THE INTERNATIONAL SCHOOL OF COSMIC RAY ASTROPHYSICS (ISCRA)

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Constraining LIV using the muon content of extensive air showers

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Lorentz Invariance Violation

The need to study a possible violation of Lorentz invariance arises from the desire to unify quantum mechanics and general relativity.

↓

General Relativity is a classical theory, but quantum effects are not negligible when energy is of the order of the Planck scale, $M_{Pl} = 1.22 \cdot 10^{28}$ eV.

Possible Lorentz Invariance violation could be observed if physical phenomena characterized by energy of the center of mass of the order of Planck scale energy are studied.

↓

Ultra High Energy Cosmic rays

See A. Castellina lectures

↓

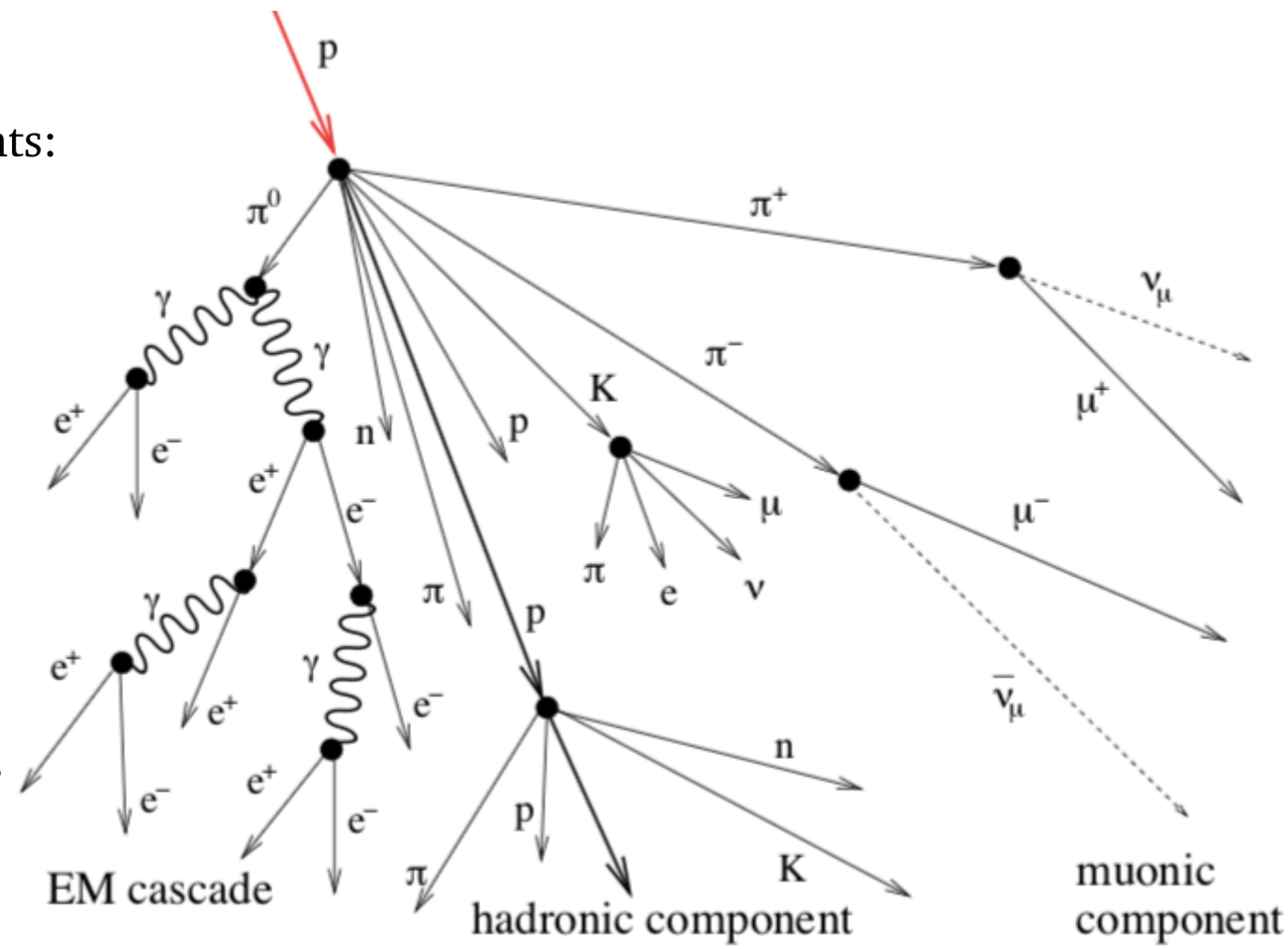
Extensive Air Showers

Extensive Air Showers

An air shower is an extensive cascade, with a length of many km, of ionized particles and electromagnetic radiation that initiates when a **primary cosmic ray** ($E > 10^{18}$ **eV)** enters the atmosphere.

The shower is composed of three components:

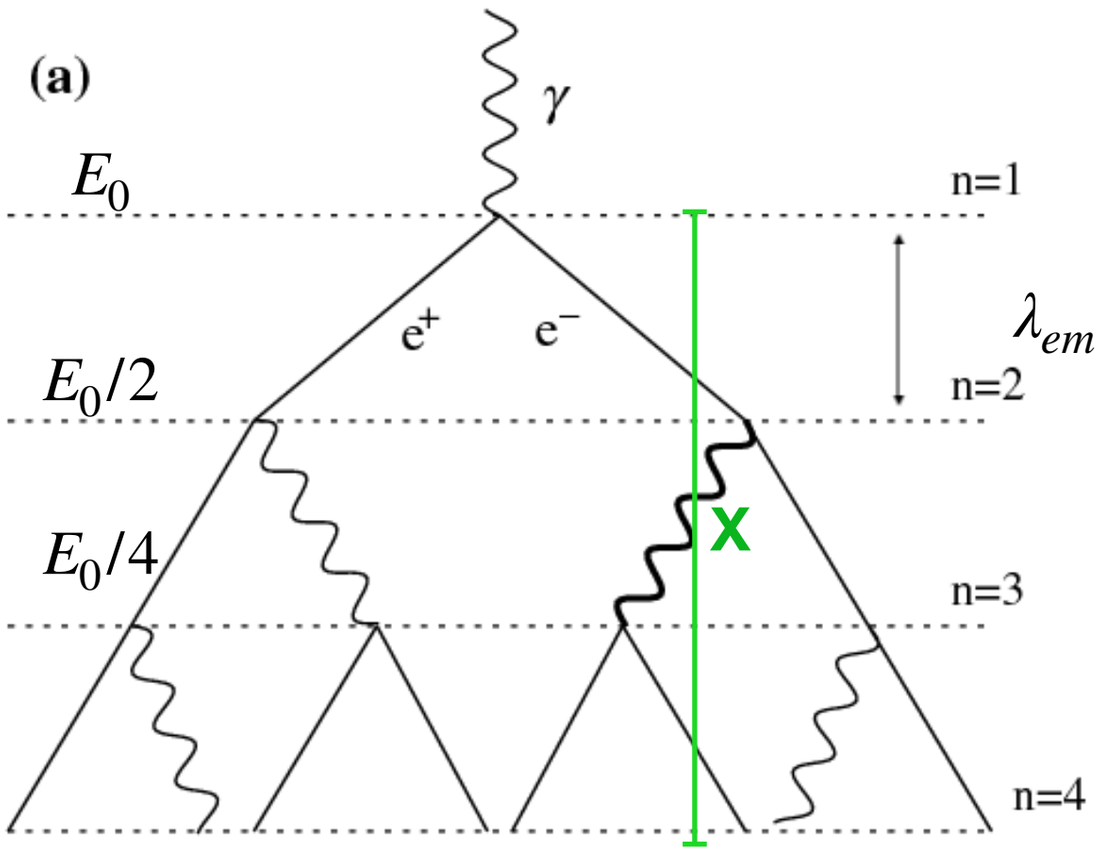
- The em component characterized by the **pair production**, the **bremsstrahlung** and the **ionization energy loss**;
- The hadronic component produced by **charged hadronic** particles involved in the **strong interactions** with the atmosphere;
- The muonic component weakly interacts and it can be detected at ground using SD.

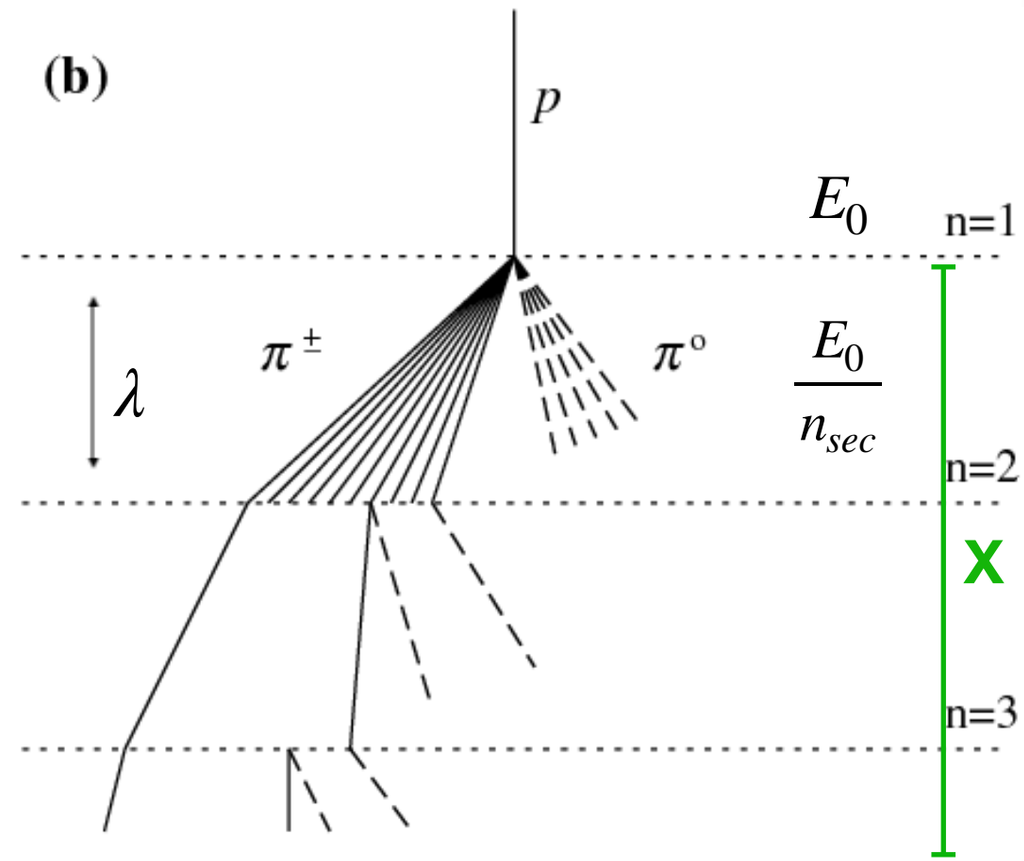


- The **lateral distribution**;
- The **Mean Longitudinal Profile**, dE/dX.

Heitler Model

See A. Castellina lectures





At the shower maximum we define:

- $N_{max} = E_0/E_c$;
- $X_{max} = X_0 + \lambda_{em} log_2(E_0/E_c)$

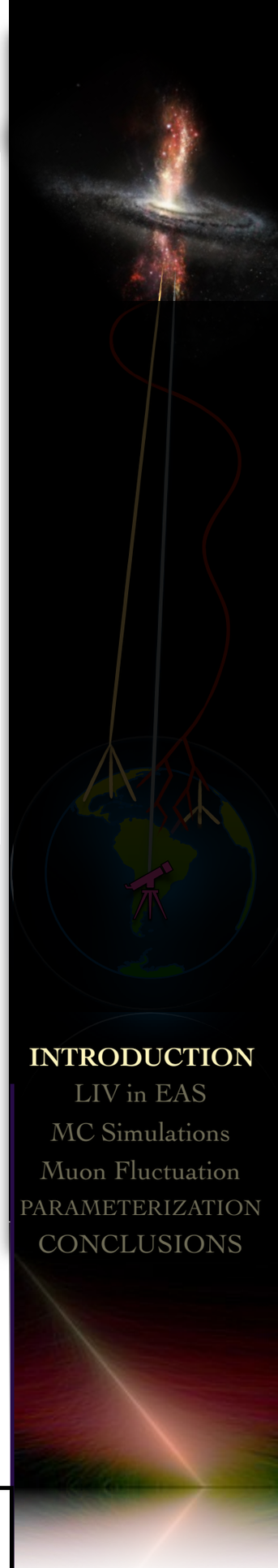
A nucleus with mass A and energy E_0 is considered as A independent nucleons with energy E_0/A each.

The superposition of the individual nucleon showers yields:

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

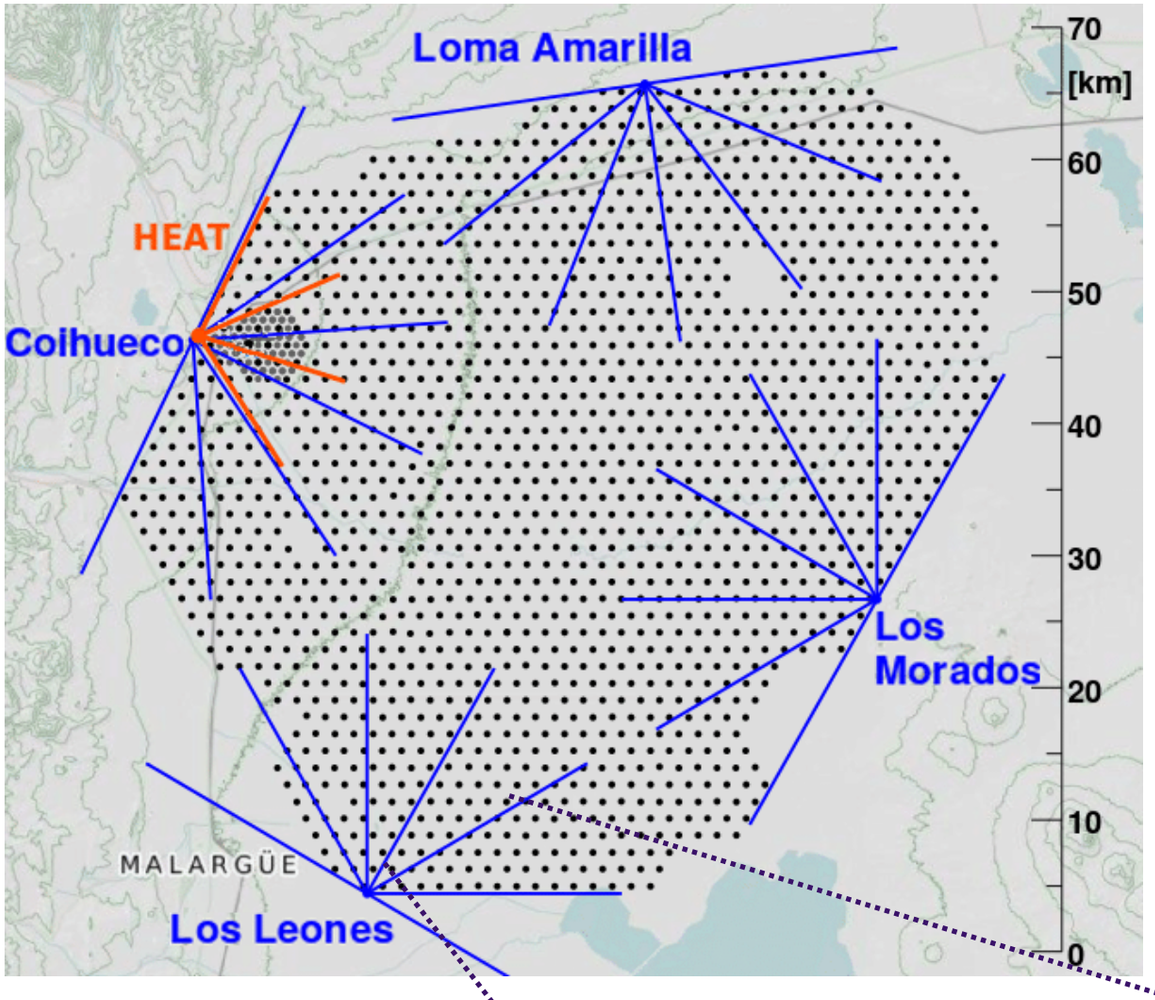
2) $N_\mu^A(X_{\max}) = A\left(\frac{E_0/A}{E_{dec}}\right)^\alpha = A^{1-\alpha} N_\mu^p(X_{\max})$

