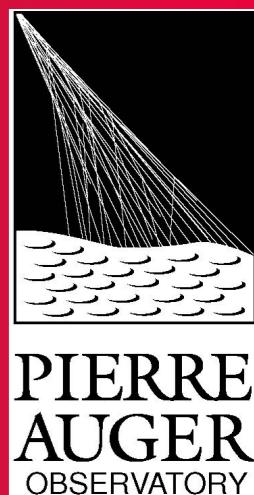




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Studio degli effetti della violazione dell'Invarianza di Lorentz negli sciami atmosferici

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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



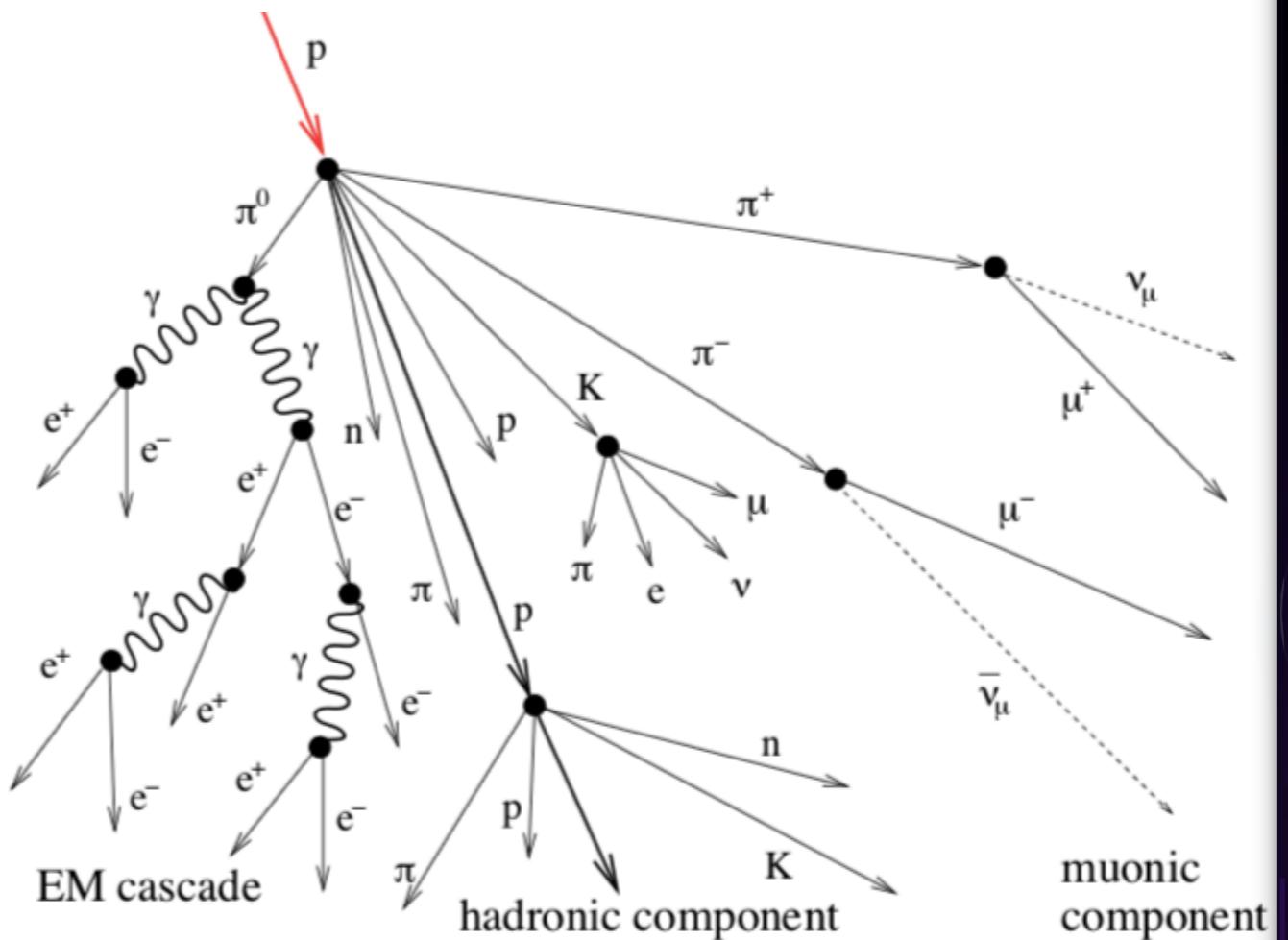
Extensive Air Showers

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:

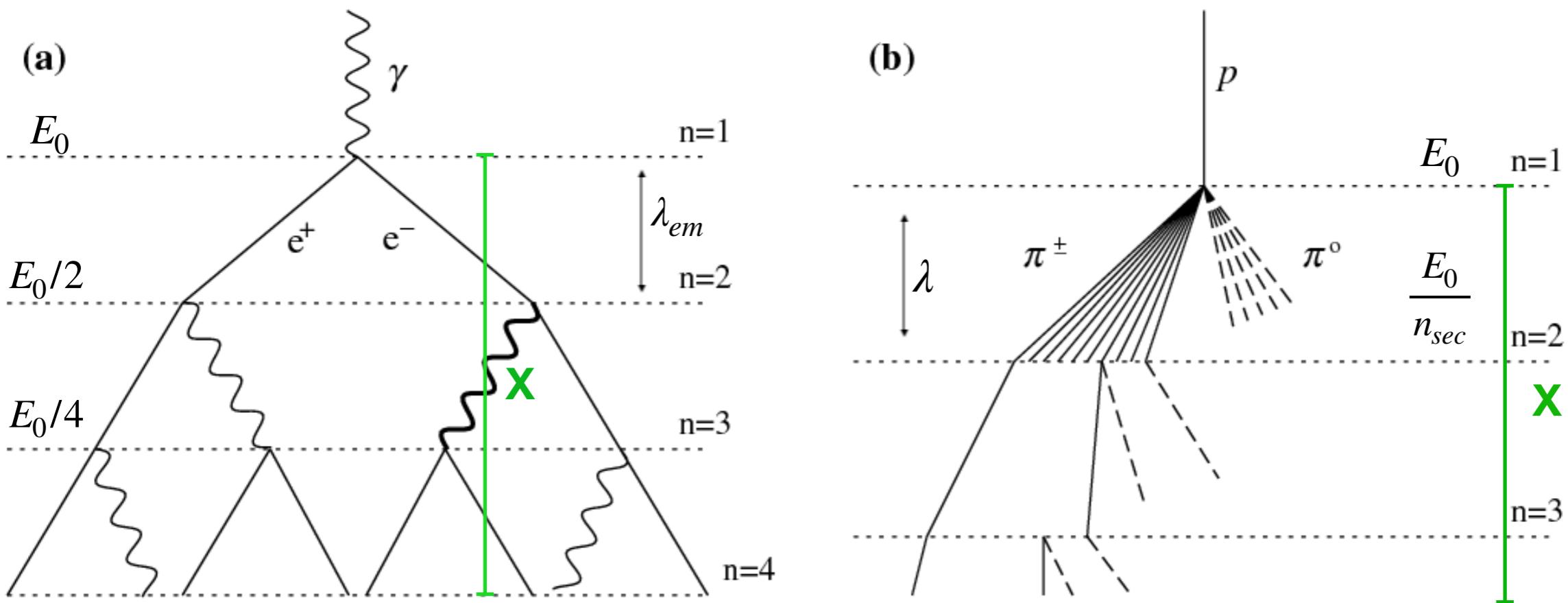
- The **em component** characterized by the **pair production**, the **bremsstrahlung** and the **ionization energy loss**;
- The **hadronic component** produced by **charged hadronic particles** involved in the **strong interactions** with the atmosphere;
- The **muonic component** weakly interacts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



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



Heitler Model



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

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



INTRODUCTION

LIV in EAS

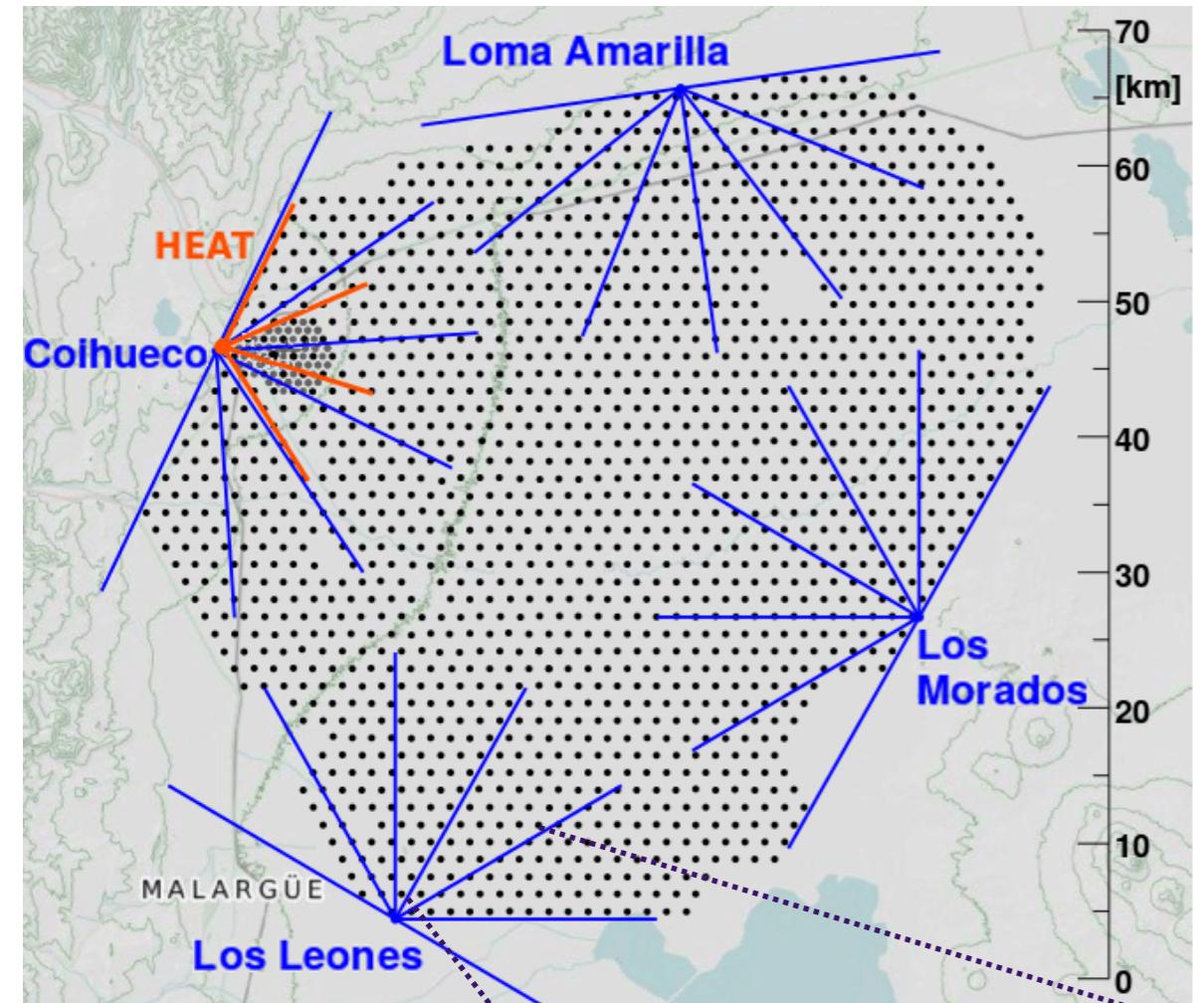
MC Simulations

RESULTS

CONCLUSIONS



Pierre Auger Observatory



HYBRID DETECTOR:

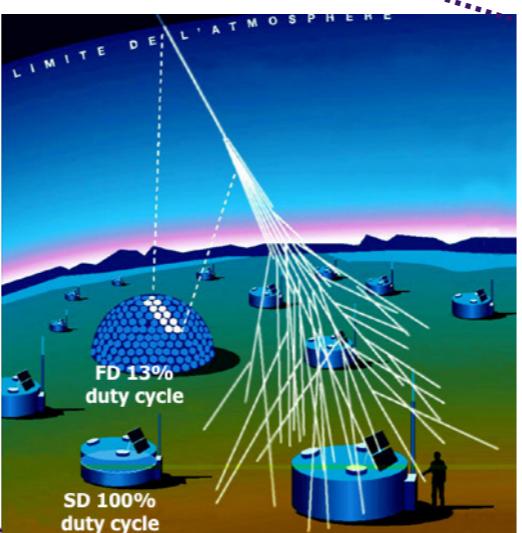
Fluorescence detector (FD)

- 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



INTRODUCTION

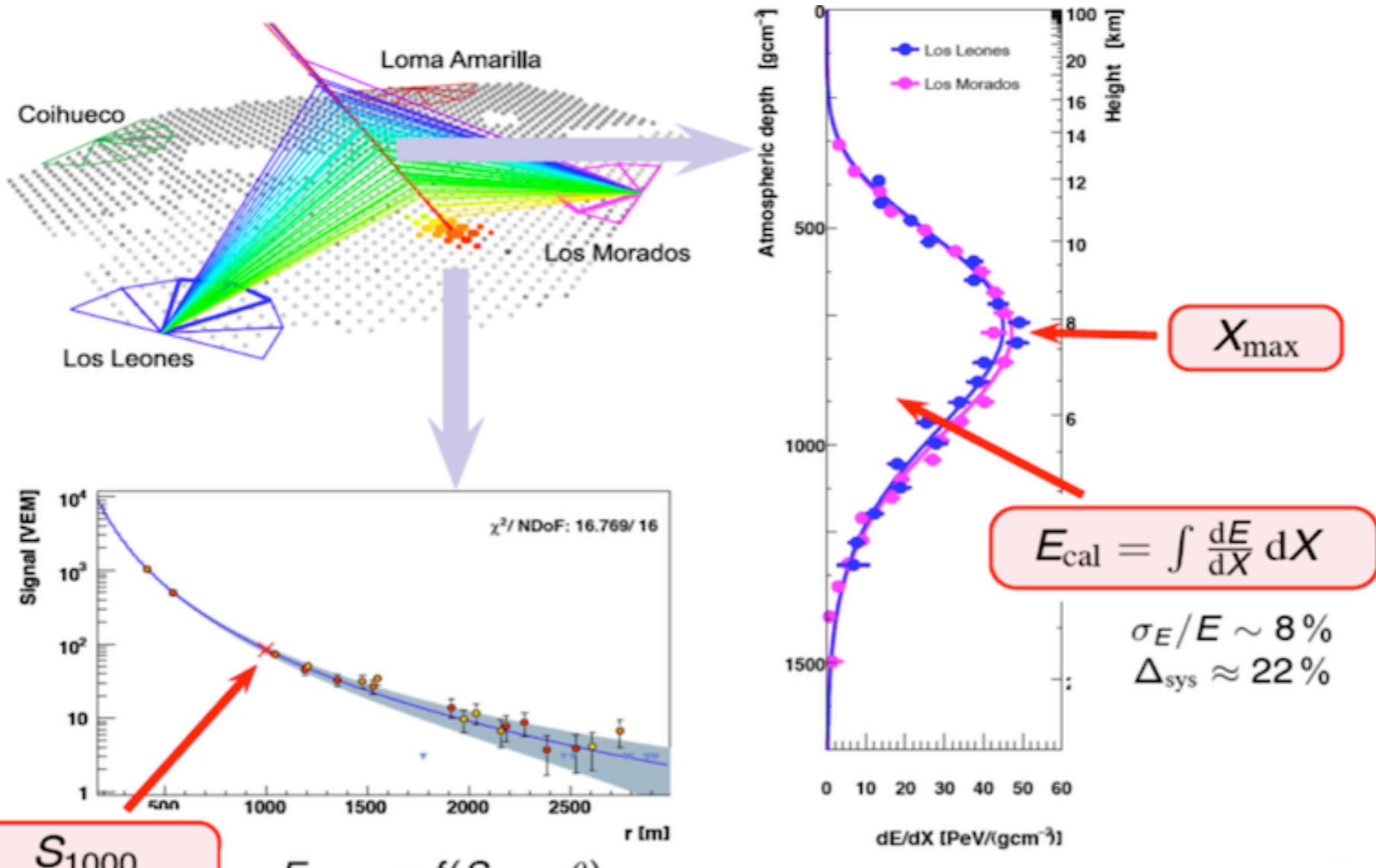
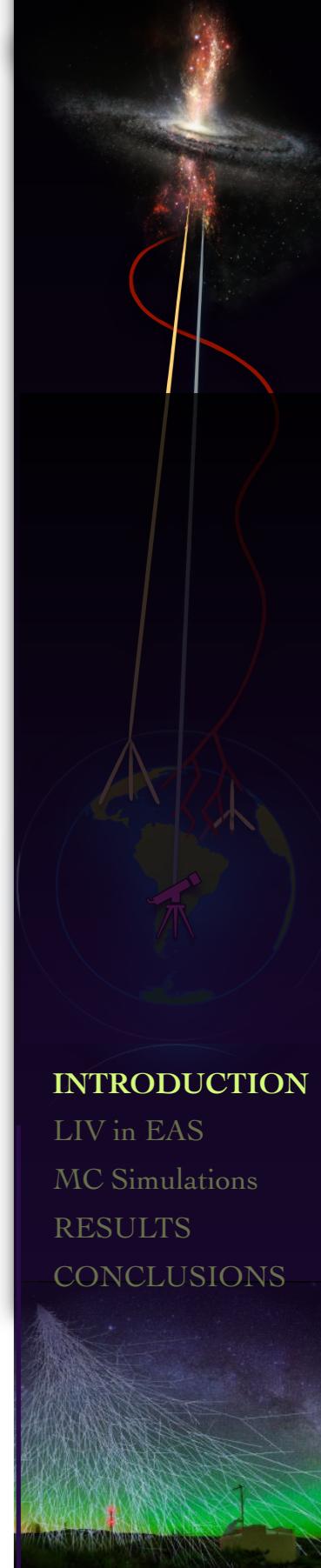
LIV in EAS

MC Simulations

RESULTS

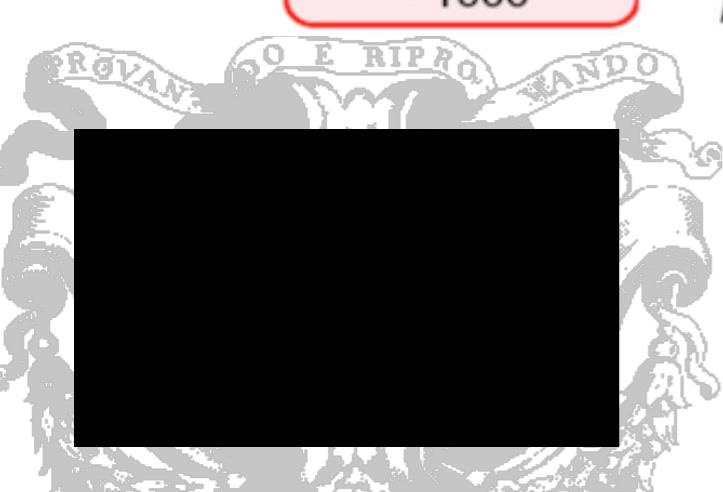
CONCLUSIONS

Hybrid Detection



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

INTRODUCTION
 LIV in EAS
 MC Simulations
 RESULTS
 CONCLUSIONS



How to break Lorentz Invariance

Modified dispersion relation

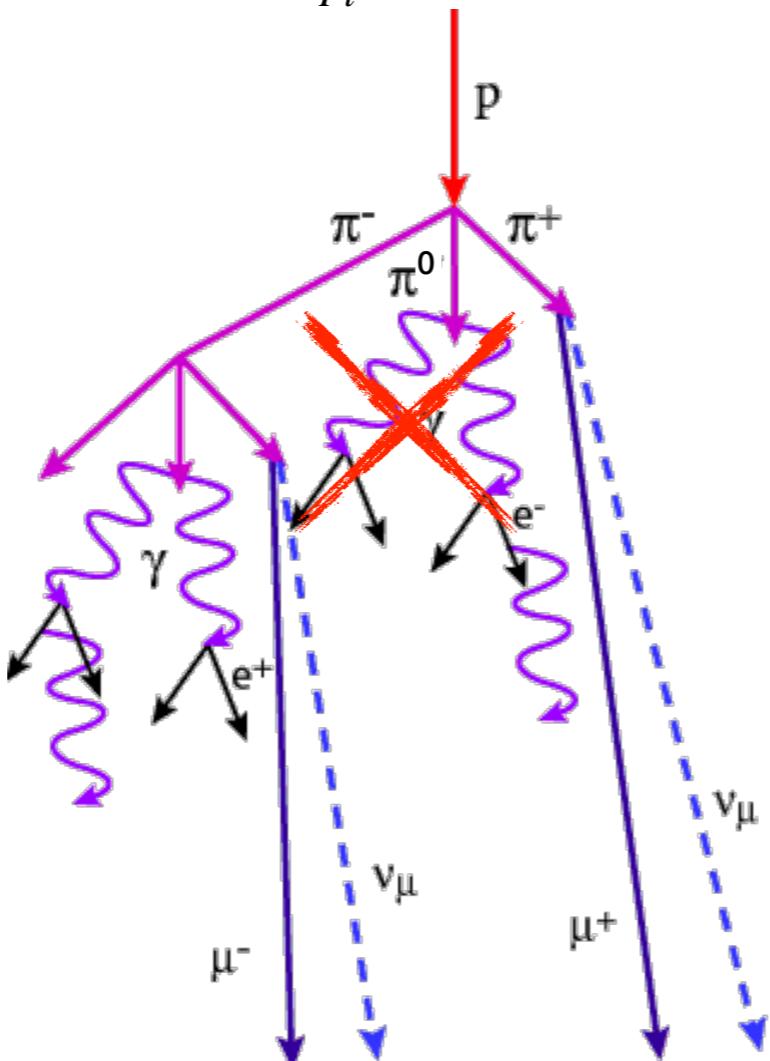
$$E^2 - p^2 = m^2 + f(\vec{p}, M_{Pl}; \eta) \longrightarrow E^2 - p^2 = m^2 + \sum_{n=0}^N \eta^{(n)} \frac{p^{n+2}}{M_{Pl}^n}$$

Where $\eta^{(n)}$ is an adimensional 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 $\eta_A = \eta/A^2$



π^0 Decay: $\pi^0 \rightarrow \gamma\gamma$

The decay is forbidden if:

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

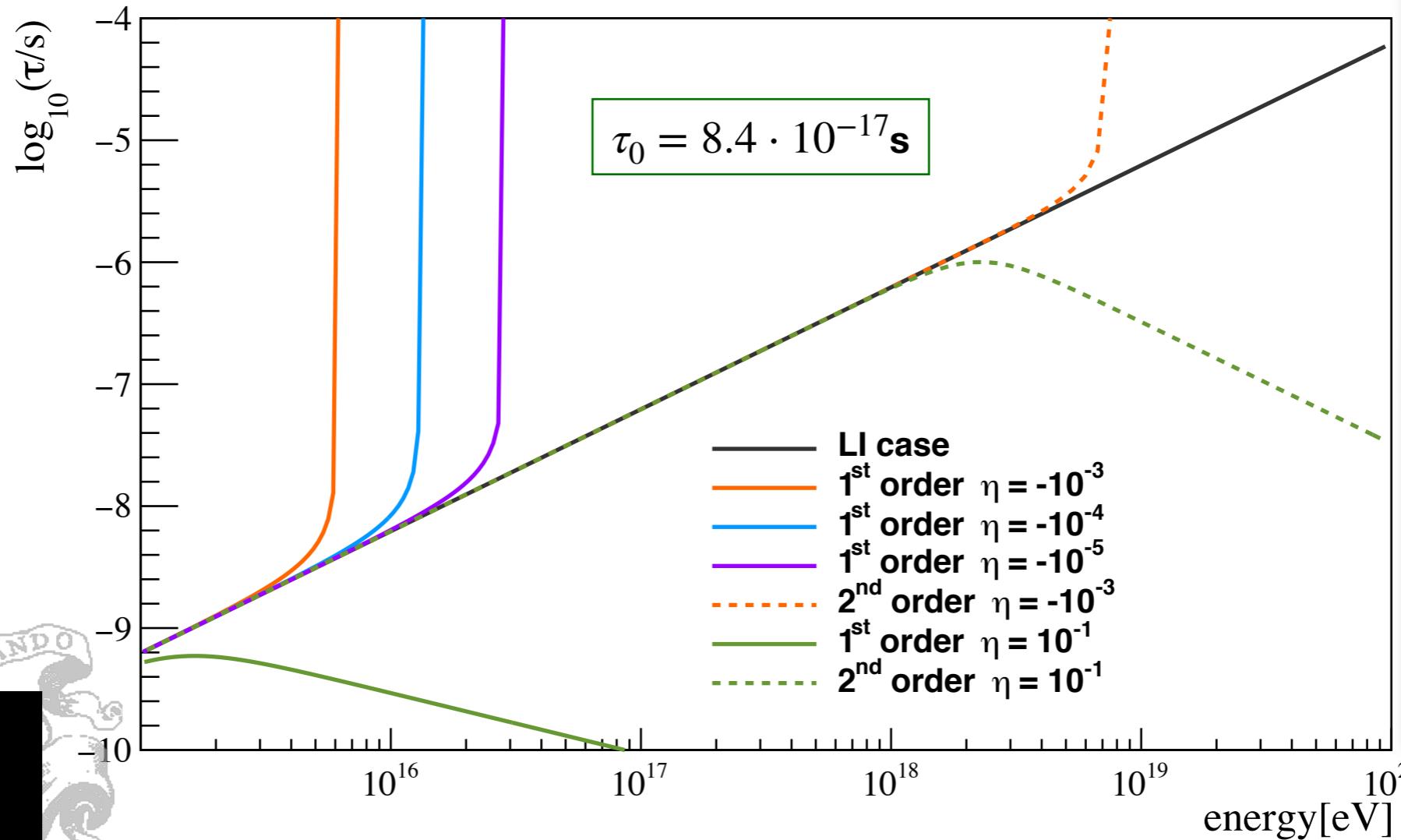
INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS

LIV: Mean Lifetime

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

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

We can define the Lorentz factor as: $\gamma_{\text{LIV}} = \frac{E}{M_{\text{LIV}}}$ In terms of the lifetime τ of particles: $\tau = \gamma_{\text{LIV}} \tau_0$



INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS

CONEX shower simulation

CONEX is a hybrid simulation code that is suited for fast one-dimensional simulations of shower profiles, including fluctuations. It combines Monte Carlo simulation of high energy interactions with a fast numerical solution of cascade equations for the resulting distributions of secondary particles.

Lorentz Invariant case

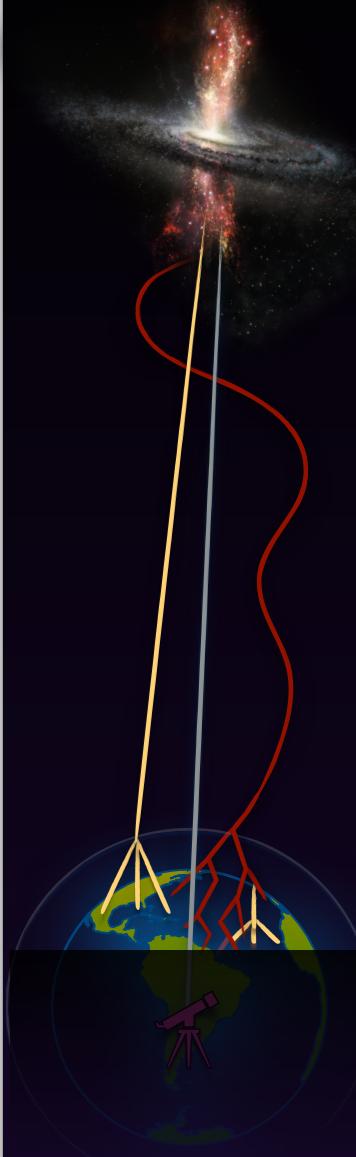
- Primary particles: H, He, N, Fe, Si;
- Primary particle energy: 10^{16} - 10^{21} eV;
- Zenith angle: $\theta = 70^\circ$;
- 21 energy bins of width $\Delta \log_{10}(E/eV) = 0.25$ ranging from 10^{16} to 10^{21} ;
- Hadronic interaction model: EPOS LHC;

In presence of LIV

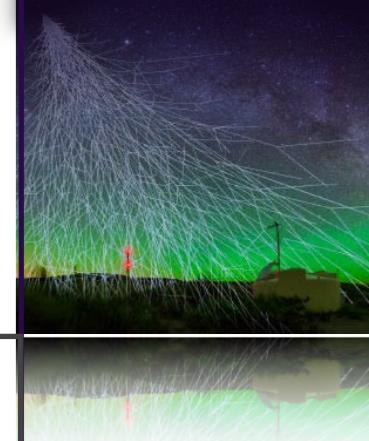
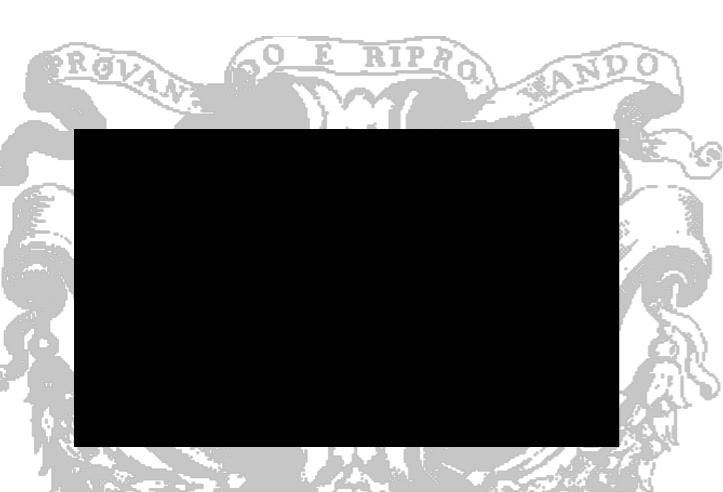
- Primary particles: H, He, N, Fe, Si;
- Primary particle energy: 10^{16} - 10^{21} eV;
- Zenith angle: $\theta = 70^\circ$;
- 21 energy bins of width $\Delta \log_{10}(E/eV) = 0.25$ ranging from 10^{16} to 10^{21} ;
- Hadronic interaction model: EPOS LHC-LIV.
- LIV parameter:
 $\eta = -10^{-3}, -10^{-4},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

