Bounds on Lorentz violation from observations of extensive air showers

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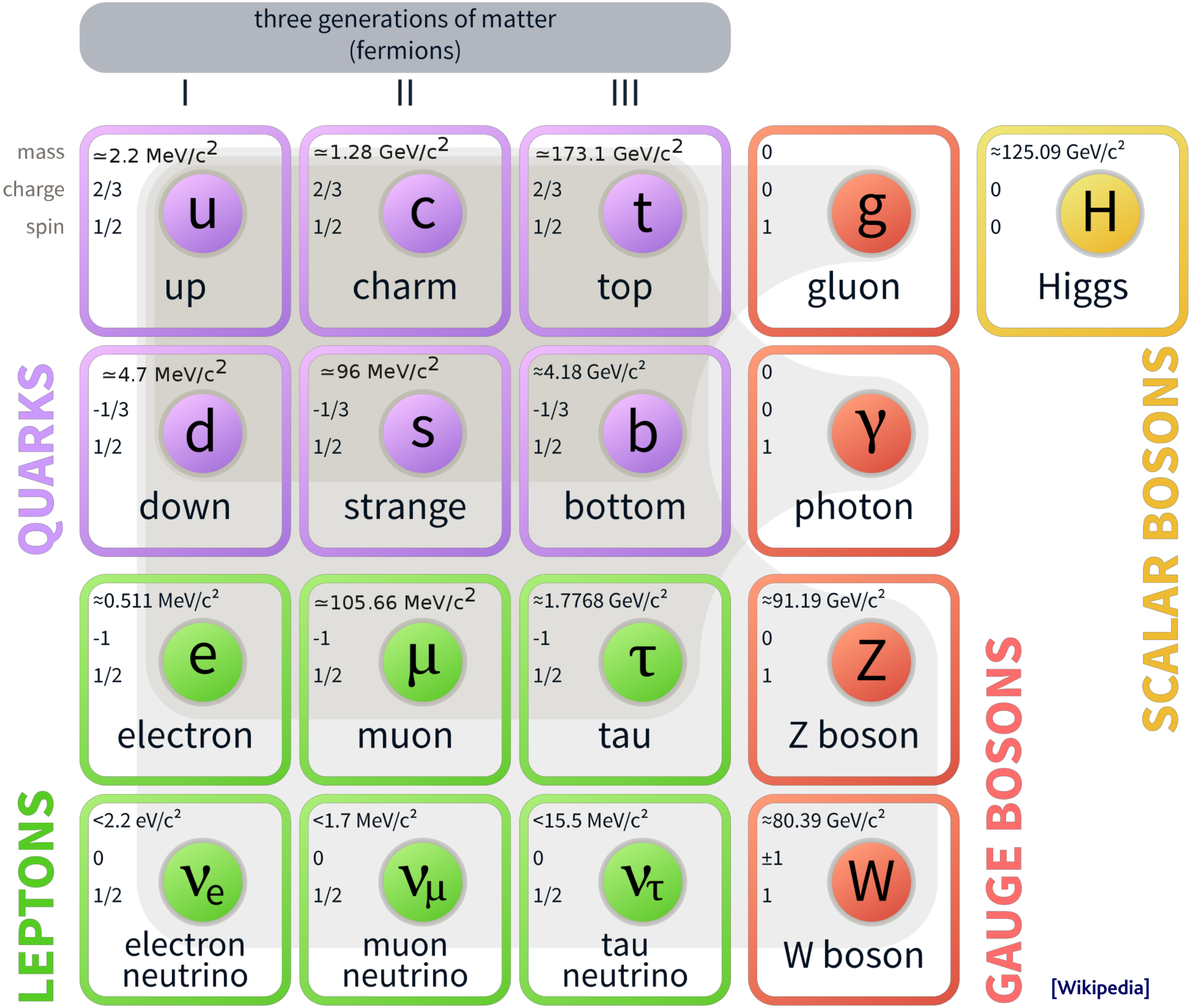
Outline

- **Introduction / Motivation**
- **Lorentz violation (LV) in the photon sector**
- **Previous bounds on LV from astroparticle physics**
- **Impact of LV on extensive air showers**
  - Analytical Heitler-like model for electromagnetic cascades
  - Simulation study with the Monte Carlo code CONEX
  - New bound on LV from observations of extensive air showers at the Pierre Auger Observatory
- **Summary**

Standard Model of Particle Physics (SM)



three generations of matter (fermions)

	I	II	III		
mass charge spin	$\simeq$2.2 MeV/c^2 2/3 1/2 u up	$\simeq$1.28 GeV/c^2 2/3 1/2 c charm	$\simeq$173.1 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	$\approx$125.09 GeV/c^2 0 0 H Higgs
QUARKS	$\simeq$4.7 MeV/c^2 -1/3 1/2 d down	$\simeq$96 MeV/c^2 -1/3 1/2 s strange	$\approx$4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	$\approx$0.511 MeV/c^2 -1 1/2 e electron	$\simeq$105.66 MeV/c^2 -1 1/2 μ muon	$\approx$1.7768 GeV/c^2 -1 1/2 τ tau	$\approx$91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	$\approx$80.39 GeV/c^2 ±1 1 W W boson	

GAUGE BOSONS

SCALAR BOSONS

[Wikipedia]

Beyond the SM

- The SM works incredibly well, but it does not provide a **complete description** of our Universe
  - **~95 %** of the content of our Universe are dark matter and dark energy
  - **Gravity** is not included in the SM

- **A more comprehensive and fundamental theory** is needed
  - In current approaches to such a theory (e.g. string theory or loop-quantum gravity), **deviations from exact Lorentz invariance may well be possible** [e.g. Jacobson, Liberati & Mattingly 2005]
  - **Small effects** should become apparent already below the Planck scale: possibility to **test LV** experimentally

How can we test LV?

- Common approach to test LV is to be as **general** as possible
  - **Experimentalists** want to systematically test LV and produce bounds without resorting to a specific theory
  - **Theorists** get a set of rather general LV constraints which their theories have to fulfill
  - Connecting both: **constantly updated compilation/review** of all existing experimental bounds on LV [Kostelecký & Russell 1997 (last update 2018)]

- Two different *ansätze*: [e.g. Jacobson, Liberati & Mattingly 2005]
  - Modify/expand the **dispersion relation** for different particles directly
  - Construct an **effective field theory** containing Lorentz-violating operators

- A specific realization of the latter ansatz is the **Standard-Model Extension (SME)** which provides a general framework to study LV in any sector of the SM [Colladay & Kostelecký 1997] [Colladay & Kostelecký 1998]

LV in the photon sector (I)

- Focus on **LV in the photon sector** within the SME:

$$\mathcal{L}(x) = \boxed{\begin{aligned}&-\frac{1}{4}F^{\mu\nu}(x)F_{\mu\nu}(x)\\ &+\bar{\psi}(x)(\gamma^{\mu}[i\partial_{\mu} - eA_{\mu}(x)] - m)\psi(x)\end{aligned}}$$
$$\boxed{-\frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}(x)F^{\rho\sigma}(x)}$$

- First two terms in the Lagrangian density correspond to **conventional QED**
- **Last term** introduces a dimension-four operator that gives LV while preserving CPT and gauge invariance [Chadha & Nielsen 1983] [Kostelecký & Mewes 2002]
- **Notes:** the Minkowski metric $\eta_{\mu\nu} = [\mathrm{diag}(+1,-1,-1,-1)]_{\mu\nu}$ and natural units $\hbar = c = 1$ are used; the Maxwell field strength tensor is defined as usual: $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$.

LV in the photon sector (II)

- The constant tensor $(k_F)_{\mu\nu\rho\sigma}$ has **19 independent, dimensionless components**
  - 10 components lead to birefringence in the photon sector: constrained to high precision (~10^{-32}) by cosmological observations

    [Carroll, Field, & Jackiw 1990]
    [Carroll & Field 1997]
    [Kostelecký & Mewes 2001]
  - 8 components lead to **direction-dependent modifications** of the photon-propagation properties: not discussed here
  - Remaining component leads to **isotropic modifications** of the photon-propagation properties
- **Isotropic, nonbirefringent LV** in the photon sector is then controlled by a **single dimensionless parameter κ**, which enters $(k_F)_{\mu\nu\rho\sigma}$ in the following way:

$$(k_F)_{\mu\nu\rho\sigma} = \frac{1}{2}(\eta_{\mu\rho}\tilde{\kappa}_{\nu\sigma} - \eta_{\mu\sigma}\tilde{\kappa}_{\nu\rho} + \eta_{\nu\sigma}\tilde{\kappa}_{\mu\rho} - \eta_{\nu\rho}\tilde{\kappa}_{\mu\sigma})$$

$$\tilde{\kappa}_{\mu\nu} = \frac{\kappa}{2}[\mathrm{diag}(3,1,1,1)]_{\mu\nu}$$

Isotropic, nonbirefringent LV

- Restriction on the **"deformation parameter" κ** from microcausality and unitarity: $\kappa \in (-1, 1]$ [Klinkhamer & Schreck 2011]
- **Photon propagation** is determined by the field equations obtained by the previous equations: the **phase velocity** of the photon is given by

$$v_{\text{photon}} = \frac{\omega}{|\vec{k}|} = \sqrt{\frac{1-\kappa}{1+\kappa}}c$$

  - **Note:** the velocity *c* refers to the maximum attainable velocity of a massive Dirac fermion (still $c = 1$ in natural units)
- For **non-zero values of κ**, certain decay processes forbidden in the conventional, Lorentz-invariant theory become **allowed**

[Jacobson, Liberati & Mattingly 2005]
[Kaufhold & Klinkhamer 2006]

  - $\kappa < 0$: **photon decay** $\tilde{\gamma} \to e^+ + e^-$
  - $\kappa > 0$: **vacuum Cherenkov radiation** $f^\pm \to f^\pm + \tilde{\gamma}$

Photon decay ($\kappa < 0$)

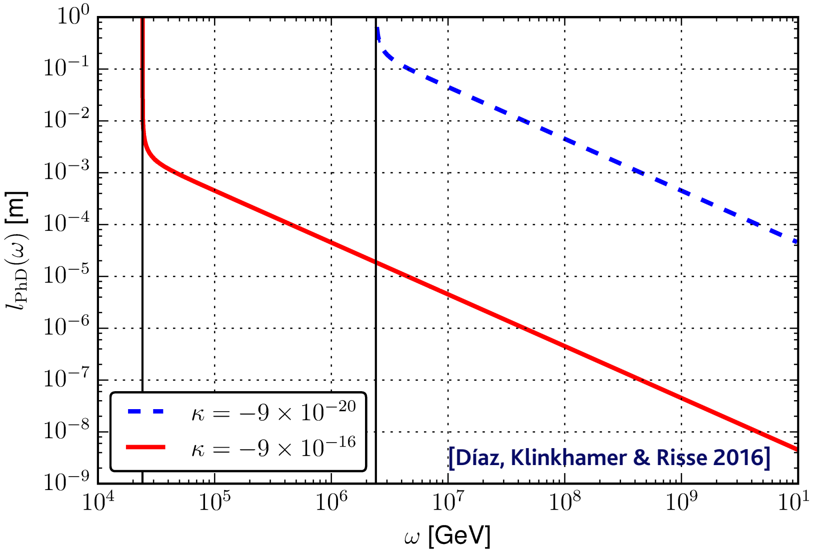
- Decay of photons above the **threshold**

$$E_\gamma^{\text{thresh}}(\kappa) = 2m_e\sqrt{\frac{1-\kappa}{-2\kappa}} \sim \frac{2m_e}{\sqrt{-2\kappa}}$$

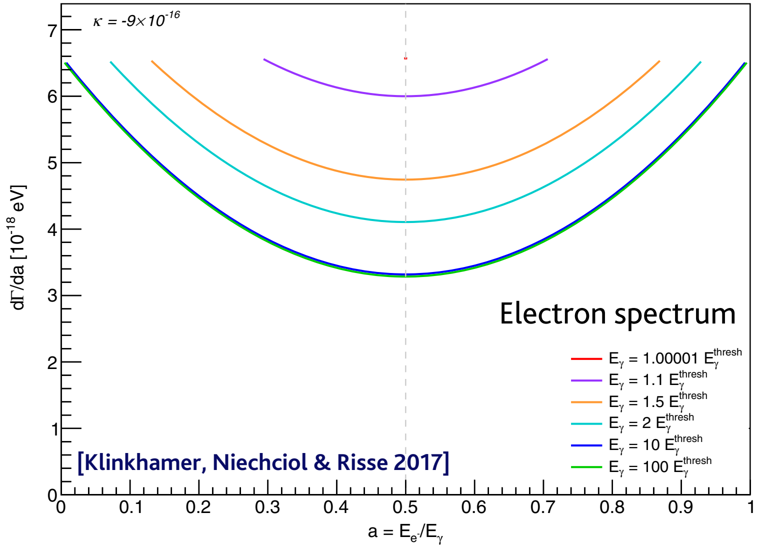
- **Decay rate** for the decay into an e$^+$/e$^-$ pair at tree level: [Klinkhamer & Schreck 2008] [Díaz & Klinkhamer 2015]

$$\Gamma_{\text{PhD}}(E_\gamma) = \frac{\alpha}{3}\frac{-\kappa}{1-\kappa^2}\sqrt{(E_\gamma)^2-(E_\gamma^{\text{thresh}})^2} \times \left(2+(E_\gamma^{\text{thresh}}/E_\gamma)^2\right)$$

- **Decay length** drops to cm-scales right at the threshold: essentially **instantaneous decay**



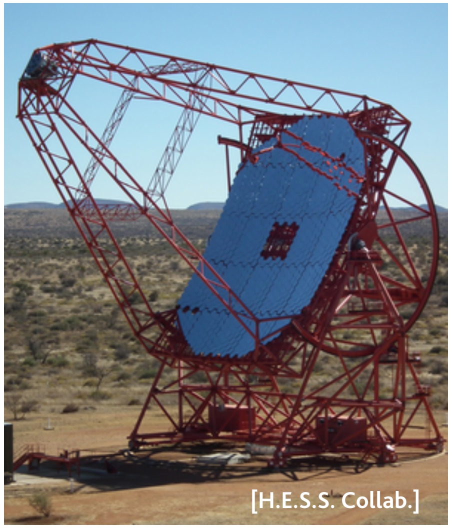
[Díaz, Klinkhamer & Risse 2016]

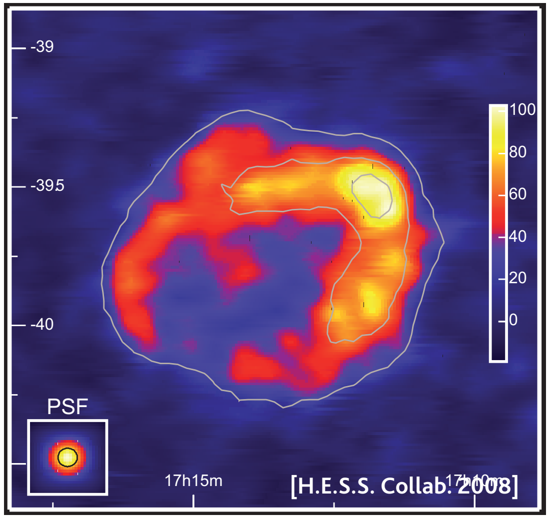


[Klinkhamer, Niechciol & Risse 2017]

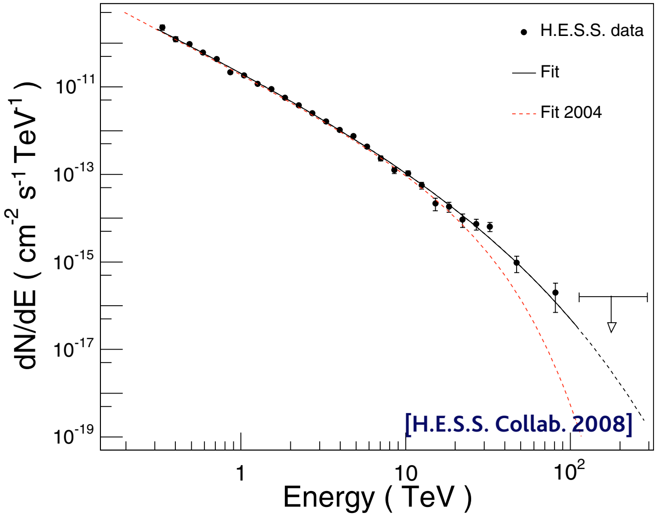
Previous bounds on LV ($\kappa < 0$)

- Exploit the quasi-instantaneous decay to derive a **bound on κ** from gamma-ray astronomy
  - **Simple argument:** if a particle with energy E originating in a distant source is measured at Earth, the LV threshold must be higher than E and a limit on κ can be derived [Beall 2005] [Coleman & Glashow 1997]
- Use **H.E.S.S. measurements** of the supernova remnant **RX J1713.7–3946** (distance ~1 kpc) [H.E.S.S. Collab. 2008]


[H.E.S.S. Collab.]