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



Pierre Auger Observatory

See A. Castellina lectures



HYBRID DETECTOR:

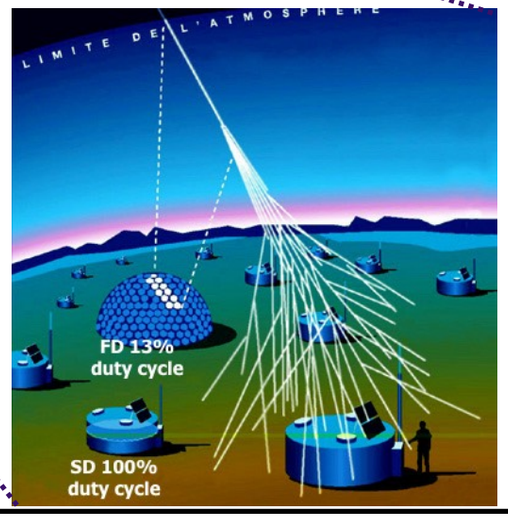
Fluorescence detector (FD)

- 24 telescopes in 4 sites, FoV: 0-30°, $E>10^{18}$ eV
- HEAT (3 telescopes), FoV: 30 - 60°, $E>10^{17}$ eV

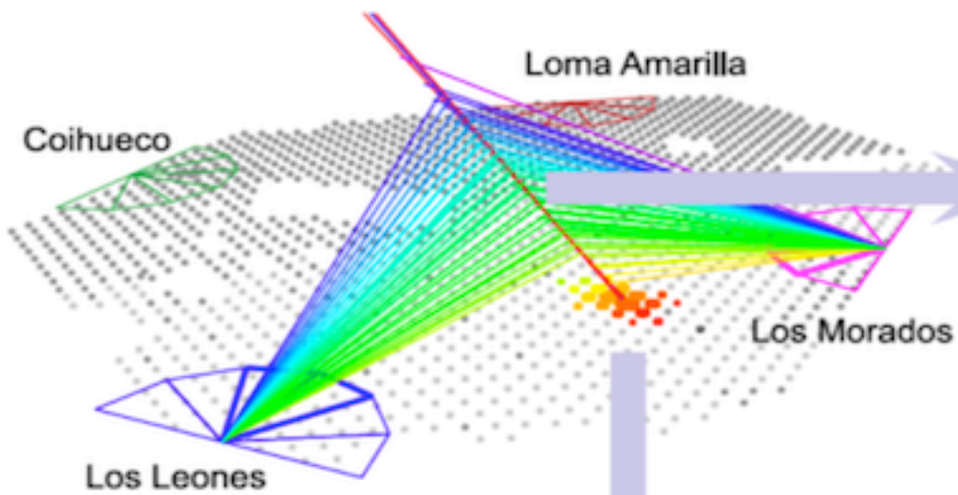
Surface detector (SD): ground array of water Cherenkov detectors

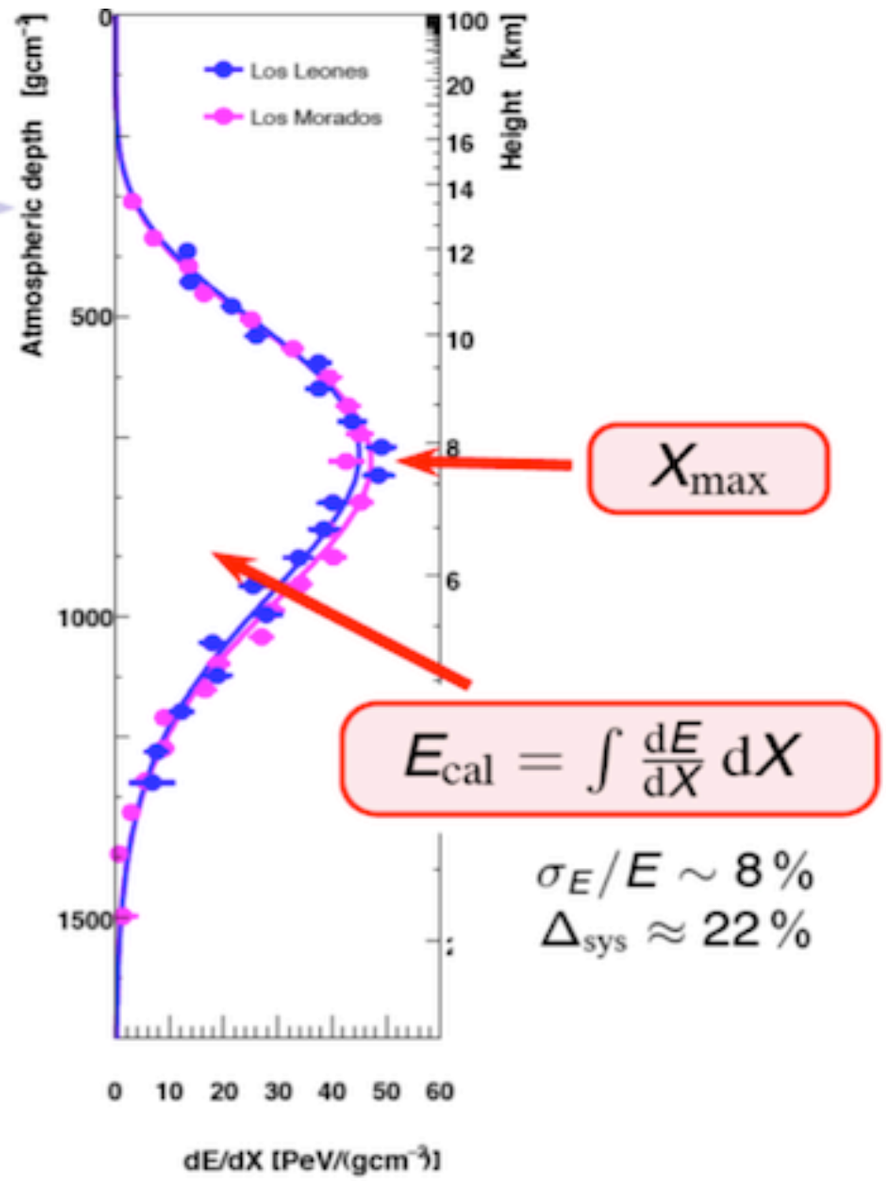
- 1660 stations in 1.5 km grid, 3000 km^2 $E > 10^{18.5}$ eV
- 61 stations in 0.75 km grid, 23.5 km^2,$E > 10^{17.5}$ eV

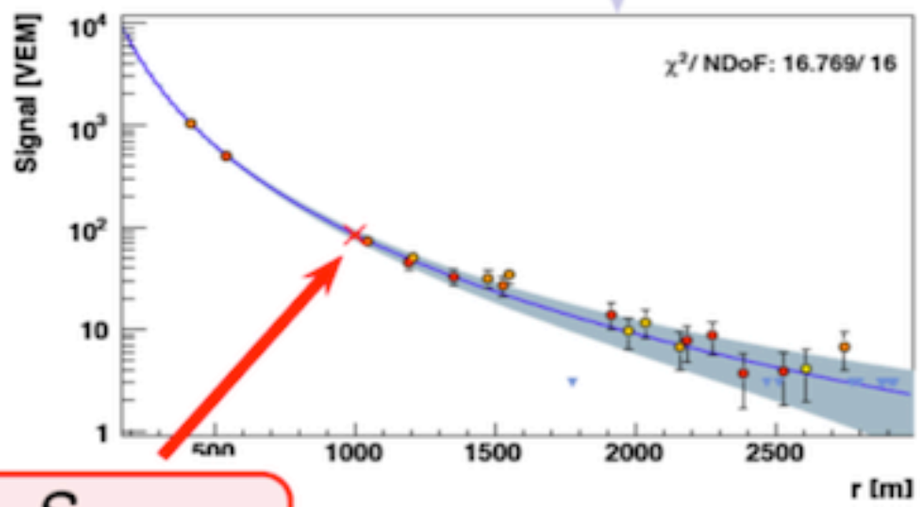
Underground muon detector



Hybrid Detection



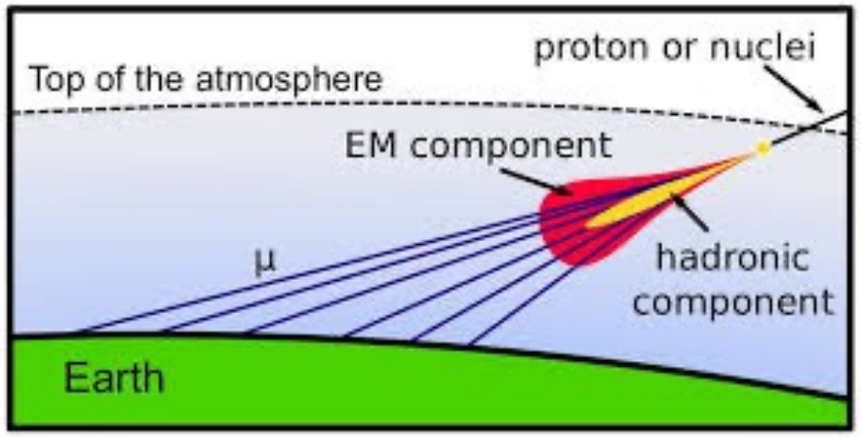


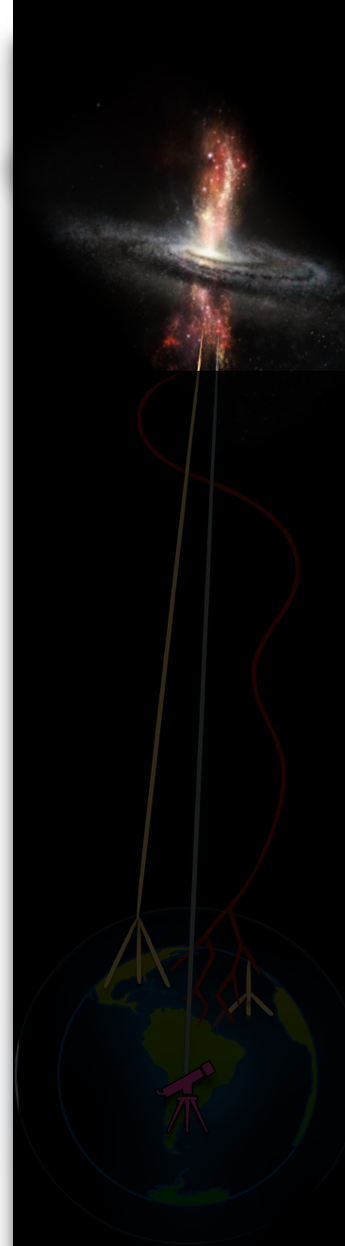


S_{1000}

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

- **Calorimetric energy measurement with the FD**
- **Lateral distribution measurement with the SD**





How to break Lorentz Invariance

<u>Modified dispersion relation</u>

$$E^2 - p^2 = m^2 + f(\vec{p}, M_{Pl}; \eta) \longrightarrow E^2 - p^2 = m^2 + \sum_{n=0}^{N} \eta^{(n)} \frac{p^{n+2}}{M_{Pl}^n}$$

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

Leading order n=1: $E^2 - p^2 = m^2 + \eta^{(1)} \frac{p^3}{M_{Pl}}$

Nuclei: $E_{A,Z}^2 - p_{A,Z}^2 = m_{A,Z}^2 + \eta_{A,Z}^{(1)} \frac{p_{A,Z}^3}{M_{Pl}}$
With $\eta_A = \eta / A^2$

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: $\gamma_{\mathrm{LIV}} = \frac{E}{m_{\mathrm{LIV}}}$

In terms of the lifetime τ of particles: $\tau = \gamma_{\mathrm{LIV}} \tau_0$

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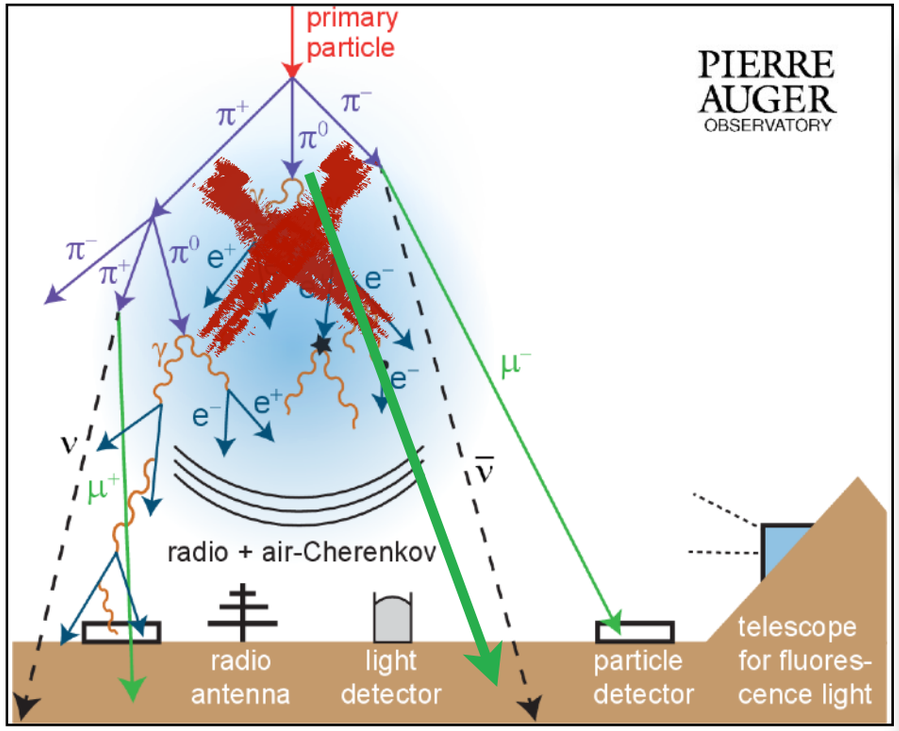
In terms of the lifetime τ of particles: $\tau = \gamma_{\mathrm{LIV}} \tau_0$

$\eta^{(n)}$ assumes both positive and negative values!

