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Investigating the properties of the EAS simulated with LIV pair production cross-sections

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Introduction

- In the paper by *N.S. Martynenko, G.I. Rubtsov, P.S. Satunin, A.K. Sharofeev and S.V. Troitsky* (DOI: 10.1103/PhysRevD.111.063010) an interesting new approach to solve the “muon puzzle” was considered:

  By using the modified $\gamma + A \rightarrow e^+e^-$ cross-sections calculated in a **Lorentz Invariance Violation** scenario they showed:

  - Primary energy E_0 is underestimated due to lower N_e in real showers than in simulations;
  - An “excess” of muons is seen, as N_μ is compared for EAS with lower E_0 in simulations.

- A parameter of the model, $\boldsymbol{M_{\mathrm{LIV}} \sim 10^{16}}$ GeV, was fitted to Pier Auger Observatory data on the muon excess.

- But only vertical showers were considered.

- Here, we investigate the wider set of EAS parameters, including inclined EAS.

Lorentz Invariance Violation and EAS physics

LIV: Add an effective term to the dispersion relation:

$$E^2 - p^2 = m^2 + f(\vec{p}, M_{\mathrm{Pl}}, \eta)$$

Expand to leading order: η - LIV parameter

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

- Usually investigated scenario:

$$\gamma_{\pi^0}^{\mathrm{LIV}} = \frac{E}{m_{\mathrm{LIV}}} > \gamma_{\pi^0}^{\mathrm{LI}}$$

  - π^0 pseudo-stability -> more energy to hadronic cascade as $\pi^0 \to 2\gamma$ is suppressed for VHE pions.

Consider a special case:

$$E_\gamma^2 - k_\gamma^2 = -\frac{k_\gamma^4}{M_{\mathrm{LIV}}^2},$$

So $n = 2$ (second order) and $\eta = -\left(\frac{M_{\mathrm{Pl}}}{M_{\mathrm{LIV}}}\right)^2$.

Consequence -> modified Bethe-Heitler $\gamma + A \to e^+e^-$ cross-section (G.I. Rubtsov et al., 2018, DOI: 10.1103/PhysRevD.86.085012):

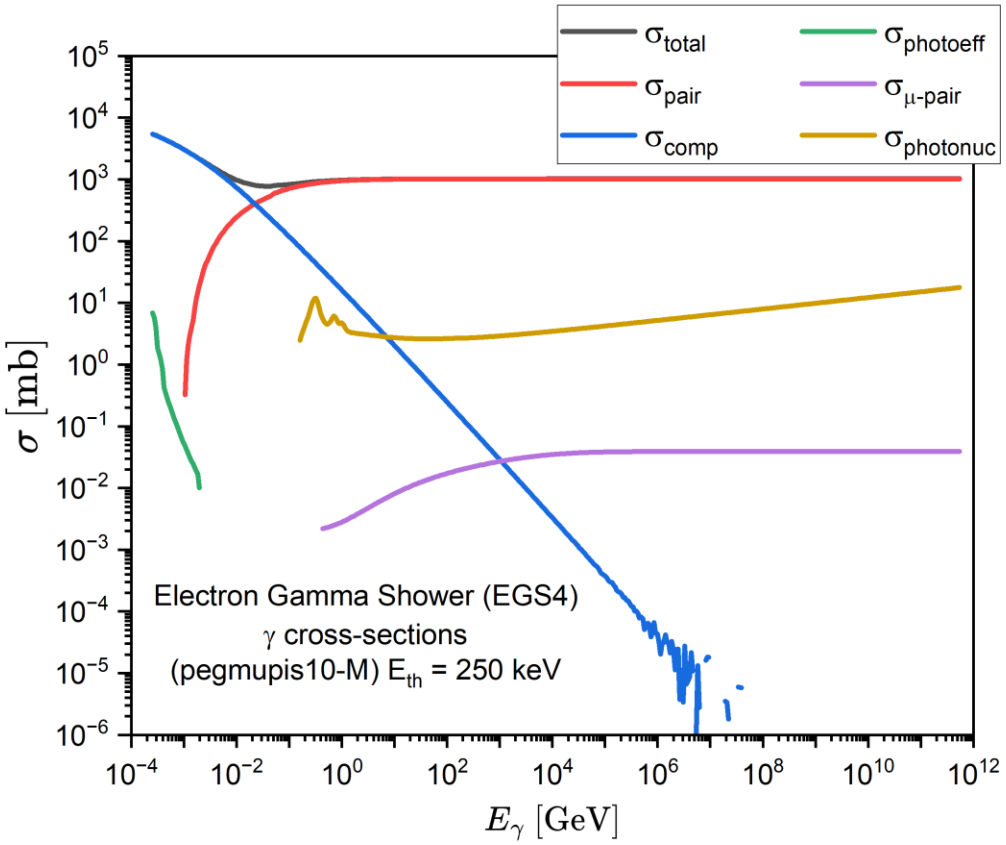
$$\frac{\sigma_{\mathrm{BH}}^{\mathrm{LIV}}}{\sigma_{\mathrm{BH}}^{\mathrm{LI}}} \cong \frac{12 m_e^2 M_{\mathrm{LIV}}^2}{7 E_\gamma^4} \log \frac{E_\gamma^4}{2 m_e^2 M_{\mathrm{LIV}}^2}.$$