[H.E.S.S. Collab. 2008]



[H.E.S.S. Collab. 2008]

- With $E_\gamma = 30\,\text{TeV}$ (±15 %): **$\kappa > -9\times10^{-16}$** (at 98 % C.L.) [Klinkhamer & Schreck 2008]

Vacuum Cherenkov radiation ($\kappa > 0$)

- Charged particles above the **threshold E_{th}** emit vacuum Cherenkov radiation:

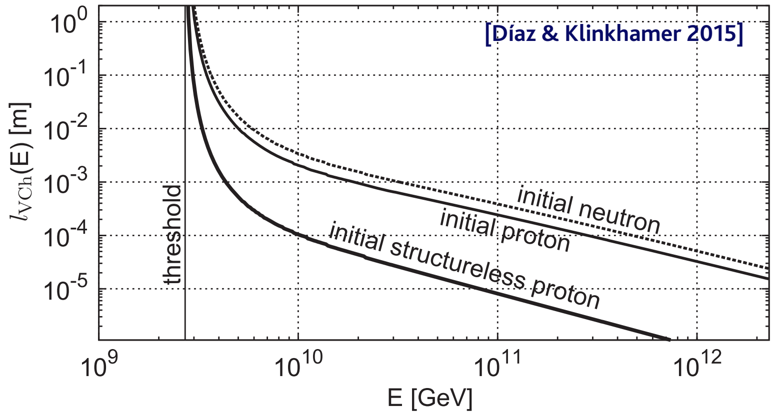
$$E_{\text{th}} = M\sqrt{\frac{1+\kappa}{2\kappa}}$$

- Assuming a structureless proton, the **radiated Cherenkov power** is given by

[Díaz & Klinkhamer 2015]

$$\begin{aligned}\hat{P}(E) = {} & \frac{\alpha}{12\kappa^3 E\sqrt{E^2-M^2}}\left(\sqrt{E^2-M^2}-E/n\right)^2 \\ & \times [2E^2(2\kappa^2+4\kappa+3) \\ & - 3M^2(1+\kappa)(1+2\kappa) \\ & - 2nE\sqrt{E^2-M^2}(1-\kappa)(4\kappa+3)]\end{aligned}$$

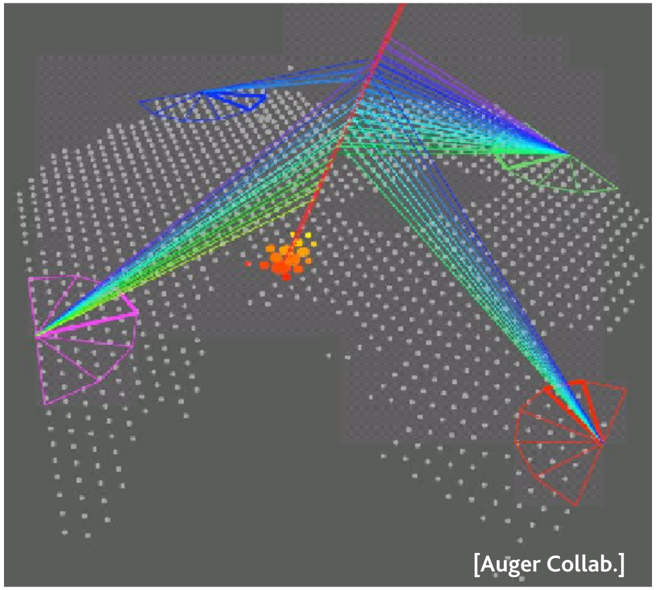
- **Radiation length** below cm-scales right at the threshold: particles above the threshold lose their energy quickly, dropping almost immediately below the threshold



Previous bounds on LV ($\kappa > 0$)

- Follow the **same argument** as for the case $\kappa < 0$
- Use measurements of **ultra-high-energy cosmic rays (UHECR)** by the **Pierre Auger Observatory** [Auger Collab. 2007]


[Auger Collab.]


[Auger Collab.]

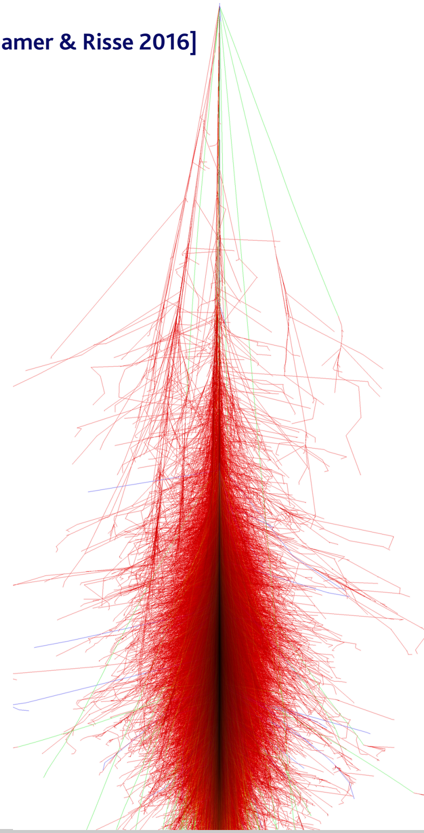
- With $E \sim 200\,\text{EeV}$ ($\pm 25\,\%$) and conservatively assuming an iron nucleus as the primary particle ($M = 52\,\text{GeV}$):
  $\kappa < 6 \times 10^{-20}$ (at 98 % C.L.) [Klinkhamer & Risse 2008] [Klinkhamer & Schreck 2008]

LV and extensive air showers

- Significantly improving the bound on $\kappa < 0$ requires **primary photons with ideally PeV-EeV energies**
  - **Prospects** of observing such photons not overly encouraging

[Niechciol (Auger Collab.) ICRC 2017]

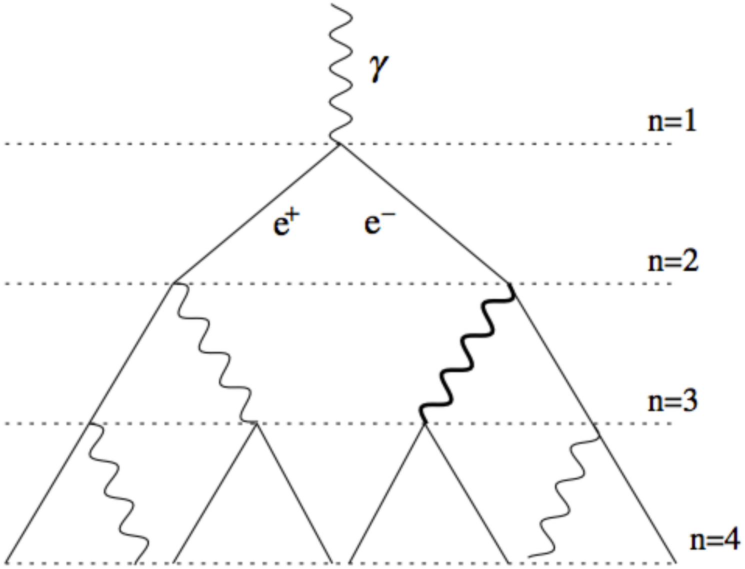
- **Alternative approach:** exploit extensive air showers initiated by (hadronic) primaries in the Earth's atmosphere [Díaz, Klinkhamer & Risse 2016]
  - **General idea**: a shower initiated by a UHE (> 10^{18} eV) primary contains at least a couple of very-high-energy photons as **secondary** particles (mainly expected in the startup phase)
  - A modification of these very-high-energy photons due to LV would lead to a **different shower development** as compared to conventional physics
  - First step: estimate the **magnitude of this difference** using a **modified Heitler model** to describe electromagnetic cascades under the assumption of LV



Conventional Heitler model

- **Heitler model** describes particle multiplication in an electromagnetic shower as a **binary tree** [Heitler 1949]
  - **Two processes taken into account:** pair production $\gamma \to e^+ + e^-$ and bremsstrahlung $e^\pm \to e^\pm + \gamma$
  - **Simplifying assumption**: each interaction occurs after exactly one splitting length $d = \ln(2)\, X_0$
  - Energy E_0 of the primary particle is **shared equally** between all secondary particles
  - Cascade continues until the energy per particle reaches the **critical energy E_c**
  - **Maximum number of particles** for a cascade initiated by a photon of energy E_0 is reached at the atmospheric depth

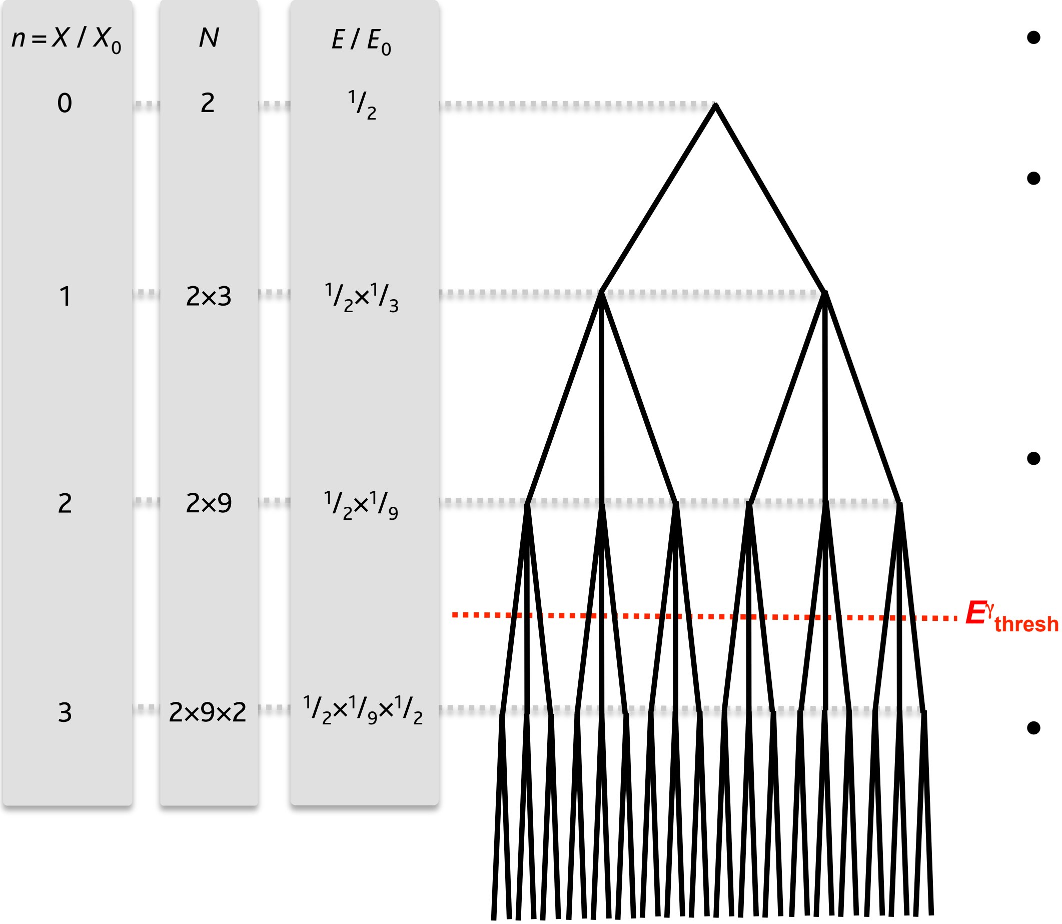
$$X_\text{max} = X_0 \ln\left(\frac{E_0}{E_\text{c}}\right)$$



Modified Heitler model

- **Modified cascade** initiated by a photon above threshold:

[Díaz, Klinkhamer & Risse 2016]



$n = X / X_0$	N	E / E_0
0	2	$^1/_2$
1	2×3	$^1/_2$×$^1/_3$
2	2×9	$^1/_2$×$^1/_9$
3	2×9×2	$^1/_2$×$^1/_9$×$^1/_2$

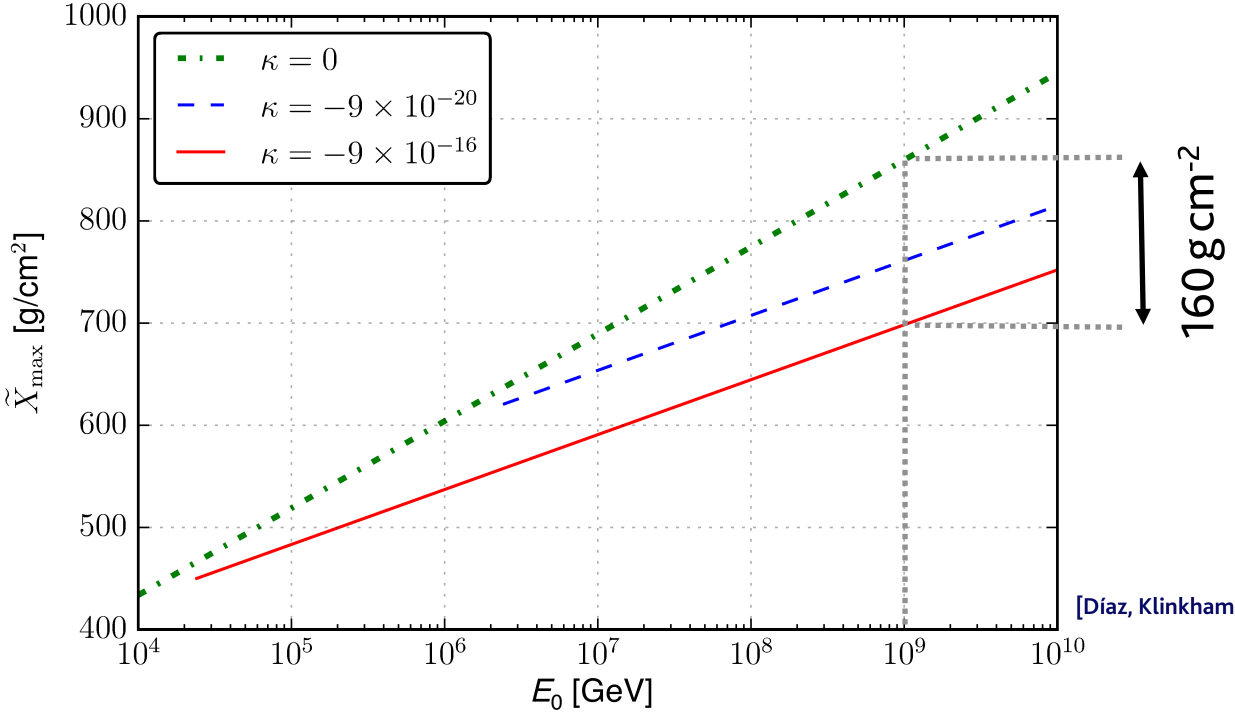
- **Instant decay** of the initial photon into two leptons
- Each lepton produces an additional photon (above threshold) via Bremsstrahlung
  $$e^{\pm} \rightarrow e^{\pm} + \tilde{\gamma} \Rightarrow e^{\pm} + e^{-} + e^{+}$$
- **Simplifying assumption**: At each interaction step, three leptons are produced which share the initial energy equally
- If the energy per particle falls **below the threshold**, the cascade continues according to the conventional Heitler model