Neutral pion decay

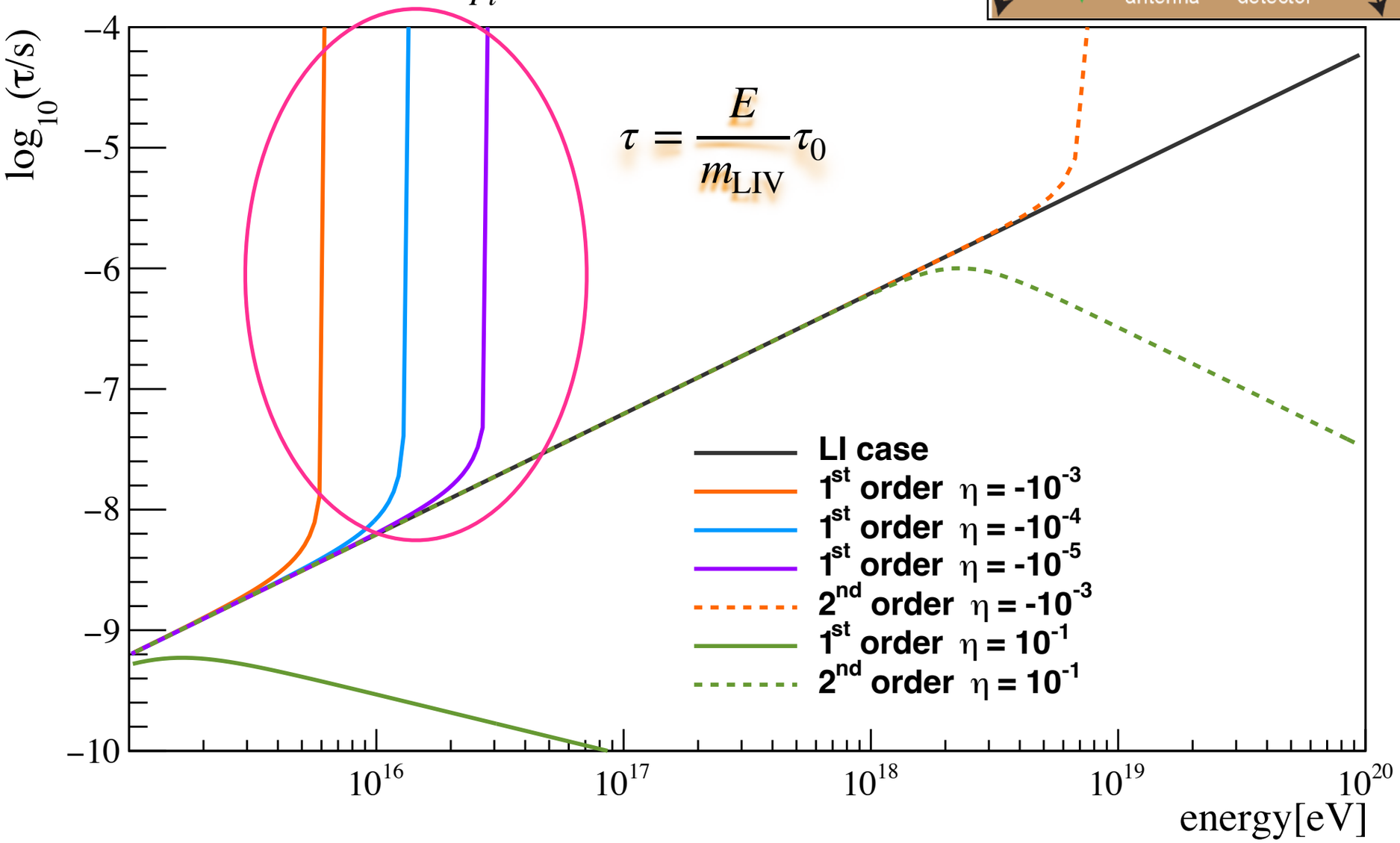
π^0 **Decay:** $\pi^0 \rightarrow \gamma\gamma$ $\quad \tau_0 = 8.4 \cdot 10^{-17}$**s**



If η_π assumes negative values!

The decay is forbidden if:

$$m_\pi^2 + \eta_\pi^{(n)} \frac{p_\pi^{n+2}}{M_{Pl}^n} < 0.$$



What to expect…

$\eta < 0$

- For increasing energy π^0 begins to interact;
- After the critical point (where $M_{\mathrm{LIV}} = 0$) the decay $\pi^0 \to \gamma\gamma$ is forbidden;

A growth of the hadronic cascade
Increase in the number of muons

Decrease in the
electromagnetic component

$\eta > 0$

- Negligible effects are produced

First order: $\eta_\gamma^{(1)} > -1.2 \cdot 10^{-10}$
(R. G. Lang, H. Martìnez-Huerta and V. De Souza 2018);

Second order: $-10^{-3} < \eta_\pi^2 < 10^{-1}$
(Maccione et al. 2009).

CONEX shower simulation

Lorentz Invariant case & in presence of LIV

Modified particle velocity definition

$$\beta = \frac{\mathbf{P}}{m\gamma_{\mathrm{LIV}}}$$

Shower Simulation Options:

Primary particles: H, He, N, Si, Fe;

Primary particle energy: 10^{14}-10^{21} eV;

Zenith angle: $\theta = 70^\circ$;

21 energy bins of width $\Delta \log_{10}(E/eV) = 0.25$ ranging from 10^{14} to 10^{21};

Hadronic interaction model: EPOS LHC-LIV, QGSJETII-04.

in presence of LIV

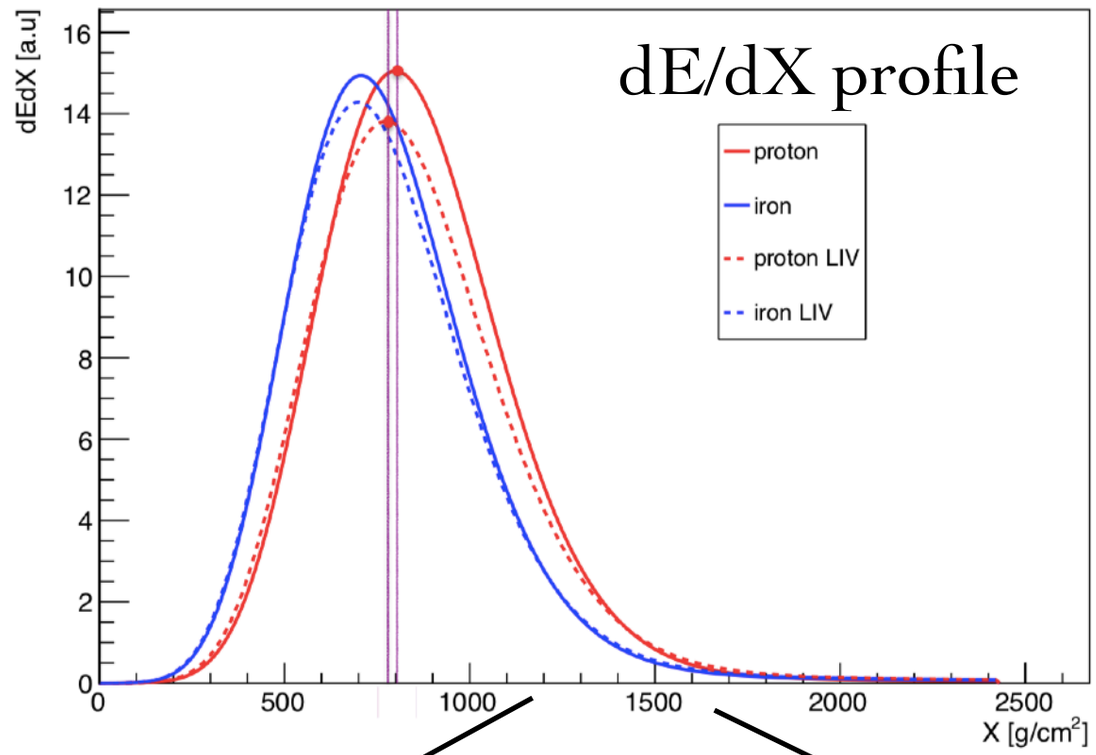
LIV parameter η:

- **1st order:** $\eta = -10^{-1}, -10^{-3}, -10^{-4}, -10^{-5}, -10^{-6}, -5 \cdot 10^{-7}, -10^{-7}, -10^{-8}$
- **2nd order:** $\eta = -1, -10^{-1}, -10^{-2}, -10^{-3}$

A number of 5000 events has been simulated for each primary particle for definite energy intervals.

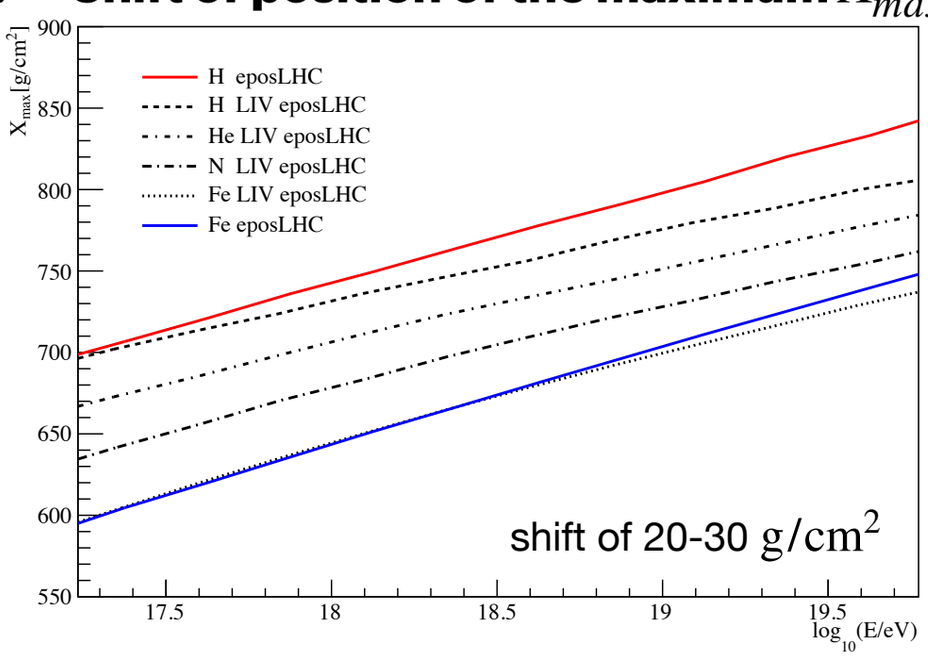
LIV effects on air shower development

ORDER OF LIV n=1
EPOS-LHC
$\eta = -10^{-3}$
at 10^{19} **eV**



Analyzing the library of simulated air shower with **CONEX**

1. Shift of position of the maximum X_{max}



2. Reduction in the normalization

- Due to a change in the number of muons at the ground;

- The calorimetric energy deposited in the atmosphere in the presence of LIV is lower than the standard one.

MUON CONTENT DISTRIBUTION

LIV effects on air shower development

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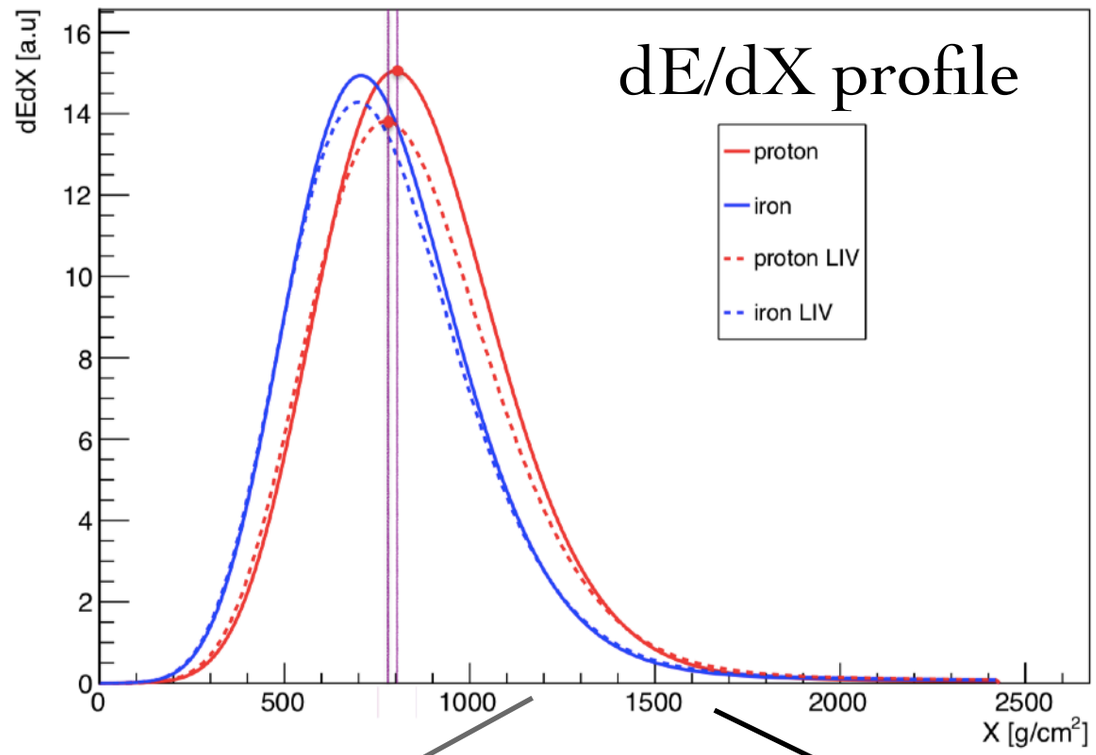

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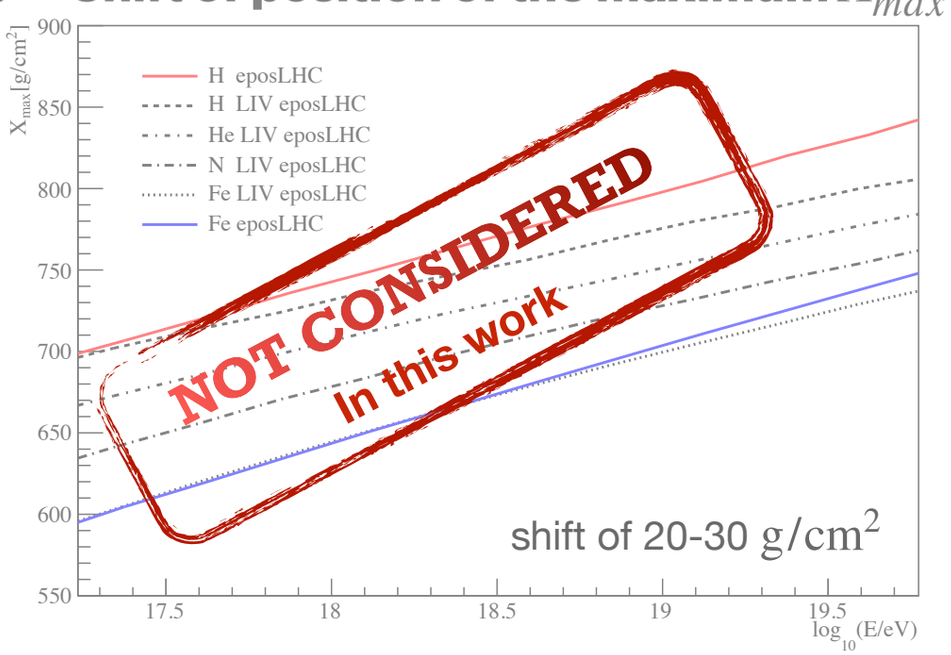

