6TH INTERNATIONAL SYMPOSIUM ON ULTRA HIGH ENERGY COSMIC RAYS

Wednesday 5th October 2022

Searches for Lorentz Invariance Violation at the Pierre Auger Observatory

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On behalf of the Pierre Auger Collaboration

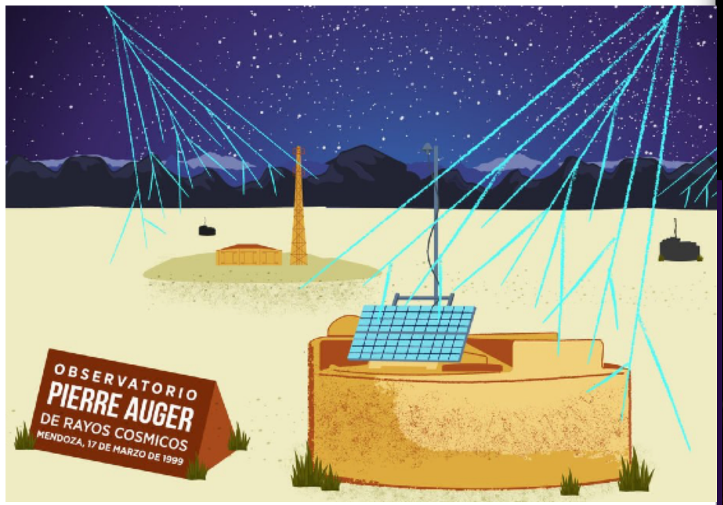
1. University of L'Aquila and INFN LNGS

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

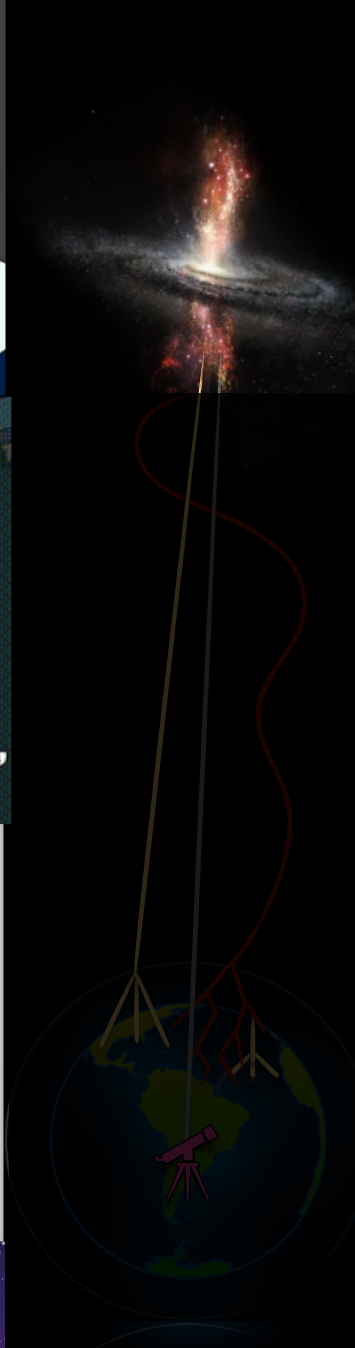
Possible **signatures** of Lorentz Invariance violation could be observed considering **physical phenomena** characterized by energy of the center of mass of the order of Planck scale!



Ultra High Energy Cosmic rays

Extragalactic propagation

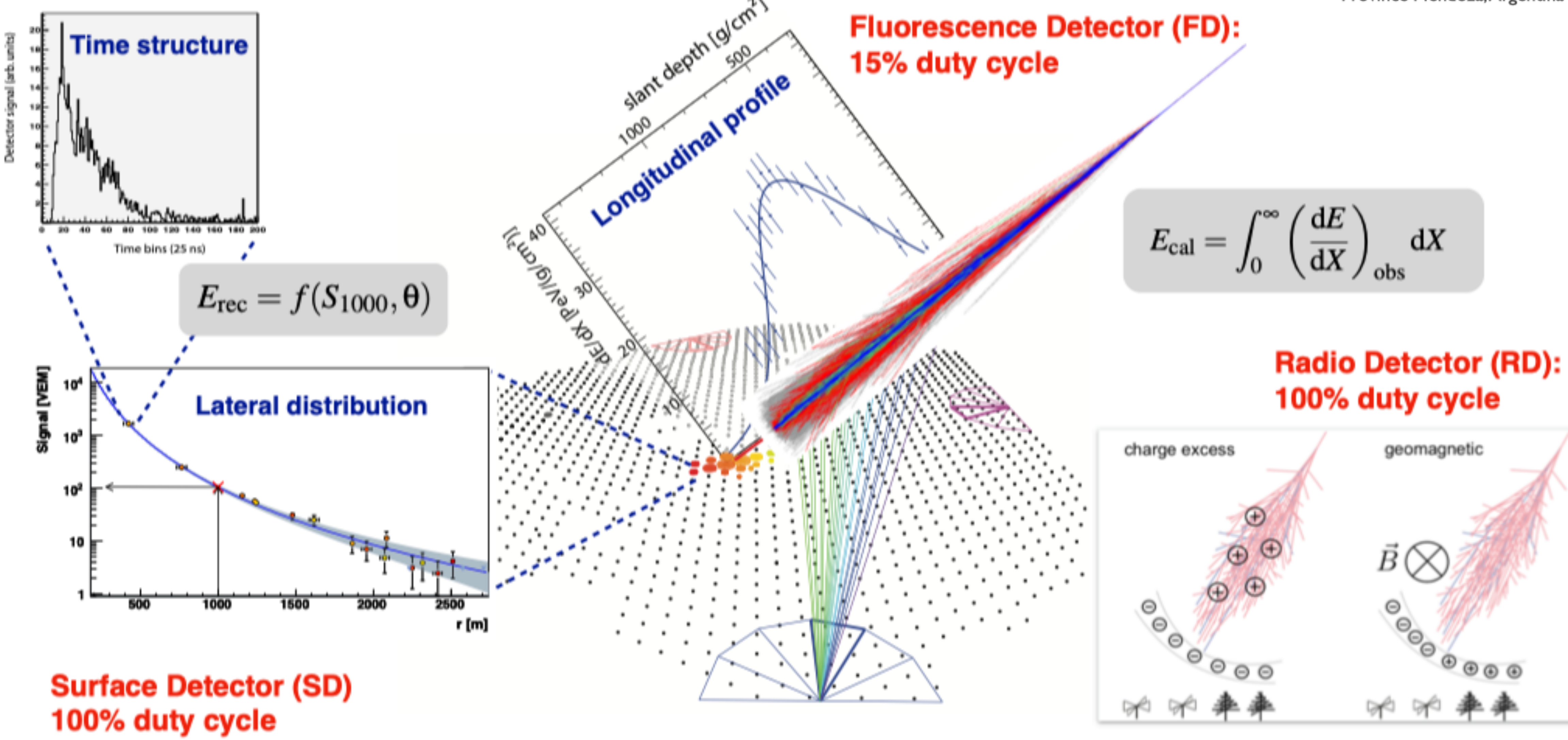
Extensive Air Showers



See P. Auger talks

Pierre Auger Observatory

The Pierre Auger Observatory has been designed to investigate the highest energy cosmic rays with energy exceeding 10^{19}eV, combining a surface array of particle detectors with fluorescence telescopes for **hybrid detection**



Calibration of the SD risetime with $X_{\rm max}$ distributions measured with the FD

The SDs measure photons and charged particles at ground level

The FDs observe longitudinal development of air showers in the atmosphere

The RDs complement this setup studying radio emission from air showers

How to break Lorentz Invariance

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

Modified dispersion relation

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

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

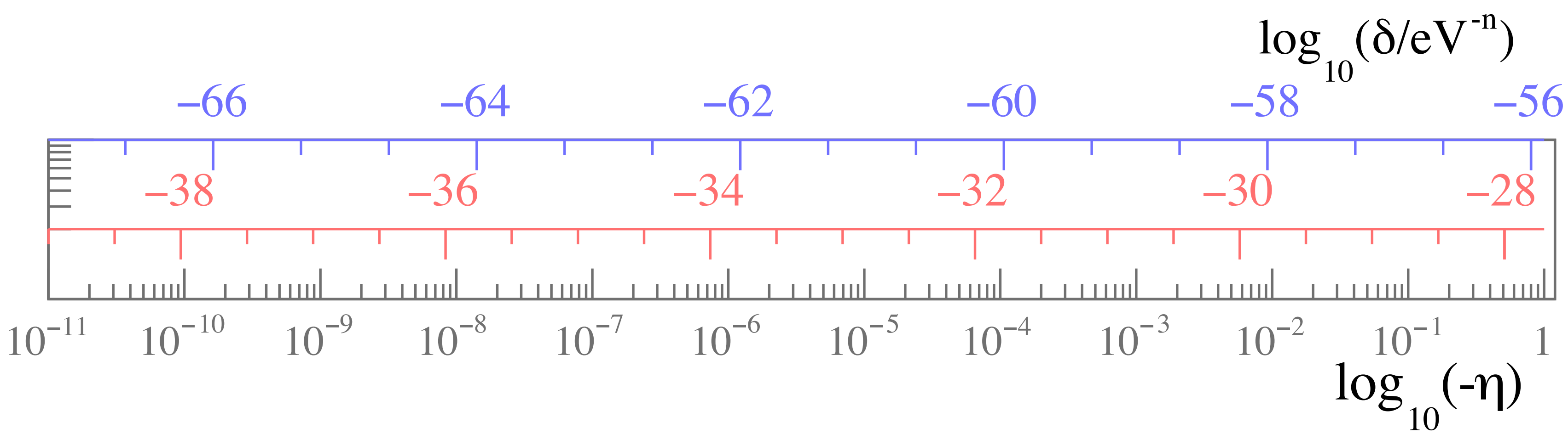
first order n=1: $E_i^2 - p_i^2 = m_i^2 + \eta_i^{(1)} \frac{p_i^3}{M_{Pl}}$

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

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



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

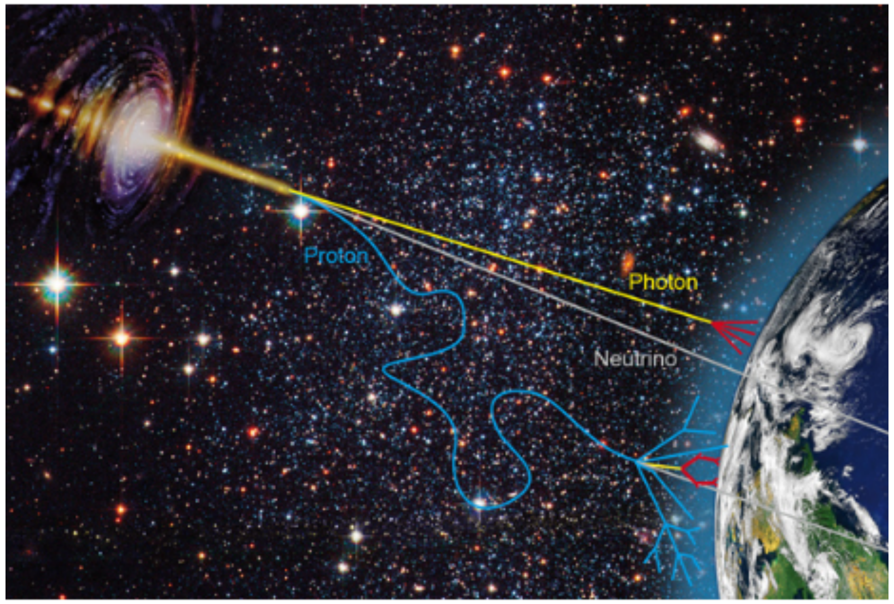
Nuclei: $E_A^2 - p_A^2 = m_A^2 + \sum_{n=0}^{N} \delta_A^{(n)} p_A^{n+2}$

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

LIV searches in the Observatory

Lorentz Invariance Violation effects and signatures on:

Extragalactic propagation



Modification of the cosmic rays interactions during the propagation through the universe

Electromagnetic sector

- Suppression of the UHE photon absorption by photons of the background;

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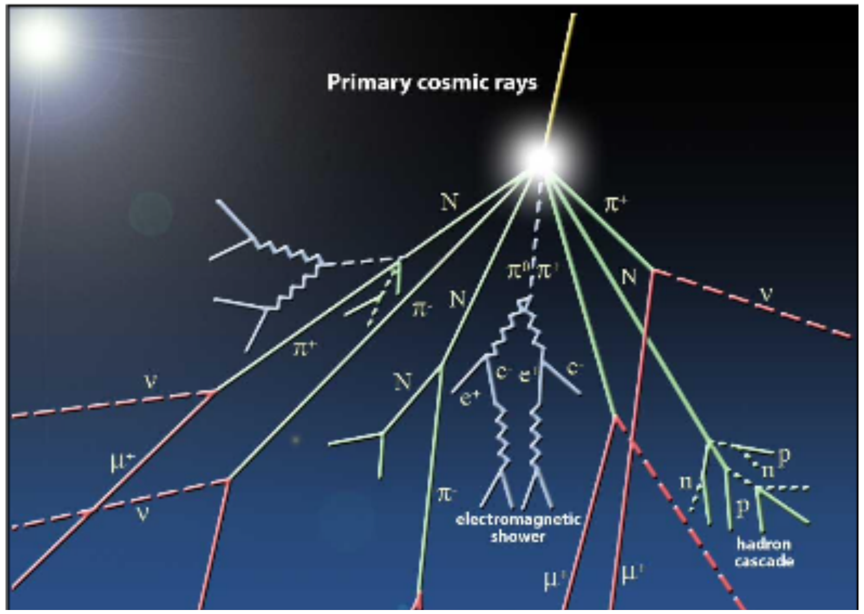
Hadronic sector

- Suppression of the pion production;
- Suppression of the nuclear disintegration;

Extensive air showers



Modification of the development of the cascade in the atmosphere

Electromagnetic sector

- Modification of BH cross sections;

Hadronic sector

- Suppression of the pion decay;

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LIV searches in the Observatory

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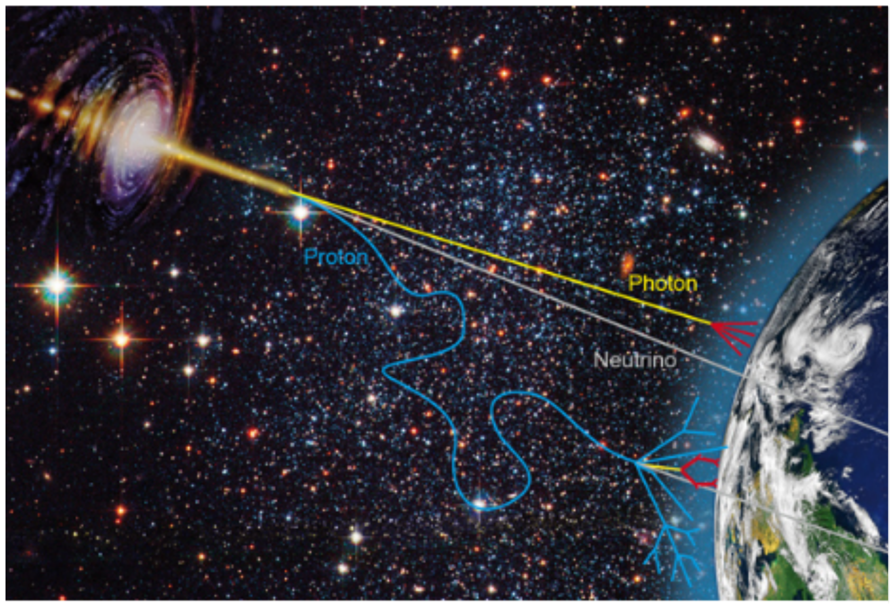

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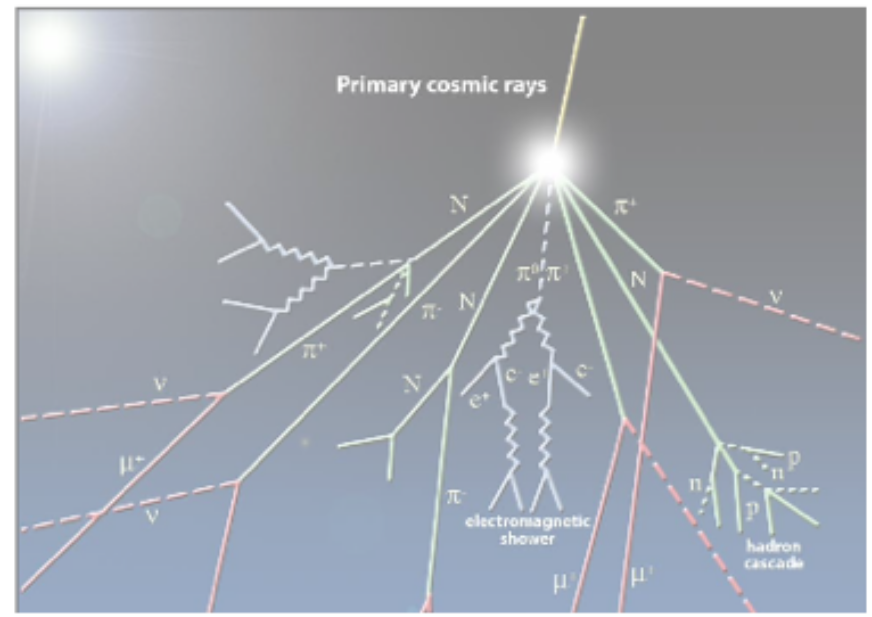

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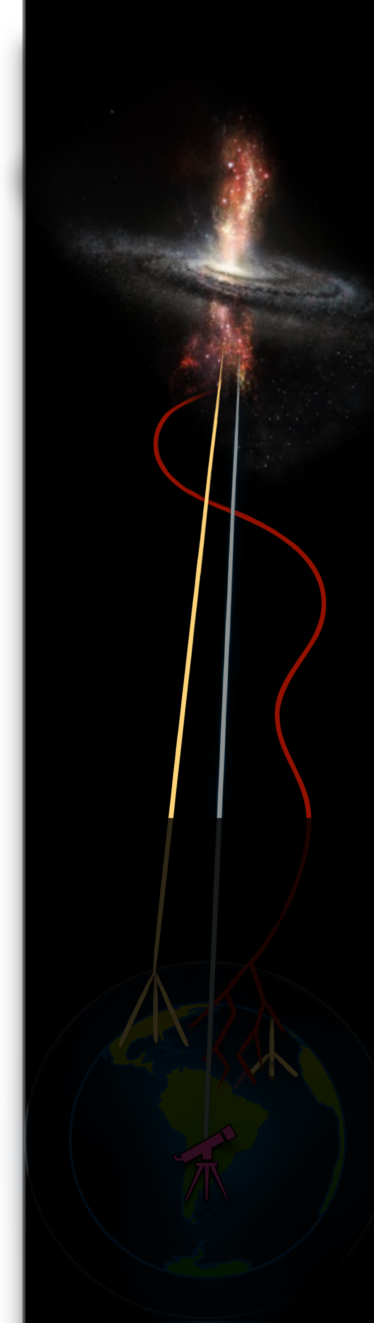
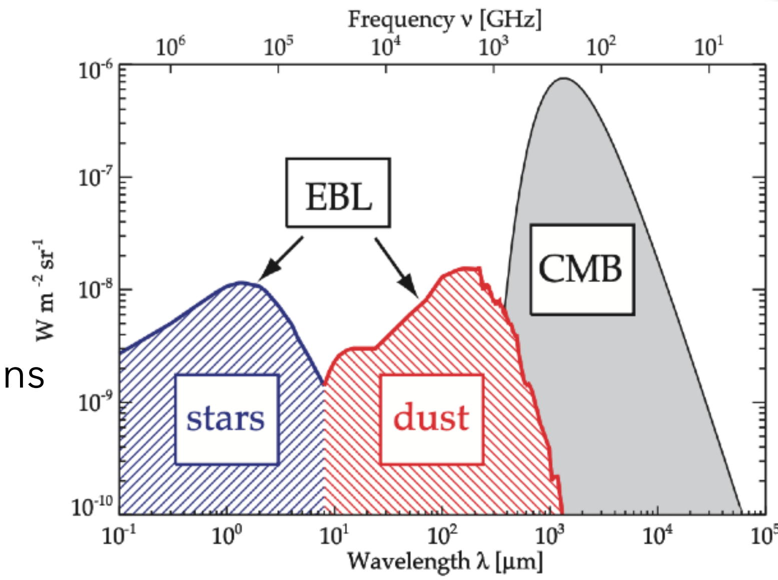


UHECRs PROPAGATION

UHECRs undergo energy losses during the propagation in the IS caused by both of the <u>expansion of the universe</u> and the interactions with the background radiation fields

In particular charged particles can interact with the **CMB** photons at highest energies and with the **EBL** at slightly lower energies



Processes due to the UHECRs interactions with astrophysical background photons

UHECRs + $\gamma_{bkg} \longrightarrow \ldots$

Nucleons: $N + \gamma_{bkg} \rightarrow \ldots$
Nuclei: $A + \gamma_{bkg} \rightarrow \ldots$
photons: $\gamma + \gamma_{bkg} \rightarrow \ldots$

- Pair production $\epsilon' > 1$ MeV

  $N + \gamma_{bkg} \rightarrow N + e^- + e^+$

- Pion production $\epsilon' > 150$ MeV

  $p + \gamma_{bkg} \rightarrow p + \pi^0$

  $p + \gamma_{bkg} \rightarrow n + \pi^+$

- Photodisintegration of Nuclei (heavier than p)

  $A + \gamma \rightarrow (A - n) + nN$

*Dependence on redshift to be considered

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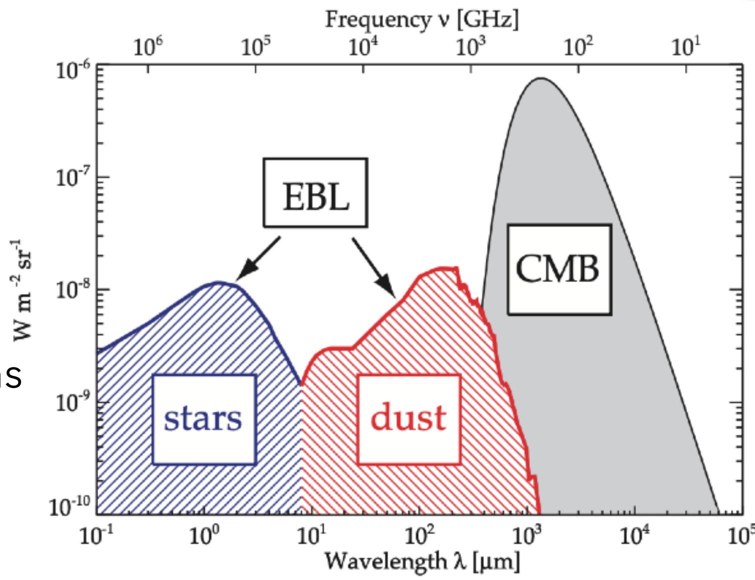

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  $p + \gamma_{bkg} \to p + \pi^0$

  $\pi^0 \to \gamma_{GZK} + \gamma_{GZK}$ source of cosmogenic photons

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Electromagnetic sector: Photon propagation

UHE photons

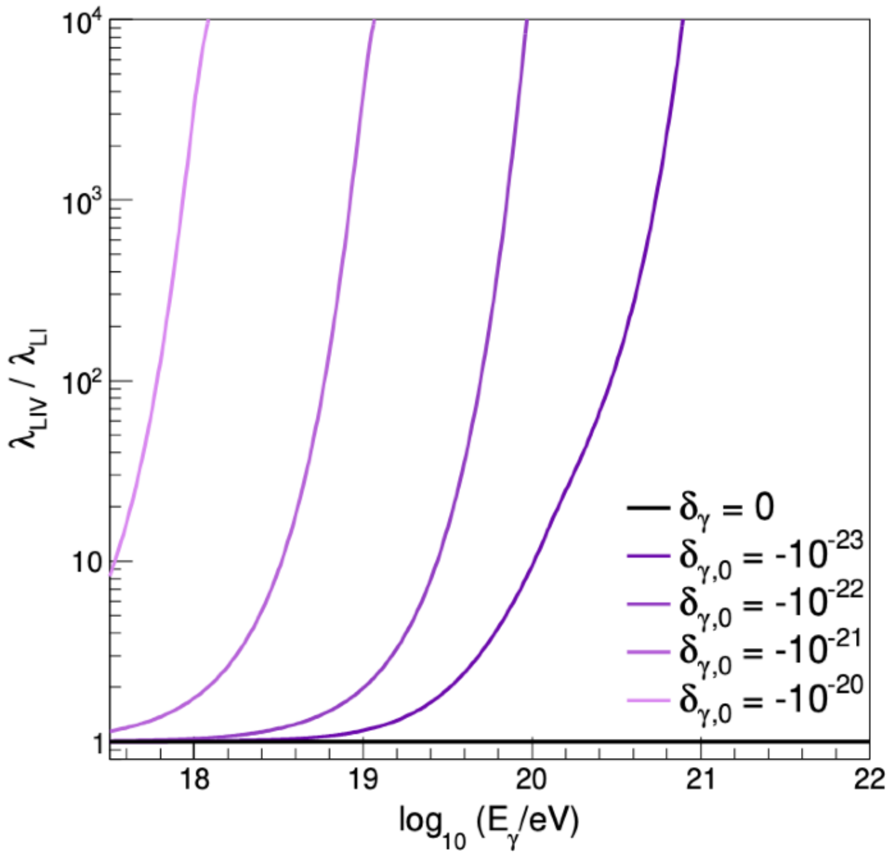
Modified process: $\gamma_{GZK} + \gamma_{bkg} \rightarrow e^- + e^+$

Expected effects

pair production inhibited at the highest energies

–> more photons could reach the ground

ORDER OF LIV
n=0,1, 2
$\delta < 0$
Subluminal LIV



- Photons produced from pion decay, propagating in extragalactic space under LIV assumptions

-Modifications in pair-production cross section ➔ increase of mean free path ➔ less interactions ➔ more photons expected (subluminal LIV)

How LIV affects the interactions during propagation?

