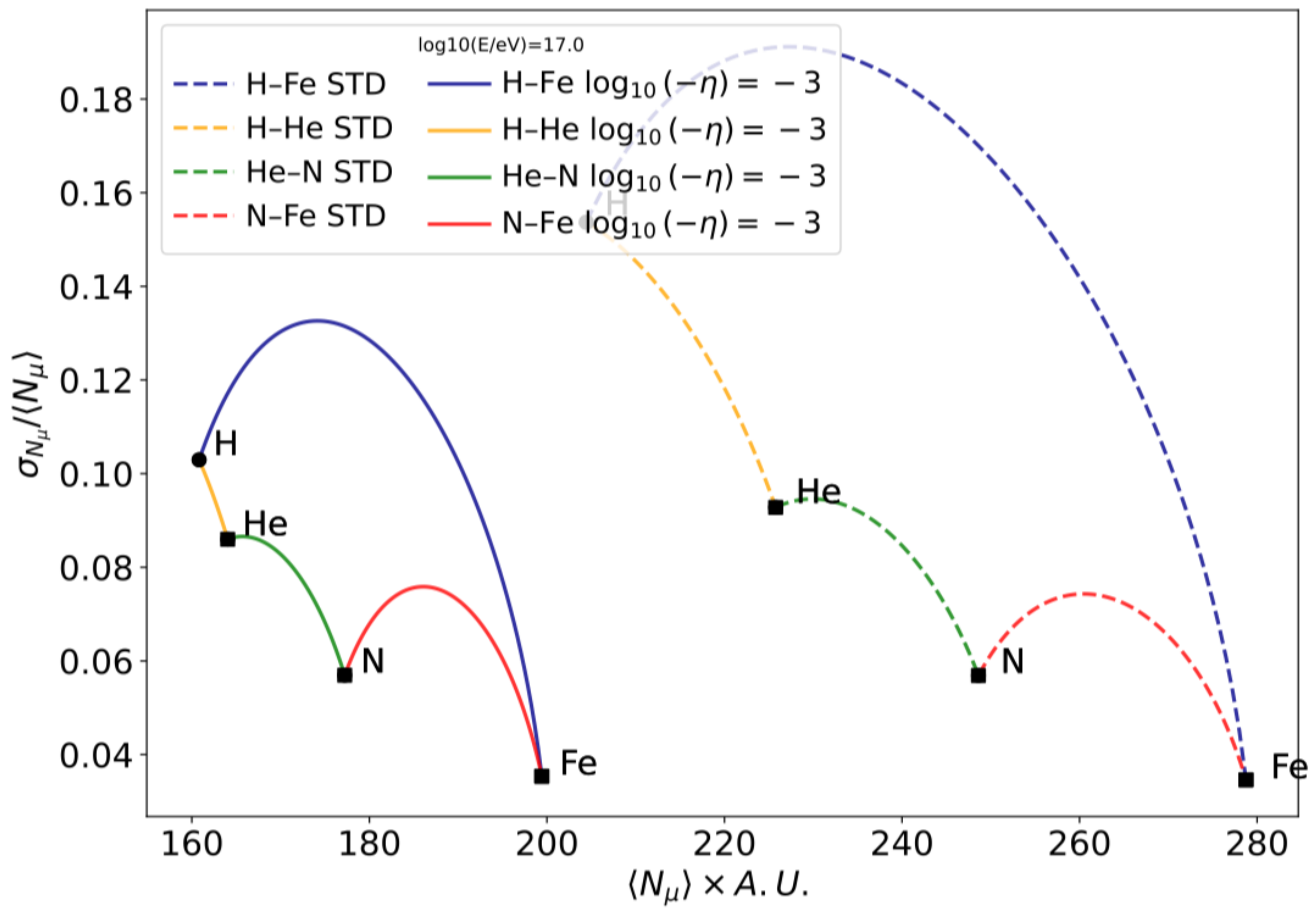
Considering the dependence of the decrease of the relative fluctuations on the different LIV strengths, a new bound for the LIV parameter can be obtained

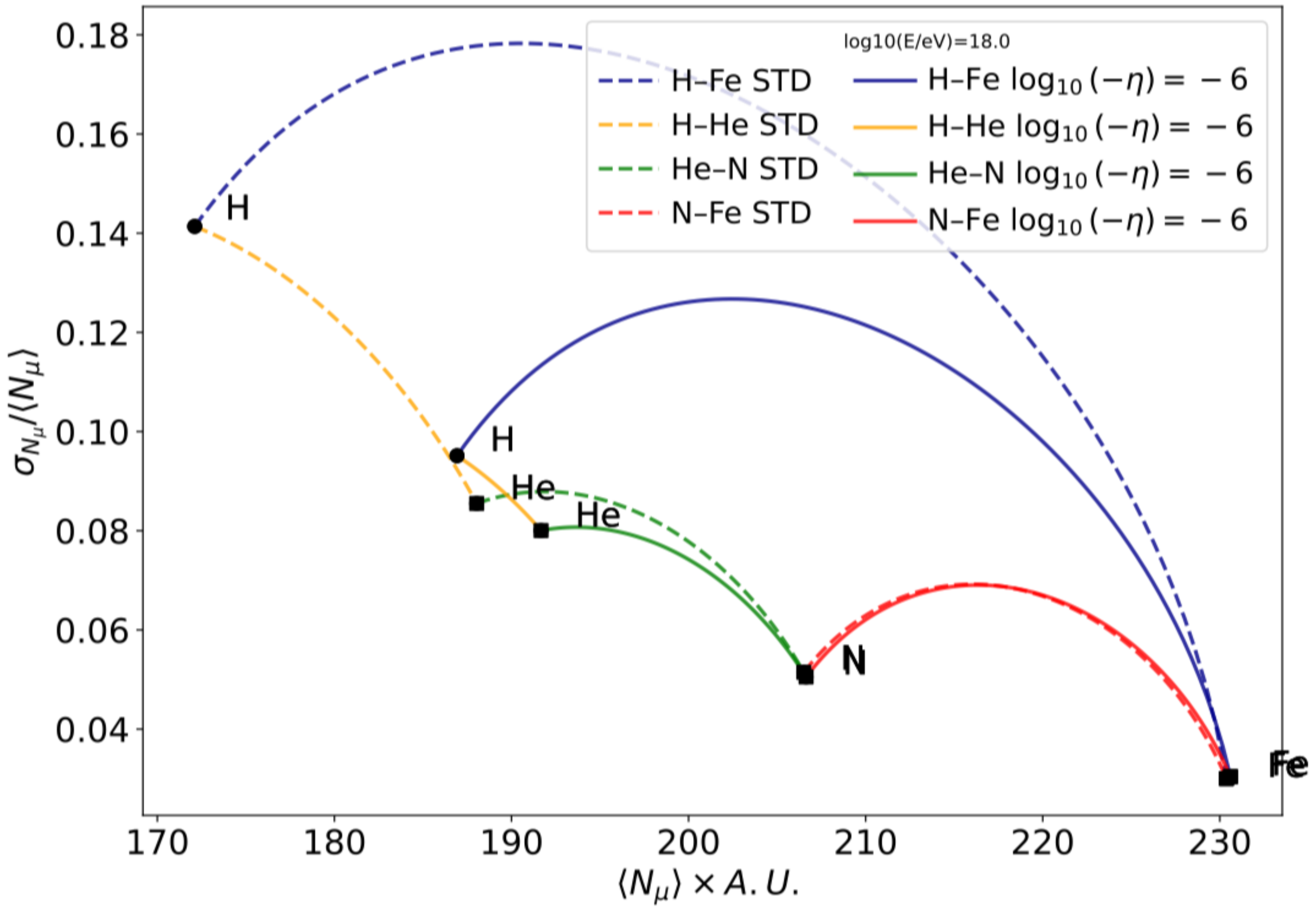
Which combination of primaries gives the most conservative LIV model?

Pierre Auger Collaboration,
Phys. Rev. D, 114 (2026) 043016,
arXiv:2605.12598.



Composition Maximizing Relative Fluctuations

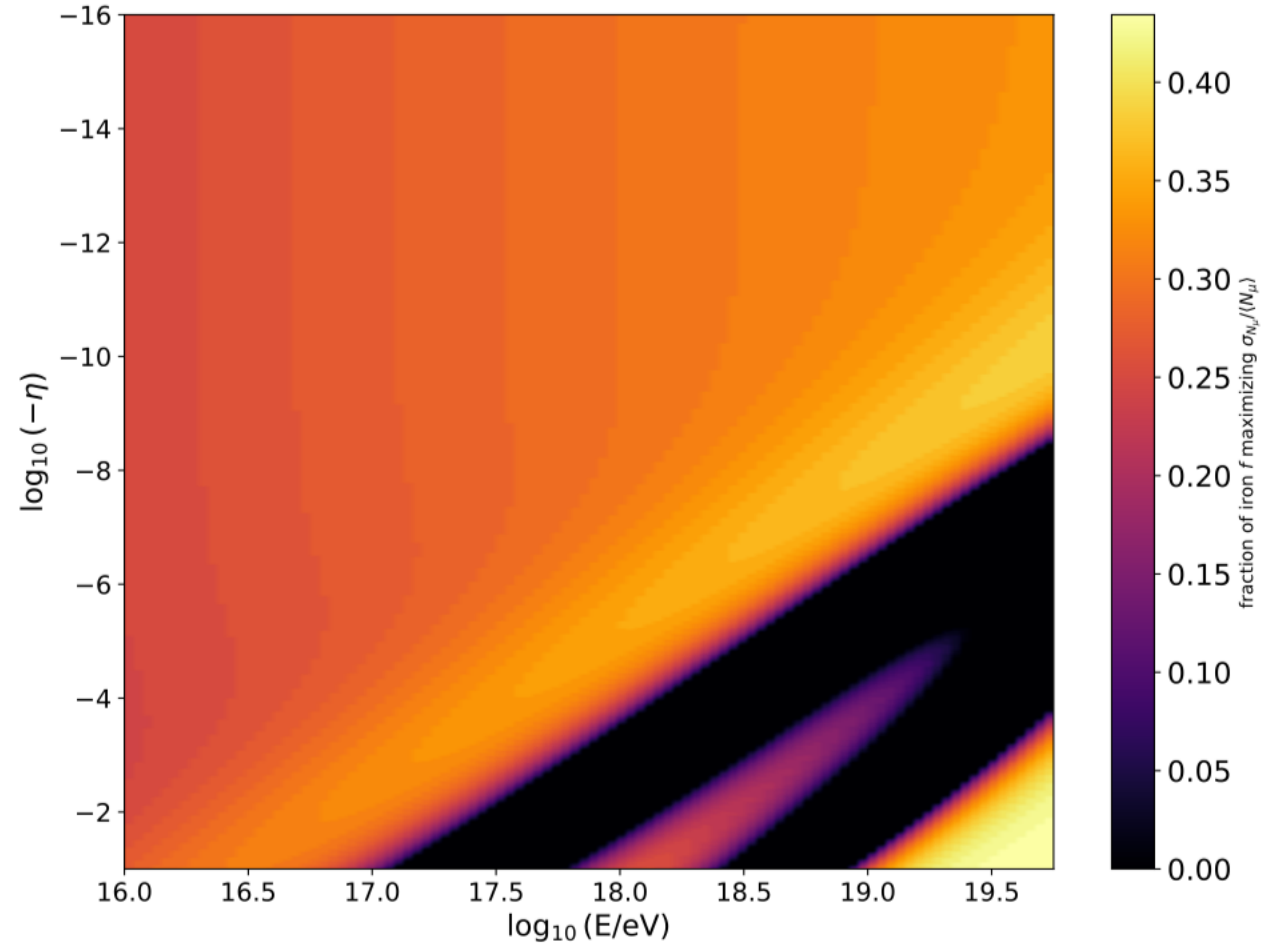




1. **Effects of the different composition scenarios:** The mixture of the two components p and Fe gives the maximum value of relative fluctuations.

