Lorentz Symmetry Violations and Ultra-High Energy Cosmic Rays (GCOS workshop)

1. Lorentz Symmetry Violation and Propagation
2. Lorentz Symmetry Violation and Air Showers

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Günter Sigl
II. Institut theoretische Physik, Universität Hamburg
http://www2.iap.fr/users/sigl/homepage.html

Lorentz symmetry violations in the Nucleon Sector

Dispersion relation between energy E, momentum p, and mass m may be modified by non-renormalizable effects at the Planck scale M_{Pl},

$$E^2 - p^2 \simeq m^2 - \xi \frac{p^3}{M_{\mathrm{Pl}}} - \zeta \frac{p^4}{M_{\mathrm{Pl}}^2} + \cdots$$

where most models, e.g. critical string theory, predict ξ=0 for lowest order.

Introducing the standard threshold momentum for pion production, N+γ->Nπ,

$$p_0 = \frac{2m_N m_\pi + m_\pi^2}{4\epsilon}$$

the threshold momentum p_{th} in the modified theory is given by

$$-\frac{p_0^3}{(m_\pi^2 + 2m_\pi m_N)M_{\mathrm{Pl}}} \frac{m_\pi m_N}{(m_\pi + m_N)^2} \left[2\xi \left(\frac{p_{\mathrm{th}}}{p_0}\right)^3 + 3\zeta \frac{p_0}{M_{\mathrm{Pl}}} \left(\frac{p_{\mathrm{th}}}{p_0}\right)^4 + \cdots \right] + \frac{p_{\mathrm{th}}}{p_0} = 1$$

Attention: this assumes standard energy-momentum conservation which is not necessarily the case.

Coleman, Glashow, PRD 59 (1999) 116008; Alosio et al., PRD 62 (2000) 053010

For $\xi \sim \zeta \sim 1$ this equation has no solution => No GZK threshold!

For $\zeta \sim 0$, $\xi \sim -1$ the threshold is at ~1 PeV!
For $\xi \sim 0$, $\zeta \sim -1$ the threshold is at ~1 EeV!

Confirmation of a normal GZK threshold would implies the following limits:

$|\xi| < 10^{-13}$ for the first-order effects.
$|\zeta| < 10^{-6}$ for the second-order effects.

But note that existence of GZK-caused "cut-off" is not sure sure these days !

Energy-independent (renormalizable) corrections to the maximal speed $V_{max} = \lim_{E \to \infty} \partial E/\partial p = 1-d$ can be constrained by substituting $d \to (\xi/2)(E/M_{Pl}) + (\zeta/2)(E/M_{Pl})^2$.