Modified Heitler model: X_{max}

- Change in X_{max} due to the **different shower development**:

$$\tilde{X}_{\text{max}} = X_0 \underbrace{\frac{\ln(2)}{\ln(3)}}_{\eta} \ln\left(\frac{E_0/2}{E^{\gamma}_{\text{thresh}}}\right) + X_0 \ln\left(\frac{E^{\gamma}_{\text{thresh}}}{E_c}\right) \qquad \text{for } E_0 > E^{\gamma}_{\text{thresh}} > E_c$$

[Díaz, Klinkhamer & Risse 2016]



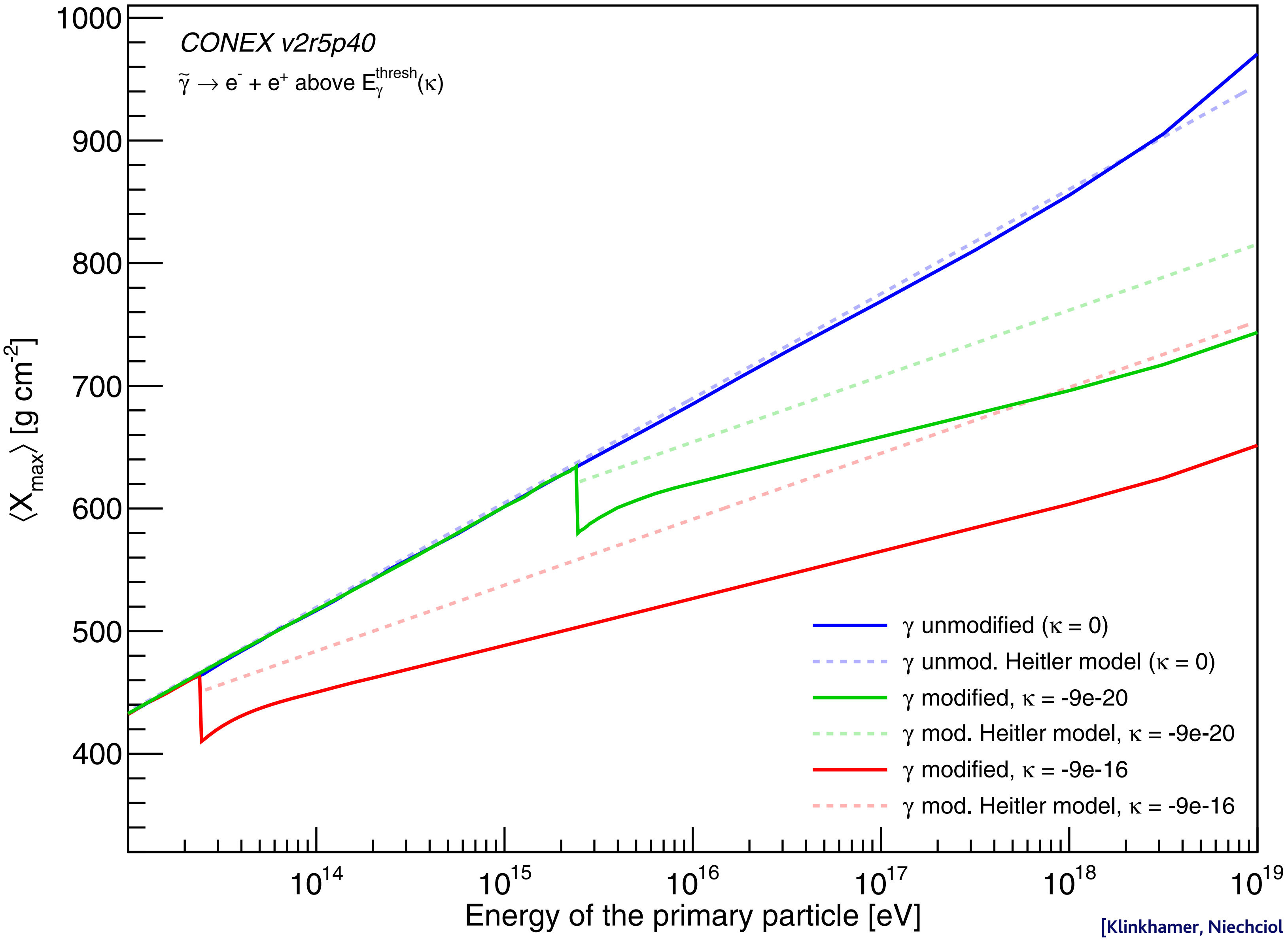
[Díaz, Klinkhamer & Risse 2016]

- **Large difference** in X_{max}, above the typical X_{max} resolution of current UHECR experiments (e.g. Auger: 26 g cm^{-2} at ~1 EeV)[Auger Collab. 2014]

MC simulations with CONEX

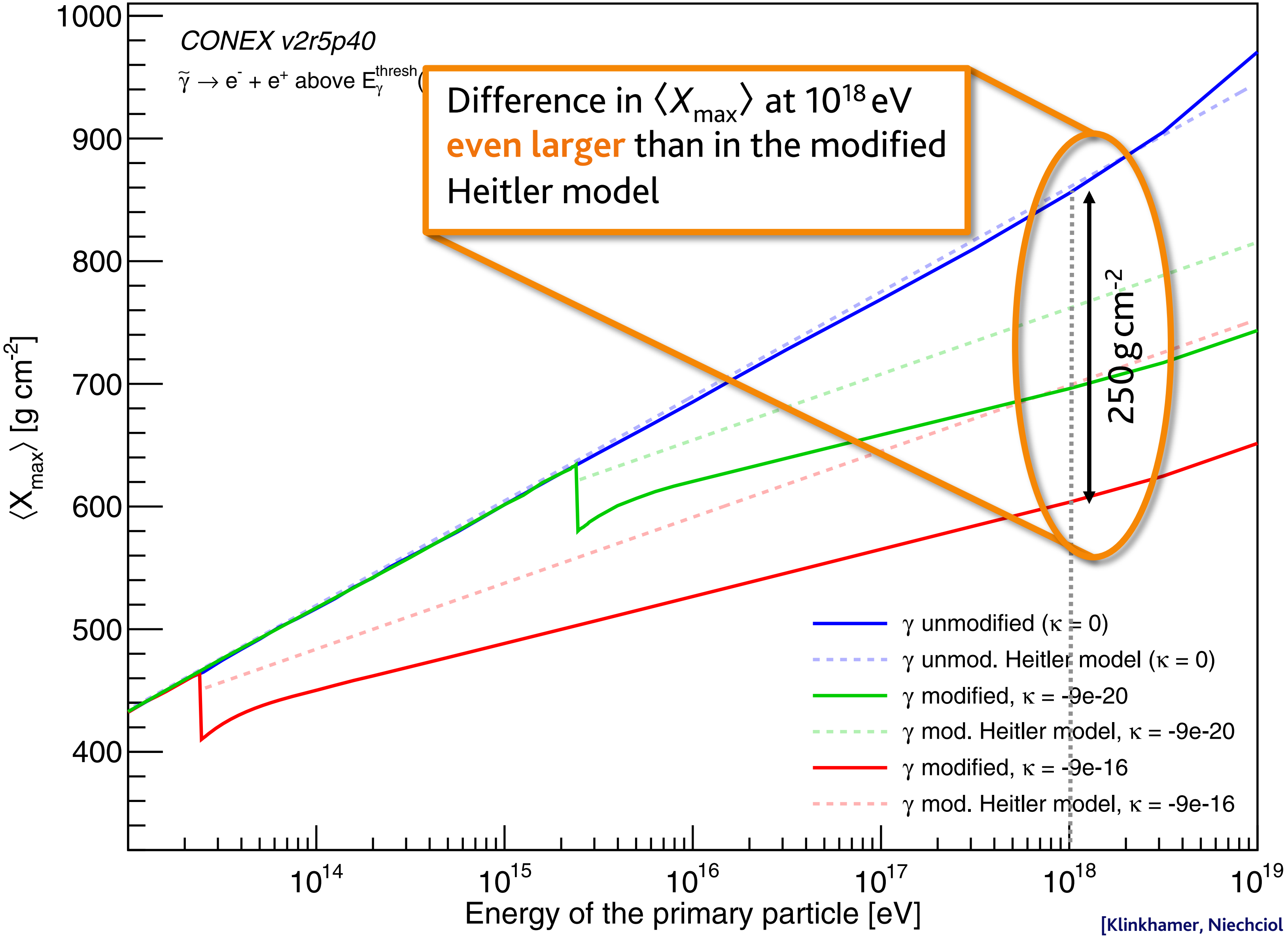
- Results of the analytical model are **encouraging**
- **Next step:** air shower simulations with the MC code CONEX
  - CONEX is a **hybrid simulation code**: combines **full MC simulation** of the particles in the air shower at high energies with a **numerical solution of cascade equations** for lower-energy subshowers [Bergmann et al. 2007] [Pierog et al. 2009]
  - **Advantages** of the hybrid approach:
    - Accurate determination of the **longitudinal shower profile and X_{max}**
    - **Less computing power and disk space needed** compared to full MC simulations (e.g. with CORSIKA)
  - **Disadvantage**:
    - Not possible to extract the distribution of secondary particles at ground level
- **Implement photon decay** into CONEX v2r5p40 [Klinkhamer, Niechciol & Risse 2017]
  - **Thanks** to T. Pierog for helping us to decipher the FORTRAN code

CONEX: photon-induced showers (I)



[Klinkhamer, Niechciol & Risse 2017]

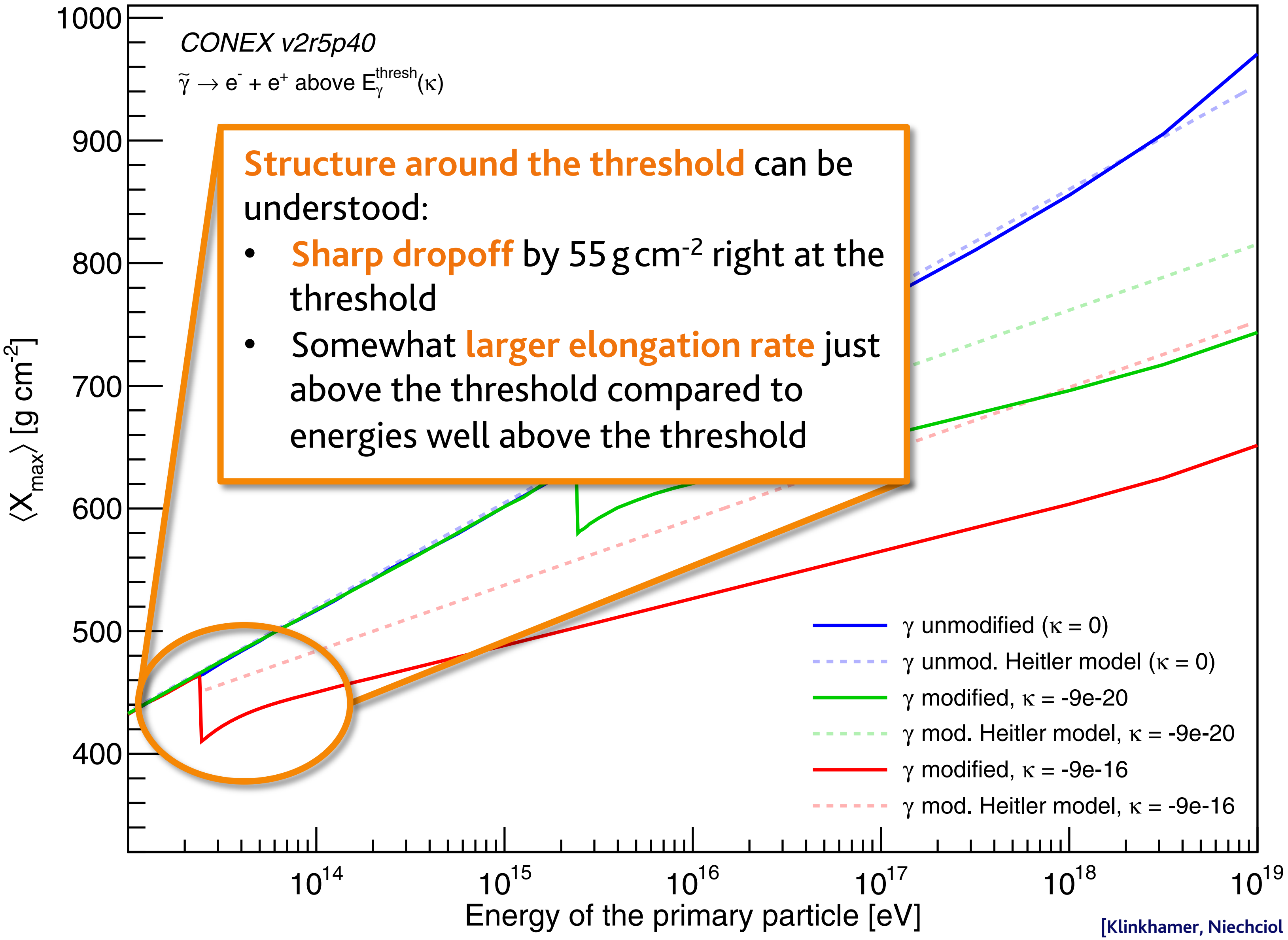
CONEX: photon-induced showers (II)



Difference in $\langle X_{\mathrm{max}} \rangle$ at 10^{18} eV **even larger** than in the modified Heitler model

[Klinkhamer, Niechciol & Risse 2017]

CONEX: photon-induced showers (III)



Structure around the threshold can be understood:

- **Sharp dropoff** by 55 g cm^{-2} right at the threshold
- Somewhat **larger elongation rate** just above the threshold compared to energies well above the threshold

[Klinkhamer, Niechciol & Risse 2017]

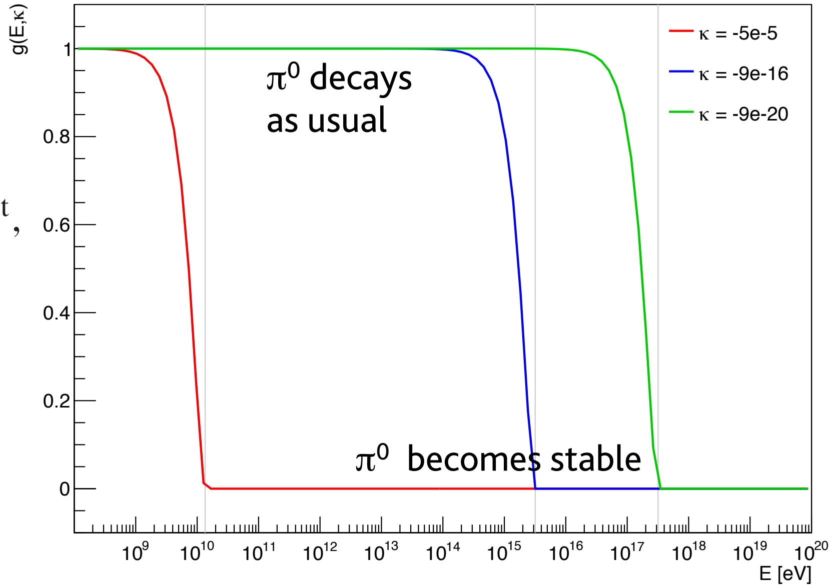
Neutral pion decay

- **Next step:** extend the study to air showers initiated by hadrons
- But before: need to **look at other processes involving photons**, since they may be changed if the standard photon is replaced by a non-standard one
- Most important process here: **neutral pion decay** $\pi^0 \to \tilde{\gamma} + \tilde{\gamma}$
- "Straightforward but tedious calculation": the **decay time of the neutral pion is modified** in the following way [Klinkhamer 2018]

$$\tau(E_{\pi^0},\kappa) = \frac{\tau_{\mathrm{SM}}}{g(E_{\pi^0},\kappa)}$$

$$g(E_{\pi^0},\kappa) = \begin{cases} \frac{\sqrt{1-\kappa^2}}{(1-\kappa)^3}\left[1 - \frac{(E_{\pi^0})^2-(m_{\pi^0})^2}{(E^{\mathrm{cut}}_{\pi^0})^2-(m_{\pi^0})^2}\right]^2, & \text{for } E_{\pi^0} < E^{\mathrm{cut}}_{\pi^0}, \\ 0, & \text{otherwise.} \end{cases}$$