$$\langle N_\mu \rangle_{\mathrm{mix}}(f;\eta) = (1-f)\langle N_\mu \rangle_{\mathrm{p}} + f\langle N_\mu \rangle_{\mathrm{Fe}}$$

$$\sigma^2_{N_\mu,\mathrm{mix}}(f;\eta) = (1-f)\sigma^2_{N_\mu,\mathrm{p}} + f\sigma^2_{N_\mu,\mathrm{Fe}} + f(1-f)(\langle N_\mu \rangle_{\mathrm{p}} - \langle N_\mu \rangle_{\mathrm{Fe}})^2$$



2. Define $\dfrac{\sigma_\mu}{\langle N_\mu \rangle} = \dfrac{\sqrt{\sigma^2(N_\mu)_{\mathrm{mix}}(f;\eta)}}{\langle N_\mu \rangle_{\mathrm{mix}}(f;\eta)}$

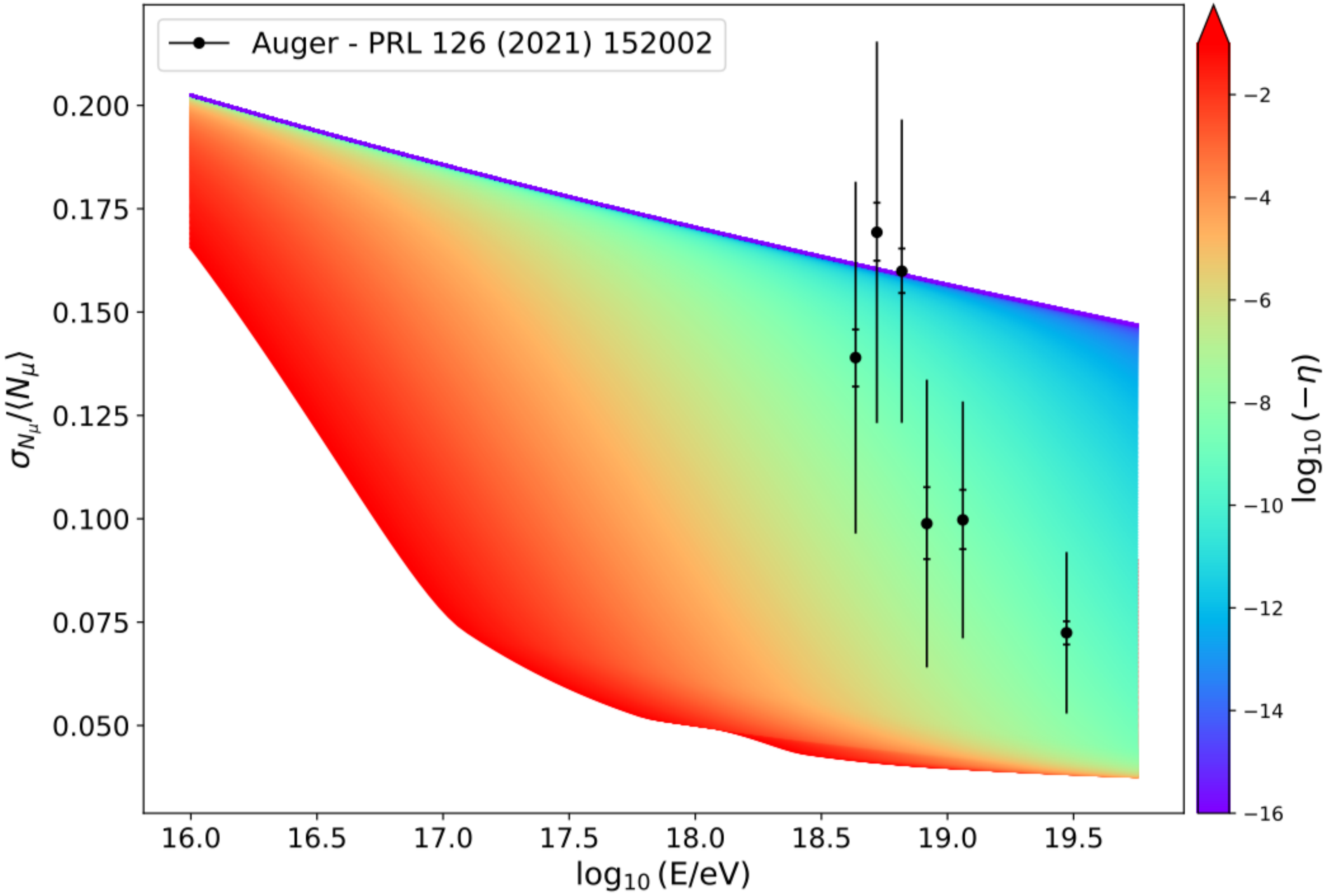
   $1-\alpha$ is the fraction of proton
   α is the fraction of iron

3. Parametrize as **function of η and energy** $\langle N_\mu \rangle_p$, $\langle N_\mu \rangle_{Fe}$, $\sigma(N_\mu)_p$ and $\sigma(N_\mu)_{Fe}$

Composition Maximizing Relative Fluctuations

C.L.	90.5%	95.5%	99.9%
$\log_{10}(-\eta)$	$-7.03^{+0.21}_{-0.50}$	$-6.82^{+0.19}_{-0.54}$	$-5.90^{+0.13}_{-0.62}$

TABLE I. Lower limits on $\log_{10}(-\eta)$ derived from this analysis at different confidence levels (CL). The asymmetric uncertainties indicate the associated systematic unceraintу from the spread between the EPOS-LHC and QGSJetII-04 predictions.



New limits with the Most conservative LIV Relative Fluctuations

Conclusions and next steps in LIV in EAS

- **First Muon Fluctuation LIV Analysis**: Used extensive air shower data from the Pierre Auger Observatory for LIV
- **New Lorentz Invariance Violation (LIV) Constraints**: Placed novel limits on space-time symmetry modifications.
- **Strongest Hadronic Sector Bounds**: Formulated the most stringent restrictions to date on hadronic LIV.
- **Composition-Independent Results**: Derived robust limits that do not rely on primary mass composition assumptions

Recently a task force inside the COST Action CA23130 – Bridging high and low energies in search of quantum gravity (BridgeQG) has been started in order to put LIV studies in air shower development in Corsika 8.

BridgeQG

https://web.infn.it/BridgeQG/

CORSIKA 8

The aim of this task force is to have LIV implementation inside shower program avoiding private and local modification of CONEX/CORSIKA

Something similar has been already done for CRPropa where the LIV option exists.

Please contact me to join us! mailing list: livcorsika@lists.infn.it

caterina.trimarelli@gssi.it tomislavterzic@gmail.com


THANK YOU!

CONEX shower simulation

To construct the LIV model and SR model for shower development and to have all the observables from the shower development that we can use to constrain LIV we run CONEX! Shower simulation tool putting the modified dispersion relation!

Lorentz Invariant case

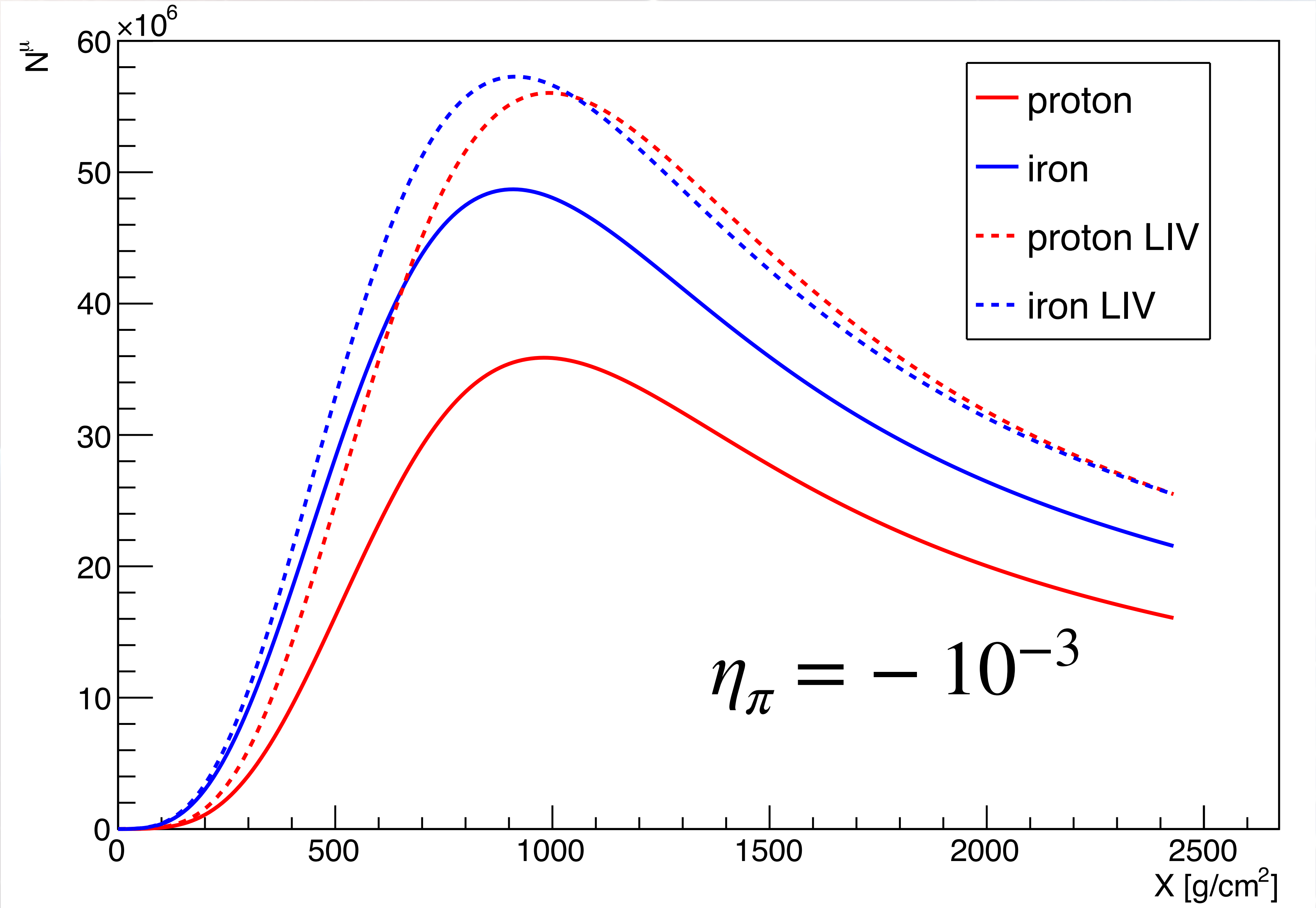
- Primary particles: H, He, N, Fe, Si;
- Primary particle energy: 10^{16}-10^{21} eV;
- Zenith angle: θ = 70°;
- 21 energy bins of width $\Delta \log_{10}(E/eV) = 0.25$ ranging from 10^{16} to 10^{21};
- Hadronic interaction model: EPOS LHC;