Influence on nuclei mean free path

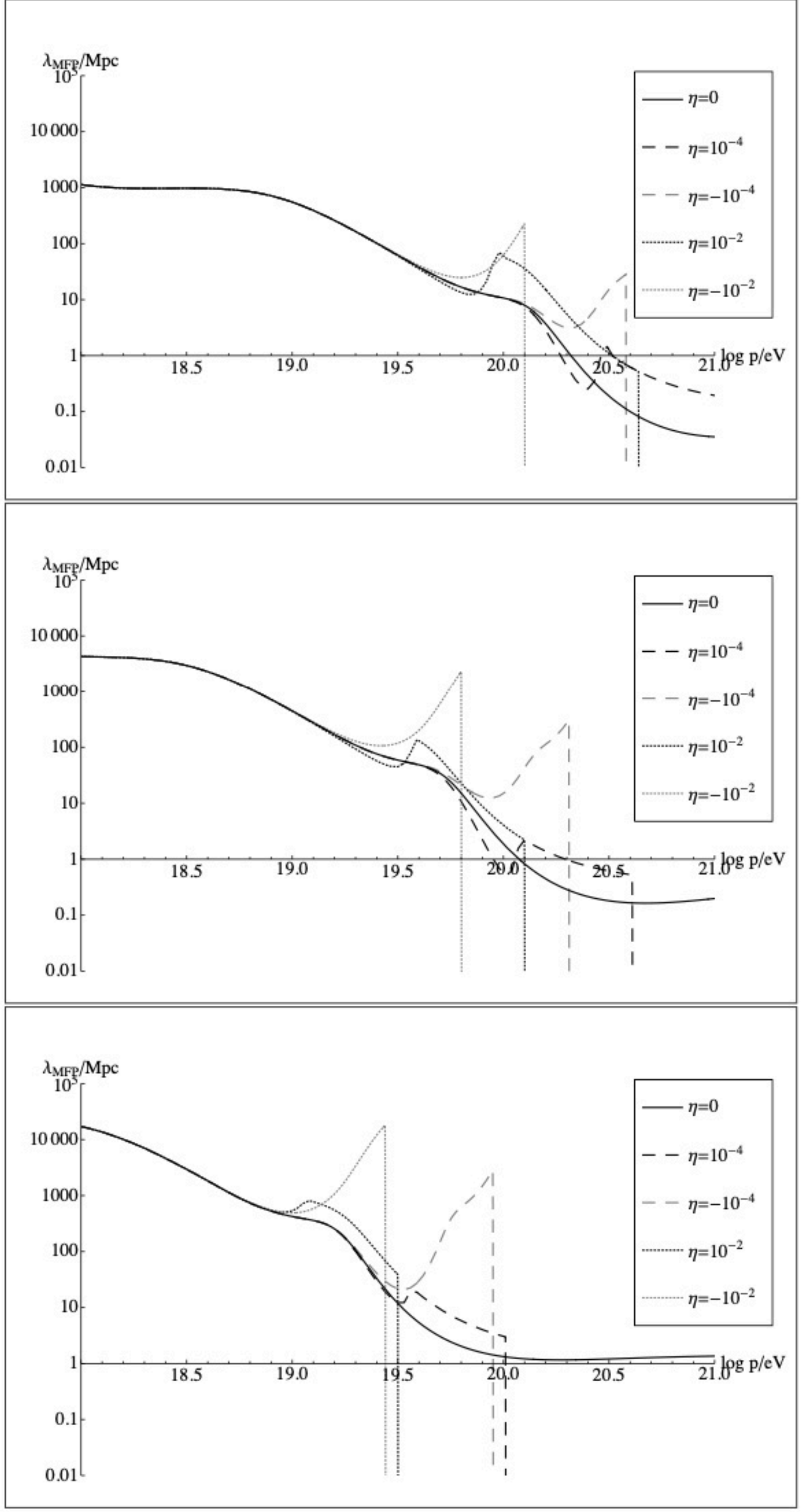


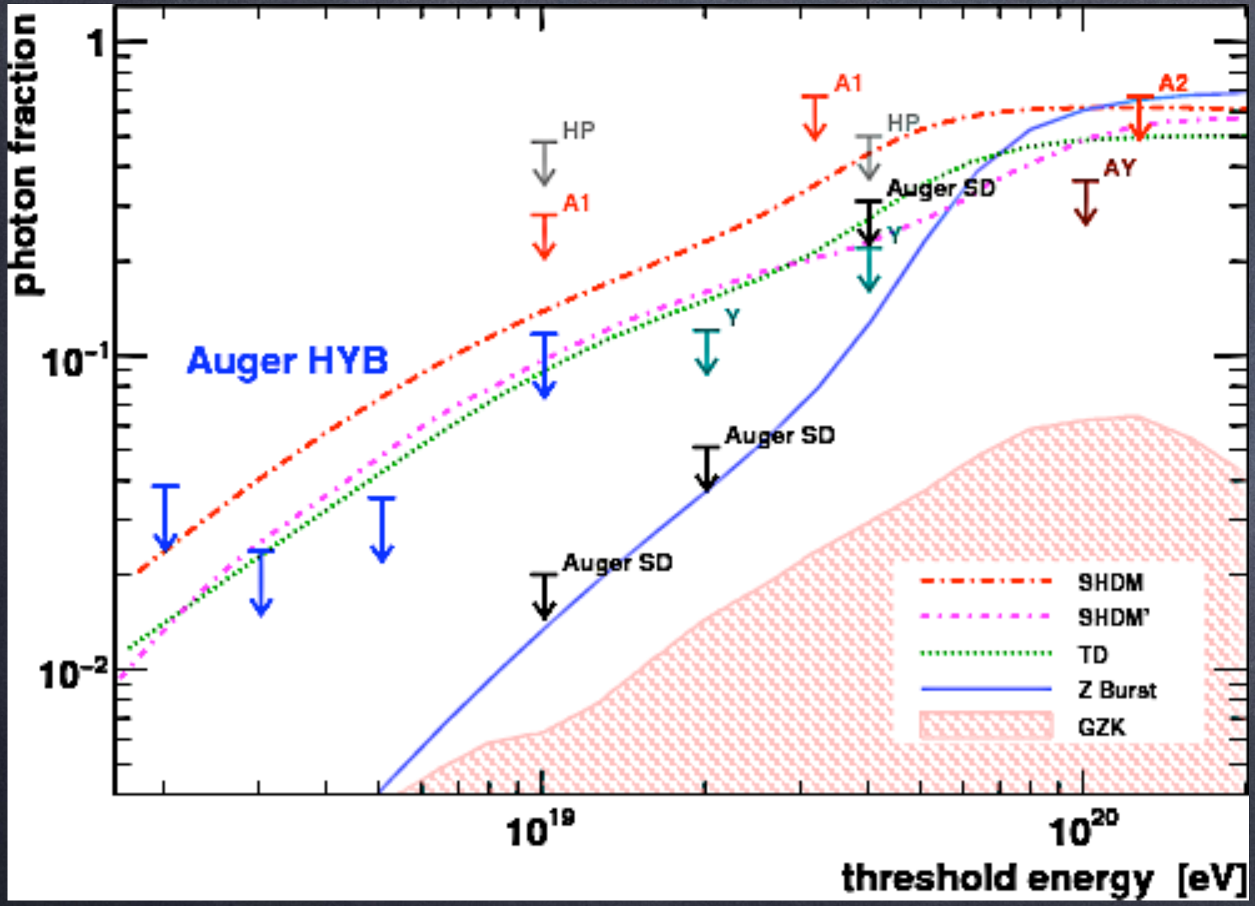
Figure 3. The mean free path of photodisintegration in the single parameter model for ^{56}Fe (top), ^{16}O (middle) and ^{4}He (bottom).

Saveliev, Macccione, Sigl, JCAP 03 (2011) 046

Lorentz Symmetry Violation in the Electromagnetic Sector

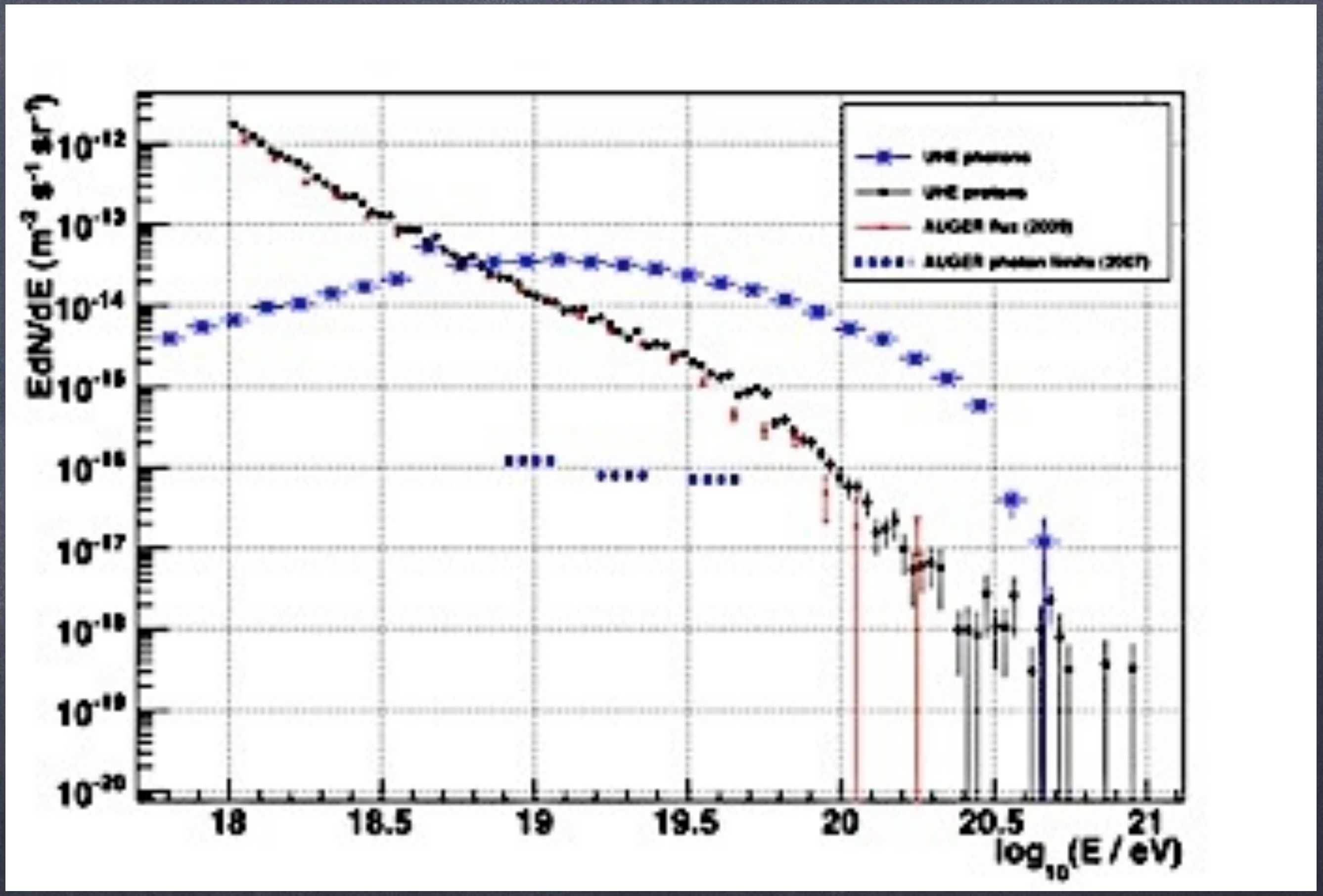
The idea:

Experimental upper limits on UHE photon fraction



Pierre Auger Collaboration, Astropart. Phys. 31 (2009) 399

Contradict predictions if pair production is absent



Maccione, Liberati, Sigl, PRL 105 (2010) 021101

Lorentz Symmetry Violation in the Photon Sector

For photons we assume the dispersion relation

$$\omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left(\frac{k}{M_{\rm Pl}}\right)^n , n \geq 1 ,$$

and for electrons

$$E_{e,\pm}^2 = p_e^2 + m_e^2 + \eta_n^{e,\pm} p_e^2 \left(\frac{p_e}{M_{\rm Pl}}\right)^n , n \geq 1 ,$$

with only one term present. Polarizations denoted with ±. For positrons, effective field theory implies $\eta_n^{p,\pm} = (-1)^n \eta_n^{e,\pm}$. Furthermore, $\xi_n^+ = (-1)^n \xi_n^-$, so that the problem depends on three parameters which in the following we denote by

$$\xi_n , \eta_n^+ , \eta_n^-$$

for each n.