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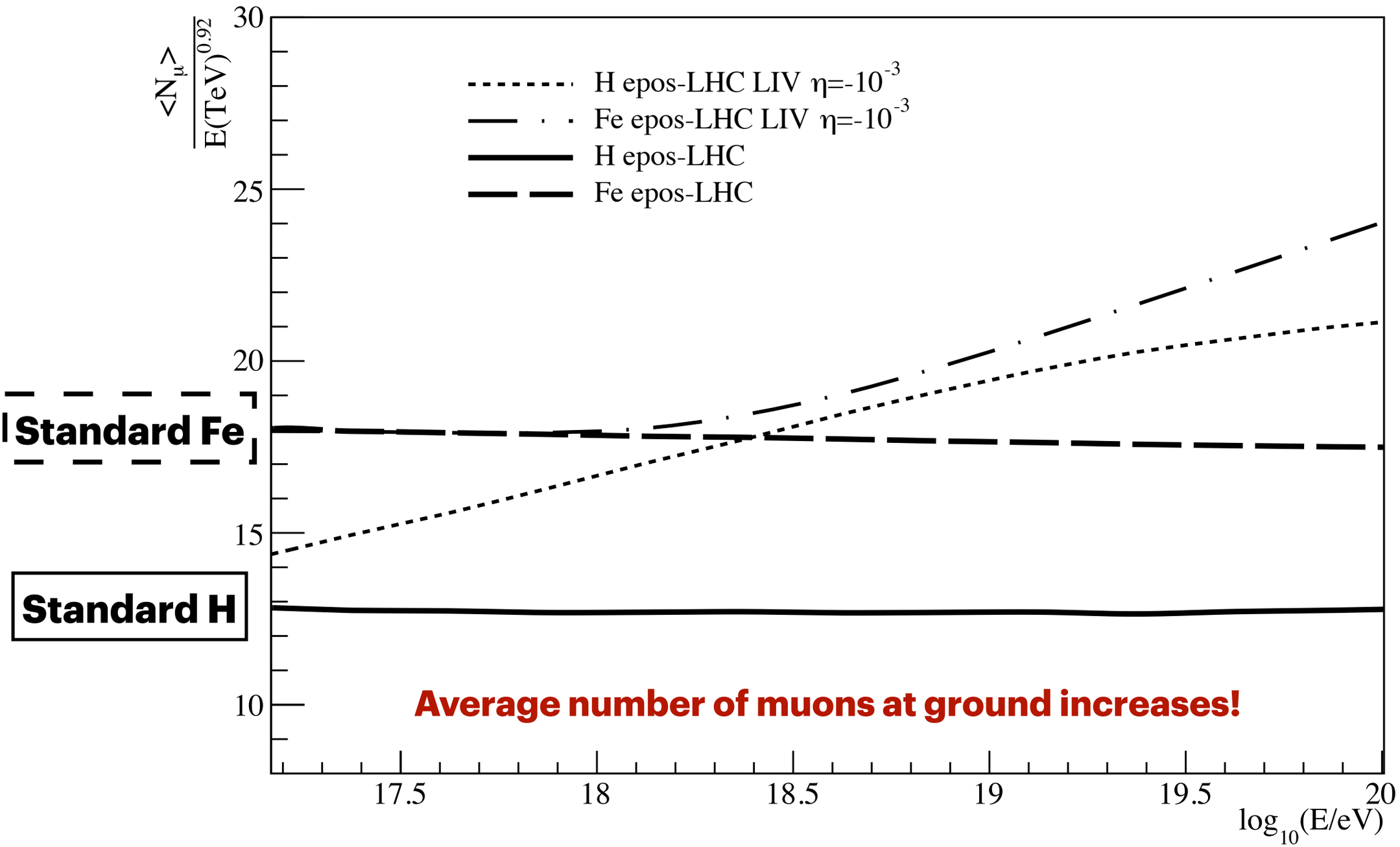
Average number of muons



ORDER OF LIV n=1
EPOS-LHC
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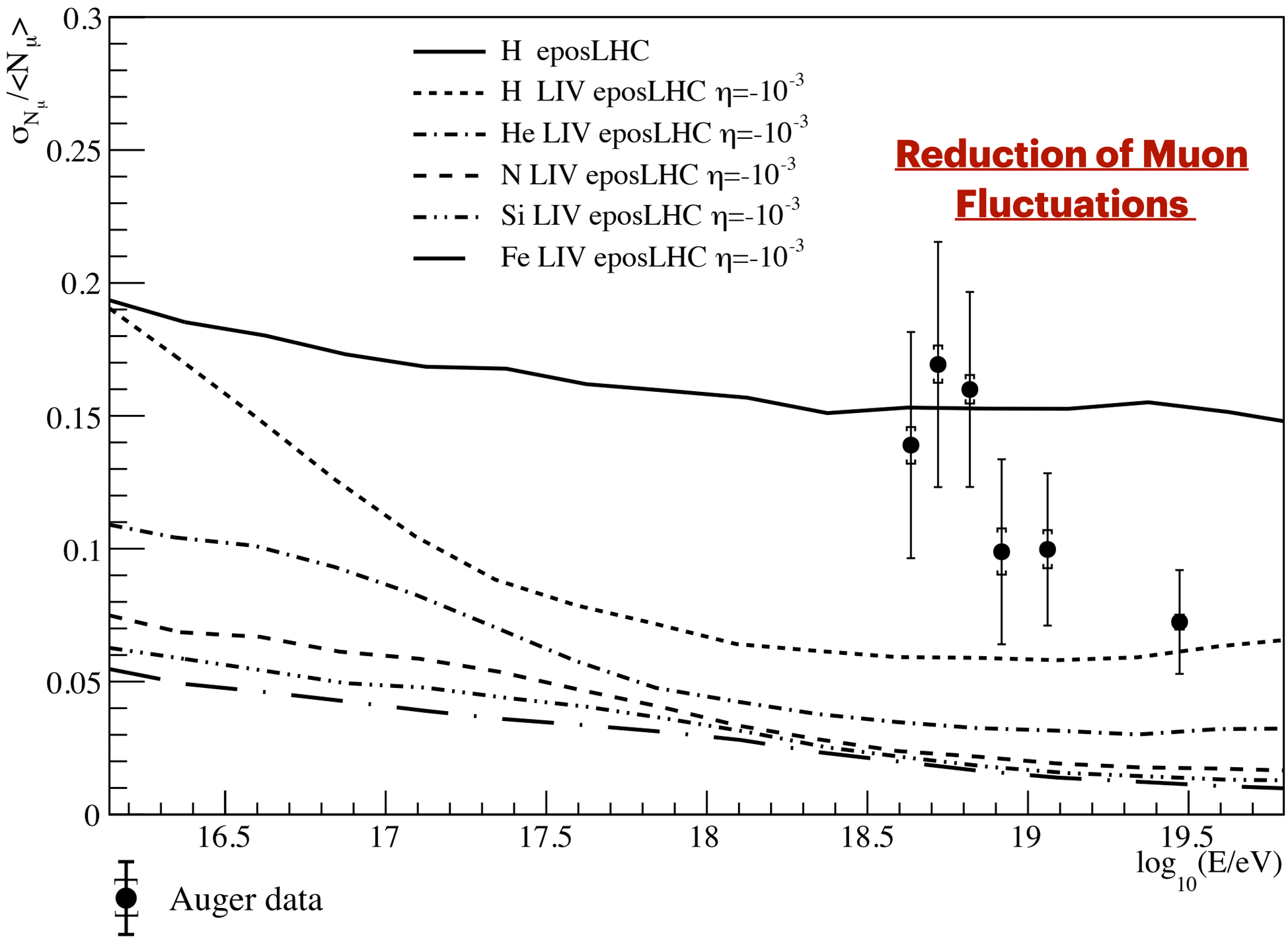
Relative Fluctuations

Ratio of the fluctuations to the average number of muons



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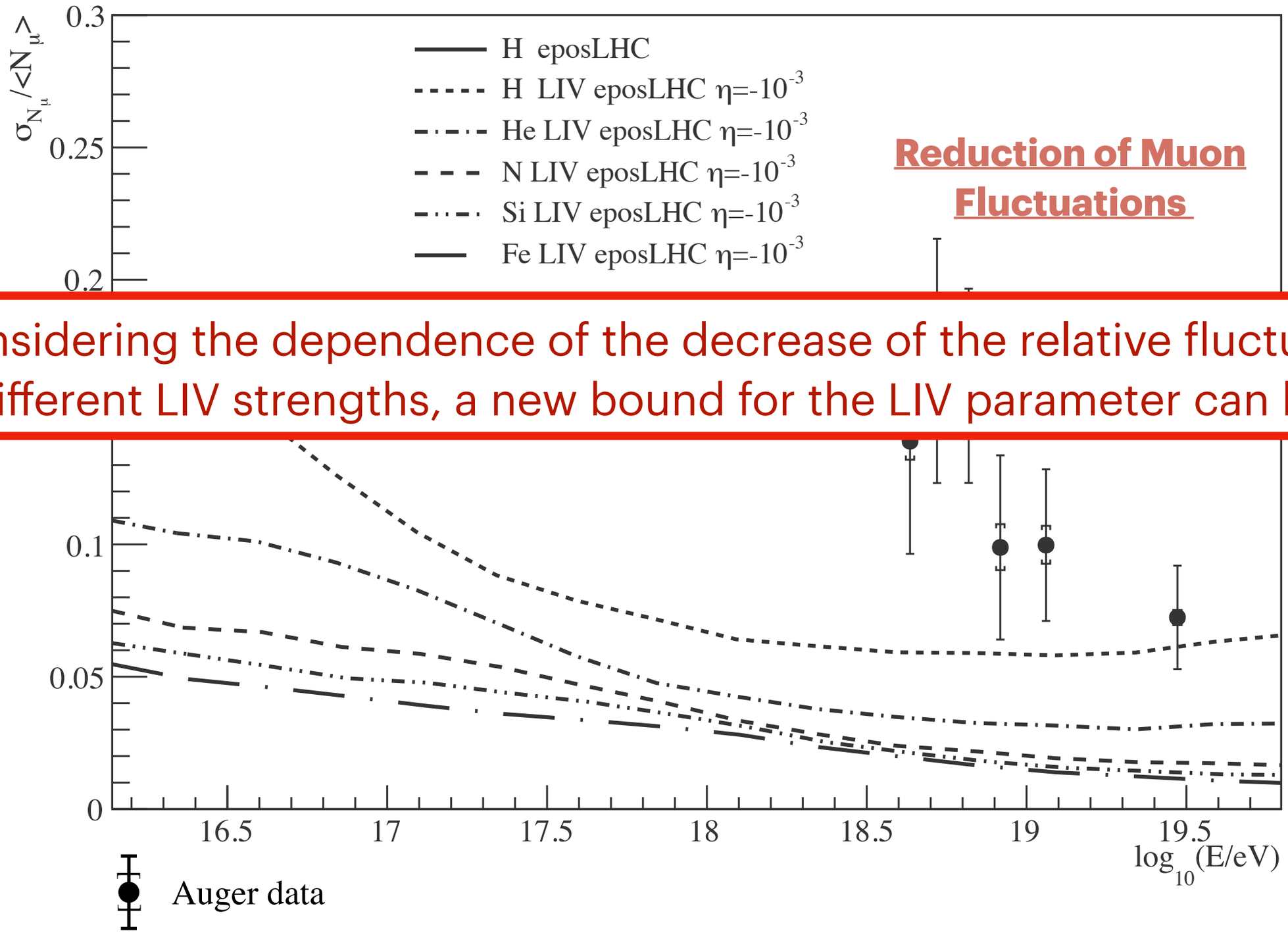


Reduction of Muon Fluctuations

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

Looking for… the most conservative relative Fluctuations

Which combination of primaries gives the most conservative LIV model?

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

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

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

$1-\alpha$ is the fraction of proton

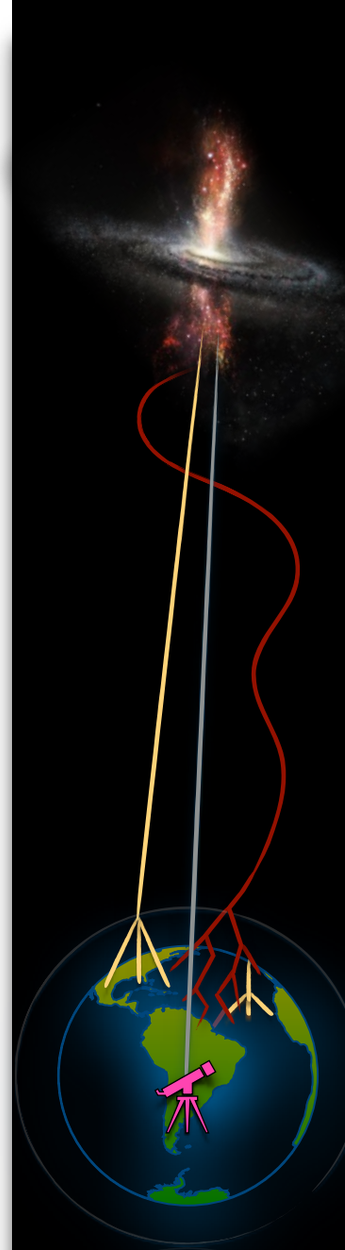
α is the fraction of iron

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

for any LIV parameter value we can calculate the most conservative LIV relative fluctuations as a function of the energy without repeating any shower simulation

We found $\max_\alpha \frac{\sigma_\mu}{\langle N_\mu \rangle} = \frac{\sqrt{RMS^2(N_\mu)(\alpha)}}{\langle N_\mu \rangle(\alpha)}$ wrt α