Looking at observables measured at ground

Simulation of GZK photons for both LIV and LI scenarios

The LIV-modified mean free path was implemented in the software packages **CRropa3/EleCa** in order to obtain the arriving GZK photon flux

 Lang, et al. ApJ2018 JCAP01 (2022) 023

Electromagnetic sector: Photon propagation

Comparing **the predicted LIV flux arriving at earth** with **the upper limits on the photons flux** measured by the Pierre Auger Observatory

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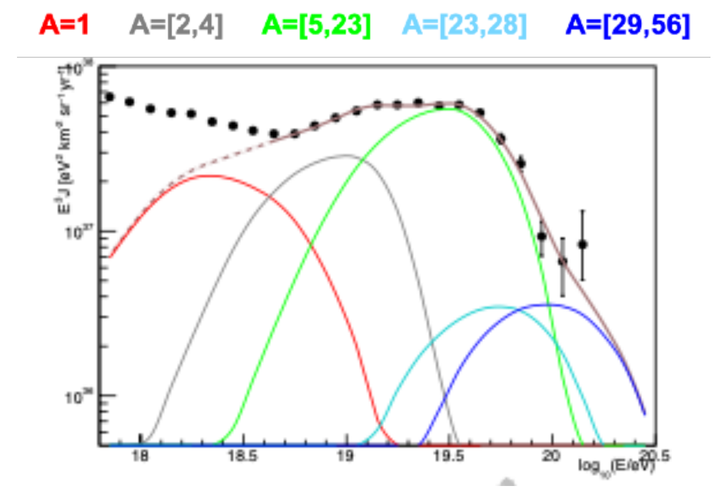
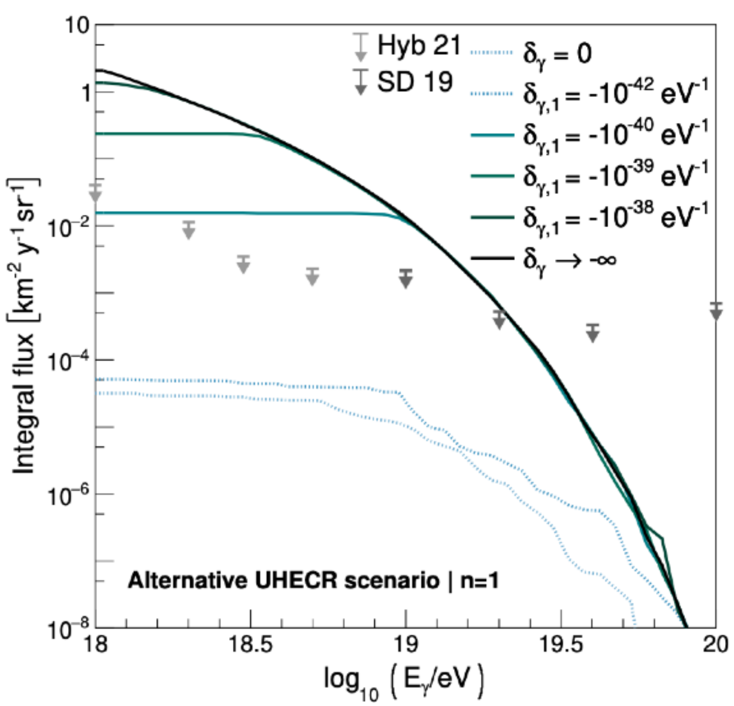
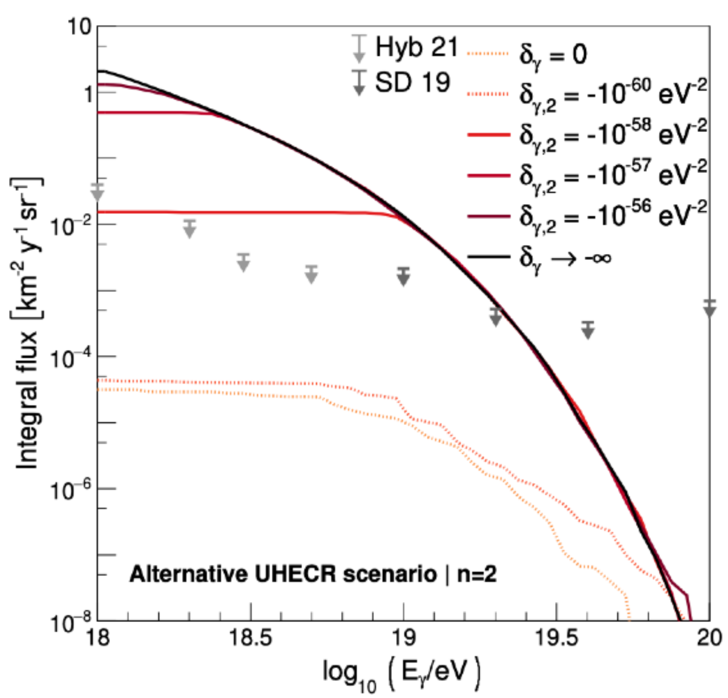
See L.Perrone talk

Considered scenarios

1. UHECRs (scenarios taken from **best fit of spectrum and composition** at escape from sources) propagating in extragalactic space (standard propagation)
2. Photons produced in extragalctic propagation by UHECRs with **additional proton component at high energies**.







$$\delta^{(1)} > -10^{-40}\,\mathrm{eV}^{-1}$$

$$\delta^{(2)} > -10^{-58}\,\mathrm{eV}^{-2}$$

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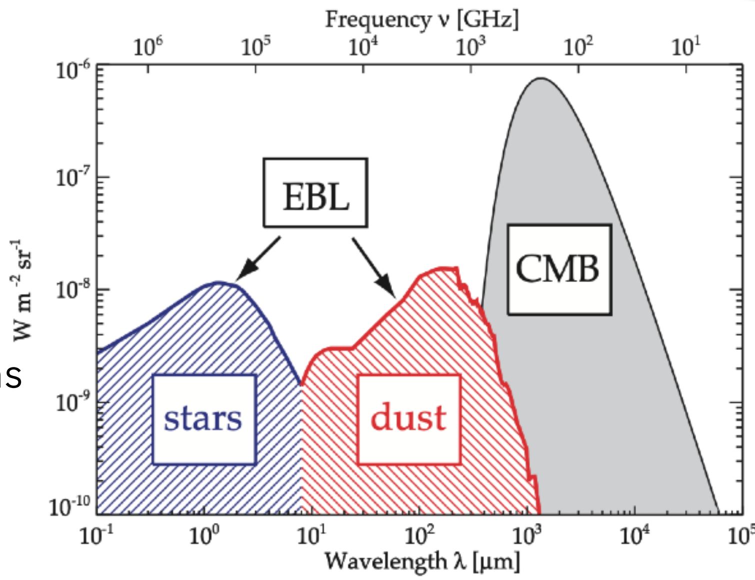

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Hadronic sector: UHECRs propagation

ORDER OF LIV
n=0,1, 2
$\delta > 0$
Superluminal LIV

The LIV-modified attenuation length for pion production and the LIV-modified energy threshold for photo disintegration were implemented in SimProp v2.4

> Above the critical energy, the number of interactions during propagation is reduced > the UHECRs interact less > the cosmic ray can travel farther than LI scenario;

How LIV affects the interactions during propagation?

Looking at observables measured at ground

Spectrum and composition given by the LIV modified 10^5 events produced with SimProv2.4 (simulations performed for 5 nuclei)

Threshold energy increases -> less interactions -> if LIV, lighter nuclear species are needed at the sources in order to reproduce the observed composition

Hadronic sector: UHECRs propagation

ORDER OF LIV
n=0,1, 2
$\delta > 0$
Superluminal LIV

Fitting the data measured by the Pierre Auger Observatory with the expected spectrum and composition at ground for both LIV and LI scenarios (combined fit)

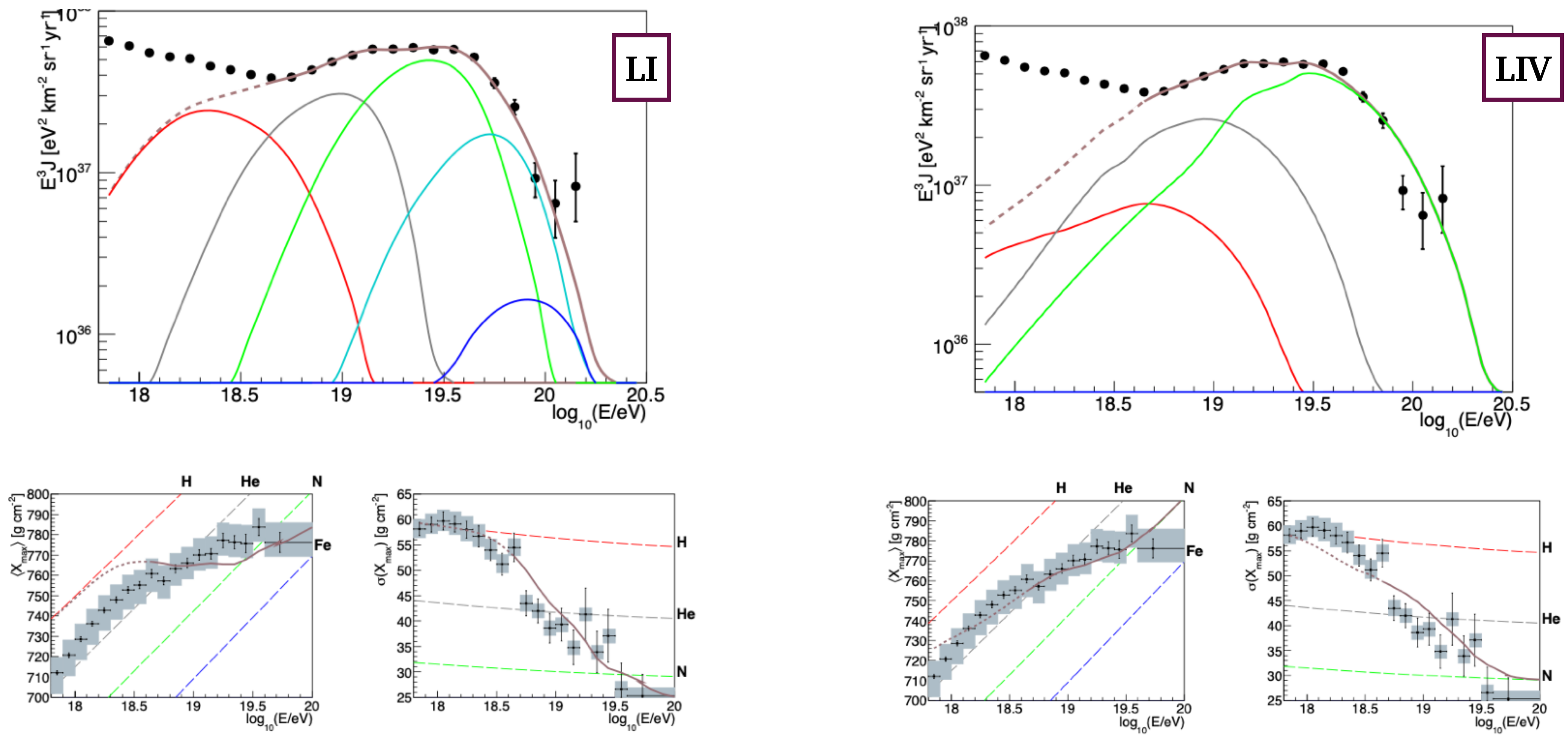
See E. Guido talk

>For each UHECR scenario the free parameters of the fit are:

The nuclei fractions, the index of the energy spectrum, the maximum rigidity, the normalization factor of the flux, the LIV parameter δ

>A log-likelihood fit gives the combination of the parameters which best describes the data

Comparing the deviances obtained in LIV and LI scenarios limits on δ have been imposed



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LIV searches in the Observatory

Lorentz Invariance Violation effects and signatures on:

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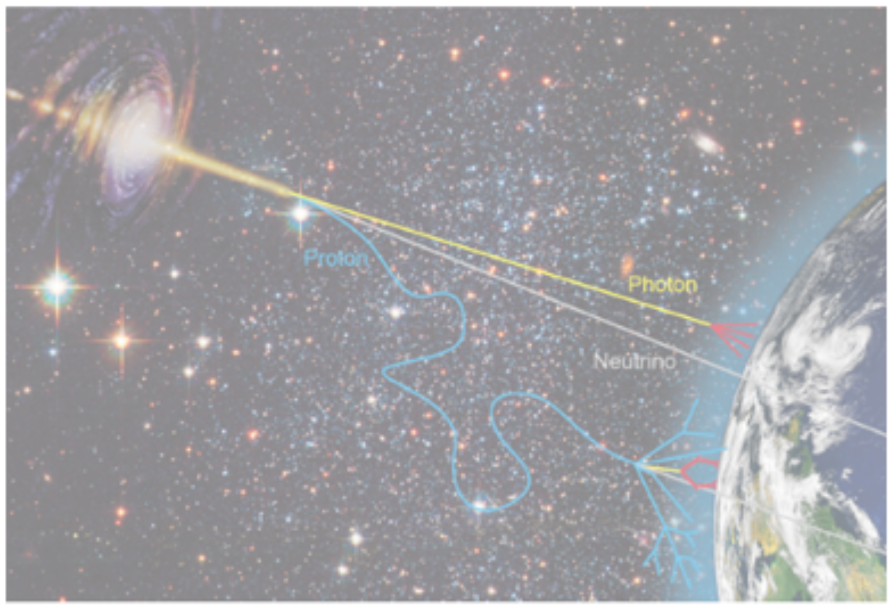

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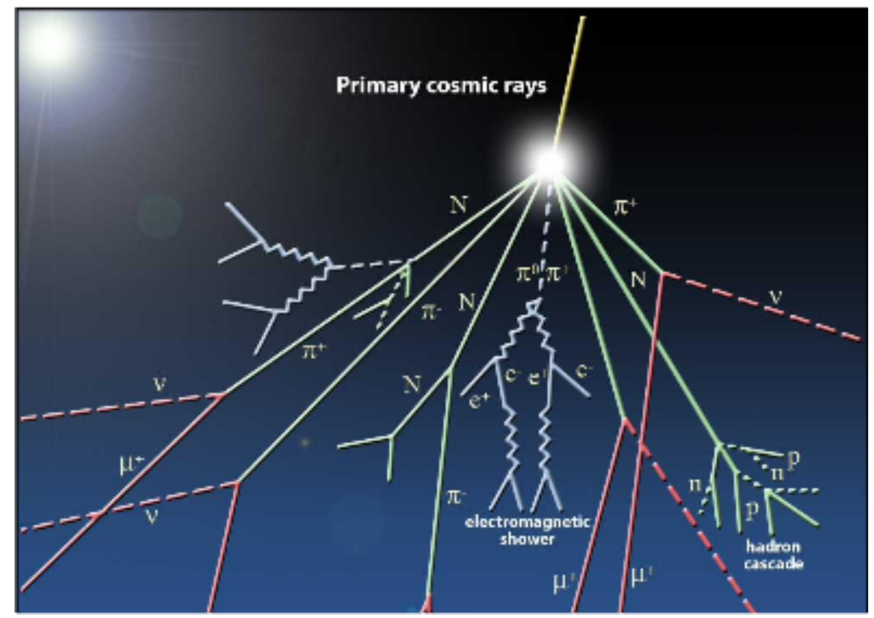
Extensive air showers



Modification of the development of the cascade in the atmosphere

Electromagnetic sector
- Modification of BH cross sections;

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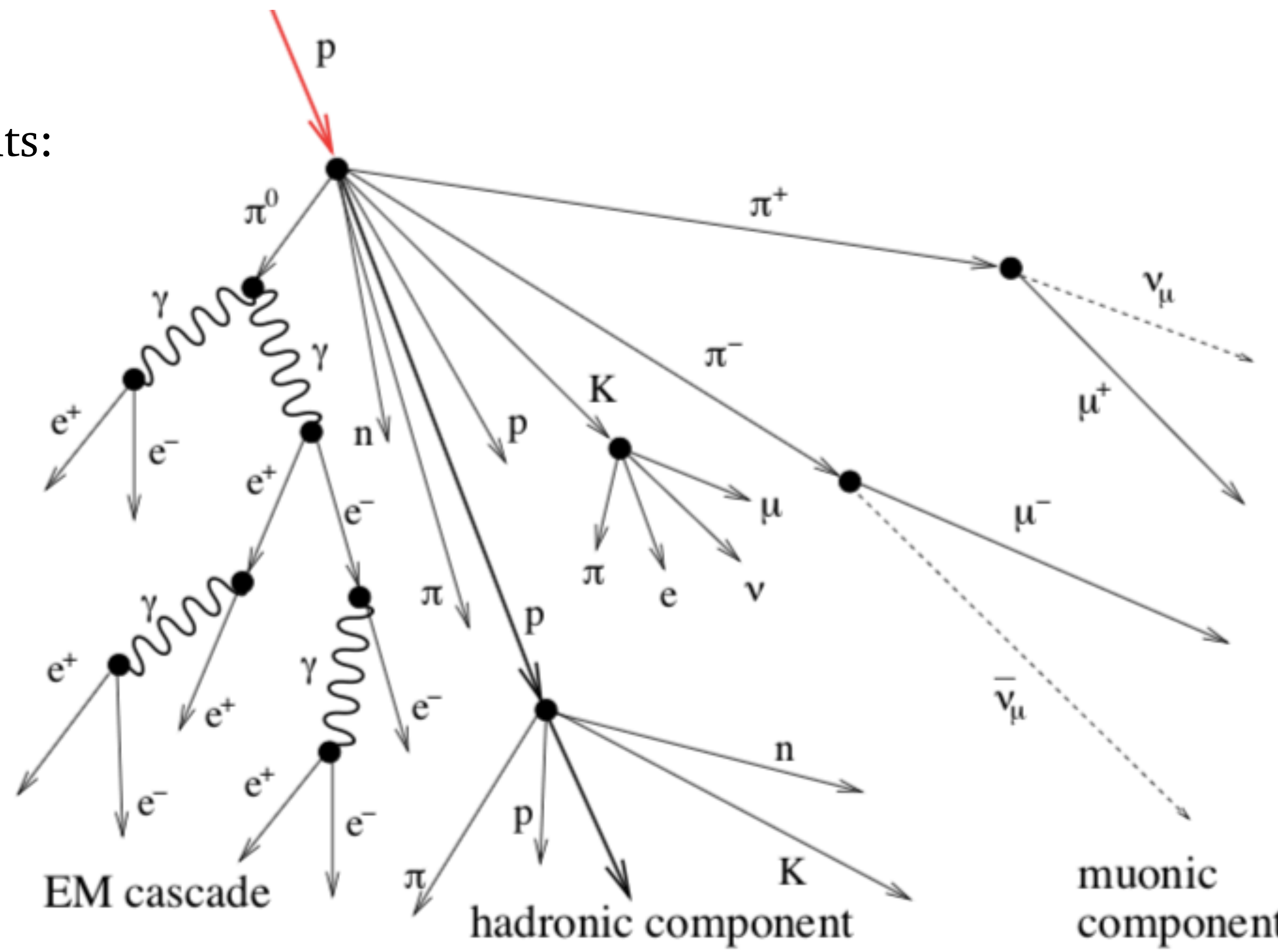
Extensive Air Showers

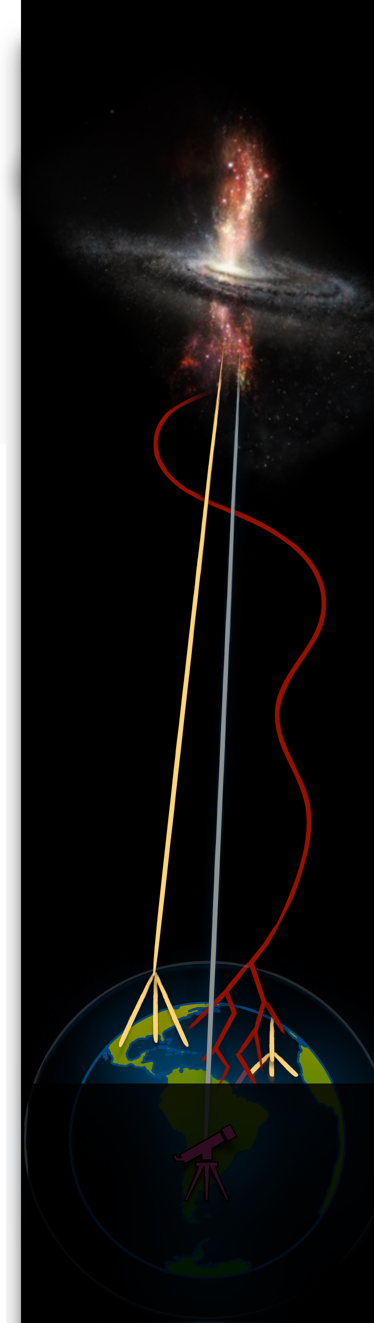
An air shower is an extensive cascade, with a length of many km, of ionized particles and electromagnetic radiation that initiates when a **primary cosmic ray** ($E > 10^{18}$ **eV)** enters the atmosphere.

The shower is composed of three components:

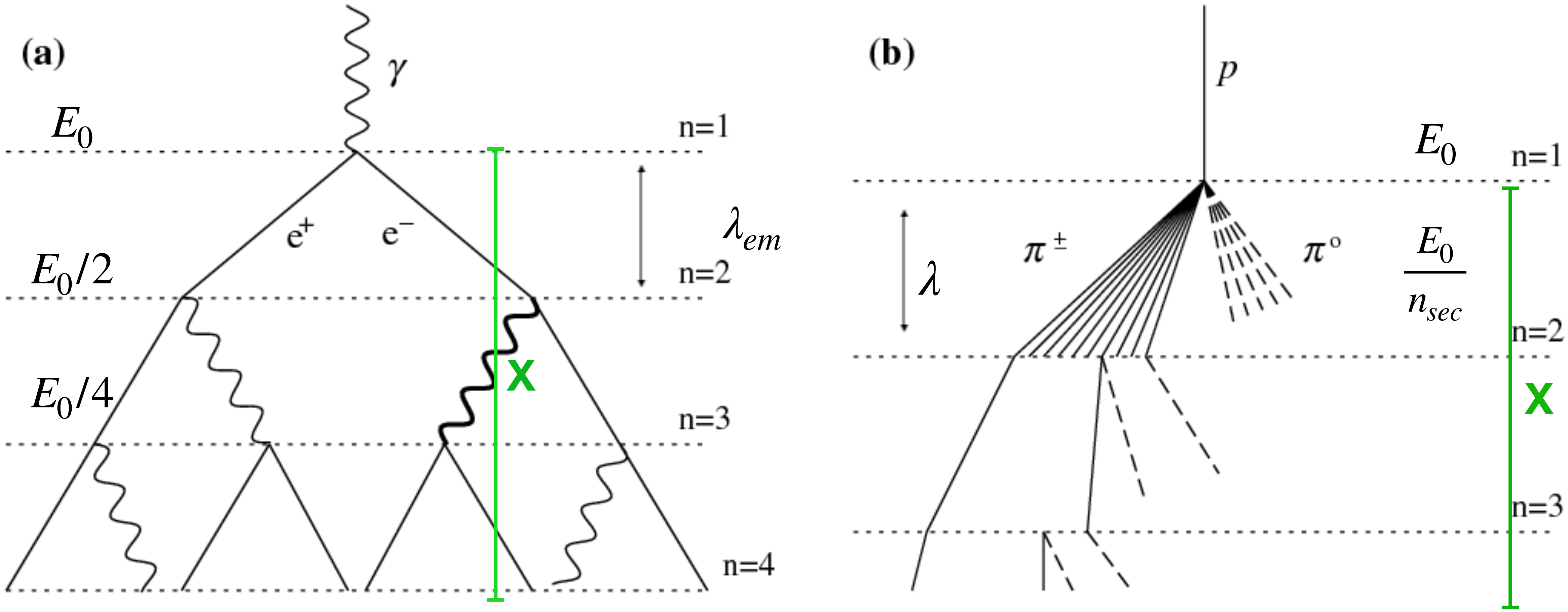
- The em component characterized by the **pair production**, the **bremsstrahlung** and the **ionization energy loss**;
- The hadronic component produced by **charged hadronic** particles involved in the **strong interactions** with the atmosphere;
- The muonic component weakly interacts and it can be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



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



Heitler Model



At the shower maximum we define:

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

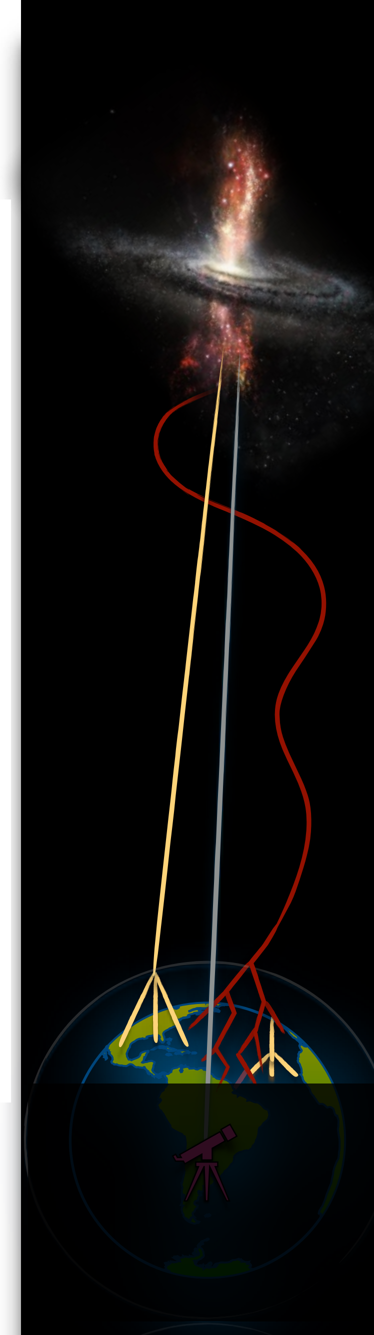
A nucleus with mass A and energy E_0 is considered as A independent nucleons with energy E_0/A each.

