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Constraining LIV using the muon content of extensive air showers

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ICRC 2021

For the first time, LIV effects have been studied using the **muon fluctuation** of extensive air showers measured at the Pierre Auger Observatory!

New Limits on LIV parameters have been derived

How to break Lorentz Invariance

<u>Modified dispersion relation</u>

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

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

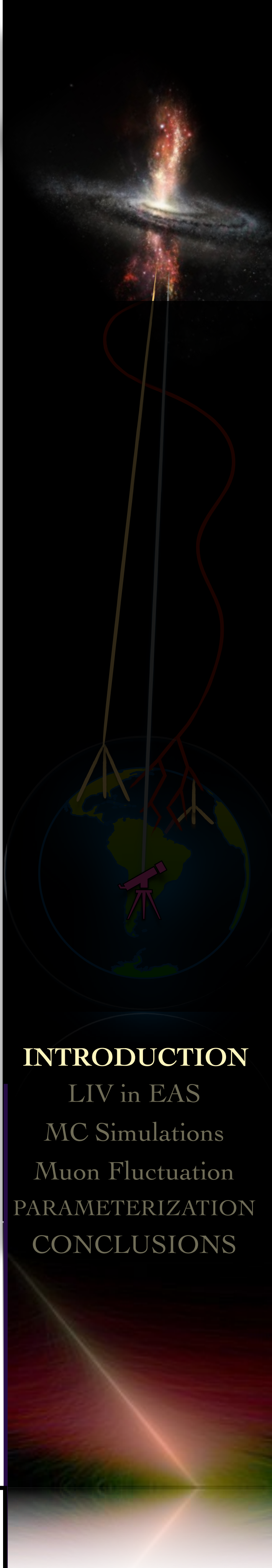
With $\eta_A = \eta / A^2$

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: $\tau = \gamma_{\mathrm{LIV}} \tau_0$



How to break Lorentz Invariance

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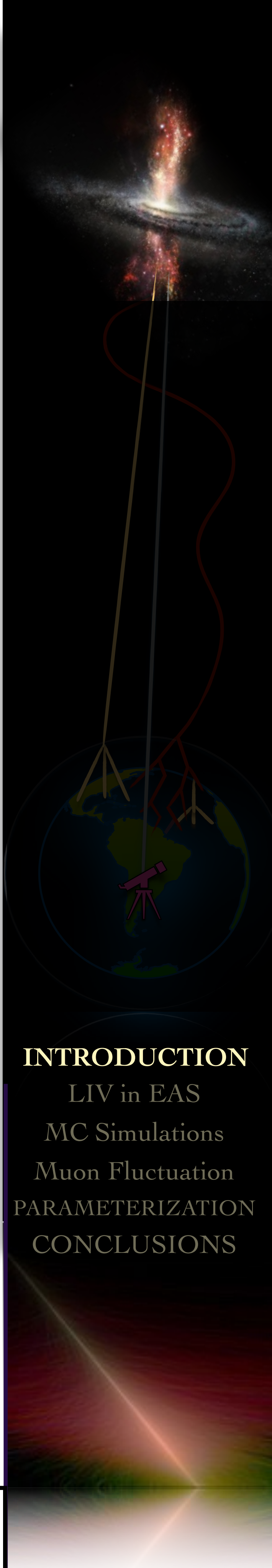
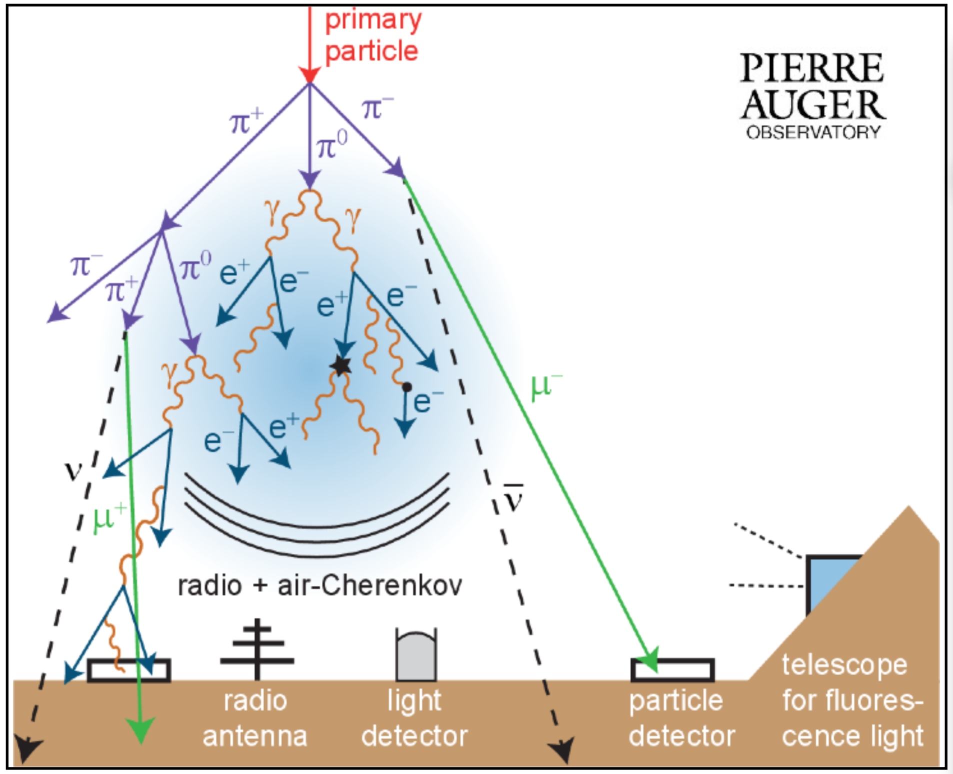
In terms of the lifetime τ of particles: $\tau = \gamma_{\text{LIV}} \tau_0$

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



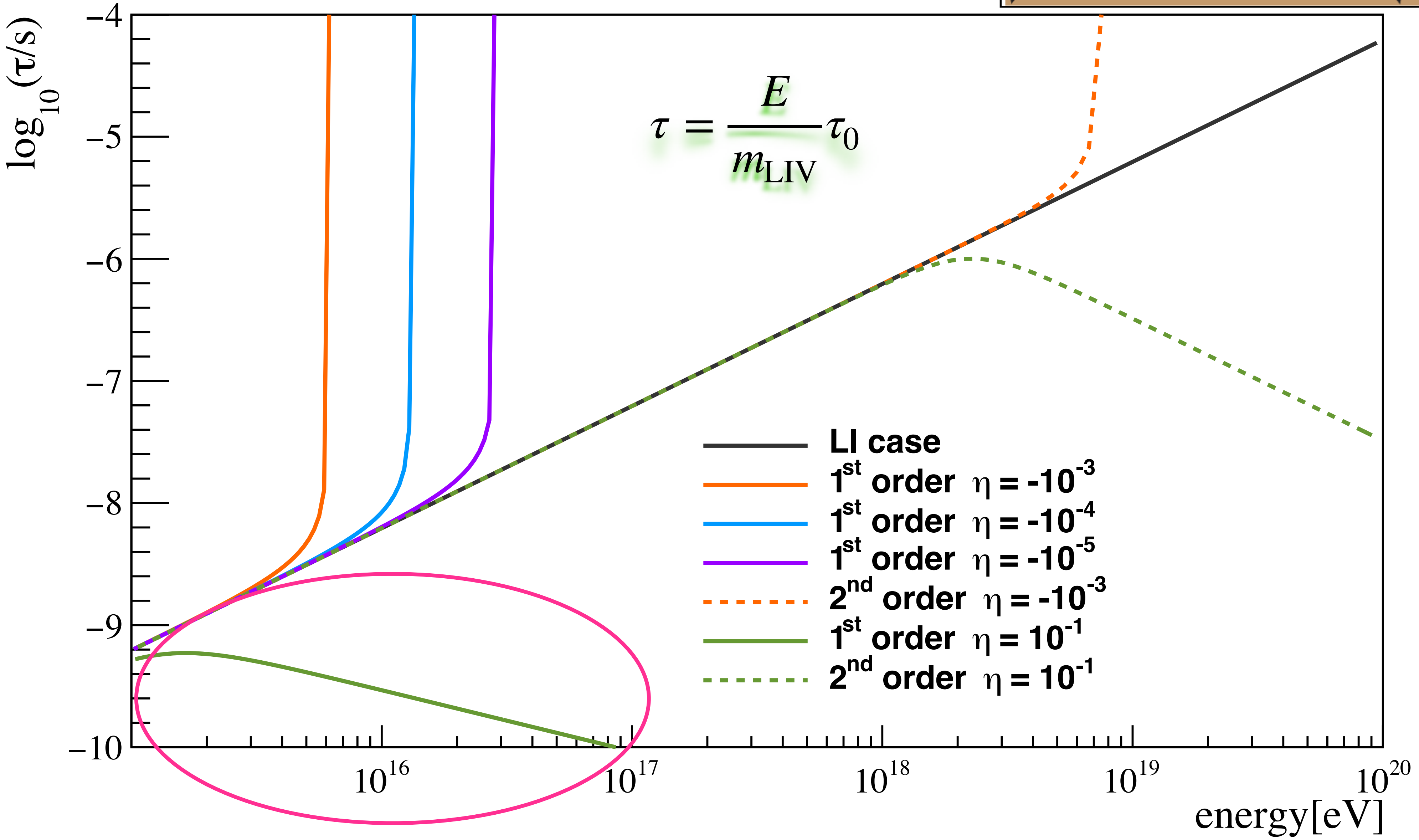
Neutral pion decay

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



If η_π assumes positive values!