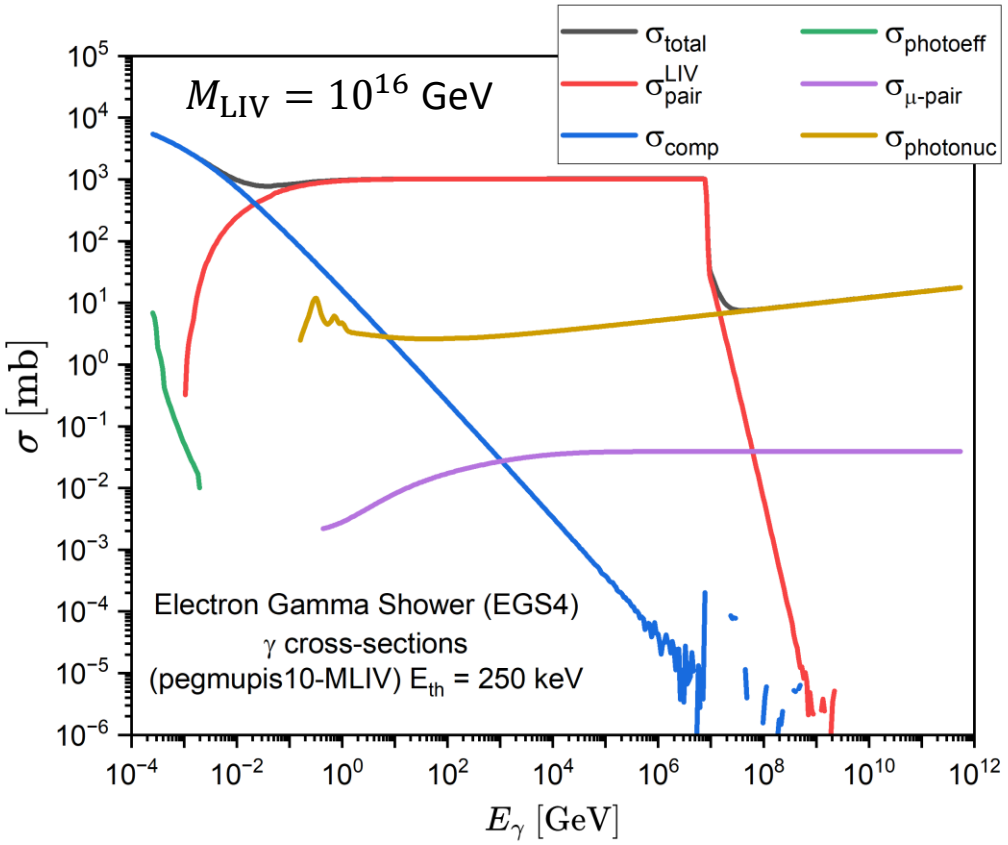
- Significant increase of VHE γ mean free path.

- We use $\boldsymbol{M_{\mathrm{LIV}} = 2 \cdot 10^{16}}$ GeV.