The superposition of the individual nucleon showers yields:

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

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

The muon fluctuation: $\dfrac{N_\mu}{\langle N_\mu \rangle} = \alpha_1 \ldots \text{—>} \dfrac{N_\mu}{\langle N_\mu \rangle} = \dfrac{\alpha_1}{A} \ldots$

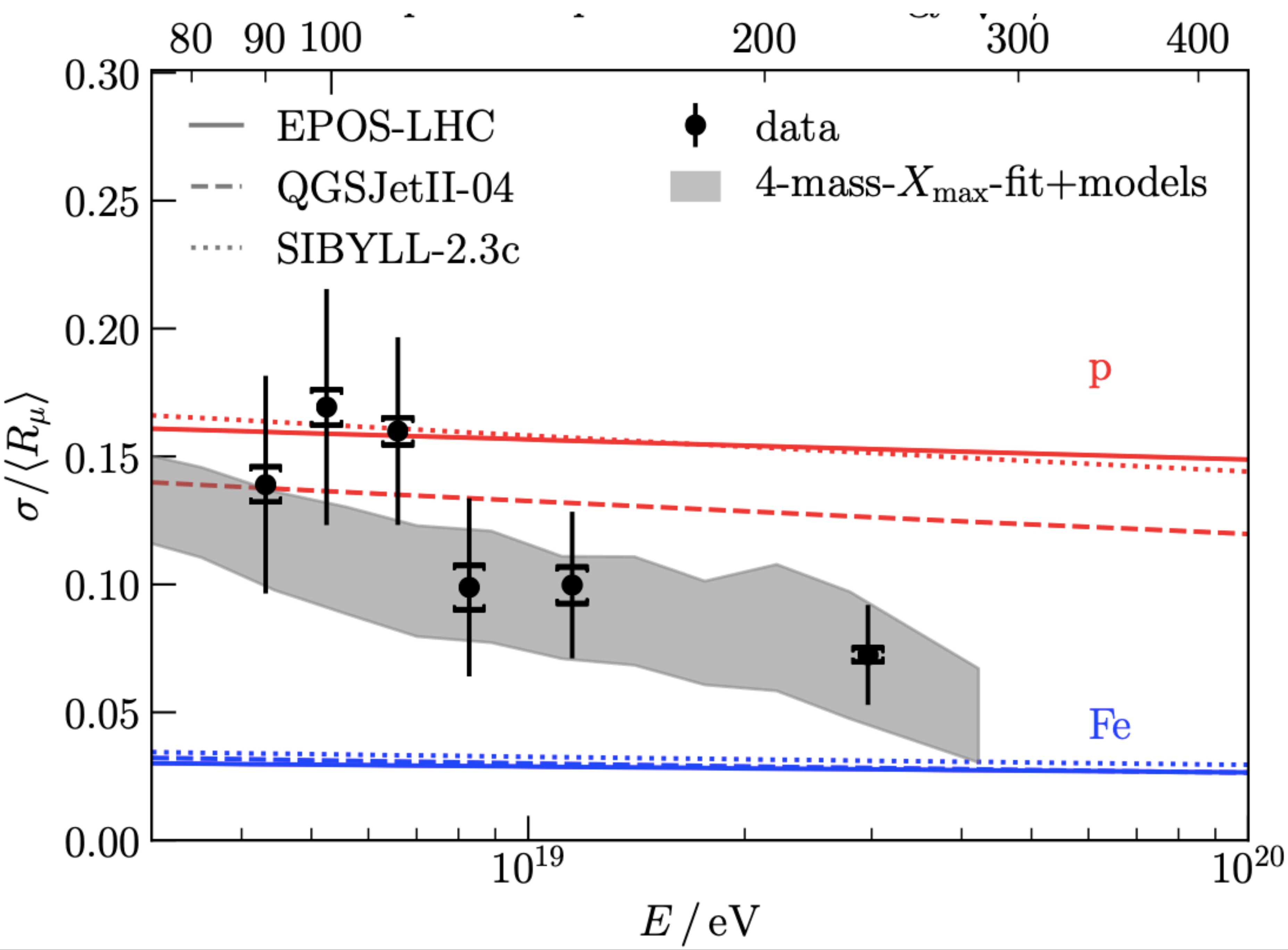


A. Aab et al. [Pierre Auger] Phys. Rev. Lett. 126 (2021) no.15, 152002

Relative Fluctuations

Ratio of the fluctuations to the average number of muons

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



How to break Lorentz Invariance

Modified dispersion relation

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

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

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

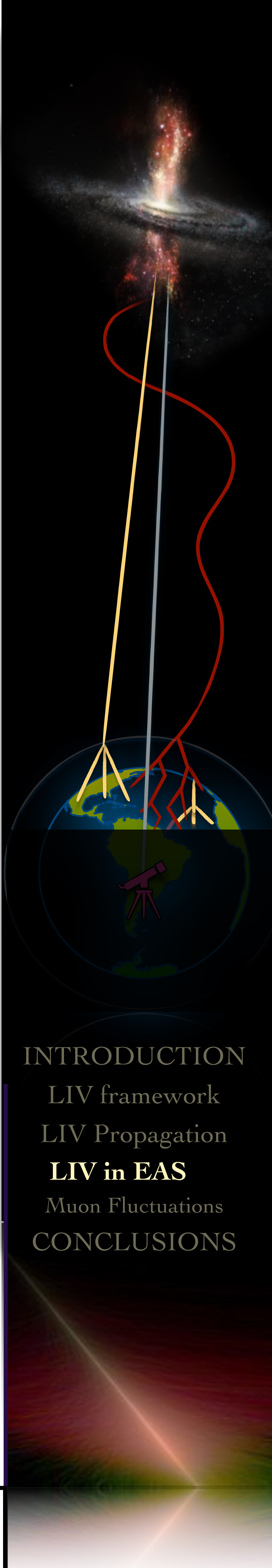
We consider the right-hand side of the modified dispersion relation as a new mass:

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

We can define the Lorentz factor as: $\gamma_{\rm LIV} = \frac{E}{m_{\rm LIV}}$

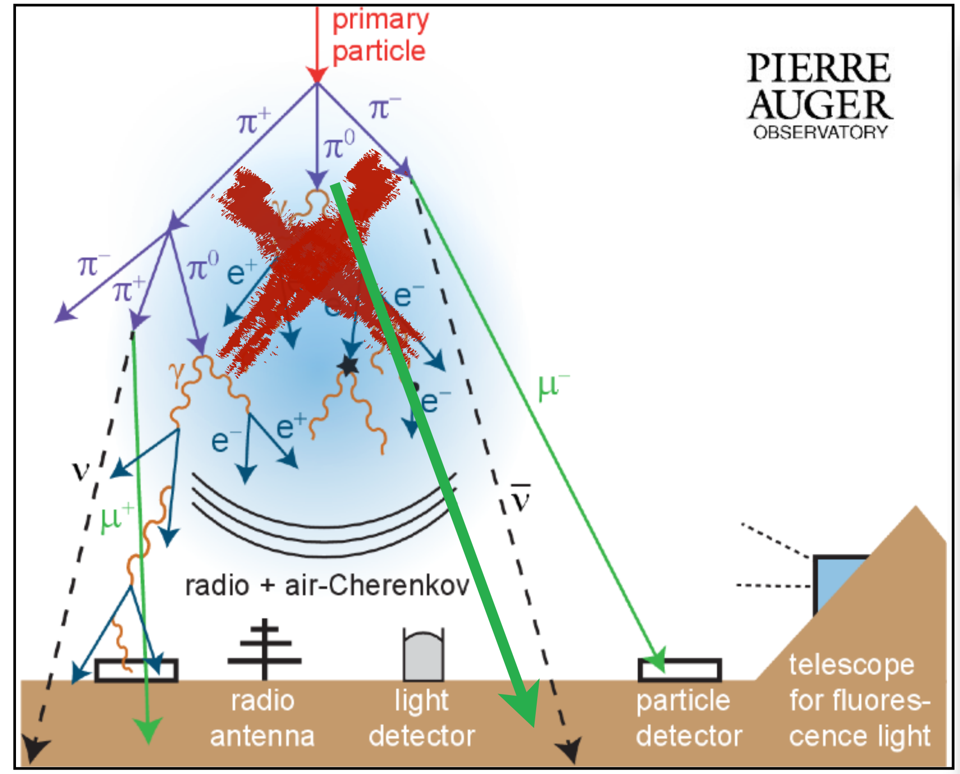
In terms of the lifetime τ of particles: $\tau = \gamma_{\rm LIV} \tau_0$

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



Neutral pion decay

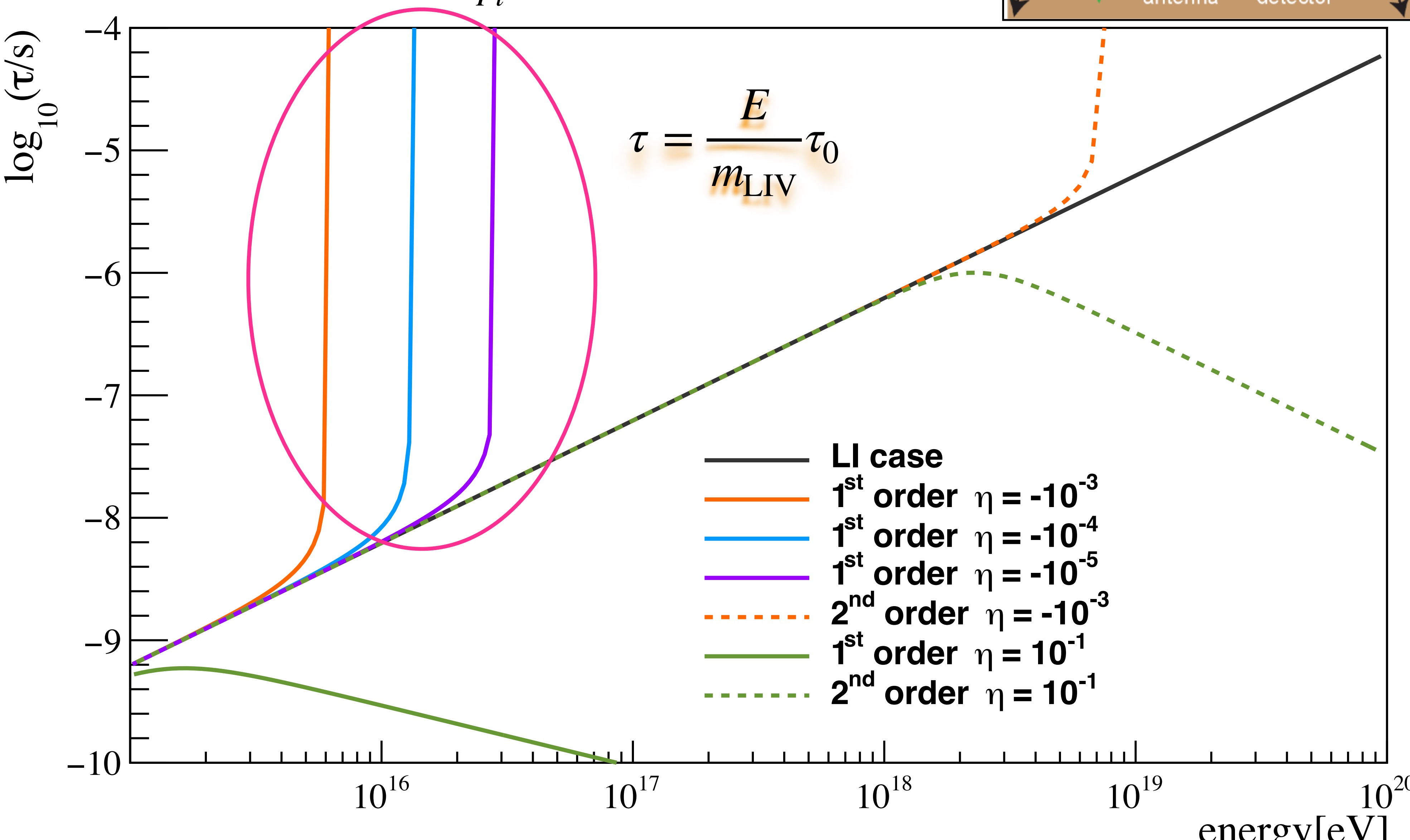
π^0 **Decay:** $\pi^0 \rightarrow \gamma\gamma$ $\tau_0 = 8.4 \cdot 10^{-17}$s

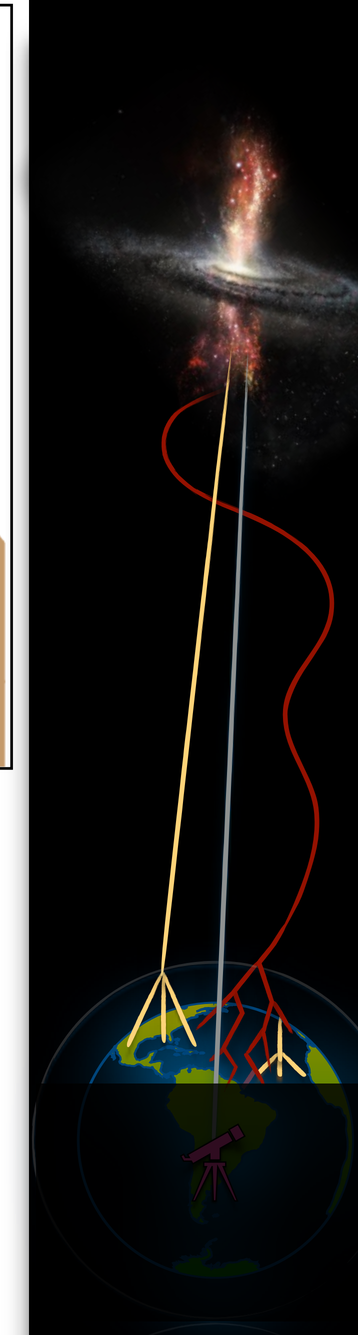


If η_π assumes negative values!

The decay is forbidden if:

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

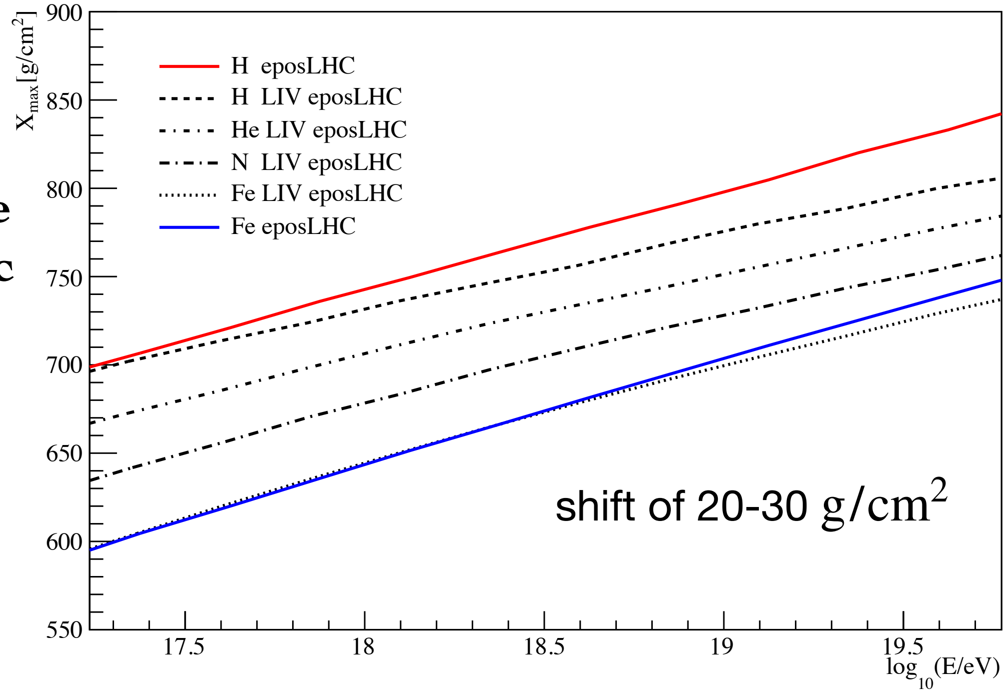




ORDER OF LIV n=1
EPOS-LHC
$\eta = -10^{-3}$

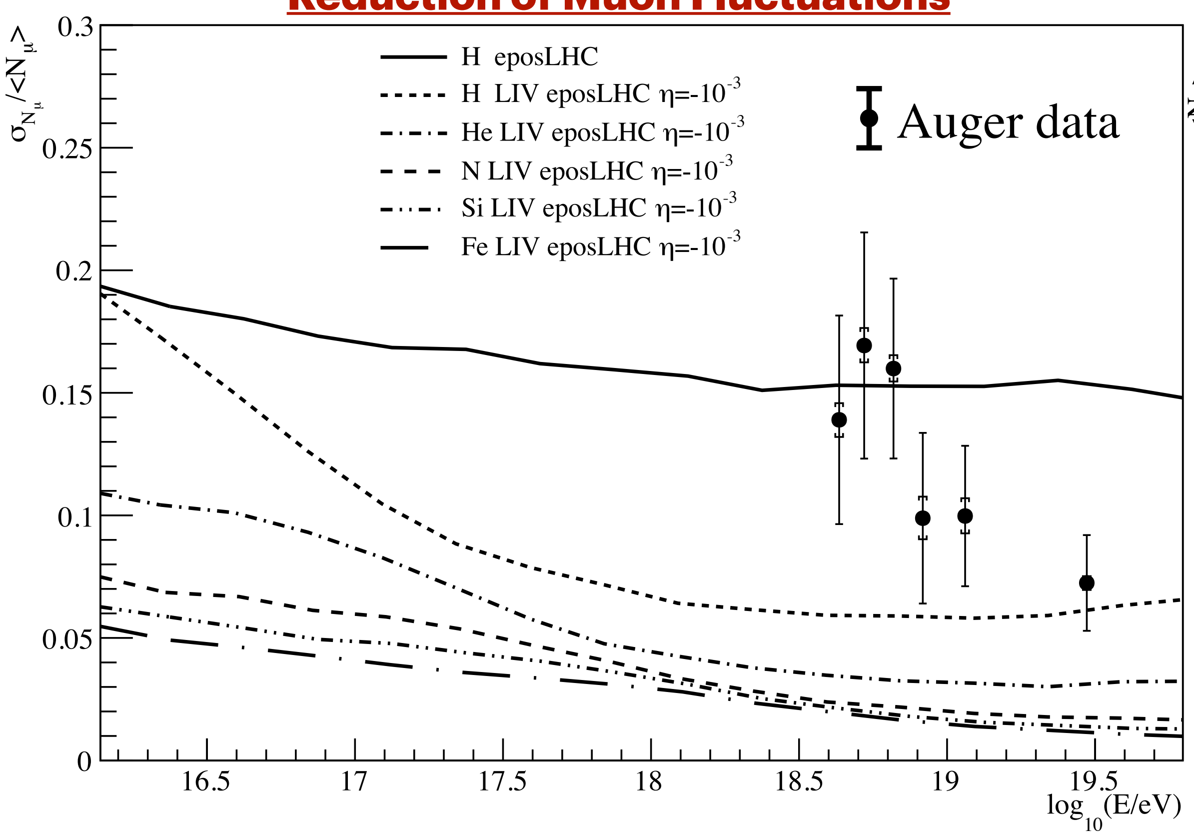
Modified shower development

Decrease in the electromagnetic component

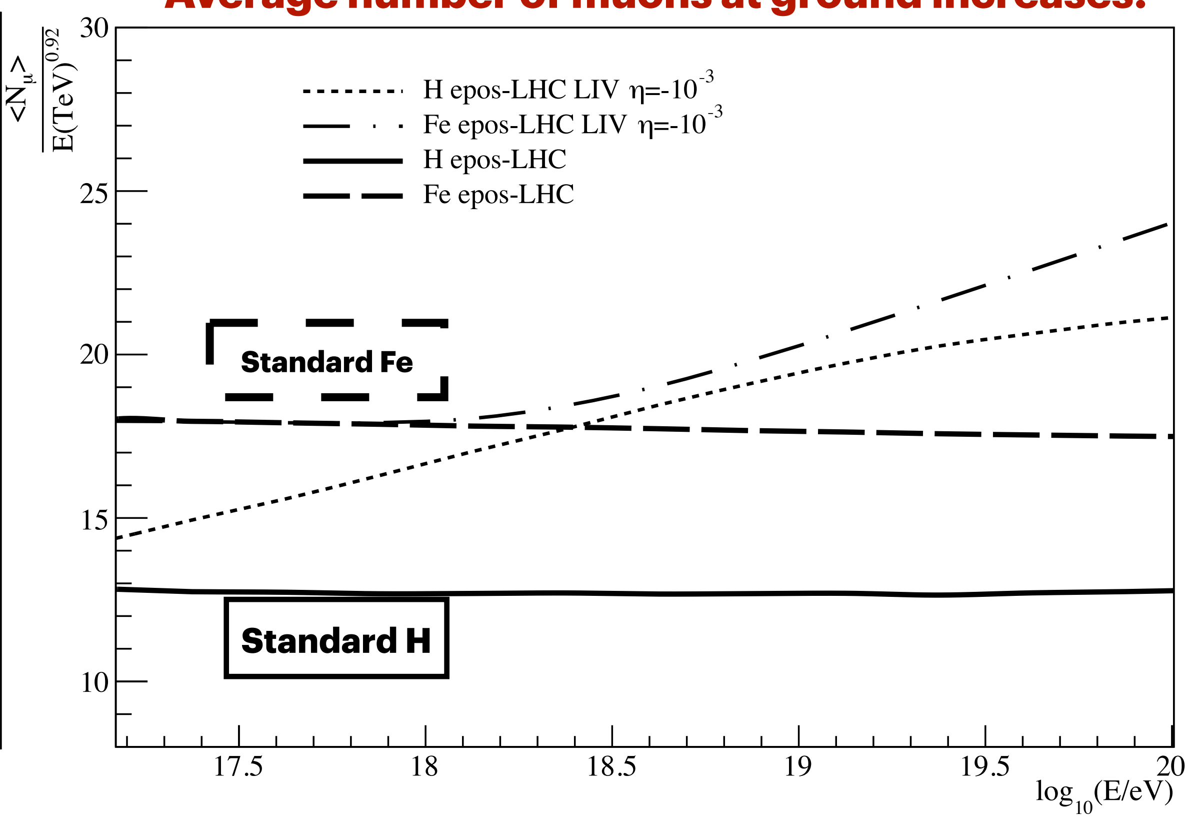


A growth of the hadronic cascade

Reduction of Muon Fluctuations



Average number of muons at ground increases!