Negligible effects are observed!



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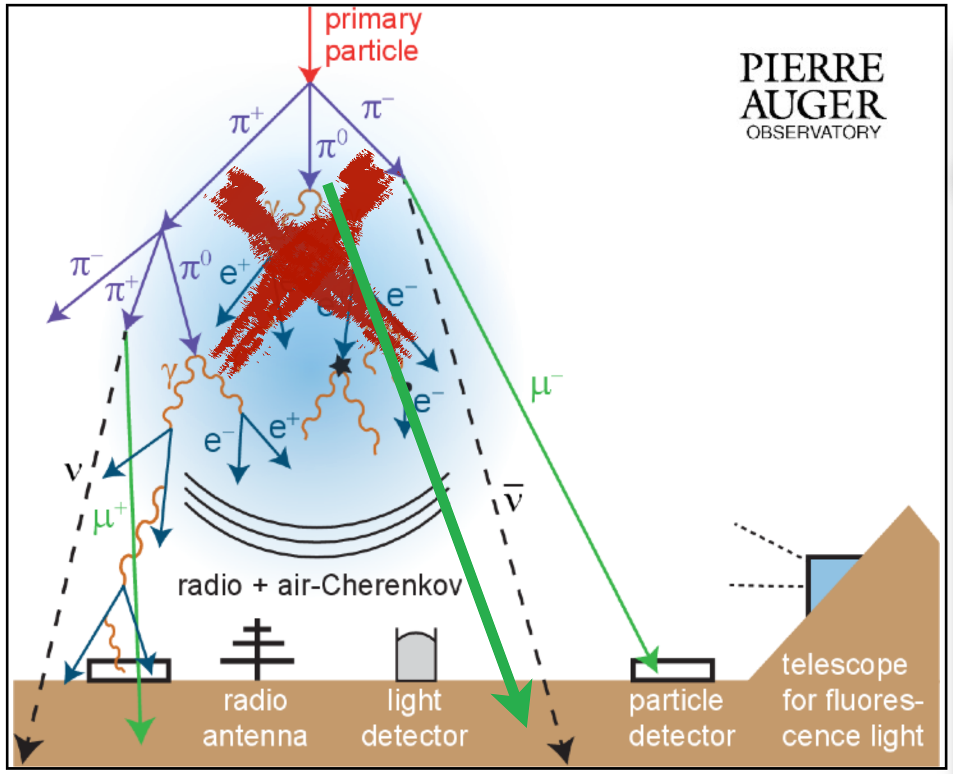
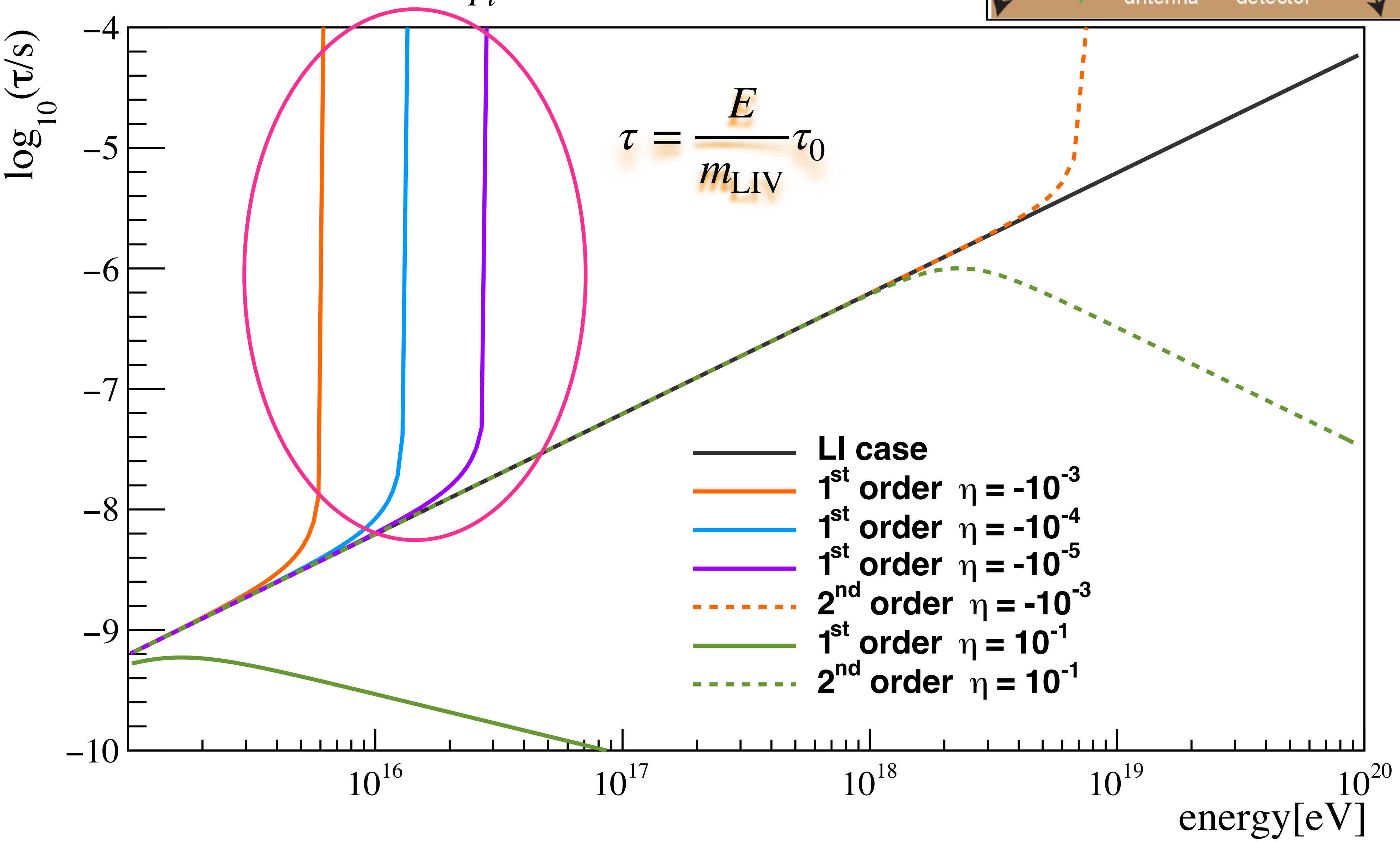


If η_π assumes negative values!

The decay is forbidden if:

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



What to expect…

$\eta < 0$

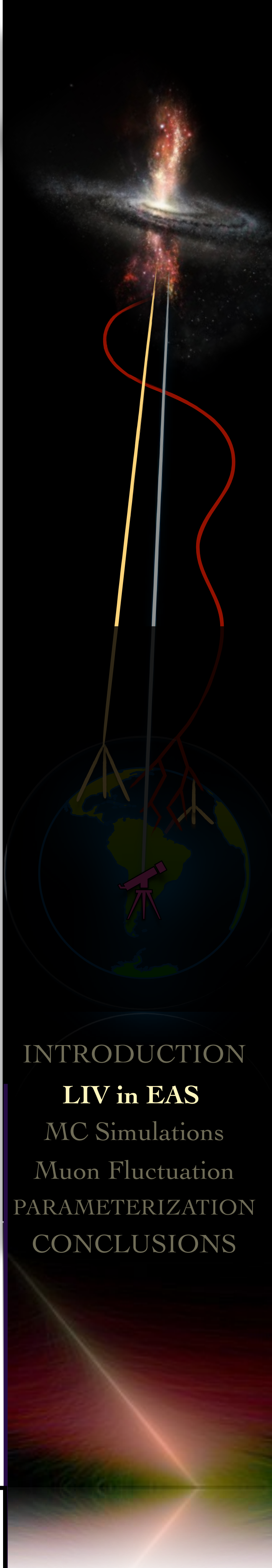
- For increasing energy π^0 begins to interact;
- After the critical point (where $M_{\mathrm{LIV}} = 0$) the decay $\pi^0 \rightarrow \gamma\gamma$ is forbidden;

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};

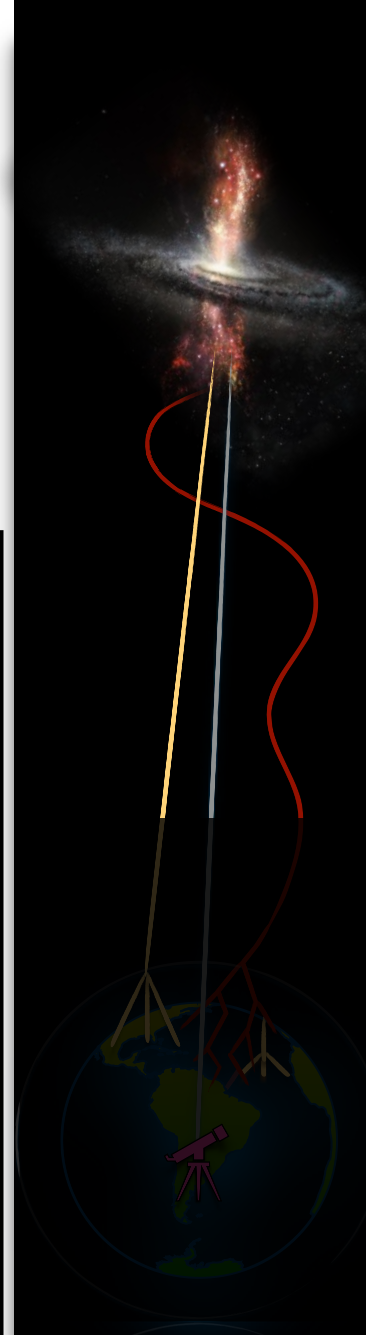
Hadronic interaction model: EPOS LHC-LIV, QGSJETII-04.