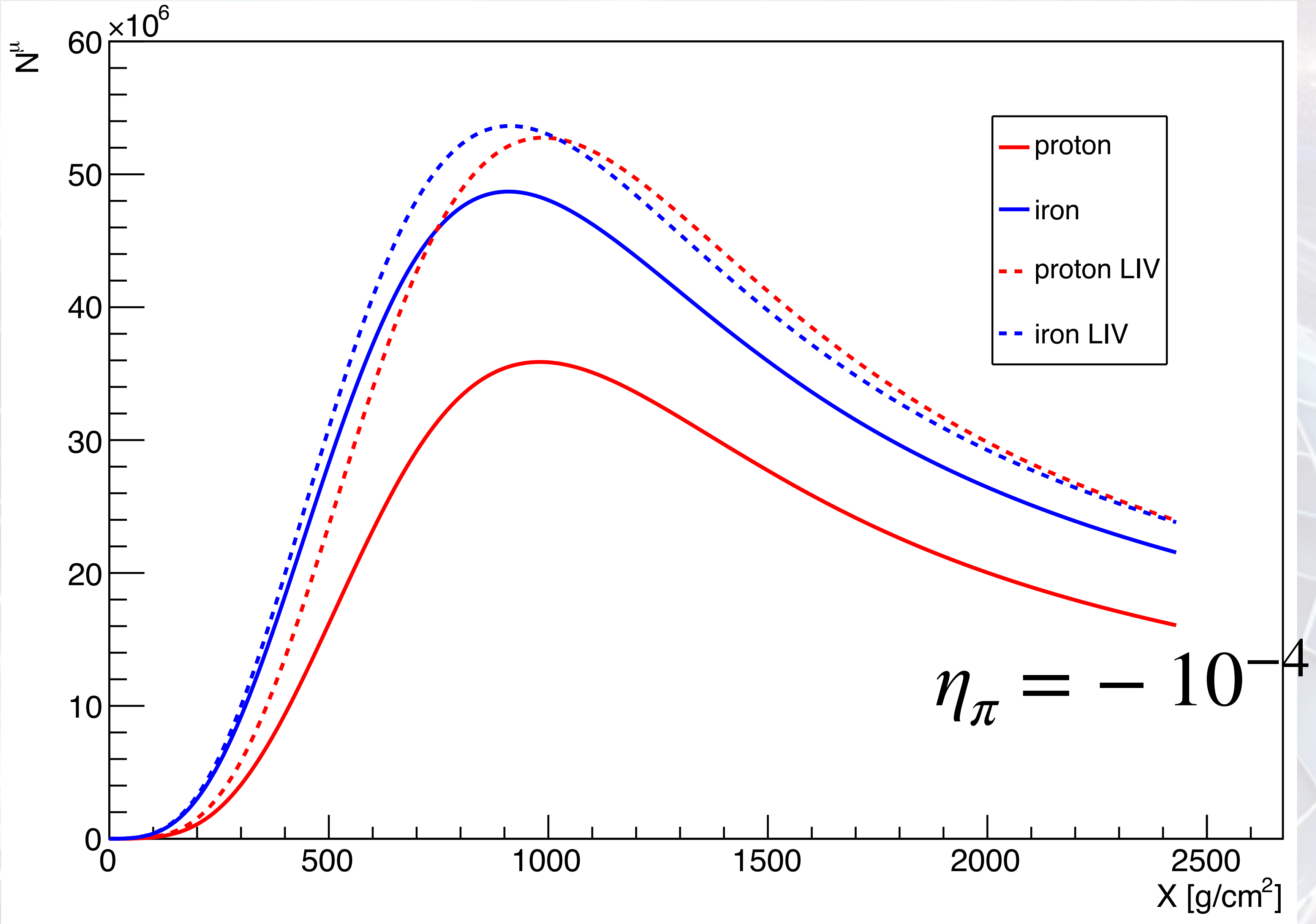
In presence of LIV

- Primary particles: H, He, N, Fe, Si;
- Primary particle energy: 10^{16}-10^{21} eV;
- Zenith angle: θ = 70°;
- 21 energy bins of width $\Delta \log_{10}(E/eV) = 0.25$ ranging from 10^{16} to 10^{21};
- Hadronic interaction model: EPOS LHC-LIV.
- LIV parameter: $\eta = -10^{-3}, -10^{-4}, -10^{-5}, 10^{-1}$;
- order of LIV is n=1,2.

Given the shower-to-shower fluctuation we look at average profile, mean values and σ of the simulated distributions..!