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

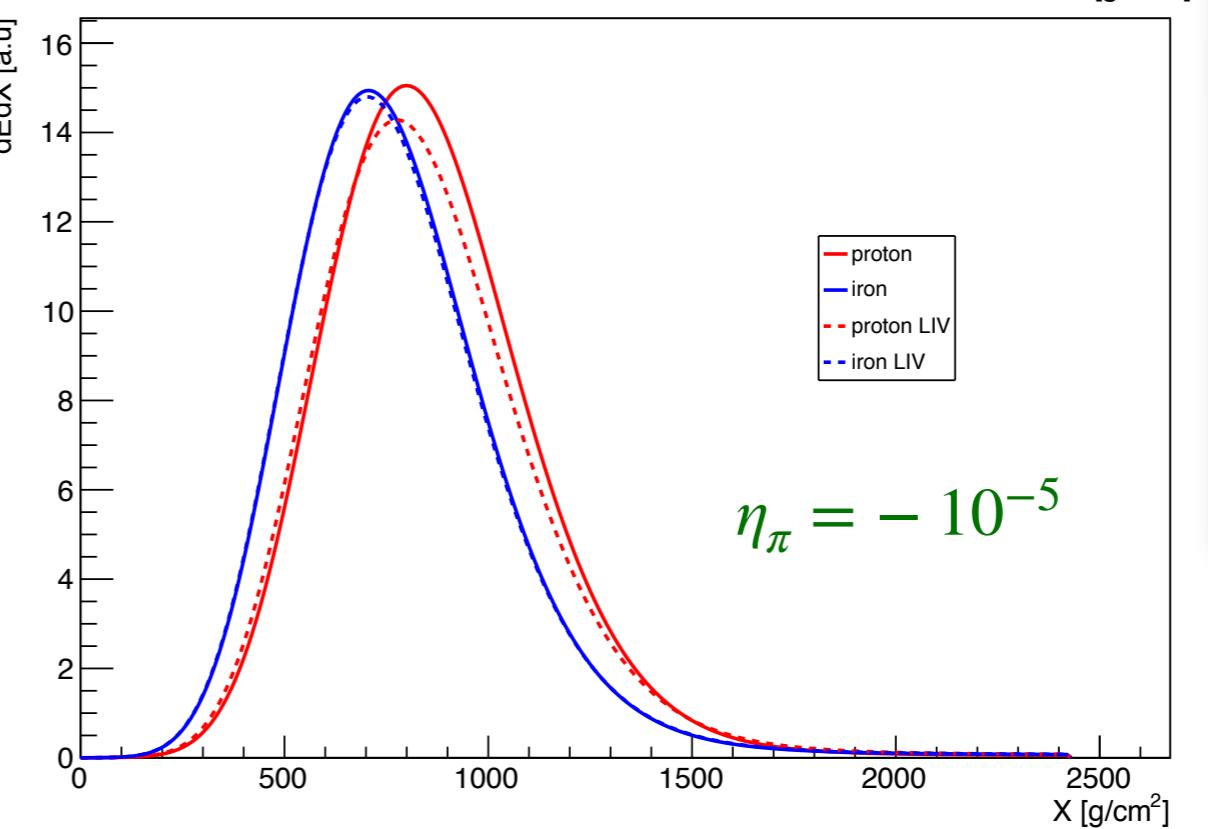
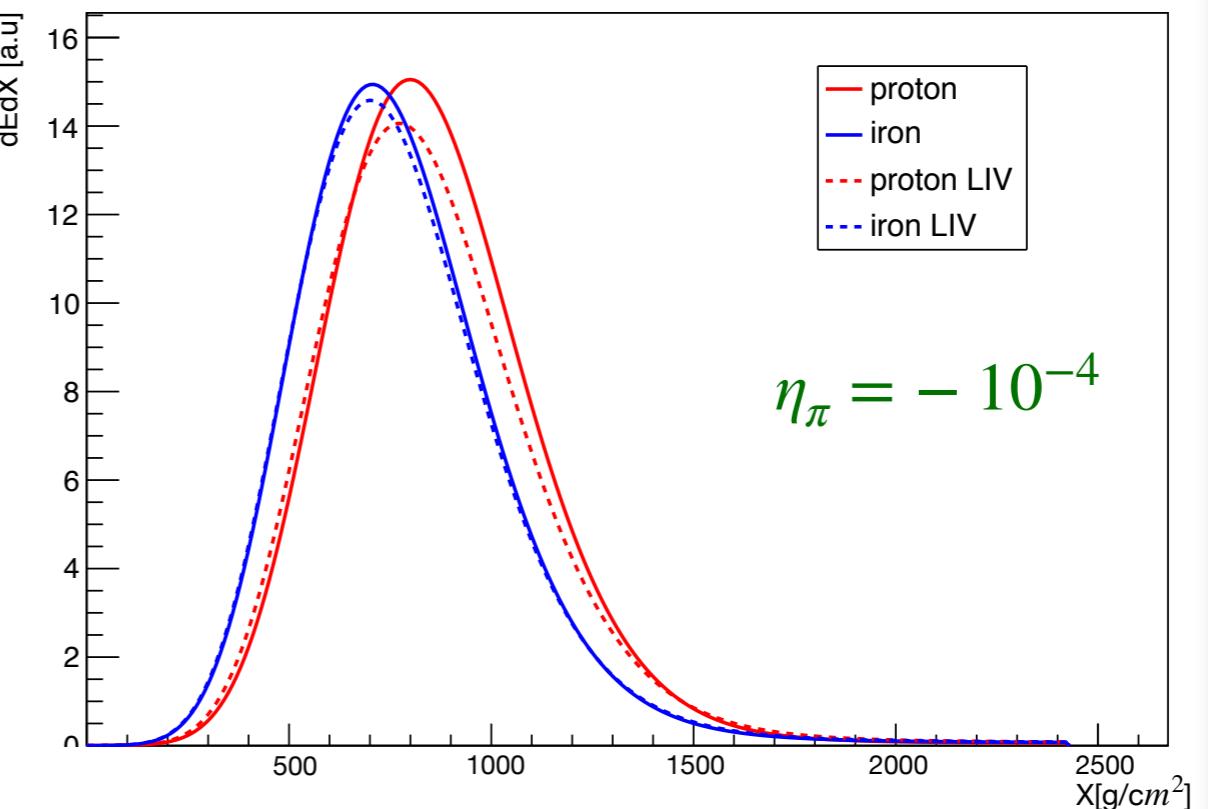
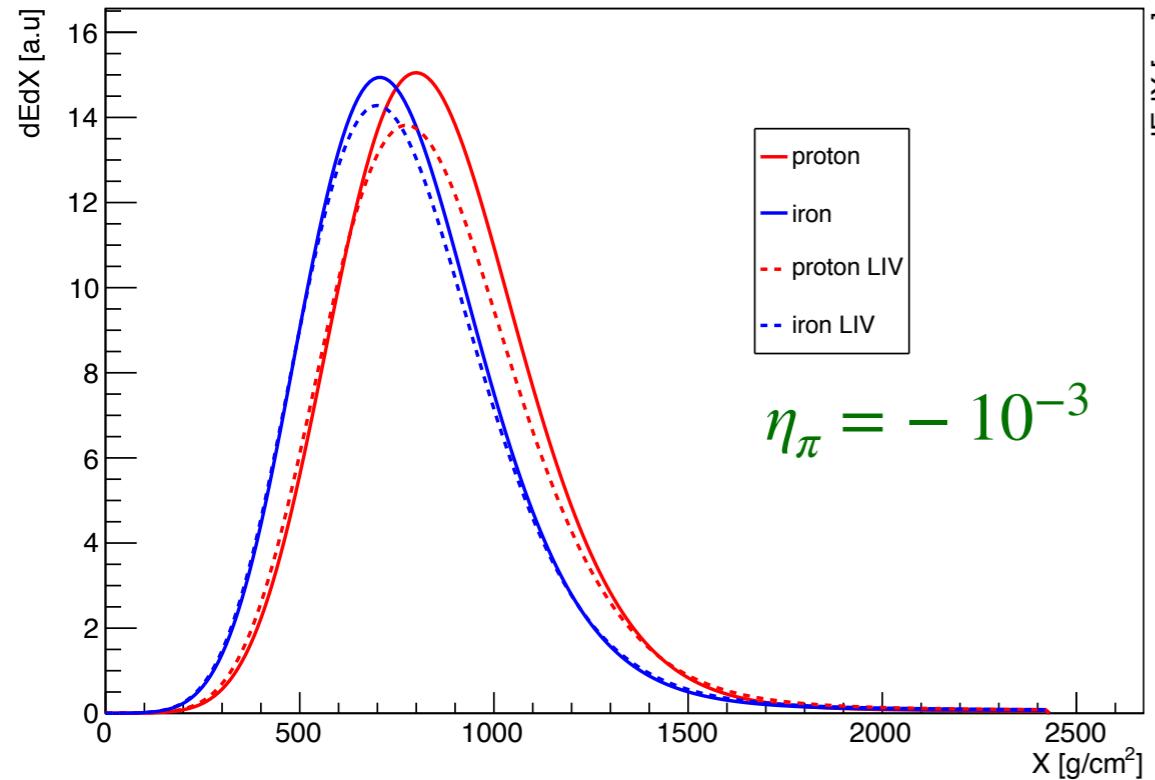
The shower simulation parameters, profiles and fit results are written to a Root file.



INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS

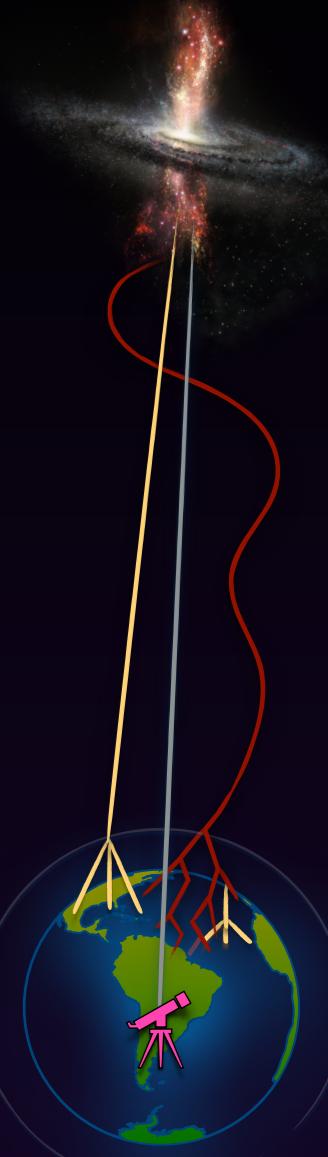


dE/dX profile



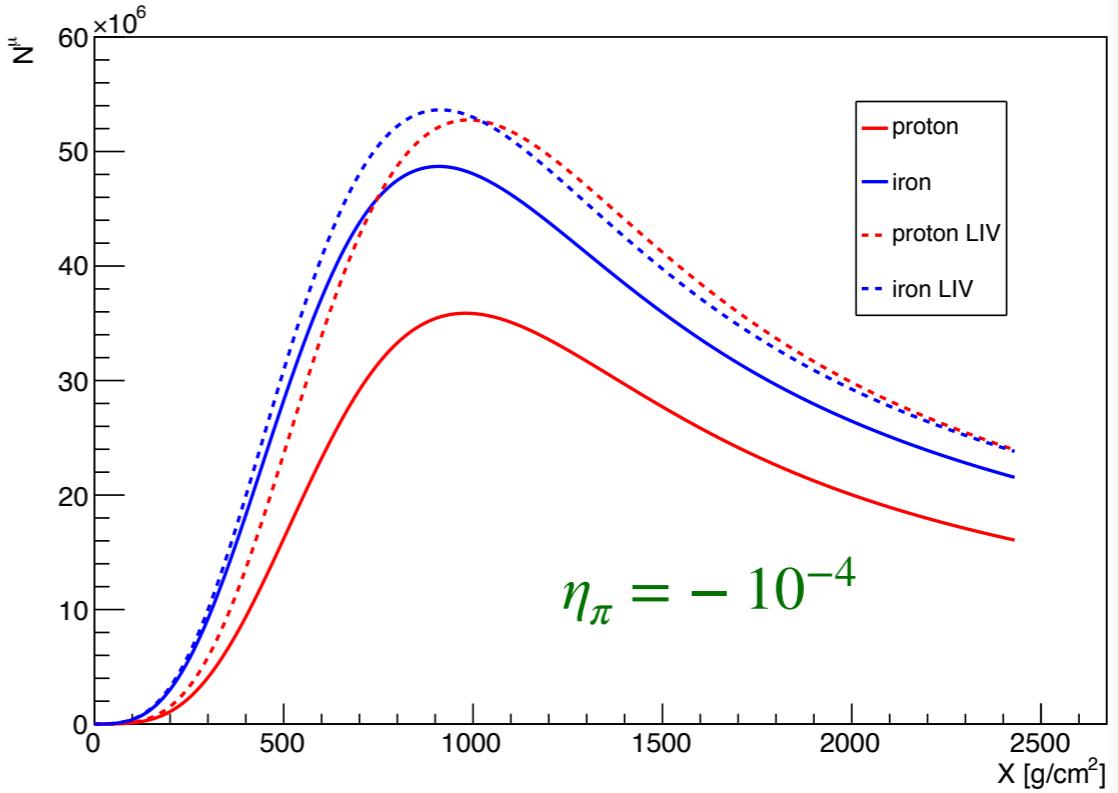
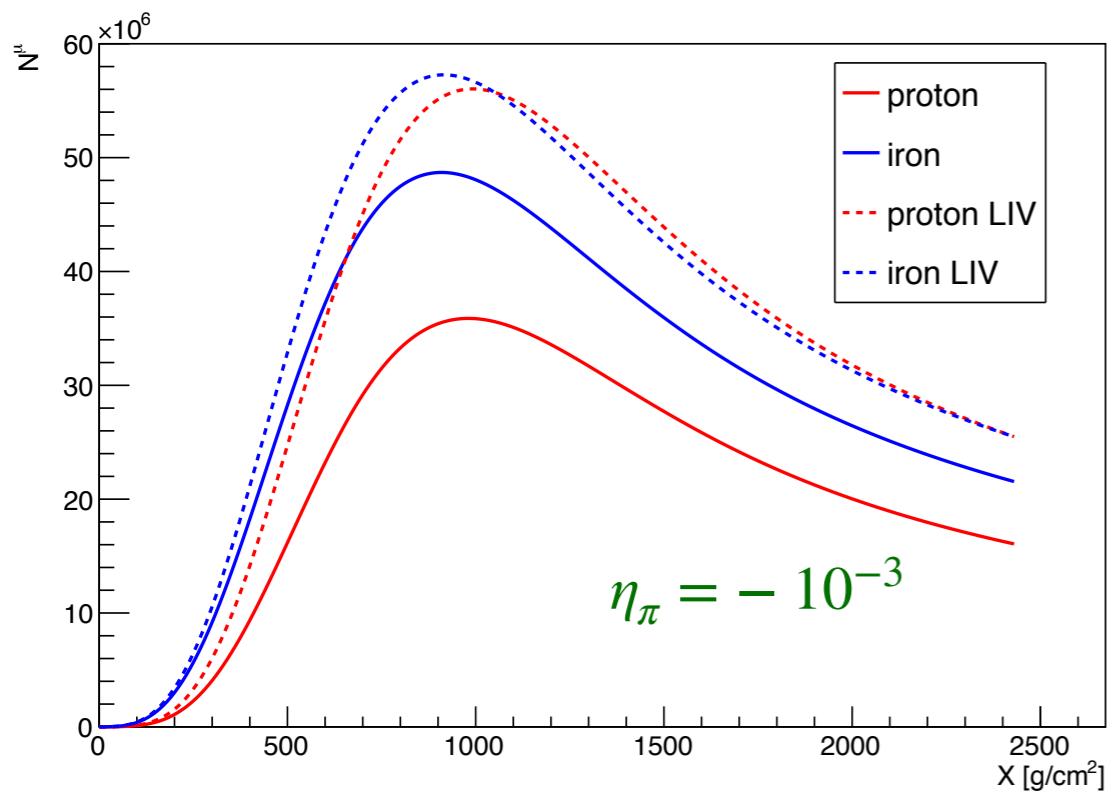
ORDER OF LIV $n=1$
EPOS-LHC at 10^{19} eV