The original work assumed a pure proton primary cosmic ray composition. This has meanwhile turned out to be unlikely, so that predicted photon fluxes are much smaller and constraints are weaker or even absent. An UHE proton component would help !

Consider pair production on a background photon of energy k_b and assume kinematics with ordinary energy-momentum conservation, with $p_e = (1-y)k$, $p_p = yk$. Using $x = 4y(1-y)k/k_{LI}$ with the threshold in absence of Lorentz invariance (LI) violation, $k_{LI}=m_e^2/\omega_b$, the condition for pair production is then

$$\alpha_n x^{n+2} + x - 1 \geq 0$$

where

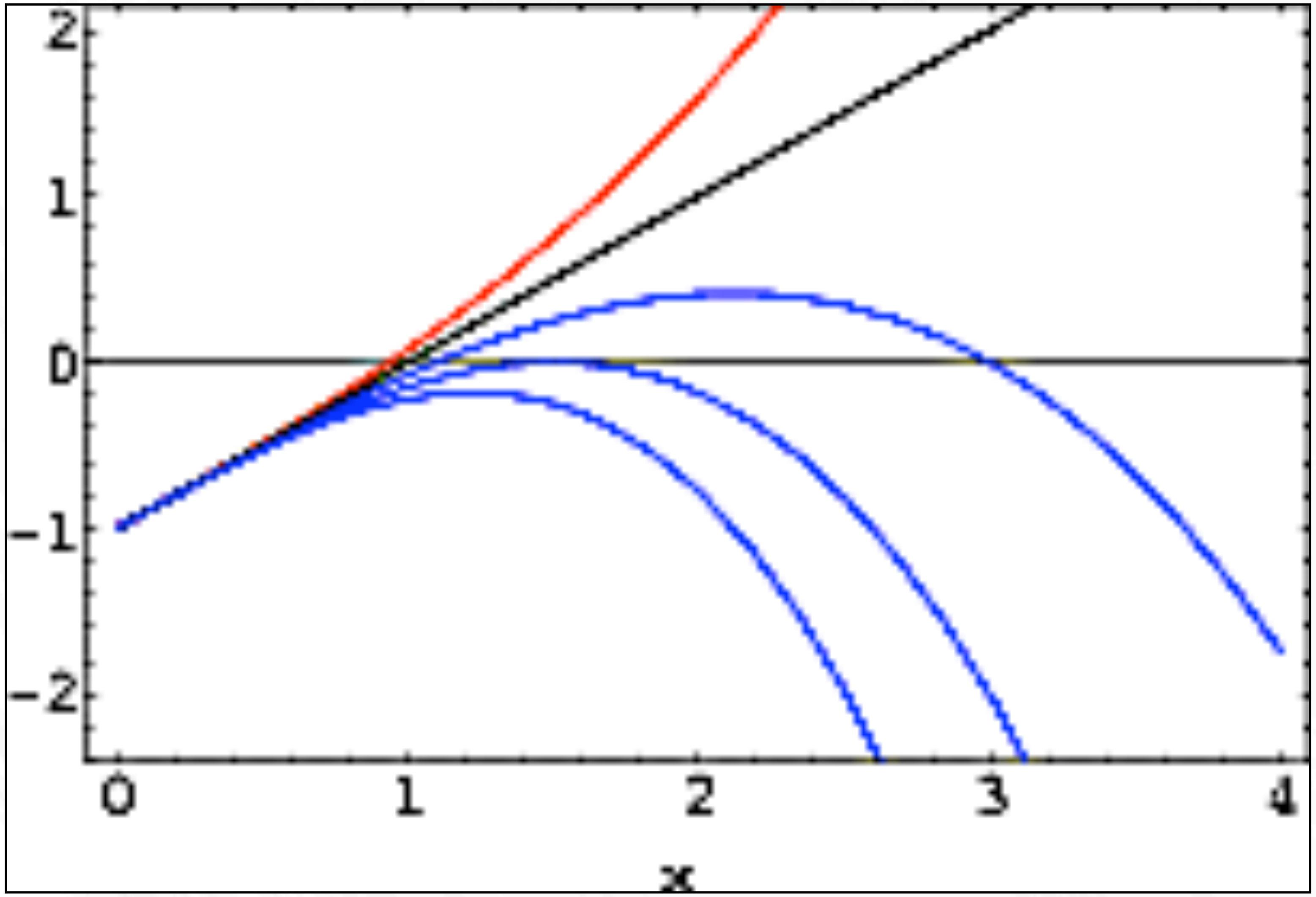
$$\alpha_n = \frac{\xi_n - (-1)^n \eta_n^{\mp} y^{n+1} - \eta_n^{\pm}(1-y)^{n+1}}{2^{2(n+2)} y^{n+1}(1-y)^{n+1}} \frac{m_e^{2(n+1)}}{k_b^{n+2} M_{\rm Pl}^n}.$$

All combinations of $\xi_n, \eta_n^+, \eta_n^-$ can occur, depending on the partial wave of the pair, governed by total angular momentum conservation. All partial waves are allowed away from the thresholds.

The condition for photon decay is

$$\alpha_n x^{n+2} - 1 \geq 0$$

There are at most two real solutions $0 \leq x_n^l \leq x_n^r$ for pair production (lower and upper thresholds):



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

For photon decay there is at most one positive real threshold.

Minimize/maximize these with respect to y.

A given combination $\xi_n, \eta_n^+, \eta_n^-$ is ruled out if, for 10^{19} eV < ω < 10^{20} eV, at least one photon polarization state is stable against decay and does not pair produce for any helicity configuration of the final pair.

In the absence of LIV in pairs for n=1, this yields:

$$\xi_1 \lesssim 10^{-12}$$

and for n=2:

$$\xi_2 \gtrsim - 10^{-6}$$

If a UHE photon were detected, any LIV parameter combination for which photon decay is allowed for at least one helicity configuration of the final pair, for both photon polarizations, would be ruled out.

For n = 1, all parameters of absolute value < 10^{-14} ruled out

For n = 2, if absolute value of both the photon and one of the electron parameters is < 10^{-6}, the second electron parameter can be arbitrarily large even once a UHE photon is seen.