Muon profile



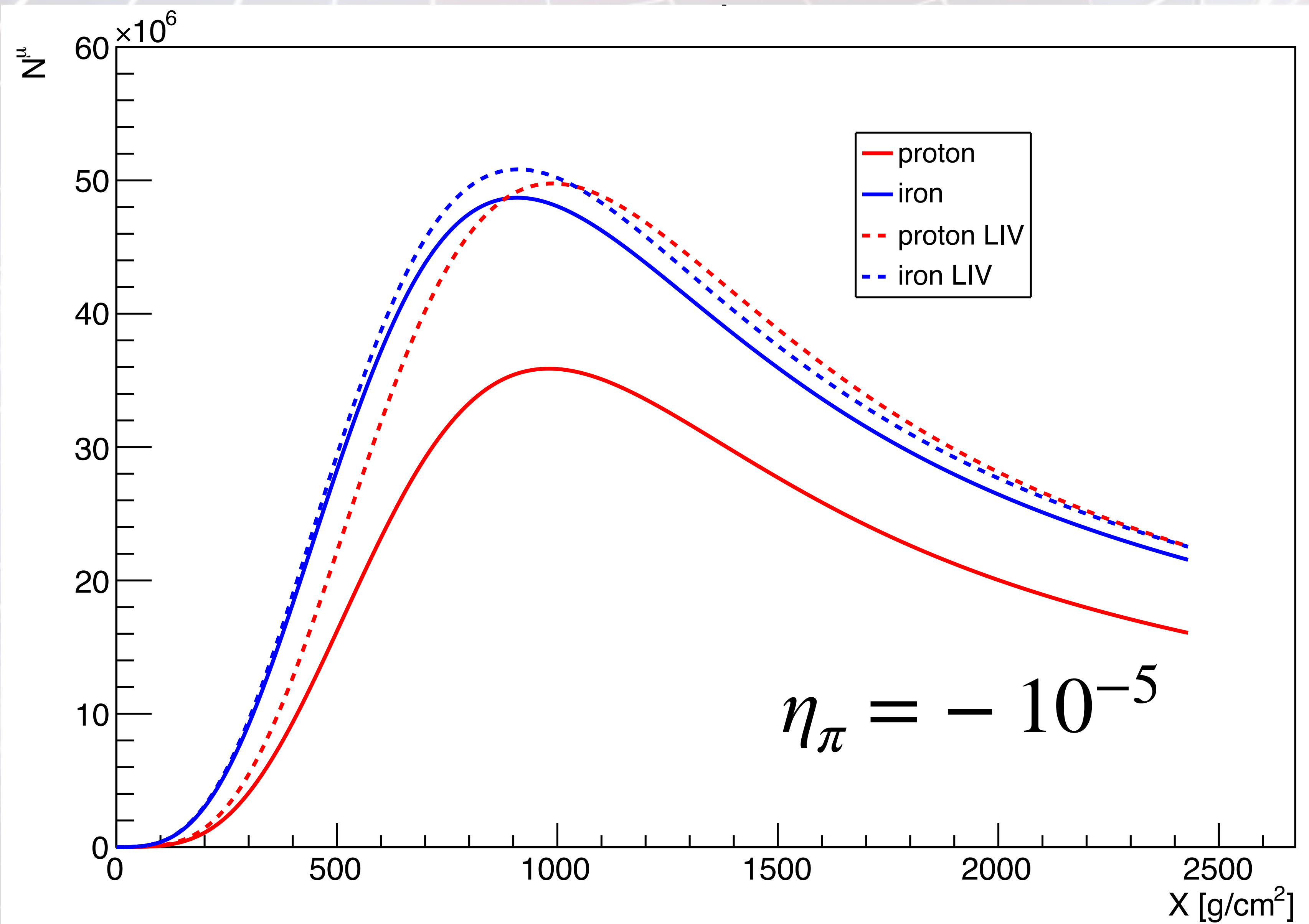


From the Heitler mod

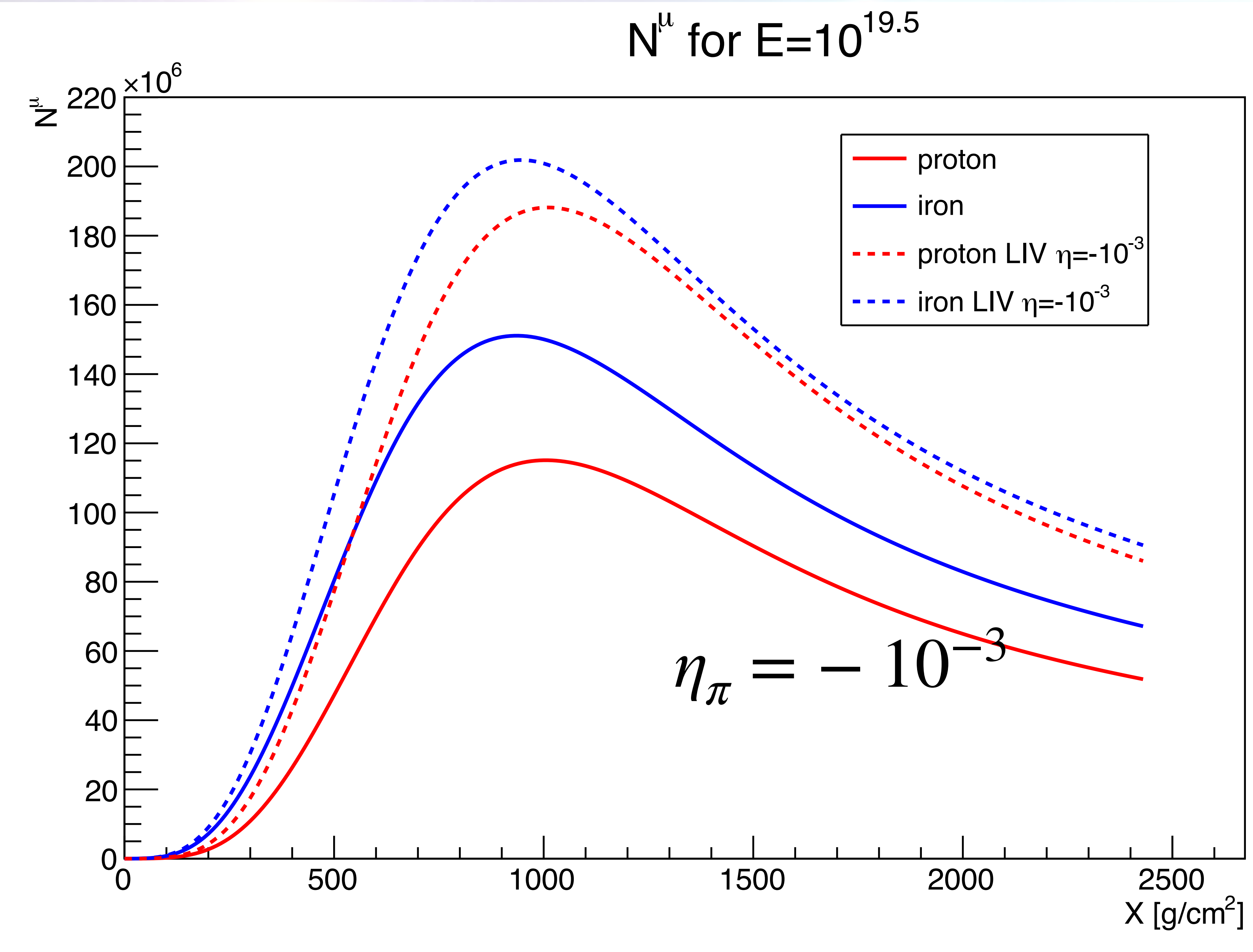
$$N_\mu^A(X_{\max}) = A\left(\frac{E_0/A}{E_{dec}}\right)^{\alpha} = A^{1-\alpha}N_\mu^p(X_{\max})$$

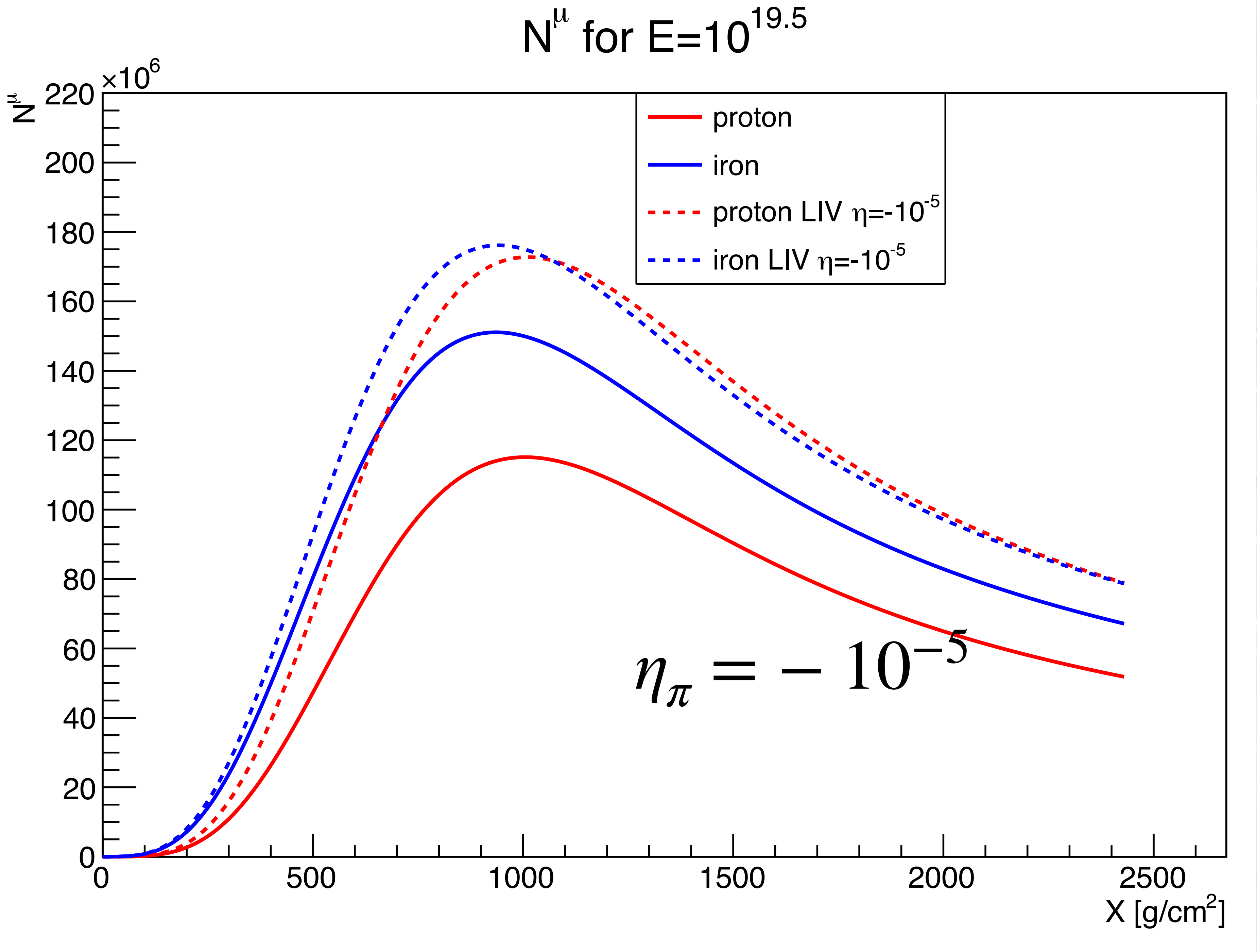
ORDER of LIV n=1 EPOS-LHC at 10^{19} eV

The number of muons increases!



Muon profile





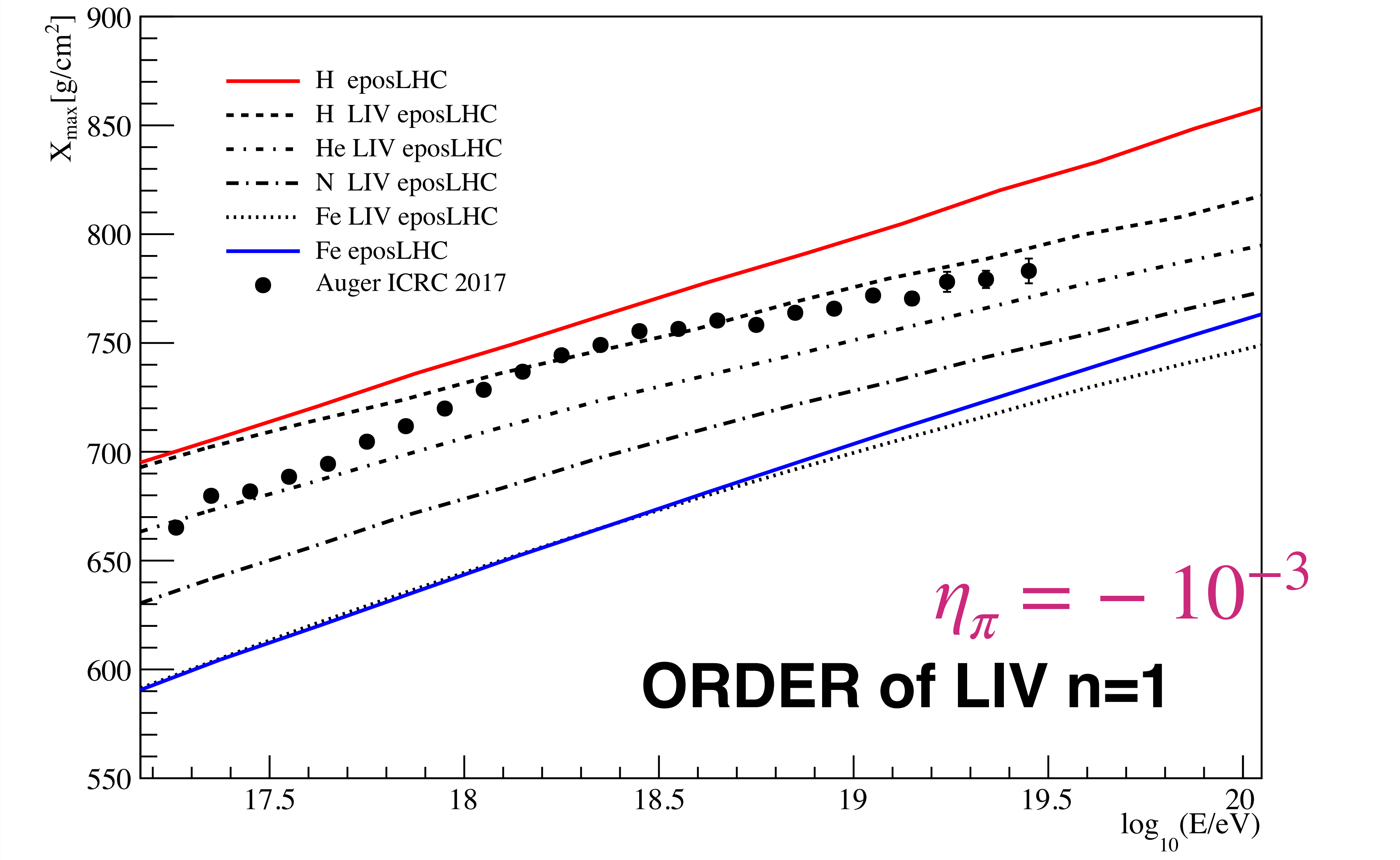
From the Heitler mod

$$N_\mu^A(X_{\max}) = A\left(\frac{E_0/A}{E_{dec}}\right)^\alpha = A^{1-\alpha}N_\mu^p(X_{\max})$$