in presence of LIV

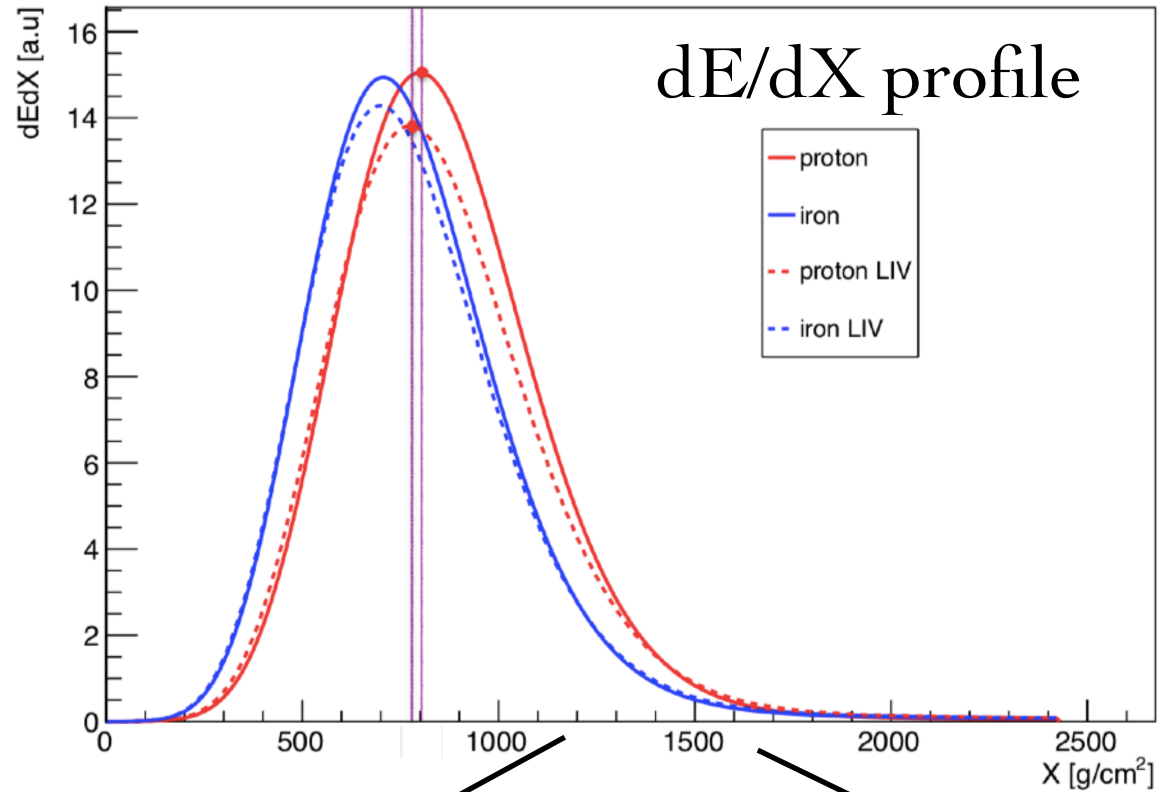
LIV parameter η:

- **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.

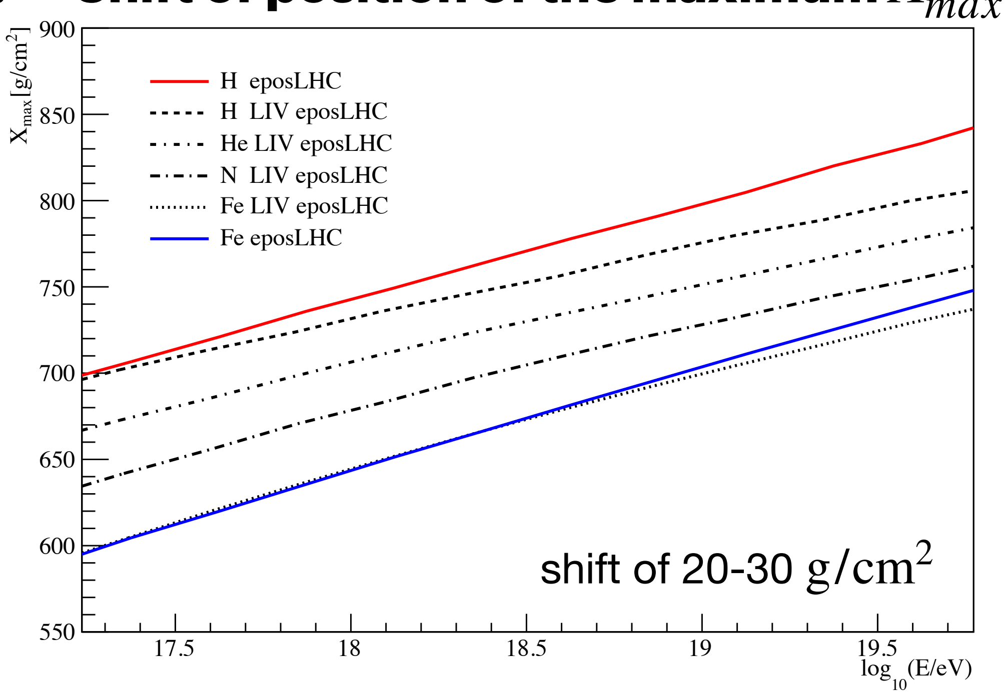


LIV effects on air shower development



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

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

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LIV in EAS
MC Simulations
Muon Fluctuation
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CONCLUSIONS

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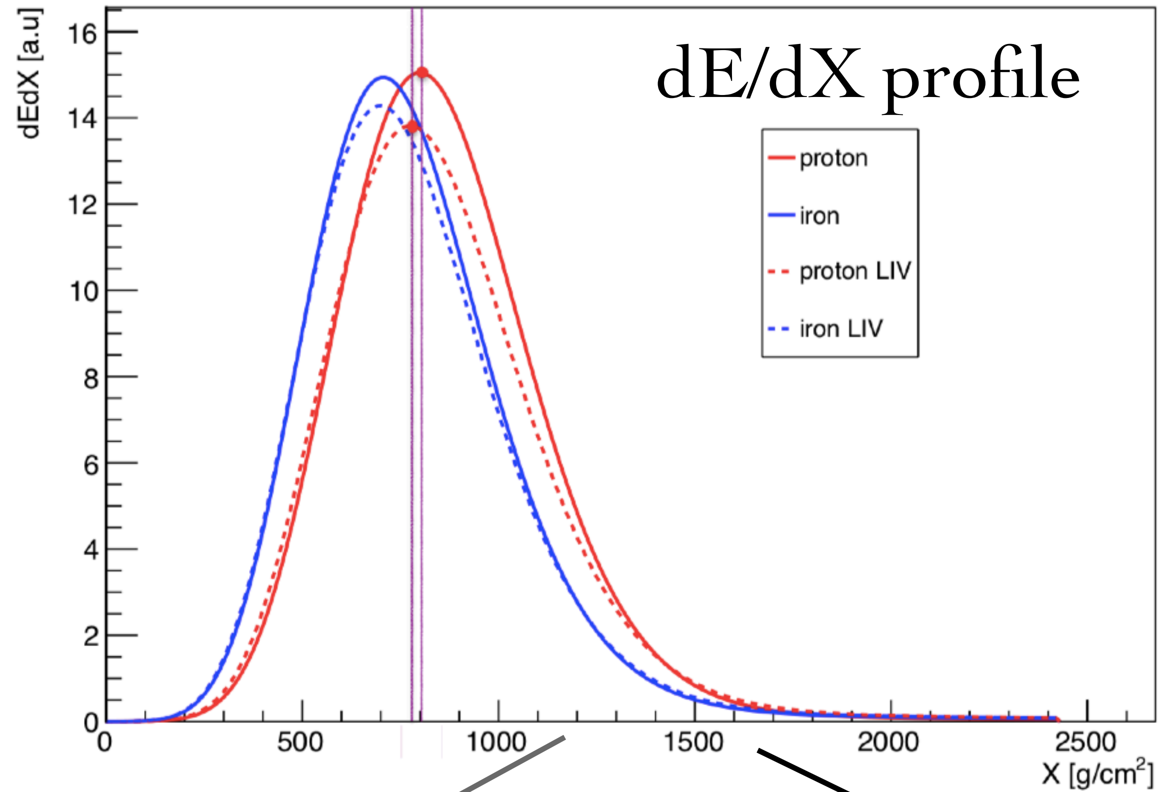