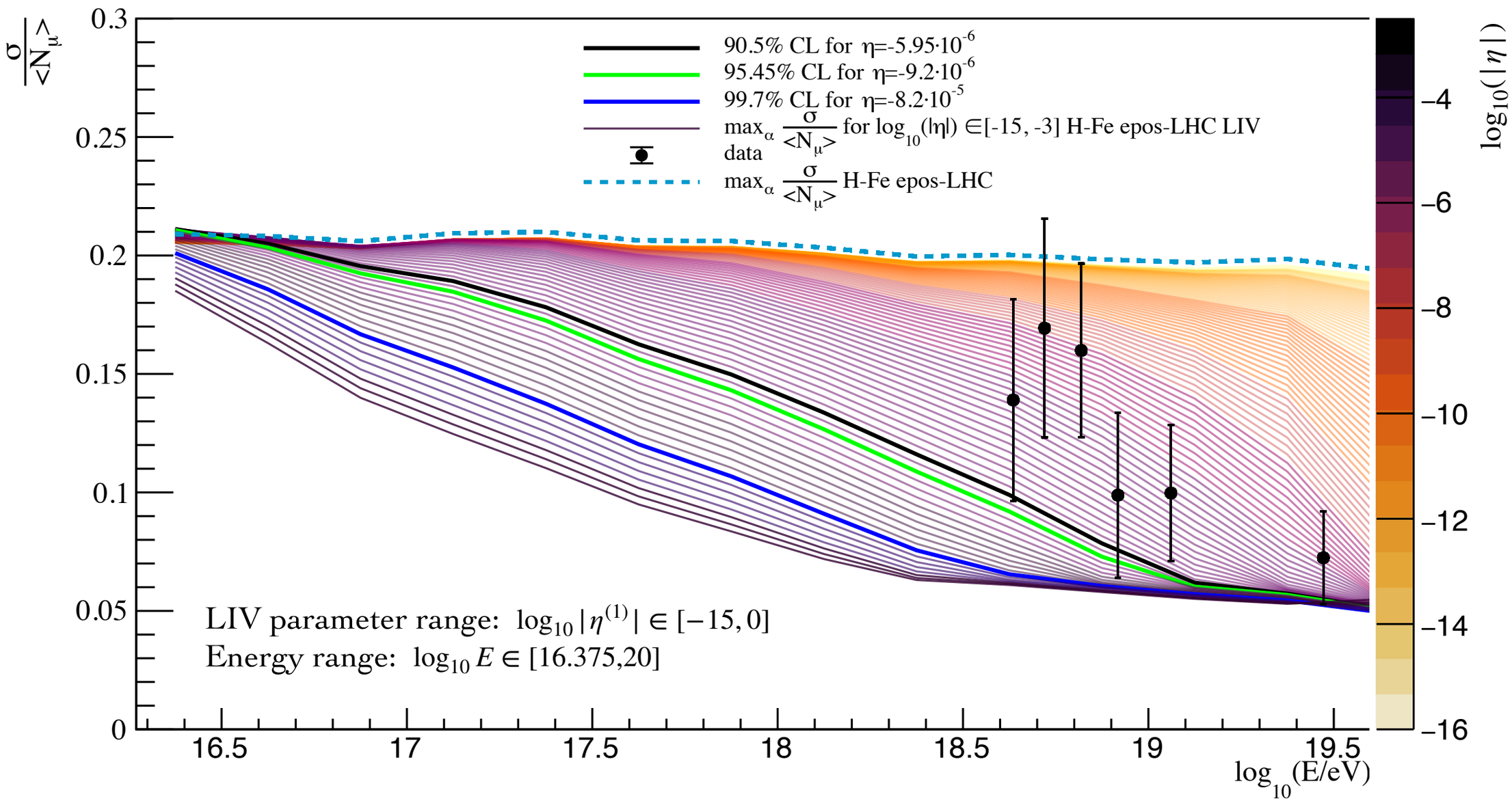
*
$$\langle N_\mu \rangle_{\text{mix}}(\alpha;\eta) = (1-\alpha)\langle N_\mu \rangle_p + \alpha \langle N_\mu \rangle_{Fe}$$
$$\sigma^2(N_\mu)_{\text{mix}}(\alpha;\eta) = (1-\alpha)\sigma^2(N_\mu)_p + \alpha\sigma^2(N_\mu)_{Fe} + (\alpha(1-\alpha)(\langle N_\mu \rangle_p - \langle N_\mu \rangle_{Fe})^2$$

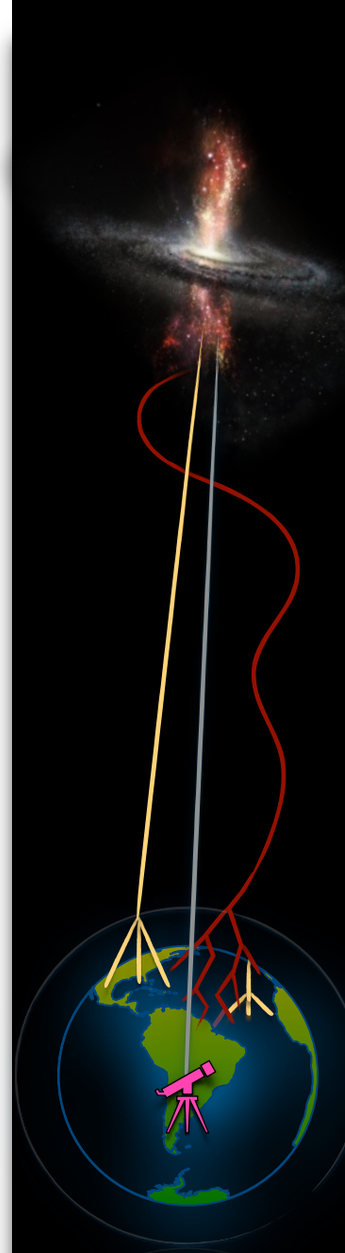


Maximum Mixed Relative Fluctuations

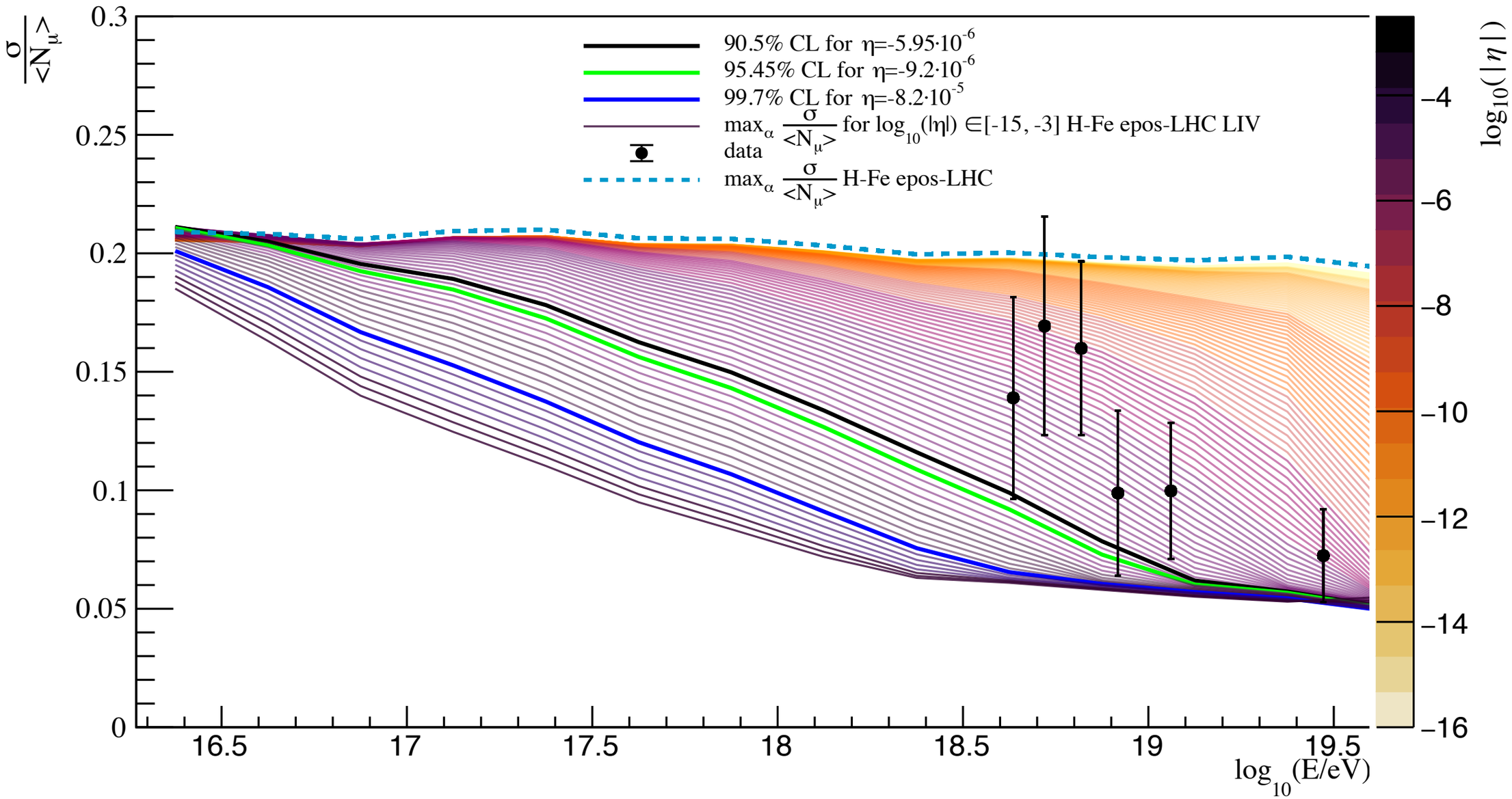
for any LIV parameter value we can calculate the most conservative LIV relative fluctuations as a function of the energy without repeating any shower simulation

Parameterized function $\max_{\alpha} \frac{\sigma_\mu}{\langle N_\mu \rangle} = \frac{\sqrt{RMS^2(N_\mu)(\alpha)}}{\langle N_\mu \rangle(\alpha)}$ wrt α





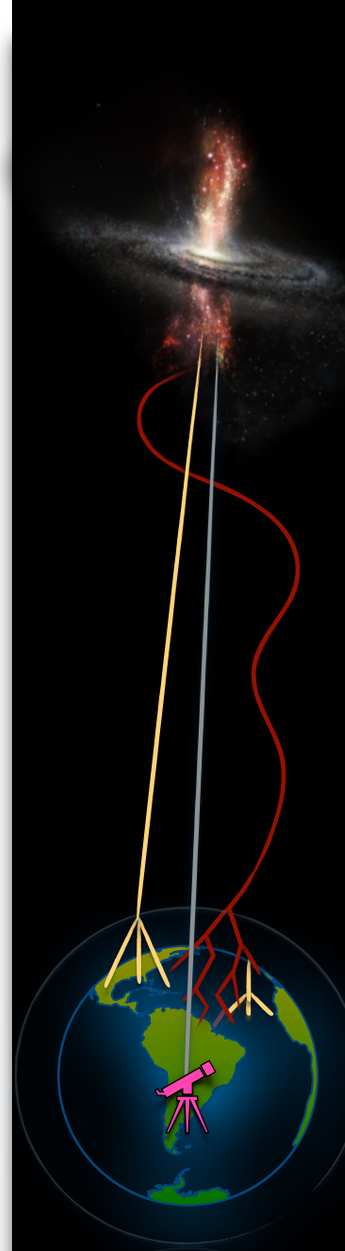
Most conservative Mixed Relative Fluctuations



χ^2 is calculated as a function of η considering all the data points

↓

Continuous confidence levels to exclude LIV models



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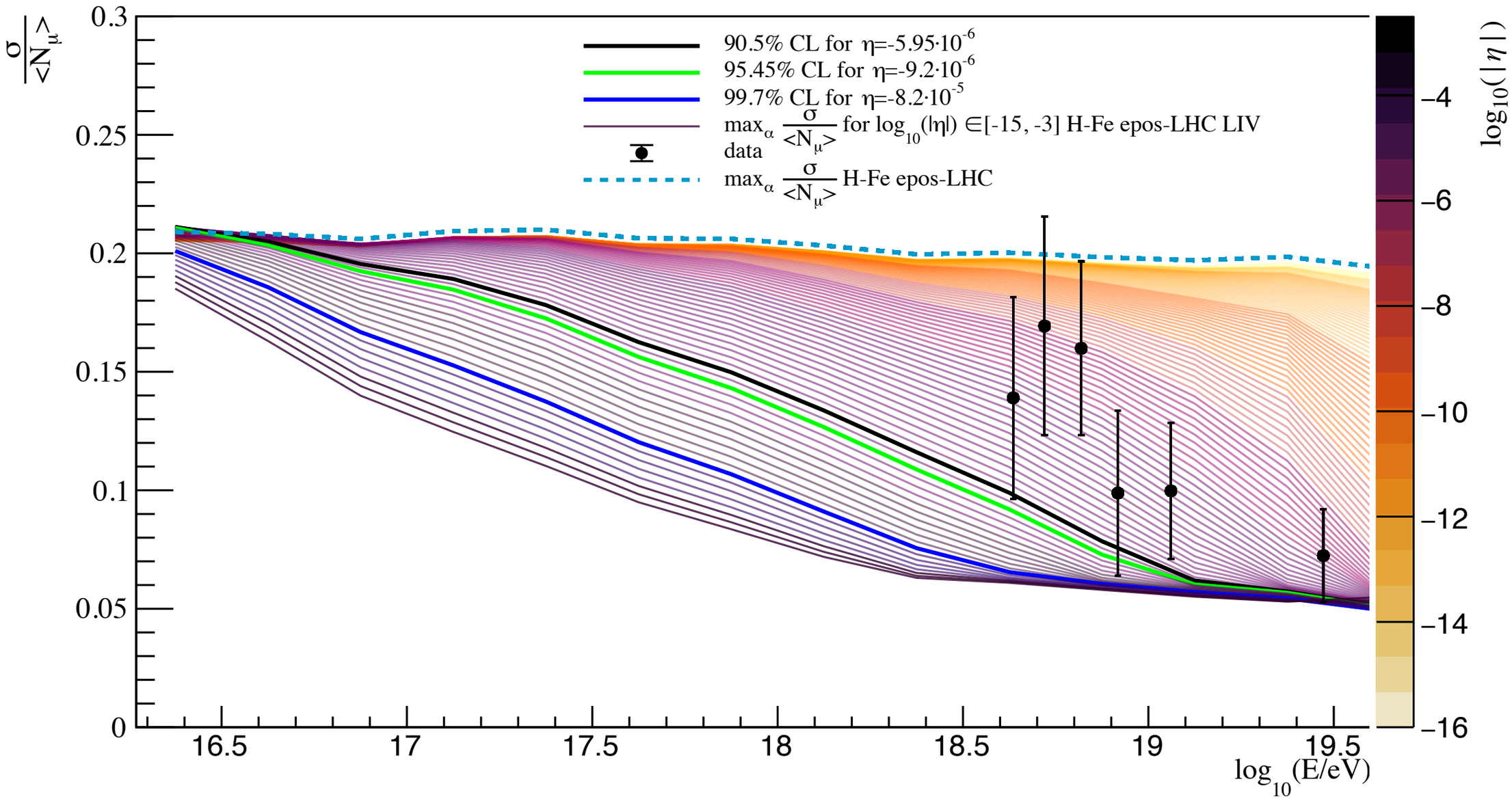
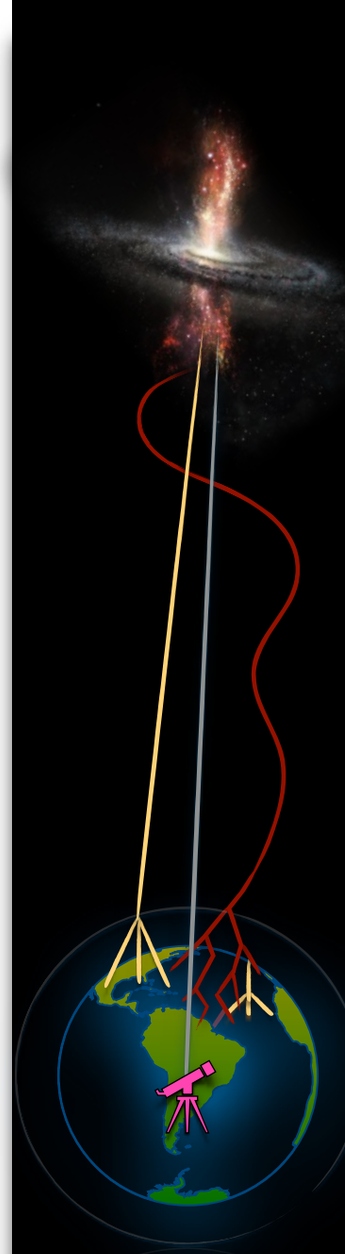


New bound!

$\eta^{(1)} > -5.95 \cdot 10^{-6}$ with (90.5% C.L.)