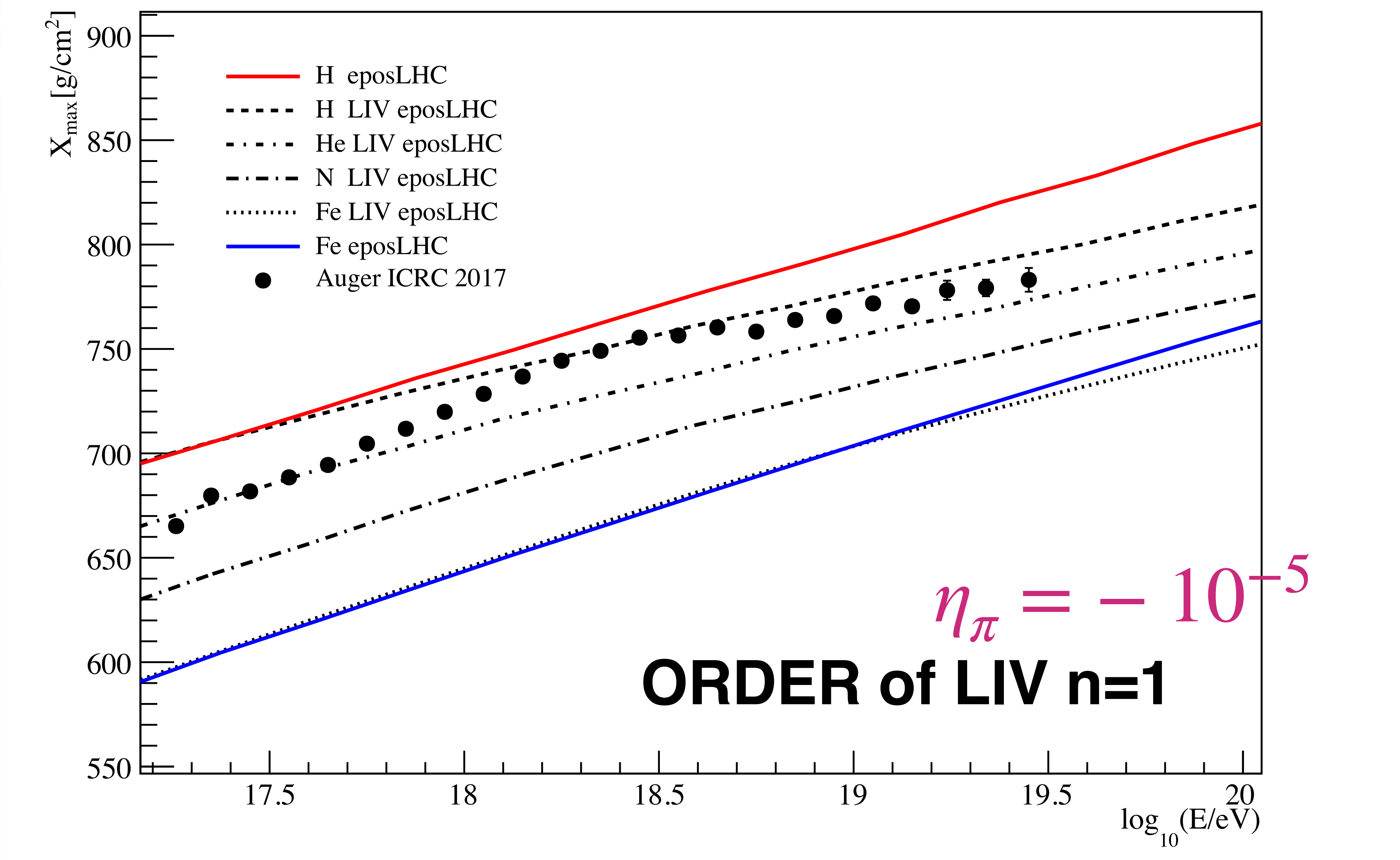
ORDER of LIV n=1 EPOS-LHC at $10^{19.5}$ eV

The difference between LIV muon profiles changes!
It depends on energy and LIV parameter values.

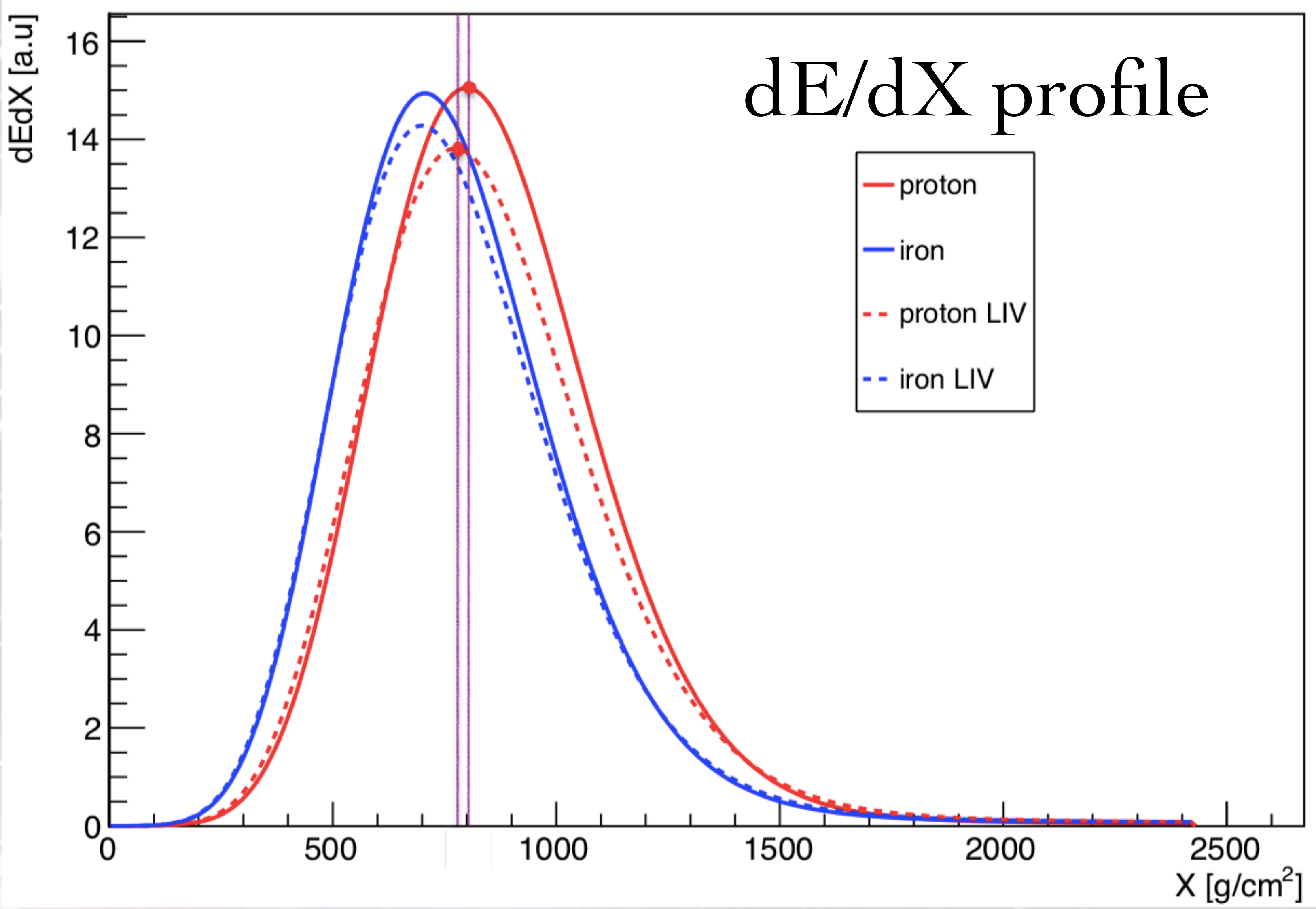
Mean Xmax



X_{max}[g/cm^2]
H eposLHC
H LIV eposLHC
He LIV eposLHC
N LIV eposLHC
Fe LIV eposLHC
Fe eposLHC
Auger ICRC 2017
$\eta_\pi = -10^{-3}$
ORDER of LIV n=1
$\log_{10}$(E/eV)