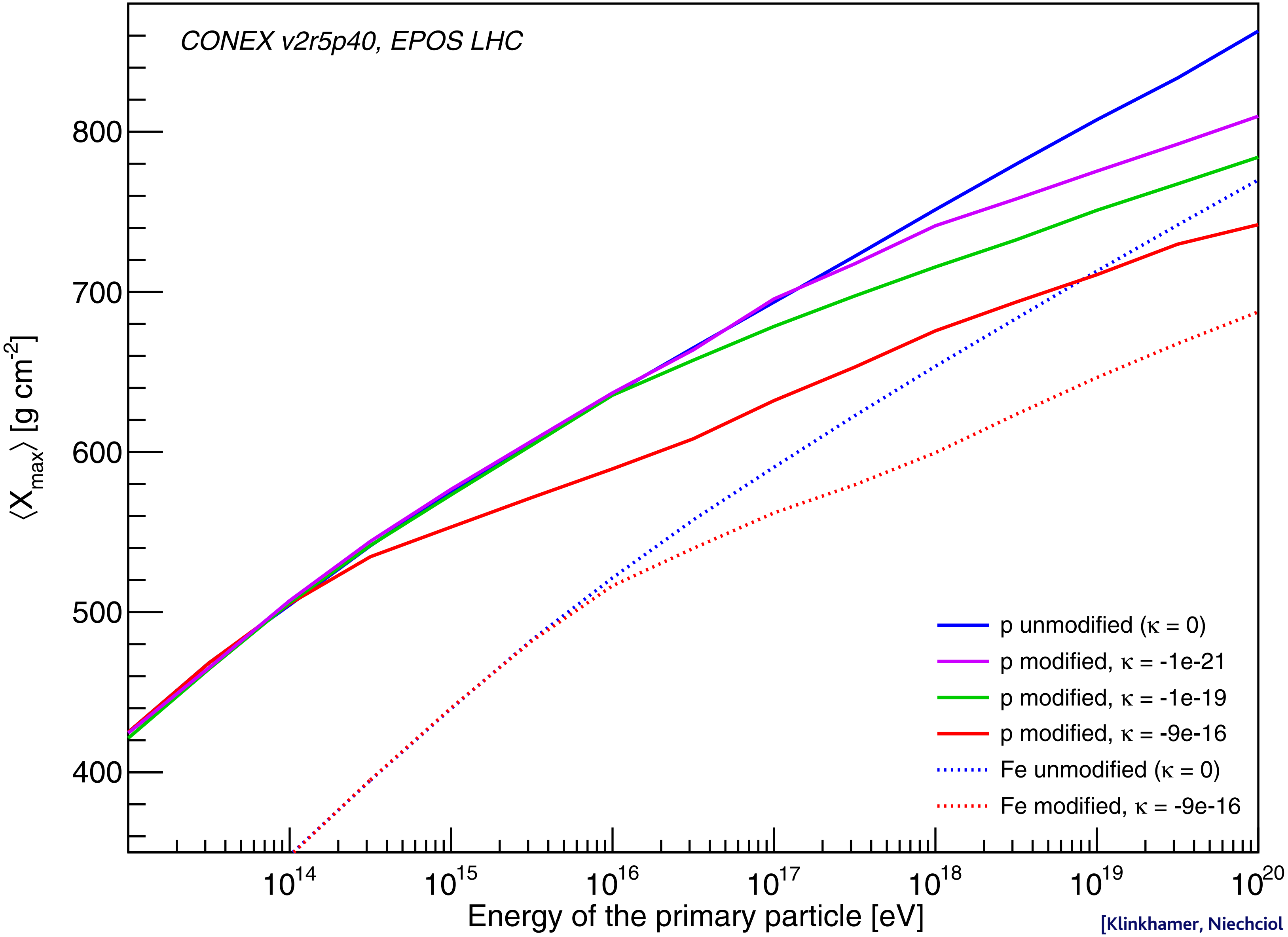
$$E^{\mathrm{cut}}_{\pi^0} = m_{\pi^0}\sqrt{\frac{1-\kappa}{-2\kappa}} \sim \frac{m_{\pi^0}}{\sqrt{-2\kappa}} \sim \frac{m_{\pi^0}}{2m_e} E^{\mathrm{thresh}}_{\gamma} \approx 132 E^{\mathrm{thresh}}_{\gamma}$$



π^0 decays as usual

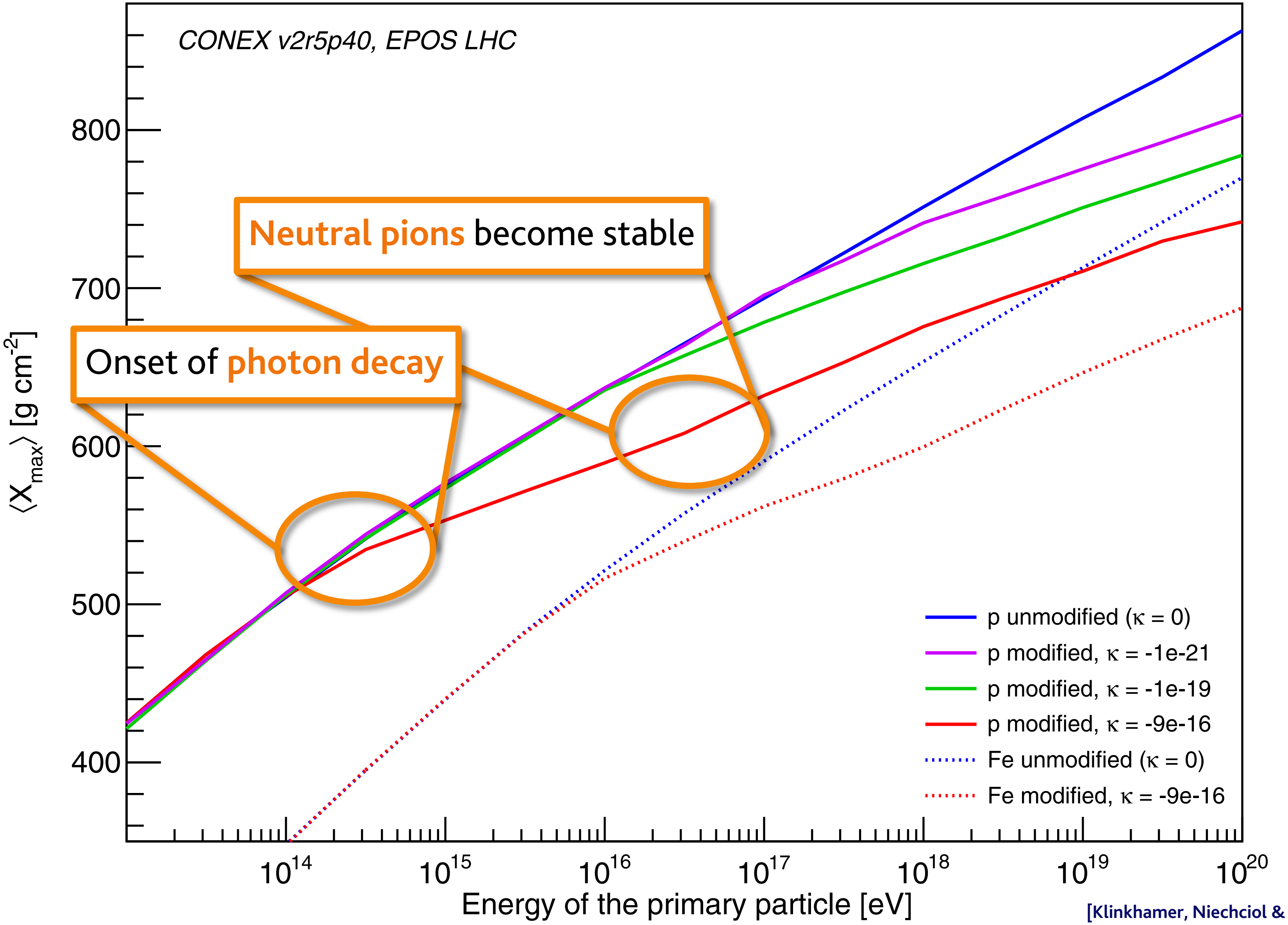
π^0 becomes stable

Hadron-induced showers: $\langle X_{\max} \rangle$ (I)



[Klinkhamer, Niechciol & Risse 2017]

Hadron-induced showers: $\langle X_{max} \rangle$ (II)

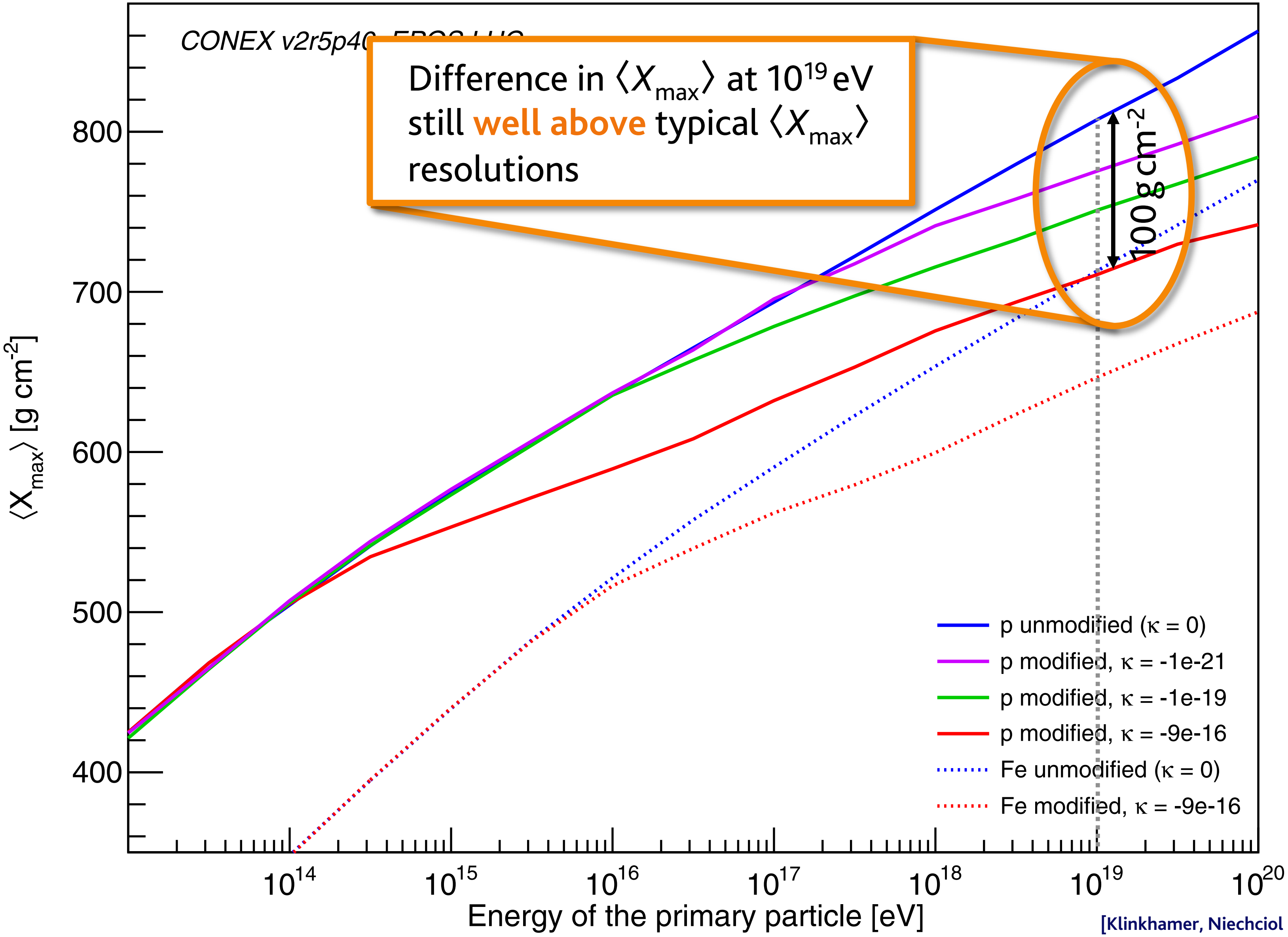


Neutral pions become stable

Onset of **photon decay**

[Klinkhamer, Niechciol & Risse 2017]

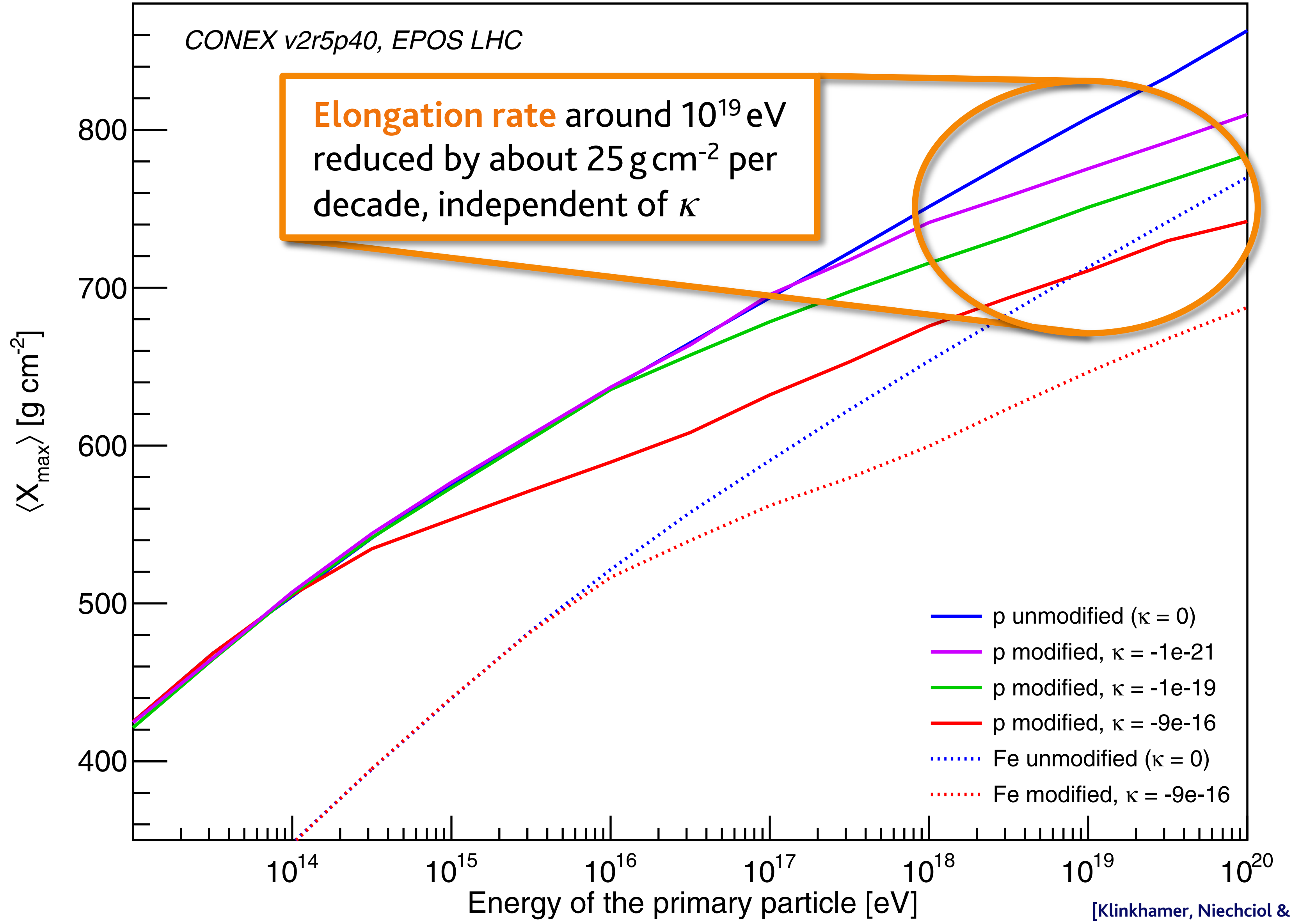
Hadron-induced showers: $\langle X_{\mathrm{max}} \rangle$ (III)