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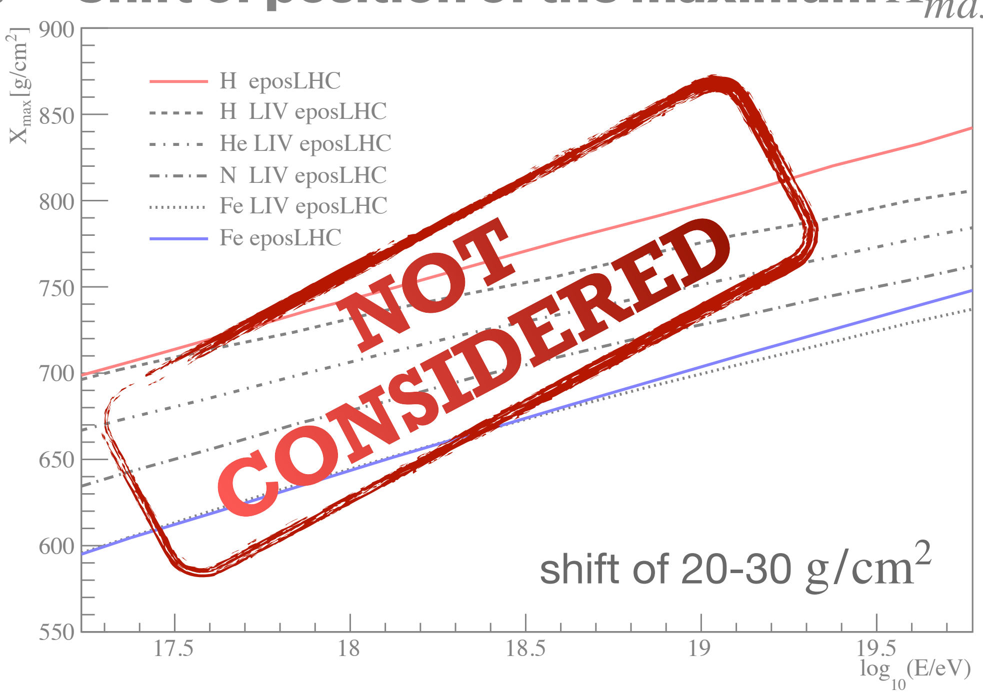

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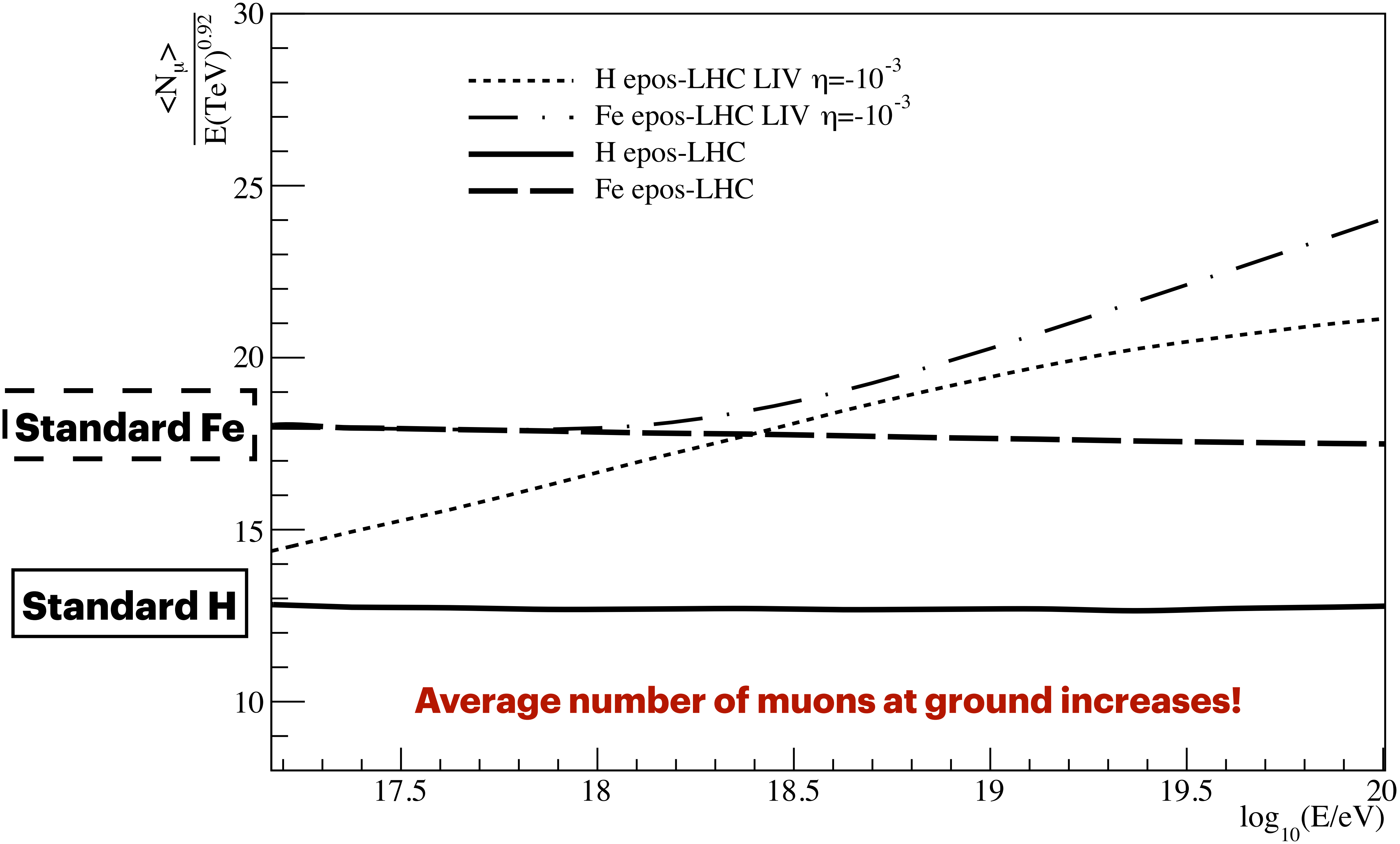
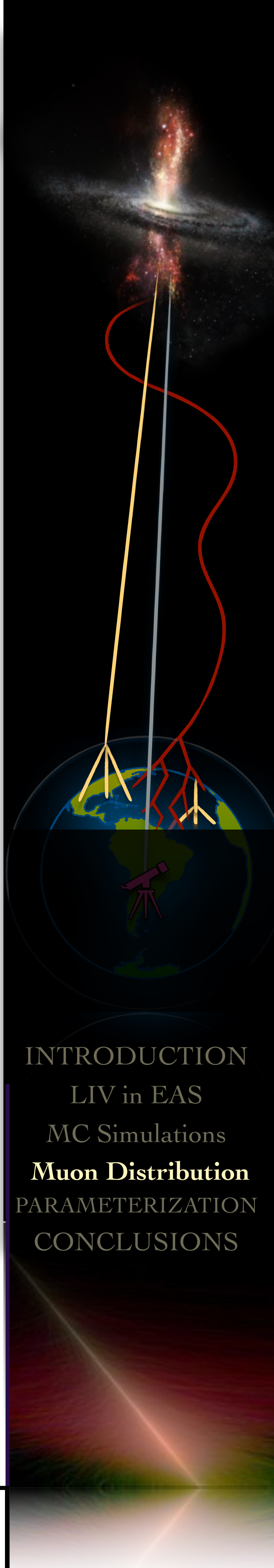
Average number of muons