1. Shift of position of the maximum X_{max}
2. Reduction in the height of the maximum



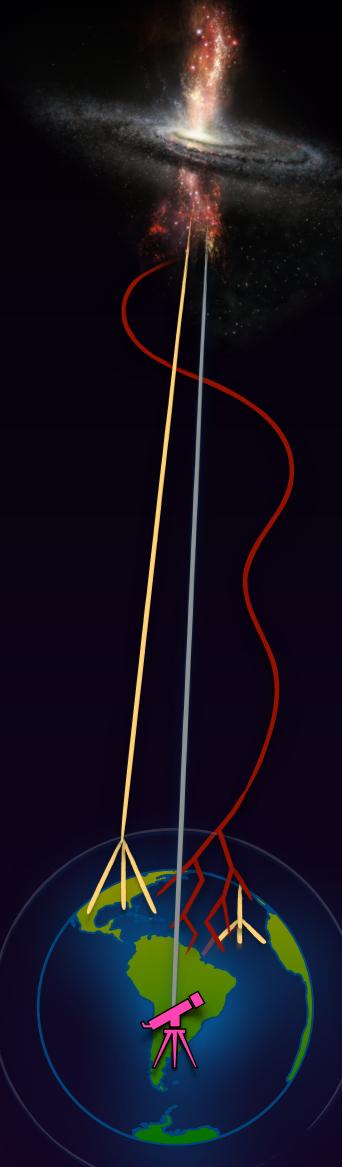
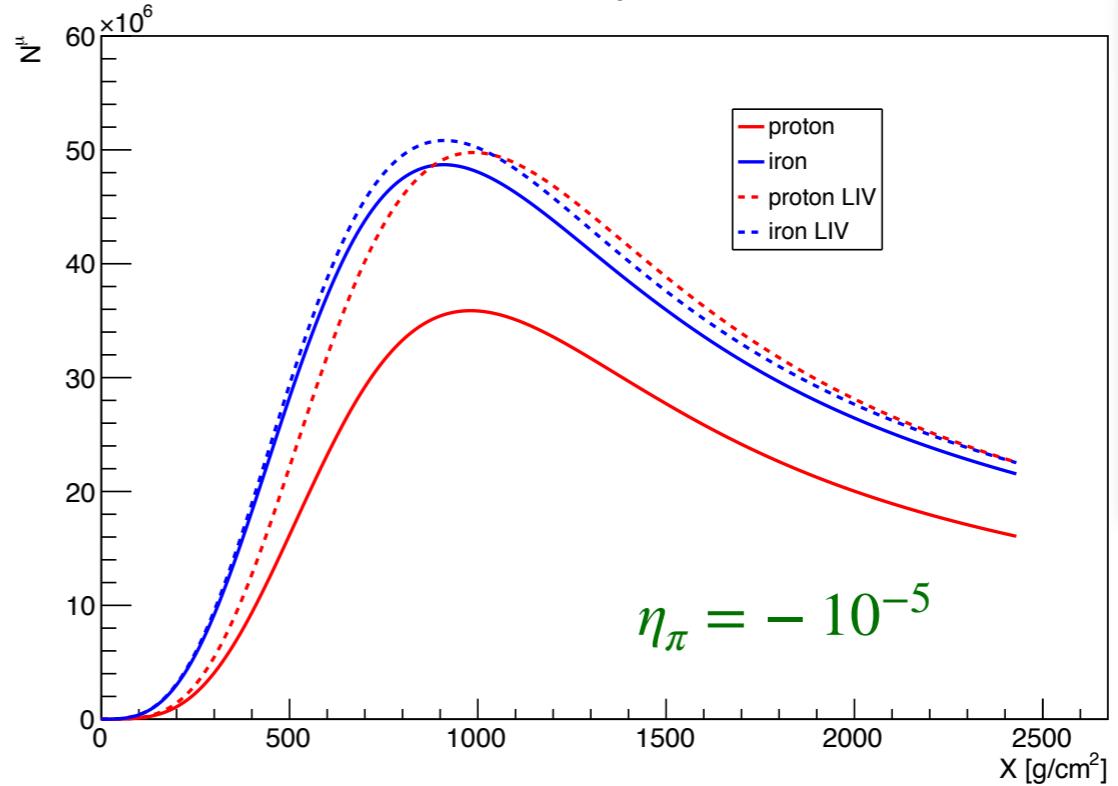
INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS

Muon profile

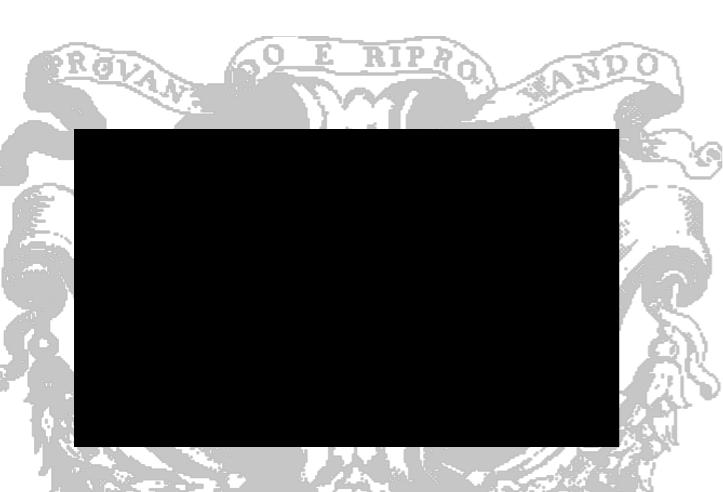


ORDER of LIV $n=1$ EPOS-LHC at 10^{19} eV

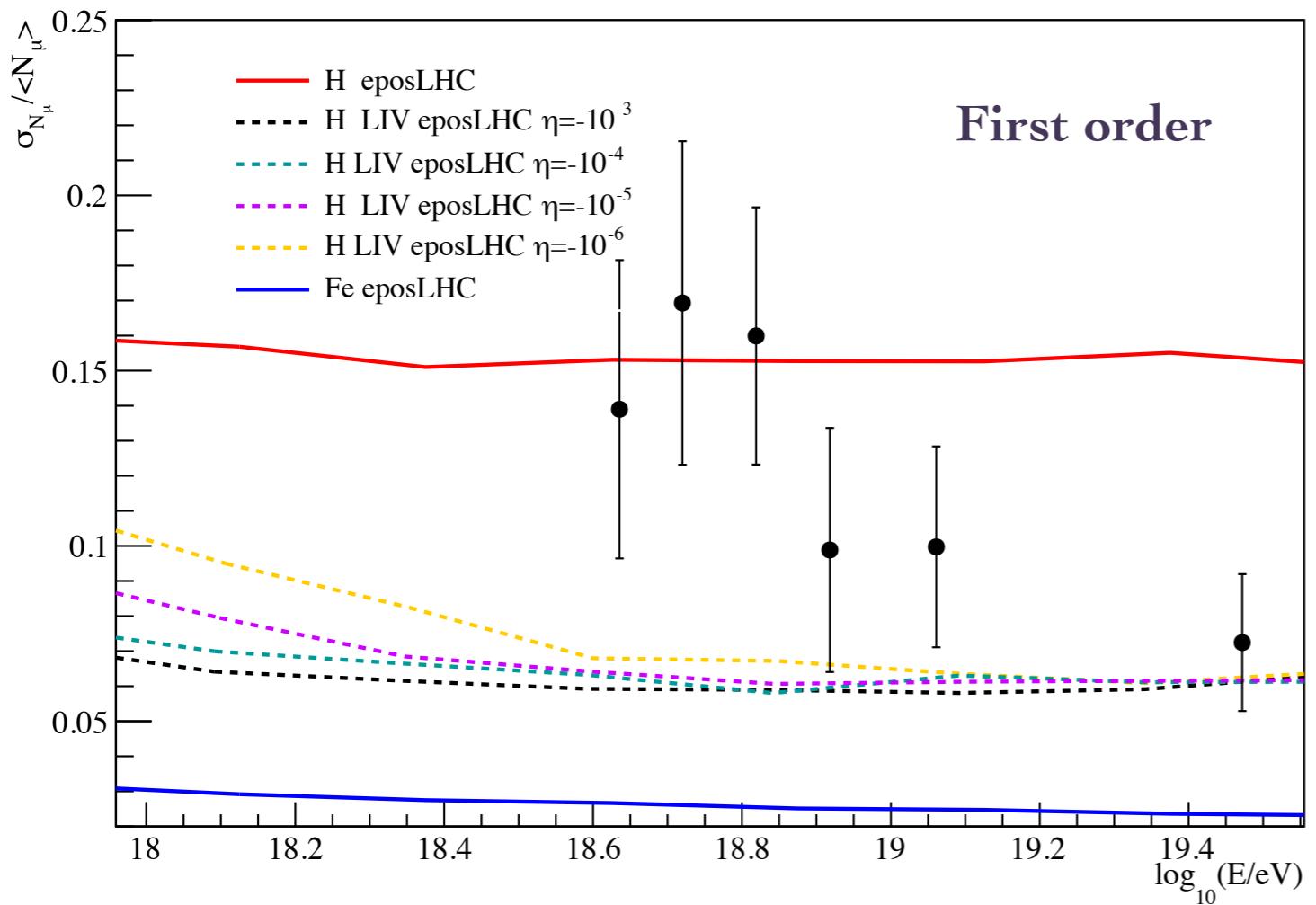
The number of muons increases!



INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS



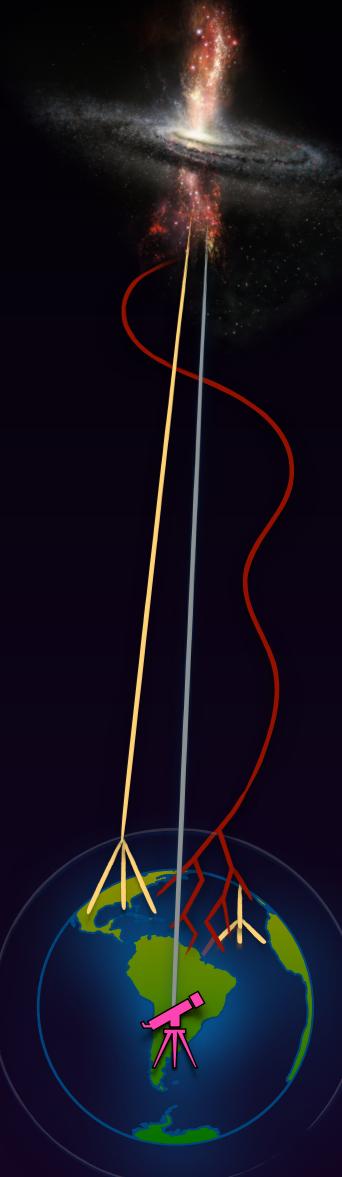
Muon Fluctuations



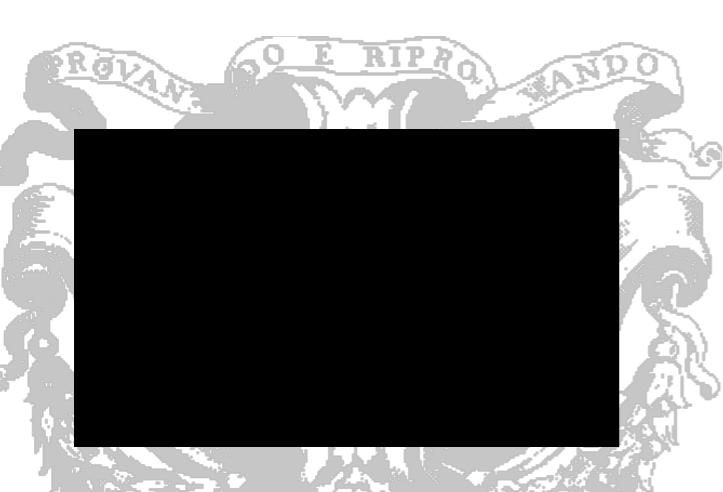
$\eta > -10^{-6}$ with (99.7% C.L.)

η	χ^2	CL %	σ
-10^{-3}	16.78284	99.9217%	3.359σ
-10^{-4}	16.232752	99.8984%	3.286σ
-10^{-5}	15.71581	99.8703%	3.2167σ
-10^{-6}	14.035656	99.7143	2.9827σ

NEW

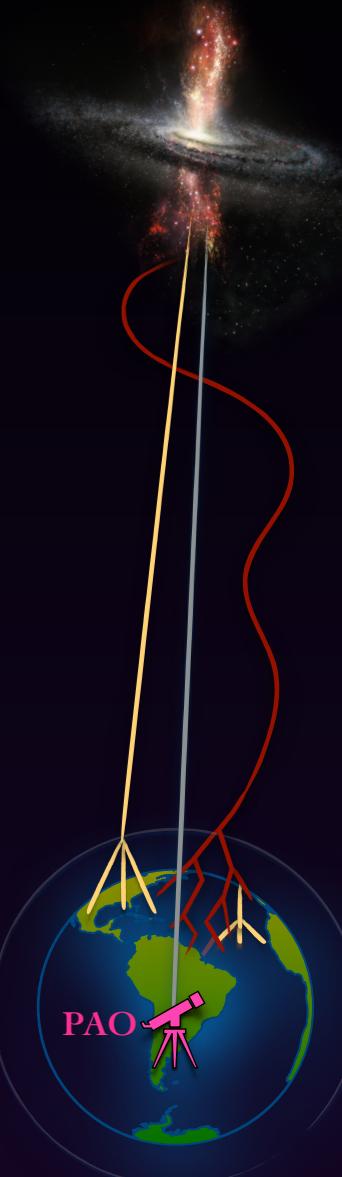
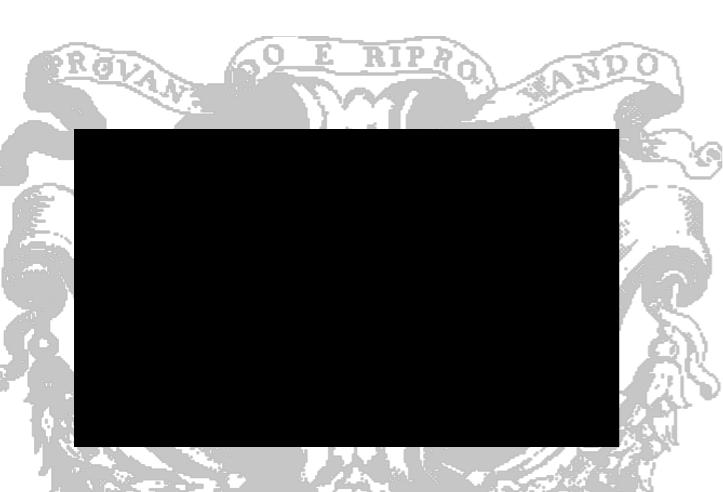


INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS



Conclusions and prospects

- ◆ We obtained an improved bound for LIV parameter values;
- ◆ Future work will involve other hadronic interaction models as QGSJETII-04 and SiBYLL 2.1-2.3 to test the results.
- ◆ The undergoing upgrade of the Auger detector (AugerPrime), will provide a measurement of the number of muons at ground with a better precision allowing a more accurate study of the Lorentz invariance violation effects.



INTRODUCTION

LIV in EAS

MC Simulations

RESULTS

CONCLUSIONS



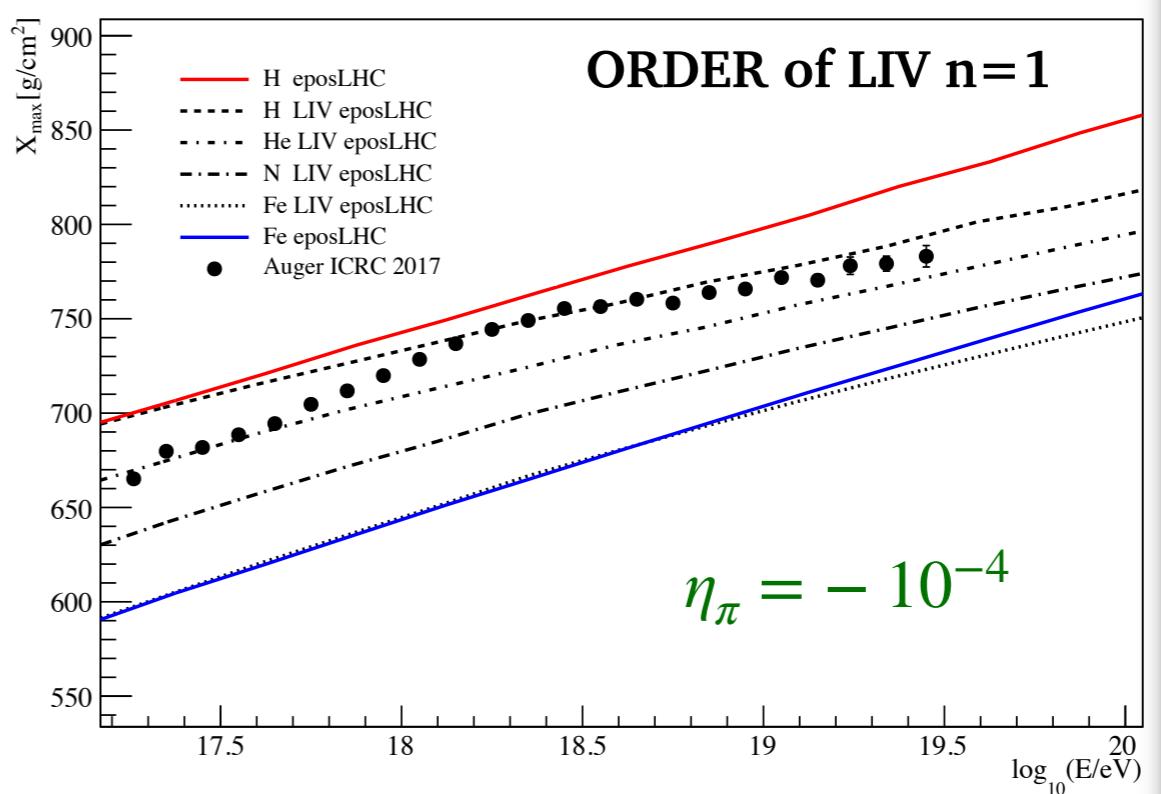
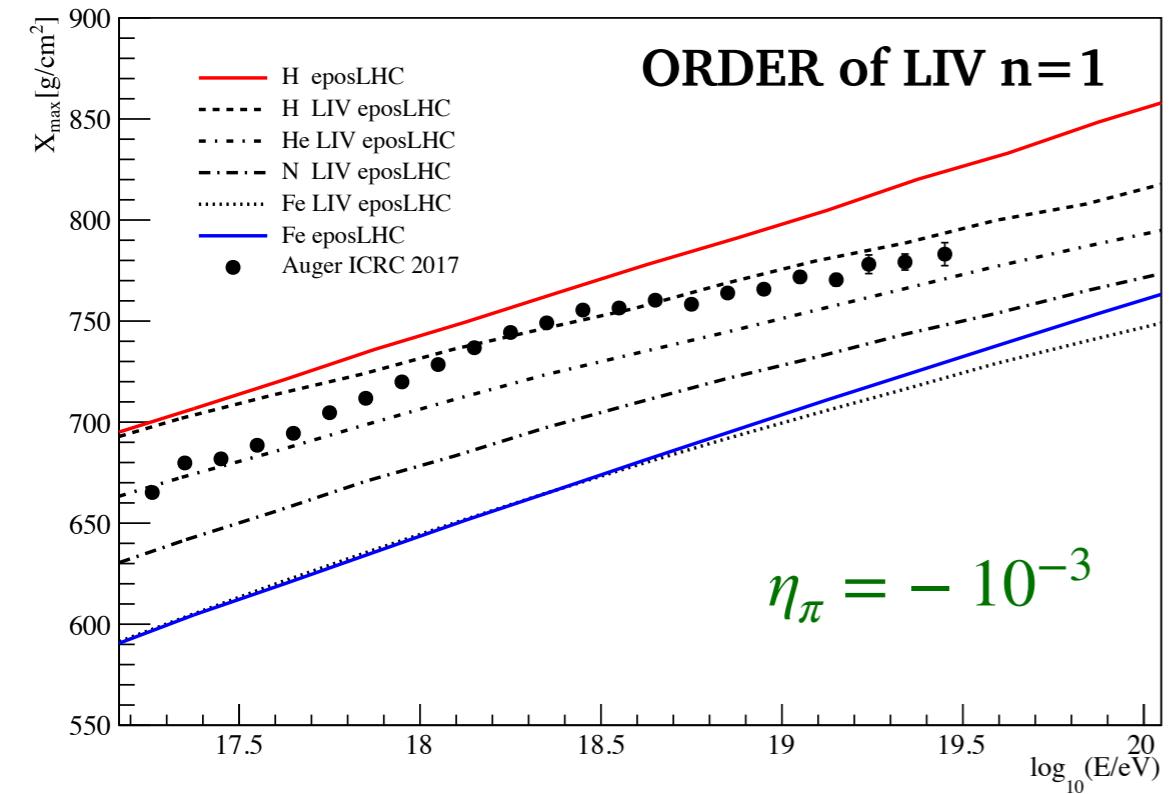
Thank you for your attention!