Summary

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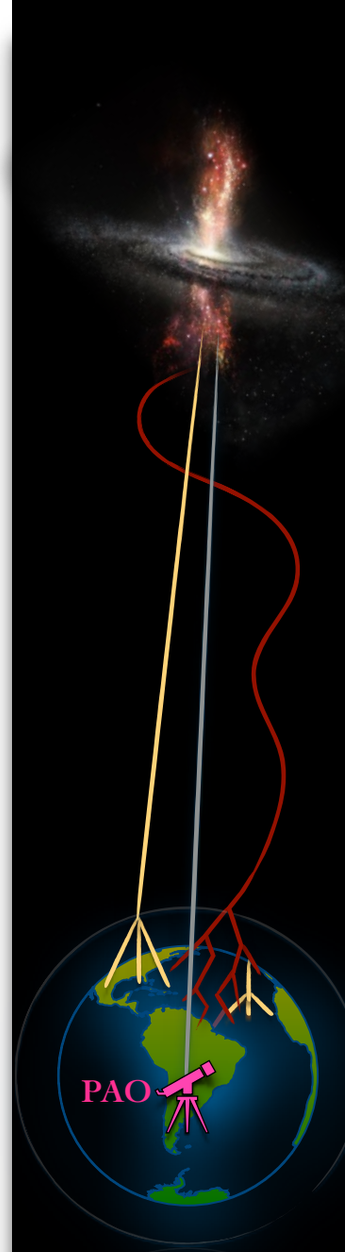
- For the first time LIV effects have been studied considering muon fluctuations;
- Using the parameterization we obtain the muon fluctuation as a function of energy without shower simulations;
- We found α that corresponds to the most conservative H-Fe mixed case;
- Using the parameterization we obtained a new bound for LIV parameter values;

Future prospects

- Limits on η parameter could be found through a combined analysis considering simultaneously muon content distribution and the mass composition derived from the $X_{\max}$ measurements;
- Future works will involve other hadronic interaction models as QGSJETII-04 and SiBYLL 2.3d;
- This analysis published soon
- Other works within PAO PoS ICRC (2015) 521 PoS ICRC (2017) 561 PoS ICRC (2019) 327

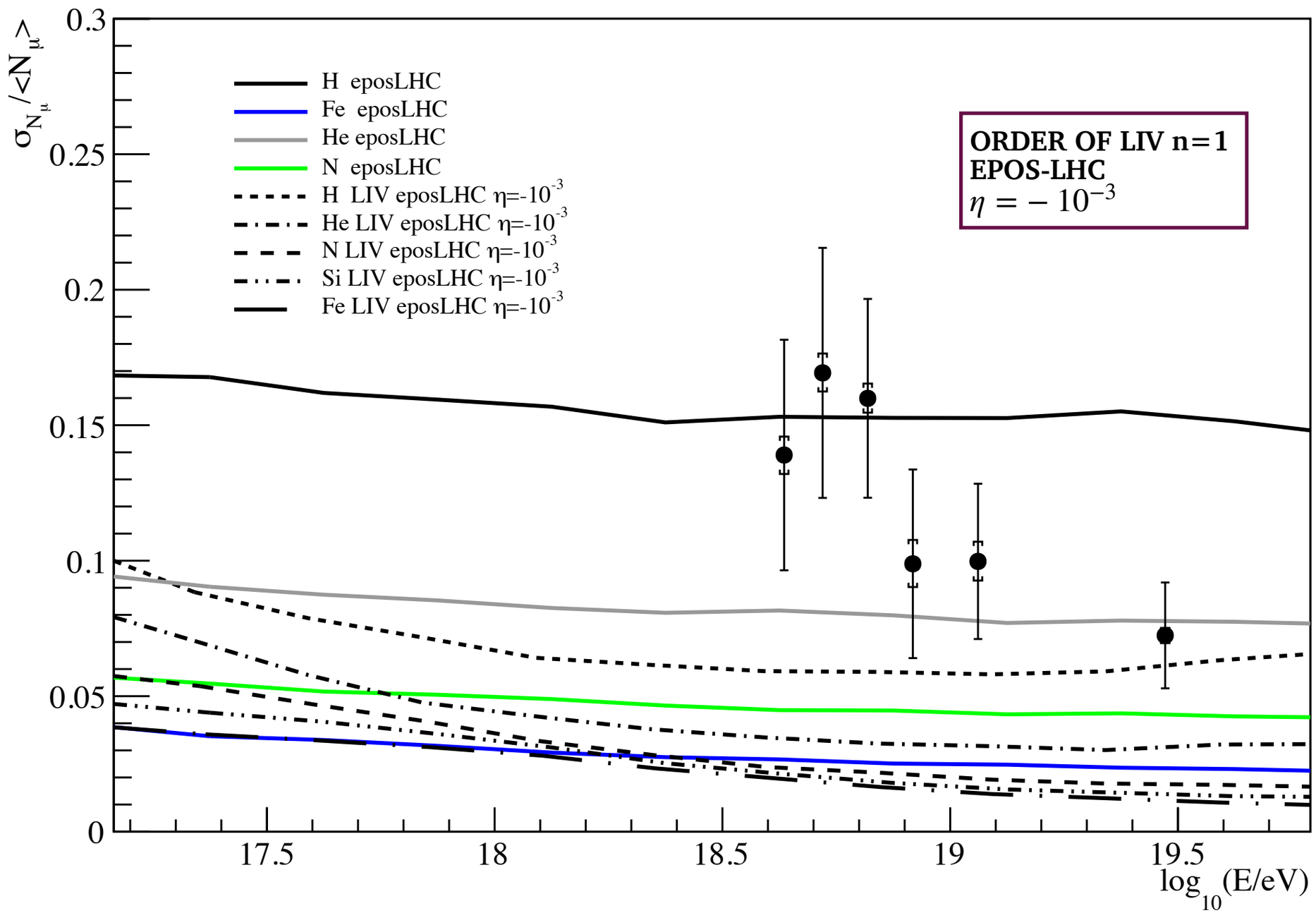


Thank you for your attention!

Backup

Muon Fluctuations

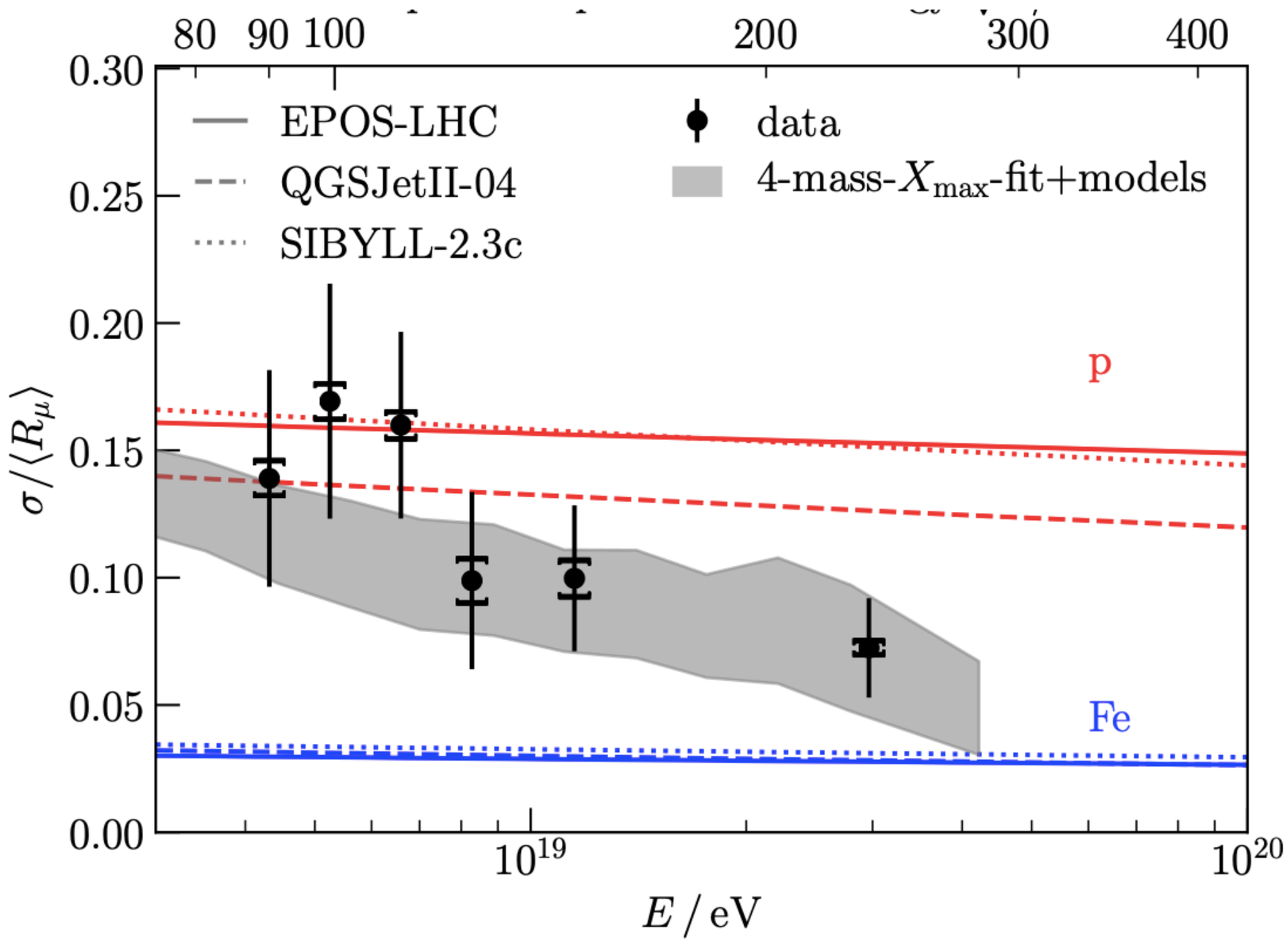
- **<u>In the standard case:</u>** $\frac{N_\mu}{\langle N_\mu \rangle} = \alpha_1 \ldots$ **—> for primary particle with mass A** $\frac{N_\mu}{\langle N_\mu \rangle} = \frac{\alpha_1}{A} \ldots$
- in the presence of LIV **<u>Reduction of Muon Fluctuations:</u>** the proton is behaving as a heavier nucleus and the fluctuations decrease

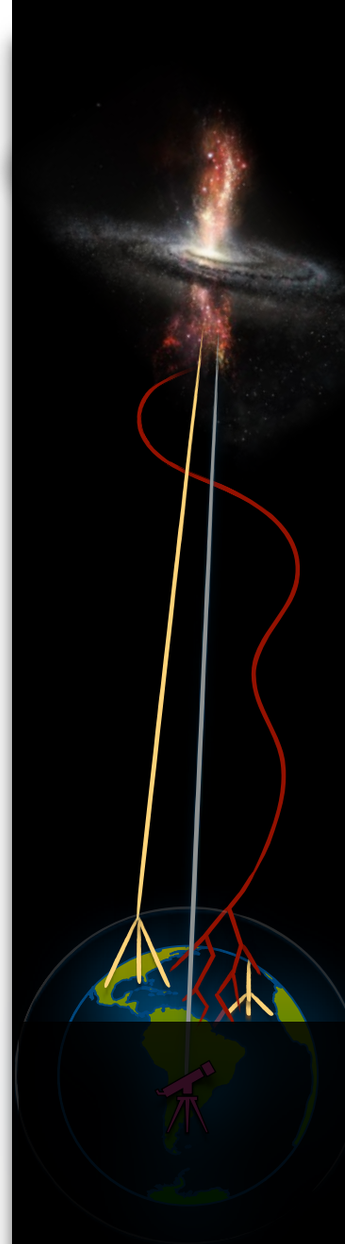


Relative Fluctuations

<u>In the standard case:</u> $\frac{N_\mu}{\langle N_\mu \rangle} = \alpha_1 \,..$ —> **for primary particle with mass A** $\frac{N_\mu}{\langle N_\mu \rangle} = \frac{\alpha_1}{A} \,..$

$\langle N_\mu(E) \rangle = m^g = CE^\beta$ —> $\sigma(m_i) = \frac{\sigma(m)}{\sqrt{N_{i-1}}}$ —> the fluctuations are mostly dominated by the first interaction!





Neutral pion decay

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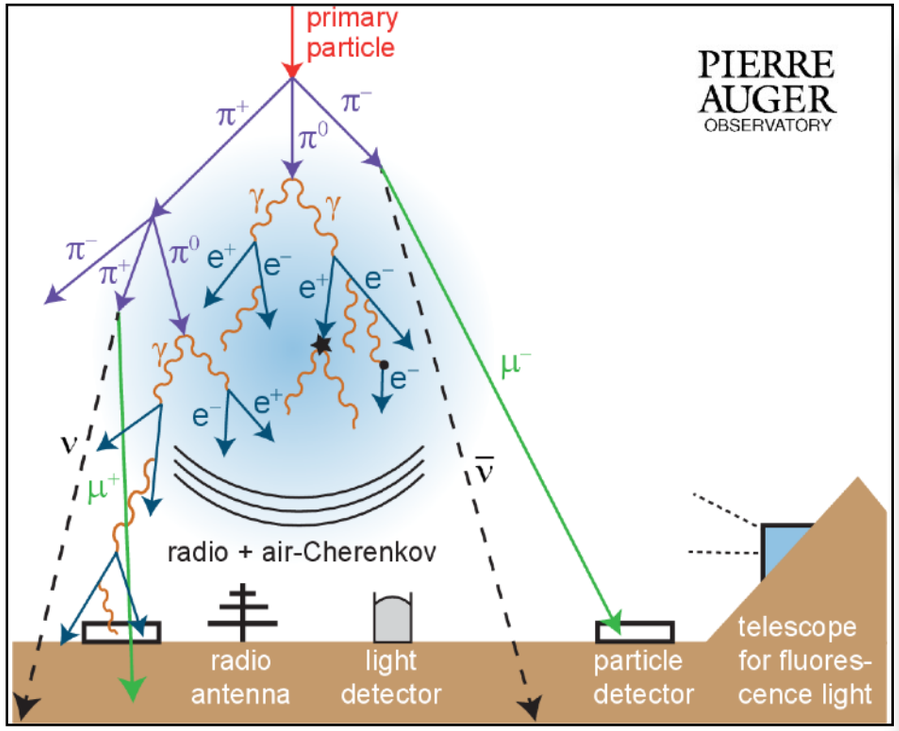
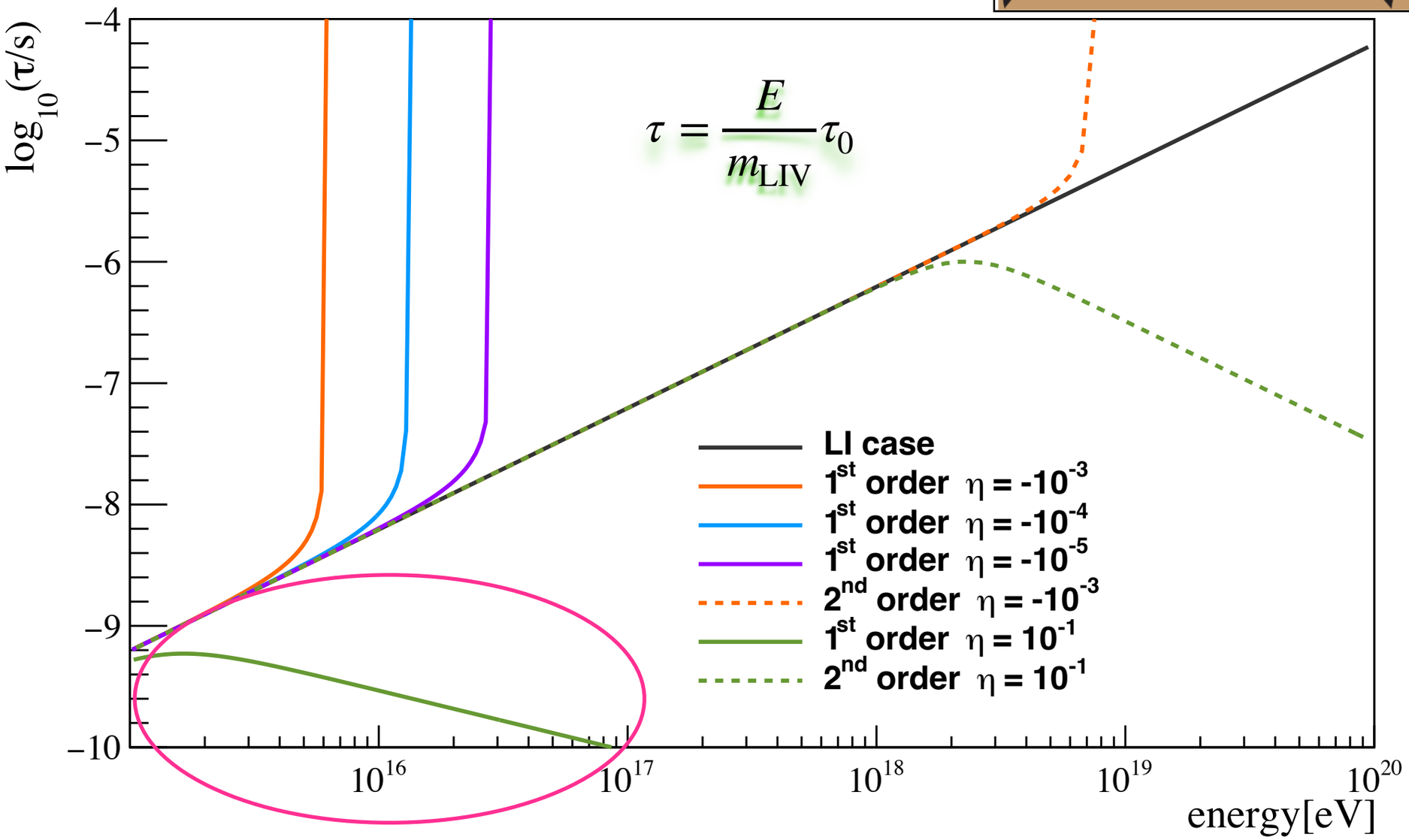


If η_π assumes positive values!