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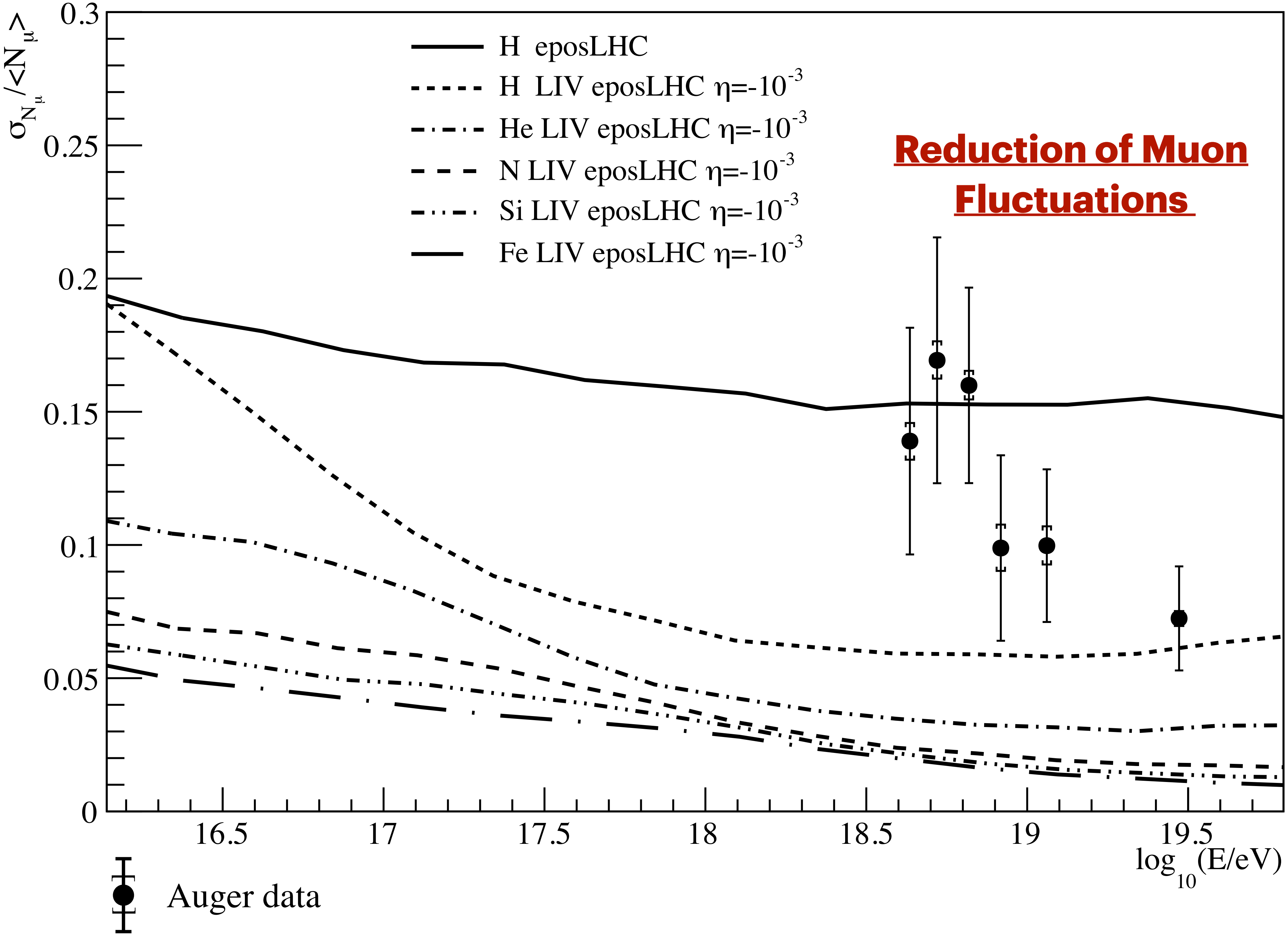
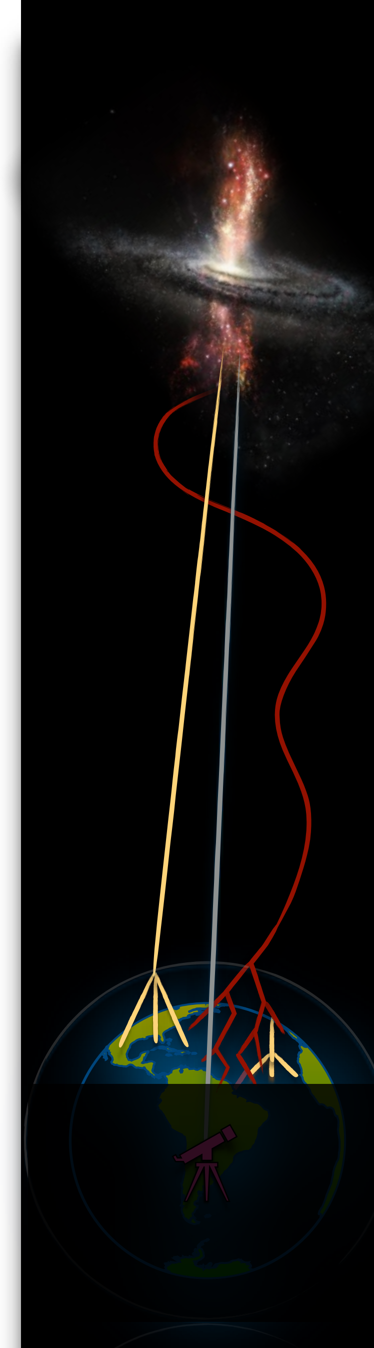
Relative Fluctuations

Ratio of the fluctuations to the average number of muons





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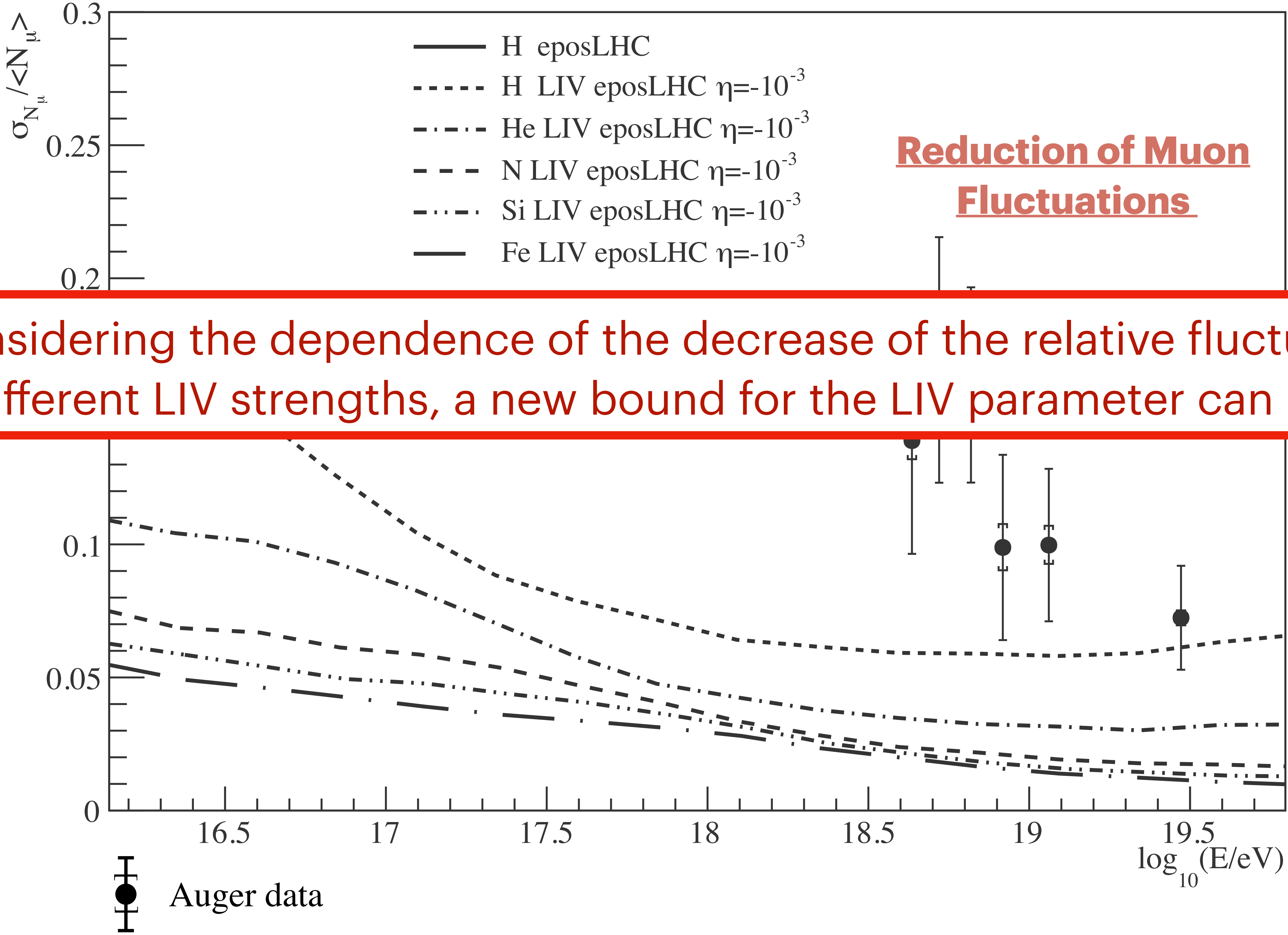


Considering the dependence of the decrease of the relative fluctuations on the different LIV strengths, a new bound for the LIV parameter can be obtained

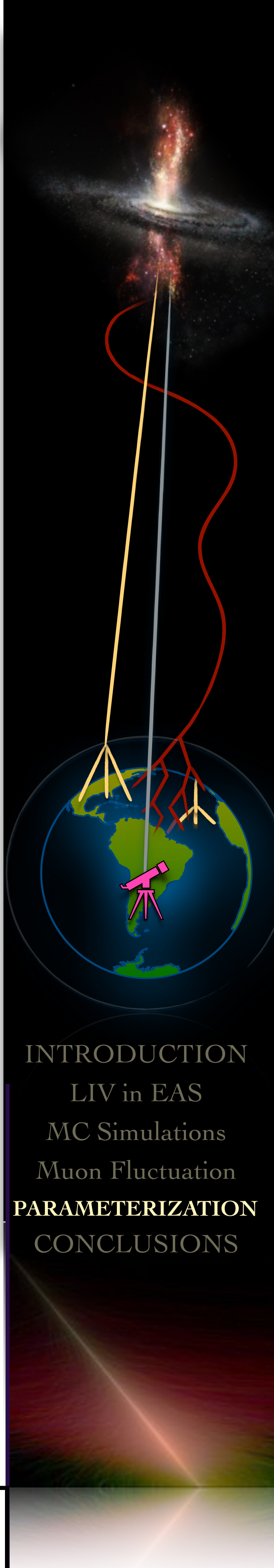
Looking for… the most conservative relative Fluctuations