Such strong limits may indicate that Lorentz invariance violations are completely absent !

Constraints for n=1

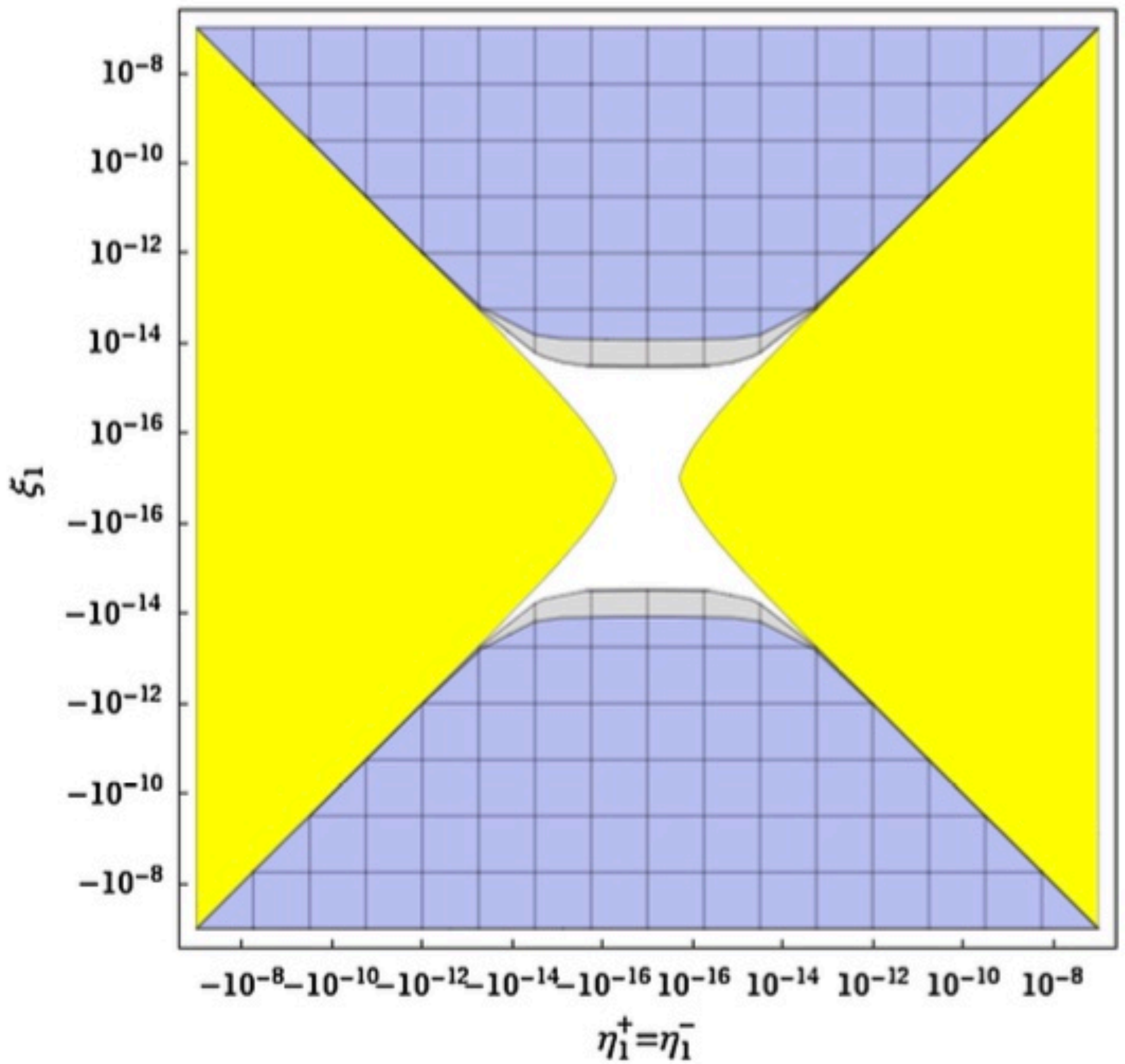
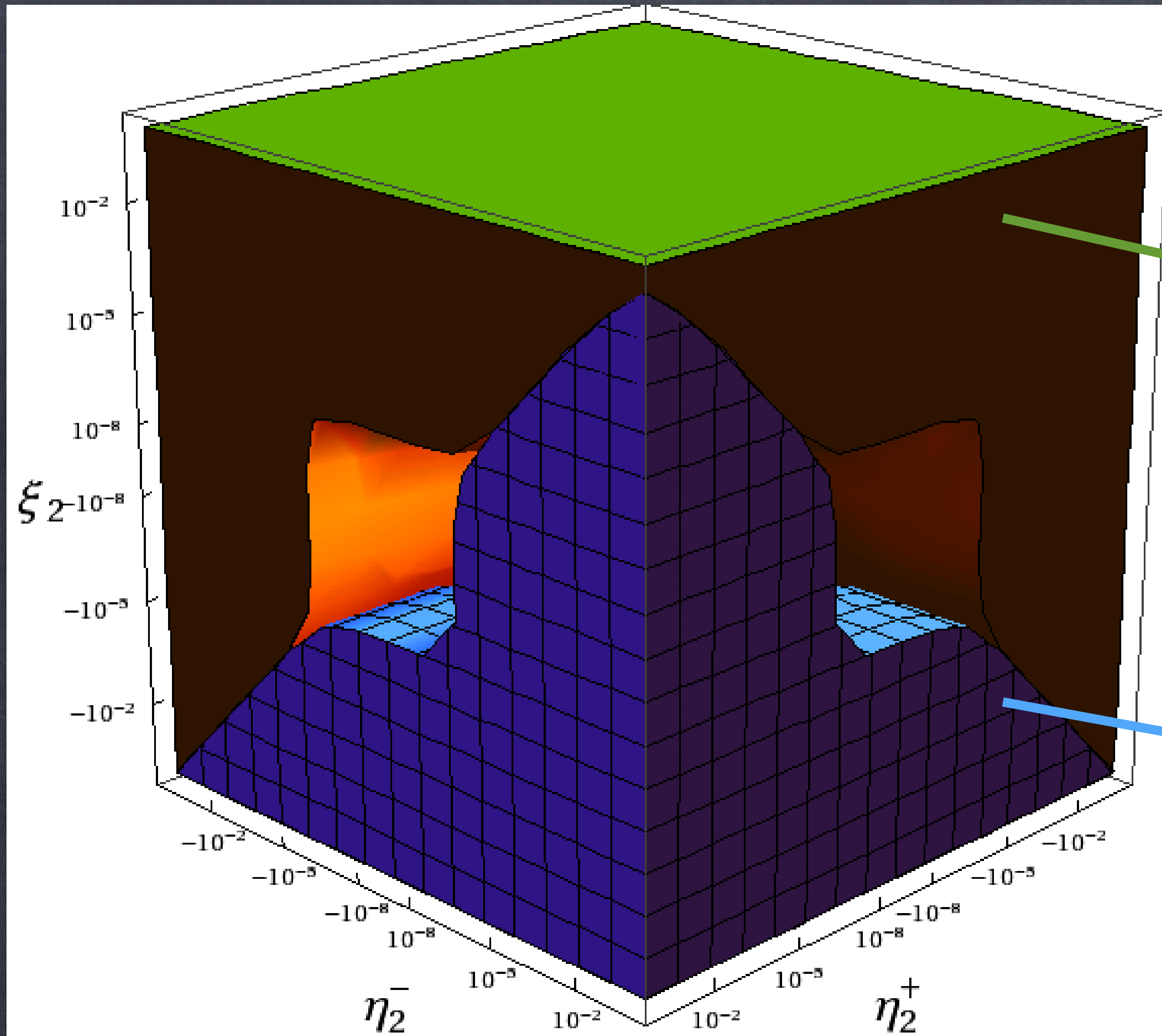


FIG. 4 (color online). Case $n = 1$, $\eta_1^+ = \eta_1^-$. Combined constraint using the current upper limits on the photon fraction in the energy range between 10^{19} and 10^{20} eV (gray plus blue shaded, checkered regions), in the energy range between 10^{19} and 5×10^{19} eV (blue region), and assuming that a 10^{19} eV photon were detected (yellow shaded region).