Modifying pair production cross-section

- Electromagnetic component of EAS is simulated by Electron Gamma Shower (EGS4) code in CORSIKA
- EGS4 uses a pre-calculated cross-sections tabulated in EGSDAT_x.x files
- Use an EGS preprocessor program (adopted for CORSIKA) pegmupis10-M to recalculate the tables:

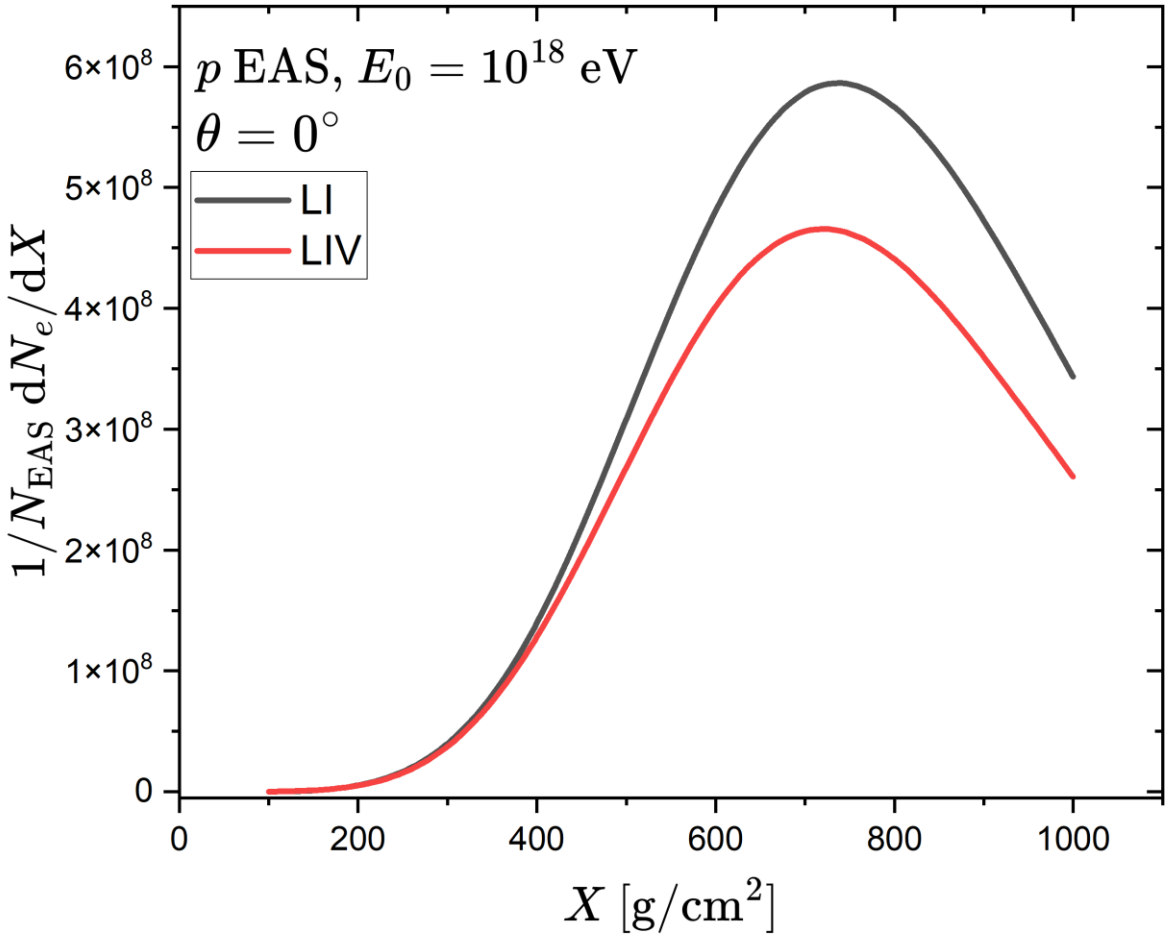




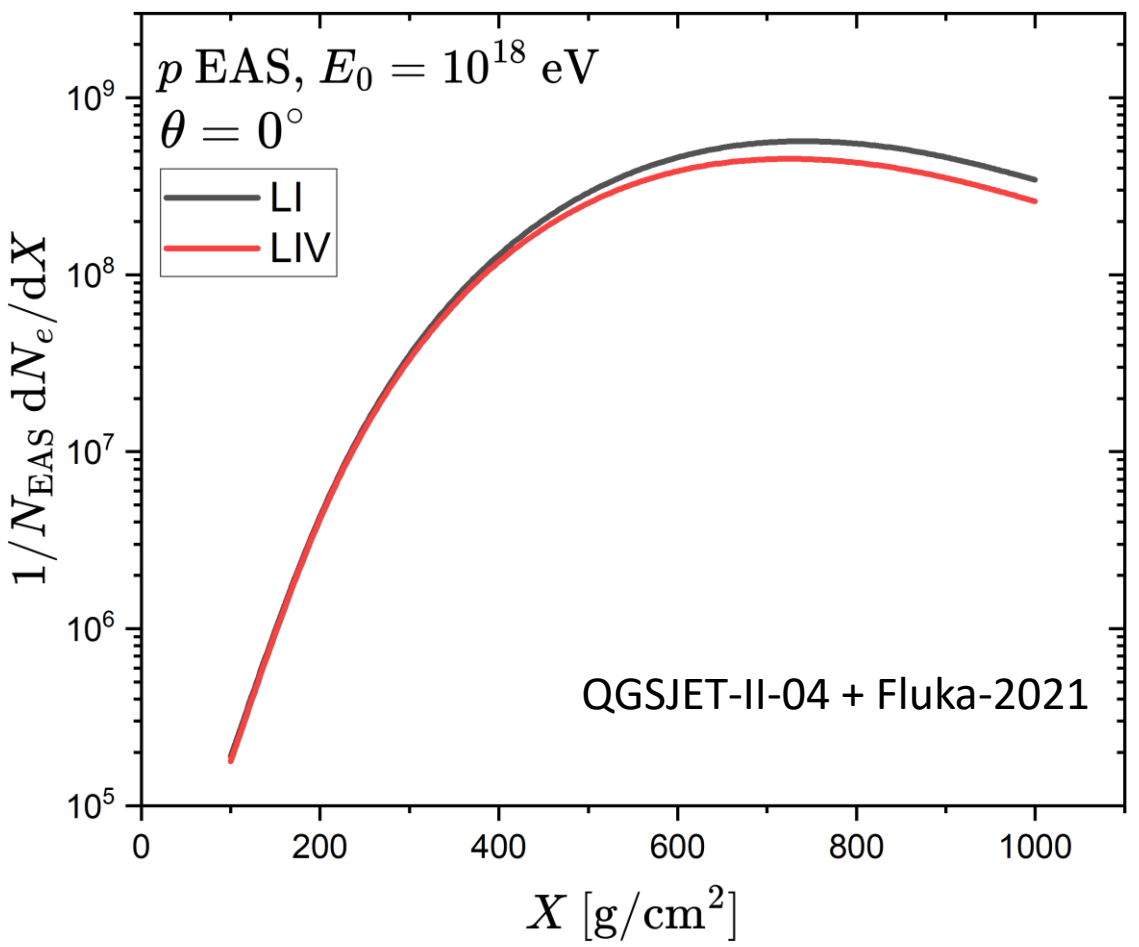
- At $M_{\mathrm{LIV}} \sim 10^{16}$ GeV the pair production cross-section practically vanishes at $E_{\gamma} \sim 10^{17}$ eV

Vertical EAS with LIV pair production: electron deficit?