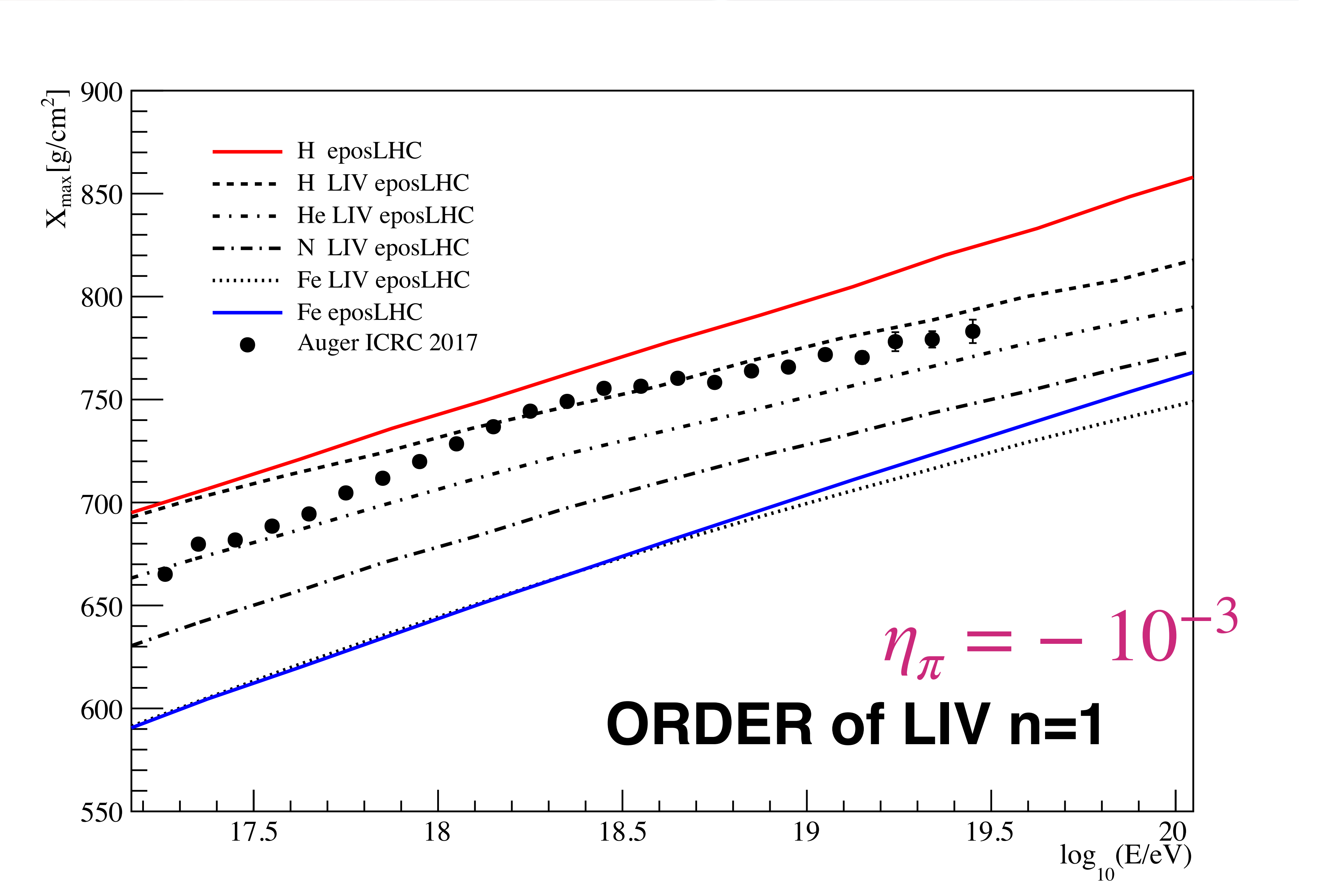


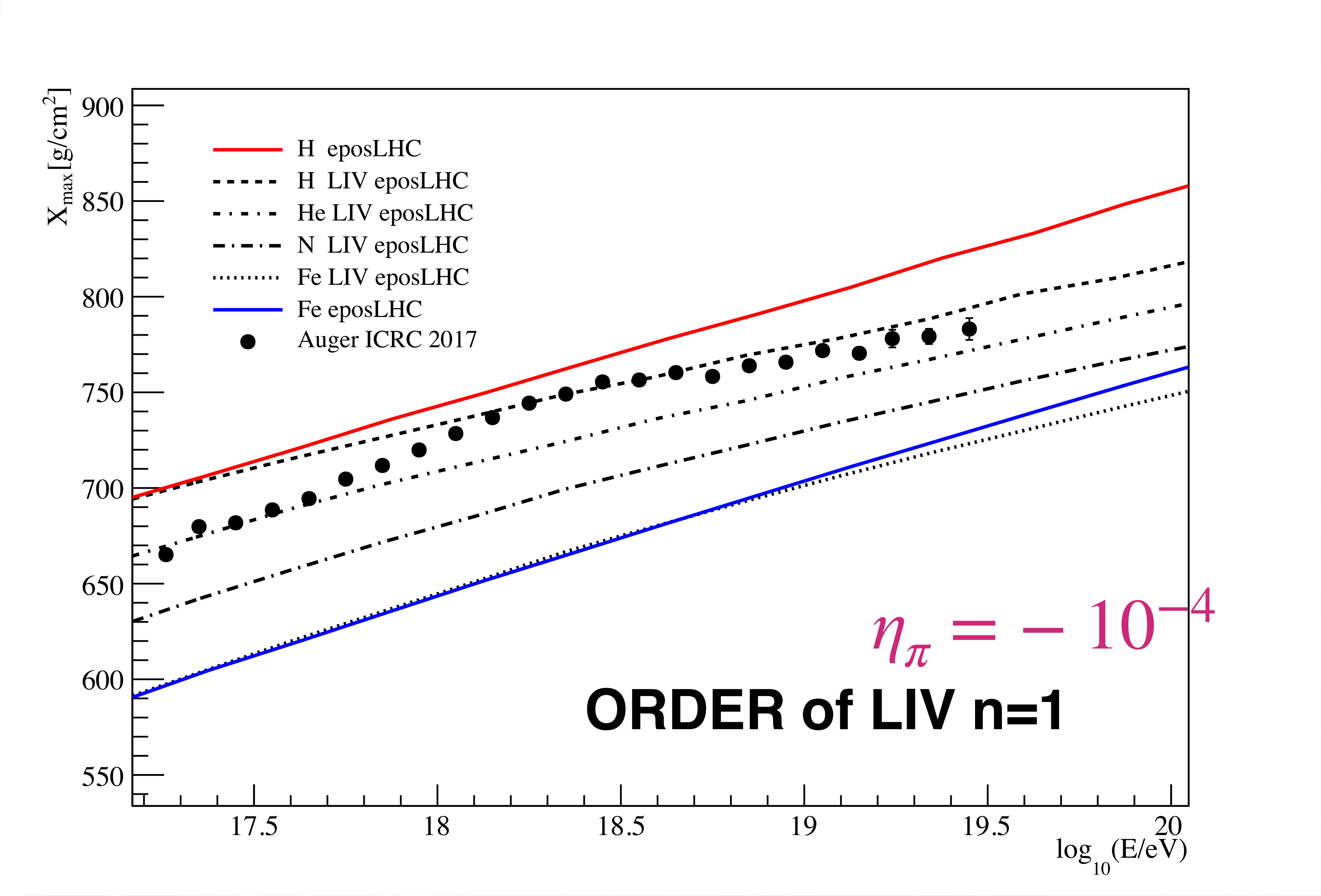
X_{max}[g/cm^2]
H eposLHC
H LIV eposLHC
He LIV eposLHC
N LIV eposLHC
Fe LIV eposLHC
Fe eposLHC
Auger ICRC 2017
$\eta_\pi = -10^{-5}$
ORDER of LIV n=1
$\log_{10}$(E/eV)

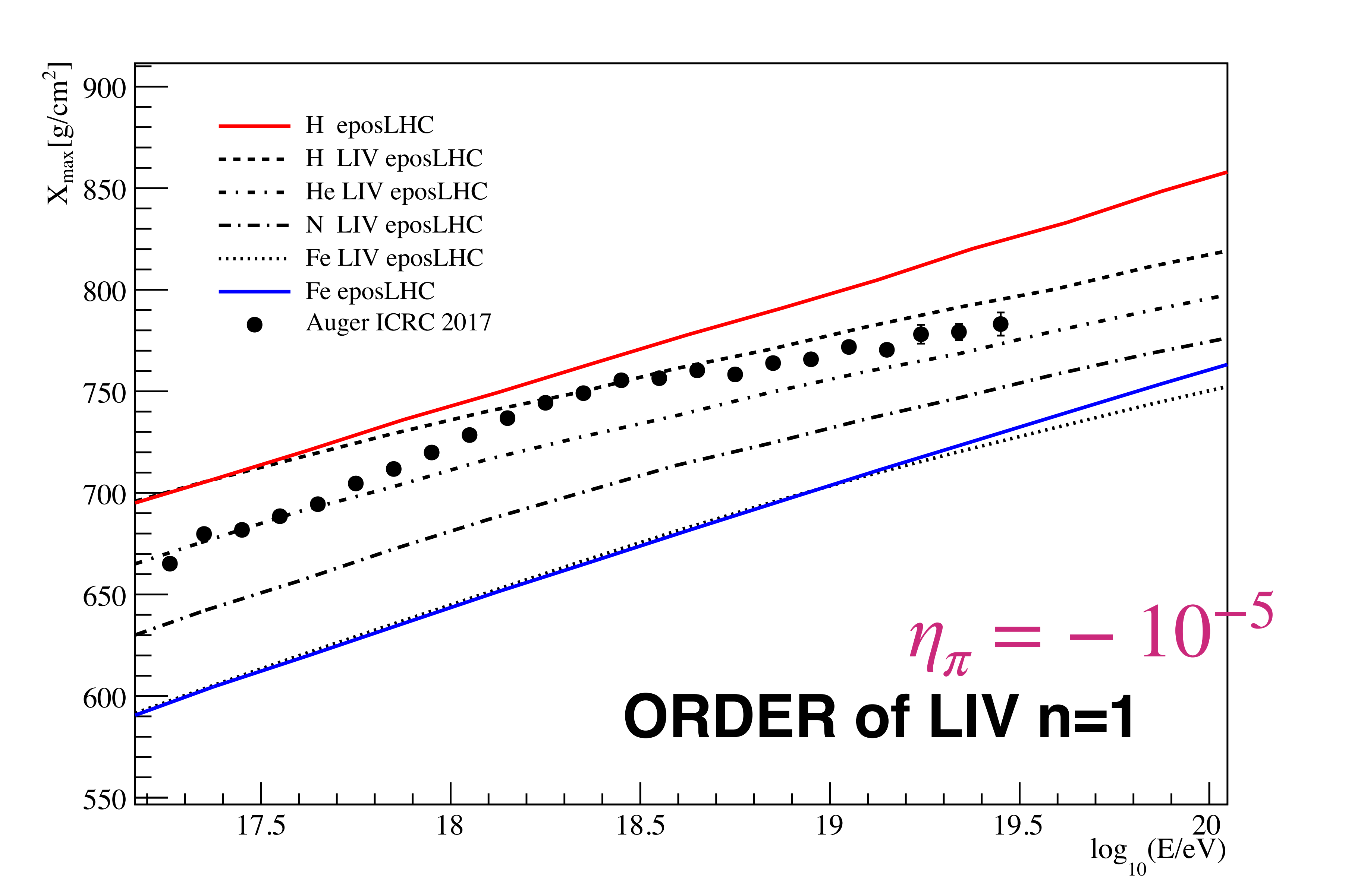


dE/dX profile
dEdX [a.u]
proton
iron
proton LIV
iron LIV
X [g/cm^2]

Mean Xmax







From the Heitler mod

$$X_{max} \propto \lambda \frac{E_0}{AE_c}$$

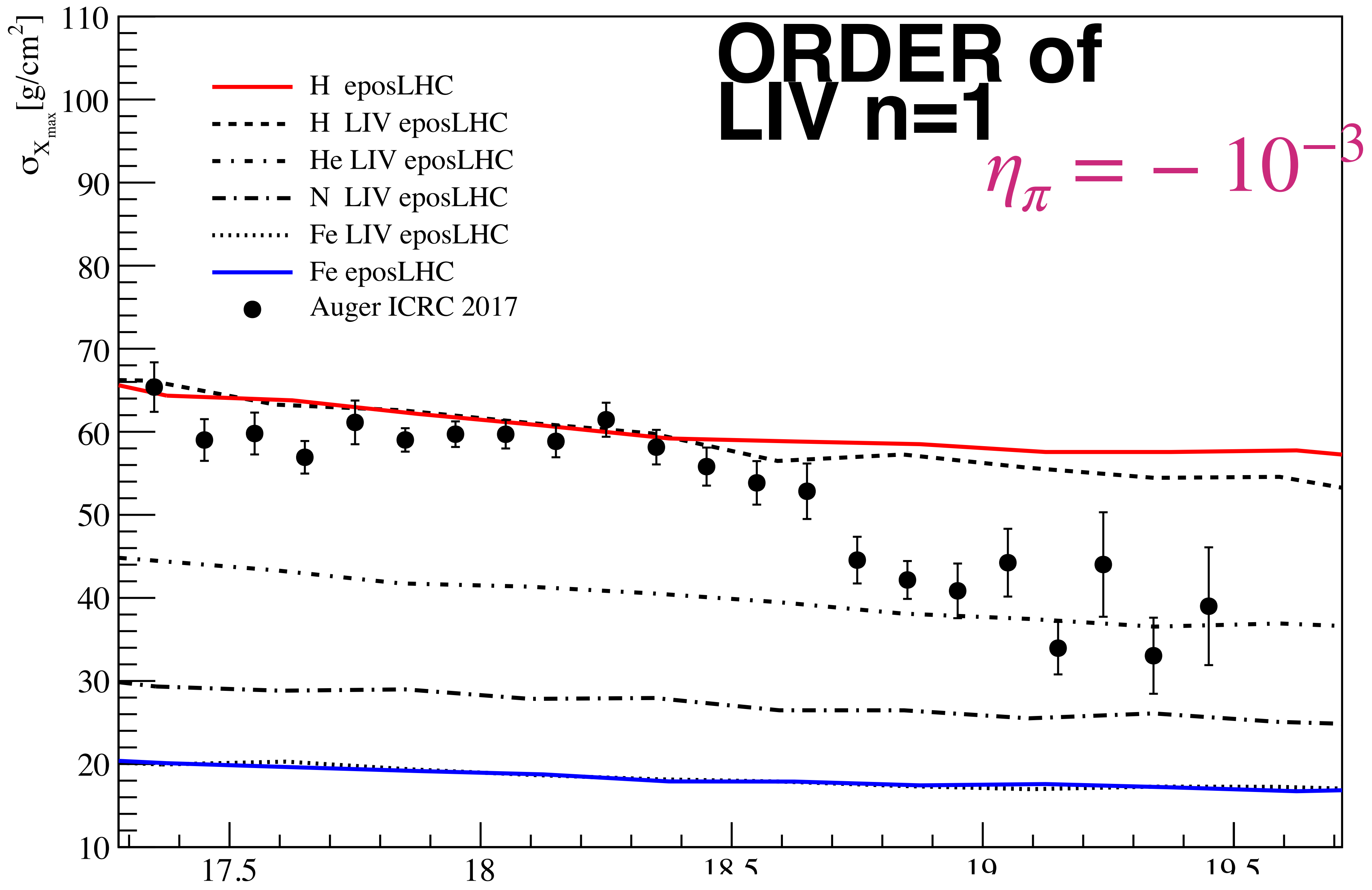
More protons expected for LIV at 1st order!!