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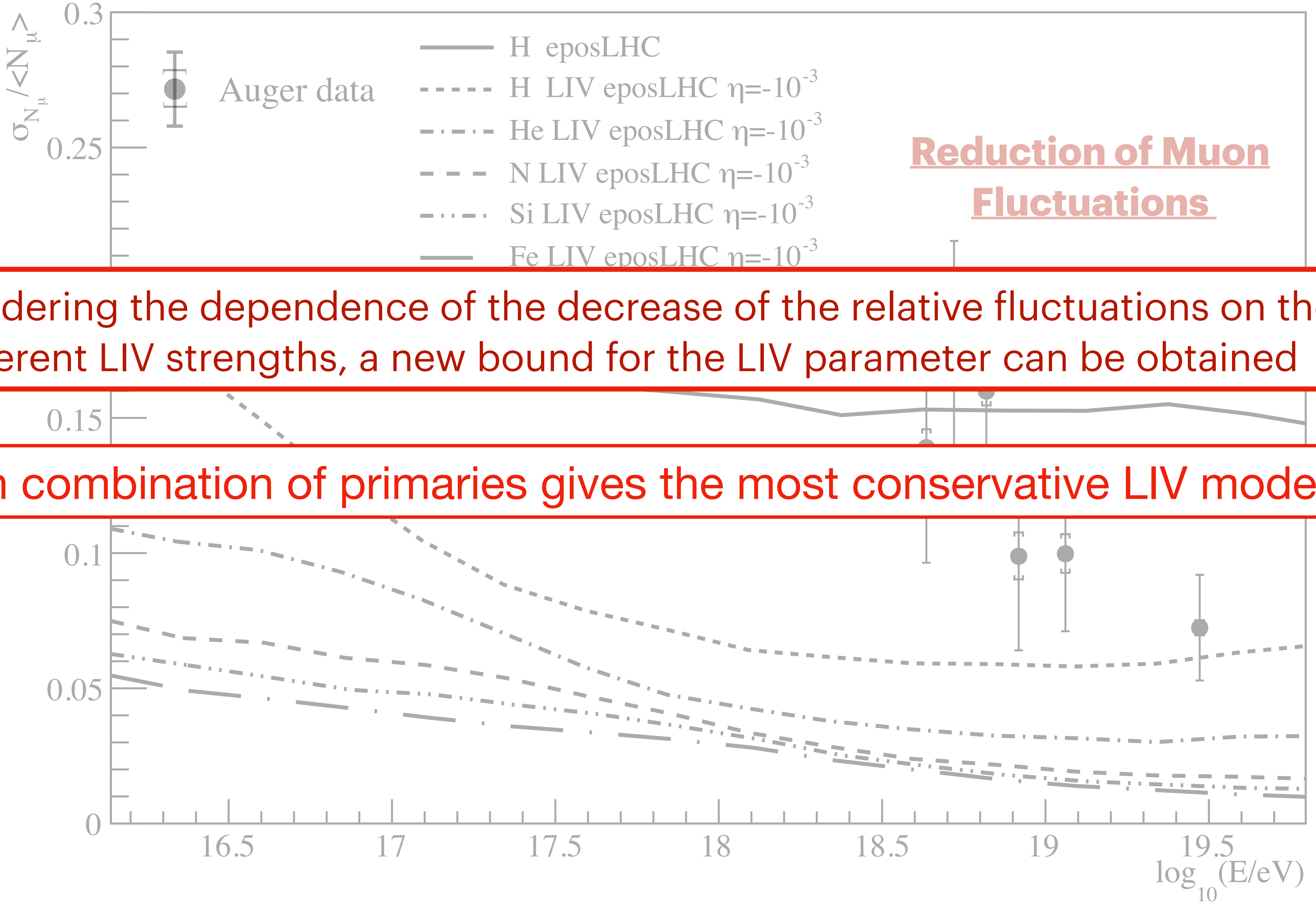
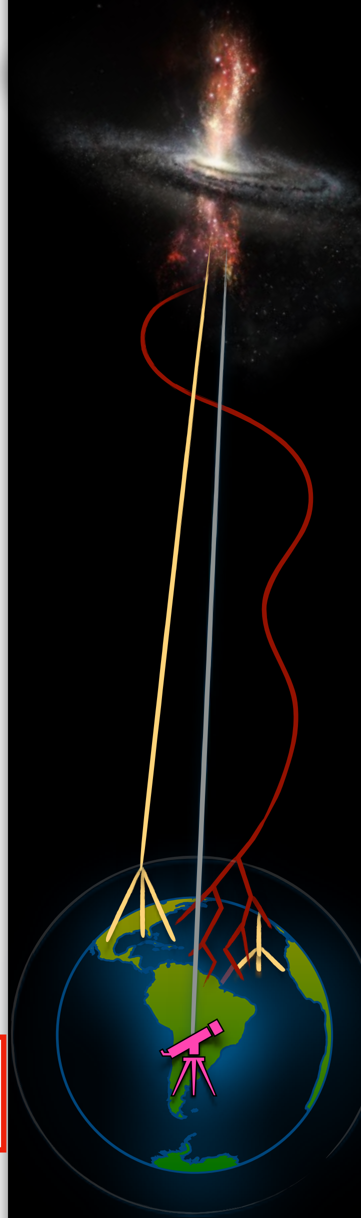
Relative Fluctuations

Ratio of the fluctuations to the average number of muons



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

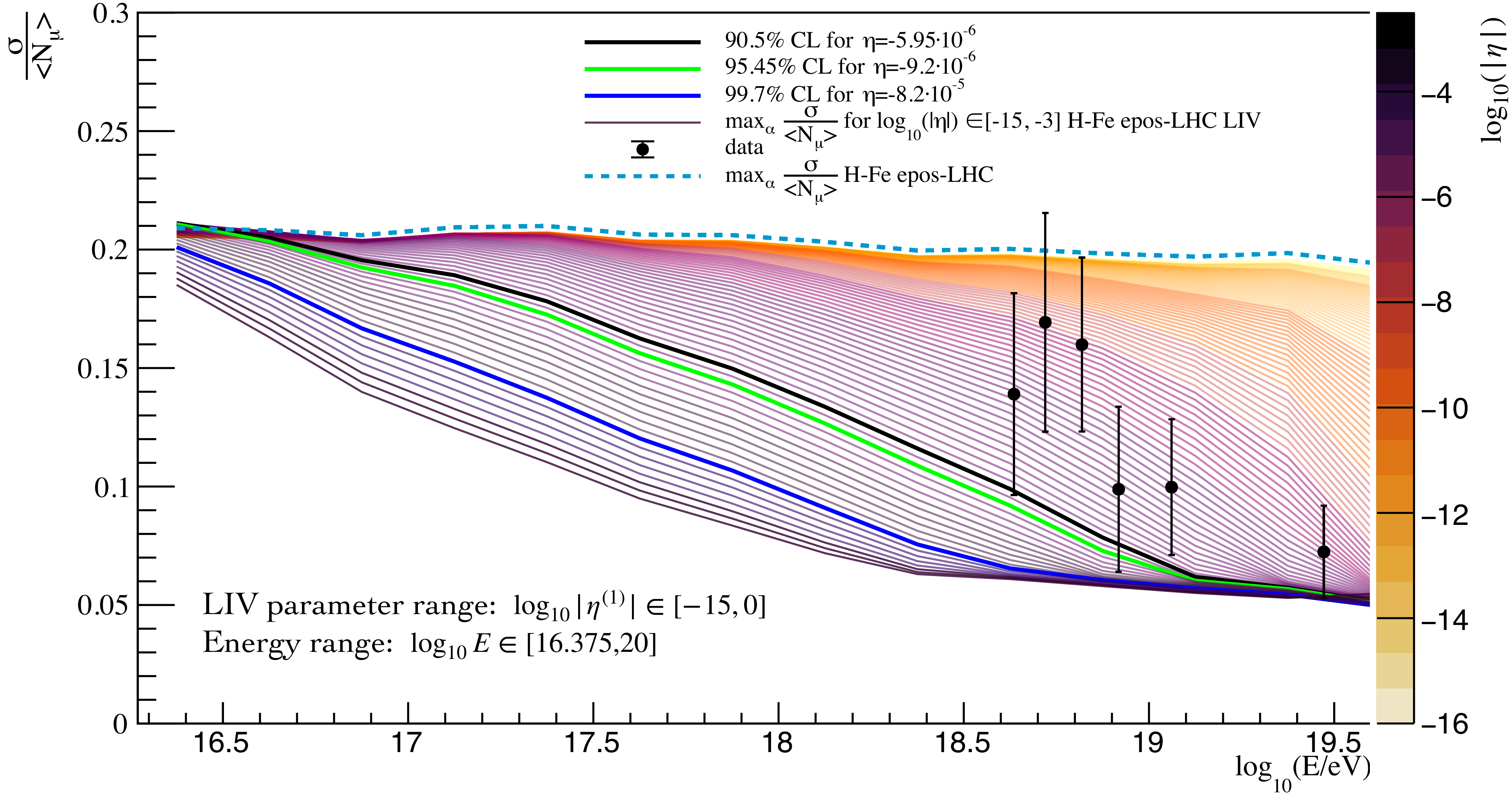
Which combination of primaries gives the most conservative LIV model?

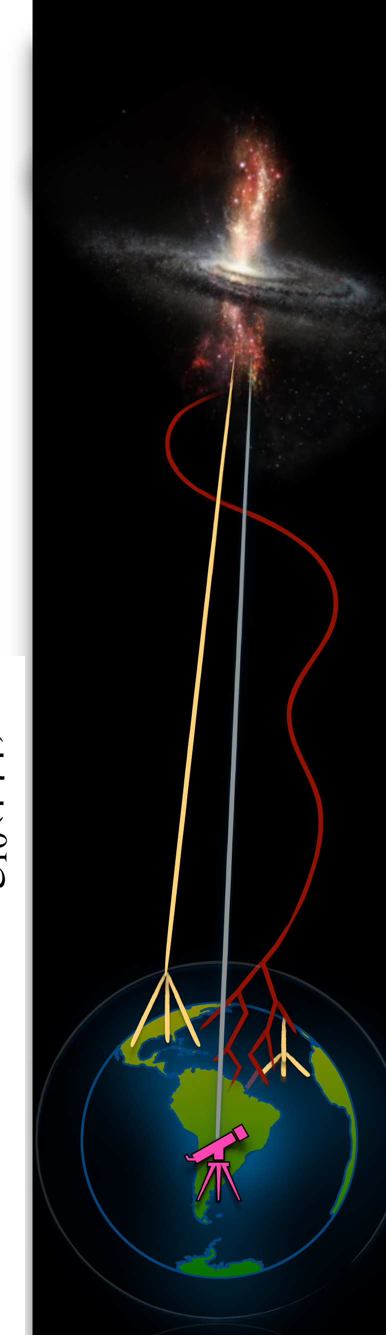


Most conservative LIV Relative Fluctuations

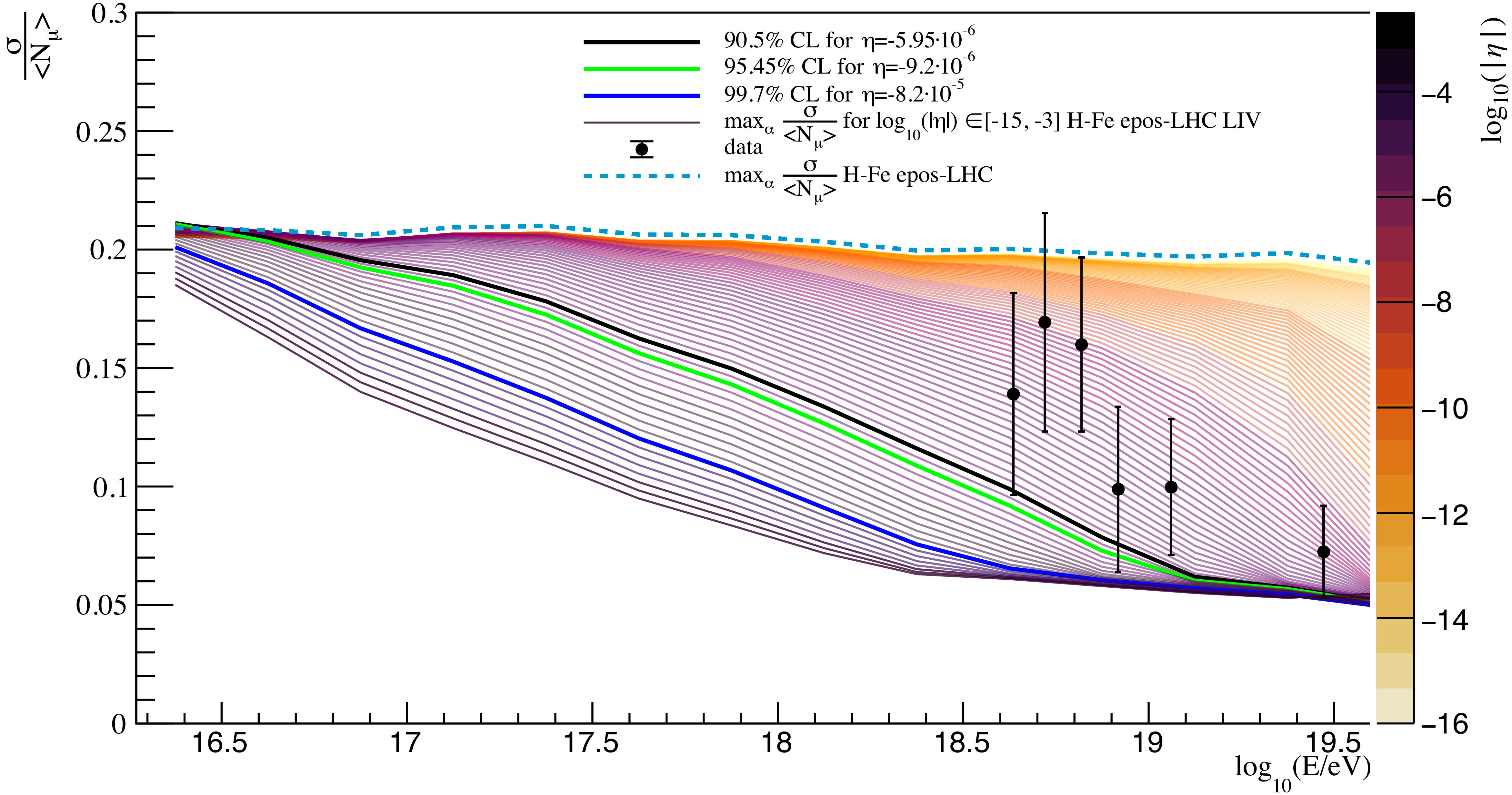
for any LIV parameter value we found the most conservative LIV relative fluctuations as a function of the energy without repeating any shower simulation

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





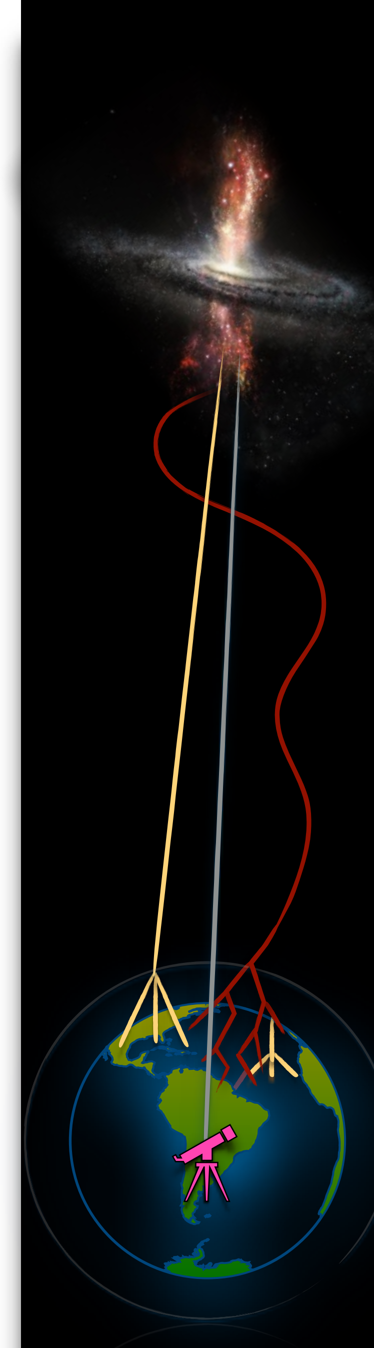
Most conservative LIV Relative Fluctuations



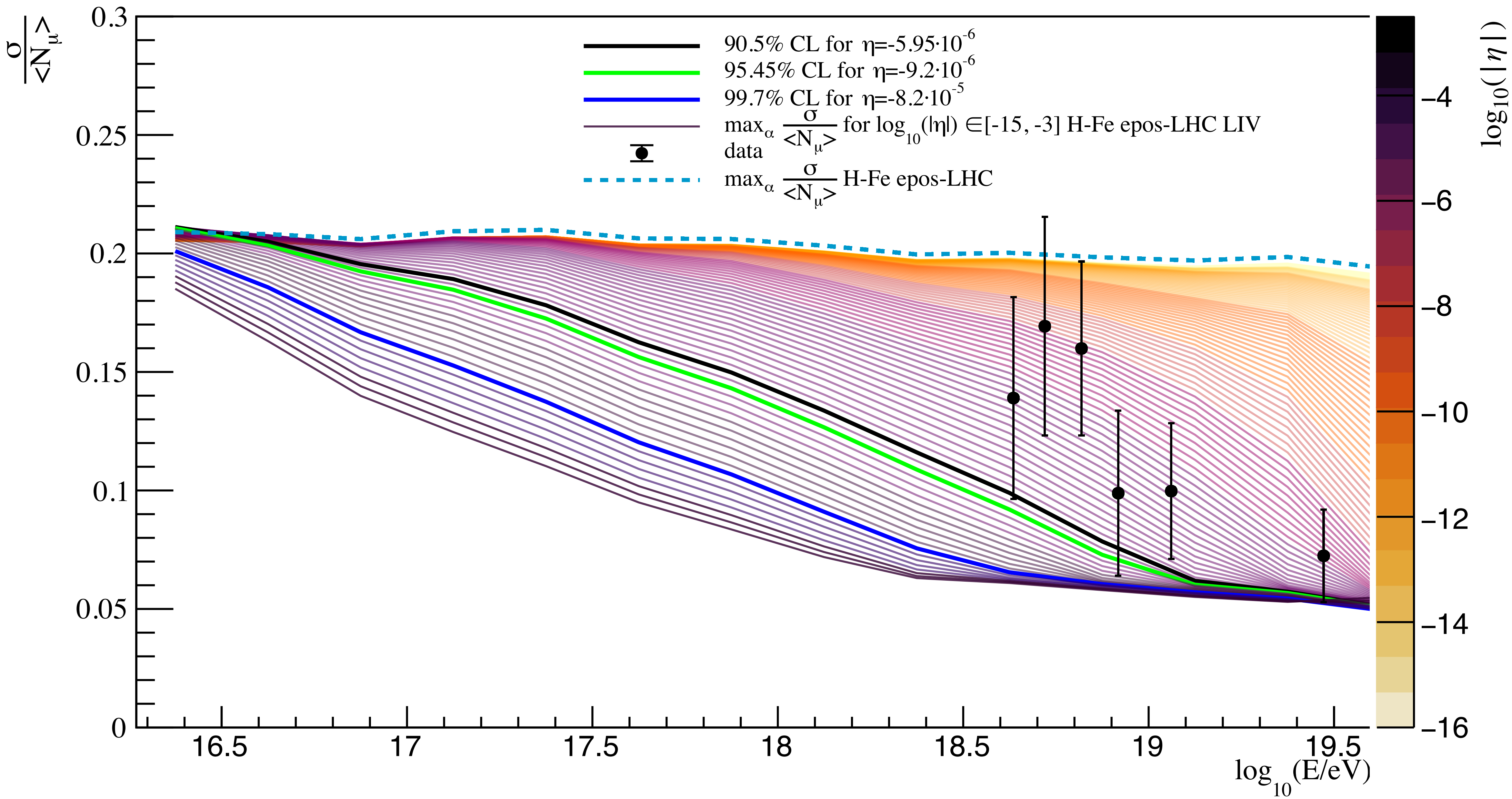
χ^2 is calculated as a function of η considering all the data points

↓

Continuous confidence levels to exclude LIV models



Most conservative LIV Relative Fluctuations



New bound!

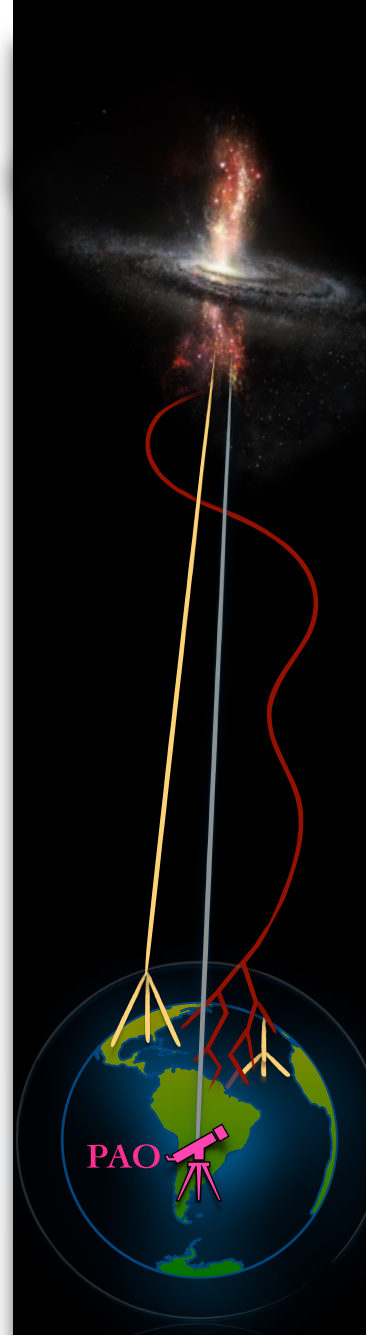
$\eta^{(1)} > -5.95 \cdot 10^{-6}$ with (90.5% C.L.)

Summary

<u>LIV can be tested with UHECRs</u>

- Extragalactic propagation of UHECRs:
    - Searches signatures in electromagnetic sector and hadronic sector;
        - Astrophysical scenarios predict low maximum energy at the sources and mixed composition
- Development of cascade of particles in atmosphere
    - Fluctuations of number of muons used for the first time to constrain LIV

Other works PoS ICRC (2015) 521 PoS ICRC (2017) 561 PoS ICRC (2019) 327

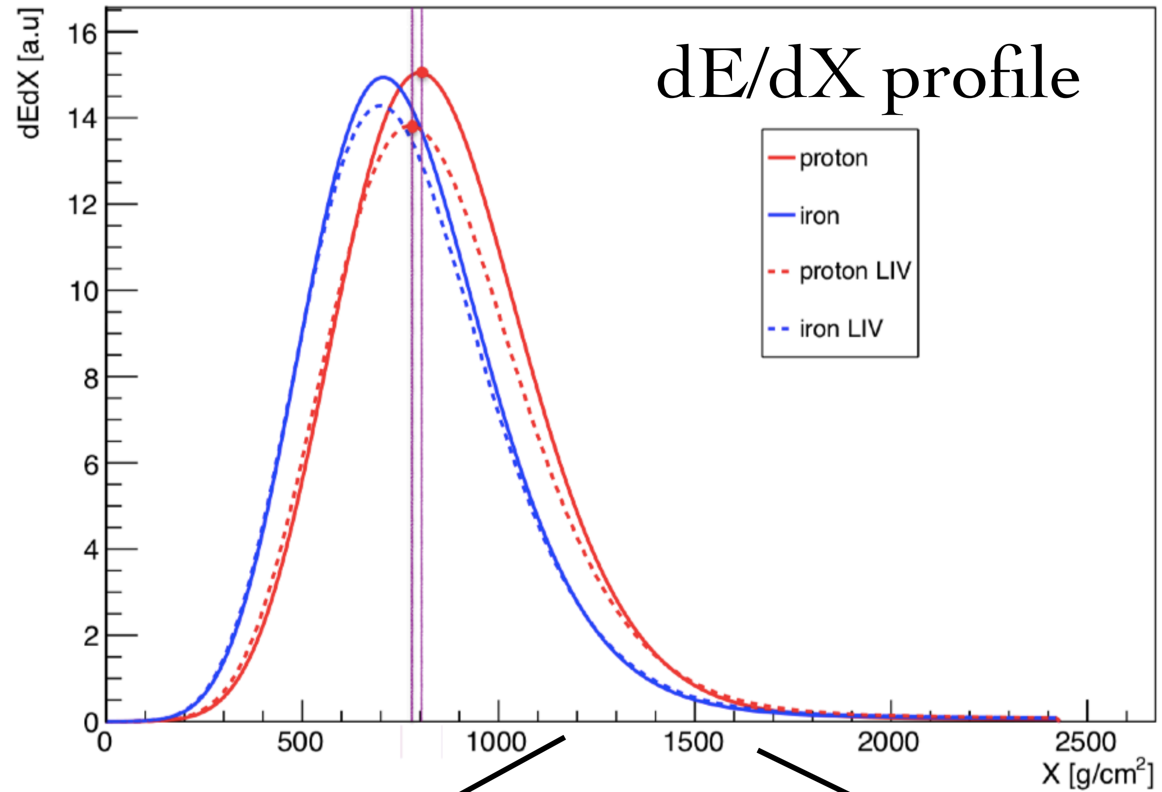



Thank you for your attention!

Backup

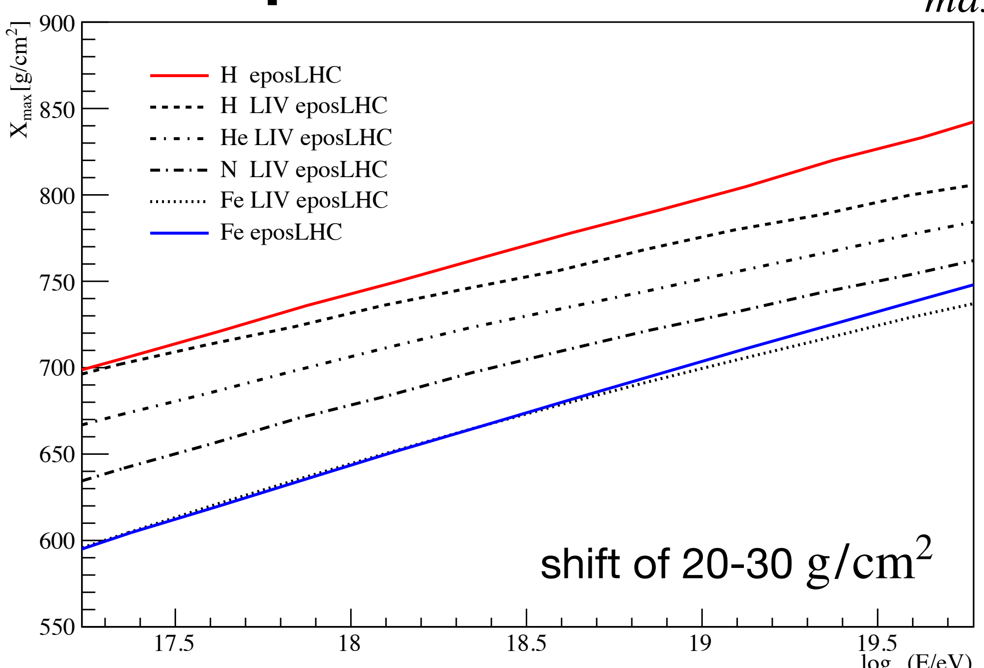
LIV effects on air shower development

SIMULATED SHOWERS
CONEX



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

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

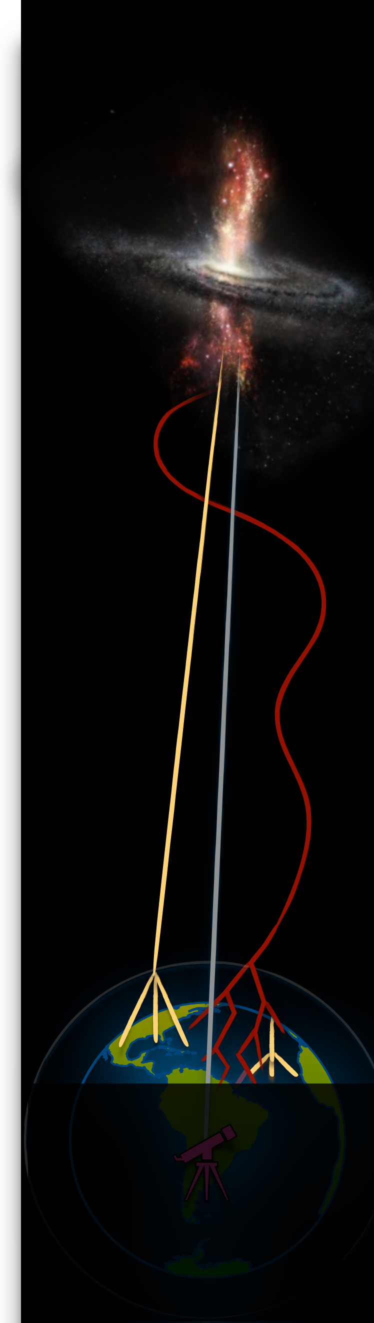


2. Reduction in the normalization

- 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.