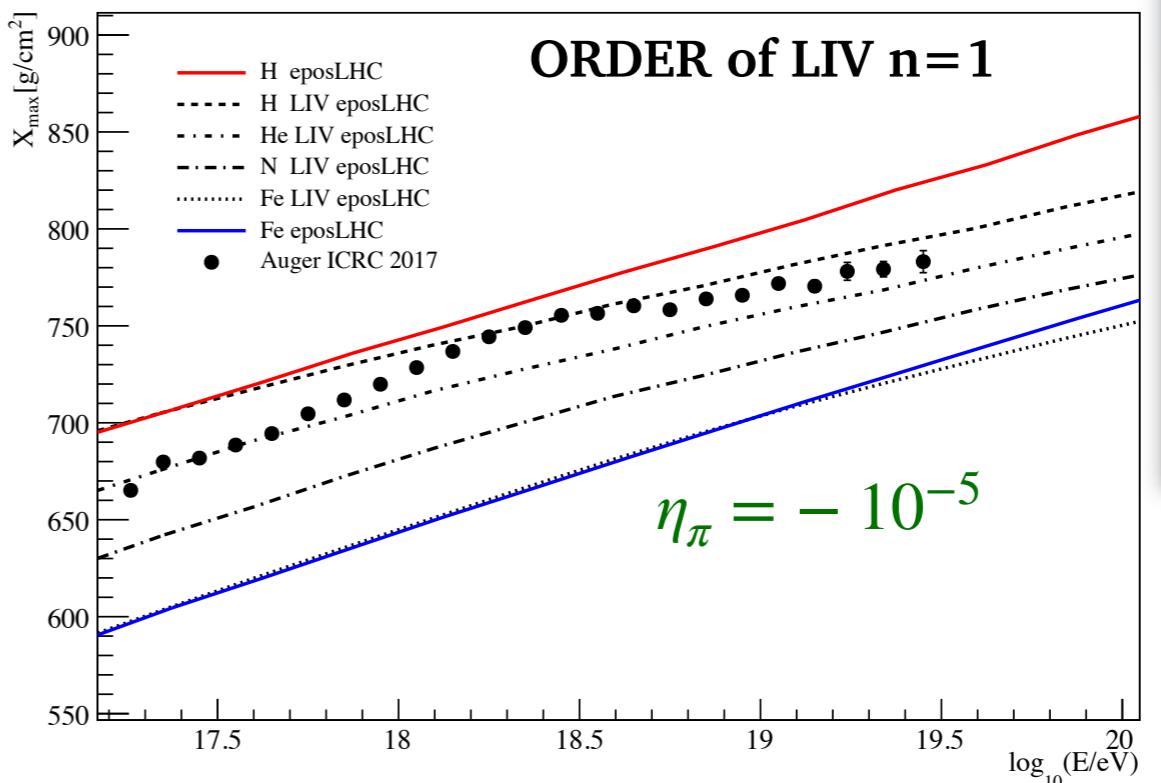
Backup



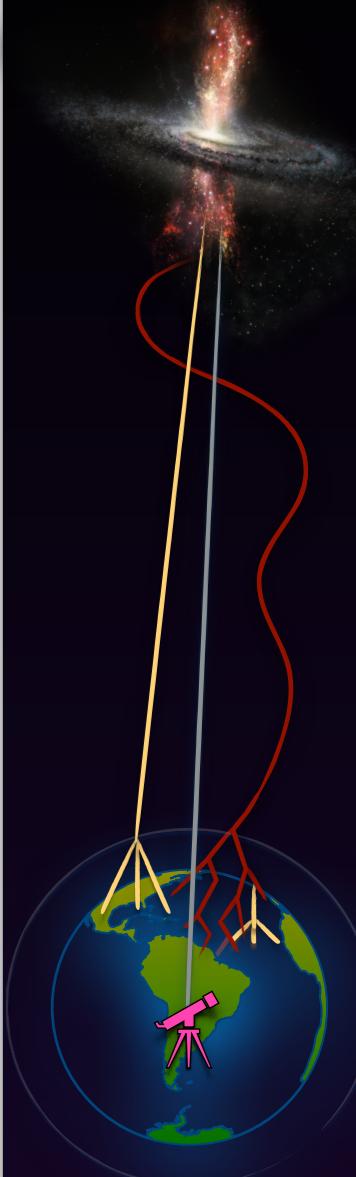
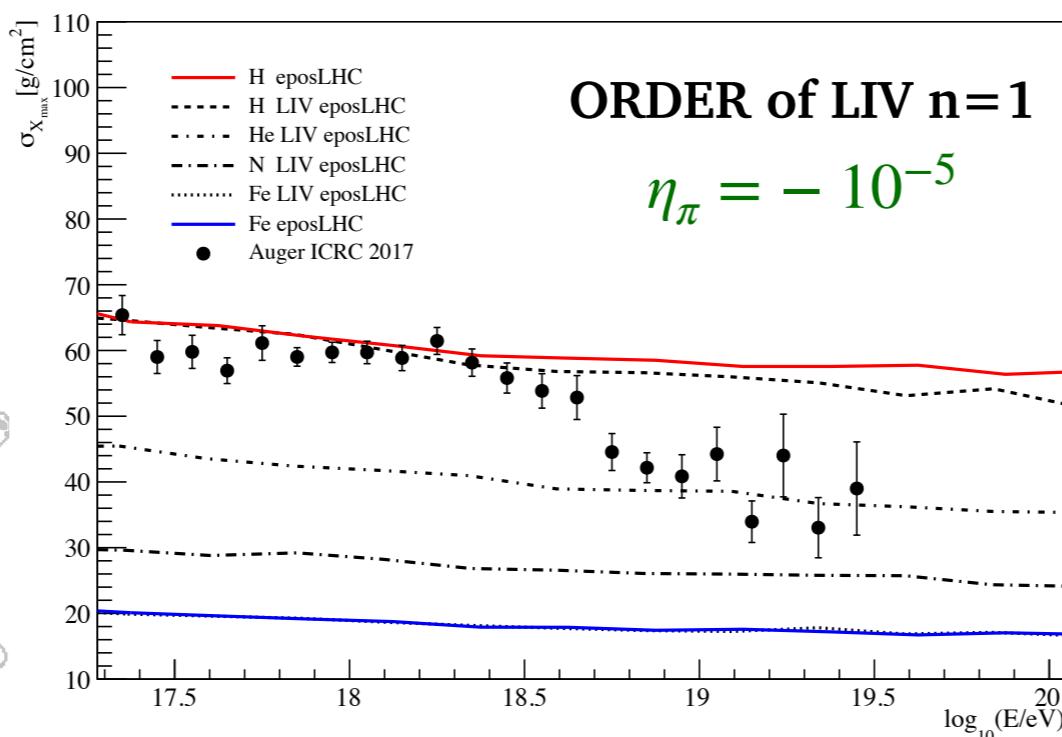
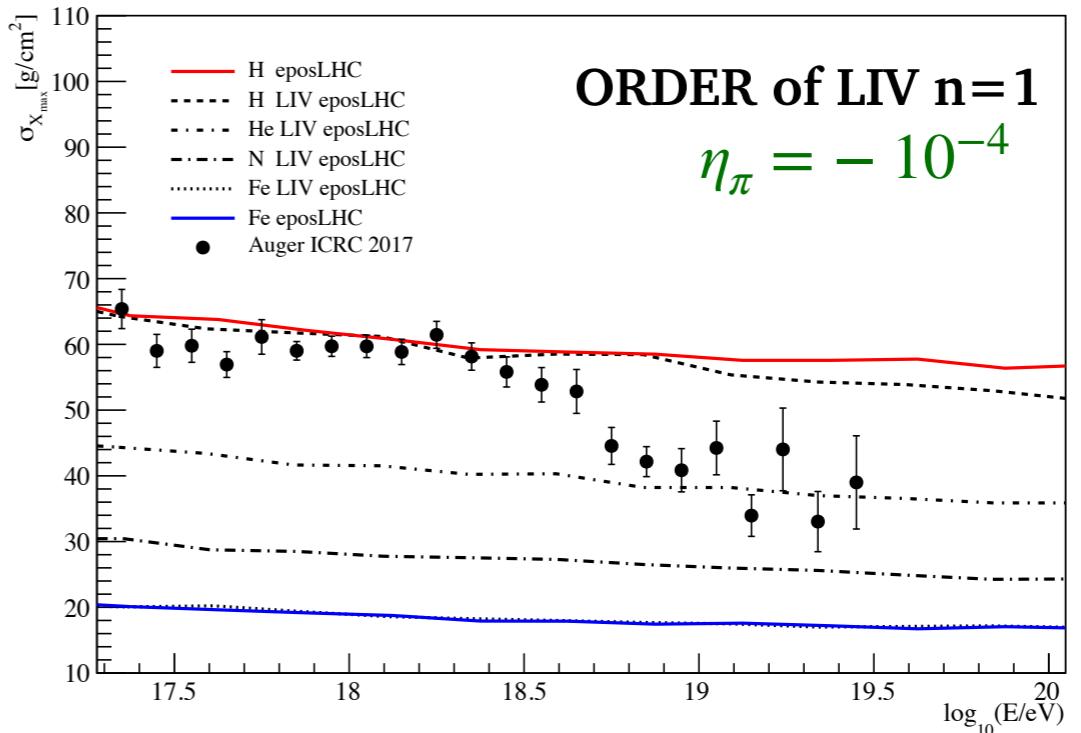
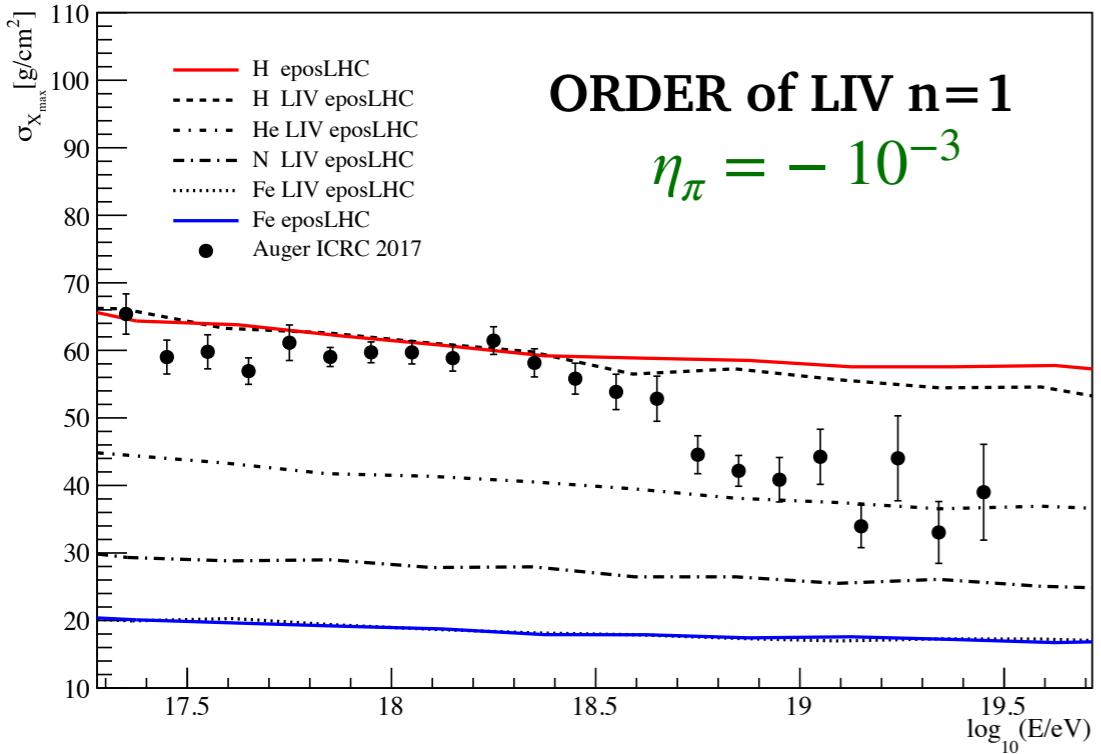
Mean Xmax



More protons expected for
LIV at 1st order!!