Galaverni, Sigl, PRD 78 (2008) 063003

Constraints for n=2



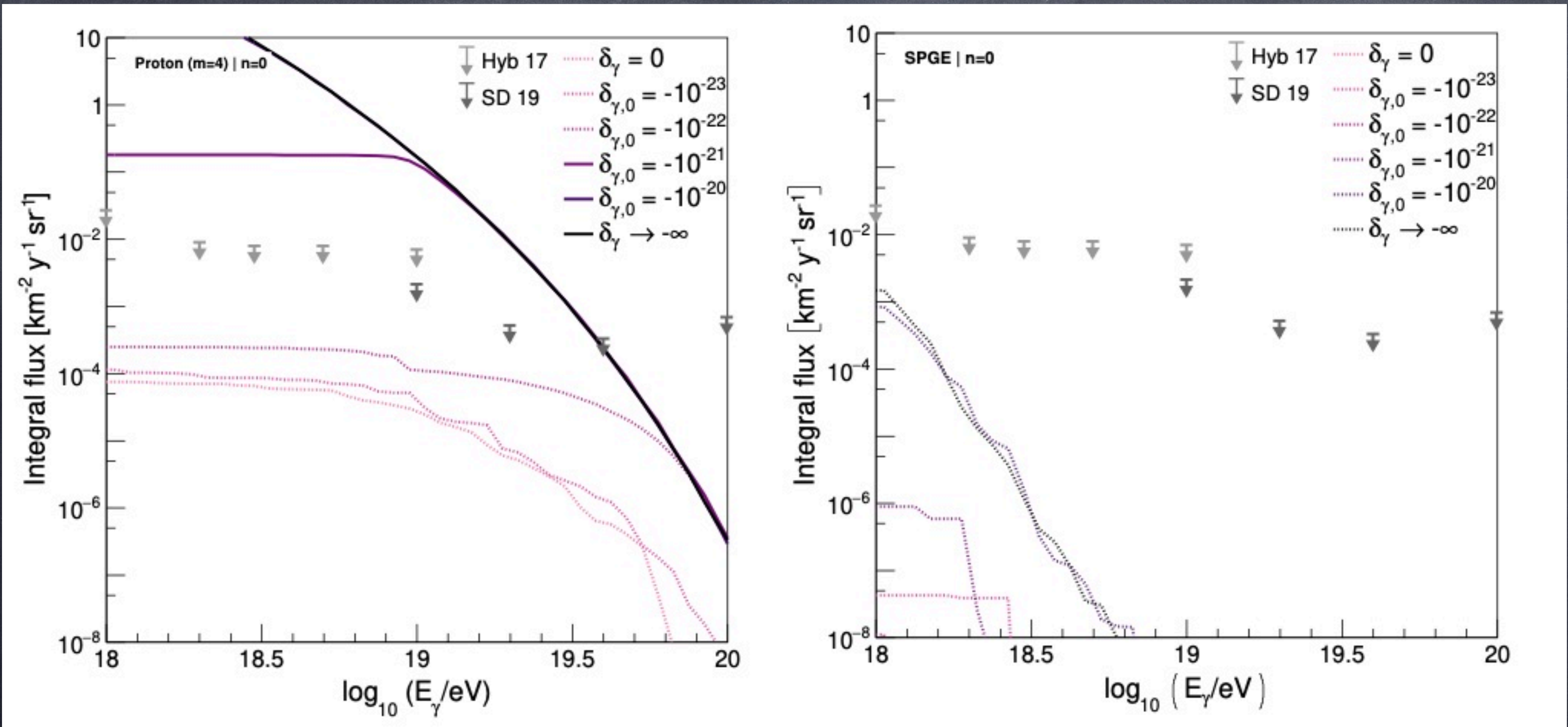
excluded if UHE photons were detected with $10^{19}\,\mathrm{eV} \lesssim E_\gamma \lesssim 10^{20}\,\mathrm{eV}$

excluded by current UHE photon flux upper limit

Galaverni, Sigl, PRD 78 (2008) 063003

Such strong limits suggest that Lorentz invariance violations are completely absent !

Scenarios for n=0 and influence of composition



pure proton composition

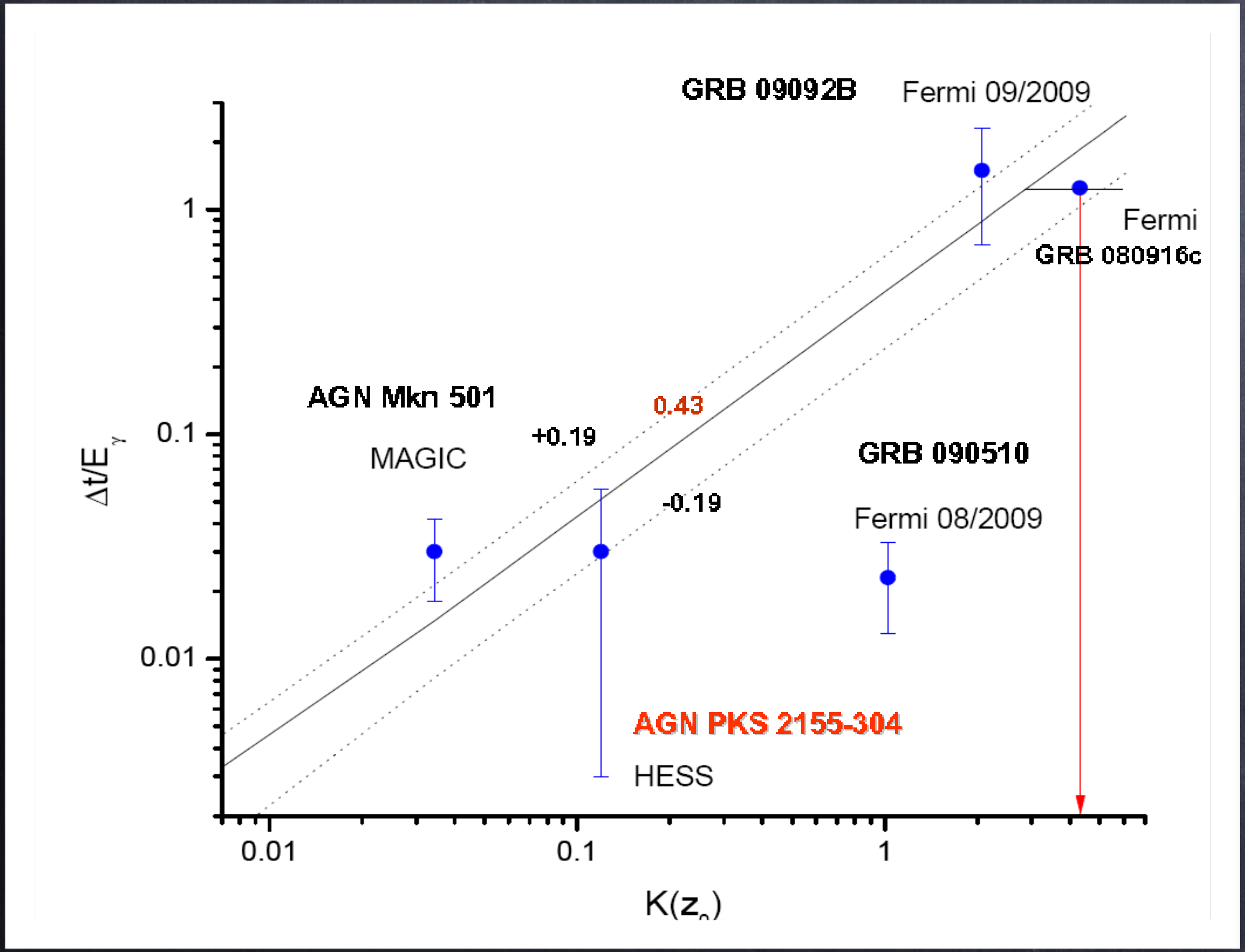
mixed composition from Pierre Auger Collaboration, JCAP 2017, 038 (2016)