Negligible effects are observed!



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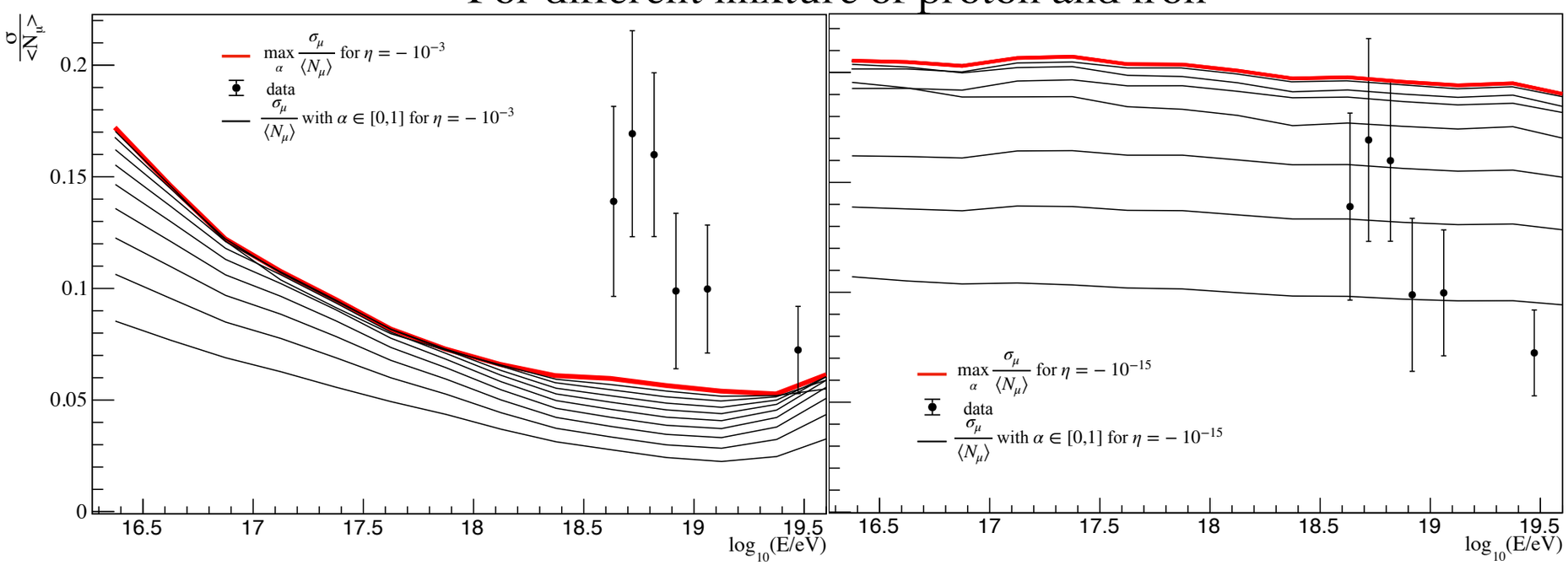
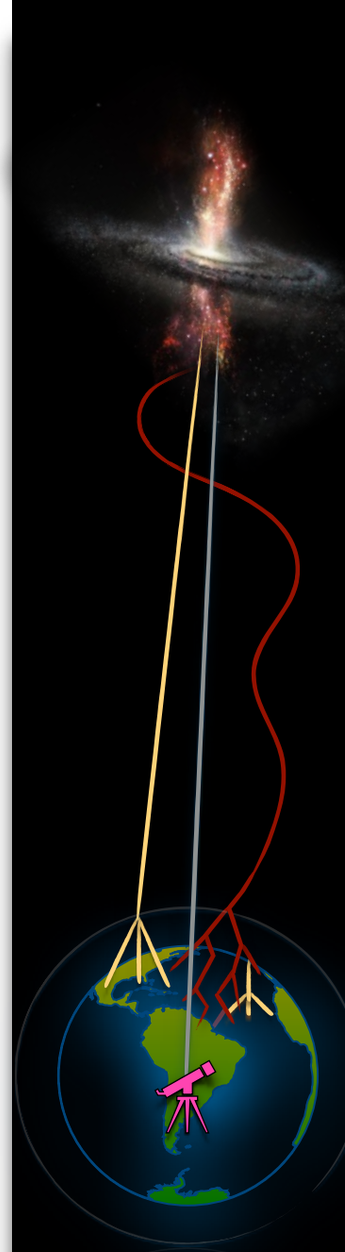
3. Parametrize as **function of η and energy** $\langle N_\mu \rangle_p$, $\langle N_\mu \rangle_{Fe}$, $\sigma(N_\mu)_p$ and $\sigma(N_\mu)_{Fe}$

For different mixture of proton and iron

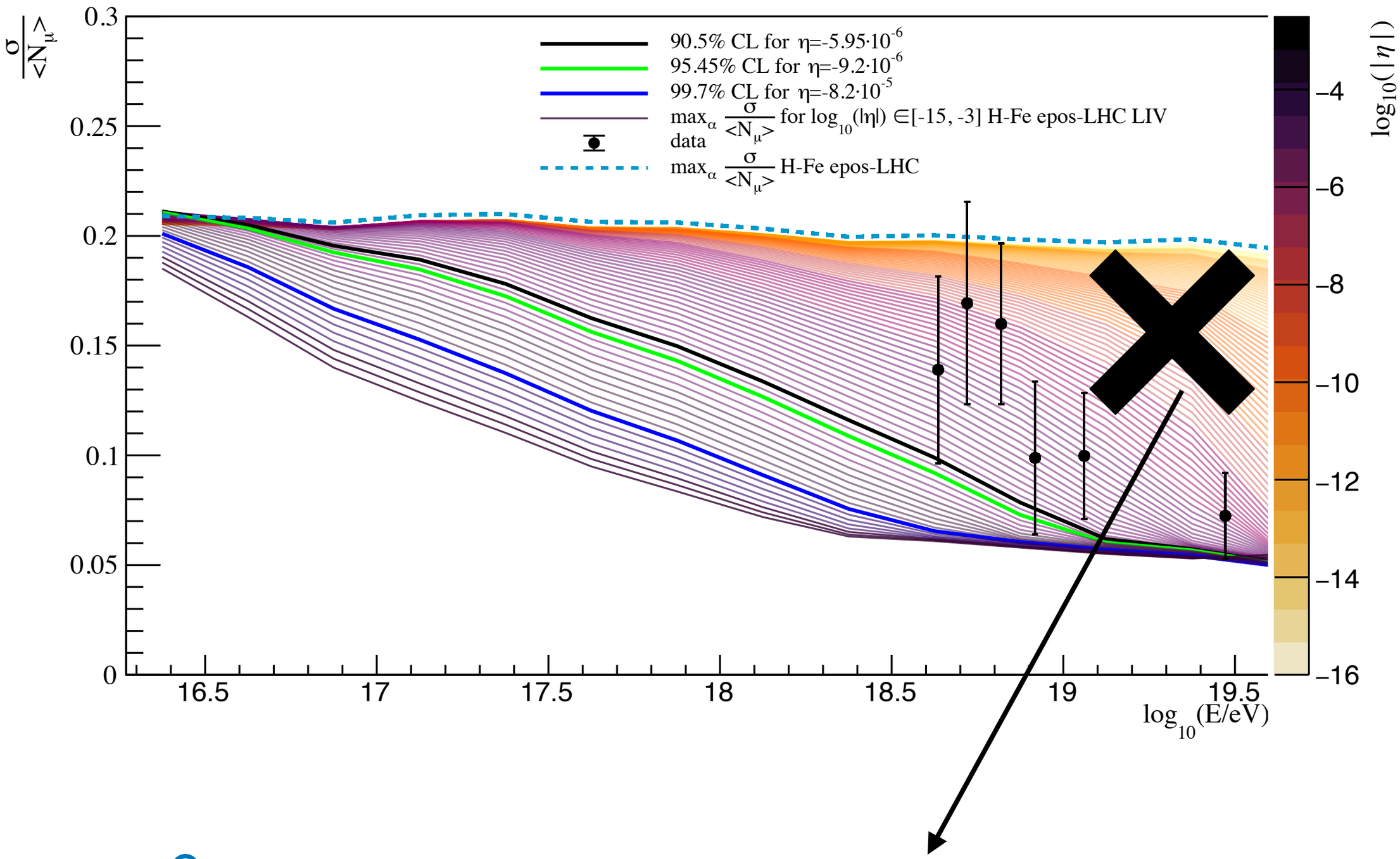


The maximum wrt α curve is always above the curves given by any other α combinations

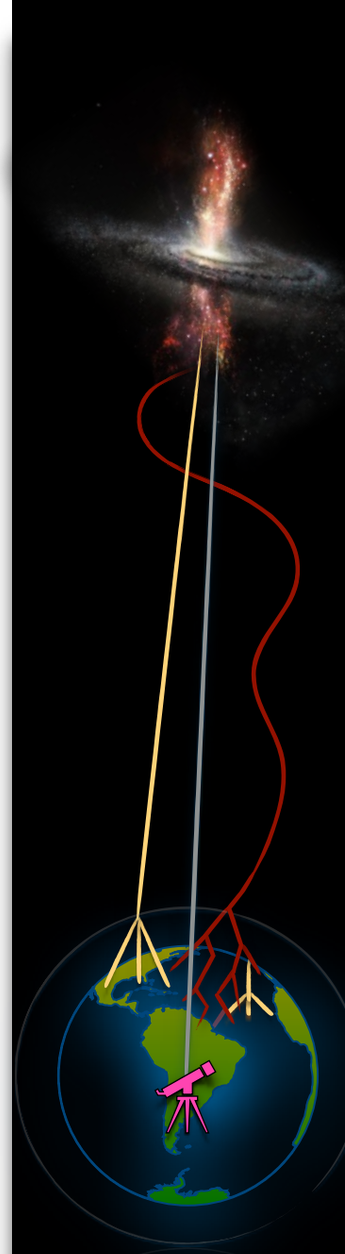
Only if the fluctuations stand below the data the $\max_\alpha \frac{\sigma_\mu}{\langle N_\mu \rangle}$ is the most conservative LIV model



Most conservative Mixed Relative Fluctuations



Only if the fluctuations stand below the data the $\max_\alpha \frac{\sigma_\mu}{\langle N_\mu \rangle}$ is the most conservative LIV model