Difference in $\langle X_{\mathrm{max}} \rangle$ at 10^{19} eV still **well above** typical $\langle X_{\mathrm{max}} \rangle$ resolutions

[Klinkhamer, Niechciol & Risse 2017]

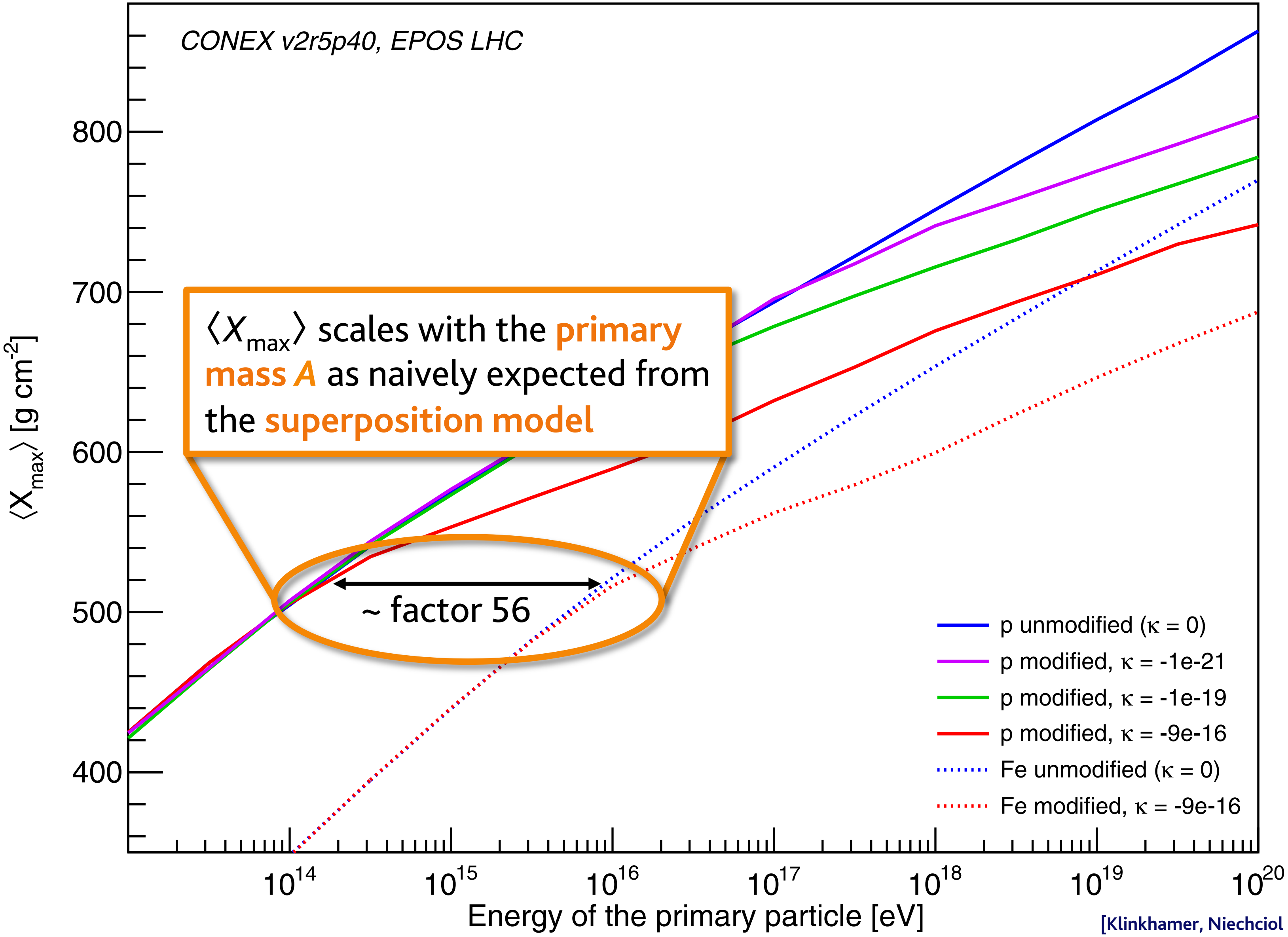
Hadron-induced showers: $\langle X_{\text{max}} \rangle$ (IV)



Elongation rate around 10^{19} eV reduced by about 25 g cm^{-2} per decade, independent of κ

[Klinkhamer, Niechciol & Risse 2017]

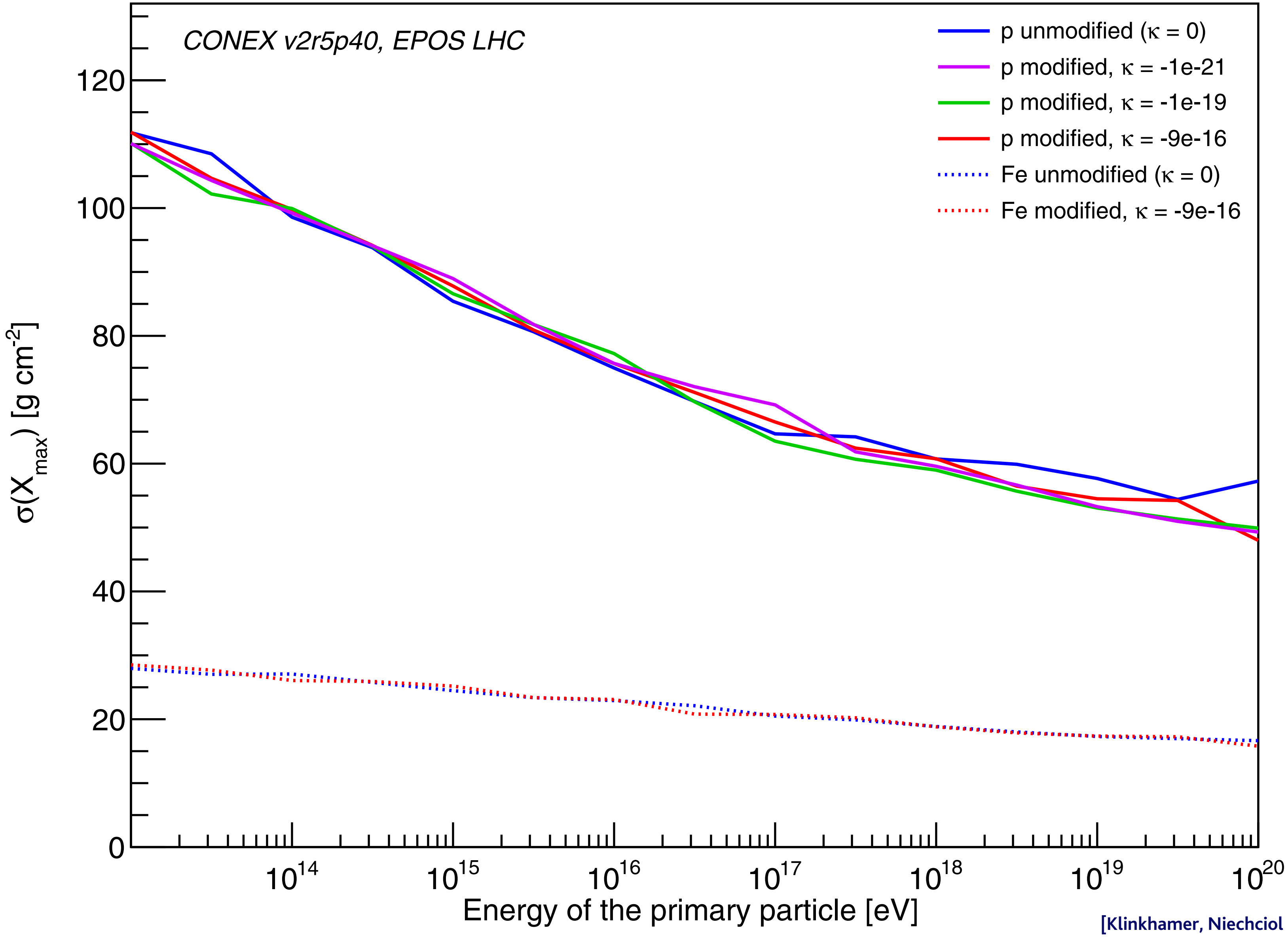
Hadron-induced showers: $\langle X_{\max} \rangle$ (V)



$\langle X_{\max} \rangle$ scales with the **primary mass *A*** as naively expected from the **superposition model**

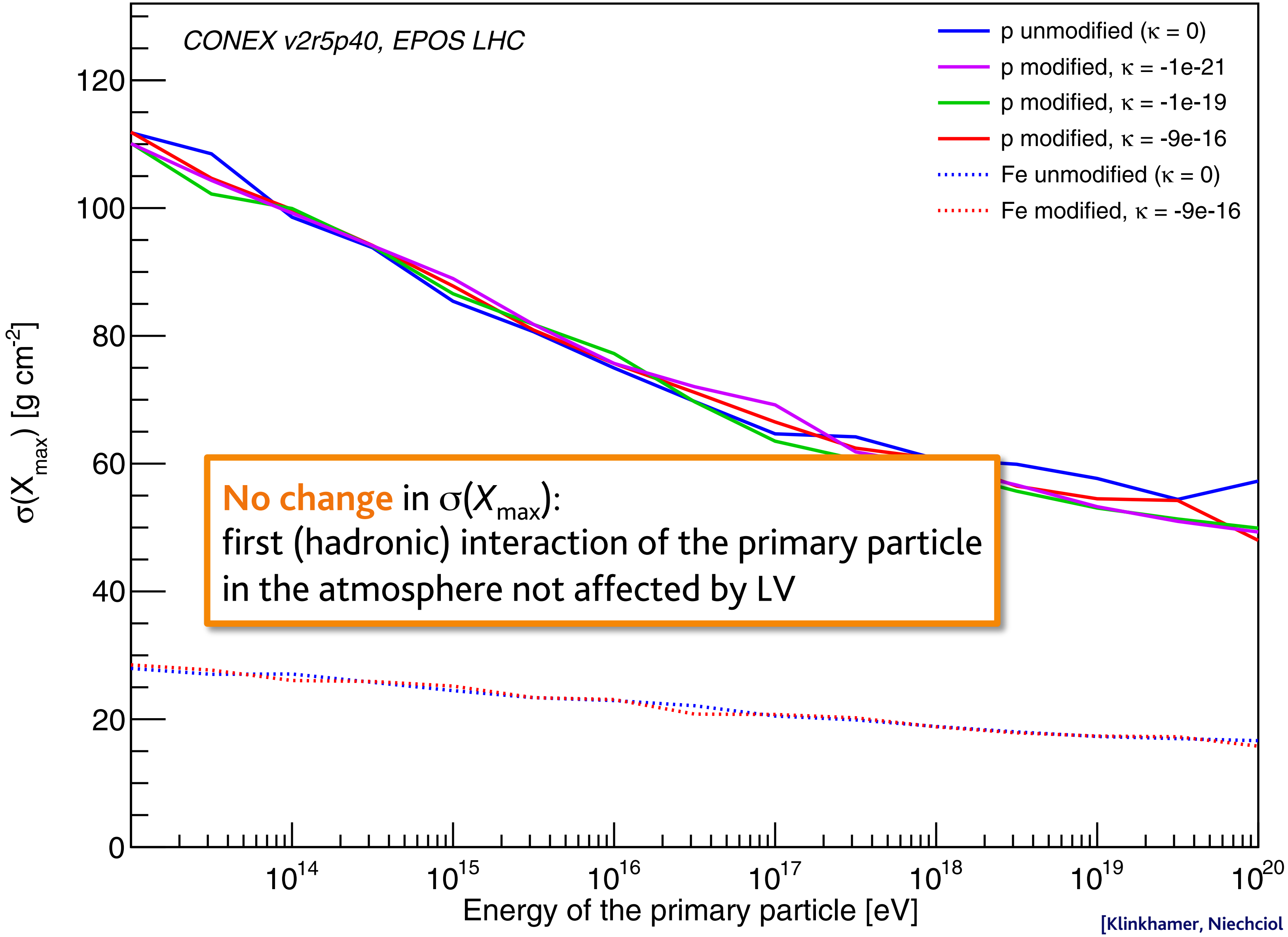
[Klinkhamer, Niechciol & Risse 2017]

Hadron-induced showers: $\sigma(X_{max})$ (I)



[Klinkhamer, Niechciol & Risse 2017]

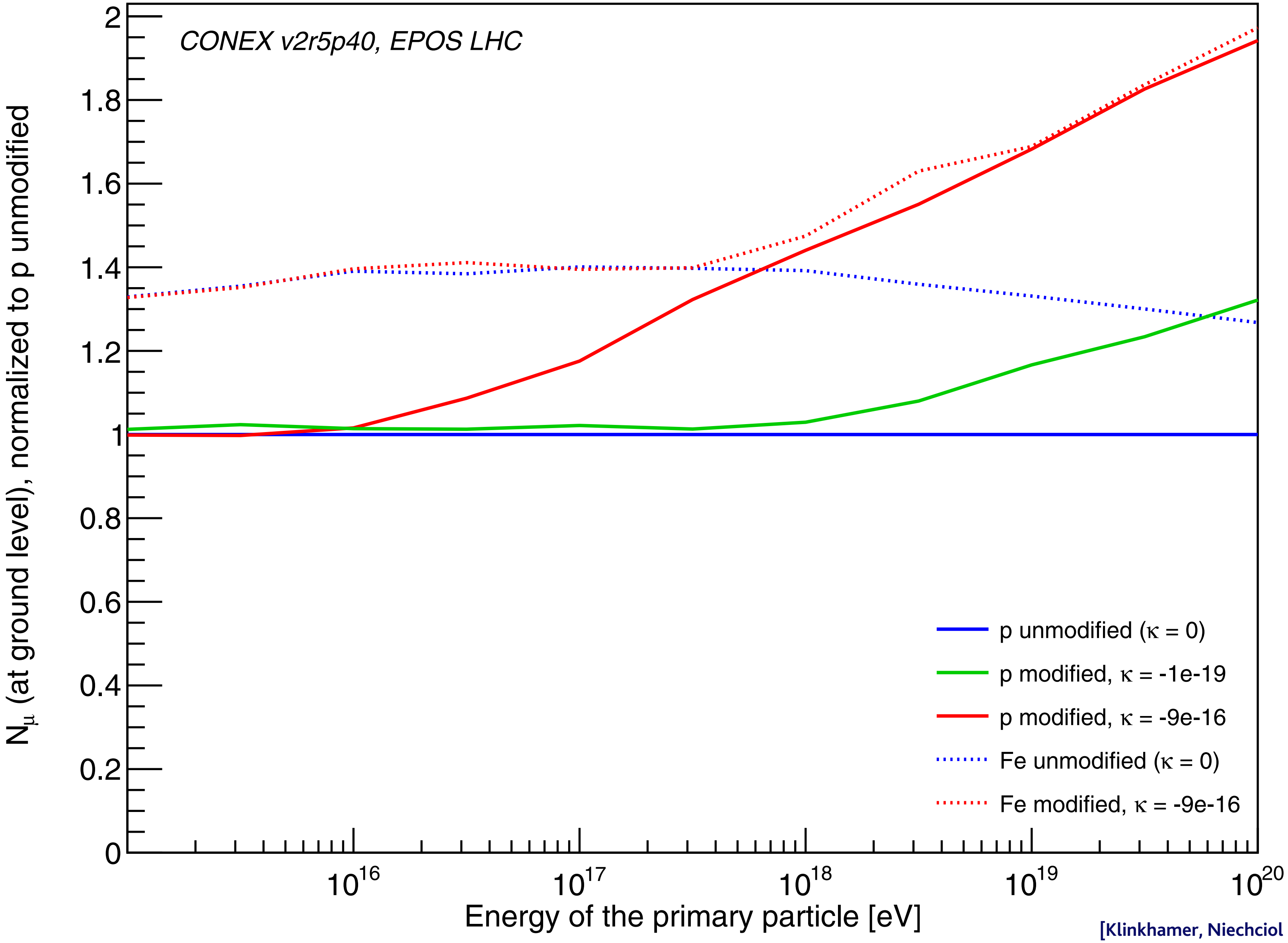
Hadron-induced showers: $\sigma(X_{max})$ (II)