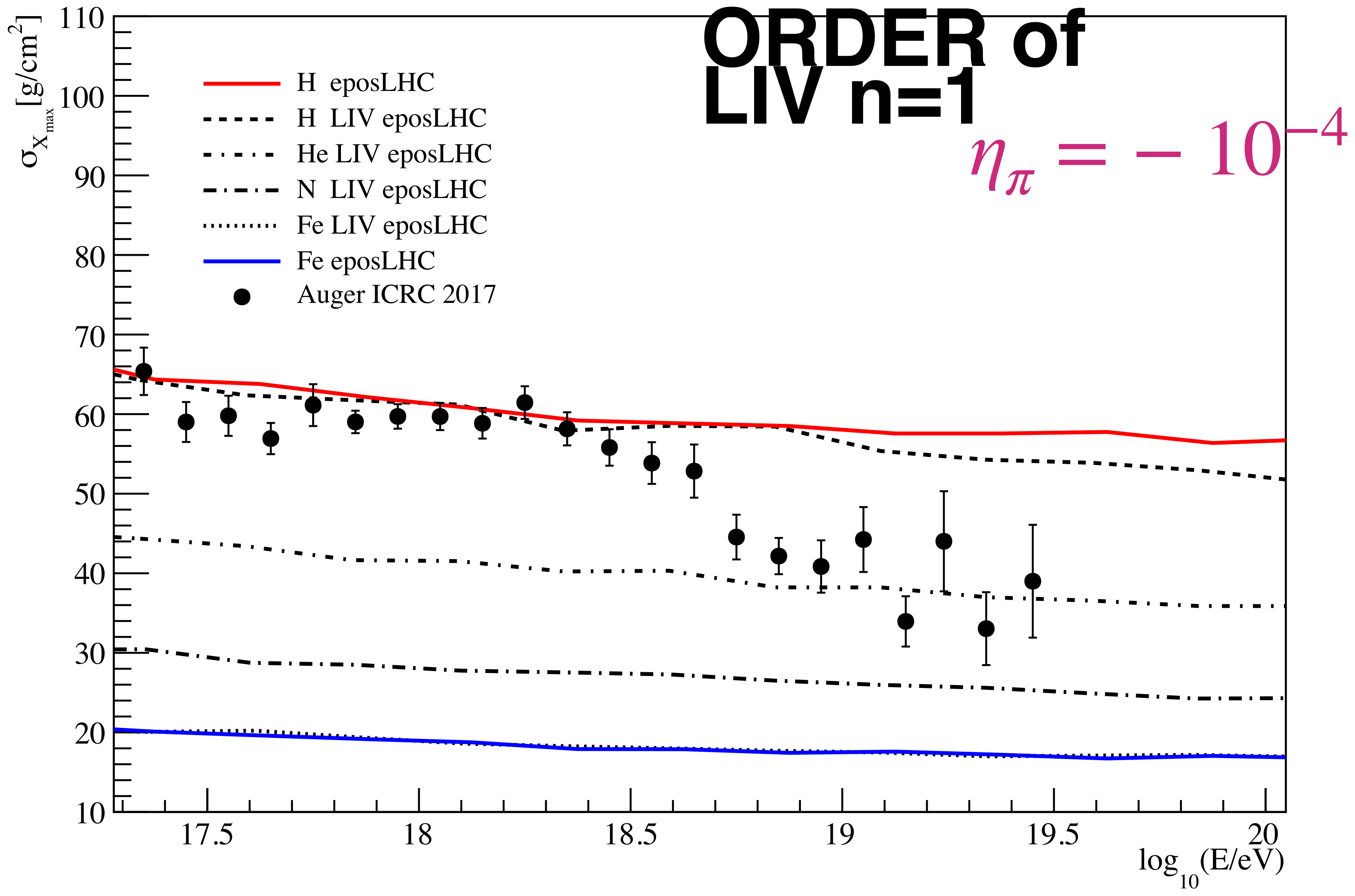
You can use this to put const

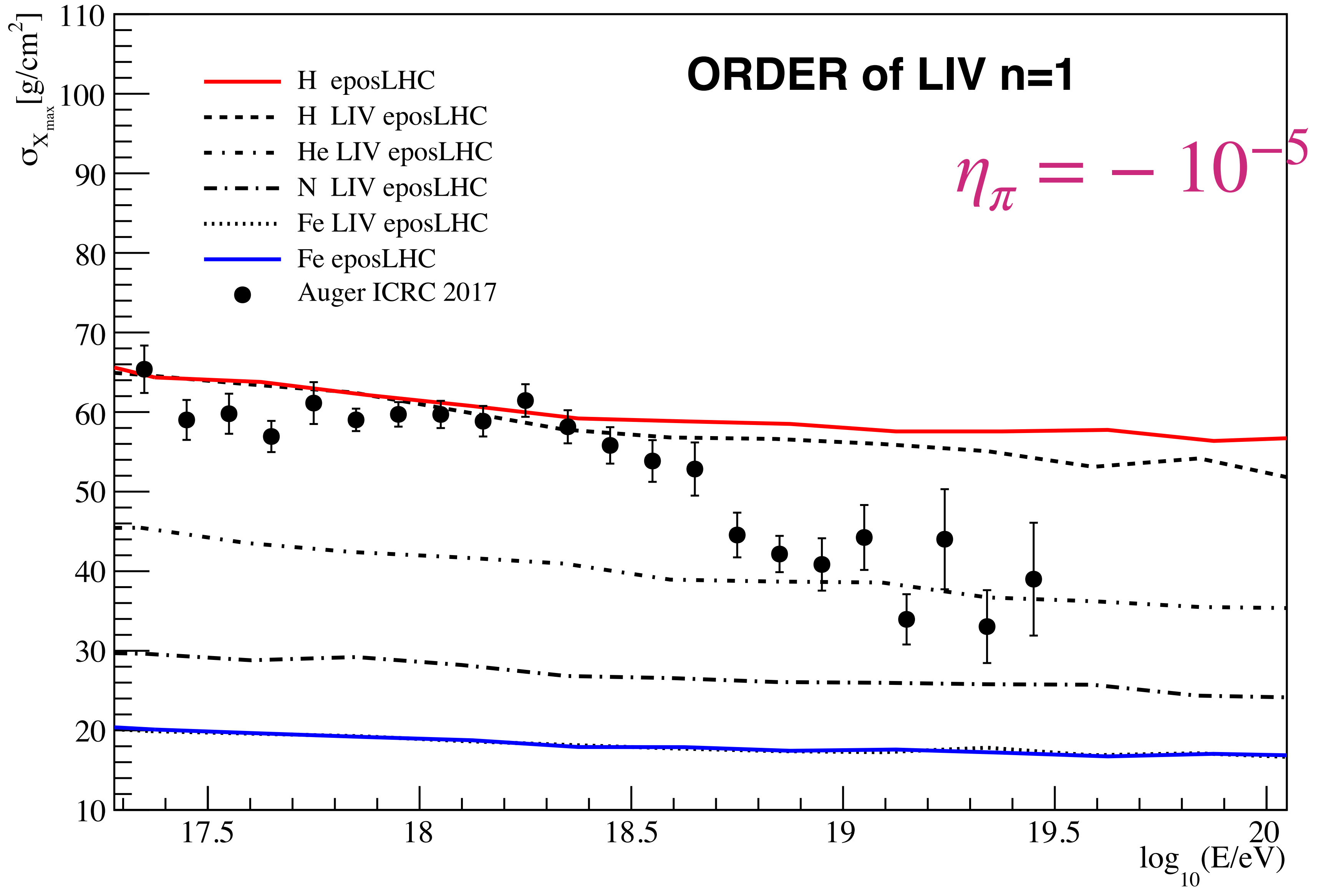
See F.R. Klinkhamer M. Niechciol M. Risse

Improved bound on isotropic Lorentz violation in the photon sector from extensive air showers

RMS Xmax







You can use this to put constrain!