1. **Effects of the different composition scenarios:** The mixture of the two components p and Fe gives the maximum value of relative fluctuations.
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 $\sigma(N_\mu)_{Fe}$

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



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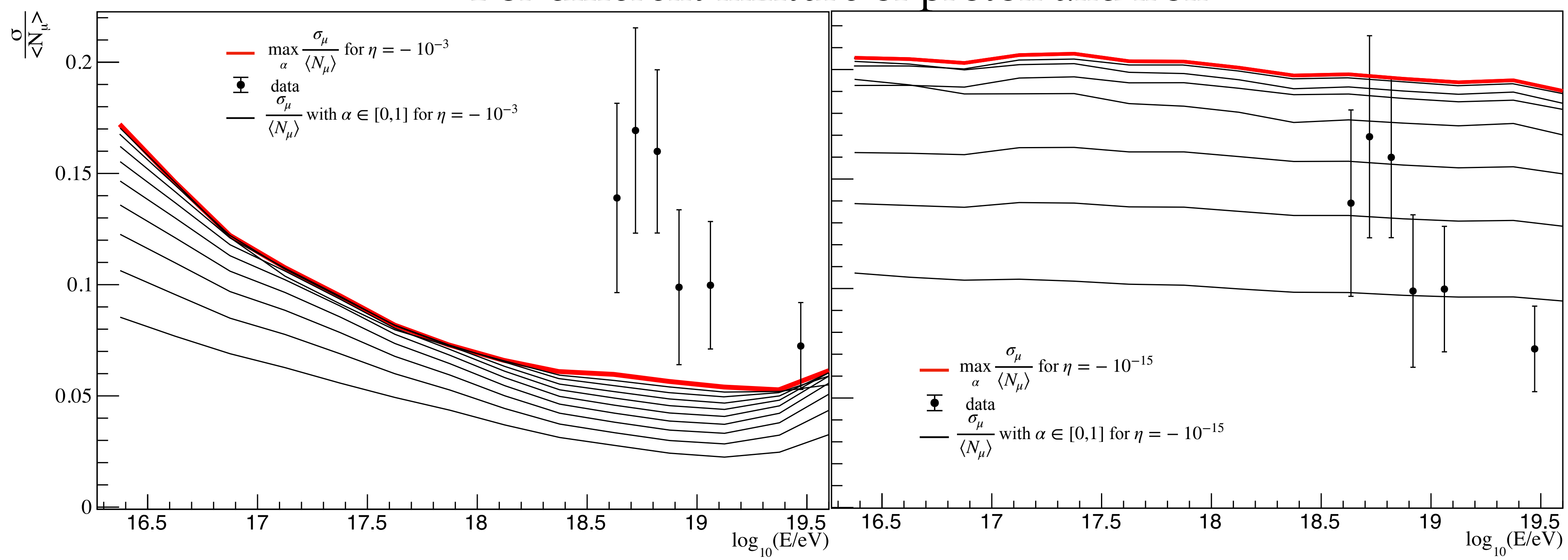
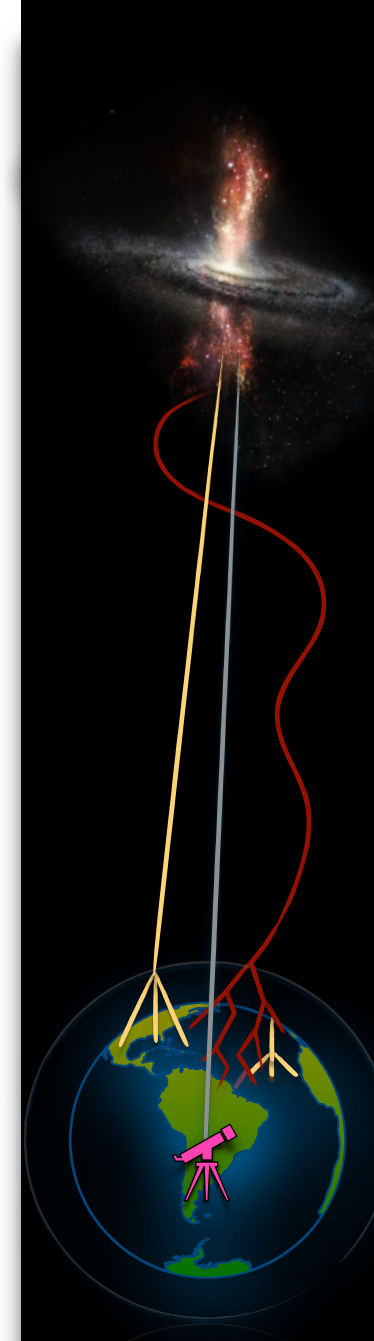
For different mixture of proton and iron



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



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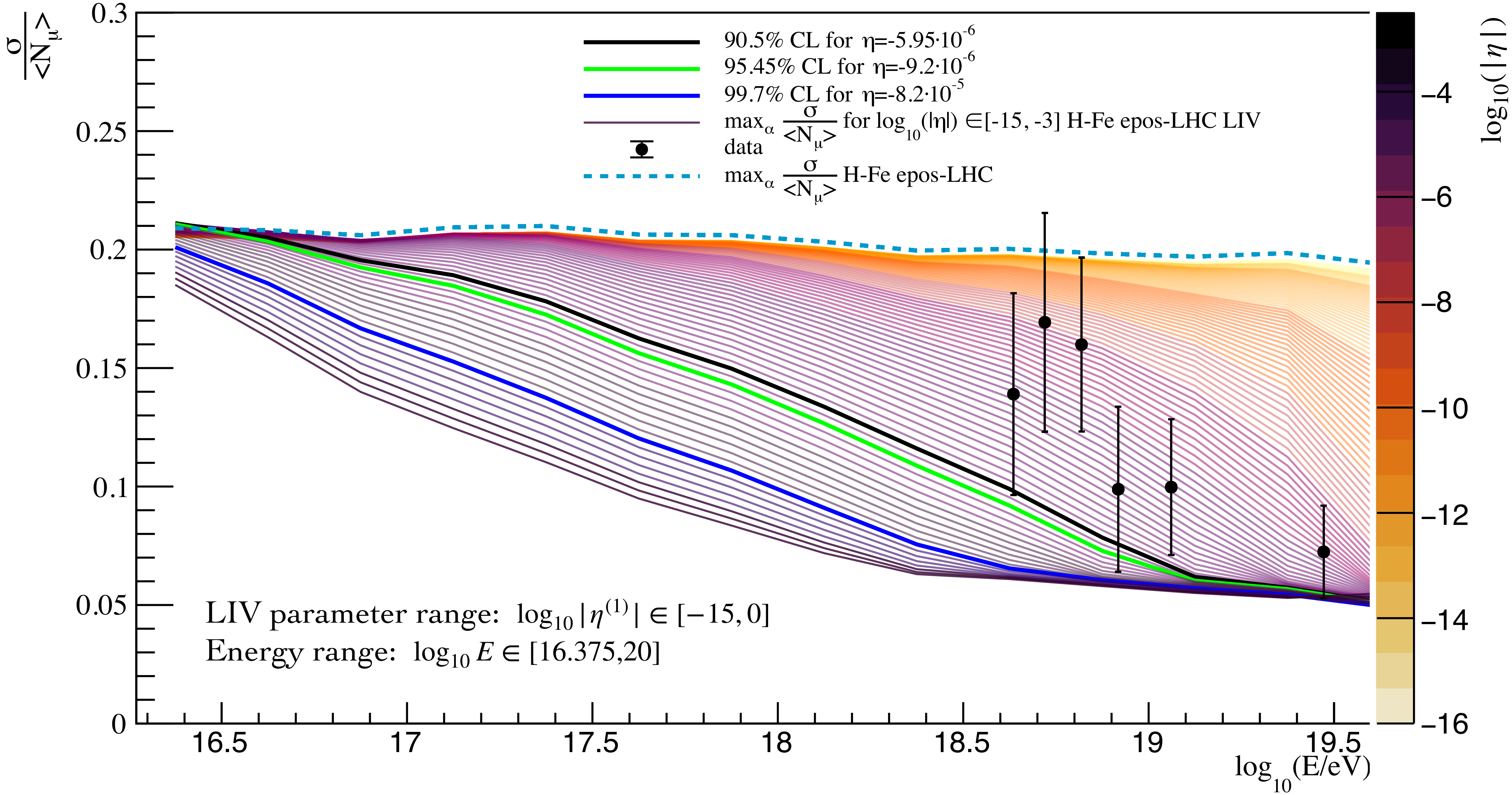
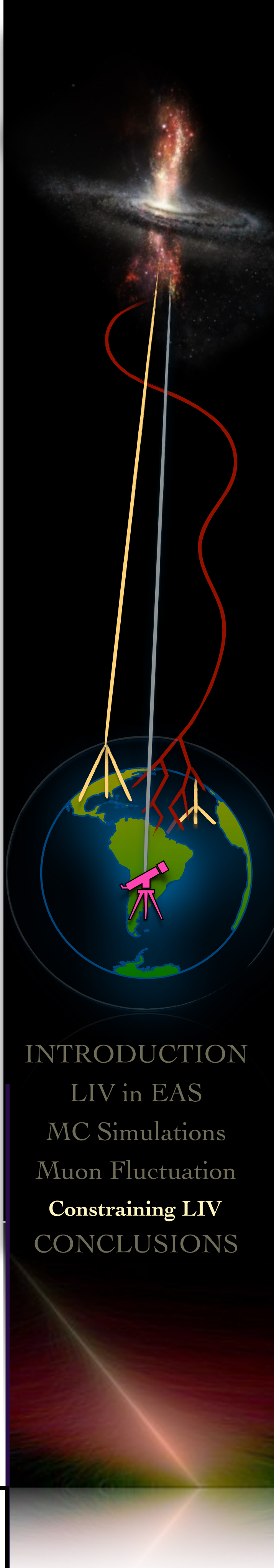
Maximum Mixed Relative Fluctuations