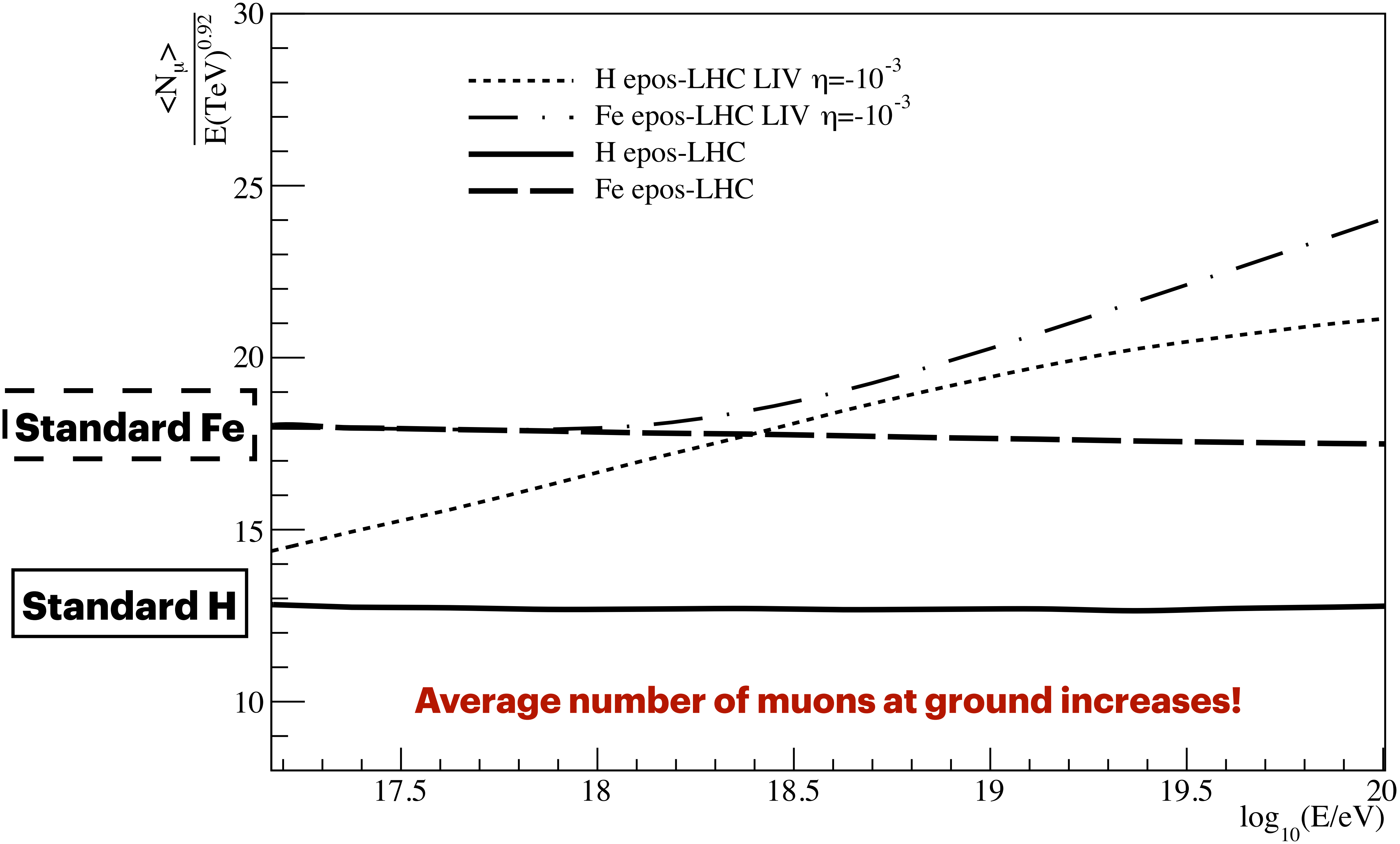
MUON CONTENT DISTRIBUTION

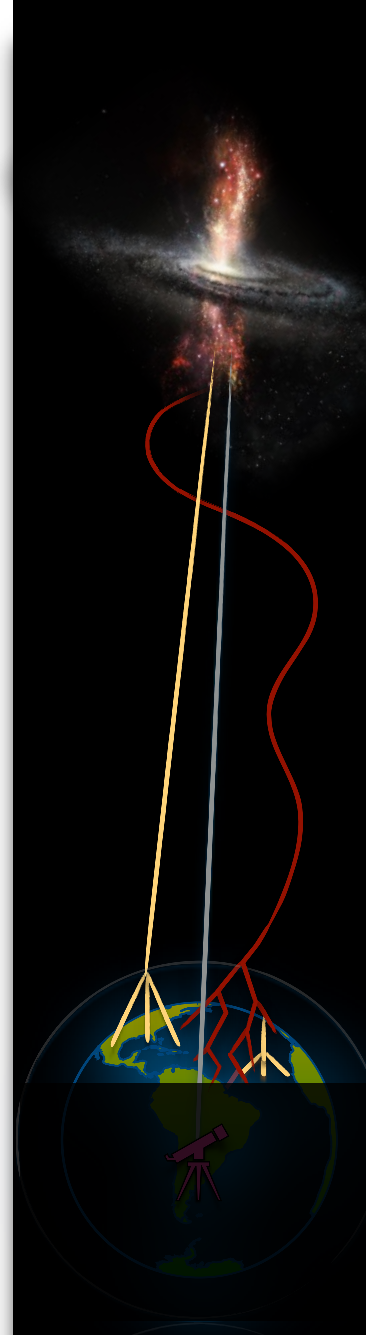


MUON CONTENT DISTRIBUTION

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

Average number of muons



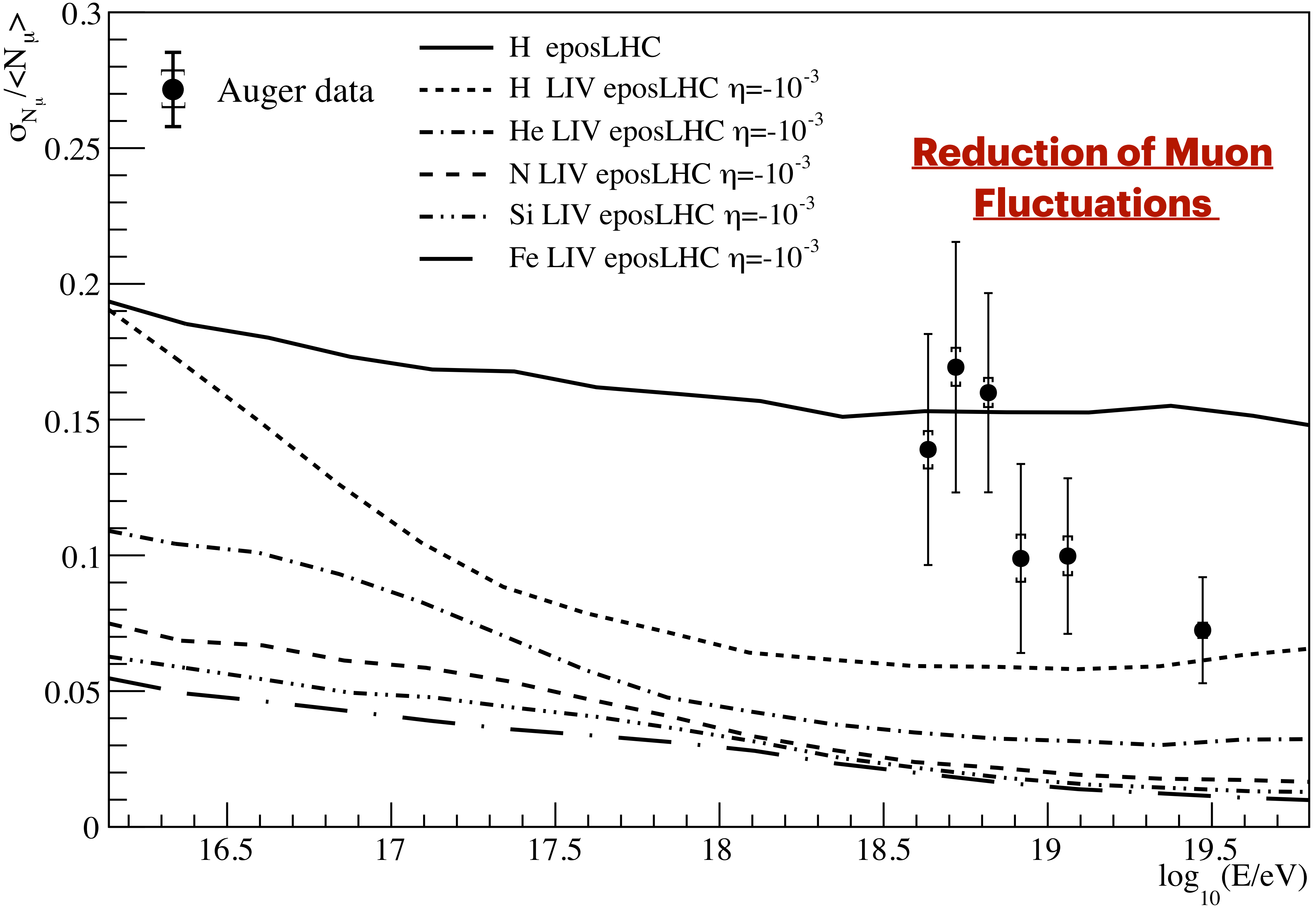


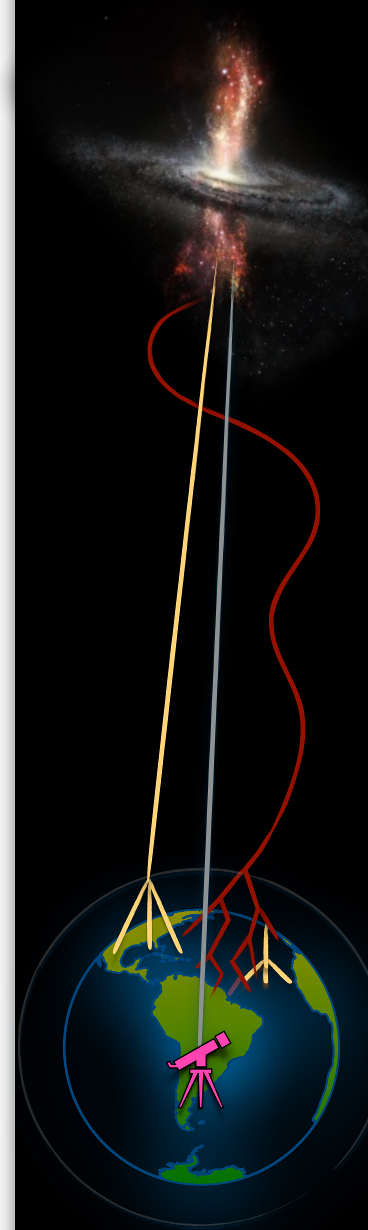
MUON CONTENT DISTRIBUTION

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

Relative Fluctuations

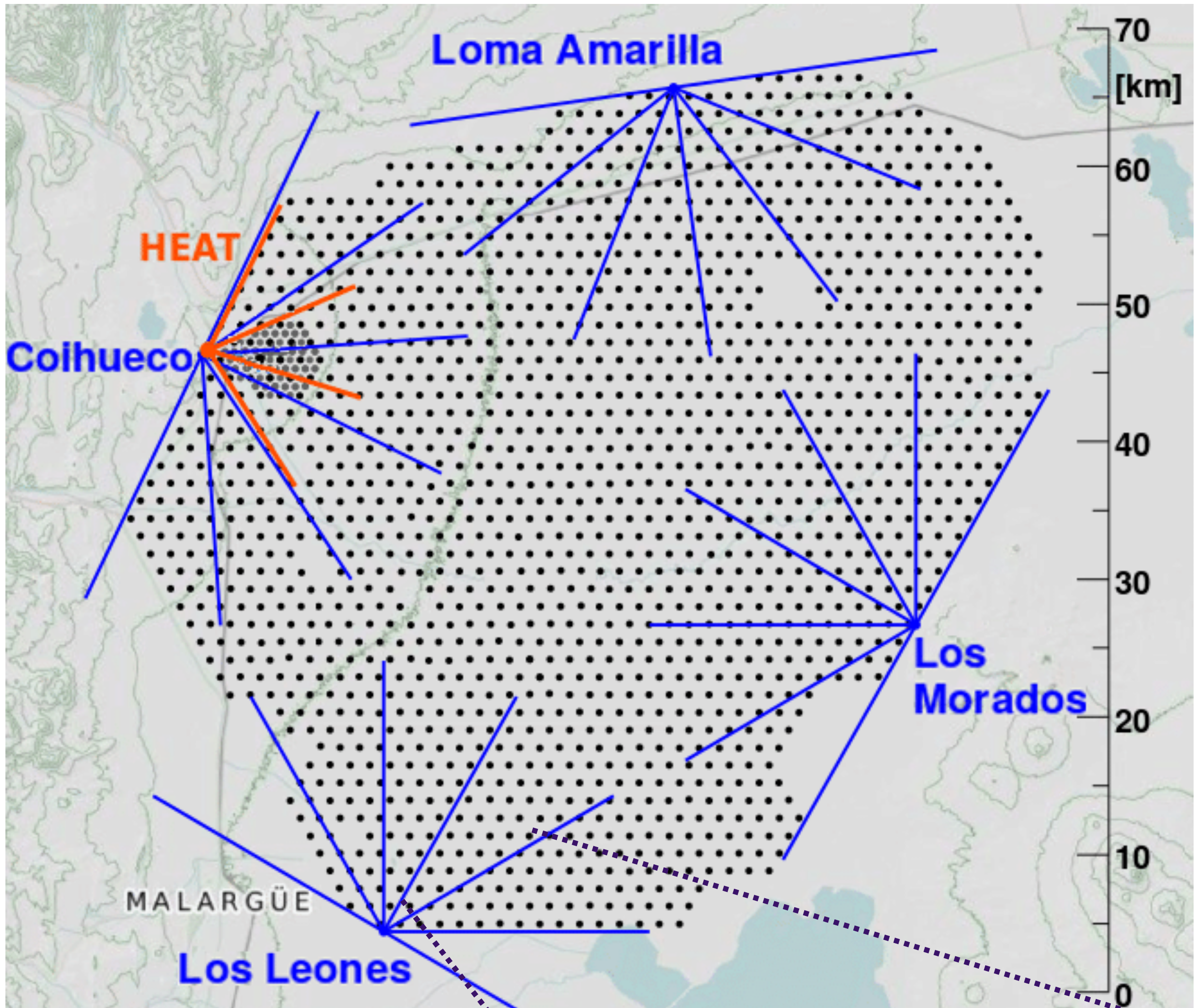
Ratio of the fluctuations to the average number of muons





Pierre Auger Observatory

See talk di qualcuno



HYBRID DETECTOR:

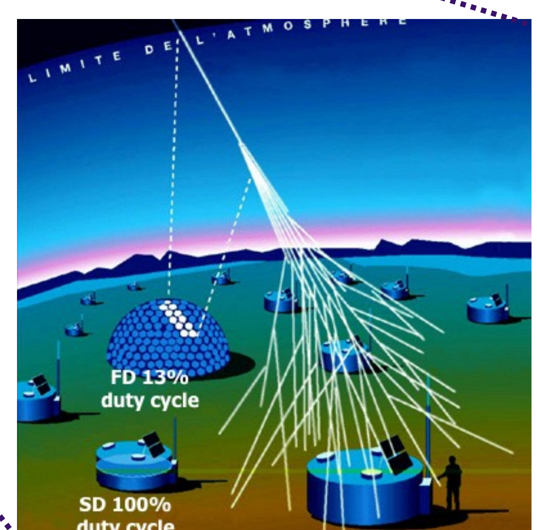
Fluorescence detector (FD)

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

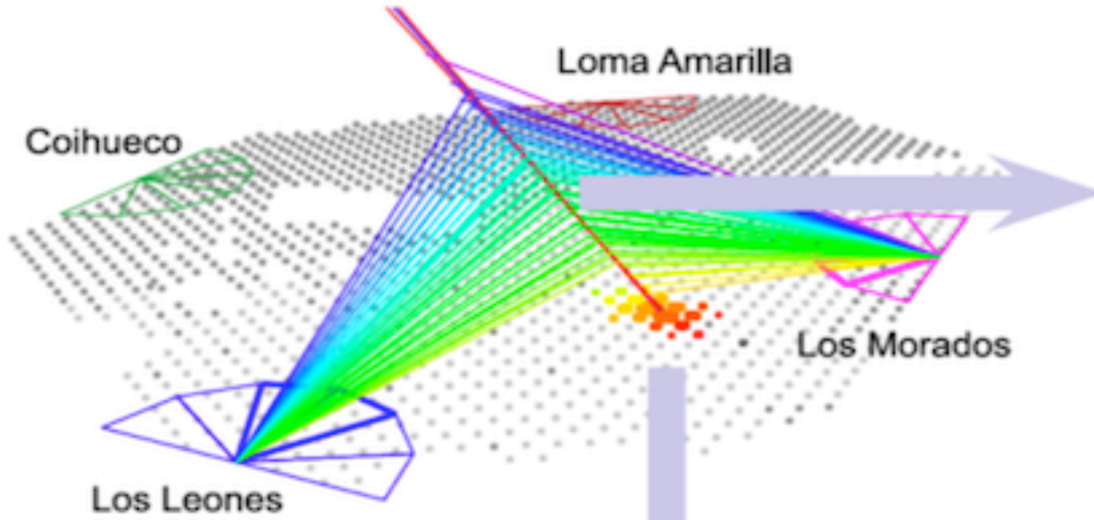
Surface detector (SD): ground array of water Cherenkov detectors

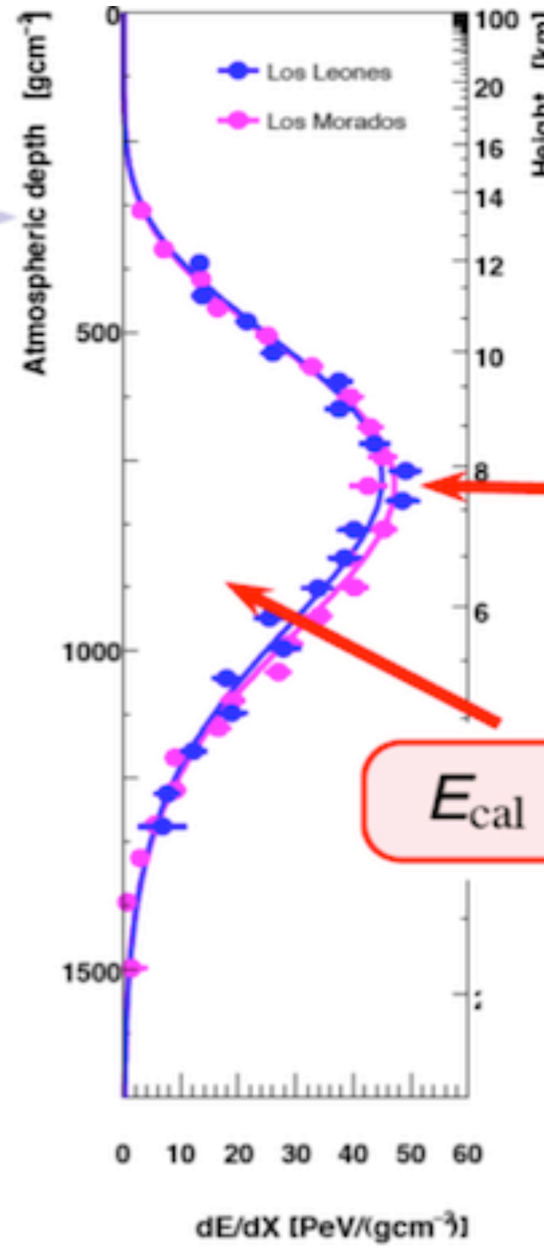
- 1660 stations in 1.5 km grid, 3000 km² E > $10^{18.5}$ eV
- 61 stations in 0.75 km grid, 23.5 km²,E > $10^{17.5}$ eV

Underground muon detector



Hybrid Detection

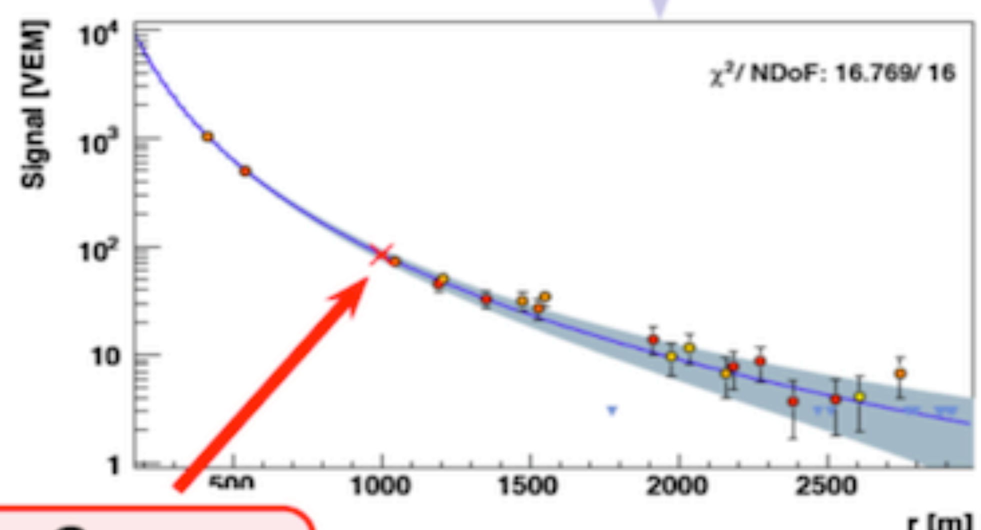




X_{max}

$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

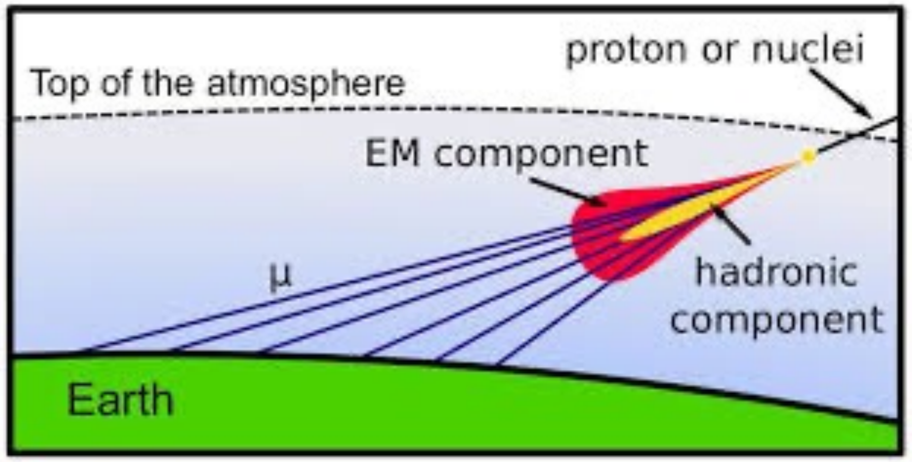
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$



S_{1000}

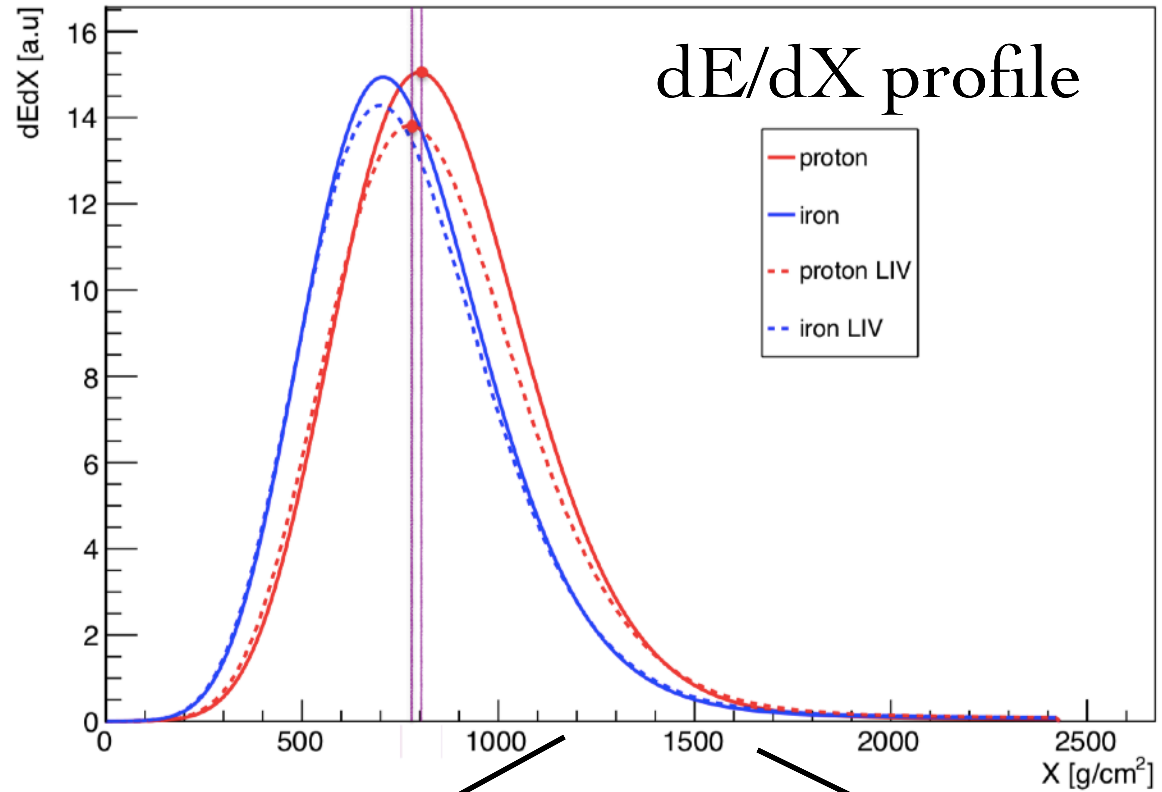
$E_{\mathrm{surface}} = f(S_{1000},\,\theta)$

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



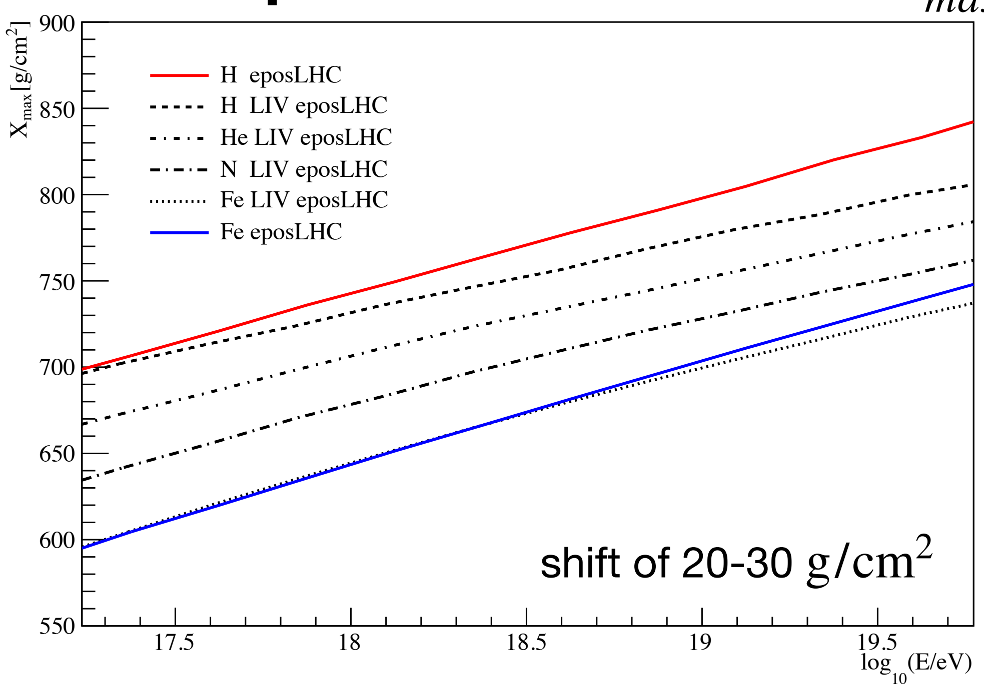
LIV effects on air shower development

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

CONEX shower simulation

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).