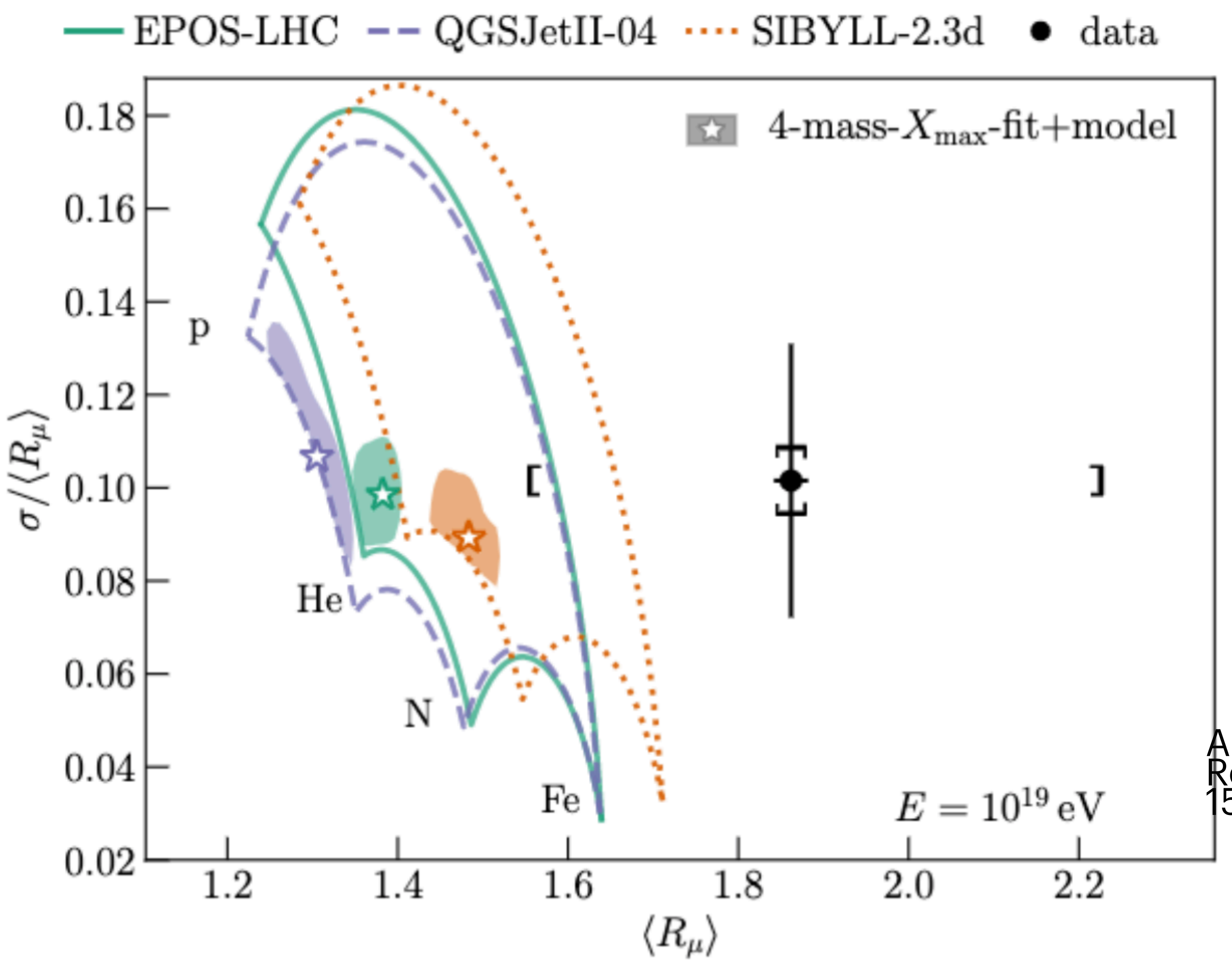
See Fabian Duenkel, Marcus Niechciol, and Markus Risse
A new bound on Lorentz violation based on the absence of vacuum Cherenkov radiation in ultra-high energy air showers

Relative Fluctuations

Effects of the different composition scenarios

The mixture of the two components p and Fe gives the maximum value of relative fluctuations.

$$\frac{\sigma_\mu}{\langle N_\mu \rangle} = \frac{\sqrt{\sigma^2(N_\mu)_{\text{mix}}(\alpha;\eta)}}{\langle N_\mu \rangle_{\text{mix}}(\alpha;\eta)}$$



A. Aab et al. [Pierre Auger] Phys. Rev. Lett. 126 (2021) no.15, 152002

Where

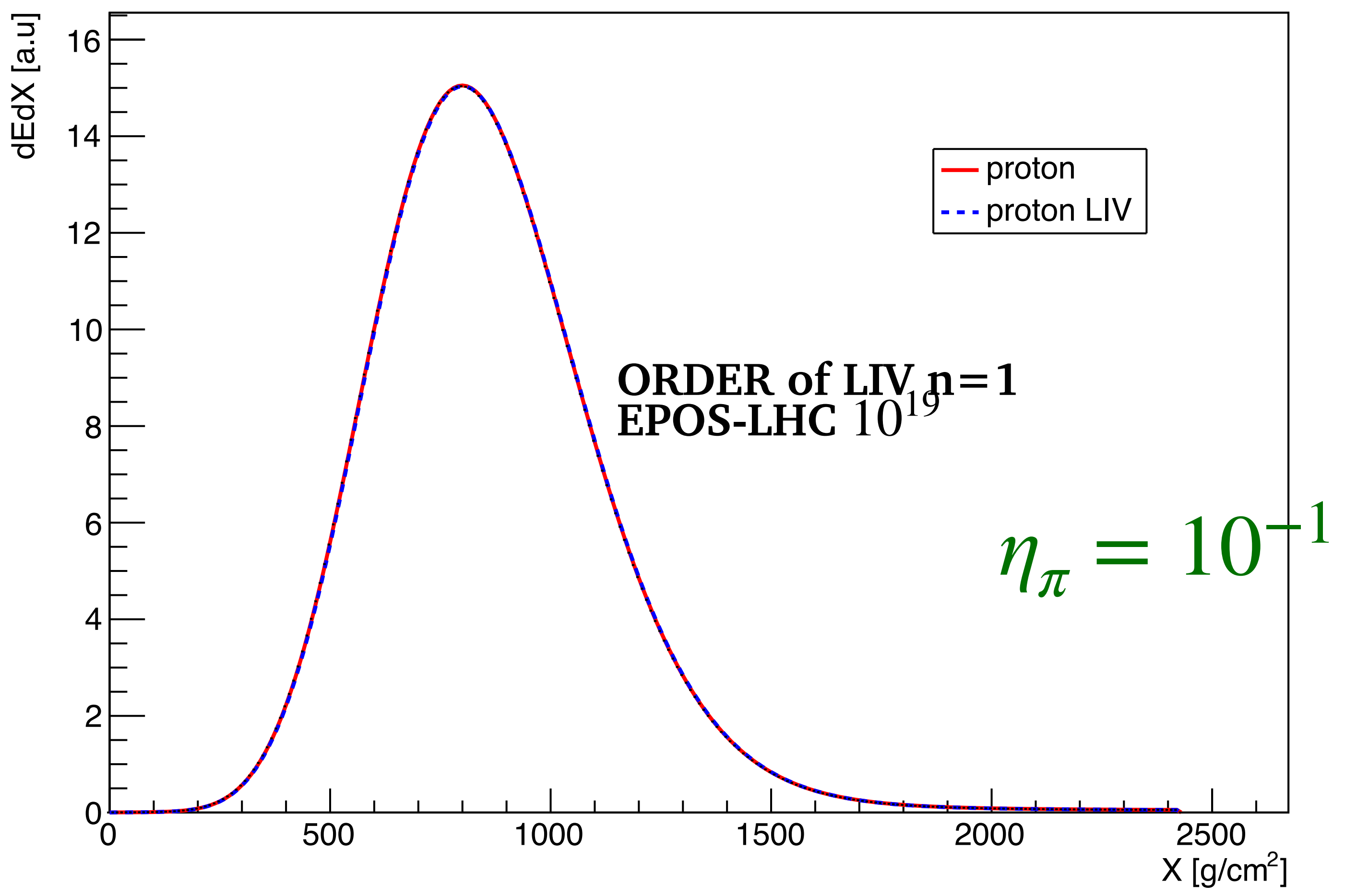
$$\langle N_\mu \rangle_{\text{mix}}(\alpha;\eta) = (1-\alpha)\langle N_\mu \rangle_p + \alpha \langle N_\mu \rangle_{Fe}$$

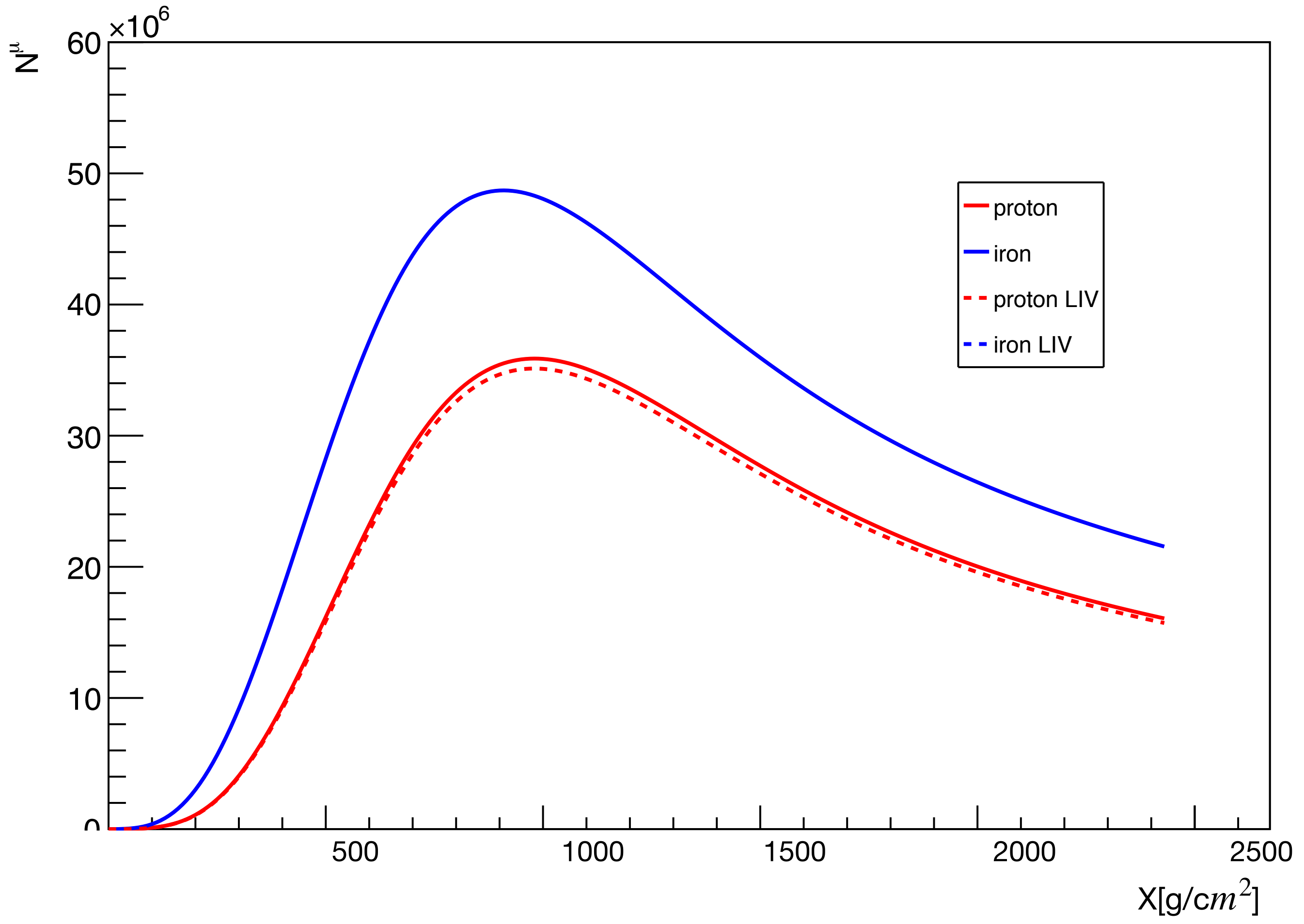
$$\sigma^2(N_\mu)_{\text{mix}}(\alpha;\eta) = (1-\alpha)\sigma^2(N_\mu)_p + \alpha\sigma^2(N_\mu)_{Fe} + (\alpha(1-\alpha)(\langle N_\mu \rangle_p - \langle N_\mu \rangle_{Fe})^2$$

See GAP-notes GAP 2011-118

$1-\alpha$ is the fraction of proton
α is the fraction of iron

$\eta_\pi > 0$





LIV SECOND ORDER