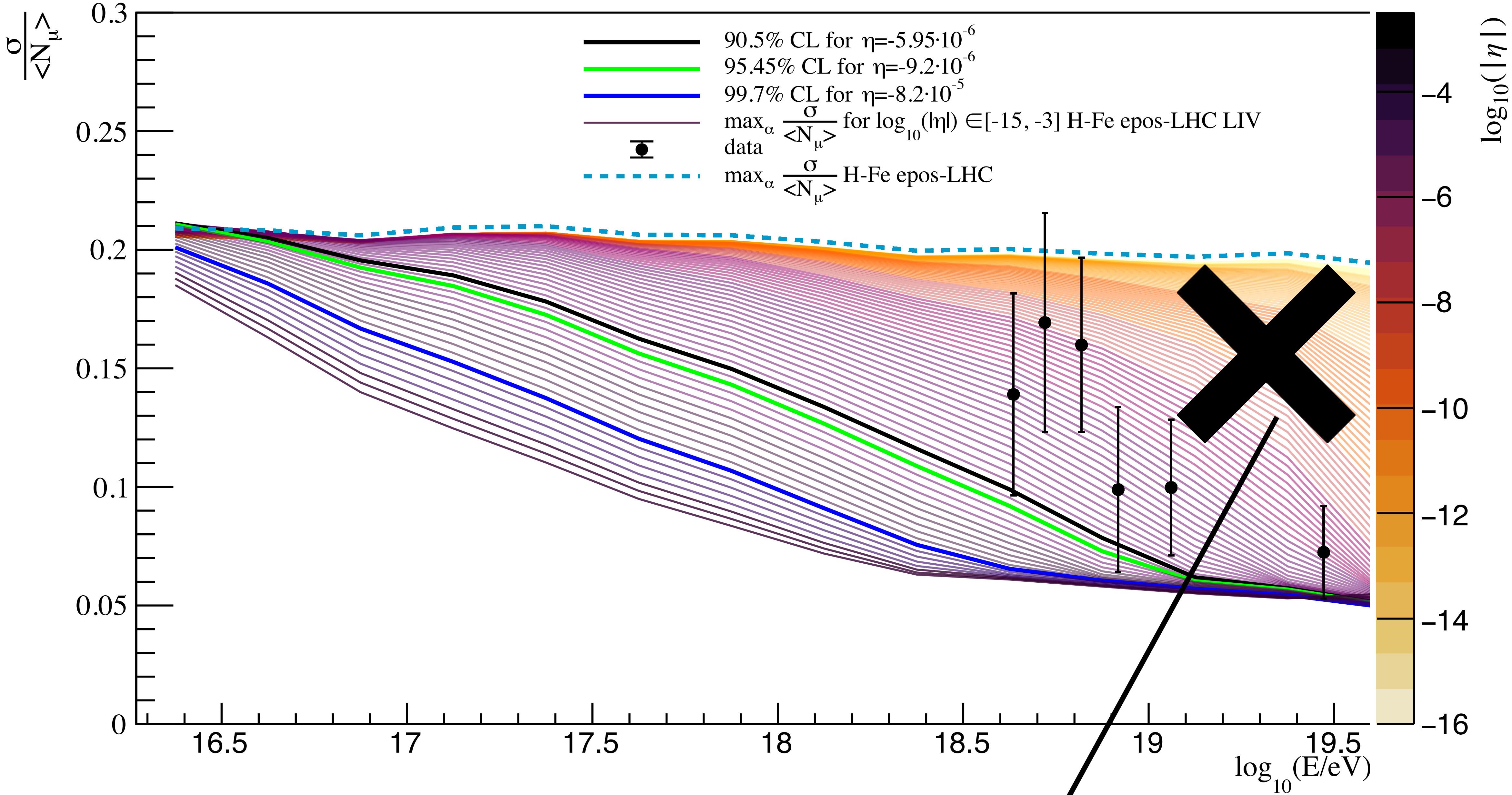
for any LIV parameter value we can calculate the most conservative LIV relative fluctuations as a function of the energy without repeating any shower simulation

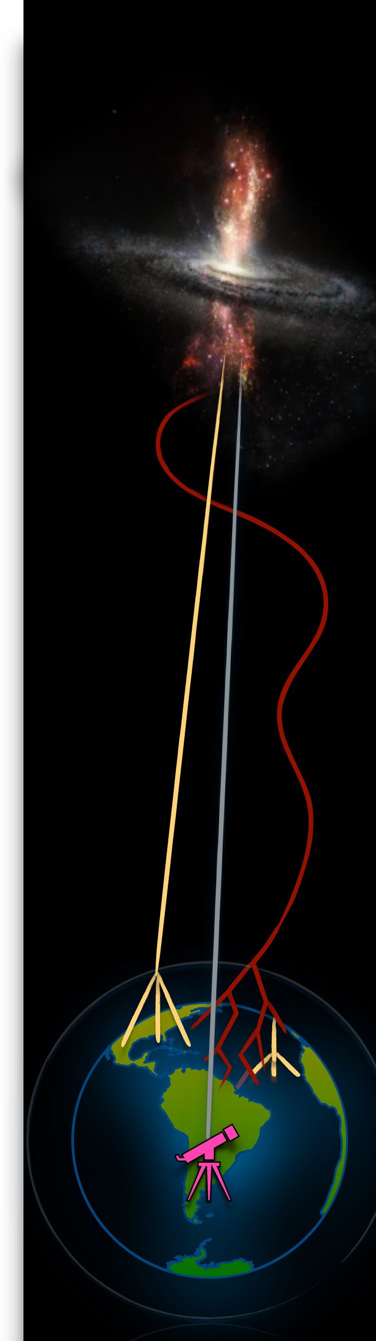
We found $\max_{\alpha} \frac{\sigma_\mu}{\langle N_\mu \rangle} = \frac{\sqrt{RMS^2(N_\mu)(\alpha)}}{\langle N_\mu \rangle(\alpha)}$ wrt α