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};

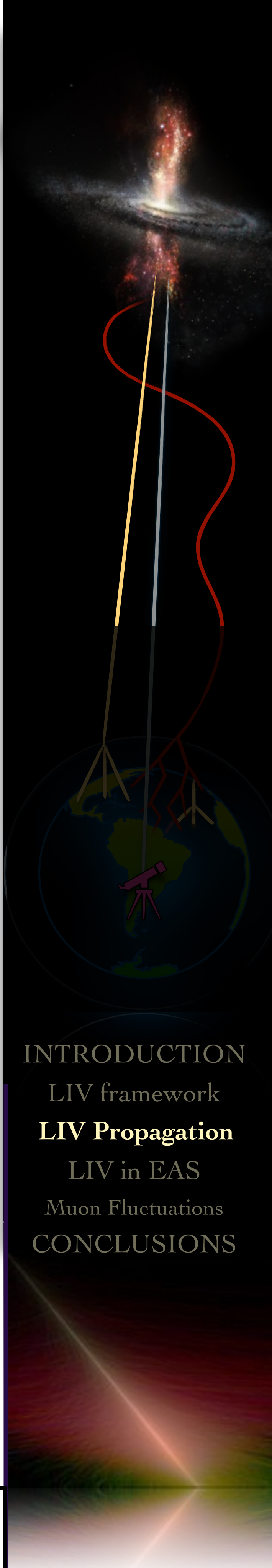
Hadronic interaction model: EPOS LHC-LIV, QGSJETII-04.

in presence of LIV

LIV parameter η:

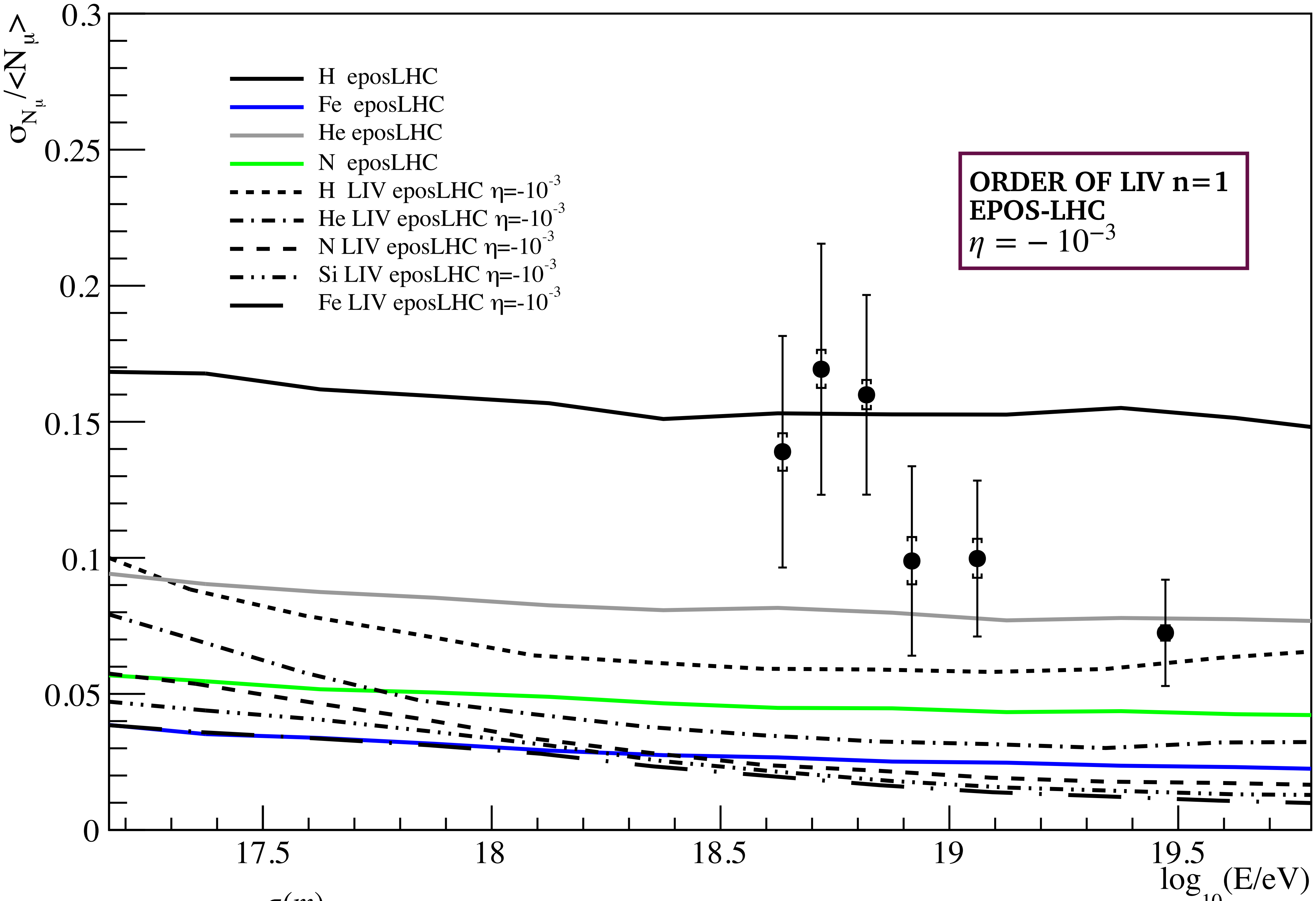
- **1st order:** $\eta = -10^{-1}, -10^{-3}, -10^{-4}, -10^{-5}, -10^{-6}, -5 \cdot 10^{-7}, -10^{-7}, -10^{-8}$
- **2nd order:** $\eta = -1, -10^{-1}, -10^{-2}, -10^{-3}$

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



Muon Fluctuations

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



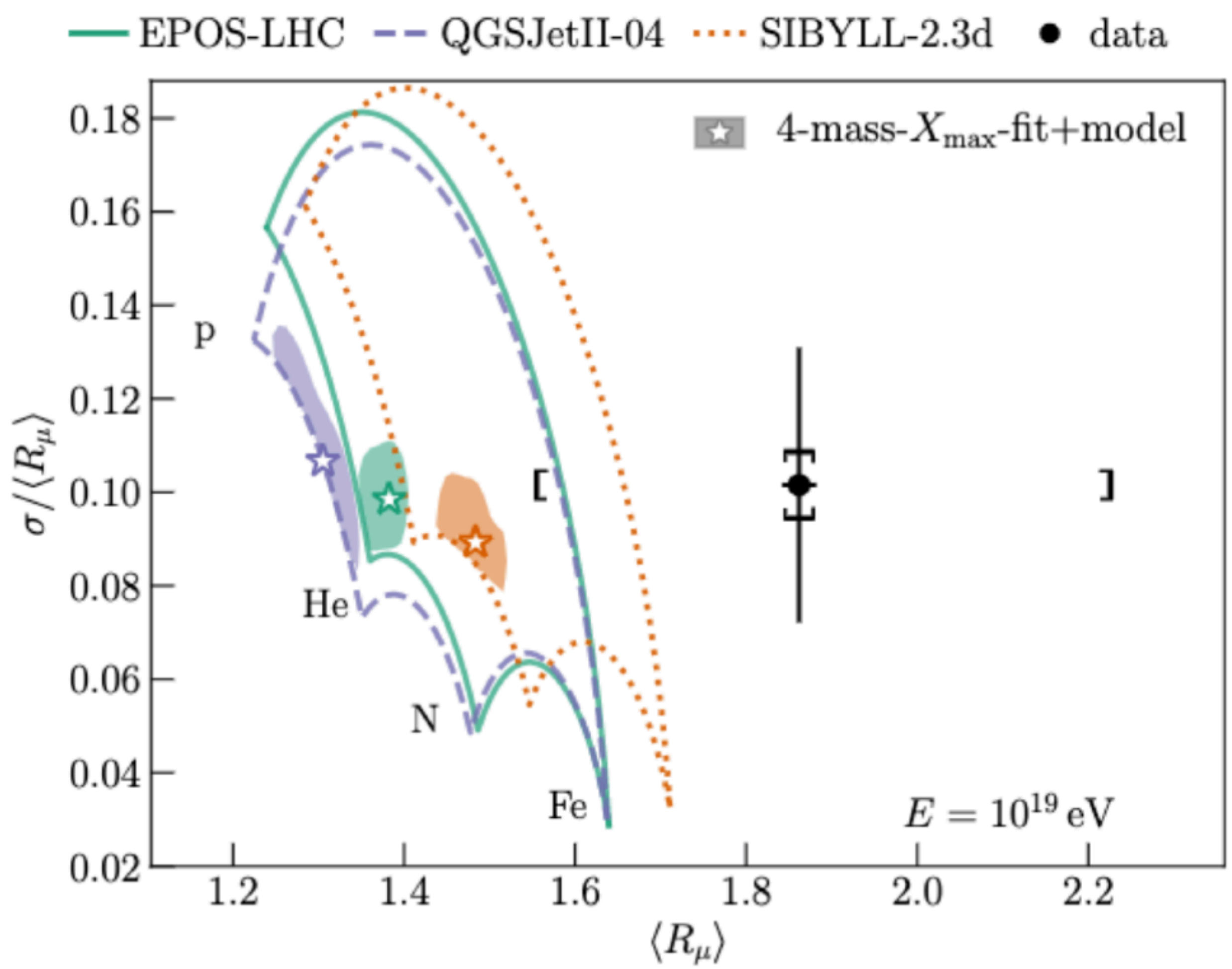
$\langle N_\mu(E) \rangle = m^g = CE^\beta$ —> $\sigma(m_i) = \frac{\sigma(m)}{\sqrt{N_{i-1}}}$ —> the fluctuations are mostly dominated by the first interaction!

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

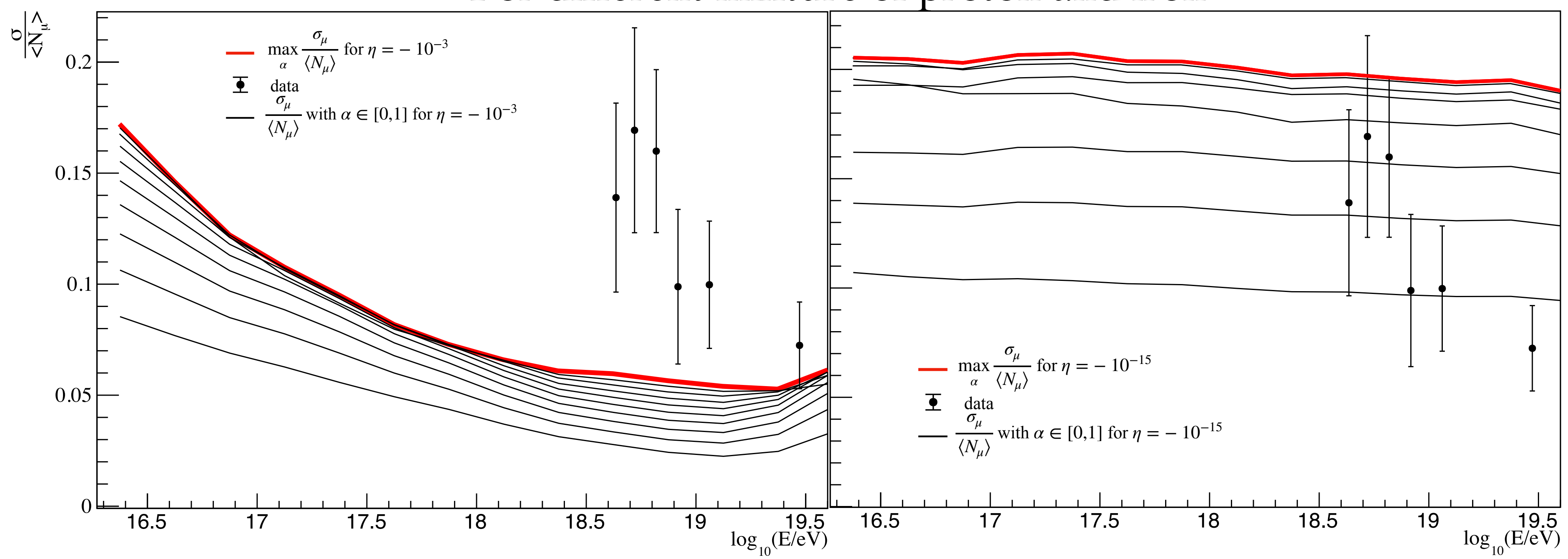
α is the fraction of iron

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

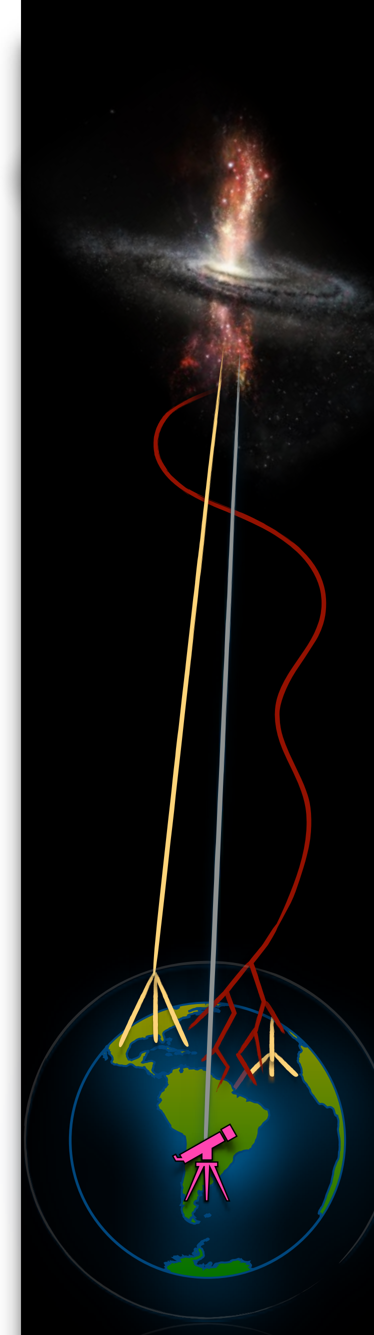
   $1-\alpha$ is the fraction of proton
   α is the fraction of iron
3. Parametrize as **function of η and energy** $\langle N_\mu \rangle_p$, $\langle N_\mu \rangle_{Fe}$, $\sigma(N_\mu)_p$ and $\sigma(N_\mu)_{Fe}$

For different mixture of proton and iron



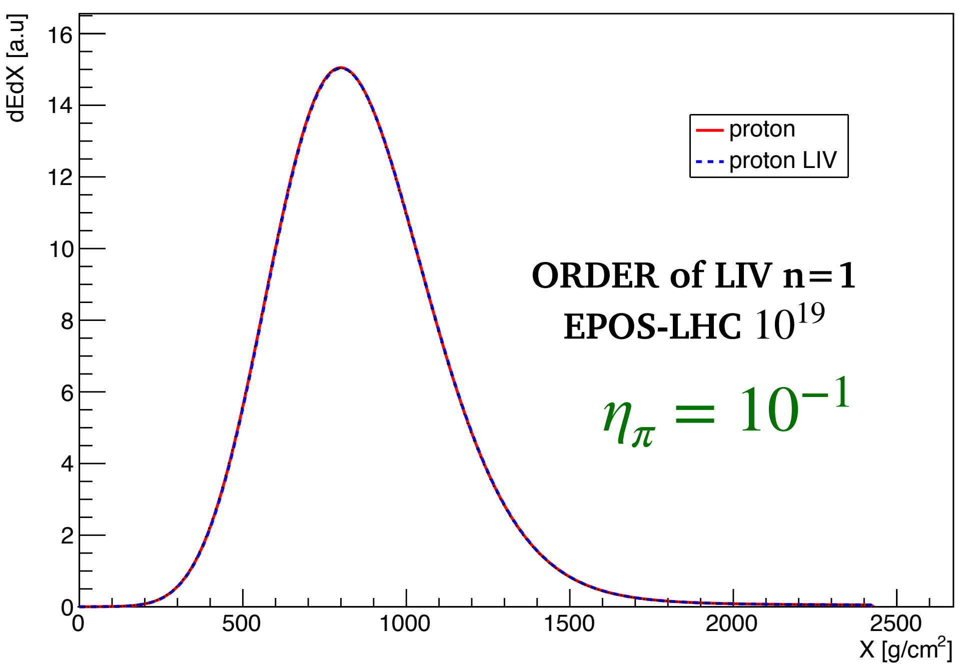
The maximum wrt α curve is always above the curves given by any other α combinations

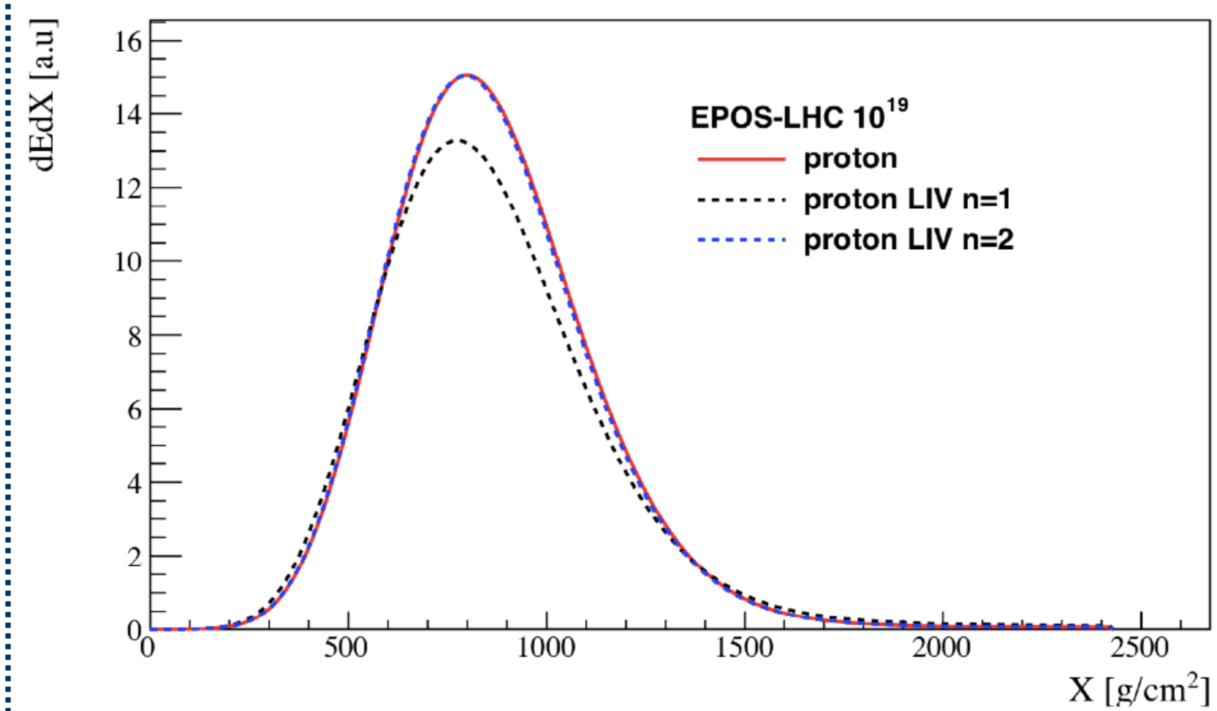
Only if the fluctuations stand below the data the $\max_\alpha \frac{\sigma_\mu}{\langle N_\mu \rangle}$ is the most conservative LIV model