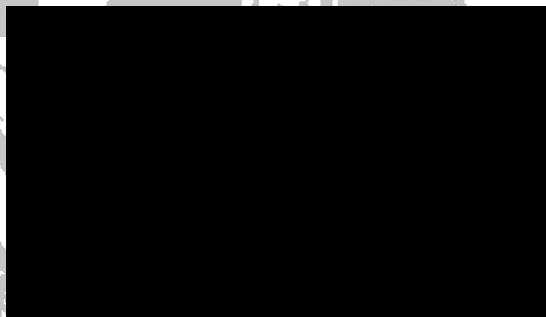
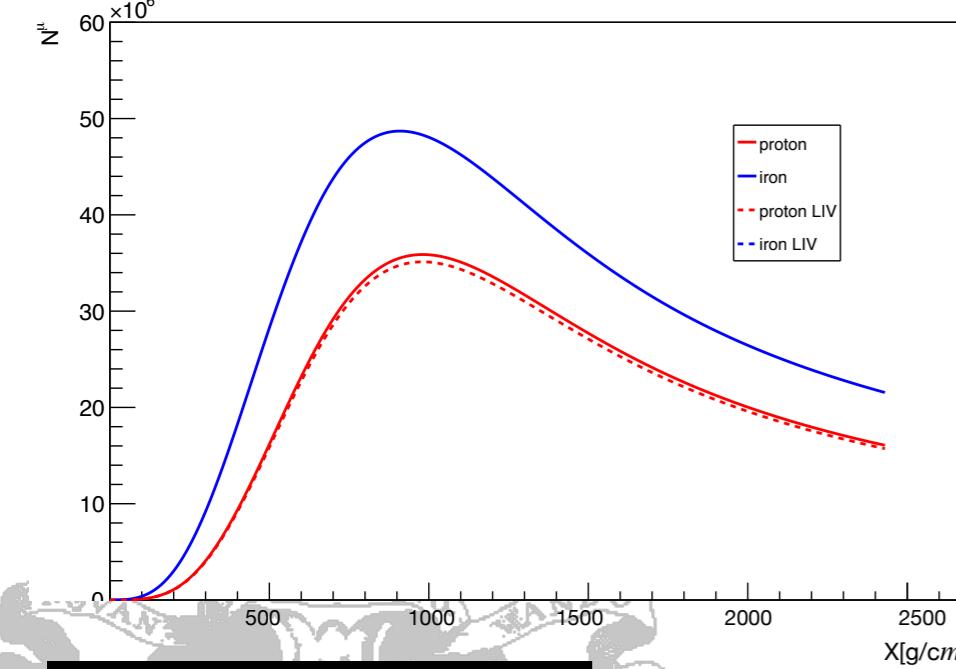
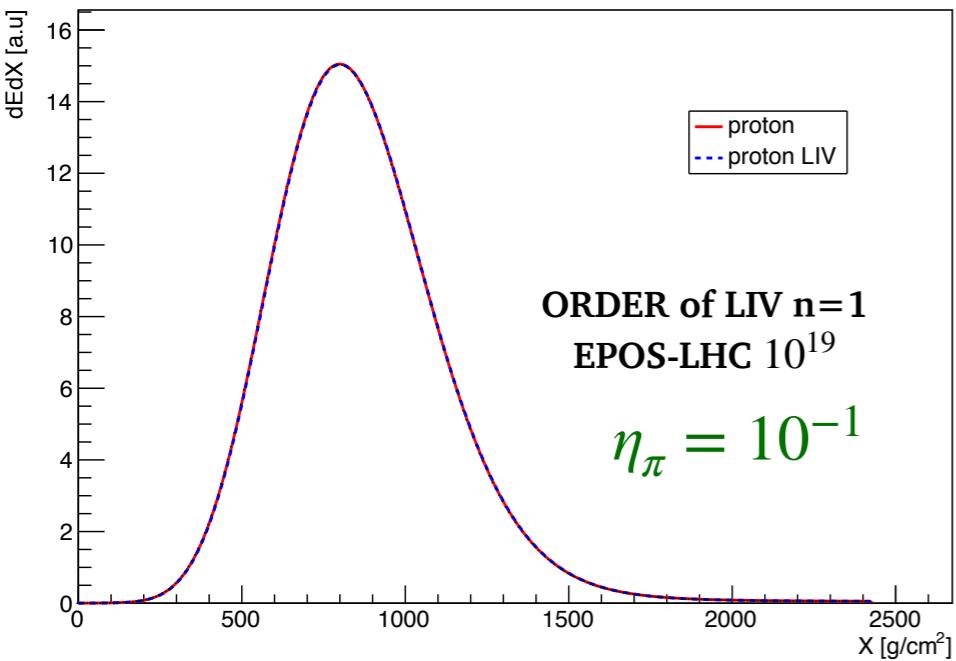


RMS Xmax

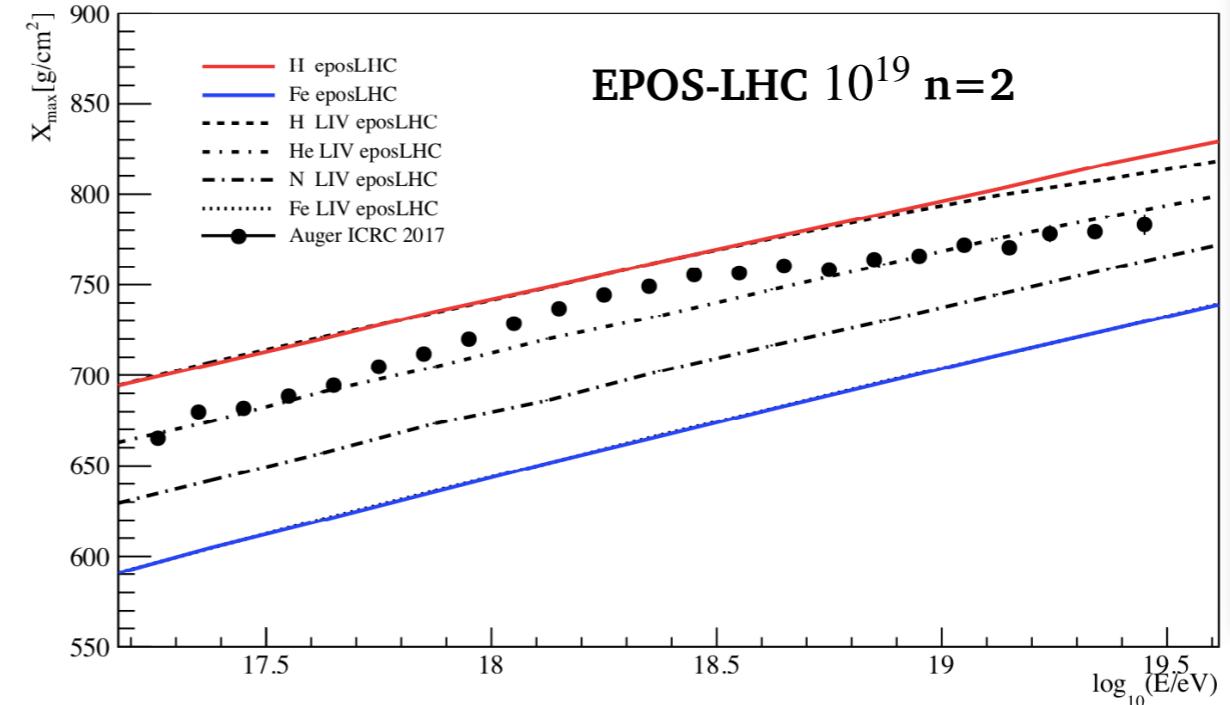
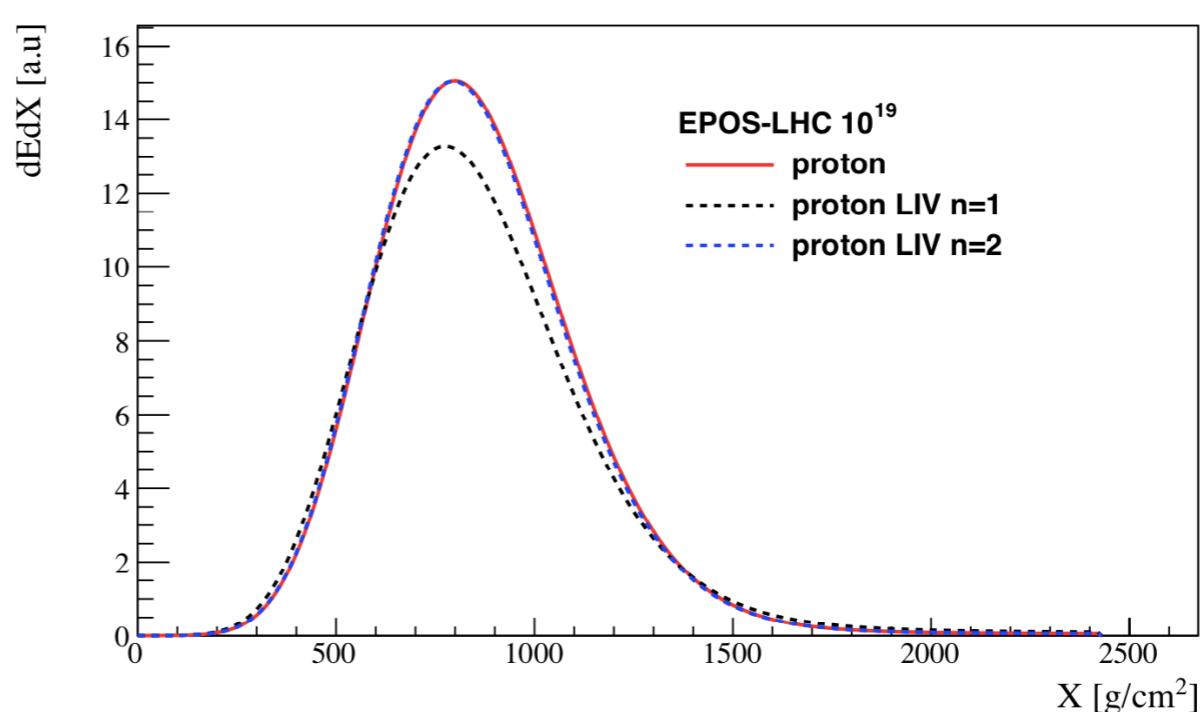


INTRODUCTION
 LIV in EAS
 MC Simulations
RESULTS
 CONCLUSIONS

$\eta_\pi > 0$



LIV SECOND ORDER



INTRODUCTION
LIV in EAS
MC Simulations
RESULTS
CONCLUSIONS