Linear scale



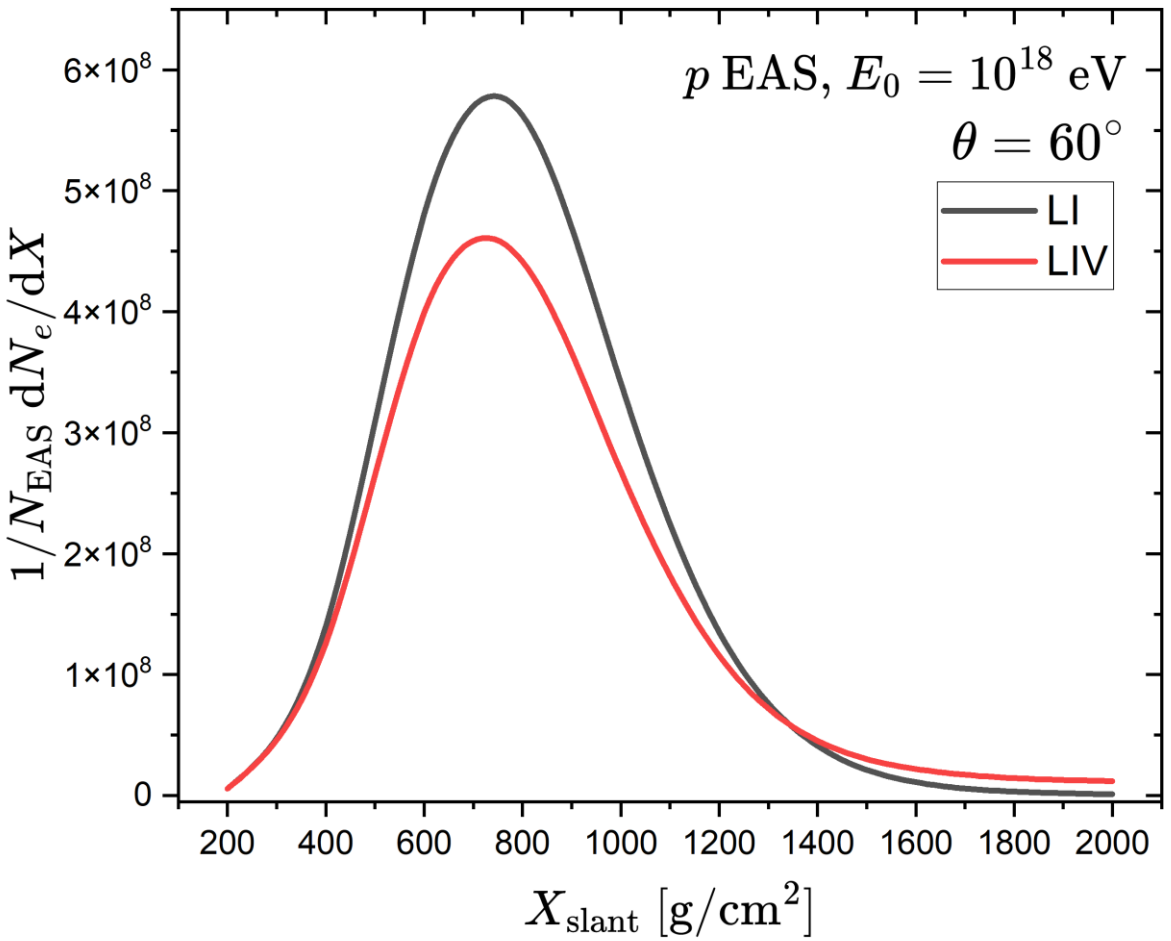
Log scale



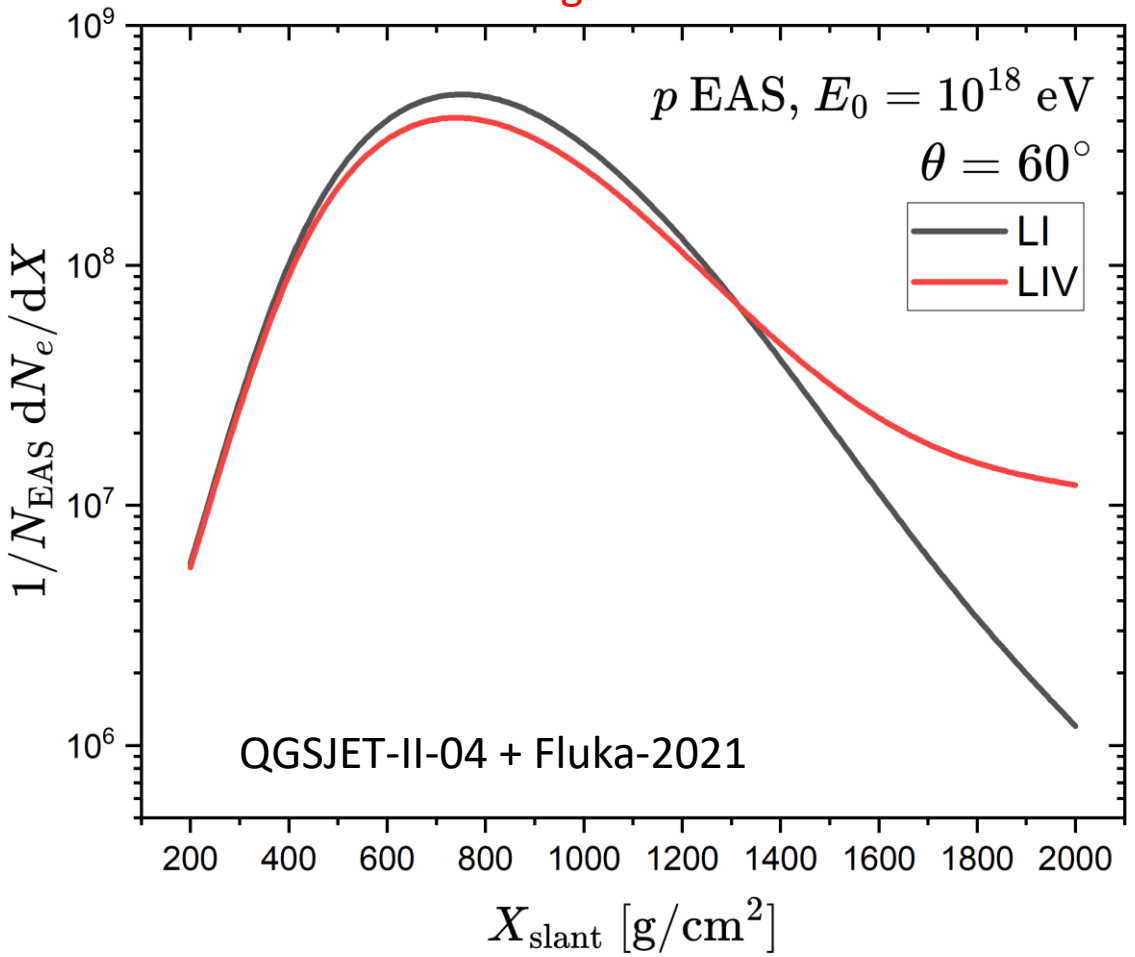
- Up to 30% decrease of N_e at ground level, $X_{\max}$ shift of ~15 g/cm^2.
- Smaller N_e could be interpreted as smaller E_0 of the primary particle.