Boncioli, Salamida et al., in preparation within Pierre Auger Collaboration

The modified dispersion relation also leads to energy dependent group velocity $V=\partial E/\partial p$ and thus to an energy-dependent time delay over a distance d:

$$\Delta t = -\xi \, d \frac{E}{M_{\rm Pl}} \simeq -\xi \left(\frac{d}{100\,{\rm Mpc}} \right) \left(\frac{E}{\rm TeV} \right) {\rm sec}$$

for linearly suppressed terms. GRB observations in TeV γ-rays can therefore probe quantum gravity and may explain that higher energy photons tend to arrive later (Ellis, Mavromatos et al.).



Ellis, Mavromatos, arXiv:1111.1178

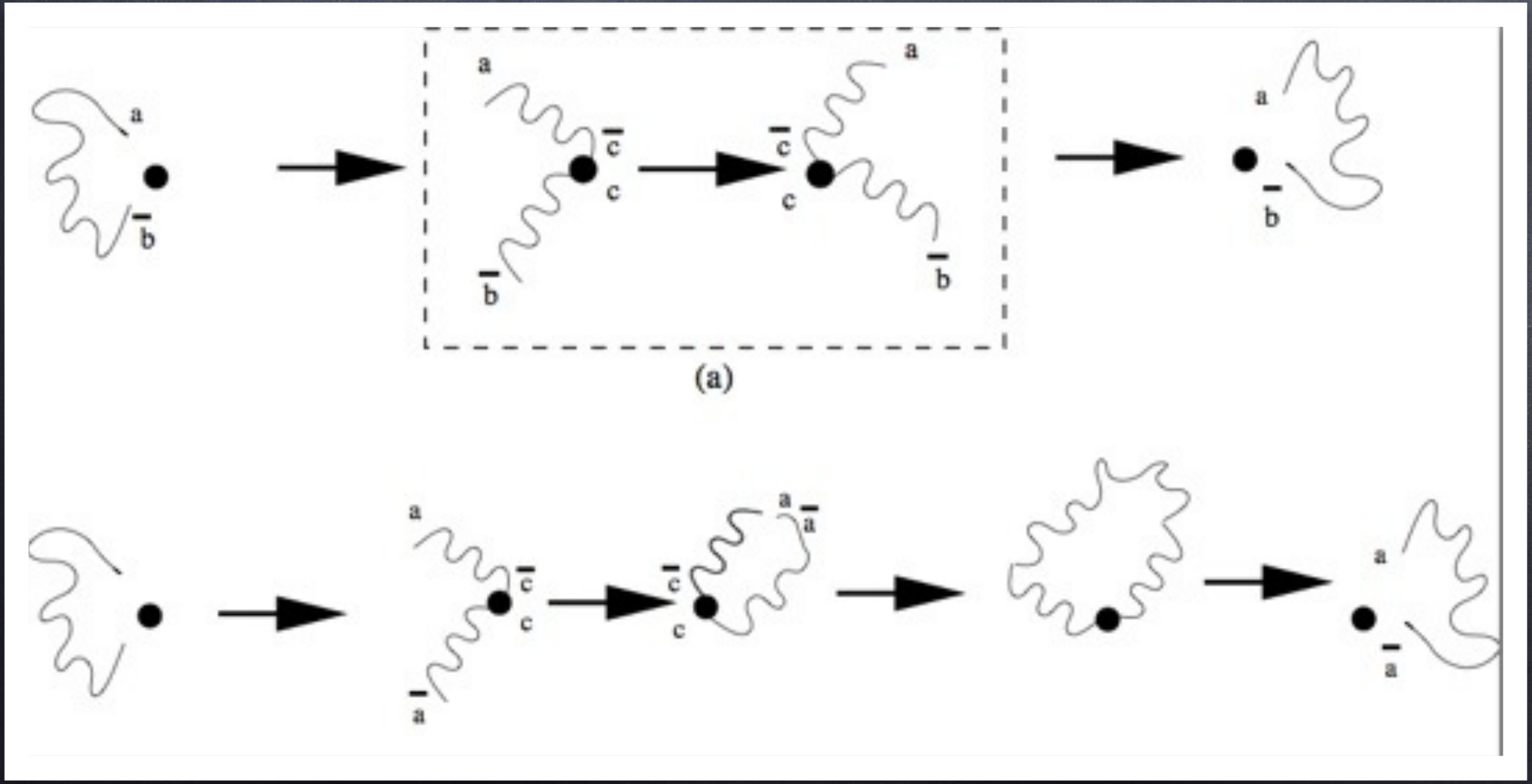
sensitivity to $\xi \gtrsim 10$, close to Planck scale but up to now no clear signature, thus upper limits are generally put.