No change in $\sigma(X_{max})$:
first (hadronic) interaction of the primary particle in the atmosphere not affected by LV

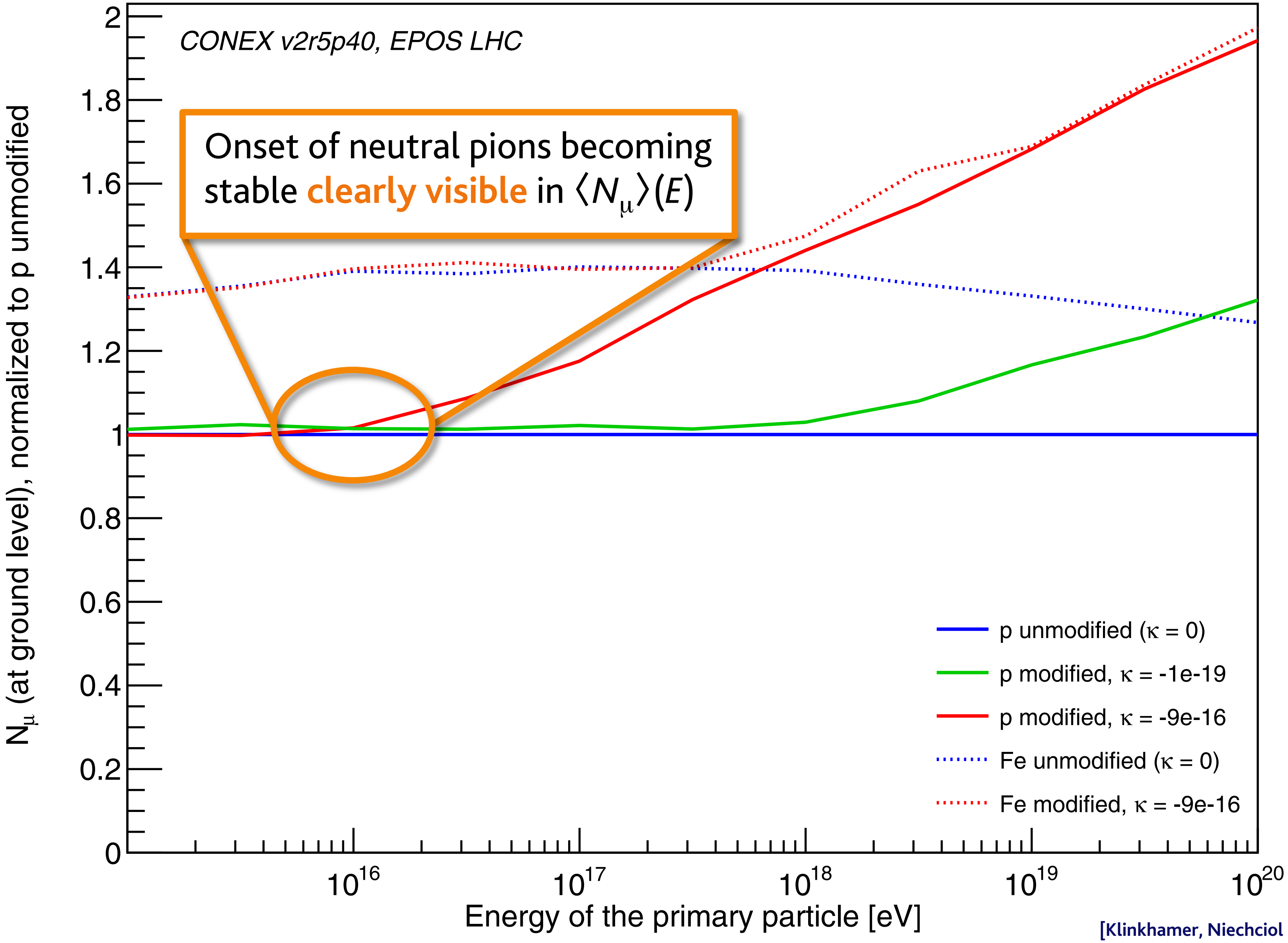
[Klinkhamer, Niechciol & Risse 2017]

Hadron-induced showers: $\langle N_\mu \rangle$ (I)



[Klinkhamer, Niechciol & Risse 2017]

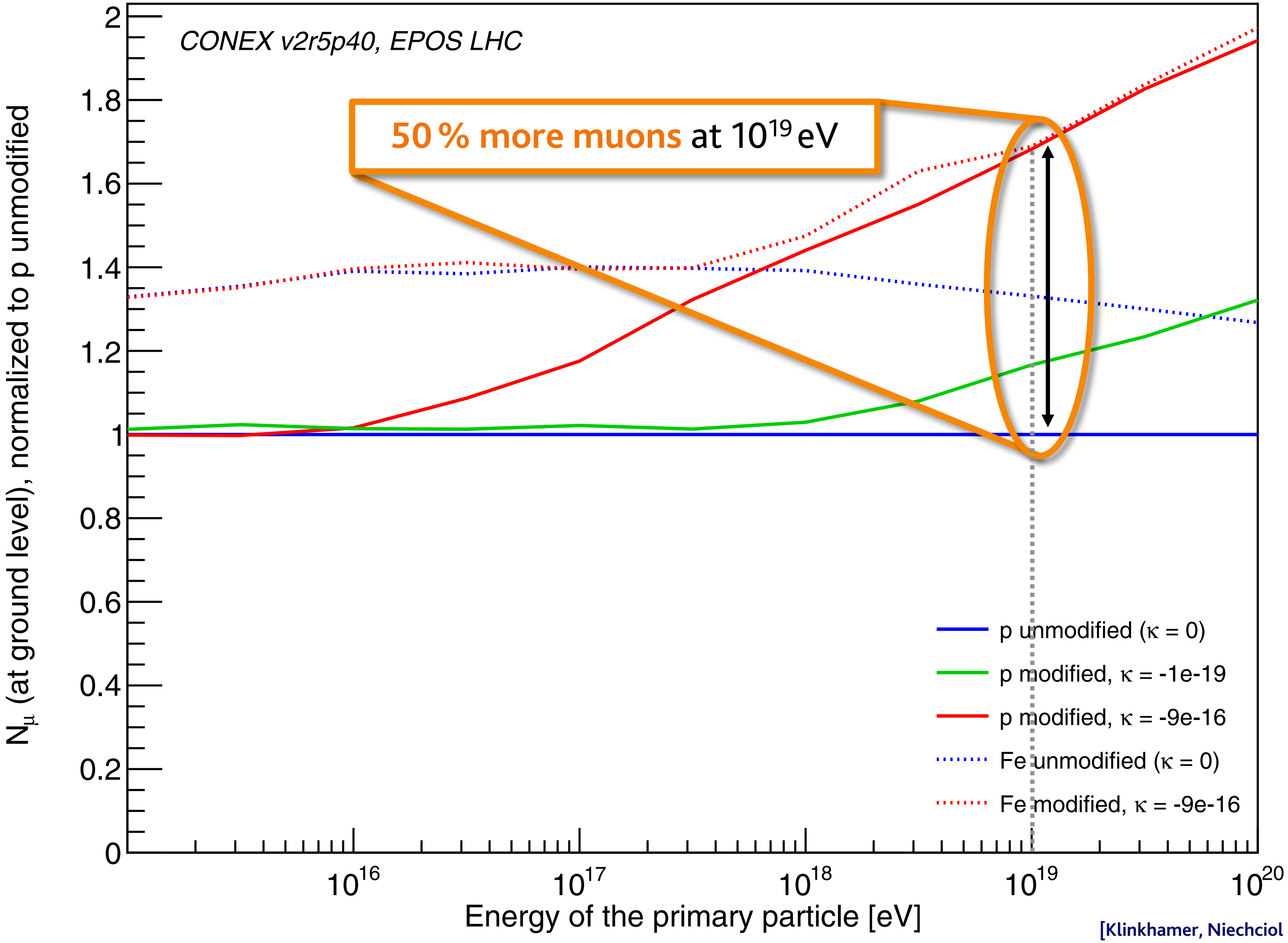
Hadron-induced showers: $\langle N_\mu \rangle$ (II)



Onset of neutral pions becoming stable **clearly visible** in $\langle N_\mu \rangle (E)$

[Klinkhamer, Niechciol & Risse 2017]

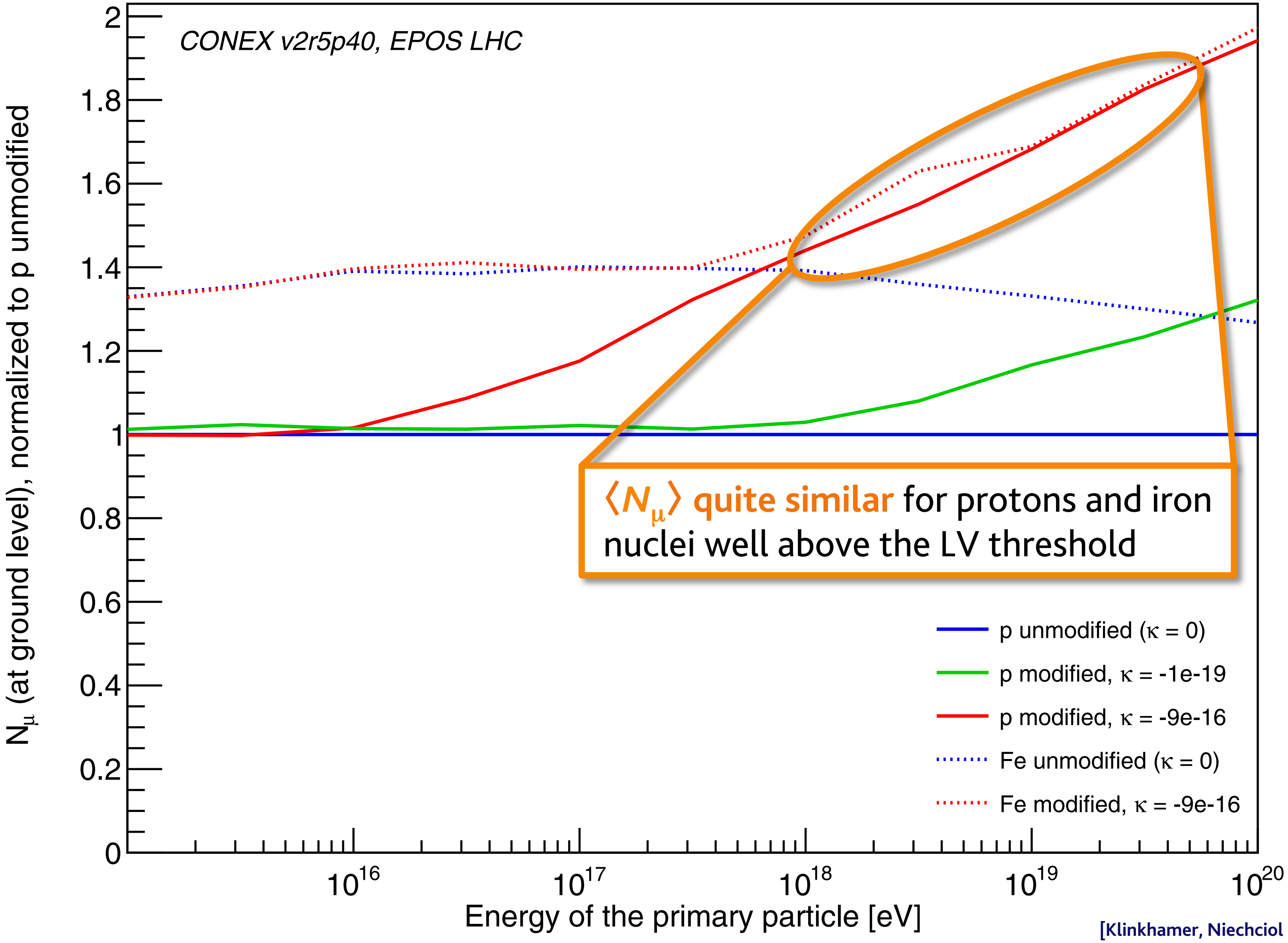
Hadron-induced showers: $\langle N_\mu \rangle$ (III)



50 % more muons at 10^{19} eV

[Klinkhamer, Niechciol & Risse 2017]

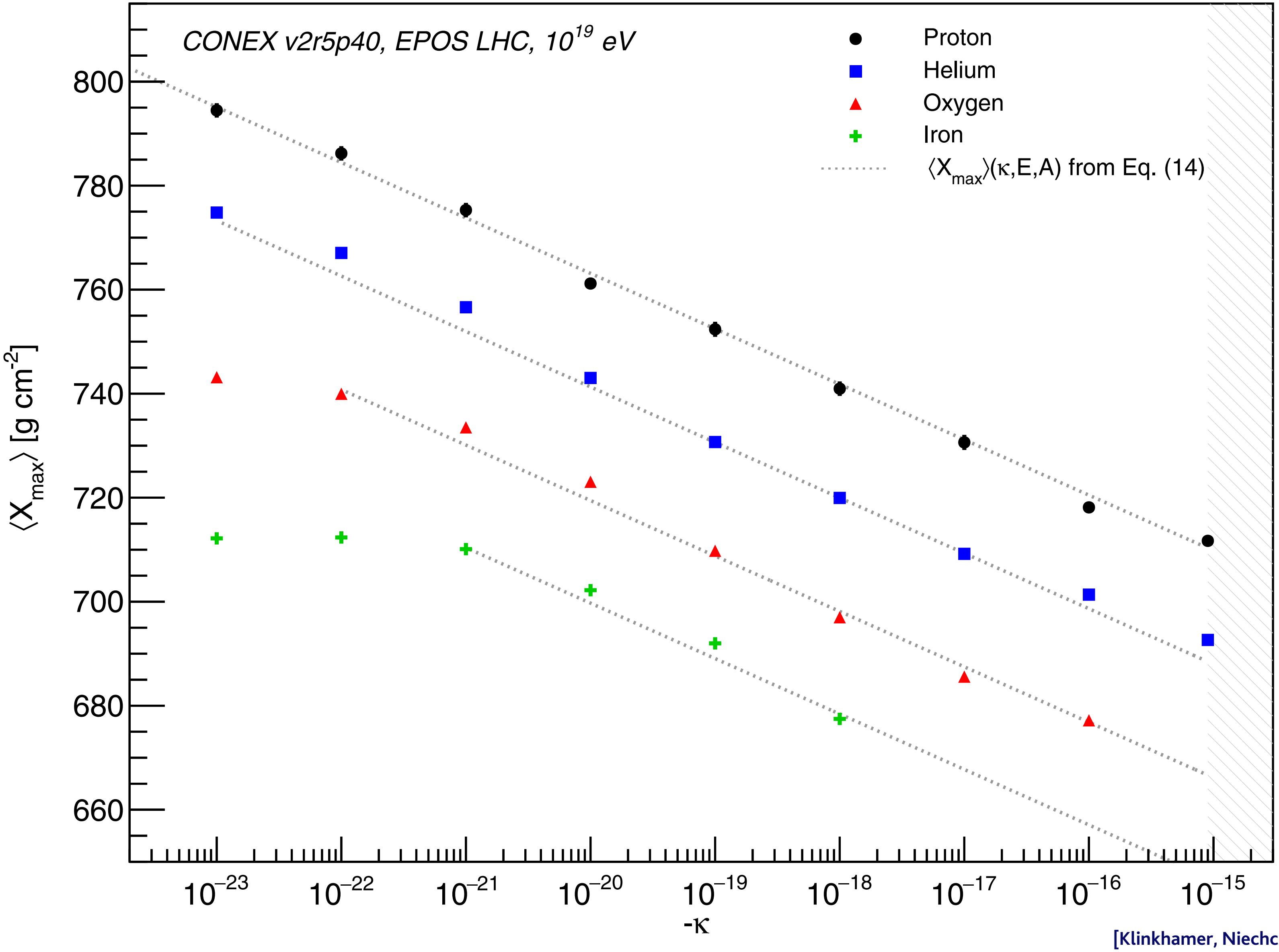
Hadron-induced showers: $\langle N_\mu \rangle$ (IV)