Inclined EAS: a different picture

Linear scale

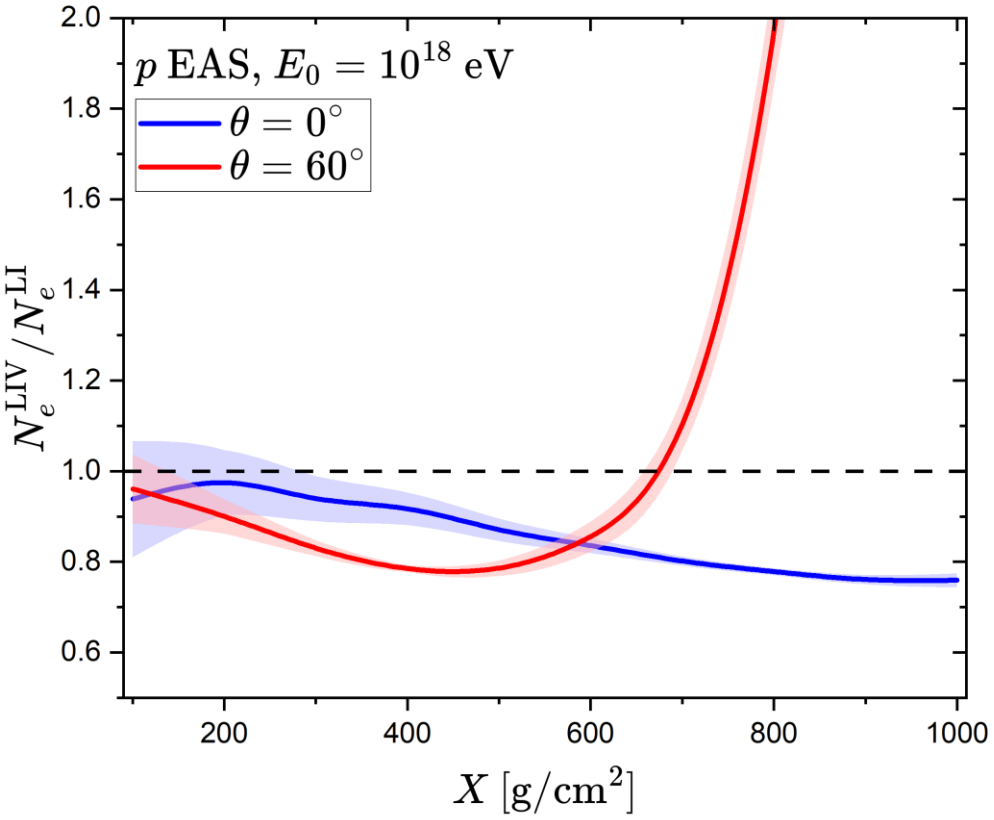


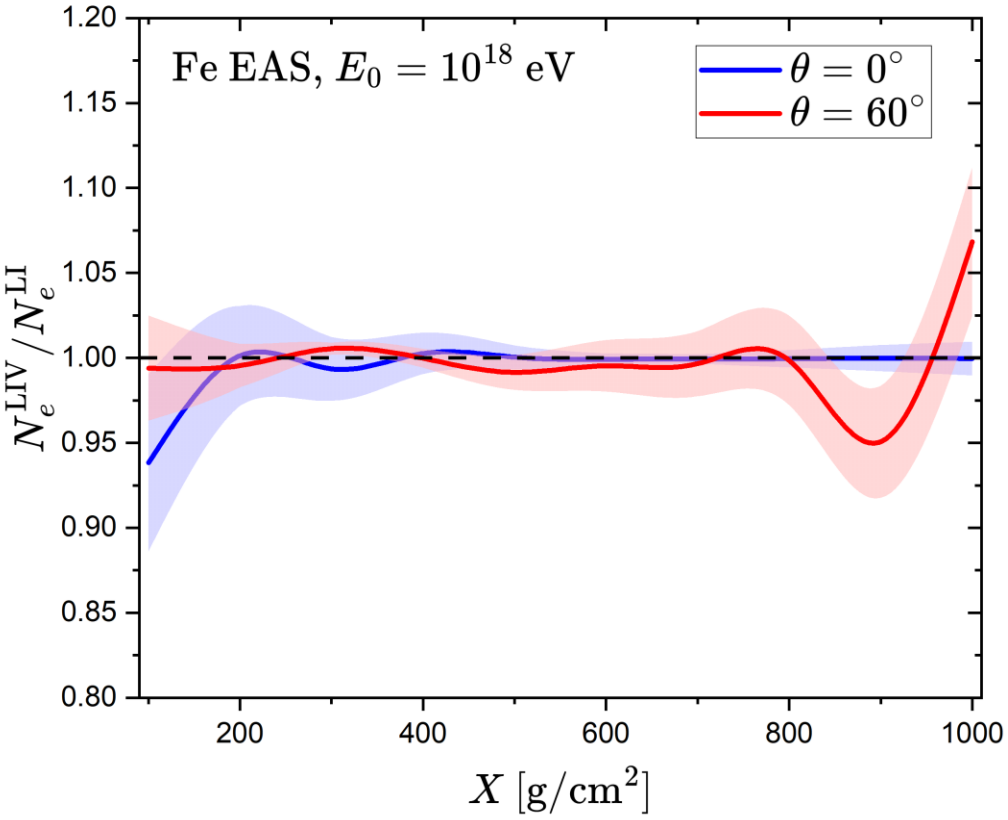
Log scale



- A decrease of N_e at first, but a significant increase at later stages.