But the UHE photon limits are inconsistent with interpretations of time delays of high energy gamma-rays from GRBs within quantum gravity scenarios based on effective field theory

Maccione, Liberati, Sigl, PRL 105 (2010) 021101

Possible exception in space-time foam models,

Ellis, Mavromatos, Nanopoulos, Phys.Lett. B 694 (2010) 61 [arXiv:1004.4167]



Similarly to cosmogenic photons, modified neutrino dispersion relation can lead to neutrino decay. Therefore, observation of a neutrino implies non-decay and thus constraints on LIV parameter

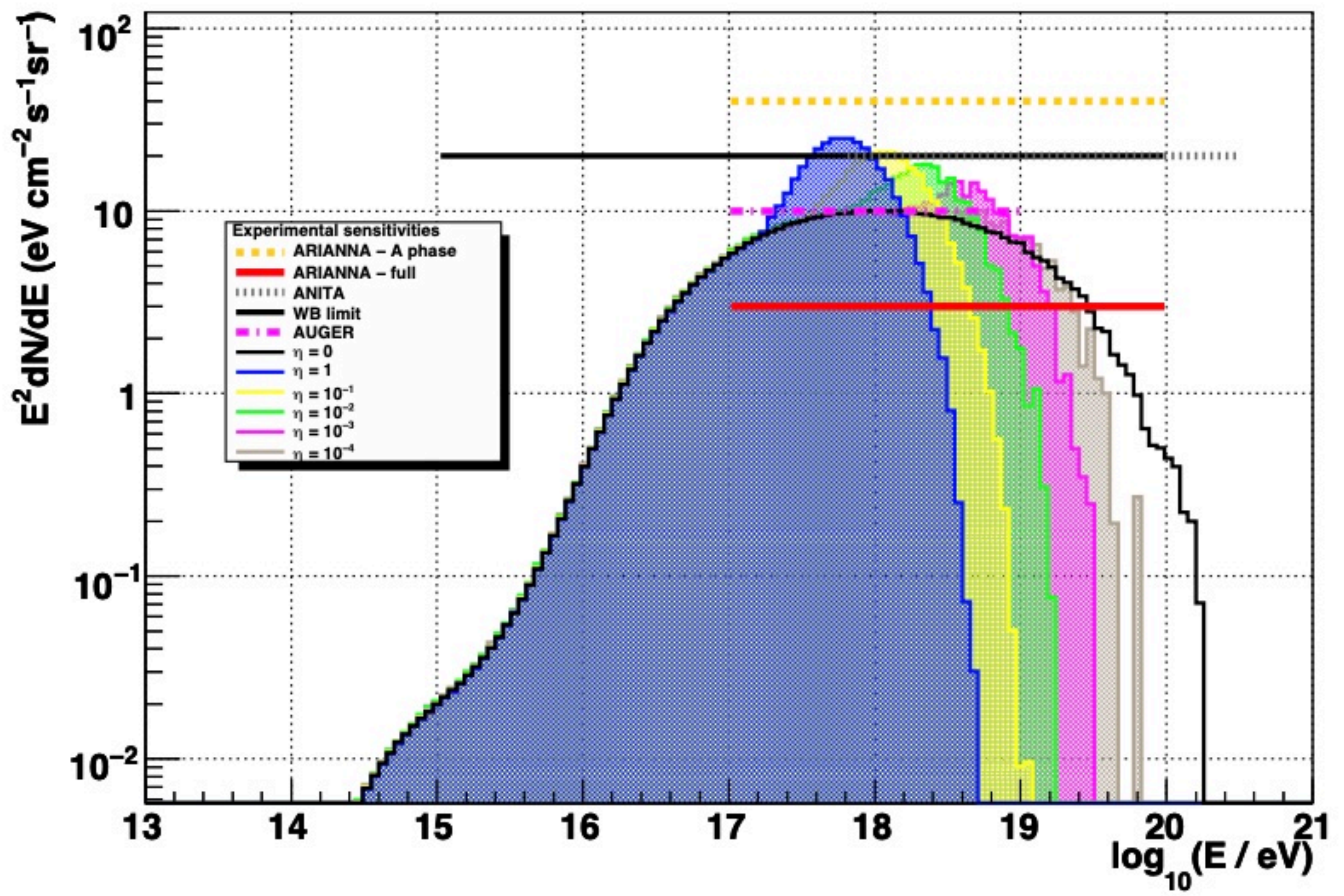


Figure 2. Evolution of the predicted LV neutrino spectra varying η_ν in the "best case scenario". Sensitivities of main UHE neutrino operating and planned experiments are shown, as found in [47, 51, 67]. The Waxman & Bahcall limit [68, 69] in the interesting energy range is shown for reference.

Mattingly et al., JCAP 02 (2010) 007

Lorentz Symmetry Violation Effects on Air Showers

Main idea is that modified decay rates of neutral and/or charged pions and muons can change shower characteristics such as the muon content and X_{max}

This could also induce threshold effects e.g. in the muon content as function of primary energy

For example, for QED by a term

$$-\frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

with $(k_F)_{\mu\nu\rho\sigma} \propto \kappa$ the photon phase velocity is related to maximal fermion velocity by

$$v_\gamma = \left(\frac{1-\kappa}{1+\kappa}\right)^{1/2} v_{\mathrm{f,max}}$$

Consider $\kappa < 0$ which leads to photon decay at energies

$$E_\gamma \gtrsim E_\gamma^{\mathrm{th}} = 2m_e\left(\frac{1-\kappa}{-2\kappa}\right)^{1/2}$$

and stability of π^0 at energies

$$E_{\pi^0} \gtrsim m_{\pi^0}\left(\frac{1-\kappa}{-2\kappa}\right)^{1/2} \simeq 132 E_\gamma^{\mathrm{th}}$$