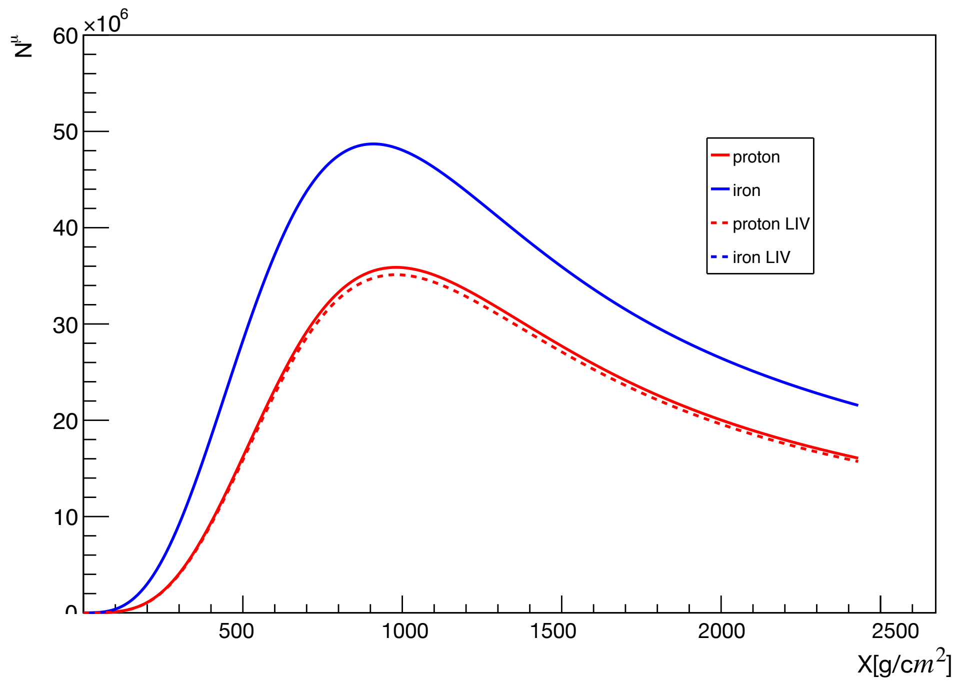


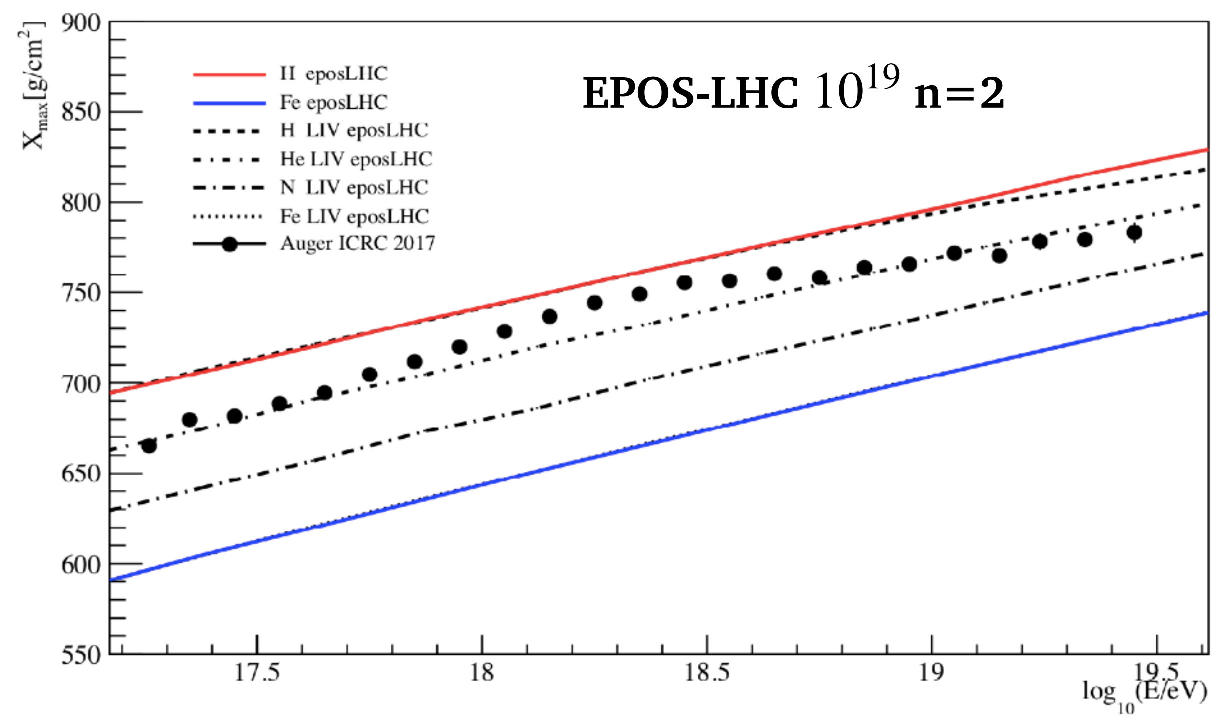
$\eta_\pi > 0$

LIV SECOND ORDER





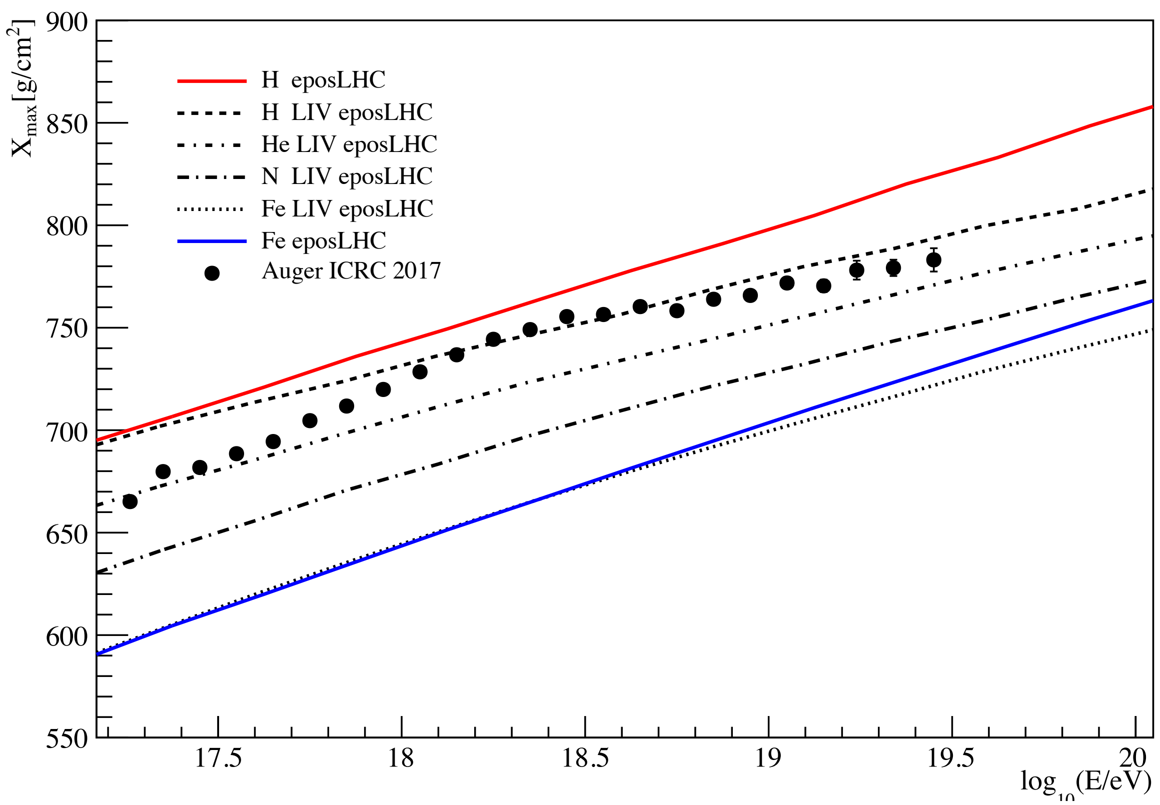


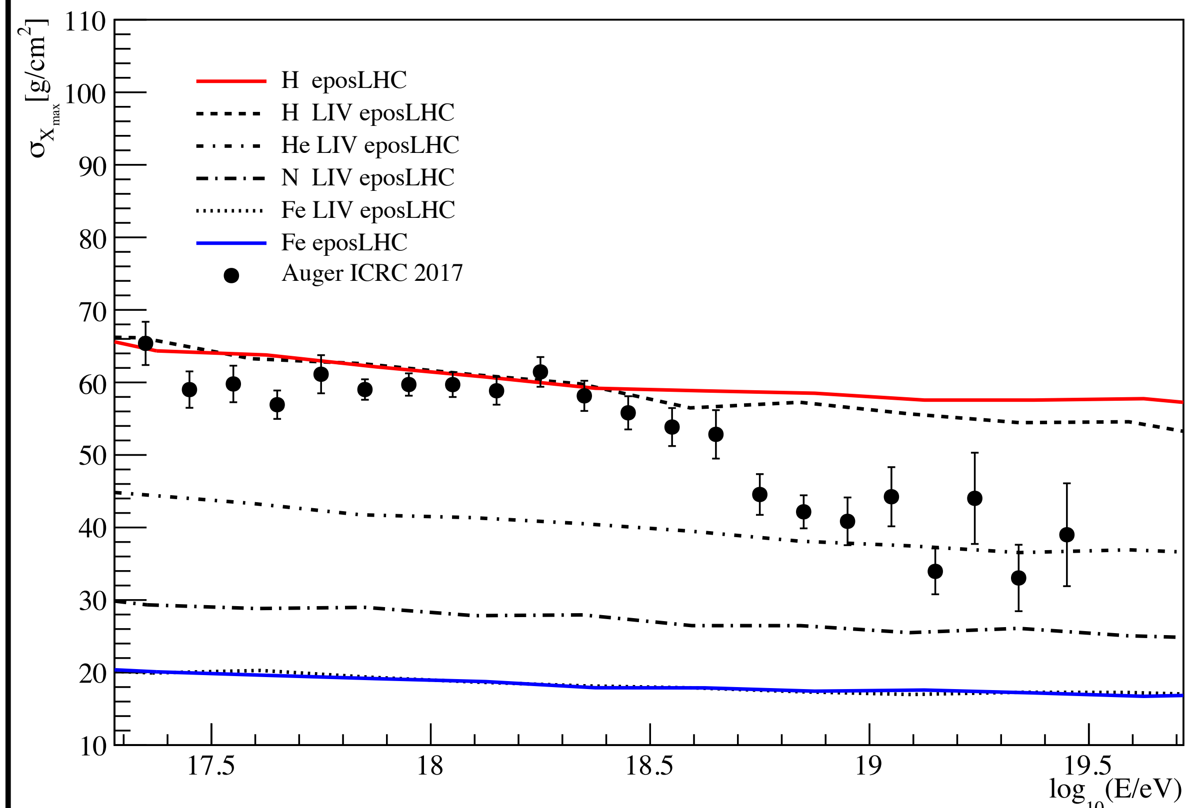


$\langle X_{max} \rangle$

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

$\sigma_{X_{max}}$





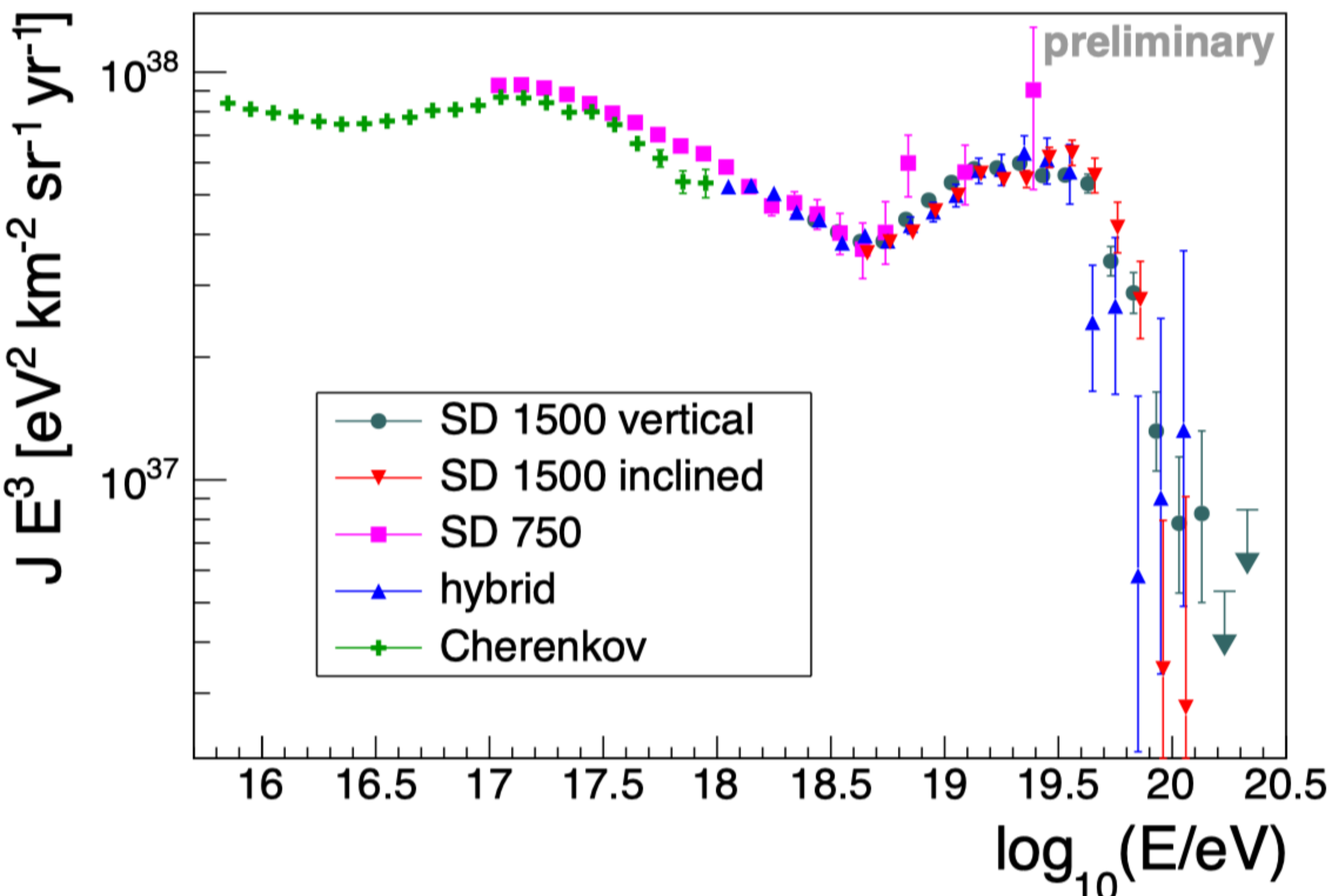
Shift of position of the maximum X_{max}

More protons expected for LIV at 1st order

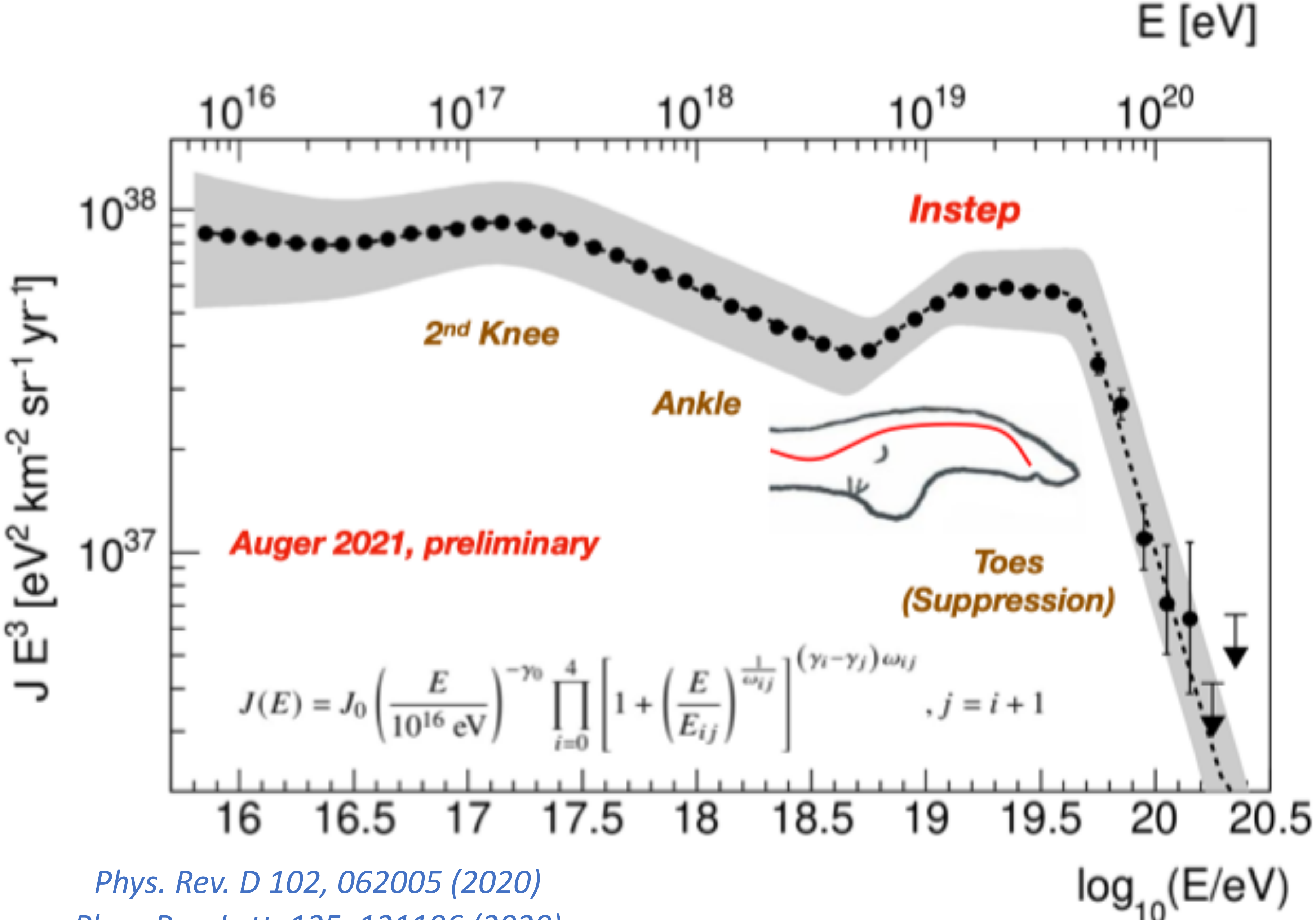
The Spectrum

Phys. Rev. D 102, 062005 (2020)
Phys. Rev. Lett. 125, 121106 (2020)

R. Engel, ICRC2021

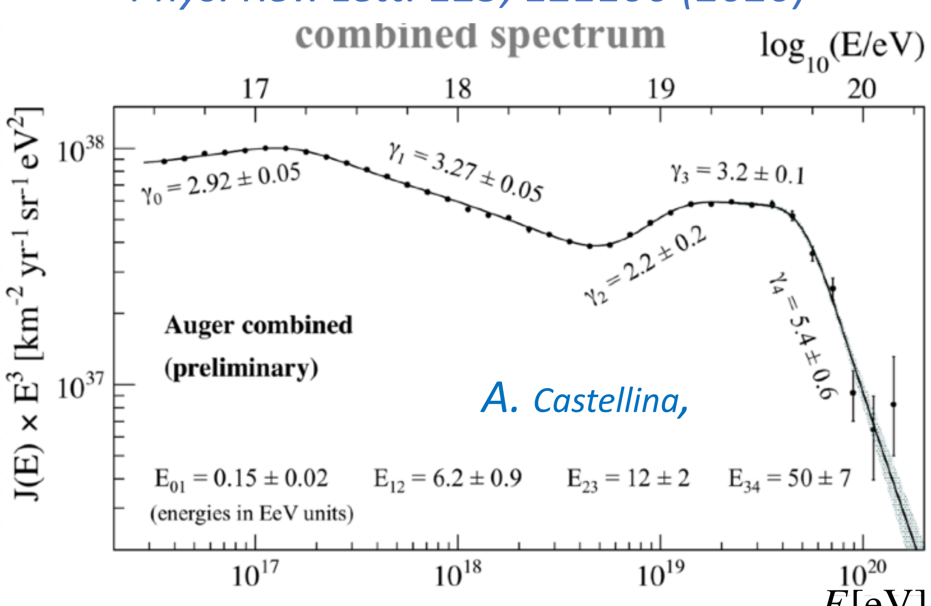


The method to derive the spectrum is entirely data-driven



Phys. Rev. D 102, 062005 (2020)

Phys. Rev. Lett. 125, 121106 (2020)

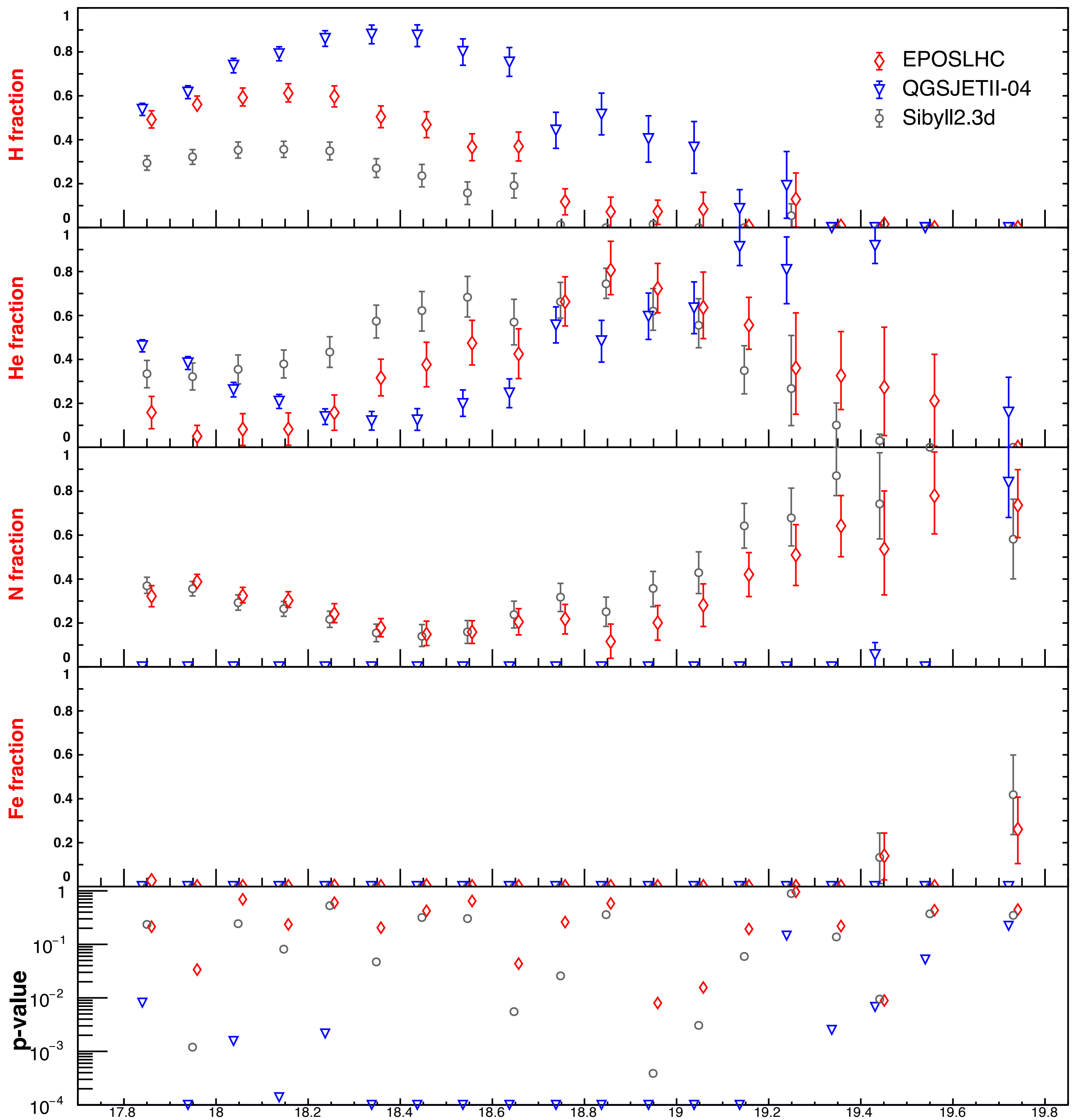


A. Castellina,

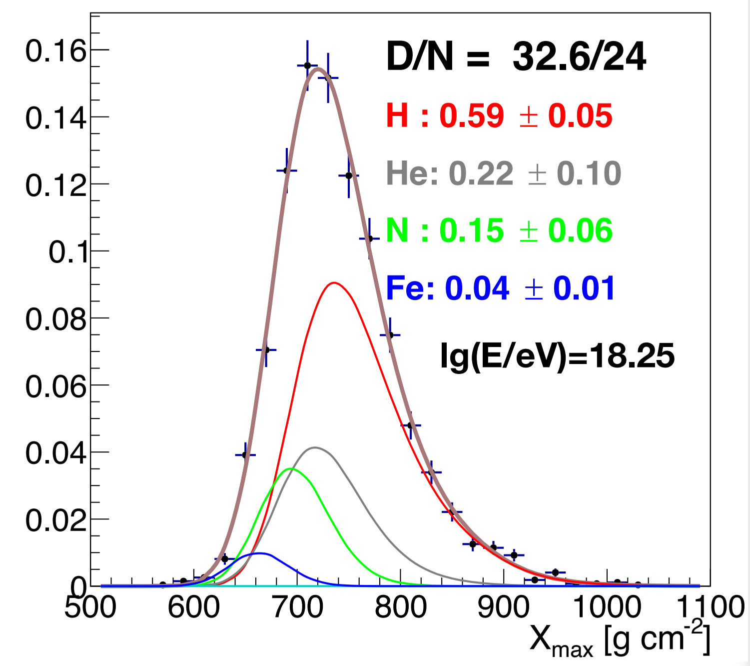
INTRODUCTION
Spectrum
Mass Composition
Anisotropy
AugerPrime
CONCLUSIONS

Mass Composition @ Earth

Measured considering the atmospheric depth at which the number of particles in an air shower reaches its maximum



$< X_{\mathrm{max}} > \propto \lg(E/A)$



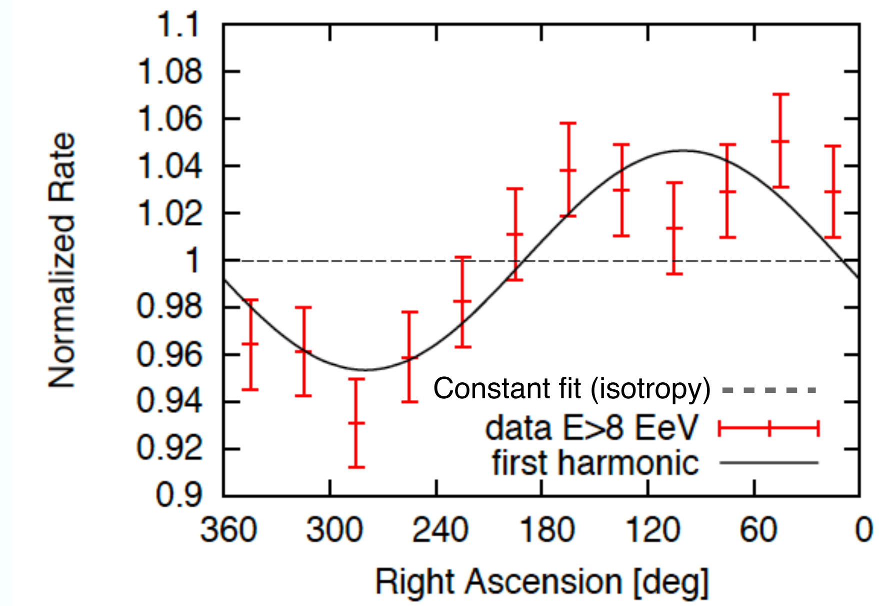
- X_{max} **distributions fitted with four-mass Gumbel function from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