$\langle N_\mu \rangle$ **quite similar** for protons and iron nuclei well above the LV threshold

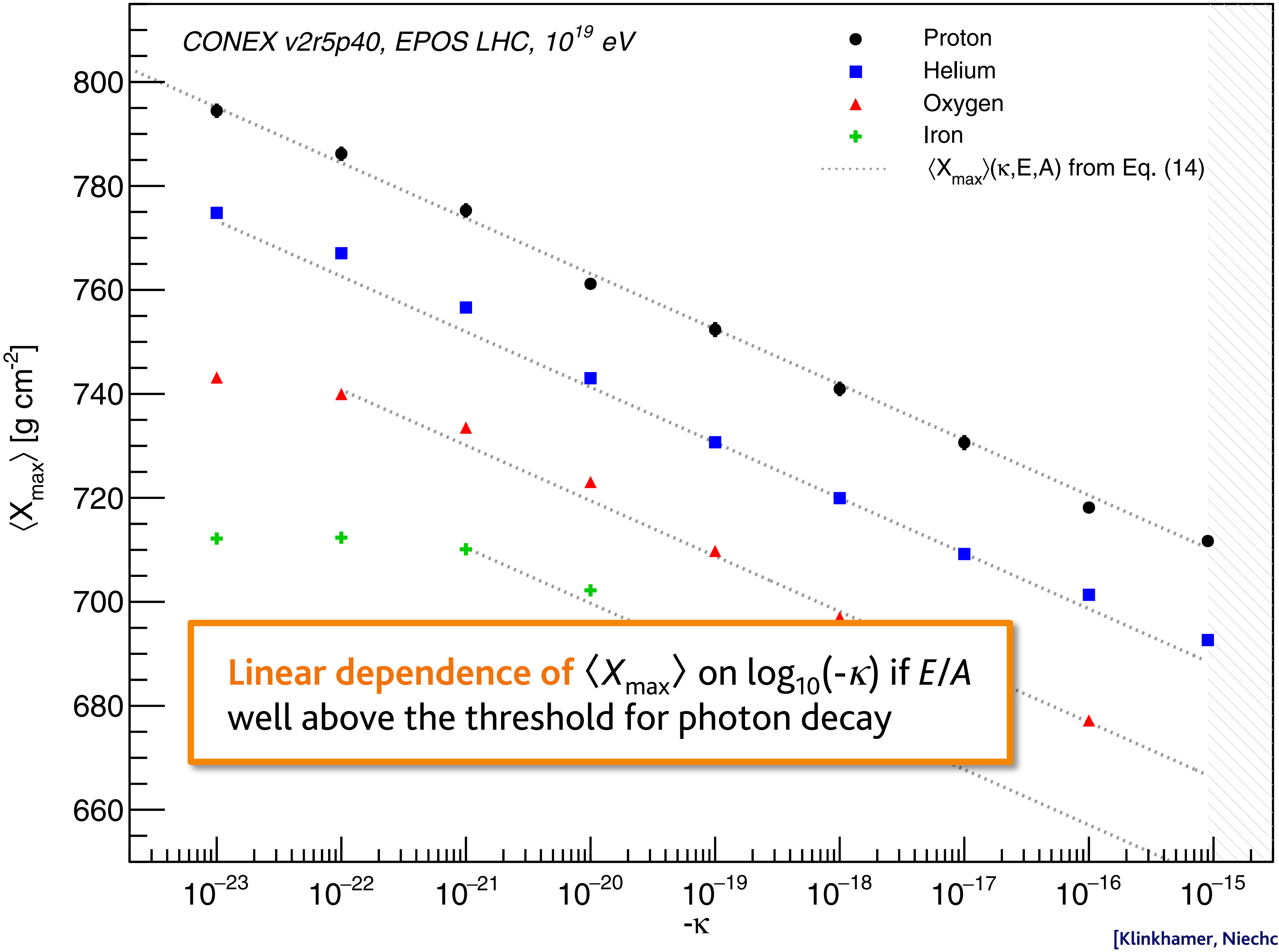
[Klinkhamer, Niechciol & Risse 2017]

$\langle X_{max} \rangle$-dependence on κ and A (I)



[Klinkhamer, Niechciol & Risse 2017]

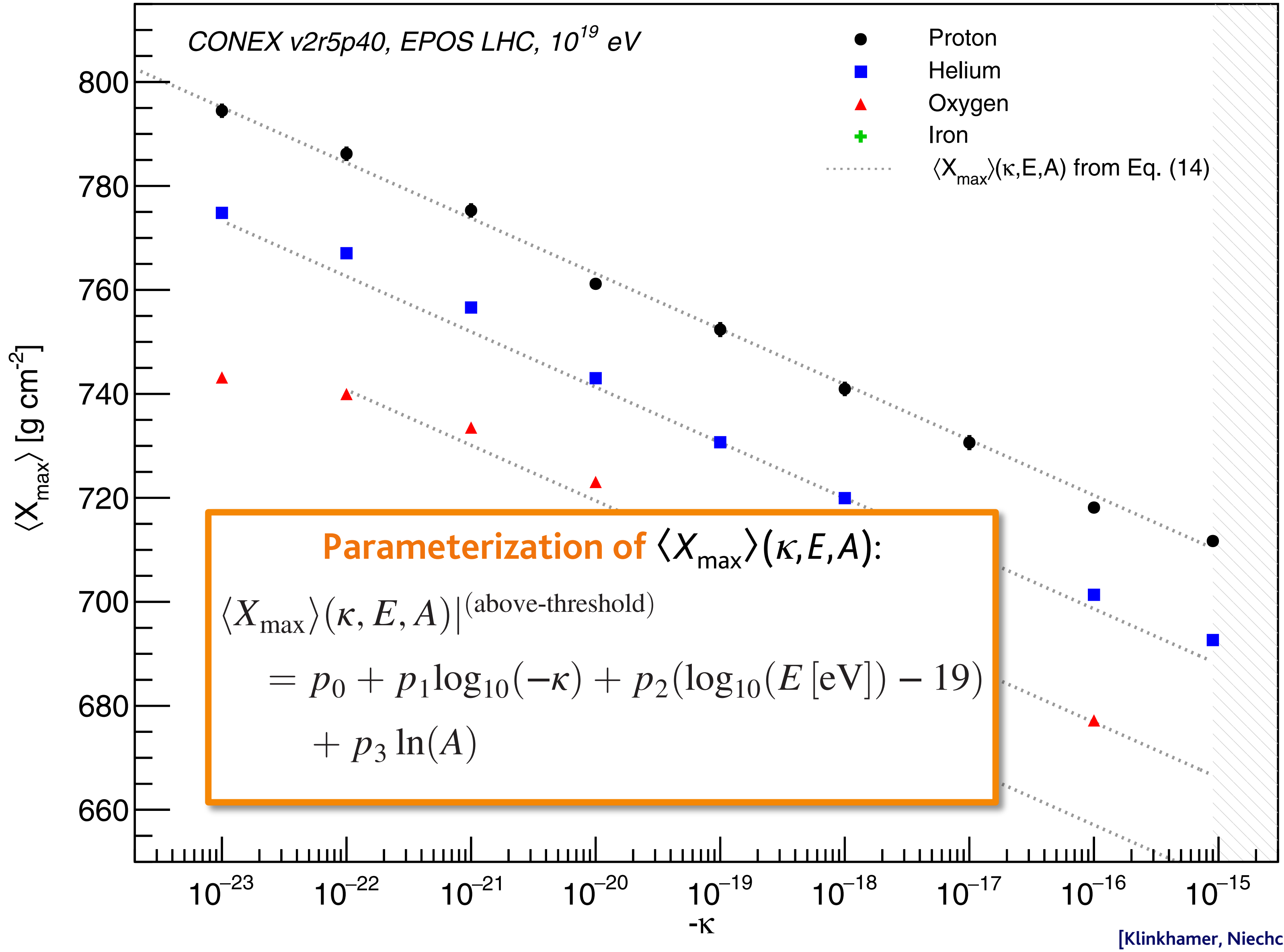
$\langle X_{max} \rangle$-dependence on κ and A (I)



Linear dependence of $\langle X_{max} \rangle$ on $\log_{10}(-\kappa)$ if E/A well above the threshold for photon decay

[Klinkhamer, Niechciol & Risse 2017]

$\langle X_{\max}\rangle$-dependence on κ and A (II)

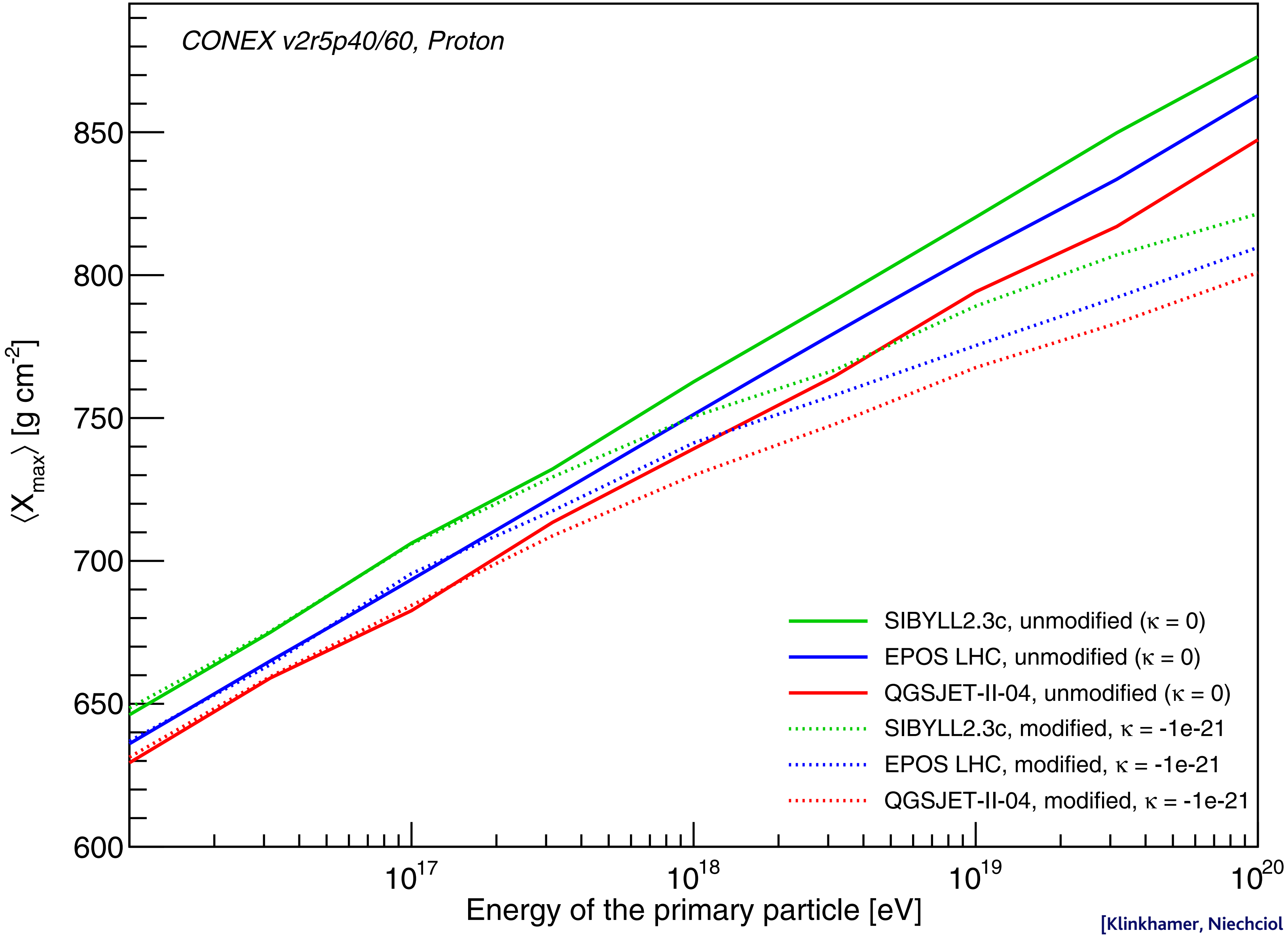


Parameterization of $\langle X_{\max}\rangle(\kappa,E,A)$:

$$\langle X_{\max}\rangle(\kappa,E,A)\big|^{\text{(above-threshold)}} = p_0 + p_1\log_{10}(-\kappa) + p_2(\log_{10}(E\,[\text{eV}]) - 19) + p_3\ln(A)$$

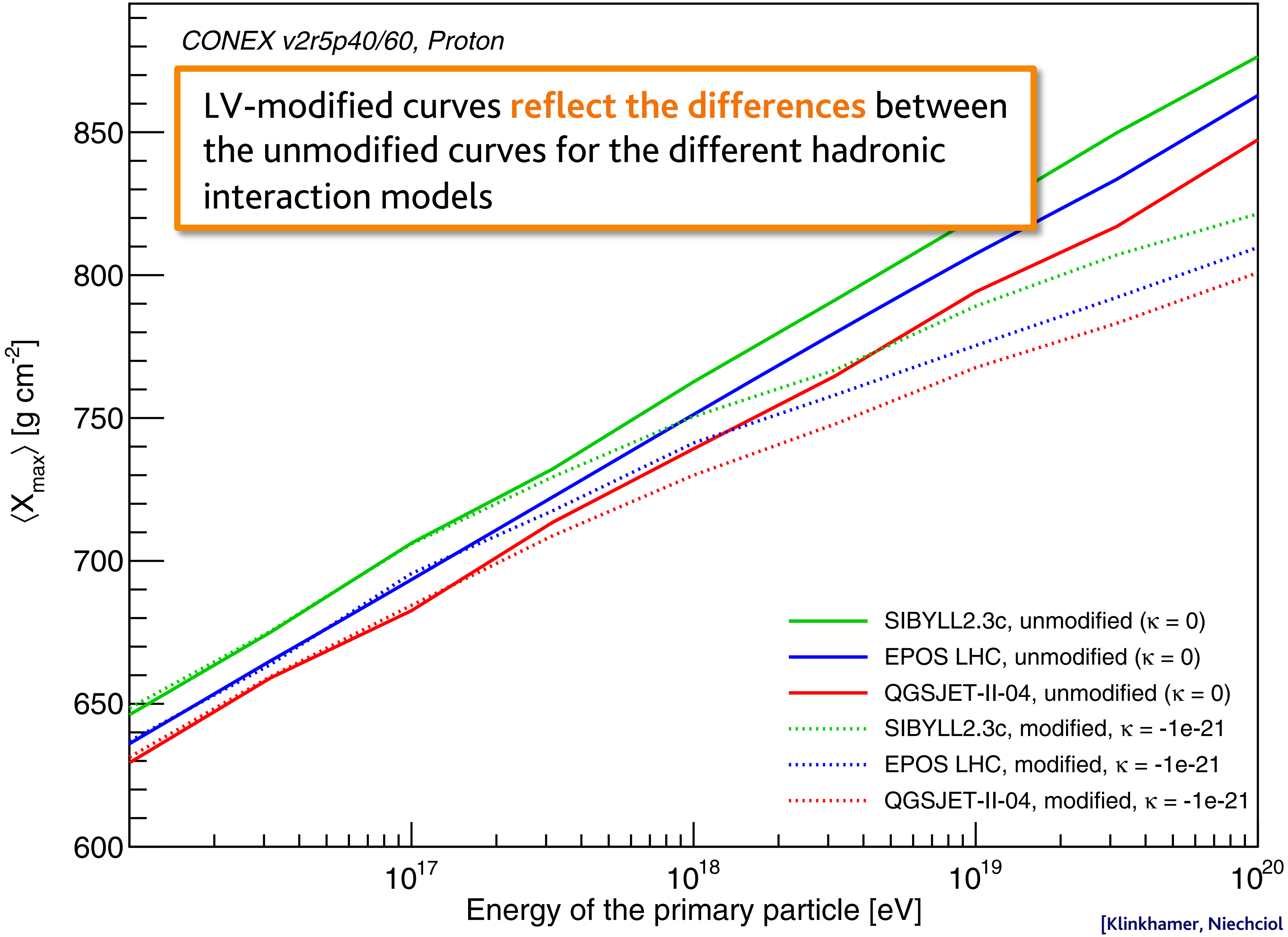
[Klinkhamer, Niechciol & Risse 2017]