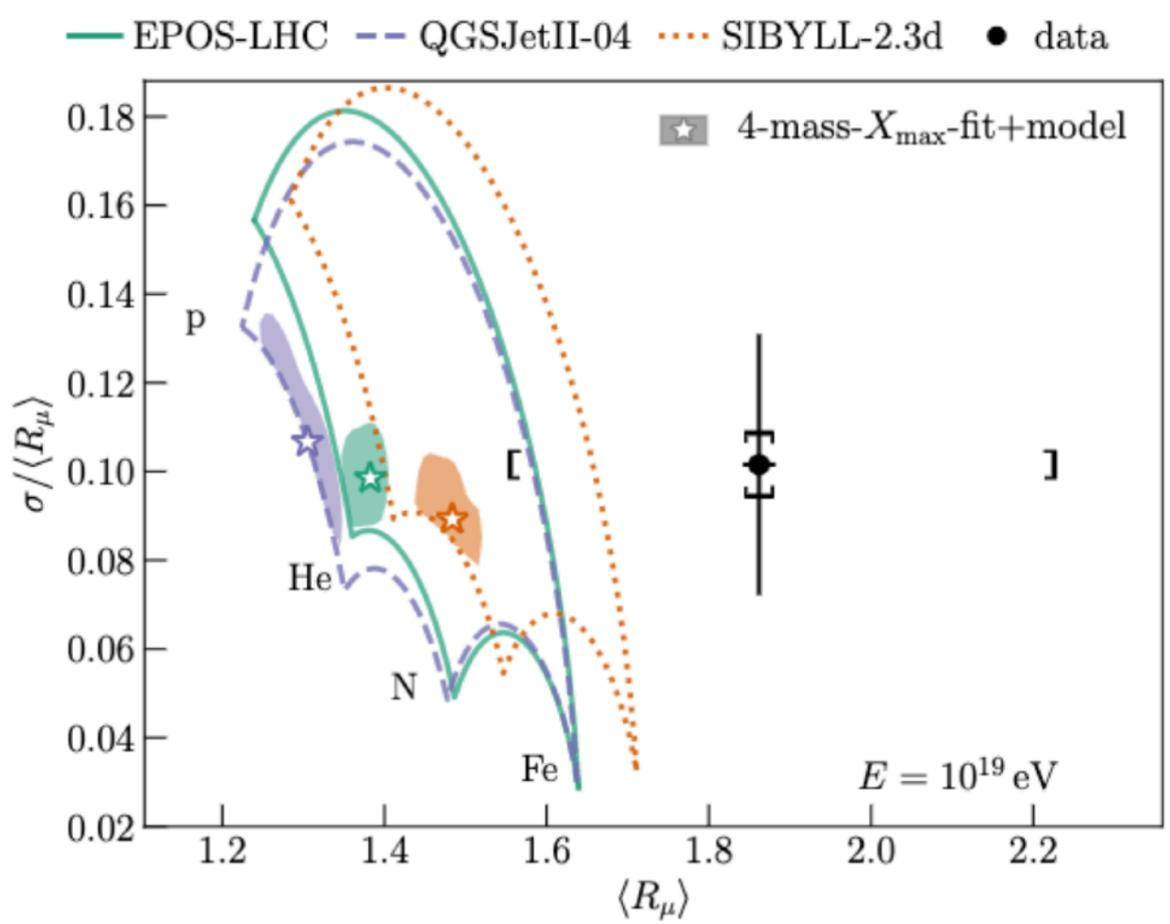


Relative Fluctuations

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

See GAP-notes GAP 2011-118

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

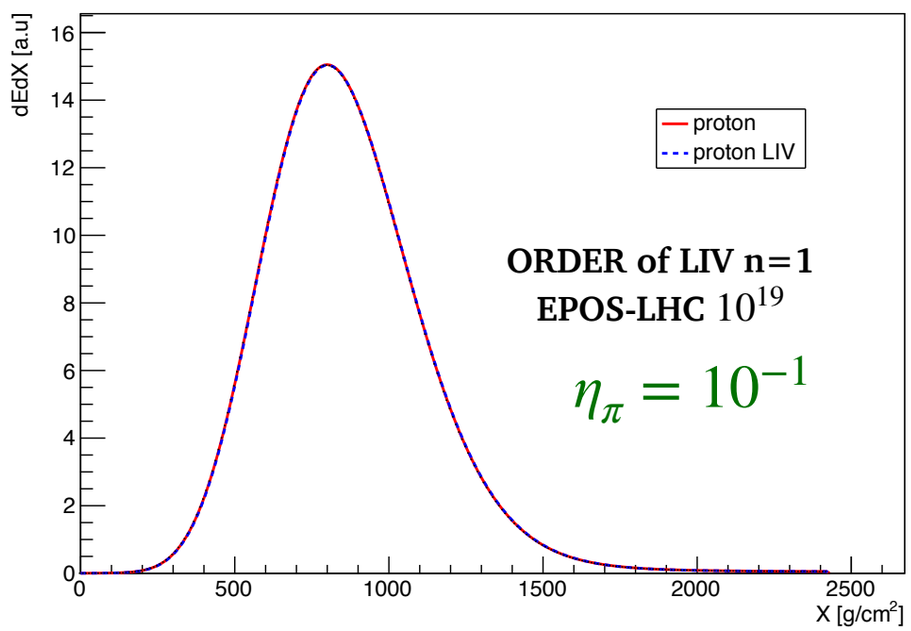
$$\sigma^2(N_\mu)_{\text{mix}}(\alpha;\eta) = (1-\alpha)\sigma^2(N_\mu)_p + \alpha\sigma^2(N_\mu)_{Fe} + (\alpha(1-\alpha)(\langle N_\mu \rangle_p - \langle N_\mu \rangle_{Fe})^2$$

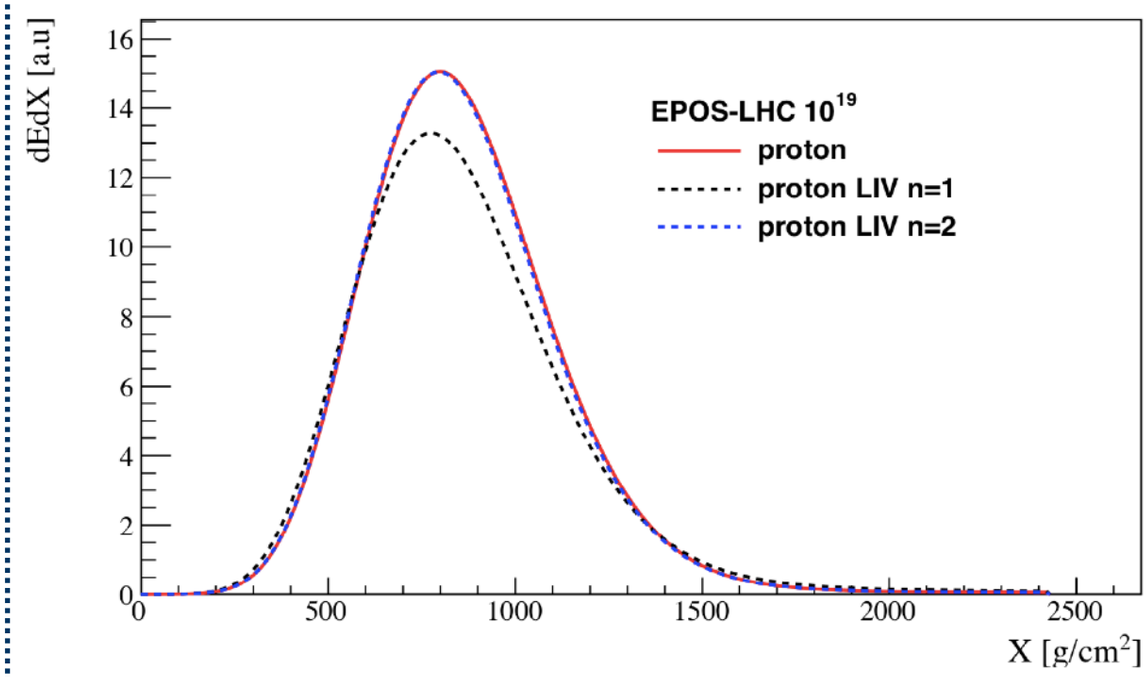
$1-\alpha$ is the fraction of proton

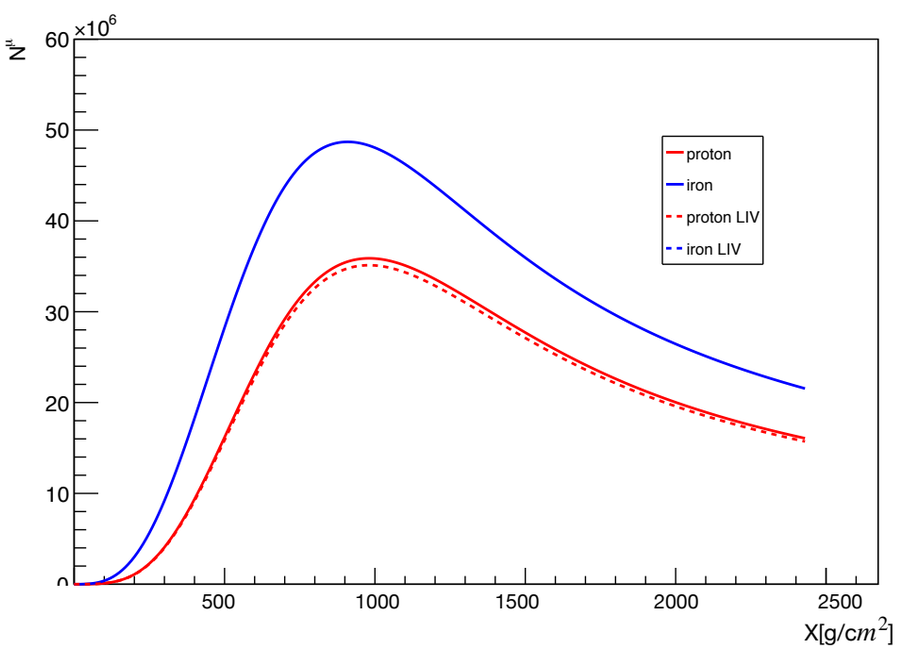
α is the fraction of iron

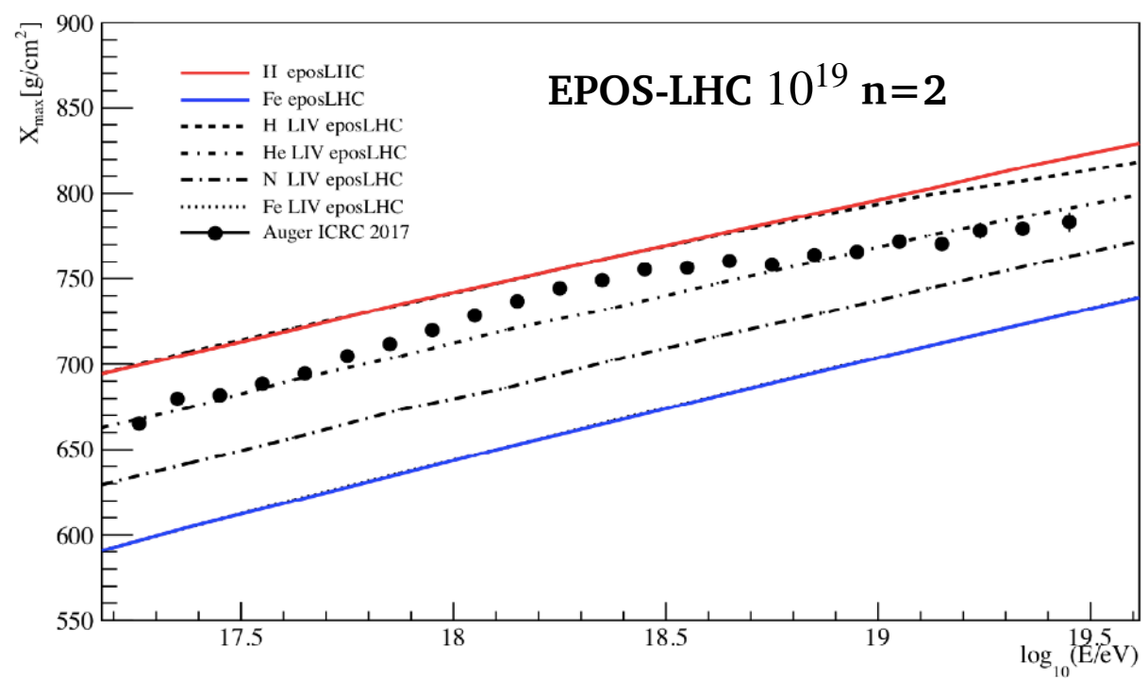
$\eta_\pi > 0$

LIV SECOND ORDER





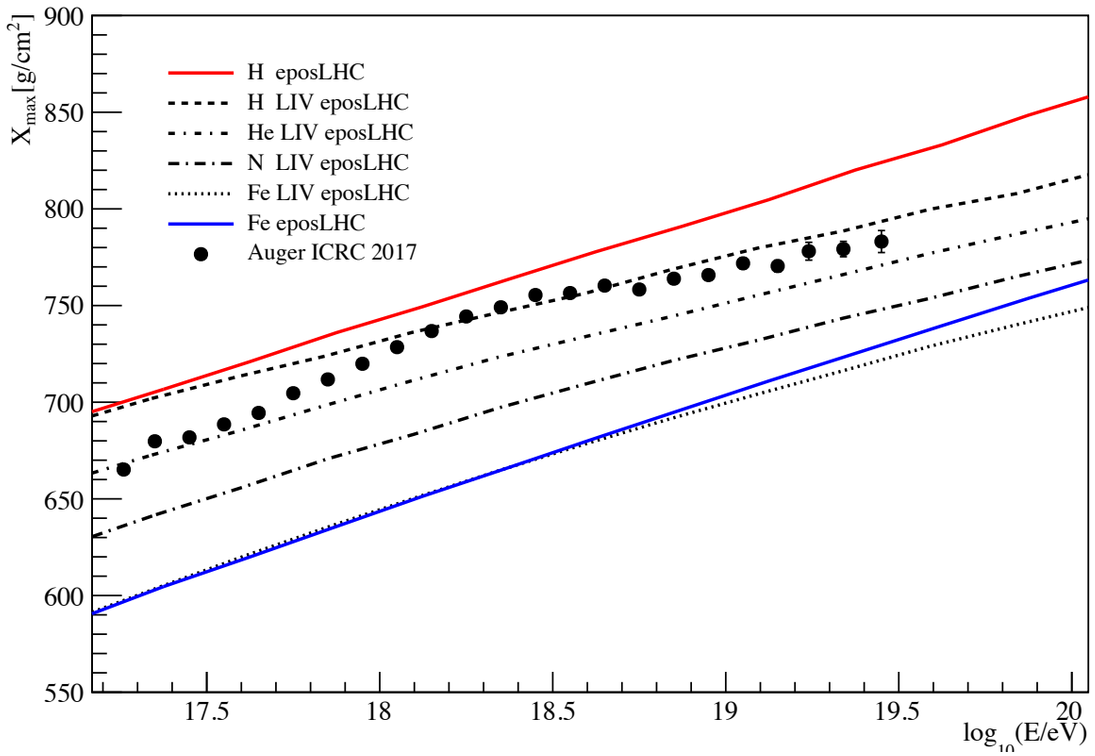


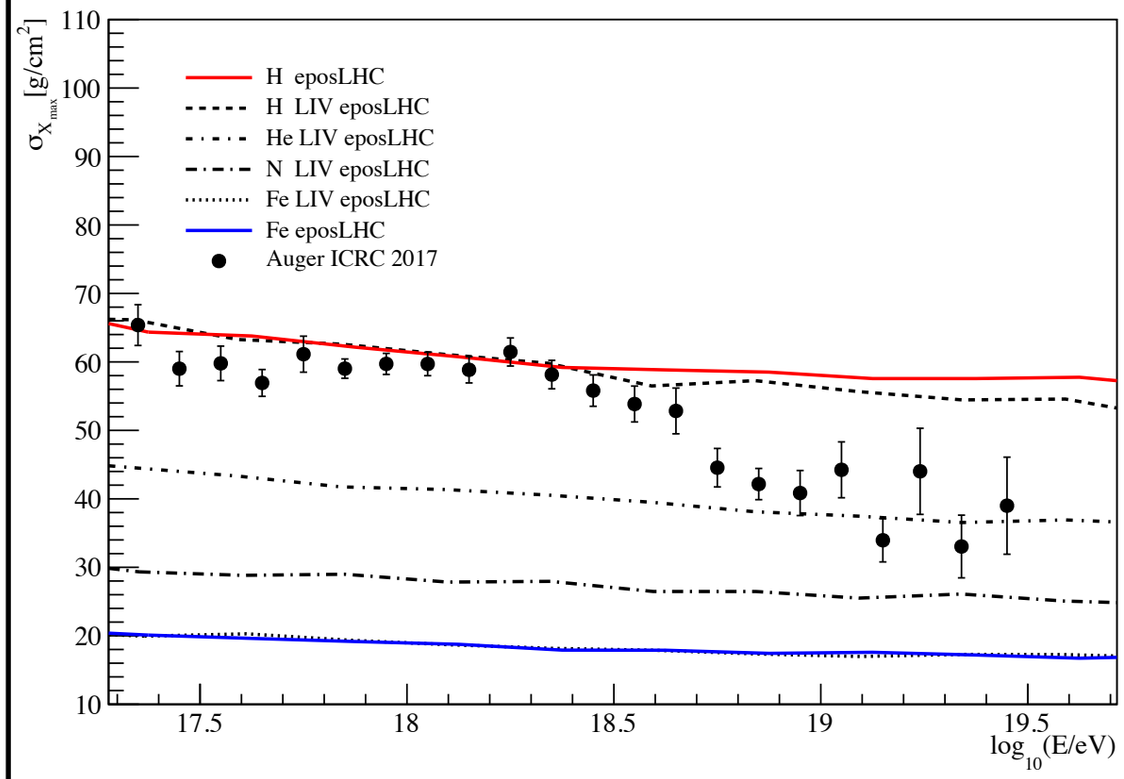


$\langle X_{max} \rangle$

ORDER OF LIV n=1
EPOS-LHC
$\eta = -10^{-3}$
at 10^{19} eV

$\sigma_{X_{max}}$





Shift of position of the maximum X_{max}

More protons expected for LIV at 1st order