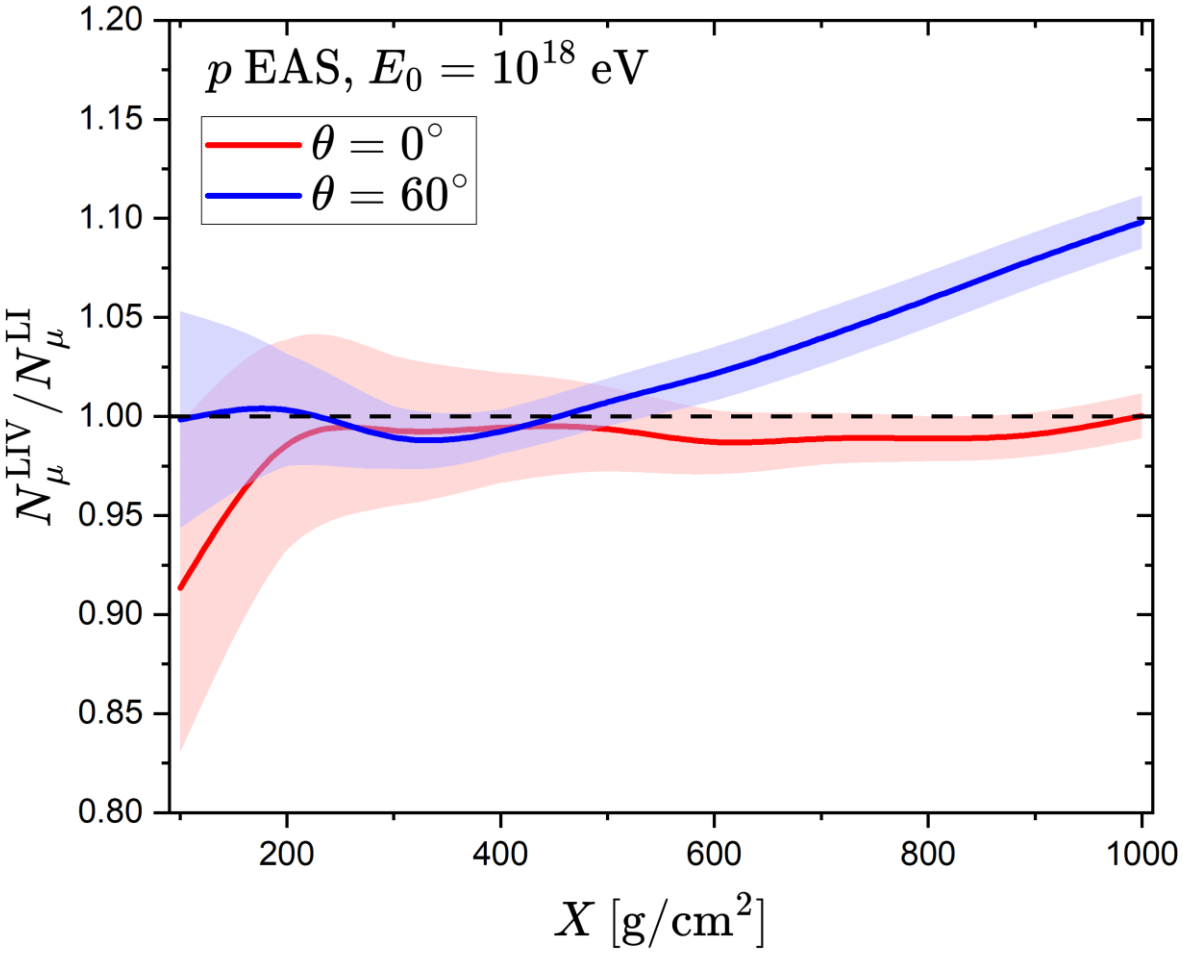
Comparing vertical and inclined showers





- LIV scenario eliminates pair production cross-sections, but photonuclear channel remains.
- Thus, a late-initiated strong EM cascade is present for the inclined showers.
- The difference is huge; such scenario is unrealistic and would lead to strong overestimation, instead of underestimation of the primary energy E_0.

Muon numbers: also a direct muon increase?



- Strong increase of the EM component in inclined EAS leads to a noticeable muon enhancement at ground (μ pair and photonuclear channels of muon production).
- However, in a more realistic case of LIV the change of the muon content should be practically invisible.

Conclusion

- EAS provide a interesting opportunity for testing the Lorentz Invariance Violation scenarios.
- But it is important to consider the complete set of measureable EAS parameters and at different registration conditions.
- The study of the zenith angle attenuation allows one to test the hypothetical LIV physics more rigorously as the slant depth of the atmosphere increases significantly.
- Apparently, the conclusion that the introduction of LIV allows solving the “muon puzzle” is premature.

Thank you for your attention!