Hadronic interaction models (I)



[Klinkhamer, Niechciol & Risse 2017]

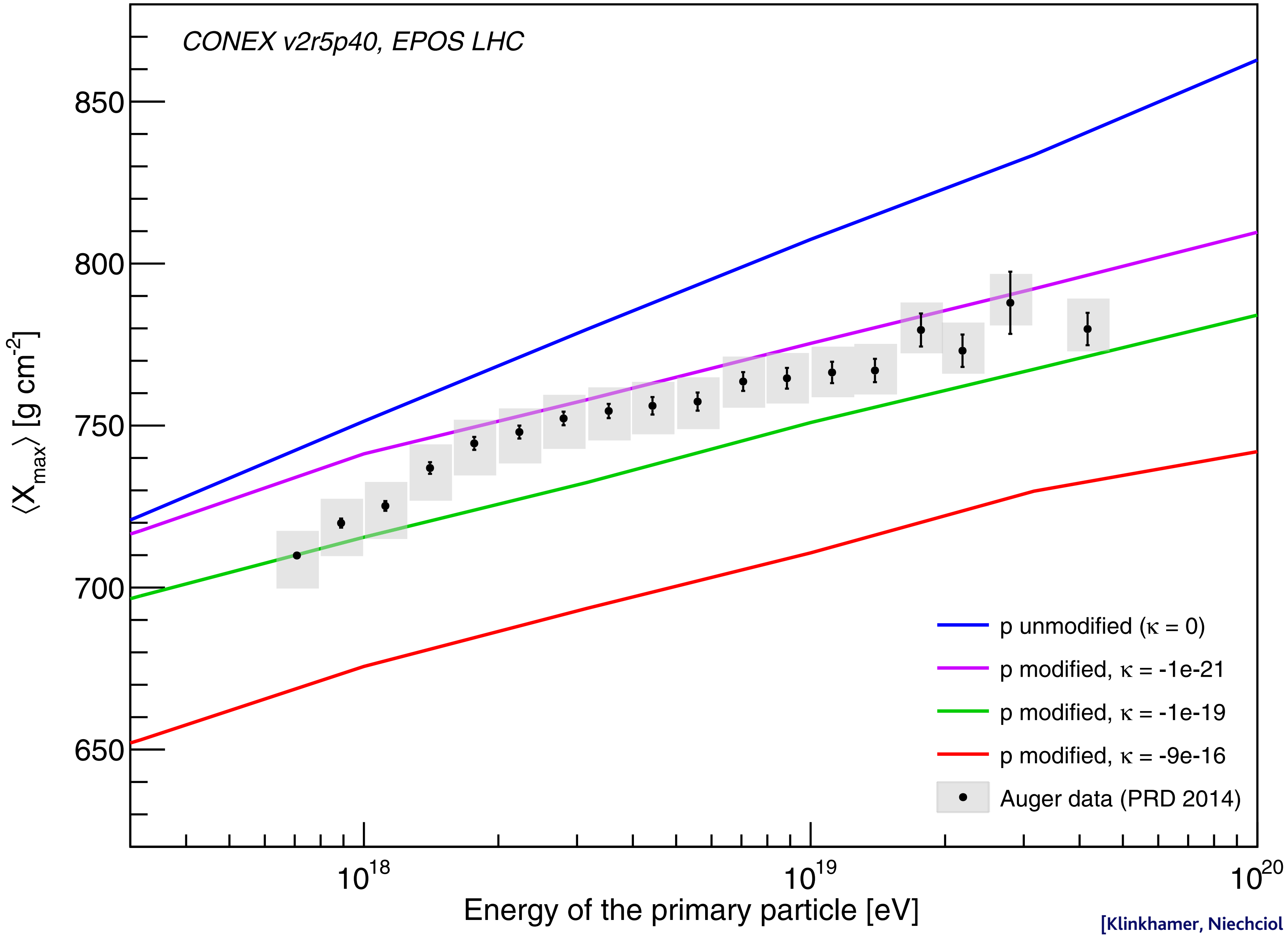
Hadronic interaction models (II)



LV-modified curves **reflect the differences** between the unmodified curves for the different hadronic interaction models

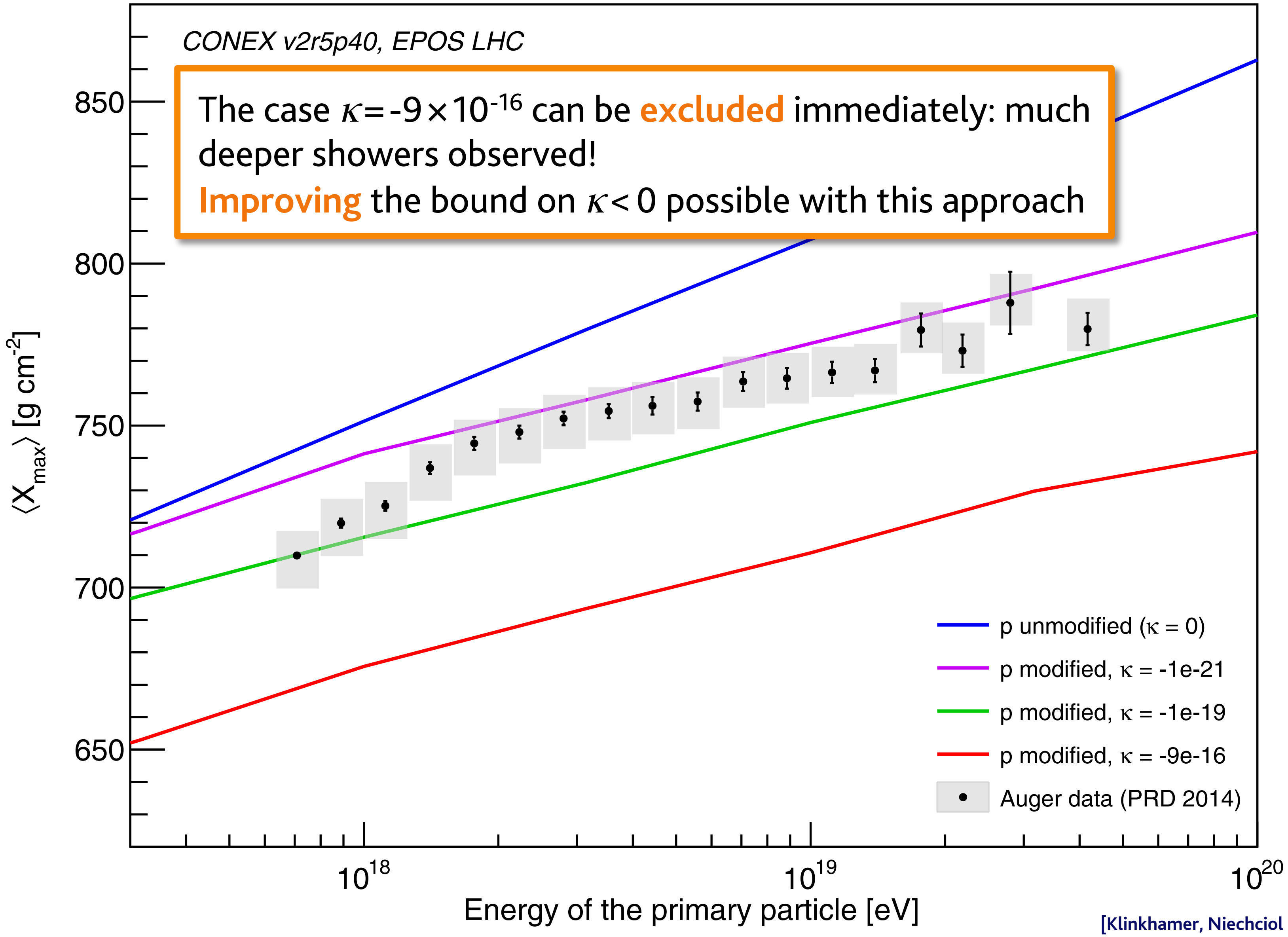
[Klinkhamer, Niechciol & Risse 2017]

Comparison to Auger $\langle X_{max} \rangle$ data (I)



[Klinkhamer, Niechciol & Risse 2017]

Comparison to Auger $\langle X_{\max} \rangle$ data (II)



The case $\kappa = -9 \times 10^{-16}$ can be **excluded** immediately: much deeper showers observed!

Improving the bound on $\kappa < 0$ possible with this approach

[Klinkhamer, Niechciol & Risse 2017]

New bound on $\kappa < 0$

- **Ingredients** to calculate an improved bound on $\kappa < 0$:
  - Focus on the energy bin around **2.8×10^{18} eV**
  - Conservatively assume a **pure proton composition**
  - Add a (conservative) systematic uncertainty of 20 g cm^{-2} due to the **choice of the hadronic interaction model** (here: EPOS LHC)

New bound: $\kappa > -3 \times 10^{-19}$ (at 98 % C.L.)

[Klinkhamer, Niechciol & Risse 2017]

- Improvement w.r.t. the previous bound: **factor ~3000**
  - To get the same improvement using the previous approach, the observation of a **primary photon with an energy of 2 PeV** would be needed
- New bound already entered the current version of the **Kostelecký/Russell compilation** of bounds on LV [Kostelecký & Russell 1997 (last update 2018)]

Future extensions of this approach

- **Further improvements** of the bound on $\kappa < 0$ are possible:
  - **Additional $\langle X_{\mathrm{max}} \rangle$ data**, e.g. from the AugerPrime upgrade of the Pierre Auger Observatory [Engel (Auger Collab.) ICRC 2015] [Auger Collab., arXiv:1604.03637]
  - **Reduced uncertainties** e.g. on the hadronic interaction models
  - Taking into account **composition constraints** (pure proton composition already excluded above 3×10^{18} eV) [Auger Collab. 2016]

- Extend the study to **additional shower observables**, e.g. $\sigma(X_{\mathrm{max}})$ or the correlation between X_{max} and the ground signal
  - NB: the latter observable would require full MC simulations (CORSIKA)

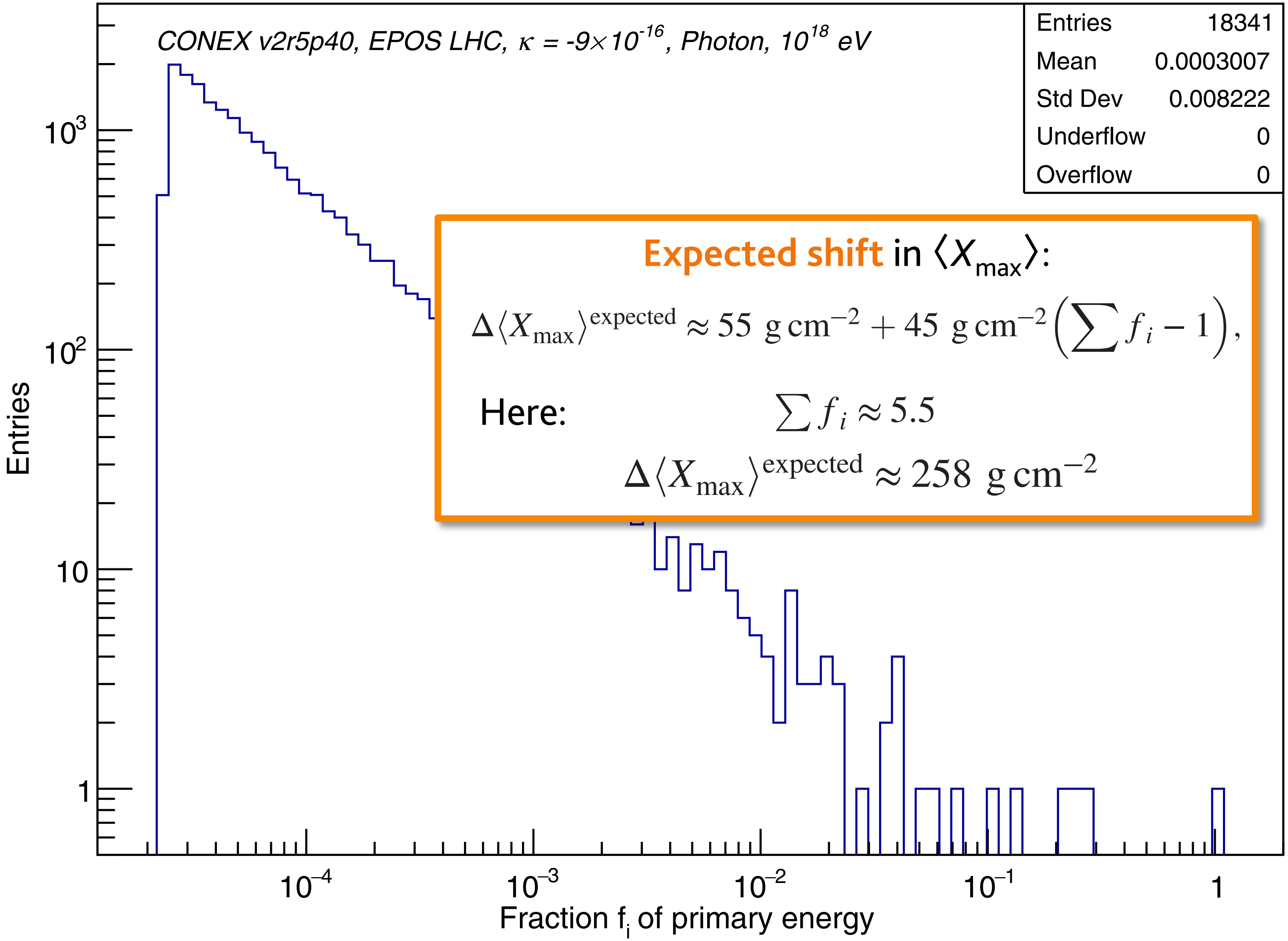
- Use a **similar approach** to explore the range **$\kappa > 0$**
  - Vacuum-Cherenkov emission from secondary electrons in the shower could lead to similar modifications of $\langle X_{\mathrm{max}} \rangle$

Summary

- Novel approach to test **isotropic, nonbirefringent LV in the photon sector** with greatly improved sensitivity
  - Approach is based on the **measurement of extensive air showers** induced by ultra-high-energy cosmic rays
- LV will lead to a **modification of $\langle X_{\mathrm{max}} \rangle$** well above the typical resolution of current experiments
  - Change is mainly due to the **decay of photons** above an energy threshold (in the case $\kappa < 0$)
- Using current $\langle X_{\mathrm{max}} \rangle$ data, an **improved bound on $\kappa < 0$** has been obtained
  - Improved existing bounds by a **factor ~3000**
- Possibility to **extend this approach** in the future to obtain even more stringent bounds

Backup

Expected shift in $\langle X_{\max}\rangle$



Expected shift in $\langle X_{\max}\rangle$:

$$\Delta\langle X_{\max}\rangle^{\text{expected}} \approx 55\ \text{g cm}^{-2} + 45\ \text{g cm}^{-2}\left(\sum f_i - 1\right),$$

Here: $\sum f_i \approx 5.5$

$$\Delta\langle X_{\max}\rangle^{\text{expected}} \approx 258\ \text{g cm}^{-2}$$

[Klinkhamer, Niechciol & Risse 2017]