Most conservative Mixed Relative Fluctuations





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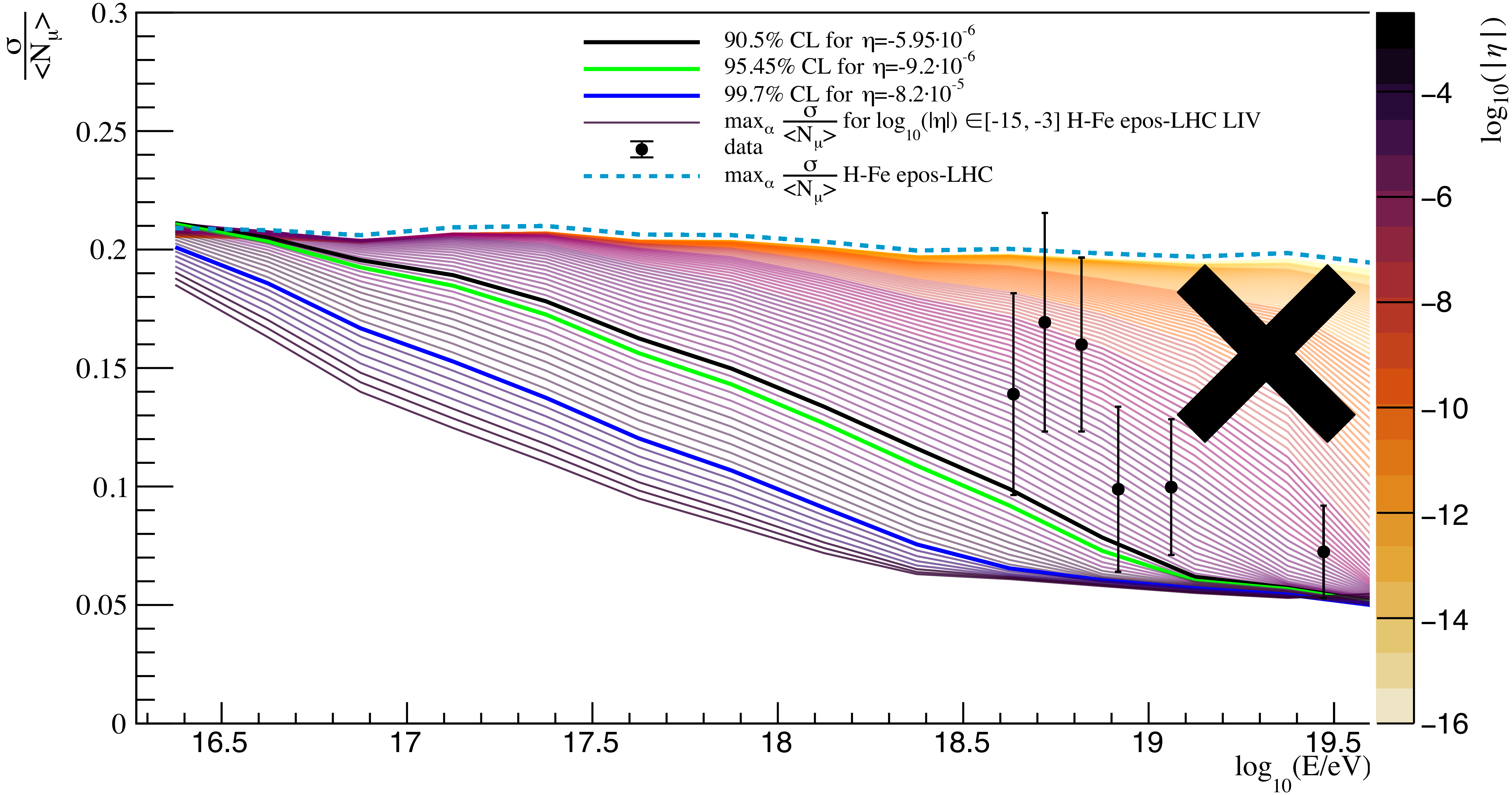
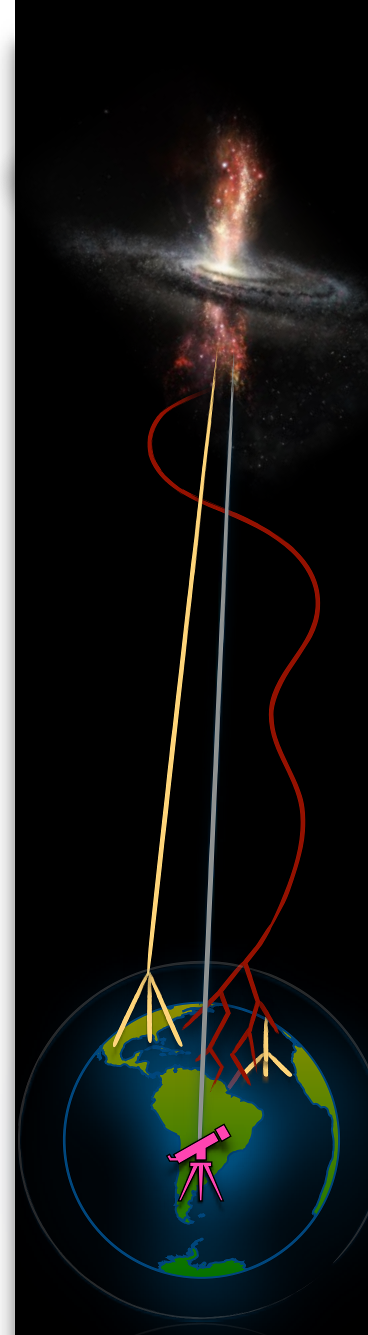
Most conservative Mixed Relative Fluctuations



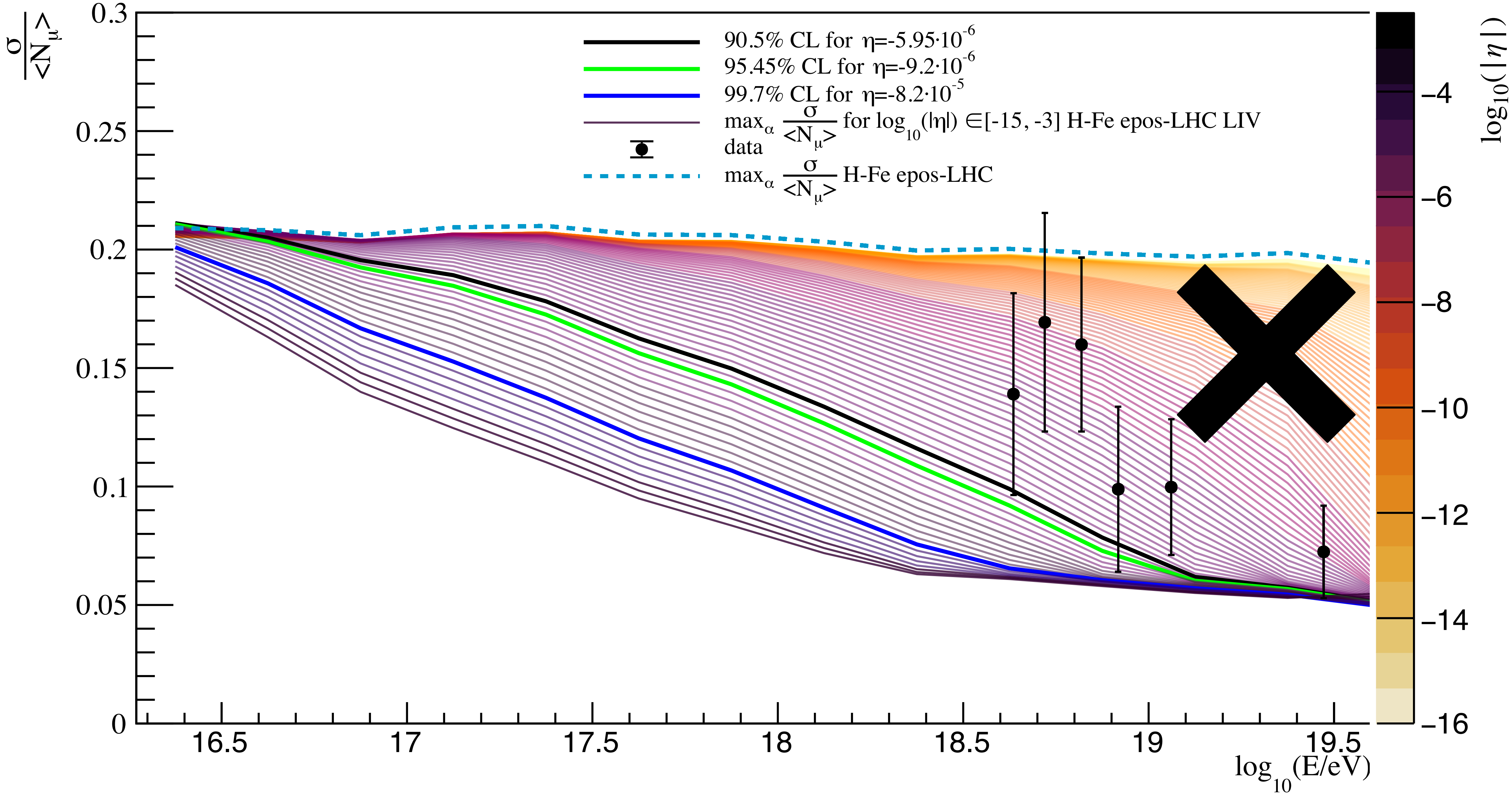


χ^2 is calculated as a function of η considering all the data points

↓

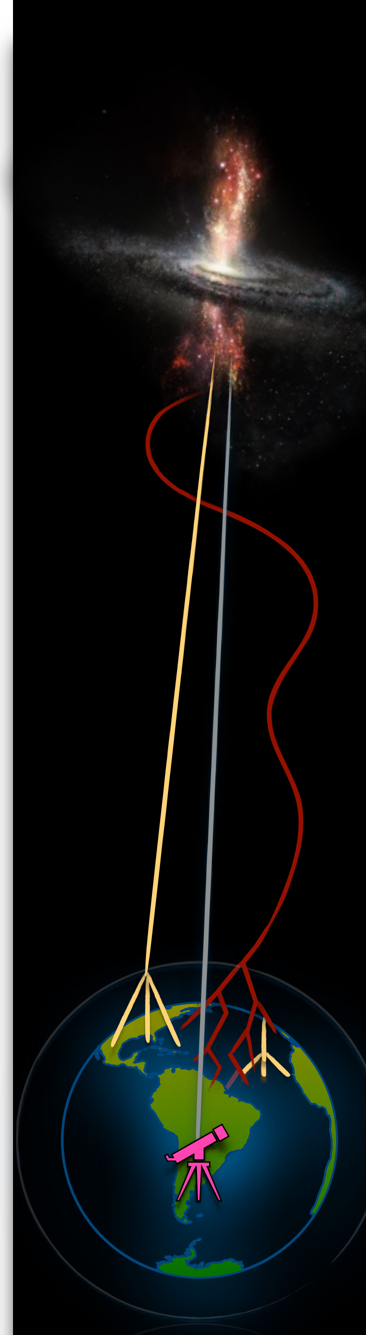
Continuous confidence levels to exclude LIV models

Most conservative Mixed Relative Fluctuations



New bound!

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



Summary

- <u>For the first time LIV effects have been studied considering muon fluctuations;</u>
- 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;
- <u>Using the parameterization we obtained a new bound for LIV parameter values;</u>

Future prospects

- A similar approach using the minimum of the relative fluctuation with respect to α could lead to the definition of a negative upper bound of the LIV parameter;
- We will use the overall procedure for LIV at 2nd order;
- 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 2.3c <u>but</u> we expect **EPOS-LHC LIV model** represents <u>the most conservative case</u>!

Thank you for your attention!