Klinkhamer, Niechciol, Risse, Phys.Rev. D 96 (2017) 116011

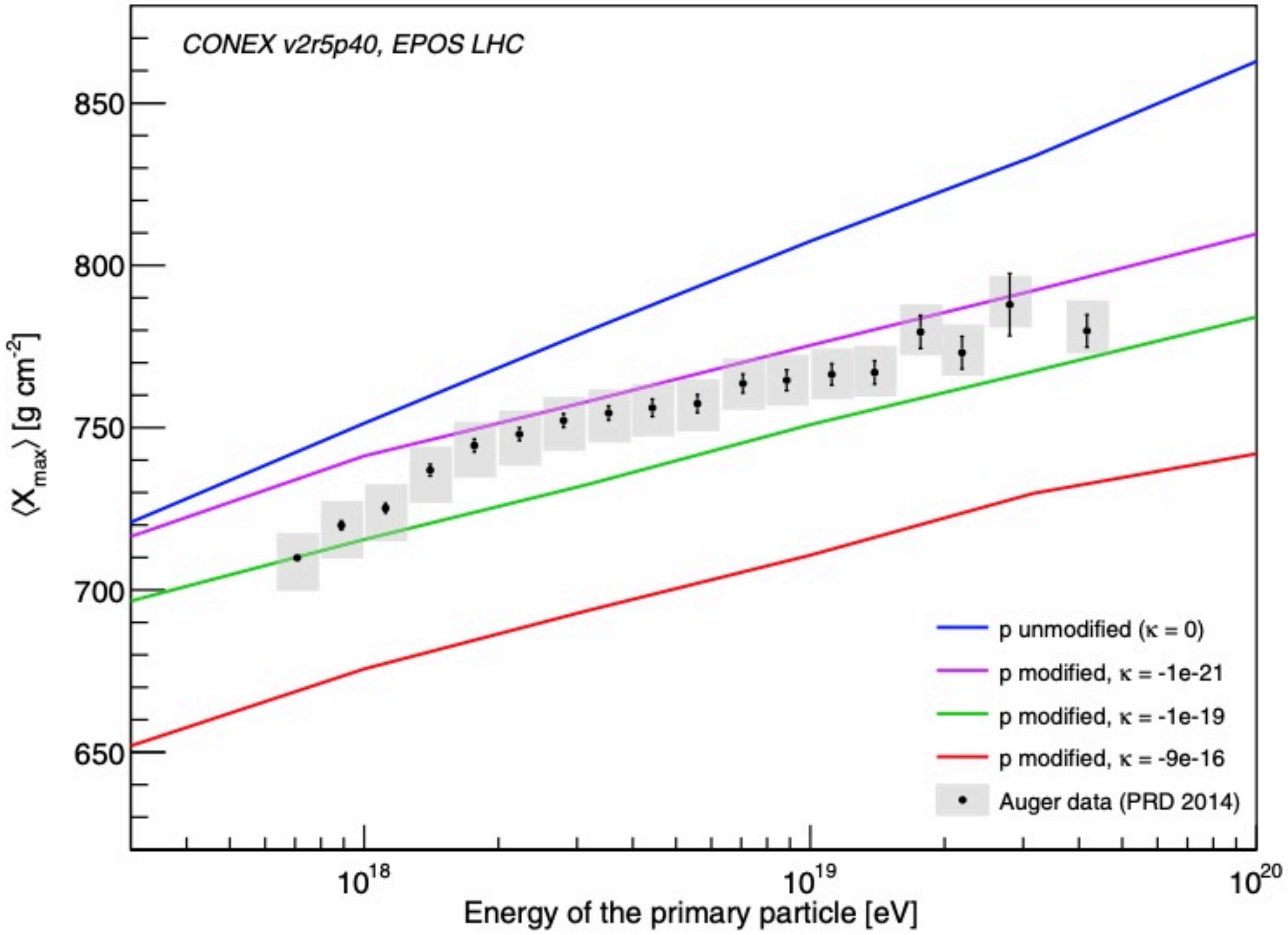


FIG. 5. Simulated values of $\langle X_{\max} \rangle$ as a function of the primary energy for primary protons compared to measured values of $\langle X_{\max} \rangle$ by the Pierre Auger Observatory [18]. The gray boxes around the data points indicate the systematic uncertainties of the measurements.

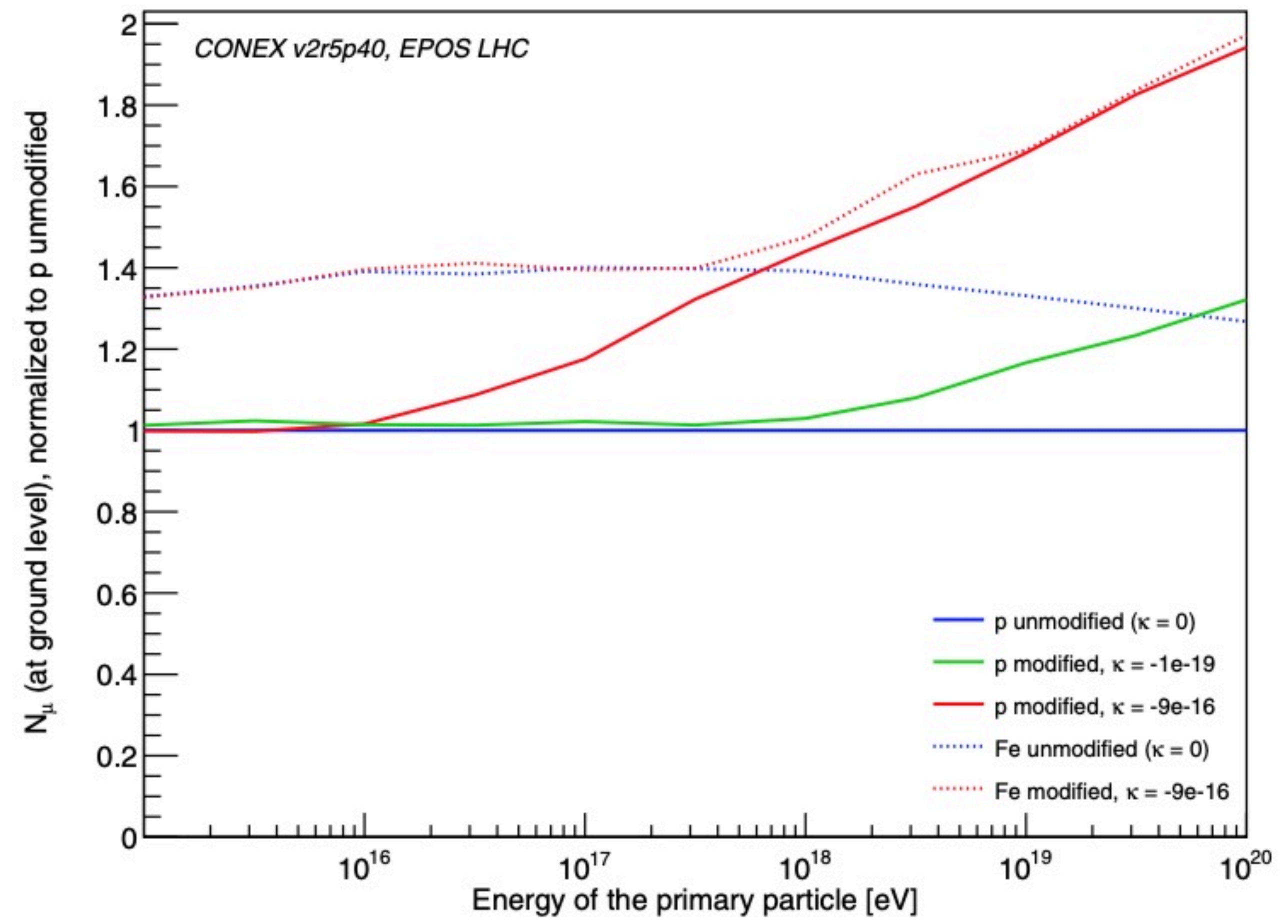


FIG. 7. Average number of ground muons, normalized to the case of unmodified proton primaries, as a function of the primary energy for primary protons and iron nuclei.

Comparison with Pierre Auger X_{max} data (photon decay accelerates shower development) then implies the limit

$$\kappa \gtrsim -3 \times 10^{-19}$$

Klinkhamer, Niechciol, Risse, Phys.Rev. D 96 (2017) 116011

Positive κ leads to vacuum Cherenkov radiation $p \to p + \gamma$ above a critical energy. Based on the highest energy event seen by Pierre Auger this gives

$$\kappa \lesssim 6 \times 10^{-20}$$

Klinkhamer, Schreck, Phys.Rev. D 78 (2008) 085026

Conclusions

1.) Both cosmic ray propagation and air showers can constrain Lorentz symmetry violations, sometimes providing the strongest possible constraints due to the high energies available.

2.) More work is needed, for example on the update of photon- and neutrino-based constraints for a mixed composition.

3.) Establishing/distinguishing existence of interactions (such as GZK) versus collision-less source physics would strengthen sensitivity to LIV (-> more statistics with GCOS)

4.) Constraints are often limited to specific scenarios -> generalisation of underlying theoretical scenarios desirable.