FractionFit code

L'Aquila group

Anisotropy: Large scale

–90° < δ < 45°



Combination of vertical and inclined showers

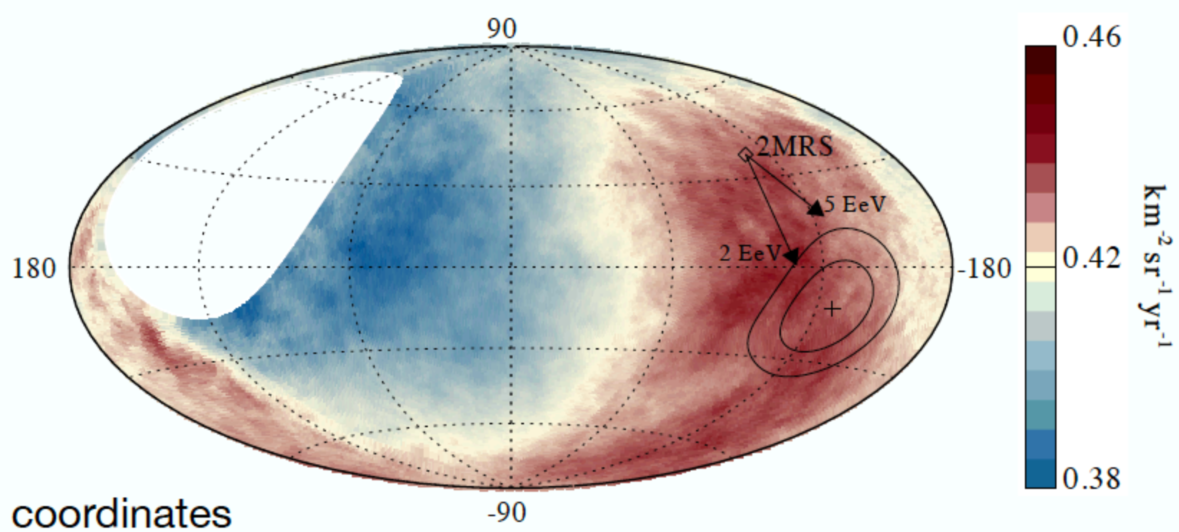
Harmonic analysis in right ascension α

	E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
→	4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
→	> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

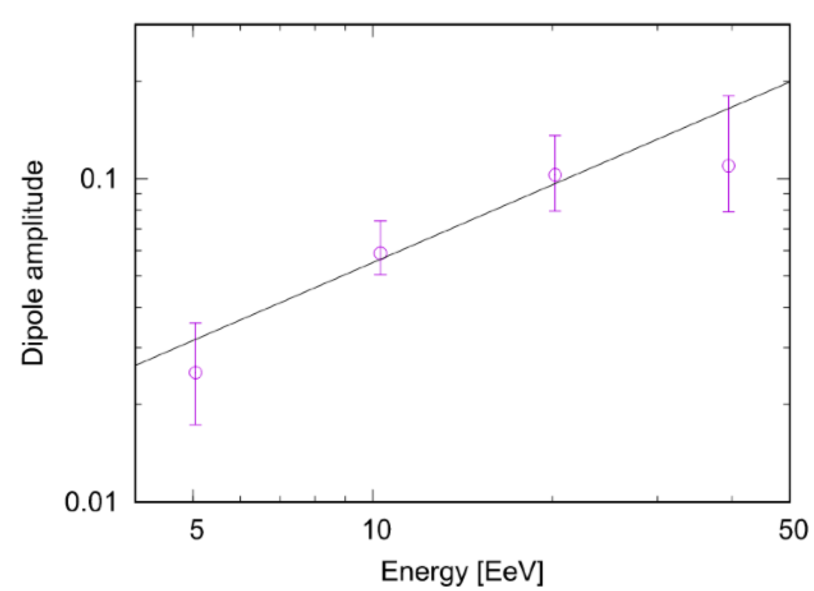
The amplitude of 3-d dipole above $8 \cdot 10^{18}$eV

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$ $(l, b) = (233°, -13°)$



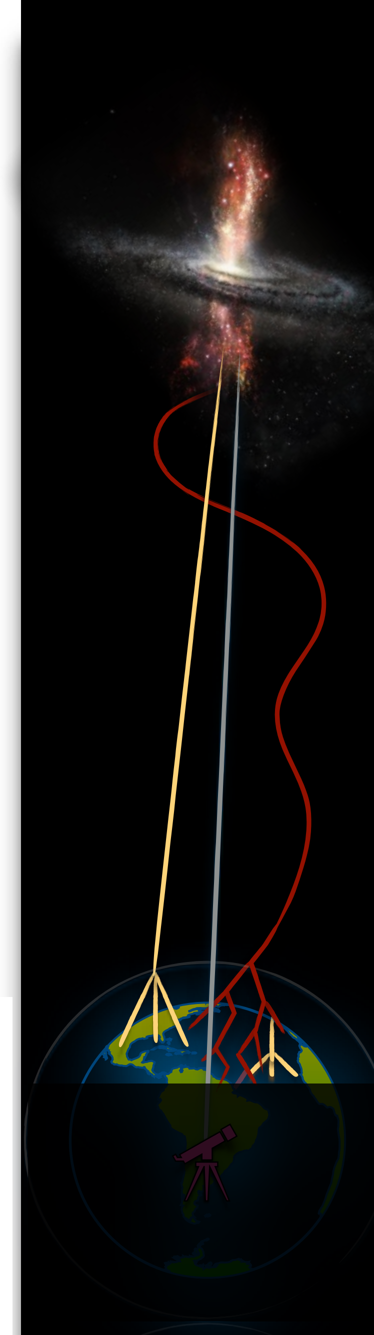
gal. coordinates

THE ASTROPHYSICAL JOURNAL, 868:4 (12pp), 2018 November 20



Auger Coll., Science (2017), APJ (2018)

This direction is about 125° from the galactic center suggesting that the anisotropy has an extragalactic origin



Anisotropy: Large scale

Auger Coll., Science (2017), APJ (2018)

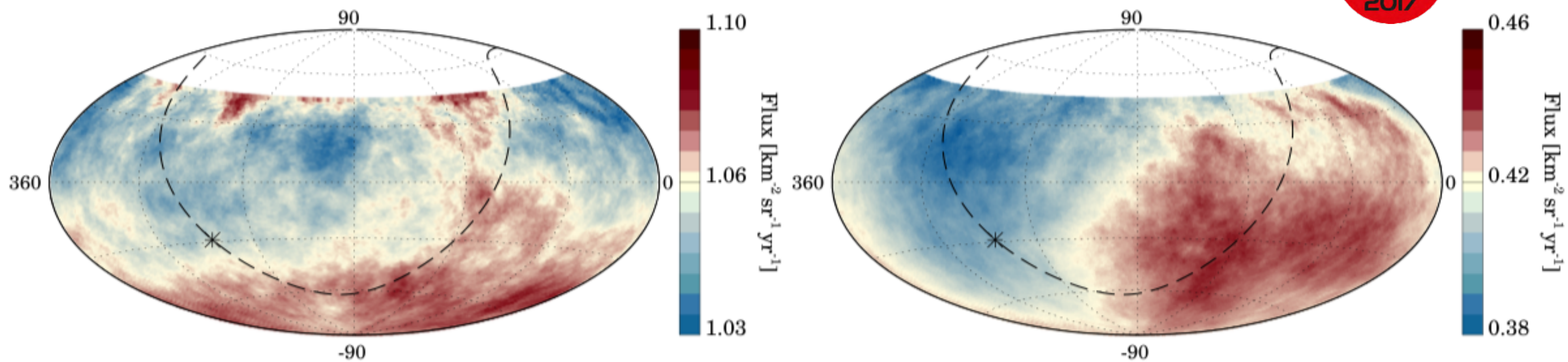


Figure 2. Maps in equatorial coordinates of the CR flux, smoothed in windows of 45°, for the energy bins [4, 8] EeV (left) and $E \geqslant 8$ EeV (right). The Galactic plane is represented with a dashed line, and the Galactic center is indicated with a star.

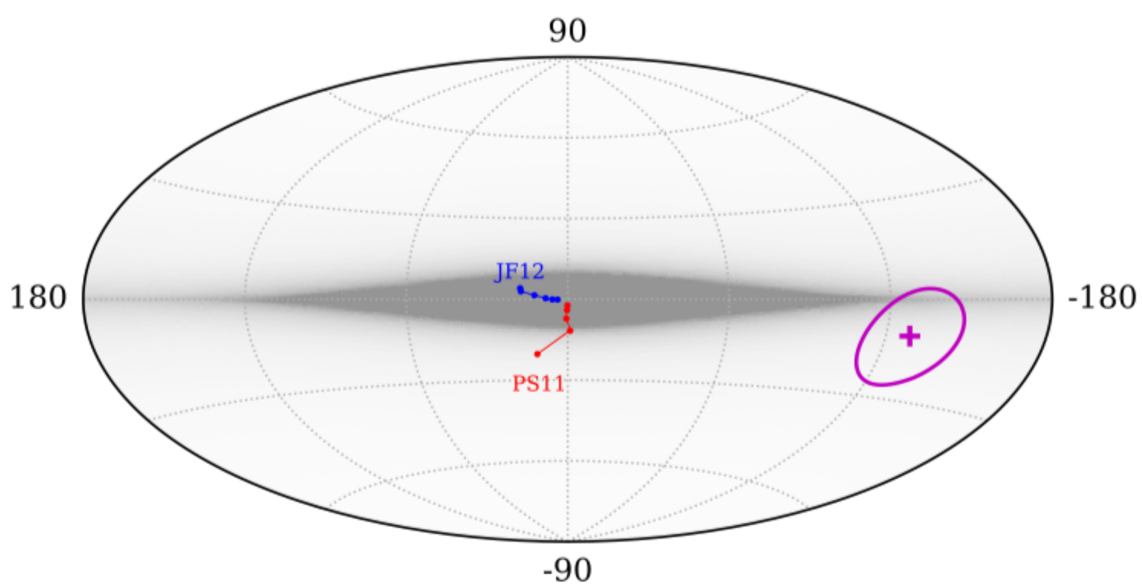
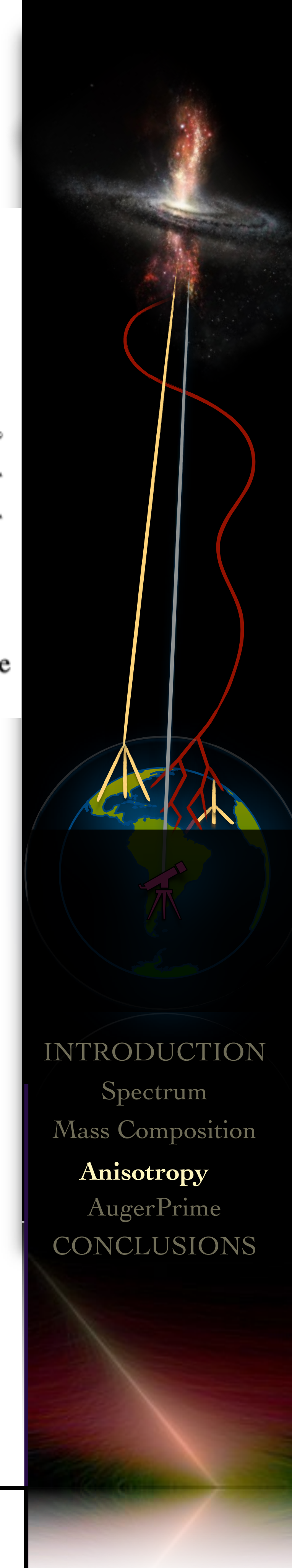


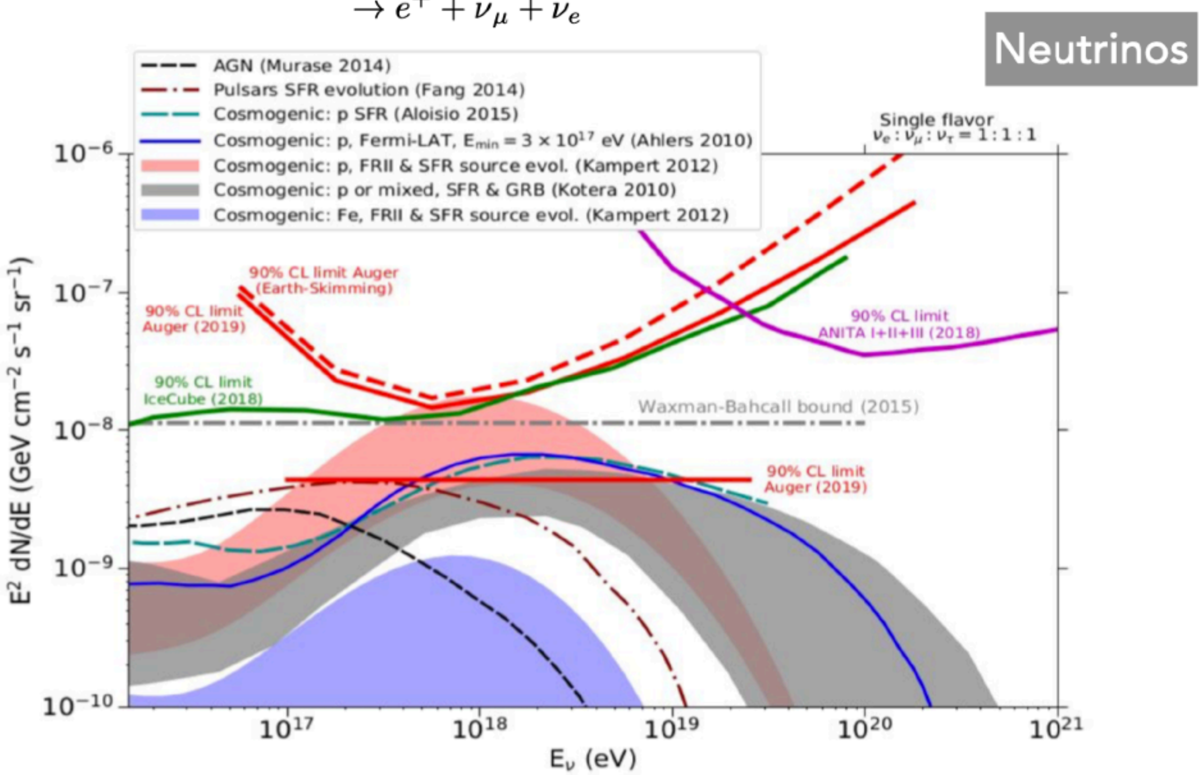
Figure 5. Map in Galactic coordinates of the direction of the dipolar component of the flux for different particle rigidities for CRs coming from Galactic sources and propagating in the Galactic magnetic field model of Jansson & Farrar (2012) (blue points) and the bisymmetric model of Pshirkov et al. (2011) (red points). The points show the results for the following rigidities: 64, 32, 16, 8, 4 and 2 EV (with increasing distance from the Galactic center). We also show in purple the observed direction of the dipole for $E \geqslant 8$ EeV and the 68% CL region for it. The background in gray indicates the integrated matter density profile assumed for the Galactic source distribution (Weber & de Boer 2010).



Cosmogenic neutrino and photon fluxes

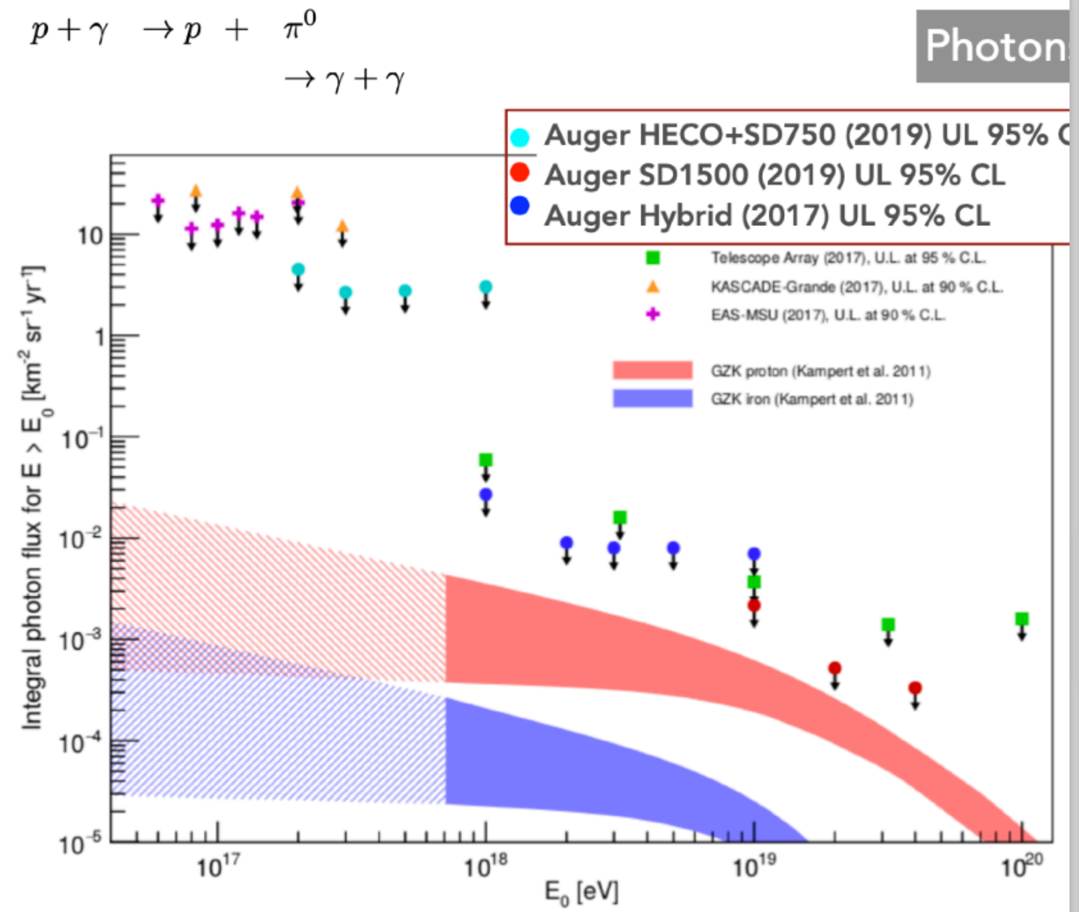
$p+\gamma \rightarrow n + \pi^+$
$\rightarrow \mu^+ + \nu_\mu$
$\rightarrow e^+ + \overline{\nu}_\mu + \nu_e$

$$k = \frac{N_{up}}{\int_{E_\nu} E_\nu^{-2}\epsilon_{tot}(E_\nu)dE_\nu}$$

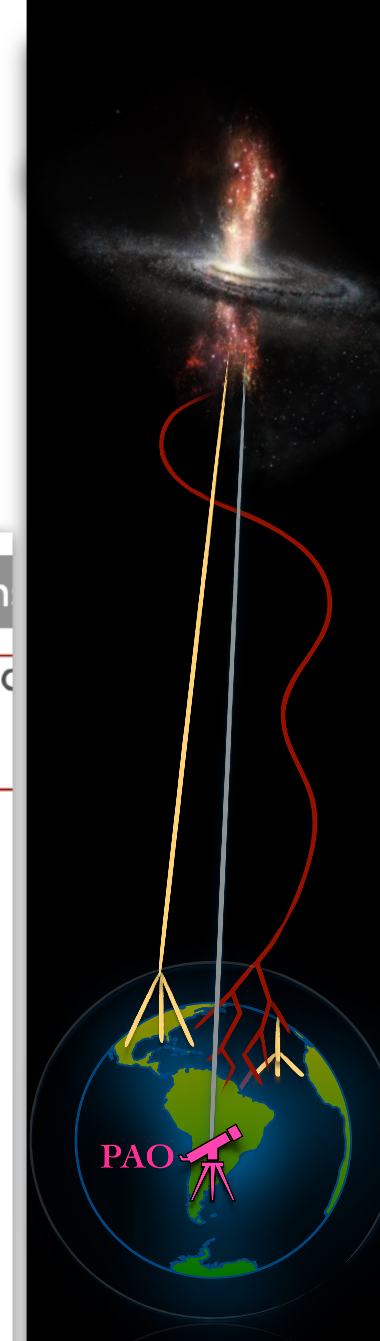


Maximum sensitivity around EeV
k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

$p+\gamma \rightarrow p + \pi^0$
$\rightarrow \gamma + \gamma$



Most sensitive EAS detector for E_γ>0.2 EeV



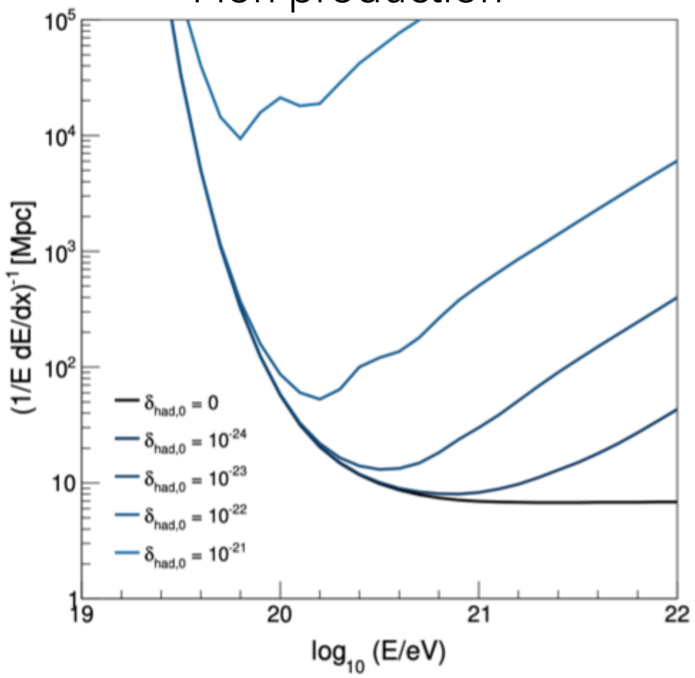
Hadronic sector: UHECRs propagation

ORDER OF LIV
n=0,1, 2
$\delta > 0$
Superluminal LIV

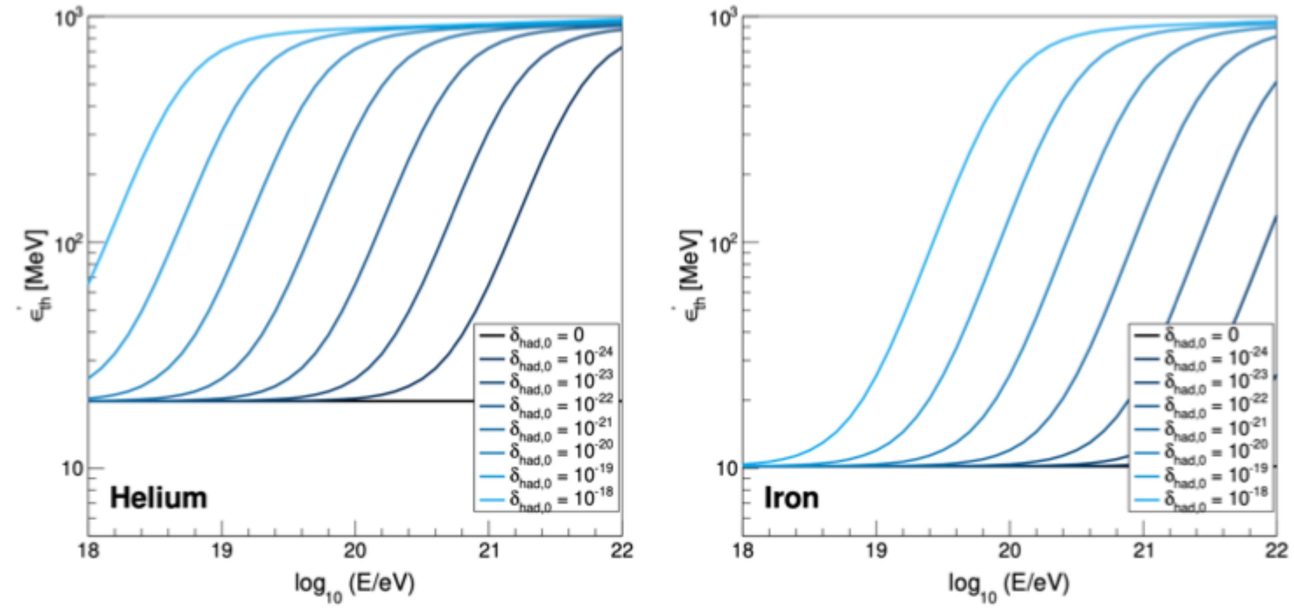
The LIV-modified attenuation length for pion production and the LIV-modified energy threshold for photo disintegration were implemented in SimProp v2.4 (simulations performed for 5 nuclei)

Modified processes:

Pion production



photodisintegration



- Above the critical energy, the number of interactions during propagation is reduced , the UHECRs interact less, the cosmic ray can travel farther than LI scenario;

How LIV affects the interactions during propagation?

Looking at observables measured at ground

INTRODUCTION
LIV framework
LIV Propagation
LIV in EAS
Muon Fluctuations
CONCLUSIONS

UHECRs PROPAGATION

$$\text{UHECRs} + \gamma_{bkg}$$

$$\downarrow$$

- Pair production $\varepsilon' > 1\,\text{MeV}$

$$p + \gamma \rightarrow p + e^+ + e^-$$

- Pion production $\varepsilon' > 150\,\text{MeV}$

$$p + \gamma \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

} Source of cosmogenic neutrinos

$$p + \gamma \rightarrow p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

} Source of cosmogenic gamma rays

UHECR nucleons & nuclei

- Disintegration $\varepsilon' > 8\,\text{MeV}$

$${}^A_ZX + \gamma \rightarrow {}^{A-1}_{Z-1}X' + p$$

$${}^A_ZX + \gamma \rightarrow {}^{A-1}_{Z}X' + n$$

$${}^A_ZX + \gamma \rightarrow {}^{A-2}_{Z-2}X'' + \alpha$$

UHECR nuclei

9

γ_{GZK}

UHE photons

Existent Limits